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ASSESSMENT OF PRESENT STATE-OF-THE-ART SAWING TECHNOLOGY OF LARGE DIAMETER INGOTS FOR SOLAR SHEET MATERIAL

FINAL REPORT

FOR PERIOD COVERING

1 SEPTEMBER 1977 THROUGH 28 FEBRUARY 1978

BY

H. I. YOO

JPL CONTRACT NO. 954830

OPTICAL COATING LABORATORY, INC.
PHOTOELECTRONICS DIVISION
15251 EAST DON JULIAN ROAD
CITY OF INDUSTRY, CA 91746

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ABSTRACT

The objective of this program is to assess the present state-of-the-art sawing technology of large diameter silicon ingots (3" and 4" diameter) for solar sheet materials. During this program, work has progressed in: (1) Slicing of the ingots with the multiblade slurry (MBS) saw, the multiwire slurry (MWS) saw and the I.D. saw, (2) Characterization of the sliced wafers, and (3) Analysis of add-on slicing cost based on SAMICS.

Multiblade slurry slicing resulted in mechanical wafer yields of 95% for the 3" diameter ingot and 84% for the 4" diameter ingot (using a 230 blade package to cut 6" ingot in length). A slicing test with the I.D. saw was performed to obtain mechanical yield versus both wafer thickness and cut rate, and the result showed a good yield (above 95%) down to 7-8 mils of wafer thickness for the 3" wafers and 11-12 mils for the 4" wafers if the cut rates were reduced to one (1) inch per minute. An ingot of 3" in diameter and 3" in length was sliced with a multiwire slurry saw to obtain wafer yield of about 97%; 163 wires were used, and wafer thickness and kerf width were 10-11 mils and 8 mils, respectively.

Thickness, taper, bow, and roughness (RMS) were measured to characterize the sliced wafers. Four inch wafers sliced with the multiblade slurry saw showed larger thickness variation (wafer to wafer) and more taper than 3" wafers. Wafers sliced with the I.D. saw indicated that taper, bow and roughness increased as the cut rate increased (This effect was significant when cut rate was increased to above

three (3) inches per minute). Comparison of the above parameters showed the wafers cut with the I.D. saw (sliced below three (3) inch per minute of cut rate) and the multiwire slurry saw have much smaller values and variations than those cut with the multiblade slurry saw, indicating the need for less removal of silicon before solar cell formation. Also, the I.D. saw wafers showed slightly better characteristics in parameters than those of the multiwire slurry saw.

Add-on slicing cost was evaluated based on Solar Array Manufacturing Industry Costing Standard (SAMICS) for three slicing types: MBS saw indicated a cost of $.80/wafer for 3" wafers and $1.41/wafer for 4" wafers while MWS saw showed $.85/wafer for 3" wafers. I.D. saw sliced at two (2) IPM of cut rate gave $.17/wafer for 3" wafer and $.24/wafer for 4" wafers showing significant advantages over the other two methods at present.

ACKNOWLEDGEMENTS

The author wishes to acknowledge and express his appreciation to the numerous individuals who contributed to this report. At OCLI slicing experiments and significant information was provided by R. Schwartz and P. Iles assisted this program in various ways. Special thanks go to K. Evans, of JPL, who took SEM pictures for blade and wafer characterization.

D. Bickler, of JPL, is the Task Manager and L. Sanchez, of JPL, is the Technical Manager for this study. Their helpful guidance and input to the study are gratefully achnowledged.

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I. INTRODUCTION

Substrate preparation in sheet form is a first step in solar cell fabrication. Sheets for silicon solar cells are often prepared from ingots sliced by mechanical means. This slicing step results in loss of silicon (called kerf loss), and this loss adds considerably to the overall cost because already much expense has accrued in forming the ingots. A number of different techniques for slicing silicon have been tried and some have seen limited to production use. Methods tried include:

- Internal or outer diameter (I.D. or O.D.) wheel saw.
- Multiblade saw, using slurry, or diamond particles plated to the blade.
- Multiwire saw, using slurry, or diamond particles plated to the blade.
- Spark discharge with wires or blades.
- Pulsed laser discharge.
- Electro-chemical removal with current (etch-cutting)
- Ultra-high pressure (100,000 psi) water jet.

Among these techniques, the I.D. saw is the most extensively used in industry and is a well developed method for preparing large area sheets from silicon ingots for solar cells. Typical shortcomings of other techniques include excessive taper, unpredictable work damage, low mechanical yield, and lack of machine productivity (mainly because of slow cutting rate). The objective of this program is to assess the present state-of-the-art sawing technology of large diameter silicon ingots for solar sheet materials, with main emphasis on the I.D. saw. Slicing by multiblade slurry slicing and multiwire slurry is compared with I.D. slicing techniques.

During this contract, work has progressed in slicing of silicon ingots with multiblade slurry (MBS) saw, internal diameter (I.D.) saw, and multiwire slurry (MWS) saw. Three inch (3") and four inch (4") ingots were sliced with both MBS saw and I.D. saw, while only a 3" ingot was sliced with the MWS saw due to the limitation of the machine used. Mechanical properties of the sliced wafers, such as thickness variation, bow, taper and surface roughness, are identified and the blades (or wires) used in the test examined using characterization techniques (such as SEM pictures, sectioning and potting techniques, etc.). Finally, add-on slicing cost was evaluated based on Solar Array Manufacturing Industry Costing Standards (SAMICS).

II. TECHNICAL DISCUSSION

1.0 SLICING EXPERIMENTS

1.1 Multiblade Slurry (MBS) Saw Slicing

Slicing experiments were conducted using a Norton 686 wafering machine (same as Varian 686). A pre-assembled blade package from Varian was loaded in the blade head and aligned and tensioned (difficulty in alignment and tensioning, especially in tensioning, forced OCLI to cease using pin type blade packages which are cheaper than pre-assembled blade packages). The blade packages with 230 blades (blade thickness 8 mils, spacer thickness 18 mils and blade depth 1/4") were used to slice 6" ingot length for both 3" and 4" diameter ingots. The slurry was a mixture of 12 lbs. of 400 grit SiC and 1.8 gallons of P.C. oil. The load on the ingot per blade was about 100 grams and a stroke length of 6 3/4" and a stroke rate of 100 cycles/minute were used in this experiment.

The total slicing time was 10 hours for the 3" ingot and 20.5 hours for the 4" ingot, and mechanical yields (the fraction of unbroken slices) were 95% and 84% for the 3" and 4" diameter ingot, respectively. The detailed slicing conditions and their results are given in Table II-1.

TABLE II-1

MBS SAW SLICING CONDITIONS

INGOT DIAMETER, CM (INCH)	7.62 (3")	10.16 (4")
BLADE PACKAGE		
Number of Blades	230	230
Spacer Thickness, mm (mils)	0.457 (18)	0.457 (18)
Blade Thickness, mm (mils)	0.203 (8)	0.203 (8)
Blade Width, mm (inch)	6.35 (1/4)	6.35 (1/4)
SLURRY		
Abrasive (400, SiC), Kg (lb)	5.4 (12)	5.4 (12)
Suspension Oil (P.C. Oil), liter (gallon)	6.8 (1.8)	6.8 (1.8)
Mix, Kg/liter (lb/gallon)	0.79 (6.7)	0.79 (6.7)
Load on Blade, gram/blade	100	90
Blade Speed, cm/sec.	57	57
Wear Ratio	---	0.048
PRODUCTIVITY (WAFER)		
cm^2/Machine/Hour	1,005	771
cm^2/Blade/Hour	4.33	3.32
Yield, %	95	85
Yielded Wafer Area, m^2	1.0	1.58
Ingot Length, cm (inch)	15.24 (6)	15.24 (6)

1.2 Multiwire Slurry (MWS) Saw Slicing

A slicing experiment was performed by Yasunaga Engineer Co., Ltd., using their YQ-100 wafering machine. The following information on slicing was furnished by the company.

A 3" diameter ingot 3" in length was mounted on a ceramic block with epoxy adhesive as in (a) of Figure II-1. (Note: Limitation of the machine prohibited slicing 4" diameter ingot or longer ingot.) With this mounting configuration, the wire started to cut the ingot and the mounting block at the time when wire reaches position A-A. As a consequence the initial slicing conditions change and the cutting speed decreases drastically. If the surface of the ceramic block is uneven, the wire often slips out of the position, causing saw marks on the surface of the wafers (graphite may be a better material for this purpose). However, there is less trouble if the ingot has a flat side and in (b) of Figure II-1. In this case, the ingot is sliced first and the mounting block afterward. A piece of glass was a suitable mounting material and gave lesser trouble than other materials.

Diameter of the wire was 0.16 mm (6.3 mils) and number of wires under cutting was 163. Slurry was a mixture of 5 Kg of 16 μm alumina powder and 3 Kg of lapping oil. Total slicing time was 8:35 hours and a mechanical wafer yield of 97% was obtained. Detailed slicing conditions are given in Table II-2.

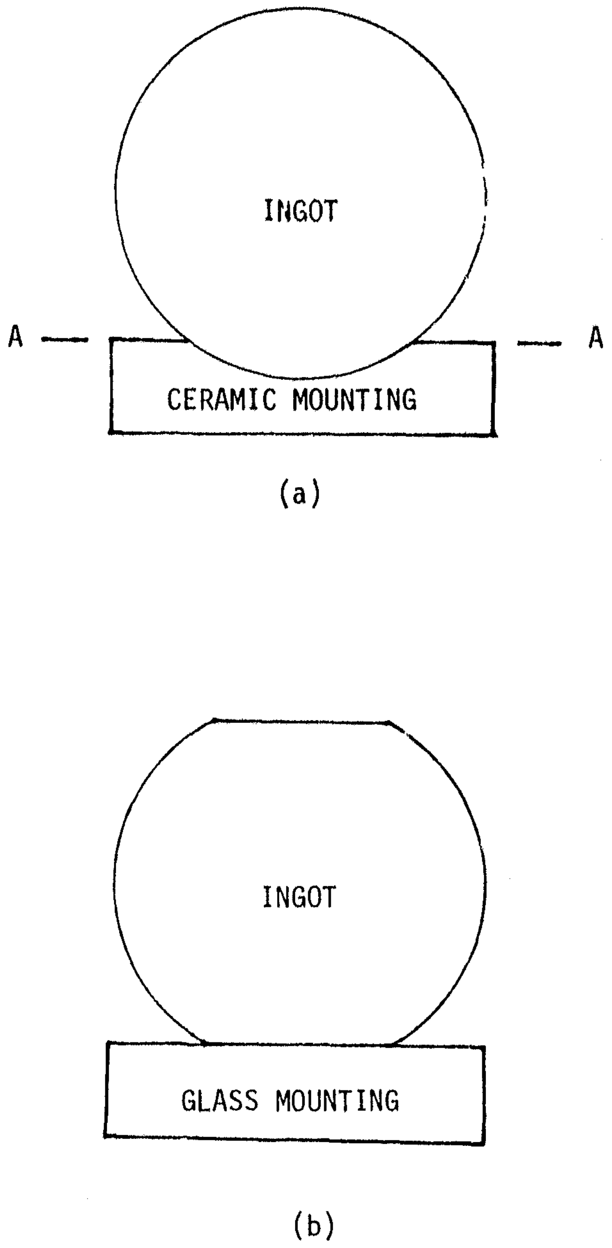


FIGURE II-1 - INGOT MOUNTING FOR MULTIWIRE SLURRY SAW SLICING
(a) ON CERAMIC
(b) ON GLASS

TABLE II-2

MWS SAW SLICING CONDITIONS

INGOT	
Diameter, cm (inch)	7.62 (3)
Length, cm (inch)	7.62 (3)
WIRE	
Roller Pitch, mm (mils)	0.47 (18.5)
Diameter of Wire, mm (mils)	0.16 (6.3)
Number of Wires Under Cutting	163
Mean Unit Weight, g/cm/wire	13
Total Wire Tension, Kg	1.7
Breaking Point of Wire, Kg	5.7
Wire Feed Rate, m/min.	8
Reciprocation of Wire, cycle/min.	65
Wears of Wire, μm	12
SLURRY	
Abrasive, GC #1000 (16μm), Kg	5
Lapping Oil, P.C. Oil, Kg	3
Wafer Thickness, mm (mils)	0.27 (10.6)
Kerf Width, mm (mils)	0.20 (7.9)
Slicing Time, hours	8:35
Mechanical Yield, %	97
Yielded Wafer Area, m^2	0.72
Productivity, cm^2/machine/hour	840

1.3 Internal Diameter (I.D.) Saw Slicing

Slicing experiments were carried out using wafering machines from Silicon Technology Corporation: Model STC-16 was used for slicing 3" ingots and Model STC-22 for 4" ingots. I.D. of a blade for STC-16 was 6" and the thickness of a diamond plated edge and core (stainless steel) of the standard blade were about 11-12 mils and 4 mils, respectively. The I.D. of a standard blade for STC-22 was 8" and the thickness of diamond edge and core were about 13-14 mils and 6 mils, respectively.

1.3.1 Wafer Yield Versus Wafer Thickness and Cut Rate

Mechanical wafer yield versus wafer thickness at two cut rates, one (1) IPM and two (2) IPM, were obtained using standard blades and a normal mode of slicing operation (described in the First Quarterly Report(1)) for both 3" and 4" ingots. The results showed good mechanical yields (above 95%) down to 7-8 mils of wafer thickness for the 3" wafers and 11-12 mils for the 4" wafers if the cut rates reduced to one (1) IPM. The slicing conditions are given in Table II-3, and the plots of mechanical yields versus wafer thickness and cut rate are given in Figure II-2 for the 3" wafer and Figure II-3 for the 4" wafer.

Difficulties in slicing thin wafers, less than 7 mils 3" wafers for example, were experienced due to the mechanical instability of a I.D. blade. At constant cut rates the stress on the blades is greatest at the beginning and end of the cut, causing flutter and surface damage(2). Programmed cut rates are designed to reduce

TABLE II-3

I.D. SAW SLICING CONDITIONS

INGOT SIZE, CM (INCH)	7.62 (3")		10.16 (4")	
Machine	STC-16		STC-22	
BLADE				
I.D., cm (inch)	15.24 (6)		20.32 (8)	
O.D., cm (inch)	42.23 (16-5/8)		55.88 (22)	
Core Thickness, mm (mils)	0.10 (4)		0.15 (6)	
Diamond Thickness, mm (mils)	0.28∿0.30 (11-12)		0.33∿0.36 (13-14)	
Blade Rotation, R.P.M.	2,100		1,650	
Blade Return Speed, cm/min (inch/min)	38.1 (15)		38.1 (15)	
Blade Stroke, cm (inch)	8.13 (3.2)		10.67 (4.2)	
Blade Dressing, After Number of Slices	50		25	
COOLANT				
Flow Rate, cc/min	120		140	
Mix Ratio, Water: Rust-Lick	80:1		80:1	
Cut Rate, Inch/Minute	1	2	1	2
Slicing Cycle, Minute/Wafer	3.4	1.8	4.5	2.4
Productivity (Wafer), cm^2/Machine/Hour	800	1,510	1,090	2,040

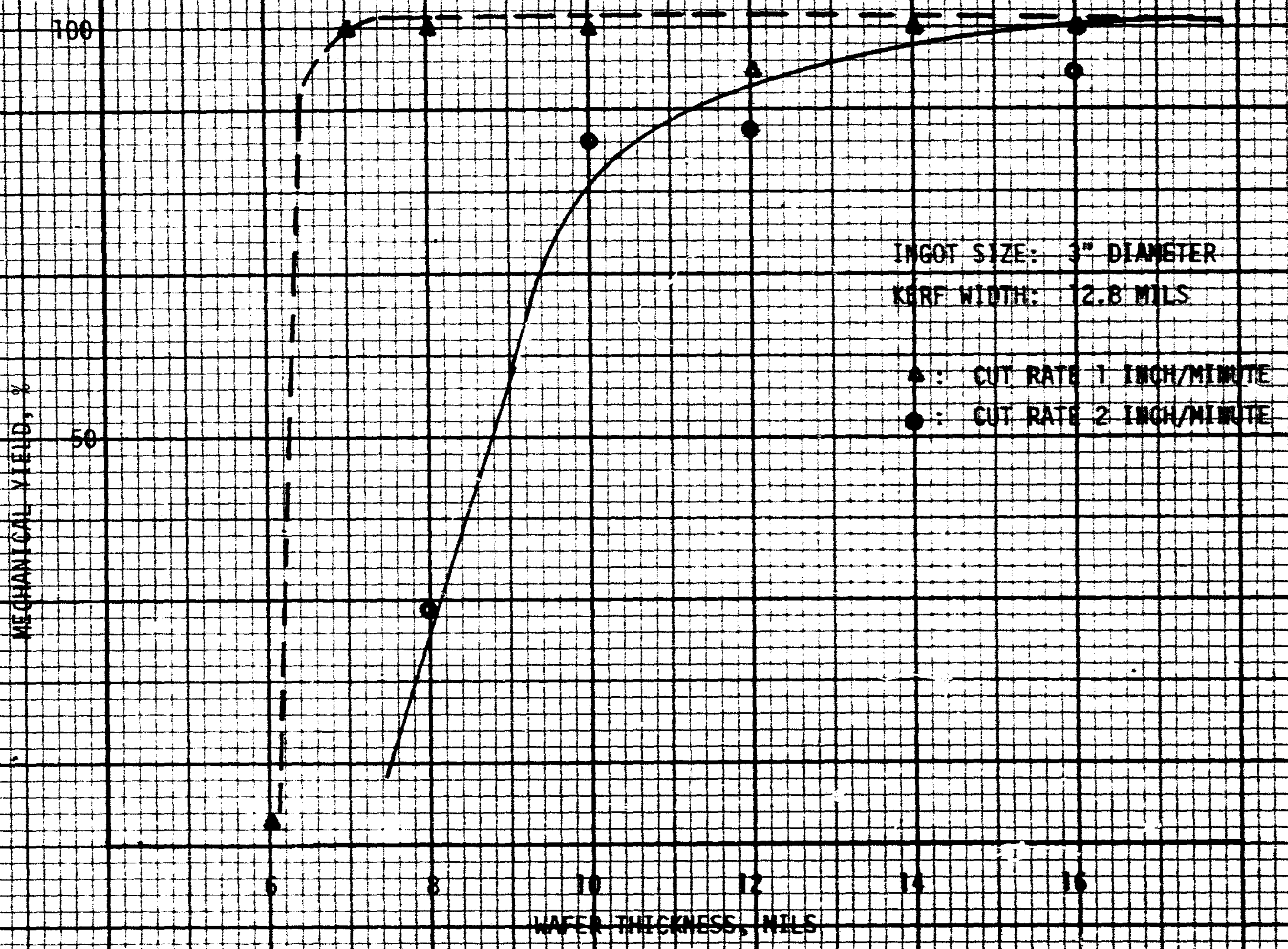


FIGURE II-2 - MECHANICAL YIELD VERSUS WAFER THICKNESS AND CUT RATE OF I.D. SAW; 3" WAFERS

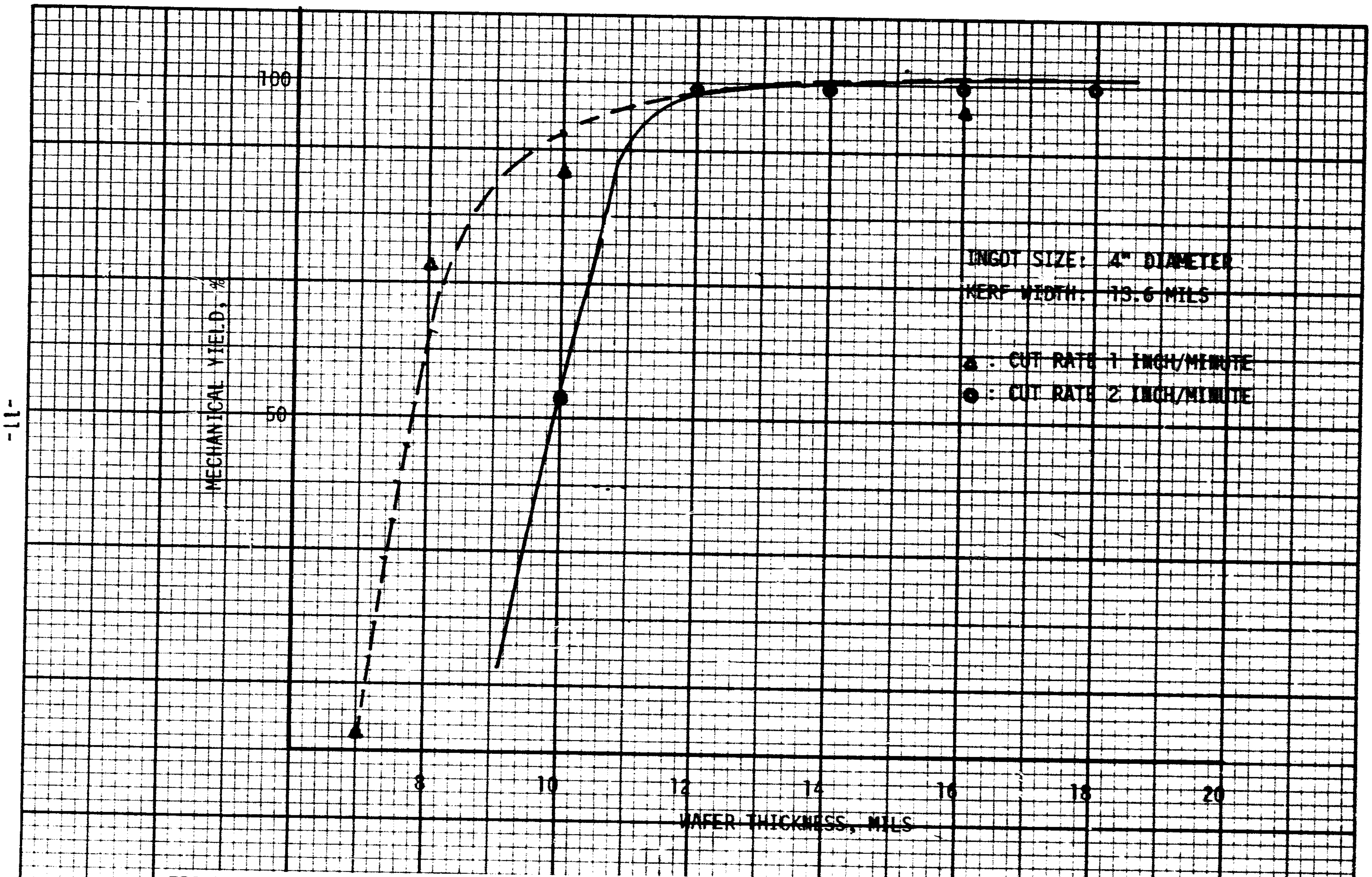
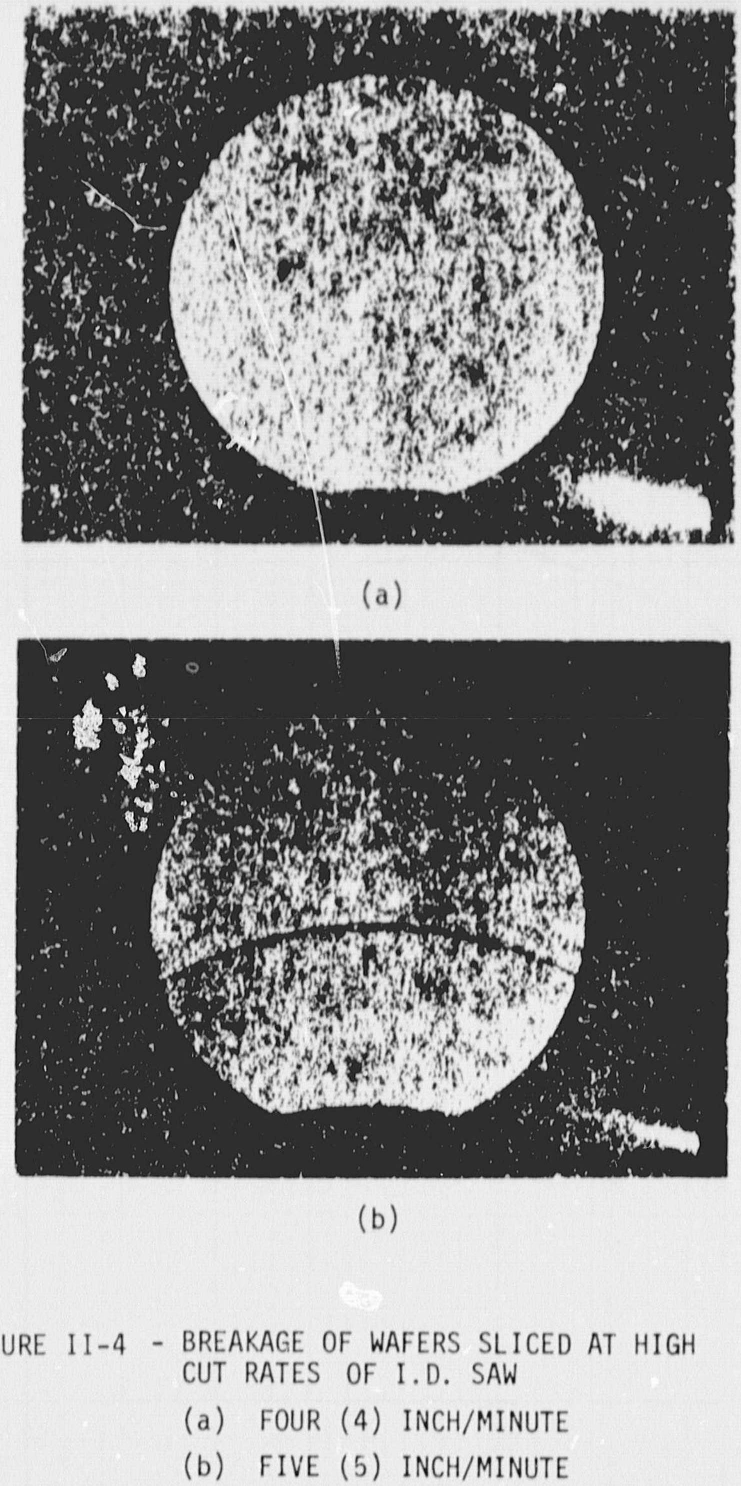


