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ERDA/JPL/954374-77/1

SLICING OF SILICON INTO SHEET MATERIAL

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

Fourth Quarterly Report, December 20, 1976—March 20, 1977

S. C. Holden

March 27, 1977

Work Performed Under Contract NAS-7-100-954374

Lexington Vacuum Division
Varian Associates
Lexington, Massachusetts

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Division of Solar Energy

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Price: Paper Copy $4.50 (domestic)
$7.00 (foreign)
Microfiche $3.00 (domestic)
$4.50 (foreign)

Printed in the United States of America
USERDA Technical Information Center, Oak Ridge, Tennessee

ERDA/JPL/954374-77/1
Distribution Category UC-63

SLICING OF SILICON INTO SHEET MATERIAL

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

FOURTH QUARTERLY REPORT

By

S. C. HOLDEN

March 27, 1977

Reporting Period December 20, 1976 to March 20, 1977

JPL Contract No. 954374

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U. S. Energy Research and Development Administration, Division of Solar Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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1.0 SUMMARY

Two demonstrations of silicon slicing were made for solar cell application. 10 cm ingots of silicon were sliced into 225 wafers (full saw capacity) with over 94% yield in both cases. Wafers 0.48 mm thick were sliced with 0.25 mm kerf loss in 19 hours. The slice thickness duplicated currently used wafers. The second demonstration produced 0.30 mm thick slices with 0.25 mm kerf loss in 24 hours. This represents a current best effort with process conditions developed under this contract.

Wafer surface damage is shown to be a fine microcrack structure which reduces to a faceted surface topography with 4 μm of etching. Abrasive particles used in MS sawing do not exhibit particle size degradation or wear of sharp edges. However, built up silicon debris may effectively blunt cutting edges of the abrasive.

Kerf loss was reduced to 0.20 mm in slicing a 10 cm ingot into 0.25 mm slices. This reduces the total silicon requirement per slice by 50 μ. Plans include the demonstration of full production capacity with the 0.15 mm thick blades used in this case and a cost analysis of MS sawing for solar cell applications.

Limits of wafer thickness (250 μ) and kerf loss (200 μ) are identified for present slicing techniques. These are explained as a result of intrinsic misalignment in the major portion of the blade package used in MS sawing. Accumulation of small component errors is shown to result in 50 to 100 μ misalignment of blades possibly resulting in fatigue of thin blades (0.10 mm) and breakage of thin slices (<250 μ).

2.0 INTRODUCTION

The purpose of this contract is to develop a technique of low cost slicing of silicon ingot for use as solar cells. The slicing technique is multiblade slurry (MS) sawing and experimental work has been done on a Varian Model 686 wafering saw.

The cost aspect of slicing can be divided into two areas. The first is the productivity of useful slices from the ingot (slices per cm). The second is the cost effectiveness of the slicing operation itself. This includes such factors as expendible materials (abrasive slurry, blades), slicing time, and operator input.

The two major advantages of MS sawing are the ability to slice thin wafers with low kerf loss and the capability of slicing 100 to 300 wafers simultaneously. The approach used in this work is to select process conditions which allow controlled slicing with high yield and the thinnest wafers possible. Also, limits to the process are explored and means of further improvement in state of the art slicing will be identified.

3.0 SLICING TESTS

Previously multiblade slurry sawing was shown to produce slices from a 10 cm silicon ingot with 0.50 mm used to make each slice. 0.20 mm blades cutting with a slurry of 0.48 kg of #600 SiC abrasive and PC oil resulted in a kerf loss of 0.25 mm, and 0.25 mm slices were produced. The capacity of the Varian multiblade slurry saw was 225 blade cutting simultaneously, and tests used 100 to 150 blades.

The past quarter's work focused on reducing the silicon required to produce a slice by using thin (0.15 and 0.10 mm) blades and by reducing spacer thickness in the blade package to 0.20 mm (0.30 mm was the thinnest previously). Also, two demonstrations of 10 cm ingot slicing were analyzed. A full machine capacity of 225 blades was used to produce wafers 0.48 mm thick (current slice thickness) and 0.30 mm thick (best effort) for Solar Power Corp.

Variations in slicing conditions (blade load, slurry concentration) were used to explore the response of the cutting system. A series of tests was completed to evaluate the useful lifetime of the abrasive slurry. Table 1 shows a summary of slicing tests performed during the past quarter.

3.1 Slurry Lifetime - #2-006C

A third 10 cm ingot (125 slices per ingot) was sliced with the same 7.6 liter volume of slurry. The slurry mix was 0.48 kg of #600 SiC abrasive per liter of PC oil. Approximately half way through the third ingot, severe slice breakage occurred and the test was aborted.

TABLE 1

SLICING TEST SUMMARY

PARAMETER \ TEST		2-006A	2-006B	2-006C
MATERIAL		Si {100}	Si {100}	Si {100}
LOAD (gram/blade)		113.4	113.4	113.4
SLIDING SPEED (cm/sec)		57.8	57.8	60.4
NUMBER OF BLADES CUTTING		125	125	125
ABRASIVE (grit size)		#600 SiC	(#600 SiC)	(#600 SiC)
OIL VOLUME (liters)		7.6	(7.6)	(7.6)
MIX (kg/liter)		0.48	(0.48)	(0.48)
KERF LENGTH (cm)		10.0 max	10.0 max	10.0 max
INGOT HEIGHT (cm)		8.62	8.62	4.75
BLADE THICKNESS (cm)		0.02	0.02	0.02
KERF WIDTH (cm)		.0255	.0238	(.0238)
ABRASIVE KERF LOSS (cm)		.0055	.0038	(.0038)
AREA/SLICE (cm^2)		73.8	73.8	46.6
CUTTING TIME (total hours)		27:00	26:15	(23:25)
EFFICIENCY	(full test)	1.07	1.01	0.69
	(typical)	1.19	1.12	0.70
	(maximum)	1.88	1.70	1.08
ABRASION RATE	(full test)	.0696	.0669	.0474
(cm^3/hr/blade)	(typical)	.0777	.0748	.0478
	(maximum)	.1228	.1135	.0737
PRODUCTIVITY	(full test)	2.73	2.81	1.99
(cm^2/hr/blade)	(typical)	3.05	3.14	2.01
	(maximum)	4.82	4.77	3.10
SLICE TAPER (cm)		+.0016	+.0016	--
ABRASIVE UTILIZATION (cm^3/kg)		64.48	124.67	162.6
OIL UTILIZATION (cm^3/liter)		30.9	59.8	78.0

TABLE 1
(continued)

SLICING TEST SUMMARY

PARAMETER \ TEST		2-022	2-023	2-024	2-025
MATERIAL		Si	Si {100}	Si {100}	Si {100}
LOAD (gram/blade)			113	225	113
SLIDING SPEED (cm/sec)			61.3	59.2	61.3
NUMBER OF BLADES CUTTING			150	125	128
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)			7.6	7.6	7.6
MIX (kg/liter)		0.36	0.24	0.48	0.36
KERF LENGTH (cm)		10.0 max	10.0 max	10.0 max	10.0 max
INGOT HEIGHT (cm)			6.83	6.83	6.83
BLADE THICKNESS (cm)		0.02	0.02	0.02	0.02
KERF WIDTH 9cm)			0.0251	0.0262	0.0259
ABRASIVE KERF LOSS (cm)			0.0051	0.0062	0.0059
AREA/SLICE (cm^2)			72.1	72.1	72.1
CUTTING TIME (total hours)			27:30	17:10	27:10
EFFICIENCY	(full test)	COLLAPSE	0.95	0.83	1.00
	(typical)	OF	1.19	1.09	1.07
	(maximum)	SPACERS	1.95	1.35	1.73
ABRASION RATE	(full test)	PIN	0.0658	0.1101	0.0687
(cm^3/hr/blade)	(typical)	&	0.0821	0.1447	0.0739
	(maximum)	EPOXY	0.1346	0.1792	0.1194
PRODUCTIVITY	(full test)		2.62	4.20	2.65
(cm^2/hr/blade)	(typical)		3.27	5.52	2.85
	(maximum)		5.36	6.84	4.61
SLICE TAPER (cm)			+0.0011	+.0011	+.0018
ABRASIVE UTILIZATION (cm^3/kg)			148.8	64.7	87.3
OIL UTILIZATION (cm^3/liter)			35.7	31.1	31.4

TABLE 1
(continued)

SLICING TEST SUMMARY

PARAMETER \ TEST	3-032	3-033	3-041
MATERIAL	Si {100}	Si {100}	Si {100}
LOAD (gram/blade)	85	85	57
SLIDING SPEED (cm/sec)	60.9	60.4	
NUMBER OF BLADES CUTTING	96	114	
ABRASIVE (grit size)	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)	7.6	7.6	7.6
MIX (kg/liter)	0.48	0.24	0.24
KERF LENGTH (cm)	10.0 max	10.0 max	
INGOT HEIGHT (cm)	8.3	8.3	
BLADE THICKNESS (cm)	0.015	0.015	0.010
KERF WIDTH (cm)	0.0216	0.0202	
ABRASIVE KERF LOSS (cm)	0.0066	0.0052	
AREA/SLICE (cm^2)	72.1	72.1	
CUTTING TIME (total hours)	26:05	28:50	
EFFICIENCY (full test)	1.16	0.99	
(typical)	1.45	1.13	
(maximum)	2.43	1.73	
ABRASION RATE (full test)	0.0597	0.0505	
(cm^3/hr/blade) (typical)	0.0748	0.0578	BROKE IN PRECONDITIONING
(maximum)	0.1253	0.0885	
PRODUCTIVITY (full test)	2.76	2.50	
(cm^2/hr/blade) (typical)	3.46	2.86	
(maximum)	5.80	4.38	
SLICE TAPER (cm)	+.0018	+.0020	
ABRASIVE UTILIZATION (cm^3/kg)	41.0	91.0	
OIL UTILIZATION (cm^3/liter)	19.7	21.8	

TABLE 1
(continued)

SLICING TEST SUMMARY

PARAMETER \ TEST		P-001	P-002
MATERIAL		Si {100}	Si {100}
LOAD (gram/blade)		170	113
SLIDING SPEED (cm/sec)		66.8	65.1
NUMBER OF BLADES CUTTING		225	225
ABRASIVE (grit size)		#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6
MIX (kg/liter)		0.48	0.36
KERF LENGTH (cm)		10.0 max	10.0 max
INGOT HEIGHT (cm)		10.0	10.0
BLADE THICKNESS (cm)		0.0203	0.0203
KERF WIDTH (cm)		0.0257	0.0257
ABRASIVE KERF LOSS (cm)		0.0057	0.0254
AREA/SLICE (cm^2)		78.5	78.5
CUTTING TIME (total hours)		19:00	23:25
EFFICIENCY	(full test)	0.94	1.17
	(typical)	1.03	1.28
	(maximum)	1.37	1.51
ABRASION RATE	(full test)	0.1062	0.0862
(cm^3/hr/blade)	(typical)	0.1166	0.0938
	(maximum)	0.1550	0.1107
PRODUCTIVITY	(full test)	4.13	3.35
(cm^2/hr/blade)	(typical)	4.53	3.65
	(maximum)	6.03	4.31
SLICE TAPER (cm)		--	--
ABRASIVE UTILIZATION (cm^3/kg)		124.4	165.9
OIL UTILIZATION (cm^3/liter)		59.7	59.7

In each test of the 2-006 series, a fresh blade package was used. The blades were 0.20 mm thick by 6.35 mm high, with 0.30 mm spacers. Wafers were 0.25 mm thick. 113 grams of blade load was used in each case with a sliding speed of approximately 58 cm/sec.

The first two tests (2-006A & B) were nearly identical in cutting rate, and slice accuracy. However, breakage of the slices began to occur near the end of the second run. Breakage was even more severe in the final run (2-006C), but the cutting rate was reduced by nearly 50%. It appears that the useful lifetime of slurry is approximately full saw capacity (225 wafers) of 10 cm silicon ingot for a 7.6 liter volume of slurry. However, a more severe limitation appears to be the breakage of thin wafers that occurs before cutting speed is diminished.

The build-up of debris in the slurry oil causes an increase in the viscosity of the slurry. This viscosity increase will cause higher drag loads on thin wafers and may limit the access of slurry to the blades. Samples of slurry oil were taken at various stages of the 2-006 tests to evaluate the condition of the silicon carbide abrasive as the slurry performance deteriorated.

3.2 Thinned Slurry Oil - #2-025

To test the premise that oil viscosity controls slice taper and the apparent "life" of slurry, a mix of 0.36 kg of #600 SiC per liter of PC oil was used at the start of a 10 cm silicon ingot slicing test. At 50% and 75% through the ingot, 30 SUS mineral oil was added to lighten the slurry. Total mix of the light oil was 20% at the end of the test.

Total cutting time was 27 hours and the thinning did not impact any factor of wafer accuracy and, in fact, reduced the cutting efficiency normally experienced with similar slurry conditions.

3.3 Slurry Mix (0.24 kg/l) - #2-023

An 0.24 kg/liter mix of #600 SiC slurry was used to slice a 10 cm ingot with 113 grams of blade load. Total cutting time was 27.5 hours and it is apparent that cutting efficiency is reduced from that experienced with 0.48 kg/liter mixes (1.19 vs. 1.60). There was no improvement in wafer accuracy, blade wear or kerf loss with the light slurry mix.

3.4 High Cutting Force (225 g/blade) - #2-024

A 10 cm ingot was sliced with 0.20 mm thick blades, 0.41 mm spacers and 225 grams per blade of cutting force. A standard 0.48 kg/liter slurry mix with #600 SiC abrasive was used. Cutting time was 17.2 hours.

Even though the cutting rate was higher than normal, cutting efficiency was low (1.00). It appears that the abrasive density is saturated for cutting ability at the higher cutting force. A heavier slurry mix may reduce cutting time at high loads even further.

