ERDA/JPL/954374-76/3

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

First Annual Report, January 9, 1976--September 19, 1976

S. C. Holden

September 27, 1976

Work Performed Under Contract No. NAS-7-100-954374

Lexington Vacuum Division
Varian Associates
Lexington, Massachusetts

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

NOTICE

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161

Price: Paper Copy $5.00 (domestic)
$7.50 (foreign)
Microfiche $3.00 (domestic)
$4.50 (foreign)

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

ERDA/JPL/954374-76/3
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

FIRST ANNUAL REPORT

By

S. C. Holden

September 27, 1976

Reporting Period January 9, 1976 to September 19, 1976

JPL Contract No. 954374

Varian Associates
Lexington Vacuum Division
121 Hartwell Avenue
Lexington, Massachusetts 02173

eb

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

TABLE OF CONTENTS

TABLE OF CONTENTS
(cont.)

PAGE

LIST OF FIGURES

LIST OF FIGURES
(cont.)

LIST OF TABLES

SUMMARY

The process of multiblade slurry sawing has been used to slice 10 cm diameter silicon ingots into wafers 0.024 cm thick using 0.050 cm of silicon per slice (0.026 cm kerf loss). Total slicing time is less than twenty hours and 143 slices were produced simultaneously.

Improvements in the process will be sought to allow increased productivity by increasing blade loading, and also reduce silicon requirement per slice by reducing the blade and wafer thicknesses. The two goals require trade-offs and an economic analysis will be used to select slicing conditions for minimum wafer cost.

Productivity (Slice area per hour per blade) is shown as a function or blade load and thickness, and abrasive size. Finer abrasive slurries have caused a reduction in slice productivity and thin blades caused a reduction of wafer accuracy. Sawing-induced surface damage has been shown to extend 18μ into the wafer.

1.0 INTRODUCTION

The purpose of this work is to investigate the process of multiblade slurry sawing, and to develop a process for the low-cost slicing of silicon into sheet material suitable for processing into solar cells.

The two major areas for cost reduction of the end product are: improved cutting rates to lower the add-on cost of sawing, and the reduction of the silicon material required to produce a slice. The improved cutting rate is approached by improving the efficiency of the cutting mechanism and by increasing the cutting forces without losing control of the blades. The reduction of silicon utilization offers a conflicting goal. Reduction of blade thickness results in a lower loading capacity; reduction of slice thickness also requires limited blade loads since shock can easily cause wafer fracture. Reducing the size of the abrasive particles, while minimizing kerf loss, reduces the efficiency of the cutting system by changing the local silicon fracture process. All of these can place limitations on the productivity of the saw. Consequently, the two goals will be approached separately, and the trade-offs identified. The final economic analysis will indicate the proper balance for a prototype production technique for solar cell quality silicon sheet.

Currently, 10 cm diameter silicon ingots can be sliced into wafers 0.024 cm thick. Total silicon used per wafer is 0.050 cm. With the present saw (Varian Model 686), 230 wafers can be sliced simultaneously in 20 hours.

2.0 MULTIBLADE SLURRY SAWING - EQUIPMENT

2.1 Cutting Mechanism

In the multiblade slurry sawing technique, loose abrasive is carried across a workpiece (generally hard materials greater than 700 kg/mm^2 hardness) by tensioned, parallel steel blades. The work material is abraded away during the reciprocation of the blades. Cutting load is limited by the stability of the blades, consequently the process is slow, but the productivity is greatly enhanced by the large number of blades involved in the slicing operation. Fig. 1 shows a 10 cm diameter ingot of silicon being sliced by this technique on a Varian Model 686 wafering saw.

2.2 Blade Packages

The multiblade slicing technique utilizes a series of long thin blades, separated at each end by individual spacers. The two opposing stacks of spacers and blade ends are compressed from the side to provide a frictional locking force, and are then drawn apart in a bladehead frame. The blades are uniformly elongated in this fashion. The bladehead is constructed to allow lateral motion of one of the clamped ends of the blade package. By this means, and by modulation of the compression force on the package ends, the two outside blades may be made to lie parallel to each other and to the sliding path of the bladehead.

Figures 2 and 3 show the two types of preassembled blade "packages" used by Varian for its Model 686 multiblade wafering saw. In Figure 2, a "pin package" is shown. The stacks of blades and spacers are held together by two threaded rods at each end. This facilitates convenient transportation and installation of the units into a wafering saw. Figure 3 shows an "epoxy package" where the assembled form is maintained by adhesive applied between the exposed ends of spacers. Typical blade dimensions are 0.02 cm thick by 0.62 cm high. Thinner and higher blades can be made

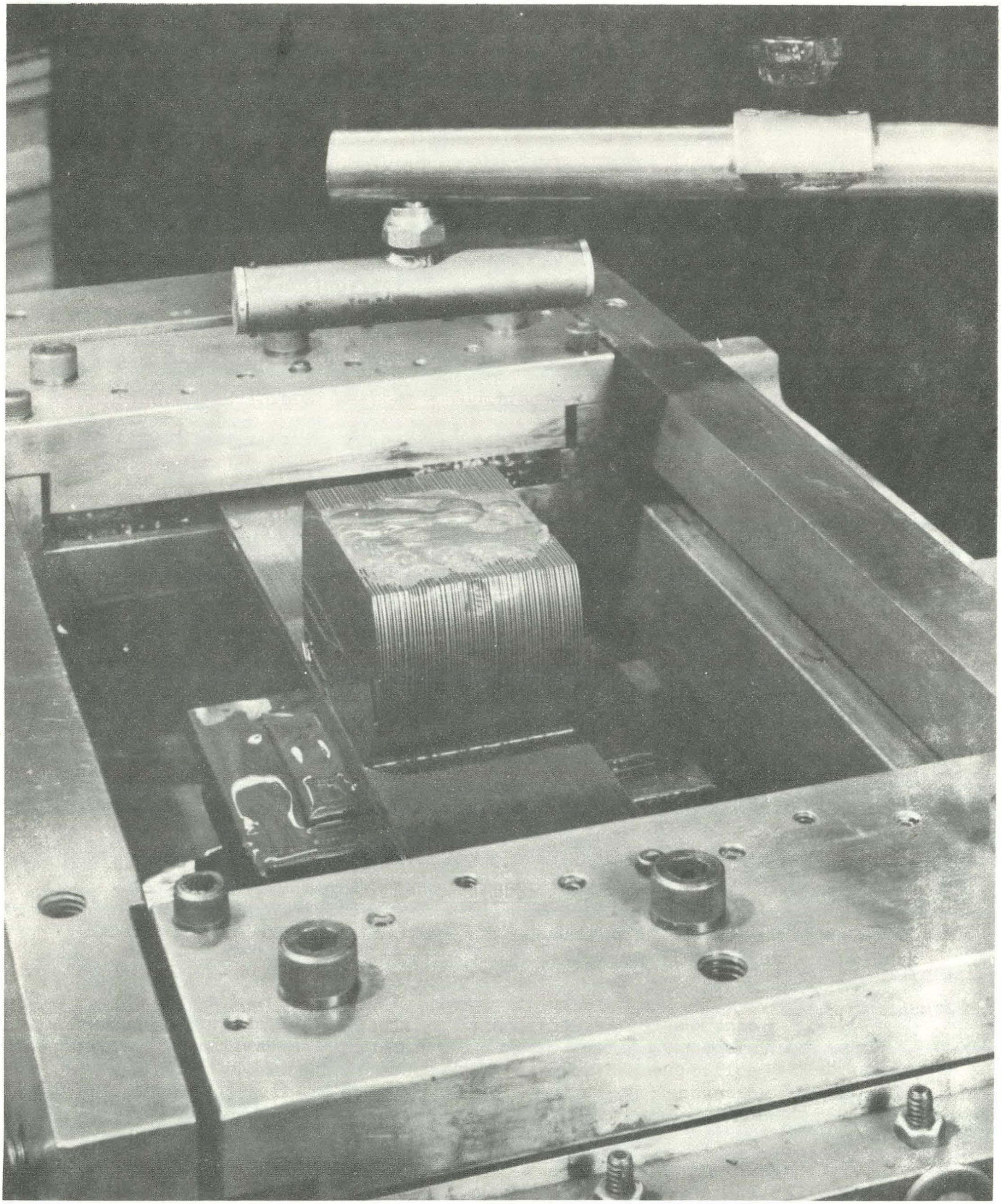


FIGURE 1

Slicing a 10 cm Silicon Ingot with a Multiblade Slurry Saw

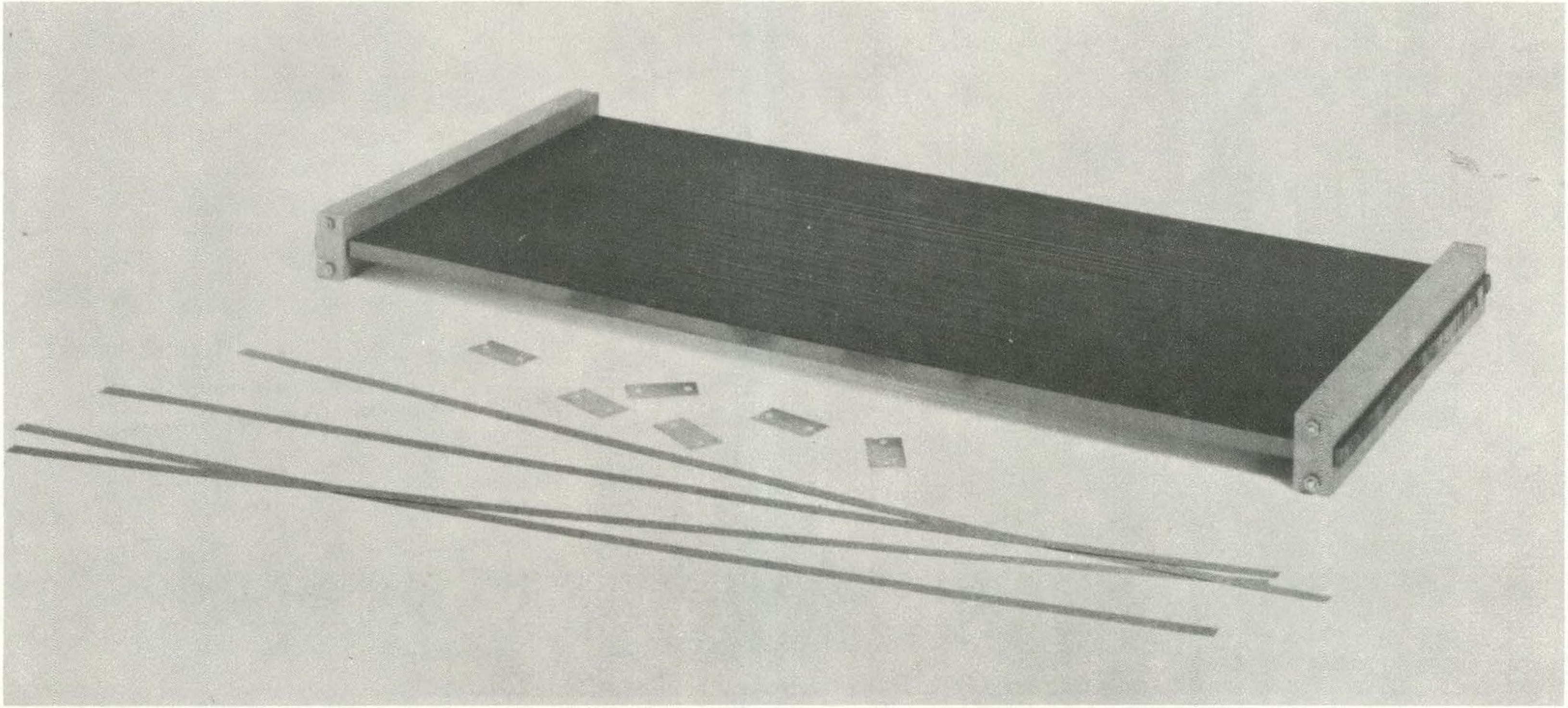


FIGURE 2

Multiblade Pin Package and Components

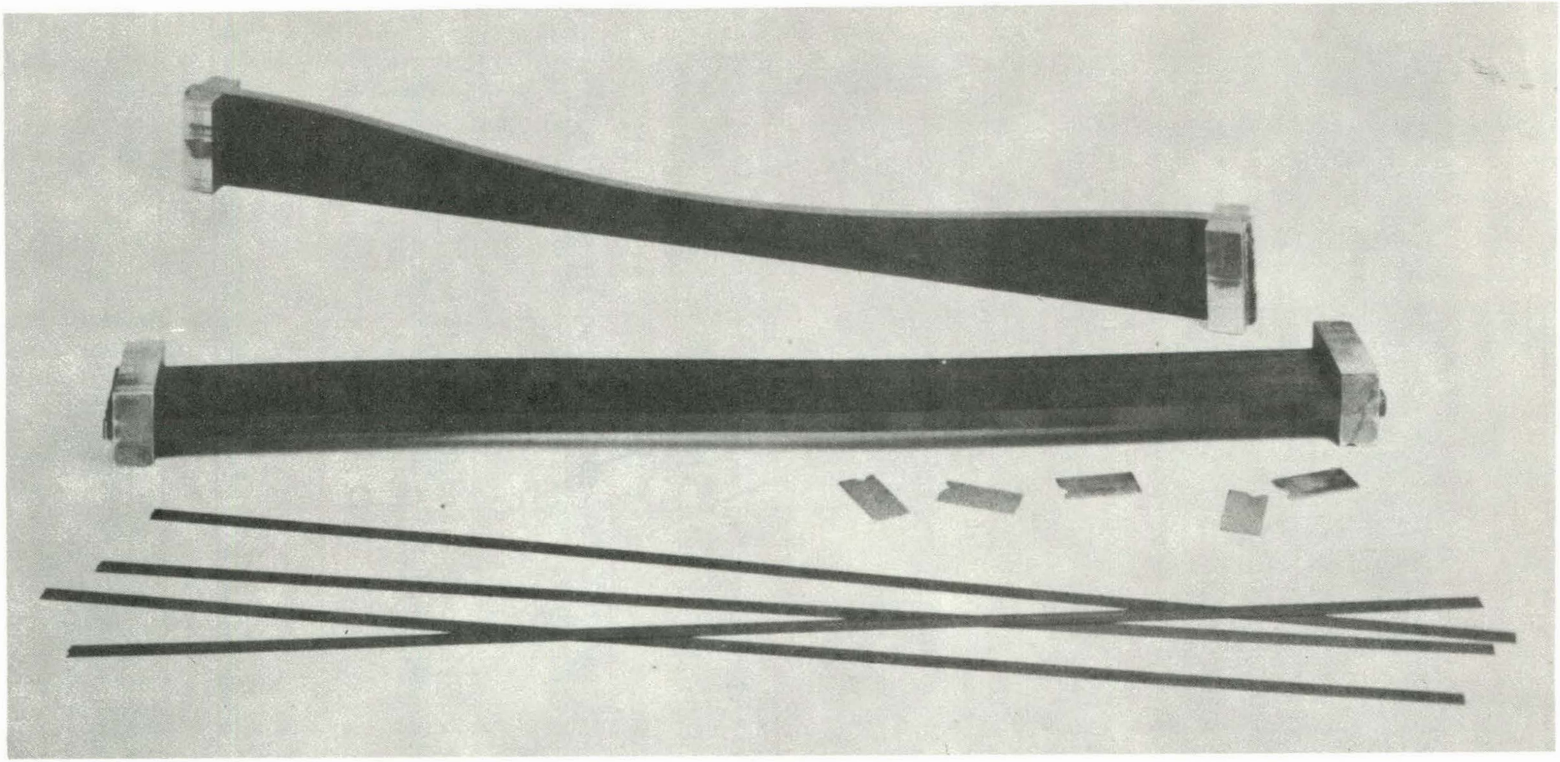


FIGURE 3

<u>Multiblade Epoxy Package and Components</u>

easily. The blades measure 38 cm between the insides of the spacers in the current bladehead design. Spacer thickness is chosen to give wafers of a specified thickness for a given set of machine conditions.

2.3 Bladehead and Drive

Figure 4 shows the modified Varian Model 686 wafering saw used for the contract testing described herein. Figure 1 shows a closeup of the bladehead, used to tension and reciprocate the blades. As mentioned above, the bladehead provides a clamping force to a blade package, and then stretches the blades to a prescribed tension or elongation. The present machine has a bladehead with two design limitations. The maximum width of blade packages that the head can accept is 18.5 cm. A modification is available to allow 21 cm of package width. With blade thickness, t_B , and spacer thickness, t_S , the maximum number of blades is given by

$$N_{max} \leq \frac{18.5}{(t_B + t_S)} \tag{2.1}$$

The bladehead can provide up to 41,000 kg of tensioning force to the blades. The hardened 1095 steel blades used for slicing presently are tensioned to a stress of 140 kg/mm^2 (80% of yield strength). With the blade height given by h_b , the maximum number of blades defined by the force limitation on the bladehead is

$$N_{max} \leq \frac{41{,}000 \text{ kg}}{(140 \text{ kg/mm}^2)(t_b \cdot h_b)} \tag{2.2}$$

Figure 5 depicts the combined limits imposed by the current bladehead on the number of slices produced at one time. The maximum number of blades able to be tensioned is shown as a function of combined blade and spacer thickness and also as a function of blade cross-section. As the blade cross-section

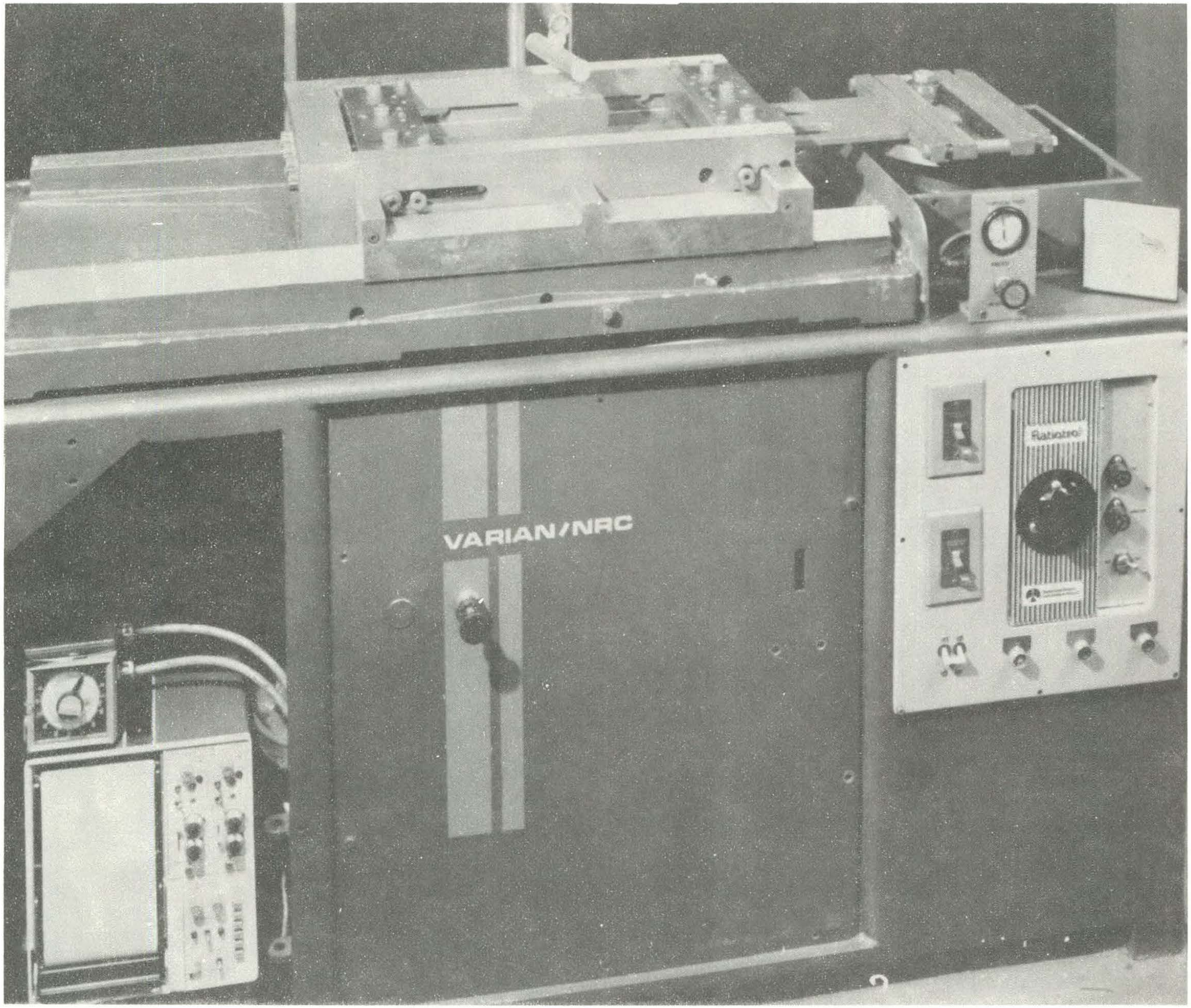


FIGURE 4

Modified Varian 686 Wafering Saw

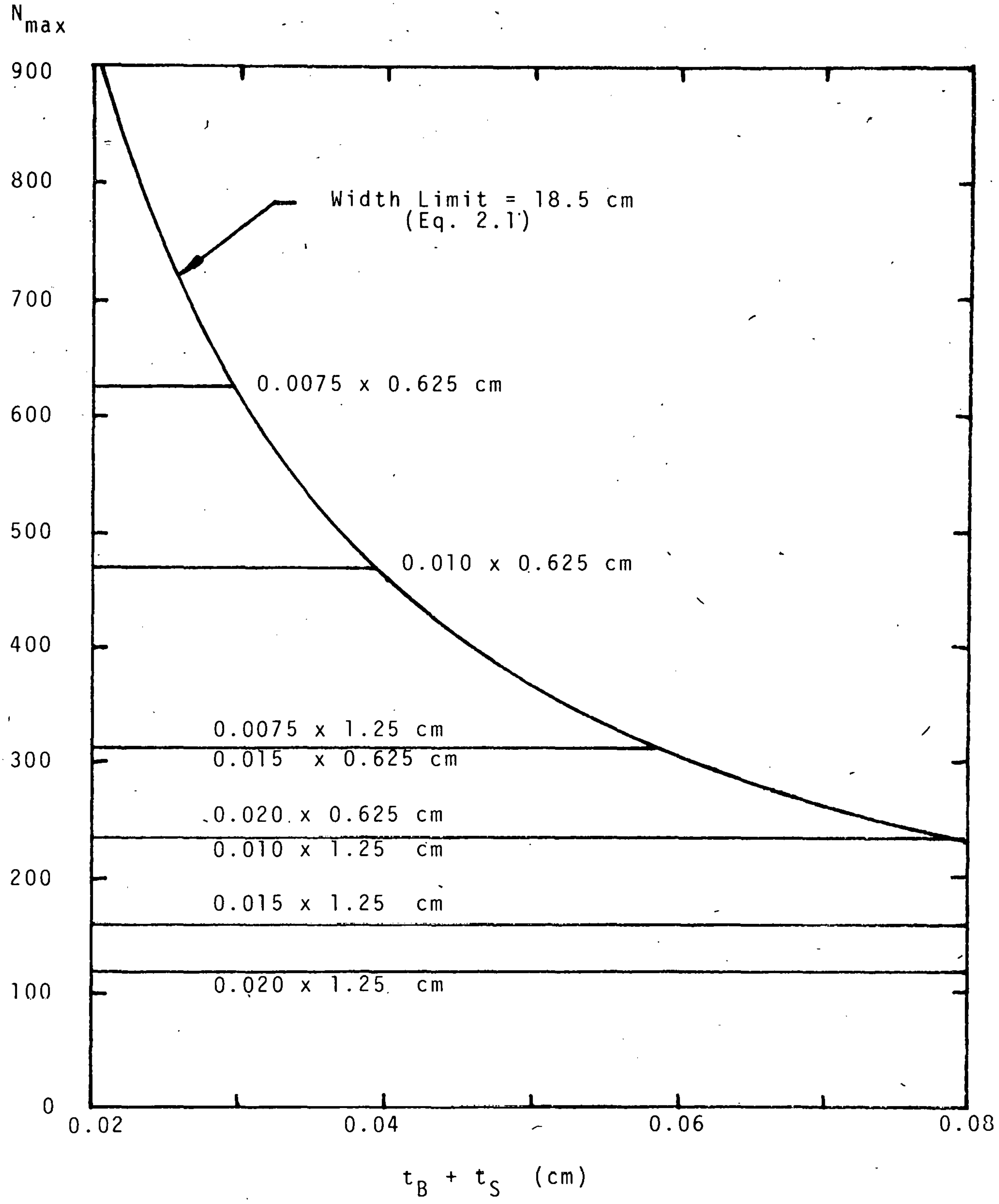


FIGURE 5

MAXIMUM NUMBER OF BLADES AS A FUNCTION OF BLADE AND SPACER THICKNESS AND BLADE CROSS SECTIONS increases (currently 0.02 x 0.625 cm) or as the blade and spacer thickness decreases (current best is 0.05 cm for 10 cm ingots) the tensioning capacity of the bladehead becomes the limiting constraint.