FIGURE II-3 - MECHANICAL YIELD VERSUS WAFER THICKNESS AND CUT RATE OF I.D. SAW: 4" WAFERS damage by maintaining constant pressure throughout the cut, resulting in more uniform surface quality and longer blade life. Experiments were performed to control cut rates manually; initially one quarter of the wafer was sliced by (approximate) linearly increasing the cut rate from 0.1 to 1.3 IPM. The middle half of the wafer was cut at constant rate (∿ 1.3 IPM) and the last quarter of the wafer was sliced with decreasing cut rate. Average cut rate was approximately one (1) IPM and a wafer thickness of about 5 mils was obtained experimentally. This result might not give any impact on reduction of wafer cost due to difficulties associated with the handling of thin wafers. However, this experiment indicates a possibility of significant improvement in wafer yields and less surface damage with uniform distribuiton.

To see the effect of cut rate on mechanical yield and wafer parameters, a cut rate of up to five (5) IPM was applied to slice 3" wafers of 12 mils thickness. From the sample size of 10 wafers, 100% wafer yield was obtained below three (3) IPM of cut rate and breakage of wafer started at three (3) IPM. At five (5) IPM of cut rate all the wafers were broken (mostly by the last cutting edge of the wafer), often showing step changes in thickness of the wafer. Figure II-4 gives a picture of broken wafers sliced at high cut rates, (a) four (4) IPM, (b) five(5) IPM, and a middle arc in (b) indicates a step change in wafer thickness. Mechanical wafer yield versus cut rate (up to 5 IPM of cut rate) is plotted in Figure II-5.



(a)

(b)

FIGURE II-4 - BREAKAGE OF WAFERS SLICED AT HIGH CUT RATES OF I.D. SAW

(a) FOUR (4) INCH/MINUTE

(b) FIVE (5) INCH/MINUTE

SLICING DIRECTION IS FROM TOP TO BOTTOM AND STEP CHANGE IN THICKNESS IS SHOWN IN (b)

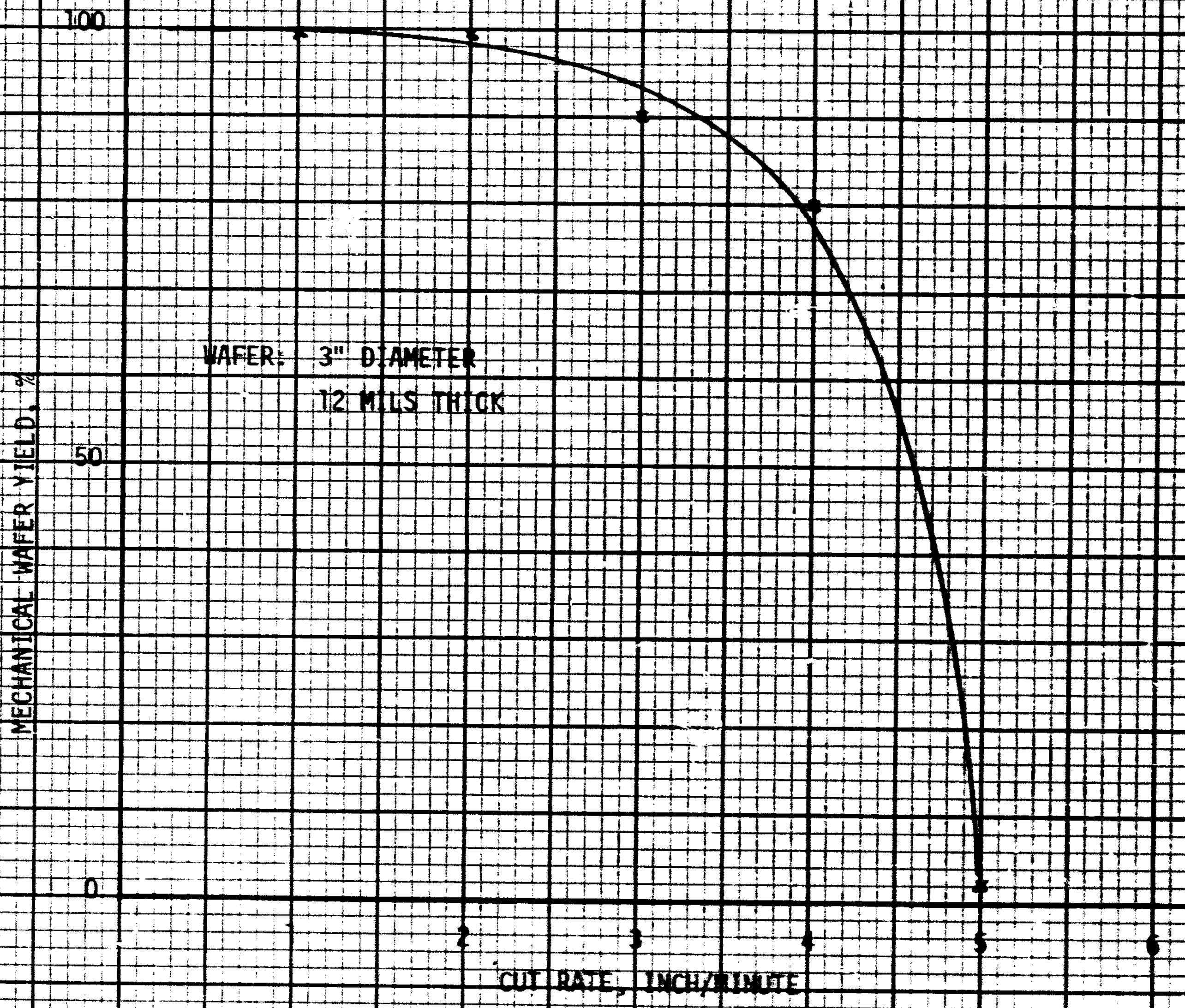


FIGURE II-5 - MECHANICAL WAFER YIELD VERSUS CUT RATE OF I.D. SAW (STANDARD BLADE)

1.3.2 Thin Blade Slicing

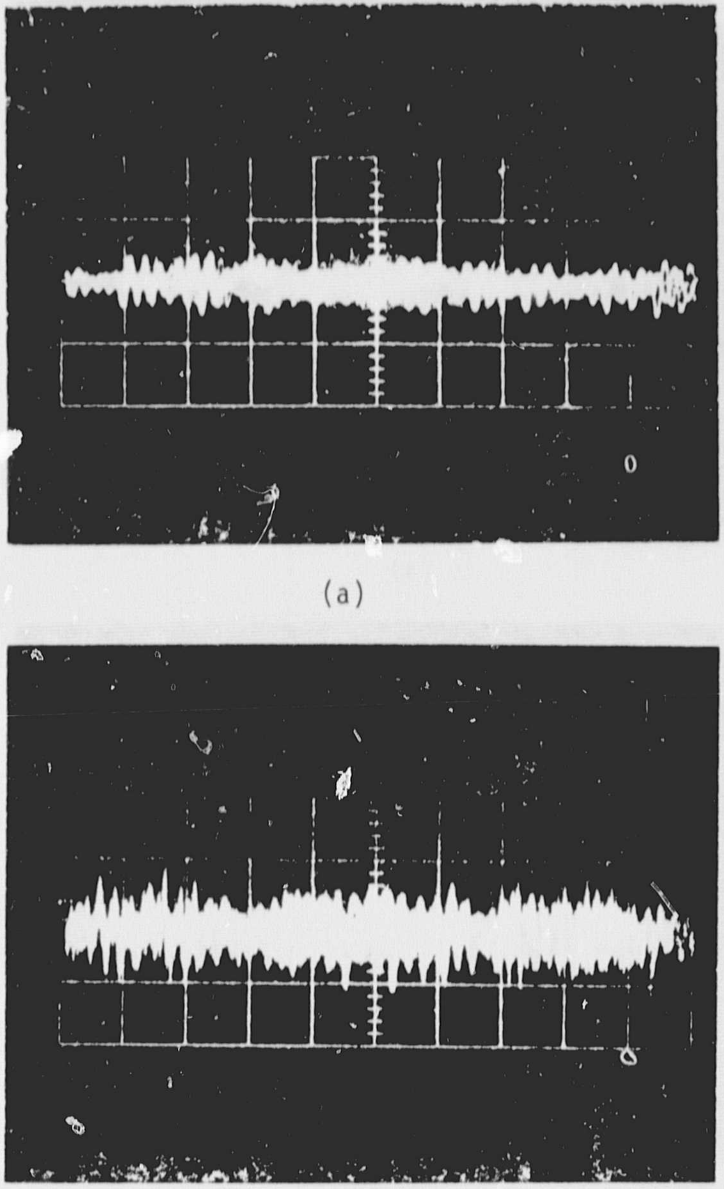
Four (4) thin I.D. blades (two for 6" I.D. blade and two for 8" I.D. blade) were delivered from Semiconductor Materials, Inc. (SMI). Thicknesses of the core and diamond edge of the blade were about 5.2-5.4 mils and 12.2-12.4 mils for 8" I.D. blade and 4.2-4.4 mils and 9.5-10 mils for 6" I.D. blade, respectively. The same tensioning procedure was applied for the blades and other slicing parameters were maintained the same.

Wafers of 12 mils in thickness were sliced from the 4" ingot at two cut rates: 1 IPM and 2 IPM. From the sample sizes of 25, mechanical yields of 100% and 85% were obtained at cut rate of 1 IPM and 2 IPM, respectively. Average kerf width was about 12 mils, showing slight increase in kerf width at higher cut rate (12.3 mils at 2 IPM of cut rate versus 12 mils at 1 IPM of cut rate). Average kerf width for 6" thin I.D. blade was about 10 mils. Quantitative slicing data could not be obtained due to short lifetime of the blades.

1.3.3 Accelerometer Results

To study the influence of mechanical vibration caused by a blade on wafer yields and quality of sliced wafers, an accelerometer (BBN, #507) was pressed on ingots to be sliced and electrical output was detected by an oscilloscope.

Figure II-6 represents the output of the accelerometer while slicing 3" ingot using 6" I.D. blade. The picture shows background noise in (a) and output at 2.5 IPM of cut rate in (b) in which increase in frequency and amplitude was noticed. The effect of blade dressing was detected by the output of the accelerometer. The top picture of Figure II-7 was taken while wafers were showing severe saw marks, and the bottom picture was taken while slicing without saw marks after blade dressing. Periodicity was observed in (a) and the period of the wave envelope was about the same R.P.M. of the I.D. blade ($\sim$ 2,100 R.P.M.). Preliminary results indicates that better surface quality could be achieved in the absence of periodicity (wave envelope) in output signal of the accelerometer.



(a)

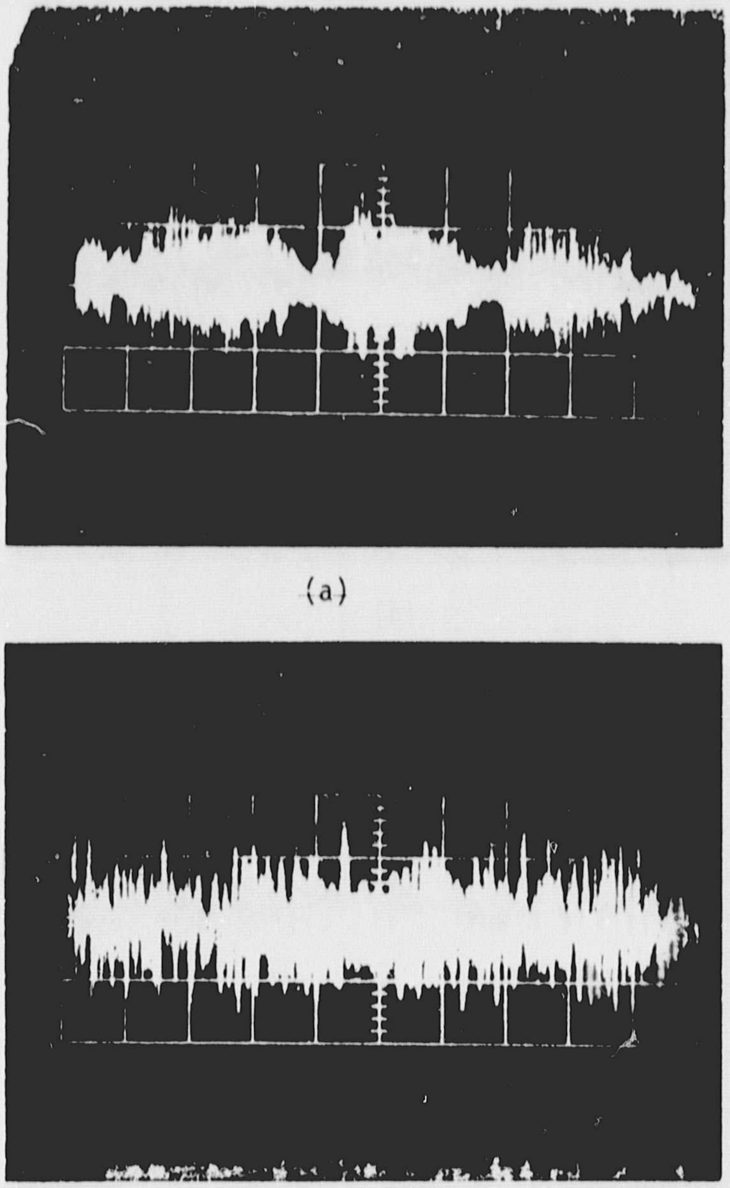
(b)

FIGURE II-6- TYPICAL OUTPUT OF AN ACCELEROMETER OF I.D. SAW SLICING.

HORIZONTAL 10ms/div AND VERTICAL 0.05V/div.

(a) WHILE IDLING

(b) WHILE SLICING



(a)

(b)

FIGURE II-7- OUTPUT OF AN ACCELEROMETER AT TWO DIFFERENT I.D. BLADE CONDITIONS.

HORIZONTAL 10ms/div AND VERTICAL 0.02V/div.

(a) BAD CONDITIONS, SHOWING SAW MARKS ETC.

(b) GOOD CONDITIONS.

2.0 CHARACTERIZATION

2.1 Wafers

After the wafers were demounted, degreased and cleaned, thickness, bow and roughness (RMS) were measured. Their average values, standard deviations, and ranges were obtained. Thickness was measured at seven points on each slice using a dial gauge (Mitutoyo, Model DGS-E), one at the center and six at points 120 degrees apart, and an average of these seven points data represented a thickness of a single wafer.

Bow is measured by supporting a wafer on three points 120 degrees apart in the periphery. The center position of the slice relative to the three points is defined as bow. Bow was measured by a Brown & Sharp bow gauge. Taper was determined by taking the difference between the maximum and minimum slice thickness measured. Surface roughness (RMS) was measured in parallel to the cutting direction, using a Metro-surf (Model 181, Airtronics, Illinois). Surface profiles of the sliced wafers were obtained on a X-Y recorder using Dek-Tak (Sloan), and SEM pictures were taken to see the surface features of the sliced wafers.

2.1.1 MBS Saw Wafers

From 60 slices of each ingot size, an average thickness of 13.2 mils for the 3" diameter ingot and 13.0 mils for the 4" ingot as obtained using the same blade package. Average bow indicated 1.1 mils for the 3" wafers and 0.81 mils for the 4" wafers, and average taper showed 1.7 mils and 2.4 mils for the 3" and 4" wafers, respectively. (See Table II-7 and Table II-8 for details.)

2.1.2 MWS Saw Wafers

An average thickness of 10.7 mils with kerf width of 7.9 mils as obtained from 32 samples of 3" sliced wafers. Average bow and roughness (RMS) were about 0.37 mils and 0.56 μm, respectively. Average taper inidcated 0.53 mils and this is mainly due to the change in kerf width, which is caused by the wear of abrasives and wire as the slicing progresses, consequently leading to thin wafers at the start and thick wafers at the last cutting edge of the wafers.

Detailed characterization parameters of the sliced wafers are given in Table II-4.

2.1.3 I.D. Saw Wafers

Definition of standard blade and thin blade was given in previous slicing experiment (Section 1.3).

Wafers Sliced By Standard Blades

From the slicing experiment which determined the wafer yields versus wafer thickness and cut rate (1 IPM and 2 IPM of cut rate), an average bow and roughness (RMS) of the 3" wafers cut at 1 IPM were about 0.52 mils and 0.37 μm, respectively, while taper showed values less than 0.2 mils. Generally, an accuracy of taper was limited by the accuracy

TABLE II-4

CHARACTERIZATION OF WAFERS SLICED WITH MWS SAW

INGOT SIZE, CM (INCH)	7.62 (3)
THICKNESS, mm (mils)	
Average	0.269 (10.61)
Standard Deviation	0.005 (0.19)
Range	0.265∿0.285 (10.43∿11.23)
TAPER, μm (mils)	
Average	13 (0.53)
Standard Deviation	5.8 (0.23)
Range	7.6∿35.6 (0.3∿1.4)
BOW, μm (mils)	
Average	9.4 (0.37)
Standard Deviation	8.1 (0.32)
Range	2.5∿38.1 (0.1∿1.5)
ROUGHNESS (RMS), μm	
Average	0.56
Range	0.46 0.78

of thickness measurements using a dial gauge. The 4" wafers showed similar values in taper and roughness (RMS). However, a slightly increased bow was observed for the 4" wafers, compared with the 3" wafers. [Detailed parameters of typical wafer thickness (about 4 mils) are given in Table II-7 and Table II-8 and those of the other wafer thicknesses were reported in reference (1)].

Effects of cut rate on wafer parameters was obtained from a 3" ingot. Wafer tickness of 12 mils was chosen and the measured parameters are given in Table II-5. Starting at 3 IPM of cut rate, significant increase in bow and taper was observed. Breakage of wafers and excessive saw marks on one face of the slices wafers started at 4 IPM of cut rate. Roughness (RMS) had a tendency to increase slowly as the cut rate increased. (Note: roughness values tabulated are measured on smooth face of the wafers, the other side of the wafer which has saw marks showed roughness (RMS) values up to 1.5 μm). Ranges and average values of bow, taper, and roughness (RMS) are plotted at different cut rates in Figure II-8, Figure II-9, and Figure II-10, respectively. Instead of thickness, kerf width versus cut rate is plotted in Figure II-11.