3.5 Thin (0.15 mm) Blades - #3-032

0.15 mm by 6.35 mm blades and 0.40 mm spacers were used to slice a 10 cm silicon ingot into 100 wafers. 85 grams of load and 0.48 kg/liter mix of #600 SiC abrasive was used. Total cutting time was 26 hours. Cutting efficiency was typically 1.45 with a maximum of 2.43. Wafer accuracy was comparable to 0.20 mm blades. Wafer thickness was 0.343 mm with 0.216 mm kerf loss, a savings of 35 microns of kerf loss. Blade wear ratio and height loss were also comparable to 0.20 mm blades.

Cutting results were not similar to those of #3-031[1] (0.15mm blades) where high slice accuracy, low blade wear and slightly concave wafer surfaces resulted. The anomaly of Test #3-031 has not been explained.

3.6 Thin Blades - #3-033

A package of 0.15 mm thick blades with 0.30 mm spacers was used to slice a 10 cm silicon ingot. Slurry mix was 0.24 kg of #600 SiC per liter of PC oil. With 85 grams of blade load, slicing time was nearly 29 hours.

The light slurry mix was used to control the cutting of thin wafers with 0.15 mm blades. The cutting time was longer than in Test #3-032 (0.48 kg/l). Typical cutting efficiency was 20% less with the lighter mix and maximum cutting efficiency was 30% lower.

Wafers were 0.255 mm thick, however, the yield was less than 70%. Slice taper was 20 microns.

3.7 Thin Spacers (0.20 mm) - #2-022

A pinned blade package with 0.20 mm thick blades and 0.20 mm thick spacers was used to explore the thinnest slicing possible with silicon ingots. Upon tensioning to 50% of full blade tension, (90 kg per blade), the spacers collapsed by buckling under the compression applied by the front lips of the bladehead.

A second package of an epoxy bonded type and the same blade and spacer size was then tensioned. The epoxy between the spacers suppressed the buckling mode until 70 to 80% (135 kg per blade) of full tension was reached.

With the present blade package geometry 0.25 to 0.30 mm spacers will be the practical limit. This allows 0.20 to 0.25 mm thick slices to be produced. Thin blades will reduce the allowable spacer size by as much as 15%.

3.8 Thin Blades (0.10 mm) - #3-041

A package of 0.10 mm thick by 6.35 mm high blades and 0.30 mm spacers was made using a controlled assembly procedure in order to avoid package assembly related blade misalignment.

As in previous efforts, blade breakage began to occur within 15 minutes of the start of cutting. The failure seems to be a fatigue problem as approximately 3,000 cycles of bladehead motion (15 minutes) is required to cause failure. A slight blade misalignment will cause a cutting path for a blade that causes it to be distorted on each stroke. This periodic deflection may induce stresses sufficient for fatigue failure of the blades.

3.9 Full Production Demonstration - Test #P-001

A 10 cm silicon ingot was sliced as a full production demonstration for Solar Power Corp. to produce silicon wafers of the same thickness as they use today. The results were analyzed as part of this effort. The wafers from Test P-001 were 0.48 mm thick, and kerf loss was 0.26 mm. Total cutting time was 19 hours and the maximum saw capacity of 225 wafers was sliced.

The blade load was 170 grams since the thick slices were produced. Cutting rate seemed to "saturate", with the higher load not resulting in a scaled increase in cutting rate. However, the slice accuracy and surface profile were of high quality, indicating that the cutting process was controlled.

This result leads to a general observation about the interaction of slurry mixture (in this case 0.48 kg of #600 SiC per liter of PC oil) and cutting force. At a given cutting force, an increased density of abrasive in the oil causes increased cutting rate with a reduction of wafer accuracy attributed to loss of cutting "control". However, Test P-001 indicates that the suitable mix of slurry may increase as blade load is increased. The abrasive mix establishes the number of particles involved in cutting on each blade. Higher particle densities may improve average cutting rate, but a degree of rolling may result, causing wandering and reduced wafer accuracy. For higher blade loads, the optimum cutting condition may be met when each abrasive particle carries a certain load. A higher particle density on the blades may be required for the proper balance of cutting rate and "control" of blades.

3.10 Full Production Demonstration - #P-002

A second slicing demonstration for Solar Power Corporation was evaluated as part of this contract work. Again, the full machine capacity of 225 blades was used to slice a 10 cm diameter silicon ingot. 0.20 mm blades and 0.36 mm spacers were used in the blade package. #600 SiC mixed at 0.36 kg/liter of slurry oil were used with the standard 7.6 liter slurry volume. 113 grams of blade load and a 65 cm/sec sliding speed resulted in a cutting time of 23½ hours.

Wafers were 0.303 mm thick and total kerf loss was 0.257 mm. Yield was better than 94%.

4.0 DISCUSSION

4.1 Wafer Thickness Limits

Two factors presently limit the thickness of 10 cm silicon wafers to 250 microns. As shown in Test #2-022, 0.20 mm spacers collapse under the full tensioning load of 0.20 by 6.35 mm blades (180 kg). Even epoxy-filled packages do not overcome the buckling failure mode. Currently 0.30 mm spacers have exhibited no failures of the sort experienced with 0.20 mm spacers. These spacers result in wafers 250 microns thick when a #600 abrasive is used. Thinner blades will reduce the tensioning force and should allow a 10-15% reduction in spacer thickness. Improved bladehead configuration may also allow reduced spacer thickness.

At thicknesses near 250 microns, wafers are barely strong enough to survive the cutting process. Yields of from 50 to 95% have been experienced when cutting this thickness of 10 cm slice. Wafer slicing in the 300 to 350 micron range has not had problems of wafer breakage, even under conditions of high cutting forces. With current slicing techniques, 300 micron wafers are "safe" with yields of 95%. It is probable that 250 micron wafers can be produced with similar yields. However, thinner wafers are not likely until the failure mode of slices is better understood.

4.2 Modes of Slice Breakage

The slicing process creates defects in the silicon surface, and around the periphery of wafers. Cracks 5 to 10 microns deep (see Section 5) result from abrasion of the wafer surfaces. Worn blade profiles pound against the diameter of the ingot during cutting fracturing the ingot. This pounding is reduced by shortening the blade stroke during the cutting process. However, the fracture still results to lesser degrees.

A damaged slice is susceptible to tensile fracture due to the stress concentration of the cracks. It is the origin of these failure stresses which must be reviewed to prevent slice breakage and allow thinner wafers to be sliced. Wafers seem to break in four distinct ways during a multiblade slicing operation. The most obvious is the complete dislodging of a slice. Occassionally slices appear to break without separating. Upon demounting and cleaning, breakage occurs in these slices with little or no effort. The presence of a pre-existing failure is only speculation. The two final failures are during demounting of the slices when the blades are withdrawn through the slices and upon cleaning. These two are not the critical problems as proper care and handling techniques will resolve them. It is the breakage of slices during the wafering process that is of concern.

The slurry is a viscous fluid and, thus, can produce drag loads as it is sheared through the wafers by blades. Similar loads of pure tension can be applied if the workpiece is dropped through the blades (as at the end of a slicing operation). From dynamometer measurements early in this contract, horizontal loads do not appear to be sufficient to fracture slices. However, viscous drag loads must not be ignored in contributing to slice failure.

Perhaps the most undefined loads are those imposed by the wandering, run-out or overturning of blades. This is especially significant since loads are cyclic and thus can produce fatigue of the slice. The predominant force of cutting is carried at the base of the cutting slot and, thus, does not necessarily affect the adjacent slices.

However, if the blade is offset from its natural path, is running out from a straight-line path or is misaligned vertically, loads on the wafers can result.

As described previously[2], misalignment is anticipated due to stacking tolerances in the blade package. The blades and spacers are of high accuracy material, but the large number of components (200 to 500) makes accumulated error significant.

4.3 Statistical View of a Blade Package

A normal distribution of thickness characteristics of blades or spacers has two characteristics. First, the expected value of thickness is a single value $E(t_s)$ or $E(t_b)$. However, one also expects a value of error (both plus and minus), which could be considered as a single valued characteristic for convenience.

$$E(t) = \sum_{i=1}^{n} \frac{t_i}{n} \qquad (1)$$

$$E(\varepsilon) = \sum_{i=1}^{n} \frac{|t_i - E(t)|}{n} \qquad (2)$$

$$t = E(t) \pm E(\varepsilon) \qquad (3)$$

The stacking of a series of components with the characteristic of Equation (3) results in a probability distribution of error of the n^{th} blade shown in Figure 1. Note that the expected thickness is ignored. The expected distance of the n^{th} component from the origin is $n \cdot E(t)$. However, the expected value of the error of the n^{th} blade is not zero if the sign of error is ignored. The coefficients of the distribution of Figure 1 are the binomial coefficients[3].

$$\binom{n}{m} = \frac{n!}{(n-m)!m!} \quad (0 \leq m \leq n) \qquad (4)$$

TOTAL ERROR

N	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9
0										1									
1									1		1								
2								1		2		1							
3							1		3		3		1						
4						1		4		6		4		1					
5					1		5		10		10		5		1				
6				1		6		15		20		15		6		1			
7			1		7		21		35		35		21		7		1		
8		1		8		28		56		70		56		28		8		1	
9	1		9		36		84		126		126		84		36		9		1

EXPECTED DISTRIBUTION OF ACCUMULATED ERRORS

FIGURE 1

Therefore, the expected value of the error of n stacked component is

$$\frac{E(\varepsilon_n)}{E(\varepsilon)} = \frac{1}{2n} \sum_{m=0}^{n} \binom{n}{m} \left| n - 2i \right| \qquad (5)$$

A few terms of the series of Equation (5) are:

$n = 0$	$\frac{E(\varepsilon_n)}{E(\varepsilon)}$ =	0
$n = 1$	=	1.00
$n = 2$	=	1.00
$n = 3$	=	1.50
$n = 4$	=	1.50
$n = 5$	=	1.88
$n = 10$	=	2.46
$n = 20$	=	3.52
$n = 50$	=	5.61
$n = 100$	=	7.98

The term for $n = 100$ was calculated using Sterlings approximation for $n!$[4].

$$n! = \sqrt{2\pi n}\; n^n e^{-n} \qquad (6)$$

The expected value of error of the n^{th} stacked component is well approximated by

$$\frac{E(\varepsilon_n)}{E(\varepsilon)} = 0.798\; n^{\frac{1}{2}} \qquad (7)$$

Misalignment of blades is determined by the difference between two stacks of spacers and blades. The error of the first blade, Δ_1, is given by

$$\Delta_1 = |\pm E(\varepsilon_{b1}) \pm E(\varepsilon_{s1}) - (\pm E(\varepsilon_{b2}) \pm E(\varepsilon_{s2}))| \qquad (8)$$

where $E(\varepsilon_{b1})$ and $E(\varepsilon_{s1})$ are the expected errors of the spacer and blade at one end of the package, and $E(\varepsilon_{b2})$ and $E(\varepsilon_{s2})$ are the errors at the opposite end. The difference between two similar stacking errors is the stacking error of twice as many components. For the blade package, the n^{th} blade is expected to be out of alignment by

$$\Delta_n = 0.798\ (2n)^{1/2} \left[E(\varepsilon_s) + E(\varepsilon_b)\right] \qquad (9)$$

where Δ_n is the run-out from end to end of the n^{th} blade. If there is an alignment forced onto both ends of a blade package (as for typical Varian saw set-ups), the maximum expected error is at the center of the blade package. For a complete package of N blades with spacers of expected error $E(\varepsilon_s)$ and blades of expected error $E(\varepsilon_b)$ and both ends aligned for zero runout, the expected runout is

$$\Delta_n = 1.129 \left[E(\varepsilon_s) + E(\varepsilon_b)\right] n^{1/2}\ (0 < n \leq N/2)$$

$$= 1.129 \left[E(\varepsilon_s) + E(\varepsilon_b)\right] (N-n)^{1/2}\ (N/2 \leq n \leq N) \qquad (10)$$

The maximum expected runout at the center of the pack is

$$\Delta_{max} = \Delta_{N/2} = 0.798 \left[E(\varepsilon_s) + E(\varepsilon_b)\right] N^{1/2} \qquad (11)$$

and the average runout is

$$\Delta_{ave} = 0.532 \left[E(\varepsilon_s) + E(\varepsilon_b)\right] N^{\frac{1}{2}} \qquad (12)$$

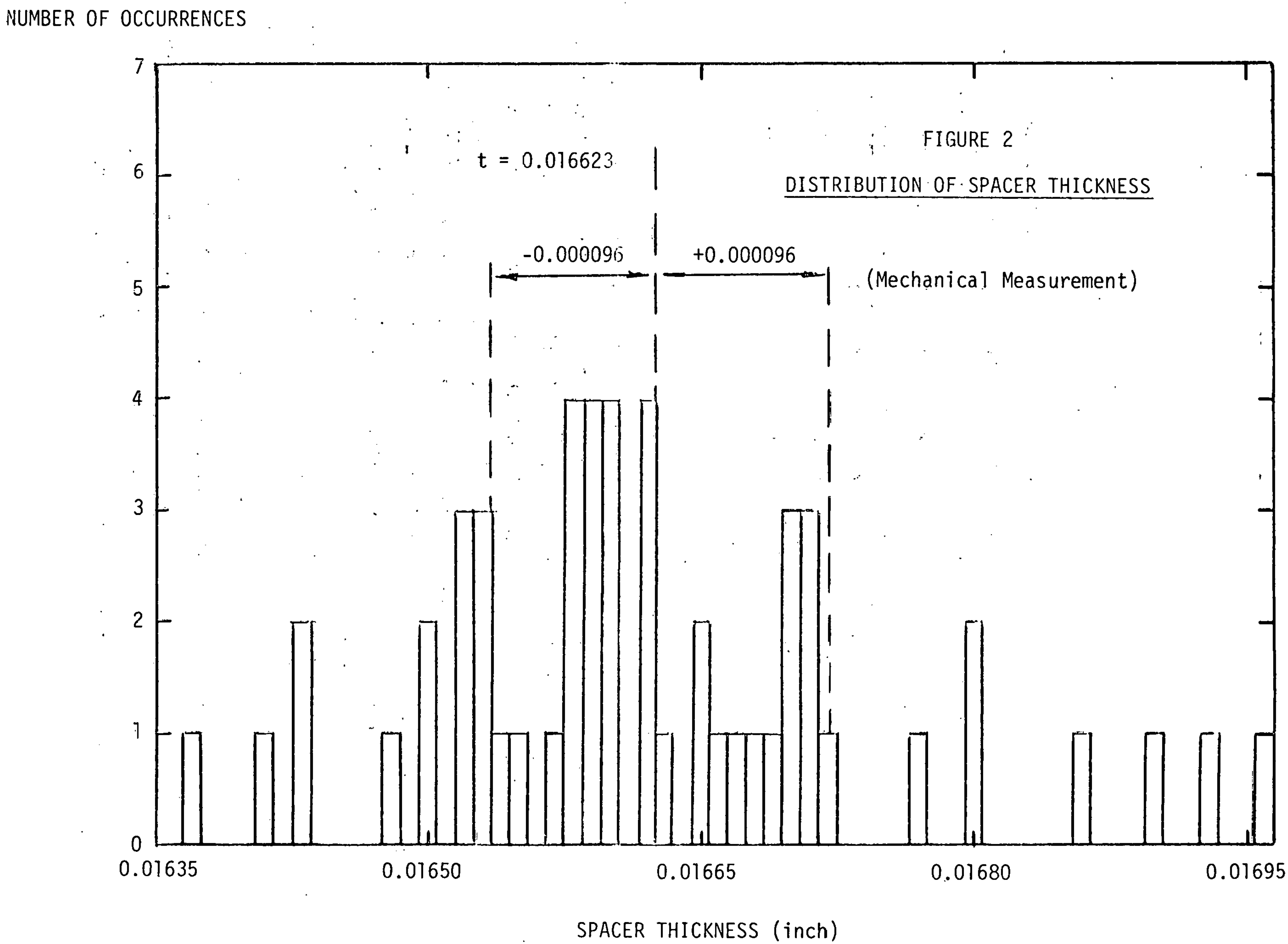
This is an expression for the expected runout of blades under ideal conditions. Other factors influencing blade alignment other than perfect stacking of components (dirt, bent components, etc.) will make the alignment worse. A similar development can be used to estimate vertical alignment of blades, except that there is no correction at the far end of the package, placing the point of highest error at the point $n = N$ rather than $n = N/2$ as in this case.

