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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 Quarterly Report, January 9, 1976–March 21, 1976

S. C. Holden

March 29, 1976

Work performed under contract No. NAS7-100

Lexington Vacuum Division
Varian Associates
Lexington, Massachusetts

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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FIRST QUARTERLY REPORT

By

S. C. Holden

March 29, 1976

Reporting Period January 9, 1976 to March 21, 1976

JPL Contract No. 954374

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

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1.0 SUMMARY

Slurry sawing is a difficult to control abrasive wear process. In order to achieve the broad program goal of low cost slicing of silicon into solar cell wafers, the process must first be clearly understood and then techniques developed to allow more controllability and higher productivity.

The theory of abrasive wear is presented to judge the efficiency of the slurry process relative to other documented forms of abrasive wear. The cutting rate of slurry sawing is related to load, kerf area, work material hardness and reciprocation speed. An explanation for the high efficiency of slurry sawing is offered in terms of binding forces on abrasive particles and the abrasive wear of brittle materials.

Results of five cutting tests are given in which kerf length is 3.88 inches and .984 inch, and cutting loads are varied from two ounces to eight ounces per blade. Reduction of cutting rate to the normalized cutting efficiency, $\bar{\varepsilon}$, shows the accuracy of the theory. The efficiency ranged from 1.13 to .86. The lower efficiencies occurred at high loads and short kerf length.

Thickness measurements show a decrease in wafer accuracy with increasing cutting load and speed. Plans for the next three months of activity are given.

2.0 INTRODUCTION

In the multiblade slurry sawing process, a multitude of evenly spaced, highly tensioned blades are reciprocated across a work piece in a bladehead frame. The work is fed upward through the reciprocating blades and loose abrasive particles, typically suspended in an oil slurry, are dripped into the cutting interface. Abrasive wear causes the blades to wear away work material until only wafers of the starting material are remaining between the blades.

The alignment of many blades in an accurate configuration, the feed, reciprocation and tensioning mechanisms are critical to the ultimate accuracy of the wafers produced in the process. However, these are not the most critical problems to consider in order to increase the productivity of the process.

The goal of this program is to investigate the low-cost slicing of bulk silicon into wafers suitable for fabrication in solar cells. The ultimate limitations of the process will be the tradeoff of cutting rate (productivity) and wafer accuracy, thickness, and size; and the useful lifetime (cost) of expendable items (blade packages, abrasive, etc.).

The process is difficult to control externally. Loose abrasive particles must be picked up by the blades, dragged across work material and perform an efficient cutting action. The blades wear out; they are driven off course if they do not cut as effectively as the rest; and any deviation from proper cutting action by one blade causes two wafers to be ruined. The major emphasis of the first half of this contract effort will be to identify how to control this process in order to allow maximum productivity.

In order to control the cutting process, one must first understand the mode of operation that occurs in the area between the blades and work material.

The first experiments have been completed and certain aspects of the cutting mechanism of slurry sawing have been identified.

3.0 TECHNICAL DISCUSSION

3.1 Abrasive Wear

The theory of abrasive wear has been considered in the literature.[1] Figure 1 shows schematically the assumptions of the theory. An abrasive particle is assumed to be a conical indenter described by an angle θ. Under a small load ΔL, the indenter generates a contact area related to the load and to the work material hardness, p.

$$\pi r^2 = \frac{\Delta L}{p} \tag{1}$$

The indenter has a projected area beneath the surface given by equation (1) and the angle θ.

$$A_p = r\,x = r^2 \tan\theta \tag{2}$$

If the indenter is moved laterally by an amount $d\ell$, the volume swept by the indenter is given by

$$dV/_{d\ell} = A_p = \frac{\Delta L \tan\theta}{\pi\, p} \tag{3}$$

Equation (3) is the idealized removal rate of work material by a single indenter. Many indenters fixed to the same moving carrier, under a total indentation force L will result in a volume of work material removal given by

$$dV/_{d\ell} = \frac{L\,\overline{\tan\theta}}{\pi\, p} \tag{4}$$

where $\overline{\tan\theta}$ is an average indenter geometry. The rate of work material removal is proportional to the normal force L , the relative sliding distance $d\ell$, and is inversely proportional to the work material hardness p . The average indenter geometry, $\overline{\tan\theta}$, can also be considered as a measure of efficiency of the abrasive system. The

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[1] Ernest Rabinowicz, Friction and Wear of Materials, John Wiley & Sons, Inc., New York (1965).

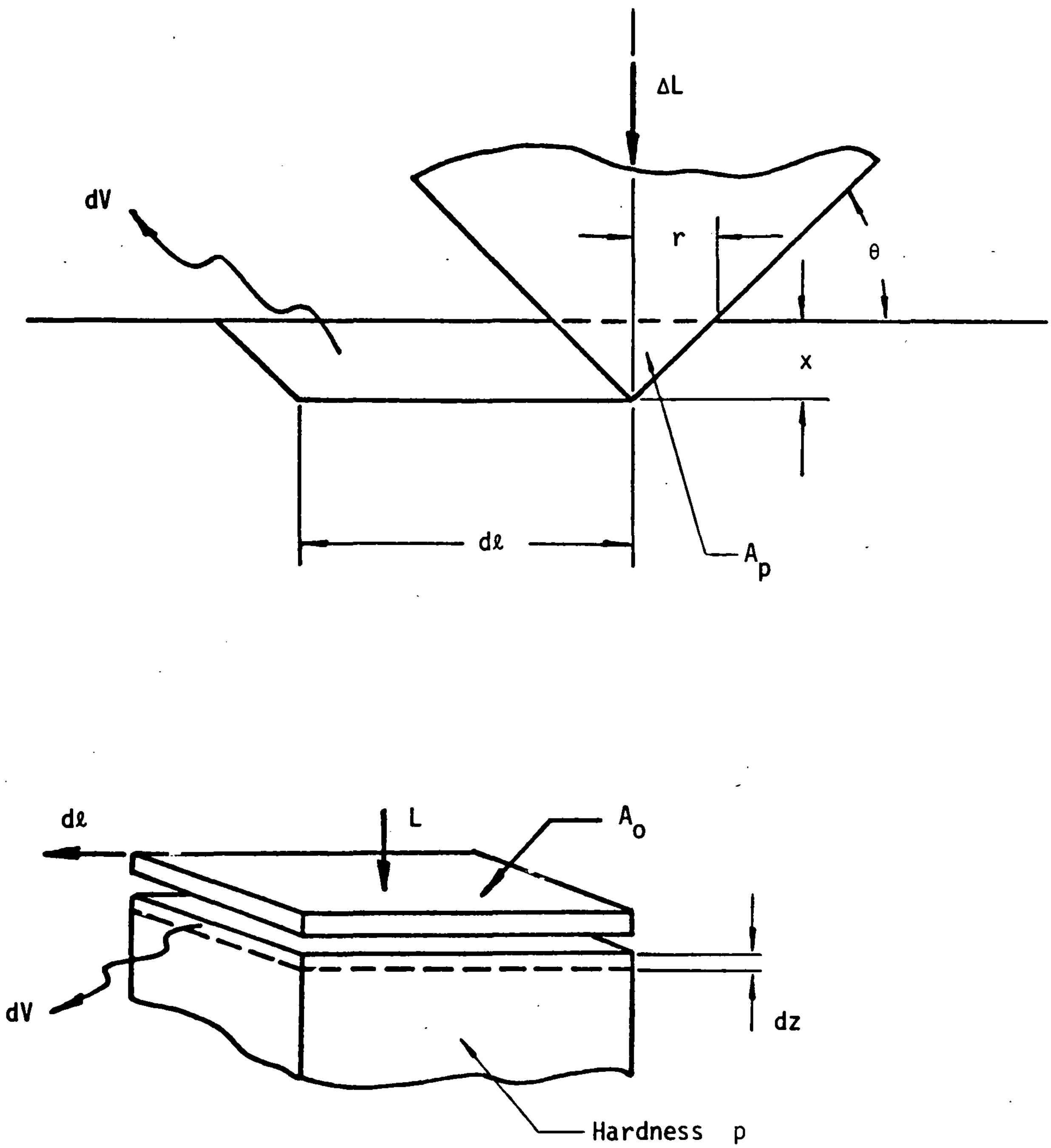


FIGURE 1

GEOMETRIES FOR ABRASIVE WEAR

significance of cutting efficiency will be considered in more detail later.

In planar abrasive wear, the cutting rate, dz/dt , can be calculated if the value of $\overline{\tan\theta}$ for the abrasive system is known.

$$\frac{dz}{dt} = \frac{L\ \overline{\tan\theta}}{\pi\ p} \left(\frac{d\ell}{dt} \right) \frac{1}{A_0} \qquad (5)$$

The downward cutting rate is related to the relative speed of the abrasive system ($d\ell/dt$), and the area of contact A_0. The rate, dz/dt can also be related to the cutting pressure L/A_0.