Wafers Sliced By Thin Blades

Twelve (12) mils wafers were sliced from the 4" ingot at two cut rates (1 IPM and 2 IPM) and the detailed wafer parameters are shown in Table II-6. In general, the wafers sliced with thin I.D. blades indicated a wider

TABLE II-5

EFFECT OF CUT RATE ON 3" WAFER PARAMETERS SLICED BY I.D. SAW

CUT RATE Inch/Min.	THICKNESS, MILS			BOW, MILS			TAPER, MILS			ROUGHNESS (RMS), μm	
	Average	Standard Deviation	Range	Average	Standard Deviation	Range	Average	Standard Deviation	Range	Average	Range
1	12.36	0.11	12.23 ∿ 12.56	0.64	0.13	0.4 ∿ 0.9	0.14	0.08	0.1 ∿ 0.3	0.35	0.29 ∿ 0.39
2	12.42	0.06	12.33 ∿ 12.50	0.45	0.18	0.2 ∿ 0.7	0.13	0.06	0.1 ∿ 0.3	0.41	0.36 ∿ 0.50
3	12.50	0.23	12.21 ∿ 13.11	1.53	0.69	0.4 ∿ 2.7	0.34	0.10	0.2 ∿ 0.5	0.41	0.36 ∿ 0.46
4	12.25	0.48	11.83 ∿ 13.54	>3	----	1.7 ∿ >3.0	0.76	0.22	0.4 ∿ 1.2	0.48	0.44 ∿ 0.52
5	11.84	0.41	11.23 ∿ 12.49	>4	----	>4.0	1.07	0.38	0.6 ∿ 1.5	0.50	0.44 ∿ 0.56

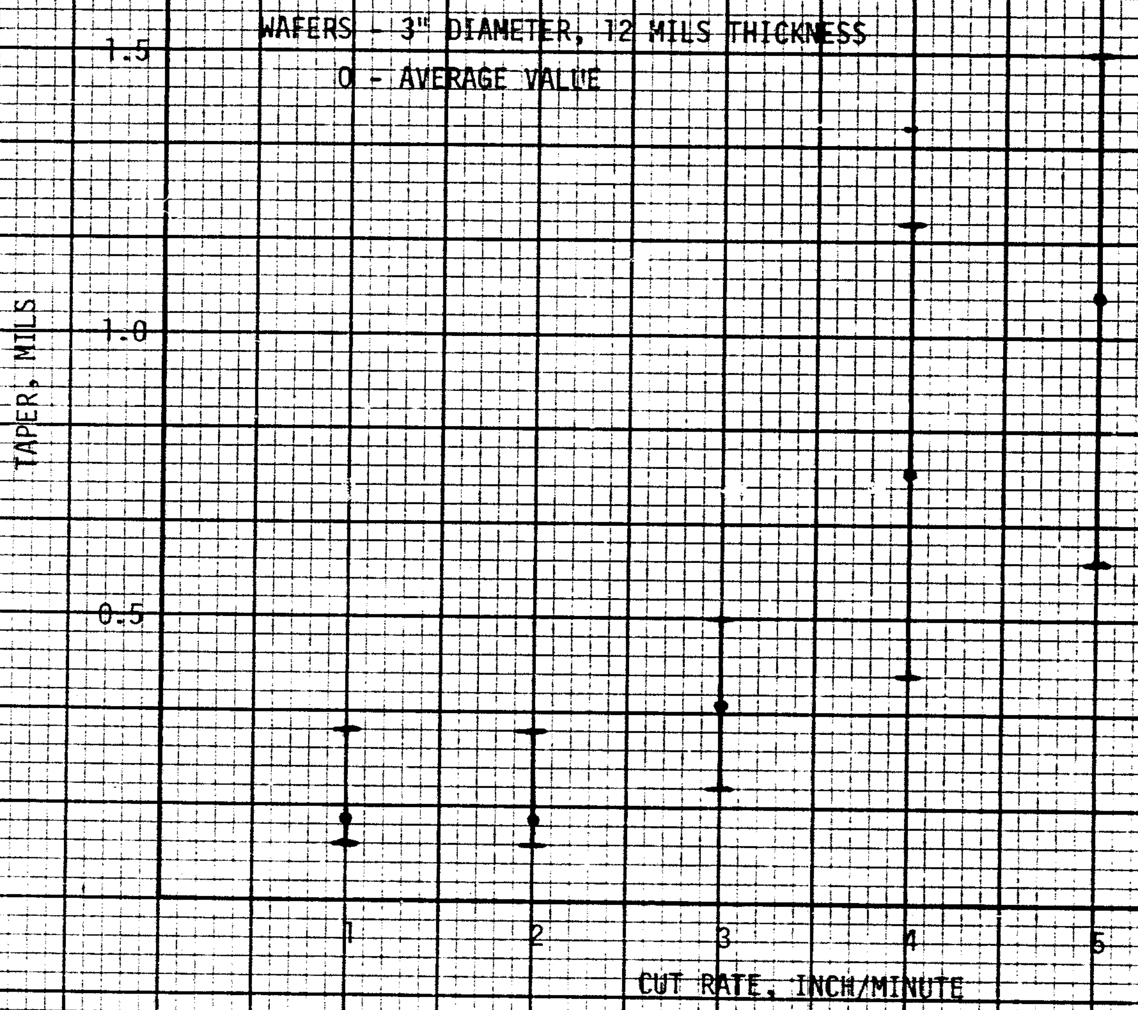


FIGURE II-8 - RANGE OF TAPER VERSUS CUT RATE OF I.D. SAW (STANDARD BLADE)

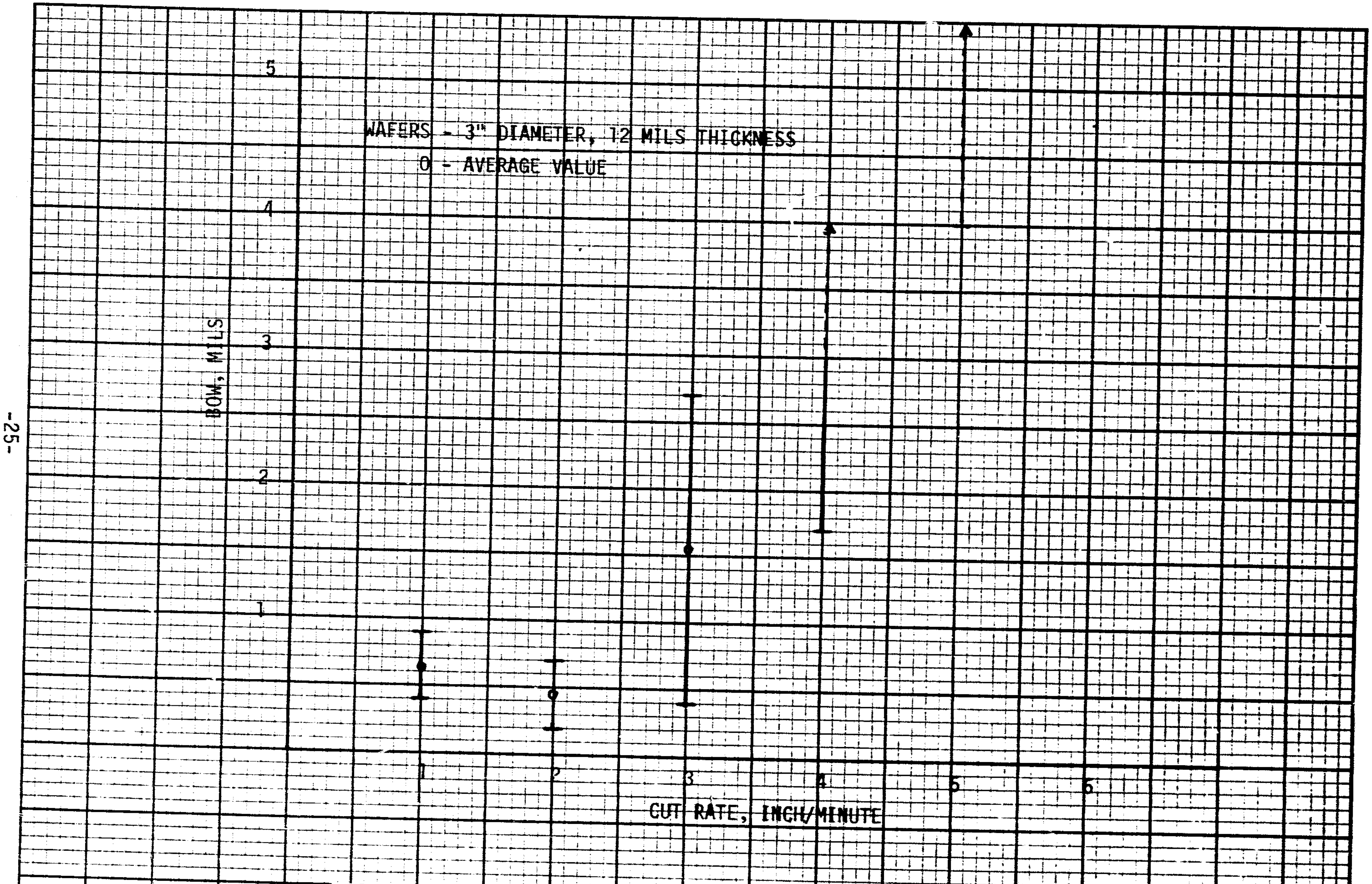


FIGURE II-9 - RANGE OF BOW VERSUS CUT RATE OF I.D. SAW (STANDARD BLADE)

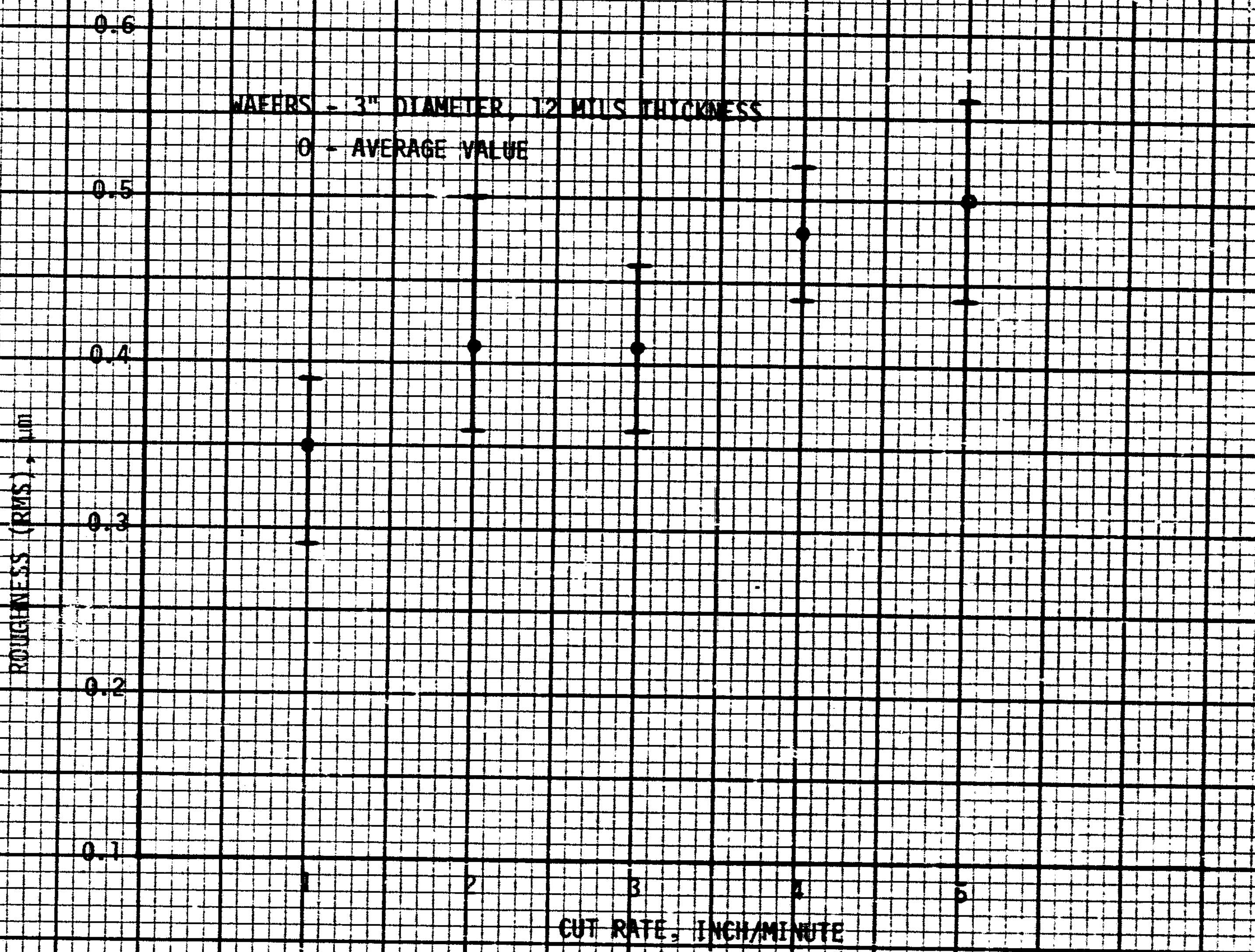


FIGURE II-10 - RANGE OF ROUGHNESS (RMS) VERSUS CUT RATE OF I.D. SAW (STANDARD BLADE)

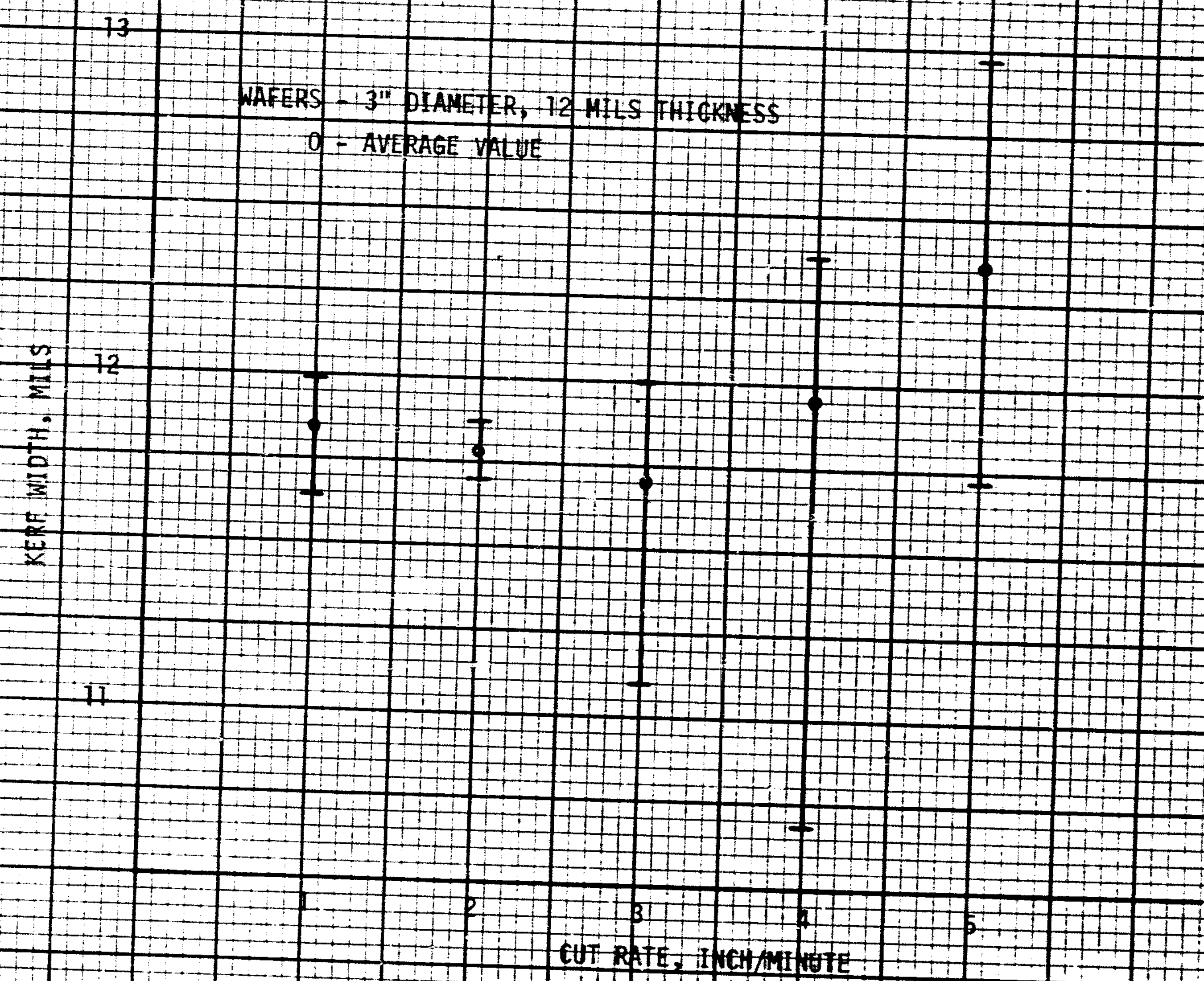


FIGURE II-11 - RANGE OF KERF WIDTH VERSUS CUT RATE OF I.D. SAW (STANDARD BLADE)

TABLE II-6

FOUR INCH WAFERS SLICED WITH A THIN I.D. BLADE

CUT RATE in/min.	THICKNESS, mils		BOW, mils		TAPER, mils		ROUGHNESS, μm	
	1	2	1	2	1	2	1	2
Average	12.18	11.91	0.41	1.74	0.4	0.8	0.47	0.48
Standard Deviation	<0.2	<0.3	0.31	0.31	<0.3	<0.3	----	----
Range	11.8∿12.4	11.6∿12.4	0.2∿1.1	1.3∿2.2	0.2∿0.8	0.3∿1.2	0.42∿0.56	0.38∿0.62

NOTE: 4" wafers sliced with a thin I.D. blade (12±0.5 mils, diamond edge and 5.0 mils core thickness, nominal).

variation in thickness and an increase in bow and taper than the wafers cut with the standard blades. In some cases, 2 mils of taper resulted from slicing a 3" ingot, using a 6" I.D. thin blade which ultimately caused short lifetime (∿ 300 cuts) of the blade. This could possibly be due to a mechanical instability (fluttering or wandering) of a blade of thin core or the difficulty of conditioning of thin diamond plated cutting edge.

2.1.4 Comparison of Wafer Parameters

The parameters obtained from the wafers of three (3) different slicing type, MBS saw, MWS saw, and I.D. saw, were compared for the evaluation of the mechanical quality of the sliced wafers.

Thickness variation, from wafer to wafer and within a single wafer, of the MBS wafer were higher than those of the I.D. saw and MWS saw. Bow and roughness (RMS) also indicated that the MBS saw wafers showed about a factor of two higher values than those with the I.D. saw wafers. In general, comparison of the parameters indicated that the wafers sliced with the I.D. saw and MWS saw had much smaller values and variations, than those with the MBS saw, indicating the need for less removal of silicon before solar cell fabrication. Wafers sliced by the I.D. saw (cut at or below 2 IPM of cut rate) showed slightly better mechanical quality than those with the MWS saw. Detailed comparison of the parameters for different slicing types is given in Table II-7 for the 3" wafers and in Table II-8 for the 4" wafers. Bow, taper, and roughness (RMS) are plotted for 3" wafers in Figure II-12, Figure II-13, and Figure II-14, respectively.

Surface profiles of the sliced wafers were obtained using a Dek-Tak from Sloan. Typical surface profiles of the wafers are given in Figure II-15: The I.D. saw wafers sliced at 2 IPM of cut rate (b) shows slightly increased surface roughness than the wafers sliced at 1 IPM of cut rate (a). However, a surface profile of a wafer sliced with MBS saw (c) shows a significant increase in roughness at the surface compared with those with the I.D. saw and MWS saw (d). Wafers sliced with the MWS saw show same surface roughness with the wafers sliced at 2 IPM of cut rate with the I.D. saw. SEM pictures of the wafers sawn by three different slicing techniques are given in Figure II-16. The pictures indicated that surface roughness increases in the order ID-MWS-MBS, showing an agreement with the results obtained from Figure II-16: This is well illustrated in (a) of the figure and also in pictures taken at high magnification (a, b, and c of the figure). One unique surface feature was observed from the wafer sliced with MWS saw, (c) in the figure, in which several distinct lines were identified. The lines could possibly be micro-cracks introduced during slicing operation. Further investigation is suggested.

TABLE II-7

COMPARISON OF 3" WAFER PARAMETERS

SLICING TYPE		MBS	MWS	I.D.	
				1 IPM	2 IPM
THICKNESS**	AVERAGE	13.2	10.6	14.0	14.0
	S. DEVIATION	1.02	0.19	<0.1	<0.1
	RANGE	10.4∿16.6	10.4∿11.3	14.0∿14.1	14.0∿14.1
BOW**	AVERAGE	1.1	0.37	0.37	1.4
	S. DEVIATION	0.51	0.32	0.17	0.18
	RANGE	0.3∿2.3	0.1∿1.5	0.1∿0.75	1.3∿1.8
TAPER**	AVERAGE	1.7	0.53	0.1	0.1
	S. DEVIATION	0.59	0.23	<0.1	<0.1
	RANGE	0.3∿3	0.3∿1.4	<0.2	<0.2
ROUGHNESS*	AVERAGE	1.2	0.56	0.37	0.57
	RANGE	0.8∿1.6	0.46∿0.78	0.34∿0.4	0.54∿0.61

* Measured in Micrometers
**Measured in Mils

TABLE II-8

COMPARISON OF 4" WAFER PARAMETERS

SLICING TYPE		MBS	I.D.	
			1 IPM	2 IPM
THICKNESS**	AVERAGE	13.0	14.1	14.1
	S. DEVIATION	1.32	<0.2	<0.1
	RANGE	9.5∿16.4	13.8∿14.2	14.0∿14.2
BOW**	AVERAGE	0.81	0.47	0.33
	S. DEVIATION	0.34	0.29	0.16
	RANGE	0.25∿1.5	0.1∿0.9	0.1∿0.6
TAPER**	AVERAGE	2.4	0.2	0.2
	S. DEVIATION	0.7	<0.1	<0.1
	RANGE	0.9∿5	<0.3	<0.3
ROUGHNESS*	AVERAGE	1.2	0.42	0.52
	RANGE	0.8∿1.5	0.36∿0.54	0.43∿0.59

* Measured in Micrometers.
**Measured in Mils.