4.4 Accuracy of a Blade Package

A series of spacers and blades was measured to evaluate the expected errors of each. Figures 2 and 3 show distributions of spacer thickness resulting from two different measuring techniques. A high precision micrometer (mechanical) resulted in an expected error of ± 0.000096 inch. The ADE thickness measurements resulted in an expected error of 0.000039 inch. Since neither technique is accurate to the precision required and since the ADE system may not give a meaningful measurement due to the large area averaging (5 mm dia), these figures are only for reference.

$$E(\varepsilon_s) = 0.000039 \text{ to } 0.000096 \text{ inch} \qquad (13)$$

Figure 4 shows the distribution of the error of blade stock. The difference of blade stacking errors (end to end) is not based on a random selection of blade thicknesses (as with spacers). Instead the difference between two ends of one blade gives the error expected for the two component error accumulation. The expected


NUMBER OF OCCURRENCES
7
6
5
4
3
2
1
0
t = 0.016623
-0.000096
+0.000096
FIGURE 2
DISTRIBUTION OF SPACER THICKNESS
(Mechanical Measurement)
0.01635
0.01650
0.01665
0.01680
0.01695
SPACER THICKNESS (inch)

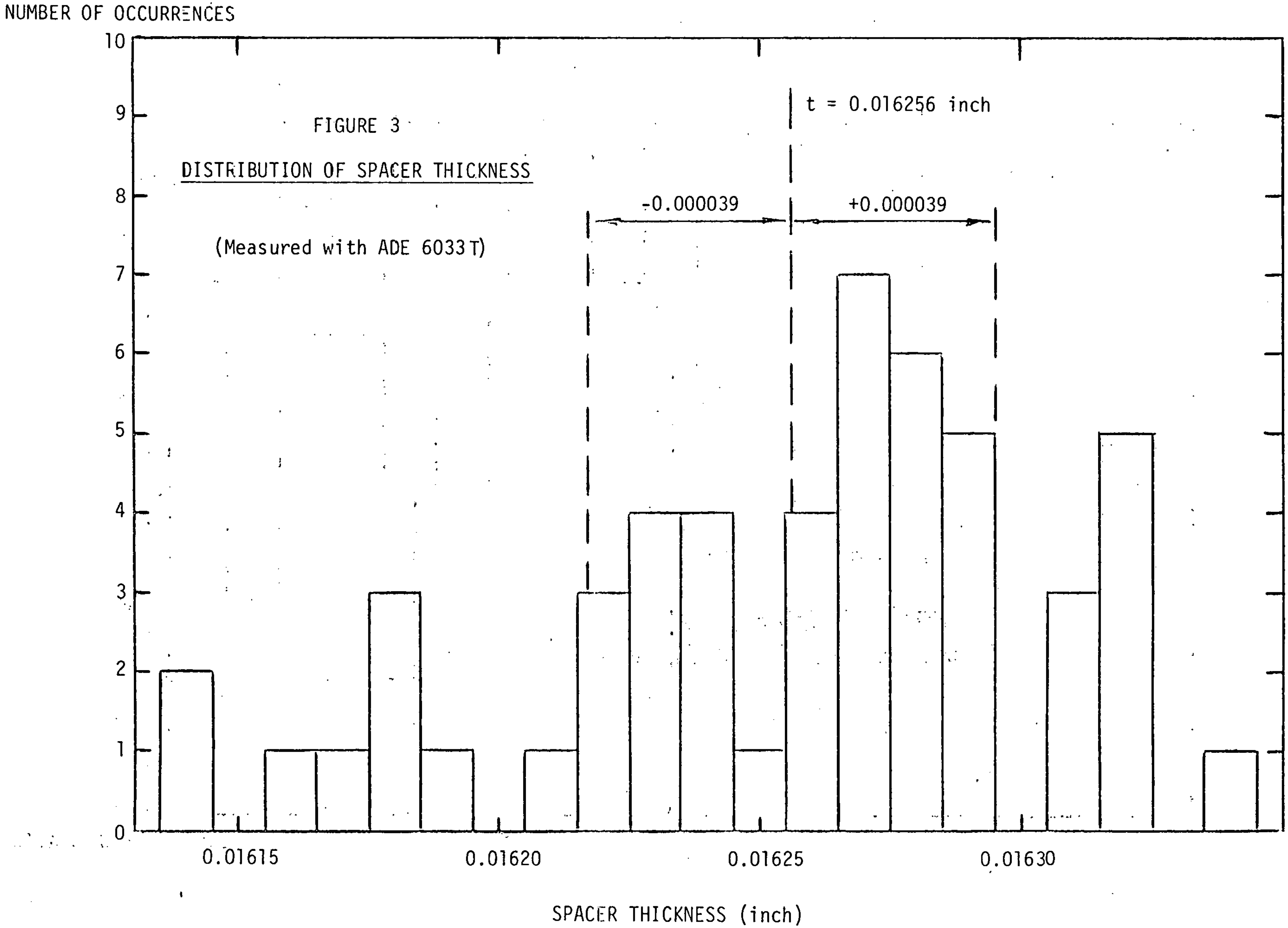


FIGURE 3

DISTRIBUTION OF SPACER THICKNESS

(Measured with ADE 6033 T)

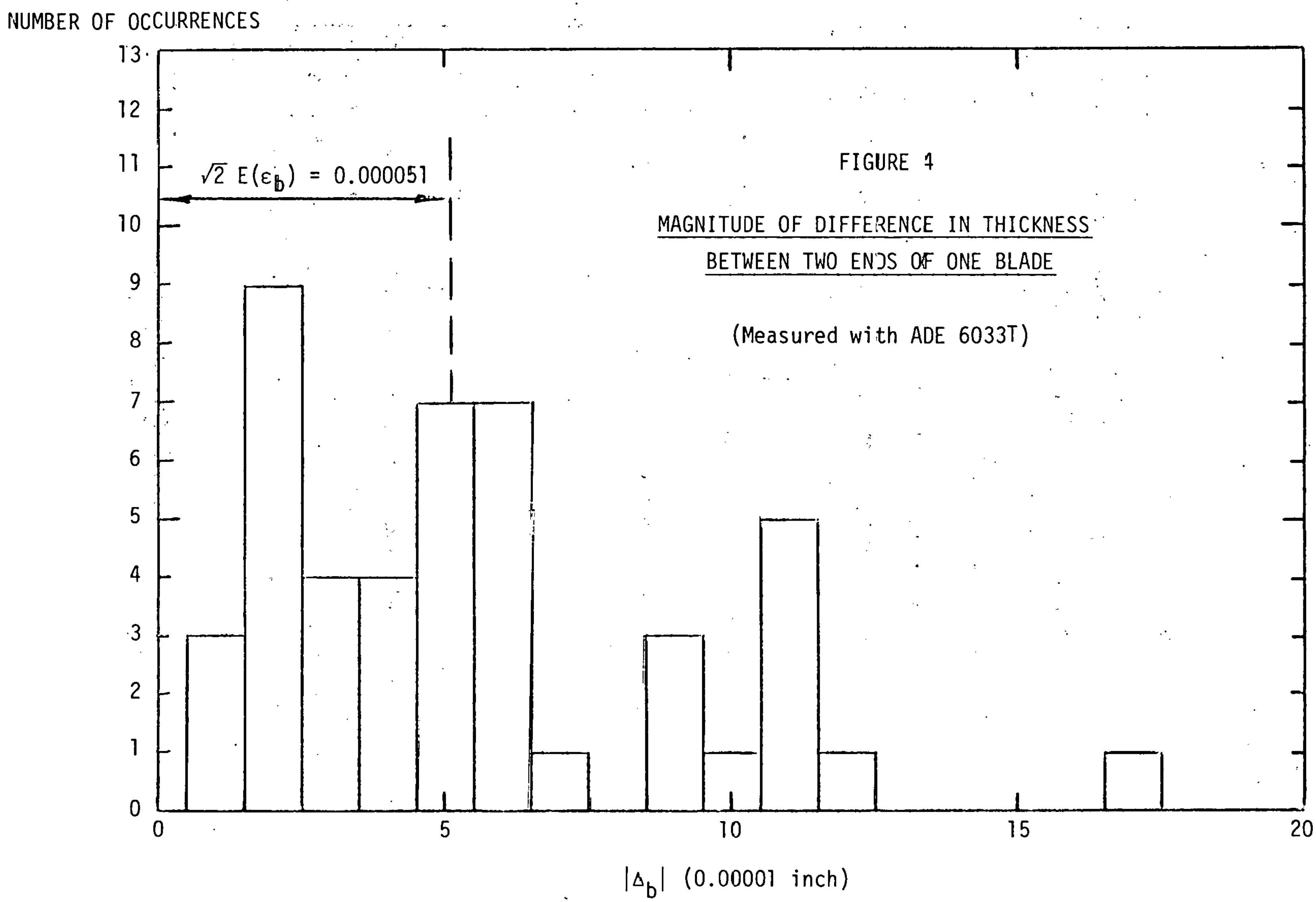


FIGURE 4

MAGNITUDE OF DIFFERENCE IN THICKNESS BETWEEN TWO ENDS OF ONE BLADE

(Measured with ADE 6033T)

magnitude of this error $E(\Delta_b)$ is compared to the single blade error by

$$E(\Delta_b) = \sqrt{2}\, E(\varepsilon_b) \tag{14}$$

From Figure 4, the expected value of blade error, assuming the way in which blades are actually stacked, is

$$E(\varepsilon_b) = 0.000036 \text{ inch} \tag{15}$$

This measurement of Equation (15) is also by the ADE technique. The mechanical measurement may give an error two to three times this value. Thus, the combined error may be assumed to be in the range.

$$E(\varepsilon_s) + E(\varepsilon_b) = 0.000075 \text{ to } 0.000200 \text{ inch} \tag{16}$$

Therefore, the maximum and average runout of a 225 blade package is expected to be

$$\begin{aligned} \Delta_{max} &= 0.00090 \text{ to } 0.00239 \text{ inch} \\ \Delta_{ave} &= 0.00060 \text{ to } 0.00160 \text{ inch} \end{aligned} \tag{17}$$

As a point of reference, the expected runout of the end (225^{th}) blade prior to its alignment will be identical to the maximum runout of an aligned package of 450 blades. In most cases this is seen to be 0.002 to 0.005 inches. From Equations (11) and (16) for 450 blades

$$\Delta_{max}(450) = 0.0013 \text{ to } 0.0034 \text{ inch} \tag{18}$$

The upper limit of error may be a good representation of a package. It is also a convenient representation of the thickness variation of wafers from this process.

4.5 Loads on Wafers from Misalignment

The load deflection characteristics of a blade were previously analyzed[5]. The stiffness of a typical (0.2 by 6.35 mm) blade at the center is

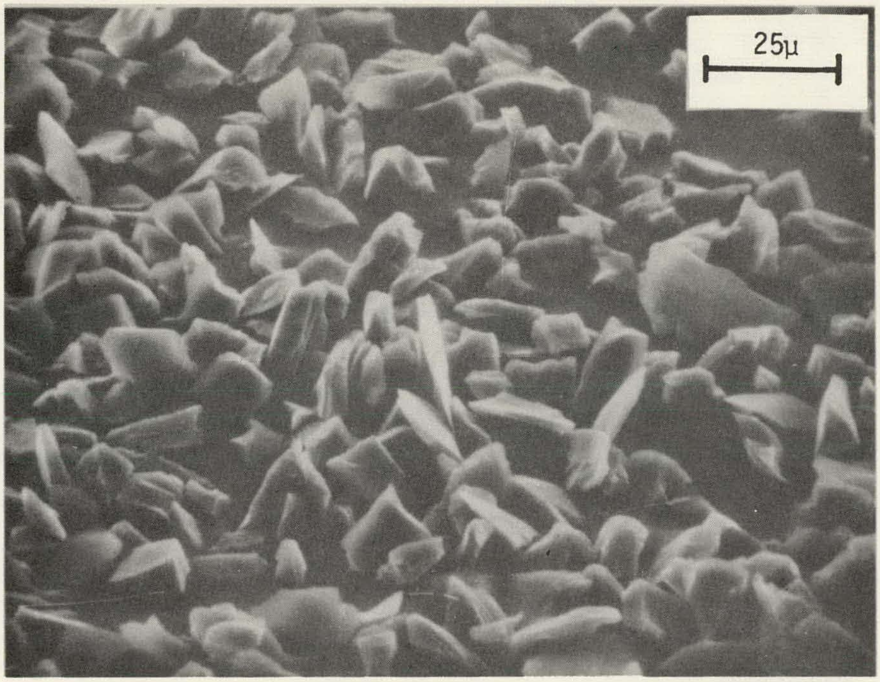
$$F/X = 1.9 \times 10^4 \text{ g/cm} \qquad (19)$$

At the end of a 20 cm stroke on a 10 cm ingot, the maximum stiffness may be as high as 4.6×10^4 g/cm. Assuming that half of the runout of a central blade is the maximum from Equation (17), the side load on a wafer is as high as 140 grams. Considering the variations from the statistical view, the shock loads imposed at the ends of the stroke and increased loads due to wandering, the breakage of a few to a large number of wafers during a slicing operation in the 250 micron thickness range is not surprising.