3.2 Abrasive Wear of Non-Planar Surfaces

In multiblade slurry sawing, the shape of the wear trough is similar to that shown in Figure 2. In the previous consideration, the applied load L was normal to the wearing surface, and thus was the only load driving abrasive particles into the work surface. In the wafering process, the indentation of particles can occur partly by a wedging process. The result can be a higher cutting rate than that predicted by the Equation (5). The normal load L is not the work producing force, so energy balance considerations do not apply. They would hold true, however, if the horizontal force were considered.

In a localized area dx, the indentation forces can be considered as normal to the surface in the trough. Using Equation (5) in a pressure form, the normal cutting rate can be given by

$$\frac{dz_n}{dt} = \frac{p_n \overline{\tan\theta}}{\pi p} \left[d\ell/dt \right] \qquad (6)$$

where p_n is the normal pressure acting on the abrasive particles indenting the surface and is equivalent to L/A_0 in Equation (5).

A necessary condition of the assumed geometry is that the surface profile is stable in time and that the normal cutting rate is given by

$$\frac{dz_n}{dt} = \cos\alpha \frac{dz}{dt} \qquad (7)$$

The vertical component of the indentation force must be supplied by the total vertical cutting force L.

$$P_v \, dx = P_n \, dx_n \cos\alpha \qquad (8)$$

or

$$P_v = P_n$$

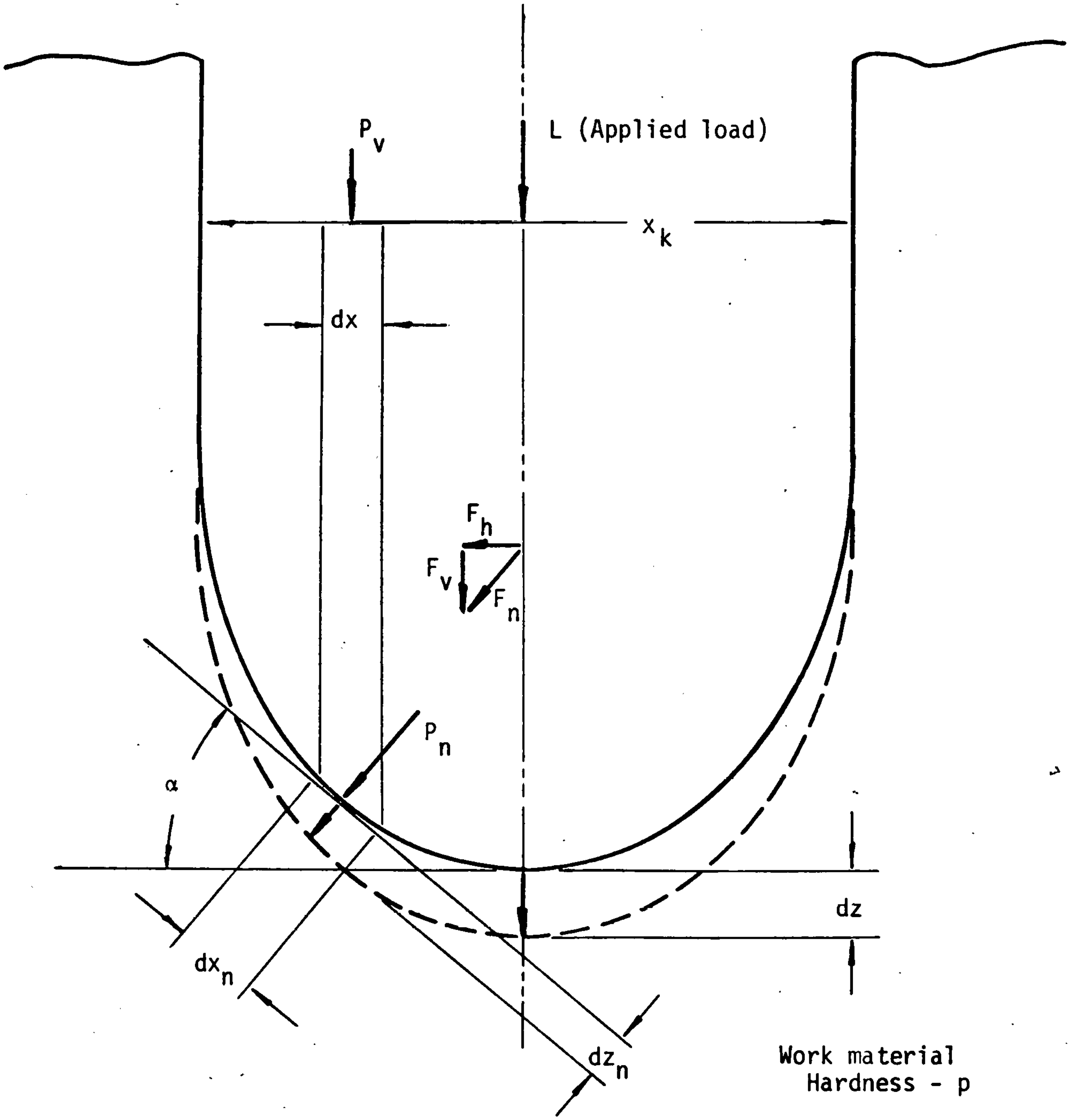


FIGURE 2

ABRASIVE WEAR OF NON-PLANAR SURFACES

The distribution of normal cutting pressure can be evaluated by combining Equations (6), (7), and (8).

$$p_n = \frac{\pi p}{\tan\theta} \left(\frac{dt}{d\ell} \right) \frac{dz}{dt} \cos\alpha \tag{9}$$

The applied load per unit depth, y_o, is given by

$$\frac{L}{y_o} = \frac{\pi p}{\tan\theta} \left(\frac{dt}{d\ell} \right) \left(\frac{dz}{dt} \right) 2 \int_o^{x_K/2} \cos\alpha \, dx \tag{10}$$

or, expressing Equation (10) in the form of Equation (5)

$$\frac{dz}{dt} = \frac{L \bar{\varepsilon}}{\pi p} \left(\frac{d\ell}{dt} \right) \frac{1}{A_o} \tag{11}$$

The cutting rate can be estimated for non-planar surfaces. However, the shape of the surface dictates the degree of binding force that contributes to the abrasive wear process. The efficiency of abrasive sawing is compared to the efficiency of planar abrasive wear by

$$\bar{\varepsilon} = \frac{\overline{\tan\theta}}{\frac{2}{x_k} \int_o^{\frac{x_k}{2}} \cos\alpha \, dx} \tag{12}$$

The area of a single blade's contact is given by the kerf width x_k and the kerf length y_m.

$$A_o = x_k \cdot y_m \tag{13}$$

As a measure of how much the binding effect could increase the apparent cutting rate of Equation (5), consider the efficiency of slurry sawing with a flat bottomed trough ($\alpha = 0$) a semicircular trough ($\alpha = \mathrm{Sin}^{-1} 2x/x_k$),

$$\bar{\varepsilon} = \overline{\tan\theta} \qquad \text{(flat bottom)}$$

$$\bar{\varepsilon} = 1.27\ \overline{\tan\theta} \qquad \text{(semicircular)} \tag{14}$$

It is apparent that a trough with steep sides and little flat bottom requires less applied load to generate the same cutting rate since the magnitude of wedging of abrasives is higher. Equation (11) has been used to judge the effectiveness of slurry sawing. However, Equation (12) will be used to judge slurry sawing in comparison with planar abrasive wear.

3.3 Cutting Efficiency

All of the parameters of Equation (11) can be measured in multi-blade slurry sawing, except for $\overline{\varepsilon}$, the efficiency. The efficiency has significance in the mechanism of cutting that occurs in the slurry sawing process.

Two abrasive wear mechanisms have been characterized in the literature. When abrasive particles are bonded to the cutting medium (for example, abrasive paper), only the work material is worn away and the process is called two-body abrasion. The second process occurs when loose abrasive is introduced between two sliding bodies. In three-body abrasion, both surfaces are abraded and the cutting rates are an order of magnitude lower than with two-body abrasion. This occurs due to the amount of time an abrasive particle supports load by rolling.

The efficiency of planar abrasion is assumed to originate from the cutting geometry of abrasive points. Many points will not be in a cutting configuration, lying with flat surfaces downward, and only a few abrasive grains will perform efficiently. Thus, $\overline{\tan\theta}$ is a necessary average of all cutting points, some of which cut, and some of which support load without cutting.