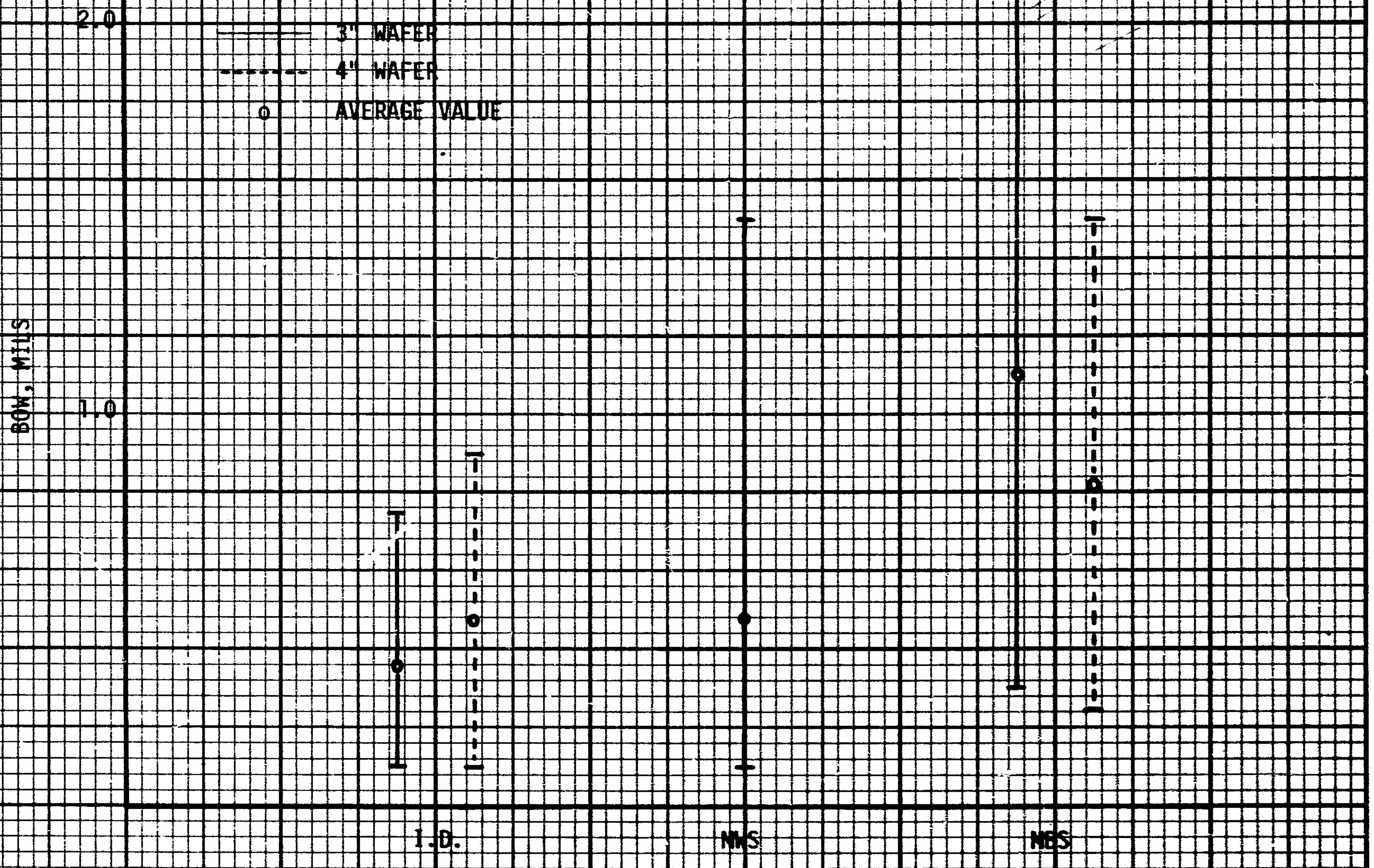


FIGURE II-12 - COMPARISON OF BOWS OF THE WAFERS SLICED BY THREE DIFFERENT SLICING TYPES

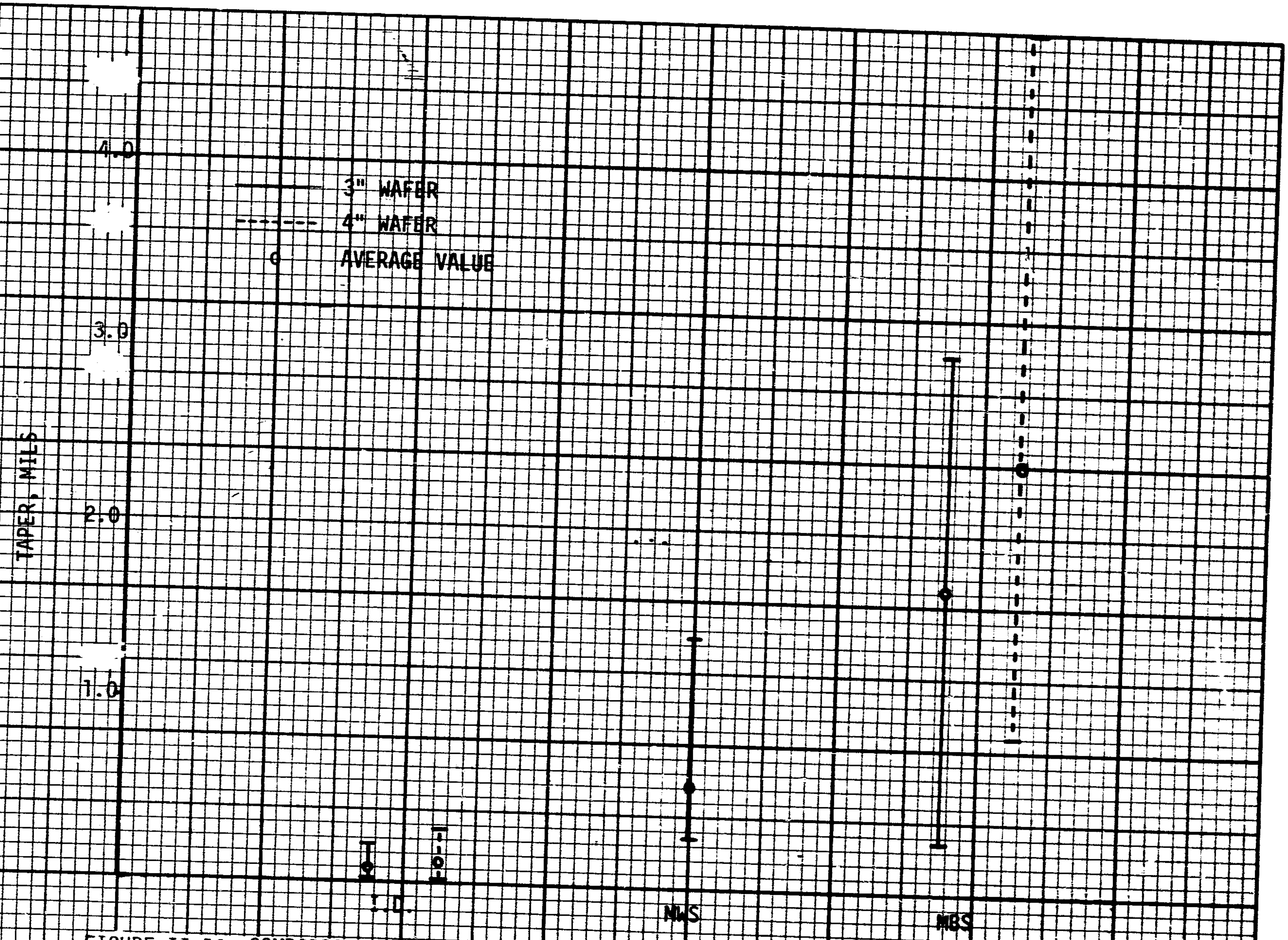


FIGURE II-13- COMPARISON OF TAPERS OF THE WAFERS SLICED BY THREE DIFFERENT SLICING TYPES

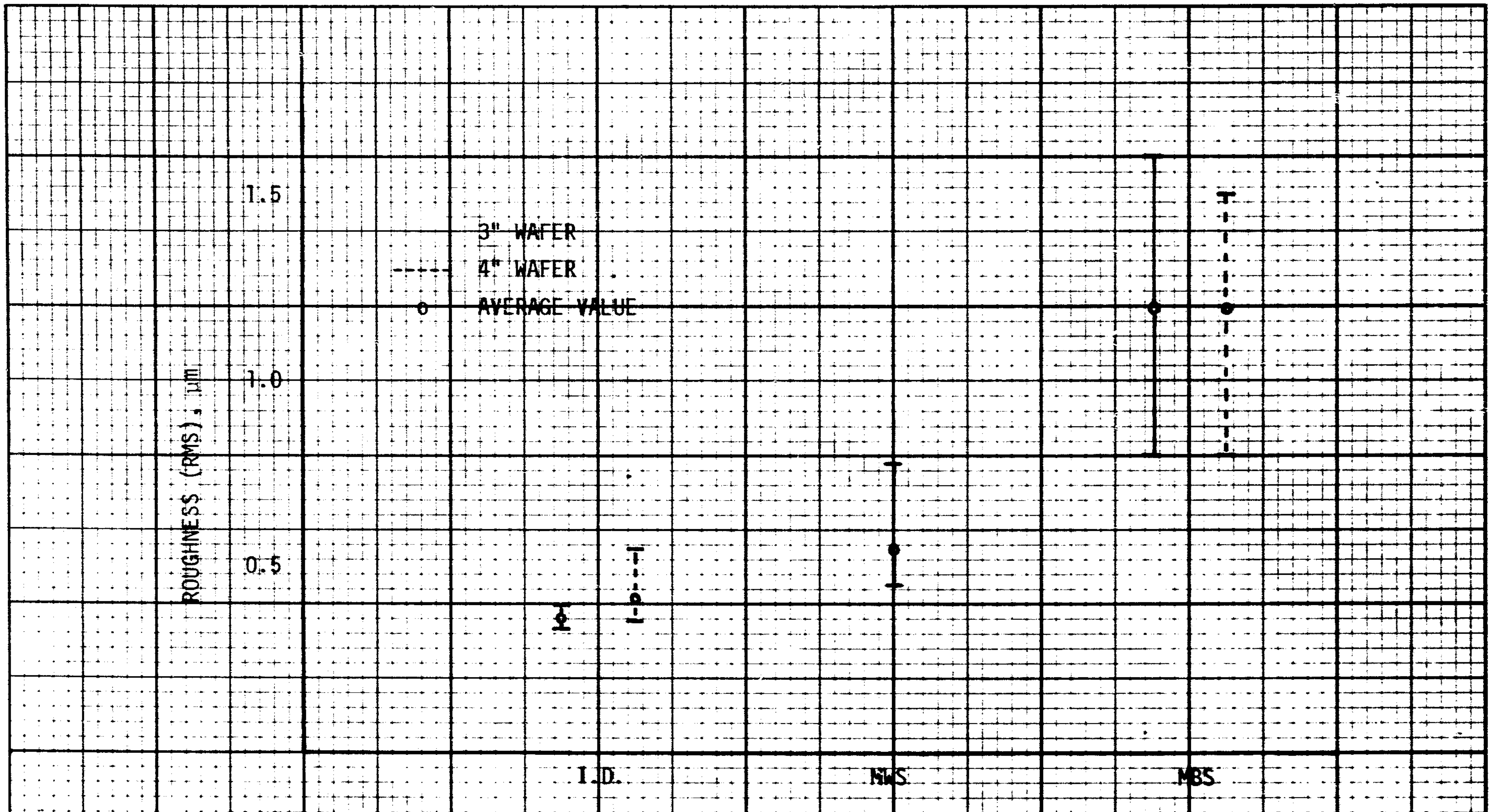
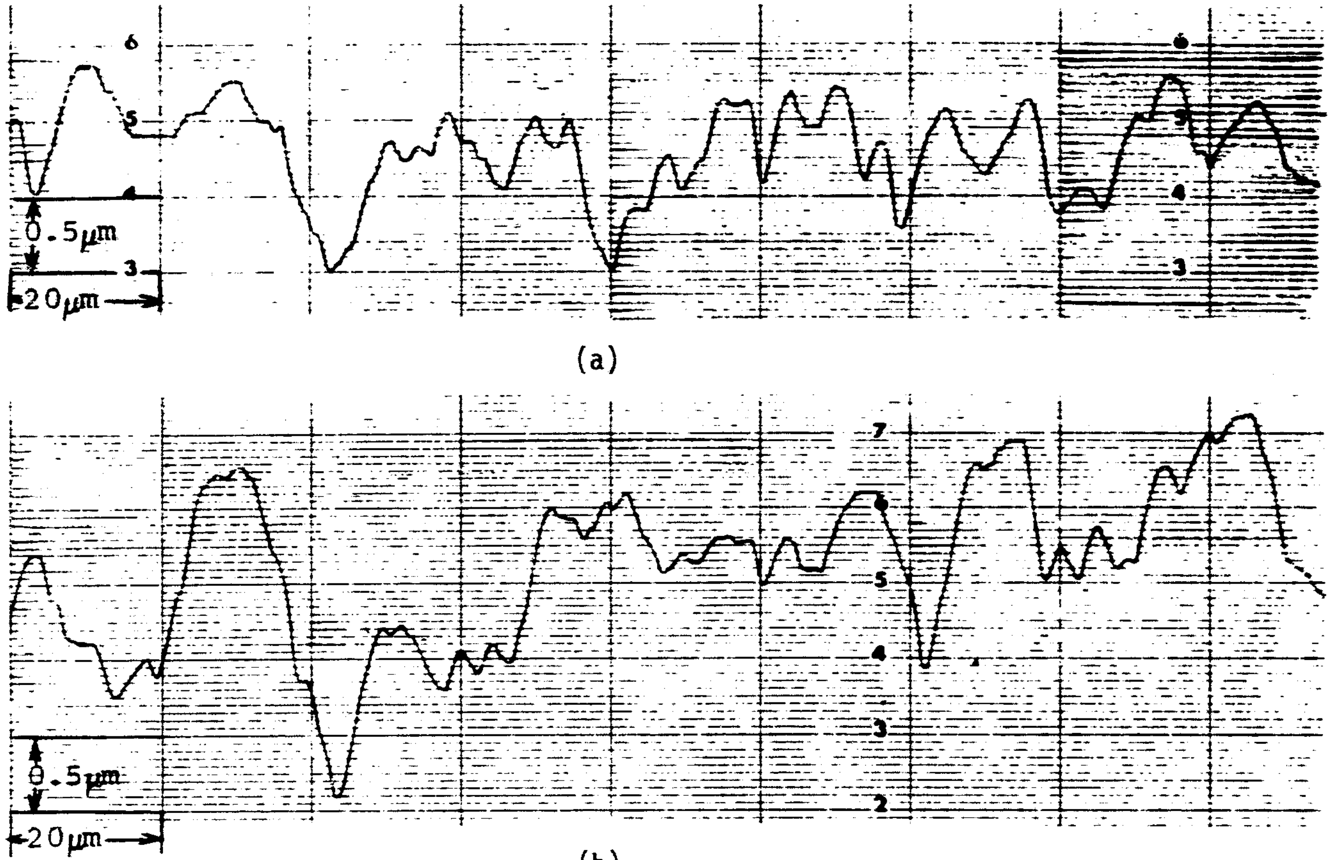


FIGURE II-14- COMPARISON OF ROUGHNESS (RMS) OF THE WAFERS SLICED BY THREE DIFFERENT SLICING TYPES



(a)

(b)

FIGURE II-15 - TYPICAL SURFACE PROFILES OF THE SLICED WAFERS

(a) AN I.D. SAW WAFER; 1 IPM OF CUT RATE

(b) AN I.D. SAW WAFER; 2 IPM OF CUT RATE

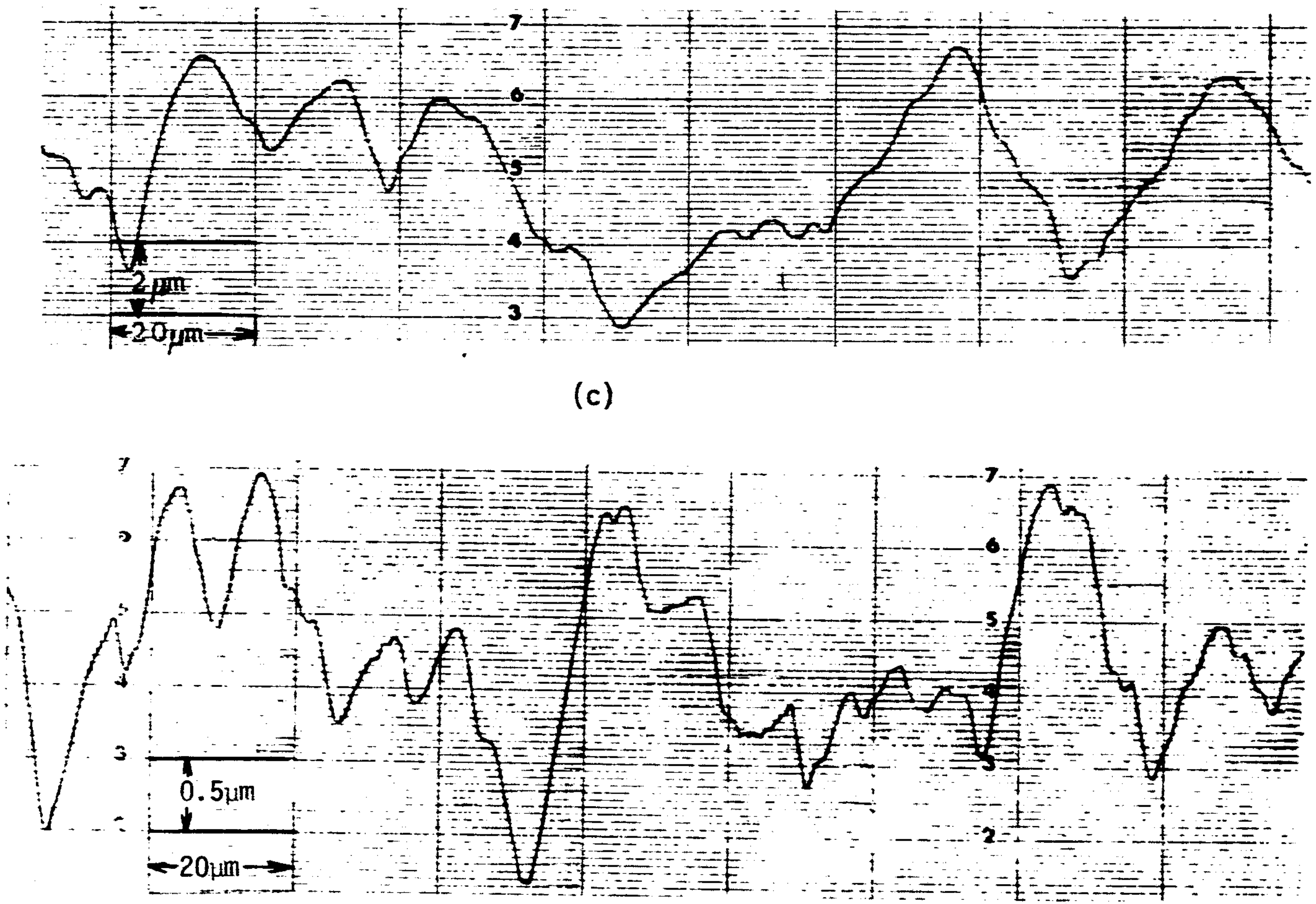
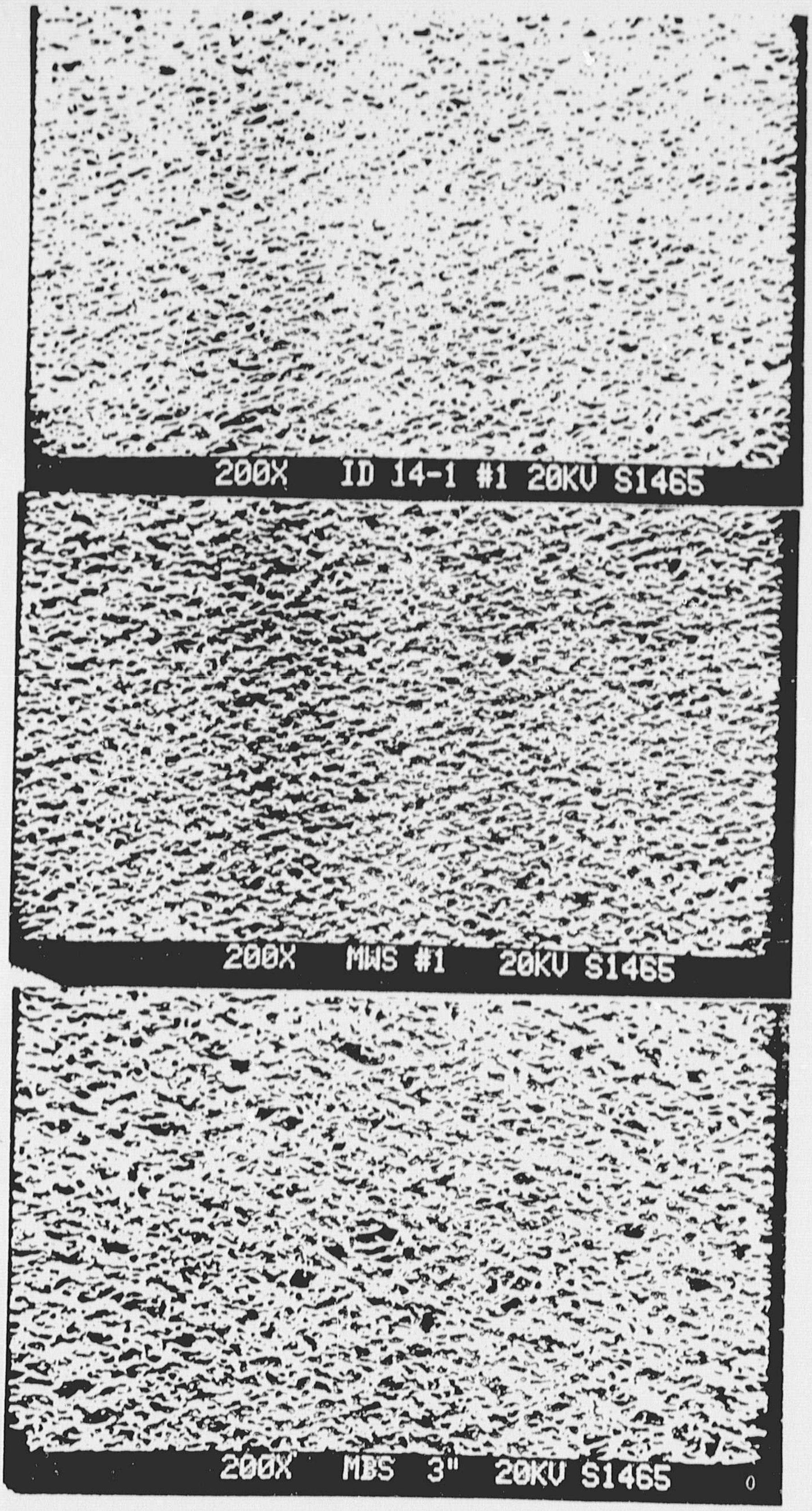
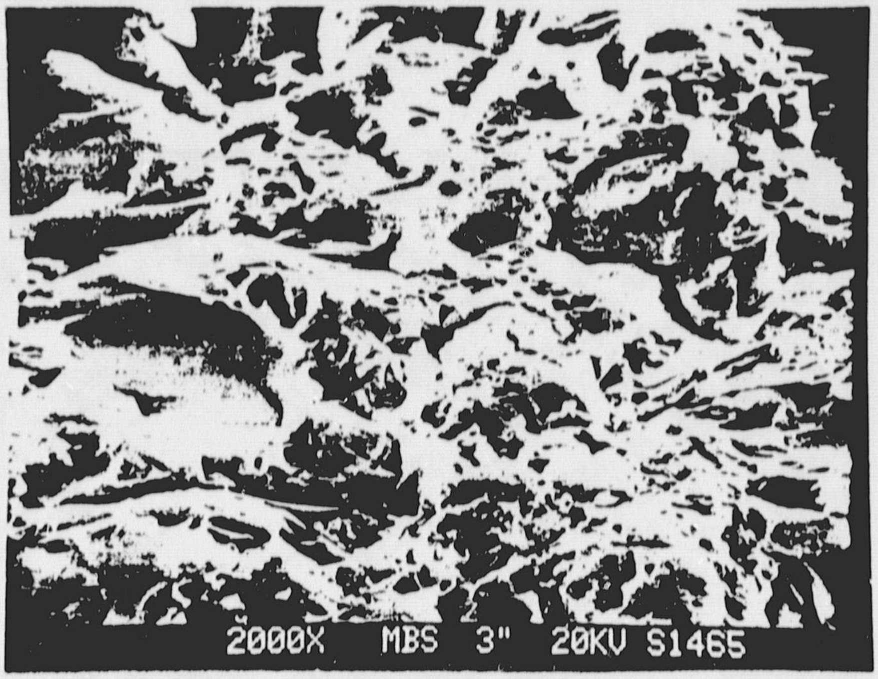


FIGURE II-15 - TYPICAL SURFACE PROFILES OF THE SLICED WAFERS

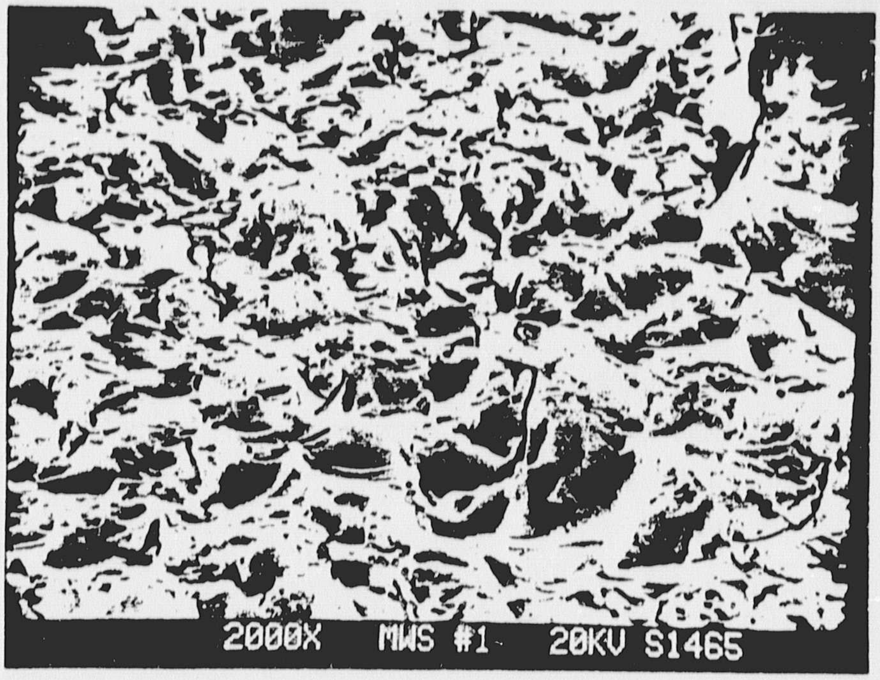
(c) A MBS SAW WAFER
(d) A MWS SAW WAFER


200X ID 14-1 #1 20KV S1465
200X MWS #1 20KV S1465
200X MBS 3" 20KV S1465
0

(a)