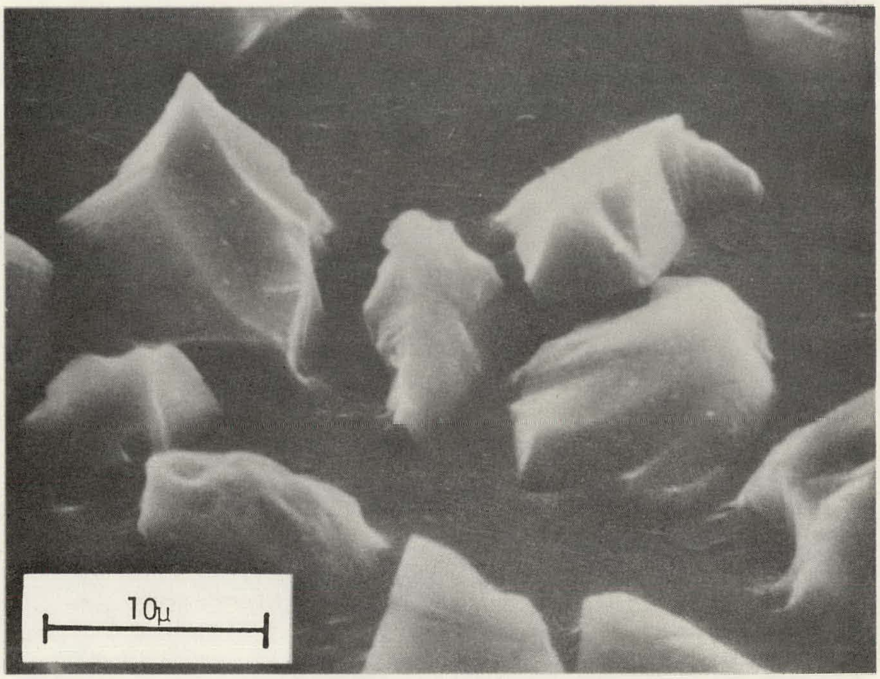
4.6 SEM Study of Abrasives

Samples of unused #600 silicon carbide abrasive and slurry samples from various stages of the slurry lifetime test series 2-006 were photographed using a scanning electron microscope. Also viewed were fresh samples of #600 Boron Carbide and a blade edge used in a slicing test. These micrographs are shown in Figures 5 through 9.

Used abrasive was separated from the slurry oil by sequentially diluting with chlorethane, allowing particles to settle and pouring off the diluted oil.



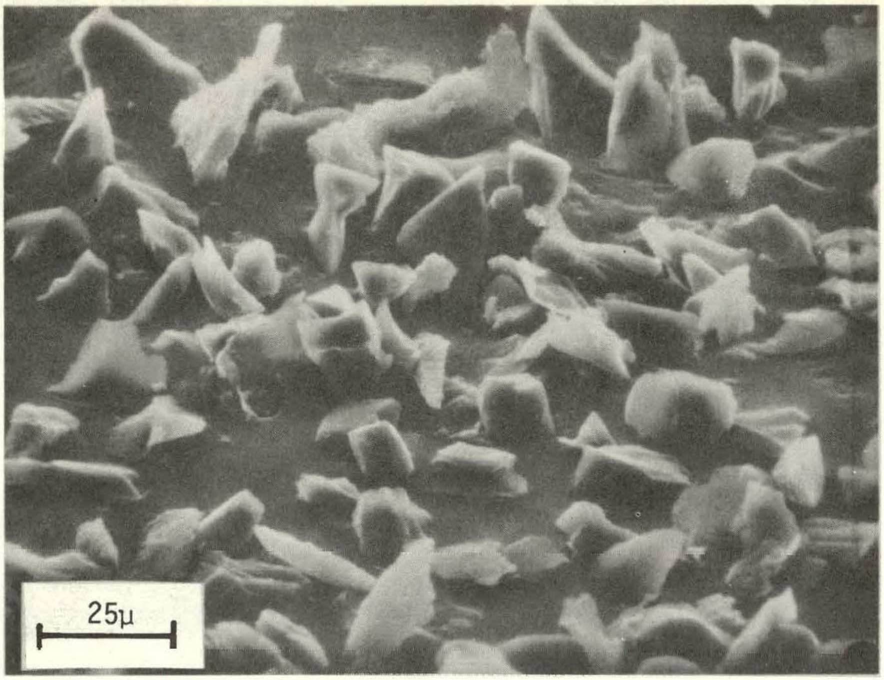
a) 700X



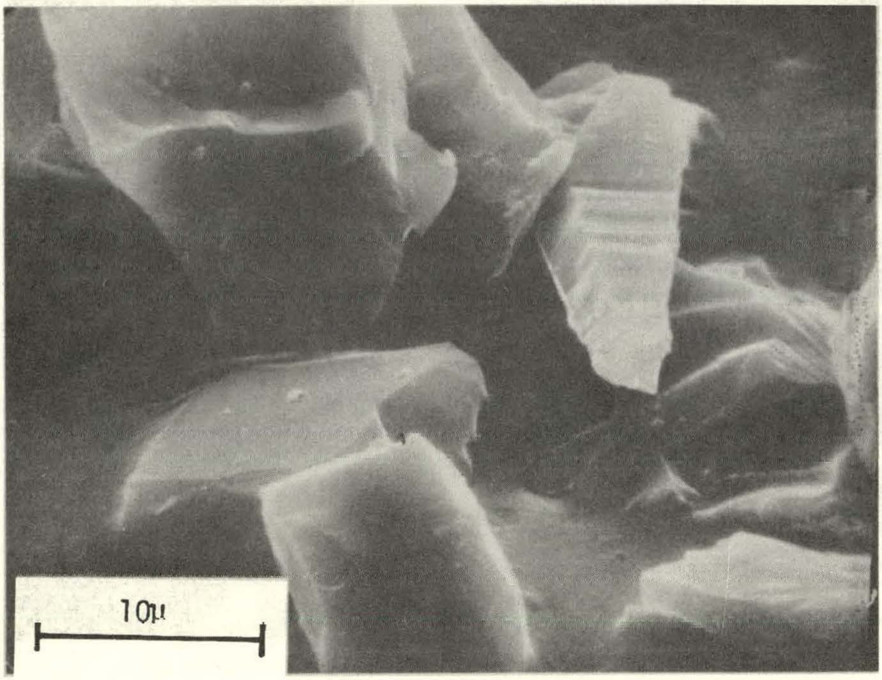
b) 3,000X

FRESH #600 SiC ABRASIVE

FIGURE 5



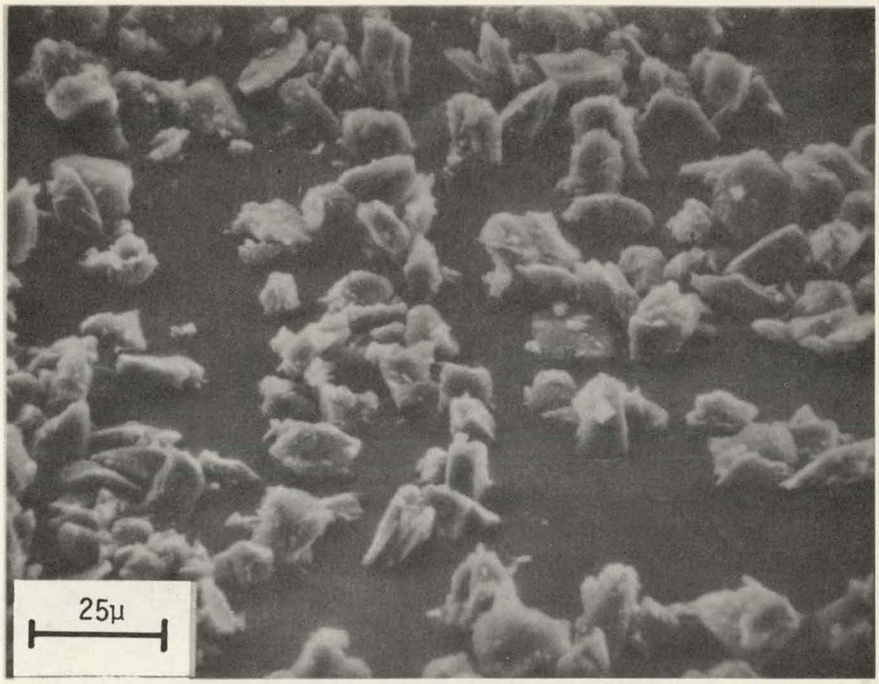
a) 700X



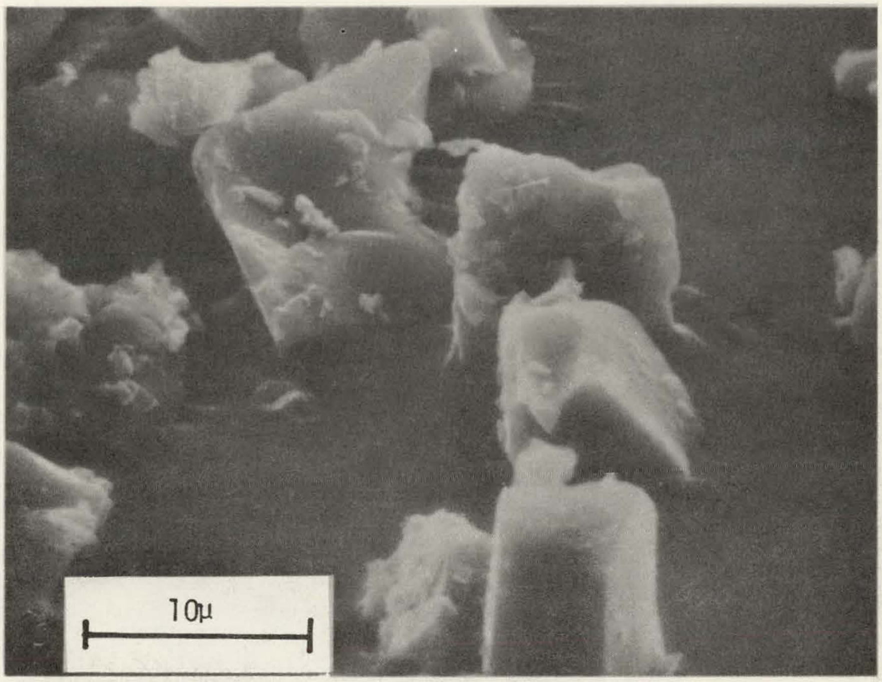
b) 3,000X

FRESH #600 B_4C ABRASIVE

FIGURE 6



a) 700X

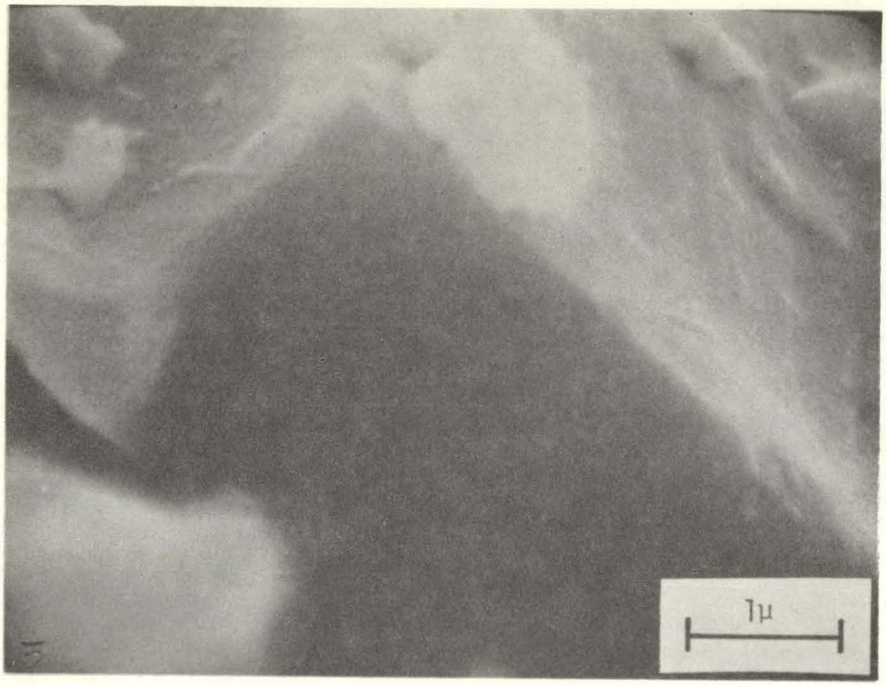


b) 3,000X

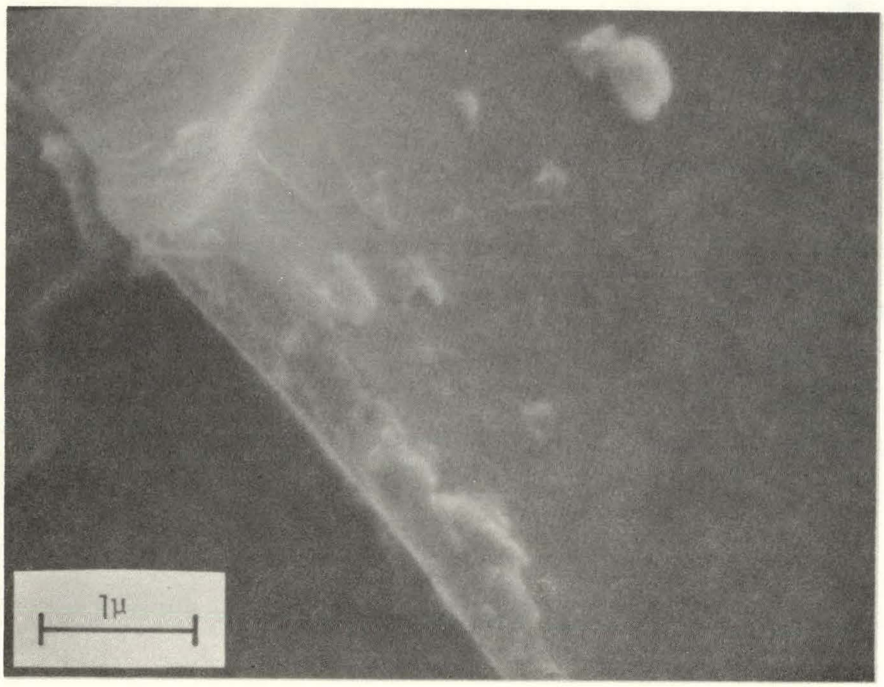
#600 SiC ABRASIVE USED IN MULTIBLADE SLURRY SAWING

