GRAPHICAL METHOD FOR STRAIGHTENING OF LONG CYLINDRICAL SECTIONS

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ABSTRACT

Graphical Method for Straightening of Long Cylindrical Sections

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The objective of this technical report is to demonstrate a practical method by which bent sections, where the bends are all in one plane, can be straighten thru a graphical method.

The report will show how a steel cylindrical tube of unknown yield stress can be straightened by simply using graph paper and a press. The method is not only simple but it also eliminates the uncertainty as to where and how much permanent deformation is required to bring the part within specified limits. A detailed step by step example is discussed in the report.

ACKNOWLEDGMENT

I wish to thank Mr. A. Martin, former chief engineer, of Heroux Inc., who helped develop this method in order to salvage landing gear pistons which were bent during the heat treatment process. This method allowed us to salvage all the pistons which would have otherwise been scrapped.

I also wish to thank Mr. J. V. Svoboda, my advisor, who was very helpful in guiding me through my report. His advise and suggestions were very well appreciated and were an important factor in the writing of this report.

I would also like to extend my thanks to Heroux Inc. for granting their permission to use the data included in this report.

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NOMENCLATURE

A	=	area
A_1	=	area below the neutral axis
A_2	=	area above the neutral axis
a	=	variable distance
b	=	variable distance
D	=	variable distance
E	=	modulus of elasticity
h	=	height
I	=	moment of inertia
k_y	=	yield curvature
k_{max}	=	maximum curvature
L	=	variable length
l	=	variable distance
M	=	bending moment
M_e	=	elastic moment
M_{max}	=	maximum moment
M_p	=	plastic moment
M_y	=	Yield moment
N	=	load application position
Q	=	left support position
R	=	right support position
R_1	=	large radius
r_1	=	small radius
T	=	half table length
W	=	force or load

x_N = location of loading point

x_1 = location of first loading point

y_N = value of y at location N

y_1 = distance to centroid

y_2 = distance to centroid

Z = section modulus

α = angle

Δ deflection

Δy = permanent deformation required to straighten section

ΔH = distance travelled by the end of the piston

σ = stress

σ_{yp} = plastic yield stress

CHAPTER 1

INTRODUCTION

Straightening of machined parts has always been a subject of great interest to industry. To manufacture straight parts is very difficult and therefore methods of straightening them had to be developed.

The steel industry has developed machines capable of accomplishing this task very accurately. In other industries, it is often necessary to salvage parts bent during production.

The first step would be to ask an employee to try to straighten the part or parts. He in turn would use a device to apply loads at different points on the part. This would be done by choosing points at random as to where the load should be applied. Now if the same employee had a method by which he could find the location to apply the load and could determine how much permanent deformation is required to straighten the part, he would accomplish the straightening job much faster and more accurately and therefore increase his chances of success.

Recently, twenty-four pistons to be used as part of an aircraft landing gear were sent for heat treatment at a local heat treating plant. When they returned, they were bent anywhere from 0.030 inch to 0.163 inch. Investigation as to why the pistons were bent showed that the pistons had been suspended by wires which passed through them as seen on figure 1-1. This, of course, placed the pistons in compression allowing them to bend when heated to the heat treatting temperature.

The problem was a serious one. Twenty-four pistons which were quite advanced in the production schedule were bent. To scrap these meant a significant loss of money and, even worse, a loss of time affecting the delivery schedule, a very important factor in today's business.

The method discussed in this paper seems to be the first to be documented. A computer library survey was done on the Concordia University's computer and only seven references were found to discuss straightening of tubes, pipes, bars and sections. Six of the references refer to straightening of sections by machines and one discusses strengthening of sections by straightening. None discusses the method developed in this paper. See Appendix 1.

The publication, '' Iron and Steel Engineer '' clearly substantiates our findings by stating: ''Press straightening is still used today where small lots of many different sizes are produced, for material having severely hooked ends and in some prestraightening applications. Most modern straightening presses are hydraulically actuated with adjustable bending strokes and other refinements. Output

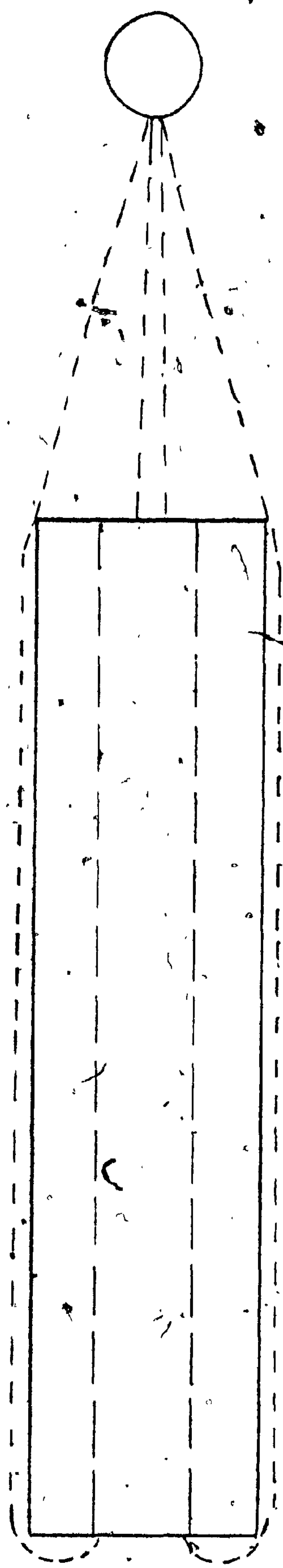


Figure 1-1 Suspended Piston During Heat Treament

however, is low and depends on a skilled operator's judgement for accuracy.''(1)

However, as stated above, this method has been practiced by many in the past. No one did it scientifically but, rather applied the resultant of the method through past experience and trial and error.

This report demonstrates that it is possible to straighten sections with the aid of a graphical method.

CHAPTER 2

PROPERTIES OF STEEL

2.1 Composition of Pistons.

Straightening of parts can be difficult using a trial and error method. The present method shows how it can be done accurately eliminating guess-work. But, let us first consider the parts that are to be straightened.

The parts are aircraft landing gear pistons made of AISI E4340 steel to Military Specification MIL-S-5000.[7] AISI E4340 is an aircraft quality alloy steel that is a steel which ''contains a significant quantity of alloying element (other than carbon and the other commonly accepted amounts of manganese, silicon, sulphur and phosphorus) added to effect changes in the mechanical or physical properties.''[6]

2.2 Heat Treatment

The highest mechanical properties of alloy steel are obtained by heat treatment. AISI E4340 steel is a heat treatable steel having high tensile strength capabilities. For our use, the pistons were heat treated to 180-200 kpsi per Military Specification MIL-H-6875.[8]

Heat treatment has the effect of transforming the crystal structure. On heating steel through the critical range, the crystal structure changes to austenite. The austenite grains are very small when first formed but grow in size as time and temperature above the actual range increases. Since MIL-S-5000 clearly states that AISI E4340 should have a grain structure size of #5 grain or finer with grains as large as #3 being permissible, (See figure 2-1 and 2-2), the soaking time and temperature must be very accurately controlled.(4) .

By slowly cooling the steel after exceeding the critical range, a fairly soft and ductile steel called annealed would be obtained. In order to attain high tensile strength, the part must be cooled rapidly. This action of quenching traps the austenite which remains unchanged to about 150°C (302°F) but then changes almost instantaneously to a hard structure called martensite. This is the hardening process.

The martensite structure that results is very brittle. In order to reach the required properties, it must be reheated or tempered. The purpose of tempering is to relieve the brittleness in the martensite structure thus improving the degree of plasticity of the steel. This is done by first relieving the internal stresses created by quenching, and then a structure of greater plasticity is developed in the steel due to crystallization of iron and alloy carbides. This results in an alloy steel which is strong, hard and tough.