(b)



(c)

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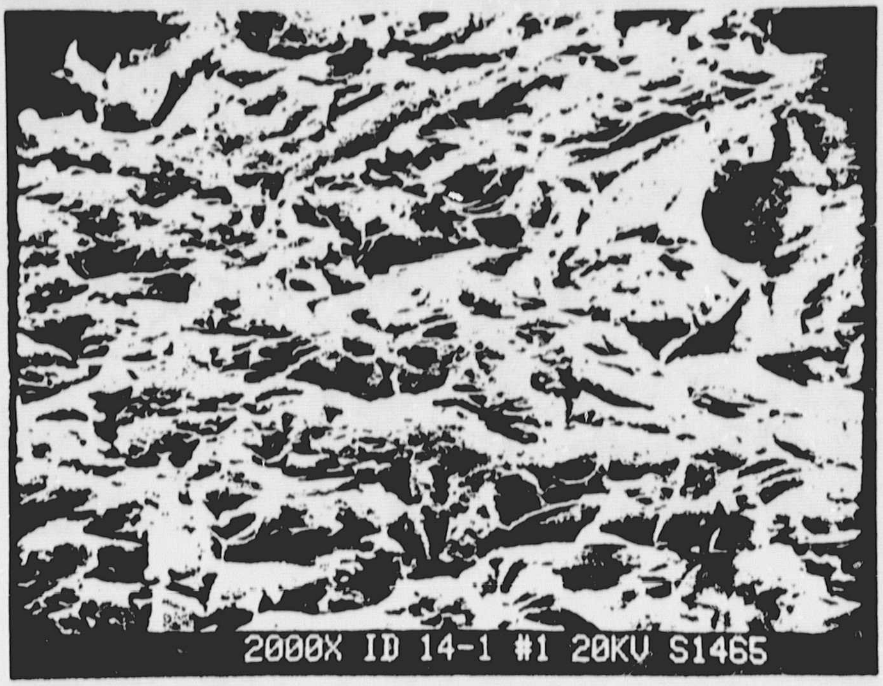


(d)

FIGURE II-16 - SEM PICTURES OF THE SURFACE OF THE WAFERS SAWN BY THREE DIFFERENT SLICING TYPES

(a) I.D., MWS AND MBS WAFERS AT LOW MAGNIFICATION; 200X

(b) MBS WAFER AT HIGH MAGNIFICATION; 2000X

(c) MWS WAFER AT HIGH MAGNIFICATION; 2000X

(d) I.D. WAFER AT HIGH MAGNIFICATION; 2000X

2.2 Blades and Wires

2.2.1 MBS Saw Blades

The wear ratio, defined by the volume of a blade worn out divided by the volume of silicon removed during cutting, was about 0.048. After one slicing experiment with a 4" ingot, wear of blade thickness was negligible and maximum wear of blade width (or depths) was about 2.6 (mm); corresponding to 40% wear of a new blade. The lifetime of a blade was considered to be 60% wear of the new blade(3) Figure II-17 shows a boundary between the wear part and intact part (blade width) of blade after one slicing of a 4" ingot.

2.2.2 MWS Saw Wires

The following information was furnished by Yasunaga Engineering Co., Ltd.

High tension wire (Music steel wire) with 0.16mm in diameter was used for the slicing and about 5800m (0.92 Kg) of the wire was consumed. Wear of the wire after slicing was approximately 12μm in diameter. Lifetime of the wire was suggested to be around 15%* wear in diameter of a new wire and used wires are not recommended for second run because the old wires have a tendency to be twisted, causing a danger of breakage of the wires in the middle of the run. Also, irregular wear of a wire (along the length and the

*Personal communication with technical staff of Geos Corporation (sales representative of Yasunaga wire saw).

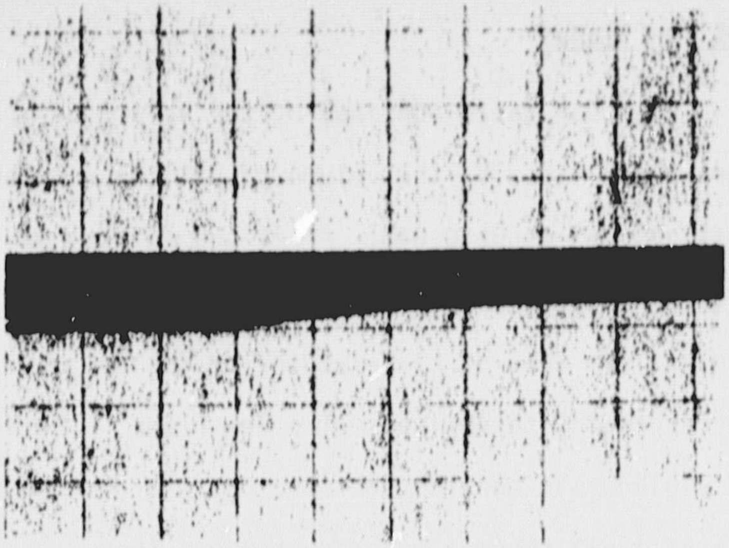
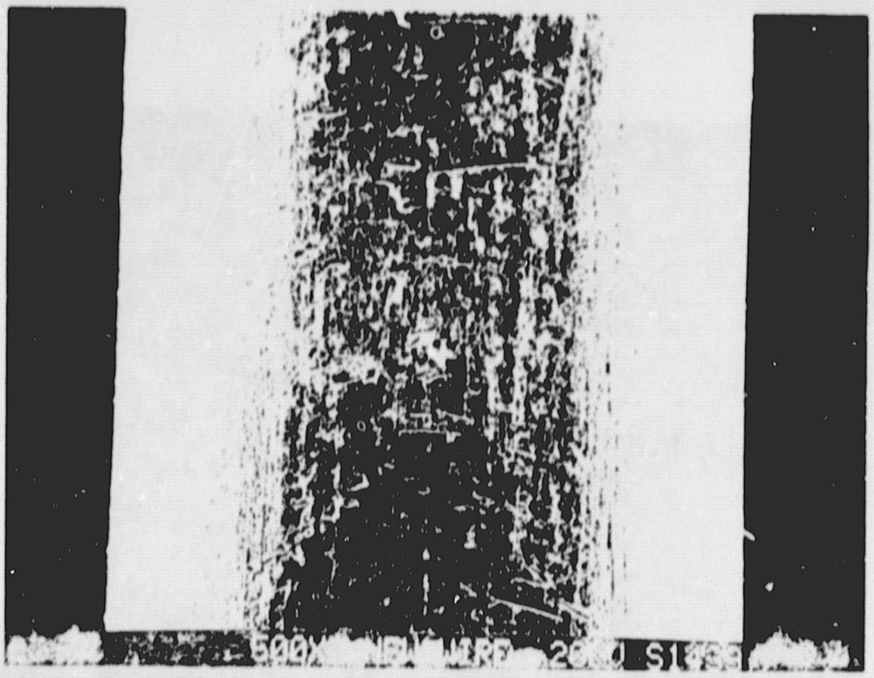
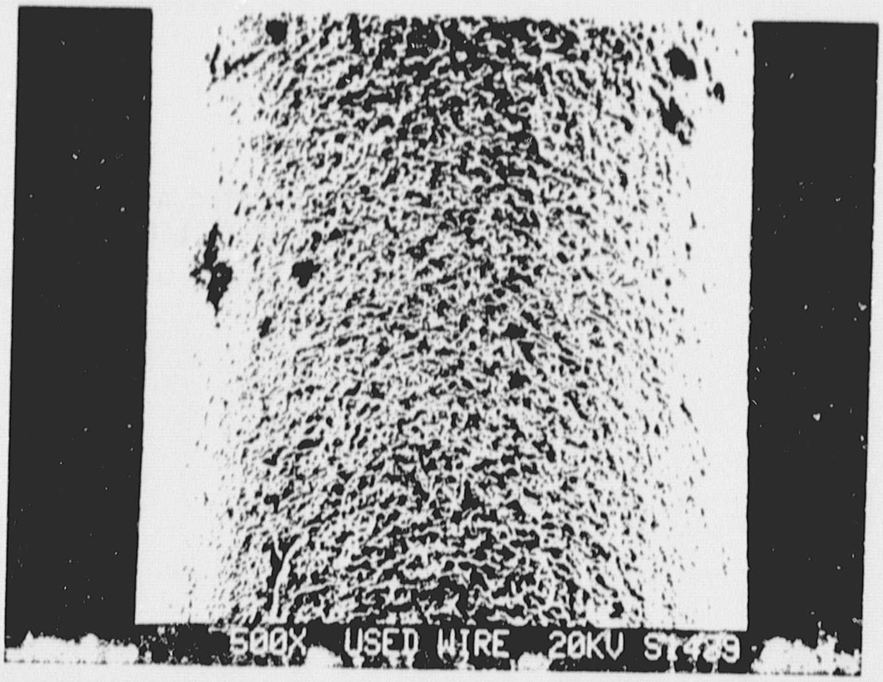


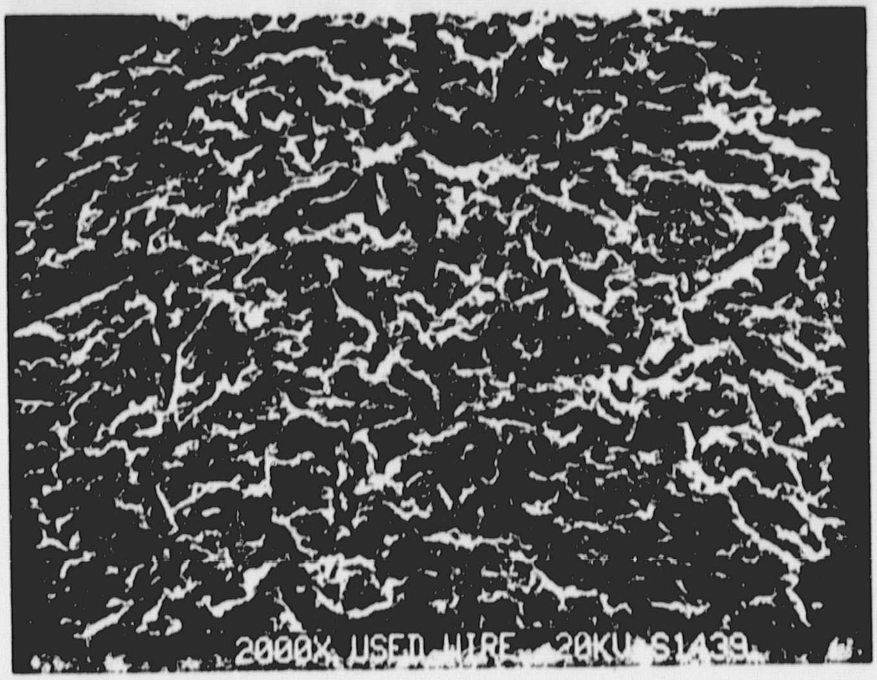
FIGURE II-17 - A BLADE FROM A MULTIBLADE PACKAGE OF A MBS SAW AFTER SLICING A 4" DIAMETER SI INGOT. A BOUNDARY BETWEEN WEAR PART AND INTACT PART IS SHOWN HERE. (0.25 INCH/DIV.)



(a)



(b)



(c)

FIGURE II-18 - SEM PICTURES OF MWS SAW WIRES:

(a) A NEW WIRE

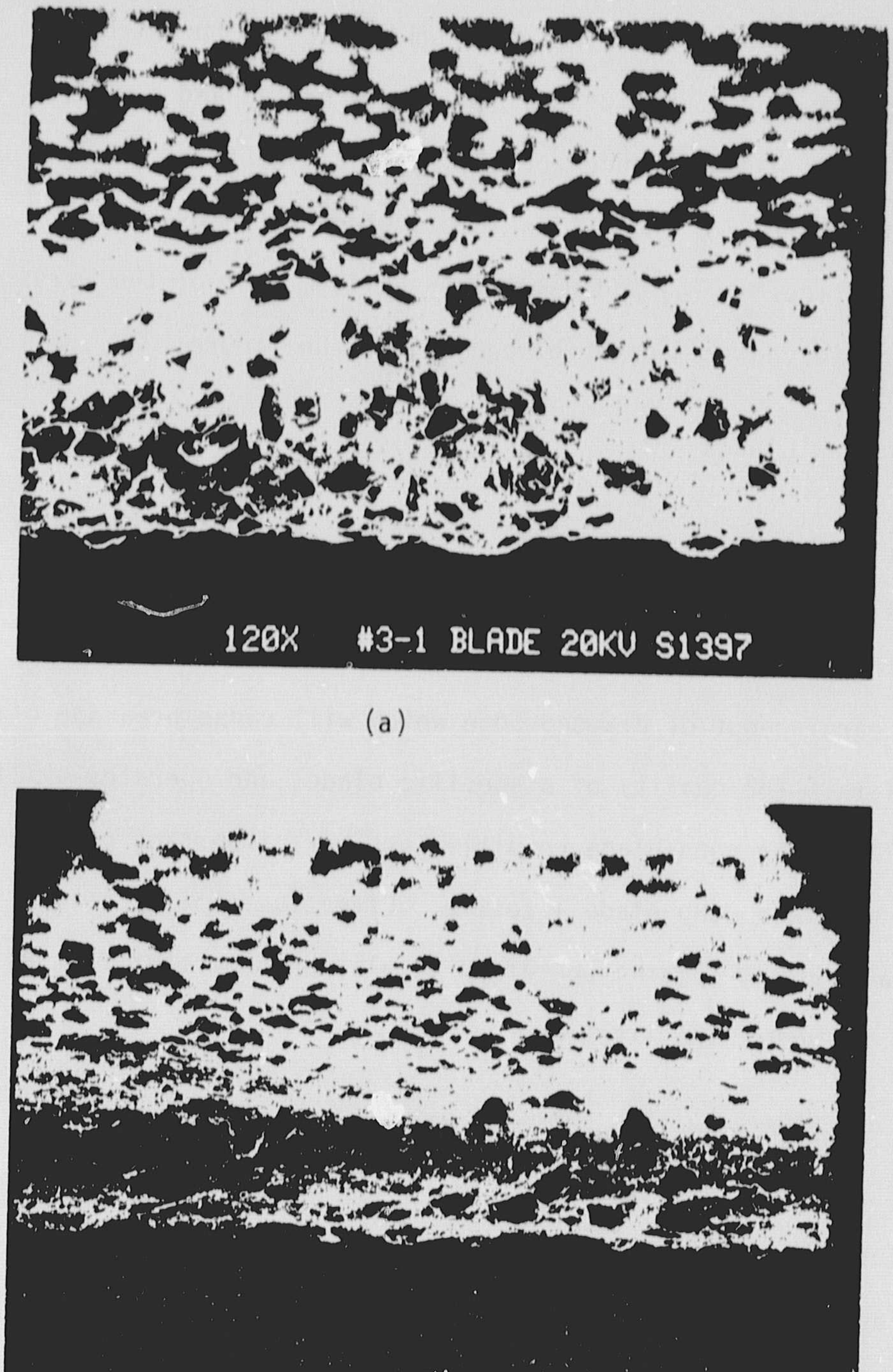
(b) A USED WIRE AFTER SLICING A SILICON INGOT OF 3" DIAMETER AND 3" IN LEGHT

(c) SURFACE FEATURE OF A USED WIRE AT HIGHER MAGNIFICATION cross section of the wire) will contribute to the wire breakage. JPL SEM pictures of a new wire (a) and a wire (b) which was used once for slicing a 3" ingot are given in figure II-18. Reduction in diameter of the used wire was notices in (b) and relatively uniform wear of the wires are observed from both (b) and (c) of the figure.

2.2.3 I.D. Saw Blades

Blade lifetime (number of cuts) is limited by various reasons: excessive taper and saw marks which cannot be corrected either by dressing or retensioning of the blade, or earning-out of diamond edge which will cause breakage of wafers. The quality of a specific blade, and operator skill to maintain good blade condition are very important parameters to maintain long blade lifetime. Effective cooling of a blade during slicing operation is also an important factor to influence the lifetime.

Under normal operation conditions (average two IPM of cut rate and mixed load conditions), the average lifetime of the standard blade was over 4,000 cuts for the 6" I.D. blade (blade for slicing 3" diameter ingots) and over 5,000 cuts for the 8" I.D. blade (blade for slicing 4" diameter ingots). SEM picutres of worn-out I.D. blades indicated excessive wear of diamond particles at the cutting edge of the blade in (b) of figure II-19, and fracture of diamond particles and glazing of the ingot



(a)

(b)

FIGURE II-19 - SEM PICTURES OF I.D. BLADES AT DIAMOND PLATED CUTTING EDGE; 120X MAGNIFICATION

(a) A NEW BLADE

(b) A WORN-OUT BLADE

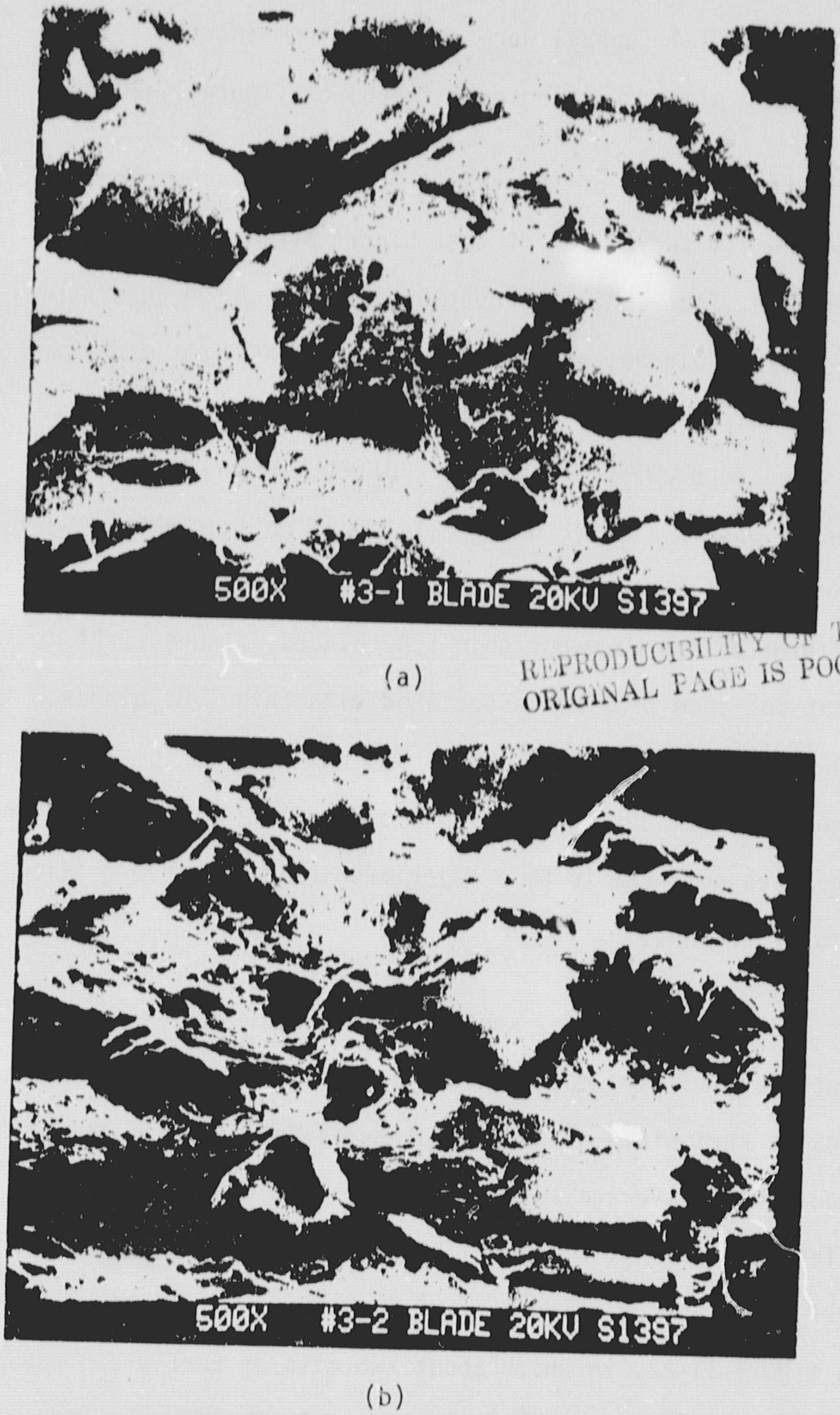


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FIGURE II-20 - SEM PICTURES OF I.D. BLADES; SIDE VIEW OF DIAMOND PLATED CUTTING EDGE; 500X MAGNIFICATION

(a) A NEW BLADE
(b) A WORN-OUT BLADE

fixing material (epoxy) were observed from the side view of diamond plated cutting edge in (b) of figure II-20.

Lifetime data of the thin I.D. blades was obtained from the limited number of test blades from Semiconductor Materials, Inc. (SMI): about 300 cuts and 3,000 cuts from two 6" I.D. blades, and 2,500 cuts and 3,000 cuts from two 8" I.D. blades, which indicates less than half of the life of standard blades. In general, difficulties of using thin blades were experienced mainly due to poor wafer yield, poor wafer quality and short lifetime of the blades. SEM pictures of the worn-out thin I.D. blades, figure II-21 point out some problems associated with thin I.D. blades, showing non-uniform wear in (a) and chipping in (b) at the cutting edge of the blades. Wear of diamond particles at the cutting edge does not seem to be a major problem of low blade lifetime at present.

For an I.D. blade, kerf width decreases as the slicing continues, mainly, due to the wear and pull-out of diamonds. Thus, a kerf width of an I.D. blade at specific conditions should be an average kerf width of the blade during the lifetime. From thin blades, both 6" I.D. and 8" I.D. kerf width versus blade history (number of cuts) are plotted in figure II-22, in which about two mils of kerf width reduction is indicated from the 8" I.D. blade. In the figure, ends of lines represent the lifetime of the blades and typical case of standard blades are obtained for comparison.