In three-body abrasion, the rolling of abrasive particles supports the applied normal load, penetration of abrasive particles rarely occurs, and the wear rate of both surfaces depends on the hardness of each.

Slurry sawing occurs by a process which can be easily compared with lapping. In order to avoid rolling of the loose abrasive, the blade material must be softer than the work material. The abrasive must be able to imbed into the blades for a sufficient period of time and act as a fixed particle. There is a practical limitation to how soft a blade may be, since the ability to tension a blade governs its stability in cutting. Consequently a blade should be chosen in order to be just soft enough in comparison with the work material to allow the two-body abrasion process to occur, but not so much that blade stability is sacrificed. If a blade is too hard, the abrasive will indent both surfaces equally, rolling will occur, low cutting rates and high rates of blade wear will result. This has been observed in the cutting of stainless steels with hardened steel blades.

The highest efficiencies of abrasive wear are .20 in the literature. Efficiencies a factor of ten lower are reported for three-body abrasion. Efficiencies of 1.00 are not uncommon in slurry sawing. This indicates that the utilization of abrasive is very effective. The higher efficiency is partly due to the wedging effect discussed previously. The brittle nature of typical work materials could cause larger volume removal than the swept volume of an indenter, and consequently a higher efficiency than with more common ductile work materials. It should be noted that efficiency, as defined for slurry sawing, can achieve values higher than unity.

4.0 EXPERIMENTAL RESULTS

The first stage of cutting tests is aimed at viewing the parameter performance of slurry sawing. Once the basics of the process is understood, it will be possible to logically identify how process cost reductions can best be achieved.

A modified Varian Model 686 Wafering Machine was set up, measured for critical alignment accuracies, and is being used to run a series of standardized cutting experiments. Blade packages, abrasives, and slurry application technique were standardized with currently used configurations and techniques.

The first cut performed was with a 4 inch diameter piece of silicon damaged in a grinding process. This was used as a general point of reference.

The next four cutting tests used standardized blocks of silicon, and the cutting force per blade was varied. The cutting rate, machine operating speed, cutting force and other information are measured in each cutting test. Using Equation (11), the cutting efficiency was determined. The sliding distance is a function of stroke length and rate and is calculated to ignore differences in both parameters during the test. The results are plotted in Figures 3 to 7.

It can be seen that the cutting rate in each test builds up slowly to a maximum level. This peak rate occurs only when the loose abrasive is able to imbed the blades and maintain two-body abrasion. Three-body abrasion seems to take during the period that blade conditioning occurs. This conditioning stage must be understood, since it is a period during which low cutting rates and high blade wear occur. Shortening it will help to increase productivity and useful blade life.

The results shown in the Figures seem to indicate a decrease in efficiency at a load of six ounces per blade. This may be due to the short 25 mm kerf length (higher cutting pressure) or the different kerf width and trough shape.

The cutting rates of silicon for all tests did follow the general trends of Equation (11), and the linearity of cutting rate with load is evident.