A scotch yoke drive system is used to recipricate the bladehead on a set of sliding ways. The convenient configuration of moving the bladehead poses a constraint on the reciprocating speed of the blades relative to the workpiece (mounted stationary). The reciprocating mass of the bladehead limits the speed of the machine to less than 120 cycles per minute at a 20 cm stroke length (average velocity 81 cm/sec). However, the bladehead mass must also accommodate the tension applied to the blades. In order to extend the capacities of the present wafering saw (increased number of blades and sliding speed) a new configuration of machines would be required.

2.4 Cutting Force and Feed Mechanism

The workpiece is mounted to a pneumatically controlled mechanism that feeds it upward into the blades. An air cylinder applies a constant cutting force to the ball bushing guided feed system. Since the resolution of this force into cutting load depends on friction in the mechanism, low cutting forces or small number of blades cannot be handled reliably. However, for cutting forces of 10 to 12 kg, the cutting force is known accurately by the applied air pressure.

2.5 Slurry Application

The cutting action of the multiblade process is supplied by an abrasive slurry consisting of a mixture of oil and graded abrasive. The mixture is pumped through an application device onto the workpiece and blades. The slurry, and debris from the cutting process are drained from an enclosed sump beneath the feed platen into the pump resevoir. The slurry is used until it is no longer able to provide adequate cutting action to the blades, and is then discarded.

The oil used for slurry must be capable of holding the abrasive in suspension for long periods of time. The abrasive is typically silicon carbide due to its low cost and acceptable cutting action.

Two types of application devices are used to distribute slurry to the cutting area. In one, slurry is pumped through a single tube, and the tube is reciprocated across the workpiece, providing a distribution to the whole workpiece. In a second, shown in Figures 1 and 4, a "sheet" of slurry is delivered through a slotted tube, covering the entire workpiece evenly. A timer controls the On-Off cycle of the pump to limit the volume of slurry delivered.

2.6 Modifications

The machine shown in Figure 4 has been modified from a standard model 686 wafering saw. It has an improved drive system, a RPM indicator for accurate speed measurement, immersion lubricated vertical feed mechanism, fully enclosed slurry return system, "pulse" slurry applicator, and facilities for a dynamometer to mount to the vertical feed platen. Vertical and horizontal cutting forces measured by the dynamometer are recorded on the chart recorder in the lower left of Fig. 4.

The slurry pump timer is shown above the recorder in the lower left of Fig. 4. The vertical feed air pressure control and the bladehead drive speed (RPM) indicator are shown in the upper right corner of the machine.

3.0 EXPERIMENTAL PROGRAM

3.1 General

The testing program for sawing began with a series of tests to characterize the response of the slurry sawing system to variations in cutting force, blade speed, abrasive size, ingot size, slurry mixture and blade thickness. By exploring the various effects under the Parameter Study tests, an understanding of the controlling mechanism of loose abrasive sawing was sought and a large information base was generated. Also, a means of judging the performance of the slurry sawing technique on a prediction basis was devised, and is discussed in Section 4.0.

Once the preliminary results were compiled, testing programs in the specific areas of Abrasives and Blades were outlined. The abrasive tests were concerned with extending the results of the early tests and finding the component of kerf loss due to abrasive particle size. Blade testing was geared toward finding a means of slicing with thin blades to reduce the silicon material lost in slicing and to improve the number of blades able to be tensioned in the bladehead. A summary of cutting tests to date is shown in Table 1.

3.2 Parameter Study

3.2.1 Preliminary Slicing - 10 cm ingot: #1-001

A 10 cm ingot of silicon was sliced with 0.020 cm thick blades, 0.024 cm thick spacers, a cutting load of 113 grams per blade, average blade speed of 68 cm/sec, with a slurry of PC oil (Process Research) and #600 SiC abrasive (Micro Abrasives) mixed with 0.24 kg abrasive per liter of oil. Total cutting time was 30.6 hours, and the ingot cross-section was 82.6 cm^2. This test used the best slicing technique known by Varian for silicon. It provided the starting reference for large ingot slicing. Wafers averaged 0.055 cm thick.

TABLE 1

SUMMARY OF SLICING TESTS

PARAMETER	TEST	1-001	1-011	1-012
MATERIAL (silicon)		{111}	{111}	{111}
LOAD (g/blade)		113	57	113
SLIDING SPEED (cm/sec)		68	68	68
NUMBER OF BLADES CUTTING		128	119	119
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6
SLURRY MIX (kg/ℓ)		0.24	0.24	0.24
KERF LENGTH (cm)		10.8 max	2.50	2.50
INGOT HEIGHT (cm)		8.74	5.00	5.00
BLADE THICKNESS (cm)		.020	.020	.020
KERF WIDTH (cm)		0.027	0.029	0.030
ABRASIVE KERF LOSS (cm)		0.007	0.009	0.010
AREA/SLICE (cm^2)		82.6	12.5	12.5
CUTTING TIME (total hrs.)		30:35	11:05	6:45
EFFICIENCY	(full test)	0.95	0.85	0.73
	(typical)	1.09	1.13	1.08
	(maximum)	1.20	1.29	1.10
ABRASION RATE (cm^3/hr/blade)	(full test)	0.073	0.033	0.056
	(typical)	0.084	0.044	0.083
	(maximum)	0.092	0.050	0.084
PRODUCTIVITY (cm^2/hr/bl)	(full test)	2.70	1.13	1.85
	(typical)	3.09	1.50	2.76
	(maximum)	3.40	1.72	2.81
SLICE TAPER (cm)		+.0021	-.0011	-.0030
ABRASIVE UTILIZATION (cm^3/kg)		138.2	23.6	24.5
OIL UTILIZATION (cm^3/ℓ)		33.2	5.7	5.9

TABLE 1 (Cont.)

PARAMETER	TEST	1-013	1-014	1-015
MATERIAL (silicon)		{111}	{111}	{111}
LOAD (g/blade)		170	227	283
SLIDING SPEED (cm/sec)		68	68	68
NUMBER OF BLADES CUTTING		119	119	119
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6
SLURRY MIX (kg/ℓ)		0.24	0.24	0.24
KERF LENGTH (cm)		2.50	2.50	2.50
INGOT HEIGHT (cm)		5.00	5.00	5.00
BLADE THICKNESS (cm)		.020	.020	.020
KERF WIDTH (cm)		0.030	0.034	- -
ABRASIVE KERF LOSS (cm)		0.010	0.014	- -
AREA/SLICE (cm^2)		12.5	12.5	12.5
CUTTING TIME (total hrs.)		5:40	4:55	- -
EFFICIENCY	(full test)	0.57	0.56	- -
	(typical)	0.87	0.86	- -
	(maximum)	0.90	0.91	- -
ABRASION RATE	(full test)	0.066	0.086	- -
(cm^3/hr/blade)	(typical)	0.1002	0.132	- -
	(maximum)	0.104	0.140	- -
PRODUCTIVITY	(full test)	2.20	2.54	- -
(cm^2/hr/bl)	(typical)	3.34	3.89	- -
	(maximum)	3.46	4.12	- -
SLICE TAPER (cm)		-.0018	-.0039	- -
ABRASIVE UTILIZATION (cm^3/kg)		24.5	27.7	- -
OIL UTILIZATION (cm^3/ℓ)		5.9	6.7	- -

TABLE 1 (Cont.)

PARAMETER TEST		1-021	1-022	1-023	1-024
MATERIAL (silicon)		{111}	{111}	{111}	{111}
LOAD (g/blade)		113	113	113	113
SLIDING SPEED (cm/sec)		68	68	68	68
NUMBER OF BLADES CUTTING		119	119	119	119
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6	7.6
MIX (kg/ℓ)		0.24	0.24	0.24	0.24
KERF LENGTH (cm)		1.25	5.00	6.88	10.64 max
INGOT HEIGHT (cm)		2.50	2.50	6.88	- -
BLADE THICKNESS (cm)		0.020	0.020	0.020	0.020
KERF WIDTH (cm)		0.030	0.028	0.030	0.027
ABRASIVE KERF LOSS (cm)		0.010	0.008	0.010	0.007
AREA/SLICE (cm^2)		3.12	12.5	47.3	91.7
CUTTING TIME (total hrs)		4:00	5:35	21:35	39:40
EFFICIENCY	(full test)	0.31	0.82	0.86	0.82
	(typical)	0.54	0.99	0.99	0.95
	(maximum)	0.55	1.12	1.16	1.01
RATE	(full test)	0.023	0.063	0.066	0.062
(cm^3/hr/blade)	(typical)	0.041	0.076	0.076	0.073
	(maximum)	0.042	0.086	0.089	0.077
PRODUCTIVITY	(full test)	0.78	2.24	2.19	2.31
(cm^2/hr/bl)	(typical)	1.38	2.71	2.53	2.69
	(maximum)	1.40	3.06	2.96	2.86
SLICE TAPER (cm)		+.0007	-.0003	+.00122	+.0011
ABRASIVE UTILIZATION (cm^3/kg)		6.1	22.8	92.6	161.5
OIL UTILIZATION (cm^3/ℓ)		1.5	5.5	22.2	38.8

TABLE 1 (Cont.)

PARAMETER TEST	1-031	1-032	1-033	1-034
MATERIAL (silicon)	{111}	{111}	{111}	{111}
LOAD (g/blade)	113	57	113	113
SLIDING SPEED (cm/sec)	68	68	68	68
NUMBER OF BLADES CUTTING	119	135	127	127
ABRASIVE (grit size)	#600 SiC	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)	7.6	7.6	7.6	7.6
MIX (kg/l)	0.24	0.24	0.24	0.24
KERF LENGTH (cm)	2.50	2.50	2.50	2.50
INGOT HEIGHT (cm)	5.00	5.00	5.00	5.00
BLADE THICKNESS (cm)	0.020	0.010	0.015	0.015
KERF WIDTH (cm)	0.031	0.022	0.027	0.025
ABRASIVE KERF LOSS (cm)	0.011	0.012	0.012	0.010
AREA/SLICE (cm^2)	12.50	12.50	12.50	12.50
CUTTING TIME (total hrs)	8:00	8:00	6:10	6:00
EFFICIENCY (full test)	0.63	0.89	0.72	0.68
(typical)	0.97	1.04	0.95	0.91
(maximum)	1.10	1.28	1.16	1.01
RATE (full test)	0.048	0.034	0.055	0.052
(cm^3/hr/blade) (typical)	0.074	0.0402	0.073	0.070
(maximum)	0.084	0.049	0.089	0.077
PRODUCTIVITY (full test)	1.56	1.56	2.03	2.08
(cm^2/hr/bl) (typical)	2.40	1.83	2.69	2.79
(maximum)	2.72	2.25	3.29	3.09
SLICE TAPER (cm)	-.0022	-.0036	-.0002	+.0006
ABRASIVE UTILIZATION (cm^3/kg)	25.3	20.4	23.5	21.8
OIL UTILIZATION (cm^3/ℓ)	6.1	4.9	5.6	5.2

TABLE 1 (Cont.)

PARAMETER TEST		1-041	1-042	1-043
MATERIAL (silicon)		{111}	{111}	{111}
LOAD (g/blade)		113	113	113
SLIDING SPEED (cm/sec)		20-81	68	68
NUMBER OF BLADES CUTTING		119	119	119
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6
MIX (kg/l)		0.24	0.12	0.48
KERF LENGTH (cm)		2.50	2.50	2.50
INGOT HEIGHT (cm)		5.00	5.00	1.25
BLADE THICKNESS (cm)		0.020	0.020	0.020
KERF WIDTH (cm)		- -	0.030	0.029
ABRASIVE KERF LOSS (cm)		(.030 est)	0.010	0.009
AREA/SLICE (cm^2)		12.50	12.50	3.12
CUTTING TIME (total hrs)		- -	8:50	3:25
EFFICIENCY	(full test)	- -	0.55	0.35
	(typical)	0.90	0.82	- -
	(maximum)	1.03	0.94	1.14
RATE	(full test)	- -	0.043	0.026
(cm^3/hr/blade)	(typical)	0.020 to 0.082	0.063	- -
	(maximum)	0.023 to 0.094	0.072	0.087
PRODUCTIVITY	(full test)	- -	1.42	0.91
(cm^2/hr/bl)	(typical)	0.68 to 2.74	2.09	- -
	(maximum)	0.77 to 3.13	2.40	3.01
SLICE TAPER (cm)		- -	-.0028	+.0014
ABRASIVE UTILIZATION (cm^3/kg)		24.5	48.9	3.0
OIL UTILIZATION (cm^3/ℓ)		5.9	5.0	1.4

TABLE 1 (Cont.)

PARAMETER	TEST	1-051	1-052	1-053	1-054
MATERIAL (silicon)		{100}	{100}	{100}	{100}
LOAD (g/blade)		113	113	170	113
SLIDING SPEED (cm/sec)		68	68	68	55
NUMBER OF BLADES CUTTING		119	119	127	164
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6	7.6
MIX (kg/l)		0.24	0.24	0.24	0.24
KERF LENGTH (cm)		2.50	5.00	6.98	5.00
INGOT HEIGHT (cm)		5.00	2.50	6.98	2.50
BLADE THICKNESS (cm)		0.020	0.020	0.020	0.020
KERF WIDTH (cm)		0.031	0.027	0.028	0.028
ABRASIVE KERF LOSS (cm)		0.011	0.007	0.008	0.008
AREA/SLICE (cm^2)		12.50	12.50	48.8	12.50
CUTTING TIME (total hrs)		8:40	8:20	21:15	10:40
EFFICIENCY	(full test)	0.58	0.53	0.56	0.53
	(typical)	0.95	0.84	0.82	0.91
	(maximum)	1.09	0.91	0.97	1.13
RATE	(full test)	0.045	0.041	0.064	0.033
(cm^3/hr/blade)	(typical)	0.073	0.064	0.095	0.056
	(maximum)	0.084	0.070	0.112	0.070
PRODUCTIVITY	(full test)	1.44	1.50	2.30	1.17
(cm^2/hr/bl)	(typical)	2.35	2.38	3.37	2.01
	(maximum)	2.69	2.58	3.99	2.50
SLICE TAPER (cm)		-.0034	-.0007	+.0015	-.0008
ABRASIVE UTILIZATION (cm^3/kg)		24.0	22.0	95.1	21.7
OIL UTILIZATION	(cm^3/ℓ)	5.8	5.3	22.8	5.2

TABLE 1 (Cont.)

PARAMETER TEST		1-061	1-062	1-063
MATERIAL (silicon)		{111}	{111}	{111}
LOAD (g/blade)		85	85	85
SLIDING SPEED (cm/sec)		53	55	55
NUMBER OF BLADES CUTTING		119	119	119
ABRASIVE (grit size)		#1200 SiC	#1000 SiC	#800 SiC
OIL VOLUME (liters)		7.6	7.6	7.6
MIX (kg/l)		.015-.12	0.24-0.36	0.12-0.24
KERF LENGTH (cm)		2.50	2.50	2.50
INGOT HEIGHT (cm)		5.00	5.00	5.00
BLADE THICKNESS (cm)		0.020	0.020	0.020
KERF WIDTH (cm)		0.025	0.025	0.027
ABRASIVE KERF LOSS (cm)		0.005	0.005	0.007
AREA/SLICE (cm^2)		12.50	12.50	12.50
CUTTING TIME (total hrs)		21:10	17:30	14:05
EFFICIENCY	(full test)	0.32	0.38	0.51
	(typical)	0.33	0.51	0.78
	(maximum)	0.39	0.62	0.90
RATE (cm^3/hr/blade)	(full test)	0.015	0.018	0.024
	(typical)	0.015	0.024	0.036
	(maximum)	0.017	0.029	0.042
PRODUCTIVITY (cm^2/hr/bl)	(full test)	0.59	0.71	0.89
	(typical)	0.59	0.95	1.35
	(maximum)	0.70	1.16	1.55
SLICE TAPER (cm)		+.0020	+.0007	+.0001
ABRASIVE UTILIZATION (cm^3/kg)		40.8	13.6	22.0
OIL UTILIZATION (cm^3/ℓ)		4.9	4.9	5.3

TABLE 1 (Cont.)

PARAMETER	TEST	2-001	2-002	2-003
MATERIAL (silicon)		{100}	{100}	{100}
LOAD (g/blade)		113	113-170-227	113
SLIDING SPEED (cm/sec)		63	68	68
NUMBER OF BLADES CUTTING		143	115	142
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6
MIX (kg/l)		0.48	0.96	0.48-0.72
KERF LENGTH (cm)		10.0 max	7.62	10.0 max
INGOT HEIGHT (cm)		8.62	7.62	8.62
BLADE THICKNESS (cm)		0.020	0.020	0.020
KERF WIDTH (cm)		0.026	0.028	0.029
ABRASIVE KERF LOSS (cm)		0.006	0.008	0.009
AREA/SLICE (cm^2)		73.8	58.1	73.8
CUTTING TIME (total hrs)		19:10	15:55	18:15
EFFICIENCY	(full test)	1.41	- -	1.53
	(typical)	1.65	1.09	1.70
	(maximum)	2.20	1.30	2.53
RATE	(full test)	0.1001	0.102	0.117
(cm^3/hr/blade)	(typical)	0.117	- -	0.130
	(maximum)	0.156	- -	0.194
PRODUCTIVITY	(full test)	3.85	3.65	4.04
(cm^2/hr/bl)	(typical)	4.50	- -	4.49
	(maximum)	6.00	- -	6.68
SLICE TAPER (cm)		+.0006	+.0011	+.0027
ABRASIVE UTILIZATION (cm^3/kg)		75.2	25.6	55.5
OIL UTILIZATION (cm^3/ℓ)		36.1	24.6	40.0

TABLE 1 (Cont.)

PARAMETER	TEST	2-011	2-012	2-031
MATERIAL (silicon)		{100}	{100}	{111}
LOAD (g/blade)		113-170-227	113-170	113
SLIDING SPEED (cm/sec)		66	67	67
NUMBER OF BLADES CUTTING		179	115	125
ABRASIVE (grit size)		#800 SiC	#800 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6
MIX (kg/l)		0.48-0.60	0.48	0.48-0.72
KERF LENGTH (cm)		10.0 max	7.62	10.0 max
INGOT HEIGHT (cm)		8.62	7.62	8.62
BLADE THICKNESS (cm)		0.020	0.020	0.020
KERF WIDTH (cm)		0.025	0.024	0.025
ABRASIVE KERF LOSS (cm)		0.005	0.004	0.005
AREA/SLICE (cm^2)		73.8	58.1	73.8
CUTTING TIME (total hrs)		24:20	23:50	19:55
EFFICIENCY	(full test)	- -	- -	1.23
	(typical)	1.13	0.65	1.68
	(maximum)	1.37	0.87	2.43
RATE	(full test)	0.076	0.058	0.093
(cm^3/hr/blade)	(typical)	- -	- -	0.127
	(maximum)	- -	- -	0.183
PRODUCTIVITY	(full test)	3.033	2.437	3.71
(cm^2/hr/bl)	(typical)	- -	- -	5.07
	(maximum)	- -	- -	7.33
SLICE TAPER (cm)		+.0019	+.0016	+.0043
ABRASIVE UTILIZATION (cm^3/kg)		72.4	44.0	42.1
OIL UTILIZATION (cm^3/ℓ)		43.5	21.1	30.3

TABLE 1 (Cont.)

PARAMETER	TEST	3-001	3-002
MATERIAL (silicon)		{111}	{111}
LOAD (g/blade)		57-85	28-46
SLIDING SPEED (cm/sec)		68	68
NUMBER OF BLADES CUTTING		150	145
ABRASIVE (grit size)		#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6
MIX (kg/l)		0.24	0.24
KERF LENGTH (cm)		10 max	7.62
INGOT HEIGHT (cm)		8.8	7.62
BLADE THICKNESS (cm)		.010	.010
KERF WIDTH (cm)		(.018)	(.018)
ABRASIVE KERF LOSS (cm)		(.008)	(.008)
AREA/SLICE (cm^2)		DNF	DNF
CUTTING TIME (total hrs)		DNF	DNF
EFFICIENCY	(full test)	- -	- -
	(typical)	1.60	1.70
	(maximum)	1.80	1.81
RATE	(full test)	- -	- -
(cm^3/hr/blade)	(typical)	- -	- -
	(maximum)	- -	- -
PRODUCTIVITY	(full test)	- -	- -
(cm^2/hr/bl)	(typical)	- -	- -
	(maximum)	- -	- -
SLICE TAPER (cm)		- -	- -
ABRASIVE UTILIZATION (cm^3/kg)		- -	- -
OIL UTILIZATION (cm^3/ℓ)		- -	- -

3.2.2 Variations in Blade Load: #1011 to #1-015

A standard rectangular block of silicon with a 2.5 cm kerf length and 5.0 cm height was cut with the same conditions as in #1-001, except that the blade load for each test was varied from 57g, 113g, 270g, 227g to 283g per blade. At 283g (#1-015), the blades wandered severely, causing broken wafers, eventually breaking the workpiece from the submount. In the other tests, cutting rate increased and wafer accuracy decreased with increasing cutting force.

3.2.3 Variation in Kerf Length: #1-021 to #1-024

Again, the "Standard" cutting conditions of #1-001 were used, but the size of the ingot was varied. At 113g of blade load, 1.25 cm by 2.50 cm high, 5.00 cm by 2.50 cm high, 6.88 cm square and a 10.6 cm diameter silicon workpieces were sliced. Cutting rates and kerf loss decreased and wafer accuracy generally improved as the kerf length increased.

3.2.4 Variation in Blade Size: #1-031 to #1-034

A standard silicon block, 2.5 cm kerf length by 5.0 cm high, was cut with blades 0.020 thick by 1.27 cm high, 0.015 cm by 0.63 cm, 0.015 cm by 1.27 cm and 0.010 cm by 0.48 cm. A cutting force of 113 g was used for all but the 0.010 cm thick blades (57 g was used). Test #1-012 was the basic reference and standard for this series. The cutting rate with 0.015 cm blades was slightly better (10%) than with 0.02 cm blades. Despite the 50% reduction of cutting force, 0.010 cm thick blades cut at a rate 70% of that of 0.020 cm blades. Wafer accuracy was degraded as the blade thickness decreased. No general trend as to the effect of blade height could be characterized.

3.2.5 Blade Speed, Abrasive Mix: #1-041 to #1-043

In test #1-041, a 2.50 cm block was sliced at a 113 g blade load. The blade speed was varied from 20 to 81 cm/sec. The cutting rate increased in proportion to bladehead speed. The high shock load developed at 120 rpm caused the block to break away from the submount, destroying the wafers.

For the early tests, slurry was made of 0.24 kg of #600 SiC abrasive per liter of PC oil. Two tests were made with 0.12 and 0.48 kg/l, using 2.50 cm kerf length and 113 g of blade loading. Cutting rate increased by 25% as the abrasive mix increased four fold.

3.2.6 {100} vs. {111} Silicon: #1-051 to #1-054

A series of early tests (all using {111} silicon) were duplicated with {100} silicon. It had been anticipated that the non-isotropic hardness and fracture behavior of silicon might lead to a difference in cutting rate. However, these tests indicated that there is no difference in slicing of the two orientations, and more recent tests where the two orientations are used interchangeably support this result even further. In tests #1-053 and #1-054, 0.041 cm spacers were used, resulting in wafers 0.033 cm thick.

3.2.7 Abrasive Size: #1-061 to #1-063

Blocks of silicon 2.5 cm by 5.0 cm high were sliced with 0.020 cm blades at 85 grams of blade load, using #1200, #1000 and #800 SiC abrasive. The mixture of abrasive to oil was reduced initially to maintain a consistent number of abrasive points per unit area of slurry film. During the tests more abrasive was added and the slurry was thinned with 30 SUS mineral oil in order to maximize the cutting rate. The optimum cutting rate and kerf loss each decreased as the abrasive particle size decreased. Wafer thickness was more consistent, but slice taper degraded as the finer abrasives were used.

3.3 Slurry Composition And Application

The preliminary testing had shown that #600 SiC abrasive gave the highest slicing productivity, and that larger ingots provided improved wafer accuracy with slightly better slice productivity. A slight effect of increased abrasive density resulting in higher cutting rates had also been noted. #800 SiC abrasive had shown lower kerf loss and adequate cutting rate (70% that of #600 SiC). A series of tests were designed to explore the cutting efficiency of #600 abrasive, the reduction of kerf width from #800 abrasive, and a possible improvement in slurry applications technique.

3.3.1 10 cm Ingot, #600 SiC: #2-001

A 10 cm ingot of silicon was sliced with 0.020 cm blades and 0.030 cm spacers, using 113g per blade, as before, but with an abrasive mix of 0.48 kg/l of oil (as in #1-043). The total cutting time was 19.17 hrs., an increase of more than 40% in the cutting productivity over previous tests. Also, the resulting wafers were 0.024 cm thick, and none had broken during cutting. Many wafers (~30%) of the 143 produced were broken during subsequent handling and cleaning.

3.3.2 Increased Abrasive Mix, Increased Cutting Load: #2-002

A 7.62 cm square block of silicon was sliced with 0.020 cm blades and 0.0.041 cm spacers, using the pulse slurry applicator and an abrasive mix of 0.96 kg/l of #600 SiC. At a cutting force of

113 g, the cutting rate was lower by 30 to 40% compared with those expected from #2-001. The blade load was increased to 170 and then 227 g with proportional increases in rate, and without an apparent degradation of wafer accuracy.

3.3.3 New Application Technique: #2-003

The pulse slurry system was again used, but to repeat test #2-001. With 0.041 cm spacers, the wafer thickness was 0.0318 cm. Total cutting time was 18.25 hrs., only 5% faster than #2-001. The pulse slurry system was shown to be effective in generating high cutting rates and good wafer accuracy.