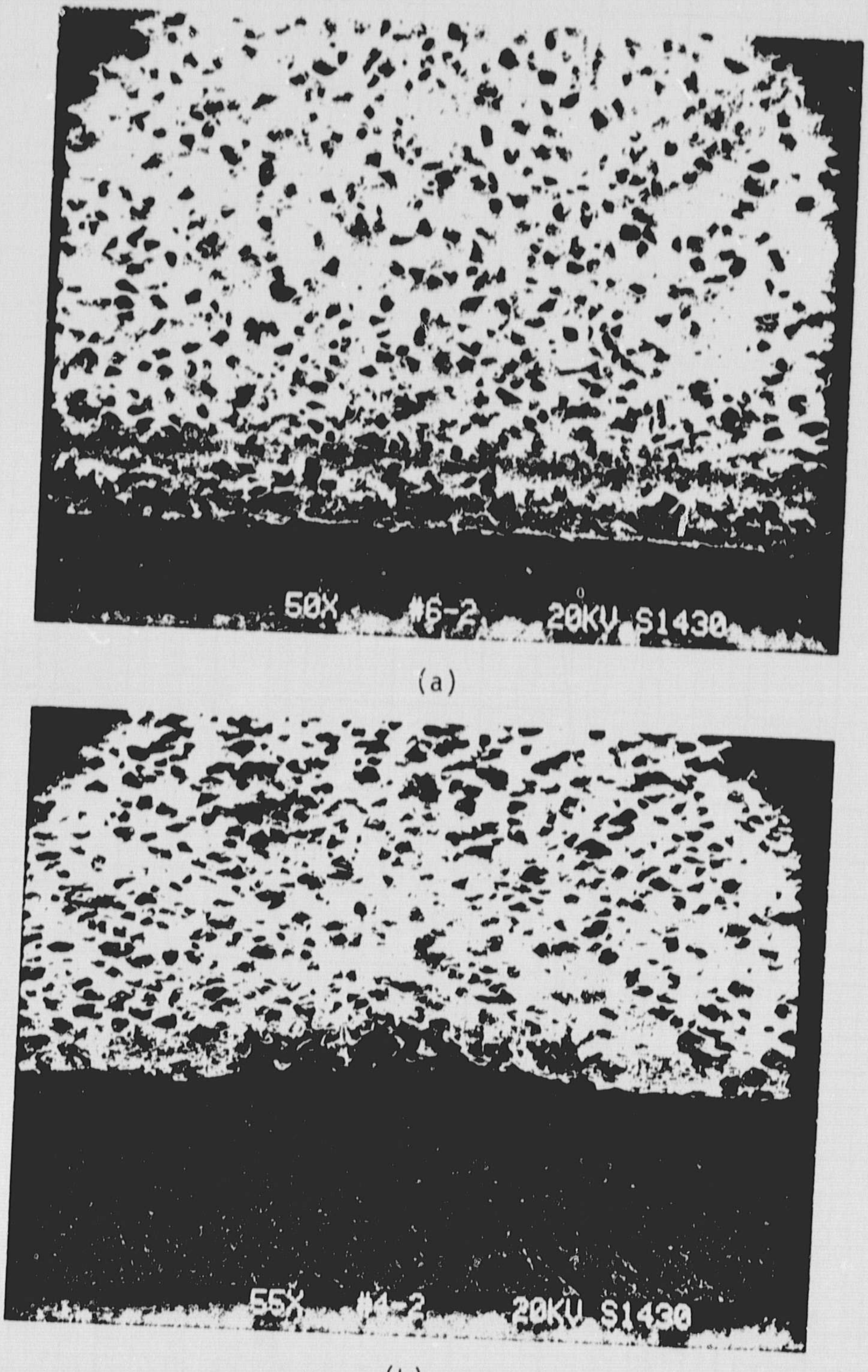

FIGURE II-21 - SEM PICTURES OF USED I.D. BLADES THIN BLADES SHOWING:

(a) IRREGULAR WEAR AT CUTTING EDGE

(b) CHIPPING AT CUTTING EDGE

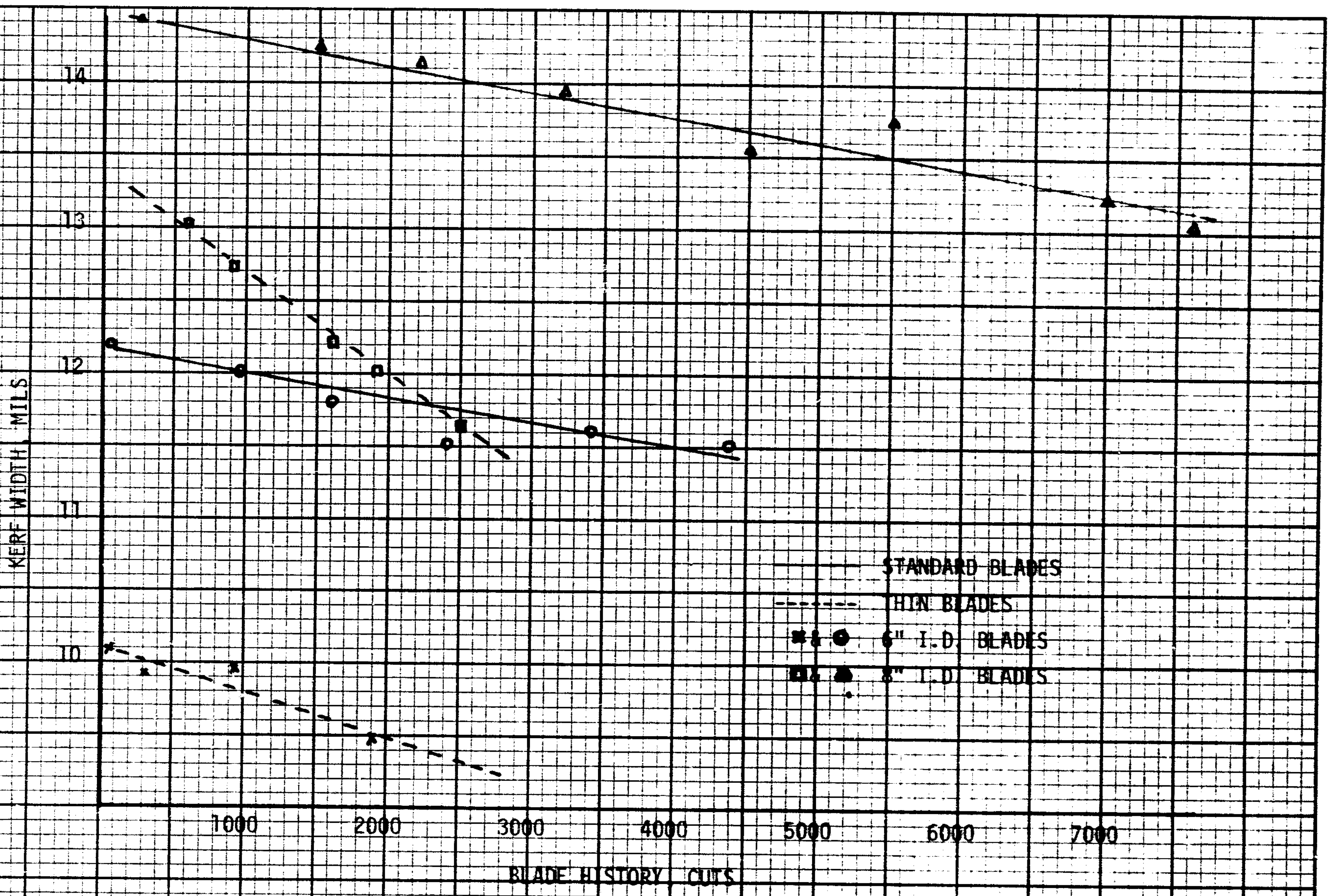

FIGURE II-22 - KERF WIDTH VERSUS HISTORY (NUMBER OF CUTS) OF I.D. BLADES

III. COST ANALYSIS

Input data for SA,OCS were obtained from the slicing experiments performed and the costs were estimated based on SAMICS Workbook (September, 1977). Cost assessment on wire saw slicing was obtained from the information supplied by the manufacturer who did a slicing test for this project. For the clarity of the assessment, major assumptions are identified and detailed input data is given in Appendices. All the cost information given here is based on the price year 1977.

1.0 ADD-ON SLICING COST

MBS saw slicing method is a batch process (versus continuous). Thus a batch of 219 wafers for the 3" wafers and 193 wafers for the 4" wafers were selected from the wafer yields obtained. Detailed input data for capital equipment, space, labor, materials and utilities is given in Appendix I. The add-on slicing costs per yielded wafer were \$0.80 and \$1.41 for the 3" wafers and the 4" wafers, respectively, corresponding to \$177/m^2 for the 3" wafers and \$174/m^2 for the 4" wafers. Important assumptions are: (1) the blade package can be used three (3) times for the 3" ingot and one and a half (1-1/2) times for the 4" ingots, and (2) the slurry is used only once; in other words, not recycled.

Add-on slicing cost for MWS saw was obtained from the slicing information sheets that OCLI sent to Yasunaga Engineering Co. A wafer yield of 97% for the 3" wafers gave a batch process of 158 yielded wafers and the cost was estimated to be around \$0.85/wafer or \$186/m^2. Detailed input data is given in Appendix III. The major assumption is that the wire and the slurry were not recycled.

Add-on slicing cost of the I.D. saw varies depending on the cut rate and yield etc. Dependence of wafer yields on wafer thickness is well demonstrated in the experiments (see Figure I-2 and Figure I-3) and, within a certain range of cut rate (i.e. below 3 IPM of cut rate), mechanical wafer yield is constant down to a certain limit of wafer thickness; this limit is estimated to be in the range of 12-14 mils. In this range slicing tests showed yields close to 100%, experimentally. However, from practical industry production, 96% wafer yield was used for the cost assessment. Detailed input data for the add-on slicing cost is given in Appendix II for both 3" and 4" wafers sliced at two (2) IPM of cut rate, giving the cost of \$0.17/wafer (\$37/m^2) for the 3" wafers and \$0.24/wafer (\$30/m^2) for the 4" wafers (same wafer thickness sawn with MBS saw was intentionally chosen for proper comparison in overall wafer cost). To see the effect of cut rate on overall add-on slicing cost, Table III-1 is included. The table suggests that significant reduction in the cost can be expected by increasing the cut rate from one (1) IPM to two (2) IPM, indicating that the cost related to the machine productivity, such as capital equipment and space, are the major factors within this range of cut rate. However, smaller reduction of the cost is expected beyond three (3) IPM of cut rate, since some other factors, such as labor and materials start to play the dominant role in the cost.

2.0 WAFER COST

Wafer cost includes material (Si) cost in addition to add-on slicing cost. Table III-2 gives wafer costs of different slicing types at various ingot price levels. The main purpose of this table is to

TABLE III-1

DEPENDENCE OF ADD-ON SLICING COST (SAMICS) ON CUT RATE OF I.D. SAW

INGOT SIZE	3"		4"	
Cut Rate, Inch/Min.	\$/wafer	\$/m^2	\$/wafer	\$/m^2
1	0.29	64	0.39	48
2	0.17	37	0.24	30
3	0.13	29	0.19	23

NOTE

1. Dependence of blade lifetime and wafer yield (96%) on cut rate of I.D. saw was not considered.

TABLE III-2

SILICON WAFER COST (SAMICS) OF DIFFERENT SLICING TYPES AT VARIOUS INGOT PRICE LEVELS

INGOT SIZE	3"						4"			
SLICING TYPE	MBS		MWS		I.D.		MBS		I.D.	
INGOT PRICE $/Kg	$/Wafer	$/m^2	$/Wafer	$/m^2	$/Wafer	$/m^2	$/Wafer	$/m^2	$/Wafer	$/m^2
150	2.5	548	1.9	417	1.5	329	4.4	543	2.8	345
120	2.0	439	1.7	373	1.2	263	3.8	469	2.3	284
90	1.7	373	1.5	329	1.0	219	3.2	395	1.8	222
50	1.3	285	1.2	263	0.6	132	2.4	296	1.1	136

NOTE

1. Ingot Price: Grind Ingot Price
2. MBS Wafer: 13.2 mils wafer thickness and 12.8 mils Kerf width for 3"
   13 mils wafer thickness and 13 mils Kerf width for 4"
3. MWS Wafer: 10.6 mils wafer thickness and 7.9 mils Kerf width for 3"
4. I.D. Saw Wafer: 13 mils wafer thickness and 12 mils Kerf width for 3"
   13 mils wafer thickness and 13 mils Kerf width for 4"

see the effect of material (Si) cost on overall wafer cost and not to compare with the cost between different slicing types because different wafer thicknesses were considered and they are also not optimized thicknesses. By decreasing ingot price three (3) times, from $150/Kg to $50/Kg, wafer cost reduced less than two (2) times for both MBS and MWS saw slicing while decreasing the cost two and a half (2-1/2) times for the I.D. saw slicing, implying material cost (Si) is dominant factor in the I.D. saw wafers while it is less dominant in the MBS and MWS saw wafers.

Thickness dependence of wafer cost was obtained from the wafers sliced with the I.D. saw. Table III-3 gives a silicon cost per unit yielded area, in which actual thickness dependence of wafer yield was considered from the slicing tests performed at two cut rates (one IPM and two IPM). A final wafer cost, which is a sum of silicon cost and add-on slicing cost, is obtained in Table III-5. Reasonable prediction in add-on cost given in Table III-4 in which yield factors are also incorporated. Figure III-1 is a plot of Table III-5, showing wafer cost versus wafer thickness and cut rate (or yield) at three different years. The figure indicates that a significant reduction in wafer cost can be achieved by decreasing both the wafer thickness and the cut rate. However, the advantages of fast cutting were observed for wafers of thickness greater than about 12 mils leading to low add-on cost.

TABLE III-3

SILICON COST (SAMICS) PER UNIT YIELDED AREA OF 3" WAFERS AS A FUNCTION OF WAFER THICKNESS; I.D. SAW

WAFER THICKNESS, MILS	YIELDS OBTAINED		COST, $/m^2					
			CUT RATE, 1 IPM			CUT RATE, 2 IPM		
	1 IPM	2 IPM	1978	1980	1982	1978	1980	1982
16	1.00	.98	259	194	108	264	198	110
14	1.00	.96	240	180	100	250	188	104
12	1.00	.92	222	166	92	241	181	100
10	1.00	.82	203	152	85	247	186	103
8	1.00	.60	184	138	77	307	230	128
6	0	0	∞	∞	∞	∞	∞	∞

NOTE

1. Kerf Width: 12 mils
2. Yields Obtained From Figure II-2
3. Cost of Ingot: 1978 - 120 $/Kg
   1980 - 90 $/Kg
   1982 - 50 $/Kg

TABLE III-4

SLICING ADD-ON COSTS (SAMICS) PER UNIT YIELDED AREA OF 3" WAFERS AS A FUNCTION OF WAFER THICKNESS; I.D. SAW

WAFER THICKNESS, MILS	COST, $\$/m^2$					
	CUT RATE, 1 IPM			CUT RATE, 2 IPM		
	1978	1980	1982	1978	1980	1982
16	55	35	15	31	20	10
14	55	35	15	31	21	10
12	55	35	15	33	22	11
10	55	35	15	37	24	12
8	55	35	15	50	33	17
6	∞	∞	∞	∞	∞	∞

ASSUMPTIONS

1. Slicing Add-On Cost at 1 Inch/Minute of Cut Rate:
   Year 1978: 55 $\$/m^2$
   1980: 35 $\$/m^2$ } At 100% Yield
   1982: 15 $\$/m^2$

2. Slicing Add-On Cost at 2 Inch/Minute of Cut Rate:
   Year 1978: 30 $\$/m^2$
   1980: 20 $\$/m^2$ At 100% Yield
   1982: 10 $\$/m^2$

TABLE III-5

WAFER COST (SAMICS) PER UNIT YIELDED AREA OF 3" WAFER AS A FUNCTION OF WAFER THICKNESS; I.D. SAW

WAFER THICKNESS, MILS	COST, $\$/m^2$					
	CUT RATE, 1 IPM			CUT RATE, 2 IPM		
	1978	1980	1982	1978	1980	1982
16	314	229	123	295	218	120
14	295	215	115	281	209	114
12	277	201	107	274	203	111
10	258	187	100	284	210	115
8	239	173	92	357	263	145
6	∞	∞	∞	∞	∞	∞

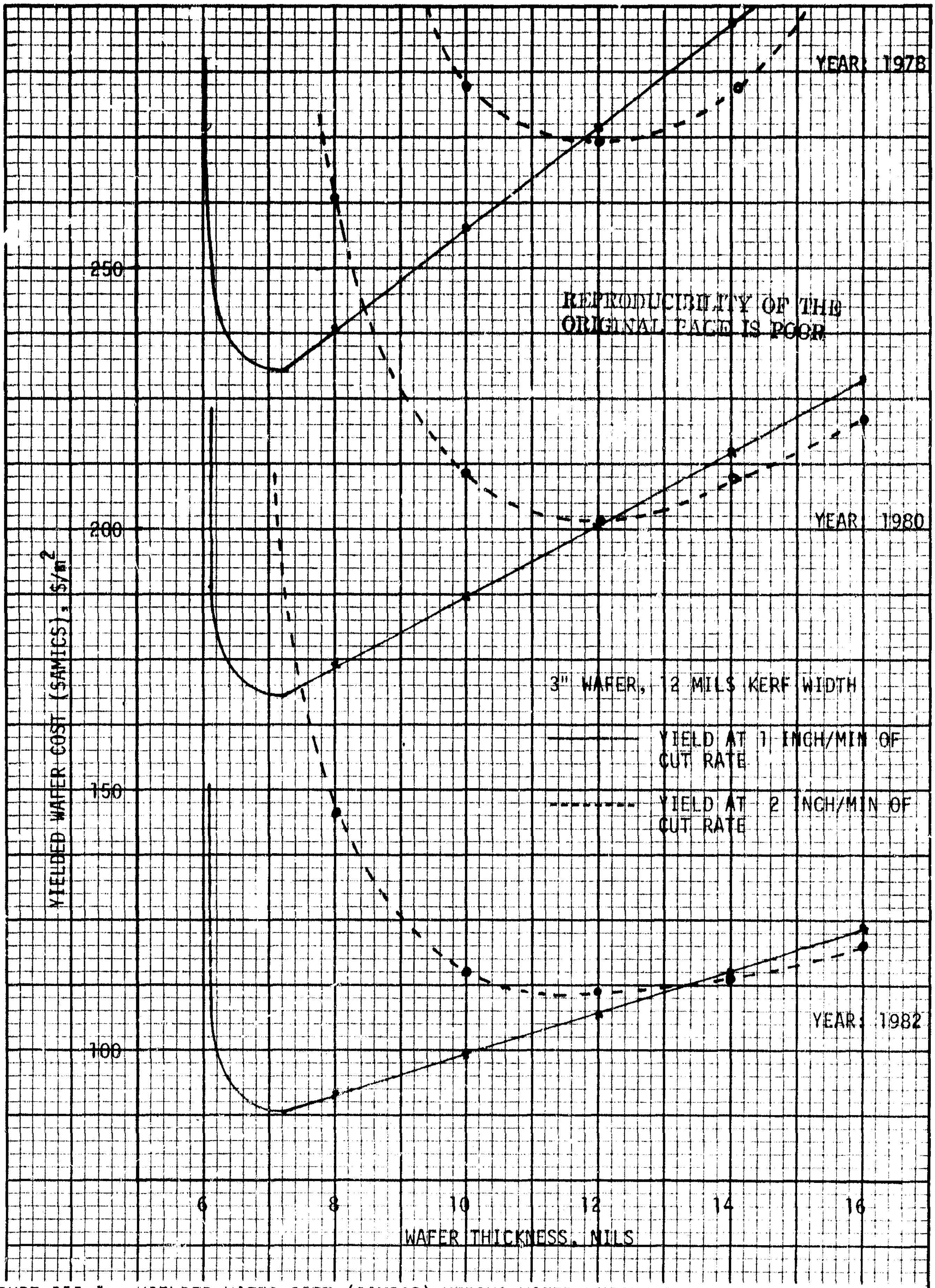

FIGURE III-1 - YIELDED WAFER COST (SAMICS) VERSUS WAFER THICKNESS OF I.D. SAW CUT WAFERS

3.0 REDUCTION POTENTIAL

3.1 MBS Saw

Assessment of add-on slicing cost from these specific slicing tests might not have used optimized slicing conditions for the MBS saw. However, the slicing condition was the one that OCLI has used to slice silicon ingots for solar cell fabrication for last ten years without giving any significant risk of spoiling whole ingots or in wafer yields. Optimistic add-on slicing costs can possibly decrease to about $0.50/wafer for the 3" wafers if the pin type blade package (price is about one third of the preassembled blade package) can be successfully applied to achieve the same wafer yield, wafer thickness and quality, and if labor related costs can be reduced by automation or elimination of P.C. oil as a suspension media.

Comparison of add-on slicing cost of different slicing types is shown in Table III-6, in which priority for future cost reduction effort can be seen. It suggests that cost reduction for the MBS saw slicing strongly depends on success in reducing the cost incurred by direct material and direct labor, especially direct material in which the blade package and slurry form a major portion of the cost. Increase in productivity, by increasing number of blades using an inexpensive method, can further reduce the cost by reducing the cost related to capital equipment and space.

TABLE III-6

COMPARISON OF ADD-ON SLICING COST (SAMICS) OF DIFFERENT SLICING TYPES

INGOT SIZE	3"						4"			
SLICING TYPE	MBS		MWS		I.D.		MBS		I.D.	
	$/Wafer	%	$/Wafer	%	$/Wafer	%	$/Wafer	%	$/Wafer	%
EQUIPMENT	0.066	8.2	0.091	10.7	0.060	34.3	0.151	10.3	0.091	37.8
SPACE	0.029	3.6	0.028	3.3	0.030	17.1	0.065	4.4	0.039	16.2
DIRECT LABOR	0.158	19.6	0.197	23.2	0.044	25.1	0.222	15.2	0.043	17.8
DIRECT MATERIALS	0.552	68.6	0.531	62.6	0.039	22.3	0.974	69.9	0.065	27.0
UTILITIES	0.001	-----	0.001	0.2	0.002	1.2	0.002	0.2	0.003	1.2
TOTAL	0.806 (177)	100	0.848 (186)	100	0.175 (38)	100	1.414 (174)	100	0.241 (30)	100

NOTE

1. Numbers in parenthesis represent add-on costs in unit of $\$/m^2$.
2. Two (2) inch/minute of cut rate was considered for I.D. saw slicing.

3.2 MWS Saw

The slicing performed may not have been most economical condition for the machine. Further reduction in cost can possibly be achieved with the existing system by better utilization of wires and slurry, and by elimination of P.C. oil as a suspension media. This will decrease both direct labor and direct material cost. By increasing the wire lifetime two times, recycling slurry twice and improvement in oil degreasing step, reduction in add-on cost for the 3" wafers can lead to about $0.50/wafer.

At present the machine has limited capacity to handle large diameter or long ingots; the maximum limit is 4" diameter and 4" in length. Scale up of the machine will bring cost reduction by increasing the machine productivity.

3.3 I.D. Saw

Among the three slicing types discussed, the I.D. saw is the only slicing method where automation from slicing of an ingot to final wafer cleaning is possible due to its continuous slicing characteristics. This automation process is commercially available with an additional capital cost. Using this system, preliminary results indicated that two cents (2¢) of cost reduction can be achieved for the 3" wafers, resulting in $0.15/wafer. Future cost reduction can be expected in the following areas; increase in machine productivity and decrease in kerf width. Machine productivity can be achieved by:

1) Ganging two or more blades

2) Programmed slicing; i.e. controlled cut rate while slicing.

and kerf width reduction can be obtained by:

1) Development of thin blade

2) Rotating crystal slicing system

Programmed slicing machines are now commercially available and overall faster cutting speed are claimed. Effectiveness of the rotating crystal system(4) was already demonstrated by slicing Gadolinium Gallium Garnet with an I.D. saw. Since the rotating crystal system only needs to cut half of a ingot, a thinner blade can be used to slice same ingot size compared to an I.D. blade without rotated crystal system, consequently leading to lower kerf loss. Blade liftime has also increased about three times mainly due to the effective cooling at the cutting edge. Thus, a most ideal slicing system for the I.D. saw could be a programmed-rotating crystal-ganged I.D. saw.