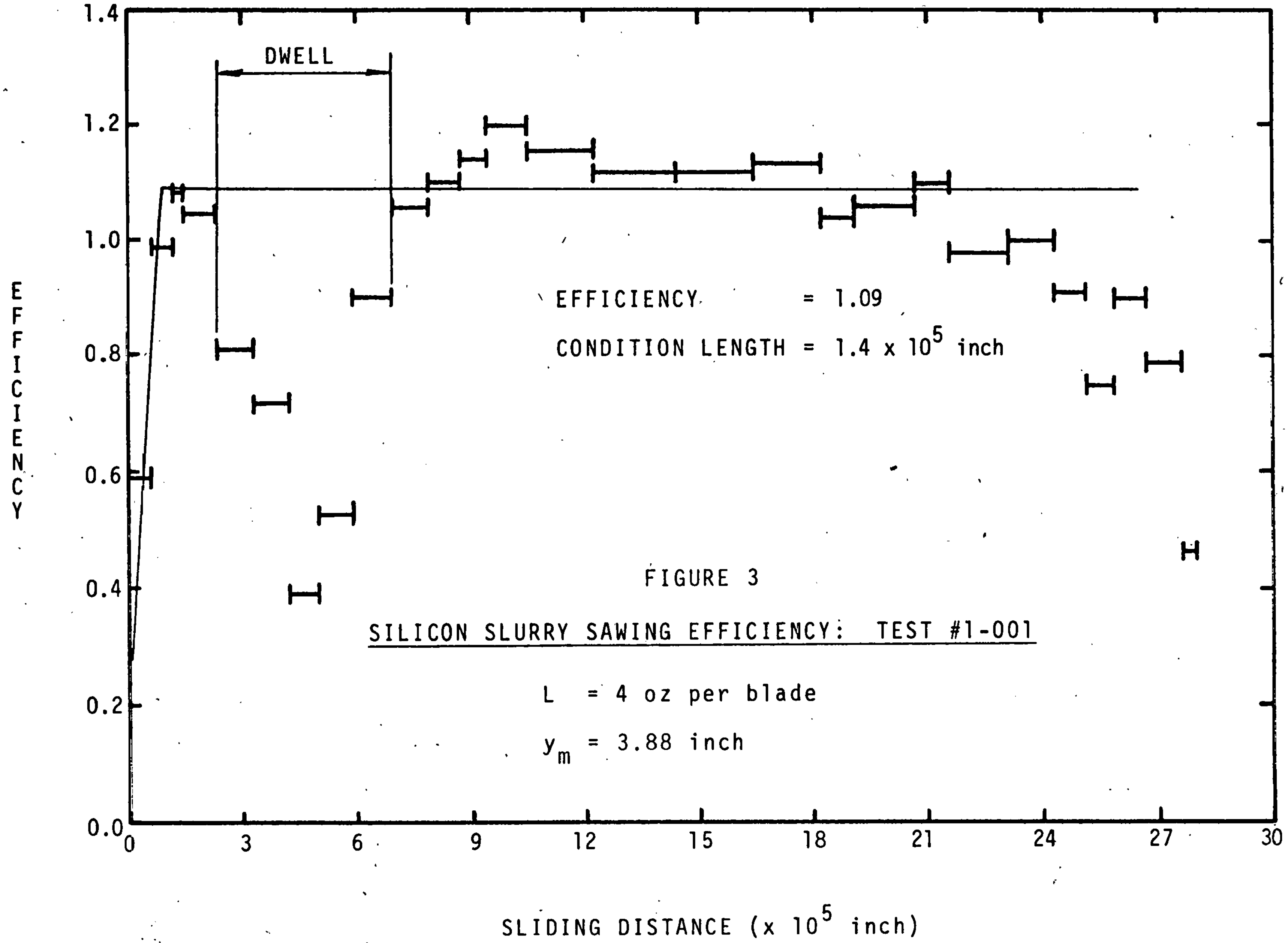


FIGURE 3

SILICON SLURRY SAWING EFFICIENCY: TEST #1-001

L = 4 oz per blade

y_m = 3.88 inch

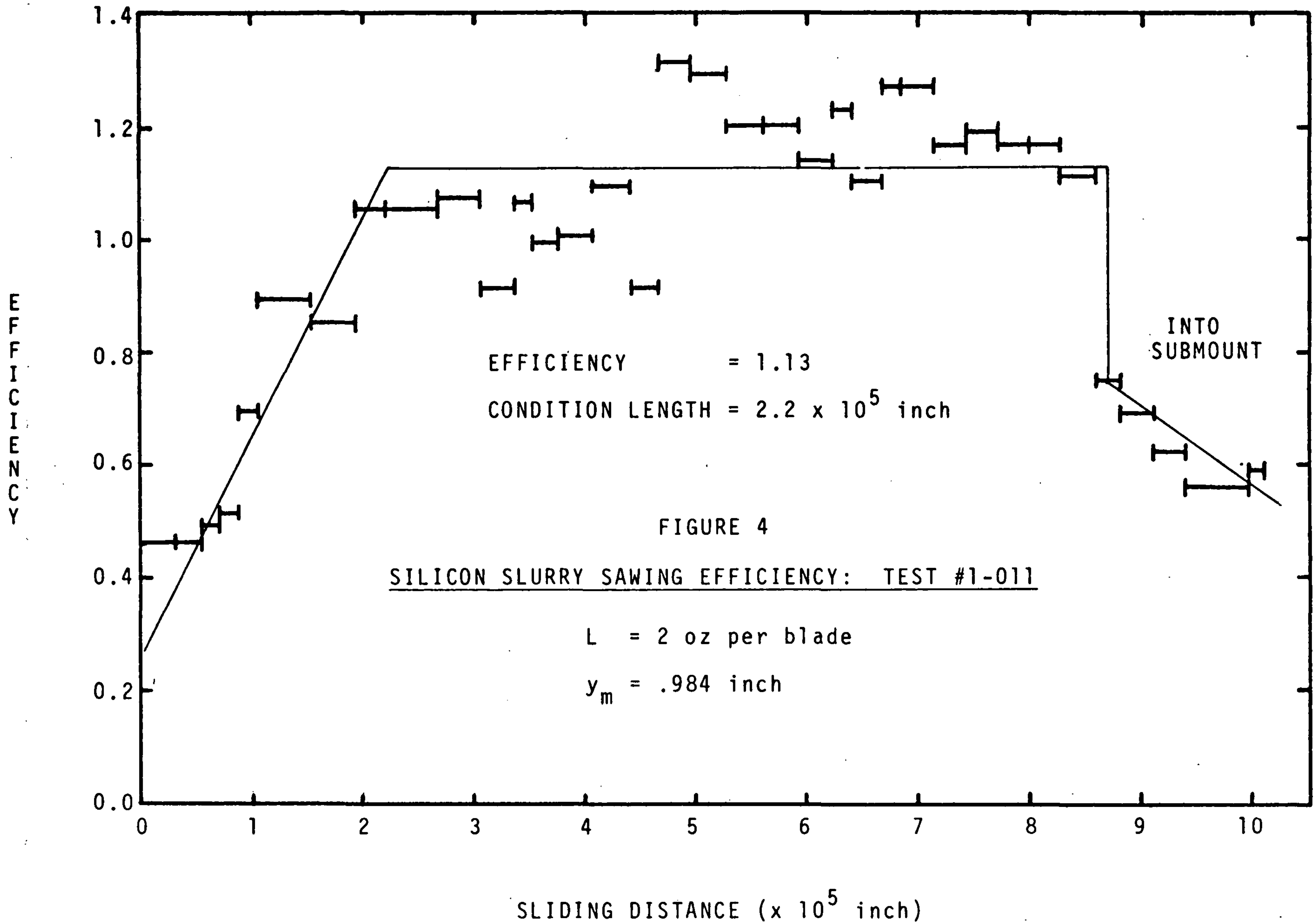


FIGURE 4

SILICON SLURRY SAWING EFFICIENCY: TEST #1-011

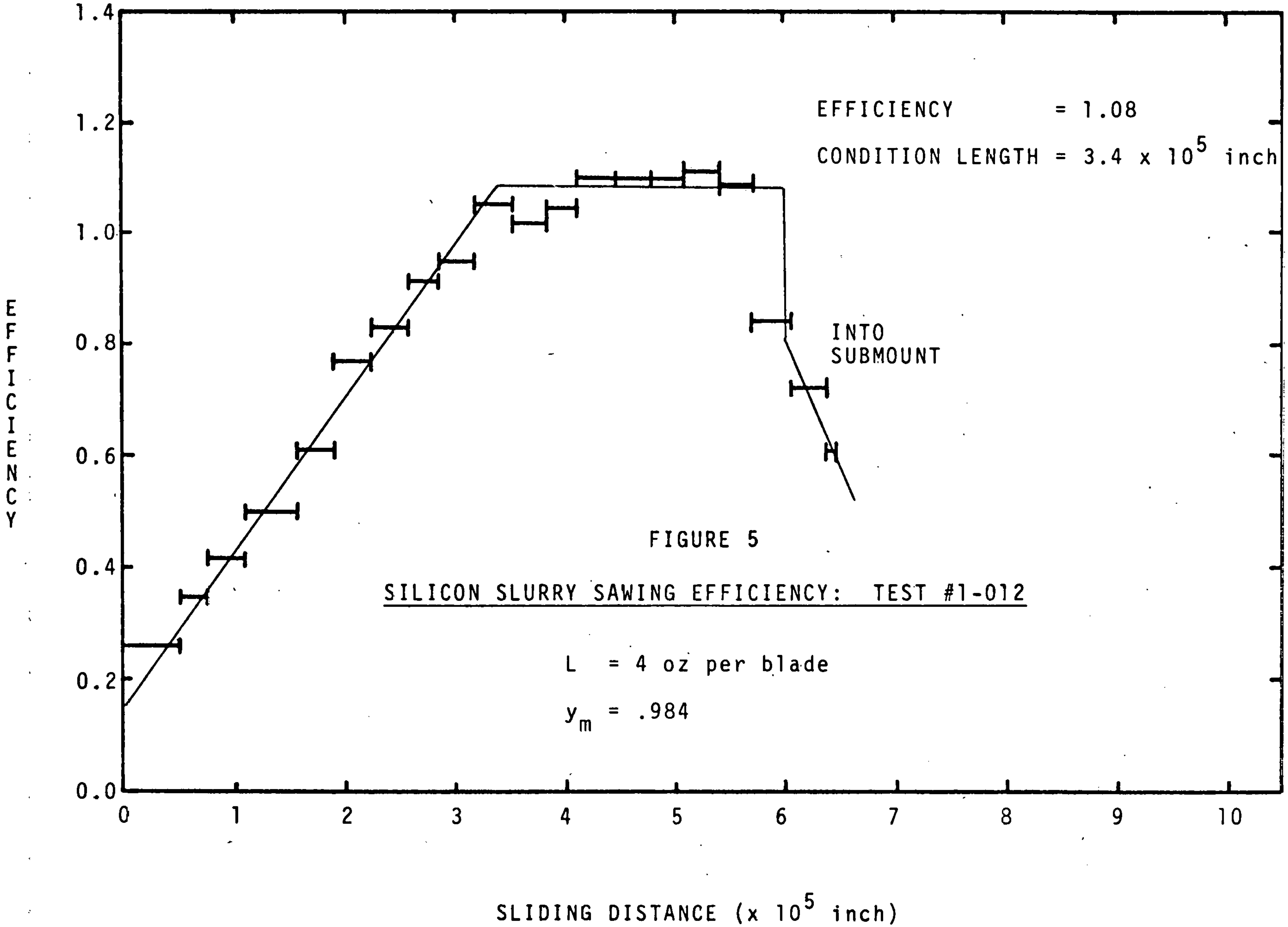


FIGURE 5

SILICON SLURRY SAWING EFFICIENCY: TEST #1-012

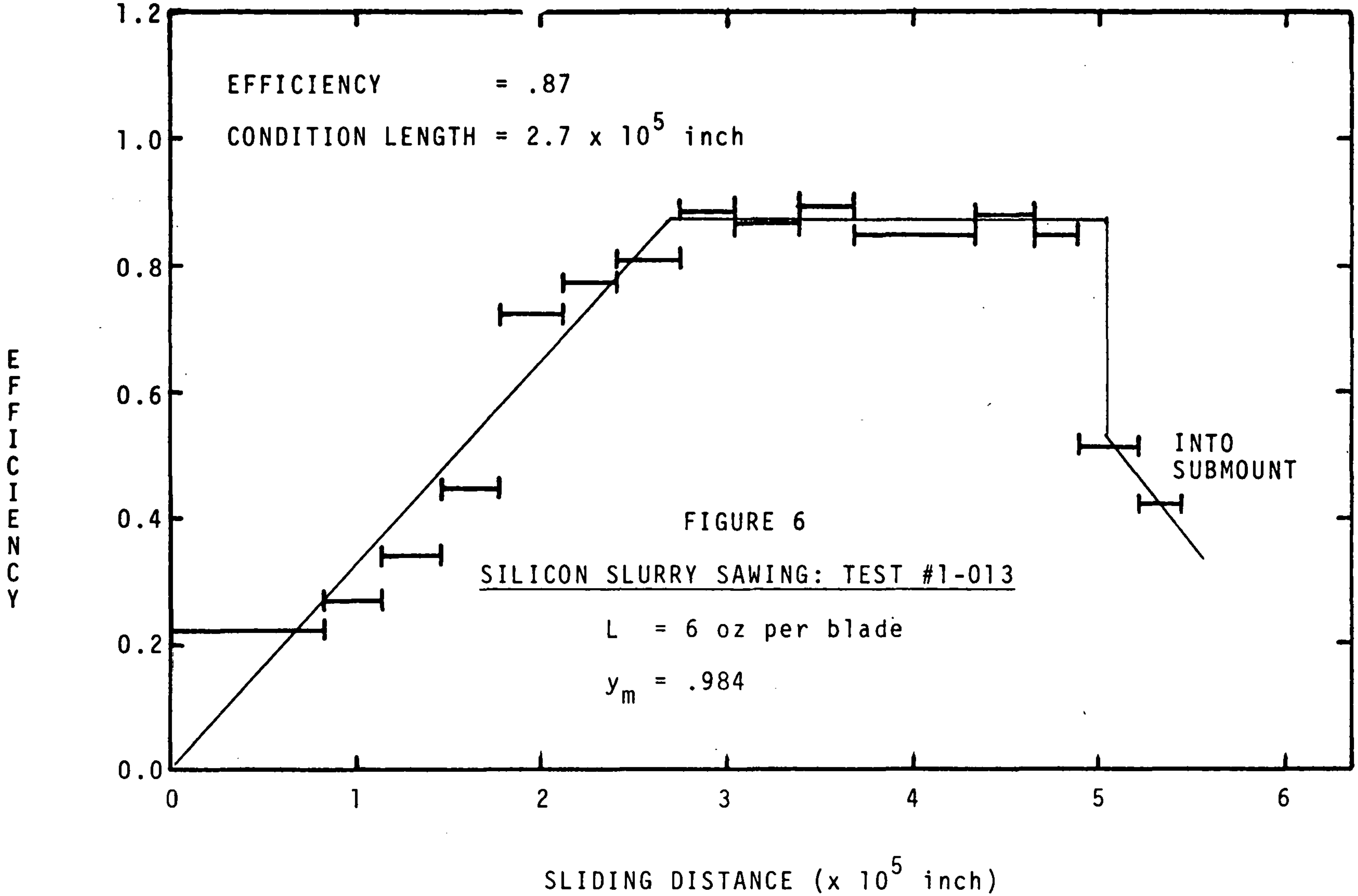


FIGURE 6

SILICON SLURRY SAWING: TEST #1-013

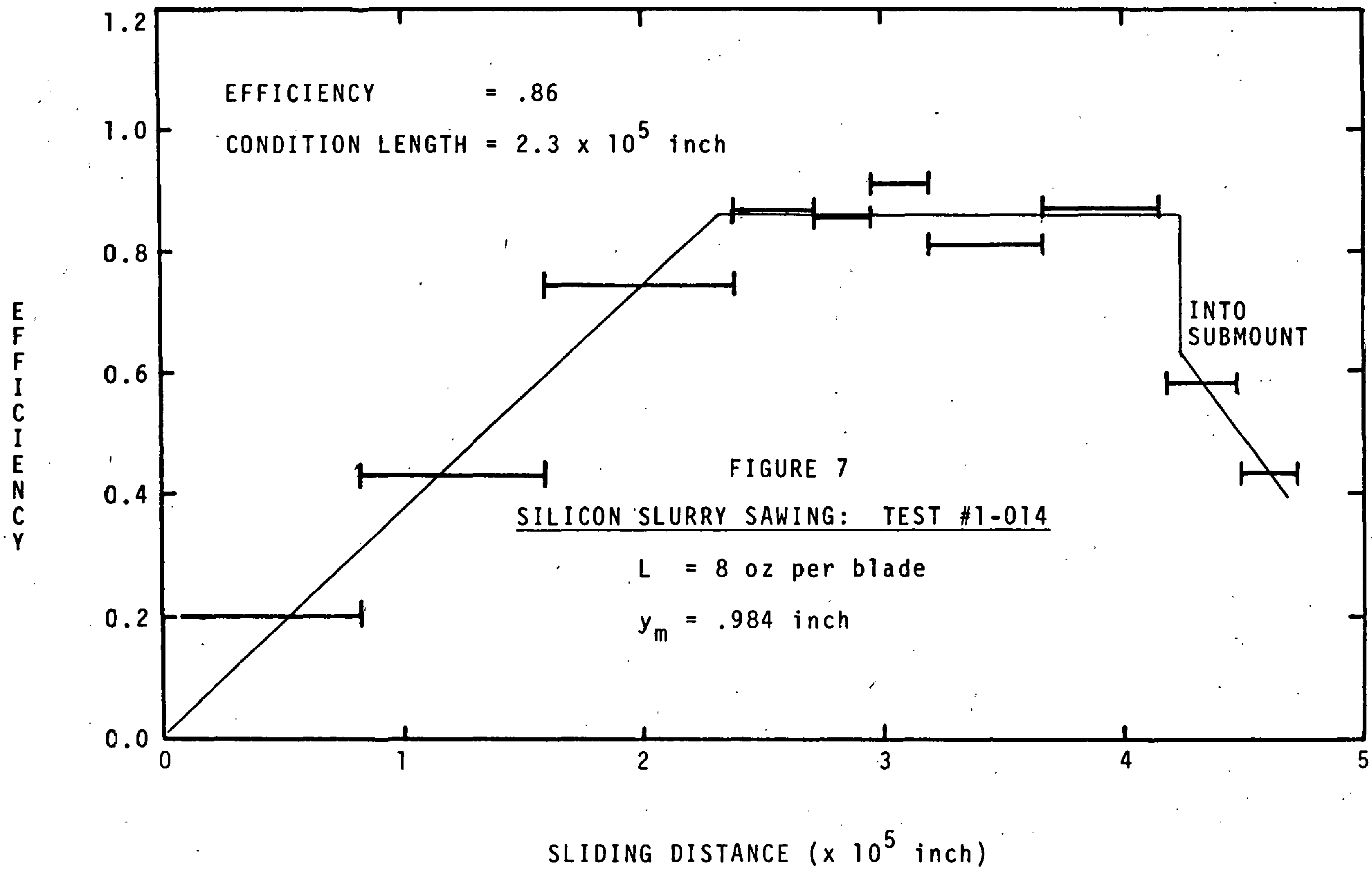


FIGURE 7

SILICON SLURRY SAWING: TEST #1-014

L = 8 oz per blade

y_m = .984 inch

5.0 CHARACTERIZATION DATA

For the early cutting tests, the only characterization data will be thickness measurements of a sampling of the wafers resulting from each run. From the first five tests, twenty to thirty wafers were measured at nine points and the dimensions recorded on standard forms

The results are reduced statistically in various ways to indicate the nature and cause of wafer accuracy. Table 1 shows a summary of the conditions and results of the five tests performed. The average of the total dimensional variation of each wafer, the average wafer thickness and the standard deviation of average wafer thickness are all recorded in Table 1.

The accuracy of resulting wafers decays as the applied load is increased. This is mostly based on the stability of blades, but data is too limited to draw any overall conclusions.

TABLE 1

SUMMARY OF CHARACTERIZATION DATA

