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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

Sixth Quarterly Report

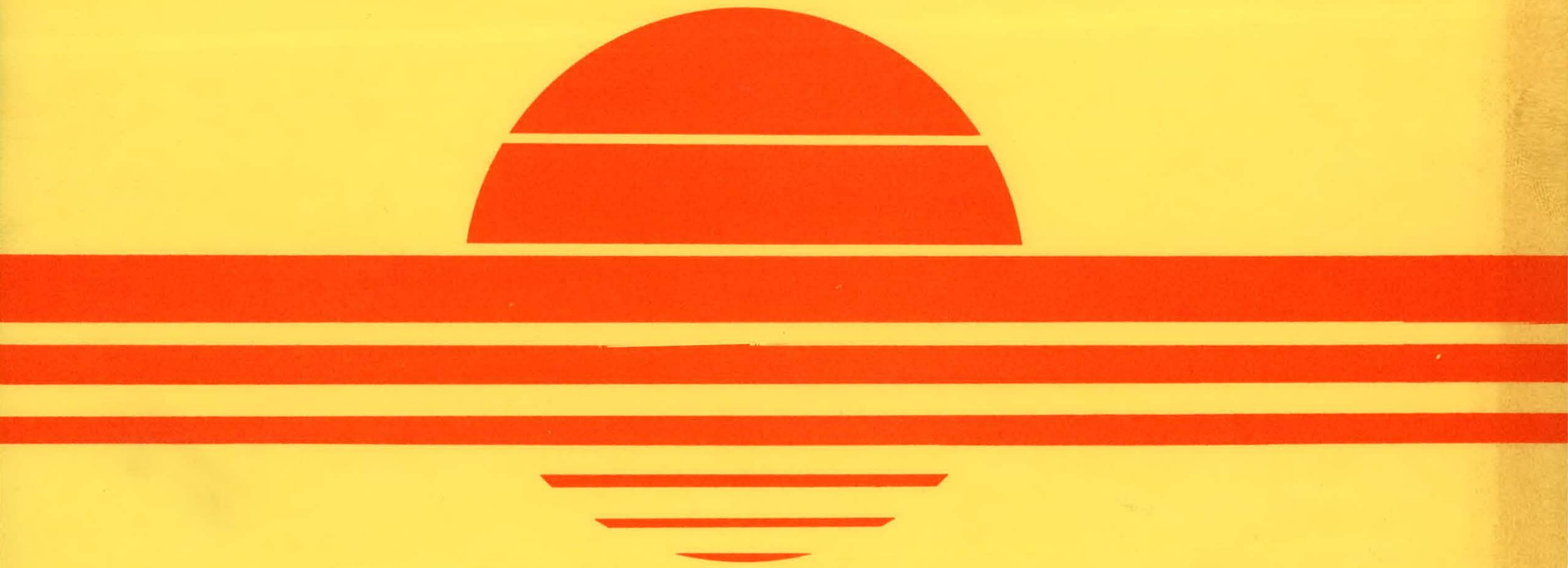
By
S. C. Holden
J. R. Fleming

MASTER

September 30, 1977

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

Varian Associates
Lexington Vacuum Division
Lexington, Massachusetts



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S. C. HOLDEN
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September 30, 1977

Reporting Period June 18, 1977 to September 18, 1977

JPL Contract No. 954374

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 SUMMARY

The "Multiple Blade Alignment Device" has been reported to JPL as a New Technology item, and is currently being reviewed for patent potential. The device has proven difficult to install on a blade package. Successful engagement of the device has resulted in an intrinsic parallelism of the ends of the package to within 3μ, compared to standard errors prior to correction of over 50μ. Measurements of blade misalignment indicate an average runout of 50μ in a 220 blade package. This compares well with predictions based on thickness variation measurements of blades and spacers.

Early cutting tests with 0.15 mm blades and 10 cm diameter ingots show lower yield and accuracy and higher cutting speed than previous standard tests. This seems to be a result of effective high abrasive concentration on the blades as a result of the slurry application technique. A similar, more dramatic reduction of yield occurs with a thin slurry oil. This appears to occur by increased slurry transport to the blades and another effective increase of abrasive packing to the cutting region.

Design of the large capacity MS saw is proceeding well, with a final conceptual design in progress. A flywheel system for work-piece drive is described. The design offers a practical conservative motion for the drive, requiring a minimum of power.

10 cm MS slices have been sent out for solar cell fabrication. 10 cm diameter and 2 cm square MS slices have been delivered for various surface preparations, and will be fabricated into cells and evaluated for performance. This will develop a minimum surface removal technique for both the damage and profiles peculiar to thin MS slices while allowing high efficiency cell production.

2.0 INTRODUCTION

This contract has as an objective the development of MS slicing as a low cost technique for the slicing of silicon for solar cells. The goals of this second phase of work are an add-on cost of MS slicing of less than $\$10/m^2$ and a conversion rate from ingot to sheet of 1.0 m^2/kg with 10-12 cm diameter silicon ingot.

The conversion capabilities were demonstrated in the first phase of work. The major sources of cost reduction are the reduction of cost for expendable materials and the increase of specific labor and saw output by increasing the multiple blade capacity by three times.

A major problem to be dealt with is the statistically predictable misalignment of blades within a multiple blade package. This problem reduces cutting stability and yield with larger numbers of blades, lower precision (lower cost) blade stock and thinner blades. A solution has been devised and is in a testing and development stage. The blade alignment technique is the key to this program.

3.0 CUTTING TESTS

Table 1 shows a summary of the conditions and results of cutting tests during the past quarter. Tests involved cutting for solar cell fabrication, testing of various abrasive and oil combinations and evaluation of improved blade alignment by correction of the end stop of the saw's bladehead. Two standard Varian 686 wafering saws are used in this test program, and are designated as machines #2 and #4. Saw #2 is intended for blade alignment device testing, blade hardness and accuracy tests, and development of miscellaneous techniques. Saw #4 is used exclusively for testing of oil and abrasive slurries. Because of the difficulties encountered with the blade alignment device, the bladehead of saw #2 has been tied up in non-cutting development.

3.1 #500 SiC Abrasive: Test #2-3-01

A package of 150 0.15 mm thick blades and 0.41 mm spacers was used to cut a 10 cm silicon ingot. A change from #600 SiC abrasive (standard) to #500 SiC resulted in a cutting time of 24.5 hours, but an increase in kerf loss for 0.20 mm (with #600) to 0.24 mm. Yield was 67%, and slice bow and taper averaged 35µ, which indicates a good controlled cutting action. However, the shift to the heavier abrasive gave an increase in kerf loss comparable to that saved by reducing blade thickness from 0.20 mm to 0.15 mm.

3.2 Lubrizol Suspension Oil: Test #2-3-02

Several tests were run using Lubrizol 5985, a suspension oil supplied by Lubrizol Corporation as a replacement for the standard PC oil. This test was run using 0.15 mm blades and 0.30 mm spacers. All conditions (tensioning, abrasive mix, abrasive, feed weight, etc.) were "standard", i.e. set at the values found to be best for PC oil.

Severe wafer breakage occurred during cutting. The yield was about 3%. The machine was checked for alignment, and it was found that the end of the bladehead well (against which the end of the blade pack is compressed) was significantly out of perpendicular relative to the feed (50 to 80 microns in 12 mm). The end blocks were shimmed to make them perpendicular to within 2.5 µm (.0001") and the test was repeated.

3.3 Lubrizol Suspension Oil: Test #2-3-03

Test #2-3-02 was repeated, except the spacers were increased to .356 mm (.014") in order to increase wafer strength. The operator had difficulty aligning the blade pack, but was able to obtain alignment within tolerances (having the blade pack parallel to the stroke within 5 µm (.0002")).

Again, severe wafer breakage occurred during cutting. The yield was about 25%. The wafer surfaces were quite wavy, and some broken wafers were measured to be .102 mm (.004") thick. These results indicated that controlled cutting had not been achieved.

The question is "can controlled cutting be achieved with Lubrizol 5985"? The major differences between 5985 and PC (standard) are viscosity and suspension power. It is difficult to believe that the much higher suspension power of 5985 is detrimental; thus, the lower viscosity of 5985 is probably the major difference.

Viscosity affects mostly the drag forces and the abrasive transport quality during cutting. Lower viscosity should decrease drag forces; again, this should not be detrimental.

Therefore, the poor performance of 5985 is likely to be due to a change in the transport and distribution of abrasive. We intend to experiment further with 5985, trying different abrasive mixes, until we obtain controlled cutting. We hope that this will be achieved at a lower abrasive mix, yielding a potentially cheaper slurry. We also hope that the higher suspending power of 5985 may allow the slurry to be used longer than a PC slurry, again reducing costs.

We are investigating two more possibilities for suspension agents. We have obtained some of the polymeric suspension agent used in 5985, and intend to mix our own cheaper oils by using lower concentrations of suspension agent. Since 5985 will suspend abrasive for a month or more, we feel that 5985 may have excessive suspension power and, consequently, excessive costly additive. Also, the Lubrizol Corporation has shown interest in trying to develop a water-based suspension agent.

3.4 Abrasive Mixture #500/#600/#800 SiC: Test #2-3-04

A mix of three abrasive sizes was used to cut a 10 cm silicon ingot, with 1/3 of the standard mix (0.36 kg/liter) made of #500, #600 and #800 SiC. Total cutting time was only 22.1 hours, less than with only #500 SiC. However, bow and taper were not as low as in #2-3-01 and kerf loss was nearly identical (0.246 mm). Yield was 83%, indicating a reasonably controlled cutting action. The results indicate two aspects of MS slicing. Firstly, it appears that the largest particles in an abrasive mix control the cutting action and kerf loss. Secondly, the abrasive mix involving a broader range of particle size seems to maintain good cutting action. It is possible that the smaller particles help support the larger particles and allow them to perform their optimum cutting action. Similar broad particle size testing will be performed with #600 SiC as the largest abrasive size.

3.5 Cell Fabrication, 10 cm Diameter: Test #2-4-01

0.15 mm blades and 0.36 mm spacers were used to cut a 10 cm silicon ingot with a standard 0.36 kg/liter mix of #600 SiC with PC oil and 85 grams of cutting force per blade. Cutting time was 22.4 hours and yield of the 0.314 mm slices was only 59%. Taper and bow were 70µ. It was felt that blade stop alignment may have impacted yield in this test. Alignment, as described previously was carried out to try to correct this condition.

3.6 Machine Proof Test: Test #2-4-02

After end stop correction, the above test (#2-4-01) was repeated. 0.41 mm spacers were used resulting in 0.36 mm slices. Cutting time was again 22.4 hours with 50% yield.

Bow and taper were 50-70μ. The indication was that proper alignment existed, but that uncontrolled cutting leading to low yield had occurred.

The best explanation for poor cutting lies in the different slurry application technique used with the present test saws. A reciprocating slurry application, as opposed to pulse-type distribution, seems to increase the effective slurry mix. Higher mix generally has given reduced cutting time and wafer yield and accuracy. The preceding tests show these conditions. A shift to a pulse-type slurry applicator will show this effect.

3.7 Wafer Dicing, Cell Fabrication: Test #2-4-03

MS slices, 0.35 mm thick were diced into 2 cm squares. The chips will be used for surface preparation and cell fabrication studies of MS slicing.

3.8 Cutting Enhancement: Test #2-5-01

Glass walls were mounted on either side of a 10 cm silicon ingot with standard conditions of MS slicing. This technique has been used very successfully with gallium arsenide and other materials. The cutting action seemed to proceed well, but the glass and ingot eventually broke loose. The result was complete fracture of the work, even though cutting time and blade wear appeared to be comparable to good cutting.

3.9 Machine Proof Test: Test #2-5-02

The second JPL saw was corrected for end stop vertical alignment and was used to cut a 10 cm silicon ingot with 0.15 mm blades and 0.41 mm spacers. Cutting time was 23 hours, but yield was only 42%. The indication is that slurry mix and application technique were not suitably matched to allow good cutting.

TABLE 1

SLICING TEST SUMMARY

PARAMETER	TEST	2-3-01	2-3-02	2-3-03	2-3-04
Material		{100} Si	{100} Si	{100} Si	{100} Si
Size	(mm)	100	100	100	100
Area/Slice	(cm^2)	78.54	78.54	78.54	78.54
Blade Thickness	(mm)	0.15 x 6.35	0.15 x 6.35	0.15 x 6.35	0.15 x 6.35
Spacer Thickness	(mm)	0.41	0.30	0.36	0.41
Blade Height	(mm)	6.4	6.4	6.4	6.4
Number of Blades		150	155	270	137
Load	(gram/blade)	85	85	85	85
Sliding Speed	(cm/sec)	67.7	64.6	61.9	71.30
Abrasive	(type/grit size)	#500 SiC	#600 SiC	#600 SiC	#500/600/800SiC(1/3
Oil Volume	(liters)	7.6 (PC)	7.6 (LUB)	716 (LUB)	7.6 (PC)
Mix	(kg/liter)	0.36	0.36	0.36	0.36 Total
Slice Thickness	(mm)	0.320	- -	0.320	0.313
Kerf Width	(mm)	0.239	- -	0.188	0.246
Abrasive Kerf Loss	(mm)	0.086	- -	0.036	0.094
Cutting Time	(hours)	24.5	27.8	32.4	22.1
Efficiency	(full test)	1.34		0.87	1.45
	(typical)	1.49	- -	1.12	1.66
	(maximum)	1.69	- -	1.30	1.94
Abrasion Rate	(full test)	0.077	- -	0.046	0.087
(cm^3/hr/bl	(typical)	0.09	- -	0.06	0.100
	(maximum)	0.10	- -	0.07	0.117
Productivity	(full test)	3.21	2.83	2.42	3.55
(cm^2/hr/bl)	(typical)	3.57	- -	3.12	4.08
	(maximum)	4.05	- -	3.63	4.76
Yield		100/149 (67%)	0/154 (0%)	20-30%	113/136(83%)
Slice Taper	(mm)	0.039	- -		0.040
Slice Bow	(mm)	0.034	- -		0.051
Abrasive Utilization	(cm^3/kg)	102.9	89.0	145.7	96.7
Oil Utilization	(cm^3/liter)	37.0	32.0	52.5	34.8
Blade Wear Ratio	(cm^3/cm^3)	0.039	0.049	0.060	0.046

TABLE 1 (cont.)

SLICING TEST SUMMARY

PARAMETER TEST	2-4-01	2-4-02		
Material	{100} Si	{100} Si		
Size (mm)	100	100		
Area/Slice (cm^2)	78.54	78.54		
Blade Thickness (mm)	0.15 x 6.35	0.15 x 6.35		
Spacer Thickness (mm)	0.36	0.41		
Blade Height (mm)	6.4	6.4		
Number of Blades	165	150		
Load (gram/blade)	85	85		
Sliding Speed (cm/sec)	64.8	64.8		
Abrasive (type/grit size)	#600 SiC	#600 SiC		
Oil Volume (liters)	7.6	7.6		
Mix (kg/liter)	0.36	0.36		
Slice Thickness (mm)	0.314	0.358		
Kerf Width (mm)	0.194	0.201		
Abrasive Kerf Loss (mm)	0.042	0.049		
Cutting Time (hours)	22.4	22.4		
Efficiency (full test)	1.24	1.28		
(typical)	1.47	1.50		
(maximum)	1.67	1.80		
Abrasion Rate (full test)	0.068	0.070		
(cm^3/hr/bl (typical)	0.08	0.08		
(maximum)	0.09	0.10		
Productivity (full test)	3.51	3.51		
(cm^2/hr/bl) (typical)	4.16	4.10		
(maximum)	4.72	4.92		
Yield	97/164 (59%)	75/144 (50%)		
Slice Taper (mm)	0.074	0.079		
Slice Bow (mm)	0.072	0.056		
Abrasive Utilization (cm^3/kg)	91.9	86.5		
Oil Utilization (cm^3/liter)	33.1	31.2		
Blade Wear Ratio (cm^3/cm^3)	0.053	0.055		

TABLE 1 (cont.)

SLICING TEST SUMMARY

PARAMETER TEST		2-5-01	2-5-02		
Material		{100} Si	{100} Si		
Size	(mm)	100	100		
Area/Slice	(cm^2)	78.54	78.54		
Blade Thickness	(mm)	0.15 x 6.35	0.15 x 6.35		
Spacer Thickness	(mm)	0.30	0.41		
Blade Height	(mm)	6.4	6.4		
Number of Blades		120	150		
Load	(gram/blade)	85	85		
Sliding Speed	(cm/sec)	63.5	66.9		
Abrasive	(type/grit size)	#600 SiC	#600 SiC		
Oil Volume	(liters)	7.6	7.6		
Mix	(kg/liter)	0.36	0.36		
Slice Thickness	(mm)	- -	0.334		
Kerf Width	(mm)	- -	0.225		
Abrasive Kerf Loss	(mm)	- -	0.073		
Cutting Time	(hours)	23.4	23.0		
Efficiency	(full test)	- -	1.36		
	(typical)	- -	1.47		
	(maximum)	- -	2.05		
Abrasion Rate	(full test)	- -	0.077		
(cm^3/hr/bl	(typical)	- -	0.08		
	(maximum)	- -	0.12		
Productivity	(full test)	3.36	3.42		
(cm^2/hr/bl)	(typical)	- -	3.70		
	(maximum)	- -	5.16		
Yield		0/119 (0%)	63/149 (42%)		
Slice Taper	(mm)	- -	0.069		
Slice Bow	(mm)	- -	0.051		
Abrasive Utilization	(cm^3/kg)	68.9	96.9		
Oil Utilization	(cm^3/liter)	24.8	34.9		
Blade Wear Ratio	(cm^3/cm^3)	0.047	0.049		

4.0 WAFER CHARACTERIZATION

Table 2 shows a summary of wafer thickness, bow and taper characterization for cutting tests performed during the past quarter. All tests involving standard cutting conditions show poor accuracy characteristics. This seems to be a result of the effectively higher abrasive concentration resulting from the reciprocating slurry system. The wafers resulting from the #500 SiC show high accuracy cutting, even those from the mix of three abrasive sizes. The kerf loss of #500 SiC is excessive, and will not allow cost effective cutting. The yield was so low with the thin Lubrizol suspension agent, that no characterization was possible. This, again, may be a result of effectively too high an abrasive mix due to increased slurry transport with the low viscosity oil.

5.0 DISCUSSION

5.1 Blade Misalignment

An important concept in understanding the present limits of MS slicing and in improving the state of the art is that of blade misalignment. Because of the stacked construction of a multiple blade package, both horizontal misalignment (runout) and vertical misalignment (tipping) of blades are expected. This misalignment is controlled by the inaccuracy of blades and spacers and the number of components. Previous estimates of blades and spacers indicated that an average end-to-end runout of as much as 50μ (0.002 inch) was expected within a 225 blade package.

A blade package of this size was tensioned within a bladehead and aligned parallel on each end within 2.5μ (0.0001 inch) by standard techniques. A precision inspection bench was used to measure the exact position of each blade within the package.

TABLE 2

WAFER THICKNESS CHARACTERIZATION SUMMARY

TEST			2-3-01	2-3-02	2-3-03	2-3-04
SLICE	Diameter	(mm)	100	100	100	100
	Area	(cm^2)	78.5	78.5	78.5	78.5
THICKNESS	Average	μ	320	- -	320	313
	Std. Dev.	μ	24	- -	71	18
TOTAL VARIATION	Average	μ	34	- -	91	36
	Std. Dev.	μ	14	- -	58	22
STD. DEVIATION	Average	μ	12	- -	38	14
	Std. Dev.	μ	6	- -	25	9
VERTICAL TTV	Average	μ	40	- -	- -	40
	Maximum	μ	99	- -	- -	120
	Minimum	μ	13	- -	- -	24
HORIZONTAL TTV	Average	μ	16	- -	- -	10
	Maximum	μ	31	- -	- -	24
	Minimum	μ	5	- -	- -	3
VERTICAL BOW	Average	μ	40	- -	- -	53
	Maximum	μ	112	- -	- -	157
	Minimum	μ	8	- -	- -	28
HORIZONTAL BOW	Average	μ	15	- -	- -	16
	Maximum	μ	58	- -	- -	40
	Minimum	μ	4	- -	- -	6
VERTICAL CL BOW	Average	μ	68	- -	- -	102
	Maximum	μ	141	- -	- -	216
	Minimum	μ	36	- -	- -	55
HORIZONTAL CL BOW	Average	μ	29	- -	- -	31
	Maximum	μ	99	- -	- -	57
	Minimum	μ	8	- -	- -	16

TABLE 2 (cont.)

WAFER THICKNESS CHARACTERIZATION SUMMARY

TEST			2-4-01	2-4-02	2-5-01	2-5-02
SLICE	Diameter	(mm)	100	100	100	100
	Area	(cm^2)	78.5	78.5	78.5	78.5
THICKNESS	Average	μ	314	358	- -	334
	Std. Dev.	μ	33	56	- -	36
TOTAL VARIATION	Average	μ	62	66	- -	65
	Std. Dev.	μ	23	43	- -	28
STD. DEVIATION	Average	μ	26	28	- -	25
	Std. Dev.	μ	11	19	- -	12
VERTICAL TTV	Average	μ	74	79	- -	69
	Maximum	μ	150	184	- -	118
	Minimum	μ	30	22	- -	32
HORIZONTAL TTV	Average	μ	16	13	- -	14
	Maximum	μ	33	30	- -	21
	Minimum	μ	4	4	- -	7
VERTICAL BOW	Average	μ	82	69	- -	61
	Maximum	μ	140	132	- -	159
	Minimum	μ	29	13	- -	17
HORIZONTAL BOW	Average	μ	19	18	- -	20
	Maximum	μ	46	46	- -	46
	Minimum	μ	4	7	- -	4
VERTICAL CL BOW	Average	μ	144	101	- -	102
	Maximum	μ	204	182	- -	211
	Minimum	μ	80	28	- -	20
HORIZONTAL CL BOW	Average	μ	33	32	- -	38
	Maximum	μ	67	79	- -	73
	Minimum	μ	11	14	- -	16

Figure 1 shows the reduction of this information to indicate the runout of each blade. An average runout of 41μ (0.0016 inch) was measured over 12 inches of the 15 inch package. This implies a full end to end runout averaging 50μ (0.0020 inch) exactly that predicted from the thickness distribution of blades and spacers. Therefore, the assumption of significant misalignment within a package is valid, and the need for an alignment correction technique to improve alignment and to allow more blades to be used simultaneously is obvious.

The blade alignment device was used on blade packages during the final month of this reporting period. The engagement of the device onto a package proved to be very difficult. Not all blades will engage with their respective gear teeth, and correction of this condition is difficult. At the end of this reporting period an alignment device was successfully installed on a fully tensioned blade package (150 0.15 mm x 6.35 mm blades and 0.35 mm spacers). The device seemed to improve the parallelism of the package. The natural parallelism of a tensioned blade package is only 100μ (0.004 inch). This is corrected by varying the compression on either end of a blade package. With the alignment device, the basic parallelism was on the order of 3μ (0.0001 inch). This blade package will be used in a cutting test during the end of September.

5.2 Abrasive Slurry

At the moment, silicon carbide is the best and most cost effective abrasive available. We hope to reduce the costs through reclamation and broader abrasive sizing (as in test #2-3-04).

Much of the cost of abrasive arises from the process of separating a narrow band of particle sizes. In slurry sawing, only the largest particles are felt to do work, and the smaller particles go along for the ride (as long as there are not <u>too</u>

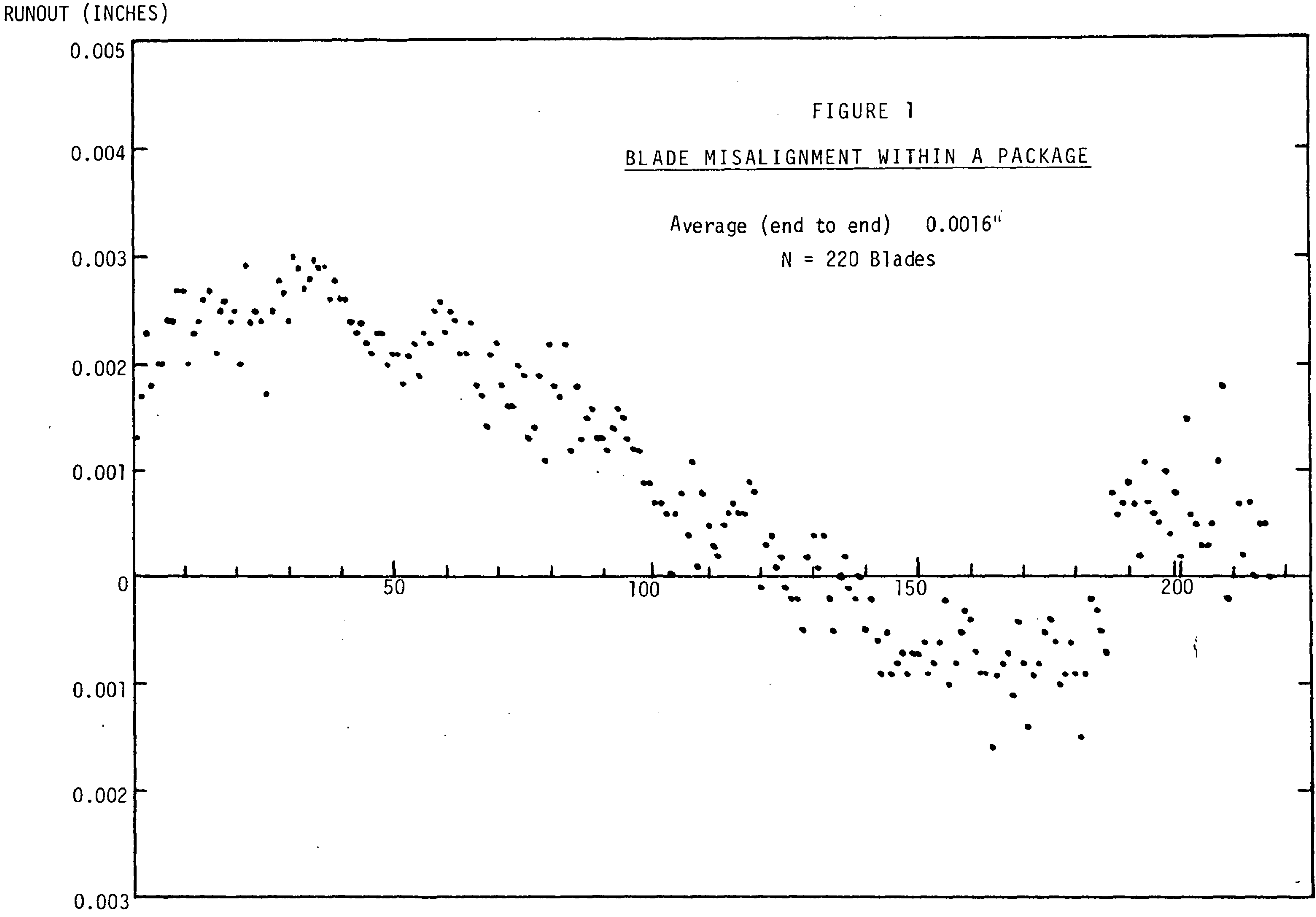

FIGURE 1

BLADE MISALIGNMENT WITHIN A PACKAGE

Average (end to end) 0.0016"
N = 220 Blades

many small particles). We are currently running tests on mixtures of grits to see if we can use a broader spectrum of particle sizes.

It appears that the failure mechanism of slurry is accumulation of debris rather than suspension agent breakdown or abrasive fracture or dulling. If debris can be removed, the rest of the slurry should be reusable. We have contacted a manufacturer as to the possibility of filtering the slurry. We are also considering centrifugal separation.