3.3.4 #800 SiC, 10 cm ingot: #2-011

A 10 cm ingot was sliced at 113 g using 0.020 cm blades and 0.041 cm spacers. The cutting rate with #800 SiC (0.48 kg/l) was slightly better than early tests with #600 (#1-001, #1-024), and improved over the rates experienced earlier with #800 SiC (#1-063). Wafers were 0.0362 cm thick. The load was raised to 170 g and to 227 g during the test and the cutting rate increased proportionally.

3.3.5 #800 SiC, 7.62 cm square ingot: #2-012

A 7.62 cm square ingot was sliced under conditions similar to #2-011. Wafer production rate was only 57% that of #2-011, indicating, as in #2-002, that a square wokpiece cannot be sliced as fast as a round one. Under 170 g of blade load, the cutting rate increased proportional to load. Wafer thickness was 0.0355 cm.

3.3.6 #600 SiC, Thin Oil: #2-031

Again, a 10 cm diameter ingot was sliced, as in #2-003, with #600 abrasive mixed 0.48 kg/l. The PC oil was diluted with 30 SUS mineral oil in a ratio of 3:1. The less viscous slurry did not change the cutting time (19.9 hrs.), but did produce wafers less accurate than in #2-001 and #2-003.

3.4 Blade Materials

The first priority in testing possible changes in blade materials was to attempt cutting of large silicon ingots with 0.010 cm thick blades. Two separate efforts were made with 0.010 cm thick, 0.63 cm high blades with 0.041 cm thick spacers. In both test #3-001 (10 cm diameter ingot) and #3-002 (7.62 cm square) severe blade wandering result ed and the partly sawn wafers broke off. Both tests provided blade loads of 28 to 85 g per blade. In test #3-002, a few blades broke during the cut. Cutting rates, considering the loads used, approached very impressive rates, comparable to the rates in #2-001.

4.0 DISCUSSION

In the "First Quarterly Report",[1] a simple description of the mechanism of abrasive sawing was proposed assuming that individual abrasive particles remove work material (silicon) at a rate proportional to the load they carry, relative sliding distance they experience, ℓ, and inversely proportional to work material hardness, p, the volume of work material abraded, V, is

$$\frac{dV}{d\ell} = \frac{L\,\bar{\varepsilon}}{\pi\,p} \tag{4.1}$$

L is the total normal load carried by the blade-abrasive system. The efficiency parameter, $\bar{\varepsilon}$, has a similar meaning to the abrasive wear coefficient, $\overline{\tan\theta}$, used in the classical formulation of abrasive wear. However, it takes into consideration the effect of non-planar contact enhancing the abrasion rate due to the applied force, L.

$$\bar{\varepsilon} = \frac{\overline{\tan\theta}}{\frac{2}{x_k}\int_0^{x_k/2} \cos\alpha\,dx} \tag{4.2}$$

The integral in the denominator of Eq (4.2) is a measure of the length of the curved blade trough between the vertical walls of the kerf. The efficiency, $\bar{\varepsilon}$, was assumed to be a measure of the average abrasion activity of individual grains, and gives a normalized level of comparison between various slicing conditions. The most easily measured quantity in a slicing test is the vertical cutting rate, dz/dt, which can be used to calculate $\bar{\varepsilon}$ if the relative sliding speed, $d\ell/dt$, kerf length, y_k, and kerf width, x_k, are known

$$\frac{dz}{dt} = \frac{L\,\bar{\varepsilon}}{\pi\,p}\left(\frac{d\ell}{dt}\right)\frac{1}{x_k y_k} \tag{4.3}$$

For silicon, p has been assumed to be the Knoop microhardness, 1150 kg/mm^2 [2]. The primary effect to be noted with abrasion as defined in Eq. (4.1) is that, for a given load, L, sliding speed, $d\ell/dt$, a fixed volume of work material is removed per unit time.

$$\frac{dV}{dt} = \frac{dz}{dt}\,(x_k\, y_k) = \frac{L\,\bar{\varepsilon}}{\pi\, p}\left(\frac{d\ell}{dt}\right) \tag{4.4}$$

In wafer production, the important output of a slicing system is the rate of wafer area production per blade.

$$\frac{dA}{dt} = \frac{dz}{dt}\, y_k = \frac{L\,\bar{\varepsilon}}{\pi\, p}\left(\frac{d\ell}{dt}\right)\frac{1}{x_k} \tag{4.5}$$

For a given efficiency and machine conditions, a higher productivity is expected with a narrower kerf loss,

4.1 Typical Slicing Test

Figure 6 shows the history of cutting rate, dz/dt, for slicing test #1-023. As the test is started, a fresh set of blades must be "conditioned" to the cutting process. In this case, slightly more than two hours were required. The cutting rate, in a square block, then stabilizes at a relatively constant level through the full ingot. Upon hitting the glass submount, the cutting rate drops by about 50%. The blades are allowed to cut fully into the submount so the full area of wafers are exposed to the "side-lapping" action of the abrasive. Otherwise, a wider base is left on wafers.

The cutting rate for the full slicing test is less than the typical or constant rate due to the slow entrance and exit cutting rates.

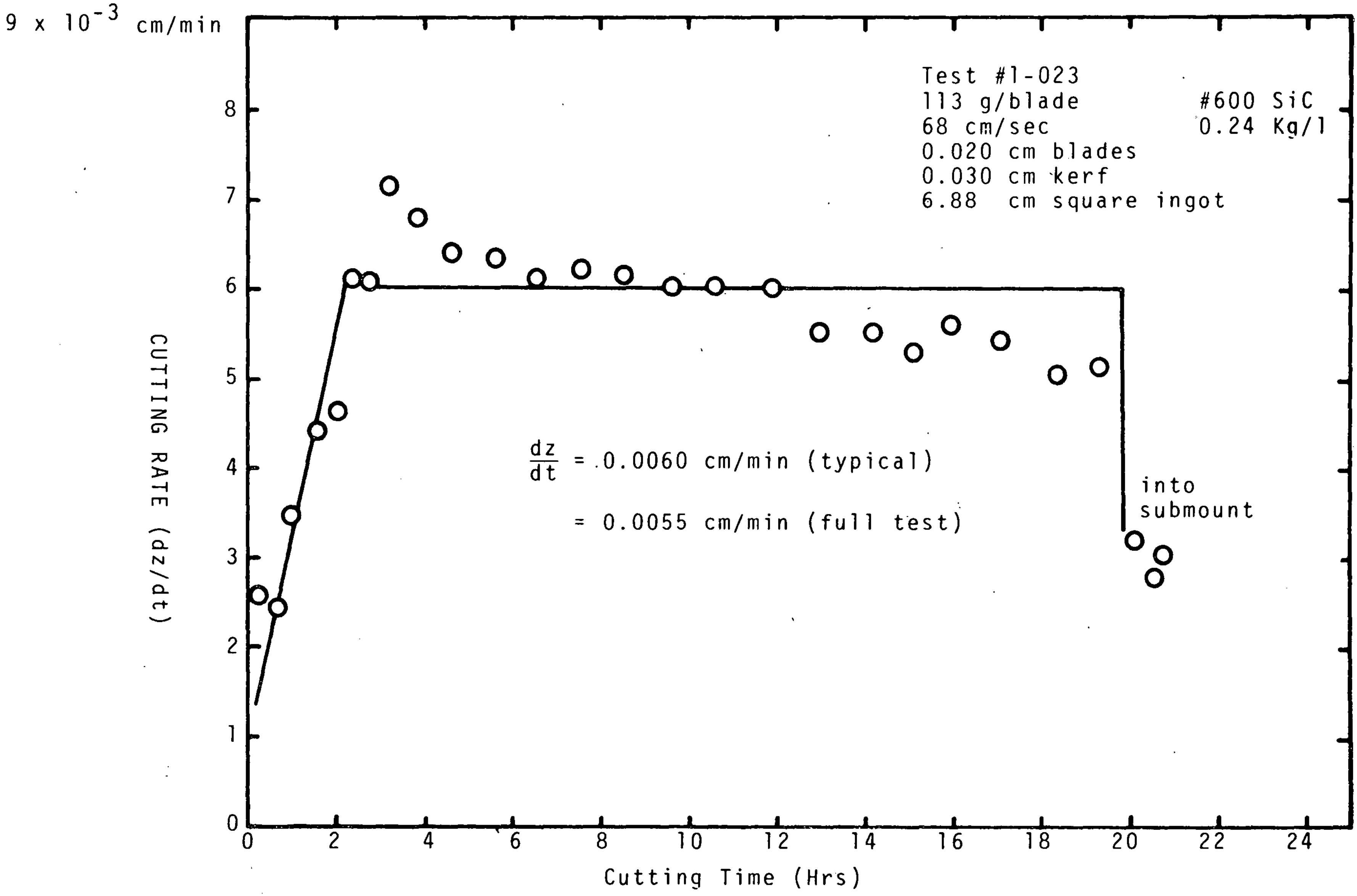


FIGURE 6

CUTTING RATE HISTORY OF SLICING TEST #1-023

4.2 Effects Of Load, Ingot Size, Sliding Speed

A cutting rate history, similar to Figure 6, is produced for each slicing test. From these, abrasion rate (cm^3/hr/Blade), productivity (cm^2/hr/Blade) and cutting efficiency $\bar{\varepsilon}$ are recorded for the full test, typical and maximum conditions. These results are recorded in Table 1.

Figure 7 shows the nearly linear increase in abrasion rate as a function of load per blade. Figure 8 indicates that abrasion rate is nearly flat with ingot size varies as predicted by Eq. (4.4) for similar slicing conditions. At short kerf lengths (less than 2.5 cm) the rate does degrade.

Figure 9 shows the results of test #1-041, where the sliding speed was varied from 20 cm/sec to 81 cm/sec. The transitions in speed would usually result in a low cutting rate, followed by a consistent, higher rate. This "conditioning" is similar to that experienced at the beginning of a slicing test. The maximum abrasion rate at 81 cm/sec is missing since the workpiece was broken at this speed. The typical abrasion rates show a linear effect with speed , as anticipated in Eq. (4.4).

4.3 Effect Of Blade Thickness - Kerf Loss

Figure 10 shows the abrasion rates resulting from tests with 0.020 cm, 0.015 cm and 0.010 cm thick blades for 113 and 57 grams per blade of loading. In all tests, a 2.5 cm kerf length and #600 SiC abrasive was used in a standard slurry. The rate of abrasion did not vary with the kerf width. In fact, as predicted by Eq. (4.5), the productivity of the thinner blades was higher for a given applied load (see Figure 11). The plot shows both full test and typical productivity (cm^2/hr/Blade) for two cutting forces.