PARAMETER	SLURRY SAWING TEST #1-001	#1-011	#1-012	#1-013	#1-014
Load (oz/blade)	4	2	4	6	8
Kerf Length (inch)	3.88	.984	.984	.984	.984
Material	111 Silicon				
Abrasive	#600 SiC				
Blade Thickness	.008				
Spacer Thickness	.025				
Average Wafer Thickness	.02226	.02170	.02102	.02113	.01978
Average Kerf Loss	.01074	.01130	.01198	.01187	.01322
Standard Deviation of Thickness	.00127	.00076	.00229	.00165	.00335
Average Total Wafer Variation	.00080	.00066	.00177	.00240	.00334

6.0 CONCLUSIONS AND RECOMMENDATIONS

Cutting rate has been shown to be linear with cutting force per blade in slurry sawing of silicon. The slurry sawing process has been shown to utilize an efficient form of two-body abrasion, based on comparisons with planar abrasive wear. Wafer accuracy improves as cutting force per blade, and consequently cutting rate, decreases.

7.0 PROJECTION OF ACTIVITY

For the next three months, plans for this contract effort are:

1. Complete parameterization tests of slurry sawing, considering variations in blade size, abrasive and kerf length.
2. Extend the theory of slurry sawing to show limits of validity of the basic theory and a preliminary analysis of wafer accuracy.
3. Characterize the difference in slicing of ⟨111⟩ and ⟨100⟩ orientation silicon (based on anisotropy).
4. Complete feedback system to form vertical feed cutting force control system.
5. Establish roughness and damage characterization procedures on relevant slicing tests.