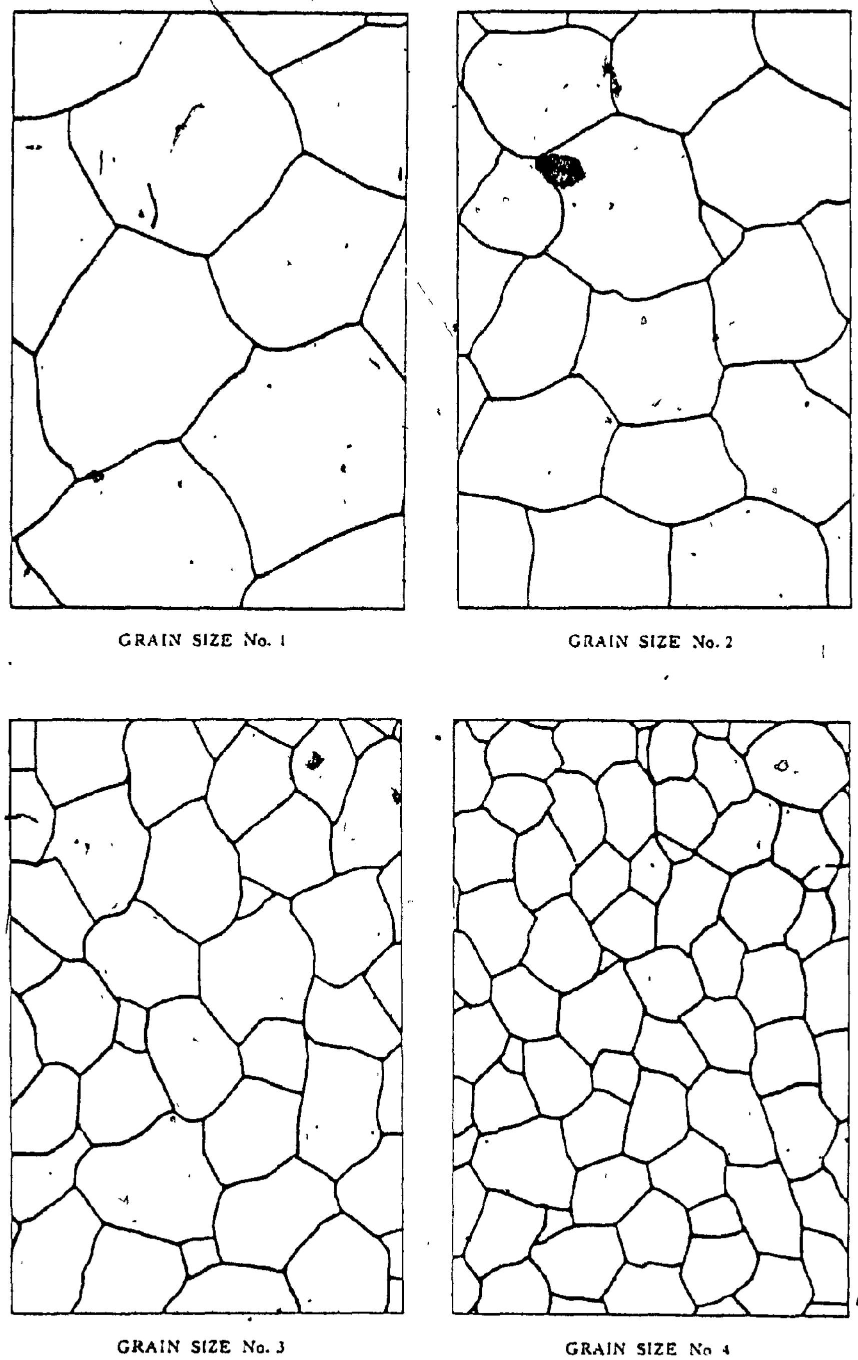


Figure 2-1 Grain Size

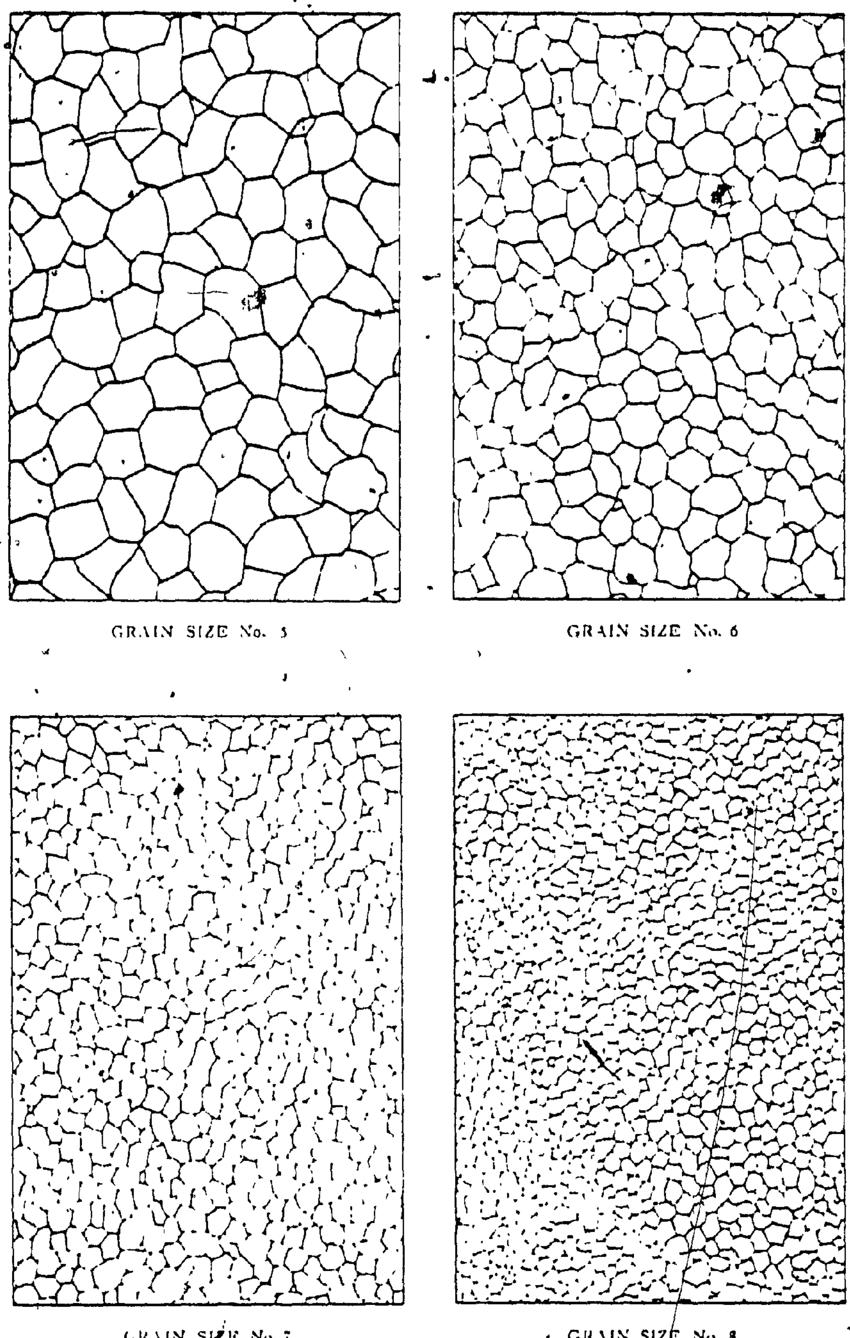


Figure 2-2 Grain Size

CHAPTER 3

STRAIGHTENING PROCEDURE

3.1 Introduction

A method was required to straighten twenty four bent pistons. Analysis showed that the general shape of the piston was that of planar curve. It was then decided to plot the curves to see the form of the curve. Looking at the graphs confirmed the curved shape but also showed that the pistons had bends at different stations. In order to remove these bends, a load had to be applied to the bend in the opposite direction. This method would not have been a problem, had there been only one bend on each piston, but they generally had many bends as will be seen later.

After a few hours of analysis and brainstorming it was realized that if straightening would start from one end of a section, working towards the center or to the other end of the part, taking each portion as a total section one might be able to straighten a multi-bend section. The following procedure is the method that was developed, and the steps to be followed are:

1) Measurements of the section.
2) Graph of the section.
3) Graph analysis.
4) Determination of stations requiring straightening.
5) Determination of the support points.
6) Permanent deformation as required to straighten the section.

However note that this report only investigate cylindrical tubes made of steel with the deformation being in one plane. Furthermore, the application of the presented method is limited to pistons with length to diameter ratio of approximately 10:1, with unknown and/or varying yield strength.

3.2 Measurements

The first step in the operation consists of measuring the amount of deformation at certain known locations along the part to be straightened. In the case of the pistons, they were installed on a pair of rollers, as seen in figure 3-1, and the deflection measured using a dial indicator accurate to 0.0005 inch. The deflection, or total indicated reading, was obtained by rotating the piston in order to find the highest point which when plotted on a graph was the " y " value. Now since the part was rotated to get the maximum deflection, the " y " value was doubled, that is we were measuring twice the deformation. The " x " value, or station as referred to throughout the text, is the length of the piston divided into the number of increments required to give the required accuracy. The pistons discussed in this report, were divided into one inch increments.

3.3 Graphical Method

The second step was to draw the contour of the part to be straightened on graph paper, the " x " axis being the length of the part and the " y " axis the maximum deflection at predetermined stations along the " x " axis.

Exaggerated View of Bent Piston

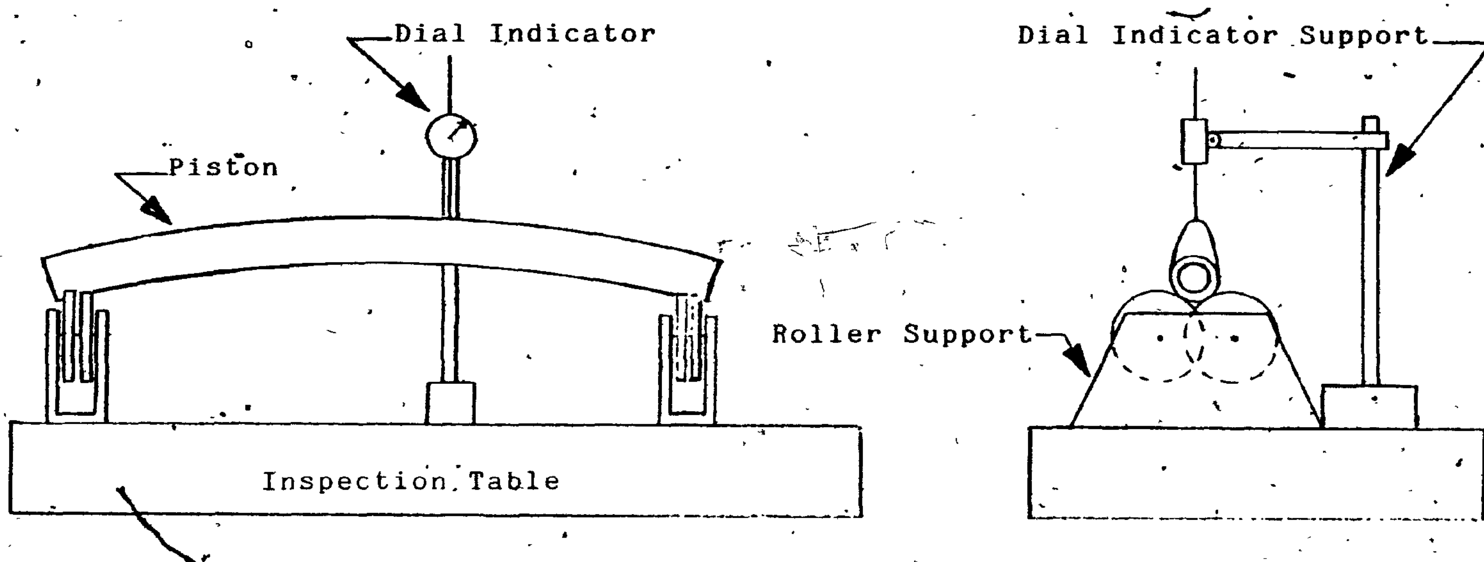


Figure 3-1 Measurement Model

While inspecting the parts, it was necessary to indicate where it was supported in order to make the measurements and also to indicate on the part the highest point at every station.

Once the graph was done and the number of stations chosen was satisfactory the graph was analyzed. At this stage, a decision is taken as to how much difference in slope can be accepted between two stations. In the case discussed in this report the highest tolerated deviation from the straight line was 0.002 inch/4 inch length. Once the above decision is taken, the location of the supports and the required deflections to straighten the part are found on the graph.

The simplest case, a bent section is seen in figure 3-2. This represents the curve of the section as measured on an inspection table at predetermined points. The object is now to straighten the section AC. In order to do so, point A must be raised to point A-1 or C to C-1 and the load required to straighten the section needs to be applied at point B where the change in slope occurs.