5.3 Prototype Design Concepts

A prototype MS saw is being designed in order to increase the number of blades used from 300 to 1000, reducing the specific labor and capitalization costs of MS slicing. Four separate configurations of the saw have been developed involving variations in the method of protecting moving parts from the abrasive slurry. Two other concepts involved means of providing the feed motion of cutting. By far, the important decision involves the protection from slurry.

The large tensioning capacity required of the bladehead (600,000 lbs.) and the necessary stiffness of that component makes the bladehead a very heavy piece. For that reason, a fundamental consideration was made to provide the reciprocating motion for cutting by a work-piece moving action. Two systems were devised to provide the vertical cutting stroke necessary. in one, the reciprocating drive system is raised into the bladehead, and in the other, the heavy bladehead is lowered onto the reciprocating workpiece. The lowered bladehead was selected since the resulting reaction loads were minimal.

Stiffness calculations on the linear ball bushing and rod drive and feed mechanisms allowed the selection and purchase of these components. These components are common to all design concepts which were considered.

Because of the need to protect mechanisms from abrasive slurry, and to allow suitable operating conditions, the choice of machine configuration was not simple. The first concept involved a large pan with an outer trough which would move with the workpiece. The pan protected the sliding system beneath it, and drained slurry into two stationary troughs for recirculation. This mechanism was fabricated, mounted onto a saw for simulated operation and run with slurry pouring onto it. The slurry did not drain well as the high viscosity fluid would accumulate on the large surface area. Standing waves resulted, and drainage points provided splashing at the ends of the stroke. The large area required for this system was not desirable either.

A second configuration relied on gravity to protect the sliding mechanism. The workpiece support dropped downward from the slide, turning upward beyond a protecting screen to support the silicon ingot adjacent to the blades. This system offered the smallest configuration, but the lateral stiffness and manufacture of the tubular support system were important drawbacks of this design.

A similar system placed the drive mechanism above the bladehead, with the workpiece slung below the blades. Access to the bladehead during setup was another drawback to this system. If "upside-down" cutting were feasible, this system would be ideal. A test will be conducted during the next quarter to demonstrate the feasibility of the upside-down ingot configuration of MS slicing.

A final concept involved a shield inside the drive components which raised above and around the sides of the bladehead. The shield had to be larger than the bladehead length plus the stroke length. It was calculated that the bladehead length would be over 100 cm (40 inches) due to the stiffness requirements. For that reason, this configuration became too unwieldy.

The technique of baffle shielding was considered instead of a bellows protection of the linear ball bushings and rods. Rubber bellows could not stand up to the long lifetime and high reciprocating speeds (>60 cm/sec). The added problem of slurry acting on these rubber boots presented an unknown additional problem. Also, in order to accommodate the bellows size, the length and diameter of the rods would have to be excessive.

The designs described above are shown in the first drawings in Appendix I. A review of the concepts indicated that advantages and disadvantages of each required a modified design. An improved version of the underslung design is now in progress, with better stiffness and manufacturing ease to the ingot support carriage. This appears to be the final design concept.

5.4 Prototype Drive Mechanism

The drive mechanism for the large MS saw was considered independently from the full machine configuration. In order to minimize the power requirement for the drive, a flywheel was chosen. This allows a conservative motion system for the drive. An ultimate flywheel involves an infinite inertial mass flywheel and an infinitely long connecting rod. An analysis was conducted to determine the necessary flywheel mass and connecting rod length.

A 200 lb. reciprocating mass and 10 inch cutting stroke were chosen as a basis for the design. The configuration chosen was that shown in Figure 2. A solid connecting rod replaces the scotch yoke type used in present machines. The equations of motion for this configuration are:

$$\ddot{\Theta} = \dot{\Theta}^2 \frac{\cos\Theta\sin\Theta + \frac{\cos\Theta(3\sin^2\Theta-1)}{L^*} + \frac{\sin\Theta\cos\Theta(2\sin^2\Theta-1)}{L^{*2}} + \frac{\cos^3\Theta\sin^2\Theta}{L^{*3}} + \frac{\cos^3\Theta\sin^3\Theta}{L^{*4}}}{I^* + \cos^2\Theta + \frac{2\cos^2\Theta\sin\Theta}{L^*} + \frac{\cos^2\Theta\sin^2\Theta}{L^{*2}}} \tag{1}$$

$$\frac{\ddot{x}}{r} = \ddot{\Theta}\left(\cos\Theta + \frac{\sin\Theta\cos\Theta}{L^*}\right) + \dot{\Theta}^2\left(-\sin\Theta + \frac{1-2\sin^2\Theta}{L^*} - \frac{\cos^2\Theta\sin^2\Theta}{L^{*3}}\right)$$

where

$$I^* = I/Mr^2$$

$$L^* = L/r \tag{2}$$

Two cases were considered in order to choose the appropriate connecting rod length, or L^*, and flywheel inertia, or I^*. The equations of motion were simulated with numerical integration under natural motion. For the selection of the flywheel, the connecting rod was allowed to be very long. For the condition $L^* = \infty$, the equations of motion reduce to

$$\ddot{\Theta} = \dot{\Theta}^2 \frac{\cos\Theta\sin\Theta}{I^*}$$

$$\frac{\ddot{x}}{r} = \ddot{\Theta}\cos\Theta - \dot{\Theta}\sin\Theta \tag{3}$$

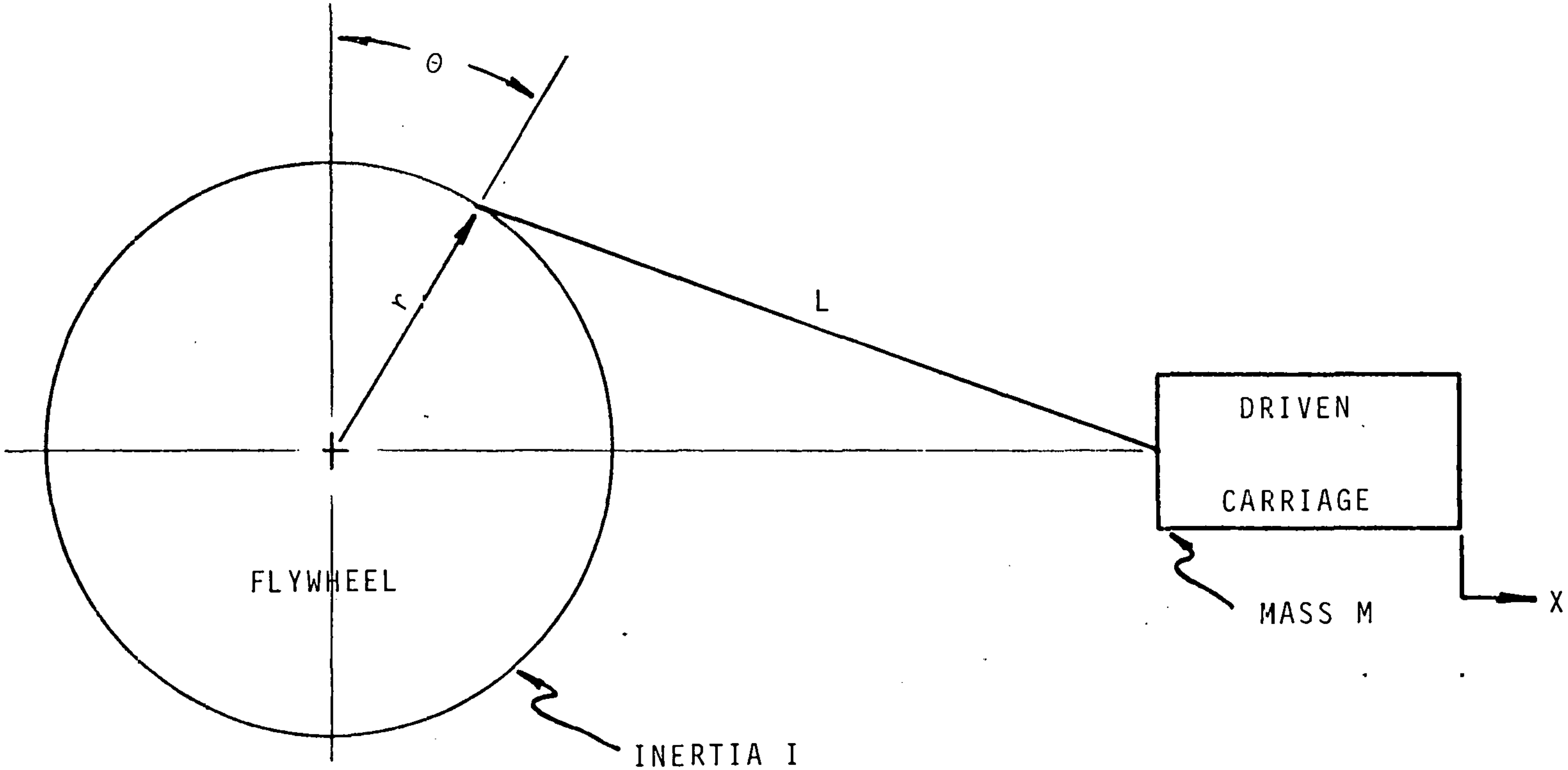

FIGURE 2

<u>SCHEMATIC OF RECIPROCATING DRIVE</u>

Figure 3 shows the simulation of one cycle of motion for various values of I* . Only a 12% increase in peak natural acceleration occurs for I* = 3 , therefore, a flywheel matching this condition will be used.

The motion of the driven mass under fixed rotational speed ($\dot{\Theta}$ = constant) was simulated for various values or L* and is shown in Figure 4. For a value of L* = 8 , only a 13% increase in peak acceleration occurs. This is the second design choice for the prototype drive system.

Figure 5 shows the acceleration of a driven mass under natural motion with I* = 3 and varying values of L* . A value of L* of more than 8 will be used. The motor drive will only be required to supply less than 20% of the reciprocating drive requirement, plus the friction losses and cutting drag power.

5.5 Solar Cell Fabrication

Fabrication of solar cells from 10 cm diameter MS slices of silicon has been arranged and subcontracted on a preliminary basis. Both full 10 cm diameter and 2 cm square wafers will be fabricated. The 2 cm fabrication will be useful to indicate proper use of the MS wafer surface, while 10 cm diameter slices will demonstrate the problems associated with solar cells made from the thin slices and distinct surface of the MS technique.

Fabrication in both modes will be used in conjunction with the surface preparation development. Results of baseline fabrication and preliminary surface preparation work should be available by the end of the next quarter.

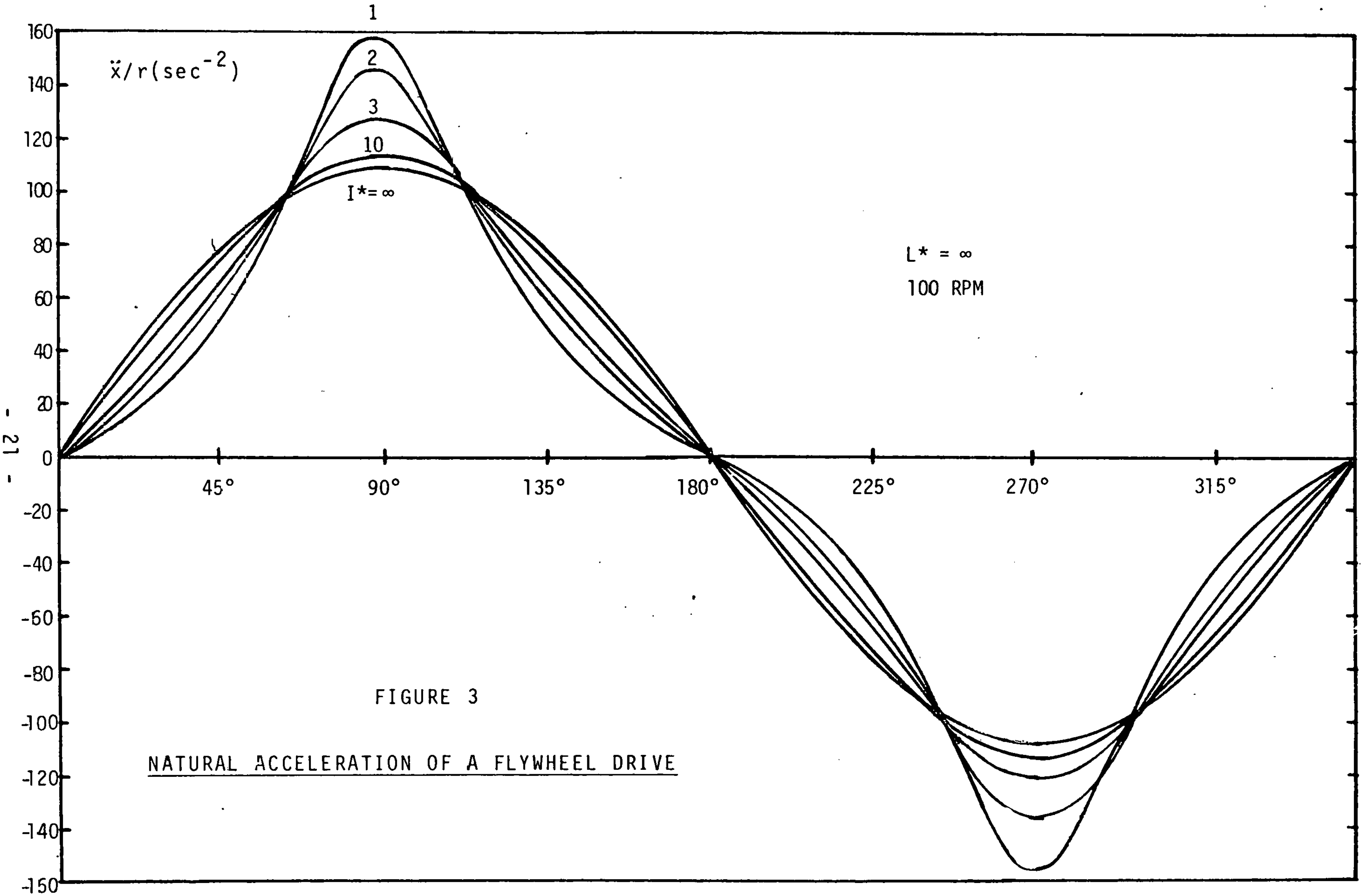

FIGURE 3

NATURAL ACCELERATION OF A FLYWHEEL DRIVE

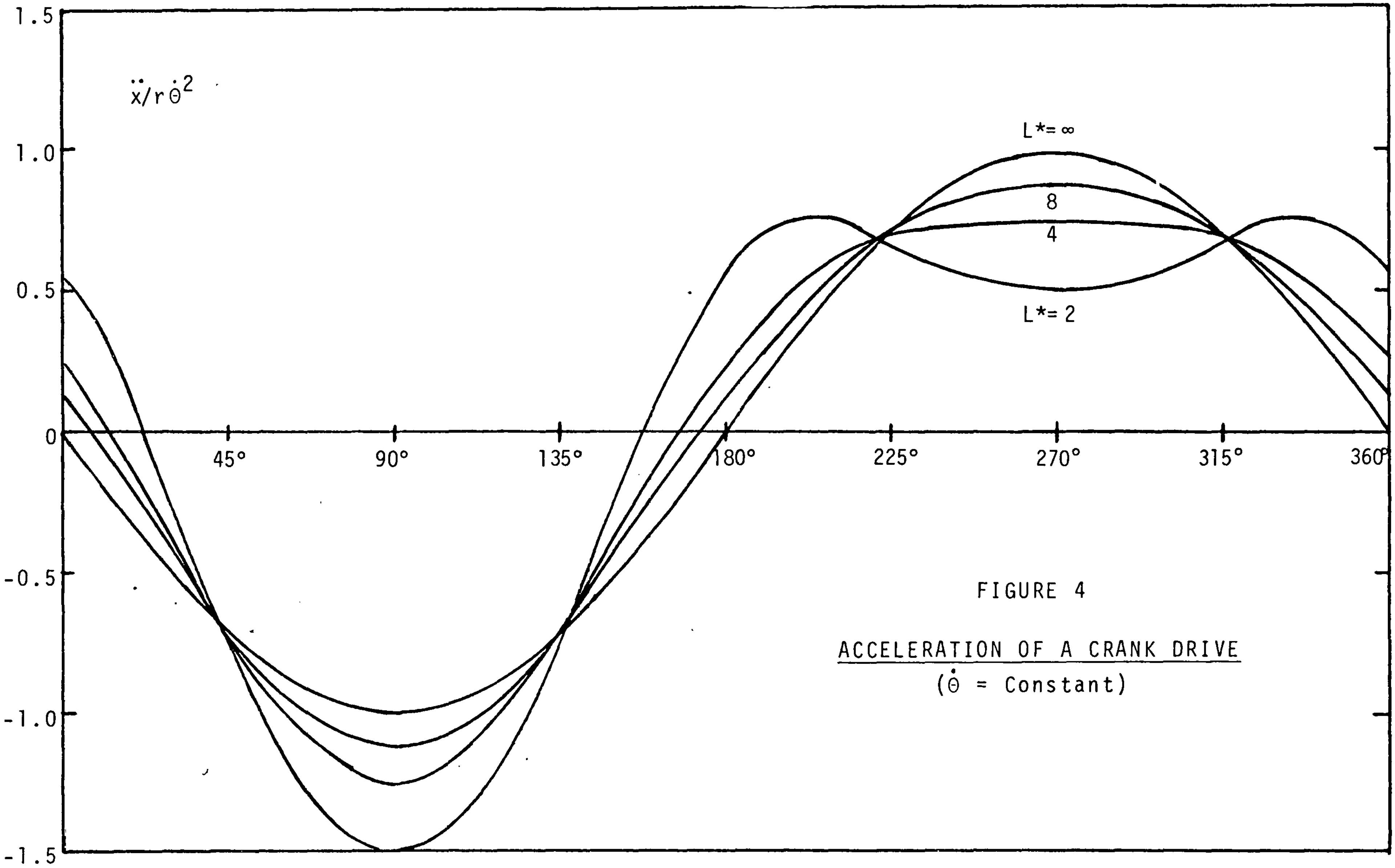

FIGURE 4

ACCELERATION OF A CRANK DRIVE
($\dot{\Theta}$ = Constant)

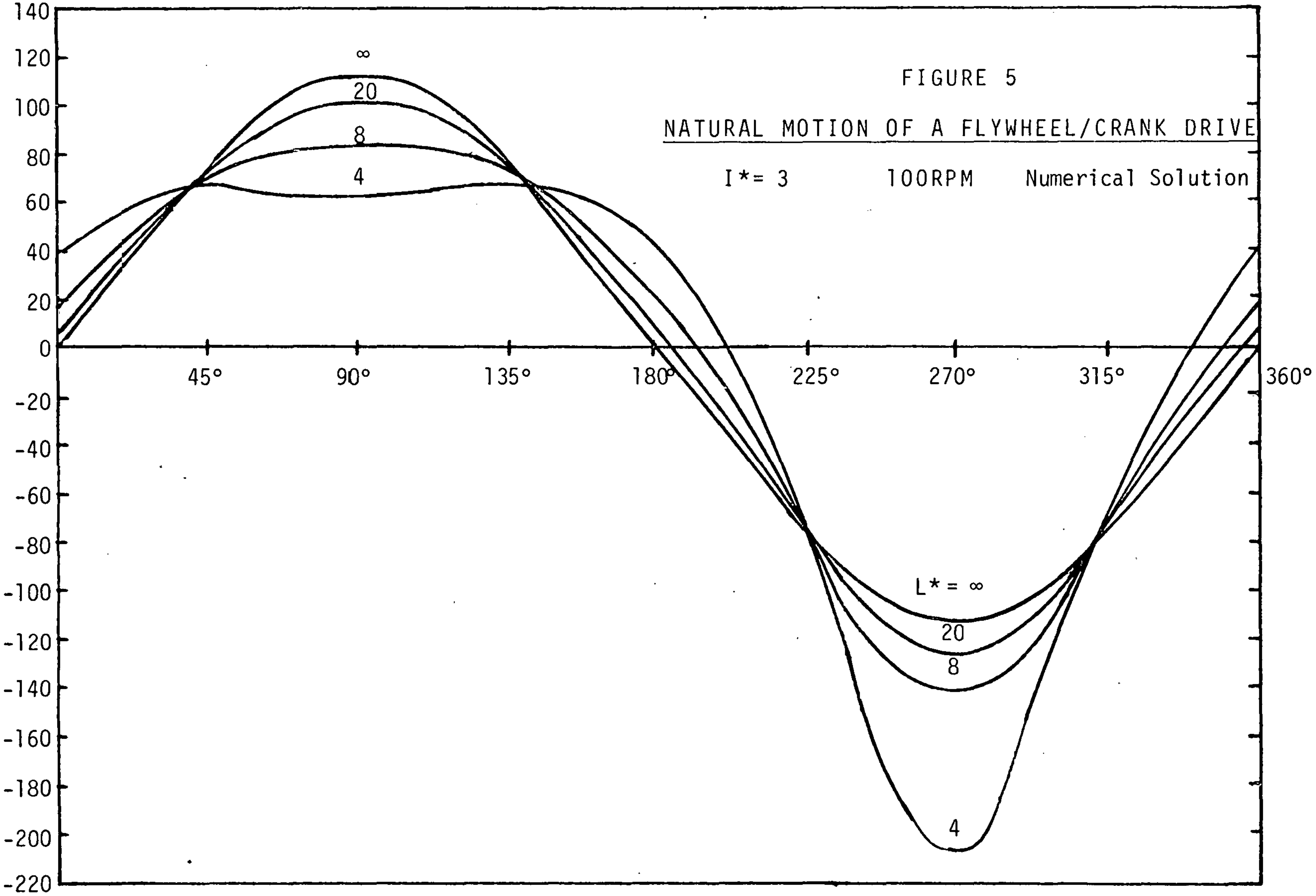

FIGURE 5

NATURAL MOTION OF A FLYWHEEL/CRANK DRIVE

I*= 3 100RPM Numerical Solution

5.6 Wafer Surface Preparation

The first series of surface preparation experiments have been planned and subcontracted. 0.30 to 0.35 mm thick silicon slices, both 10 cm diameter and 2 cm square, are being prepared by syton polishing, cupric ion polishing, planar etching and texture etching to depths of 5, 10, 15 and 20 microns (nominal). Groups of each size wafer will be prepared according to this matrix. One prepared slice of each grouping will be retained for SEM micrography and damage characterization. The remaining slices will be fabricated into solar cells and characterized for V_{oc}, I_{sc}, fill factor and efficiency against baseline slices. From these results, a technique of minimal material removal, suitable for MS slices will be established.

6.0 CONCLUSIONS AND RECOMMENDATIONS

- Blade misalignment has been shown to cause a reduction of wafer yield and accuracy. As a result of testing, an improvement in tipping accuracy has been developed as a modification to existing equipment.
- The blade alignment device is proving very difficult to use. Proper engagement of the rack gears with the blades is difficult to achieve.
- Measurements of blade misalignment supports earlier statistical evaluation of a multiblade package.
- Proper MS cutting action is only achieved with a proper combination of abrasive size, mix, application technique and oil type. The choice is critical when dealing with large diameter, thin slices and minimal stability blades for low kerf loss.

7.0 PLANS

Plans for the next quarter include:

- Order 12 cm silicon ingot for cutting tests.
- Complete wafer strength tests.
- Complete laboratory saw.
- Evaluate preliminary cell fabrication/surface preparation results. Plan next test sequence.
- Improve technique of blade alignment. Demonstrate impact on cutting.
- Begin final design/fabrication of large scale prototype.
- Continue slurry/blade development.

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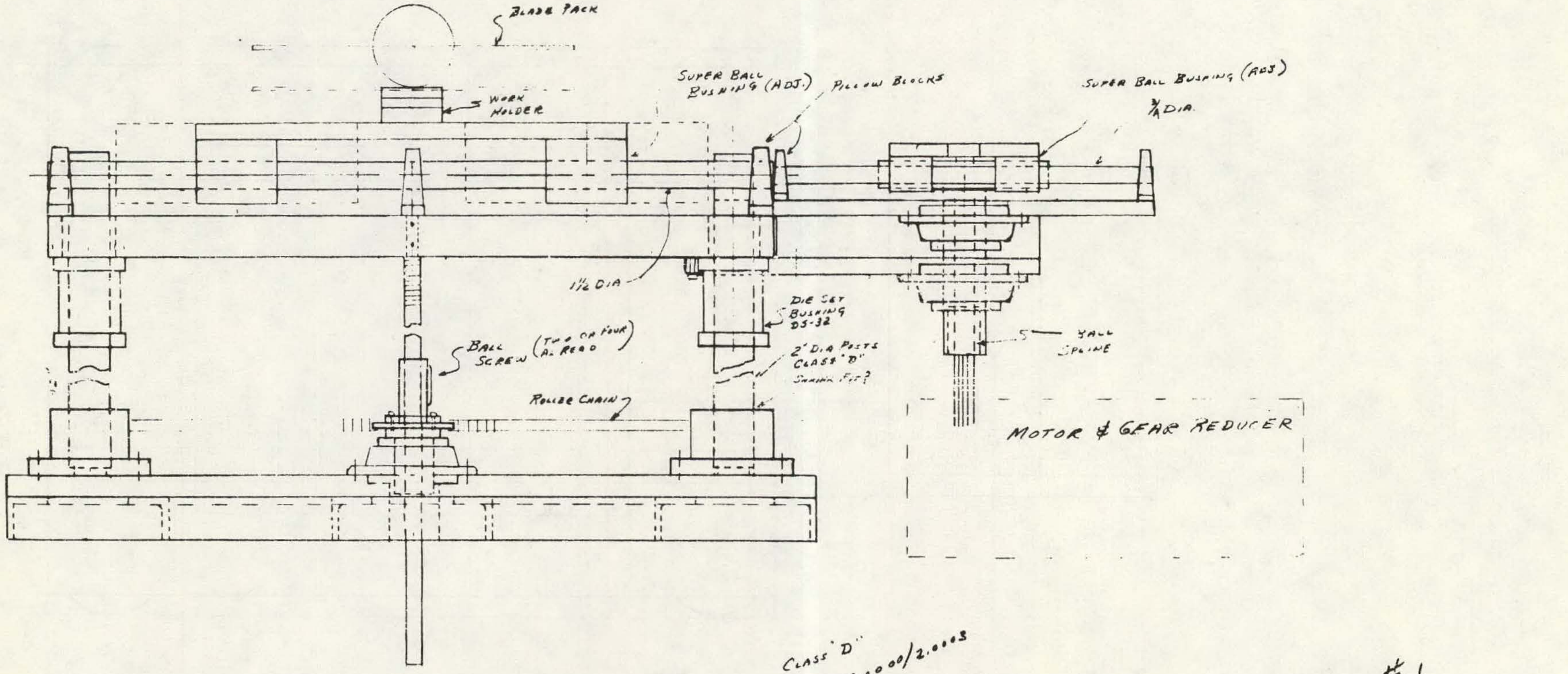
APPENDIX I

- New Technology
- Engineering Drawings & Sketches

NEW TECHNOLOGY

A "Multiple Blade Alignment Device" described in previous reports has been reported to JPL as an item of New Technology. The device was conceived as a portion of Phase II of this contract, and is presently under development. A patent on the "Multiple Blade Alignment Device" is currently being pursued by the Varian Patent Office. Actual use of the technique with MS slicing is anticipated in late September and October of 1977.