APPENDIX

- New Technology
- Man-Hours and Costs
- Program Plan (Updated)
- Engineering Sketches
  - Reference Flat - Silicon
  - End Stop Gauge

NEW TECHNOLOGY

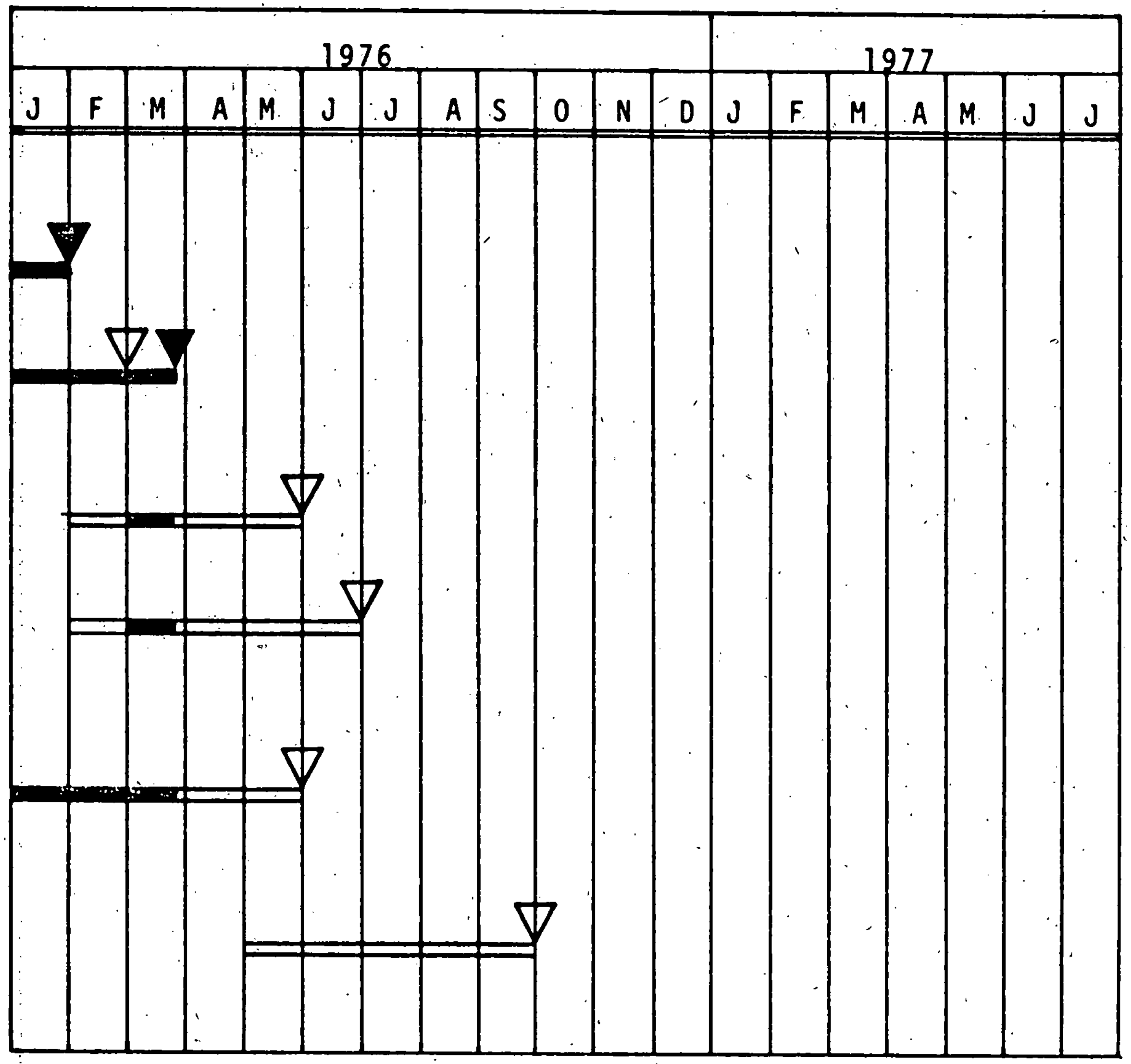
There was no new technology developed during the reporting period.

MAN-HOURS AND COSTS

During the reporting period of January 9, 1976 to March 21, 1976, the man-hours for this contract totalled 479.0 hours, and the costs were $11,171. There were no expenditures prior to January 9, 1976.

SLICING OF SILICON INTO SHEET MATERIALS

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



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.

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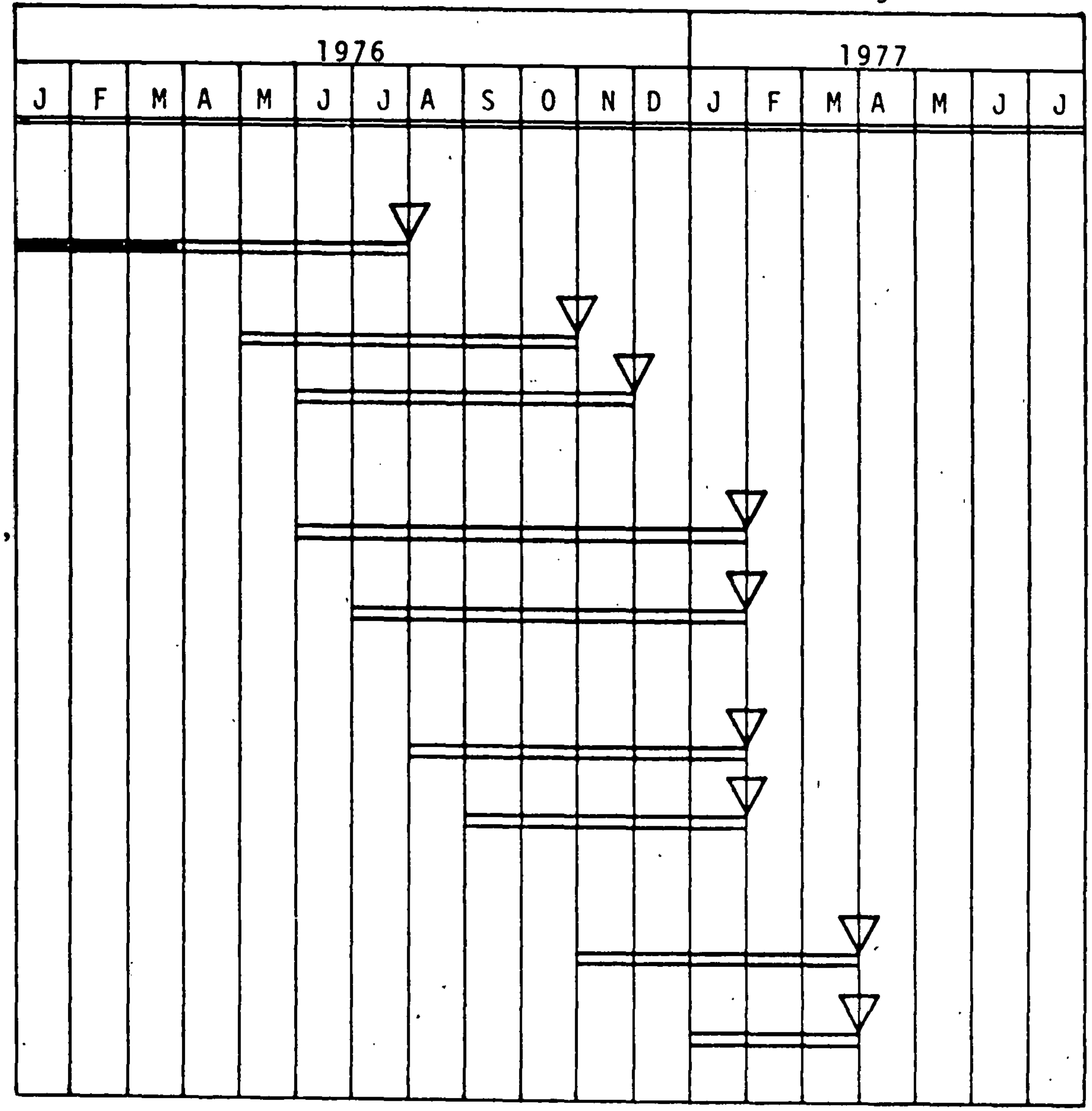
3. Load Balancing
   - 3.1. Build feedback control system - rate and force interaction
   - 3.2. Cutting performance vs. results of 1.3.
   - 3.3. Wafer characterization
4. Blade Materials
   - 4.1. Cutting tests - optimum blade material, thickness, etc. for silicon
   - 4.2. Wafer characterization
5.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