Choosing to raise point C to C-1 while the piston is supported at A and C, a line is drawn from point A to C and from A to C-1 which is the point where C must go in order to straighten AC. The distance B to B-1 is 0.100 inch. Now, since this is a total indicated reading, it is realized that

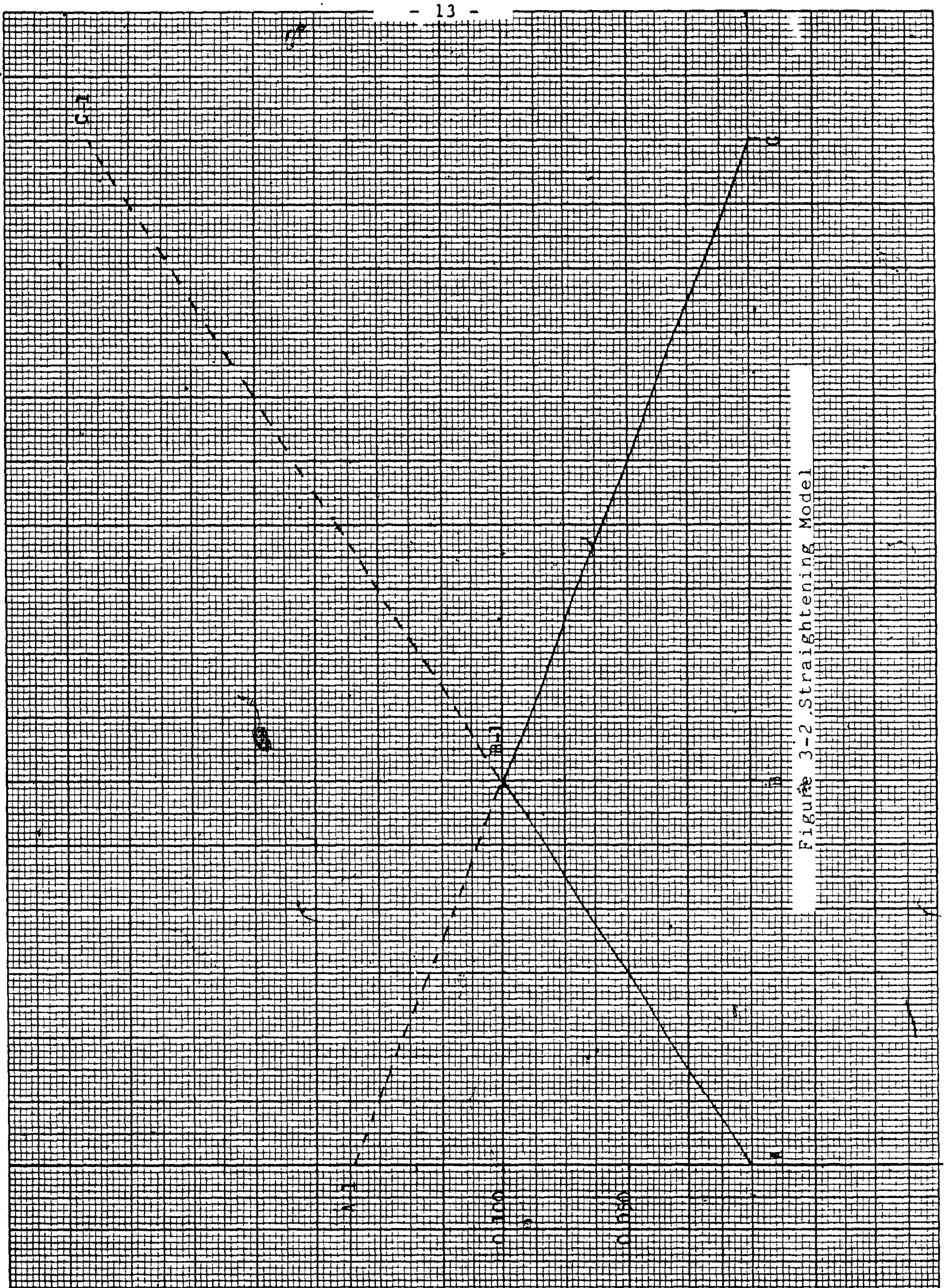


Figure 3-2 Straightening Model

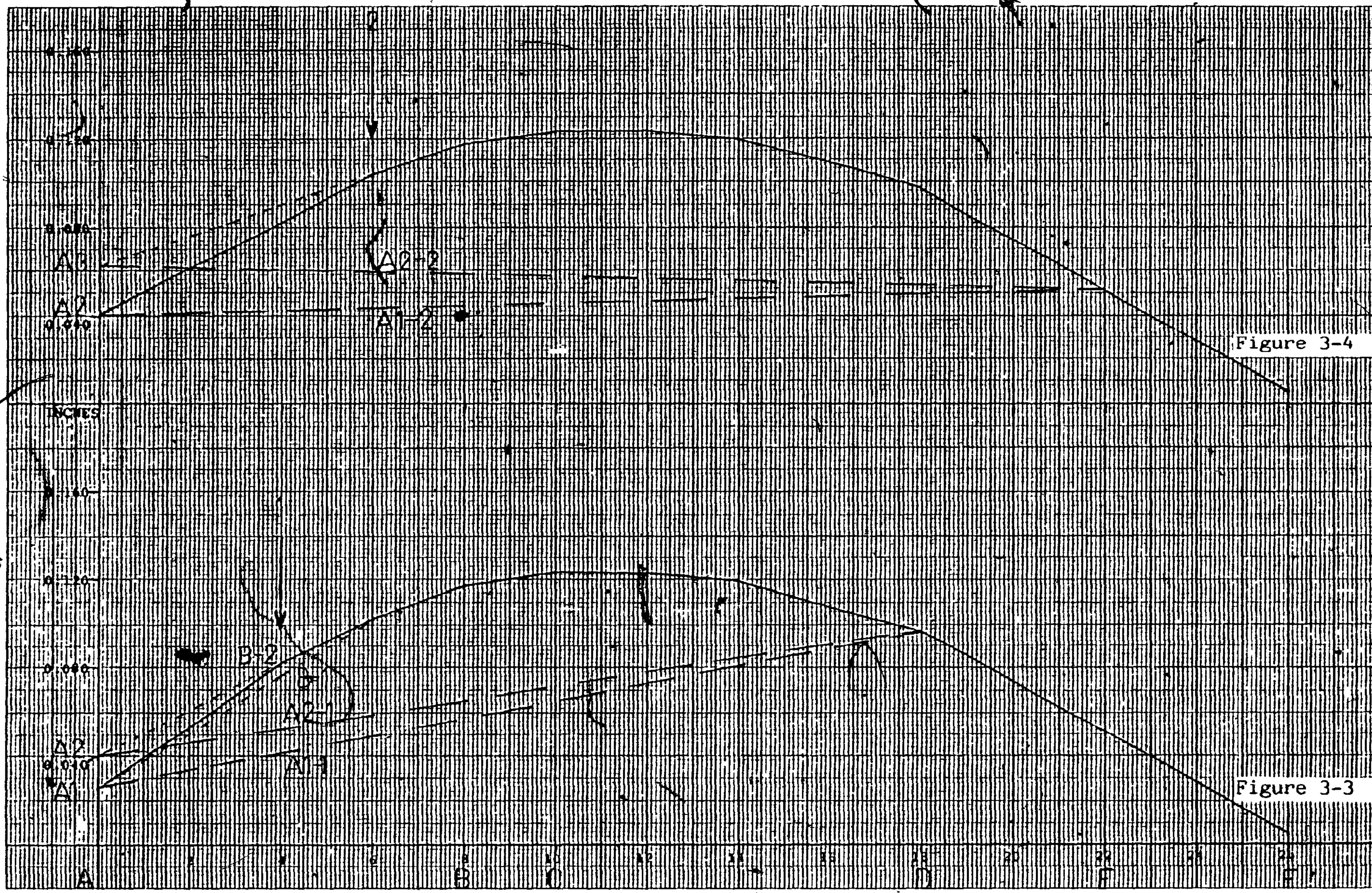
to straighten the part, a deflection of only one half of this reading is required (ref. para 3.2). Therefore taking one half of 0.100 inch which is 0.050 inch, a load would be applied at B to give the section a 0.050 inch permanent deformation. This operation would bring AC into a straight line accomplishing the objective. This method can now be applied to parts which are bent in more than one place as seen in the detailed example which follows.

3.4 Detailed Example

Looking at figure 3-3, we have the graph of a bent piston. The curve shown, reflects the actual shape of the piston. Points A and F are predetermined, as the support points used for inspection and points B, C, D and E are alternate support points chosen for convenience. The dimensions of the table are a key factor in the choice of our support points. As seen in figure 4-1 in chapter 4, the table was only thirty-two inches long with a six inch diameter hole in the center.

From figure 3-3, it can be seen that the maximum deflection is 0.123 inch. The object is now to raise points A and F to be in a straight line with stations 10 and 12, making the piston straight.

Looking at figure 3-3, it can be seen that there is a change in slope at stations 4, 6, 8, 12, 14 and 18. Now, in order to make this piston straight, these changes in slope must be eliminated. Let us now proceed step by step refering



First and Second Straightening Load

to figures 3-3 through 3-10.

To remove the bend at station 4, the piston would be supported at A and D. Now to make the line between stations 0 and 6 straight, point A1 must be raised to A2. To do this, a load needs to be applied at station 4 because the change in slope originates from station 4. From point D, the support point, a line is drawn to A1, and then another line to A2, which is the point where A1 must be after straightening.

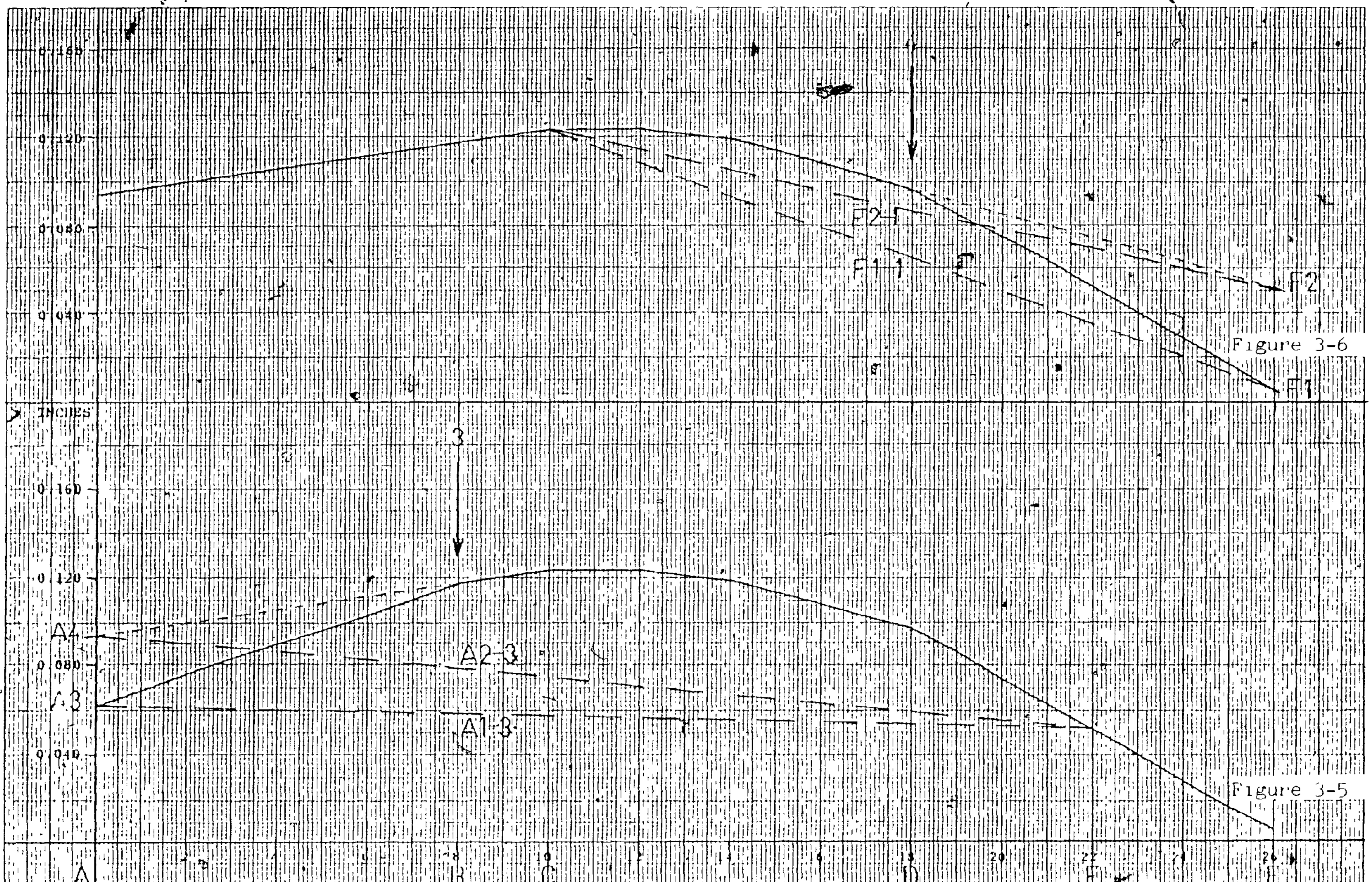
In order to find the amount of permanent deformation required to straighten portion 0-6 of the piston, we take, at station 4, one half the distance between A1-1 and A2-1, which is 0.0055 inch (ref. para 3.2 and 4.1). The reason for taking half the distance between A1-1 and A2-1 is that the measurement shown is the total indicated reading. The required load is then applied to give the piston 0.0055 inch of permanent deformation and by so doing, section 0-6 of the piston is straightened.