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LAYOUT #1
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CONCEPT #1

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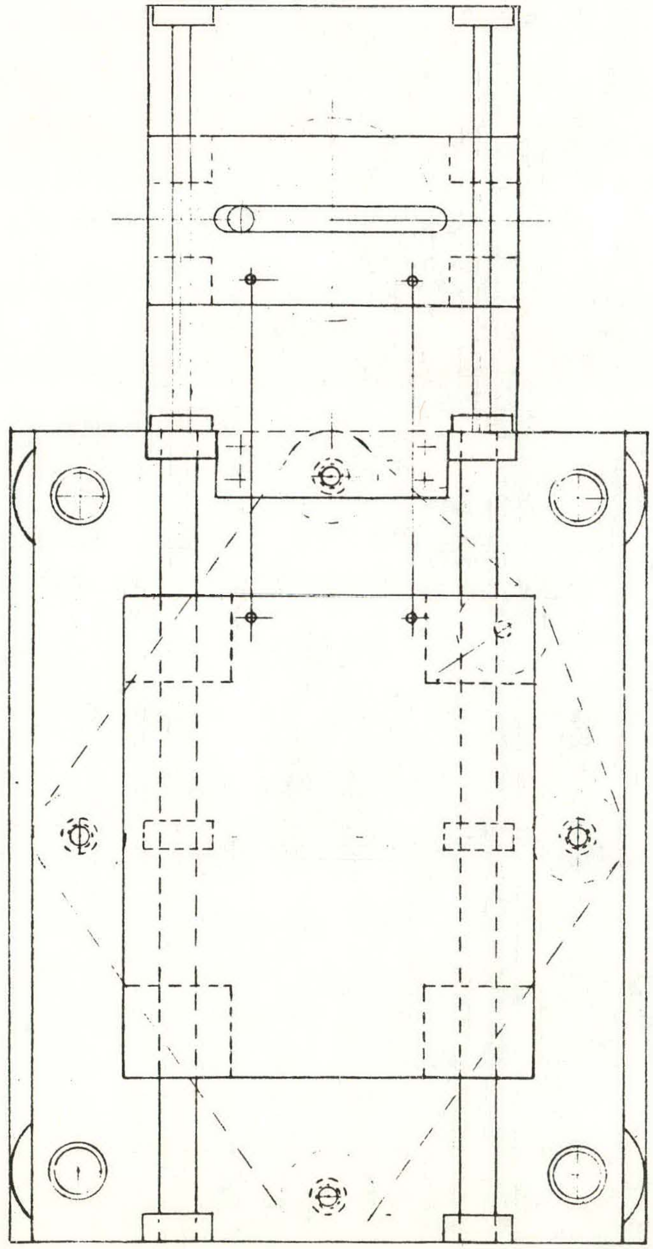
C-S0001

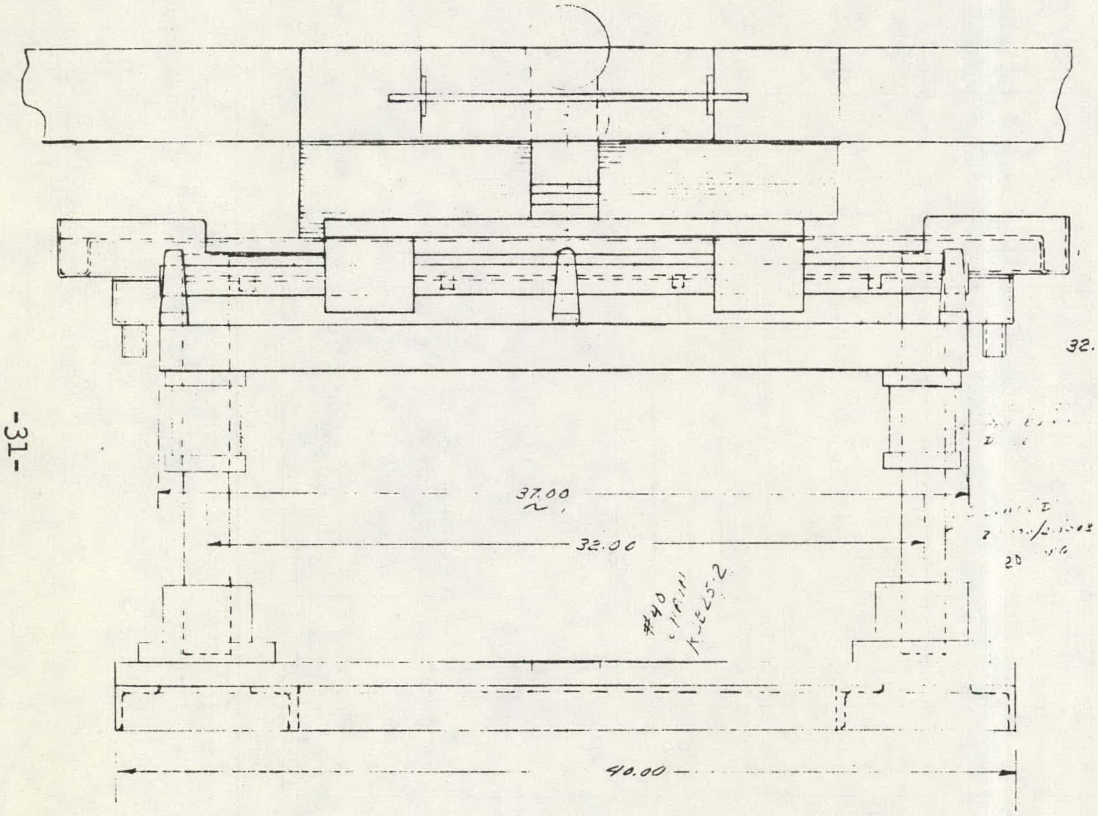
C-S0002



CONCEPT #1

LAYOUT #1
SHEET 2

C-S0002



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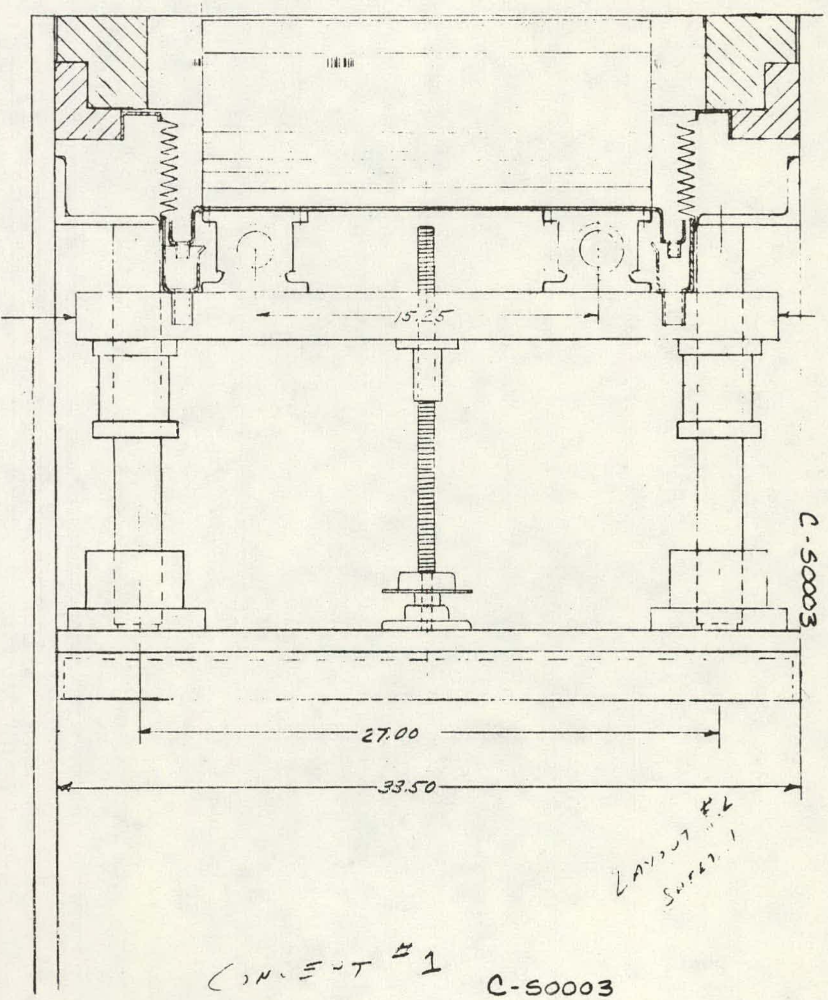

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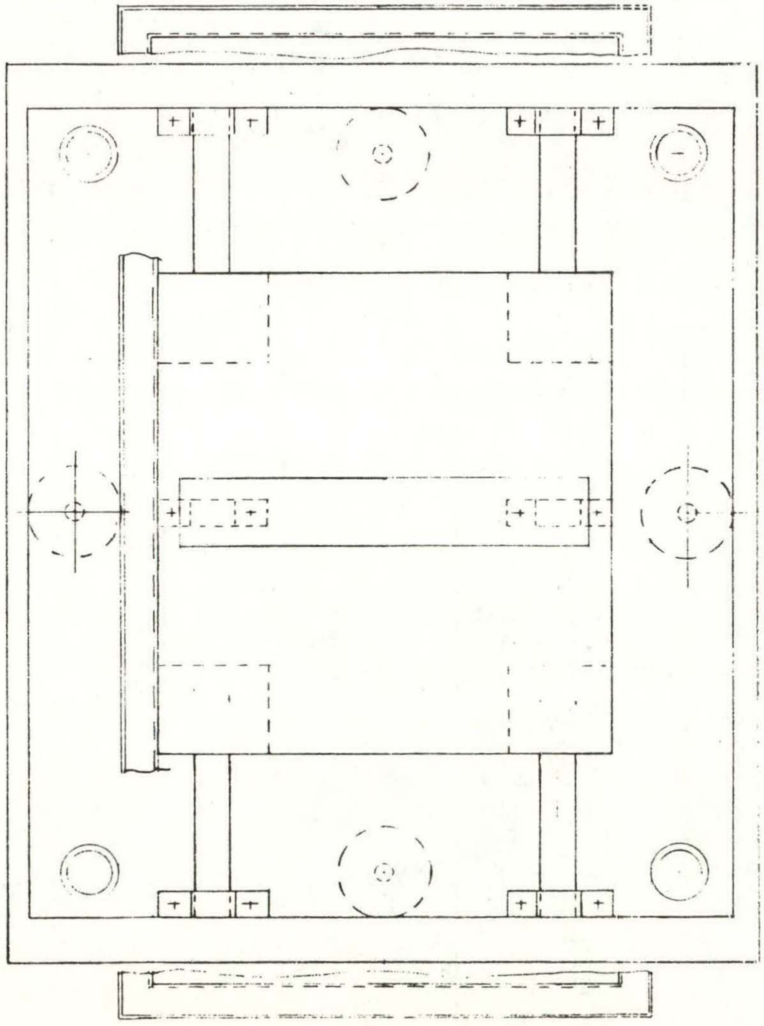
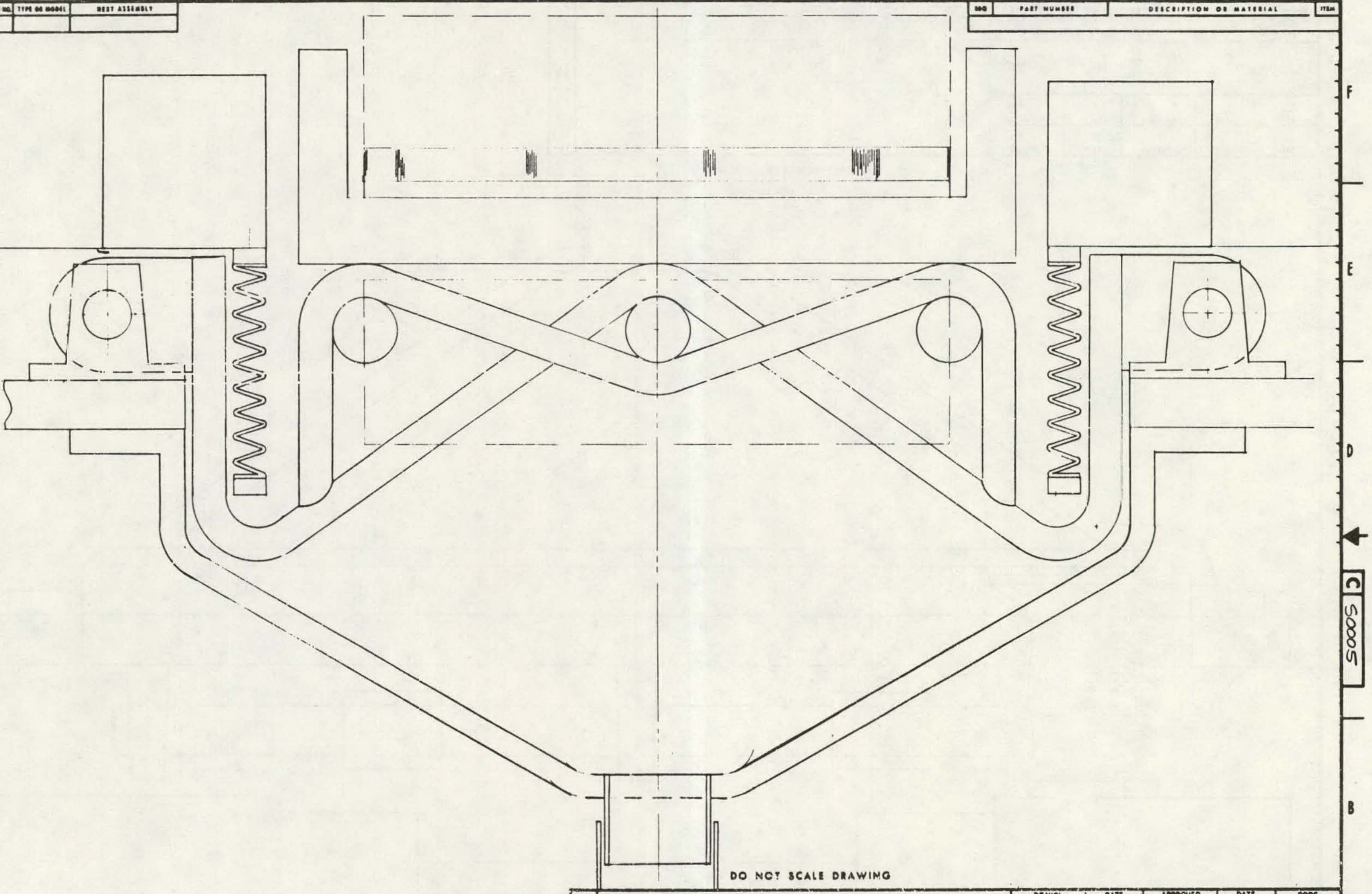
CONCEPT #1

LAYOUT #2 SHEET 2

C-S0004





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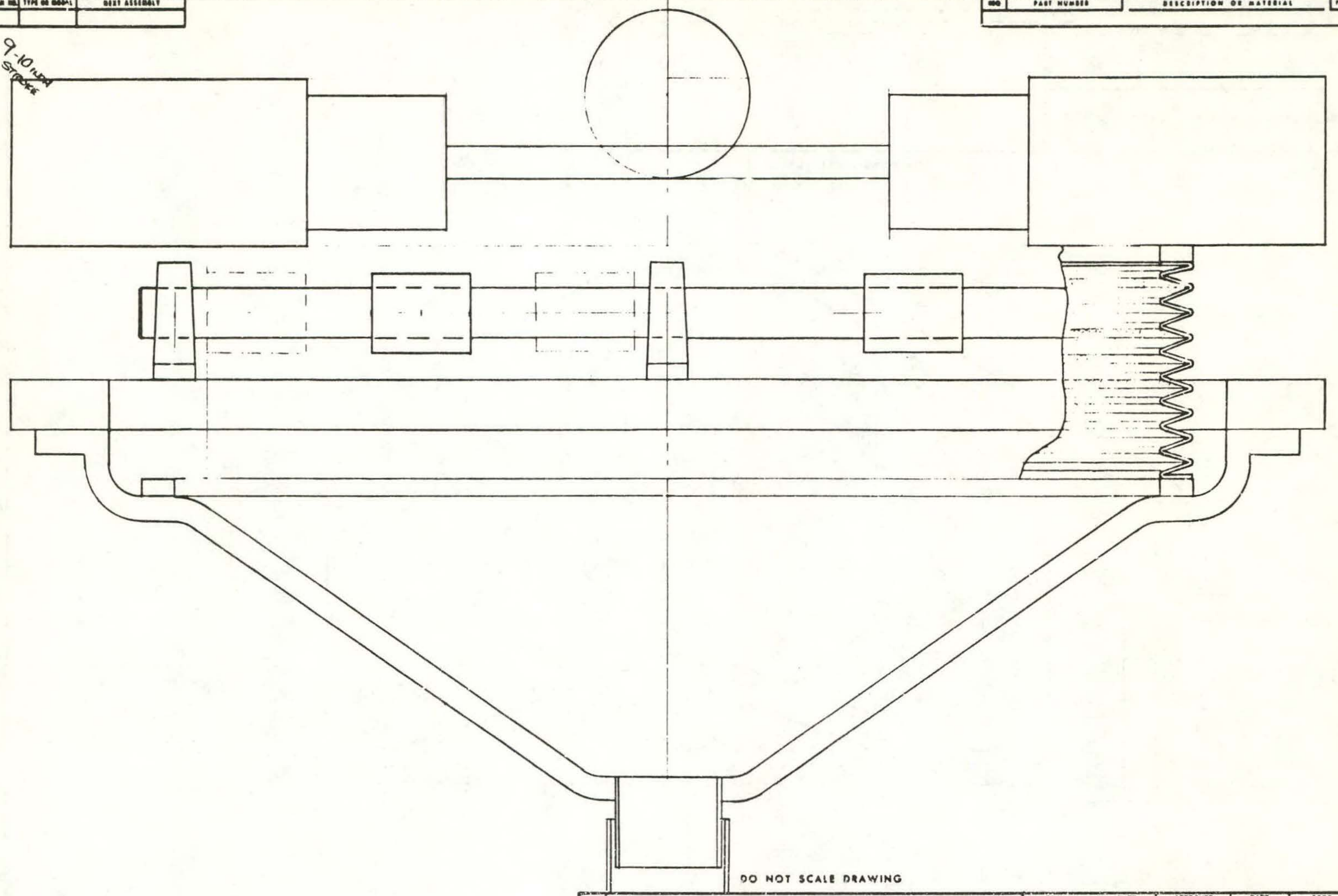

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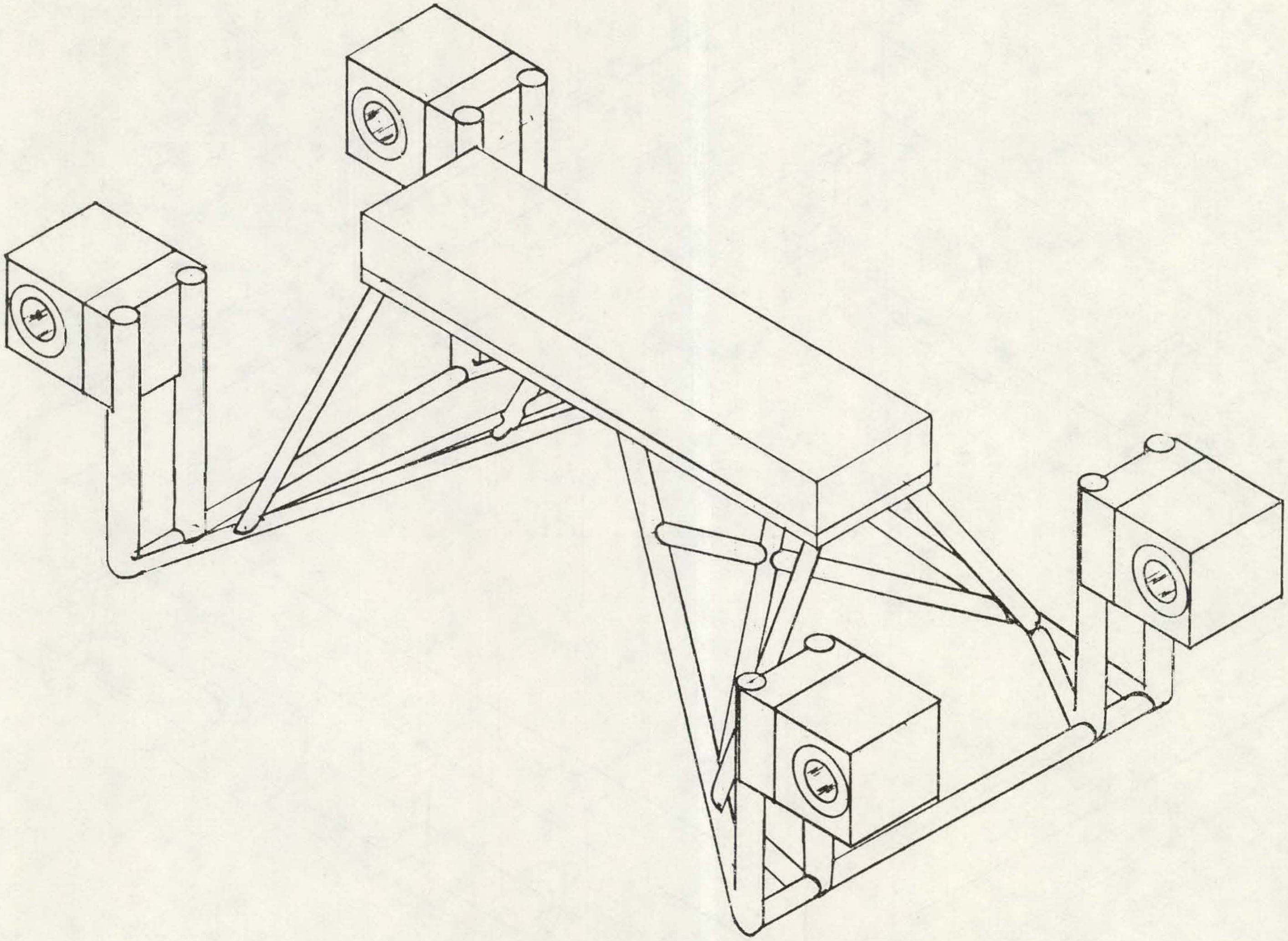

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1 of 2

Workholder Frame
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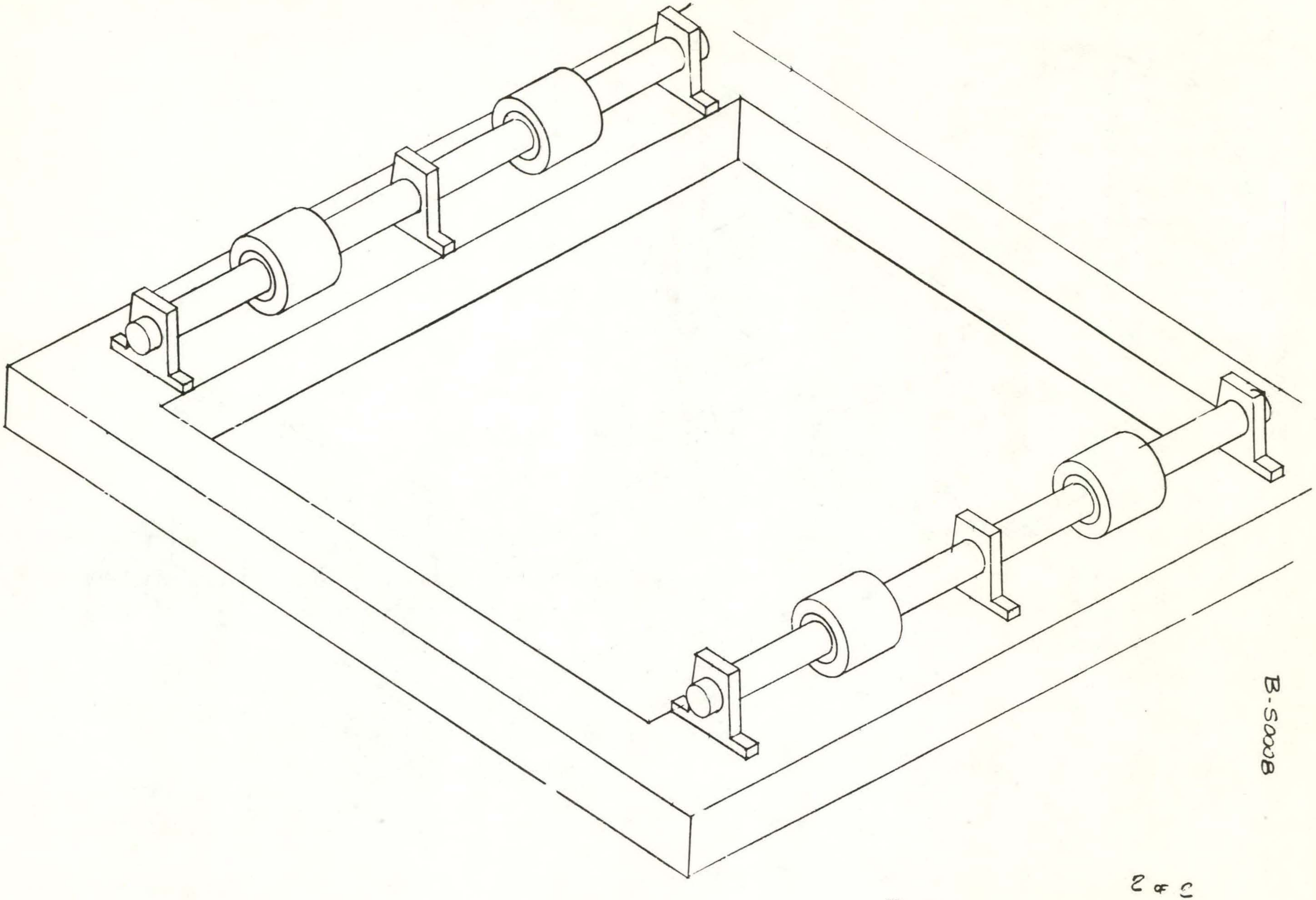