(Separated from slurry used in Test 2-006A through 2006C. Silicon abrasion to 78.0 cm^3/liter of oil and 163 cm^3/kg of abrasive)

FIGURE 7



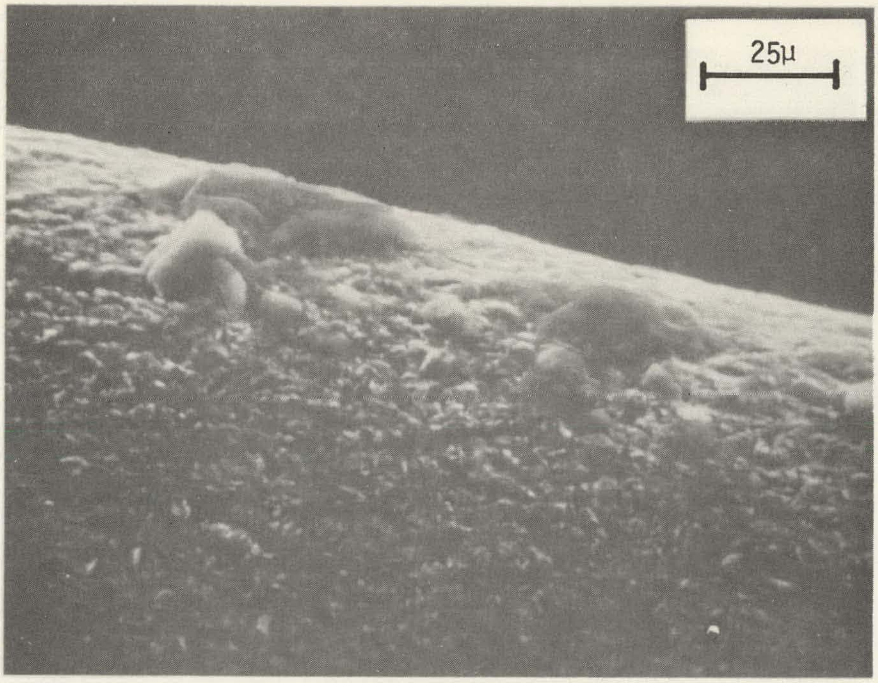
a) 20,000X
RETENTION
OF
SHARP
EDGES



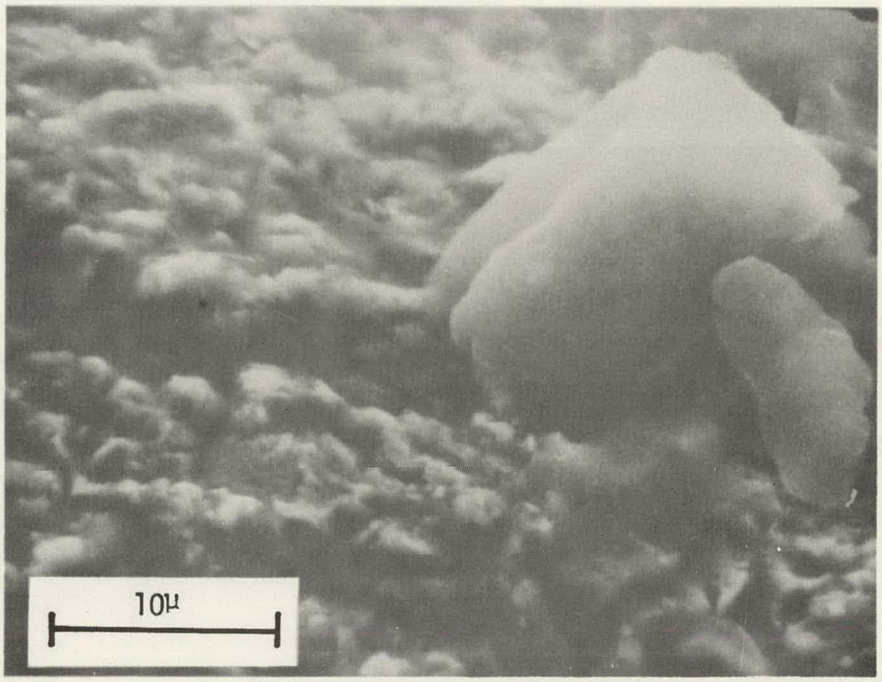
b) 20,000X
BUILDUP
OF
DEBRIS

DETAIL OF #600 SiC ABRASIVE USED IN MULTIBLADE SLURRY SAWING

FIGURE 8



a) 700X



b) 3,000X
IMBEDDED
ABRASIVE
PARTICLE

CUTTING EDGE OF A BLADE USED IN MULTIBLADE SLURRY SAWING

(From Test #3-031)

FIGURE 9

TABLE 2

SUMMARY OF BLADE WEAR

TEST	BLADE SIZE (mm)	FINAL HEIGHT (mm)	WEAR RATIO
2-006A	0.20 x 6.35	4.06	0.047
2-006B	0.20 x 6.35	3.86	0.056
2-006C	0.20 x 6.35	4.90	0.052
2-023	0.20 x 6.35	3.91	0.054
2-024	0.20 x 6.35	3.99	0.049
2-025	0.20 x 6.35	4.17	0.046
3-032	0.15 x 6.35	3.76	0.051
3-033	0.15 x 6.35	3.58	0.056
P-001	0.20 x 6.35	3.76	0.053
P-002	0.20 x 6.35	3.81	0.051

The particle size for all #600 abrasive was 10 microns on the average. The size of particles did not appear to decrease from fresh to fully used slurry. However, the used abrasive was decorated with particles of silicon 0.4 to 1 micron in diameter.

There was no large scale change in the appearance of the silicon carbide through the cutting history of the slurry. However, there was occassionally a build-up of silicon along the sharp edges of the silicon carbide. This condition appears similar to the built-up edge (BUE) on the wear land of machine cutting tools (Figure 8b). The accumulation of silicon particles adhering to the cutting edges of silicon carbide may effectively blunt the edges and reduce the tendency to cut the silicon workpiece.

The appearance of the silicon carbide was such that the possibility of abrasive breakdown or blunting causing a limit to slurry life was not apparent. Instead it appears that silicon debris causing viscosity increase may be the limit to the lifetime of cutting ability of slurry.

Also, it is apparent that the major difference between silicon carbide and boron carbide abrasive is a slightly larger particle size for boron carbide. The cleaved, sharp particles are both of similar shapes.

Figure 9 shows an abrasive particle which has remained imbeded in a blade. This is not a common occurrence, but the imbedding of abrasive particles was never assumed to be permanent. Instead, a quasi-static imbedding is most likely.

4.7 Blade Wear

No change in typical blade wear has been observed during the cutting tests of 10 cm silicon ingots. Table 2 shows the summary of blade wear during the past quarter. With both 0.20 and 0.15 mm blades, wear ratio (loss of blade vs. loss of silicon) is between 0.04 and 0.05. The loss of blade height during slicing is typically 2.5 mm. For a 6.35 mm high blade, this does not allow slicing through 2 10 cm ingots, but would allow slicing through a 12 cm ingot (44% more slice area). No useful changes of slicing conditions have impacted blade wear.

5.0 WAFER CHARACTERIZATION

Two physical aspects of wafers are important to the finished solar cell. The geometry of wafers sliced during this quarter is described in Table 3. The damage imparted to the wafers during abrasion was viewed with an SEM.

5.1 Wafer Geometry

The summary of wafer geometry shown in Table 3 indicates no departures from wafer accuracy previously reported. The variation of wafers is similar to the expected runout of blades derived in Section 4.4. A few trends in accuracy are important.

Low slurry mix (#2-023) resulted in reduced thickness accuracy, but a slightly reduced kerf loss. The high cutting force (#2-024) did not degrade slice accuracy significantly, but kerf loss was increased by 7 to 8 microns. The thinning of slurry (#2-025) seemed to increase the taper of wafers.

0.15 mm blades resulted in thickness consistency and taper similar to 0.20 mm blades. However, a change of slurry mix from 0.48 kg/liter to 0.24 kg/liter reduced kerf loss by 13 microns. Accuracy was only slightly improved by this reduction.

5.2 Wafer Surface Damage

Figures 10 to 15 show SEM micrographs etched and unetched surfaces of wafers sliced with three different abrasives. The etched surfaces were prepared using a 5 minute Wright etch. Measurements indicated that 4 microns of surface was removed.

TABLE 3

SUMMARY OF WAFER CHARACTERIZATION

TEST		2-006A	2-006B	2-006C
THICKNESS (AVE)	cm	0253	0270	DNF
STD. DEVIATION	cm	0022	0029	
TOTAL VARIATION (AVE)	cm	0040	0057	
STD. DEVIATION	cm	0015	0024	
STD. DEVIATION (AVE)	cm	0015	0022	
STD. DEVIATION	cm	0006	0009	
VARIATION (AVE WAFER)	cm	0016	0017	
TAPER (AVE WAFER)	cm	0016	0017	
BOW (AVE)	μm	--	--	
TAPER (AVE)	μm	30	--	
WAVINESS (p-p) (10^{-2}m)	μm	23	48	
ROUGHNESS (p-p) (10^{-4}m)	μm	2.3	2.3	
ROUGHNESS (RMS)	μinch	15-16	14-16	
STEPS	μm		8.5	
DAMAGE DEPTH ($<10^4/cm^2$)	μm			

TABLE 3
(continued)

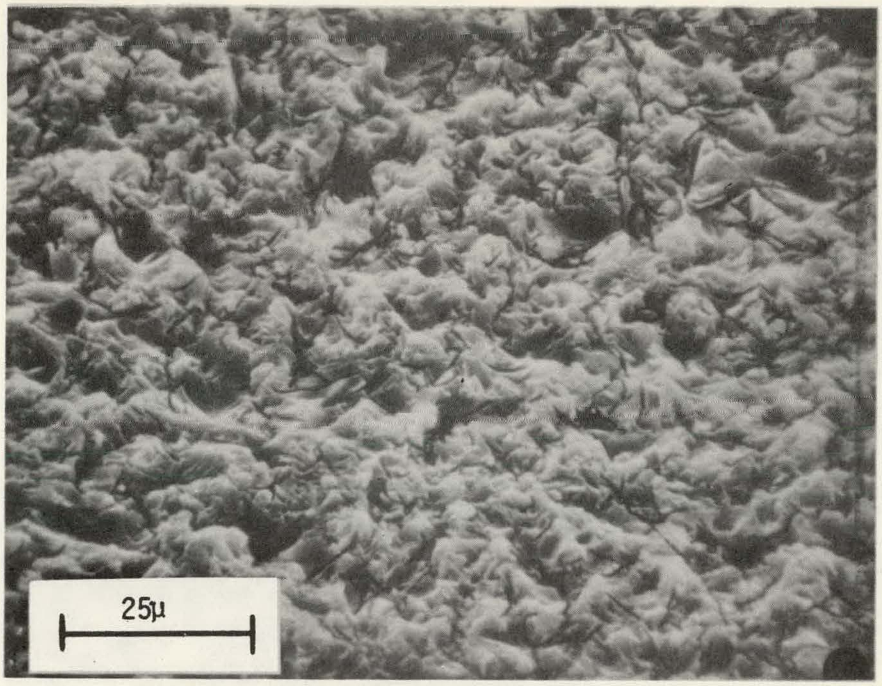
SUMMARY OF WAFER CHARACTERIZATION

TEST		2-022	2-023	2-024	2-025
THICKNESS (AVE)	cm	DNF	0257	0348	0248
STD. DEVIATION	cm		0030	0025	0011
TOTAL VARIATION (AVE)	cm		0049	0041	0043
STD. DEVIATION	cm		0035	0015	0019
STD. DEVIATION (AVE)	cm		0018	0016	0017
STD. DEVIATION	cm		0011	0006	0007
VARIATION (AVE WAFER)	cm		0023	0018	0020
TAPER (AVE WAFER)	cm		0013	0010	0018
BOW (AVE)	μm		--	--	68
TAPER (AVE)	μm		22	19	35
WAVINESS (p-p) (10^{-2}m)	μm		16	38	15
ROUGHNESS (p-p) (10^{-4}m)	μm		2	3	3
ROUGHNESS (RMS)	μinch		21-24	16-19	15-18
STEPS	μm		--	--	--
DAMAGE DEPTH (<10^4/cm^2)	μm				