The same results would have been possible if we had used supports at stations zero and six inches. By so doing, we would have simulated the general case, as seen on figure 3-1, and discussed in paragraph 3.3. One can therefore see from figure 3-3, that the distance between A2-1 and A1-1 is equivalent to the distance between B1 and B2, if the piston was supported at stations zero and six inches. The amount of permanent deformation required to straighten the piston would be different in both cases but would yield the same result: a straight section.

The next step is to straighten station 0 to 8 by raising point A2 to A3 choosing points A and E as supports as shown in figure 3-4. From point E, a line is drawn to A2 and also to A3. At station 6, where the load is to be applied, the permanent deformation required is 0.009 inch. Stations 0 to 8 inches are now in a straight line.

Continuing with stations 0 to 10 inches, point A3 needs to be raised to A4. Again supporting the piston at points A and E, a line is drawn from E to A3 and to A4. At station 8 a load is applied to give a permanent deformation equal to half the distance between A1-3 and A2-3 that is 0.009 inch. Stations 0 to 12 inches have now been straightened (figure 3-5).

Let us now raise F1 to F2, applying the load at station 18. Choosing the supports to be C and F, a line is drawn from C to F1 and C to F2. At station 18, the distance between F1-1 and F2-1 is 0.022 inch. From this reading, the total permanent deformation required at this point is found to be 0.011 inch. Stations 14 to 26 are now in a straight line (figure 3-6). We then continue by straightening stations 12 to 26. In order to achieve this, F2 will have to be raised to F3 by applying the load at station 14, which



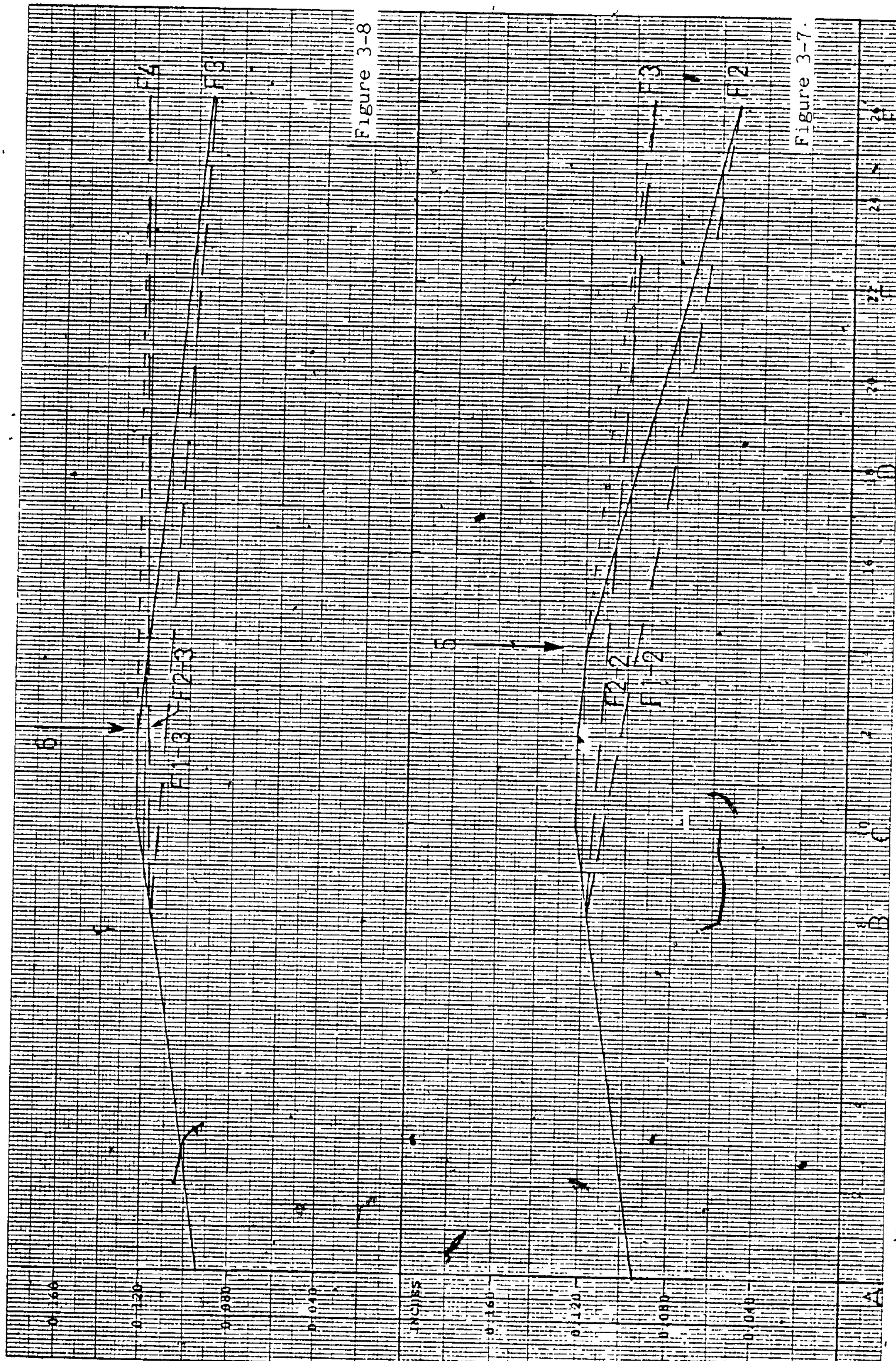
Third and Fourth Straightening Load

is the point where there is a change in slope. The permanent deformation required is found again by choosing supports, in this case B and F, and drawing a line from B to F2 and from B to F3. The deformation is then one half the distance between F1-2 and F2-2 which is 0.007 inch. Stations 12 to 26 are now in a straight line (figure 3-7).

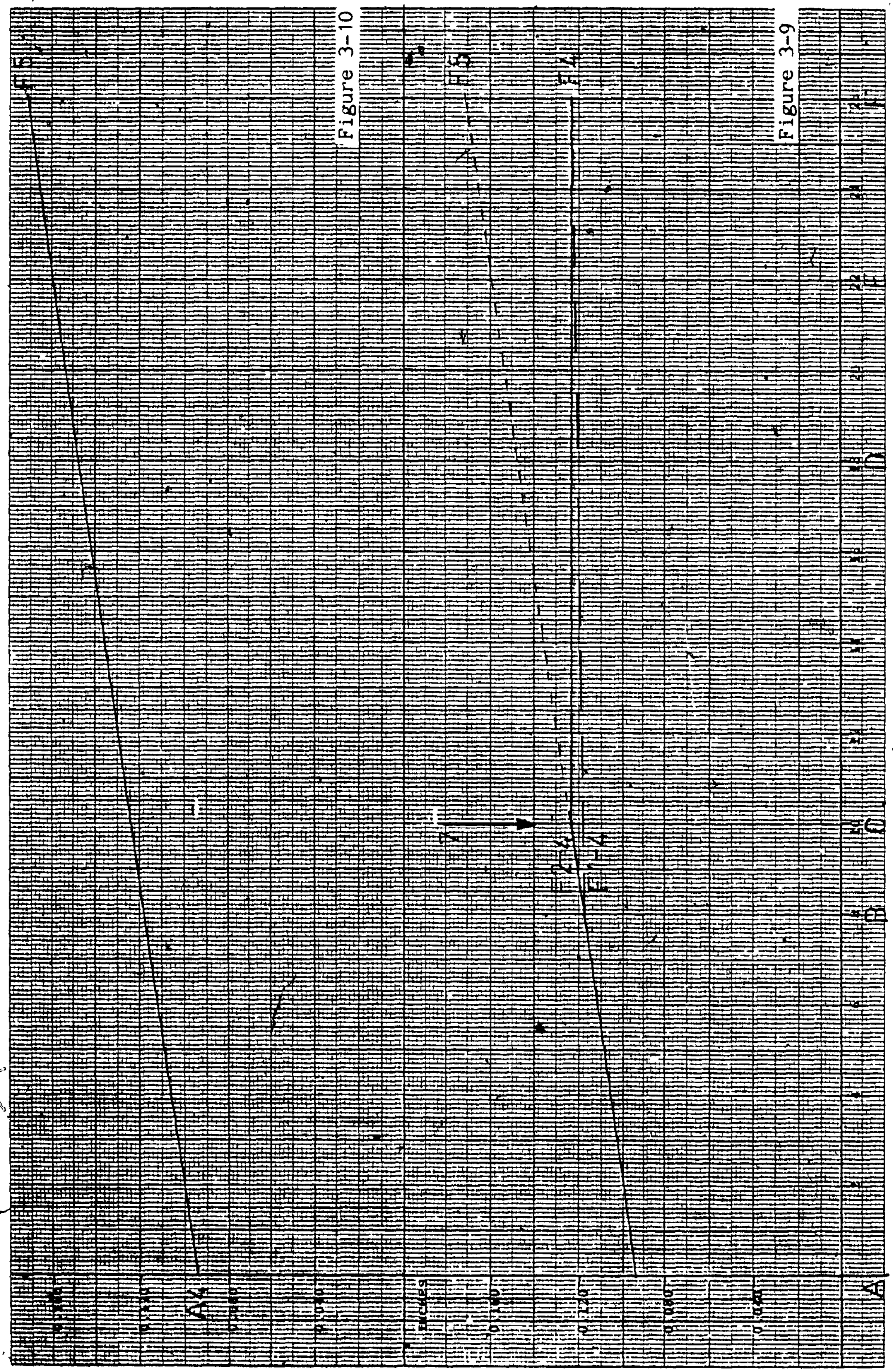
The next step is to straighten stations 10 to 26 by raising F3 to F4 while supported at B and F. Again a line is drawn from B to F3 and B to F4. At station 12 where the load is to be applied the permanent deformation required is found to be equal to one half the distance between F1-3 and F2-3 and that is 0.004 inch (figure 3-8).

Finally, stations 0 to 26 require straightening by applying a load at station 10 while supported at B and F. Drawing a line from B to F4 and B to F5, F1-4 and F2-4 are read to be 0.004 inch, therefore requiring a load to give station 10 a 0.002 inch of permanent deformation. This final loading makes the piston straight, joining points A4 to F5 in a straight line (figure 3-9 and 3-10).

