DESIGN OF A TENSION LOAD CELL

Thesis by

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ABSTRACT

A tension load cell is designed along the two following main ideas:

— Decrease the pressure by which the applied load is measured.

— Design a thinner and therefore more flexible diaphragm.

After calculation of the stresses produced in the diaphragm, a thinner but still strong diaphragm is designed as well as the equipment necessary to build it.

The shape and dimensions of the diaphragm being determined, the tension load cell is then designed.

Working drawings of the parts of the mold and the tension load cell are given at the end of the work, in the appendix.

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I. INTRODUCTION

Different companies manufacture various systems for load measurement and among them tension load cells, which are based on the following principle:

The load (L), which is to be measured, acts upon a diaphragm (A), which has a single corrugation with cylindrical sides. This diaphragm works like a piston and induces in the oil-filled cavity (B) a pressure proportional to the load (L), provided that the active area of the diaphragm remains constant, i.e., that the stroke of the diaphragm is sufficiently short. This pressure is then measured by the pressure gauge (C) giving a value for the load (L). (See Fig. 1, page 4.)

This leads to the following remarks:

The bigger L is, the higher the oil pressure is. Under this high pressure two things happen:

1) The oil volume decreases and the hose (D) stretches proportionally to the pressure. The result is that the stroke of the diaphragm will tend to become too important. Therefore, the assumption of constant area is vitiated, and the pressure is not proportional to the load anymore.

2) The diaphragm has to withstand very high stresses. It must therefore be built very strongly and, with the type of construction used

today, it is a very stiff diaphragm, particularly in the region which should be as flexible as possible: the corrugation. This stiffness introduces a parasite loading in the system and therefore decreases the accuracy of the measurements.

So, the two problems appear, the solution of which is the purpose of this work:

1) Decrease the pressure in the cavity (B).

2) Design a stronger and a more flexible diaphragm (i. e., a thinner one).

II. BASES OF DESIGN

In the introduction, the two problems to be considered in this study have been defined. The different possible solutions must now be looked at. A choice of one solution which will satisfy as well as possible the different conditions must be made.

The problem of pressure

There are two ways to decrease the pressure inside B:

1) Increase the surface of the diaphragm. Since the size of the device is limited, this solution is not sufficient and another solution must be found.

2) Split the load (L) by putting a certain number of diaphragms in parallel as represented in Fig. 2. Applying this solution to the particular problem of the tension load cell gives the schematic arrangement shown in Fig. 3. This is the solution which will be at the basis of the design of the apparatus.

It must be pointed out that this solution presents another advantage. If a stack of three elements is considered, each calculated for a load $\frac{L}{3}$, by connecting one, two, or the three

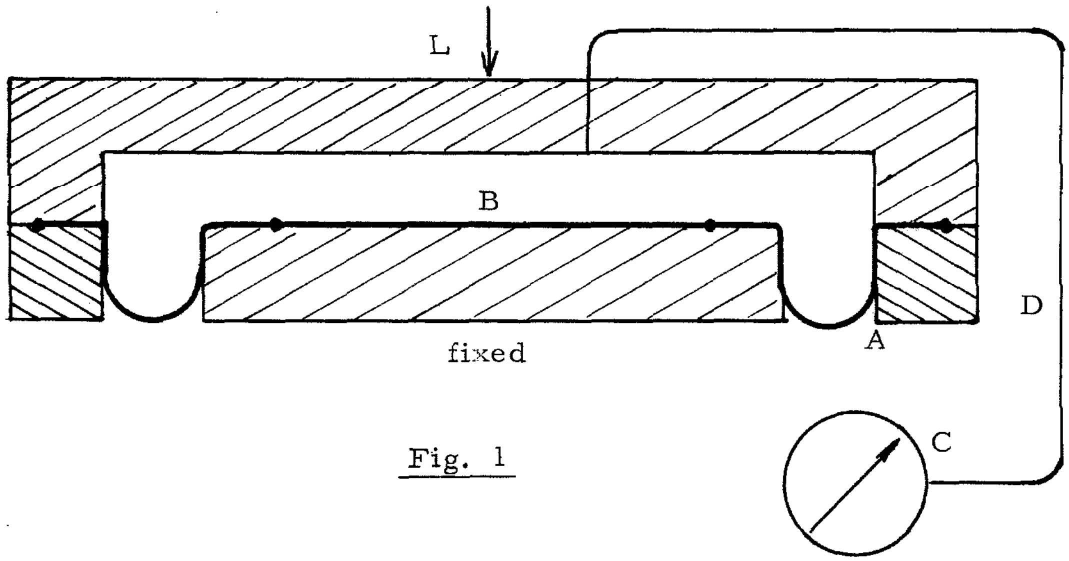


Fig. 1

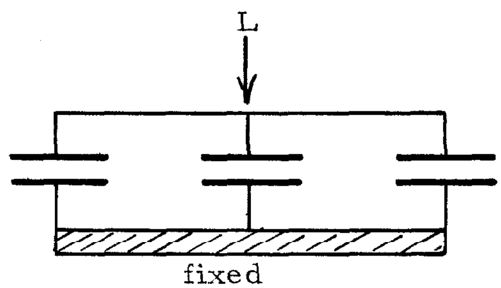


Fig. 2

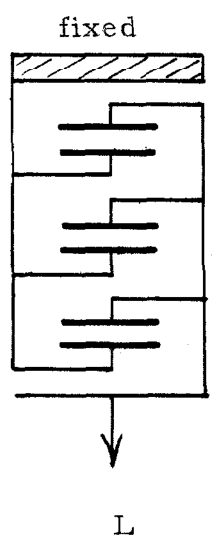


Fig. 3

cells to the pressure gauge, it is possible to get three different ranges or possible measurements: 0 to $\frac{L}{3}$, 0 to $\frac{2L}{3}$, and 0 to L.

This property gives the system a much greater versatility than the ones built today.

The lines along which the problem of the reduction of pressure will be treated have now been defined.

The problem concerning the diaphragm is left to be considered.

The problem of the diaphragm

The diaphragm to be designed must be strong and as flexible as possible (i. e. , as thin as possible). This double goal can be achieved by using the methods of the tire industry:

Tire carcasses are built up of plies. An individual ply consists of nylon cord fabric which has been coated with a rubber compound. The nylon cord fabric itself consists of nylon cords parallel and equally spaced, tied loosely together with very light threads, called picks. Some tires are built up of four plies, some of only two plies. Only the case of a two plies structure will be considered here.

It is assumed that the plies can be obtained from any tire builder. However, it should be pointed out that the diameter of the nylon cords used in the tire industry ranges from 0.022" to 0.035".

The region of the diaphragm where the stresses are the most important is the corrugation. This part will therefore be built as a tire, the beads of the tire being replaced by two circular wires shown in (1) and (2) on Fig. 4. Around these wires a ply will be wrapped in the manner indicated in Fig. 4, making, therefore, actually two plies. On top of these two plies a rubber coat will be added.

The flat center part of the diaphragm will be made only of rubber.

The lines along which the design of the diaphragm will be conducted are now defined. But, further details concerning the forces in the diaphragm produced by the pressure are necessary.

<u>Normal forces in the diaphragm</u>

Considering the unit element ABCD on the diaphragm (see Fig. 5), the general equations of equilibrium are:

$$\mathrm{I}\quad \begin{cases} \dfrac{d}{d\varphi}(N_\varphi r_o) - N_\theta r_1 \cos\varphi + Y r_1 r_o = 0 \\ N_\varphi r_o + N_\theta r_1 \sin\varphi + Z r_1 r_o = 0 \end{cases}$$

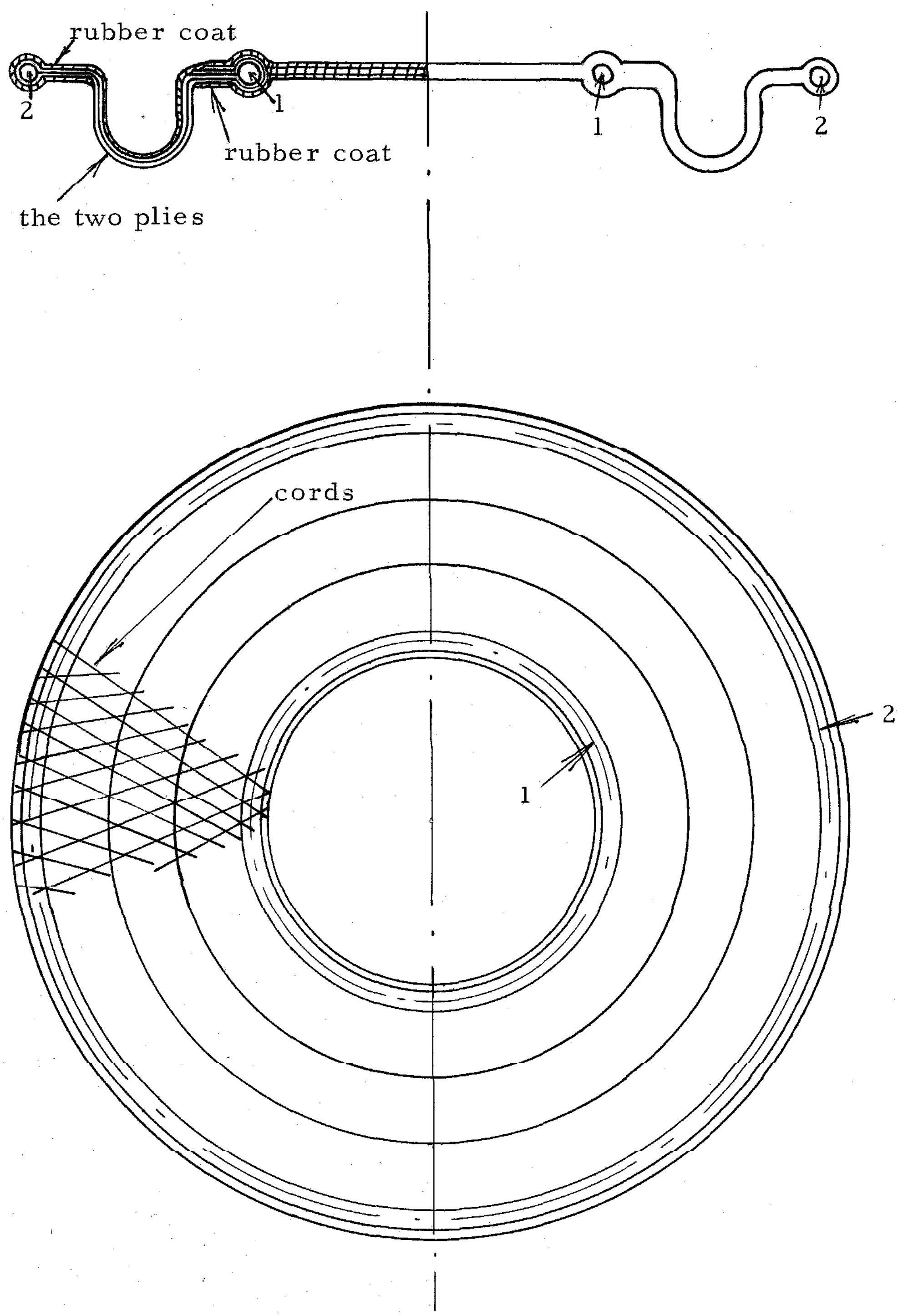
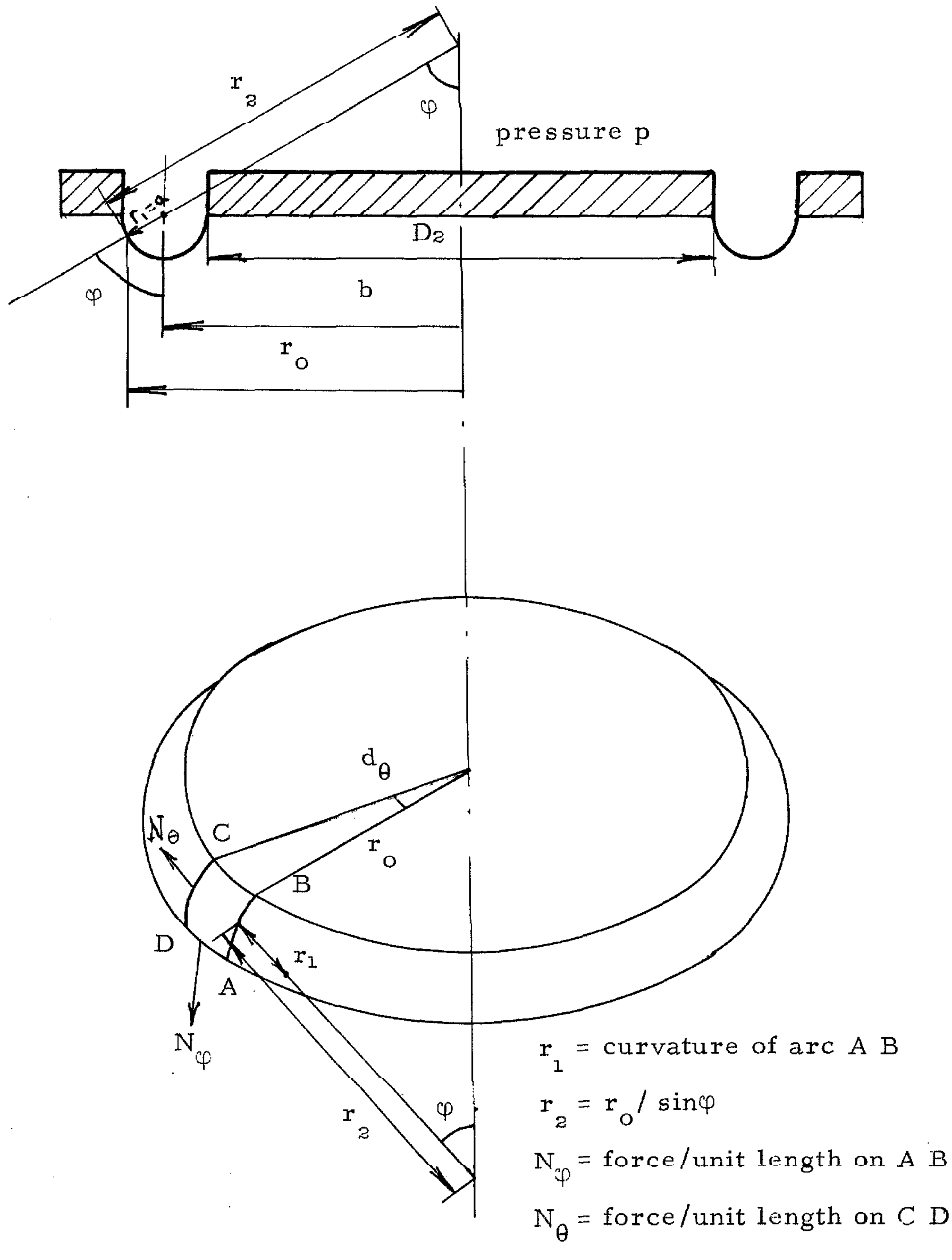


Fig. 4



r_2
φ
pressure p
$r_1 = a$
D_2
φ
b
r_o
d_θ
N_θ
C
r_o
B
D
r_1
A
N_φ
r_2
φ
r_1 = curvature of arc A B
$r_2 = r_o / \sin\varphi$
N_φ = force/unit length on A B
N_θ = force/unit length on C D

Fig. 5

The definition of the different symbols is given on Fig. 5.

Y and Z are the tangential and normal components of the acting force. In this case, $Y = 0$; $Z = -p$, pressure applied.

$$r_1 = a$$

$$r_o = b + a\sin\varphi, \ \varphi \text{ varying from } -\frac{\pi}{2} \text{ to } \frac{\pi}{2}.$$

Therefore the system I becomes:

$$\begin{cases} (1) \ \dfrac{d}{d\varphi}\left[N_\varphi (b + a\sin\varphi)\right] - N_\theta \, a\cos\varphi = 0 \\ (2) \ N_\varphi (b + a\sin\varphi) + N_\theta \, a\sin\varphi - pa(b + a\sin\varphi) = 0 \end{cases}$$

Differentiating (2):

$$\begin{cases} (2') \ \dfrac{d}{d\varphi}\left[N_\varphi (b + a\sin\varphi)\right] + N_\theta \, a\cos\varphi + \dfrac{\partial N_\theta}{\partial\varphi} a\sin\varphi \\ \qquad\qquad -pa^2 \cos\varphi = 0 \\ (1) \ \dfrac{d}{d\varphi}\left[N_\varphi (b + a\sin\varphi)\right] - N_\theta \, a\cos\varphi = 0 \end{cases}$$

Therefore, N_θ is the solution of the following differential equation:

$$\frac{\partial N_\theta}{\partial\varphi} a\sin\varphi + 2N_\theta \, a\cos\varphi = pa^2 \cos\varphi$$

or;

$$\frac{\partial N_\theta}{\partial\varphi} + 2N_\theta \frac{\cos\varphi}{\sin\varphi} = pa \frac{\cos\varphi}{\sin\varphi}$$

The general solution of this first order differential equation is:

$$N_\theta = e^{-2\int \frac{\cos\varphi}{\sin\varphi}\,d\varphi} \left[\int pa\,\frac{\cos\varphi}{\sin\varphi}\, e^{2\int \frac{\cos\varphi}{\sin\varphi}\,d\varphi}\, d\varphi + C \right]$$

$$N_\theta = e^{-2\ln\sin\varphi} \left[\int \frac{pa}{2}\,\frac{2\cos\varphi}{\sin\varphi}\, e^{2\ln\sin\varphi}\, d\varphi + C \right]$$

$$N_\theta = e^{-2\ln\sin\varphi} \left[\frac{pa}{2}\, e^{2\ln\sin\varphi} + C \right]$$

$$N_\theta = \frac{pa}{2} + C\, e^{-2\ln\sin\varphi}$$

The constant C must still be determined:

For $\varphi = 0$, $\sin\varphi = 0$, $\ln(0) = -\infty$, $e^{-2\ln\sin\varphi} \to \infty$

But N_θ must stay finite. Therefore, C must be equal to zero.

And:

$$N_\theta = \frac{pa}{2} .$$

N_φ can now be calculated using equation (2):

$$N_\varphi\,(b + a\sin\varphi) + \frac{pa^2}{2}\,\sin\varphi - pa\,(b + a\sin\varphi) = 0$$

Finally:

$$N_\varphi = \frac{pa}{2}\;\frac{2b + a\sin\varphi}{b + a\sin\varphi}$$

The variations of N_φ in function of the different parameters will now be considered:

— Variations in function of φ:

$$\frac{\partial N_\varphi}{\partial \varphi} = - \frac{pa^2 b}{2} \frac{\cos\varphi}{[b + a\sin\varphi]^2} < 0$$

N_φ decreases when φ increases.

$$(N_\varphi)\ \max = \frac{pa}{2} \frac{2b - a}{b - a}$$

— Variations in function of a:

$$\frac{\partial N_\varphi}{\partial a} = \frac{pa}{2} \frac{(b + a\sin\varphi)\sin\varphi - (2b + a\sin\varphi)\sin\varphi}{[b + a\sin\varphi]^2}$$

$$+ \frac{p}{2} \frac{2b + a\sin\varphi}{b + a\sin\varphi}$$

$$\frac{\partial N_\varphi}{\partial a} = \frac{p}{2} \frac{-ab\sin\varphi + 2b^2 + 3ab\sin\varphi + a^2\sin^2\varphi}{[b + a\sin\varphi]^2}$$

$$\frac{\partial N_\varphi}{\partial a} = \frac{p}{2} \frac{2b^2 + 2ab\sin\varphi + a^2\sin^2\varphi}{[b + a\sin\varphi]^2} > 0$$

N_φ increases with a.

— Variations in function of b:

$$\frac{\partial N_\varphi}{\partial b} = \frac{pa^2}{2} \frac{\sin\varphi}{(b + a\sin\varphi)^2} \quad \begin{cases} > 0 \text{ for } \varphi > 0 \\ < 0 \text{ for } \varphi < 0 \end{cases}$$

N_φ increases as b increases for $\varphi > 0$

N_φ decreases as b increases for $\varphi < 0$

The principal results can now be summarized here:

1) $N_\theta = \frac{pa}{2}$, $(N_\varphi)\ \max = \frac{pa}{2} \frac{2b - a}{b - a}$

2) N_θ and N_φ increase with a.

3) N_φ increases with b on the outside part of the corrugation and decreases with b on the inside.

Result (3) does not lead to any useful conclusion in the choice of b. Results (1) and (2) bring two conclusions:

1) The radius (a) must be chosen as small as possible. On the other hand, considerations of easy molding and of the possibility of a sufficient stroke, lead to an inferior limit for a. It was decided to take a = 0.25 in. It can be remarked here that a is small compared to b. An approximate value for N_φ can therefore be obtained for the next calculations:

N_φ = pa

2) Knowing N_φ and N_θ, the optimum angle made by the cord with N_φ direction can be computed. Let β be this angle. A real length of the cord equal to $\frac{1}{\cos\beta}$ and a projected length, $\tan\beta$, on the N_θ direction, correspond to a projected length 1 on the N_φ direction. (See Fig. 6 a) The forces applied on the cord length $\frac{1}{\cos\beta}$ are $F_\theta = N_\theta$, $F_\varphi = \tan\beta \, N_\varphi$. (See Fig. 6b.)

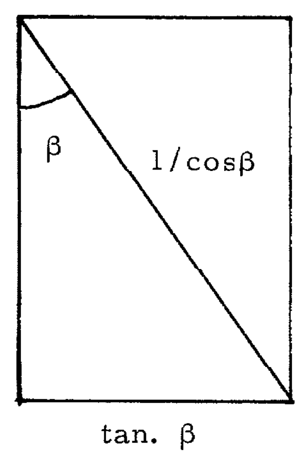


Fig. 6-a

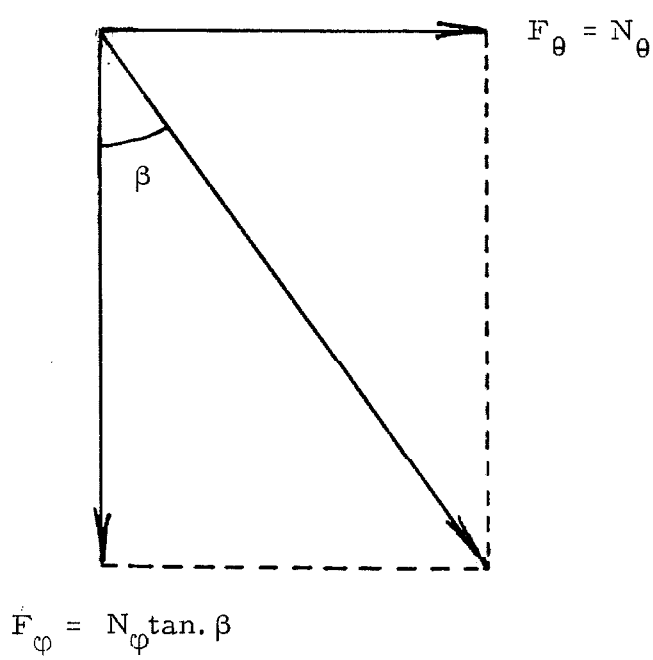


Fig. 6-b

β is therefore given by:

$$\tan\beta = \frac{N_\theta}{N_\varphi \tan\beta}$$

$$\tan^2\beta = \frac{N_\theta}{N_\varphi} \simeq \frac{1}{2}$$

$$\tan\beta = \frac{1}{\sqrt{2}} = 0.706$$

$$\beta = 35^\circ\ 14' \simeq 35^\circ$$

The bases of the design are now defined. It would be interesting for the clarity of the work to summarize them here:

1) To obtain a lower pressure, use a cell made of a stack of elements grouped in parallel. It would not be practical to group more than five elements per cell, in the writer's opinion.

2) To build a strong and thin diaphragm, use two nylon cord plies identical to the ones used in the tire industry. The angle of a cord with the N_φ direction should be $\beta = 35^\circ$.

3) The forces in the diaphragm have the following values:

$$N_\varphi = pa$$

$$N_\theta = \frac{pa}{2}$$

It is now possible to go into further detail of the constituents of the diaphragm: diameter of the nylon cords and of the metallic wires constituting the "beads" of the diaphragm.

III. DESIGN OF THE DIAPHRAGM

The capacity of the different crane scales built in the industry can go from 500 to 75,000 pounds.

Assuming that the maximum number of elements which can be used in a cell is five, we will consider three different types of element: A, B, C, which can be grouped as follows:

Type of Element	Number of Elements	Capacity(lbs)
A	1	500
	2	1000
	3	1500
	4	2000
	5	2500
B	1	3000
	2	6000
	3	9000
	4	12000
	5	15000
C	1	15000
	2	30000
	3	45000
	4	60000
	5	75000

The diaphragm inside each A, B, or C-type element has therefore to support a pressure corresponding respectively to a load of 500, 3000, 15000 lbs. This gives us the following results:

Pressure on the diaphragm

The pressure induced by a load (L) has the following expression:

$$p = \frac{4L}{\pi D_1^2}$$

with:

L = load

D_1 = active diameter of the diaphragm. (See Fig. 5.)

= 4, 5, 7 in. respectively for the A, B, C types.

The pressure on the diaphragm is therefore:

$$\text{Type A:} \quad p = \frac{4 \cdot 500}{\pi \cdot 16} = \frac{2000}{\pi \cdot 16} \simeq 40 \text{ psi}$$

$$\text{Type B:} \quad p = \frac{4 \cdot 3000}{\pi \cdot 25} = \frac{12000}{\pi \cdot 25} \simeq 155 \text{ psi}$$

$$\text{Type C:} \quad p = \frac{4 \cdot 15000}{\pi \cdot 49} = \frac{60000}{\pi \cdot 49} \simeq 390 \text{ psi}$$

N_φ and N_θ can now be computed.

Forces N_φ and N_θ

They are given by $N_\varphi = pa$, $N_\theta = \frac{pa}{2}$.

Therefore:

Type of Element	p (psi)	a (in.)	N_φ (lb/in)	N_θ (lb/in)
A	40	1/4	10	5
B	155	1/4	40	20
C	390	1/4	100	50

Resulting dimensions of the nylon cords

The ply has x cords per inch, and each cord has a diameter (d). If d is measured in inches, the following empirical relation exists between the two quantities x and d: $x \cdot d = 700 \cdot 10^{-3}$.

The same surface as the one considered in Fig. 6a, on page 13, will be considered again. The force (R) applied on the cords contained in this surface is $R = \frac{N_\varphi \tan\beta}{\cos\beta}$. The number of cords is $x \sin\beta$. The surface of these cords is $x \sin\beta \frac{\pi d^2}{4}$. The following equation of equilibrium can be written, knowing that the tensile strength of a nylon cord is 60,000 psi:

$$N_\varphi \frac{\tan\beta}{\cos\beta} = 60,000\ x \sin\beta \frac{\pi d^2}{4} .$$

with:

$$x = \frac{700 \cdot 10^{-3}}{d}$$

This gives:

$$N_\varphi\ 1.5 = 60,000 \cdot 700 \cdot 10^{-3} \cdot \frac{\pi d}{4}$$

$$d = N_\varphi \frac{1.5}{42} \quad 10^{-3} \quad \frac{4}{\pi}$$

$$d = 4.5\ 10^{-5}\ N_\varphi$$

Computation of the safety factor

F: a . b . c . d

a: Ratio of the ultimate strength of the material to the elastic limit: a = 2.

b: Depends on the character of the stress within the material. The load will not vary too much once it is applied. Therefore, b = 1.

c: Depends on the manner in which the load is applied to the apparatus. In the case considered the load can be applied suddenly. Therefore, c = 2.

d: Factor of "ignorance". It will be taken equal to 1.5.

The value of the safety factor is F = 6. This gives the following expression for d:

$$d = 27 . 10^{-5} \, N_{\varphi} \text{ lb/in.}$$

Resulting minimum diameters of the nylon cords

Type of Element	N_{φ} (lb/in.)	d (in.)
A	10	0.003
B	40	0.011
C	100	0.027

It has been seen earlier that the usual diameters of the cords used in the tire industry range from 0.022 to 0.035 in.

It appears from the results above that a 0.022 inch cord would be largely sufficient to withstand the applied forces on the types A and B, and almost sufficient for type C. Moreover, if smaller cords were available, they could be used to build the A and B type diaphragm, which would therefore be still much thinner.

The diameters of the "bead" wires have still to be determined.

Calculation of the two "bead" wires diameters:

The "hoop tension" induced by a uniformly distributed radial force N_φ on a circular ring of radius c has the following expression: $P = cN_\varphi$.

The minimum diameter of the wires can therefore be determined.

		inside wire		diameter d'	outside wire		diameter d'
Type	N_φ (lb/in.)	c (in.)	cN_φ (lb)	(safety factor: 3) (in.)	c (in.)	cN_φ (lb)	(safety factor: 3) (in.)
A	10	1.5	15	0.026	2.5	25	0.032
B	40	1.75	70	0.054	3.5	140	0.072
C	100	3	300	0.106	4	400	0.121

Notice that the safety factor here has been taken equal only to 3 because, even if the load is applied suddenly, the hydraulic system and the rubber part of the diaphragm play the role of a shock absorber. Therefore, the coefficient c of the above given formula for the safety factor can be taken equal to 1.