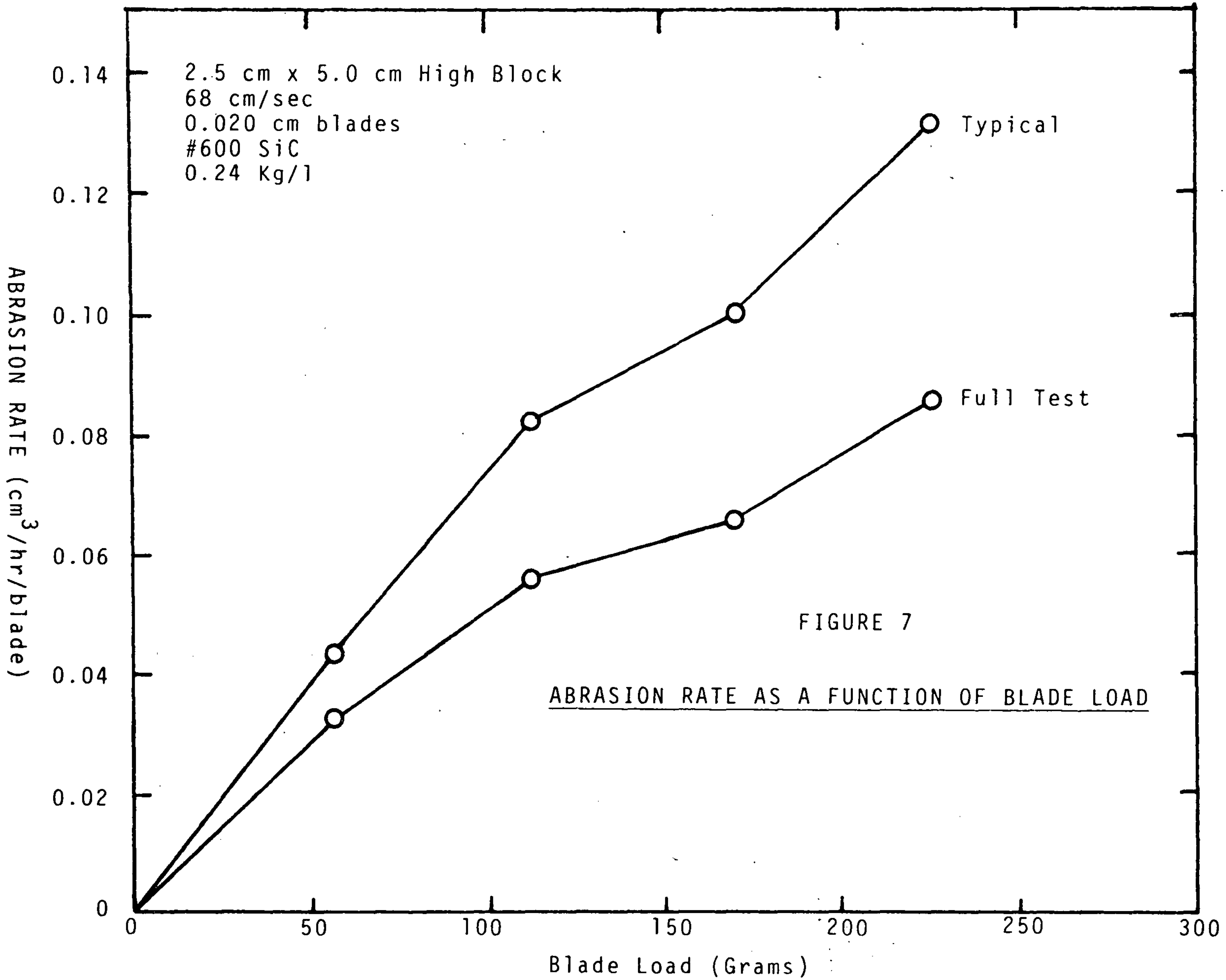


FIGURE 7

<u>ABRASION RATE AS A FUNCTION OF BLADE LOAD</u>

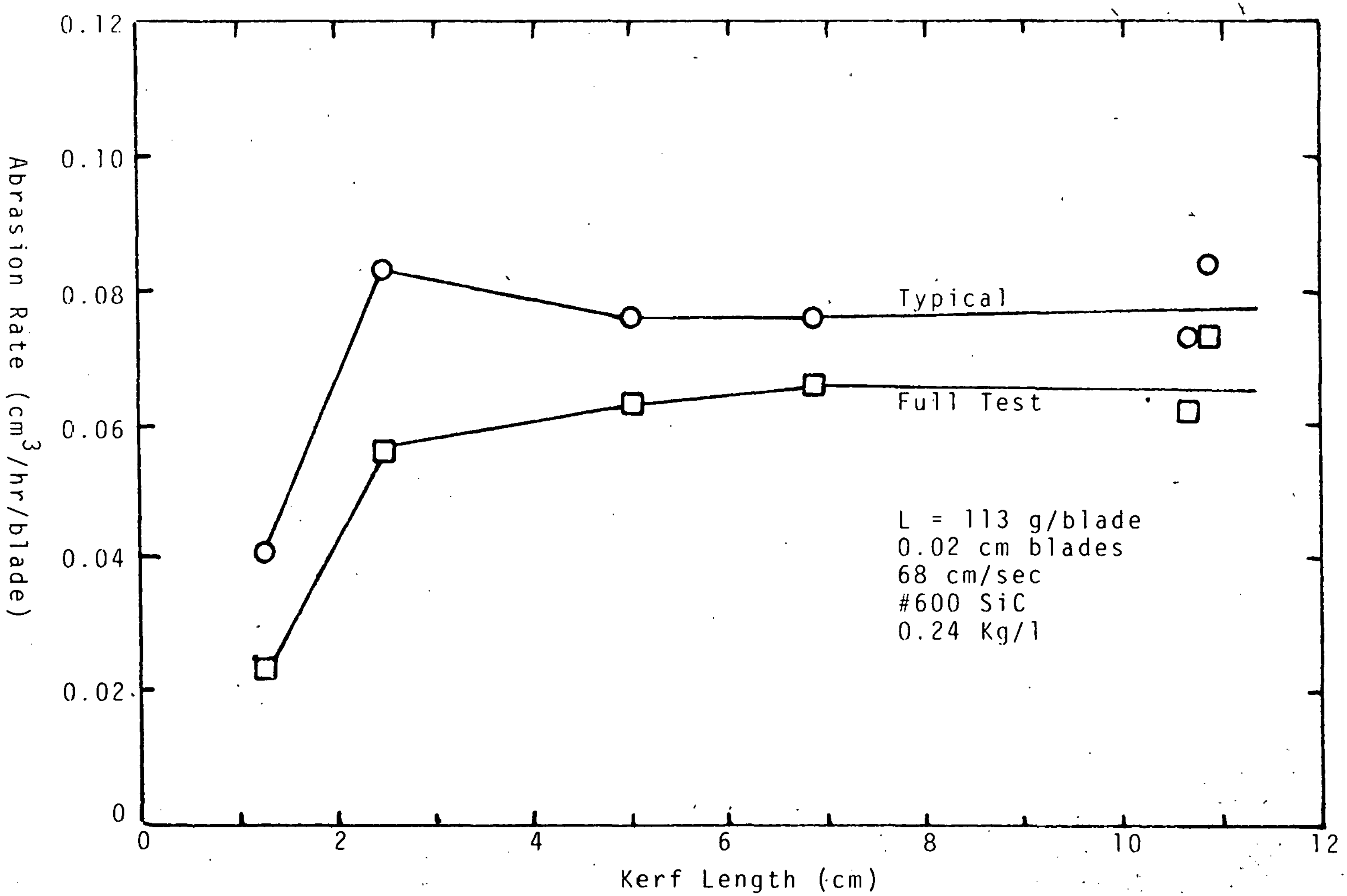


FIGURE 8

ABRASION RATE VS. KERF LENGTH

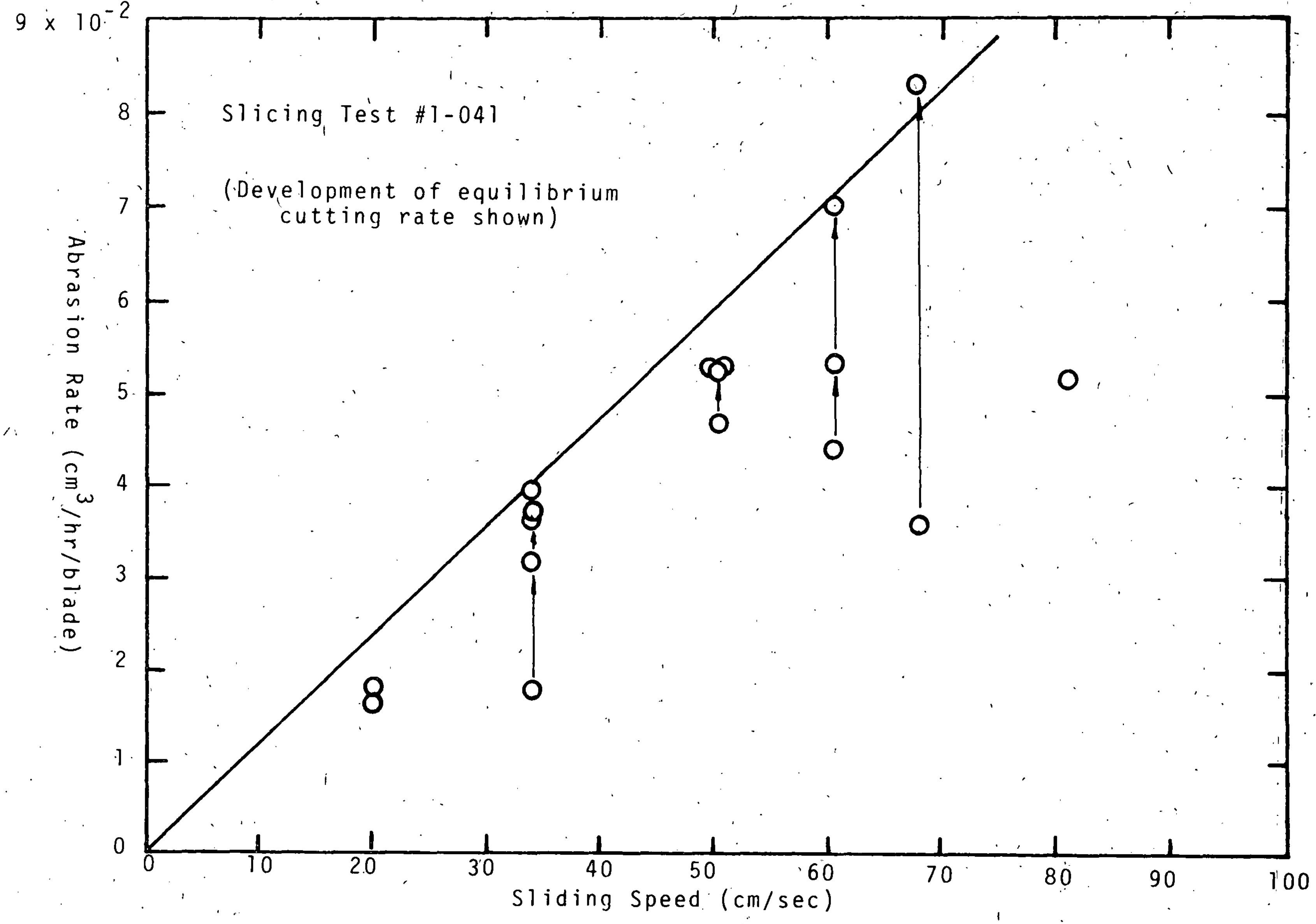


FIGURE 9

ABRASION RATE AS A FUNCTION OF SLIDING SPEED

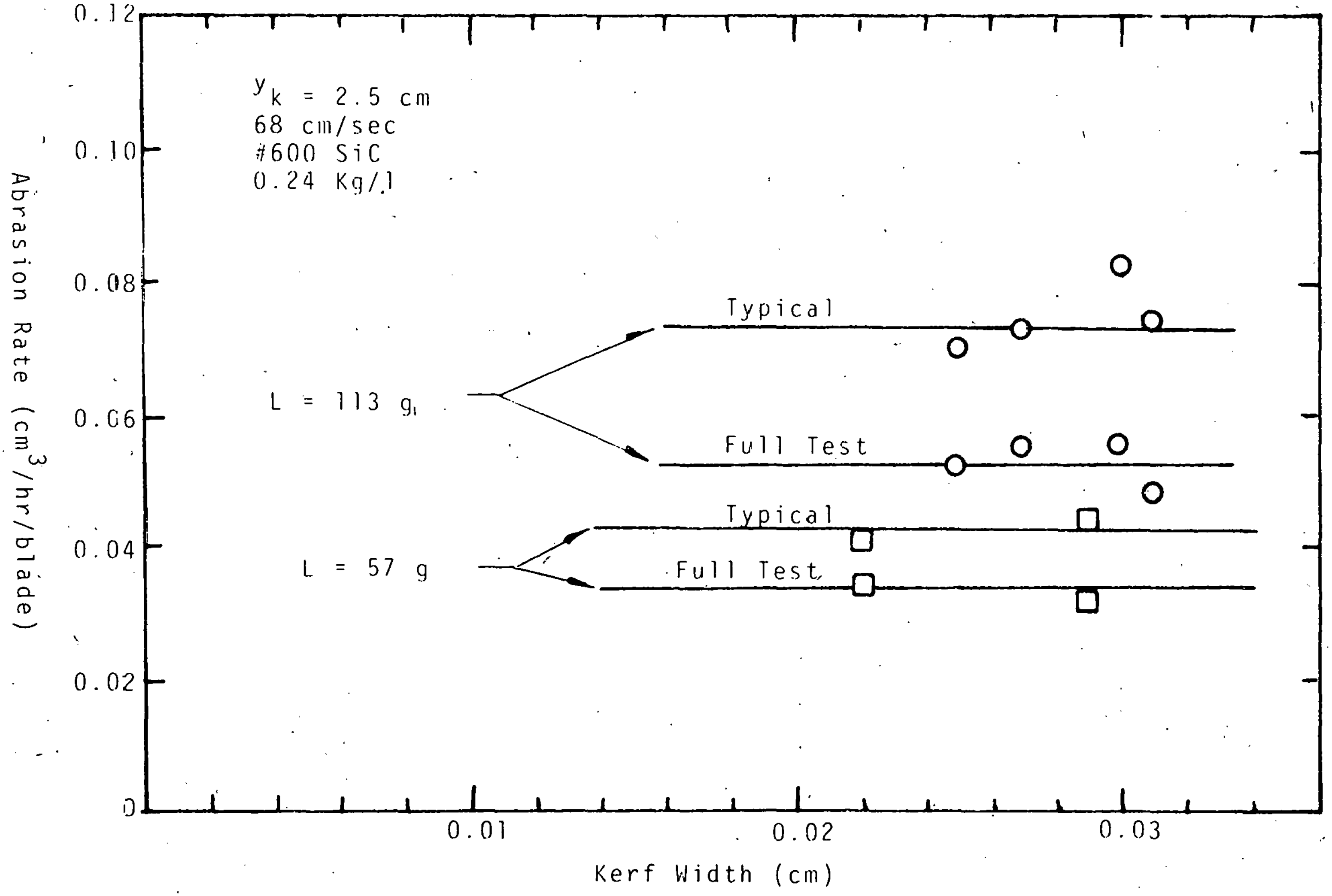


FIGURE 10

ABRASION RATE AS A FUNCTION OF KERF WIDTH

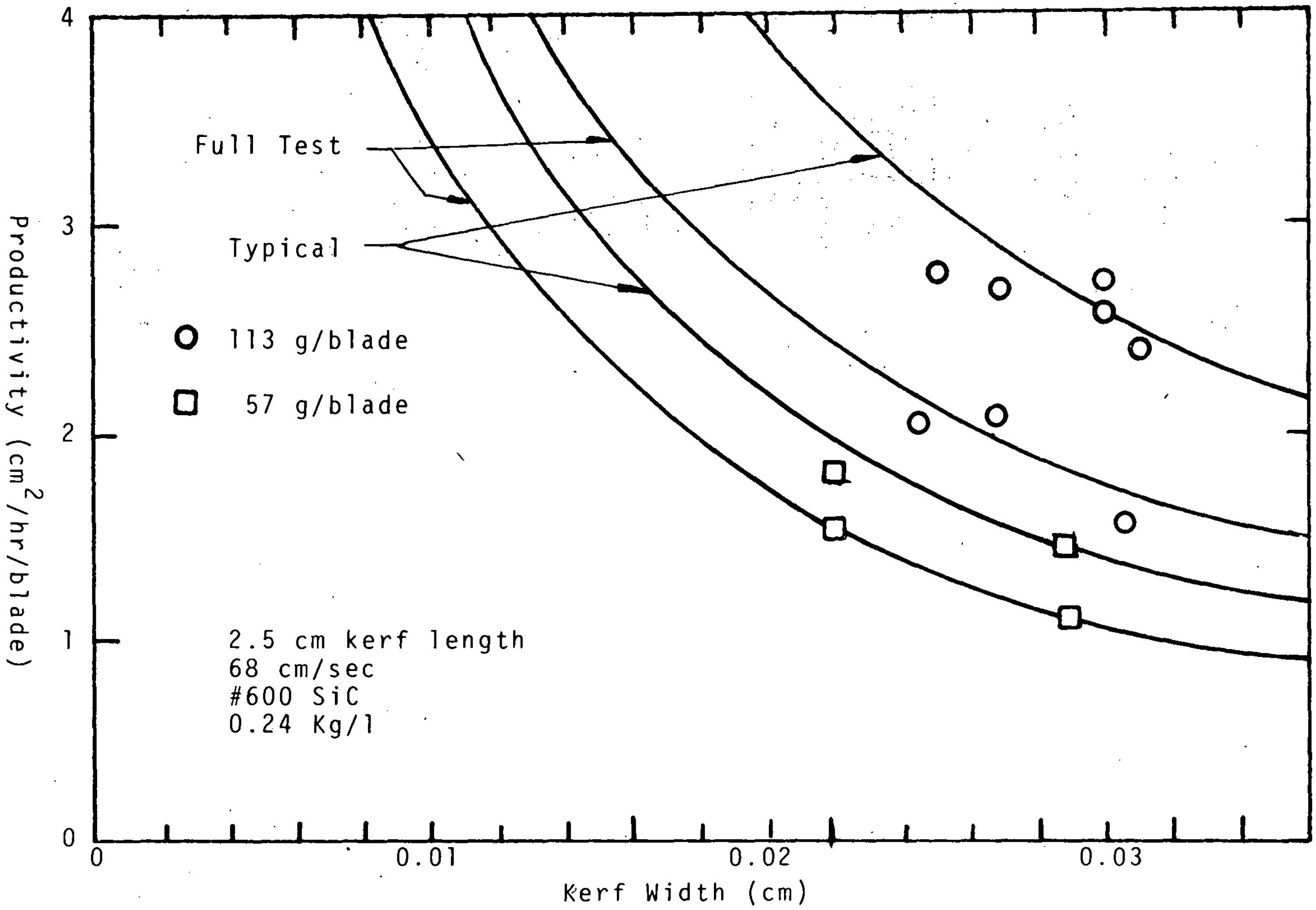


FIGURE 11

PRODUCTIVITY FOR VARIOUS KERF WIDTHS

However, since the abrasive component of kerf loss (kerf width less blade thickness) is significant, only a 22% increase in productivity occurred with a reduction of blade thickness from 0.020 cm to 0.010 cm .

4.4 Improved Efficiency

The concept of cutting efficiency seems to accurately characterize the abrasion of productivity rates of slurry sawing. The typical efficiency of all slicing tests using #600 SiC is shown in Figure 12. The major correlation for variations in slicing efficiency is with cutting pressure, defined as the cutting force divided by the kerf length and kerf width. For the tests using a standard slurry mix (0.24 kg/l), the efficiency is stable over a wide pressure range. It only drops over a pressure of 2.5 kg/cm^2 , corresponding to the reduction of abrasion rates at high loads or short kerf lengths.

The increase of cutting efficiency with a simple change of slurry mix (0.48 kg/l) was significant. The resulting efficiencies are shown in Figure 12 on the upper curve, and the observed productivity is shown in Figure 13 as a function of blade load.

4.5 Effect Of Abrasive Size

The maximum abrasion rate and productivity are shown in Figure 14 for the series of tests in which abrasive size was varied. Also shown is the improvement encountered at higher load, and with 10cm diameter ingots for both #600 SiC and #800 SiC. The smaller abrasive particles result in lower slice productivity. The increase in productivity from #800 to #600 will have to be weighed against the additional kerf loss from the larger abrasive. Table 2 is a listing of the size of various abrasive particles from Micro Abrasives Corp.

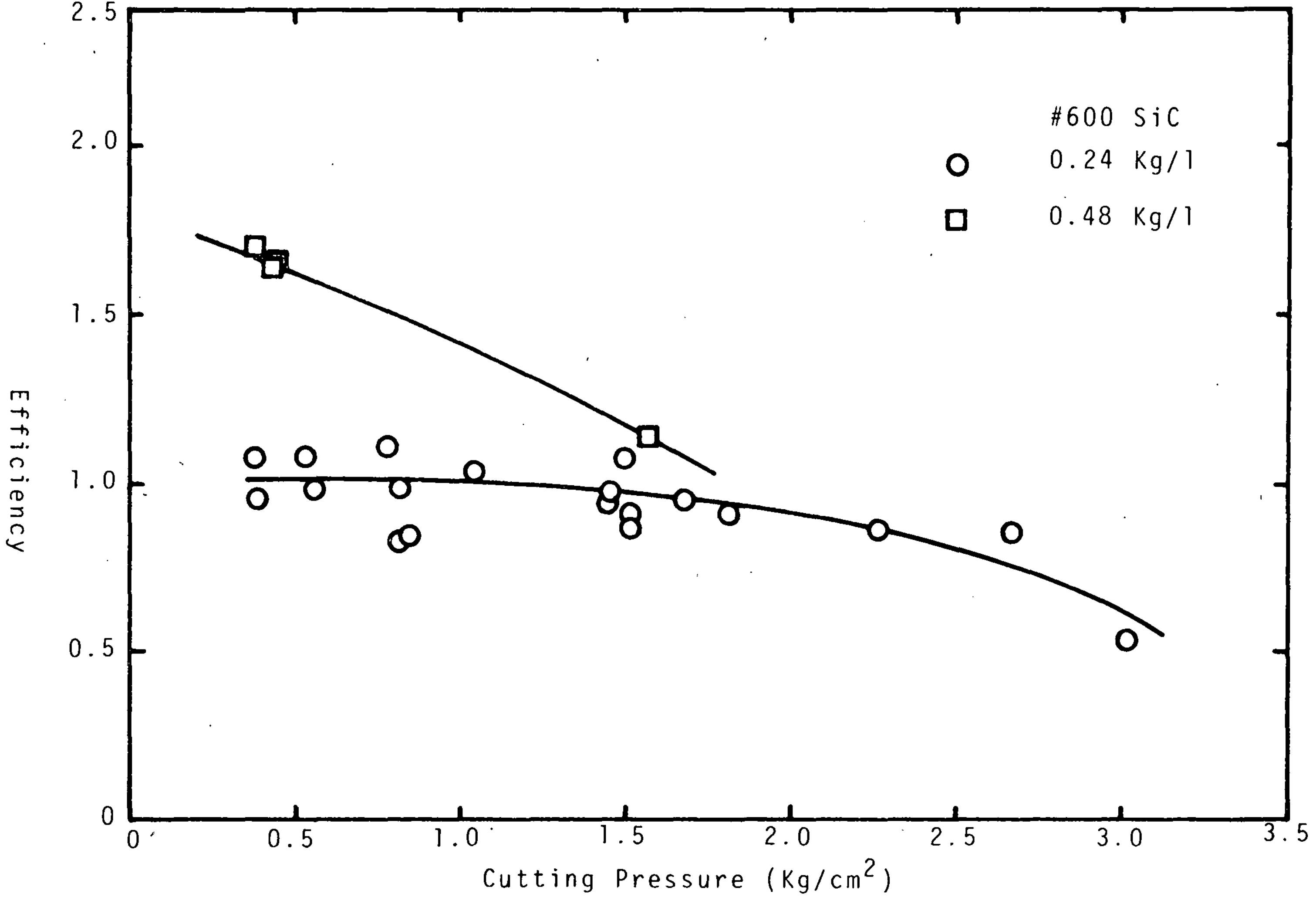


FIGURE 12

EFFICIENCY (TYPICAL) AS A FUNCTION OF CUTTING PRESSURE

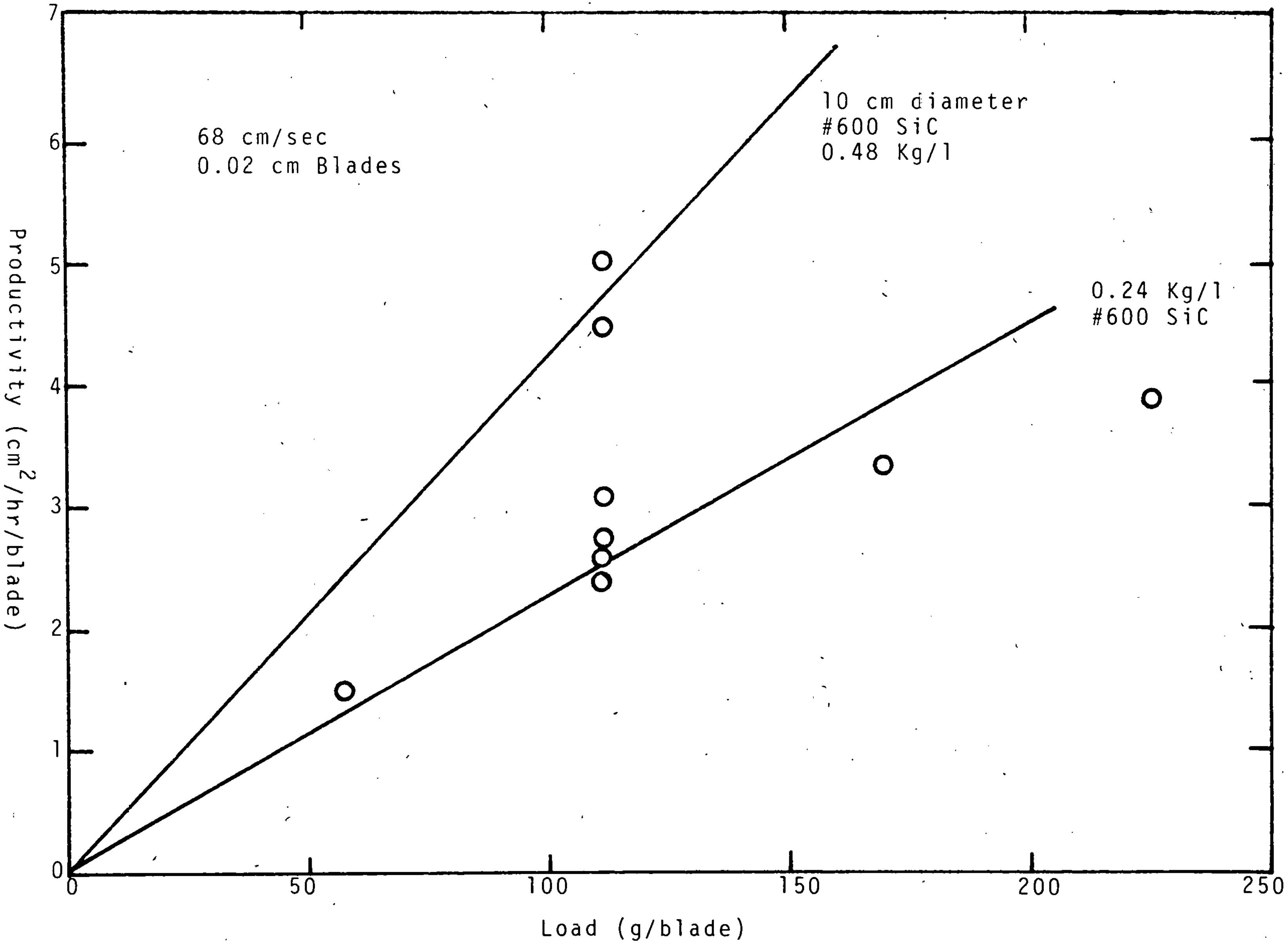


FIGURE 13

PRODUCTIVITY AS A FUNCTION OF BLADE LOAD

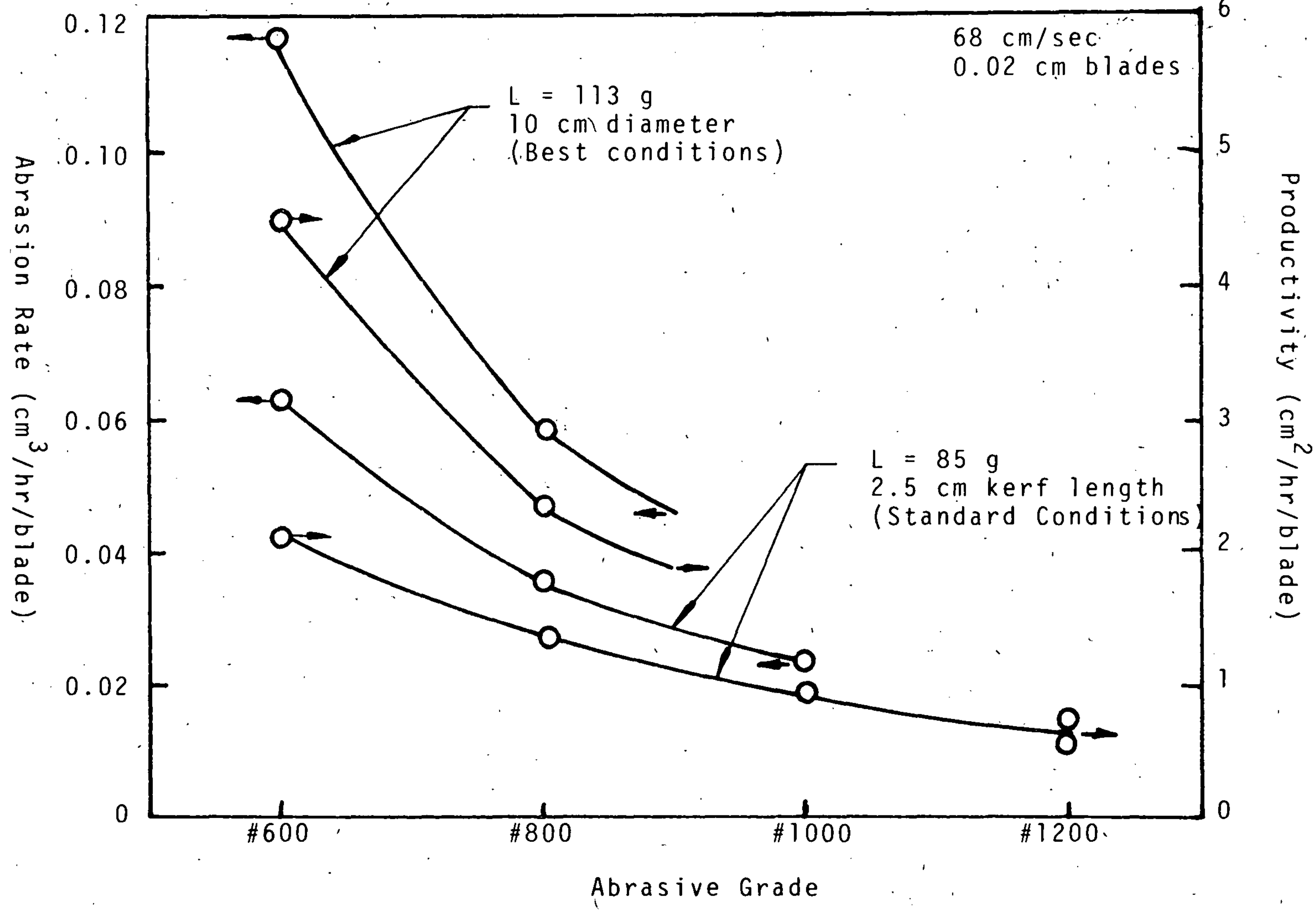


FIGURE 14

ABRASION RATE AND PRODUCTIVITY FOR VARIOUS GRIT SIZES

TABLE 2

AVERAGE PARTICLE SIZE OF SiC ABRASIVE

(Information from Micro Abrasives Corp.)

GRIT SIZE	RANGE		50% SIZE	
	MICRONS	INCHES	MICRONS	INCHES
400	16-60	.00063-.00236	28	.00110
500	11-46	.00043-.00181	23	.00091
600	8-35	.00031-.00138	16	.00063
800	5-28	.00020-.00110	12	.00047
1000	1-24	.00004-.00094	10	.00039
1200	.5-21	.00002-.00083	7	.00028

The kerf loss due to the various abrasive particle sizes is shown in Figure 15. As expected, the abrasive kerf loss, X_a , decrease with particle size. The total kerf loss, X_k , is defined as the blade thickness, t_B , plus the abrasive kerf loss, X_a , or "side wear".

$$X_k = t_B + X_a \tag{4.6}$$

The abrasive kerf loss is shown to decrease with cutting pressure in Figure 16. This effect may be related to the improved cutting efficiency of the abrasive system (Figure 12). When the blades are capable of unobstructed cutting, there may be less lateral wandering of blades, reducing the overall kerf loss (and thus the apparent abrasive loss).

4.6 Cutting Force History - Dynamometer Results

A Dynamometer was used to record the vertical and horizontal components of force occurring during slicing experiments. The instrument was fabricated to give a full scale sensitivity of as low as 2 pounds vertical and 1 pound horizontal when used with a Hewlett Packard Model 7402A Oscillographic Recorder with 17403A AC carrier preamplifiers. It utilizes a full-wave bridge of semiconductor strain gauges. The results showed that the performance of the vertical feed system is predictable and may cause problems with thin wafers.

The vertical feed has a set of four preloaded ball bushings which guide four posts from an upper platen. There is a preload friction which must be overcome in order to move the platen upward or downward. Assuming this to be a constant F_f , and the feed system to have an effective weight W , the pressure, p , applied to the cylinder of area A_p results in a cutting force F_c which depends on the direction of motion, $\dot{x}$, of the fixed platen (positive upward).