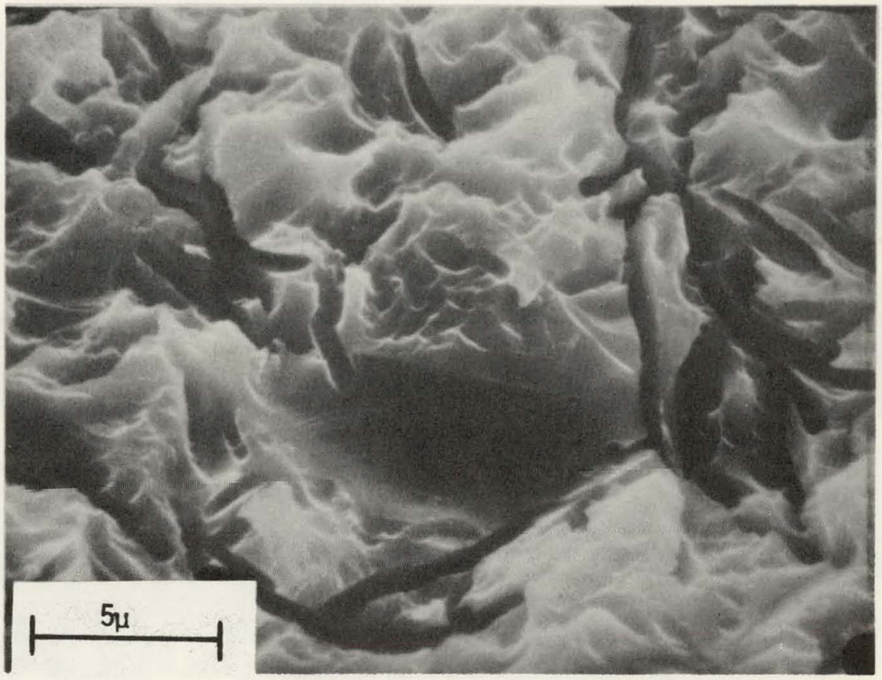
TABLE 3
(continued)

SUMMARY OF WAFER CHARACTERIZATION

TEST		3-032	3-033	P-001	P-002
THICKNESS (AVE)	cm	0343	0255	0048	0303
STD. DEVIATION	cm	0019	0018	0007	0015
TOTAL VARIATION (AVE)	cm	0046	0044	0047	0036
STD. DEVIATION	cm	0027	0021	0015	0014
STD. DEVIATION (AVE)	cm	0018	0017	0017	0014
STD. DEVIATION	cm	0011	0009	0006	0006
VARIATION (AVE WAFER)	cm	0020	0022	--	--
TAPER (AVE WAFER)	cm	0018	0019	--	--
BOW (AVE)	μm	50	--	--	--
TAPER (AVE)	μm	--	21	--	10
WAVINESS (p-p) (10^{-2}m)	μm	70	62	--	29
ROUGHNESS (p-p) (10^{-4}m)	μm	30	3	--	25
ROUGHNESS (RMS)	μinch	14-16	24-28	17-20	13-17
STEPS	μm	30	--	--	--
DAMAGE DEPTH ($<10^4/cm^2$)	μm				



a) 1,000X

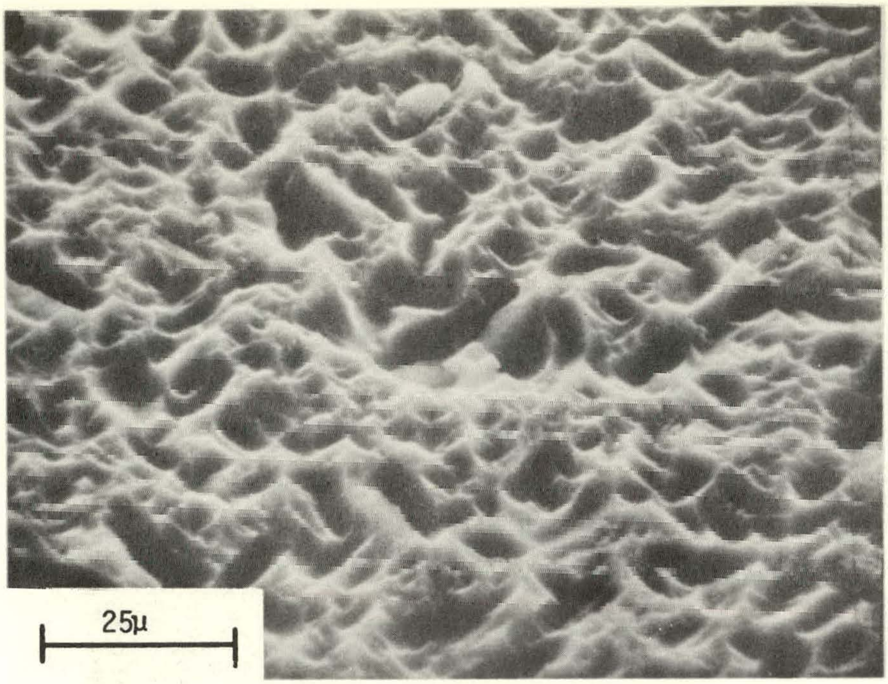


b) 5,000X

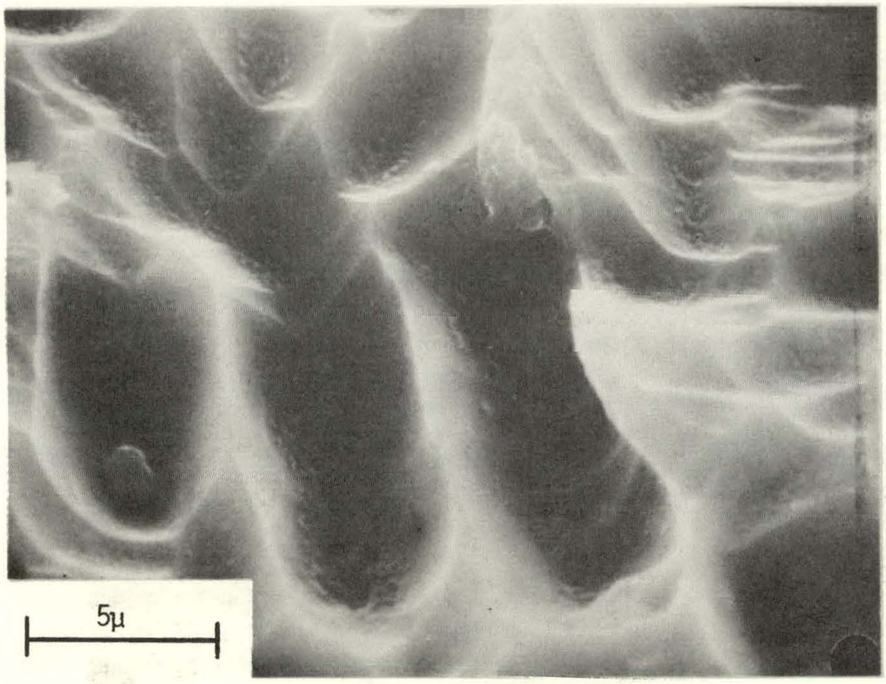
UNETCHED SURFACE OF A MULTIBLADE SLURRY SAWN SILICON WAFER

({100} Surface viewed at 45° from normal. #600 SiC abrasive used -- Test #2-001)

FIGURE 10



a) 1,000X

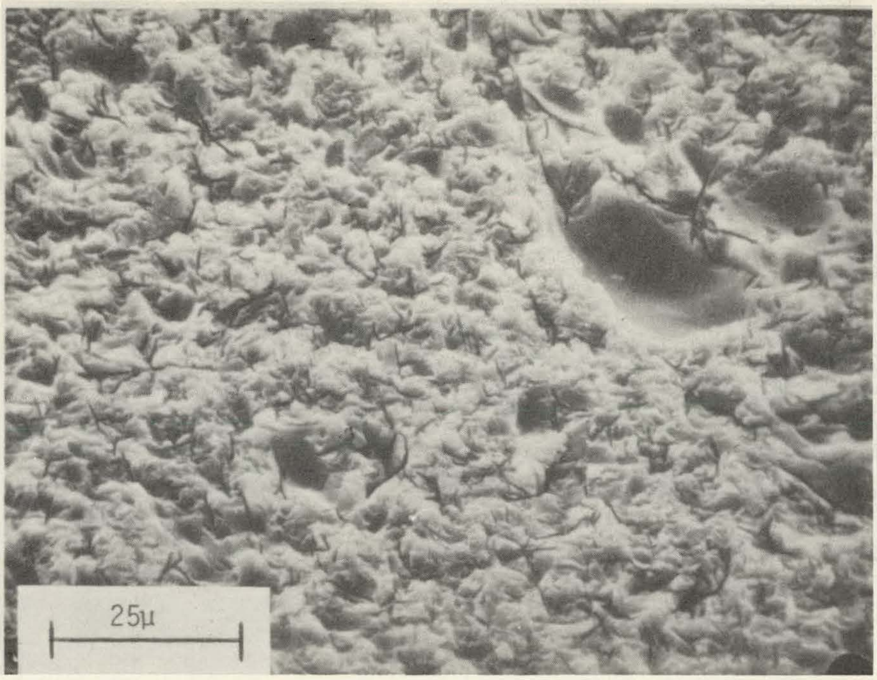


b) 5,000X
(ROTATED
FROM
ABOVE)

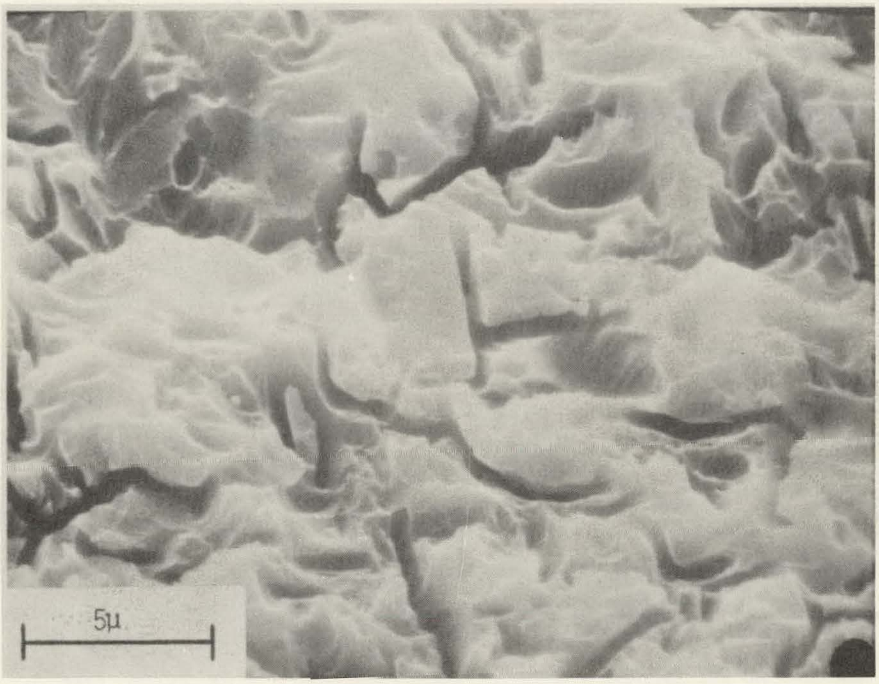
ETCHED SURFACE OF A MS SAWN SILICON WAFER

({100} Surface viewed at 45°. #600 SiC abrasive - Text #2-001 4μ removed with 5 minute Wright etch)

FIGURE 11



a) 1,000X

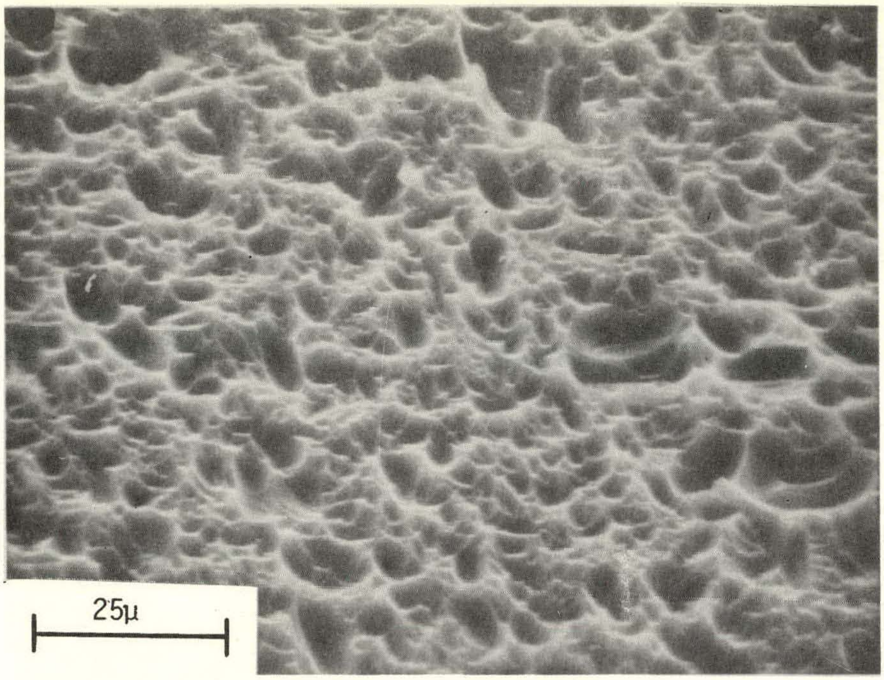


b) 5,000X

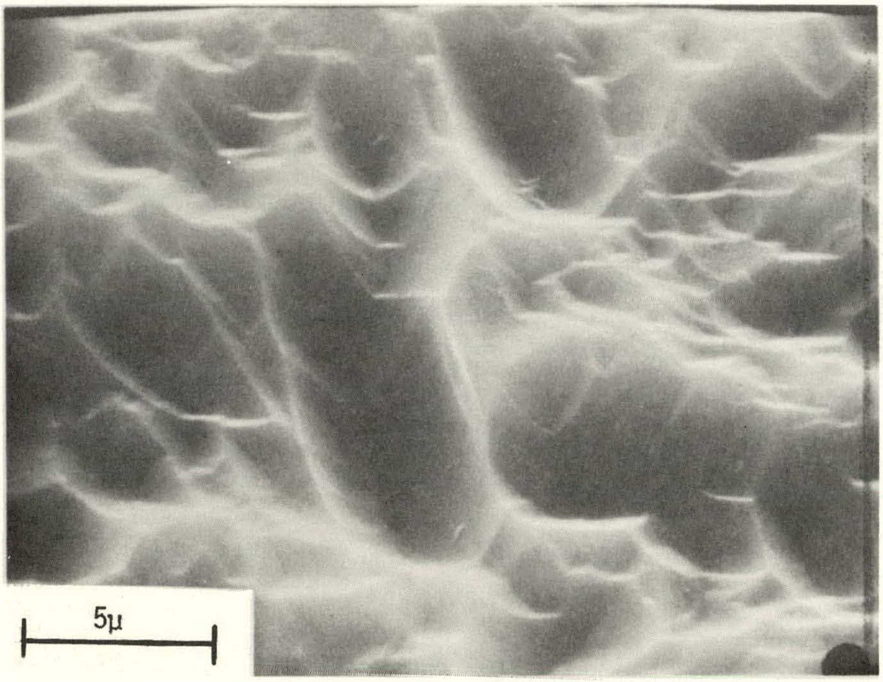
UNETCHED SURFACE OF A MS SAWN SILICON WAFER - #800 SiC