For a question of simplicity, it is better to take the same diameter for the two wires. Therefore, the diameter must be chosen as if the outside wire alone was considered.

All the elements necessary to the building of the diaphragm are now known. Only the question of how to mold it remains. As these further developments will lead to the precise drawings of the apparatus, it seems wise here not to remain in the generality of the studies made so far. Therefore, from now on, only one type of cell will be considered and it will be the type B. Here are summarized the principal results concerning type B.

1) Measurements of the outer "bead" wire:

   $D_2 = 7.00$ in.

   $c_2 = 0.072$ in.

2) Measurements of the inner "bead" wire:

   $D_3 = 3.50$ in.

   $c_3 = 0.072$ in.

3) The diameter of the nylon cords used will be 0.022 in. This diameter could be smaller, but

the fact that smaller nylon cords are not used in the tire industry makes this choice necessary.

4) The rubber layer covering the fabric should be as thin as possible. The limits are those imposed by the possibility of the operation of calendering. It has been decided to use a layer of 0.010 in. thickness.

5) The middle plate of the diaphragm will be made of a rubber layer of 0.040 in. thickness covered on each side by a rubber layer of 0.010 in. thickness.

6) In order to keep the corrugation of the diaphragm as thin and flexible as possible, only one rubber layer is applied on the two plies, on the inside of the corrugation.

This is all that is necessary to draw a section of the diaphragm designed. This drawing is given on Fig. 7.

One problem still remains to be treated: how to mold the diaphragm?

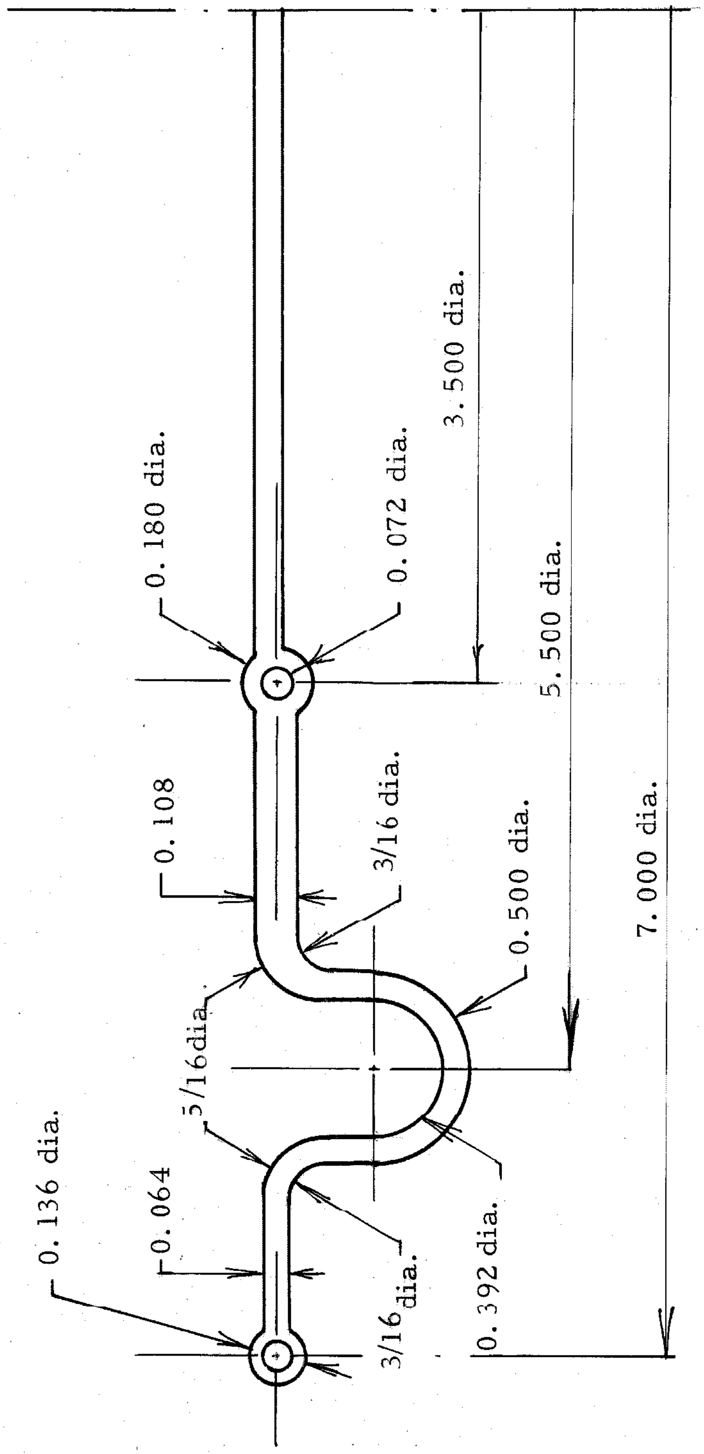

0.180 dia.
0.072 dia.
3.500 dia.
5.500 dia.
7.000 dia.
0.108
3/16 dia.
0.500 dia.
5/16dia.
0.136 dia.
0.064
3/16dia.
0.392 dia.

Fig. 7

IV. MOLDING THE DIAPHRAGM

Two important points must be kept in mind in designing the molding equipment:

1) The nylon cords must have, before molding, the length they will have in the finished diaphragm and must be stretched as little as possible during the molding operation.

2) The two "bead" wires are already welded and circular before the beginning of the shaping of the diaphragm. They should, therefore, be taken as references in the operation.

The two points stressed above lead to the following solution.

The solution adopted

The two 'bead" wires will form the bases of a frustrum of cone of revolution. The distance of the two planes containing the 'bead" wires will be so that the length of the apothem of the frustrum of cone is equal to the developed length of the radial section of the diaphragm taken from one "bead" wire to the other. (See Fig. 8.)

The way of shaping the diaphragm appears now clearly, as shown on Fig. 9.

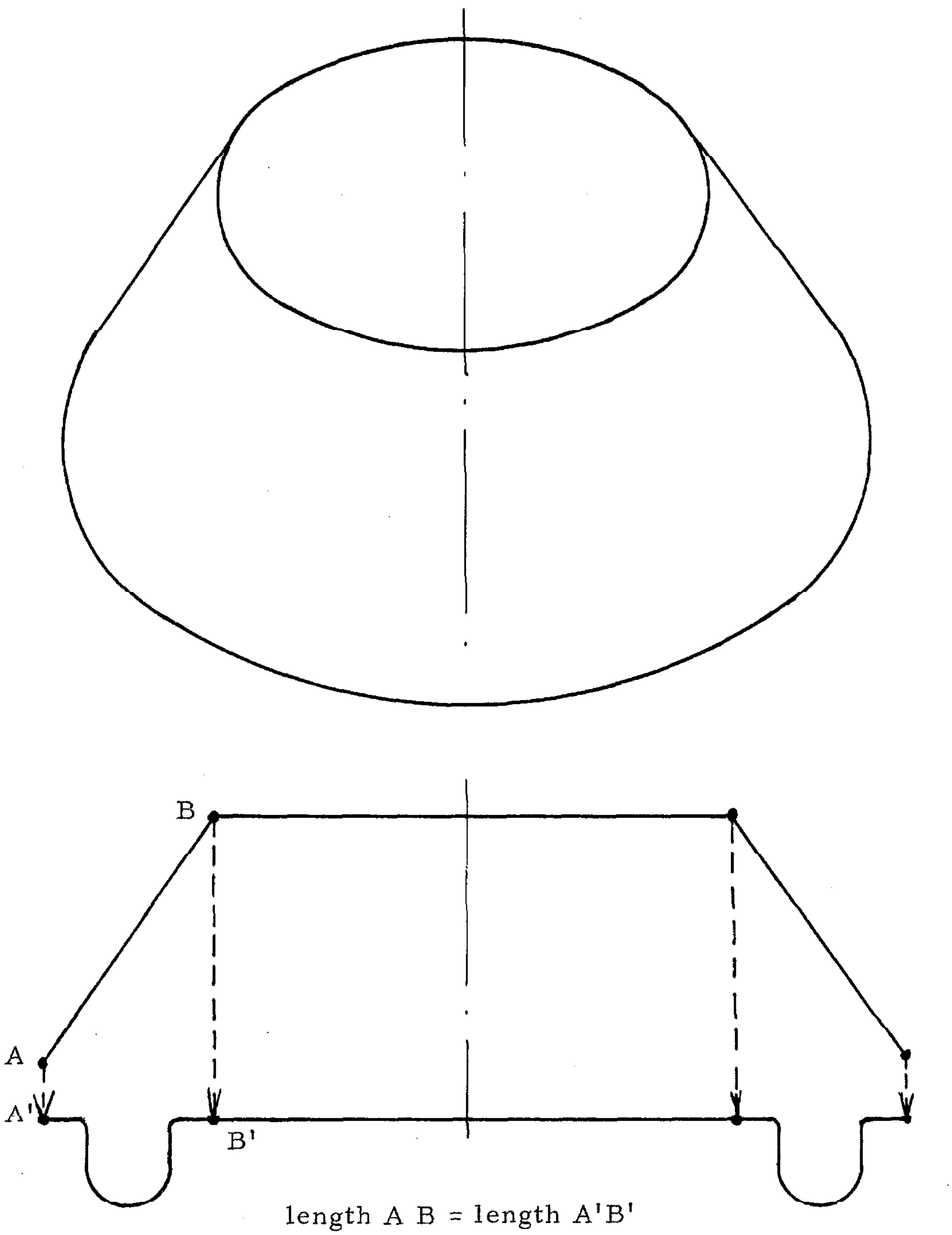
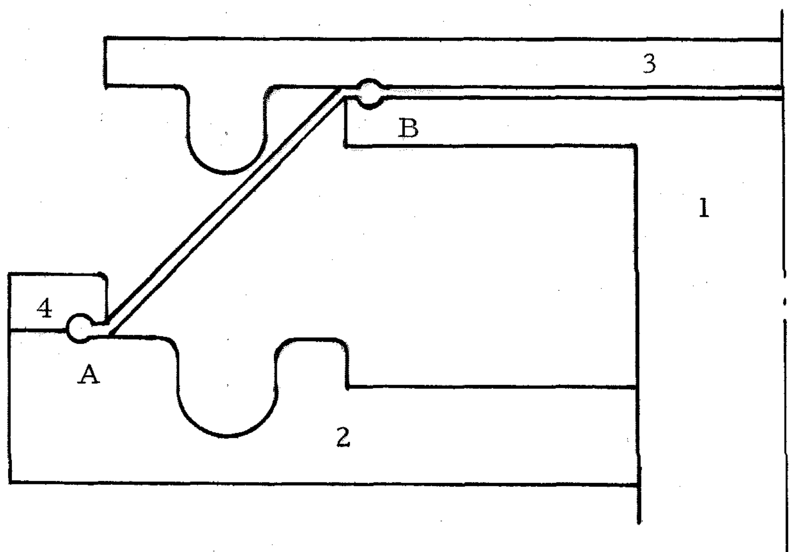
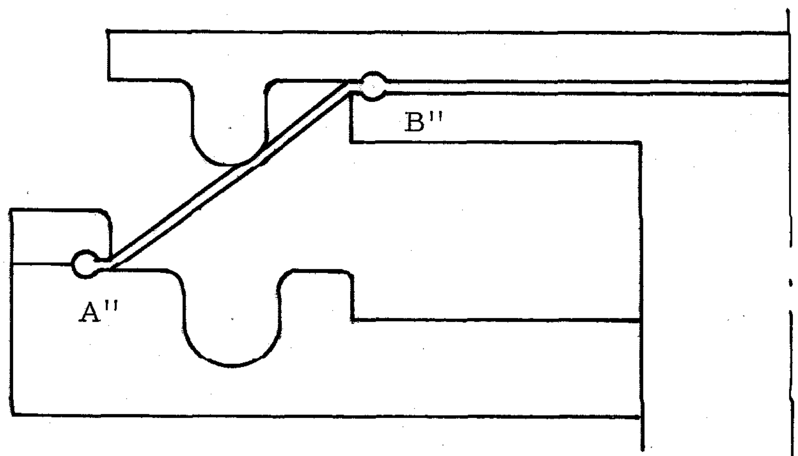


Fig. 8

(I)



(II)



(III)

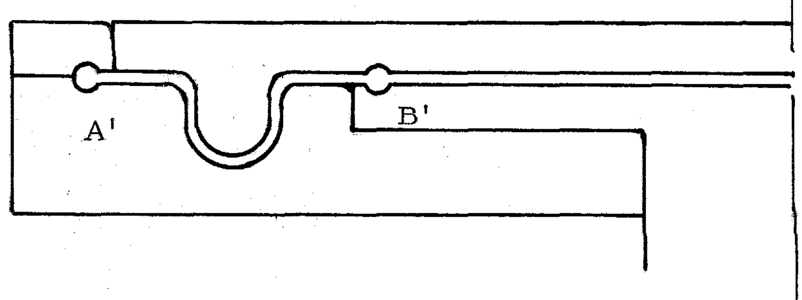


Fig. 9

— The initial shape is one of a frustrum of cone of revolution. The two beads A and B are clamped in their respective positions: A between parts (1) and (3), B between parts (2) and (4). (See Fig. 9, I.)

— By a vertical translation of part (2), part (3) staying at the same place, the "bead" wires are put into the final position A'B'. During this operation, parts (2) and (3) give the corrugation its definitive shape. (See Fig. 9, III.)

— An intermediate position, A'' B'', is shown on Fig. 9, II.

It must now be explained in some detail how the rubber layers, plies and "bead" wires will be placed in position so as to form the frustrum of cone.

Building the initial shape

Following Fig. 10, the steps of the operation are:

— I: Parts (1) and (2) are in position. On (1) a disk of 0.010 in. rubber layer is laid; on (2) a ring of 0.010 in. rubber layer is laid.

— II: The ply is put in position between A and B, the cords making the proper angle (35°) with the apothem. On top of it is placed at A the outer "bead" wire.

— III: Then the ply is folded around the outer 'bead" wire up to B, thus forming the second ply. On top of it is

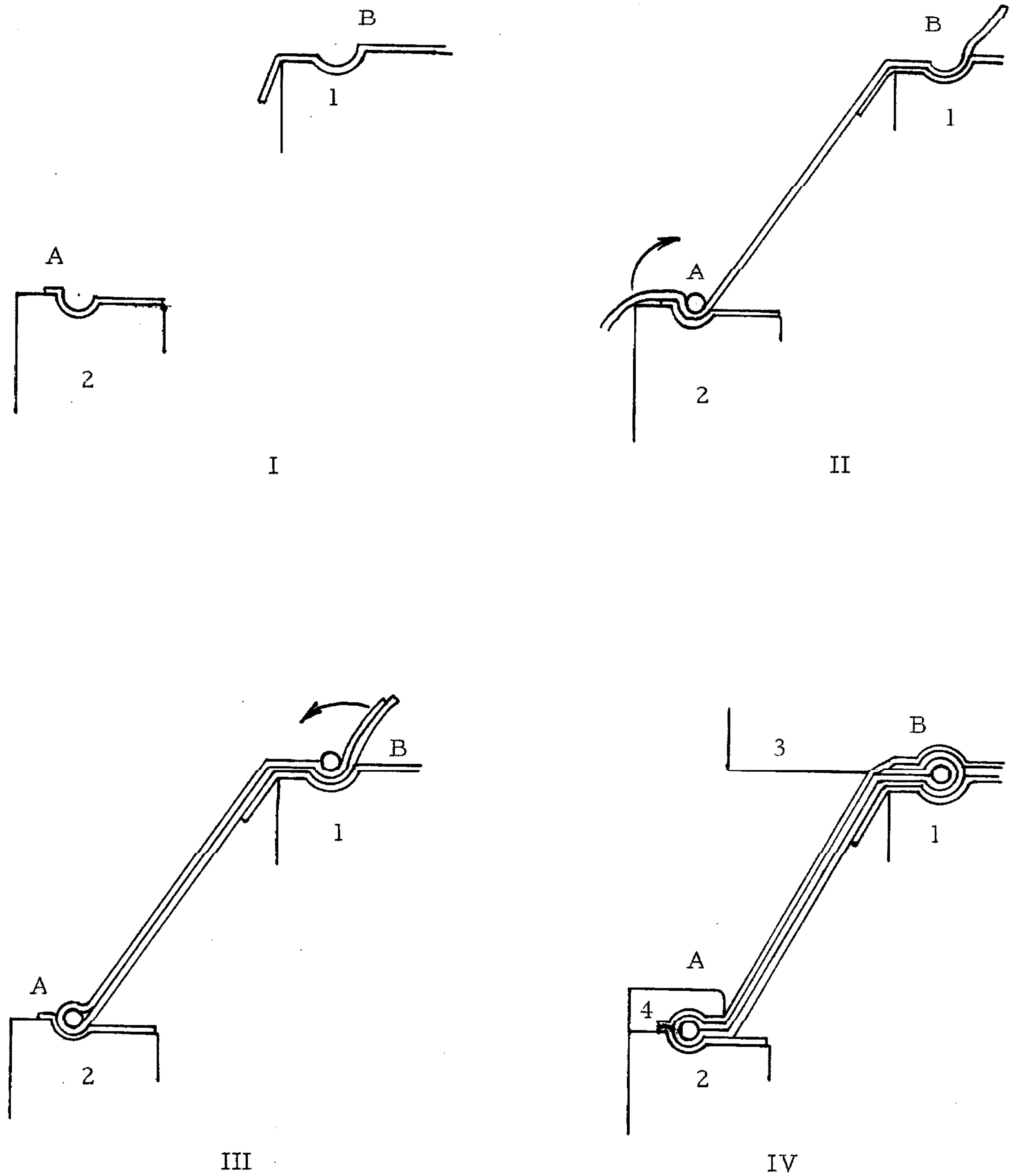


Fig. 10

placed at B the inner "bead" wire.

— IV: The part of the two plies which is still free is then folded around the inner "bead" wire. On the center plate is laid a disk of 0.040 in. rubber layer, and on top of the plies and the central plate is placed a final 0.010 in. rubber layer. The ply, which in fact makes two plies after having been folded around the outer "bead" wire, is therefore anchored around the two "bead" wires. It is then clamped between (2) and (4) at A and (1) and (3) at B and the frustrum of cone is ready for the shaping operation explained above.

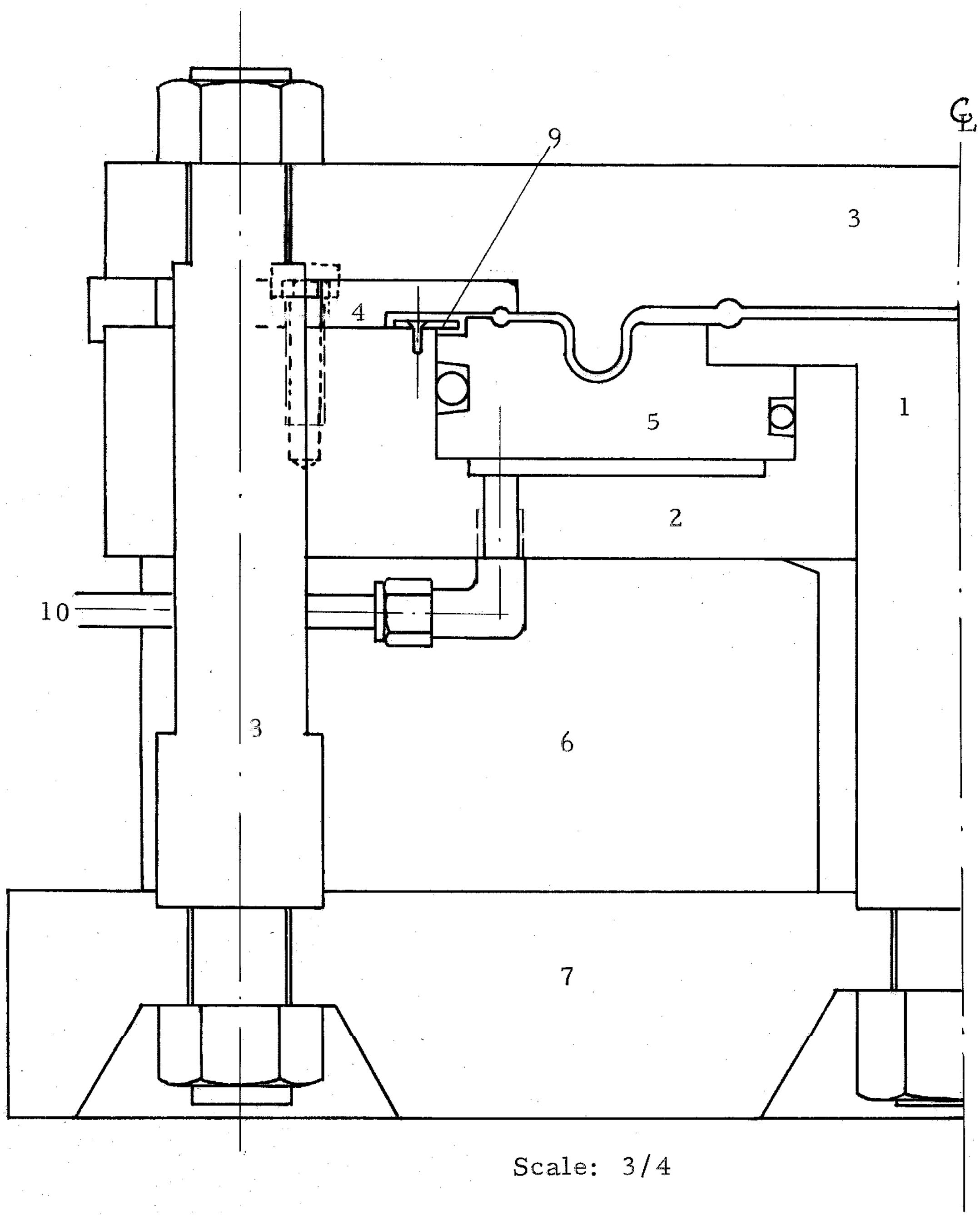
One operation is left to be performed: the curing or vulcanization of the diaphragm.

The vulcanization process

This operation is performed in the industry by simultaneous application of pressure (350 psi) and temperature (350^{o}F) during $\frac{1}{2}$ hour.

Referring to the assembly drawing of the mold given on Fig. 11, the vulcanization will involve the following steps:

— Part (2) containing a hydraulic piston (5) is in its high position. Between part (2) and part (7) a series of blocks (6) is placed. The purpose of these blocks is to keep (2) in position and prevent it from bending when the pressure is applied.



Scale: 3/4

Fig. 11

— The mold is then placed in an oven and the pipe 10 is joined to a hand pump situated outside the oven.

— The mold is heated at $350^{\circ}F$ and at the same time the hand pump builds up on the diaphragm a pressure of 350 psi, by means of the hydraulic piston (5) which apply pressure not only directly on the corrugated part of the diaphragm, but indirectly, through part (1) to the central flat part of the diaphragm.

The pressure to apply to the diaphragm is 350 psi. But the piston has not the same surface area as the diaphragm; therefore, the pressure which must be induced on the piston by the hand pump is:

$$p = 350 \cdot \frac{\pi\,(3.5)^2}{\pi\,[(4)^2 - (1.25)^2]} = 350 \cdot \frac{12.2\,\pi}{\pi[16 - 1.6]}$$

$$p \simeq 300 \text{ psi}$$

It must be noticed here that this application of pressure can be performed only after part (1) has been unbolted from part (7) so as to allow it a certain displacement.

— After half an hour of this treatment the rubber is cured and the diaphragm is ready to be used in the tension load cell.

It would be good now to describe the particular features of the different parts of the mold.

Particular features of the mold

The working drawings of the parts are given in the appendix. The mold is made of steel for the three following reasons:

1) During the operation of vulcanization, the mold is subject to a temperature of 350°F. It is therefore interesting to chose steel which has a low expansion: its linear expansion per unit length per deg. F. is 0.0000063. In comparison, the coefficient of expansion of aluminum is double this.

2) During vulcanization, the mold is also subject to high stresses produced by the application of pressure. The high mechanical properties of steel are therefore indicated here. It is interesting to note that the strength of steel at 350°F. is 125% of its strength at 70°F.

3) Rubber does not stick to steel during molding, but it does to aluminum.

During its vertical translation, part (2) is guided by the three bars (8) on the outside and part (1) at its center.

Parts (3), (7), and (8) are the three parts which have to support the load produced by application of the pressure.

The minimum necessary thickness of part (3) must be calculated; we will then use the same thickness for part (7).

Part (3) can be considered as a circular flat plate with a load concentrated at the center upon a circular area with radius r = 3.5 in. In fact, the load is applied on a circular area of radius 3.5 in., which is almost all the surface of the plate, radius 5 in. In any case, we will consider that the load is concentrated at the center which is the most unfavorable case.

Bach's formulas give the following thickness for the plate:

$$t = 1.2\sqrt{\frac{W(1 - \frac{2r}{3R})}{S}}$$

With:

W: Total load in pounds = 350 $\pi(3.5)^2$ = 13,400 lb.

R: Radius of plate in inches = 5 in.

r: Radius of the circular area on which the load is concentrated = 3.5 in.

S: Fiber stress in pounds per square inch. According to previous calculations and to the fact that the load is a dead load and is applied gradually, the safety factor will be taken equal to 3 and S has the value $\frac{60,000}{3}$ = 20,000 psi.

Therefore:

$$t_1 = 1.2\sqrt{\frac{13,400\,(1 - \frac{7}{16.5})}{20,000}} = 1.2\sqrt{\frac{13,000 \,.\, 0.57}{20,000}}$$

$$t_1 = 1.2\sqrt{0.38} = 1.2 \,.\, 0.61$$

$$t_1 = 0.73 \text{ in.}$$

The thickness of the plate (3) will therefore be taken at least equal to $\frac{3}{4}$ in. The same thickness will be taken for plate (7).

It would also be interesting to calculate the deflection at the center of parts (3) and (7) produced by the application of the pressure. It is given by the following formula:

$$S = 0.053 \frac{WR^2}{Et^3} = 0.053 \frac{13,400 (5)^2}{30,000,000 (0.75)^3}$$

$$S = 0.053 \frac{13,400 \; . \; 25}{30,000,000 \; . \; 0.41}$$

$$S = 0.053 \; . \; 0.027 = 0.0014 \text{ in.}$$

The deflection can be considered as negligible.

The minimum diameter of the bar (8) should now be determined. The ultimate strength is 60,000 psi. The safety factor is equal to 3. Therefore:

$$\pi \frac{d_1^2}{4} 20,000 = \frac{13,400}{3}$$

$$d_1^2 = \frac{13,400}{20,000} \frac{4}{3} \frac{1}{\pi} = 0.28$$

$$d_1 = 0.53$$

The thinnest region of the bar corresponds to the place where it is bolted to part (3). Therefore, the initial load produced in the bolt by tightening must be taken into account. The diameter will be taken equal to $\frac{3}{4}$ in.

As the diaphragm must be molded with good precision, the different parts must, from the initial position to the final position where the diaphragm is shaped, stay in the same alignment. Therefore, the tolerances and allowances at the places where the parts are sliding in each other must be of the medium fit type. This is the case for the sliding of (1) in (2), (5) in (2), (4) in (3), (1) in (5), and (8) in (2). To this necessary close tolerance is added a necessary good surface quality. The required surface on these sliding parts is an 8 microinch surface.

It must also be pointed out that part (8) which ties parts (3) and (7) together must be bolted at the right place on these two parts. This leads to very close tolerance for the spotfaces on (3) and (7) where (8) is placed.

The last point to be stressed is the one concerning the piston (2). The type of sealing chosen is a Parker O-Ring seal, calculated for 1500 psi max. The dimensions of the groove are given on the working drawings. The numbers of the O-Rings which were chosen are Parker 333 and Parker 443.

The molding equipment necessary to the fabrication of the diaphragm is now designed. The last thing to design is the tension load cell which will utilize this diaphragm.

V. DESIGN OF THE TENSION LOAD CELL

The type B diaphragm alone will be considered and in order to obtain easier and more understandable drawings, a cell composed of only three elements will be designed.

Main ideas

As it has been explained before, the elements will be grouped in parallel. This means that all the parts (1) have to be joined together, as well as all the parts (2). Fig. 12 gives an idea of the arrangement.

The question remains of how to join the parts (1) together, or the parts (2) together. A solution would have been to join the parts (2) by the center of the cell, the parts (1) being joined by the outside. At one time this solution was considered, but had to be rejected because the diaphragm would have had a very complicated shape and would have been too difficult to build.