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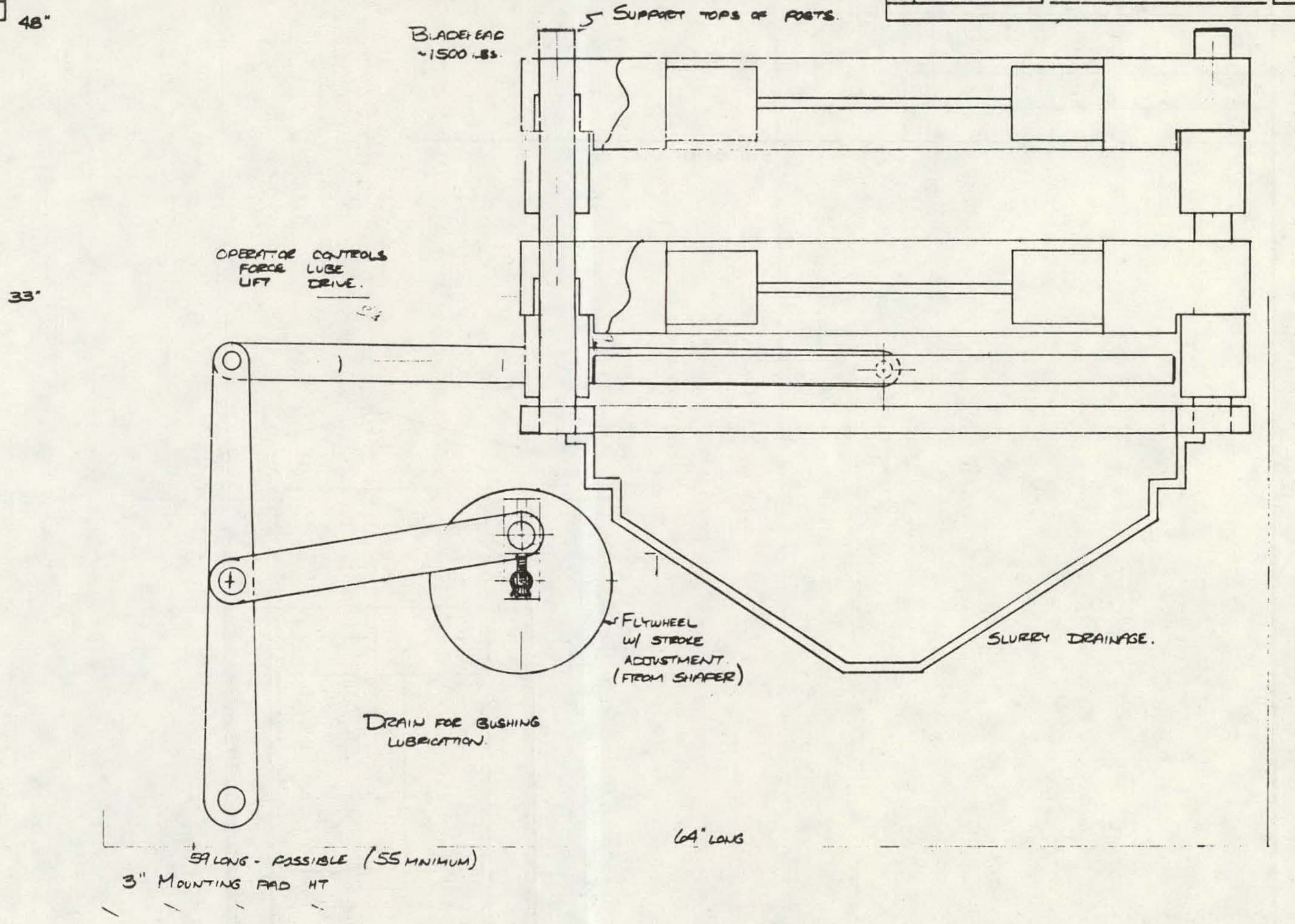
2 of 2



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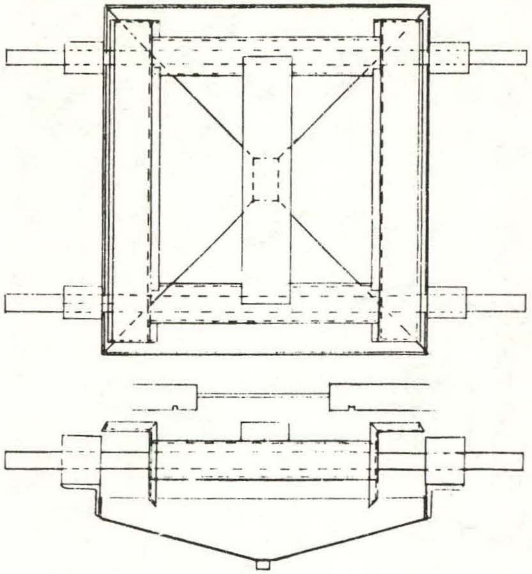

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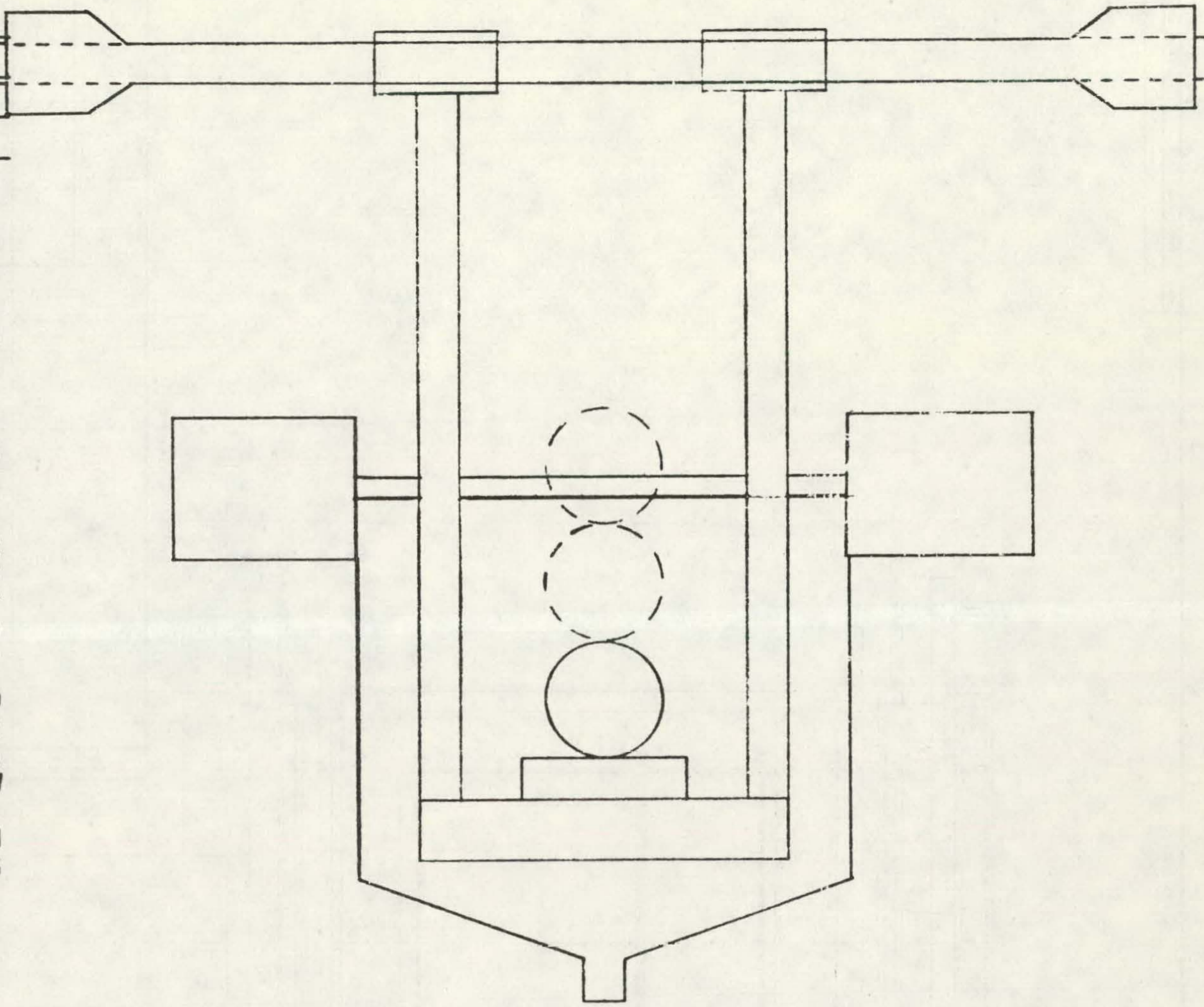

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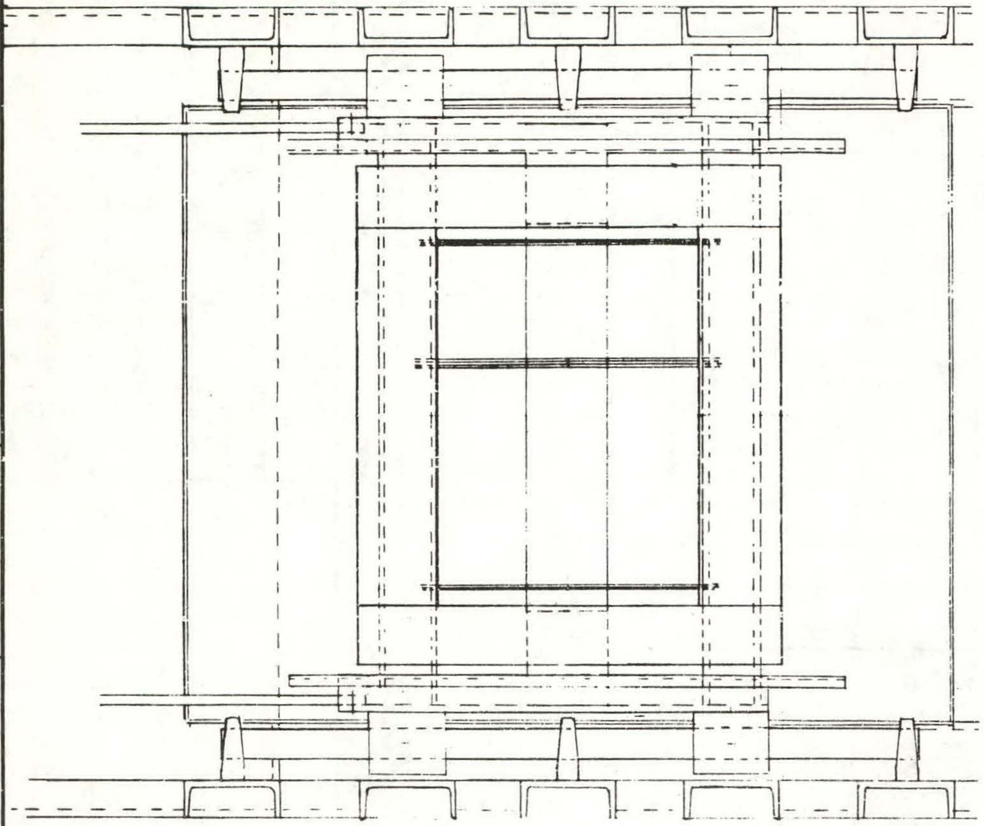

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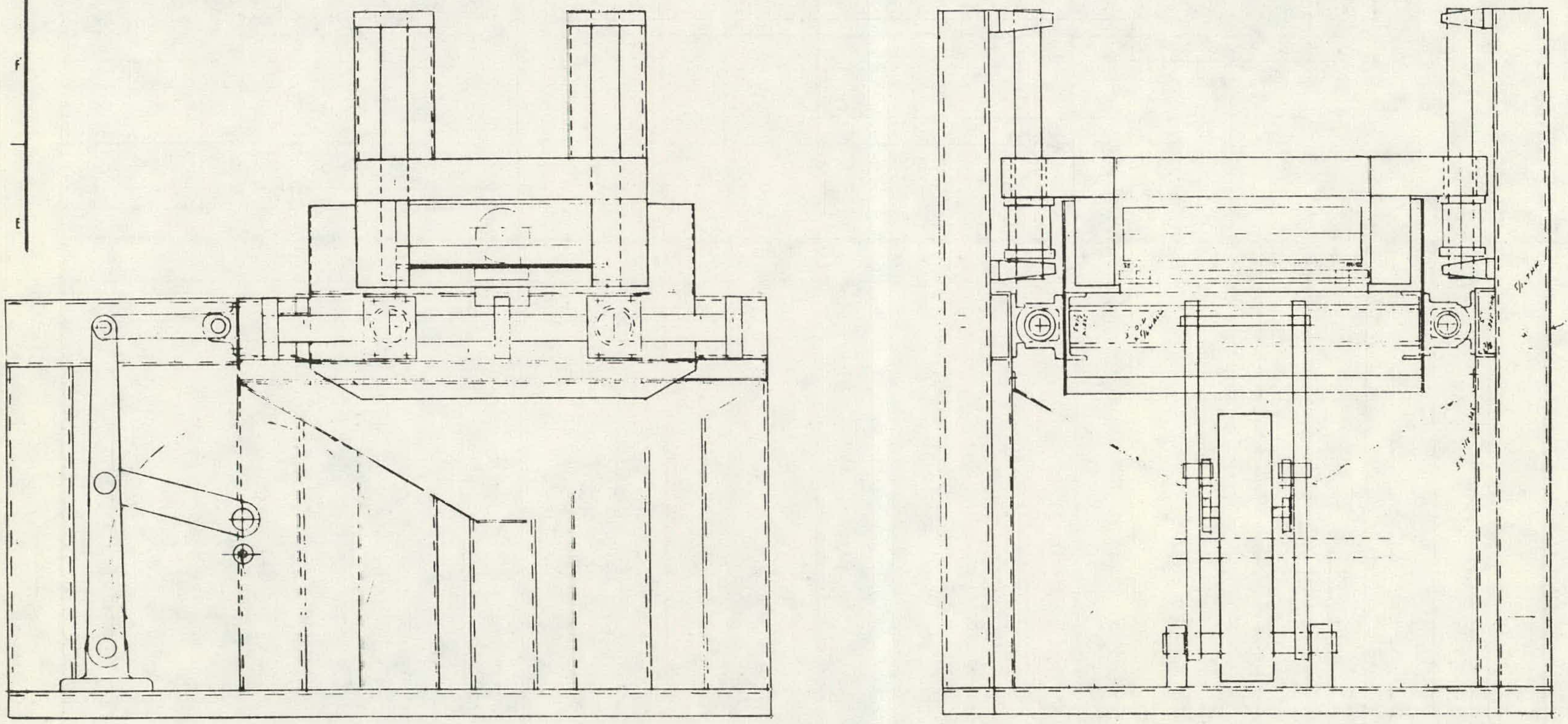

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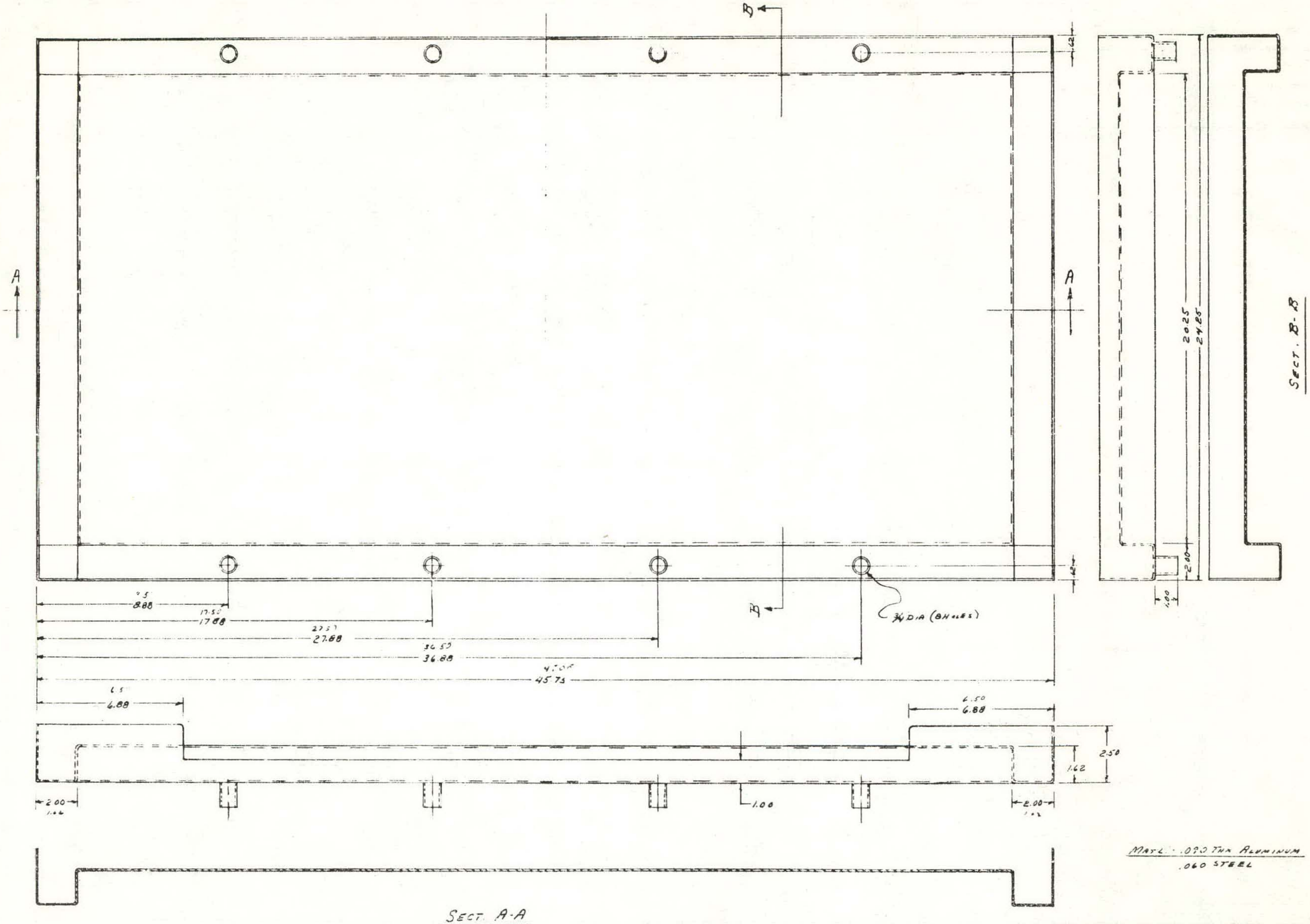

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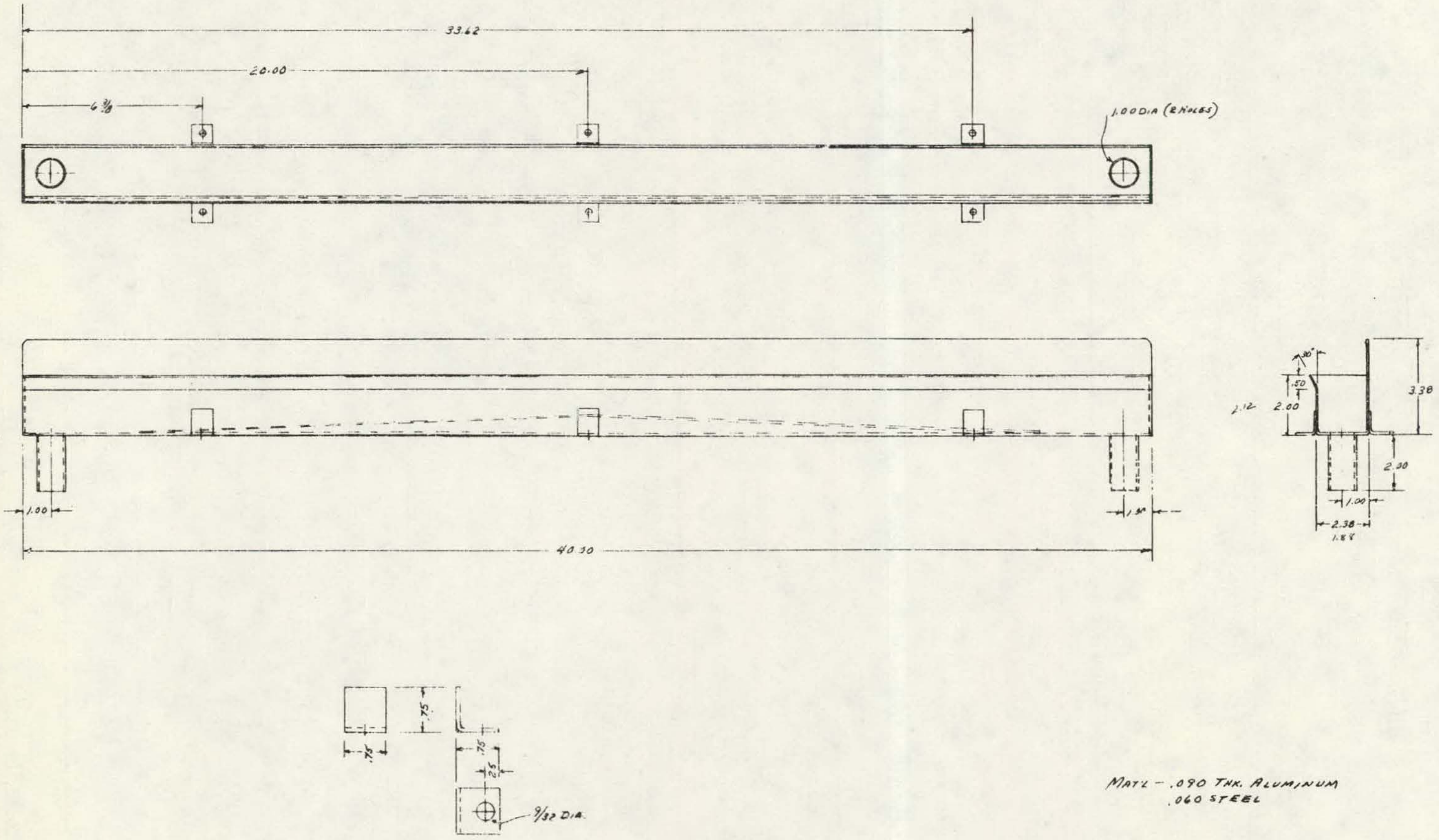

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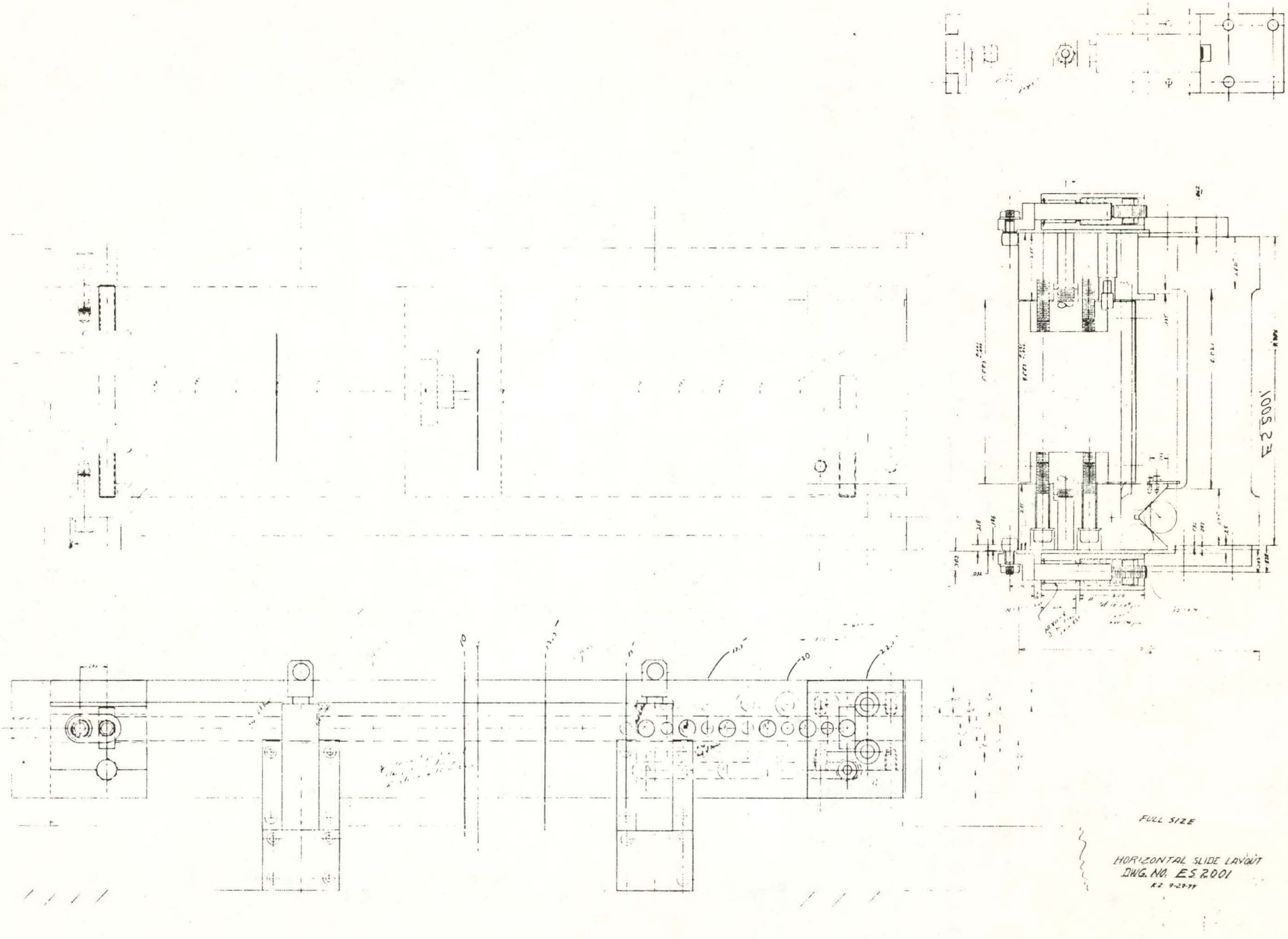