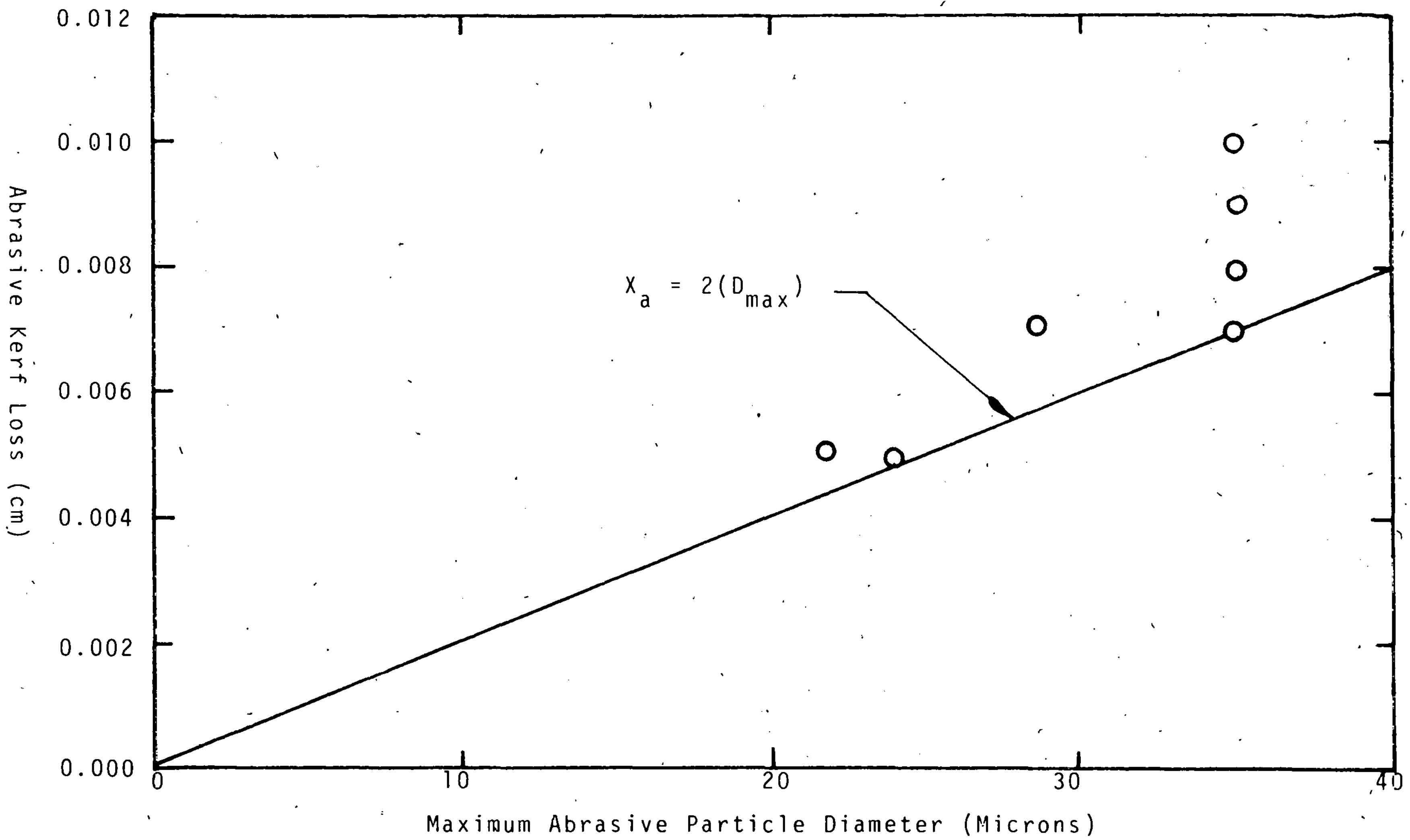


FIGURE 15

<u>ABRASIVE KERF LOSS AS A FUNCTION OF ABRASIVE SIZE</u>

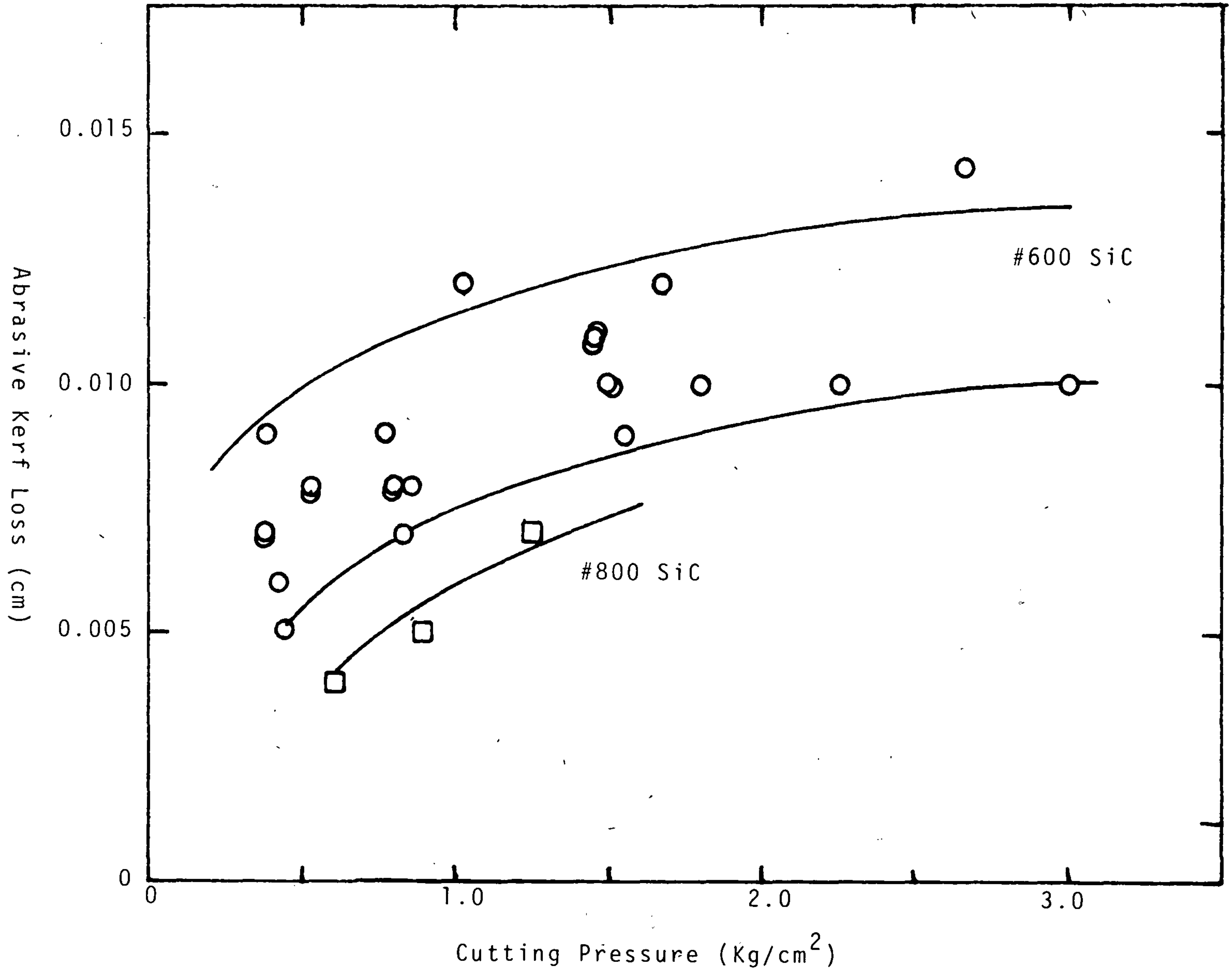


FIGURE 16

ABRASIVE KERF LOSS AS A FUNCTION OF CUTTING PRESSURE

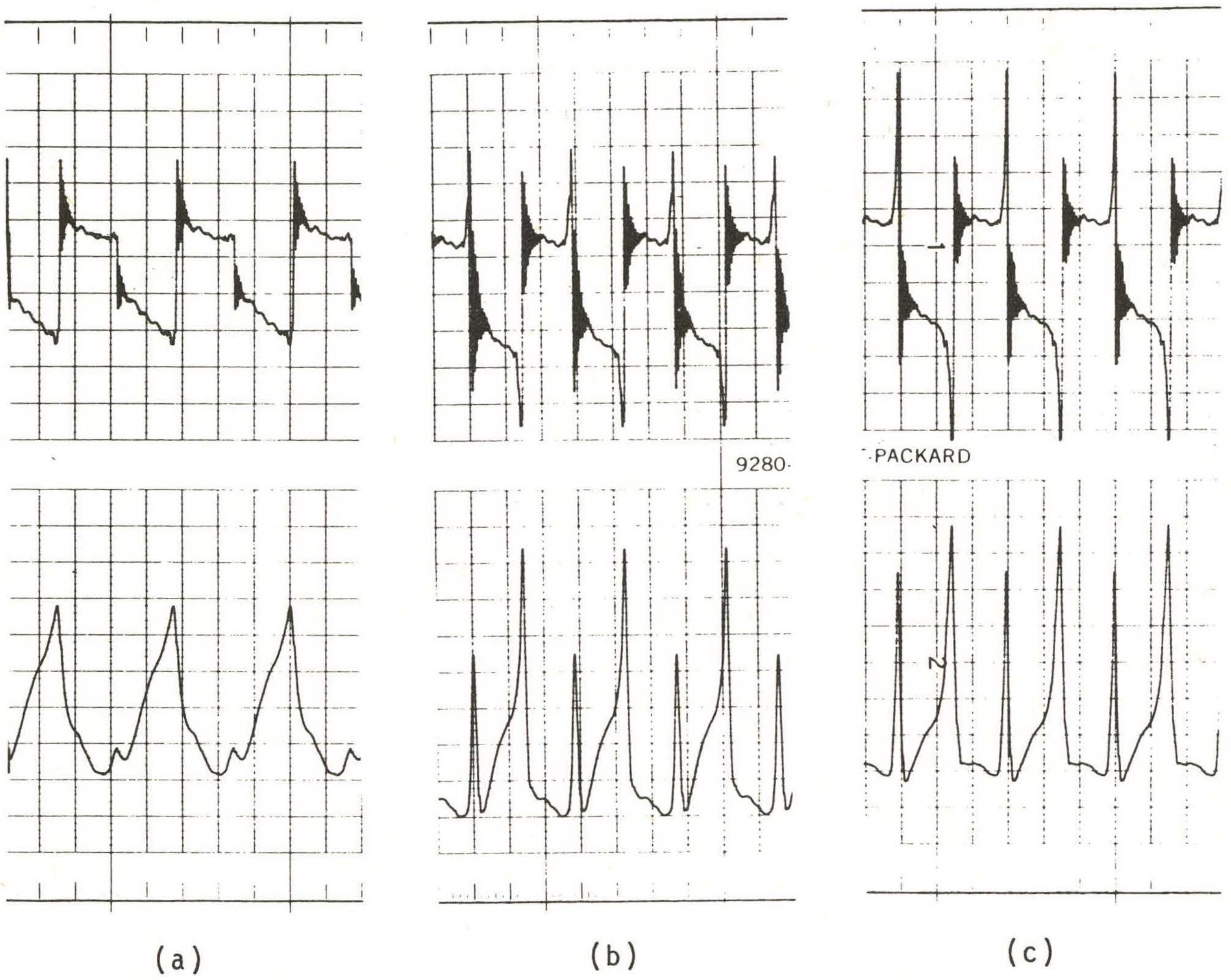
$$F_c = p\,A_p - W - F_f \frac{\dot{x}}{|\dot{x}|} \qquad (4.7)$$

When no load is applied in cutting, the feed will rise on an applied air pressure of 37 psi, and will fall when the pressure is lowered to 22 psi. With the air cylinder having 2.36 in^2 of area, the effective weight of the system is 70 pounds, and the feed friction is 18 pounds in either direction.

This means that, when the cutting force is applied in the normal fashion a load increment of 36 pounds will result if the feed must move downward during the stroke of the bladehead. This occurs at the beginning of cutting since the bottom of blades do not lie parallel to the stroke plane of the bladehead, and the feed is forced downward at one end of each stroke. (See Figure 17 (a)). As the blades wear, each end is radiused and the feed must respond downward at each end of the stroke to compensate. Figure 17 (b) and (c) shows the accumulation of this condition during slicing test #1-063. Figure 18 shows that the peak forces at the end of the stroke are about 36 pounds above the average applied cutting force. As the stroke rate is increased to 1.7 sec^{-1}, the force increases by 7 pounds and the peak forces become more severe. This is due to inertia of the feed imposed by the abrupt end configuration of the worn blades (high local acceleration). This peak load is applied to the work at the end of each storke, and corresponds to an increment of 58 grams per blade when 140 blades are used.

4.7 Blade Wear

Table 3 shows the reduction in height of the blade packages used for all tests to date. The wear ratio, r , was defined in the "Second Quarterly Report" [3] as



Horizontal
Cutting
Force

50 lbf full scale
0.1 sec/mm

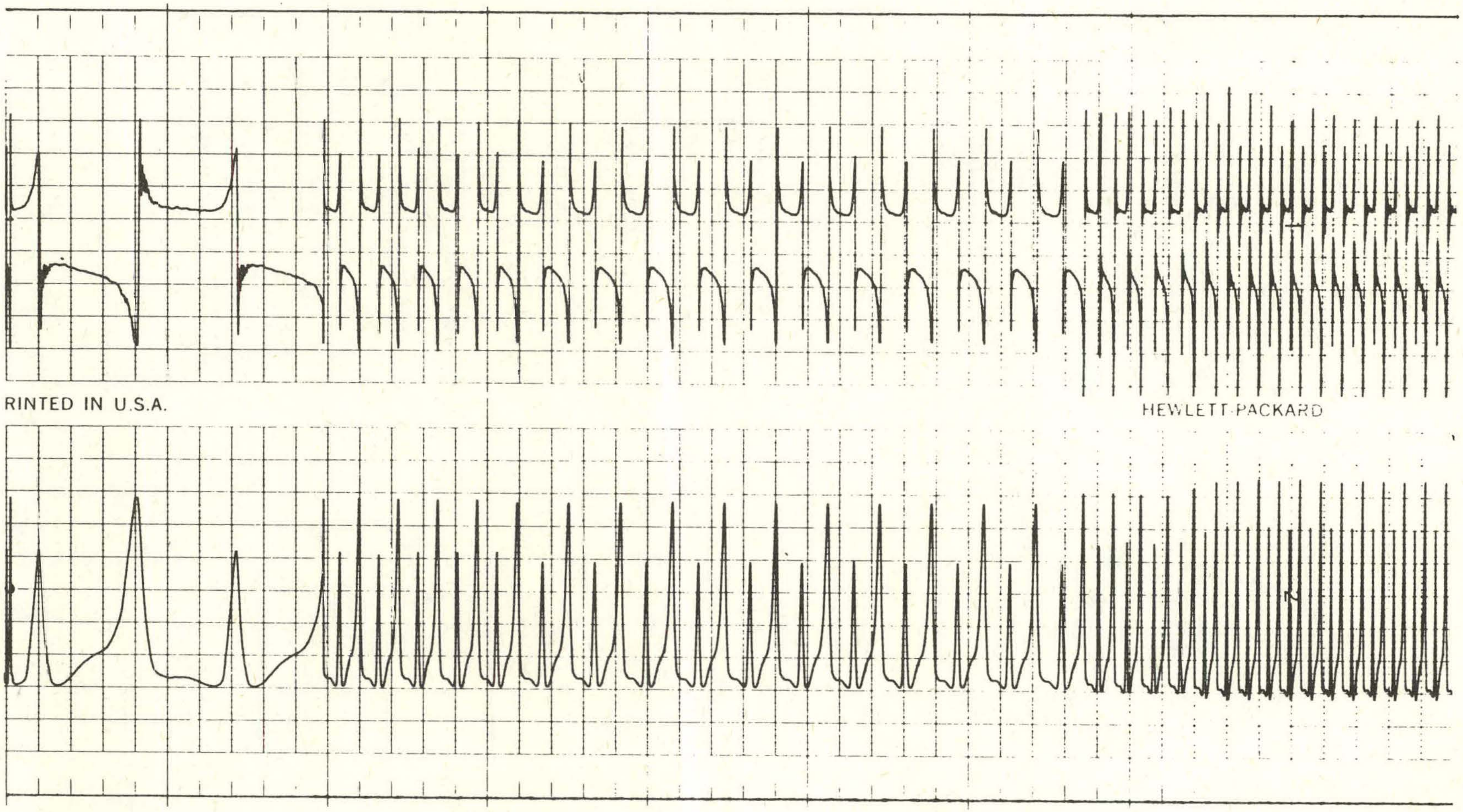
Vertical
Cutting
Force

100 lbf full scale
0.1 sec/mm

CUTTING TEST #1-063

FIGURE 17

DEVELOPMENT OF CUTTING FORCE DURING A SLICING TEST



Top: Horizontal Cutting Force (50 lbf FS)
Bottom: Vertical Cutting Force (100 lbf FS)

0.1 sec/mm Horizontal Scale
Cutting Test #1-063

FIGURE 18

VARIATION OF CUTTING FORCE WITH INCREASING MACHINE SPEED

TABLE 3

RECORD OF BLADE WEAR IN SLURRY SAWING

TEST	ORIGINAL HEIGHT (cm)	FINAL HEIGHT (cm)	WEAR RATIO r
1-001	0.635	0.381	0.045
1-011	0.635	0.569	0.076
1-012	0.635	0.572	0.069
1-013	0.635	0.572	0.070
1-014	0.635	0.574	0.060
1-015	0.635	--	--
1-021	0.635	0.612	0.085
1-022	0.635	0.569	0.077
1-023	0.635	0.460	0.050
1-024	0.635	0.371	0.041
1-031	1.270	1.204	0.070
1-032	0.475	0.401	0.056
1-033	1.270	1.199	0.065
1-034	0.635	0.564	0.070
1-041	0.635	0.599	0.049
1-042	0.635	0.572	0.069
1-043	0.635	0.610	0.096
1-051	0.635	0.572	0.067
1-052	0.635	0.574	0.079
1-053	0.635	0.505	0.037
1-054	0.635	0.559	0.074
1-061	0.635	0.572	0.110
1-062	0.635	0.498	0.149
1-063	0.635	0.536	0.100
2-001	0.635	0.391	0.047
2-002	0.635	0.452	0.047
2-003	0.635	0.424	0.040
2-011	0.635	0.351	0.062
2-012	0.635	0.396	0.070
2-031	0.635	0.417	0.048
3-001	0.635	--	--
3-002	0.635	--	--

$$r = \frac{h_o \ell_s t_B}{x_k y_k z_o} = \frac{h_o \ell_s t_B}{x_k A_w} \qquad (4.8)$$

Where h_o is the loss in blade height, ℓ_s is the stroke length, t_B is blade thickness, x_k is kerf width, y_k is kerf length, z_o is ingot height; or, for irregular shapes, A_w is the ingot cross-sectional area. A decrease of blade wear with cutting pressure is shown in Figure 19. Blade wear is higher with finer abrasives.

4.8 Problems Associated With Full Ingot Slicing

As shown in Section 4.1, the initial cutting rate in an ingot is lower than the maximum rate under equilibrium conditions. As the ingot area increases, the reduction of full test productivity from this effect is minimized. Figure 20 indicates that with 10 cm ingots, full slicing productivity is as high as 90% of the typical productivity.

Two distinct problems exist as the blades must cut through the bottom of the ingot into the submount, as described earlier. The transition of work material (silicon to mounting wax to glass, presently), forces the cutting system to achieve a new equilibrium configuration, similar to the conditioning stage at the beginning of a cut. In the case of mounting wax, the cutting process may vary drastically. Blades can cease cutting individually, overload and tip sideways. This can cause an undercut to wafer surfaces at the bottom of the ingot corresponding to the height of the blades at the exit point. To cure this problem, a continuum of silicon would be an ideal solution. Instead, ceramic

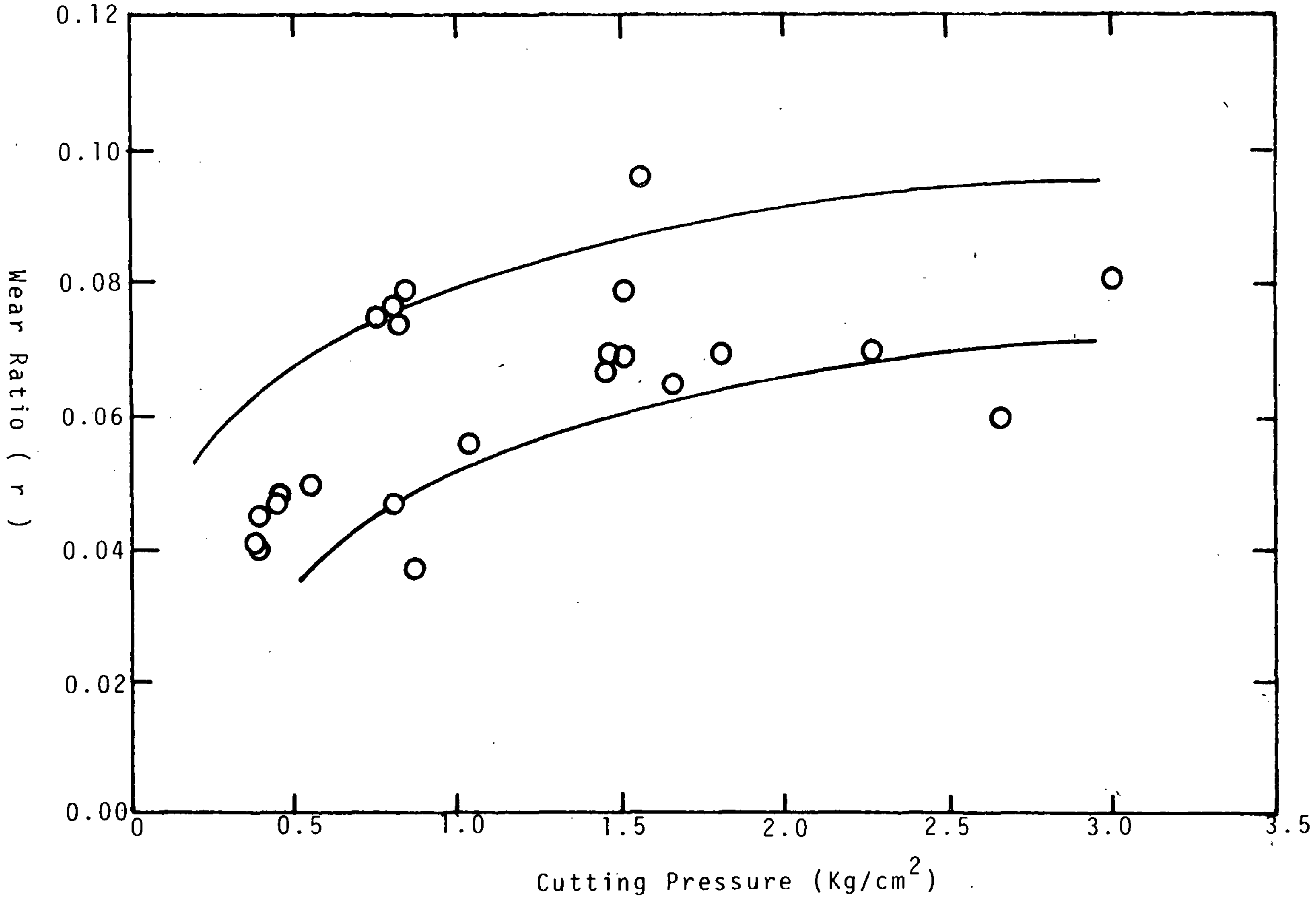


FIGURE 19

BLADE WEAR AS A FUNCTION OF CUTTING PRESSURE

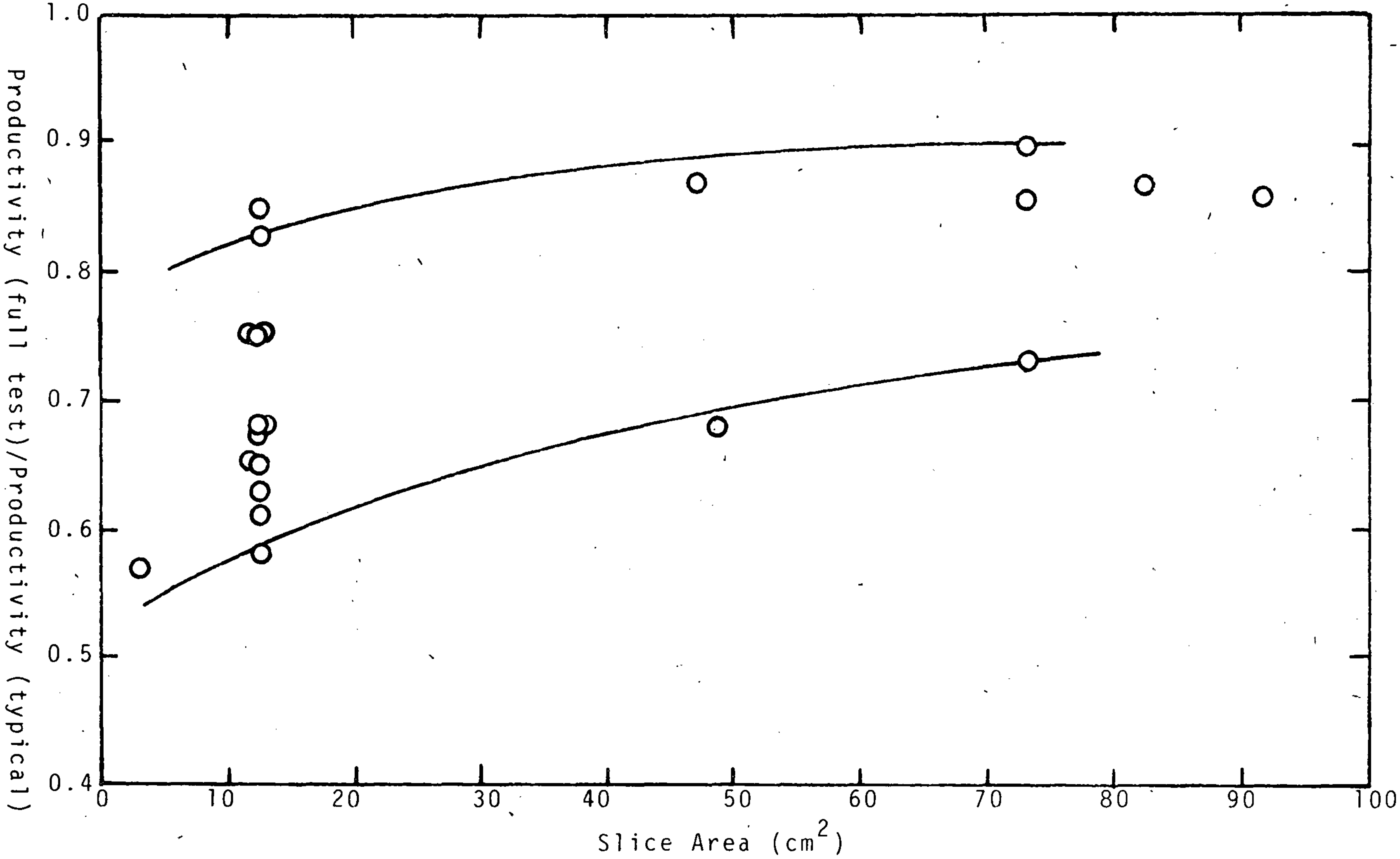


FIGURE 20

EFFECT OF SLICE AREA ON PRODUCTIVITY DEGRADATION adhesives will be tried with hard ceramic mounting blocks.

The second effect is the "marrying" of wafers at the bottom of the cut. Under the surface tension of the slurry oil, wafers tend to bend together and close the gaps between. This could cause surface undulations of as much as 25 μ under the continued side lapping at the top of blades, and may also limit the access of slurry to the blades.

In order to prevent this, plaster is applied to the top of a wafer stack in order to maintain the separation existing at the beginning of a cut. A more refined version of this technique will be devised for use with thin, large diameter wafers.

4.9 General Comments

Multiblade slurry sawing is no more than another means of material removal by abrasive wear. It contains the necessary elements of relative motion, hard abrasive cutting points, abrasive carriers (blades), and imposed normal load. The major difference between it and other processes is that the abrasive is fed to the carriers in a loose form in the hope that particles will become attached and provide a cutting action.

This effect makes slurry sawing differ from grinding in that the existence of abrasive in a cutting configuration on the blades is not assured. However, the continual replenishment of abrasive can sustain useful cutting edges without the requirement of fragmentation of fixed abrasives in order to avoid reduction of cutting rates caused by adhesive wear of the cutting edges. The process of slurry sawing is most similar to lapping in practice, but there are many blades (laps) which must perform cutting in nearly equal fashion. Should a variation in cutting capability occur between blades, overloading can occur to the slower blades. It is the ability to provide a level of control to the cutting system that may allow the maximum use of the process. If all blades can reliably maintain a useful configuration of abrasive on their edges, then they may be pushed to their loading limit without fear of temporary overloading due to variations in this cutting capability. Then, a blade package (100 or more blades) may be expected to behave as a single blade.

The important result to achieve in slurry sawing is a quasi-static equivalent of a fixed abrasive blade. Achievements of this end condition depends on a large number of factors. The transport of abrasive slurry to the blades is controlled by slurry viscosity (initial), application technique, and possibly by the interblade spacing and the reduction of slurry transport properties under the buildup of silicon debris in the oil. The degree of "bounce" or the workpiece under the action of worn blade ends and the number of abrasive particles per volume of oil have also shown a significant effect in increasing slicing rates in silicon. At best, the end result of cutting is achieved through a strongly interactive process.

At the root of the process is the cutting mechanism of hard materials. An abrasive particle can produce the cutting rates observed with this process only by a mechanism of localized brittle fracture. A useful characterization of this process is provided by Finnie et. al.[4] They relate the fracture process to the Hertzian stresses beneath the abrasive and to the probability of a sufficiently weak flaw within that stressed region or material. They are led to a conclusion that a brittle-ductile transition can occur as the stressed zone is reduced. This may explain the reduction of cutting rate with finer abrasive experienced with slurry sawing of silicon. The basic information is applicable only to simple cases of abrasion (notably erosion).

In silicon, the flaw system may be induced by previous cutting action.

Improvement in slurry sawing can occur in two fundamental areas, already proposed. The first is the increase of loads on the cutting system, reflected mostly by the stable control of the cutting process to a large number of individual abrasive carriers. The second is to externally effect the efficiency of the cutting process. This may be mostly aided by an understanding of the local fracture process of silicon, a subject on which there is little or no information.

5.0 WAFER CHARACTERIZATION

5.1 Thickness and Surface Profile

Table 4 is a summary of the thickness measurements and characteristics and the surface profile results for wafers from the slicing tests. The techniques for measurement are described in Appendix 2. Also in the Appendix are the record forms used for slicing tests, wafer measurement and surface profile characterization.

The nature of loose abrasive sawing can lead to a few assumptions about the necessary characteristics of wafers. The blade package is constructed of over 100 blades and 100 spacers, and the steel stock from which these are made has a small, but distinct variation in thickness. The outside blades can be aligned parallel to the bladehead stroke, but this parallelity is lost due to accummulation of thickness variations within the package. The thickness of wafers must vary, at best, according to the planes swept by the blades. This variation in thickness is defined by the tolerance of blades and spacers, and increases with the number of blades used.