Thus, the only remaining solution is to join the parts (1) and also the parts (2) by the outside. The diaphragm is circular. Each element must be built around this diaphragm and will therefore have a cylindrical shape, as will have the complete cell. Under the load (L), the three elements must stay in alignment and the parts (1) and (2) must stay parallel to each other,

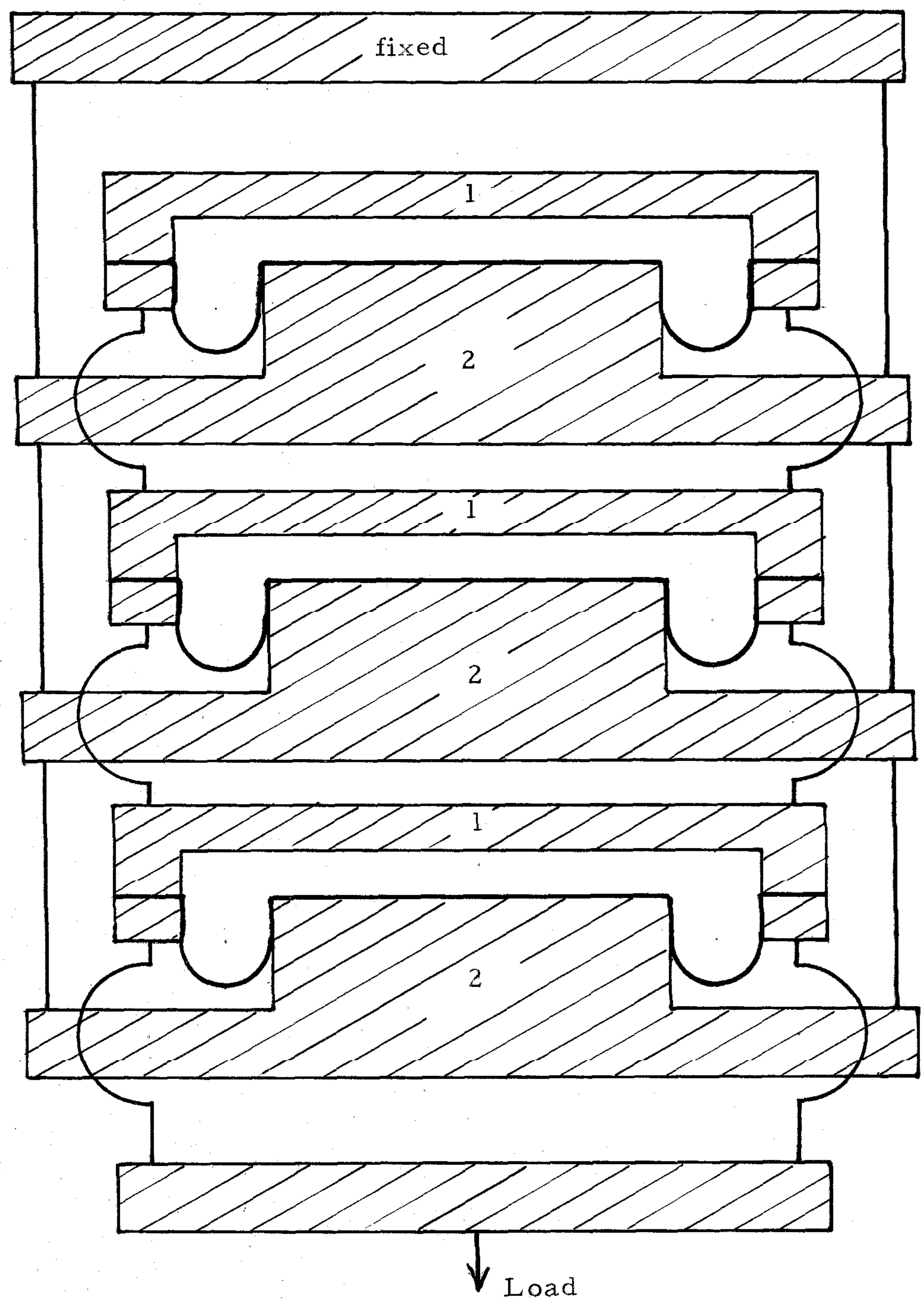


Fig. 12

in order to obtain accurate measurements of L. It was, therefore, decided to join the parts (1) by three bars equally spaced on the outside of the element. The parts (2) are joined in the same way, (See Fig. 13). In order to prevent as much as possible misalignment or non-parallelism, the clearance between a bar joining the parts (1) and a part (2) is 1/8 in. (and vice versa). For the same reason, the clearance between a part (1) and the following part (2) is 1/8 in.

Particular features of the tension load cell

The working drawings of the tension load cell are given in the appendix. Note that on the assembly drawing, Fig. 14, the three elements of the cell from top to bottom are not represented cut at the same place, in order to show different characteristics of the cell:

1) The top element shows how the plate (1) is joined to the bar (5) by means of a split ring (4). It shows also the clearance between part (2) and the bar (5).

2) The middle element shows how the diaphragm is clamped between part (1) and part (3). It shows also how the hydraulic hose goes out of the cell. It is then joined to the number of other hoses necessary to obtain the required range of measure-

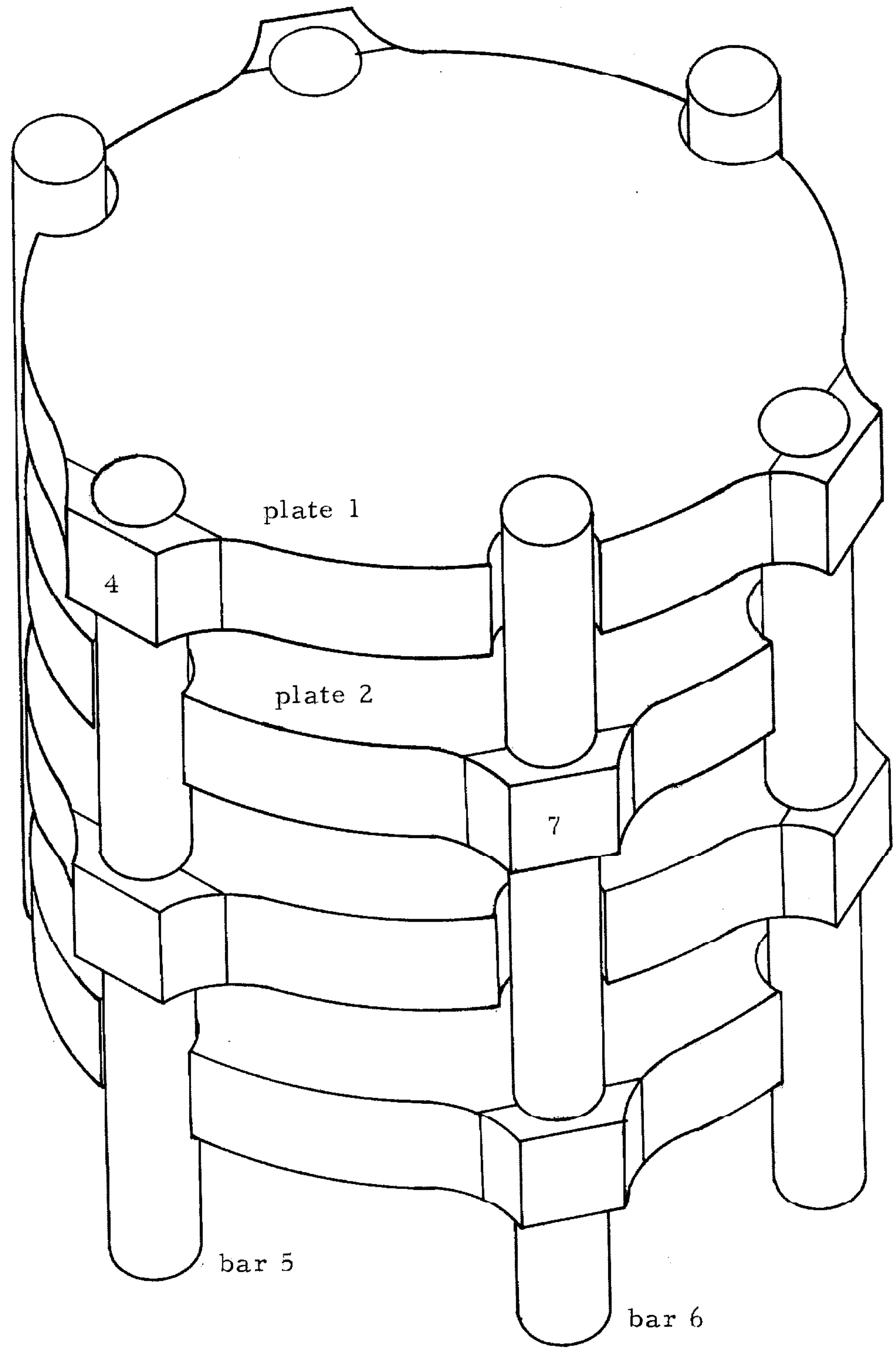


Fig. 13

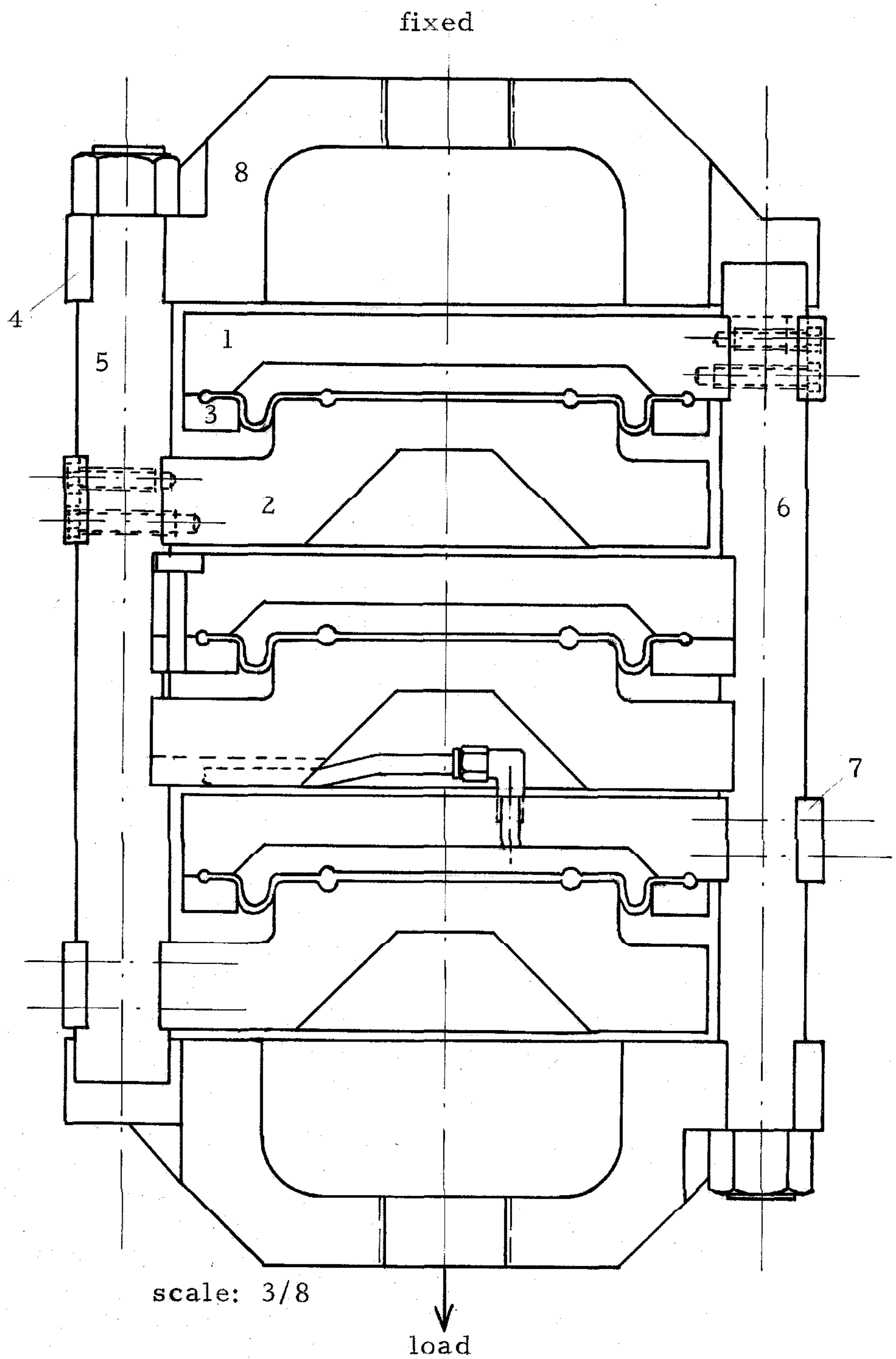


Fig. 14

ment. The main hose is then connected to the pressure gauge. A check valve should be provided which would permit the reloading of the system.

3) The bottom element shows how the part (2) is joined to the bar (6) by means of a split ring (7).

Note that the bars and split rings are built in exactly the same way whether they join the parts (1) or the parts (2) together.

As in the case of the mold, the two important dimensions to calculate are the thickness of the parts (1) and (2) and the diameter of the bar (5).

Applying Bach's formula:

$$t_2 = 1.2 \sqrt{\frac{W\left(1 - \frac{2r}{3R}\right)}{S}}$$

With the same definitions for the symbols as before:

$W = 3000$ lb.

$r = 3$ in.

$R = 4$ in.

$F =$ safety factor $= 2 \,.\, 2 \,.\, 2 \,.\, 1.5 = 12$

$$S = \frac{60,000}{F} = \frac{60,000}{12} = 5,000$$

Therefore:

$$t_2 = 1.2 \sqrt{\frac{3000\left(1 - \frac{6}{12}\right)}{5,000}} = 1.2 \sqrt{\frac{1,500}{5,000}}$$

$$t_2 = 1.2 \sqrt{0.3} = 1.2 \,.\, 0.55$$

$$t_2 = 0.66 \text{ in.}$$

The minimum thickness of the parts (1) and (2) will be taken, therefore, equal to 0.75 in.

The minimum diameter of the bar (5) should now be determined. The ultimate strength is 60,000 psi. The safety factor is equal to 12. Therefore:

$$\frac{\pi d_2^2}{4} \; 5,000 = \frac{9,000}{3} = 3,000$$

$$d_2^2 = \frac{3,000}{5,000} \; \frac{4}{\pi} = 0.77.$$

$$d_2 = 0.88 \text{ in.}$$

The minimum diameter will therefore be taken equal to 1 in.

The tolerances are close only at the places where the diaphragm is clamped between parts (1) and (3) or lies on part (2). The fastening of the bar (5) to the part (1), as well as the fastening of the bar (6) to the part (2), necessitate close tolerances. These are specified on the working drawings.

No particular requirements are made on the quality of the surface.

This was the last step of the proposed study. It remains now only to draw the conclusions brought about by it.

VI. CONCLUSION

It must be pointed out first of all that, of the two problems set forth at the beginning of the study, the problem of the diaphragm is the one on which the biggest part of the work was concentrated. It involved the studies of the methods used in the tire industry; made clear the fact that not many publications are available on the subject; and led eventually to the visit of a tire manufacturing company. It involved also a detailed calculation of the stresses produced in the diaphragm and the design of the molding equipment necessary to build this diaphragm.

Once the shape of the diaphragm was established, the design of the load cell followed without too many problems, except the one of trying to make the cell as compact as possible.

These studies could be pursued particularly by trying to use thinner nylon cords. It would also be interesting to try out the idea of joining the series of plates by the center of the cell. This study would lead to the design of a different diaphragm.

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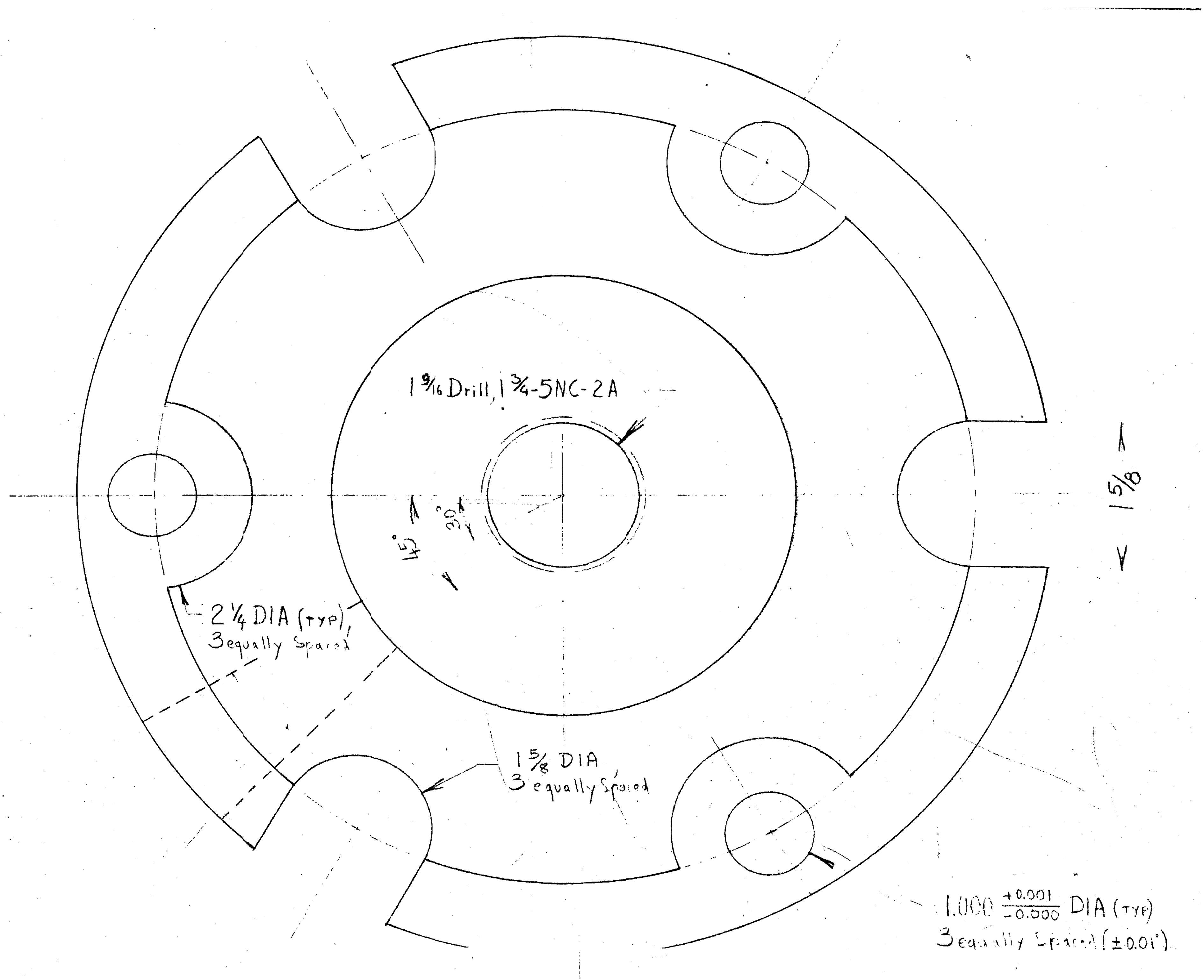
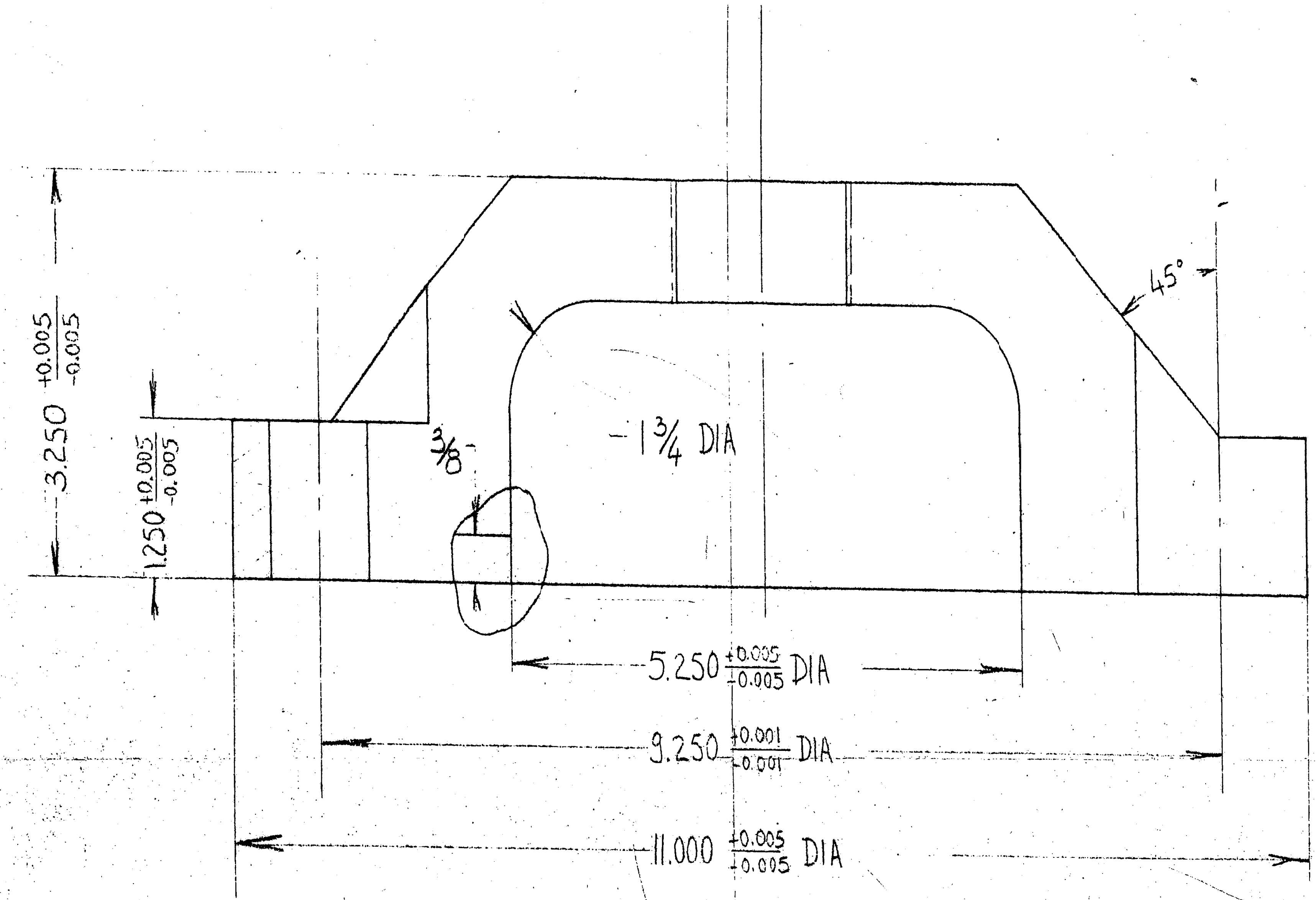
6. Properties of Nomex, High Temperature Resistant Nylon Fiber, Technical Service Section, E. I. du Pont de Nemours and Company, Inc., Wilmington 98, Delaware, NP-33, October 1963.

VIII. APPENDIX

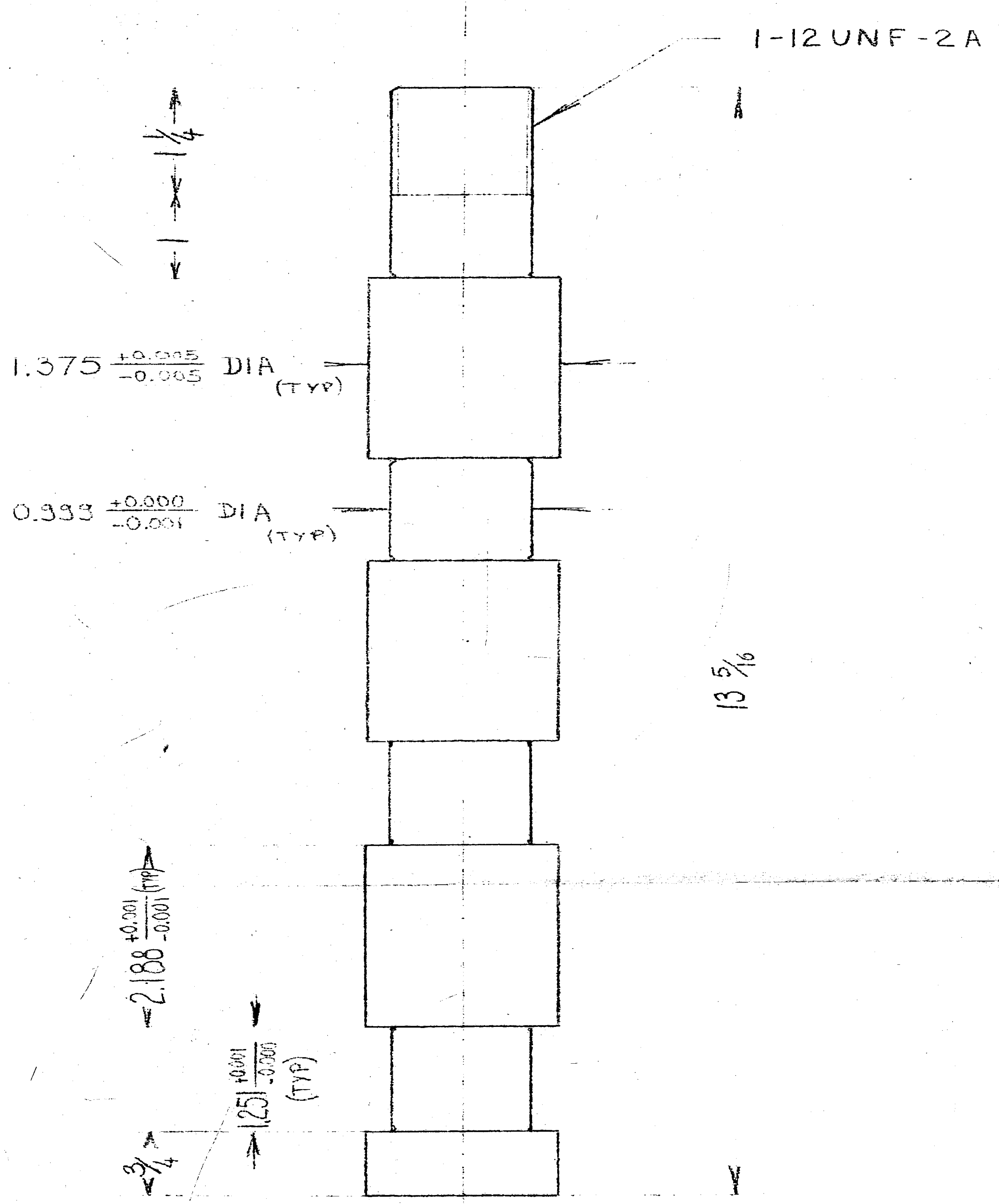


1 9/16 Drill, 1 3/4-5NC-2A
45°
30°
2 1/4 DIA (TYP), 3 equally Spaced
1 5/8 DIA 3 equally Spaced
1 5/8
1.000 +0.001 -0.000 DIA (TYP) 3 equally Spaced (±0.01°)



32√ UNLESS OTHERWISE NOTED

8	CASING	2	AISI 1040 STEEL
PART NO.	NAME	NO. REQ.	MATERIAL
CALIFORNIA INSTITUTE of TECHNOLOGY			DRAWN BY J.H. CALLE
TENSION LOAD CELL			DATE MAY. 10-1965
			SCALE: 1 / DWG. NO. 7