The method was repeated for twenty four pistons with results as accurate as 0.002 inch. In some cases the accuracy was only 0.010 inch, but this was due to the fact that in some instances, where the difference in slope between each station was small, the best line between three



Fifth and Sixth Straightening Load



Seventh Straightening Load and Final Result points was used inducing a small error. Greater accuracy is certainly possible but due to the fact that the pistons had to be finish machined, the accuracy achieved was sufficient, and we were able to return to the original schedule with very little lost time.

The induced stress of cold working was, of course, not a problem since the next step after straightening the pistons was heat treatment which relieved the internal stresses created by cold working the pistons. The heat treatment method was also modified to place the pistons in tension rather than in compression.

CHAPTER 4

STRESS ANALYSIS

4.1 Loading Stress and Deflection

Looking back at the method used to straighten the pistons, one can see that they were subjected to transverse forces inducing bending of the member in its axial plane. They can therefore be considered as beams freely supported with a concentrated load at a point.

In order to induce the required deflection to reach the yield point, the force W should be calculated.(9) Since the pistons were in the annealed condition, the tensile strength,

$$\sigma = \frac{W\ a\ b}{Z l} \qquad (4\text{-}1)$$

from which

$$W = \frac{\sigma\ Z l}{a\ b} \qquad (4\text{-}2)$$

where

a= variable distance, distance from support to load.

b= variable distance, distance from support to load.

l= length between supports.

W= force

Z= section modulus

σ= stress

Now knowing W, the deflection required to reach yield can be calculated by

$$\Delta = \frac{Wa^2b^2}{3\ EIl} \qquad (4\text{-}3)$$

where

E= modulus of elasticity

I= moment of enertia

Δ= deflection

Once Δ is known, we add the permanent deformation required to straighten the section to the Δ required to reach yield. This gives the total stroke required to straighten the part.

In theory, the calculation of W and Δ is easy, but in practice, the results were not consistent. It, of course, was tried for a few pistons but we were unable to obtain success. After investigation, it was found that the pistons all had different annealed strength. This was due to the fact that they had been air cooled rather than furnace cooled (See Appendix 2). The formulas above are useful only when the yield stress is known and homogeneous throughout the part. It is however not always the case and thus the above method is not very practical. To by-pass the above problem, we applied a load on the piston so as to give the section a permanent deformation equal to the amount calculated on the graph. The permanent deformation reading was taken directly under the loading point as seen on figure 4-1.

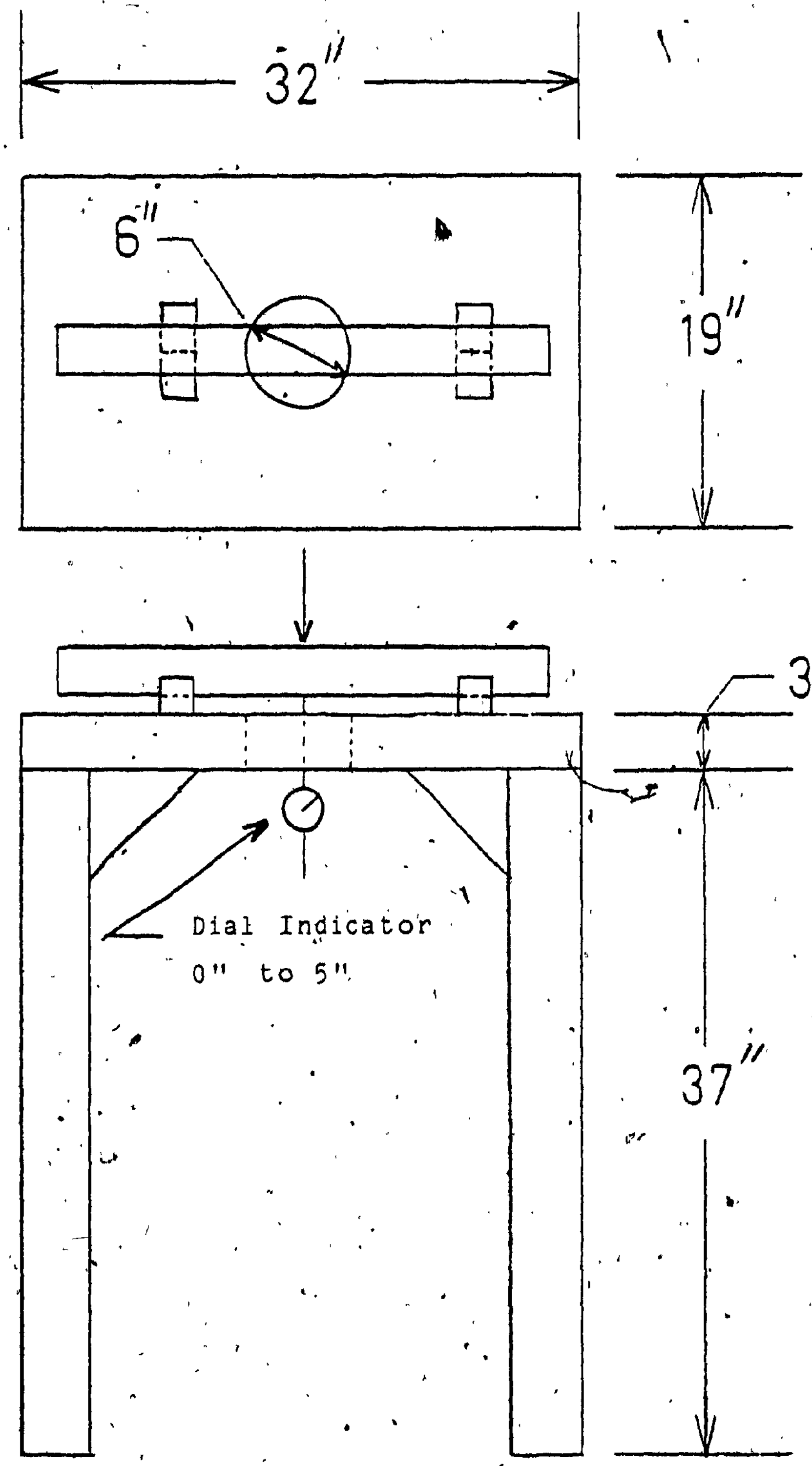


Figure 4-1 Support Table

If we assume that the supports always remain at the ends and the loading cylinder is moved, the mathematical calculation of the permanent deformation can be found through the geometry of triangles. Looking at figure 4-2, the shape of a bent section can be determined. Now, in order to straighten this section, point A must be raised to point B. Therefore choosing our supports as mentioned earlier at A and C, we draw a dotted line between C and B and between C and A, thus forming two right angle triangles ACO and BCO. The object is now to find DE by the use of trigonometry. From figure 4-2, we have OA, AB, OC and FC. Therefore the angle ACO is equal to

$$\tan ACO = \frac{AO}{OC} \qquad (4\text{-}4)$$

and the angle BCO is equal to

$$\tan BCO = \frac{BO}{OC} \qquad (4\text{-}5)$$

In order to find DE we join points D and F by a straight dotted line thus forming two other right angle triangles DCF and ECF, proportional to BCO and ACO respectively.

Since the triangles are similar, it can be seen that AO is proportional to EF and BO is proportional to DF. Therefore since the required unknown is DE, we must find DF. From similar triangles:

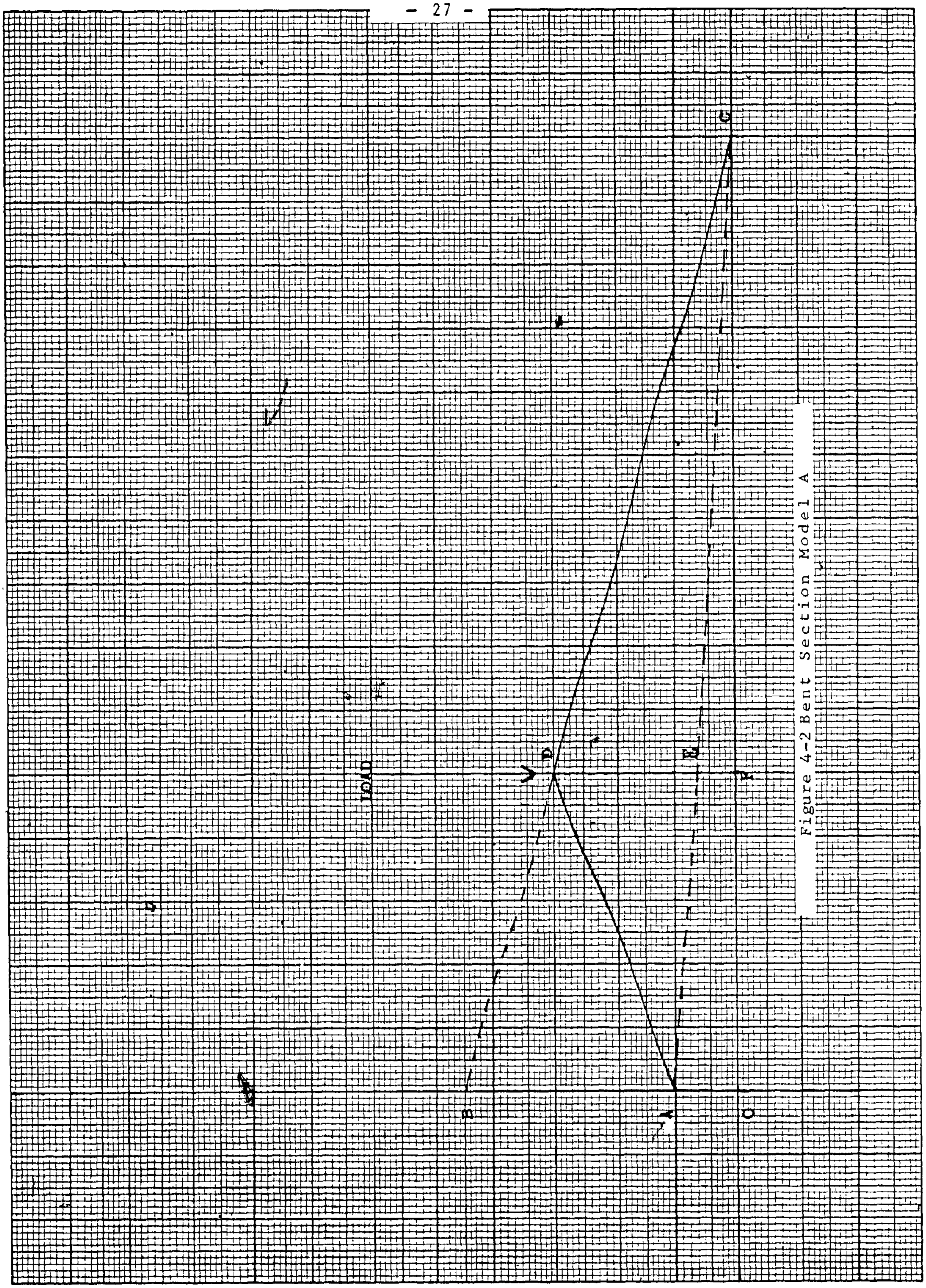


Figure 4-2 Bent Section Model A

$$\frac{DF}{FC} = \tan BCO = \frac{BO}{OC} \tag{4-6}$$

from which

$$DF = \frac{(BO)\ (FC)}{(OC)} \tag{4-7}$$

Now since ACO is similar to ECF we find

$$EF = (\tan ACO)\ FC \tag{4-8}$$

and from equations 4-7 and 4-8, we obtain

$$DE = DF - EF \tag{4-9}$$

The permanent deflection can now be found by dividing DE by two (ref. para 3.2).