4.0 DISCUSSION

Since the ultimate goal of JPL-DOE program is expressed in unit of dollar per electrical peak output ($/Wp), the cost of silicon sheet ($/m^2) has to be converted to $/Wp through an intermediate conversion parameter (or a mechanical-electrical conversion parameter); m^2/Wp. Minimum $/m^2 does not necessarily lead to minimum $/Wp because the electrical quality of the sliced wafers (surface damage) and thickness dependence of solar cell output, for example, were not considered in the formation of the silicon sheet. This gives an expression:

$$\$/\mathrm{Wp} = (\$/\mathrm{m}^2) \times (\mathrm{m}^2/\mathrm{Wp})$$

Once the conversion parameter (m^2/Wp) is obtained as a function of solar cell thickness, the wafer thickness, which will give a minimum $/Wp, can be obtained by minimization of the product of two functions; $/m^2 and m^2/Wp. This process is illustrated in Figure III-2 for the case of the I.D. saw wafers.

The conversion parameter, m^2/Wp, also depends on the type of solar cell fabrication, i.e., methods of junction formation, with and without back surface field, etc. Thus, proper choice of a fabrication process which is suitable to terrestrial solar cell application should be made. This suggests that a systems approach is needed to optimize slicing process (it may be called a subsystem of a whole solar module fabrication process), in which input is a ingot and output is wafers which will provide maximum electrical power output after solar cell fabrication. Slicing conditions can be internal variables of this subsystem.

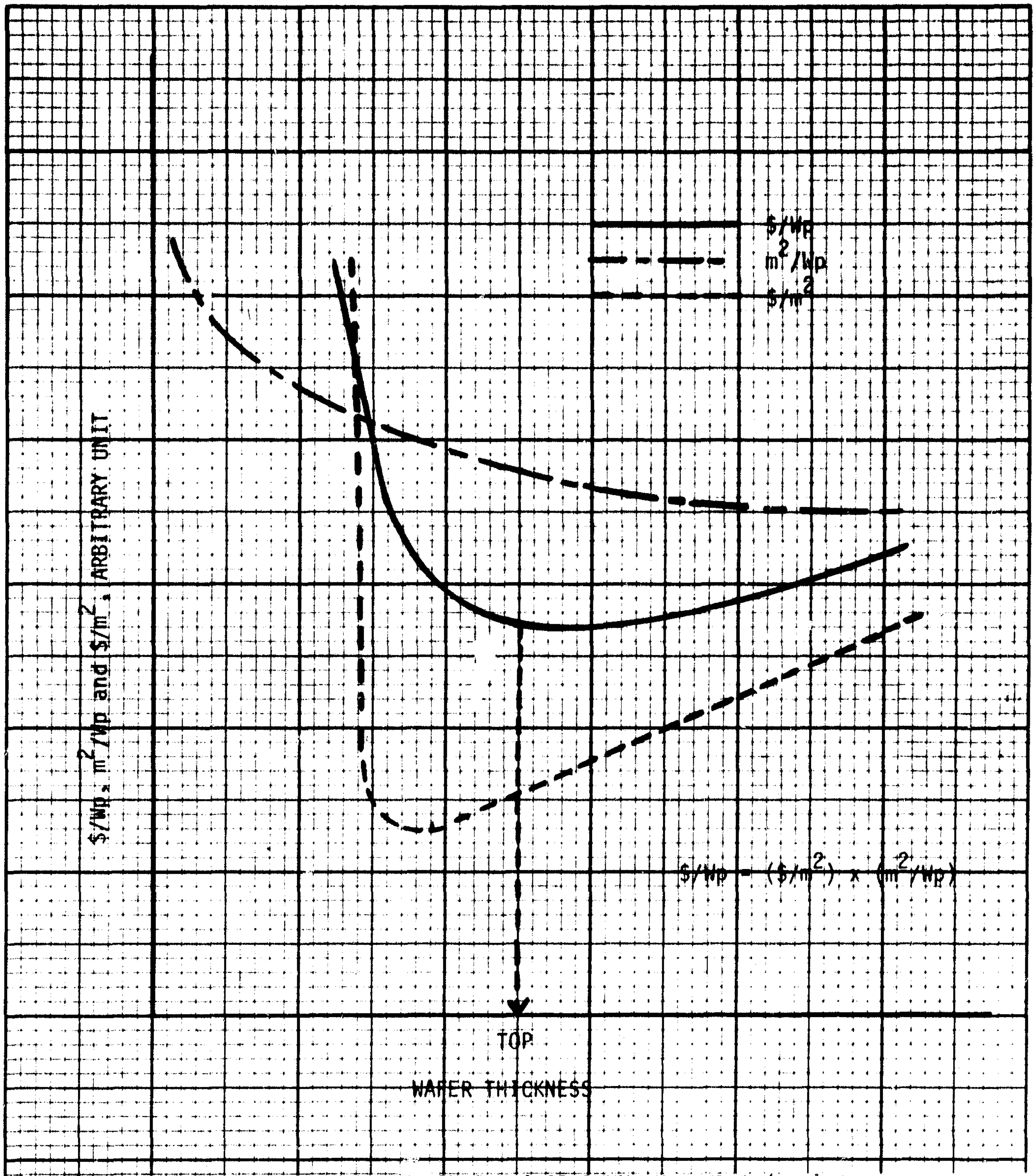

FIGURE III-2 - AN ILLUSTRATION O[illegible]INDING A OPTIMUM THICKNESS (TOP) OF I.D. WAFERS

IV. CONCLUSIONS AND RECOMMENDATIONS

Evaluation of the slicing experiments performed indicated:

- SAMICS cost assessment indicated that the I.D. saw slicing is more favorable than the MBS saw and MWS saw techniques at present, and its capability of automation, which is essential for large volume production, adds advantage over the other two methods. Preliminary results indicated that the I.D. saw slicing technique will meet the slicing goal in 1982 without significant innovation of the slicing techniques. However, significant improvement in blade package, slurry, wire and machine capacity are needed to meet the goal for the MBS saw and MWS saw.

- An advantage of lower kerf loss by the MWS saw slicing was obtained at an expense of higher add-on slicing cost over the I.D. saw and MBS saw.

- Mechanical wafer parameters such as thickness variation, taper, bow and roughness, were considerably better for wafers sliced with the I.D. saw and MWS saw than for those with the MBS saw. Wafers sawn with the I.D. saw (sliced at two IPM of cut rate) showed slightly better parameters than those with the MWS saw.

- The add-on slicing cost should be assessed with the specification of thickness, kerf loss, and diameter of the wafers to be sliced, because they are the major parameters which will strongly influence the overall slicing cost. Finally the surface damage generated by the slicing methods should be investigated and the electrical power output that can be obtained from the sliced wafer should be incorporated in the overall assessment. In other words, a systems approach in necessary to obtain optimum slicing conditions.

- Preliminary results using thin I.D. blades was not successful mainly due to low lifetime of the blade. Development of I.D. blades which will give low kerf loss with long life is needed.

- The following areas of development of I.D. saw machine design are suggested, to achieve further reduction of the cost:

  (1) Improvement in machine productivity.

  (2) Use of a rotating crystal system.

  (3) Development of techniques to detect mechanical instability (or vibration) of I.D. blades while slicing, either due to blade head or loosness of blade tension etc.

V. REFERENCES

1. H. I. Yoo, "Assessment of Present State-of-the-Art Sawing Technlogy of Large Diameter Ingots for Solar Sheet Material," First Quarterly Report, 1977.

2. The Staff of STC, "Selecting and Using the I.D. Diamond Blade," Industrial Diamond Review, p.p. 10, January, 1975.

3. S. C. Holden, "Slicing of Silicon Into Sheet Material," (Varian Associates, Lexington Vacuum Division) JPL Contract 954374, Third Quarterly Report, p.p. 3, December, 1976.

4. J. Grandia and J. Hill, "Improved Slicing and Orientation Techniques for I.D. Sawing," Solid State Technology, p.p. 40, February, 1978.

APPENDIX I

APPLICATION OF SAMICS TO THE MULTIBLADE SLURRY (MBS) SAW SLICING

SLICING OF 3" WAFERS

A. DESCRIPTION OF THE SLICING

1. Batch Process: 219 Yielded Wafers Per Batch

2. Average Slicing Cycle: 10.6 Hours/Batch

Slicing Time:	10	Hours
Machine Down-Time*:	0.6	Hours
Total	10.6	Hours/Batch

3. Wafers Per Operating Minute: $\frac{219}{10 \times 60}$ = 0.364 Wafers/Operating Minute

4. Process Usage Time Fraction: $\frac{10}{10.6} = 0.94$

B. EQUIPMENT AND MANUFACTURING SPACE

1. Salvage Value: 10% of the New Machine Price

2. Manufacturing Space: Three (3) Times of a Machine Space

C. DIRECT LABOR REQUIREMENT

1. General Assembler:

Ingot Mount on Graphite:	15	Minutes
Ingot Mount on Machine:	6	Minutes
Ingot Demount From Machine:	6	Minutes
Wafer Demount and Degrease:	90	Minutes
Final Clean:	13	Minutes
Operator's Attention:	24	Minutes
Total	154	Minutes/Batch
	= 2.57	Hours/Batch

PRSN * YRS Conversion

PRSN * YRS/Machine/Shift = $2.57 \times \frac{8}{10.6} \times \frac{1}{8} = 0.242$

For Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

PRSN * YRS = 0.242 x 4.7 = 1.14

SLICING OF 3" WAFERS (Continued)

2. Maintenance Mechanics II

Blade Package Tensioning and Alignment: 0.5 Hours/Batch

PRSN * YRS Conversion

PRSN * YRS/Machine/Shift $= 0.5 \times \frac{8}{10.6} \times \frac{1}{8} = 0.047$

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

$$\text{PRSN * YRS} = 0.047 \times 4.7 = 0.22$$

D. DIRECT MATERIAL REQUIREMENT

1. Blade Package: Three (3) Batches can be Sliced Using a Blade Package
2. Slurry: Slurry was Used for One Batch Slicing Only

*Machine Down Time (Hours/Batch)

Blade Package Alignment and Tensioning:	0.33 Hours
Ingot Mount:	0.1 Hours
Ingot Demount:	0.1 Hours
Miscellaneous:	0.07 Hours
Total	0.6 Hours/Batch

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Drive, Pasadena, California 91103

A1 Process Referent MBS

A2 Description (Optional) Slicing of 3" diameter silicon ingot by MBS saw.

PART 1 – PRODUCT DESCRIPTION

A3 Product Referent MBS-3

A4 Name or Description 3" wafers sliced by MBS saw. Kerf width 12.8 mils and wafer thickness 13.2 mils.

A5 Units Of Measure Wafer (a batch of 219 wafers)

PART 2 – PROCESS CHARACTERISTICS

A6	Output Rate	0.364	Units (given on line A5) Per Operating Minute
A7	Average Time at Station	-----	Calendar Minutes
A8	Process Usage Time Fraction	0.94	Average Number of Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS

A9	Component Referent	Varian-686		
A10	Base Price Year For Purchase Price	77		
A11	Purchase Price ($ Per Component)	25,000		
A12	Anticipated Useful Life (Years)	7		
A13	Salvage Value ($ Per Component)	2,500		
A14	Cost of Removal & Installation ($/Component)	300		

Format A Process Description (Continued)

A14 Process Referent (From Page 1) MBS

PART 4 – DIRECT REQUIREMENTS PER MACHINE

A16 Catalog Number	A17 Requirement Description	A18 Amount Required Per Machine	A19 Units
A 2064 D	Manufacturing Space (Type A)	50	Square Feet
B 3064 D	General Assembler	1.14	PRSN * YRS
B 3736 D	Maintenance Mechanics II	0.22	PRSN * YRS

PART 5 – DIRECT REQUIREMENTS PER BATCH (A continuous process has a "batch" of one unit)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Batch	A23 Units
G 1012 D	Shellac Clear Spray	0.1	Can
G 1030 D	Cement, Do All No Load	0.4	Lbs.
G 1016 D	Graphite Beam Mount	0.5	Each
G 1032 D	SiC, 400 Grit	12	Lbs.
G 1034 D	P.C. Oil	1.8	Gal.
G 1036 D	TCE, Tech. Grade	2	Gal.
G 1038 D	Multiblade Package	1/3	Pkg.

(Continued - Attachment A)

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A24 Product Reference	A25 Product Name	A26 Yield Factor (Usable Output/Input)	A27 Units
GSIG	Grind 3" Si Ingot	135	Wafer/Kg

Prepared by A. Yoo **Date** 3/1/78

ATTACHMENT A

PART 5 - DIRECT REQUIREMENTS PER BATCH (Continued from Page 2)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Machine	A23 Units
C 1032 B	Electricity	5	KW Hour
D 1064 D	Rejected Wafers	11	Wafer

COMMODITIES PER CYCLE

P11 Catalog Number	P12 Annual Quantity	P13 Uninflated Price	P14 Inflated Price	P15 Commodities Expense
G 1012 D	45.7	$ 3.01		$ 137
G 1030 D	182.8	$ 5.24		$ 958
G 1016 D	228.3	$ 1.88		$ 429
G 1032 D	5,480	$ 1.35		$ 7,398
G 1034 D	822	$ 4.74		$ 3,896
G 1036 D	913	$ 3.50		$ 3,196
G 1038 D	152.2	$ 175.00		$ 26,636

UTILITIES PER CYCLE

P16 Catalog Number	P17 Annual Quantity	P18 Uninflated Price	P19 Inflated Price	P20 Utilities Expense
C 1032 B	2,283	$ 0.032		$ 73

Prepared by ____________________ **Date** __________

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena, Calif 91103

PROCESS WORK SHEET

P1 PROCESS REFERENCE MBS

LABOR PRICES AND COSTS PER MACHINE

P2 Catalog Number	P3 Inflated Price	P4 Cost	P2 Catalog Number	P3 Inflated Price	P4 Cost
B 3064 D	$ 8,748	$ 9,973			
B 3736 D	$ 12,744	$ 2,804			

BYPRODUCTS PER CYCLE

P5 Catalog Number	P6 Annual Quantity	P7 Uninflated Price	P8 Inflated Price	P9 Byproduct Expense	P10 Byproduct Revenue
D 1064 D	4,800	$ - 0.041			$ 197

COMPANY WORK SHEET

W1 Wafco

W2 3" Wafers, 100,000

W3 MBS

W4 3" Ingot

W5 135 Wafer/Kg

W6 740.7 Kg

W7 274,725

W8 466,992

W9 0.588

W10 $ 22,800

W11 $ 13,406

W12 50

W13 29.4

W14 $ 12,777

W15 $ 7,513

W16 -------

W17 $ 42,650

W18 $ 73

W19 $ 197

W20 $ 13,406

W21 29.4

W22 $ 7,513

W23 -------

W24 $ 42,650

W25 $ 73

W26 $ 197

W27 -------

W28 -------

W29 $ 42,650

W30 $ 0.80

W31 -------

Prepared by JC Yoo Date 3/1/78

SLICING OF 4" WAFERS

A. DESCRIPTION OF THE SLICING

1. Batch Process: 193 Yielded Wafers Per Batch
2. Average Slicing Cycle: 21.5 Hours/Batch

Slicing Time:	20.5 Hours
Machine Down-Time*:	1.0 Hours
Total	21.5 Hours/Batch

3. Wafers Per Operating Minute: $\frac{193}{20.5 \times 60} = 0.157$ Wafers/Operating Minute
4. Process Usage Time Fraction: $\frac{20.5}{21.5} = 0.95$

B. EQUIPMENT AND MANUFACTURING SPACE

1. Salvage Value: 10% of the New Machine Price
2. Manufacturing Space: Three (3) Times of a Machine Space

C. DIRECT LABOR REQUIREMENT

1. General Assembler:

Ingot Mount on Graphite:	15	Minutes
Ingot Mount on Machine:	6	Minutes
Ingot Demount on Machine:	6	Minutes
Wafer Demount and Degrease:	90	Minutes
Final Clean:	13	Minutes
Operator's Attention:	27	Minutes
Total	157	Minutes/Batch
	= 2.62	Hours/Batch

PRSN * YRS Conversion

PRSN * YRS/Machine/Shift $= 2.62 \times \frac{8}{21.5} \times \frac{1}{8} = 0.122$

For Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

PRSN * YRS $= 0.122 \times 4.7 = 0.573$

SLICING OF 4" WAFERS (Continued)

2. Maintenance Mechanics II

Blade Pakage Tensioning and Aligning: 1 Hours/Batch

PRSN * YRS Conversion

$$\text{PRSN * YRS/Machine/Shift} = 1 \times \frac{8}{21.5} \times \frac{1}{8} = 0.047$$

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

$$\text{PRSN * YRS} = 0.047 \times 4.7 = 0.22$$

D DIRECT MATERIAL REQUIREMENT

1. Blade Package: One and a Half $(1\frac{1}{2})$ Batches can be Sliced Using a Blade Package
2. Slurry: Slurry was Used for One Batch Slicing Only

*Machine Down Time (Hours/Batch)

Blade Package Alignment and Tensioning:	0.7 Hours
Ingot Mount:	0.1 Hours
Ingot Demount:	0.1 Hours
Miscellaneous:	0.1 Hours
Total	1.0 Hours/Batch

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

A1 Process Referent MBS

A2 Description (Optional) Slicing of 4" diameter Si ingot by MBS saw

PART 1 – PRODUCT DESCRIPTION

A3 Product Referent MBS-4

A4 Name or Description 4" wafers sliced by MBS saw, Kerf width 13 mils and wafer thickness 13 mils.

A5 Units Of Measure Wafer (a batch of 193)

PART 2 – PROCESS CHARACTERISTICS

A6	Output Rate	0.157	Units (given on line A5) Per Operating Minute
A7	Average Time at Station	-----	Calendar Minutes
A8	Process Usage Time Fraction	0.95	Average Number of Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS

A9	Component Referent	Varian-686		
A10	Base Price Year For Purchase Price	77		
A11	Purchase Price ($ Per Component)	25,000		
A12	Anticipated Useful Life (Years)	7		
A13	Salvage Value ($ Per Component)	2,500		
A14	Cost of Removal & Installation ($/Component)	300		

Format A Process Description (Continued)

A14 Process Referent (From Page 1) MBS

PART 4 – DIRECT REQUIREMENTS PER MACHINE

A16 Catalog Number	A17 Requirement Description	A18 Amount Required Per Machine	A19 Units
A 2064 D	Manufacturing Sapce (Type A)	50	Square Feet
B 3064 D	General Assembler	0.573	PRSN * YRS
B 3736 D	Maintenance Mechanic II	0.22	PRSN * YRS

PART 5 – DIRECT REQUIREMENTS PER BATCH (A continuous process has a "batch" of one unit)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Batch	A23 Units
G 1012 D	Shellac Clear Spray	0.1	Can
G 1030 D	Cement, Do All No Load	0.4	Lbs.
G 1018 D	Graphite Beam Mount	1	Each
G 1032 D	SiC, 400 Grit	12	Lbs.
G 1034 D	P.C. Oil	1.8	Gal.
G 1036 D	TCE, Tech. Grade	2	Gal.
G 1038 D	Multiblade Package	2/3	Pkg.

(Continued - Attachment A)

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A24 Product Reference	A25 Product Name	A26 Yield Factor (Usable Output/Input)	A27 Units
GSIG	Grind 4" Si Ingot	67.2	Wafer/Kg

Prepared by H Goo **Date** 3/1/78

ATTACHMENT A

PART 5 - DIRECT REQUIREMENTS PER BATCH (Continued from Page 2)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Machine	A23 Units
C 1032 B	Electricity	10	KW Hour
D 1064 D	Rejected Wafers	37	Wafer

COMMODITIES PER CYCLE

P11 Catalog Number	P12 Annual Quantity	P13 Uninflated Price	P14 Inflated Price	P15 Commodities Expense
G 1012 D	51.8	$ 3.01		$ 156
G 1030 D	207.3	$ 5.24		$ 1,086
G 1018 D	518	$ .88		$ 456
G 1032 D	6,218	$ 1.35		$ 8,394
G 1034 D	933	$ 4.74		$ 4,422
G 1036 D	1,036	$ 3.50		$ 3,626
G 1038 D	345.4	$ 175.00		$ 60,445

UTILITIES PER CYCLE

P16 Catalog Number	P17 Annual Quantity	P18 Uninflated Price	P19 Inflated Price	P20 Utilities Expense
C 1032 D	5,181	$ 0.032		$ 166

Prepared by ______________________ Date ____________

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

PROCESS WORK SHEET

P1 PROCESS REFERENCE MBS-4

LABOR PRICES AND COSTS PER MACHINE

P2 Catalog Number	P3 Inflated Price	P4 Cost
B 3064 D	$ 8,748	$ 5,013
B 3736 D	$ 12,744	$ 2,804

P2 Catalog Number	P3 Inflated Price	P4 Cost

BYPRODUCTS PER CYCLE

P5 Catalog Number	P6 Annual Quantity	P7 Uninflated Price	P8 Inflated Price	P9 Byproduct Expense	P10 Byproduct Revenue
D 1064 D	19,160	$ -0.19			$ 3,640

COMPANY WORK SHEET

W1 Wafco

W2 4" Wafer, 100,000

W3 MBS-4

W4 4" Ingot

W5 67.2 Wafer/Kg

W6 1,488.1 Kg

W7 636,943

W8 471,960

W9 1.35

W10 $22,800

W11 $30,780

W12 50

W13 67.5

W14 $7,817

W15 $10,553

W16 -------

W17 $78,585

W18 $166

W19 $3,640

W20 $30,780

W21 67.5

W22 $10,553

W23 -------

W24 $78,585

W25 $166

W26 $3,640

W27 -------

W28 -------

W29 $78,585

W30 $1.41

W31 -------

Prepared by H. Yoo Date 3/1/78

APPENDIX II

APPLICATION OF SAMICS TO THE INTERNAL DIAMETER (I.D.) SAW SLICING

SLICING OF 3" WAFERS

A. DESCRIPTION OF THE SLICING

1. A Continuous Process

Cut Rate: Two (2) Inch/Minutes
Wafer Yield: 96%

2. Average Slicing Cycle Per Wafer: 1.912 Minutes

Slicing Time:	1.875 Minutes
Machine Down Time*:	0.037 Minutes
Total	1.912 Minutes

3. Wafers Per Operating Minute:

$$\frac{1}{1.875} = 0.533 \text{ Wafers/Operating Minute}$$

4. Process Usage Time Fraction:

$$\frac{1.875}{1.912} = 0.98$$

B. EQUIPMENT AND MANUFACTURING SPACE

1. Salvage Value: 10% of the New Machine Price

2. Manufacturing Space: Three (3) Times of a Machine Space

C. DIRECT LABOR REQUIREMENT

1. General Assembler

Ingot Mount:	0.023 Minutes
Blade Dressing:	0.014 Minutes
Wafer Demount:	0.100 Minutes
Final Clean:	0.060 Minutes
Operator's Attention:	0.030 Minutes
Total	0.227 Minutes/Wafer

PRSN * YRS Conversion

PRSN * YRS/Machine/Shift:

$$0.227 \times \frac{8 \times 60}{1.912} \times \frac{1}{8 \times 60} = 0.119$$

SLICING OF 3" WAFERS (Continued)

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

$$\text{PRSN} * \text{YRS} = 0.119 \times 4.7 = 0.56$$

2. Maintenance Mechanics II

Blade Mount and Tensioning: 0.017 Minutes/Wafer

PRSN * YRS/Machine/Shift:

$$0.017 \times \frac{8 \times 60}{1.912} \times \frac{1}{8 \times 60} = 0.009$$

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vaction and Sick Days Etc.

$$\text{PRSN} * \text{YRS} = 0.009 \times 4.7 = 0.042$$

D. DIRECT MATERIAL REQUIREMENT

1. Six Inch (6) I.D. Blade

Lifetime of the Blade: 3,000 Cuts

*Machine Down Time (Minutes/Wafer)

Blade Replacement, Tensioning and Initial Blade Dressing:	0.015 Minutes
Two Tensioning in Blade Life:	0.005 Minutes
Blade Dressing:	0.014 Minutes
Miscellaneous:	0.003 Minutes
Total	0.037 Minutes/Wafer

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

A1 Process Referent I.D.