6.5	CROSS BAR	6	AISI 1040 STEEL
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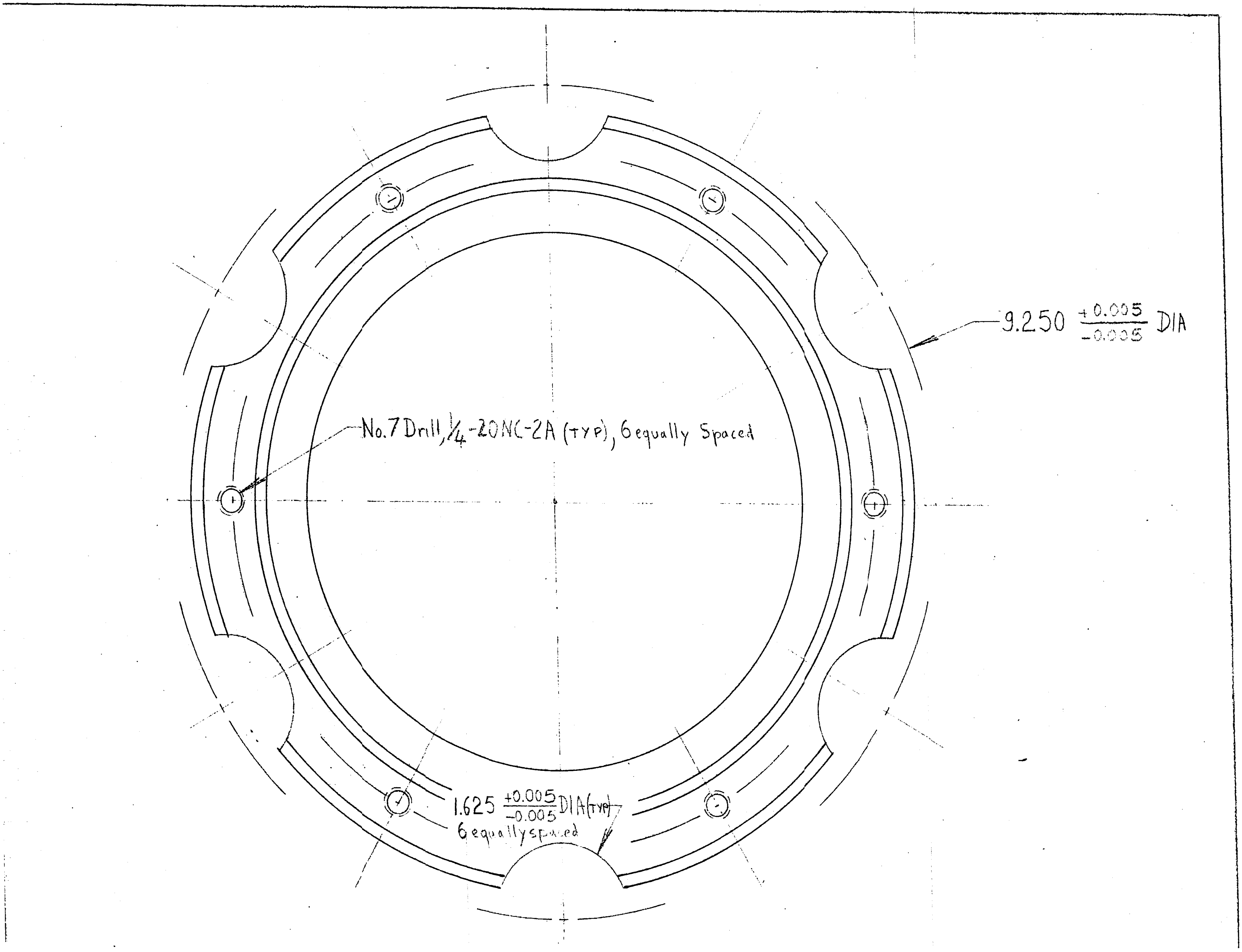
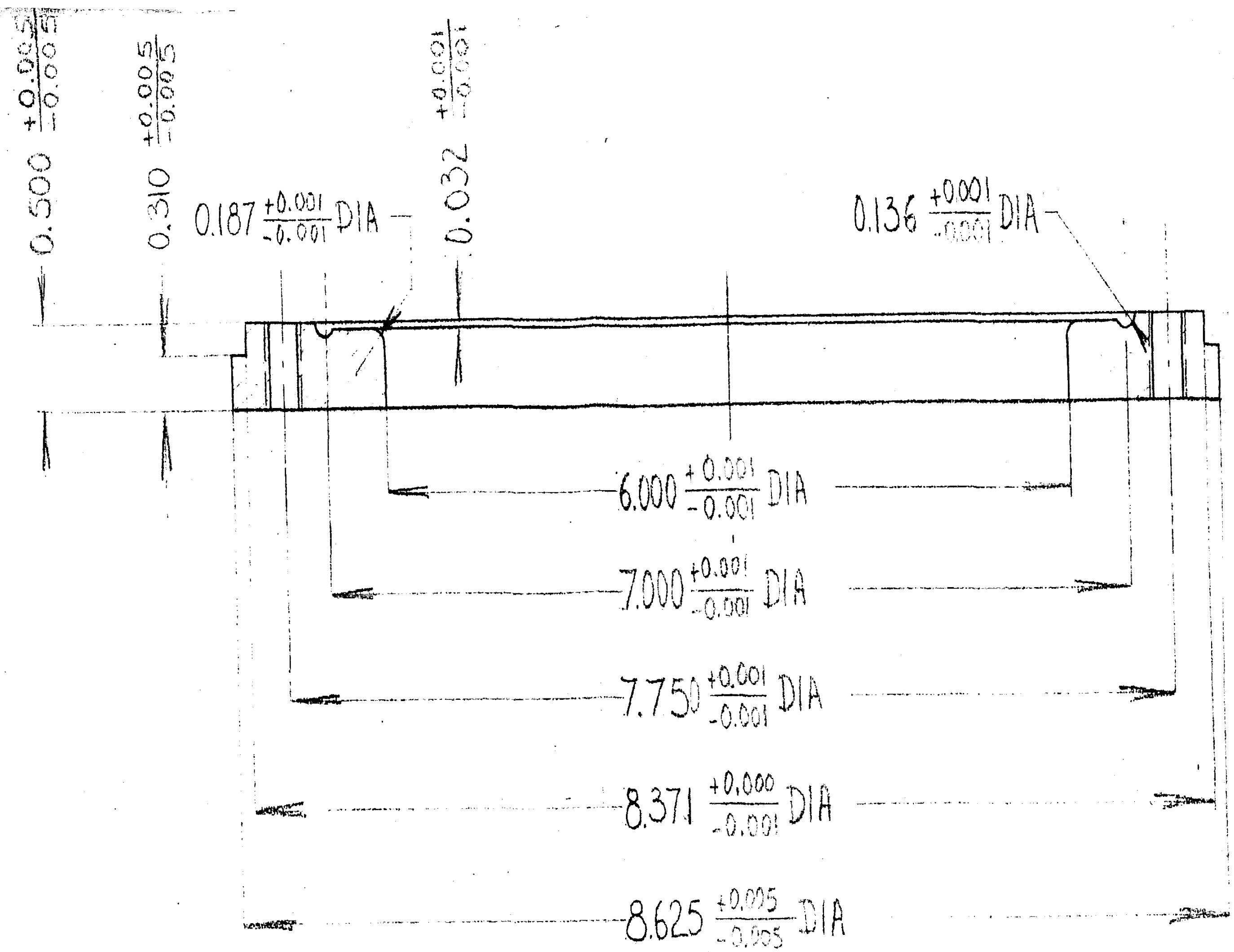
CALIFORNIA INSTITUTE of TECHNOLOGY			DRAWN BY J.H. CALLE
TENSION LOAD CELL			DATE MAY. 10. 1965
			SCALE: 1 DWG NO. 6

32 √ UNLESS OTHERWISE NOTED

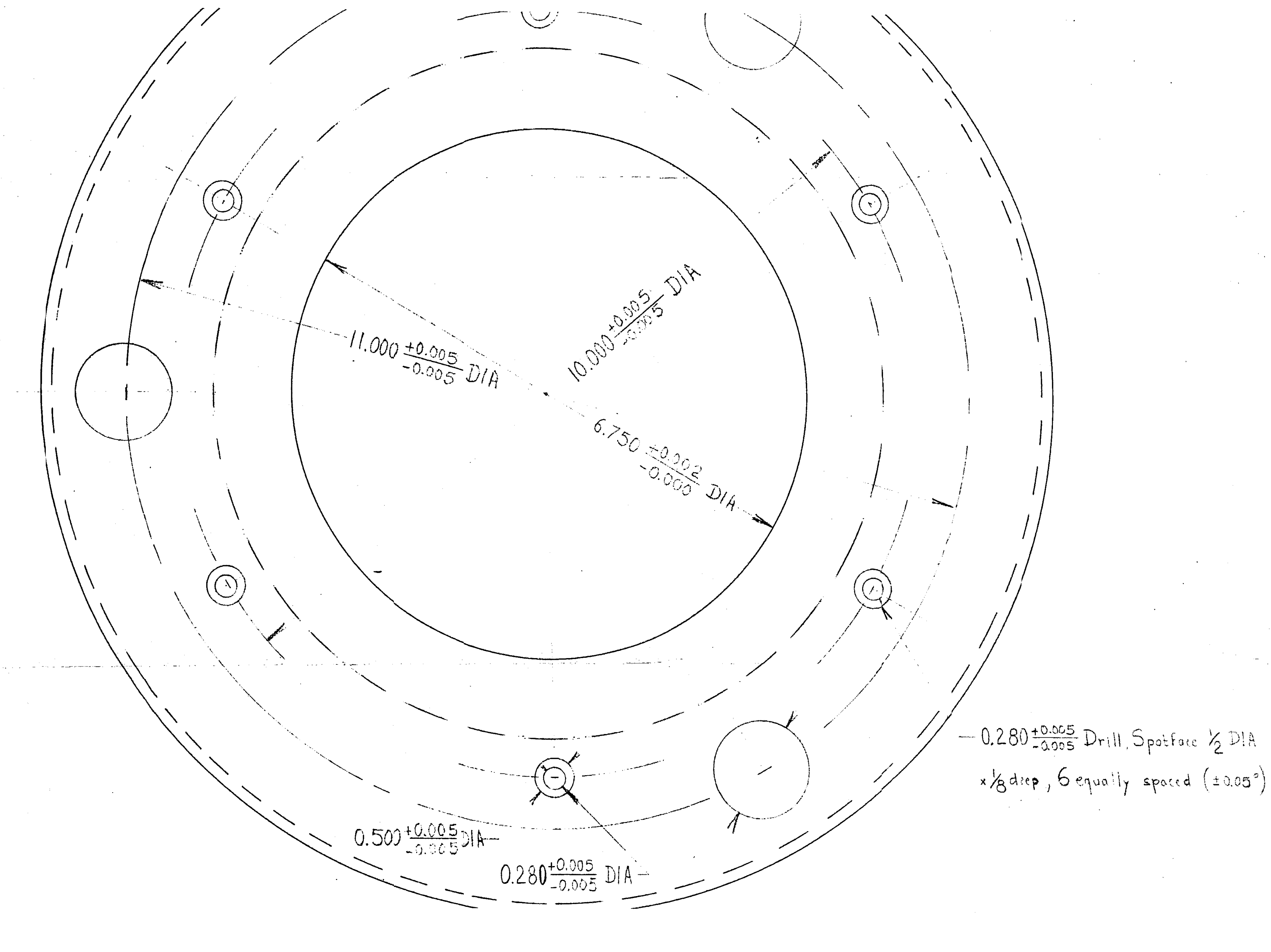


No.7 Drill, 1/4-20NC-2A (TYP), 6 equally Spaced
9.250 +0.005/-0.005 DIA
1.625 +0.005/-0.005 DIA (TYP)
6 equally spaced

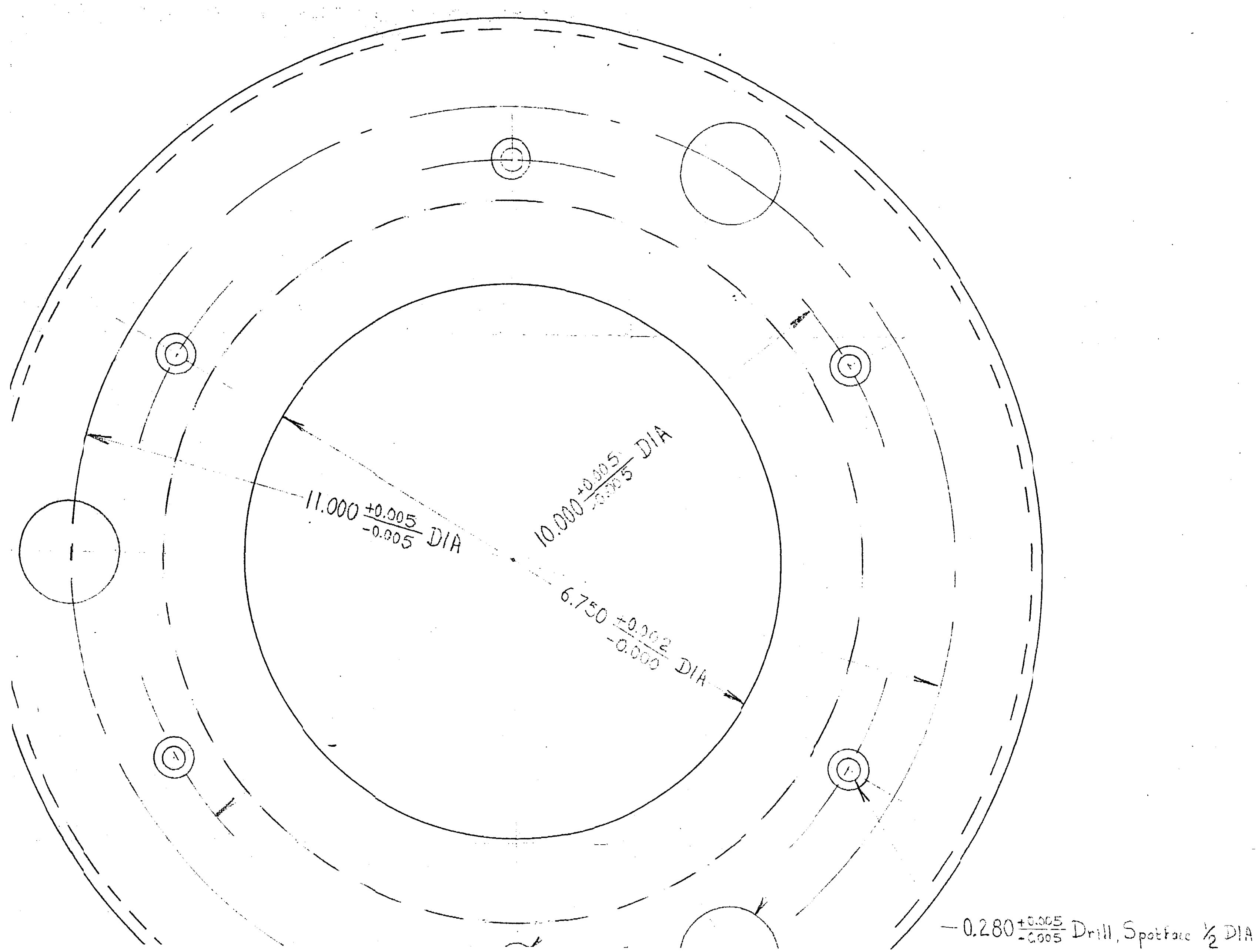


32√ UNLESS OTHERWISE NOTED

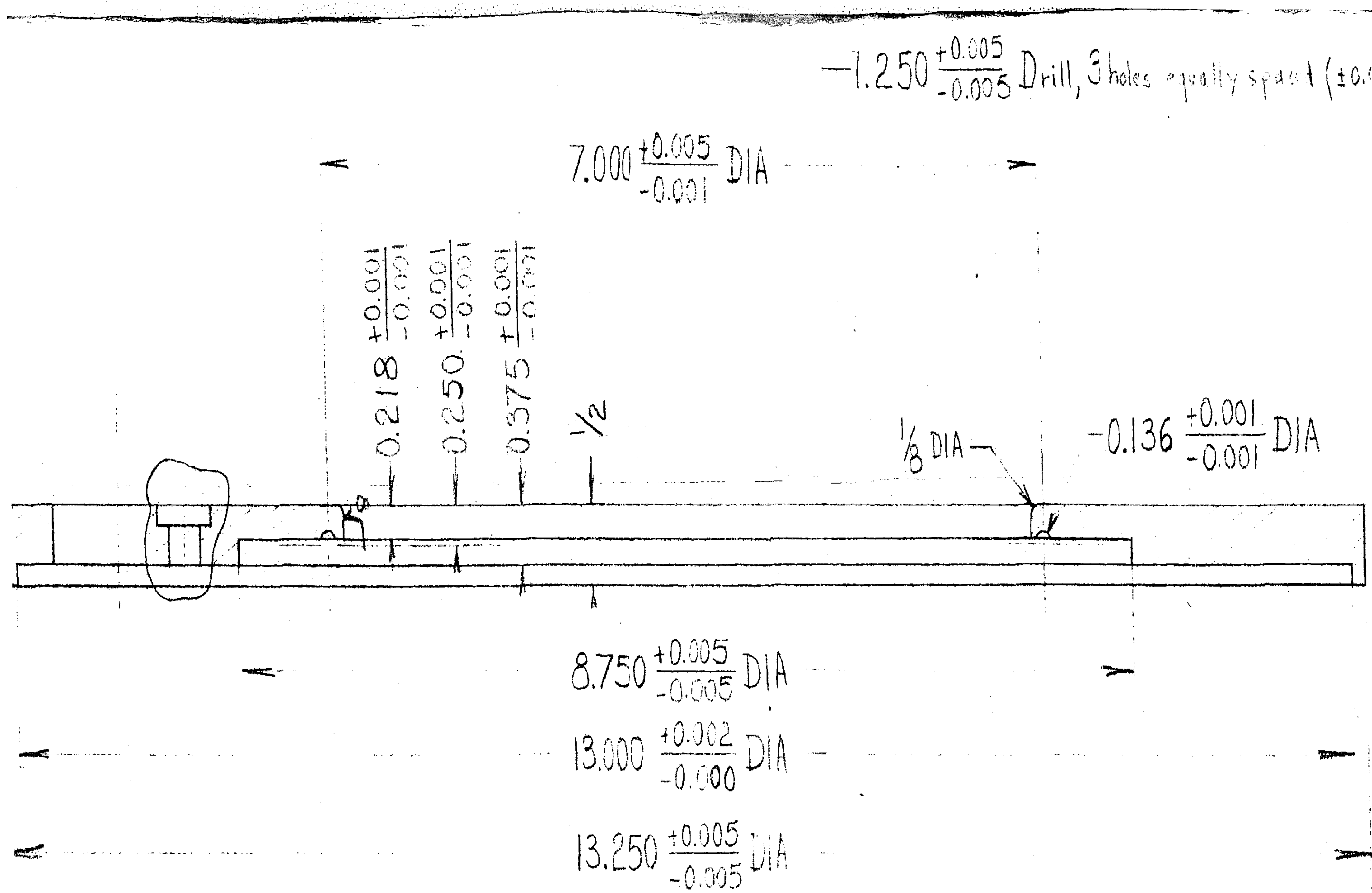
3	CLAMP	3	AISI 1040 STEEL
PART NO.	NAME	NO. REQ	MATERIAL
CALIFORNIA INSTITUTE of TECHNOLOGY			DRAWN BY J.H. CALLE
TENSION LOAD CELL			DATE MAY-10-1965
			SCALE: 1 — DWG. NO. 4



11.000 $\frac{+0.005}{-0.005}$ DIA
10.000 $\frac{+0.005}{-0.005}$ DIA
6.750 $\frac{+0.002}{-0.000}$ DIA
0.500 $\frac{+0.005}{-0.005}$ DIA
0.280 $\frac{+0.005}{-0.005}$ DIA
0.280 $\frac{+0.005}{-0.005}$ Drill, Spotface ½ DIA
x ⅛ deep, 6 equally spaced (±0.05°)

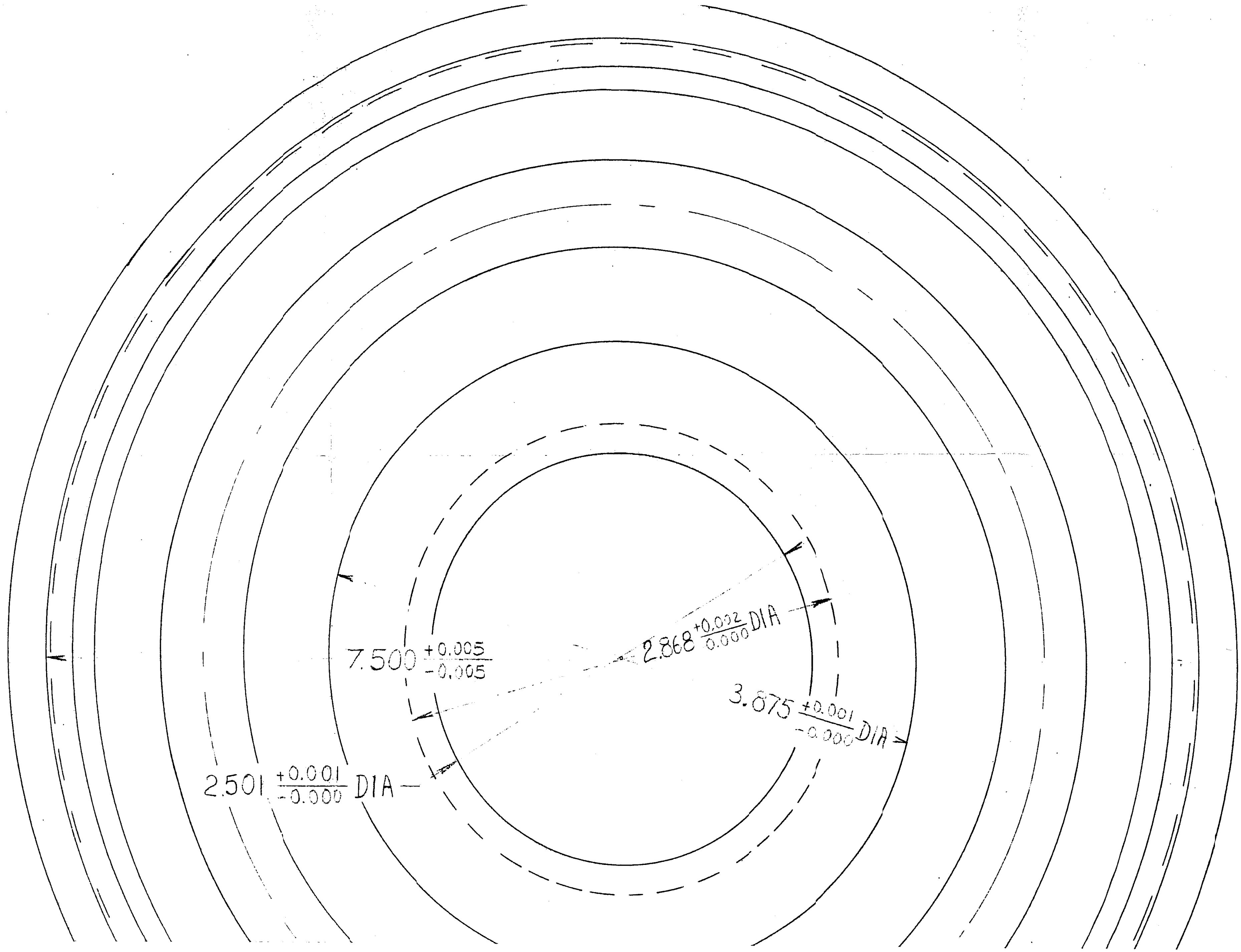


11.000 +0.005 -0.005 DIA
10.000 +0.005 -0.005 DIA
6.750 +0.002 -0.000 DIA
0.280 +0.005 -0.005 Drill, Spotface ½ DIA

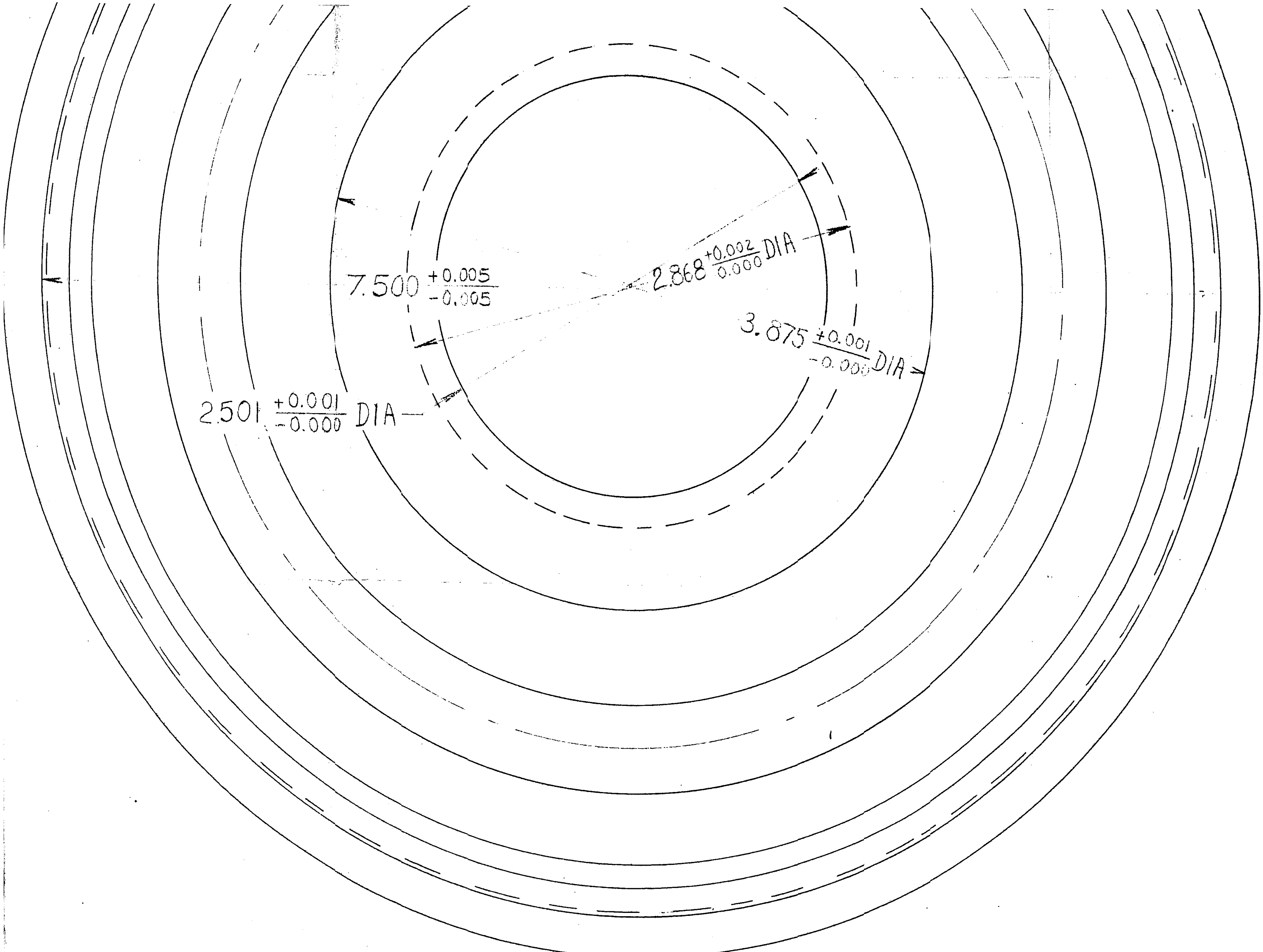


32√ UNLESS OTHERWISE NOTED

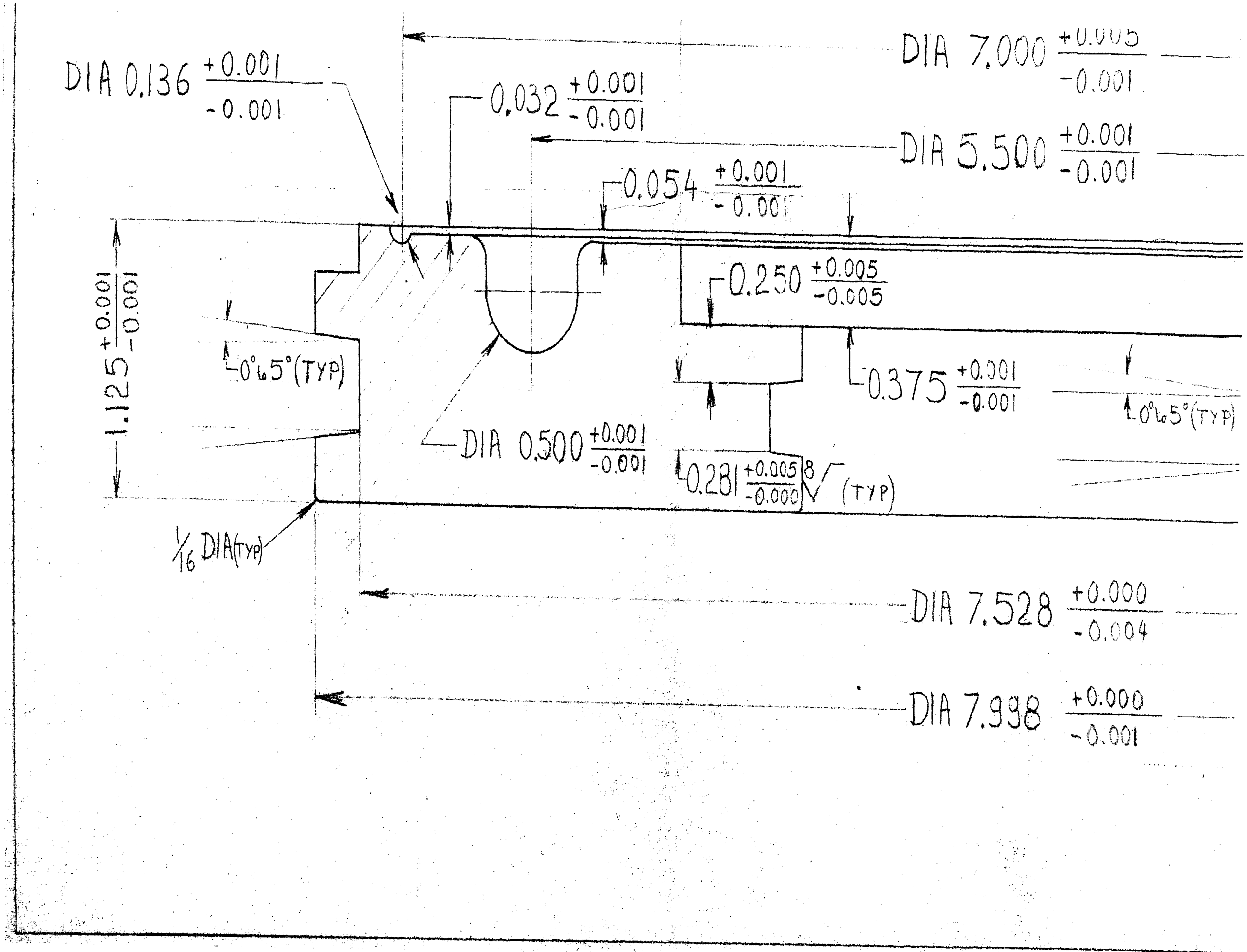
4	CLAMP	1	AISI 1040 STEEL
PART No.	NAME	NO. REQ'D	MATERIAL
CALIFORNIA INSTITUTE OF TECHNOLOGY			DRAWN BY J.M.CALI
DIAPHRAGM MOLD			DATE MAY 10 196
			SCALE: 1 DWG. NO.