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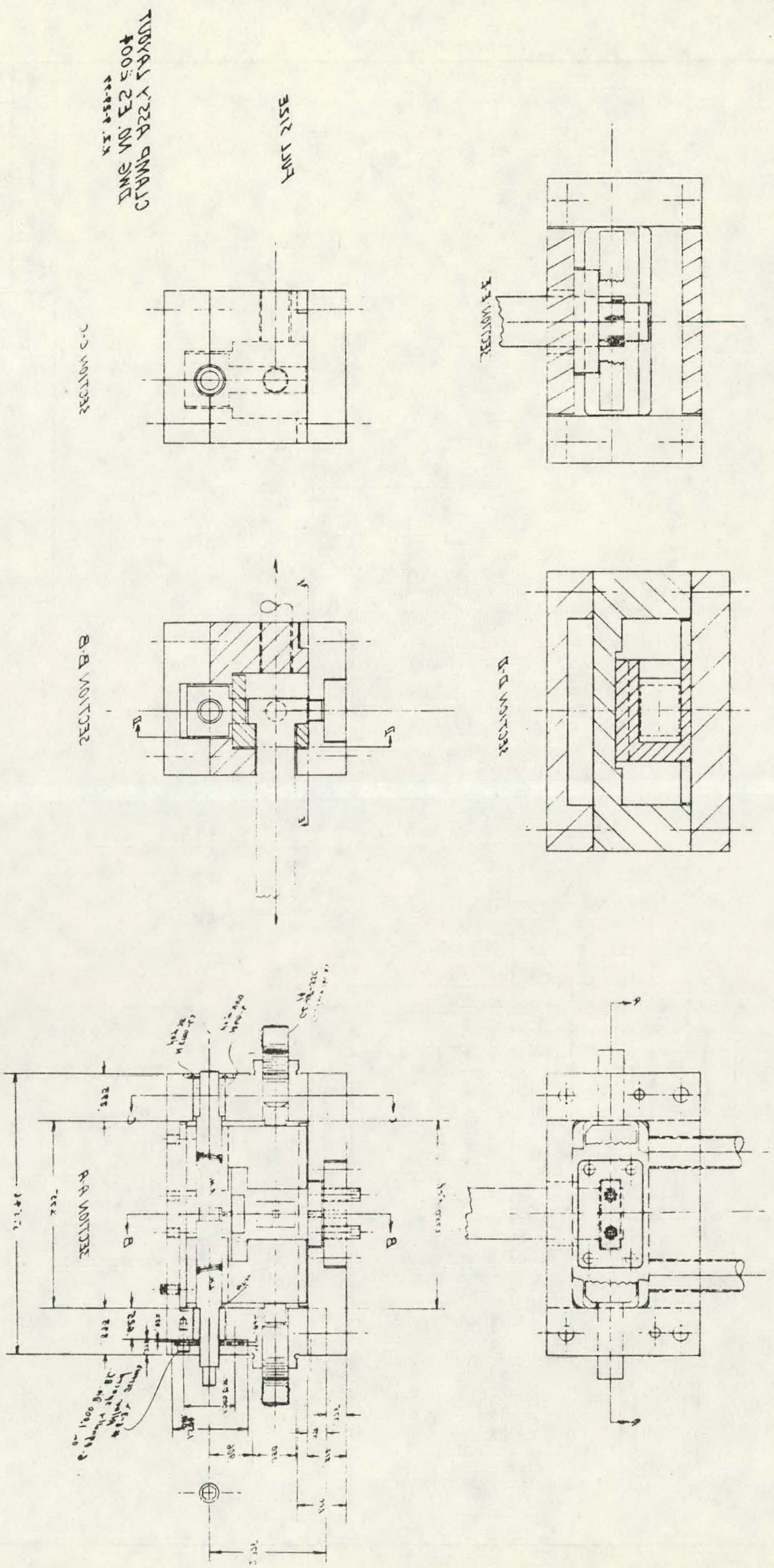
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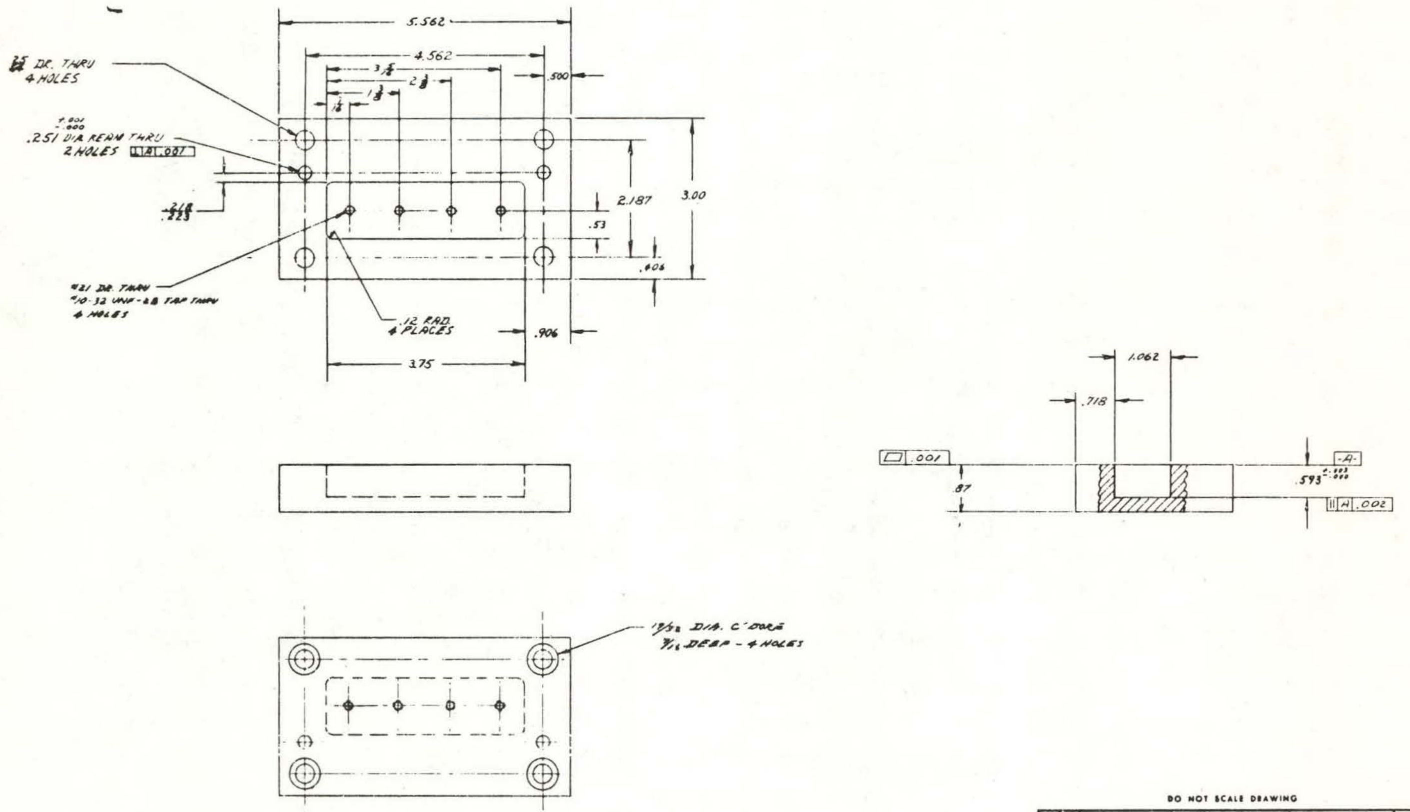

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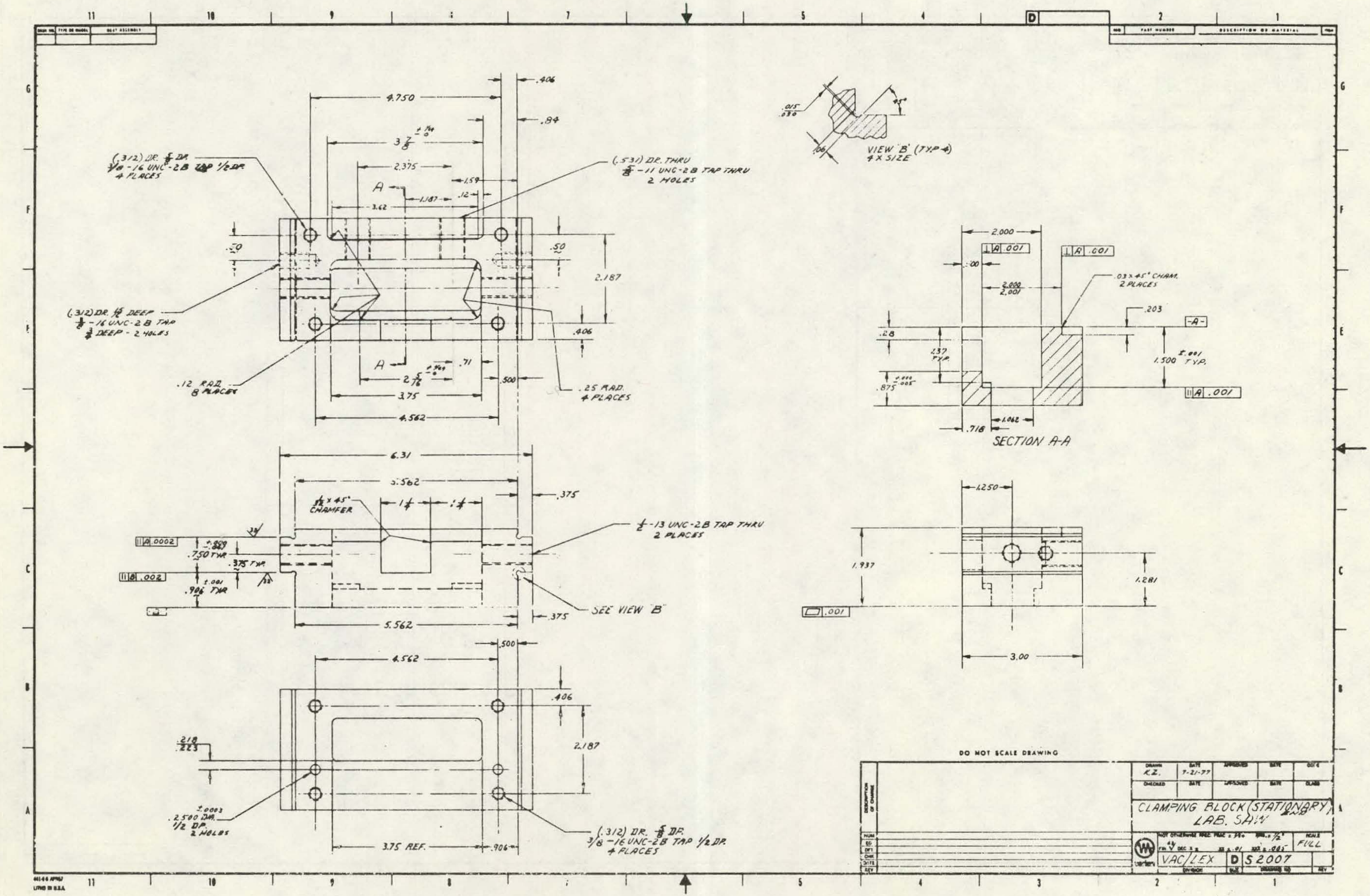
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B .002
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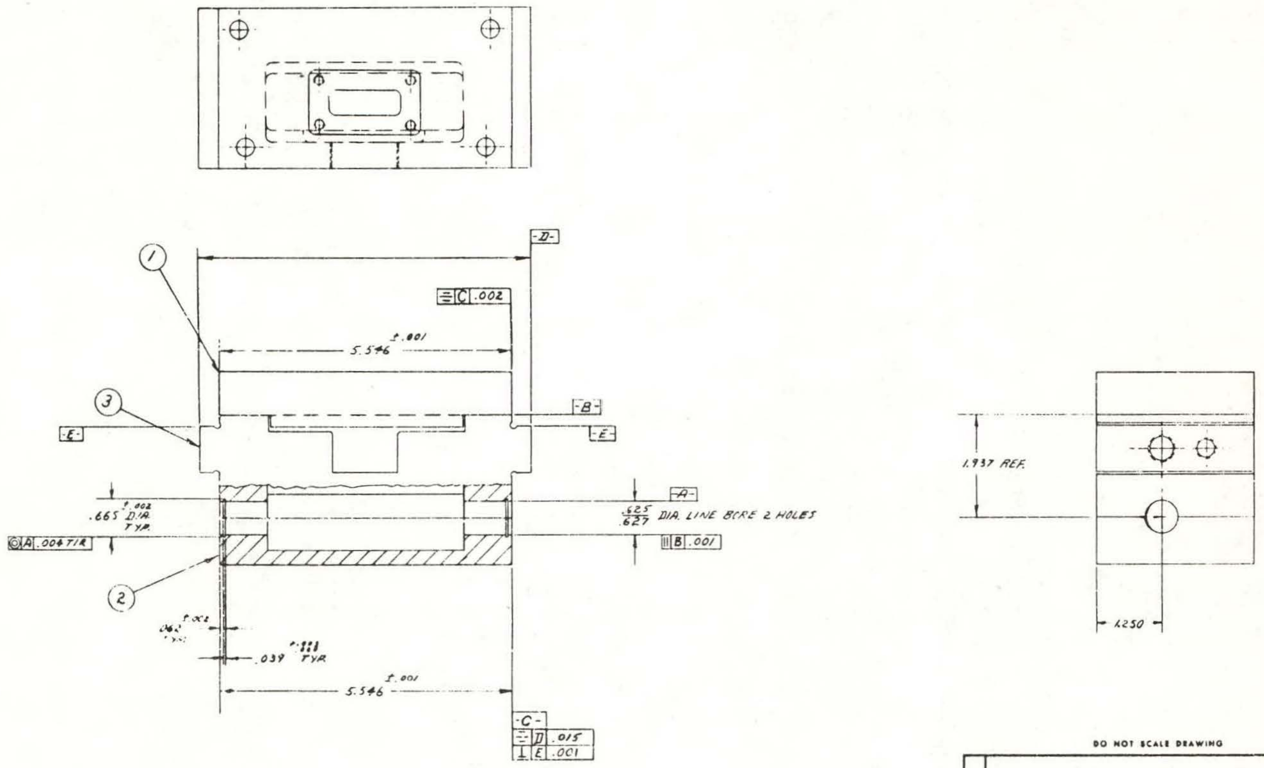

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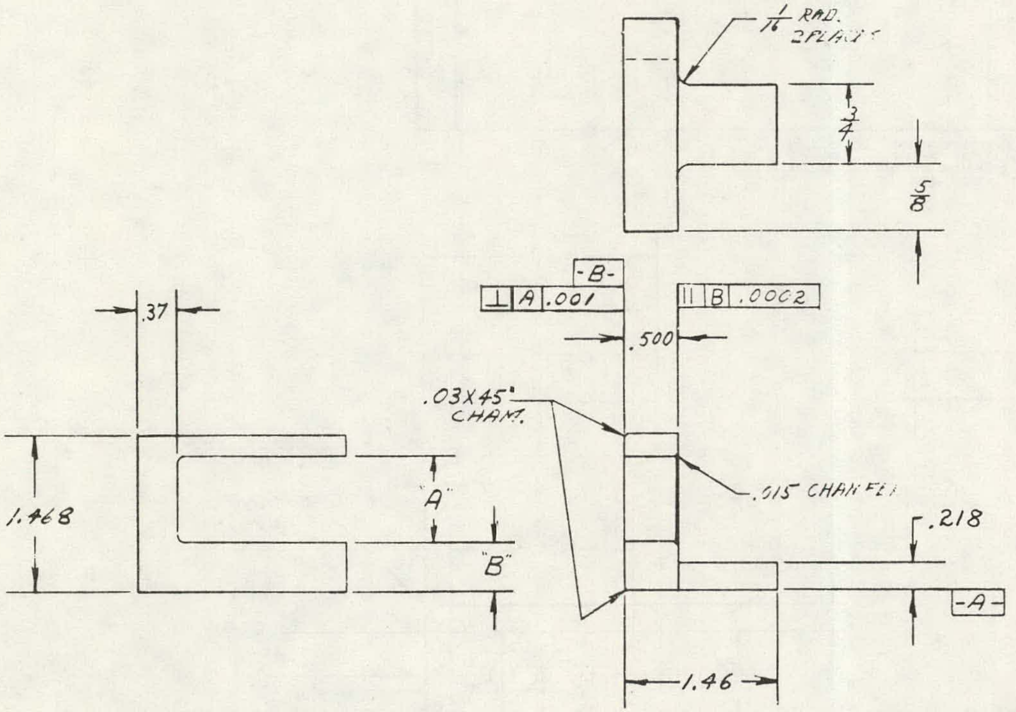

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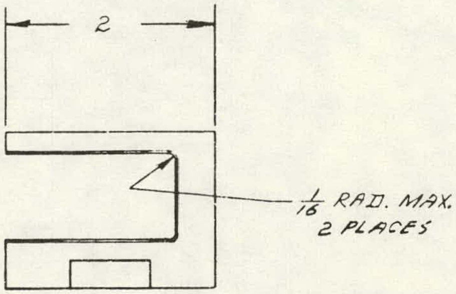
2	.562	.562	.50



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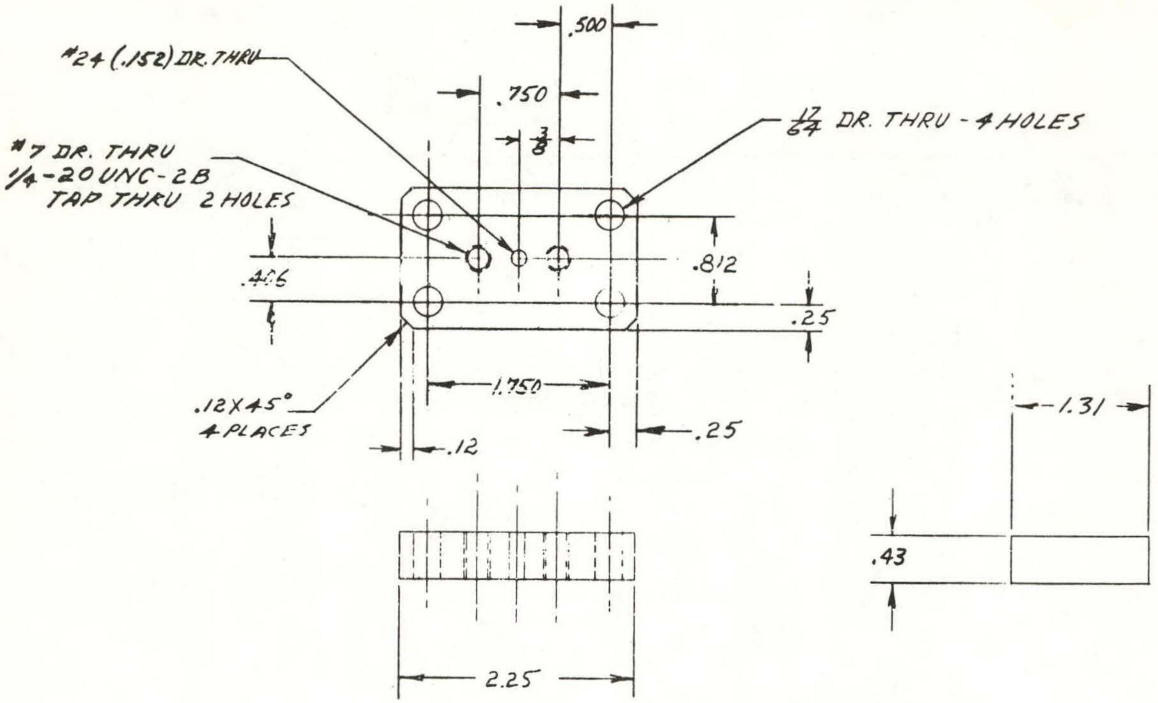

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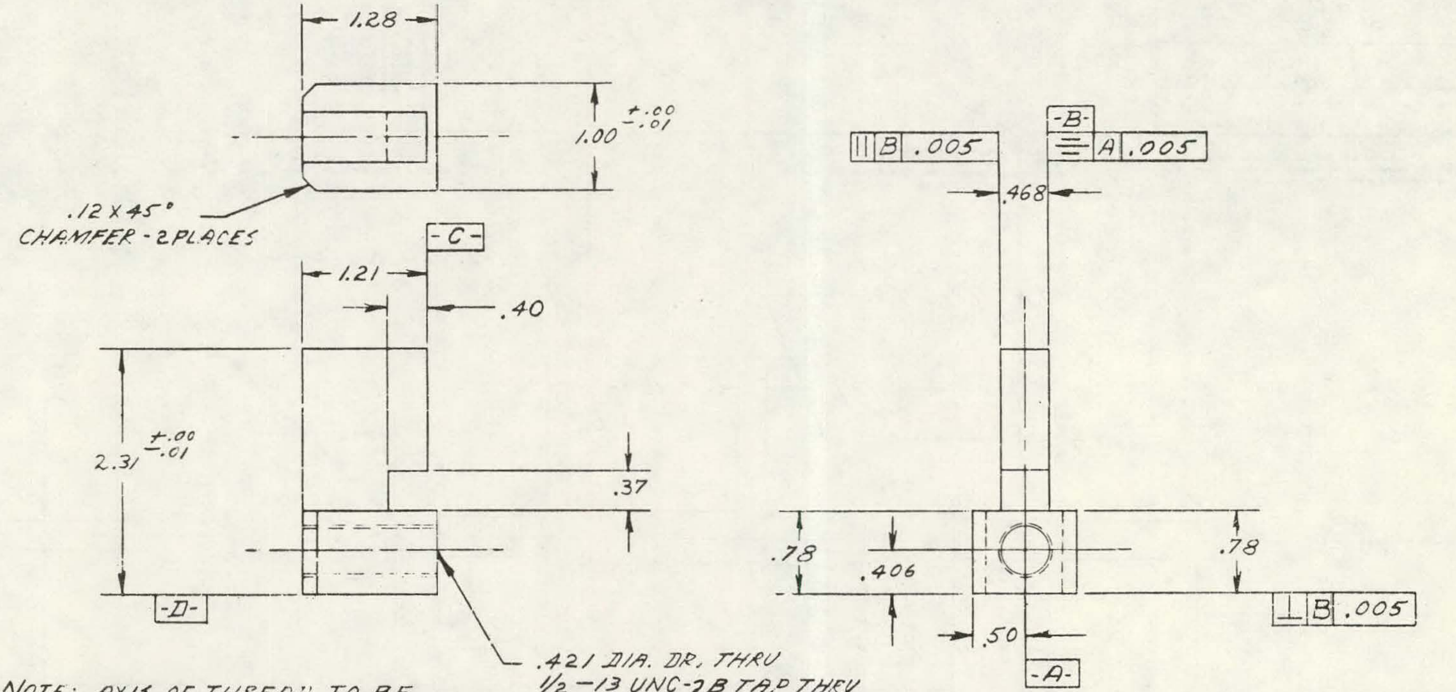

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NOTE: AXIS OF THREAD TO BE PERPENDICULAR TO SURFACE -C- WITHIN .001 AND PARALLEL TO -D- WITHIN .001

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1	R.H.

NOTE: OVER CUT THREADS AT ASSEMBLY FOR LOOSENESS REQUIRED

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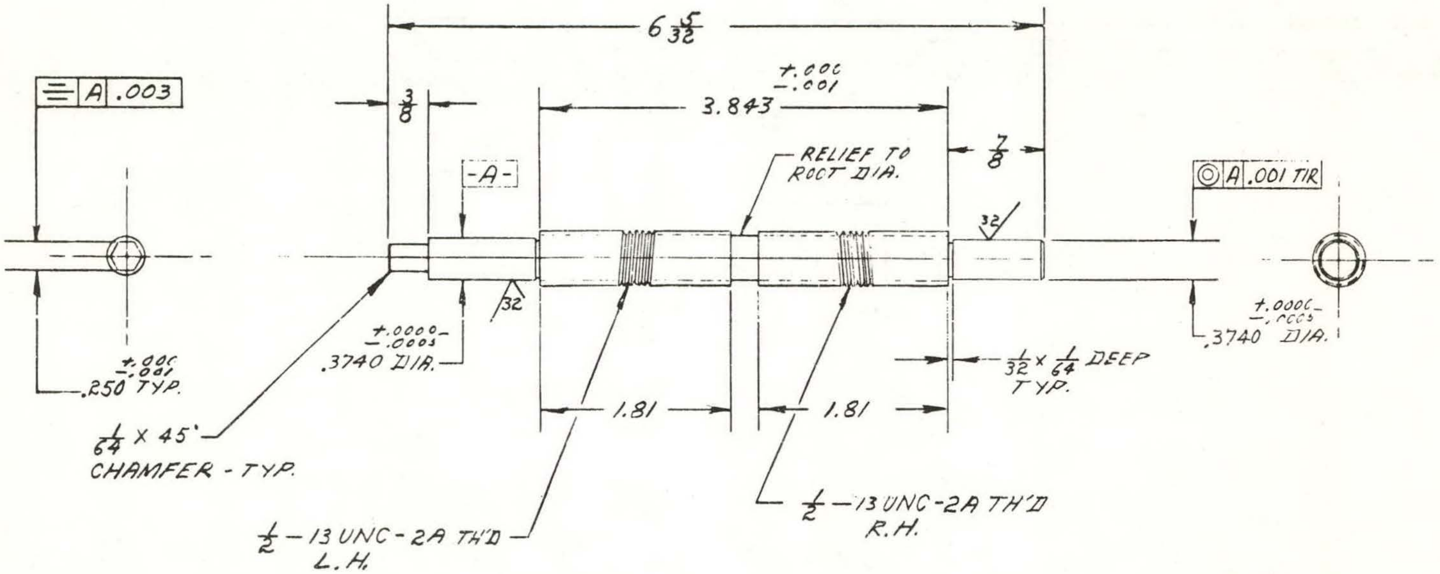

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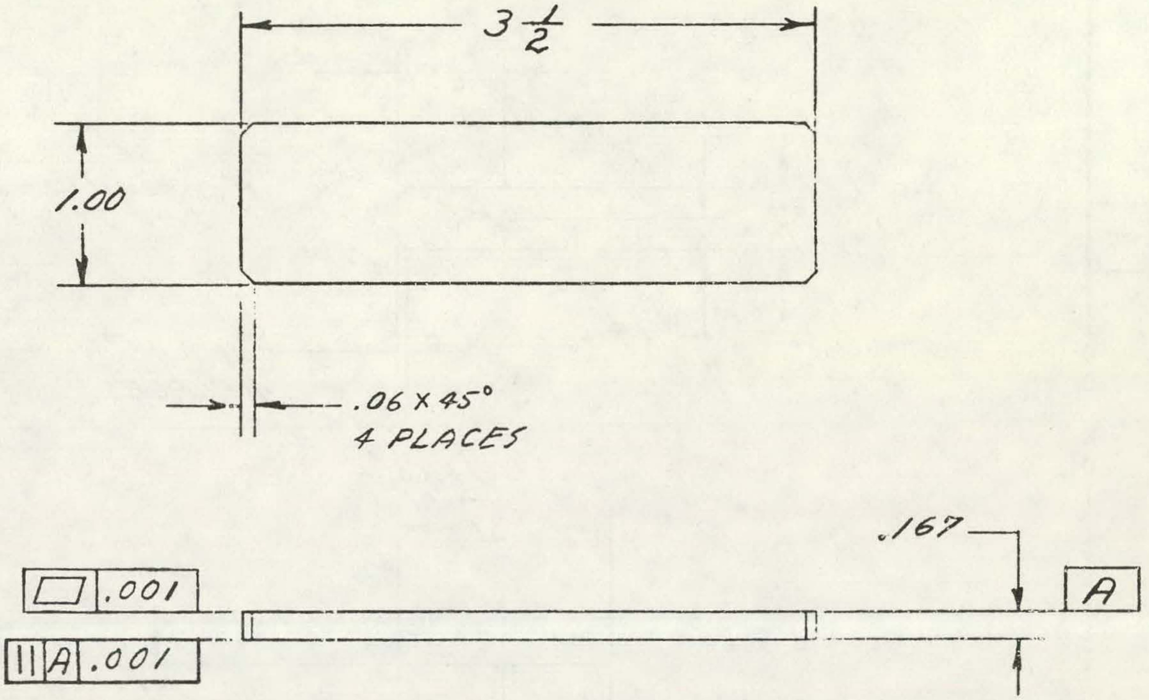

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UNLESS OTHERWISE SPECIFIED
BREAK ALL SHARP EDGES
DIMENSIONS ARE IN INCHES

DRAWN	DATE	APPROVED	DATE	CODE
K.Z.	7-21-77			
CHECKED	DATE	APPROVED	DATE	CLASS

BOTTOM GIB
LAB. SAW

NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/2° SCALE FULL
FIN. 63√ DEC .X ± .XX ± .01 .XXX ± .005

DIVISION	SIZE	DRAWING NO.	REV
VAC/LEX	A	S2013	

varian

DESCRIPTION OF CHANGE

NUM	
EO	
DFT	
CHK	
DATE	
REV	

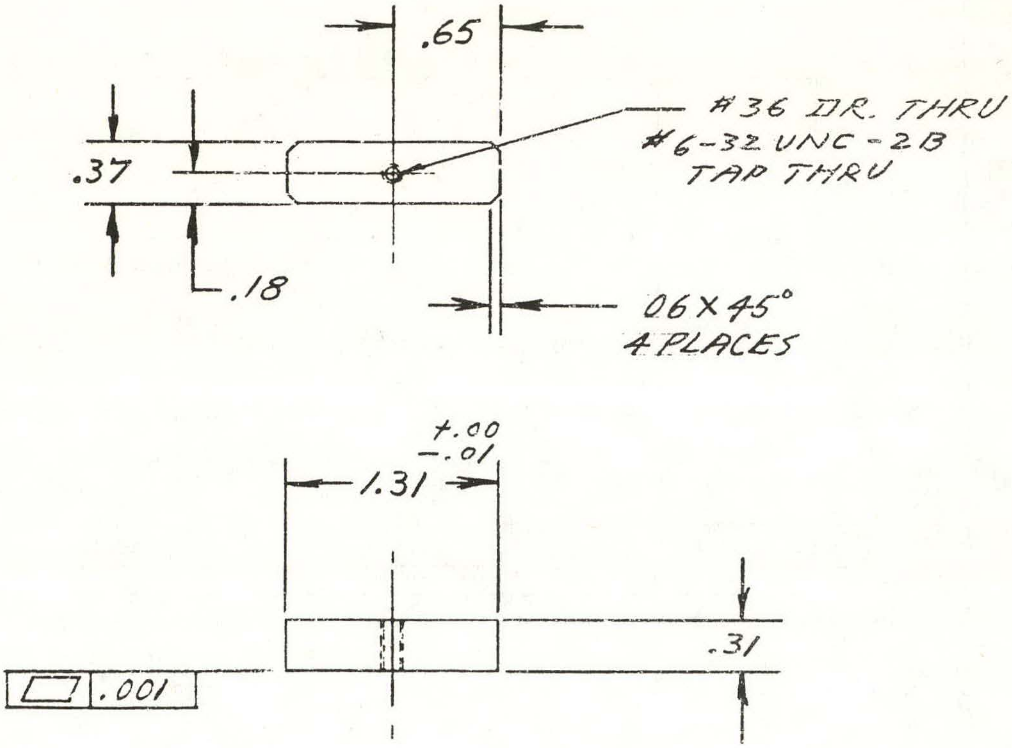
LITHO IN U.S.A.