Wandering of blades can define another component of wafer error. If a blade shifts to the side during cutting, a thinning of one wafer and corresponding thickening of the adjacent wafer will result. The result will be major undulations in the opposing surfaces.

The abrasive kerf loss at each side of the blade contributes to another component of surface profile. With fixed abrasives, this component is a constant loss to be added to the path of a blade, and thus does not contribute to errors. In Slurry Sawing, variations in the abrasive component does occur as cutting proceeds. Along the stroke direction, the wafer surface should be

TABLE 4

SUMMARY OF WAFER CHARACTERIZATION

TEST		1-001	1-011	1-012
THICKNESS (AVE)	cm	.0565	0551	0534
STD. DEVIATION	cm	.0020	0017	0045
TOTAL VARIATION (AVE)	cm	.0032	0019	0058
STD. DEVIATION	cm	.0017	0012	0038
STD. DEVIATION (AVE)	cm	.0014	0010	0030
STD. DEVIATION	cm	.0007	0006	0020
VARIATION (AVE WAFER)	cm	.0022	0010	0037
TAPER (AVE WAFER)	cm	.0021	0011	0030
BOW (AVE)	μm	- -	15	8
TAPER (AVE)	μm	- -	26	11
WAVINESS (p-p) (10^{-2}m)	μm	- -	11	48
ROUGHNESS (p-p) (10^{-4}m)	μm	- -	2	2
ROUGHNESS (RMS)	μinch	- -	16-19	19-24
STEPS	μm	- -	4	19
DAMAGE DEPTH (>10^4/cm^2)	μm		18.8	

TABLE 4 (Cont.)

TEST		1-013	1-014	1-015
THICKNESS (AVE)	cm	0573	0502	- -
STD. DEVIATION	cm	0061	0085	- -
TOTAL VARIATION (AVE)	cm	0052	0085	- -
STD. DEVIATION	cm	0053	0050	- -
STD. DEVIATION (AVE)	cm	0028	0045	- -
STD. DEVIATION	cm	0030	0027	- -
VARIATION (AVE WAFER)	cm	0029	0045	- -
TAPER (AVE WAFER)	cm	0018	0039	- -
BOW (AVE)	μm	72	- -	- -
TAPER (AVE)	μm	85	32	- -
WAVINESS (p-p) (10^{-2}m)	μm	15	12	- -
ROUGHNESS (p-p) (10^{-4}m)	μm	1.8	1.8	- -
ROUGHNESS (RMS)	μinch	18-22	16-22	- -
STEPS	μm	13	55	- -
DAMAGE DEPTH ($>10^4/cm^2$)	μm		17.7	

TABLE 4 (Cont.)

TEST		1-021	1-022	1-023	1-024
THICKNESS (AVE	cm	0536	0555	0535	0569
STD. DEVIATION	cm	0021	0029	0013	0030
TOTAL VARIATION (AVE)	cm	0027	0022	0034	0038
STD. DEVIATION	cm	0022	0014	0016	0023
STD. DEVIATION (AVE)	cm	0014	0012	0018	0020
STD. DEVIATION	cm	0011	0007	0008	0012
VARIATION (AVE WAFER)	cm	0014	0010	0021	0011
TAPER (AVE WAFER)	cm	0007	0003	0012	0011
BOW (AVE)	μm	10	20	13	17
TAPER (AVE)	μm	27	36	22	34
WAVINESS (p-p) $(10^{-2}m)$	μm	20	5	11	14
ROUGHNESS (p-p) $(10^{-4}m)$	μm	1	1.5	1.4	2
ROUGHNESS (RMS)	μinch	25-45	14-17	13-16	14-17
STEPS	μm	8	4	14	- -
DAMAGE DEPTH (10/cm)	μm				

TABLE 4 (Cont.)

TEST		1-031	1-032	1-033	1-034
THICKNESS (AVE)	cm	0526	0519	0516	0535
STD. DEVIATION	cm	0022	0044	0051	0035
TOTAL VARIATION (AVE)	cm	0034	0057	0035	0042
STD. DEVIATION	cm	0024	0029	0029	0022
STD. DEVIATION (AVE)	cm	0019	0030	0018	0022
STD. DEVIATION	cm	0012	0015	0014	0011
VARIATION (AVE WAFER)	cm	0026	0039	0018	0018
TAPER (AVE WAFER)	cm	0022	0036	0002	0006
BOW (AVE)	μm	10	- -	28	40
TAPER (AVE)	μm	22	35	29	38
WAVINESS (p-p) (10^{-2}m)	μm	13	9	16	27
ROUGHNESS (p-p) (10^{-4}m)	μm	1.9	1.5	2.0	2.0
ROUGHNESS (RMS)	μinch	18-20	16-17	22-25	35-50
STEPS	μm	4	3	6	21
DAMAGE DEPTH ($>10^4/cm^2$)	μm				

TABLE 4 (Cont.)

TEST		1-041	1-042	1-043
THICKNESS (AVE)	cm	- -	0534	0552
STD. DEVIATION	cm	- -	0045	0017
TOTAL VARIATION (AVE)	cm	- -	0046	0022
STD. DEVIATION	cm	- -	0036	0015
STD. DEVIATION (AVE)	cm	- -	0023	0011
STD. DEVIATION	cm	- -	0018	0008
VARIATION (AVE WAFER)	cm	- -	0028	0014
TAPER (AVE WAFER)	cm	- -	0028	0014
BOW (AVE)	µm	- -	23	- -
TAPER (AVE)	µm	- -	44	- -
WAVINESS (p-p) (10^{-2}m)	µm	- -	17	- -
ROUGHNESS (p-p) (10^{-4}m)	µm	- -	2.0	- -
ROUGHNESS (RMS)	µinch	- -	16-19	20-24
STEPS	µm	- -	15	- -
DAMAGE DEPTH (>10^4/cm^2)	µm			

TABLE 4 (Cont.)

TEST		1-051	1-052	1-053	1-054
THICKNESS (AVE)	cm	0524	0566	0333	0332
STD. DEVIATION	cm	0025	0011	0013	0026
TOTAL VARIATION (AVE)	cm	0043	0016	0044	0018
STD. DEVIATION	cm	0019	0009	0022	0013
STD. DEVIATION (AVE)	cm	0022	0008	0017	0009
STD. DEVIATION	cm	0009	0005	0009	0006
VARIATION (AVE WAFER)	cm	0034	0007	0025	0008
TAPER (AVE WAFER)	cm	0034	0007	0015	0008
BOW (AVE)	μm	17	21	6	8
TAPER (AVE)	μm	29	15	6	7
WAVINESS (p-p) (10^{-2}m)	μm	34	15	14	9
ROUGHNESS (p-p) (10^{-4}m)	μm	2.2	1.5	1.5	1.4
ROUGHNESS (RMS)	μinch	20-22	17-19	15-16	17-19
STEPS	μm	4	40	13	13
DAMAGE DEPTH (>10^4/cm^2)	μm				

TABLE 4 (Cont.)

TEST		1-061	1-062	1-063
THICKNESS (AVE)	cm	0592	0591	0573
STD. DEVIATION	cm	0007	0014	0027
TOTAL VARIATION (AVE)	cm	0029	0035	0018
STD. DEVIATION	cm	0015	0022	0011
STD. DEVIATION (AVE)	cm	0015	0015	0009
STD. DEVIATION	cm	0008	0009	0005
VARIATION (AVE WAFER)	cm	0020	0013	0009
TAPER (AVE WAFER)	cm	0020	0007	0001
BOW (AVE)	μm	- -	15	44
TAPER (AVE)	μm	- -	52	24
WAVINESS (p-p) (10^{-2}m)	μm	- -	15	18
ROUGHNESS (p-p) (10^{-4}m)	μm	- -	1.1	1.6
ROUGHNESS (RMS)	μinch	14-16	10-12	12-13
STEPS	μm	- -	5	- -
DAMAGE DEPTH (>10^4/cm^2)	μm			

TABLE 4 (Cont.)

TEST		2-001	2-002	2-003
THICKNESS (AVE)	cm	0245	0334	0318
STD. DEVIATION	cm	0017	0016	0017
TOTAL VARIATION (AVE)	cm	0036	0026	0046
STD. DEVIATION	cm	0014	0014	0009
STD. DEVIATION (AVE)	cm	0011	0013	0024
STD. DEVIATION	cm	0004	0007	0004
VARIATION (AVE WAFER)	cm	0020	0011	0044
TAPER (AVE WAFER)	cm	0006	0011	0027
BOW (AVE)	μm	- -	- -	- -
TAPER (AVE)	μm	20	6	28
WAVINESS (p-p) (10^{-2}m)	μm	88	8	40
ROUGHNESS (p-p) (10^{-4}m)	μm	1.5	1.5	2.0
ROUGHNESS (RMS)	μinch	17-19	15-16	18-19
STEPS	μm	- -	- -	30
DAMAGE DEPTH (>10^4/cm^2)	μm			

TABLE 4 (Cont.)

TEST		2-011	2-012	2-031
THICKNESS (AVE)	cm	0362	0374	0355
STD. DEVIATION	cm	0040	0009	0058
TOTAL VARIATION (AVE)	cm	0051	0043	0100
STD. DEVIATION	cm	0033	0010	0043
STD. DEVIATION (AVE)	cm	0024	0017	0038
STD. DEVIATION	cm	0016	0005	0015
VARIATION (AVE WAFER)	cm	0019	0022	0049
TAPER (AVE WAFER)	cm	0019	0016	0043
BOW (AVE)	μm	- -	- -	- -
TAPER (AVE)	μm	- -	38	- -
WAVINESS (p-p) (10^{-2}m)	μm	24	40	50
ROUGHNESS (p-p) (10^{-4}m)	μm	1.5	2.2	2.0
ROUGHNESS (RMS)	μinch	17-18	10-12	13-15
STEPS	μm	36	6	- -
DAMAGE DEPTH ($>10^4/cm^2$)	μm			

flat and parallel since the state of abrasive was fixed at the time that surface was created. However, variations in the surface measured in the feed direction can be expected.

The result of the above will be wafers that will vary in thickness by a minimum amount due to blade package configuration. Further variation will be due to blade wander. The degree of surface undulation will be a measure of the adequate state of abrasive charging on blades.

5.2 Results of Thickness Characterization

The standard deviation of average wafer thickness ranges from 7 to 85μ. Figure 21 shows the variation as a function of cutting pressure. At low pressure cutting, the variation is between 10 and 30 μ , and the increases at higher blade pressure indicating blade wander. A notable case is the difference between #2-001 and #2-003 (17μ) and #2-031 (58μ) where the thinning of slurry oil allowed blade wander and thickness variation. Although cutting rates were nearly identical, the control of cutting was loss with the thinning of slurry oil.

Another characterisitic of wafers is taper, wafers being thinner on the top than on the bottom. It has been presumed that the "breakdown" of abrasive was responsible, where abrasive size was continuously reduced as the slurry was used resulting in a reduction of abrasive kerf loss fhrough the workpiece. The taper and direction of taper (positive taper being wafers which are thicker at the bottom) is recorded in Table 1. Also, recorded are two parameters which measure the utilization of the slurry. Abrasive utilization is the total kerf volume abraded compared to the weight of fresh abrasive used for a test. Oil utilization is the kerf volume compared to the volume of oil used to make the slurry for a test. Figure 22 shows such taper compared

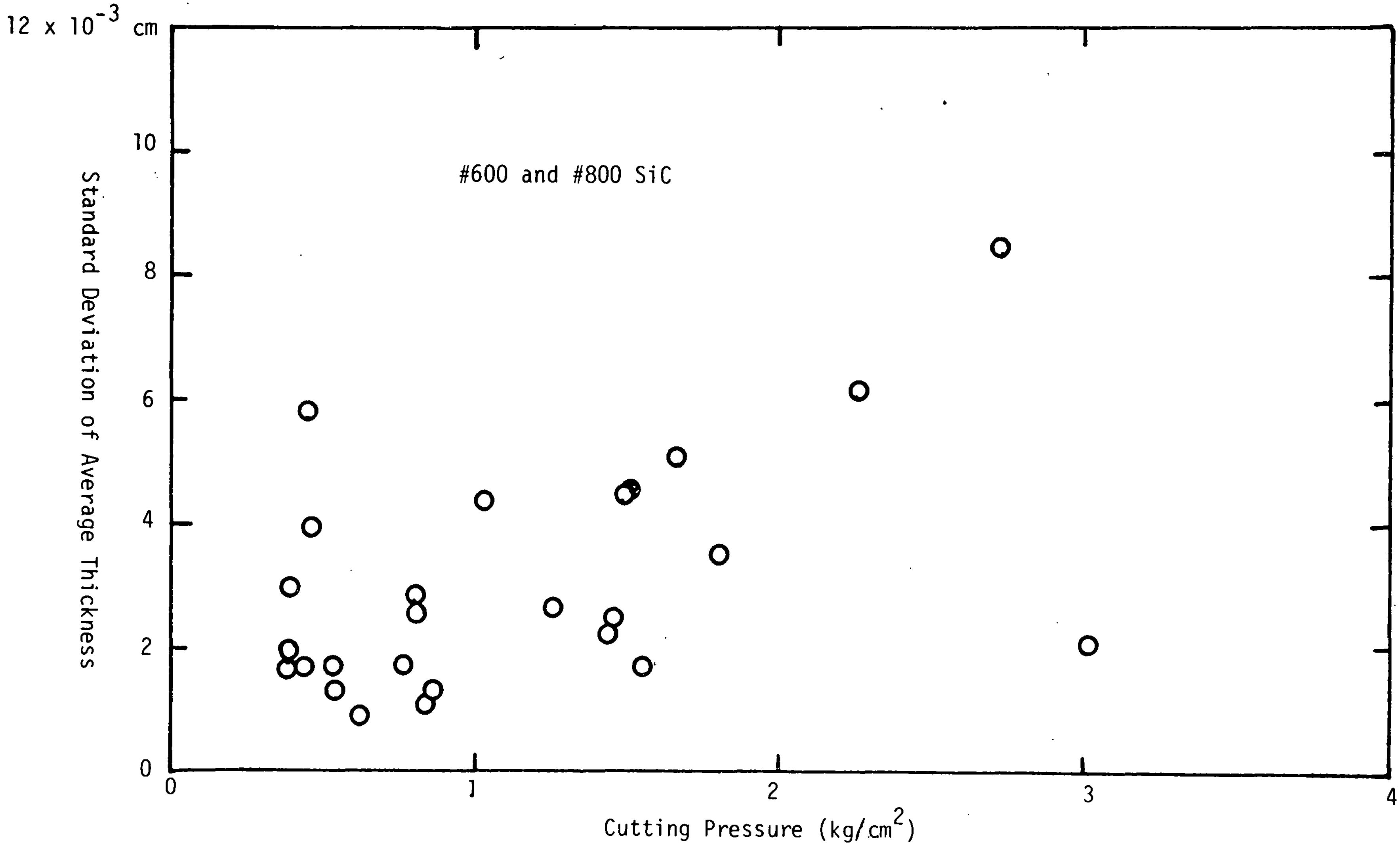


FIGURE 21

THICKNESS ACCURACY AS A FUNCTION OF CUTTING PRESSURE

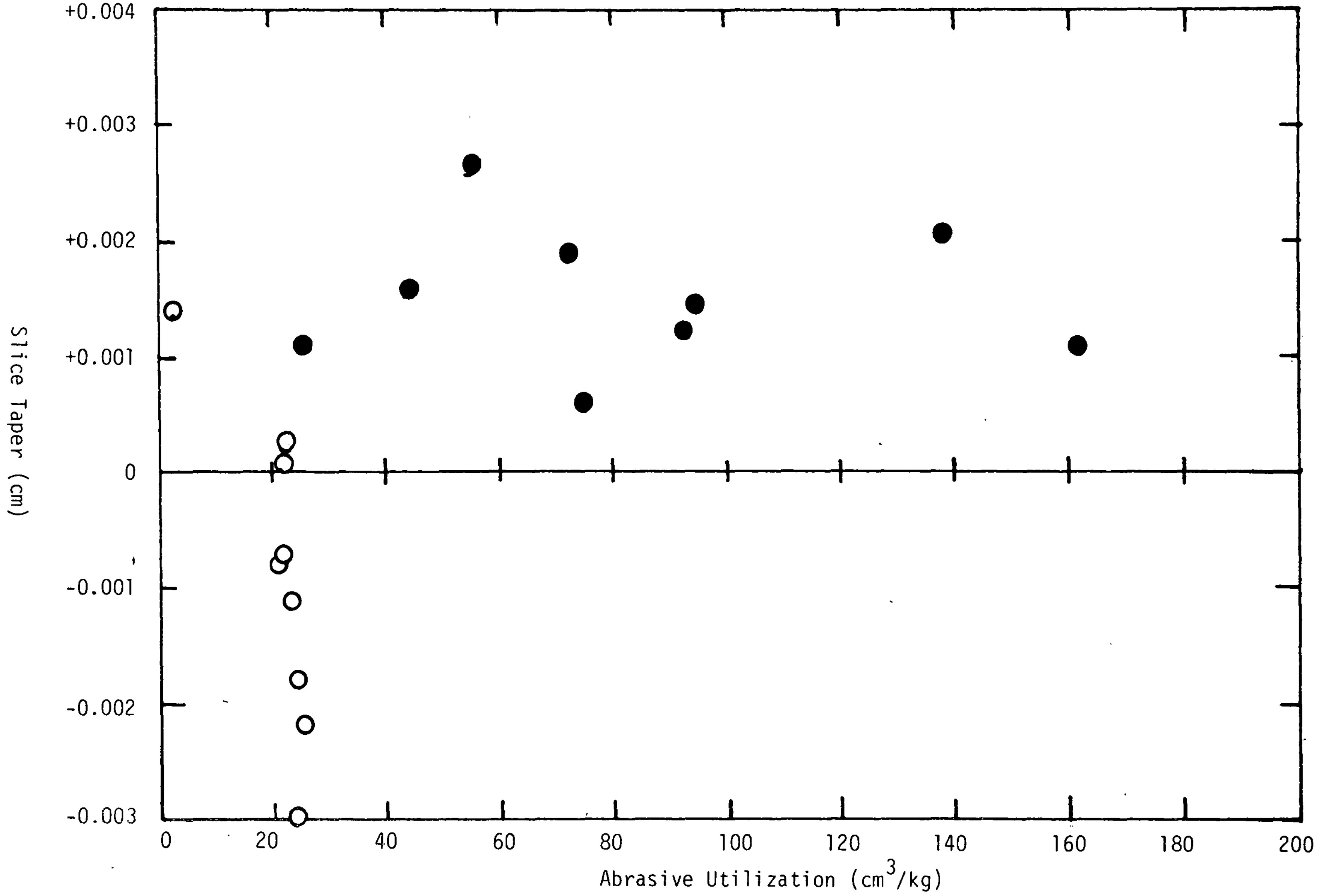


FIGURE 22

SLICE TAPER AS A FUNCTION OF ABRASIVE UTILIZATION to abrasive utilization. There is no clear trend. The black data points are the tests with wafers over 40 cm^2 in cross-section. However, there is an apparent correlation of such taper with oil utilization. (Figure 23). The buildup of silicon debris increases the slurry viscosity. The transport or abrasive is reduced and "restriction" of abrasive to the blades may induce taper. In #2-031, the taper is extreme, possibly due to the larger relative viscosity increase in the thinner slurry oil.

5.3 Results Of Surface Profile Characterization

Figure 24 shows a reproduction of surface profile traces of a sample wafer from slicing test #2-001. The top trace is across the 10 cm slice, showing the relatively flat even surface produced along the blade stroke. In the vertical direction, large surface undulations are apparent. However, the opposite surfaces seem to be mostly parallel. There is a thinning of the top of the slice, and some thickness irregularity. The "S" shape of the slice may be due to lateral shifting of the vertical feed during its upward stroke.

In contrast, Figure 25 shows a slice profile from Test #2-031. The thickness measurements had indicated that control of the blades was poor when the thinned slurry oil was used. The profile indicates irregular thickness, and random surface undulation, supporting the earlier premise.

Due to the nature of the process, slurry sawing will produce relatively irregular wafers. However, the ability to control blades in a stable cutting mode can be detected with surface profile and thickness characterization. These techniques will measure the impact of process alteration, which will not show up as variations in cutting rates, but will impact the accuracy of wafers.