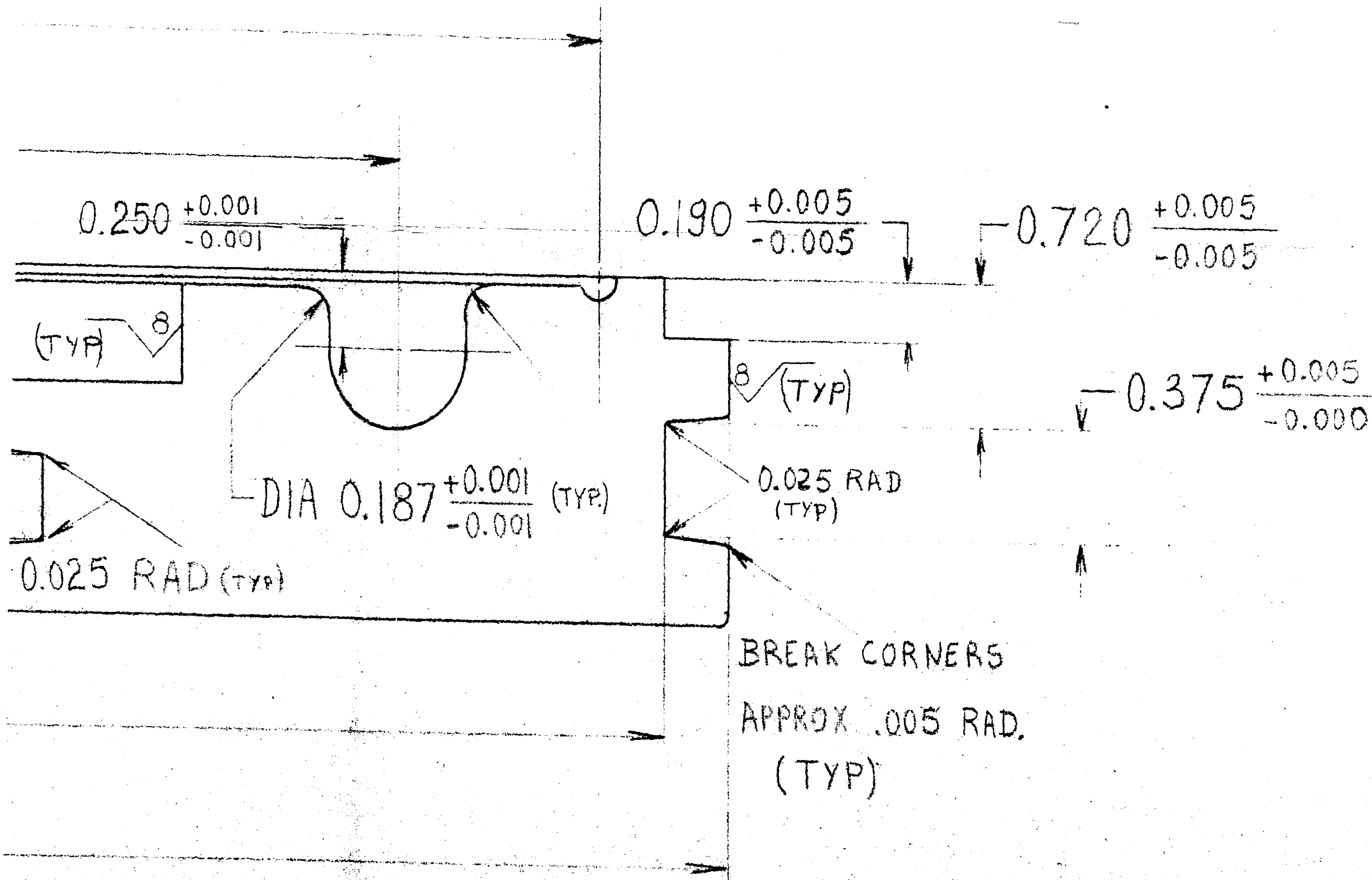


7.500 +0.005 -0.005
2.868 +0.002 0.000 DIA
3.675 +0.001 -0.000 DIA
2.501 +0.001 -0.000 DIA



7.500 +0.005 -0.005
2.868 +0.002 0.000 DIA
3.875 +0.001 -0.000 DIA
2.501 +0.001 -0.000 DIA


DIA 0.136 +0.001 -0.001
0.032 +0.001 -0.001
DIA 7.000 +0.005 -0.001
DIA 5.500 +0.001 -0.001
0.054 +0.001 -0.001
0.250 +0.005 -0.005
1.125 +0.001 -0.001
0°6.5° (TYP)
0.375 +0.001 -0.001
0°6.5° (TYP)
DIA 0.500 +0.001 -0.001
0.281 +0.005 -0.000
8
(TYP)
1/16 DIA (TYP)
DIA 7.528 +0.000 -0.004
DIA 7.998 +0.000 -0.001



32 UNLESS OTHERWISE NOTED

5	FEMALE MOLD CYL.	1	AISI 1040 STEEL
PART NO.	NAME	NO. RQD	MATERIAL

CALIFORNIA INSTITUTE OF TECHNOLOGY

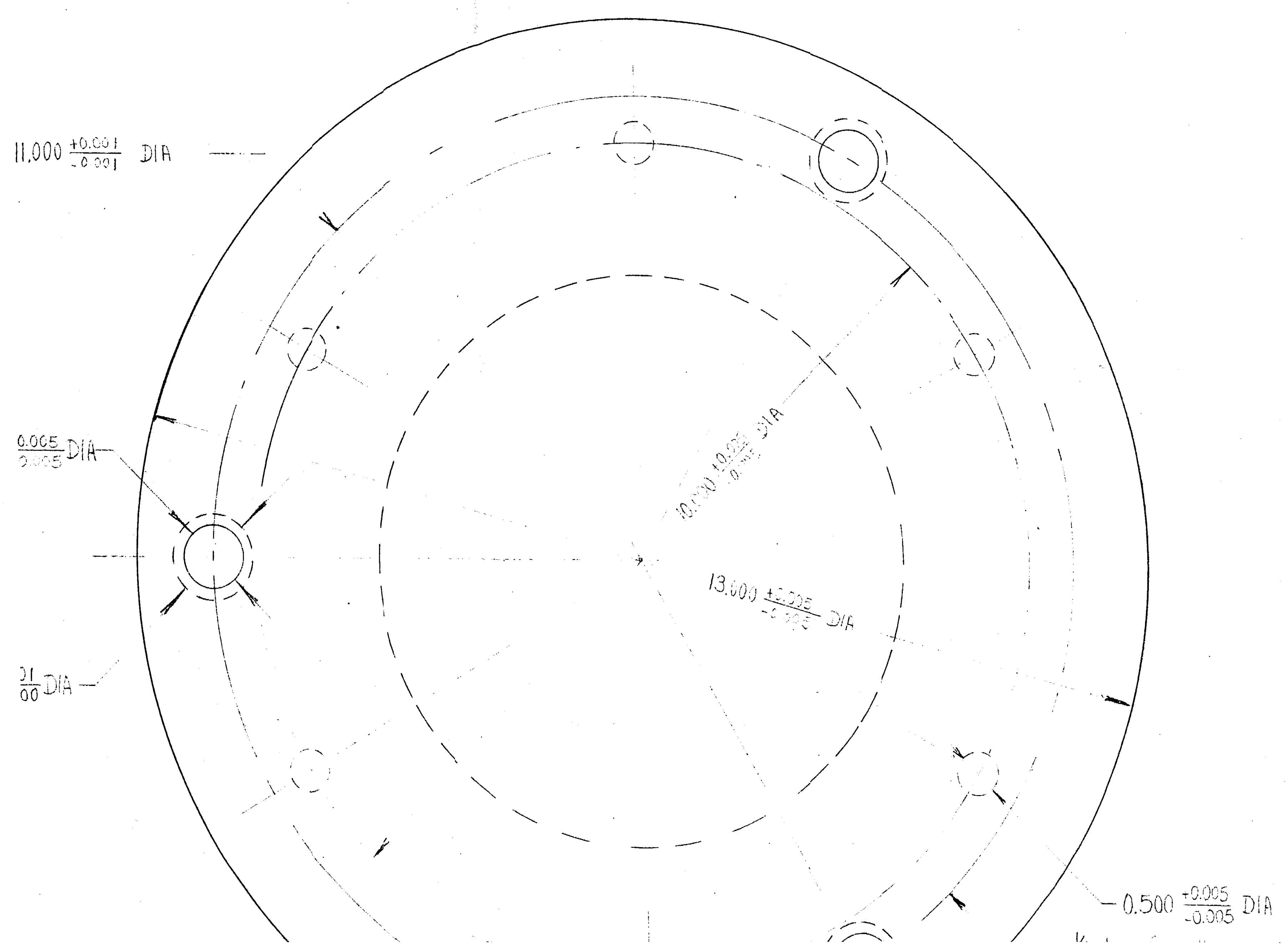
DRAWN BY J. M. CALIE

DIAPHRAGM MOLD

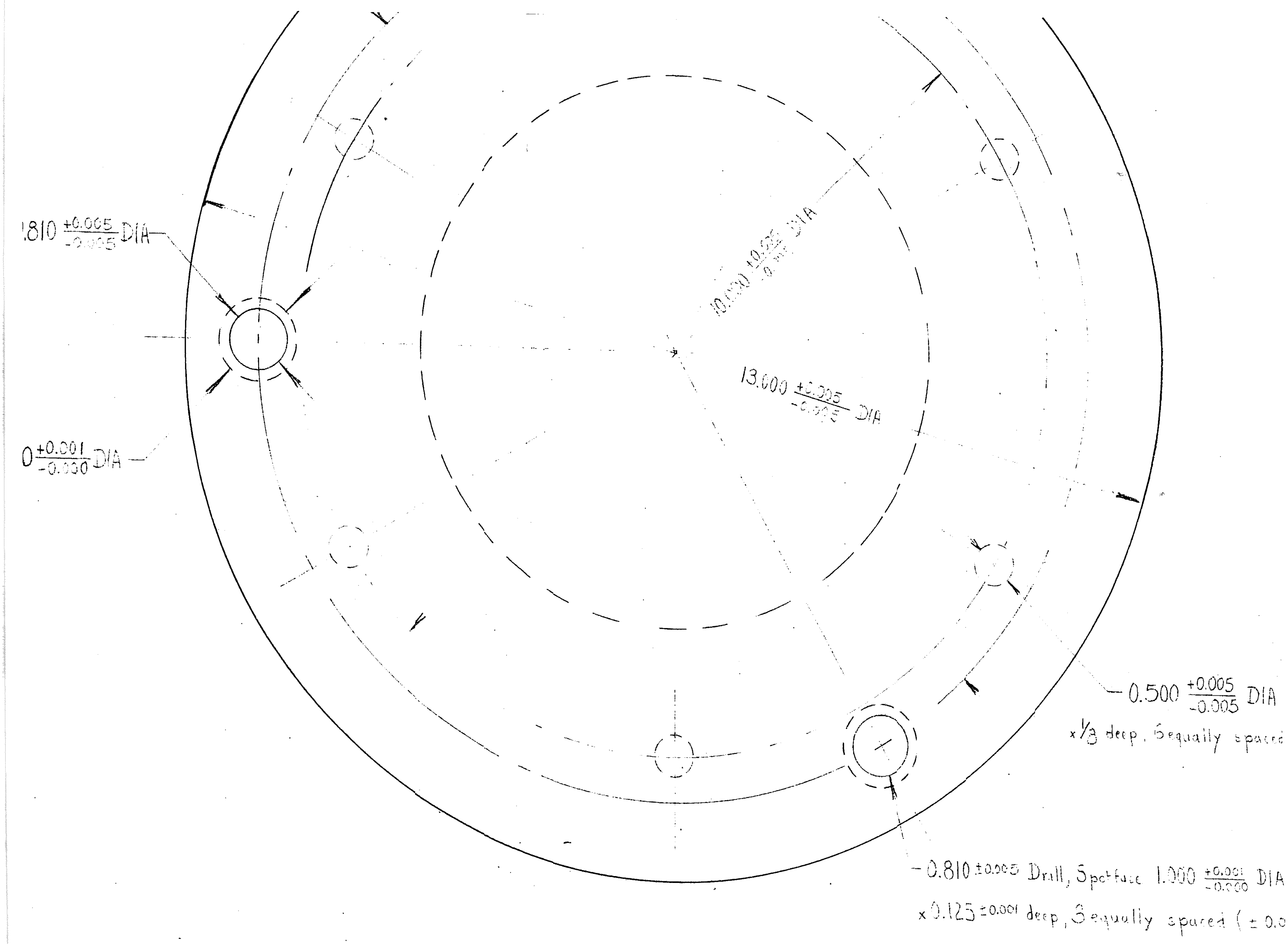
DATE MAY-10-1965

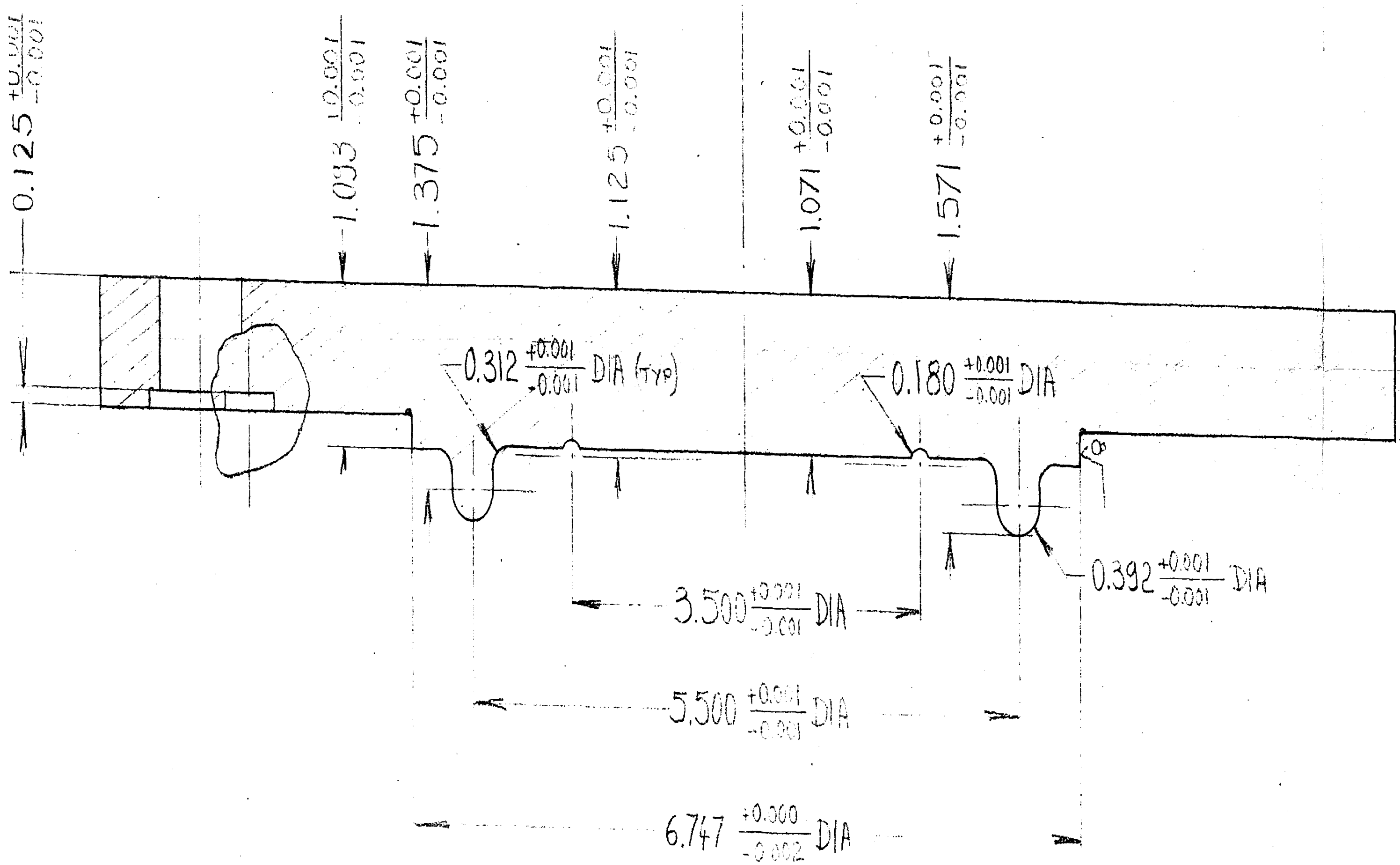
DWG. NO. 6

SCALE: 2 x FULL



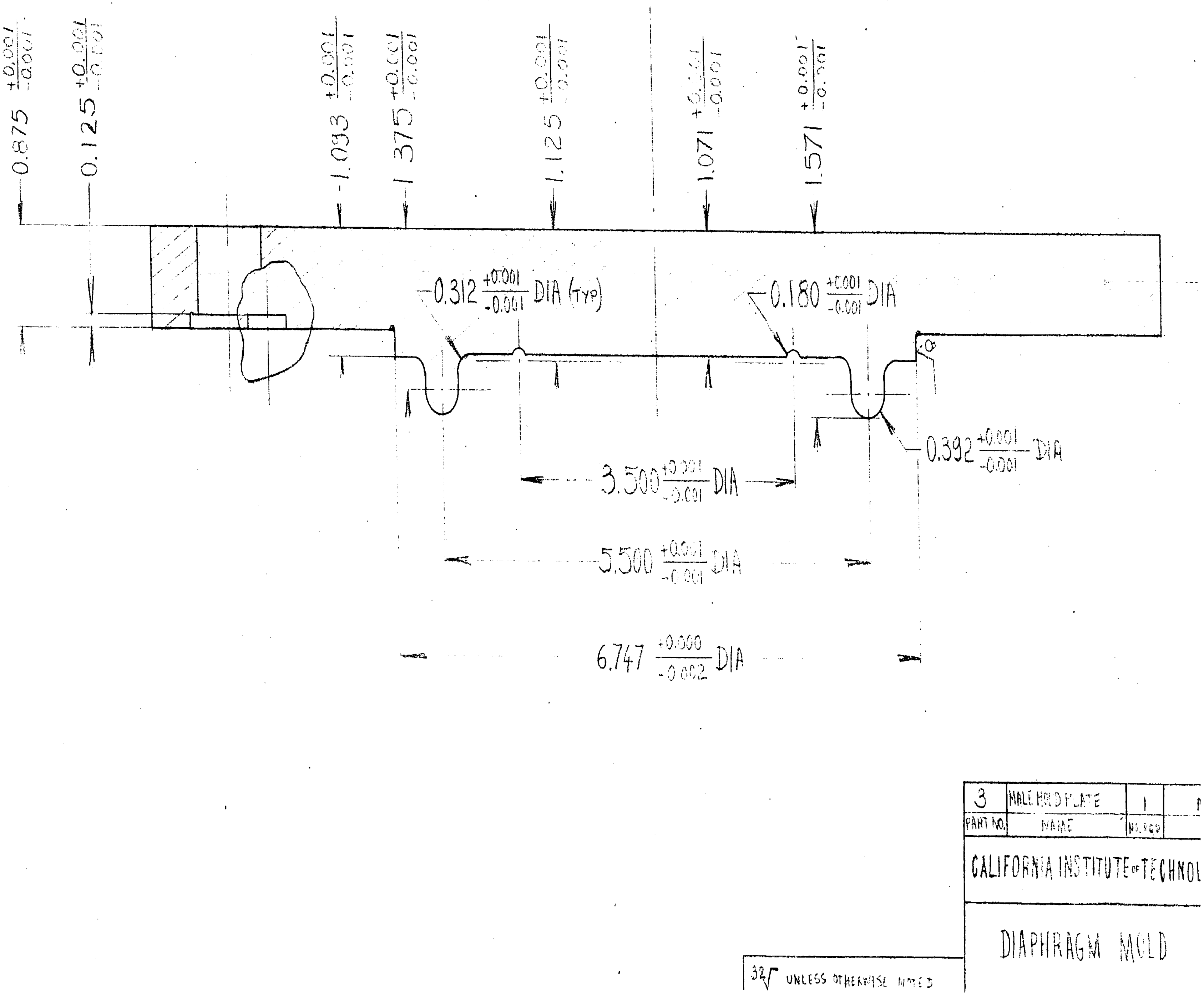
11.000 +0.001 -0.001 DIA
0.005 0.005 DIA
13.000 +0.005 -0.005 DIA
0.500 +0.005 -0.005 DIA

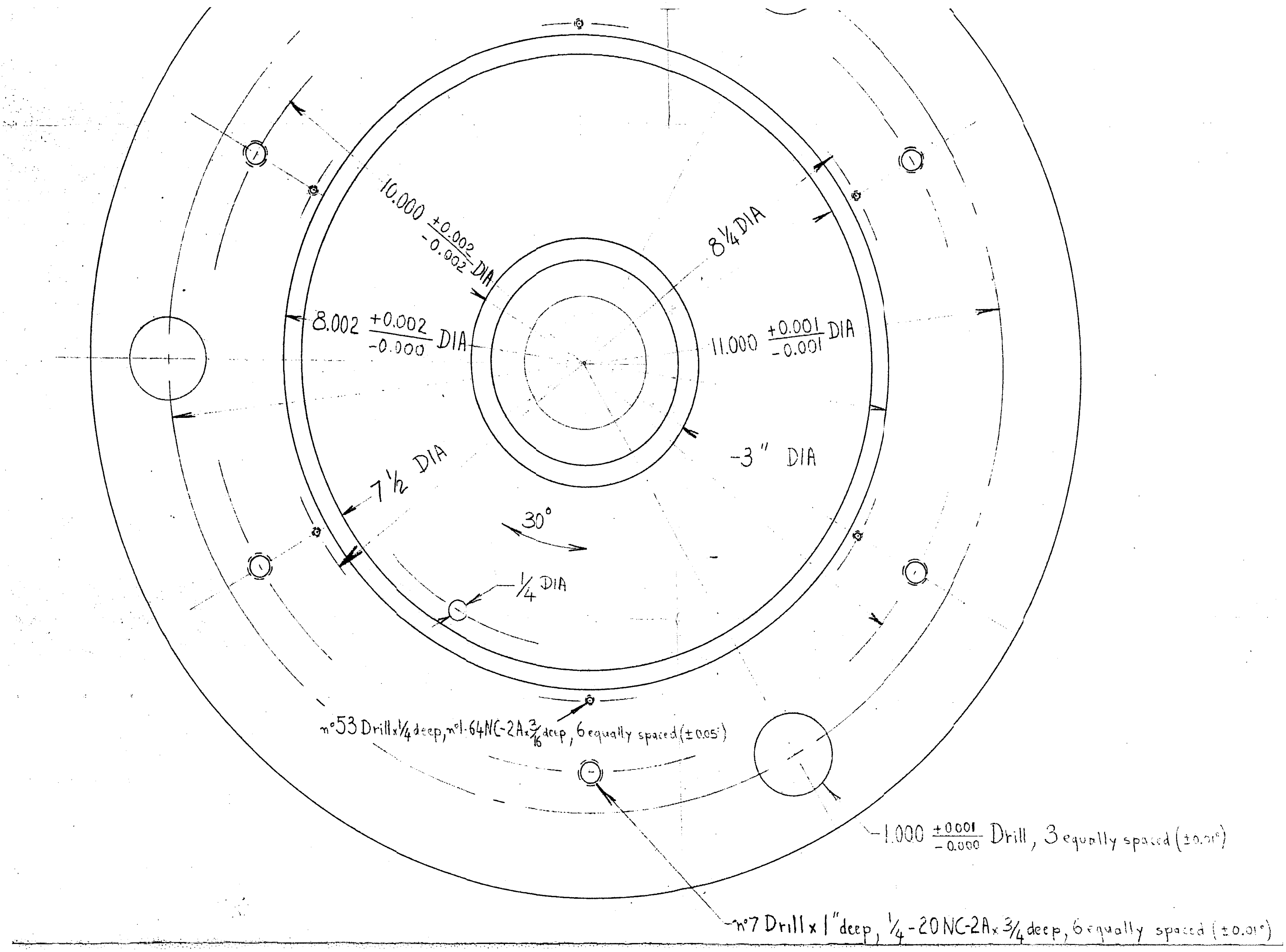

.810 $^{+0.005}_{-0.005}$ DIA
0 $^{+0.001}_{-0.000}$ DIA
10.000 $^{+0.005}_{-0.005}$ DIA
13.000 $^{+0.005}_{-0.005}$ DIA
0.500 $^{+0.005}_{-0.005}$ DIA
x 1/3 deep, 5 equally spaced
0.810 ±0.005 Drill, Spotface 1.000 $^{+0.001}_{-0.000}$ DIA
x 0.125 ±0.001 deep, 5 equally spaced (± 0.0