44163 MAY

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

A

DO NOT SCALE DRAWING



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DIMENSIONS ARE IN INCHES

DRAWN	DATE	APPROVED	DATE	CODE
K.Z.	7-21-77			
CHECKED	DATE	APPROVED	DATE	CLASS

TOP GIB
LAB. SAW

NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/2°
FIN. 63√ DEC .X ± .XX ± .01 .XXX ± .005
SCALE FULL

varian

DIVISION	SIZE	DRAWING NO.	REV
VAC/LEX	A	S2014	

DESCRIPTION OF CHANGE

NUM
EC
DFT
CHK
DATE
REV

LITHO IN U.S.A.

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

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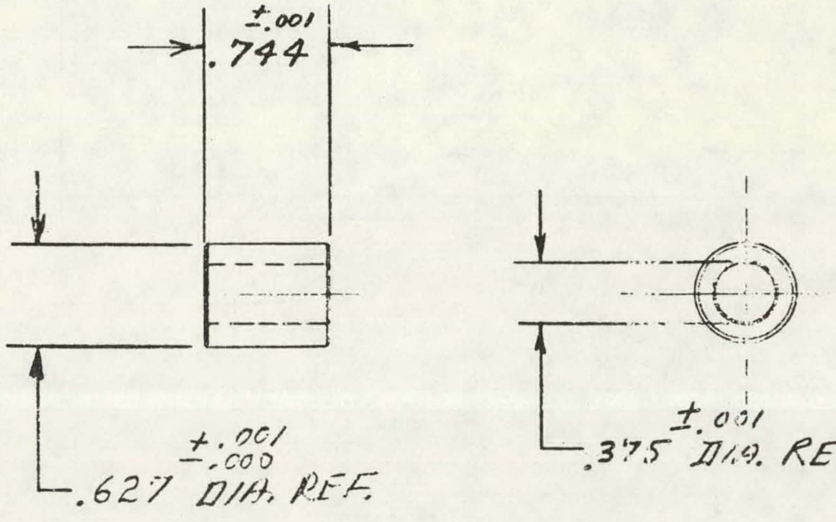

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DIMENSIONS ARE IN INCHES

DRAWN	DATE	APPROVED	DATE	CODE
R.Z.	7-21-77			
CHECKED	DATE	APPROVED	DATE	CLASS

ALTERED BOSTON GEAR BUSHING M610-6
LAB. SAW

NOT OTHERWISE SPEC: FRAC ± ANG ±
FIN. $\overset{63}{\surd}$ DEC .X ± .XX ± .XXX ±
SCALE FULL

varian

DIVISION	SIZE	DRAWING NO.	REV
VAC/LEX	A	S 2015	

DESCRIPTION OF CHANGE

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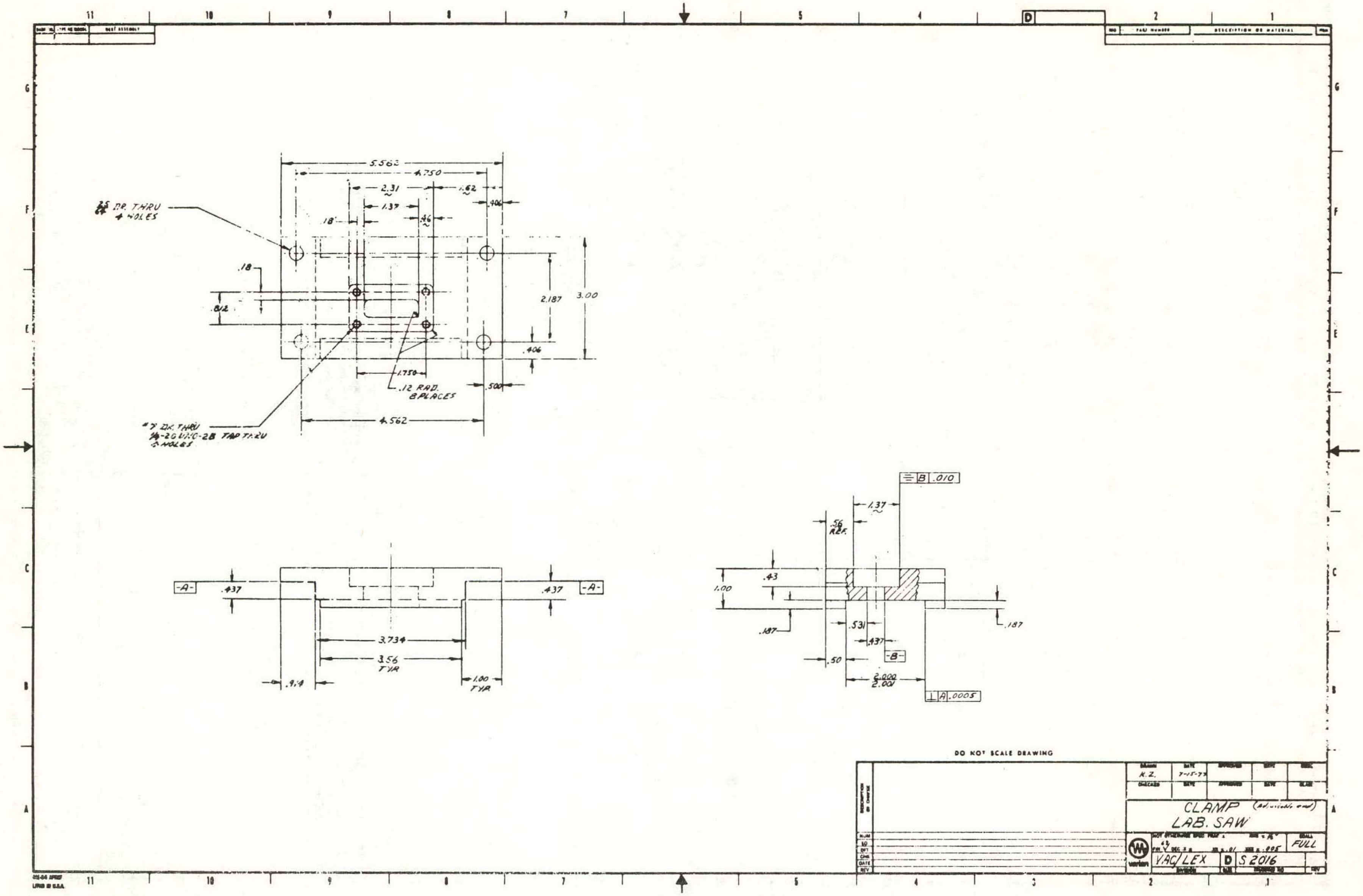
EO	
DFT	
CHK	
DATE	
REV	