({100} Surface viewed at 45°. #800 SiC abrasive - Text #2-011)

FIGURE 12



a) 1,000X

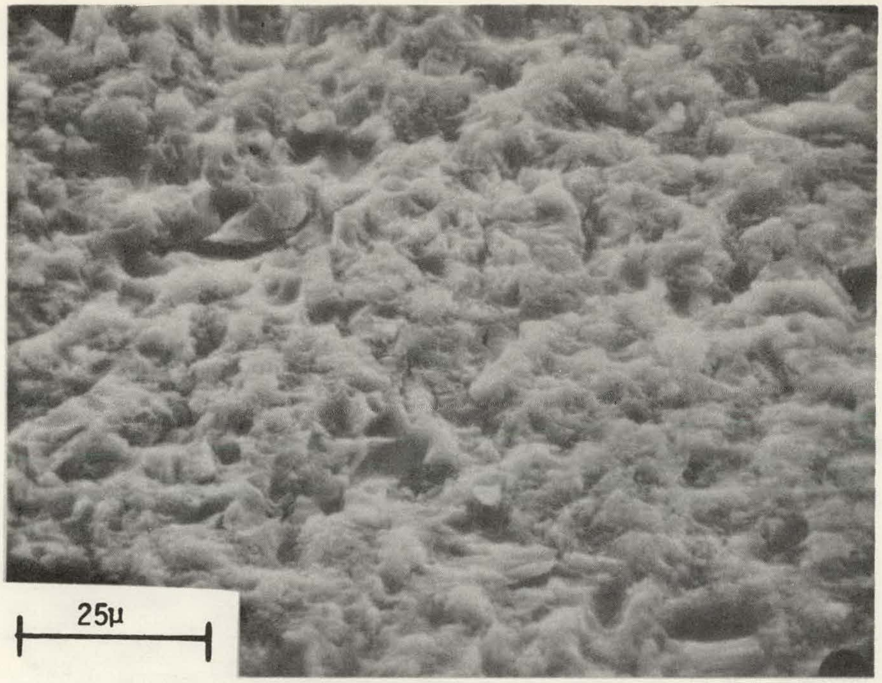


b) 5,000X

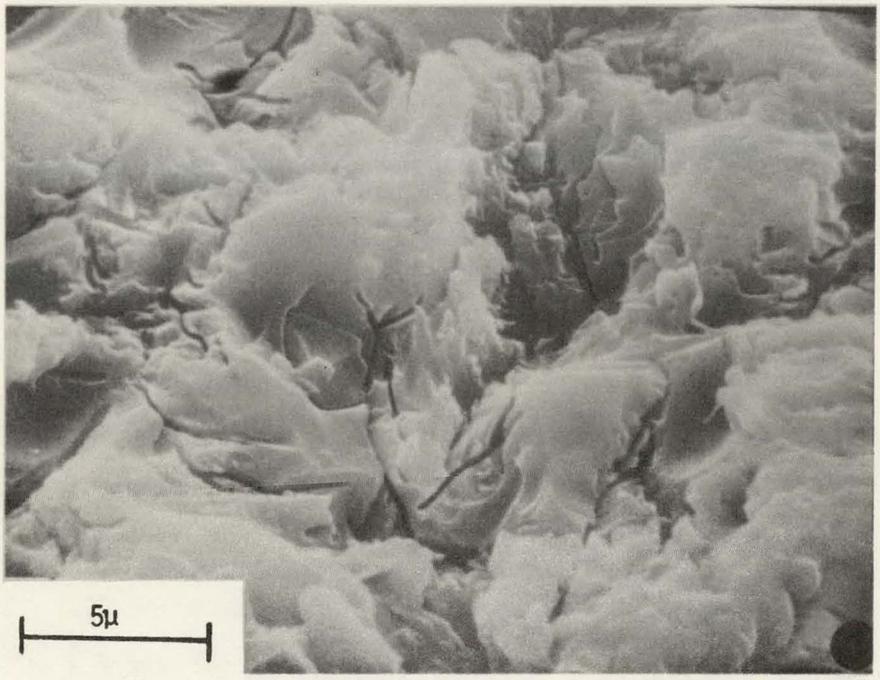
ETCHED SURFACE OF A MS SAWN SILICON WAFER - #800 SiC

({100} Surface viewed at 45°. #800 SiC abrasive - Test #2-011. 4μm removed with 5 minute Wright etch)

FIGURE 13



a) 1,000X

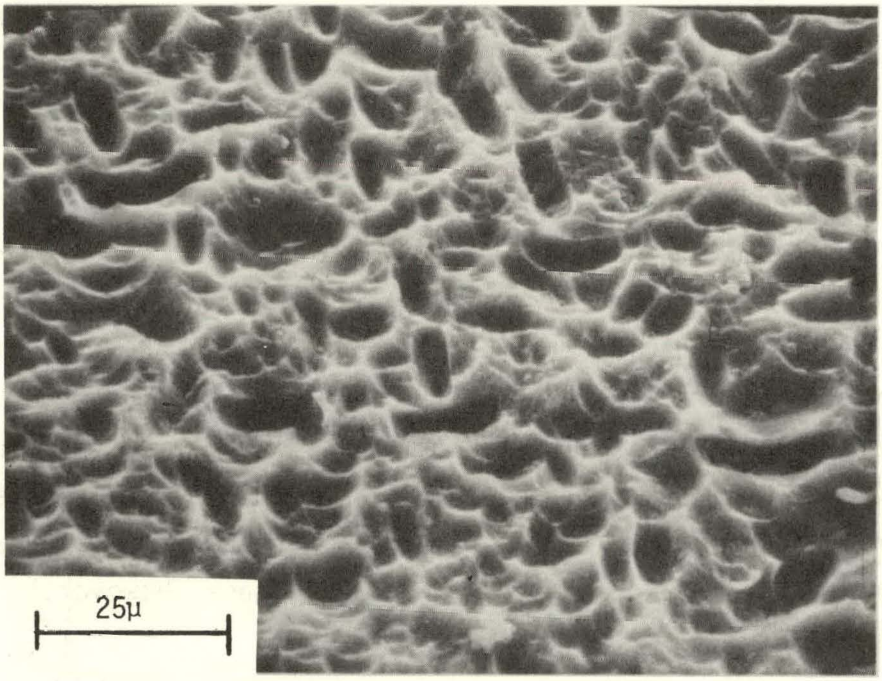


b) 5,000X

UNETCHED SURFACE OF A MS SAWN SILICON WAFER - #600 B_4C

({100} Surface viewed at 45°. #600 B_4C abrasive - Test #2-041)

FIGURE 14



1,000X

ETCHED SURFACE OF A MS SAWN SILICON WAFER - #600 B_4C

({100} Surface viewed at 45°. #600 B_4C abrasive - Test #2-041. 4μm removed with 5 minute Wright etch)

FIGURE 15

All surfaces indicate a fine (1 to 10 micron) interspacing of cracks. These are likely Hertzian fractures produced as abrasive particles passed over the surface. The network appears to result in material removal by intersection of cracks producing free silicon particles. Figure 10b shows a void from which a particle was formed.

The etched ⟨100⟩ surfaces show the remnants of major cracks oriented 90° apart. Presumably these are cracks which were oriented along ⟨111⟩ planes and propagated deeper than the rest. The cracks appear to be no deeper than 5 to 10 microns. The Wright etch has caused the cracks to widen into a coarse topography after minimal material removal.

The surface sliced with finer (#800) silicon carbide abrasive has a finer crack network. The particle voids (Figure 12a) are much larger (30 microns) than with #600 SiC. This result is even obvious under a low power optical microscope. The #600 Boron Carbide resulted in a crack network of a different appearance. The spacing is comparable to #600 SiC, but the cracks are much finer. They did not seem to open as much as those produced with #600 SiC. The etched wafer appears the same, however.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Wafers of 10 cm silicon ingot can be sliced 250 to 300 microns thick with kerf loss from 200 to 250 microns. Wafer thickness below 250 microns is limited by practical spacer thickness and more importantly by the tendency of thin wafers (~250 microns) to break during slicing. Kerf loss below 200 microns is not now possible since thin blades fatigue and break early in the slicing operation.

Slurry can last through a full saw capacity of 10 cm wafers 225 slicers). However, the mechanism of slurry failure is not obvious from SEM micrographs of used silicon carbide slurry. Blades 6.35 mm high can easily last through a 10 cm ingot, and blade wear ratios should allow a 12 cm ingot to be sliced.

Further work should be done for means of improving blade package accuracy. This may allow thinner blades to be used and thinner slices to be sliced by reducing misalignment within the stacked blade package. The alignment must not rely on the statistical accumulation of small component errors.

7.0 PLANS

Plans for the duration of the contract are:

1) Test high cutting force with high abrasive concentration (0.20 mm blades).

2) Test 0.15 mm blades with high cutting force (140 g).

3) Build and test supporting workholder. Test with 0.15 mm blades and 0.30 mm spacers.

4) Demonstrate full production capacity slicing with 0.20 and 0.15 mm blades.

5) Prepare economic evaluation of slicing costs. Evaluate production demonstrations for cost effectiveness.

REFERENCES

1 S. C. Holden, SLICING OF SILICON INTO SHEET MATERIAL, THIRD QUARTERLY REPORT, Varian Associates, ERDA/JPL 954374-76/4, December 27, 1976, pg. 11.

2 Ibid, pg. 22.

3 HANDBOOK OF CHEMISTRY AND PHYSICS, The Chemical Rubber Co., Cleveland, 1966, pg. A-242.

4 R. L. Anderson and T. A. Bancroft, STATISTICAL THEORY IN RESEARCH, McGraw-Hill Book Company, New York, 1952, pg. 11.

5 S. C. Holden, op. cit., pg. 16

APPENDIX

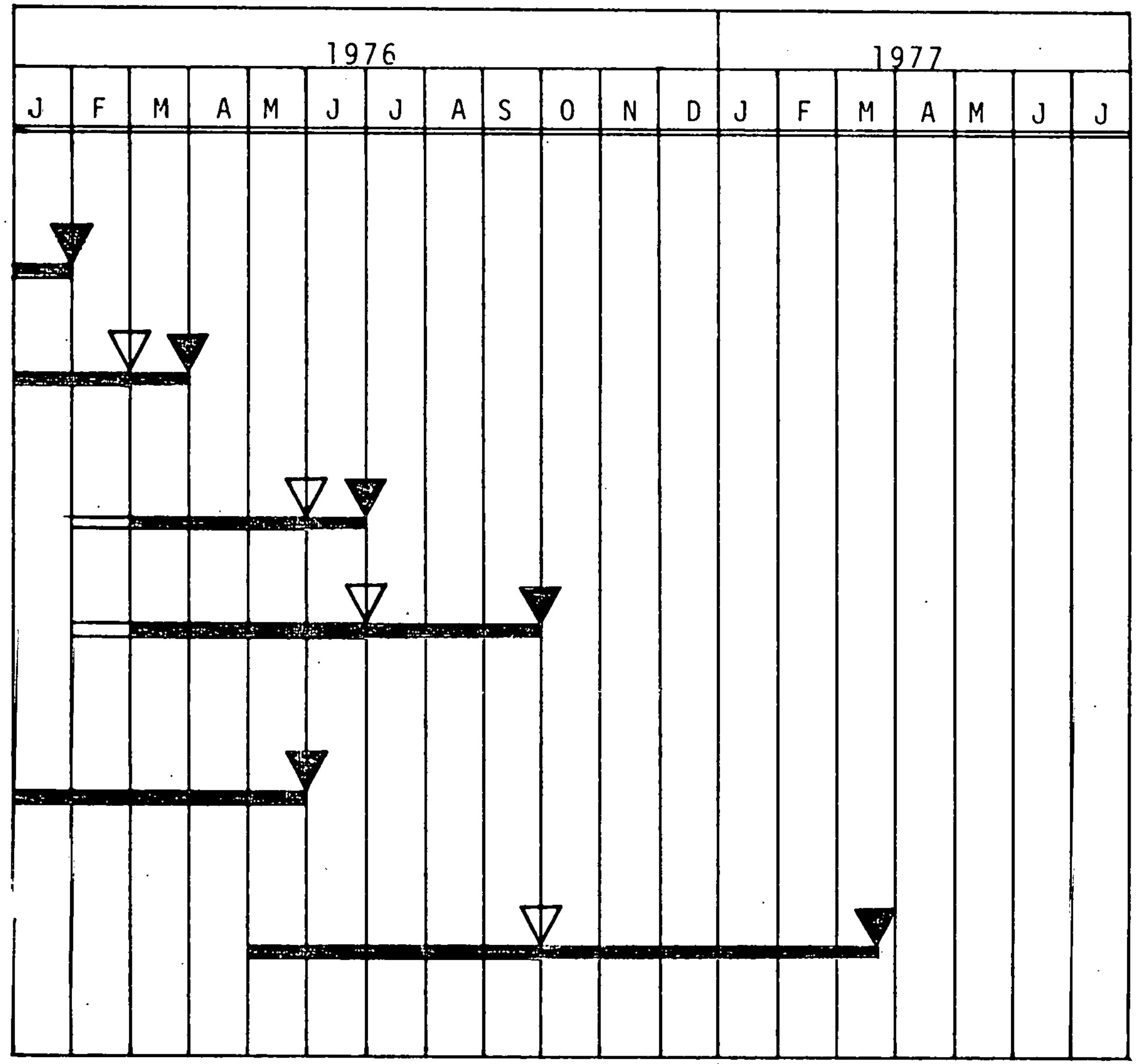
PROGRAM PLAN (UPDATED)

SLICING OF SILICON INTO SHEET MATERIALS

Varian Associates
Lexington Vacuum Division
JPL Contract No. 954374
Starting Date: 1/9/76

Program Plan

1. Background Parameter Study
   - 1.1. Establish standardized cutting format and data collection technique
   - 1.2. Modify saw, measure accuracy, build dynamometer
   - 1.3. Slicing tests - effects of load, speed, slurry, work configuration on rate, wear, wafer accuracy, etc.
   - 1.4. Wafer characterization
2. Theoretical Model
   - 2.1. Parameterize system performance from modified abrasive wear viewpoint
   - 2.2. Establish practical limits to theory - wafer accuracy and thickness, blade instability, abrasive blunting, etc.