It must also be noted that the load is applied perpendicular to the part when resting on the table. Therefore the arrows on the graphs should be at a slight angle when, on the graph, supports other than 0 and 26 are used. However due to the small values of " y " compared to the length of the part, we can consider the loading angle to be negligible.

4.2 Plastic Deformation

In order to obtain the desired permanent deflection, the piston was subjected to a load high enough to exceed the yield stress and to produce a permanent deformation equal to the amount calculated on the graph. Such bending of a steel section beyond the elastic range of strain is called plastic bending.[14]

Let us consider a steel beam with the stress-strain diagram shown on figure 4-3. Since the elastic limit stress and the yield stress are almost identical and since the plastic strain during yielding can be much greater than the elastic strain before yielding, it is customary to idealize this stress-strain diagram as shown on figure 4-4. In this diagram, it is assumed that proportionality between stress and strain holds up to the yield stress and that for any increase in strain beyond this point, the stress remains equal to the yield stress. It is also assumed that the material has equal yield point in tension and in compression.[10] Assuming the beam is made of an elastic-plastic material, and subjected to pure bending, and if the bending moments, M, are small, and the maximum stress in the beam is less than σ_y, the beam is considered to be in the ordinary elastic bending condition with a linear stress distribution as shown in figure 4-5a.[11]

If the bending moment is increased above the yield moment M_y, the strain at the extreme fibers will continue to increase and they will finally exceed the yield strain E_y. However because of the plastic conditions, the maximun stress will remain constant and equal to the yield stress σ_y (see figure 4-5b). The outer portions of the beam have become plastic while the central core remains elastic. By further increasing the bending moment the plastic region extends inward towards the neutral axis until the conditions of figure 4-5c are reached.

At this stage the strain in the extreme fibers is

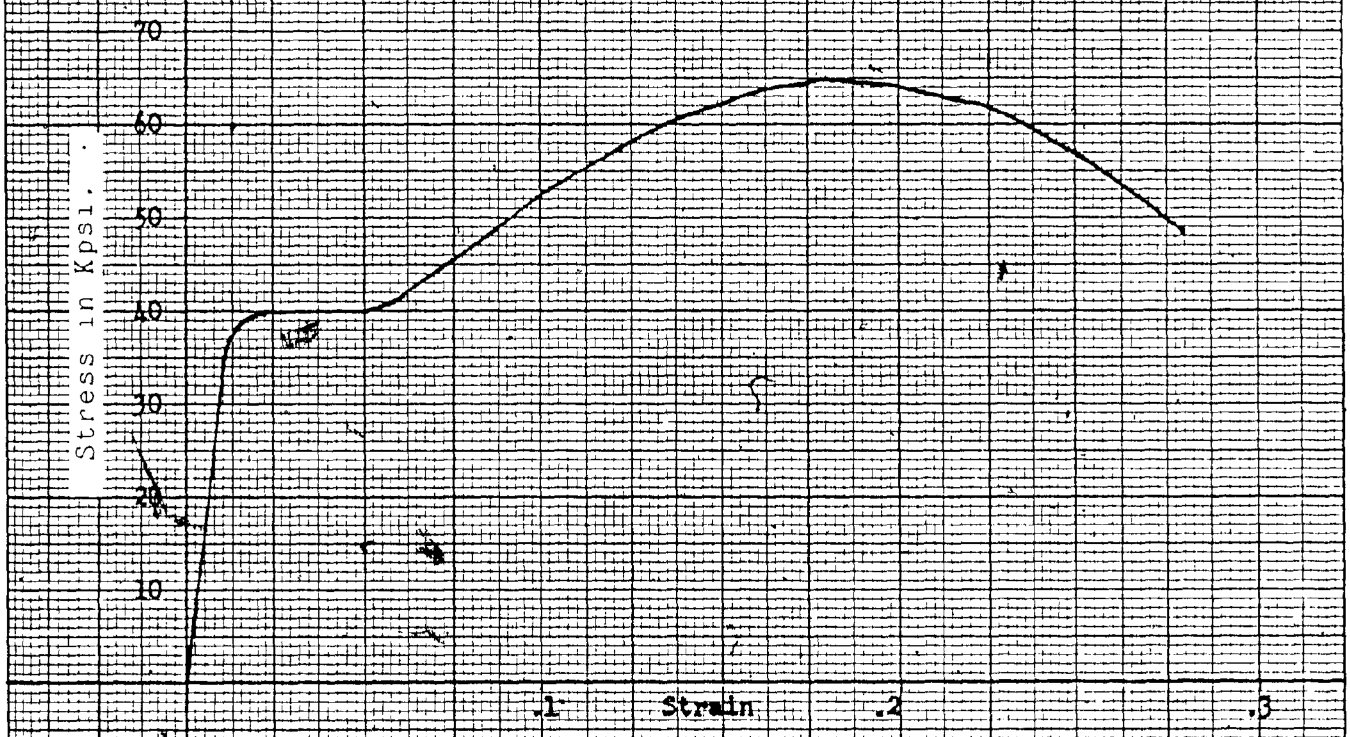


Figure 4-3 Stress-Strain Diagram (actual)

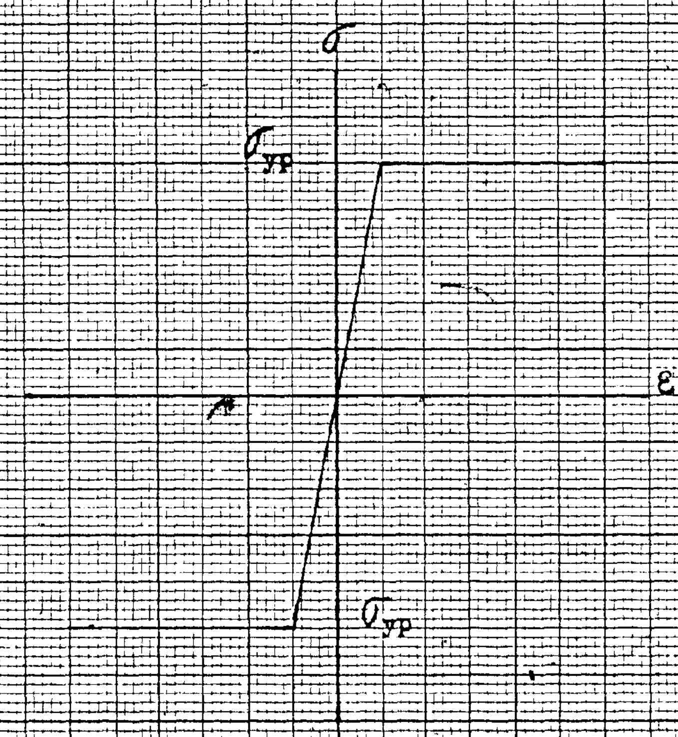


Figure 4-4 Stress-Strain Diagram (idealized)

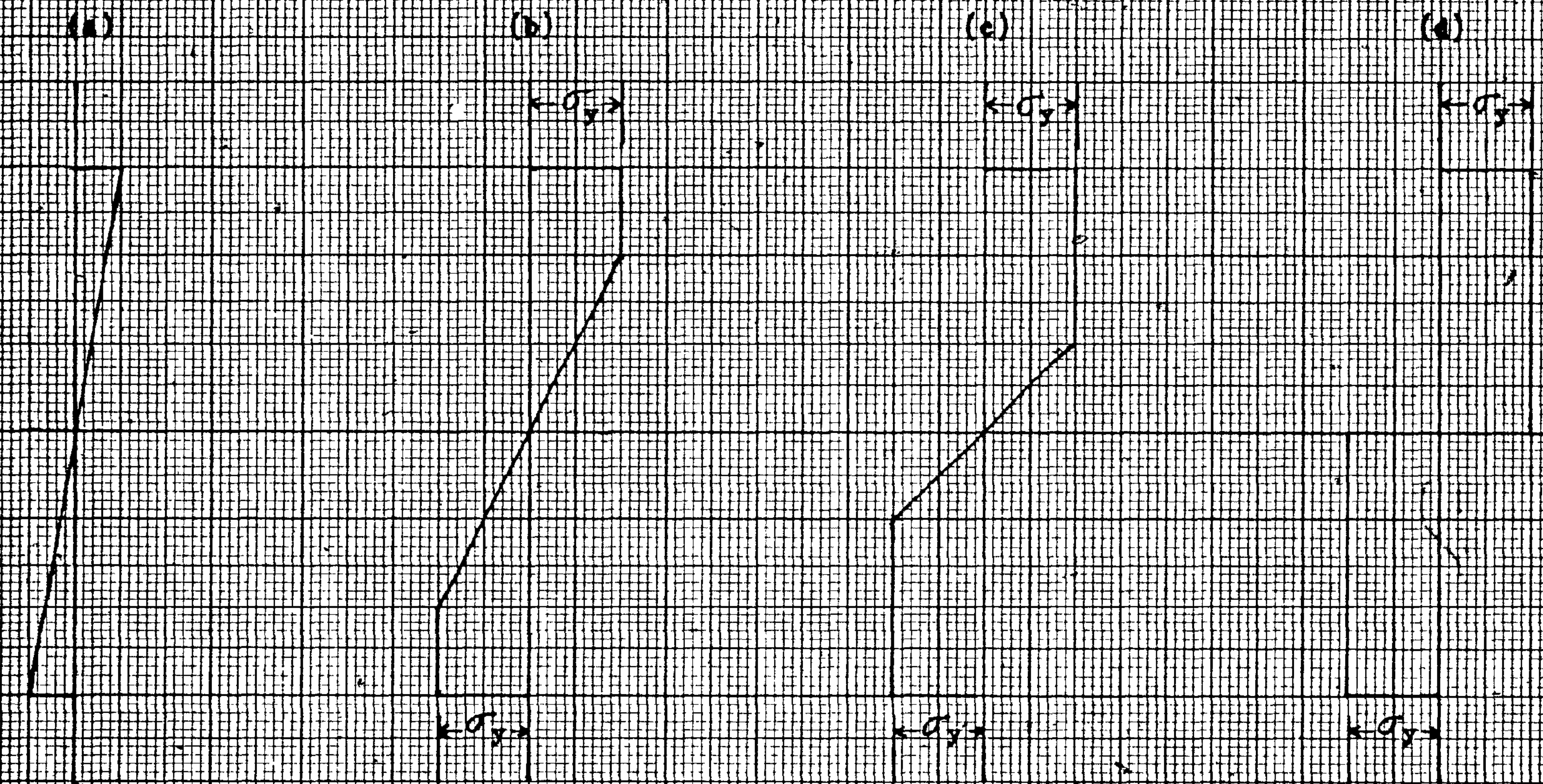


Figure 4-5 Stress Distribution

perhaps ten to fifteen times the yield strain and the elastic core is almost non-existent. Thus for all practical purposes, the beam has reached its ultimate moment resisting capability and the idealized stress distribution pattern can be drawn up as in figure 4-5d. The bending moment corresponding to this idealized stress distribution is called the plastic moment M_p, and represents the maximum moment that a beam of elastic-plastic material can be subjected to.