LITHO IN U.S.A.
4143 MAY

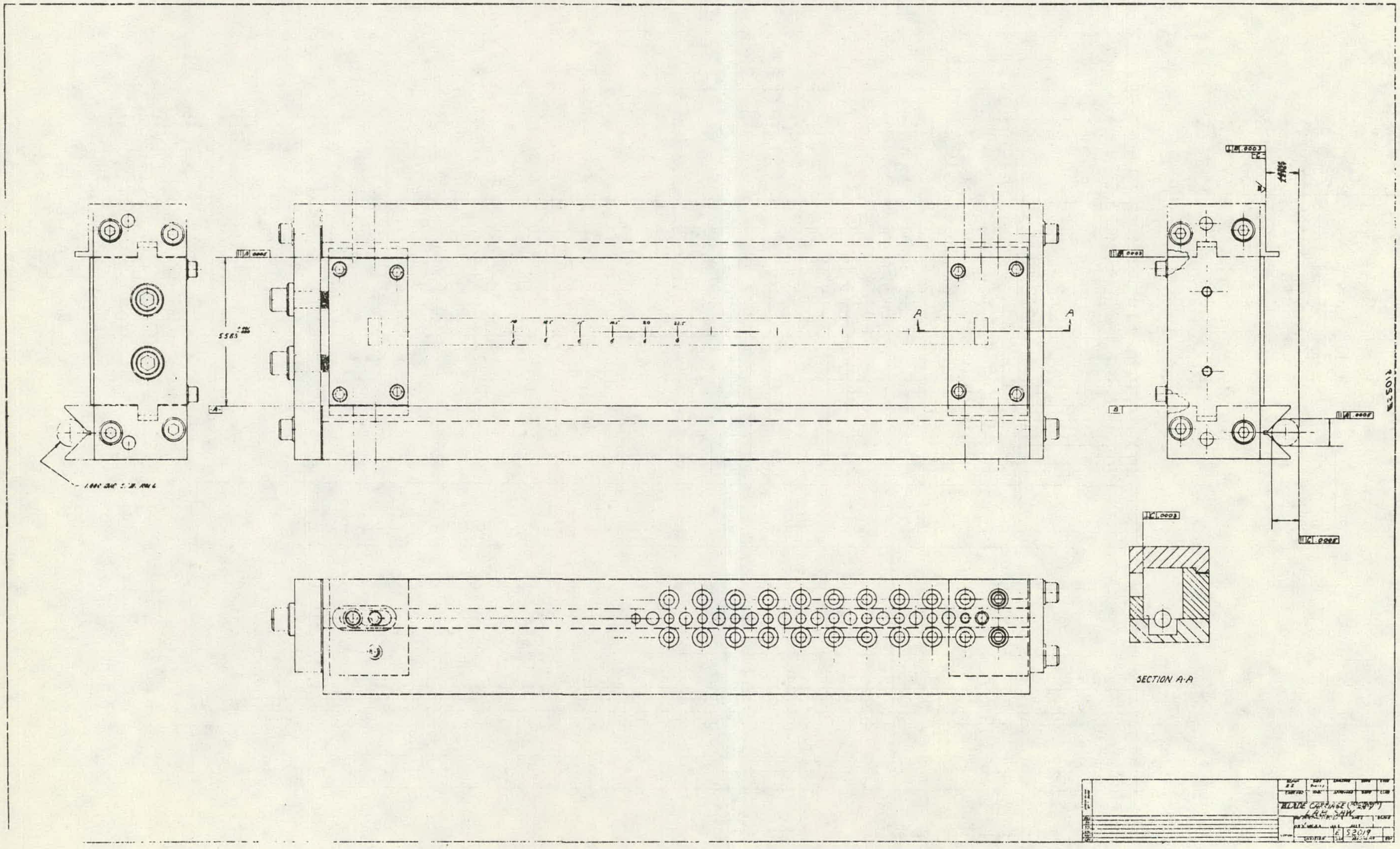


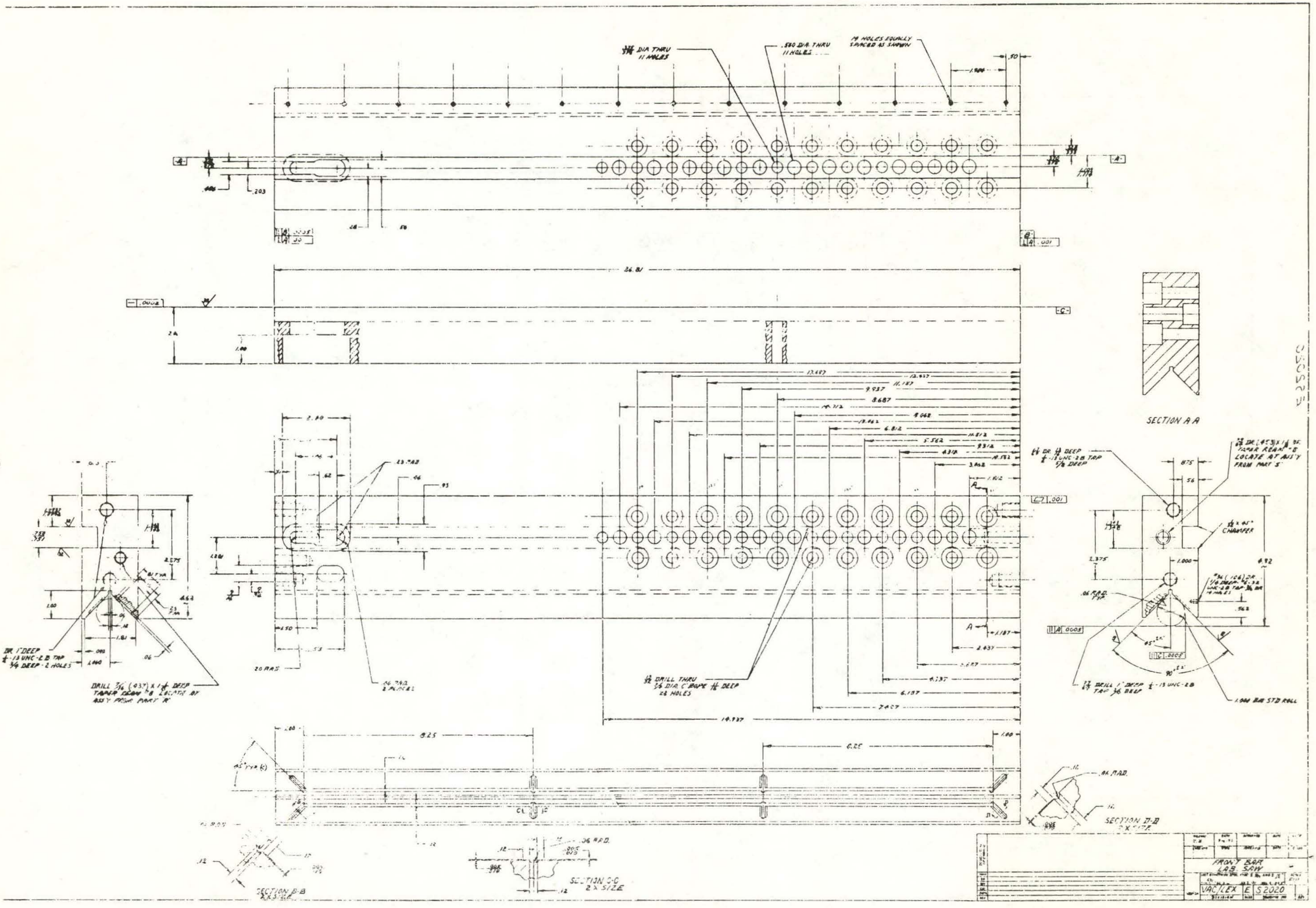
DO NOT SCALE DRAWING

K.Z.
7-15-77

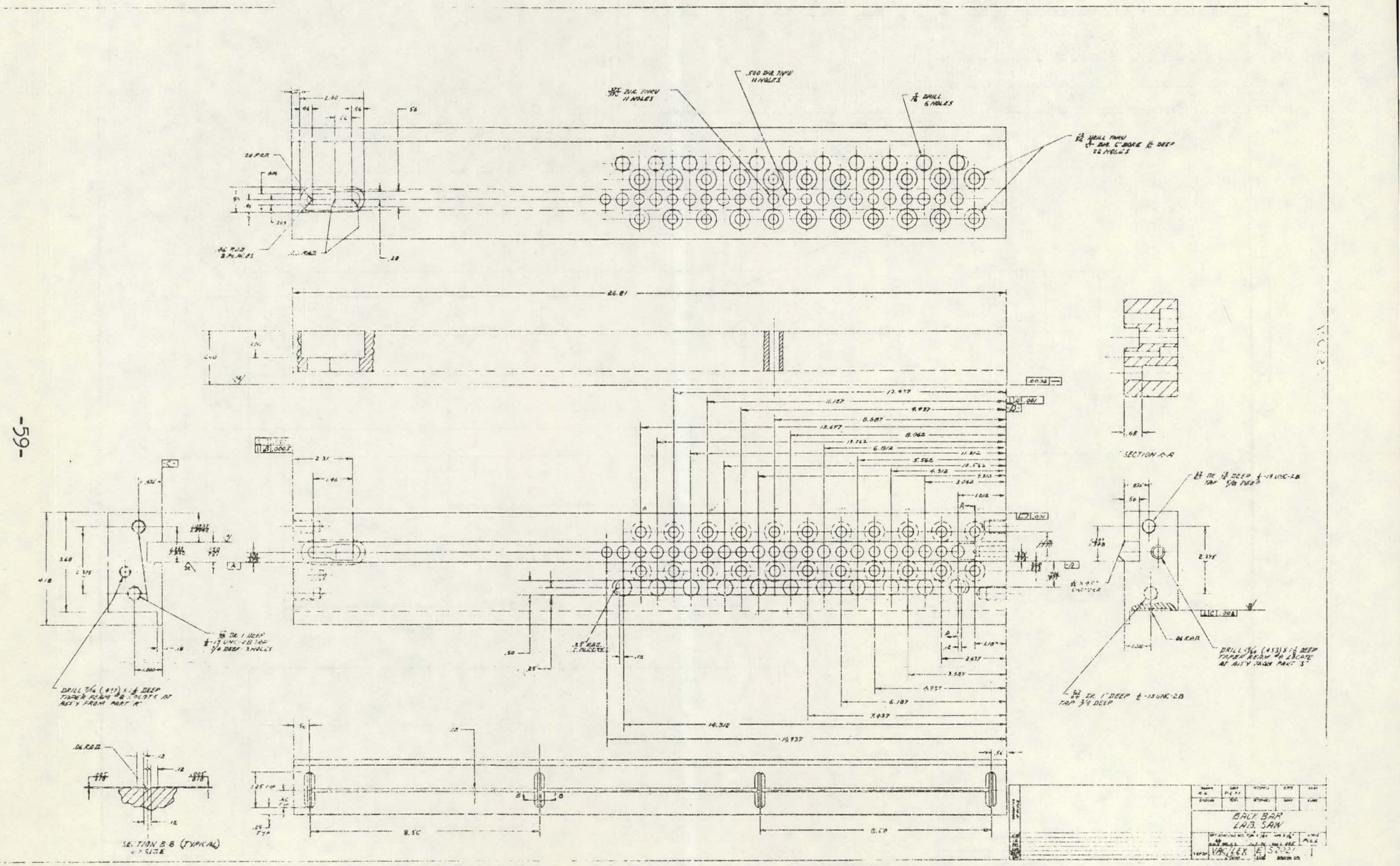
CLAMP (adjustable end)
LAB. SAW

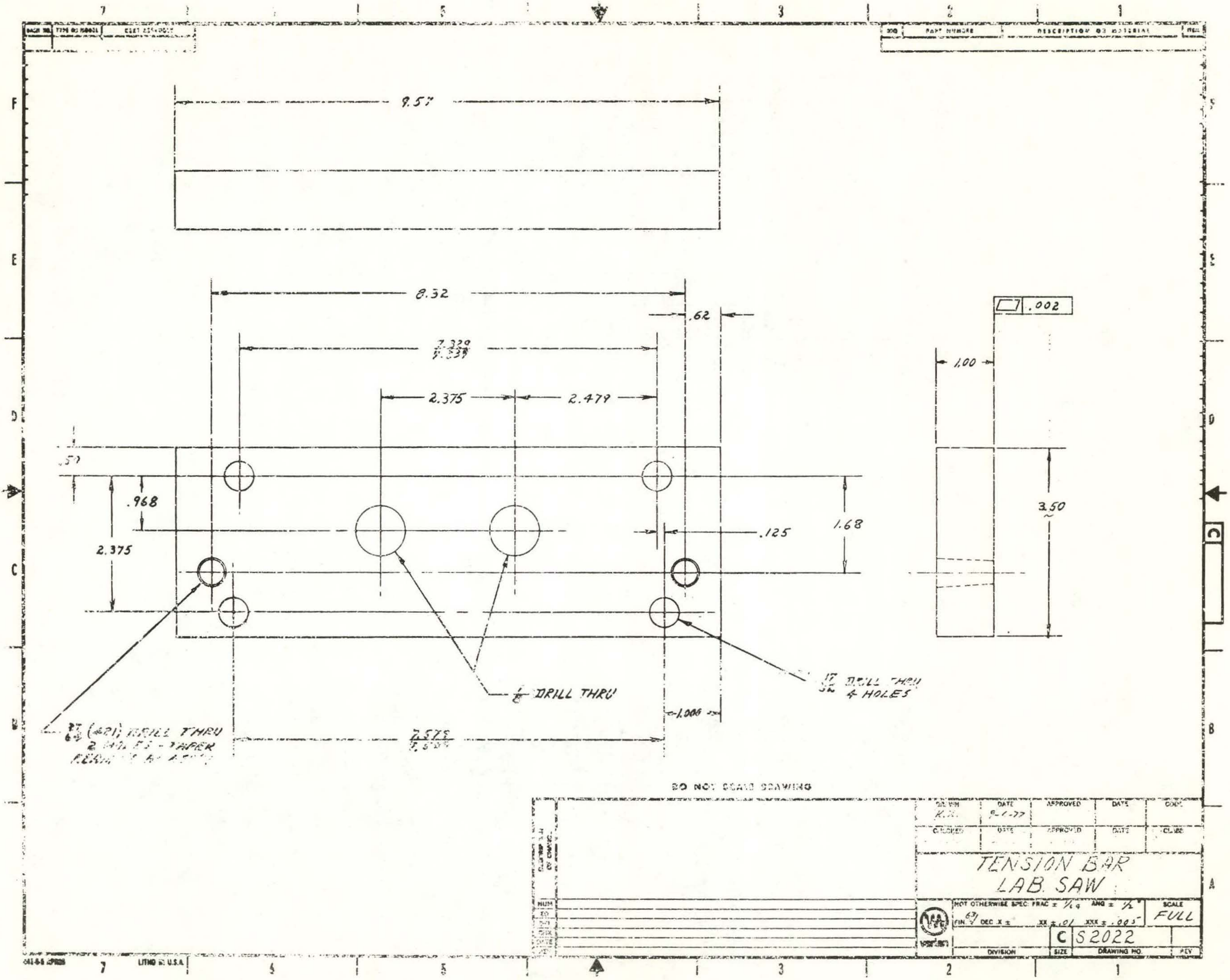
FULL
VAC/LEX
D S 2016

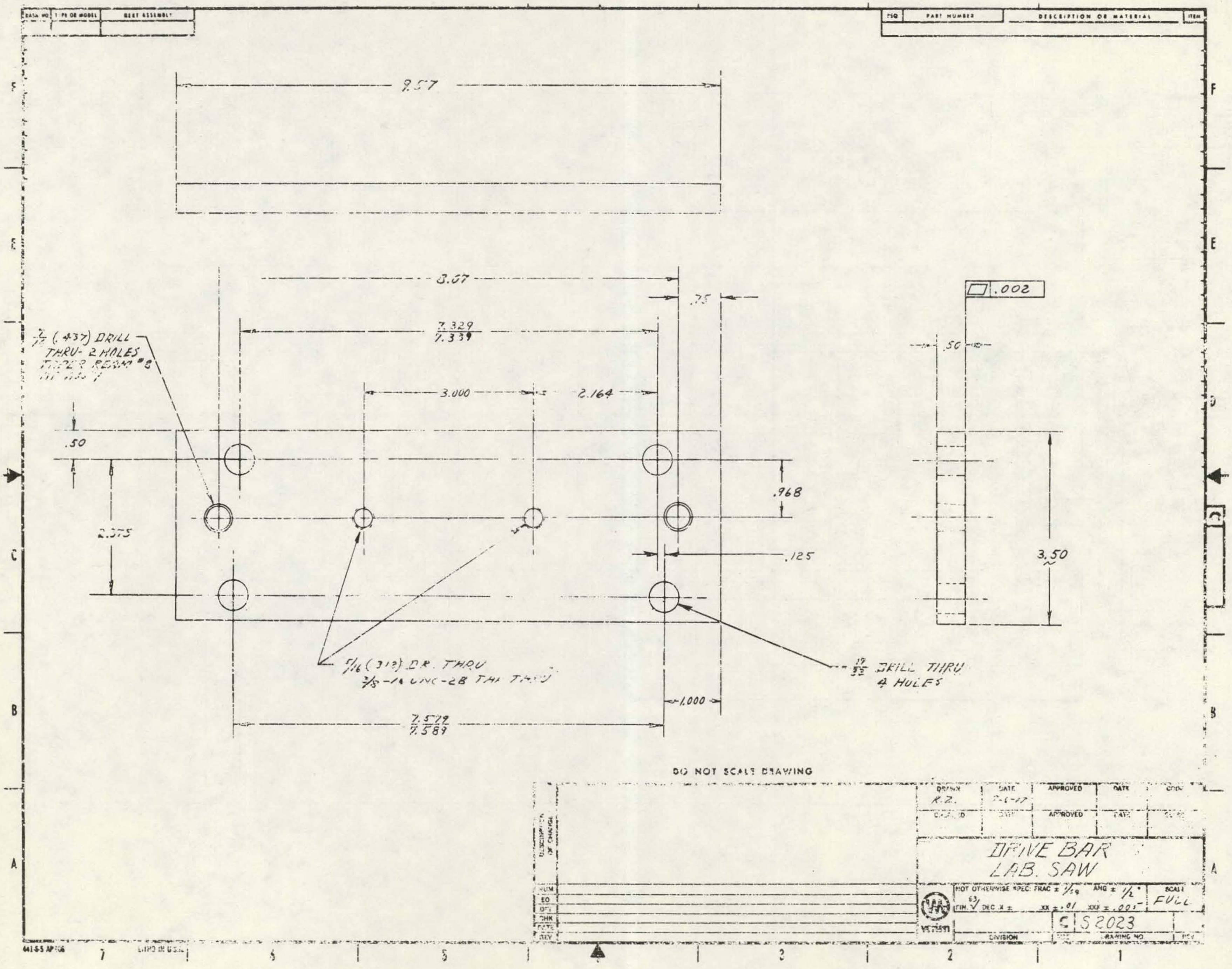

5.563
A
B
A
A
.0005
.0003
.0005
.0003
.0005
SECTION A-A
BLADE CARRIAGE
LAM SAW
E
52019

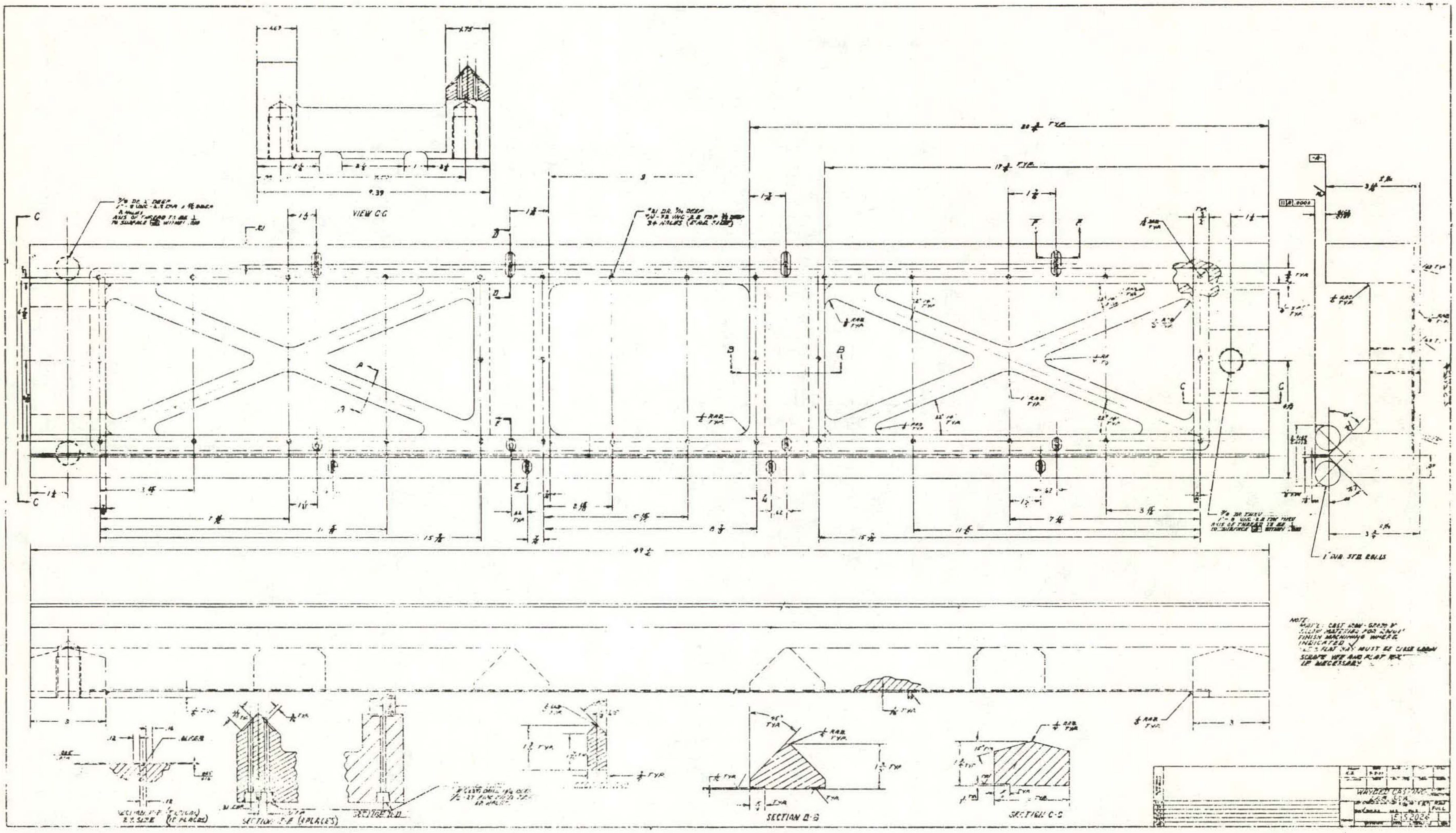


DIA THRU 11 HOLES
.580 DIA THRU 11 HOLES
14 HOLES EQUALLY SPACED AS SHOWN
1.900
.50
.203
26.81
SECTION A A
23 RAD
2.375
DR 1" DEEP ¼-13 UNC-2B TAP ¾ DEEP - 2 HOLES
DRILL 7/16 (.437) X 1¼ DEEP TAPER REAM #8 LOCATE AT ASS'Y FROM PART "R"
20 RMS
.06 RAD 2 PLACES
½ DRILL THRU ¾ DIA. C'BORE ½ DEEP 22 HOLES
13.687
12.937
11.187
9.937
8.687
8.062
6.812
5.562
4.312
3.062
1.812
1.187
2.437
6.137
14.937
¼ DR. ½ DEEP ¼-13 UNC-2B TAP 5/8 DEEP
TAPER REAM #8 LOCATE AT ASS'Y FROM PART "S"
.875
⅛ X 45° CHAMFER
1.000
.06 RAD. TYP.
.563
1.000 DIA STD ROLL
DRILL 1" DEEP ¼-13 UNC-2B TAP ⅝ DEEP
8.25
6.25
1.00
.06 RAD.
SECTION D-D 2 X SIZE
SECTION B-B 2 X SIZE
SECTION C-C 2 X SIZE
.06 RAD.
FRONT BAR LAB. SAW
VAC/LEX
E
S2020
ES2020


.500 DIA THRU 11 HOLES
11 HOLES
6 HOLES
22 HOLES
2.40
26.81
12.437
11.187
9.937
8.687
13.687
8.062
6.812
11.812
5.562
10.562
4.312
3.062
1.812
SECTION A-A
.68
2.375
3.68
4.18
1.18
2.437
3.687
4.937
6.187
7.437
14.312
14.937
DRILL 7/16 (.437) X 1½ DEEP TAPER REAM "B" LOCATE AT ASS'Y FROM PART "R"
1/4-13 UNC-2B TAP 3/4 DEEP 3 HOLES
1/4-13 UNC-2B TAP 3/4 DEEP
.06 RAD.
DRILL 29/64 (.453) X 1½ DEEP TAPER REAM "A" LOCATE AT ASS'Y FROM PART "S"
1/2-13 UNC-2B
TAP 3/4 DEEP
.06 RAD
SECTION B-B (TYPICAL)
1.25 TYP
8.50
8.50
BACK BAR
LAB. SAW
VAC/LEX
E
52027

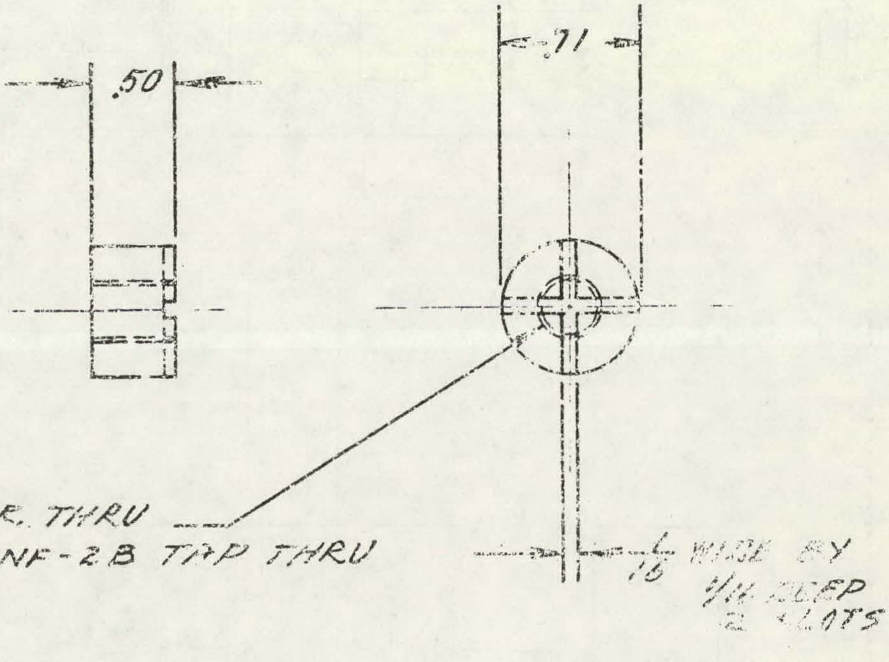

9.57
8.32
.62
7.329
7.339
2.375
2.479
1.00
.002
.57
.968
2.375
.125
1.68
3.50
$\frac{27}{64}$ (#21) DRILL THRU
2 HOLES - TAPER
REAM
$\frac{1}{2}$ DRILL THRU
$\frac{17}{32}$ DRILL THRU
4 HOLES
1.006
7.575
DO NOT SCALE DRAWING
DRAWN
K.K.
DATE
9-1-77
APPROVED
DATE
CODE
CHECKED
DATE
APPROVED
DATE
CLASS
TENSION BAR
LAB. SAW
NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/2°
FIN. 63 DEC .X ± .XX ± .01 .XXX ± .005
SCALE
FULL
varian
C
S2022
DIVISION
SIZE
DRAWING NO.
REV
LITHO IN U.S.A.


DATA NO
TYPE OR MODEL
NEXT ASSEMBLY
FSQ
PART NUMBER
DESCRIPTION OR MATERIAL
ITEM
F
E
D
C
B
A
9.57
8.07
.75
7.329
7.339
.50
3.000
2.164
.50
.968
2.375
.125
3.50
.002
7/16 (.437) DRILL
THRU- 2 HOLES
5/16 (.313) DR. THRU
3/8-16 UNC-2B THR THRU
17/32 DRILL THRU
4 HOLES
1.000
7.579
7.589
DO NOT SCALE DRAWING
DESCRIPTION OF CHANGE
NUM
EO
OPT
CHK
DATE
REV
DRAWN
R.Z.
DATE
APPROVED
DATE
CHECKED
APPROVED
DRIVE BAR
LAB. SAW
NOT OTHERWISE SPEC: FRAC ± 1/64
ANG ± 1/2°
FIN. 63√
DEC .X ±
.XX ± .01
.XXX ± .005
SCALE
FULL
DIVISION
C
S 2023
DRAWING NO.
7
6
5
4
3
2
1
441-6-5 AP 66
LITHO IN U.S.A.


VIEW C-C
SECTION B-B
SECTION C-C
SECTION E-E
SECTION D-D
SECTION F-F
49 1/2
20 3/4 TYP.
17 3/4 TYP.
1" DIA. STD. BALLS
NOTE:
MAT'L: CAST IRON - GRADE
FINISH MACHINING WHERE INDICATED
SCRAPE VEE AND FLAT
IF NECESSARY
WAYGED CASTING
FULL
E 52026

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

DO NOT SCALE DRAWING



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R.Z.	9-13-77			
CHECKED	DATE	APPROVED	DATE	CLASS

LOADER NUT
LAB. SAW

NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± [illegible]
FIN. 63/√ DEC .X ± [illegible] .XX ± .0[illegible] .XXX ± [illegible]

SCALE
FULL

varian

A
S[illegible]02

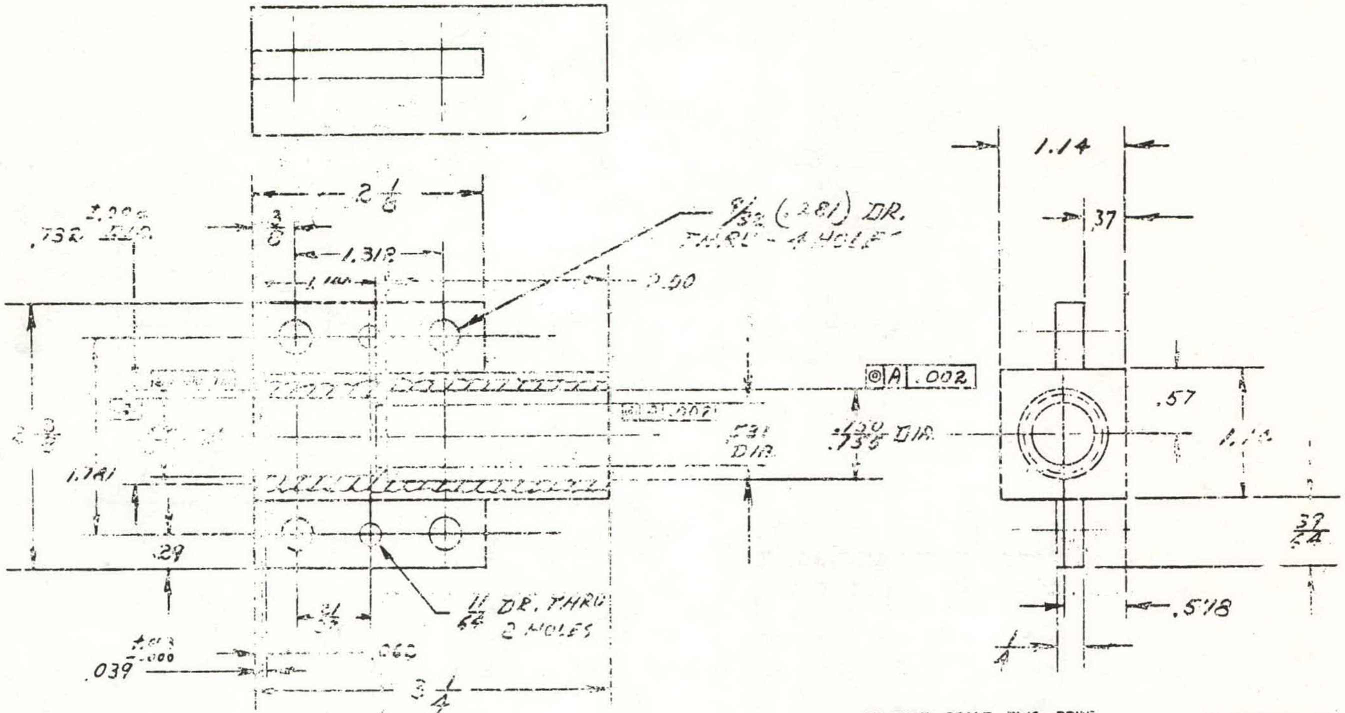
DIVISION
SIZE
DWG NO.
REV

CHK
DATE
REV

DASH NO	TYPE OF MODEL	NEXT ASSEMBLY

REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

DO NOT SCALE DRAWING



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DESCRIPTION OF CHANGE

NUM
EO
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CHK
DATE
REV

DRAWN	DATE	APPROVED	DATE	CODE
R. B.	9-15-77			
CHECKED	DATE	APPROVED	DATE	CLASS

LOADER HOUSING
LAB. SAW

NOT OTHERWISE SPEC. FRAC ± 1/64 ANG ± 1/2°
FIN. 63 √ DEC .X ± .XX ± .01 .XXX ± .005

SCALE FULL

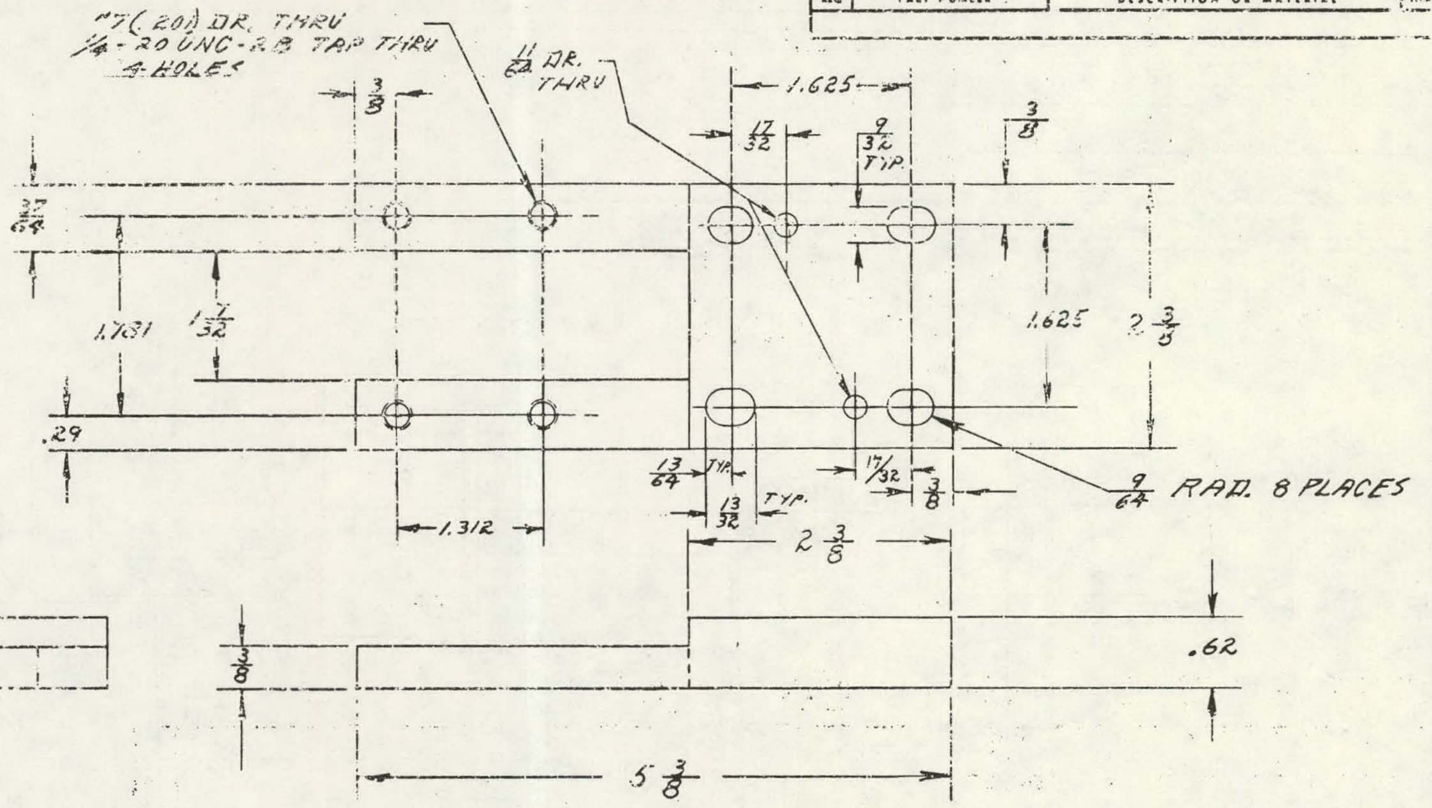
varian

DIVISION	SIZE	DRAWING NO.	REV
	B	S 2026	

LITHO IN U.S.A.

DASH NO	TYPE OR MODEL	NEXT ASSEMBLY

REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM



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BREAK ALL SHARP EDGES
DIMENSIONS ARE IN INCHES

DRAWN	DATE	APPROVED	DATE	CODE
E.Z.	9-17-77			
CHECKED	DATE	APPROVED	DATE	CLASS

LOADER BASE
LAB. SAW

NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/2° | SCALE FULL
FIN. 63/ DEC .X ± .XX ± .01 .XXX ± .005

varian

DIVISION	SIZE	DRAWING NO.	REV
	B	S 2027	

5

DASH NO	TYPE OR MODEL	NEXT ASSEMBLY

REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

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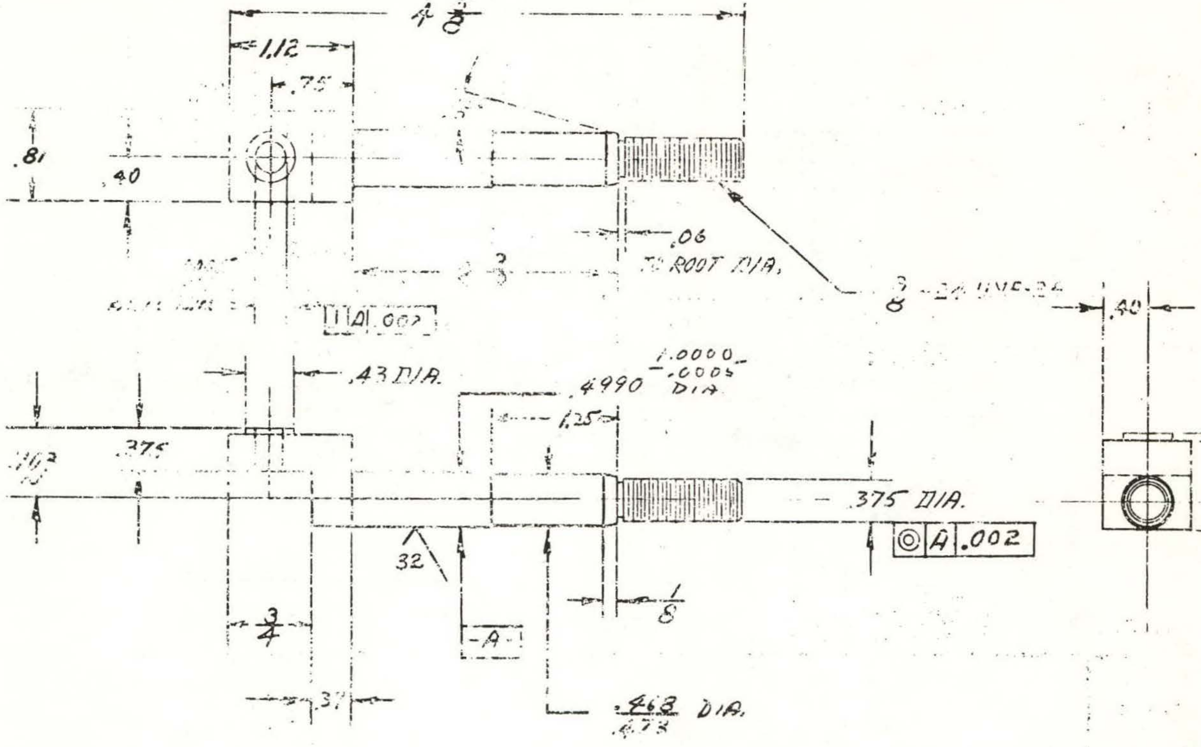

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R.Z.	7-13-77			
CHECKED	DATE	APPROVED	DATE	CLASS

CAMROD HOLDER
LAB. SAW

UNLESS OTHERWISE SPECIFIED FRAC ± 1/64 ANG ± 1/2°
FIN 63✓ DEC .X ± .XX ± .01 .XXX ± .005

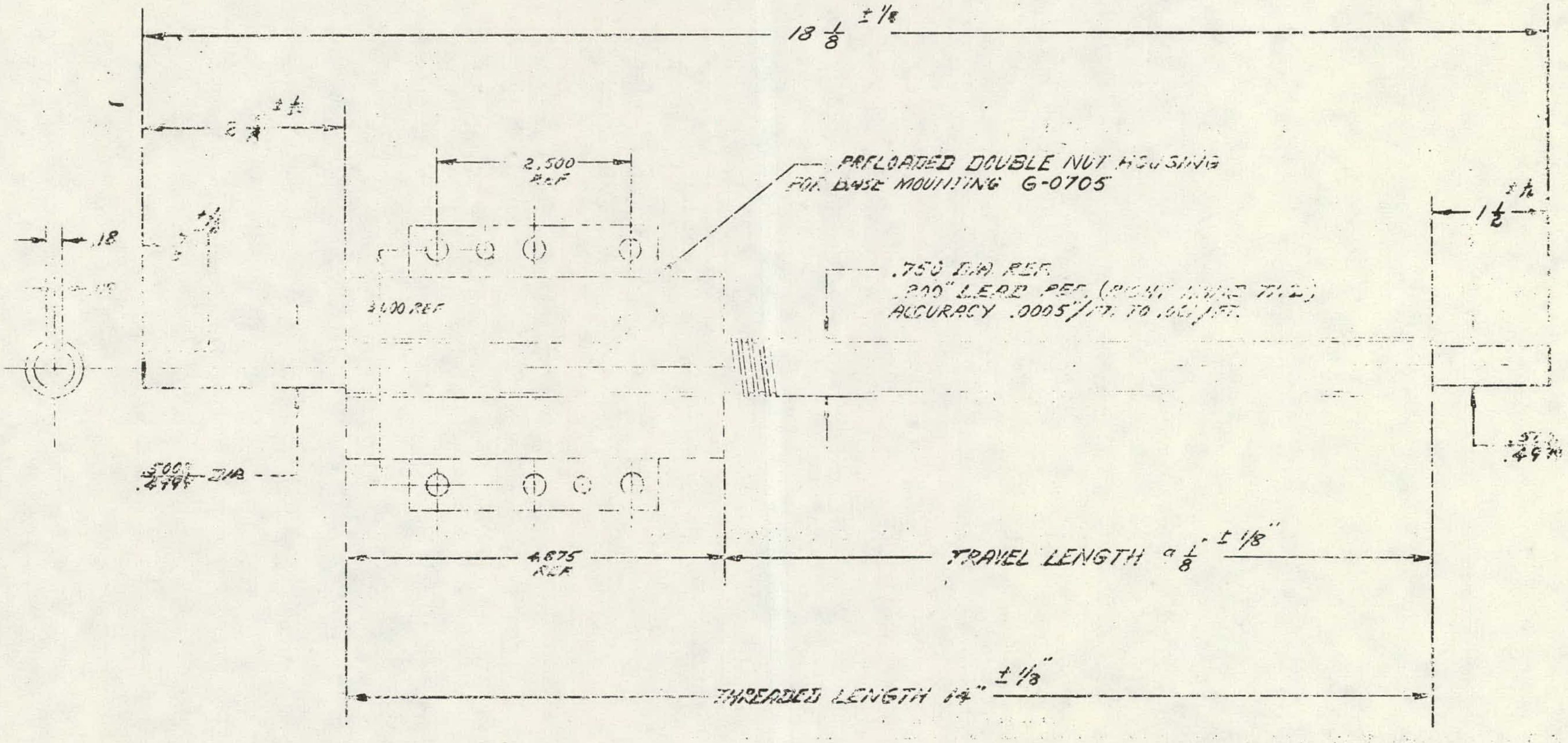
SCALE FULL

varian

B S2028

DIVISION | SIZE | DRAWING NO. | REV

441 6-6 JUN 56 LITHO IN U.S.A.



DO NOT SCALE DRAWING

DRAWN	DATE			
K. Z. Ziegler	9-29-75			
CHECKED				

BEAVER BALL BRG, SCR. & HOUSING
STANDARD ASS'Y EXCEPT AS SHOWN

FIN. ✓ DEC .X ± .XX ± .01 .XXX ±

SCALE FULL

varian

DIVISION

SIZE C

DRAWING NO. S2029

NUM
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DFT
CHK
DATE
REV

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APPENDIX II

- Man-Hours and Costs
- Program Plan (Updated)

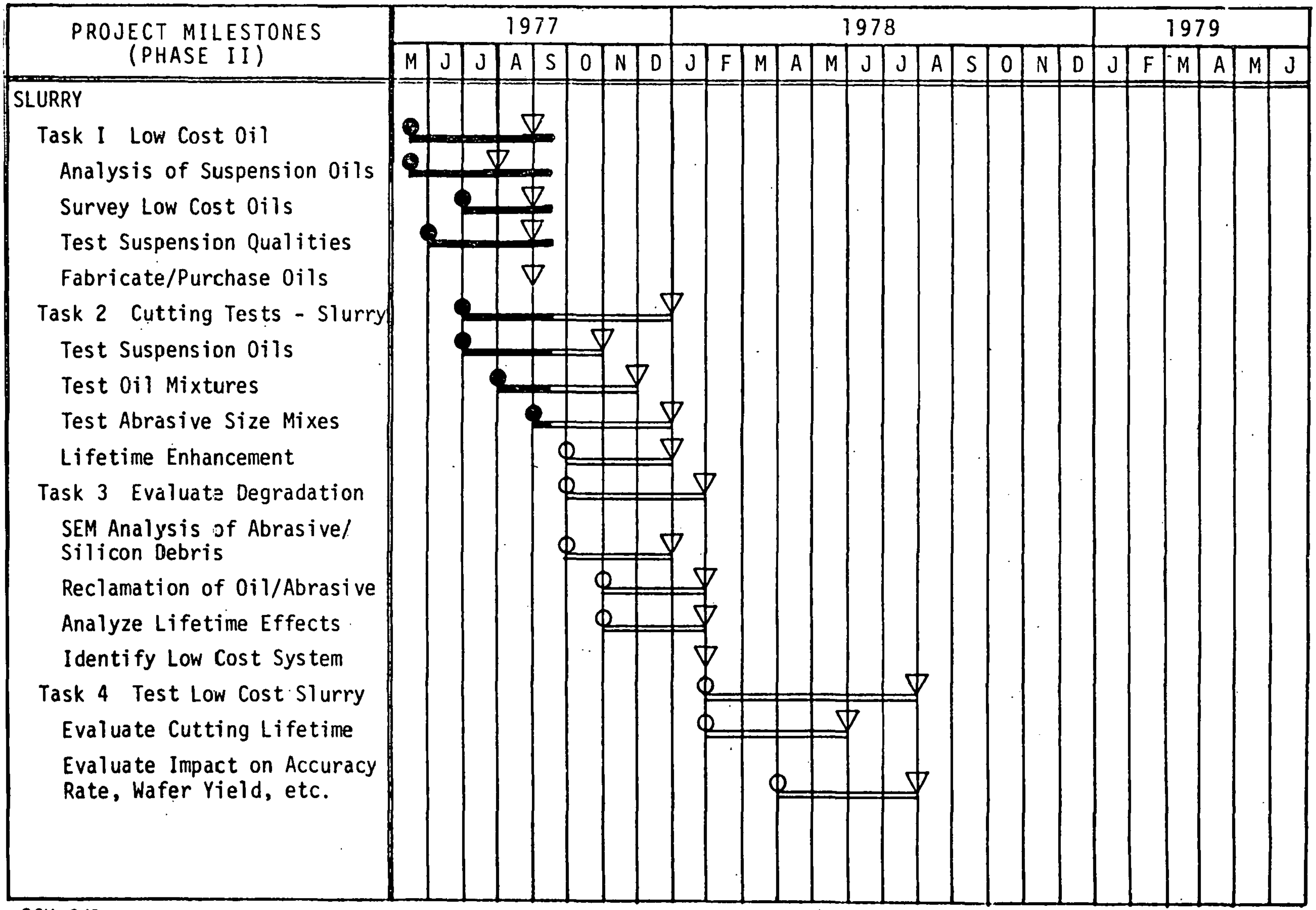
MAN-HOURS AND COSTS (PHASE II)

During the reporting period of June 18, 1977 to September 18, 1977, total man-hours were 2101.3 hours and total costs were $85,986. Previous expenditures were 558.0 hours and $50,256. As of September 18, 1977, total program man-hours were 2659.3 hours and total program costs were $136,242.