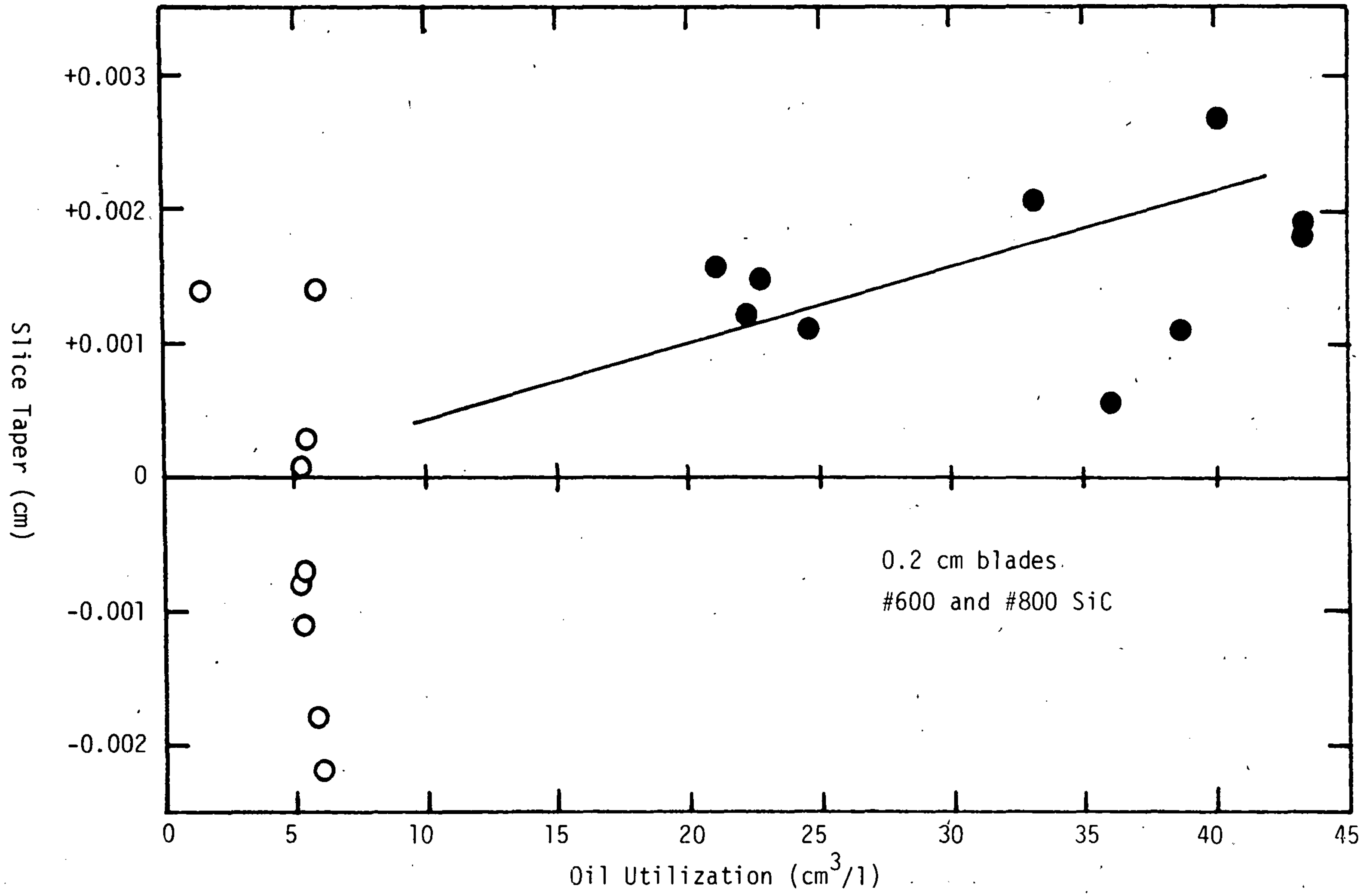


FIGURE 23

SLICE TAPER AS A FUNCTION OF OIL UTILIZATION

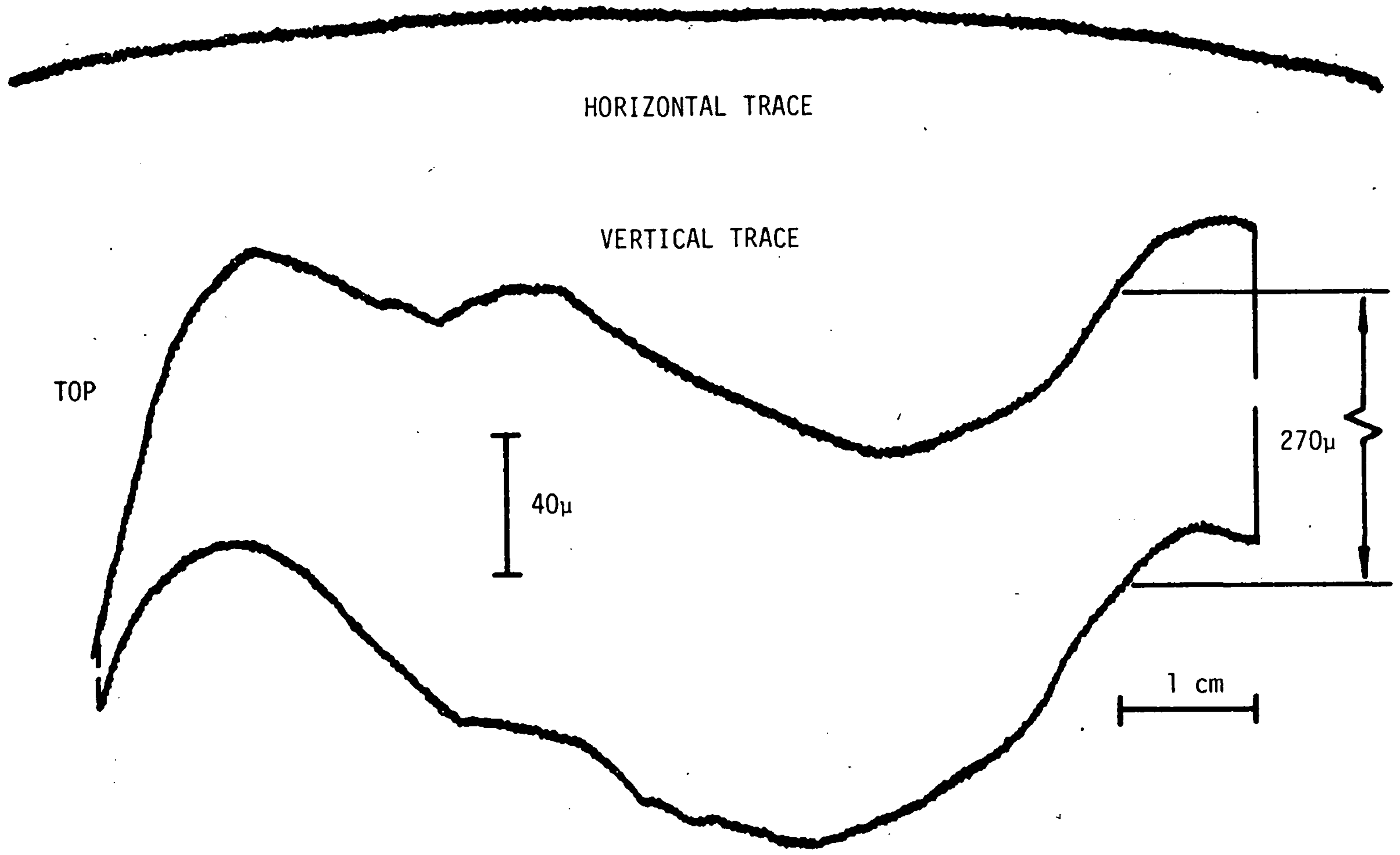


FIGURE 24

SURFACE PROFILE FOR SLICING TEST #2-001

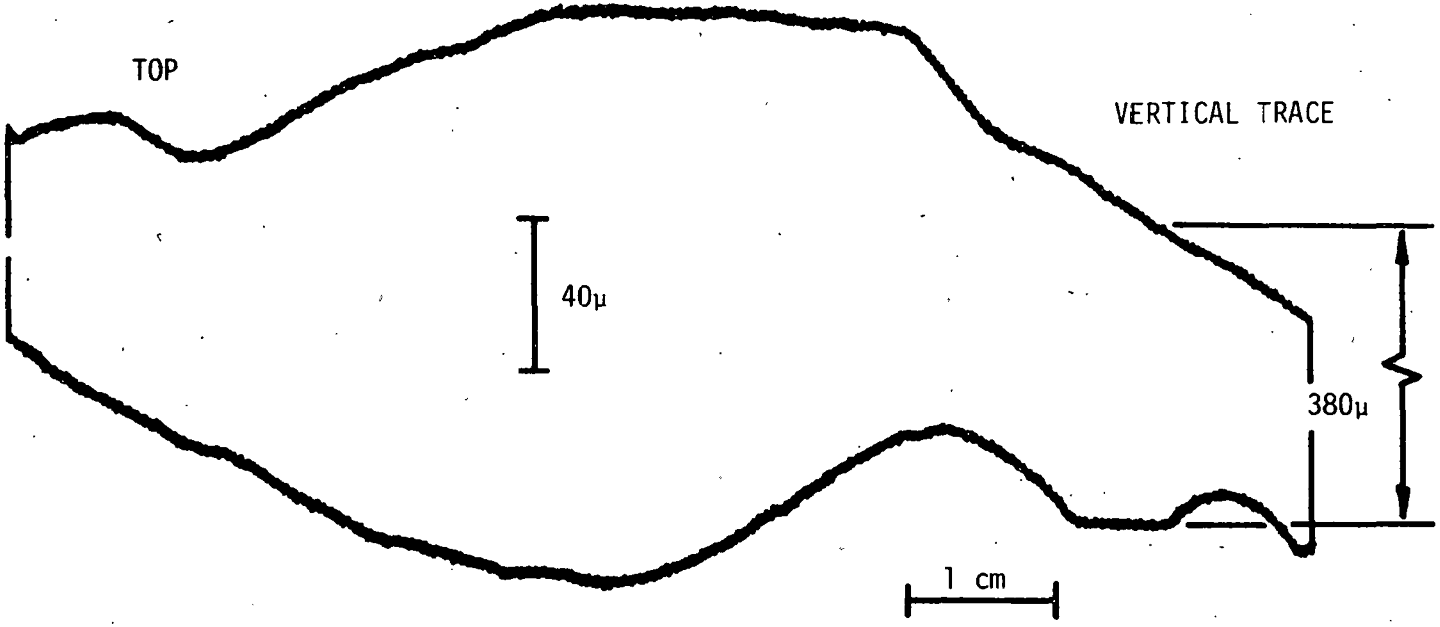


FIGURE 25

SURFACE PROFILE FOR SLICING TEST #2-031

5.4 Surface Damage Characterization

A procedure for the step-etching of as-sawed silicon wafers has been devised. Saw-induced damage is revealed by dislocation etch pits and varies appreciably with sawing conditions, and the damage has been found to extend inward more than a few microns. As shown by Figure 26 for a wafer from cutting test #1-011, the dislocation density remains above 10^4 per cm^2 until a depth of 18.8 μ (0.74 mil) is reached, and its value is 640 per cm^2 at 27.8 μ (1.11 mil). In slicing test #1-014, where blade loading was 4 times higher, the damage density at the surface is lower than in #1-011, but the slope of the damage vs. depth curve is lower.

The step-etching procedure is conventional. A satisfactorily nonselective and conveniently slow etchant was developed from the commonly used 3 HNO_3 (conc.) : 1 HF (conc.): 1 CH_3COOH (glacial) chemical polishing reagent by increasing the proportion of nitric acid to 30:1:1. This composition gives sufficient oxidizing power to maintain planarity, while the greatly reduced rate of oxide removal yields an effective etch rate of approximately 2μ per minute. The Wright etchant is used to reveal defects, and ceresine (microcrystalline) wax is used to mask against etching; the wax is readily removed by chloroethylene with ultrasonic agitation. Step heights are measured with a Sloan Dek Tak surface profilometer.

The correlation between sawing variables and surface damage, by means of step-etching, will be continued in the next quarter. The data to be obtained are of the form shown in Figure 26: the dislocation density as a function of depth below the original surface.

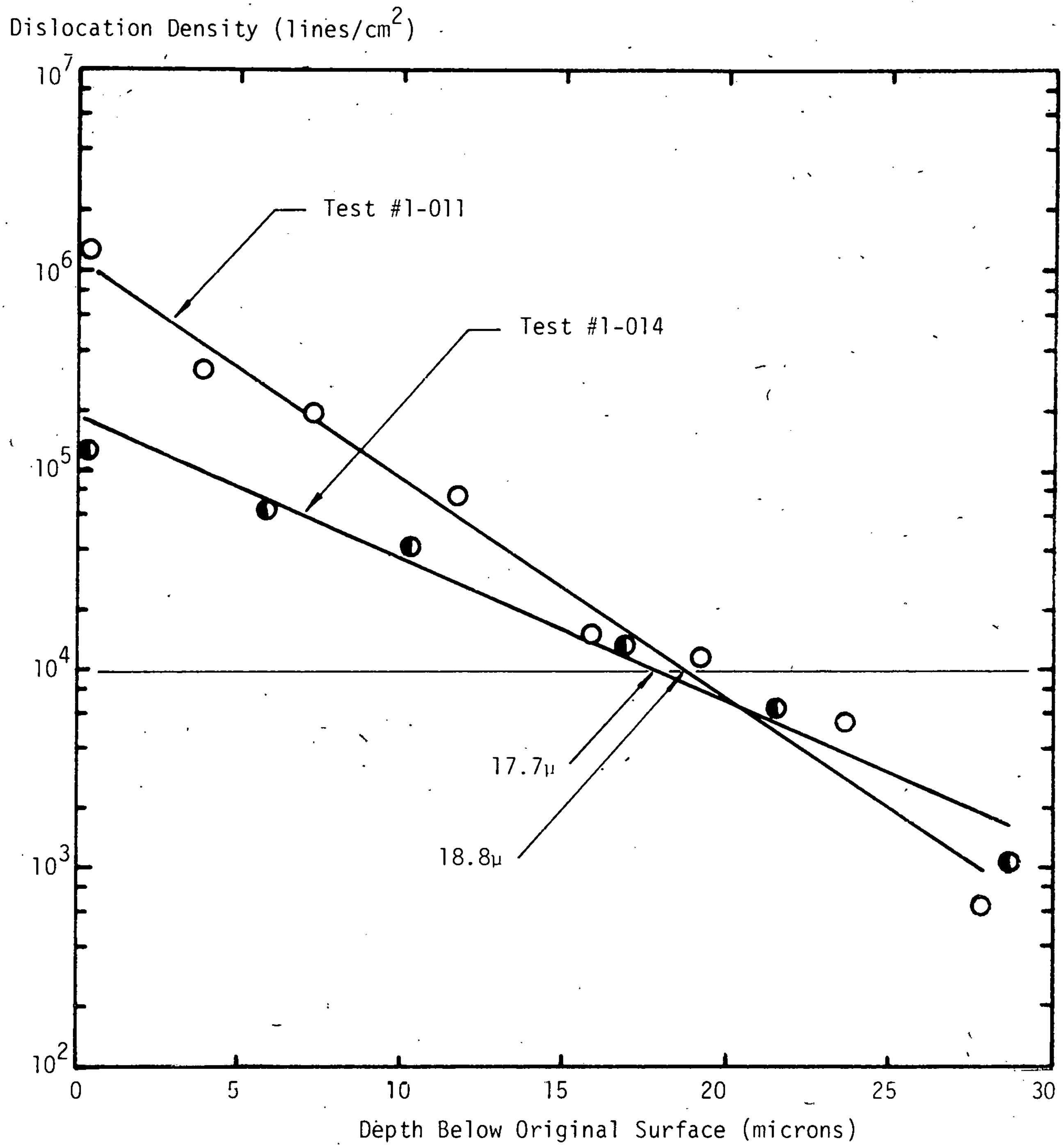


FIGURE 26

DISLOCATION DENSITY AS A FUNCTION OF DEPTH

6.0 CONCLUSIONS

- Cutting rates in Multiblade slurry sawing can be characterized by a fixed volumetric rate of material abrasion. The rate increases linearly with cutting force and slicing speed. For a given load and speed, the wafer productivity (area/hour) increases as blade thickness is decreased.
- A decrease in abrasive particle size reduces the material loss in slicing, but reduces the productivity of the process as well. #800 abrasive produces 0.002 cm less kerf loss than #600 SiC, in slicing a 10 cm ingot. Its cutting rate is less than 70% of that produced with #600 grit.
- By increasing the density of abrasive in a slurry mix, from 0.24 to 0.48 kg/l, cutting rate in a 10 cm diameter silicon ingot was increased by 40 to 50%.
- Thinning of the carrier oil in a slurry mix produces cutting rates comparable to those with unthinned oil, but the wafer accuracy and taper are noticeably degraded.
- Increase in the abrasive slurry viscosity as silicon debris accumulates seems to control the taper or silicon wafers.
- A round ingot can be sliced at 70% higher ultimate cutting rate than a square ingot. This may result from improved slurry transport during the "bounce" of the vertical feed at the end of the bladehead stroke.
- Surface damage in preliminary wafers extends 18μ into the slice surface before the dislocation density is less than 10^4 per square centimeter.
- A 10 cm ingot of silicon can be sliced into wafers 0.024 cm thick using a total of 0.050 cm of silicon per slice in 20 hours. 143 wafers have to be sliced simultaneously, and a current capacity of 230 is available.

7.0 FUTURE WORK

The major areas of emphasis during the final nine months of the program will be:

- Evaluate wafer surface damage characteristics as a function of fabrications parameters.
- Devise process requirements to allow slicing with thin blades (0.010 cm thick or less).
- Manipulate slurry makeup and application to allow higher cutting loads (greater than 120 grams per blade) with 0.020 cm thick blades without a loss of accuracy.
- Establish minimum slice capabilities of slurry sawing and determine processing tradeoffs required.
- Formulate economic analysis from above inputs to evaluate minimum silicon slice cost.
- Devise and test final low cost wafering process with current machine.

REFERENCES

1. S. C. Holden, "Slicing of Silicon into Sheet Material, First Quarterly Report", Varian Associates, ERDA/JPL - 76/1; March 29, 1976, pp 3-9.

2. V. M. Glazov, and V. N. Vigdorovich, Micro-hardness of Metals and Semiconductors, Consultants Bureau, New York; London, 1971, pg. 203.

3. S. C. Holden, "Slicing of Silicon into Sheet Material, Second Quarterly Report", Varian Associates, ERDA/JPL 954374 - 76/2; June 25, 1976, pg. 18.

4. H. L. OH, K.P.L. Oh, S. Vaidyanathan and J. Finnie, "On the Shaping of Brittle Solids by Erosion and Ultrasonic Cutting", The Science of Ceramic Machining and Surface Finishing, S. J. Schneider, Jr. (ed.), National Bureau of Standards Special Publication 348; May, 1972., pp 119-132.

APPENDIX 1

- Man-Hours and Costs
- Program Plan (Updated)
- Engineering Drawings and Sketches

MAN-HOURS AND COSTS

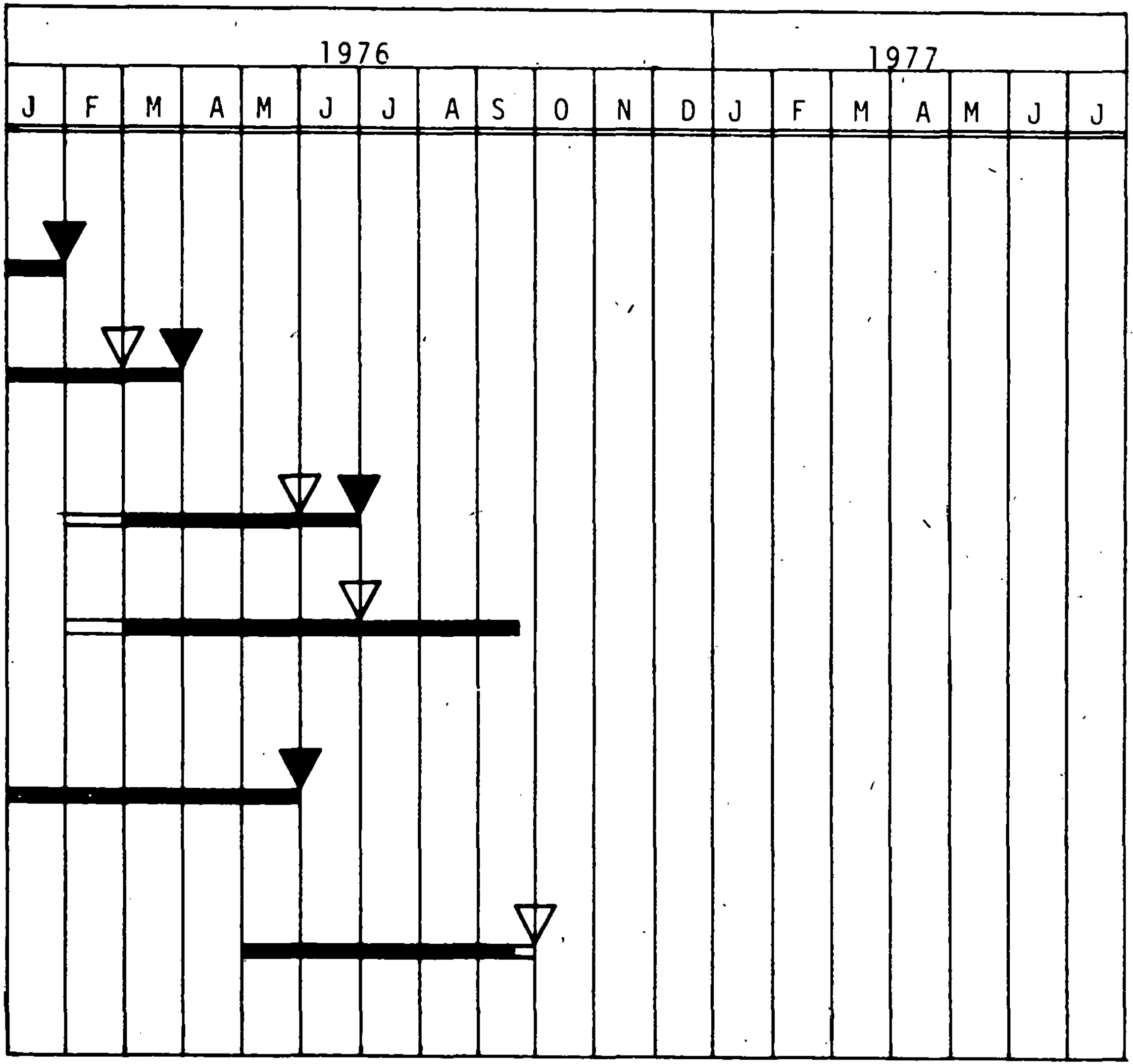
During the reporting period of January 9, 1976 to September 19, 1976, total man-hours were 2175.4 hours, and total costs were $75,431. There were no previous expenditures.

SLICING OF SILICON INTO SHEET MATERIALS

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

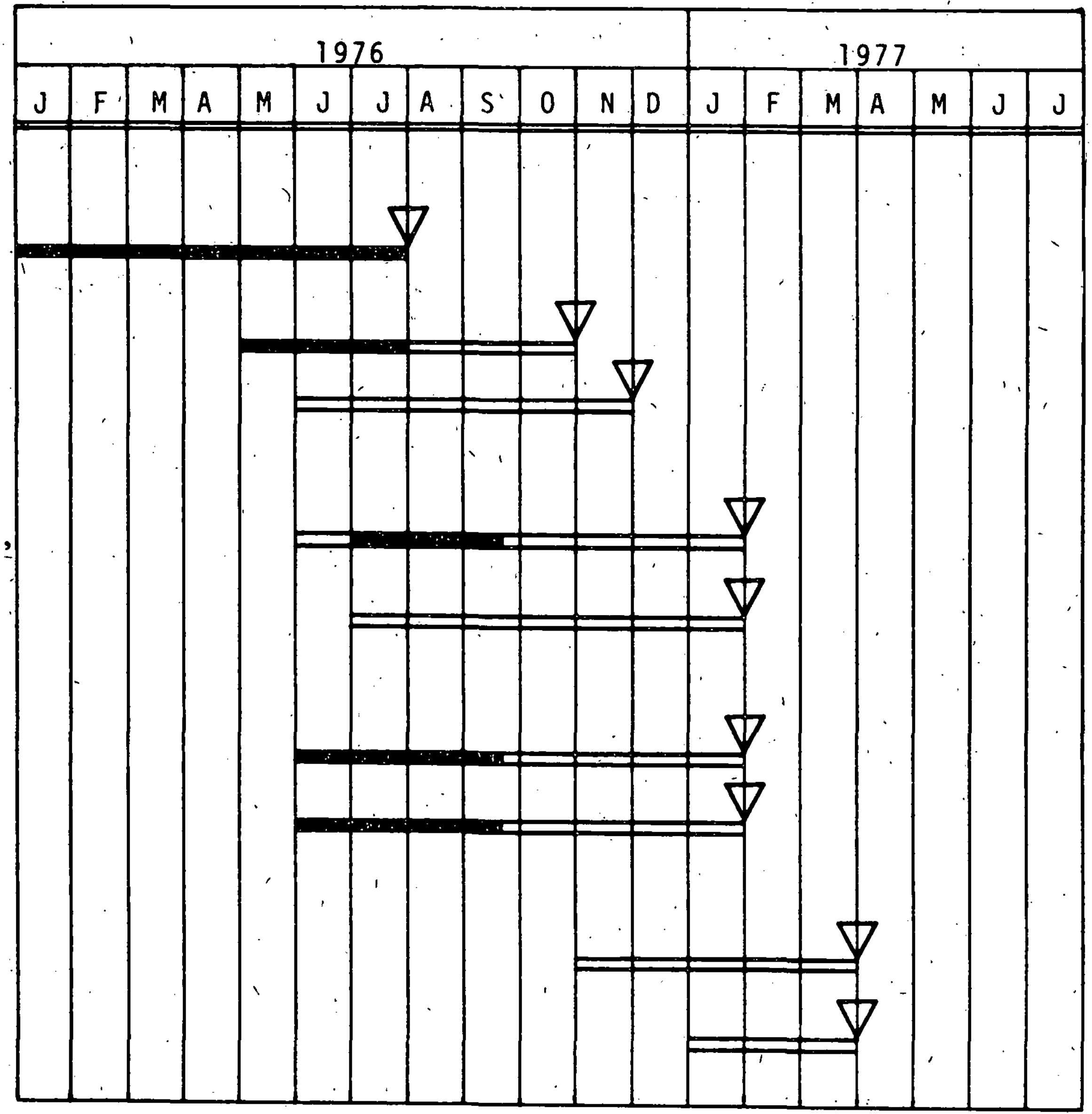
Program Plan
Page 1 of 5

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 9/19/76

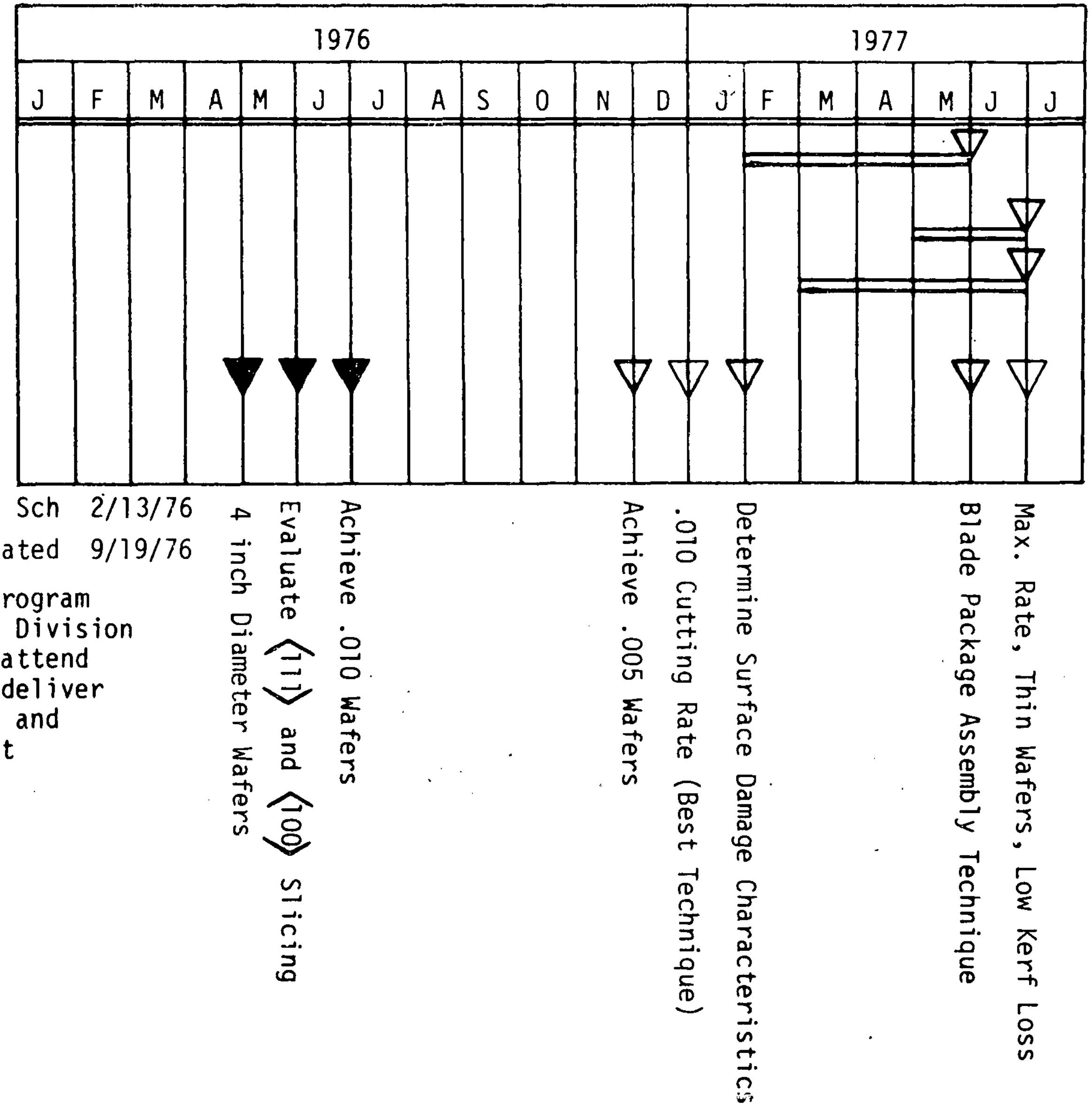
3. Load Balancing
    3.1. Build feedback control system - rate and force interaction
    3.2. Cutting performance vs. results of 1.3.
    3.3. Wafer characterization
4. Blade Materials
    4.1. Cutting tests - optimum blade material, thickness, etc. for silicon
    4.2. Wafer characterization
5. Abrasives
    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 9/19/76