To find the plastic moment is very important since it is the limiting moment that the beam can withstand. To find M_p, we begin by locating the neutral axis of the cross section. If the section is rectangular, the neutral axis is located at the center. Above the neutral axis, the fibers are in compression and below the neutral axis, the fibers are in tension. Then since the sum of all the internal force must reduce to a couple equal to M . it follows that:[10]

$$\sigma_{yp}A_1 - \sigma_{yp}A_2 = 0 \qquad (4\text{-}10)$$

and

$$\sigma_{yp}A_1y_1 + \sigma_{yp}A_2y_2 = M_p \qquad (4\text{-}11)$$

where A_1 = area below the neutral axis

A_2 = area above the neutral axis

y_1 = distance to their centroid

y_2 = distance to their centroid

σ_{yp} = plastic yield stress

From equation 4-10, we obtain $A_1 = A_2 = A/2$, where $A = A_1 + A_2$, that is the total cross sectional area. If A_1 and A_2 are replaced by A/2 in equation 4-11, it follows that:

$$M_p = \sigma_{yp} \frac{A}{2}(y_1 + y_2) \qquad (4-12)$$

where M_p is the plastic moment.

For the particular case of a rectangular cross section, $y_1 = y_2 = h/4$, and A=bh

$$M_p = \sigma_{yp}\frac{bh}{2}\left(\frac{h}{4} + \frac{h}{4}\right)$$

$$= \sigma_{yp}\frac{bh^2}{4} \qquad (4-13)$$

where b= base of rectangle

h= height of rectangle

To compare, the maximum elastic moment is :

$$M_e = \sigma_{yp}\ Z = \sigma_{yp}\frac{bh^2}{6} \qquad (4-14)$$

where M_e is the elastic moment.

Therefore dividing the plastic moment by the elastic moment, we obtain:

$$\frac{M_p}{M_e} = \frac{\frac{bh^2}{4}}{\frac{bh^2}{6}} = \frac{3}{2} = 1.5 \qquad (4-15)$$

It can be seen from this result that a rectangular section can sustain 50% more load before unlimited deflection occurs than caused by its first yield.[13] Each different cross section exhibits a different value for the ratio $\frac{M_p}{M_e}$ called the shape factor. In the case of a piston, considering the preceding procedure, it follows that:

$$M_p = \sigma_{yp}\frac{A}{2}\ (y_1+y_2) \qquad (4\text{-}16)$$

if:

$$\frac{A}{2} = A_1 = A_2 = \frac{\pi}{2}\ (R^2 - r^2) \qquad (4\text{-}17)$$

and

$$y_1 = y_2 = \frac{4}{3\pi}\ \frac{(R^2 + Rr + r^2)}{(R + r)} \qquad (4\text{-}18)$$

where R= large radius

r= small radius

Replacing in equation 4-16

$$M_p = \frac{\sigma_{yp}\frac{\pi}{2}\ (R^2-r^2)\ (2)}{}\ \left(\frac{4}{3\pi}\right)\ \left(\frac{(R^2+Rr+r^2)}{(R + r)}\right)$$

$$= \frac{\sigma_{yp}\ (R^2-r^2)\ (R^2+Rr+r^2)\ 4}{3\ (R+r)} \qquad (4\text{-}19)$$

which is the plastic moment. Now the elastic moment, as we know is:[9]

$$M_e = \sigma_{yp}\ Z \qquad (4\text{-}20)$$

where

$$Z = \frac{0.785\ (R^4-r^4)}{R} \qquad (4\text{-}21)$$

therefore

$$M_e = \sigma_{yp}\frac{(0.785)\ (R^4-r^4)}{R} \qquad (4\text{-}22)$$

Now taking $\frac{M_p}{M_e}$ we have:

$$\frac{M_p}{M_e} = \frac{\dfrac{4\,\sigma_{yp}\,(R^2-r^2)(R^2+Rr+r^2)}{3(R+r)}}{\sigma_{yp}\dfrac{(0.785)(R^4-r^4)}{R}} \qquad (4\text{-}23)$$

$$\frac{M_p}{M_e} = \frac{4\,(R^2-r^2)(R^2+Rr+r^2)(R)}{3(0.785)(R+r)(R^4-r^4)} \qquad (4\text{-}24)$$

$$= \frac{1.70(R^2-r^2)(R^2+Rr+r^2)(R)}{(R+r)\,(R^4-r^4)} \qquad (4\text{-}25)$$

$$= \frac{1.70(R)(R^3-r^3)}{(R^4-r^4)} \qquad (4\text{-}26)$$

Thus the shape factor is dependent upon R and r, but from tables in reference books the shape factor for a circular ring usually varies between 1.25 and 1.70. [12] In the case of the piston worked upon the shape factor is 1.44 based on R=2.850 " and r=2.125 ".

Once the beam has reached the plastic moment M_p, it will continue to deform without any increase in the applied bending moment thus forming a hinge, or better known as a plastic hinge. The term plastic hinge arises from the fact that the beam under a large moment will have a small zone which is plastic thus allowing the beam to rotate at the hinge cross section. To briefly explain the plastic hinge concept, let us consider a simple beam subjected to a concentrated load at the center (figure 4-6b). The bending moment diagram as seen on figure 4-6b shows a triangular shape with maximum bending moment being $\frac{WL}{4}$.

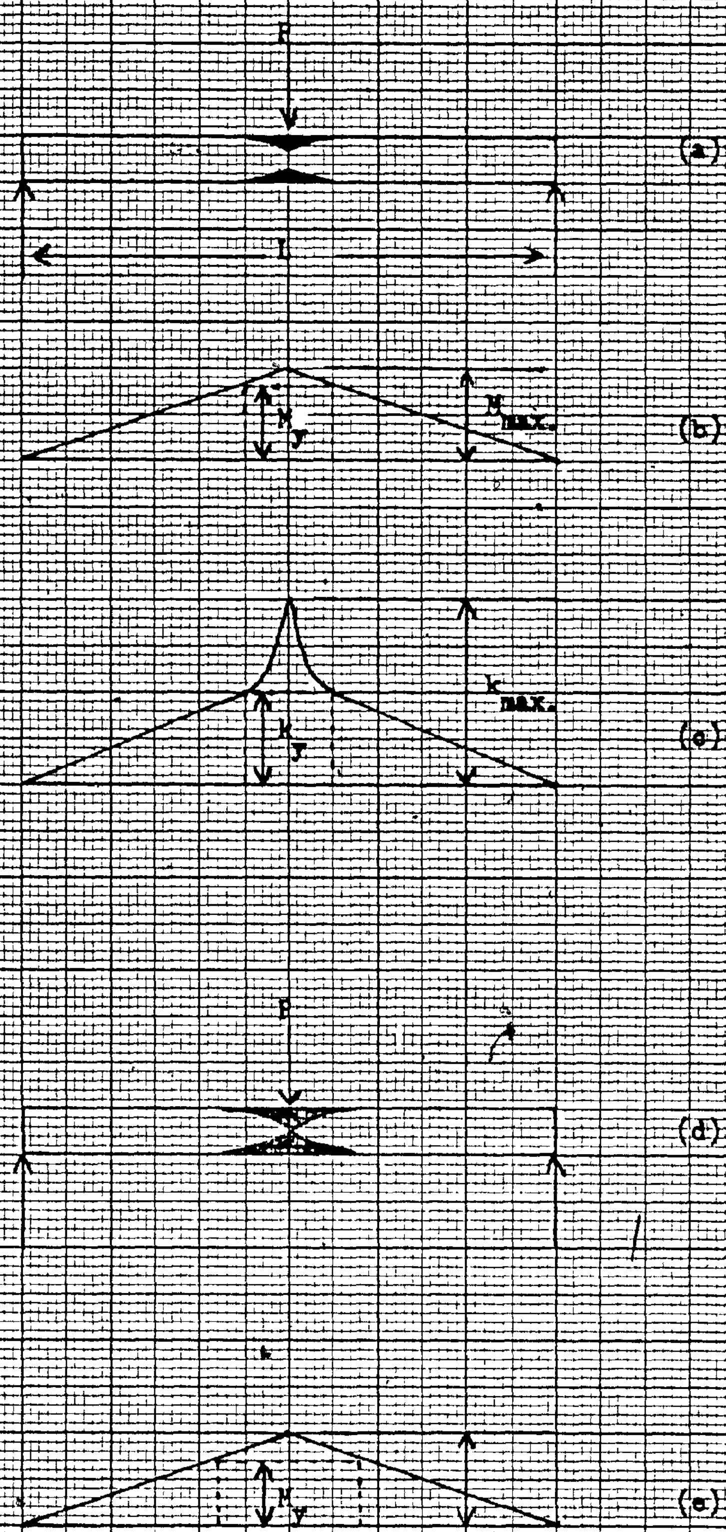


Figure 4-6 Plastic Hinge

If the maximum bending moment is greater than the yield moment, M_y, but less than the plastic moment M_p, we obtain a region in the central part of the beam, called a region of contained plastic flow (figure 4-6a). The dark areas on the figures show the fully plastic zones. The curvature diagram (figure 4-6c) shows that the curvature increases linearly from the ends of the beam toward the middle until the edges of the plastic region is obtained At this stage, the curvature is equal to the yield value k_y. From this stage the curvature increases at a much faster rate and it reaches k_{max}. at the center of the beam. The maximum curvature remains finite as long as an elastic core exists at the center of the beam.

As the load is increased and the maximum bending moment approches the plastic moment, the region of plasticity extends farther inward toward the neutral axis at the middle of the beam. Finally when M_{max} is equal to M_p the cross section at the center of the beam is completely plastic (figure 4-6d, 4-6e). Thus the beam behaves like two ridgid bars linked together by a plastic hinge, allowing them to rotate relative to one another. (11)

4.3 Internal Process

From experimental results, it can be seen that the method, described in this paper, gave good results.

The internal process which allowed the piston to be straightened will now be described. Since no heat was used, the pistons could be classified as being cold worked or strain hardened.