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/76 (I) 5/19/77 (II)

Phase II
Program Plan
Page 1 of 8

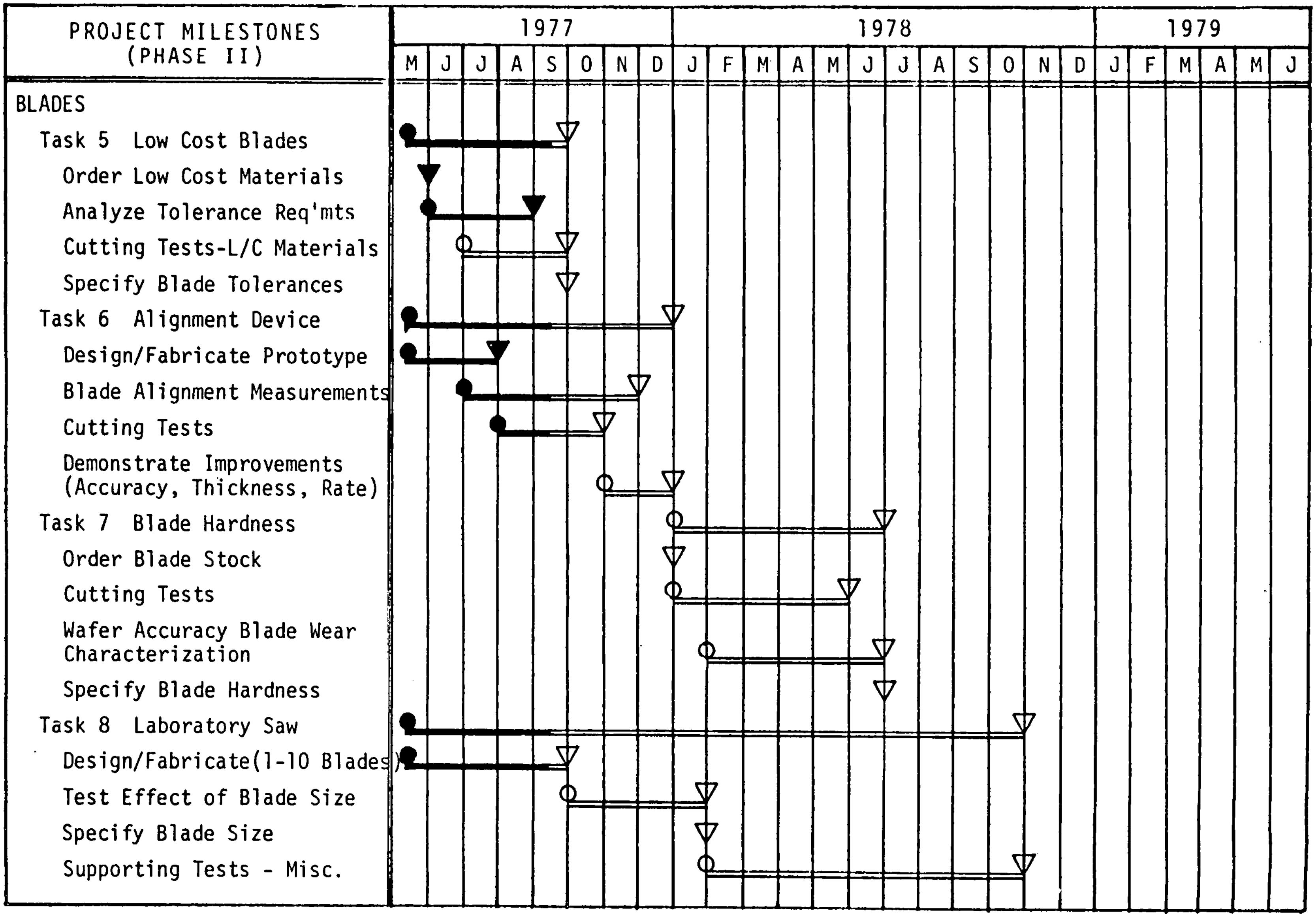


SCH 6/15/77
Updated 9/30/77

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/76 (I) 5/19/77 (II)

Phase II
Program Plan
Page 2 of 8

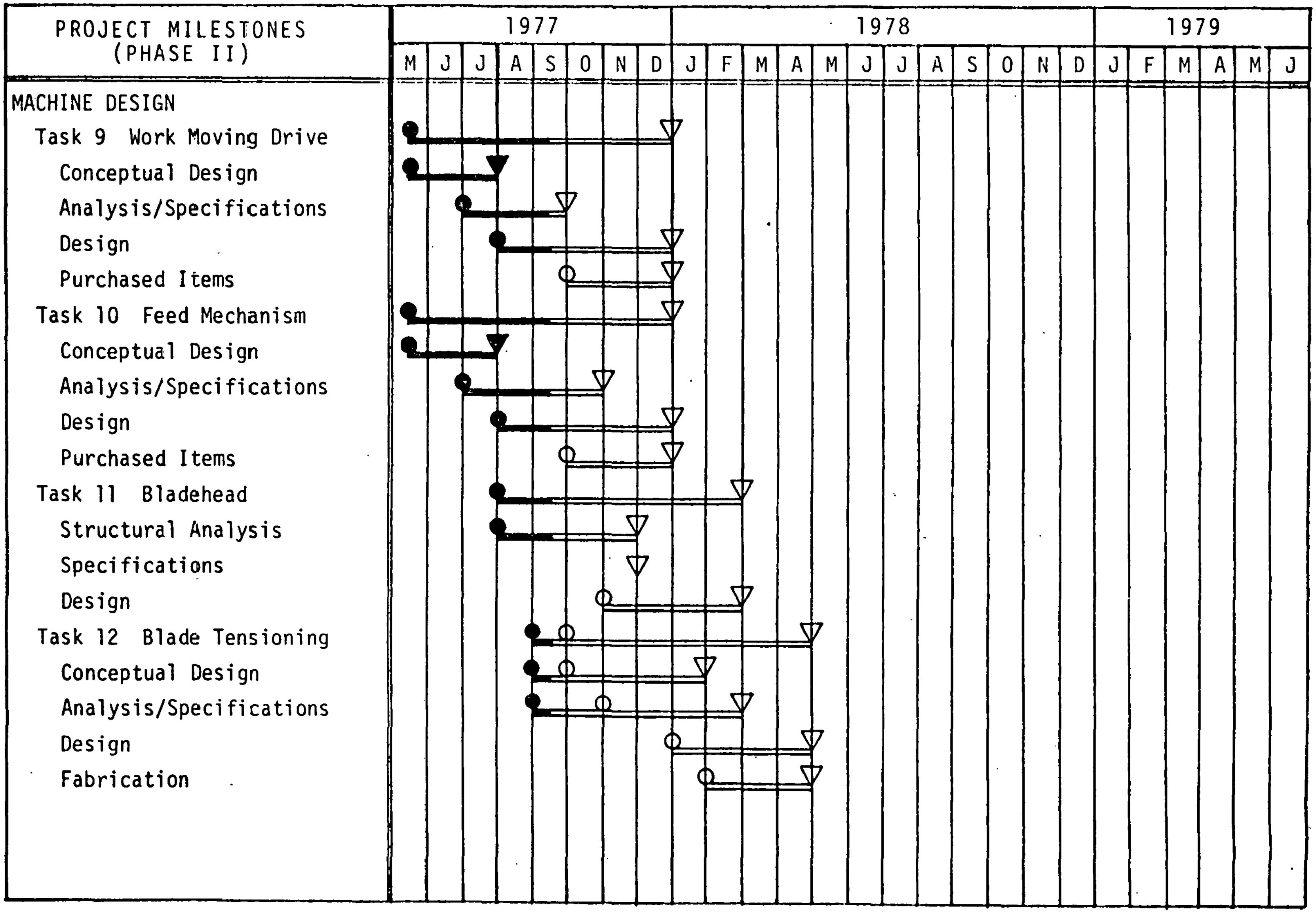


SCH 6/15/77
Updated 9/30/77

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/76 (I) 5/19/77 (II)

Phase II
Program Plan
Page 3 of 8

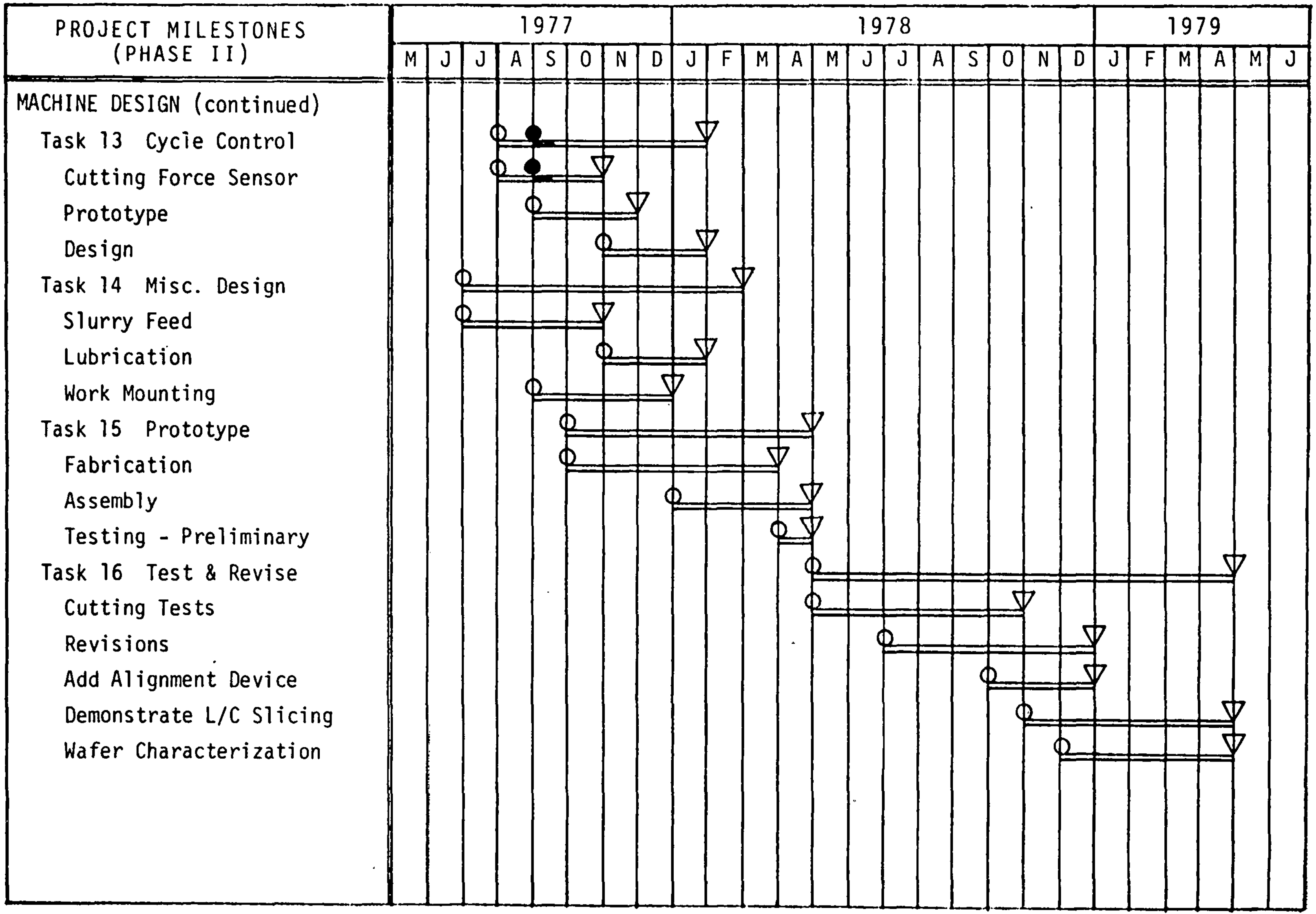


SCH 6/15/77
Updated 9/30/77

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/76 (I) 5/19/77 (II)

Phase II
Program Plan
Page 4 of 8



SCH 6/15/77
Updated 9/30/77

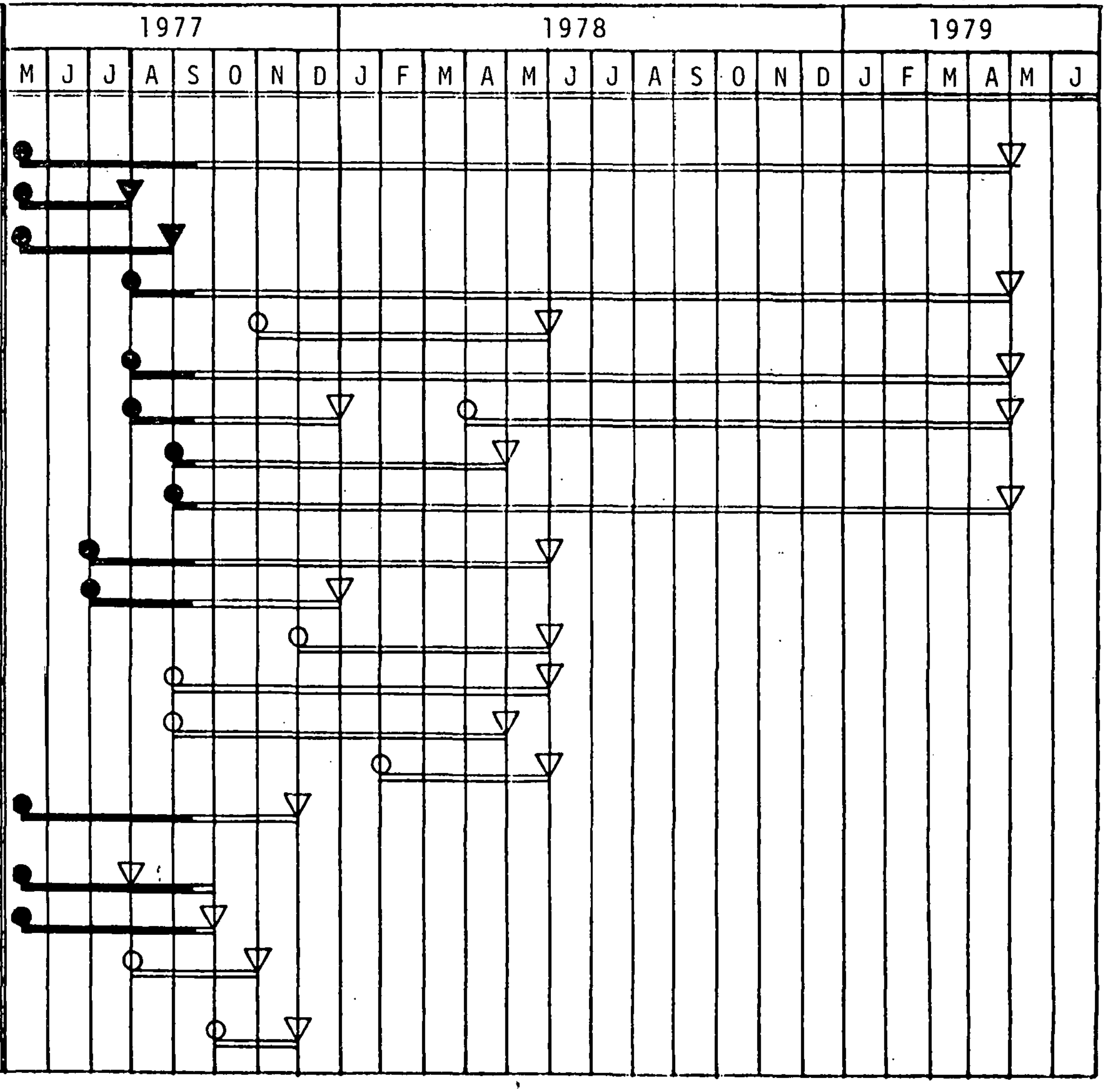
SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/75 (I) 5/19/77 (II)

Phase II
Program Plan
Page 5 of 8

PROJECT MILESTONES
(PHASE II)

PROCESS INTERFACE
- Task 17 Comp. Cost Analysis
  - Identify Cost Elements
  - Baseline Cost Analysis
  - Update - MS Slicing
  - Other Slicing Techniques
- Task 18 Cell Fabrication
  - Fabricate Standard Slices
  - Fabricate Prepared Wafers
  - Evaluate V_{oc}, I_{sc}, FF, eff.
- Task 19 Surface Preparation
  - Chem/Mech. Damage Removal
  - Combined Removal Techniques
  - Evaluate Cell Performance
  - Damage Characterization
  - Optimize Removal Techniques
- Task 20 Mech. Wafer Testing
  - Design/Fabricate 4 Point Bending Fixture
  - Background Analysis
  - Test Wafer Strength
  - Specify Handling/Cutting Limitations of Wafers



SCH 6/15/77
Updated 9/30/77

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/76 (I) 5/19/77 (II)

Phase II
Program Plan
Page 6 of 8

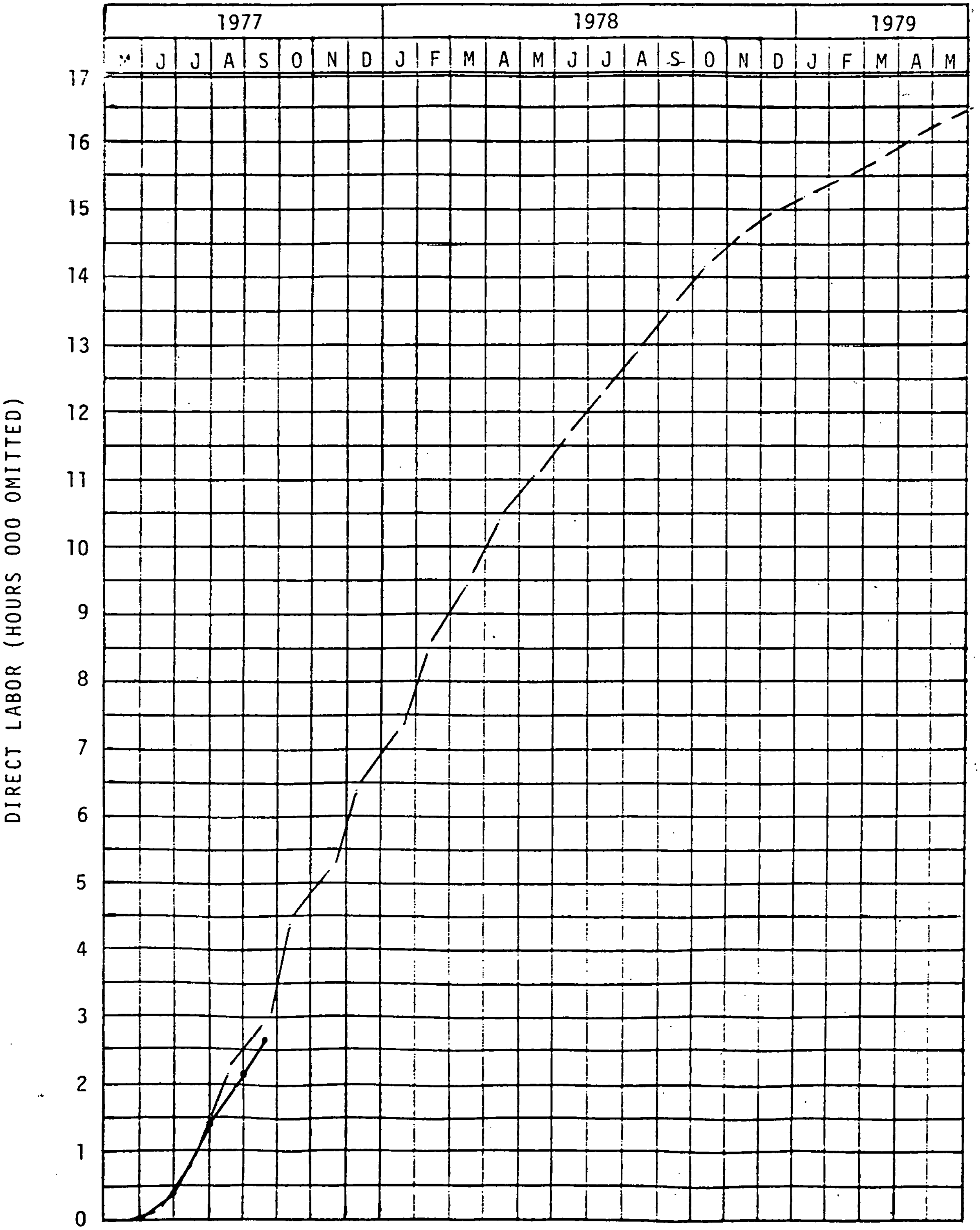
PROJECT MILESTONES (PHASE II)	1977								1978												1979					
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
REPORTS																										
Financial Package		▼	▼	▼	▼	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽
Monthly Technical Progress		▼		▼	▼		▽	▽		▽	▽		▽	▽		▽	▽		▽	▽		▽	▽		▽	
Quarterly Technical Progress		▼			▼			▽			▽			▽			▽			▽			▽			
Interim Summary																										
Draft Final Report																									▽	
Final Report																										▽
TRAVEL																										
Project Integration Meetings			▼			▽			▽			▽			▽			▽			▽			▽		
MAJOR EQUIPMENT																										
2 Test Saws	▼																									
Wafer Measuring Station	▼																									
Silicon Purchases		▼						▽						▽												

SCH 6/15/77
Updated 9/30/77

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date? 1/9/76 (I) 5/19/77 (II)

Phase II
Program Plan
Page 7 of 8



SCH 6/14/77
Updated 9/30/77

Total Hours: 16,435
Hours to Date: 2659.3

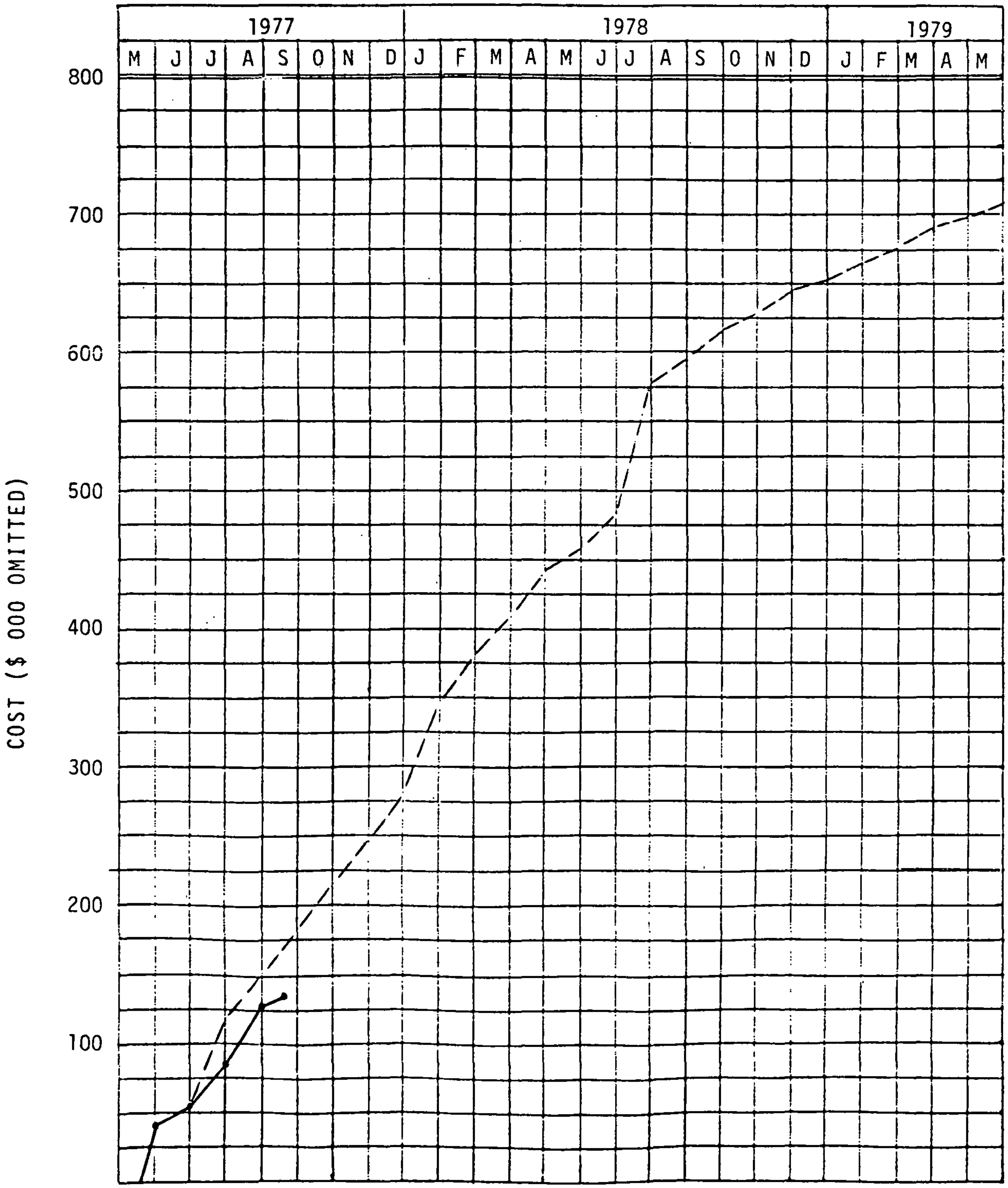
Planned ------
Incurred ———

PROGRAM LABOR SUMMARY

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/76 (I) 5/19/77 (II)

Phase II
Program Plan
Page 8 of 8



SCH 6/14/77
Updated 9/30/77

Total Cost: $708,210
Incurred Cost: $136,242

Planned -------
Incurred ———

PROGRAM COST SUMMARY

☆U.S. GOVERNMENT PRINTING OFFICE: 1978-740-094/1225