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

8. Milestones



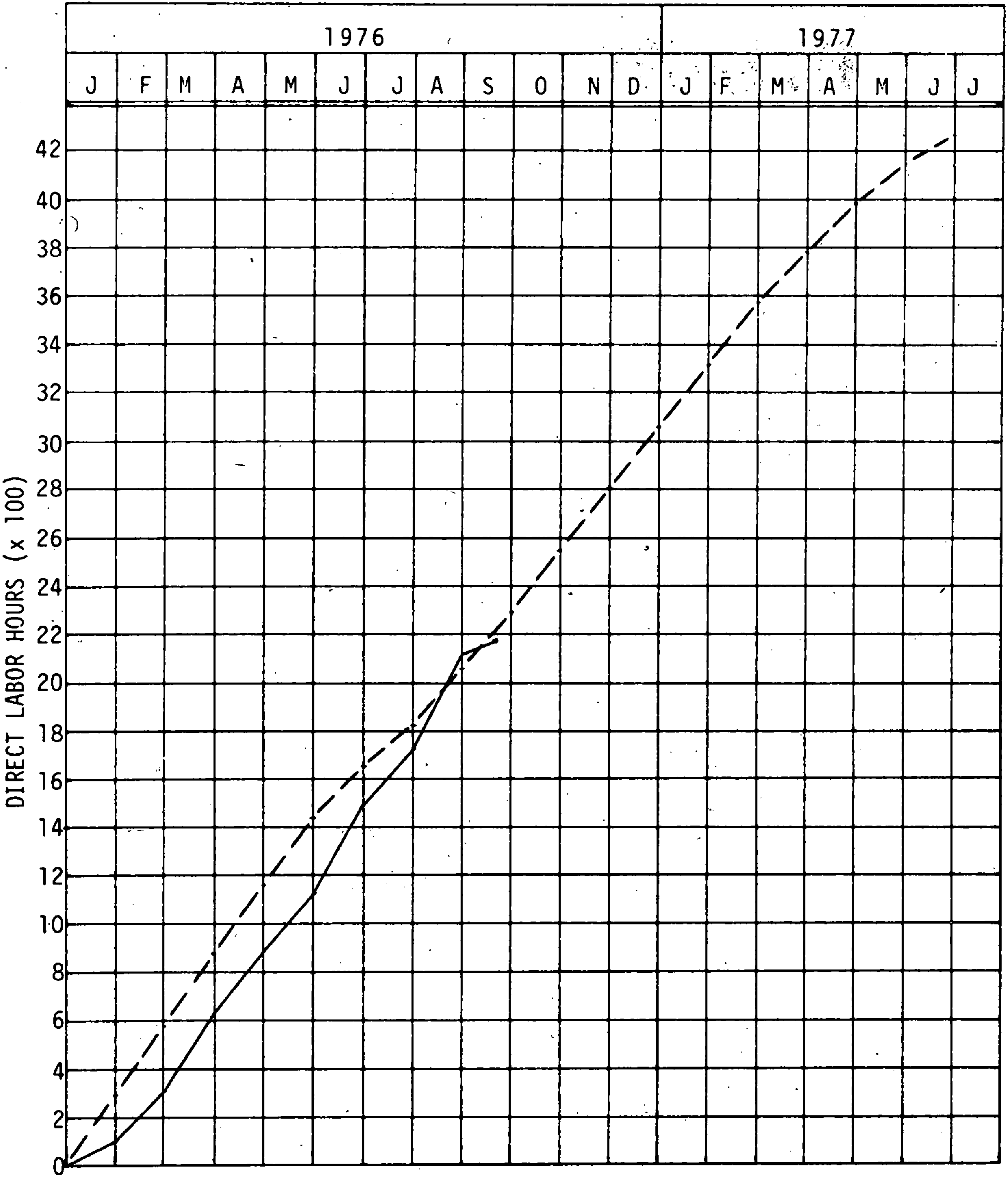
Sch 2/13/76
Updated 9/19/76

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
Page 4 of 5



Sch 1/22/76
Updated 9/19/76

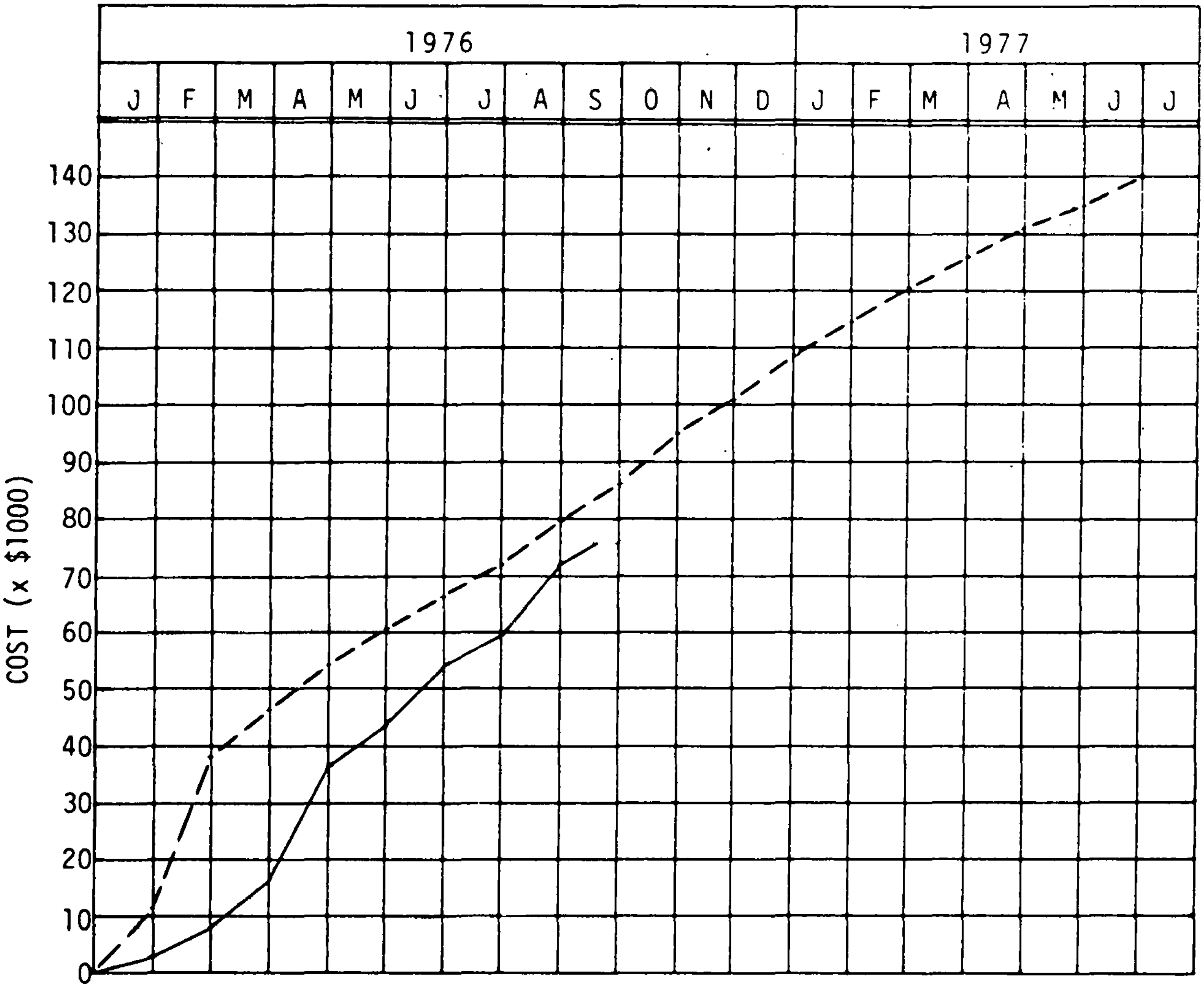
TOTAL HOURS: 4,260 PLANNED HOURS — — —
HOURS TO DATE: 2,175.4 INCURRED HOURS ———

PROGRAM LABOR SUMMARY

SLICING OF SILICON INTO SHEET MATERIALS

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

Program Plan
Page 5 of 5



Sch 1/22/76
Updated 9/19/76

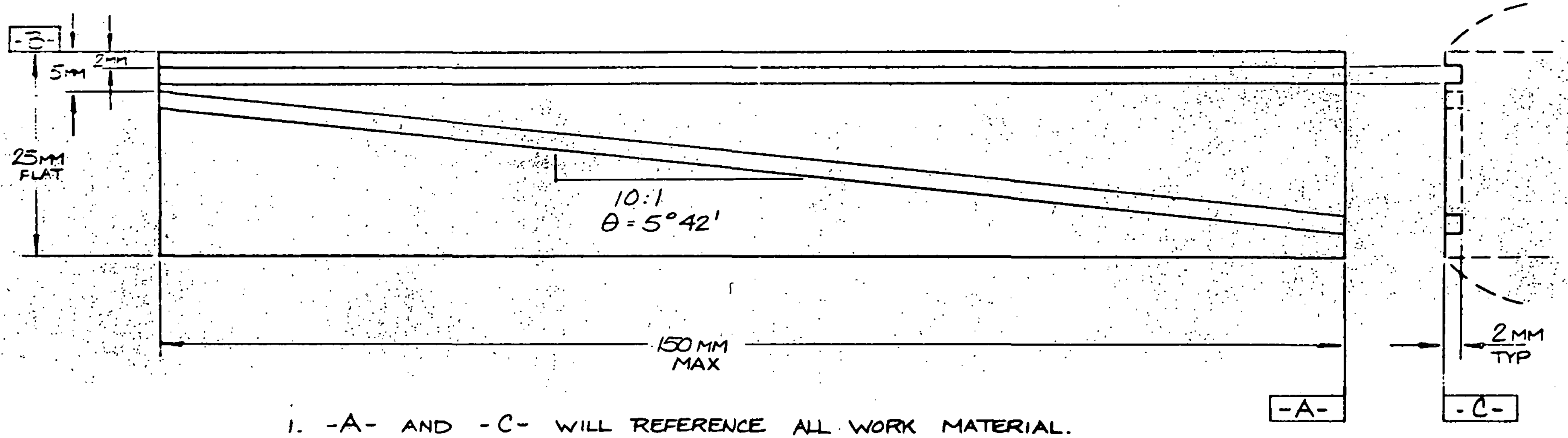
TOTAL COST: $140,000
COST TO DATE: 75,431

PLANNED COST – – –
INCURRED COST ——

PROGRAM COST SUMMARY

NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL

DO NOT SCALE DRAWING



1. -A- AND -C- WILL REFERENCE ALL WORK MATERIAL.
2. FOR NARROW BLOCKS, MAXIMUM LENGTH WILL BE GIVEN BY $L_{MAX} = 10(\text{WIDTH} - 10\text{ MM})$
3. USE FOR ALL WORK SHAPES. IDENTIFY -A- AND -C- FOR SLABBING.
4. TOLERANCE ± .25 MM

DRAWN SCH	DATE 2.3.76	APPROVED	DATE	CODE
CHECKED	DATE	APPROVED	DATE	CLASS

REFERENCE FLAT- SILICON

NOT OTHERWISE SPEC: FRAC ± ANG ± SCALE [illegible]

FIN. ✓ DEC .X ± .XX ± .XXX ±

varian

DIVISION	SIZE	DRAWING NO
VAC/LEX	B	JPL-001

DESCRIPTION OF CHANGE

NUM

EO

DFT

CHK

DATE

REV

LITHO IN U.S.A.

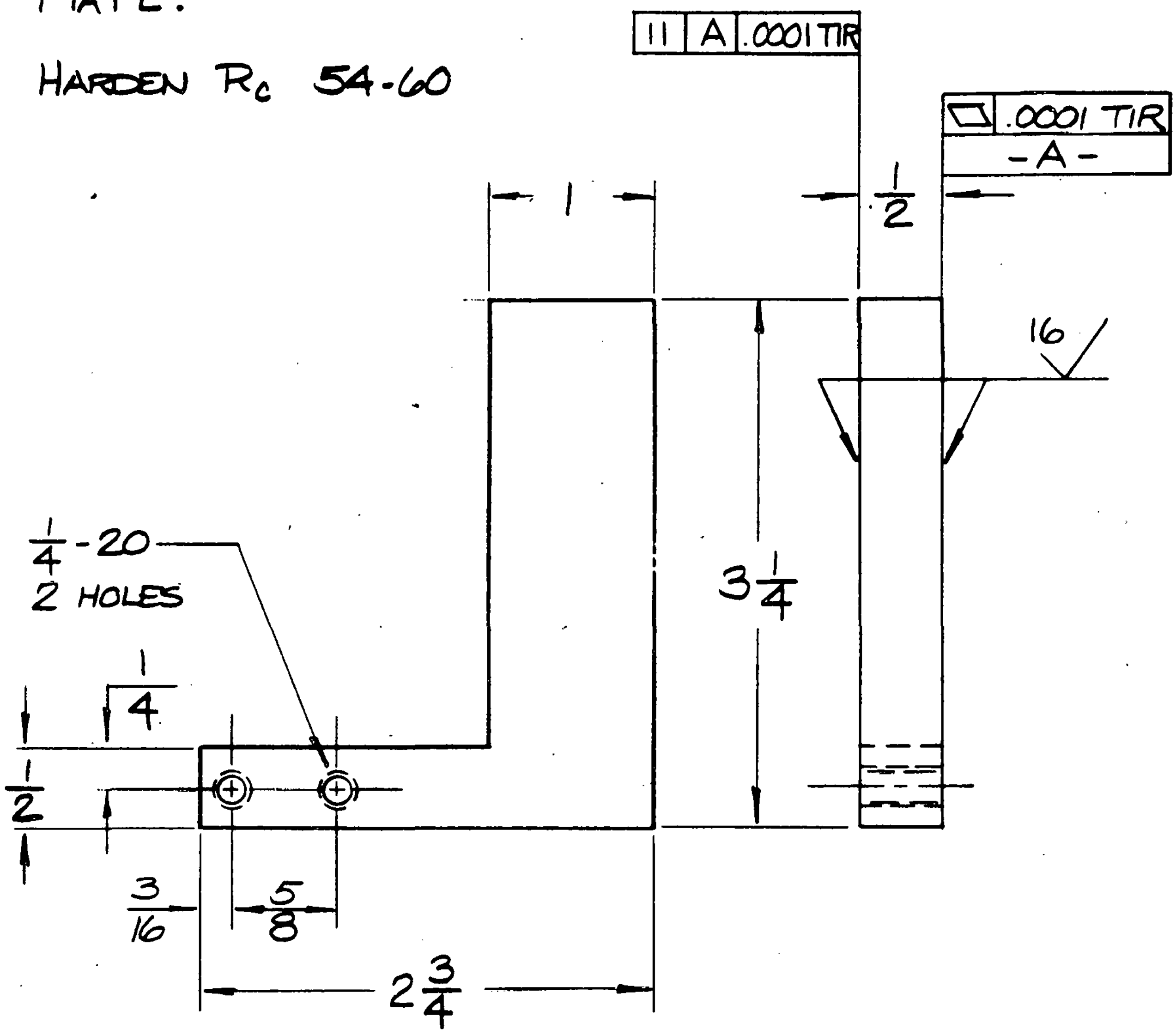
DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

A JPL-002

DO NOT SCALE DRAWING

MAT'L:

HARDEN R_c 54-60



DRAWN	DATE	APPROVED	DATE	CODE
SCH	3·8·76			
CHECKED	DATE	APPROVED	DATE	CLASS

END STOP GUAGE

NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ±

FIN. 63 √ DEC .X ± .XX ± .XXX ±

SCALE FULL

varian

VAC/LEX	A	JPL-002	
DIVISION	SIZE	DRAWING NO.	REV

DESCRIPTION OF CHANGE

NUM
EO
DFT
CHK
DATE
REV

LITHO IN U.S.A.

APPENDIX 2

- SLICING TEST: SPECIFICATION/SUMMARY
- SLICING TEST: OPERATION RECORD
- WAFER CHARACTERIZATION: THICKNESS MEASUREMENTS
  SURFACE PROFILE AND ROUGHNESS

SLICING OF SILICON INTO SHEET MATERIAL

VARIAN ASSOCIATES
LEXINGTON VACUUM DIVISION
JPL CONTRACT #954374

SLICING TEST: SPECIFICATION/SUMMARY

PAGE ____ of ____

Description: ____________________ Date: ____________________
Machine: ____________________
Operator: ____________________
Engineer: ____________________

Material: ____________________
Hardness: ____________________ Slice section: ____________________
Mounting details: ____________________

Blade package: ____________________
No. blades: ____________________ Tensioning: ____________________
Abrasive: ____________________
Vehicle: ____________________ Ratio: ____________________
Application: ____________________

Cutting speed: ____________________ Stroke: ____________________
Cutting force: ____________________ Blades cutting: ____________________
Pressure: ____________________ Balance: ____________________

Cutting time: ____________________ Actual: ____________________
Slice thickness: ____________________ Actual: ____________________
Kerf width: ____________________ Actual: ____________________
Tolerance: ____________________ Actual: ____________________
Worn blade: ____________________ Used: ____________________
Wear ratio: ____________________ Effectiveness: ____________________

Comments: ____________________

SCH 1/30/76

SLICING OF SILICON INTO SHEET MATERIAL

VARIAN ASSOCIATES
LEXINGTON VACUUM DIV.
JPL CONTRACT #954374

SLICING TEST: OPERATION RECORD
PAGE ____ of _____

DESCRIPTION: ____

____ OPERATOR: ____________

	TIME		SPEED	STROKE	BLADES	FEED WEIGHT		INDIC.	CUT	CUT	
DATE	OF DAY	ELAPSED	(RPM)	LENGTH	CUTTING	TOTAL	BLADE	READ.	DEPTH	RATE	COMMENTS

SCH 1/30/76

WAFER CHARACTERIZATION

THICKNESS MEASUREMENTS

Wafers produced in slicing tests will be measured for thickness at nine points according to a format given below. For each cutting test, a number of wafers will be selected for thickness characterization, and will be measured in a consistent format using the reference flat for orientation purposes. The thicknesses will be recorded on a standard form for each run (Wafer Measurements: Slicing Test). Statistical reductions of the data will be used for evaluation of a particular cutting test.

The following pages will be used for reference as the standard measurement technique:

1) Wafer Measurement: Statistics
2) Wafer Measurement: Terminology
3) Wafer Measurement: Statistical Format

SURFACE PROFILE AND ROUGHNESS

Representative wafers will be measured for surface profile using a Sloan Dek-Tak. The instrument is equipped with a range doubler, allowing a full scale measurement of 200 microns. Surface roughness (in micro-inches rms) will be measured using a Micrometrical type QC profilometer amplimeter and Type V Mototrace. The surface characteristics will be recorded on the form: Slicing Test: Surface Profile.

WAFER MEASUREMENT: STATISTICS

1) Measure each of n wafers at nine (9) points for thickness. Orient by reference flat as shown in "Wafer Measurement: Statistical Format".

$$X_{ij}\left|\begin{array}{l} i=1 \text{ to } n\\ j=1 \text{ to } 9\end{array}\right.$$

i = Number of wafer
j = Measurement position
n = Total number of wafers
X = Thickness in .0001 inches

2) For each wafer (i = constant):

$$\overline{X}_i = \frac{\sum_{j=1}^{9} X_{ij}}{9} \qquad \sigma_i = \frac{\left[\sum_{j=1}^{9} (X_{ij}-\overline{X}_i)^2\right]^{1/2}}{9}$$

$$\Delta X_i = (X_{ij})_{max} - (X_{ij})_{min}$$

3) For n wafers:

$$\overline{\overline{X}} = \frac{\sum_{i=1}^{n} \overline{X}_i}{n} \qquad \sigma_{\overline{\overline{X}}} = \frac{\left[\sum_{i=1}^{n} (\overline{X}_i - \overline{\overline{X}})^2\right]^{1/2}}{n}$$

$$\overline{\sigma} = \frac{\sum_{i=1}^{n} \sigma_i}{n} \qquad \sigma_{\overline{\sigma}} = \frac{\left[\sum_{i=1}^{n} (\sigma_i - \overline{\sigma})^2\right]^{1/2}}{n}$$

$$\overline{\Delta X} = \frac{\sum_{i=1}^{n} \Delta X_i}{n} \qquad \sigma_{\overline{\Delta X}} = \frac{\left[\sum_{i=1}^{n} (\Delta X_i - \overline{\Delta X})^2\right]^{1/2}}{n}$$

4) For n wafers (composite, j = constant):

$$\overline{X}_j{}^c = \frac{\sum_{i=1}^{n} X_{ij}}{n} \qquad \sigma_j{}^c = \frac{\left[\sum_{i=1}^{n} (X_{ij} - \overline{X}_j)^2\right]^{1/2}}{n}$$

WAFER MEASUREMENT: TERMINOLOGY

X_{ij} = Thickness of i^{th} wafer at the j^{th} measurement point.

$\bar{X}_i$ = Average thickness of the i^{th} wafer.

σ_i = Standard deviation of thickness of i^{th} wafer.

ΔX_i = Maximum difference in thickness of i^{th} wafer.

$\bar{\bar{X}}$ = Average of $\bar{X}_i$ for n wafers.

$\sigma_{\bar{\bar{X}}}$ = Standard deviation of average of $\bar{X}_i$.

$\overline{\Delta X}$ = Average of maximum thickness variation per wafer.

$\sigma_{\overline{\Delta X}}$ = Standard deviation of maximum thickness variation.

$\bar{\sigma}$ = Average of standard deviation of thickness for n wafers.

$\sigma_{\bar{\sigma}}$ = Standard deviation of $\bar{\sigma}$ for n wafers.

$\bar{X}_j^{c}$ = Average thickness of j^{th} point of measurement for n wafers (composite wafer thickness).

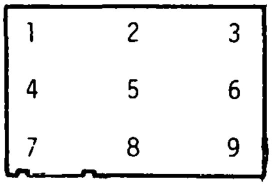
σ_j^{c} = Standard deviation of average thickness of j^{th} point for n wafers.

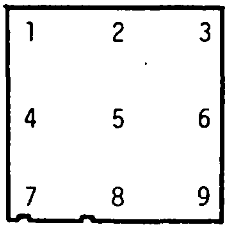
SLICING OF SILICON INTO SHEET MATERIAL

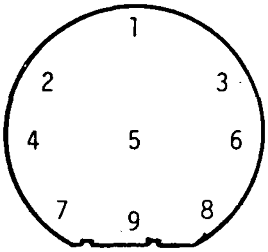
VARIAN ASSOCIATES
LEXINGTON VACUUM DIVISION
JPL CONTRACT #954374

SLICING TEST: WAFER MEASUREMENTS

PAGE 1 of 1







Description: STATISTICAL FORMAT

Date: By: SCH 2/12/76

Comments:

NO.	1	2	3	4	5	6	7	8	9	Δ	$\bar{t}$	σ
1	x_{11}	x_{12}	x_{13}	→	→	→	→	x_{18}	x_{19}	Δx_1	$\bar{x}_1$	σ_1
2	x_{21}								↓	Δx_2	$\bar{x}_2$	σ_2
3	x_{31}								↓	↓	↓	↓
↓	↓								↓	↓	↓	↓
↓	↓								↓	↓	↓	↓
↓	↓								↓	↓	↓	↓
i	x_{i1}	→	→	→	→	→	→	→	x_{i9}	Δx_i	$\bar{x}_i$	σ_i
↓	↓								↓	↓	↓	↓
↓	↓								↓	↓	↓	↓
↓	↓								↓	↓	↓	↓
↓	↓								↓	↓	↓	↓
n	x_{n1}	→	→	→	→	→	→	→	x_{n9}	Δx_n	$\bar{x}_n$	σ_n
$\bar{t}$	$\bar{x}_1^c$	$\bar{x}_2^c$	→	→	→	→	→	→	$\bar{x}_9^c$	$\overline{\Delta x}$	$\bar{\bar{x}}$	$\bar{\sigma}$
σ	σ_1^c	σ_2^c	→	→	→	→	→	→	σ_9^c	$\sigma_{\overline{\Delta x}}$	$\sigma_{\bar{\bar{x}}}$	$\sigma_{\bar{\sigma}}$

SCH 1/30/76

SLICING OF SILICON INTO SHEET MATERIAL

VARIAN ASSOCIATES
LEXINGTON VACUUM DIVISION
JPL CONTRACT #954374

SLICING TEST: SURFACE PROFILE

PAGE ____ of ____

DESCRIPTION: ____________________

DATE: ____________________ BY: ____________________

COMMENTS: ____________________

WAFER:							
TRACE:							
VERT (FS):							
HORIZ MAG:							
FILTER:							
RANGE:							
BOW:							
TAPER:							
ROUGHNESS:							
SCALE:							
ROUGHNESS:							
SCALE:							
ROUGHNESS:							
SCALE:							
STEPS:							