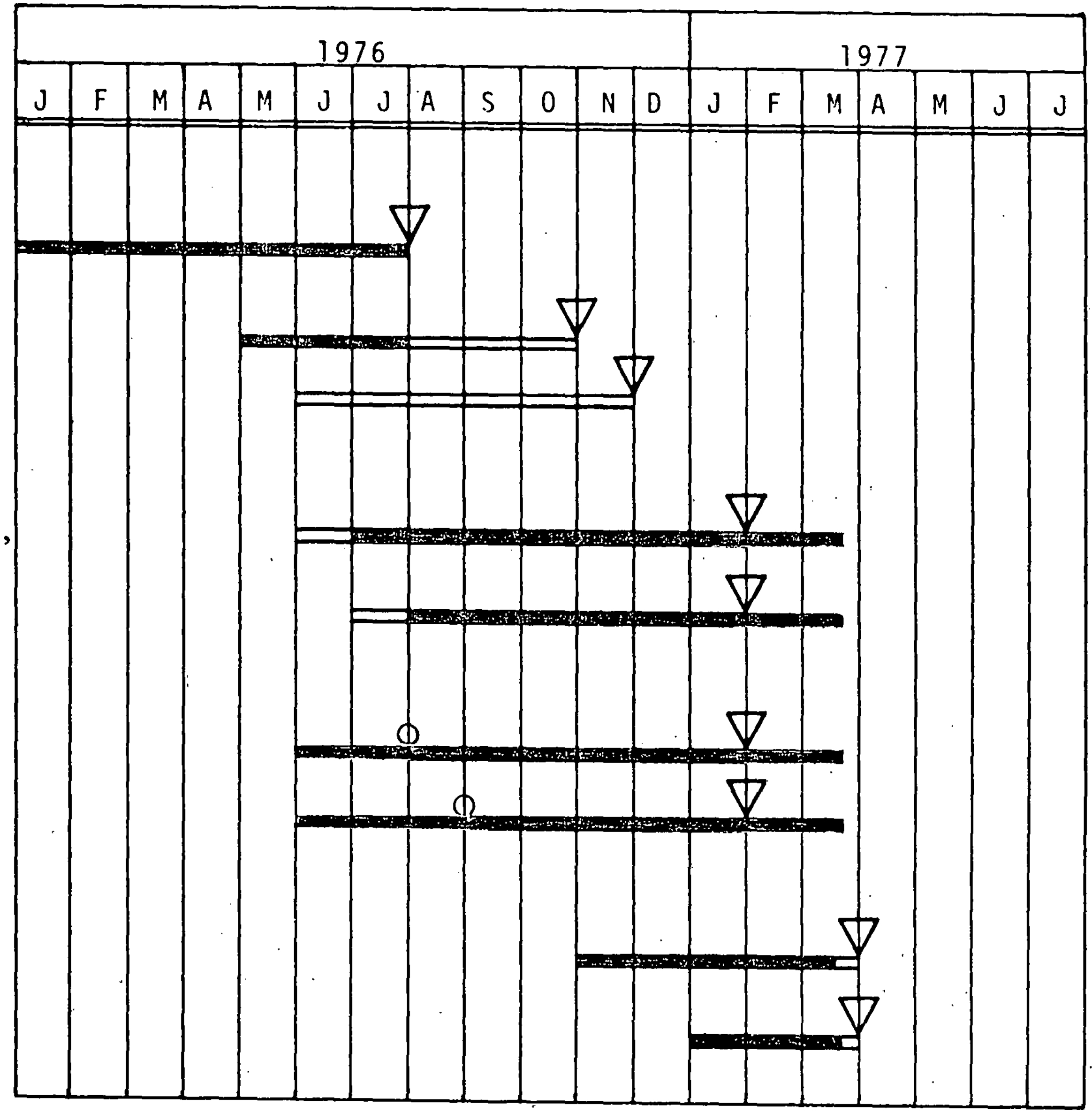
Sch 1/22/76
Updated 3/27/77

3. Load Balancing
   - 3.1. Build feedback control system - rate and force interaction
   - 3.2. Cutting performance vs. results of 1.3.
   - 3.3. Wafer characterization

4. Blade Materials
   - 4.1. Cutting tests - optimum blade material, thickness, etc. for silicon
   - 4.2. Wafer characterization

5. Abrasives
   - 5.1. Cutting tests - optimum size, slurry mix, application technique
   - 5.2. Wafer characterization

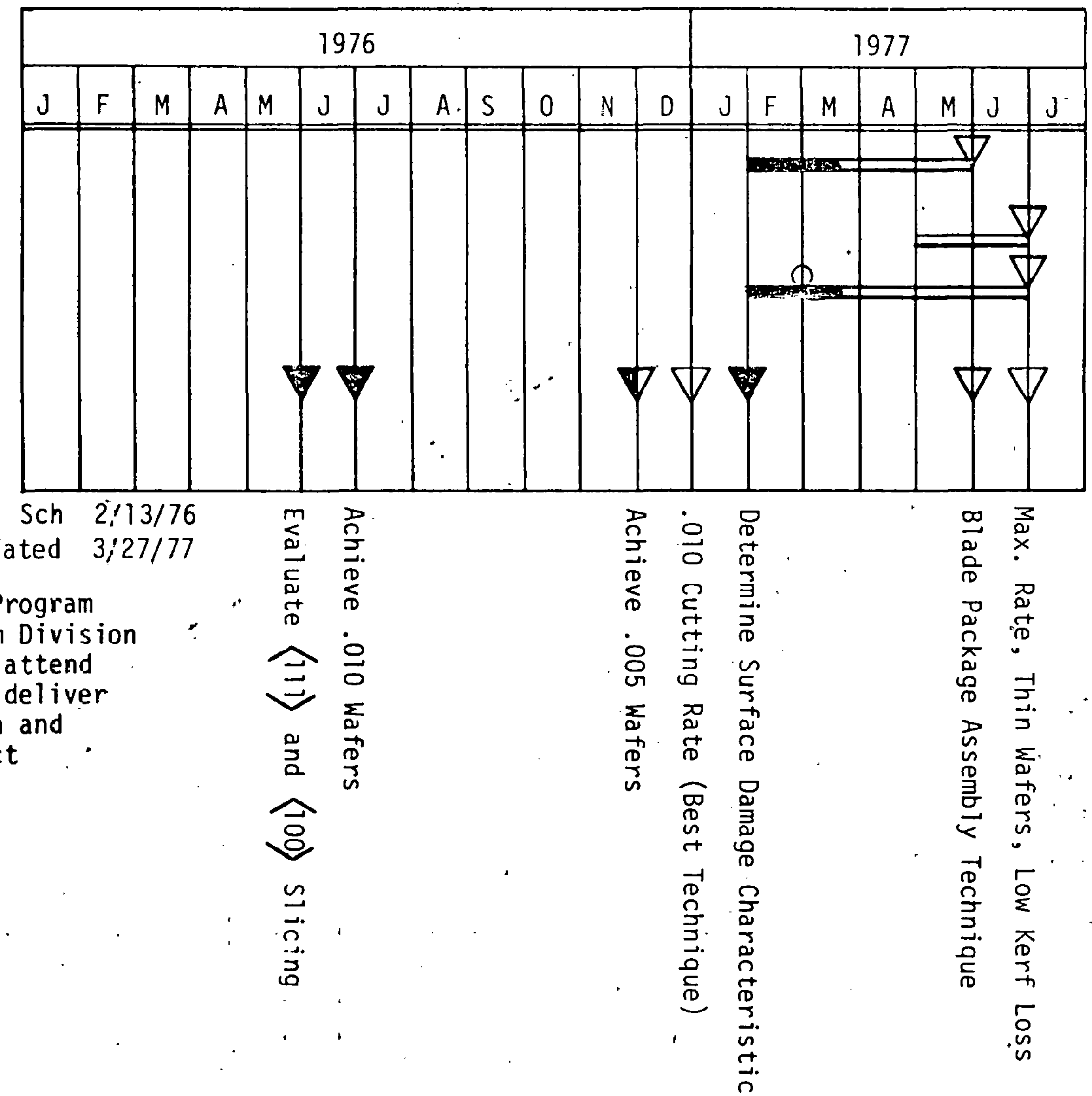
6. Prototype Production Technique
   - 6.1. Optimize previous results within guidelines of wafer specifications
   - 6.2. Modify equipment



Sch 1/22/76
Updated 3/27/77

7. Evaluation
   - 7.1. Cutting tests with final system
   - 7.2. Economic evaluation, scale-up potential
   - 7.3. Wafer characterization

8. Milestones



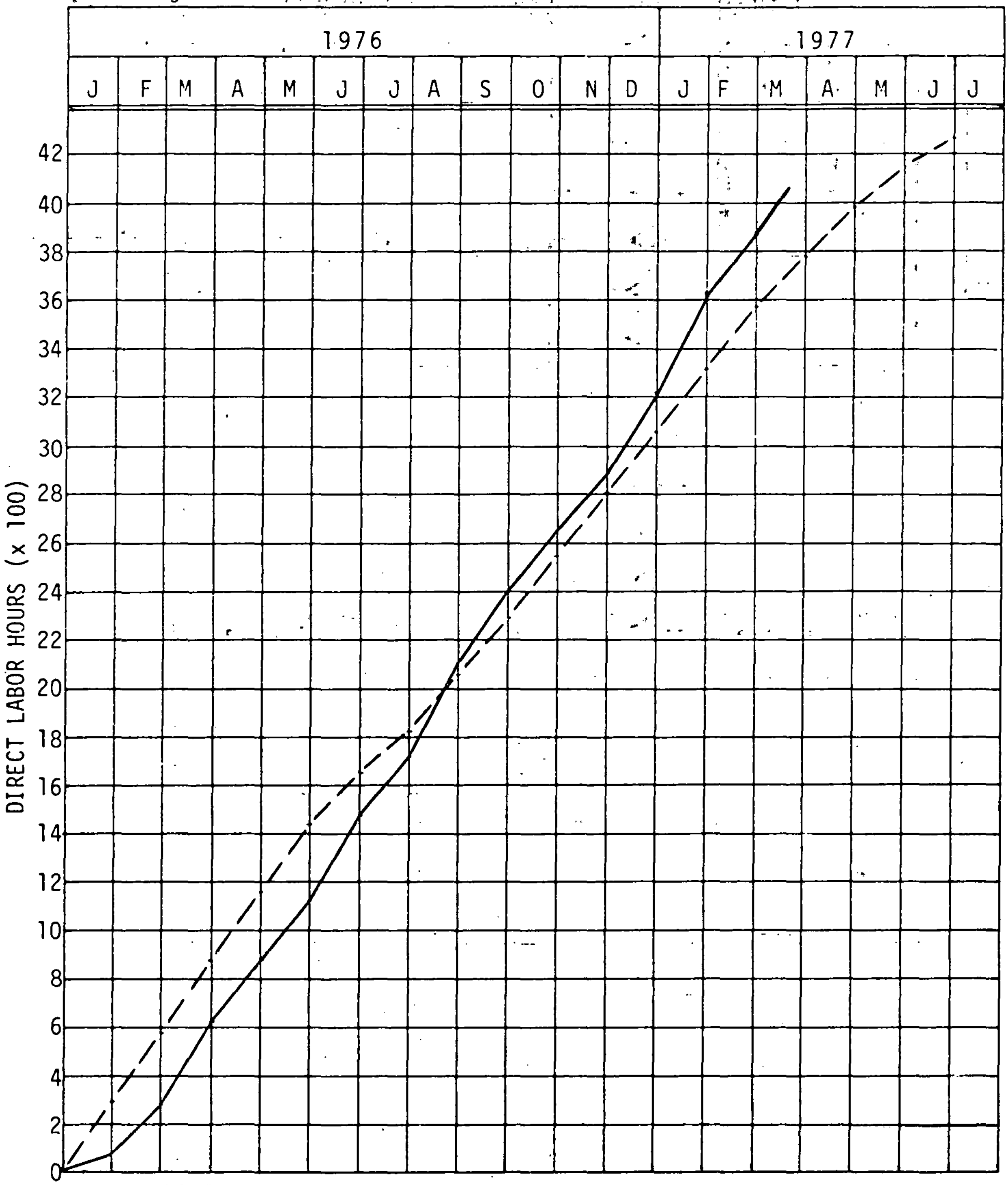
Sch 2/13/76
Updated 3/27/77

NOTE: In addition to the above Program Plan, the Lexington Vacuum Division of Varian Associates will attend the required meetings and deliver the required documentation and samples as per JPL Contract No. 954374.

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates
Lexington Vacuum Division
JPL Contract No. 954374
Starting Date: 1/9/76

Program Plan



Sch 1/22/76
Updated 3/27/77

TOTAL HOURS: 4,260 PLANNED HOURS — — —
HOURS TO DATE: 4,064.1 INCURRED HOURS ———

PROGRAM LABOR SUMMARY