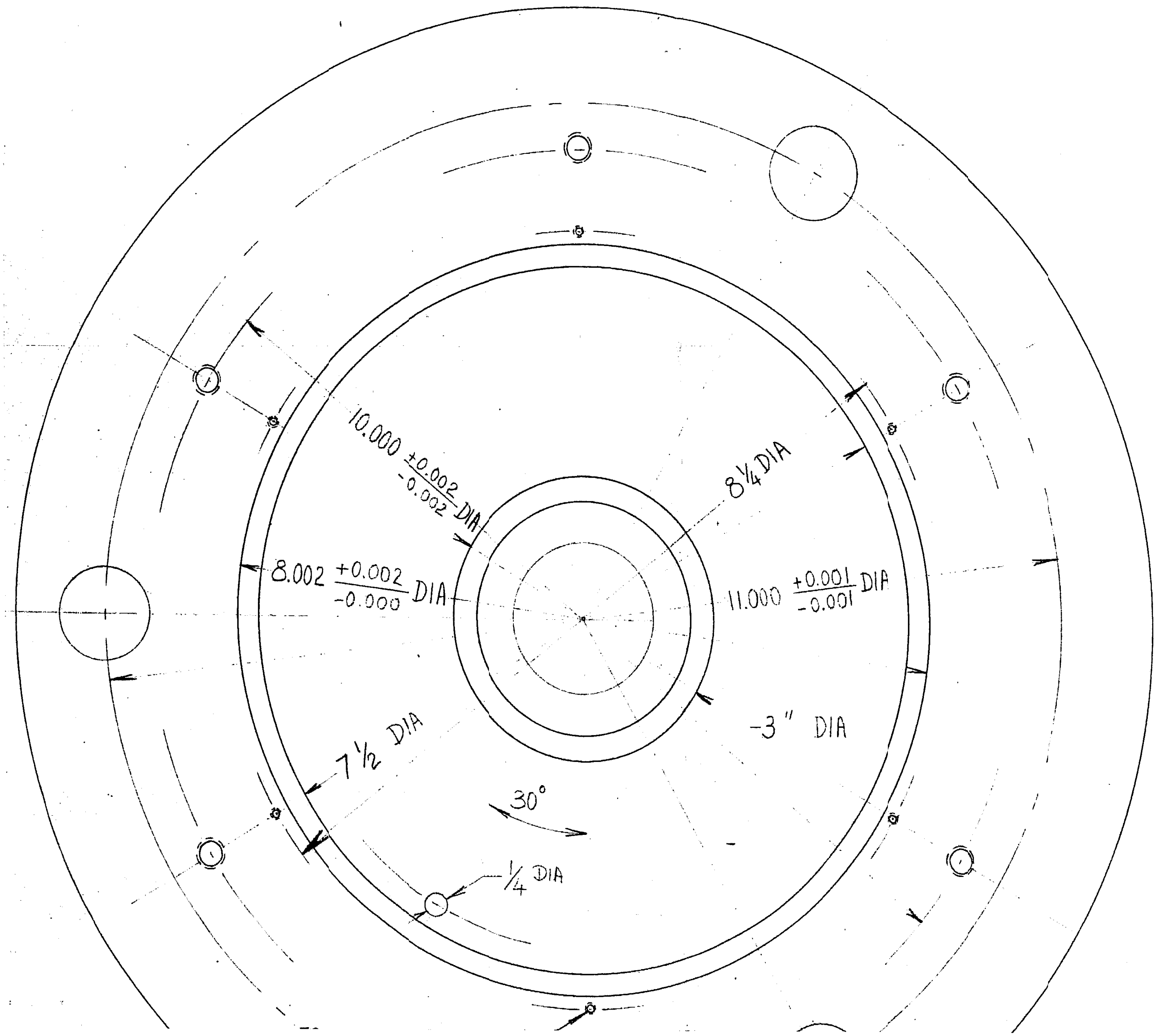


32√ UNLESS OTHERWISE NOTED

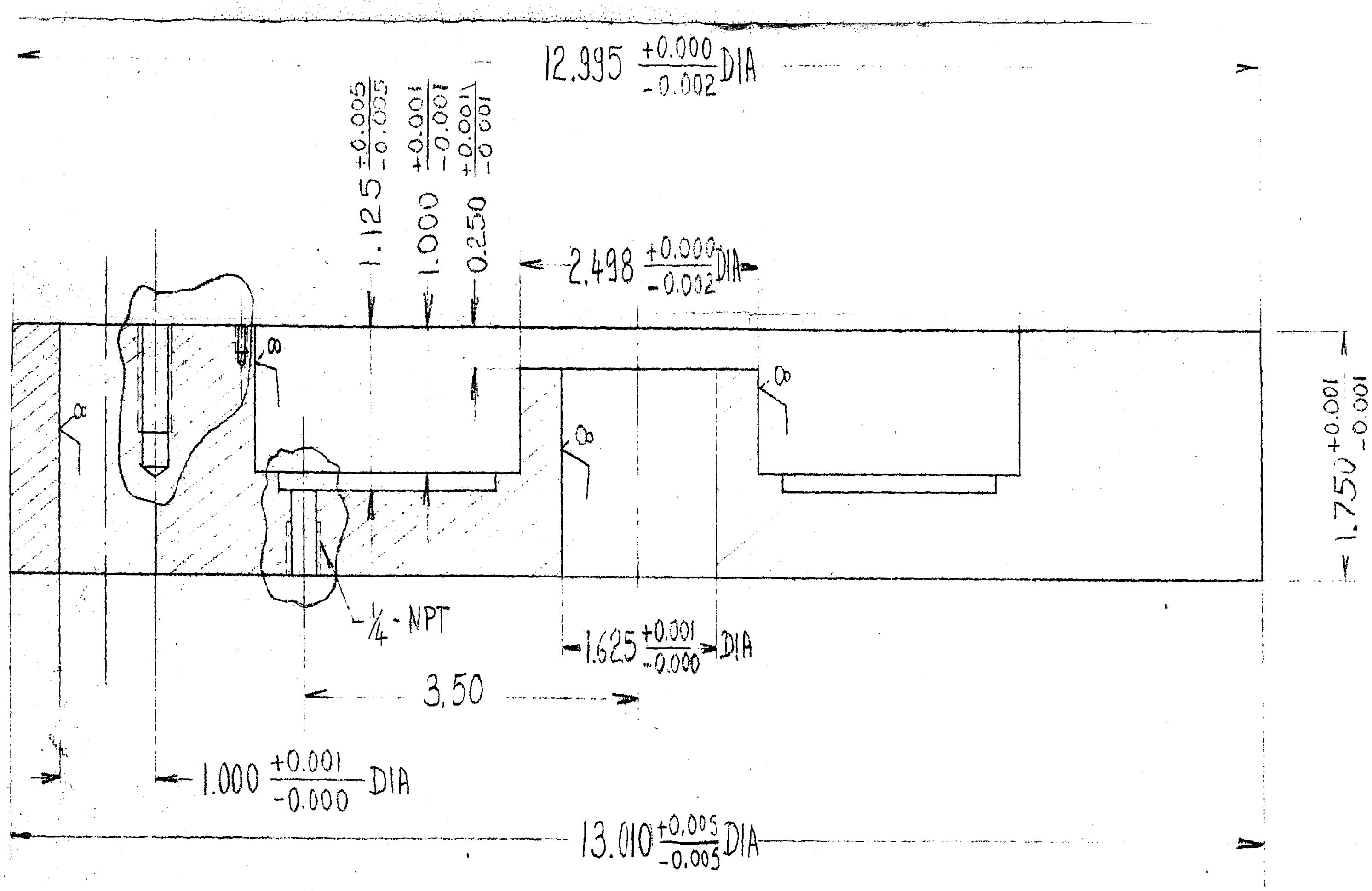
3	MALE MOLD PLATE	1	AISI 1040 STEEL
PART NO.	NAME	NO. RQD	MATERIAL
CALIFORNIA INSTITUTE OF TECHNOLOGY			DRAWN BY J.M CALLE
DIAPHRAGM MOLD			DATE: MAY 10 1965
			SCALE: 1 — DWG. NO. 4


0.875 +0.001 -0.001
0.125 +0.001 -0.001
1.093 +0.001 -0.001
1.375 +0.001 -0.001
1.125 +0.001 -0.001
1.071 +0.001 -0.001
1.571 +0.001 -0.001
0.312 +0.001 -0.001 DIA (TYP)
0.180 +0.001 -0.001 DIA
0.392 +0.001 -0.001 DIA
3.500 +0.001 -0.001 DIA
5.500 +0.001 -0.001 DIA
6.747 +0.000 -0.002 DIA
32 UNLESS OTHERWISE NOTED
3
MALE MOLD PLATE
1
PART NO.
NAME
NO. REQ
CALIFORNIA INSTITUTE OF TECHNOL
DIAPHRAGM MOLD


10.000 +0.002 -0.002 DIA
8¼ DIA
8.002 +0.002 -0.000 DIA
11.000 +0.001 -0.001 DIA
-3" DIA
7½ DIA
30°
¼ DIA
n°53 Drill x ¼ deep, n°1-64NC-2A x 3/16 deep, 6 equally spaced (±0.05°)
-1.000 +0.001 -0.000 Drill, 3 equally spaced (±0.01°)
-n°7 Drill x 1" deep, ¼-20NC-2A x ¾ deep, 6 equally spaced (±0.01°)



10.000 +0.002/-0.002 DIA
8¼ DIA
8.002 +0.002/-0.000 DIA
11.000 +0.001/-0.001 DIA
-3" DIA
7½ DIA
30°
¼ DIA



32√ UNLESS OTHERWISE NOTED

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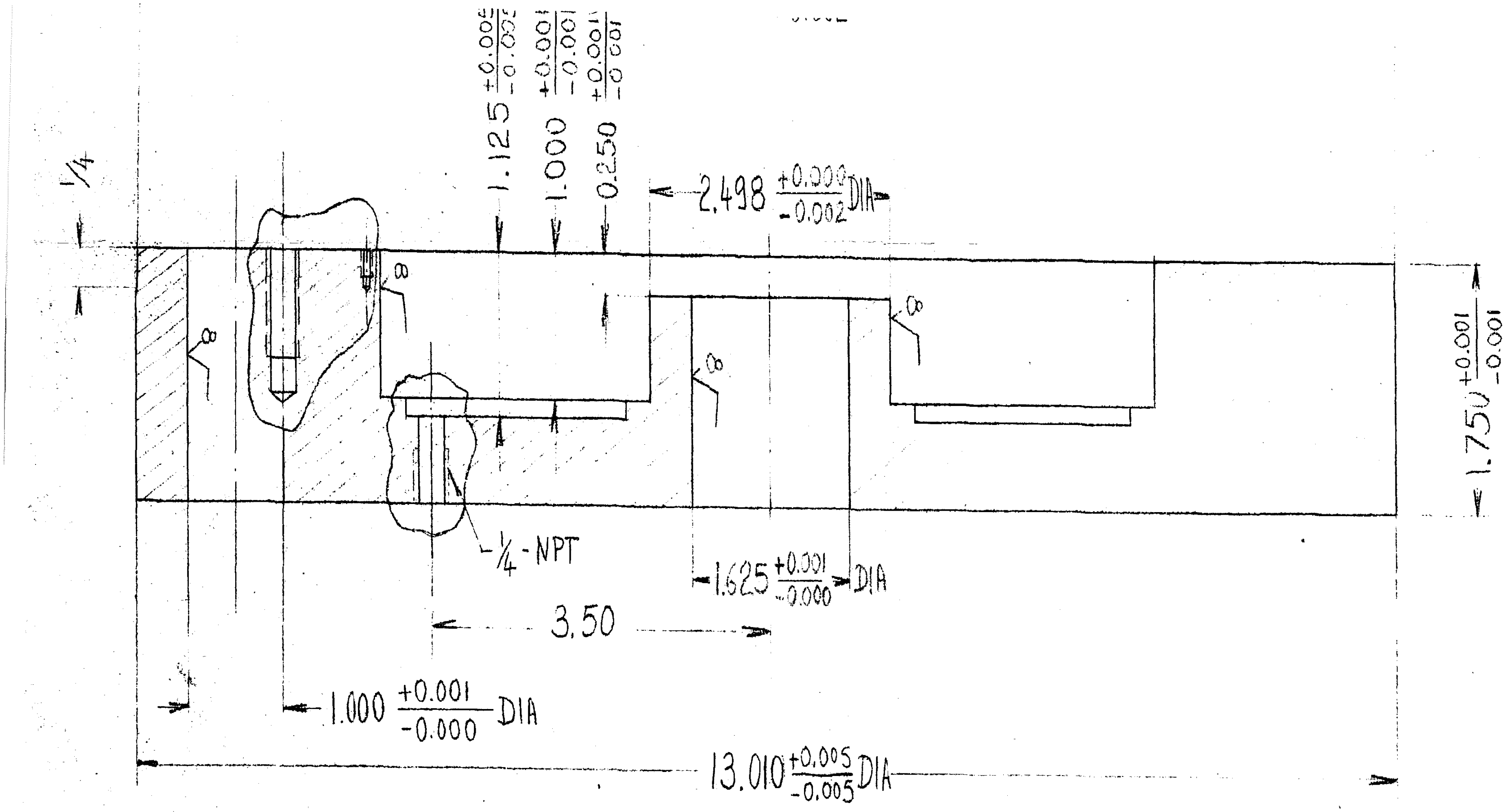
CALIFORNIA INSTITUTE OF TECHNOLOGY	DRAWN BY J.H. CALL
DIAPHRAGM MOLD	DATE: MAY-10-196
	SCALE 1 · DWG NO.



2	CYLINDER HOLDER	1	AISI 1040 ST
PART No	NAME	NO. RQD	MATERI

CALIFORNIA INSTITUTE OF TECHNOLOGY

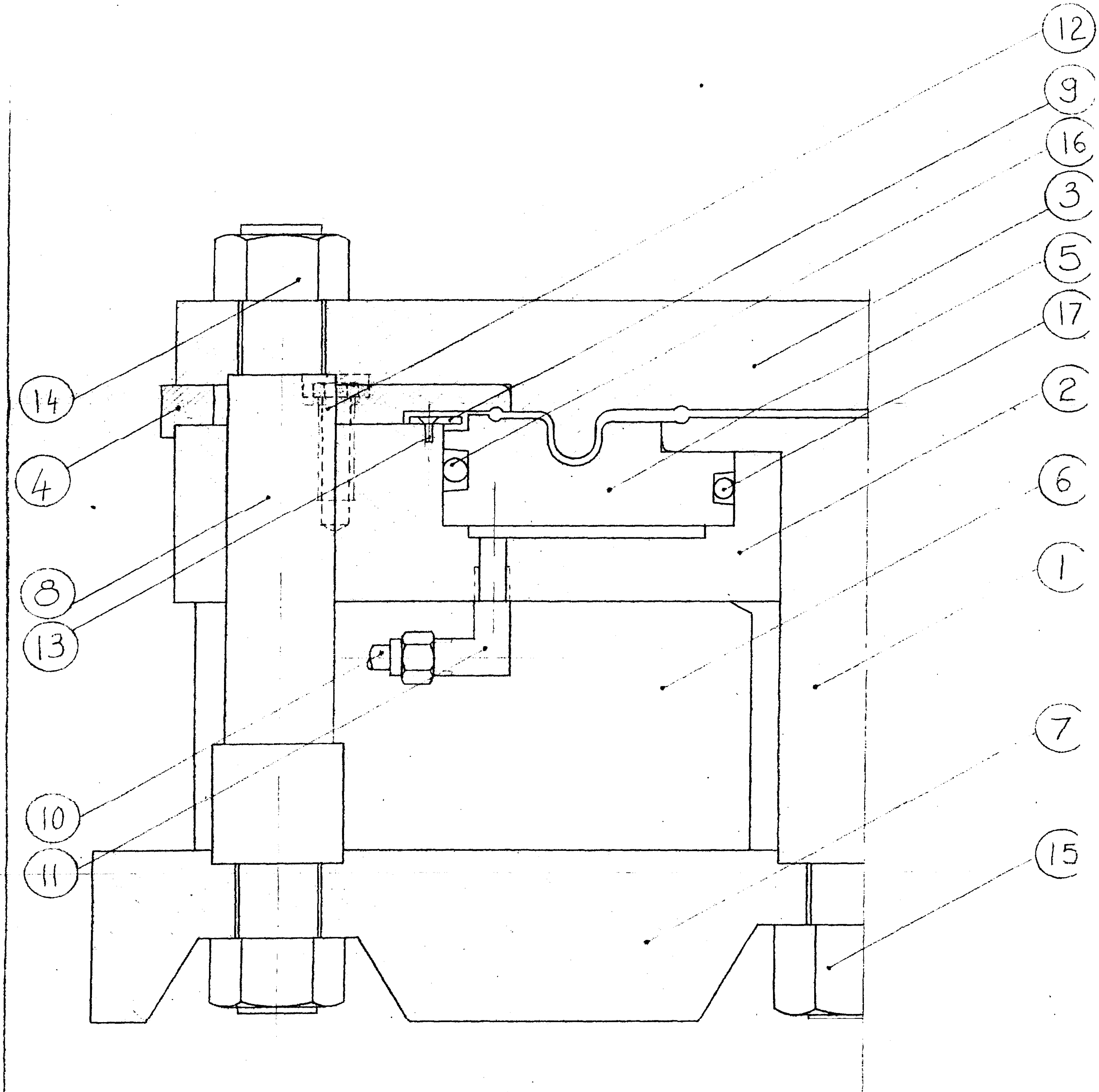
DRAWN BY

DIAPHRAGM MOLD

DATE: M

SCALE 1

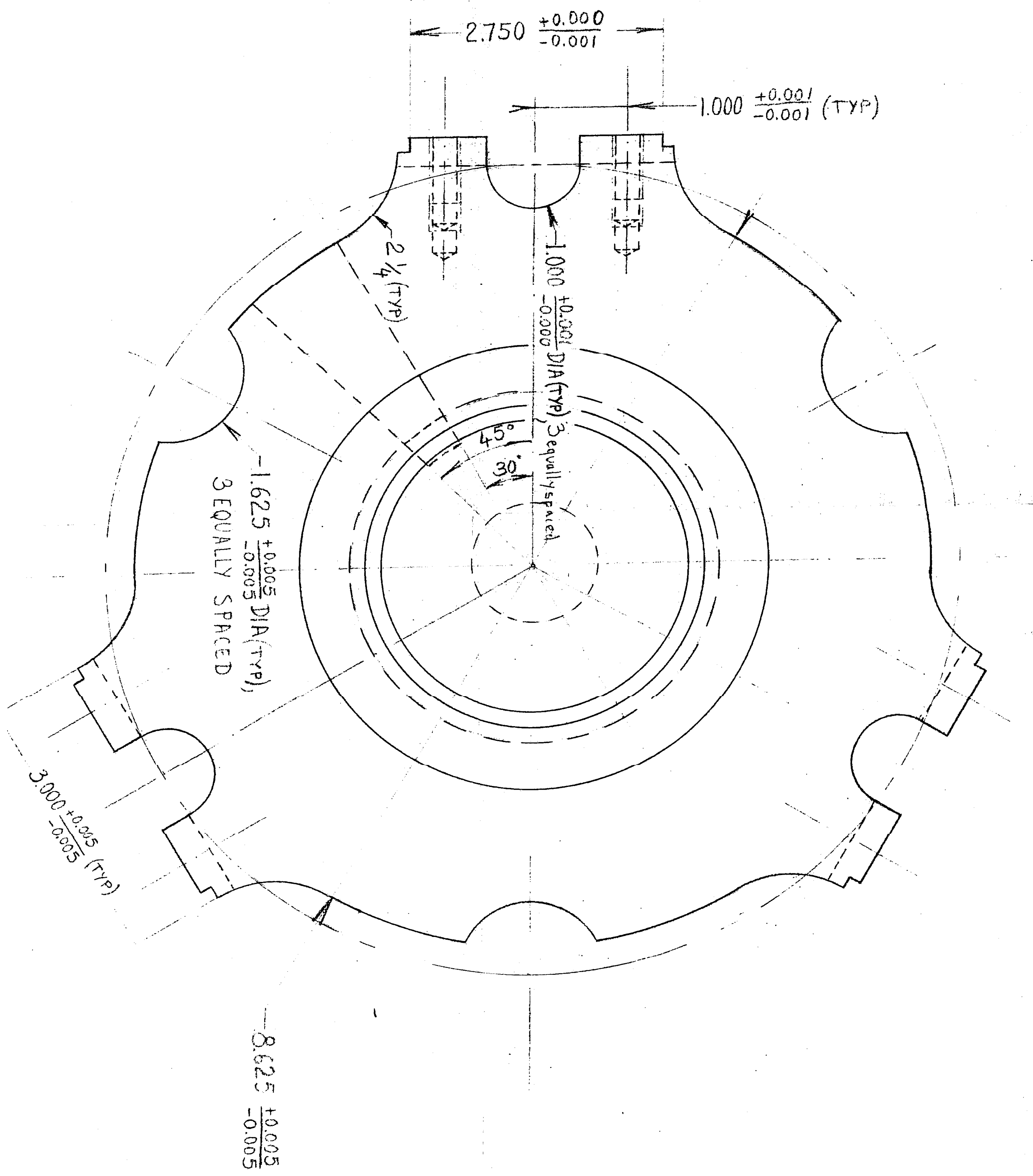
32√ UNLESS OTHERWISE NOTED

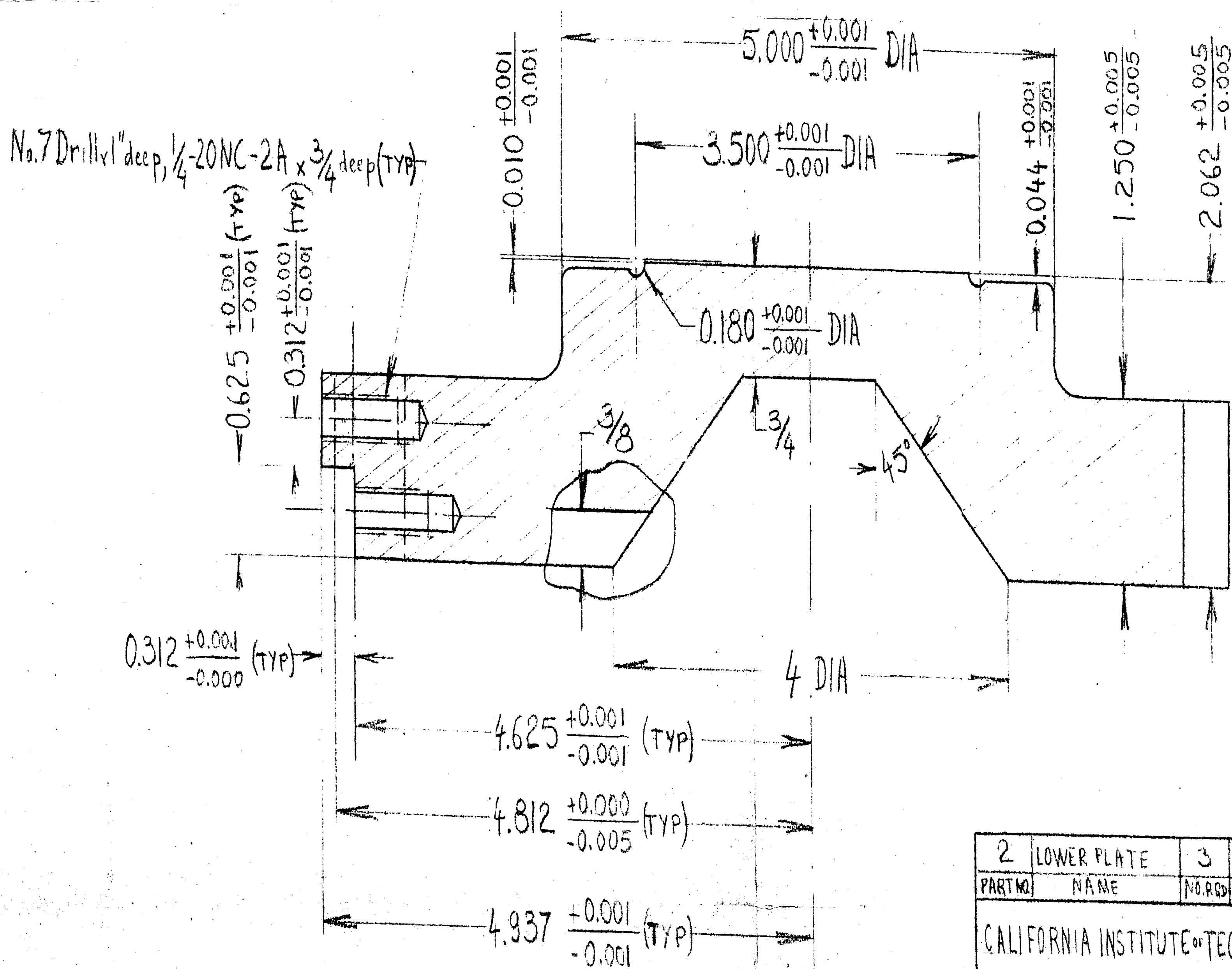


12
9
16
3
5
17
2
6
1
7
15
14
4
8
13
10
11

NO.	PART	DWG.
1	CENTER BAR	2
2	CYLINDER HOLDER	3
3	MALE MOLD PLATE	4
4	CLAMP	5
5	FEMALE MOLD CYLINDER	6
6	BLOCK	7
7	BASE PLATE	8
8	CROSS BAR	9
9	CYLINDER RETAINER	10
10	1/4" O.D. COPPER TUBE	
11	1/4" I.D. ELBOW	
12	1/4-20 UNC-2A x 1 Semifin Hex Bolt	
13	No.0-80 NF-3 x 1/4 Flat Hd Cap Screw	
14	3/4-10 UNC-2A Semifin Hex Nut	
15	1-8 UNC-2A Semifin Hex Nut	
16	O-Ring Parker No. 333	
17	O-Ring Parker No. 443	

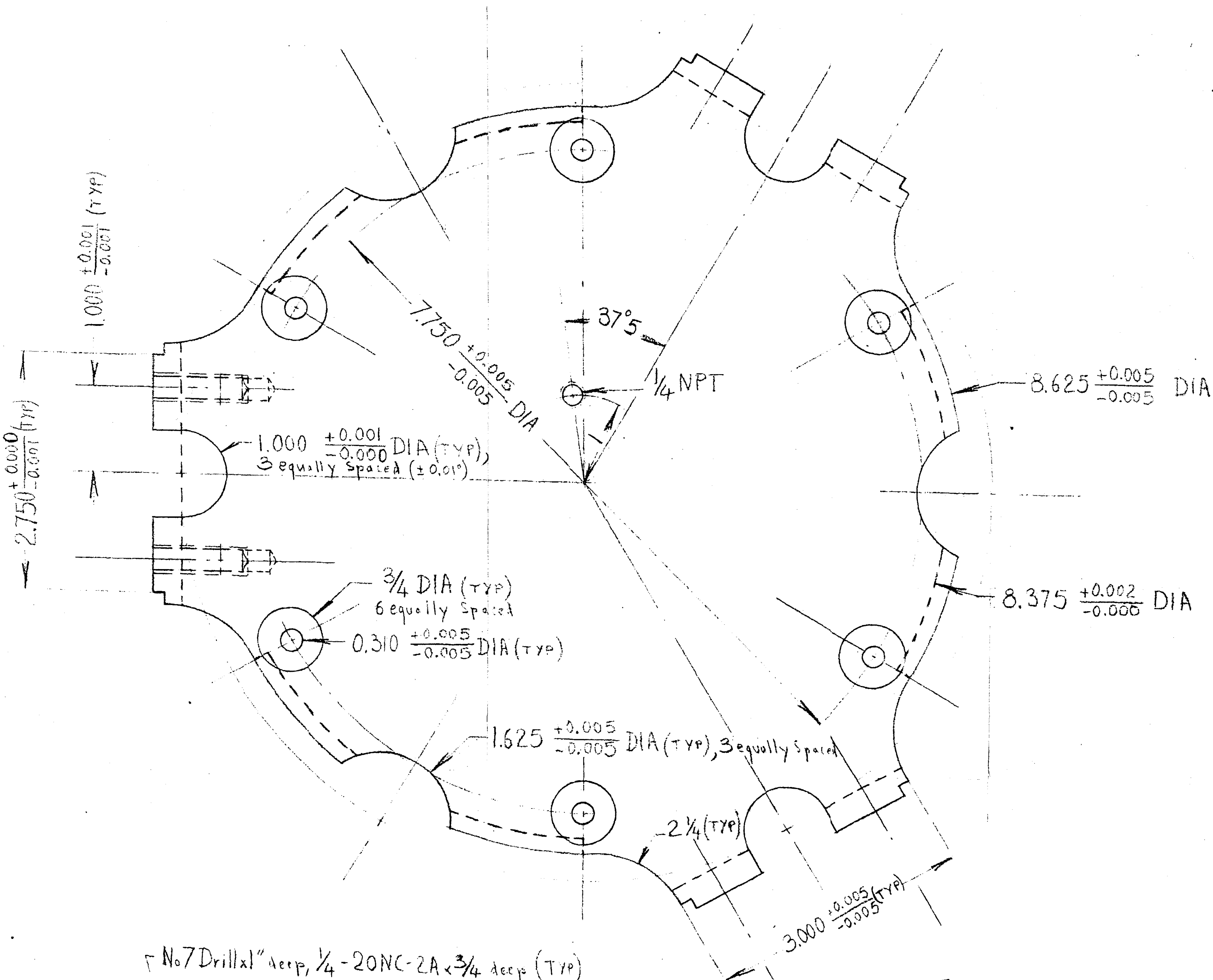
ASSEMBLY DRAWING	AISI 1040 STEEL MATERIAL
CALIFORNIA INSTITUTE OF TECHNOLOGY	DRAWN BY J.M. CALLE
DIAPHRAGM MOLD	DATE MAY-10-1965 SCALE: 1 DWG. NO. 1


2.750 +0.000 -0.001
1.000 +0.001 -0.001 (TYP)
2 1/4 (TYP)
1.000 +0.001 -0.000 DIA (TYP) 3 equally spaced
45°
30°
1.625 +0.005 -0.005 DIA (TYP), 3 EQUALLY SPACED
3.000 +0.005 -0.005 (TYP)
8.625 +0.005 -0.005