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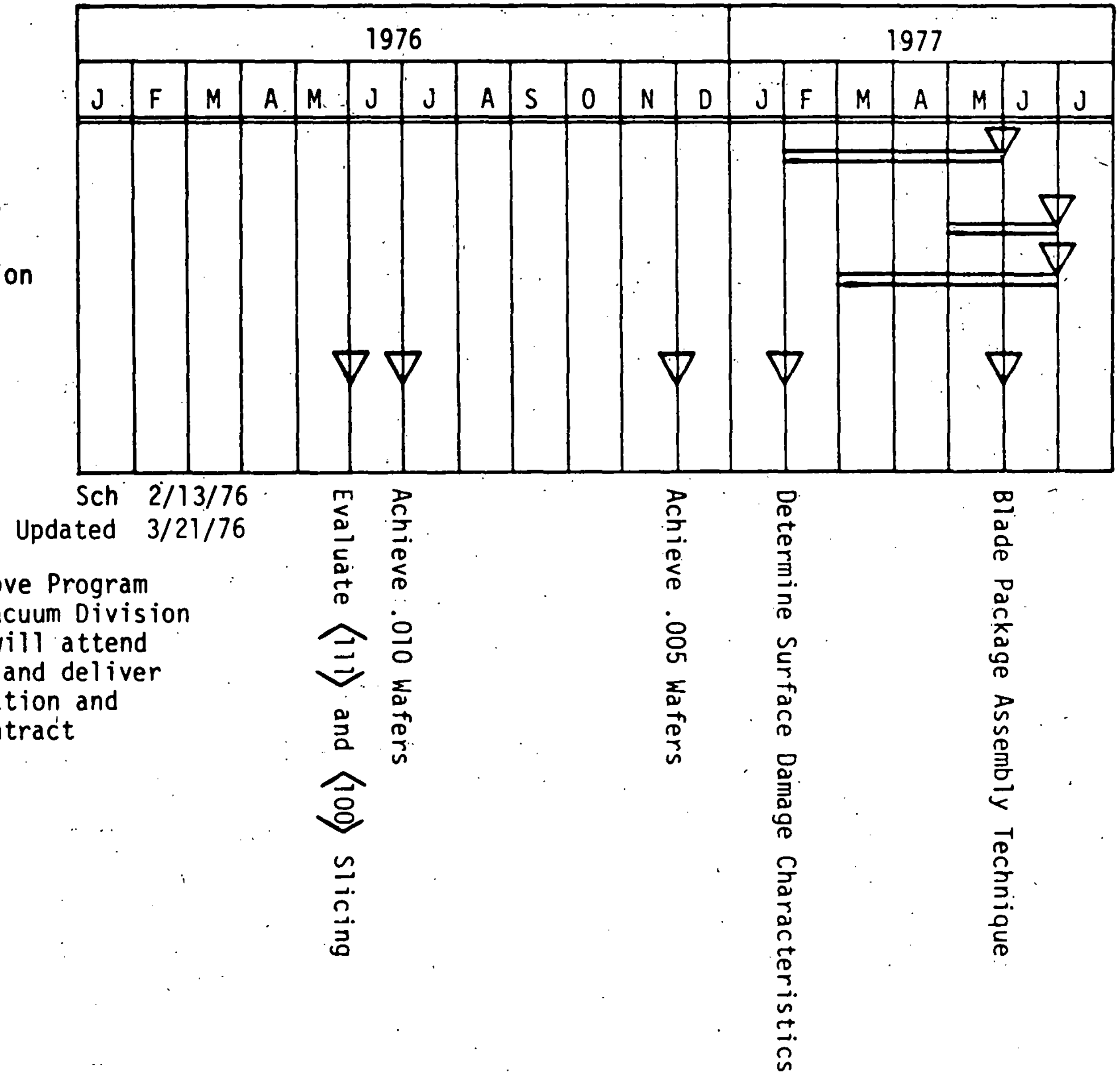
7. Evaluation
   - 7.1. Cutting tests with final system
   - 7.2. Economic evaluation, scale-up potential
   - 7.3. Wafer characterization

8. Milestones



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
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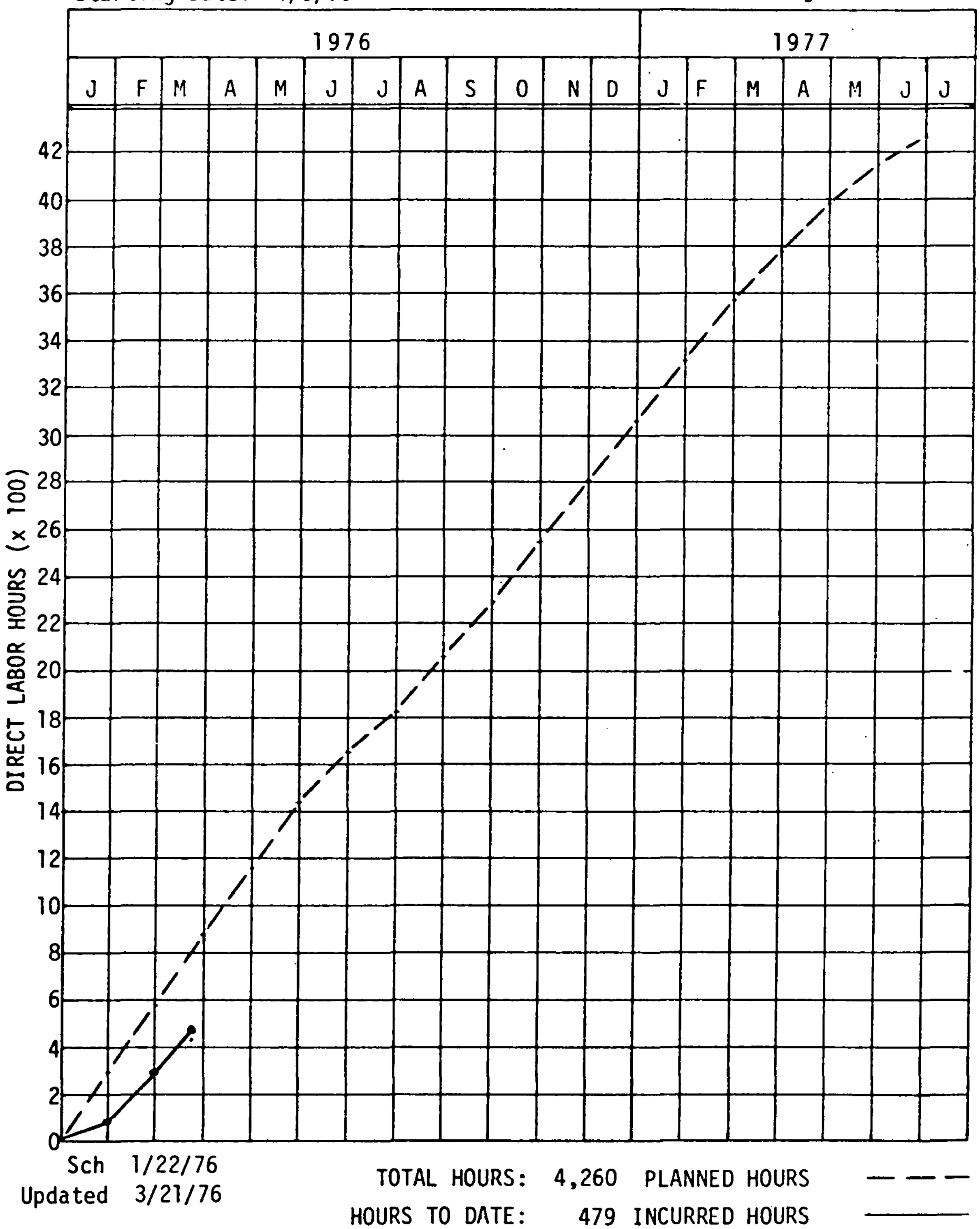