A2 Description (Optional) Slicing of 3" diameter silicon ingot with I.D. saw.

PART 1 – PRODUCT DESCRIPTION

A3 Product Referent I.D.-3-13-2

A4 Name or Description 3" wafers sliced with I.D. saw, 13 mils wafer thickness, 12 mils Kerf width, at two in/min of cut rate.

A5 Units Of Measure Wafer

PART 2 – PROCESS CHARACTERISTICS

A6	Output Rate	0.533	Units (given on line A5) Per Operating Minute
A7	Average Time at Station	-----	Calendar Minutes
A8	Process Usage Time Fraction	0.98	Average Number of Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS

A9	Component Referent	STC-16		
A10	Base Price Year For Purchase Price	1977		
A11	Purchase Price ($ Per Component)	35,000		
A12	Anticipated Useful Life (Years)	7		
A13	Salvage Value ($ Per Component)	3,500		
A14	Cost of Removal & Installation ($/Component)	400		

Format A Process Description (Continued)

A14 Process Referent (From Page 1) I.D.

PART 4 – DIRECT REQUIREMENTS PER MACHINE

A16 Catalog Number	A17 Requirement Description	A18 Amount Required Per Machine	A19 Units
A 2064 D	Manufacturing Space (Type A)	80	Square Feet
B 3064 D	General Assembler	0.56	PRSN * YRS
B 3736 D	Maintenance Mechanics II	0.042	PRSN * YRS

PART 5 – DIRECT REQUIREMENTS PER BATCH (A continuous process has a "batch" of one unit)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Batch	A23 Units
G 1012 D	Shellac Clear Spray	1.25×10^{-4}	Can
G 1014 D	Epoxy Paste	4.17×10^{-5}	Gal.
G 1016 D	Graphite Beam Mount	2.16×10^{-3}	Each
G 1020 D	Coolant, Rust-Lick	0.95×10^{-3}	Gal.
G 1026 D	6" I.D. Diamond Wheel Blade	3.33×10^{-4}	Each
G 1022 D	Blade Dressing Stick	1×10^{-4}	Each
G 1024 D	Blade Dressing Stick	1×10^{-3}	Each

(Continued - Attachment A)

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A24 Product Reference	A25 Product Name	A26 Yield Factor (Usable Output/Input)	A27 Units
GSIG	Grind 3" Si Ingot	148	Wafer/Kg

Prepared by H. Yoo **Date** 3/1/78

ATTACHMENT A

PART 5 - DIRECT REQUIREMENTS PER BATCH (Continued from Page 2)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Machine	A23 Units
C 1032 B	Electricity	0.045	KW Hours
C 1128 D	Water, Cooling	0.07	Cubic Feet
G 1040 D	I.D. Blade Tensioning Fluid	2.1×10^{-5}	Gal.
D 1064 D	Rejected Wafer	0.04	Wafer

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

PROCESS WORK SHEET

P1 PROCESS REFERENCE I.D.

LABOR PRICES AND COSTS PER MACHINE

P2 Catalog Number	P3 Inflated Price	P4 Cost	P2 Catalog Number	P3 Inflated Price	P4 Cost
B 3064 D	$ 8,748	$ 4,899			
B 3736 D	$12,944	$ 544			

BYPRODUCTS PER CYCLE

P5 Catalog Number	P6 Annual Quantity	P7 Uninflated Price	P8 Inflated Price	P9 Byproduct Expense	P10 Byproduct Revenue
D 1064 D	4,000	$ -0.041			164

COMMODITIES PER CYCLE

P11	P12	P13	P14	P15
Catalog Number	Annual Quantity	Uninflated Price	Inflated Price	Commodities Expense
G 1012 D	12.5	$ 3.01		$ 38
G 1014 D	4.17	$ 23.63		$ 99
G 1016 D	216	$ 1.88		$ 406
G 1020 D	95	$ 3.65		$ 347
G 1026 D	33.3	$ 57.00		$ 1,898
G 1022 D	10	$ 3.44		$ 34
G 1040 D	2.1	$ 22.00		$ 46
G 1024 D	100	$ 1.08		$ 108

UTILITIES PER CYCLE

P16	P17	P18	P19	P20
Catalog Number	Annual Quantity	Uninflated Price	Inflated Price	Utilities Expense
C 1032 B	4,500	$ 0.032		$ 144
C 1128 D	7,000	$ 0.00566		$ 40

Prepared by ______________________ Date ____________

COMPANY WORK SHEET

W1 Wafco
W2 3" Wafer, 100,000
W3 I.D.
W4 3" Si Ingot
W5 148 Wafer/Kg
W6 675.7 Kg
W7 187,617 Minutes
W8 486,864 Minutes
W9 0.385
W10 $ 31,900
W11 $ 12,282
W12 80 Sq. Ft.
W13 30.8 Sq. Ft.
W14 $ 5,443
W15 $ 2,096
W16 -------

W17 $ 2,976
W18 $ 184
W19 $ 164
W20 $ 12,282
W21 30.8 Sq. Ft.
W22 $ 2,096
W23 -------
W24 $ 2,976
W25 $ 184
W26 $ 164
W27 -------
W28 -------
W29 $ 2,976
W30 $ 0.17
W31 -------

Prepared by K Yoo Date 3/1/78

SLICING OF 4" WAFERS

A. DESCRIPTION OF THE SLICING

1. A Continuous Process

Cut Rate: Two (2) Inch/Minutes
Wafer Yield: 96%

2. Average Slicing Cycle Per Wafer: 2.532 Minutes

Slicing Time: 2.500 Minutes
Machine Down Time*: 0.032 Minutes
Total 2.532 Minutes/Wafer

3. Wafers Per Operating Minute:

$$\frac{1}{2.500} = 0.4 \text{ Wafers/Operating Minutes}$$

4. Process Usage Time Fraction:

$$\frac{2.500}{2.532} = 0.99$$

B. EQUIPMENT AND MANUFACTUIRNG SPACE

1. Salvage Value: 10% of the New Machine Price

2. Manufacturing Space: Three (3) Times of a Machine Space

C. DIRECT LABOR REQUIREMENT

1. General Assembler

Ingot Mount: 0.023 Minutes
Blade Dressing: 0.014 Minutes
Wafer Demount: 0.100 Minutes
Final Clean: 0.060 Minutes
Operator's Attention: 0.030 Minutes
Total 0.227 Minutes/Wafer

PRSN * YRS Conversion

PRSN * YRS/Machine/Shift:

$$\frac{0.227}{2.532} = 0.09$$

SLICING OF 4" WAFERS (Continued)

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

PRSN * YRS = 0.09 x 4.7 = 0.42

2. Maintenance Mechanics II

Blade Mounting and Tensioning: 0.013 Minutes/Wafer

PRSN * YRS/Machine/Shift:

$$\frac{0.013}{2.532} = 0.005$$

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

PRSN * YRS = 0.005 x 4.7 = 0.024

D. DIRECT MATERIAL REQUIREMENT

1. Eight Inch (8") I.D. Blade

Lifetime of the Blade: 4,000 Cuts

*Machine Down Time (Minutes/Wafer)

Blade Replacement, Tensioning and Initial Blade Dressing:	0.011 Minutes
Two Tensioning in Blade Life:	0.004 Minutes
Blade Dressing:	0.014 Minutes
Miscellaneous:	0.003 Minutes
Total	0.032 Minutes/Wafer

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

A1 Process Referent I.D.

A2 Description (Optional) Slicing of 4" diameter silicon ingot with I.D. saw.

PART 1 – PRODUCT DESCRIPTION

A3 Product Referent I.D.-4-13-2

A4 Name or Description 4" wafers sliced with I.D. saw, 13 mils wafer thickness, 13 mils Kerf width, at two in/min of cut rate.

A5 Units Of Measure Wafer

PART 2 – PROCESS CHARACTERISTICS

A6	Output Rate	0.4	Units (given on line A5) Per Operating Minute
A7	Average Time at Station	-----	Calendar Minutes
A8	Process Usage Time Fraction	0.99	Average Number of Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS

A9	Component Referent	STC-22		
A10	Base Price Year For Purchase Price	1977		
A11	Purchase Price ($ Per Component)	40,000		
A12	Anticipated Useful Life (Years)	7		
A13	Salvage Value ($ Per Component)	4,000		
A14	Cost of Removal & Installation ($/Component)	400		

Format A Process Description (Continued)

A14 Process Referent (From Page 1) I.D.

PART 4 – DIRECT REQUIREMENTS PER MACHINE

A16 Catalog Number	A17 Requirement Description	A18 Amount Required Per Machine	A19 Units
A 2064 D	Manufacturing Space (Type A)	80	Square Feet
B 3064 D	General Assembler	0.42	PRSN * YRS
B 3736 D	Maintenance Mechanics II	0.024	PRSN * YRS

PART 5 – DIRECT REQUIREMENTS PER BATCH (A continuous process has a "batch" of one unit)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Batch	A23 Units
G 1012 D	Shellac Clear Spray	1.25×10^{-4}	Can
G 1014 D	Epoxy Paste	10.4×10^{-4}	Gal
G 1018 D	Graphite Beam Mount	3.7×10^{-3}	Each
G 1020 D	Coolant, Rust-Lick	1.3×10^{-3}	Gal.
G 1028 D	8" I.D., Diamond Wheel Blade	2.5×10^{-4}	Each
G 1022 D	Blade Dressing Stick	1×10^{-4}	Each
G 1024 D	Blade Dressing Stick	1×10^{-3}	Each

(Continued - Attachment A)

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A24 Product Reference	A25 Product Name	A26 Yield Factor (Usable Output/Input)	A27 Units
GSIG	Grind 4" Si Ingot	76.8	Wafer/Kg

Prepared by H. Yoo Date 3/1/78

ATTACHMENT A

PART 5 - DIRECT REQUIREMENTS PER BATCH (Continued from Page 2)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Machine	A23 Units
C 1032 B	Electricity	0.06	KW Hours
C 1128 D	Wafer, Cooling	0.07	Cubic Feet
G 1040 D	I.D. Blade Tensioning Fluid	2.1×10^{-5}	Gal.
D 1064 D	Rejected Wafer	0.04	Wafer

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

PROCESS WORK SHEET

P1 PROCESS REFERENCE I.D.

LABOR PRICES AND COSTS PER MACHINE

P2	P3	P4	P2	P3	P4
Catalog Number	**Inflated Price**	**Cost**	**Catalog Number**	**Inflated Price**	**Cost**
B 3064 D	$ 8,748	$ 3,674			
B 3736 D	$ 12,944	$ 311			

BYPRODUCTS PER CYCLE

P5	P6	P7	P8	P9	P10
Catalog Number	**Annual Quantity**	**Uninflated Price**	**Inflated Price**	**Byproduct Expense**	**Byproduct Revenue**
D 1064 D	4,000	$ -0.073			292

COMMODITIES PER CYCLE

P11 Catalog Number	P12 Annual Quantity	P13 Uninflated Price	P14 Inflated Price	P15 Commodities Expense
G 1012 D	12.5	$ 3.01		$ 38
G 1014 D	10.4	$ 23.63		$ 246
G 1018 D	370	$ .88		$ 326
G 1020 D	130	$ 3.65		$ 475
G 1028 D	25	$ 150.00		$3,750
G 1022 D	10	$ 3.44		$ 34
G 1024 D	100	$ 1.08		$ 108
G 1040 D	2.1	$ 22.00		$ 46

UTILITIES PER CYCLE

P16 Catalog Number	P17 Annual Quantity	P18 Uninflated Price	P19 Inflated Price	P20 Utilities Expense
C 1032 B	6,000	$ 0.032		$ 192
C 1128 D	7,000	$ 0.00566		$ 40

Prepared by ______________________ Date ______________

COMPANY WORK SHEET

W1 Wafco

W2 4" Wafer, 100,000

W3 I.D.

W4 4" Si Ingot

W5 76.8 Wafer/Kg

W6 1302.1 Kg

W7 250,000 Minutes

W8 491,832 Minutes

W9 0.508

W10 $ 36,400

W11 $ 18,502

W12 80 Sq. Ft.

W13 40.6 Sq. Ft.

W14 $ 3,985

W15 $ 2,024

W16 -------

W17 $ 5,023

W18 $ 232

W19 $ 292

W20 $ 18,502

W21 40.6 Sq. Ft.

W22 $ 2,024

W23 -------

W24 $ 5,023

W25 $ 232

W26 $ 292

W27 -------

W28 -------

W29 $ 5,023

W30 $ 0.24

W31 -------

Prepared by H. Yoo Date 3/1/78

APPENDIX III

APPLICATION OF SAMICS TO THE MULTIWIRE SLURRY (MWS) SAW SLICING

SLICING OF 3" WAFERS

A. DESCRIPTION OF THE SLICING

1. Batch Process: 158 Yielded Wafers Per Batch

2. Average Slicing Cycle: 9.5 HOurs/Batch

Slicing Time:	8.58 Hours
Machine Down Time*:	0.92 Hours
Total	9.5 Hours/Batch

3. Wafers Per Operating Minutes:

$$\frac{158}{8.58 \times 60} = 0.307$$

4. Process Usage Time Fraction:

$$\frac{8.58}{9.5} = 0.90$$

B. EQUIPMENT AND MANUFACTUIRNG SPACE

1. Salvage Value: 10% of the New Machine Price

2. Manufacturing Space: Three (3) Times of a Machine Space

C. DIRECT LABOR REQUIREMENT

1. General Assembler

Ingot Mount on Ceramic:	10 Minutes
Ingot Mount on Machine:	5 Minutes
Ingot Demount From Machine:	5 Minutes
Wafer Demount and Degrease:	65 Minutes
Final Clean:	10 Minutes
Operator's Attention:	25 Minutes
Total	120 Minutes/Batch = 2 Hours/Batch

PRSN * YRS Conversion

PRSN * YRS/Machine/Shift:

$$2 \times \frac{8}{9.5} \times \frac{1}{8} = 0.21$$

SLICING OF 3" WAFERS (Continued)

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

$$\text{PRSN} * \text{YRS} = 0.21 \times 4.7 = 0.99$$

2. Maintenance Mechanics II

Wiring:	20 Minutes
Arrange Angle and Position:	20 Minutes
Total	40 Minutes/Batch
	= 0.67 Hours/Batch

PRSN * YRS Conversion

PRSN * YRS/Machine/Shift:

$$0.67 \times \frac{8}{9.5} \times \frac{1}{8} = 0.071$$

For an Operation of Three (3) Shifts Per Day, 345 Days Per Year, Including Vacation and Sick Days Etc.

$$\text{PRSN} * \text{YRS} = 0.071 \times 4.7 = 0.33$$

D. DIRECT MATERIAL REQUIREMENT

1. Slicing Wire (High Tension Wire): 0.92 Kg of the Wire was Consumed in a Batch Process.
2. Slurry: Slurry was Used for One Batch of Slicing Only.

*Machine Down Time (Hours/Batch)

Wiring Time:	0.33 Hours
Ingot Mount:	0.08 Hours
Ingot Demount:	0.08 Hours
Arrange Ingot Positon:	0.33 Hours
Miscellaneous:	0.10 Hours
Total	0.92 Hours/Batch

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

JPL
JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

PROCESS DESCRIPTION

A1 Process Referent: MWS

A2 Description (Optional): Slicing of 3" diameter silicon ingot by MWS saw.

PART 1 – PRODUCT DESCRIPTION

A3 Product Referent: MWS-3

A4 Name or Description: 3" wafers sliced by MWS saw. Kerf width 7.9 mils and wafer thickness 10.6 mils.

A5 Units Of Measure: Wafer (a batch of 158)

PART 2 – PROCESS CHARACTERISTICS

A6 Output Rate: 0.307 Units (given on line A5) Per Operating Minute

A7 Average Time at Station: ----- Calendar Minutes

A8 Process Usage Time Fraction: 0.90 Average Number of Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS

A9	Component Referent	Yasunaga YQ -100		
A10	Base Price Year For Purchase Price	77		
A11	Purchase Price ($ Per Component)	28,000		
A12	Anticipated Useful Life (Years)	7		
A13	Salvage Value ($ Per Component)	2,800		
A14	Cost of Removal & Installation ($/Component)	300		

Format A Process Description (Continued)

A14 Process Referent (From Page 1) MWS

PART 4 – DIRECT REQUIREMENTS PER MACHINE

A16 Catalog Number	A17 Requirement Description	A18 Amount Required Per Machine	A19 Units
A 2064 D	Manufacturing Space (Type A)	40	Square Feet
B 3064 D	General Assembler	0.99	PRSN * YRS
B 3736 D	Maintenance Mechanics II	0.33	PRSN * YRS

PART 5 – DIRECT REQUIREMENTS PER BATCH (A continuous process has a "batch" of one unit)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Batch	A23 Units
G 1012 D	Shellac Clear Spray	0.1	Can
G 1014 D	Epoxy Paste	6×10^{-3}	Gal
G 1014 D	Ceramic Block for Mounting	1	Each
G 1042 D	16 um Alumina Lapping Powder	11	Lbs.
G 1034 D	P.C. Oil	.88	Gal
G 1036 D	TCE, Tech. Grade	1.4	Gal
G 1046 D	High Tension Wire	.92	Kg

(Continued - Attachment A)

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A24 Product Reference	A25 Product Name	A26 Yield Factor (Usable Output/Input)	A27 Units
GSIG	Grind 3" Si Ingot	193.8	Wafer/Kg

Prepared by H. Yoo Date 3/1/78

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California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

PROCESS WORK SHEET

P1 PROCESS REFERENCE MWS

LABOR PRICES AND COSTS PER MACHINE

P2	P3	P4
Catalog Number	**Inflated Price**	**Cost**
A 2064 D	$ 8,748	$ 8,661
B 3736 D	$ 12,744	$ 4,206

P2	P3	P4
Catalog Number	**Inflated Price**	**Cost**

BYPRODUCTS PER CYCLE

P5	P6	P7	P8	P9	P10
Catalog Number	**Annual Quantity**	**Uninflated Price**	**Inflated Price**	**Byproduct Expense**	**Byproduct Revenue**
D 1064 D	3,000	$ -0.029			$ 87

COMMODITIES PER CYCLE

P11 Catalog Number	P12 Annual Quantity	P13 Uninflated Price	P14 Inflated Price	P15 Commodities Expense
G 1012 D	63.3	$ 3.01		$ 191
G 1014 D	3.8	$ 23.63		$ 90
G 1044 D	633	$ .21		$ 133
G 1042 D	6,962	$ .80		$ 5,570
G 1034 D	557	$ 4.74		$ 2,640
G 1036 D	886	$ 3.50		$ 3,101
G 1046 D	582	$ 50.00		$ 29,100

UTILITIES PER CYCLE

P16 Catalog Number	P17 Annual Quantity	P18 Uninflated Price	P19 Inflated Price	P20 Utilities Expense
C 1032 B	1,329	$ 0.032		$ 43

Prepared by ______________________ Date ____________

ATTACHMENT A

PART 5 - DIRECT REQUIREMENTS PER BATCH (Continued from Page 2)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Machine	A23 Units
C 1032 B	Electricity	2.1	KW Hours
D 1064 D	Rejected Wafers	5	Wafer

COMPANY WORK SHEET

W1 Wafco
W2 3" Wafers, 100,000
W3 MWS
W4 3" Ingot
W5 193.8 Wafers/Kg
W6 516 Kg
W7 325,733 Minutes
W8 447,120 Minutes
W9 0.729
W10 $ 25,500
W11 $ 18,590
W12 40 Sq. Ft.
W13 29.2 Sq. Ft.
W14 $ 12,867
W15 $ 9,380
W16 -------

W17 $ 40,825
W18 $ 43
W19 $ 87
W20 $ 18,590
W21 29.2 Sq. Ft.
W22 $ 9,380
W23 -------
W24 $ 40,825
W25 $ 43
W26 $ 87
W27 -------
W28 -------
W29 $ 40,825
W30 $ 0.85
W31 -------

Prepared by H. Yoo Date 3/1/78

APPENDIX IV

A NEW COST ACCOUNT CATALOG FOR SAMICS

NEW COST ACCOUNT CATALOG

CATALOG NO.	ITEM DESCRIPTION	UNIT	PRICE*
G1012D	SHELLAC CLEAN SPRAY	Can	$ 3.01
G1014D	EPOXY PASTE	Gal.	$ 23.63
G1016D	GRAPHITE BEAM MOUNT (12" x $1\frac{3}{8}$" x $\frac{3}{8}$")	Ea.	$ 1.88
G1018D	GRAPHITE BEAM MOUNT (7" x 2" x $\frac{1}{2}$")	Ea.	$ .88
G1020D	COOLANT (RUST-LICK)	Gal	$ 3.65
G1022D	BLADE DRESSING MATERIAL, ALUMINA STICKS (1" x 1" x 6")	Ea.	$ 3.44
G1024D	BLADE DRESSING MATERIAL, ALUMINA STICKS ($\frac{1}{2}$" x $\frac{1}{2}$" x 6")	Ea.	$ 1.08
G1026D	6" I.D. DIAMOND WHEEL BLADE	Ea.	$ 57.00
G1028D	8" I.D. DIAMOND WHEEL BLADE	Ea.	$150.00
G1030D	CEMENT, DO ALL NO LOAD	Lb.	$ 5.24
G1032D	SiC, 400 GRIT	Lb.	$ 1.35
G1034D	P. C. OIL	Gal.	$ 4.74
G1036D	T.C.E. (TECHNICAL GRADE)	Gal.	$ 3.50
G1038D	MULTIBLADE PACKAGE (PRE-ASSEMBLED IN 1 $\frac{1}{2}$") (230 BLADES, 8 MILS x 18 MILS, WITH $\frac{1}{4}$" BLADE WIDTH)	Pkg.	$175.00
G1040D	I.D. BLADE TENSIONING FLUID, STC	Gal.	$ 22.00

(CONTINUED)

Price Year: 1977

NEW COST ACCOUNT CATALOG (Continued)

CATALOG NO.	ITEM DESCRIPITON	UNIT	PRICE*
G1042D	16 µm ALUMINA LAPPING POWDER	Lb.	$ .80
G1044D	CERAMIC BLOCK 3" x 4" x 0.31"	Ea.	$ .21
G1046D	HIGH TENSION (MUSIC STEEL) WIRE 0.16 mm DIAMETER	Kg.	$ 50.00

Price Year: 1977

APPENDIX V

ABBREVIATIONS

ABBREVIATIONS

MBS: Multiblade Slurry

MWS: Multiwire Slurry

I.D.: Internal Diameter

IPM: Inch Per Minute

SEM: Scanning Electron Microscope

RMS: Root Mean Square

SAMICS: Solar Array Manufacturing Industry Costing Standards