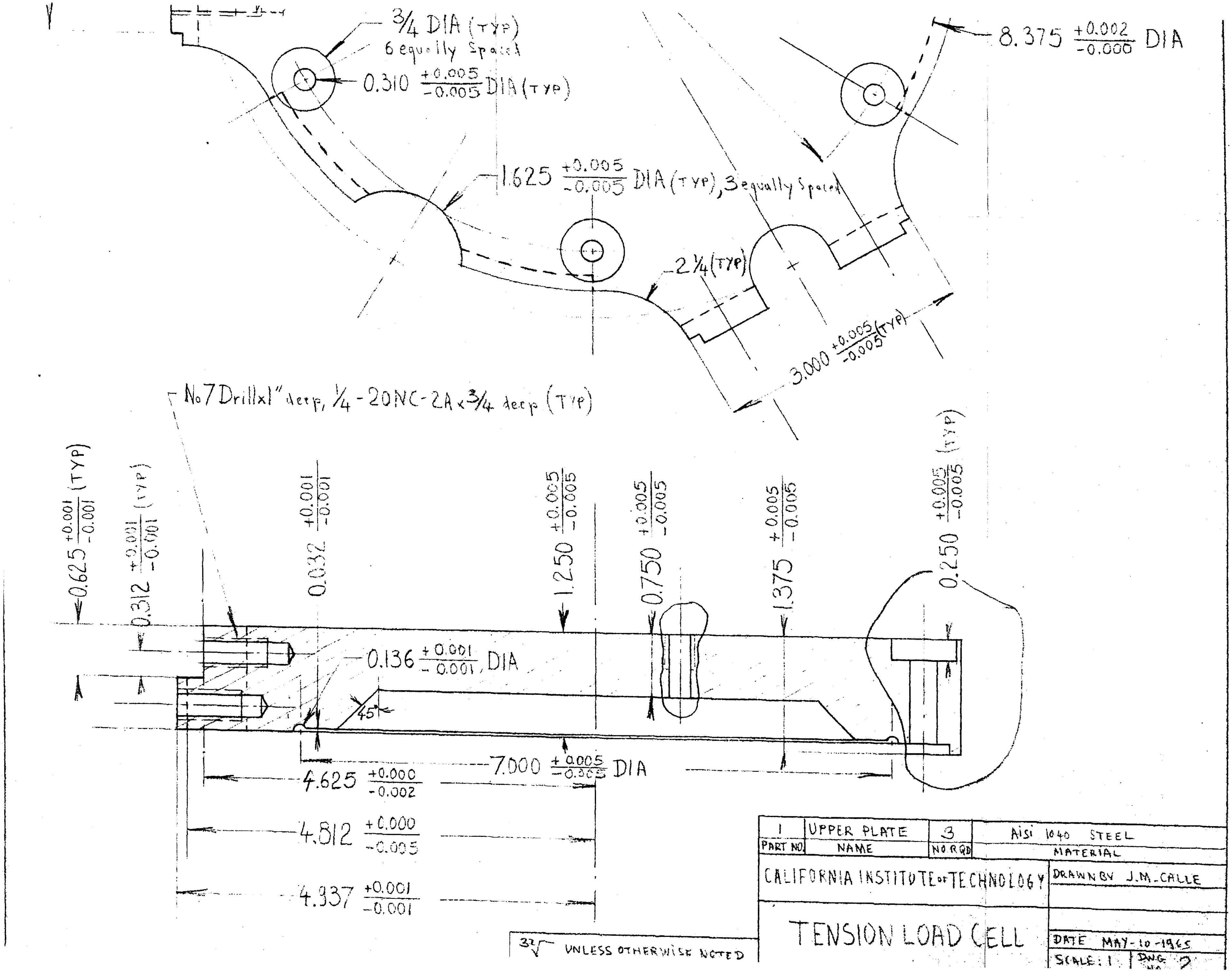


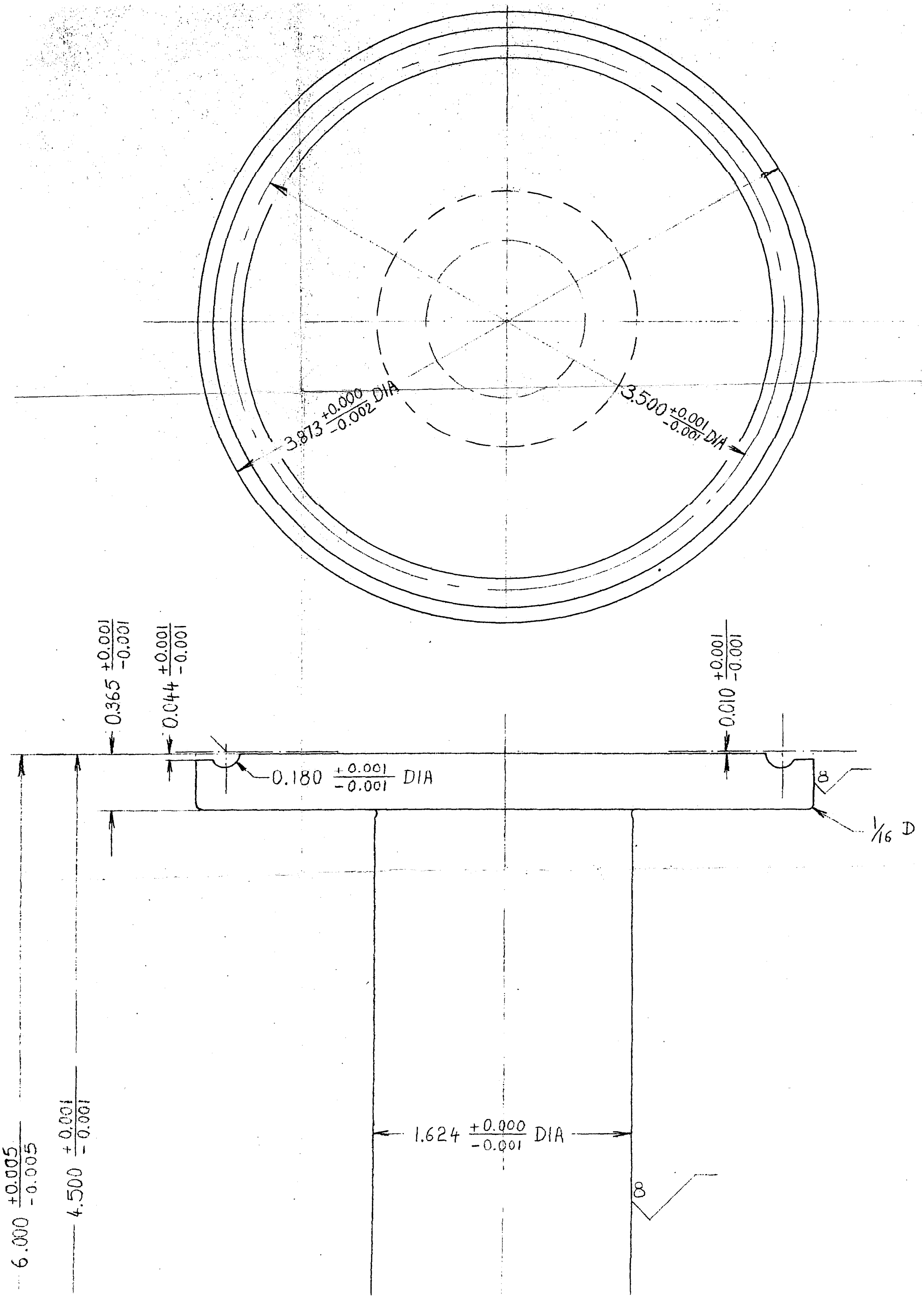
32 √ UNLESS OTHERWISE NOTED

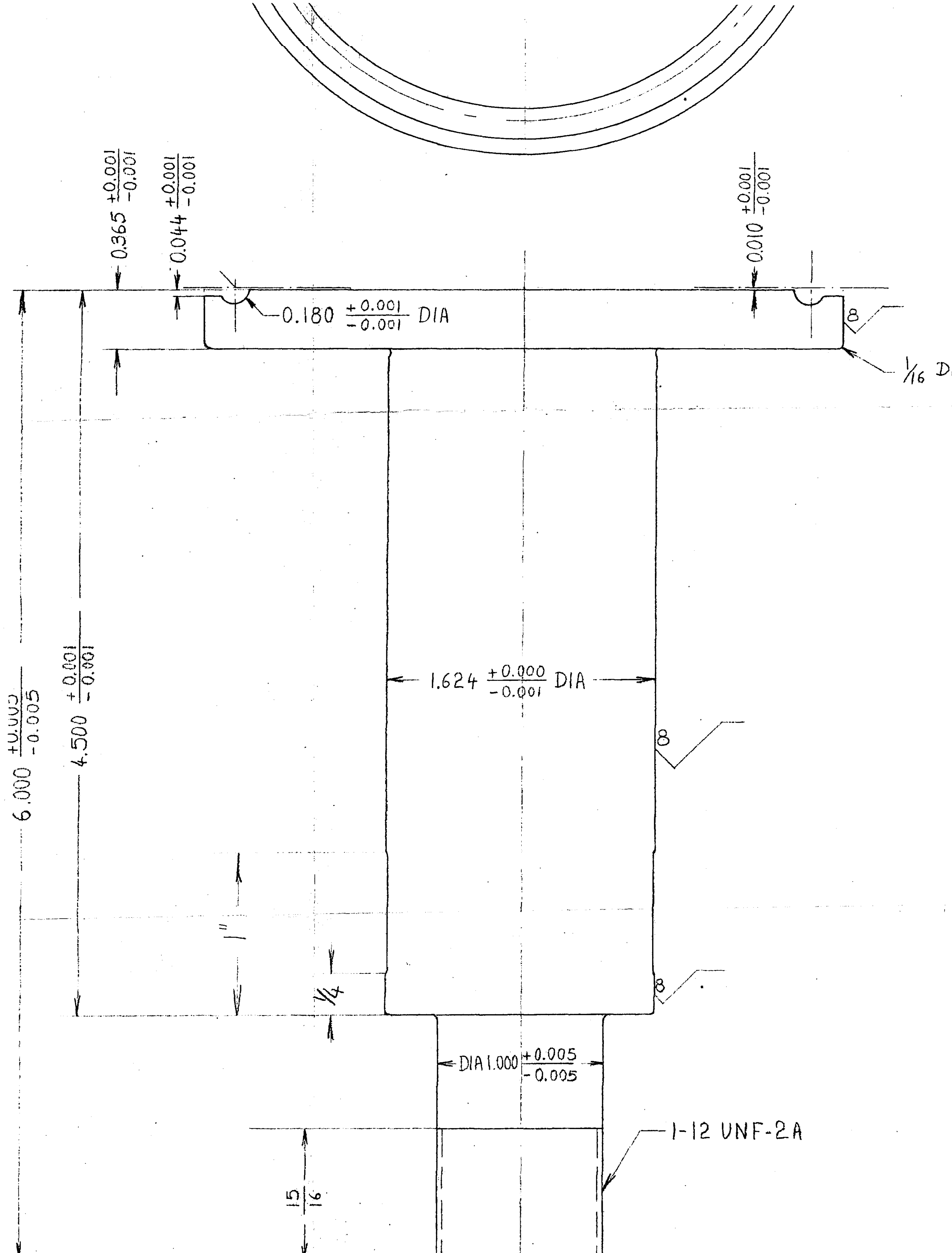
2	LOWER PLATE	3	AISI 1040 STEEL
PART NO.	NAME	NO. RQD	MATERIAL
CALIFORNIA INSTITUTE OF TECHNOLOGY			DRAWN BY J.H. CALLE
TENSION LOAD CELL			DATE MAY-10-1965
			SCALE 1 — DWG. NO. 3



1.000 +0.001 -0.001 (TYP)
2.750 +0.000 -0.001 (TYP)
7.750 +0.005 -0.005 DIA
37°5
1/4 NPT
8.625 +0.005 -0.005 DIA
1.000 +0.001 -0.000 DIA (TYP), 3 equally Spaced (±0.01°)
3/4 DIA (TYP) 6 equally Spaced
0.310 +0.005 -0.005 DIA (TYP)
8.375 +0.002 -0.000 DIA
1.625 +0.005 -0.005 DIA (TYP), 3 equally Spaced
2 1/4 (TYP)
3.000 +0.005 -0.005 (TYP)
No7 Drill x1" deep, 1/4-20NC-2A x 3/4 deep (TYP)

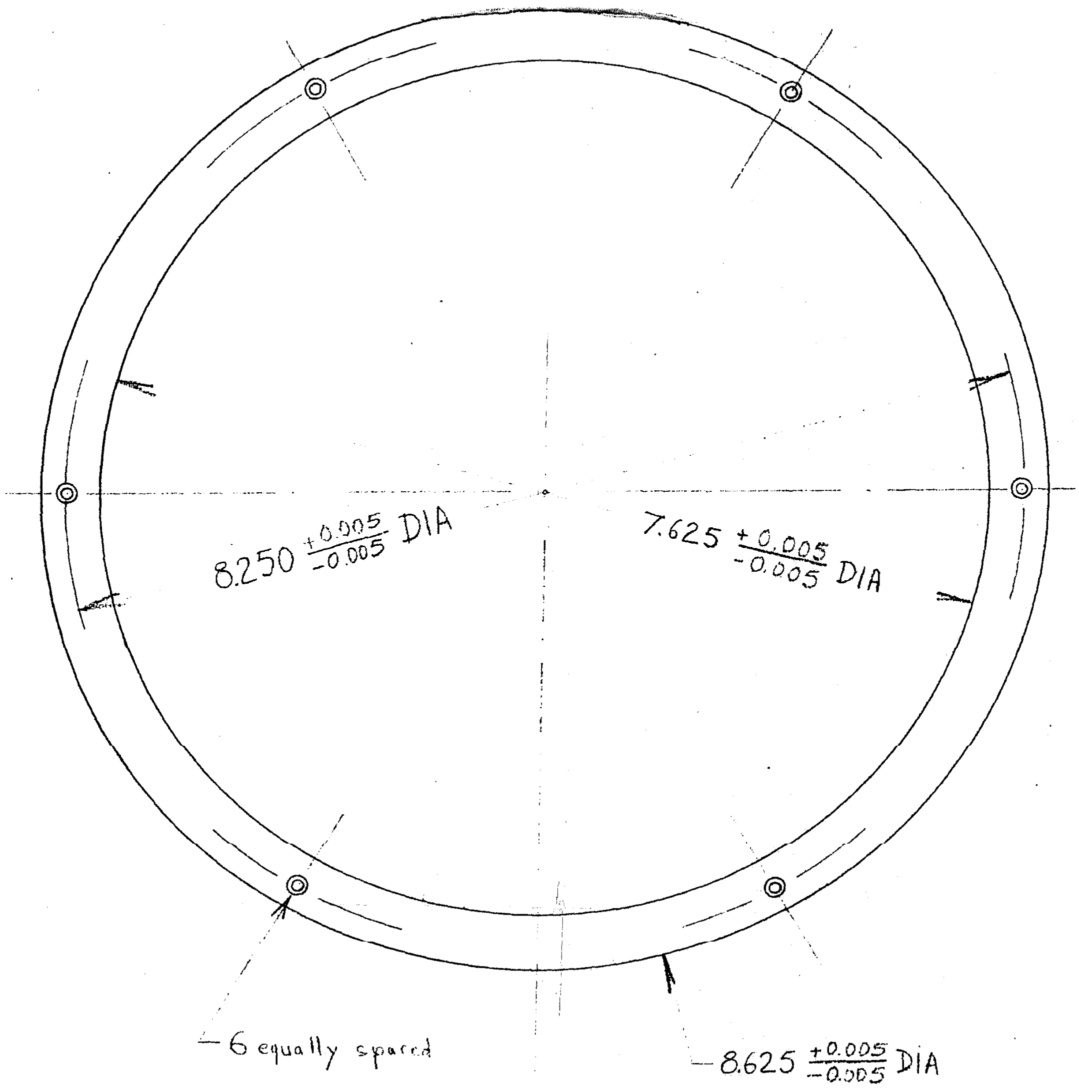

3/4 DIA (TYP) 6 equally Spaced
0.310 +0.005 -0.005 DIA (TYP)
8.375 +0.002 -0.000 DIA
1.625 +0.005 -0.005 DIA (TYP), 3 equally Spaced
2 1/4 (TYP)
3.000 +0.005 -0.005 (TYP)
No 7 Drill x 1" deep, 1/4-20NC-2A x 3/4 deep (TYP)
0.625 +0.001 -0.001 (TYP)
0.312 +0.001 -0.001 (TYP)
0.032 +0.001 -0.001
1.250 +0.005 -0.005
0.750 +0.005 -0.005
1.375 +0.005 -0.005
0.250 +0.005 -0.005 (TYP)
0.136 +0.001 -0.001 DIA
45°
7.000 +0.005 -0.005 DIA
4.625 +0.000 -0.002
4.812 +0.000 -0.005
4.337 +0.001 -0.001
1
UPPER PLATE
3
AISI 1040 STEEL
PART NO
NAME
NO RQD
MATERIAL
CALIFORNIA INSTITUTE OF TECHNOLOGY
DRAWN BY J.M. CALLE
TENSION LOAD CELL
DATE MAY-10-1965
SCALE: 1
DWG NO 2
32 UNLESS OTHERWISE NOTED

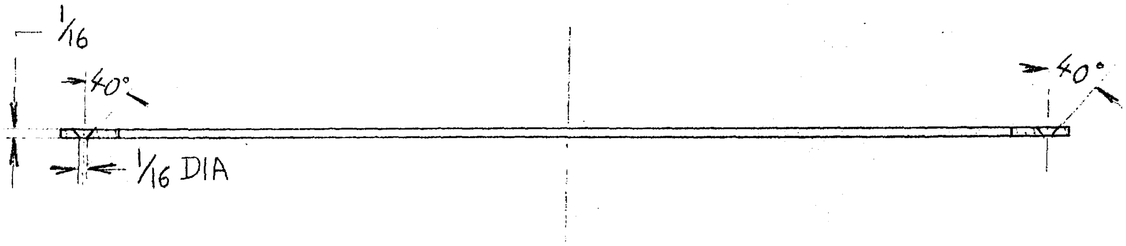

3.873 +0.000 -0.002 DIA
3.500 +0.001 -0.001 DIA
0.365 +0.001 -0.001
0.044 +0.001 -0.001
0.010 +0.001 -0.001
0.180 +0.001 -0.001 DIA
8
1/16 D
6.000 +0.005 -0.005
4.500 +0.001 -0.001
1.624 +0.000 -0.001 DIA
8



1	CENTER BAR	1	AISI 1040 STE
PART NO.	NAME	NO. RQD	MATERIAL

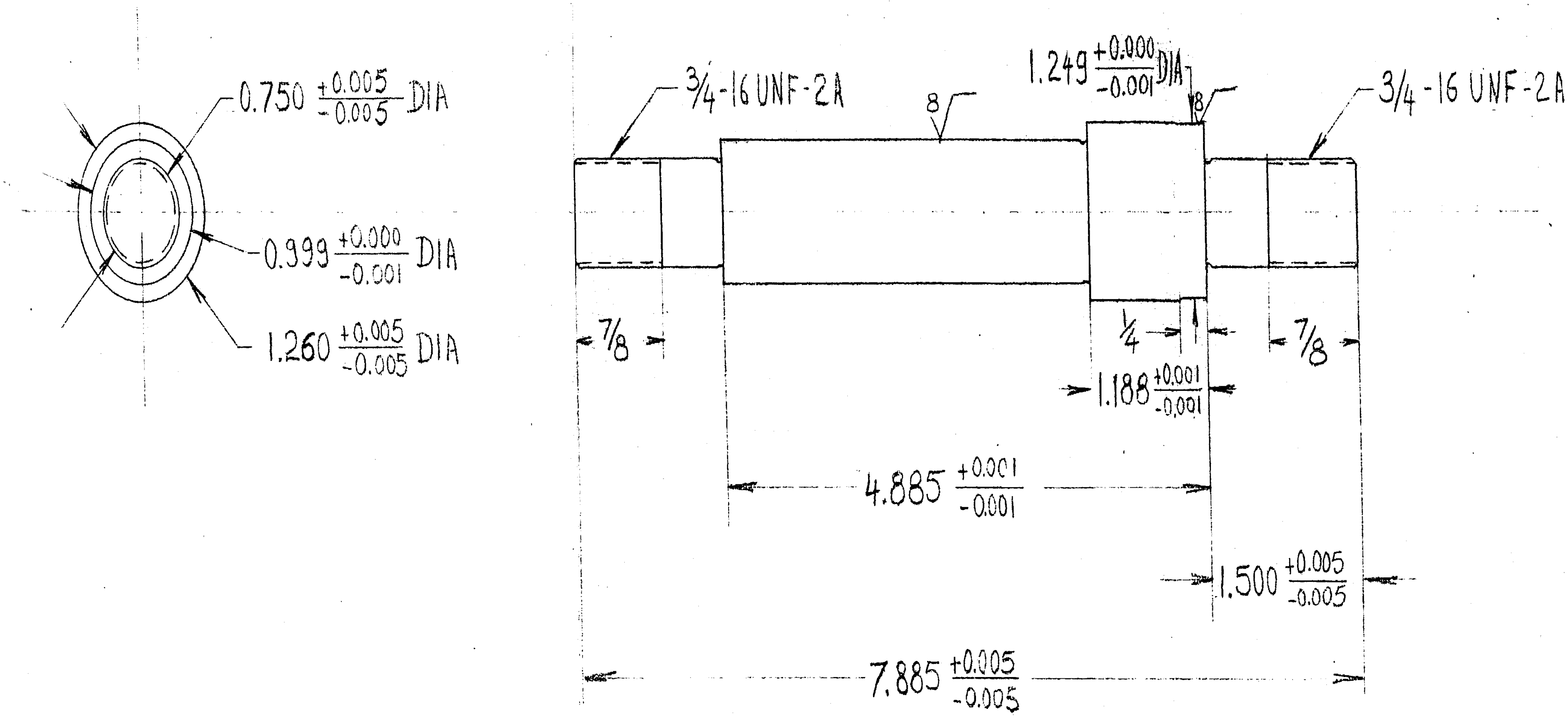
CALIFORNIA INSTITUTE of TECHNOLOGY | DRAWN BY





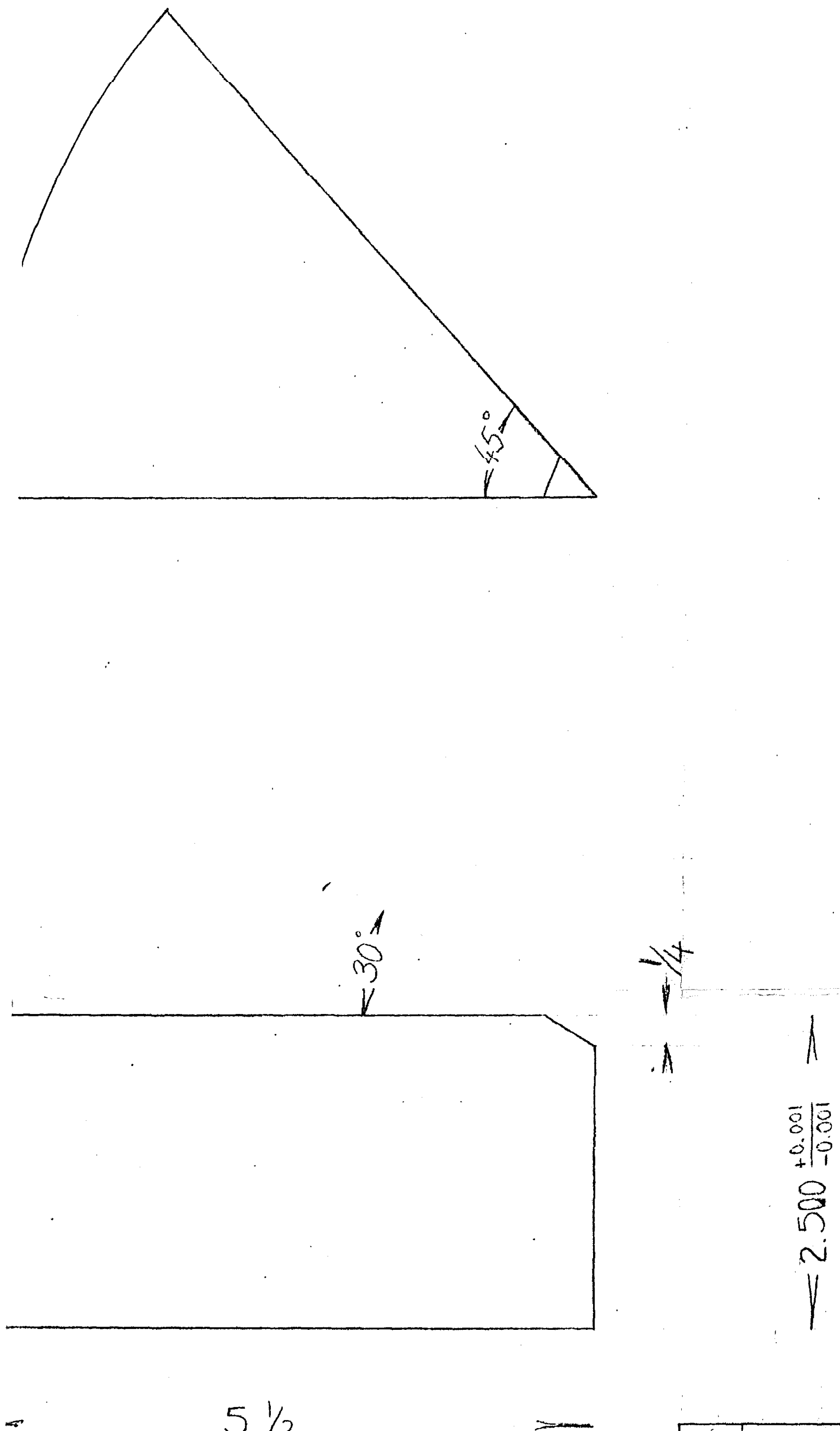
9	CYLINDER RETAINER	1	AISI 1040 STEEL
PART No	NAME	NO. REQ	MATERIAL
CALIFORNIA INSTITUTE of TECHNOLOGY			DRAWN BY J.M. CALLE
			CHECKED BY
DIAPHRAGM MOLD			APPROVED BY
			DATE MAY-10-1965
			SCALE: 1 · DWG. NO. 10

32√ UNLESS OTHERWISE NOTED



8	CROSS BAR	3	AISI 1040 STEEL
PART NO.	NAME	NO. RQD.	MATERIAL
CALIFORNIA INSTITUTE OF TECHNOLOGY			DRAWN BY J.H. CALLE
DIAPHRAGM MOLD			DATE: MAY 10 1965
			SCALE: 1 · DWG. NO. 9