PROGRAM LABOR SUMMARY

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

Program Plan
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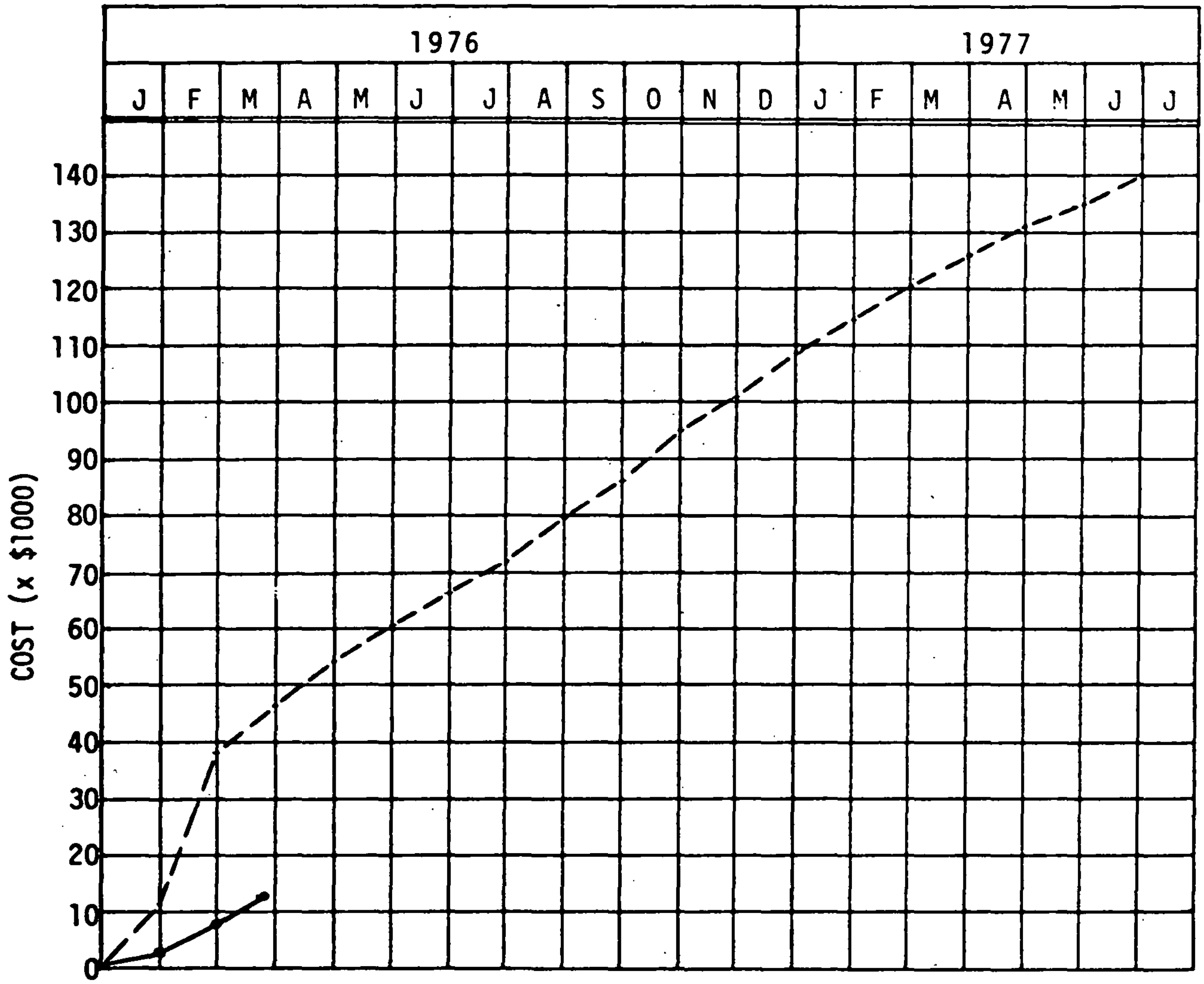

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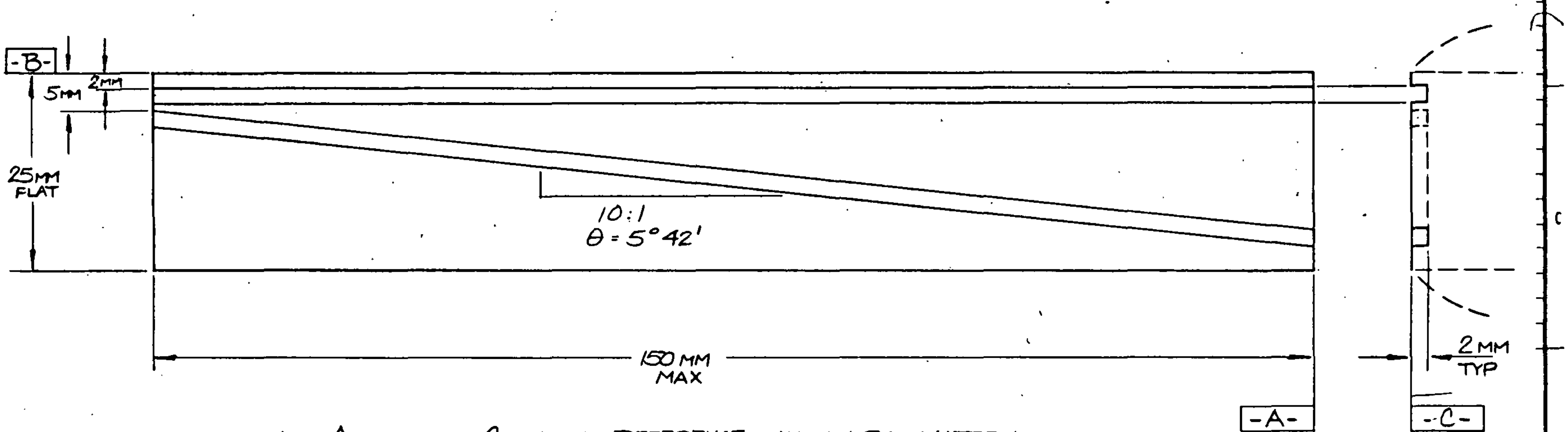
TOTAL COST: $140,000
COST TO DATE: $ 11,171

PLANNED COST – – –
INCURRED COST ———

PROGRAM COST SUMMARY



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

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REFERENCE FLAT- SILICON

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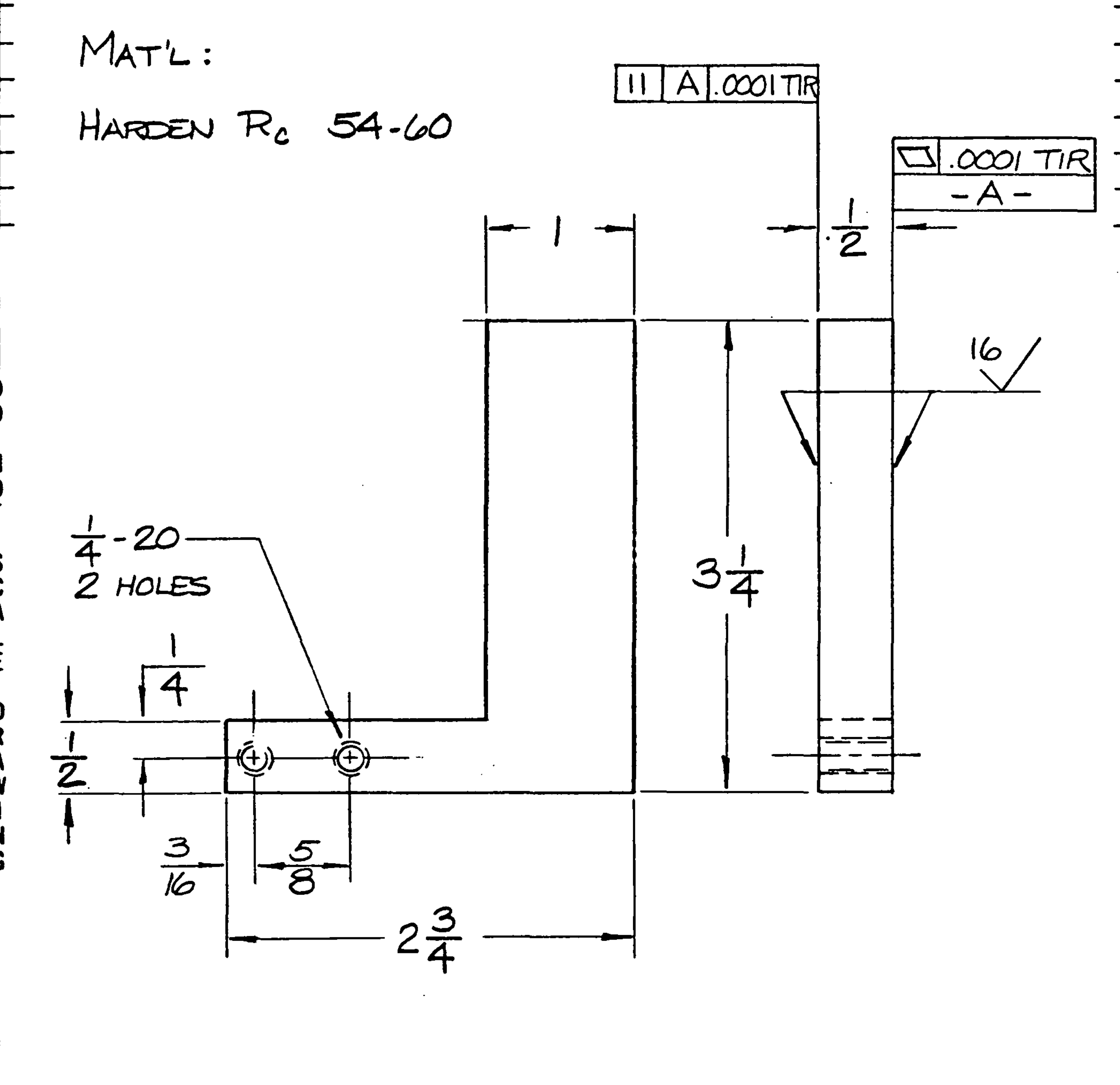

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