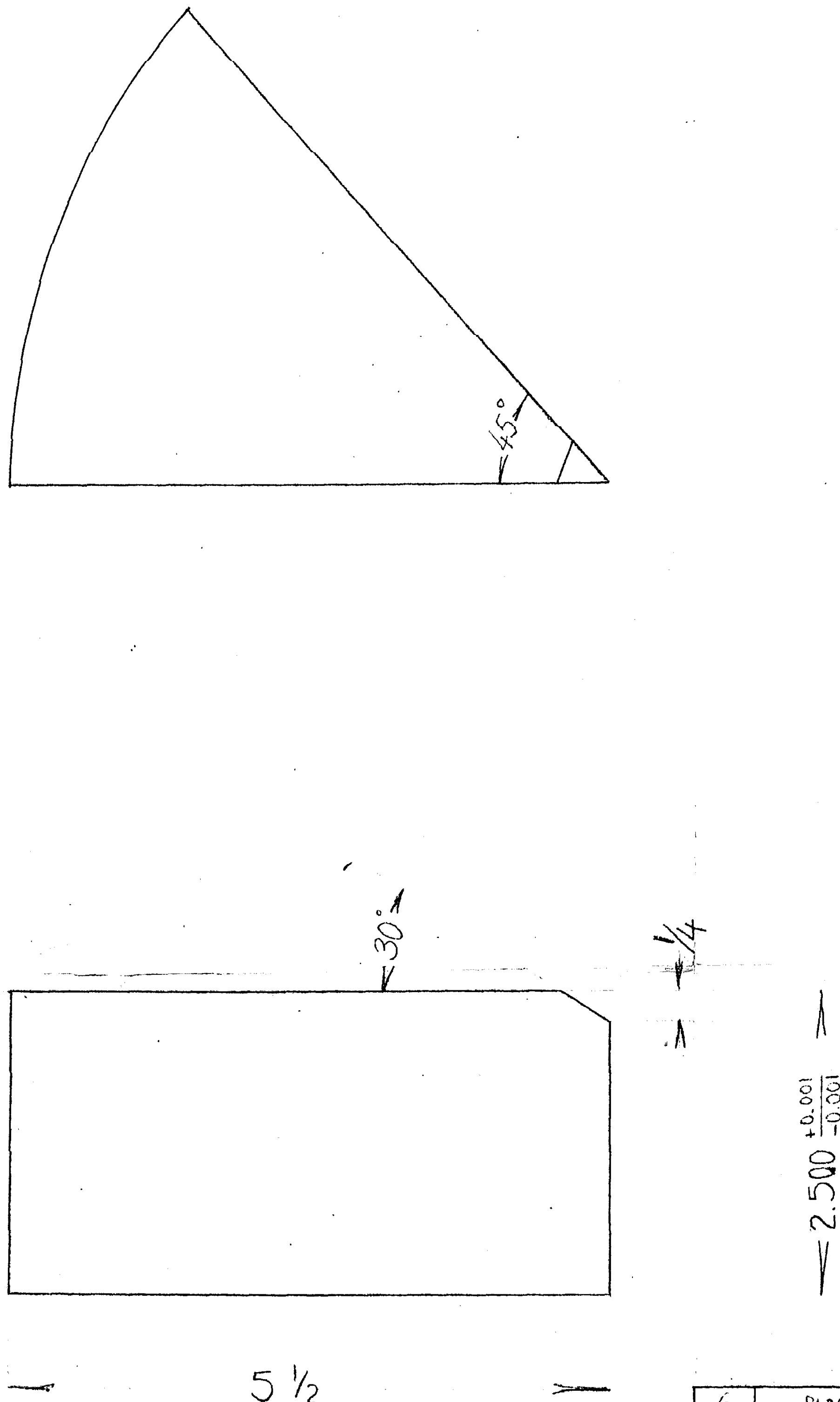
32√ UNLESS OTHERWISE NOTED



6	BLOCK	6	AISI 1040 STEEL
PART NO	NAME	NO. RQD	MATERIAL

CALIFORNIA INSTITUTE OF TECHNOLOGY	DRAWN BY J. M. CALLE
DIAPHRAGM MOLD	DATE MAY-10-1965
	SCALE: 1 DWG. NO. 7

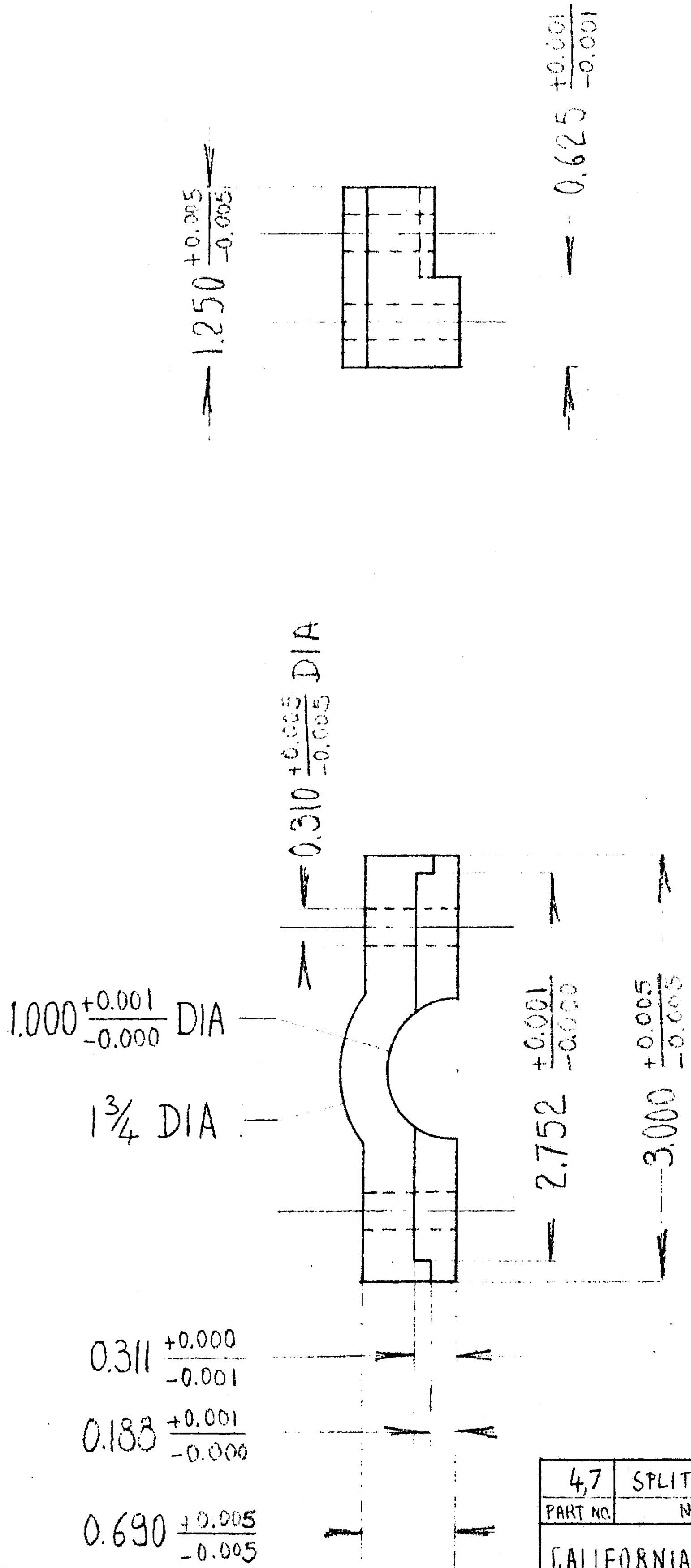
32√ UNLESS OTHERWISE NOTED



6	BLOCK	6	AISI 1040 STEEL
PART NO.	NAME	NO. RQD	MATERIAL

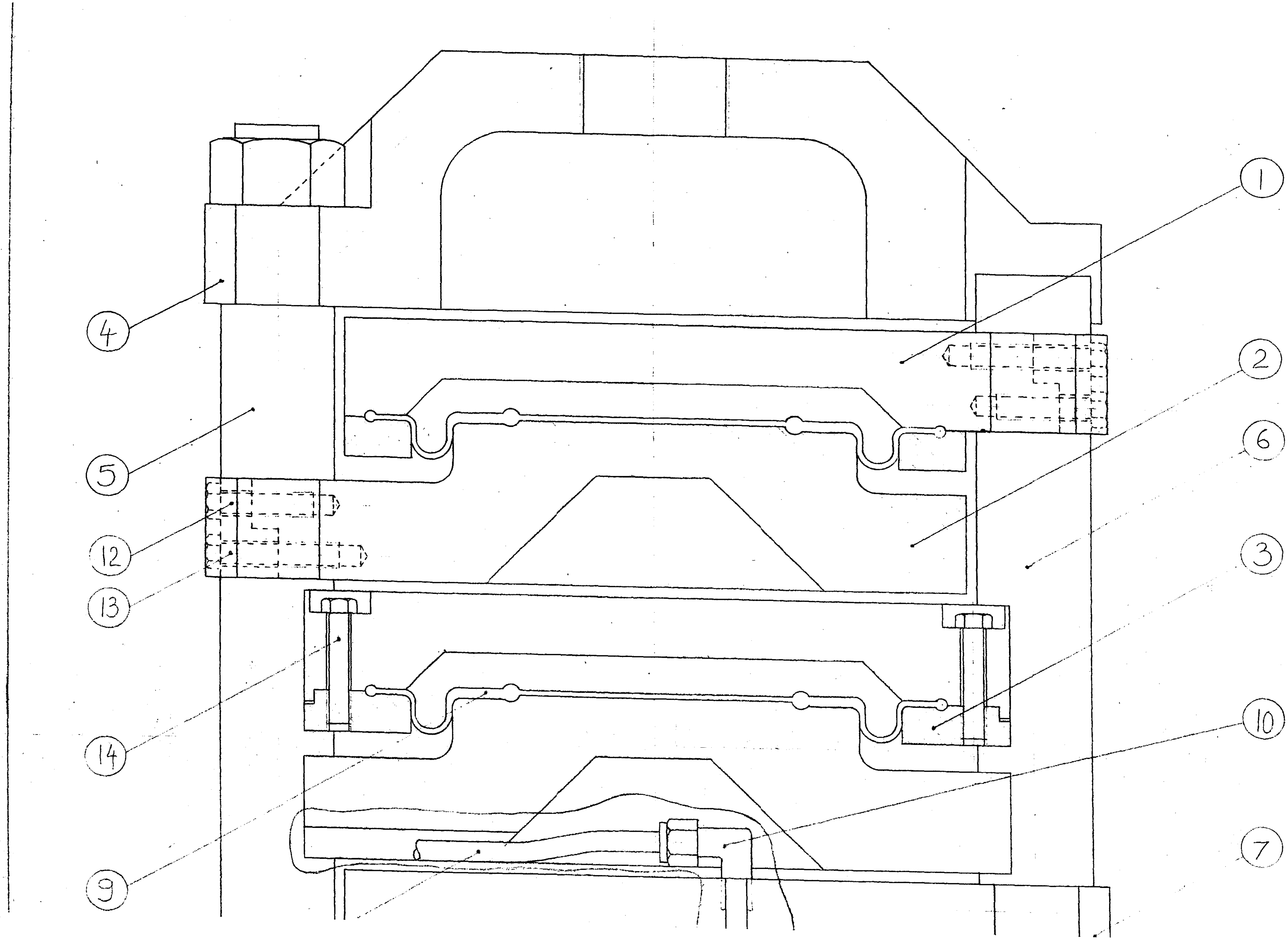
CALIFORNIA INSTITUTE OF TECHNOLOGY	DRAWN BY J.N
DIAPHRAGM MOLD	DATE MAY-(
	SCALE: 1

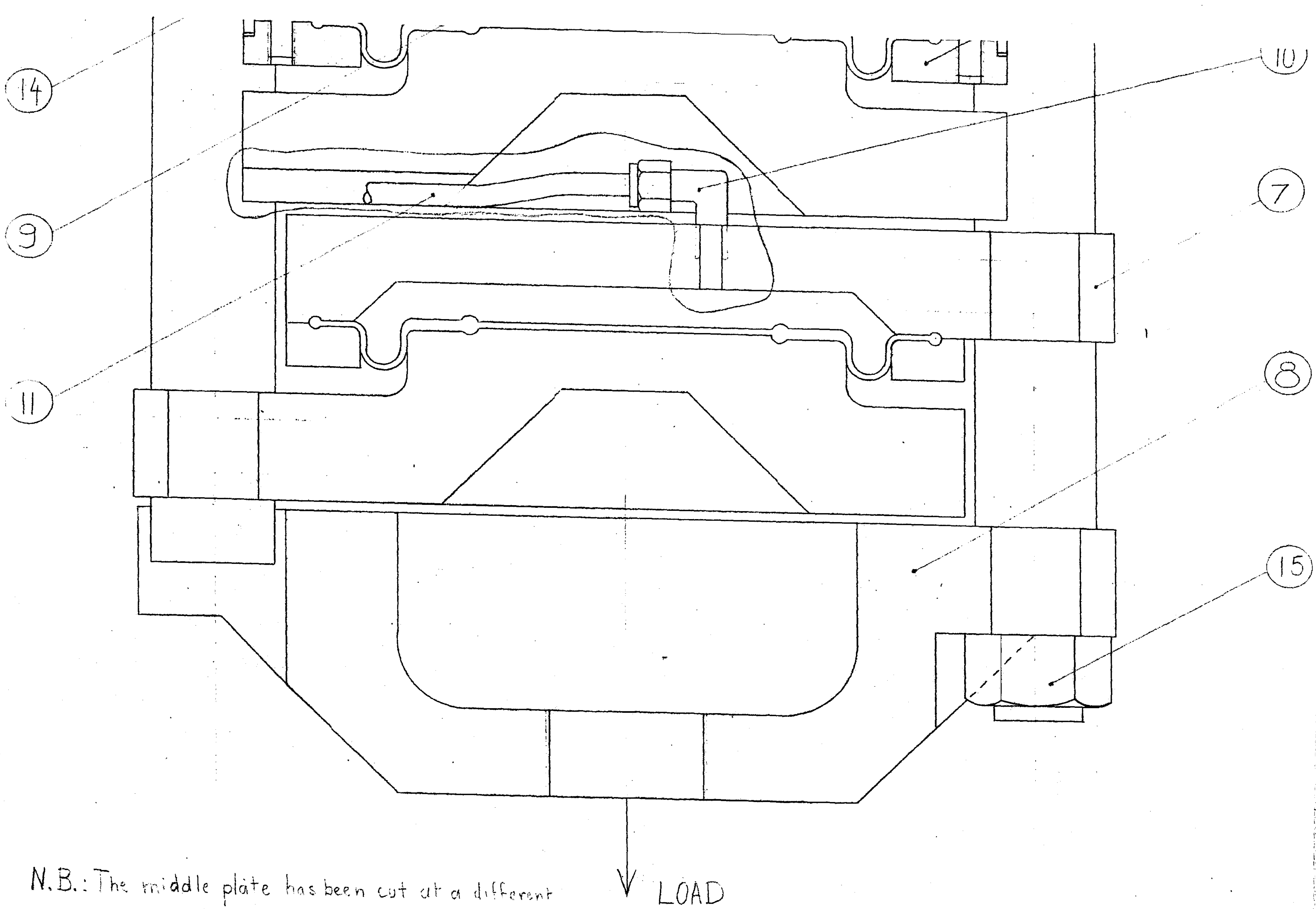
$^{32}\sqrt{}$ UNLESS OTHERWISE NOTED



4,7	SPLIT RING	18	AISI 1040 STEEL
PART NO.	NAME	NO. RQD	MATERIAL

CALIFORNIA INSTITUTE OF TECHNOLOGY	DRAWN BY J.H. CALLE
TENSION LOAD CELL	DATE MAY-10-1965
	SCALE 1 DWG NO. 5


1
2
6
3
10
7
4
5
12
13
14
9

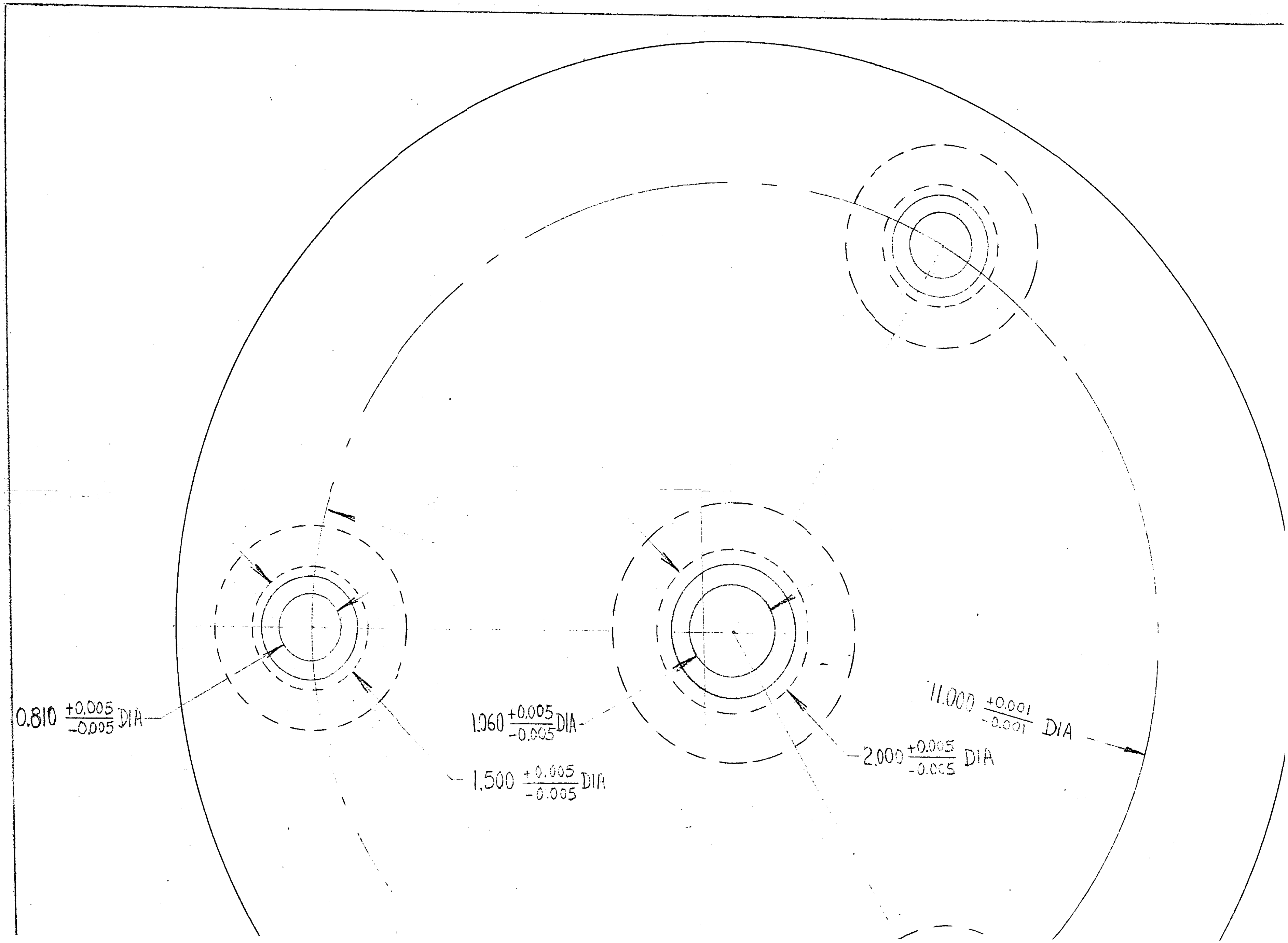


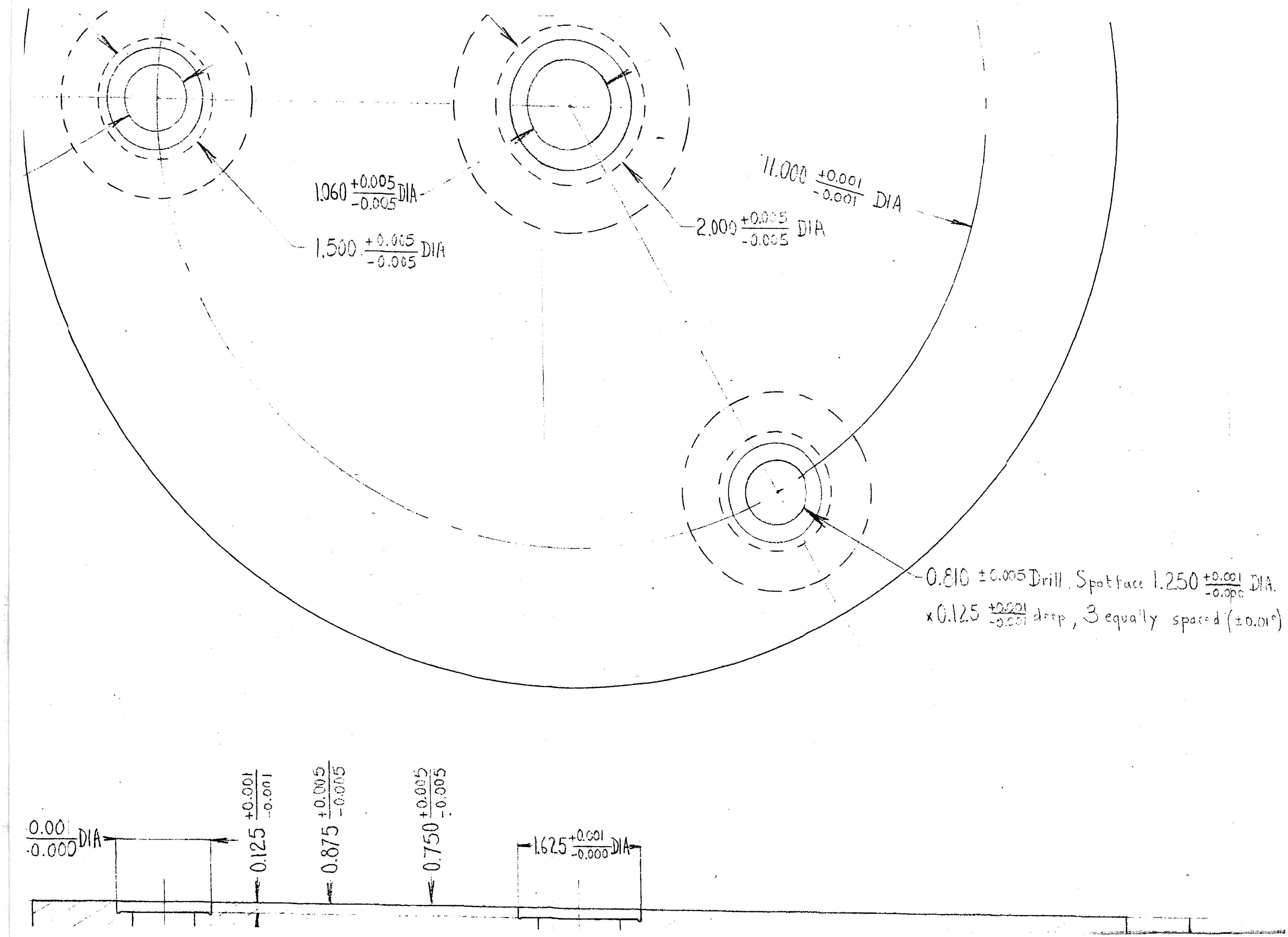
N.B.: The middle plate has been cut at a different angle, in order to show the fastening of 1 and 3

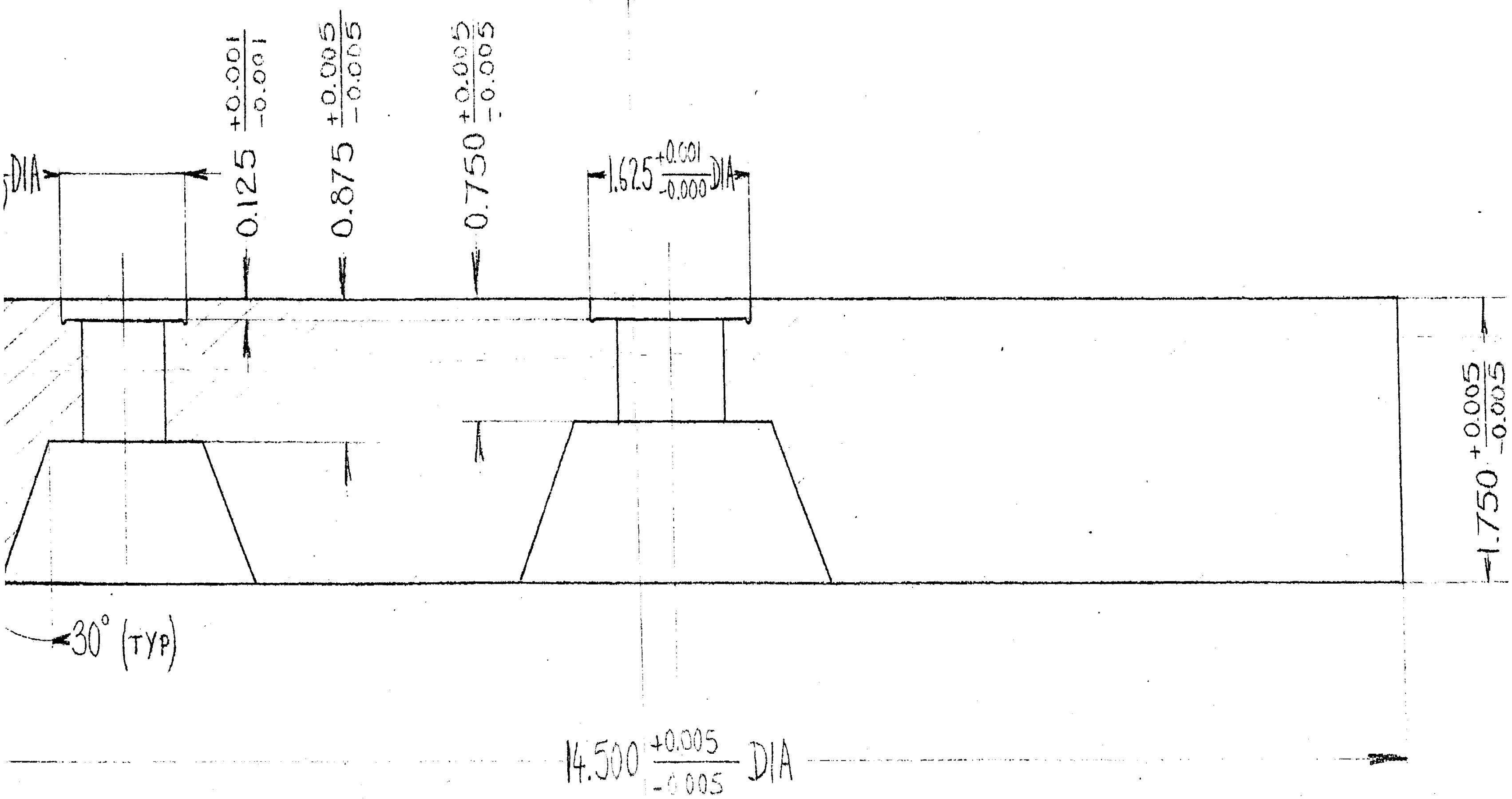
NO.	PART	DWG.
1	UPPER PLATE	2
2	LOWER PLATE	3
3	CLAMP	4
4	SPLIT RING	5
5	CROSS BAR	6
6	CROSS BAR	6
7	SPLIT RING	5
8	CASING	7
9	DIAPHRAGM	
10	1/4" I.D. ELBOW	
11	1/4" O.D. COPPER TUBE	
12	1/4-20 UNC-2A x 1 1/8 Semifin Hex Bolt	
13	1/4-20 UNC-2A x 1 1/2 Semifin Hex Bolt	
14	1/4-20 UNC-2A x 1 3/8 Semifin Hex Bolt	
15	1-8 UNC-2A Semifin Hex Nut	

ASSEMBLY DRAWING	AISI 1040 STEEL MATERIAL	
CALIFORNIA INSTITUTE of TECHNOLOGY	DRAWN BY J.H. CALLE	
TENSION LOAD CELL	DATE MAY-10-1965	
	SCALE: 1	DWG No. 1

32√ UNLESS OTHERWISE NOTED

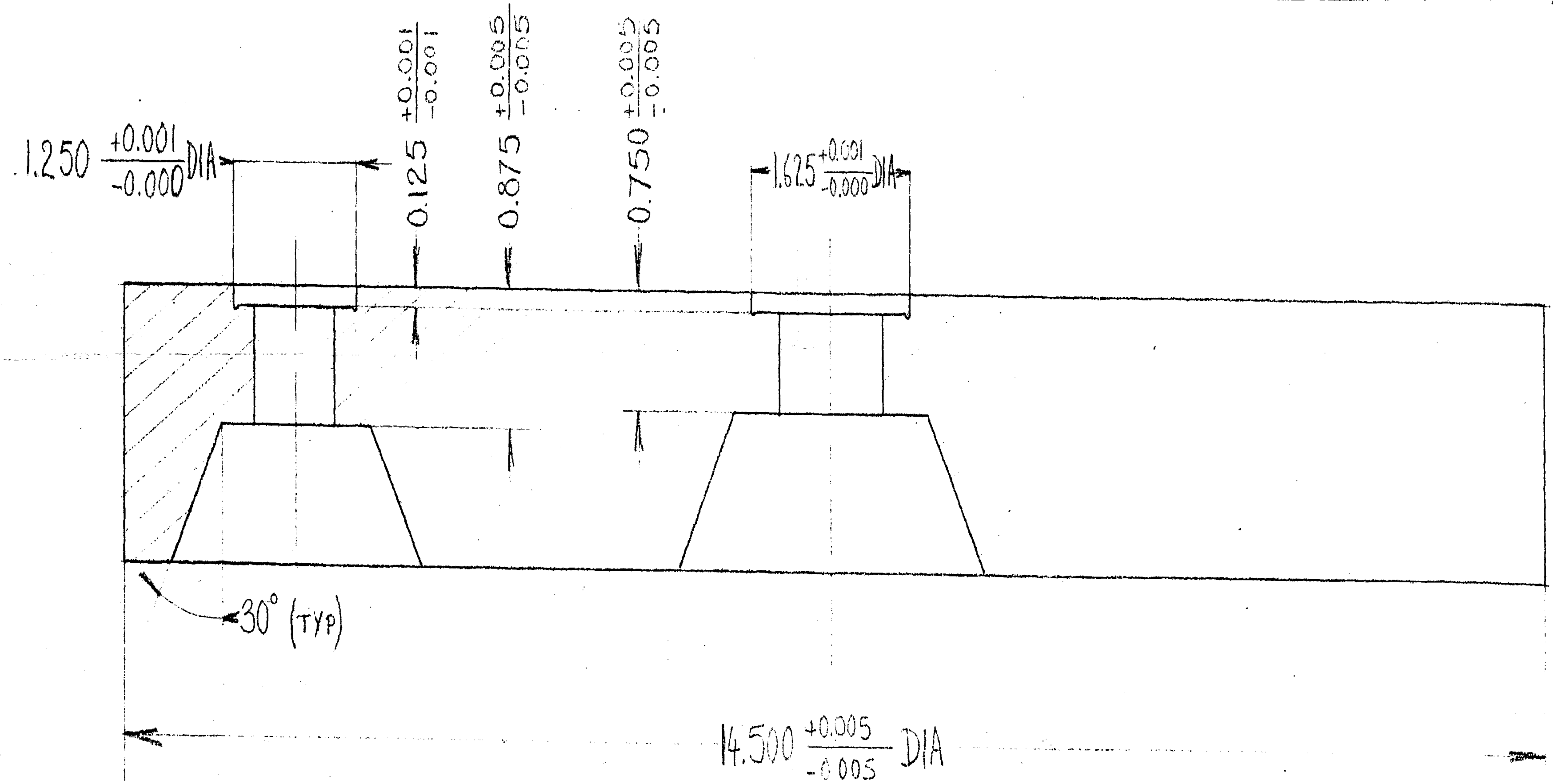

0.810 +0.005 -0.005 DIA
1.060 +0.005 -0.005 DIA
1.500 +0.005 -0.005 DIA
2.000 +0.005 -0.005 DIA
11.000 +0.001 -0.001 DIA


1.060 +0.005 -0.005 DIA
1.500 +0.005 -0.005 DIA
2.000 +0.005 -0.005 DIA
11.000 +0.001 -0.001 DIA
0.810 ±0.005 Drill, Spotface 1.250 +0.001 -0.000 DIA.
x 0.125 +0.001 -0.001 deep, 3 equally spaced (±0.01°)
0.001 -0.000 DIA
0.125 +0.001 -0.001
0.875 +0.005 -0.005
0.750 +0.005 -0.005
1.625 +0.001 -0.000 DIA



32√ UNLESS OTHERWISE NOTED

7	BASE PLATE	1	AISI 1040 STEEL
PART No.	NAME	NO. REQ'D	MATERIAL
CALIFORNIA INSTITUTE OF TECHNOLOGY			DRAWN BY J.H. CALLE
DIAPHRAGM MOLD			DATE: MAY-10-1965
			SCALE: 1 — DWG. No. 8



32 UNLESS OTHERWISE NOTED

7	BASE PLATE	1
PART No.	NAME	NO. REQ'D

CALIFORNIA INSTITUTE of TECH

DIAPHRAGM MOLD