Metals not strained or deformed are composed of crystals which are arranged in an orderly pattern. These metals are composed of many crystals called grains. When the metal is deformed to its plastic limit, or cold worked at low enough temperature such as room temperature, the metal is strain hardened. Strain hardening results from the rearrangement of the atoms into a distorted lattice, that is the atomic bonds between the atoms are broken and place changes occur in the atomic lattice.[15] This place changing is the change of position of atoms relative to each other, therefore causing an irreversal action to take place even upon release of the load. The part is said to have yielded. Although the atoms have rearranged themselves along the slip planes, the new atomic bonds are as strong as the old ones. Therefore in general, the fact that a part has yielded does not necessarily mean that the part has failed. As a matter of fact, this plastic deformation produces an increase in tensile strength, yield strength, hardness and also a decrease in ductility. The operation of cold working also creates internal stresses in the material which can be good or bad for the parts, depending on their use. If these internal stresses are not helpfull or required, they can be relieved by heat treatment of the part following cold work.[15] During heat treatment, two distinct processes occur. The first is called recovery which has the effect of relieving internal stresses. This occurs at low temperature and does not cause any appreciable changes in hardness or microstructure. The second process is called recrystalisation and grain growth. When the temperature is increased to a sufficient degree, the small unstrained grains begin to replace the strained grains of the cold worked metal.[15] Eventhough the pistons have been cold worked all the internal stresses can be relieved by heat treatment.

CHAPTER 5

COMPUTER METHOD

5.1 Computer Program Development

Since at the time of the bent piston incident, a computer was not readily available, the straightening method was not computerized. Today, three years after the incident, a small computer program has been developed to calculate the permanent deformation required to straighten the section and also locate the right and left supports. Although the program development follows a slightly different route, compared to the graphical method, both methods are similar and achieve the end results of straightening the section.

Let us start with a bent section as shown on figure 5-1. The objective is to find the slope of each line between each measurement station and to align one with the other. This step is repeated until all the stations are aligned with each other therefore making the section straight.

The section ABC has a bend at station two inches. The object is to raise point A to point E by applying a load at B, so that ABC will become EBC, a straight section. The first step consist of obtaining the slope of line AB between stations zero and two. This

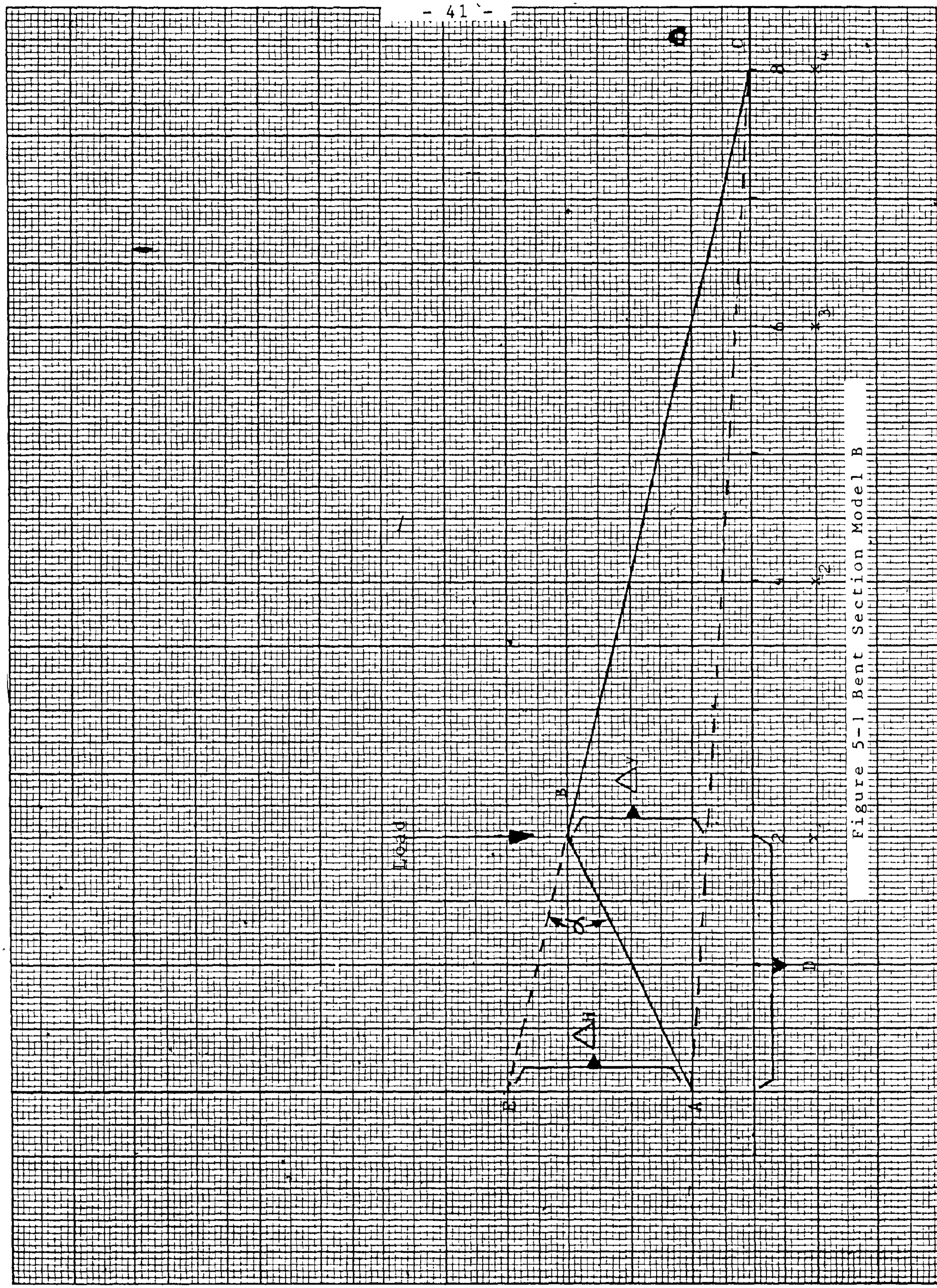


Figure 5-1 Bent Section Model B

in done by taking the "y" value or delection, at B less the "y" value at A and dividing by D, the distance between measurement stations. The second step is to obtain the slope of line BC between stations two and four. This is also done by taking the "y" value at station four less the "y" value at station two and dividing by D. Now that both slopes are known, it is possible to find the angle alpha by simply subtracting the slope of BC from the slope of AB.

Generalizing, the straightening angle can be calculated as:

$$\alpha = \frac{y_n - y_{n-1}}{D} - \frac{y_{n+1} - y_n}{D}$$

$$= \frac{(2)(y_n) - (y_{n-1} + y_{n+1})}{D} \qquad (5\text{-}1)$$

where y_n is located at the load application point. The next step consists of finding ΔH. Since the slopes are very small, we can assume that AB is equal to D, from which

$$\Delta H = \alpha\,(x_1 - QD), \qquad (5\text{-}2)$$

where Q is the position of the left support and x_1 is the location of the first loading point. It is known that ΔH is proportionnal to Δy and the value of Δy is dependant upon the location of the supports. If we have the right support located at station eight and the left support at station zero, then our problem gives:

$$\Delta_y = \frac{\Delta H\ (RD - x_1)}{(RD - QD)} \qquad (5\text{-}3)$$

where R is the position of the right support. Now if x_1 comes from $x_n = ND$ where $N = x/D$ which equals lenght of section divided by the spacing between measurements:

$$\Delta_y = \frac{\Delta H\ (RD - ND)}{(RD - QD)} \qquad (5\text{-}4)$$

and replacing ΔH by its value, from equation 5-2,

$$\Delta_y = \frac{\alpha (x_1 - QD)\ (RD - ND)}{(RD - QD)} \qquad (5\text{-}5)$$

$$\Delta_y = \frac{\alpha (ND - QD)\ (RD - ND)}{(RD - QD)} \qquad (5\text{-}6)$$

where N is the load application position equal to one on figure 5-1, Q is the left support position equal to zero on figure 5-1 and R is the right support position equal to four on figure 5-1. Since α is dependant on D, we can replace α by αD (from equation 5-1) and divide everywhere by D in equation 5-6. By so doing the general equation becomes:

$$\Delta y = \frac{\alpha (N - Q)\ (R - N)}{(R - Q)} \qquad (5\text{-}7)$$

Remembering that the "y" value on the graph are equal to the total indicated reading (ref. para 3.2), Δy must be divided by two in order to get the permanent deformation required to straighten the section at point B. Therefore Δy becomes:

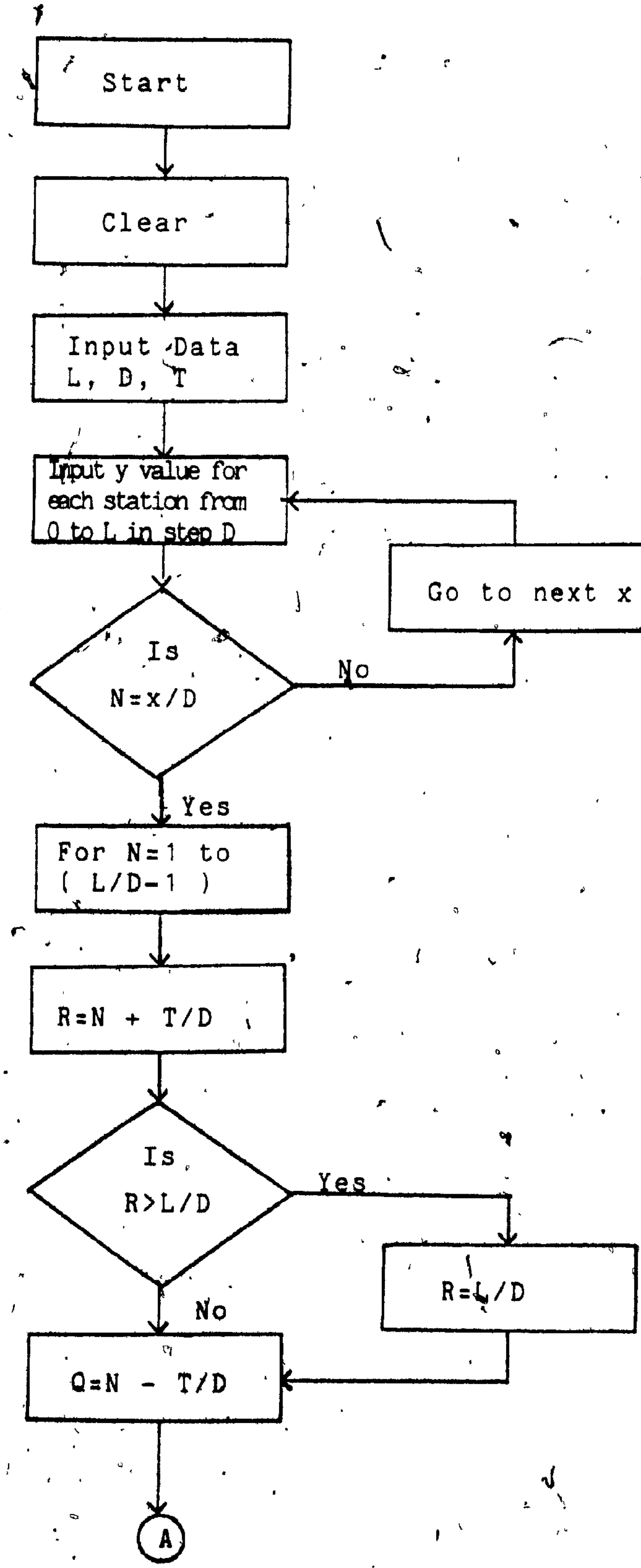
$$\Delta y = \frac{\alpha (N-Q)\ (R-N)}{2\ (R-Q)} \qquad (5\text{-}8)$$

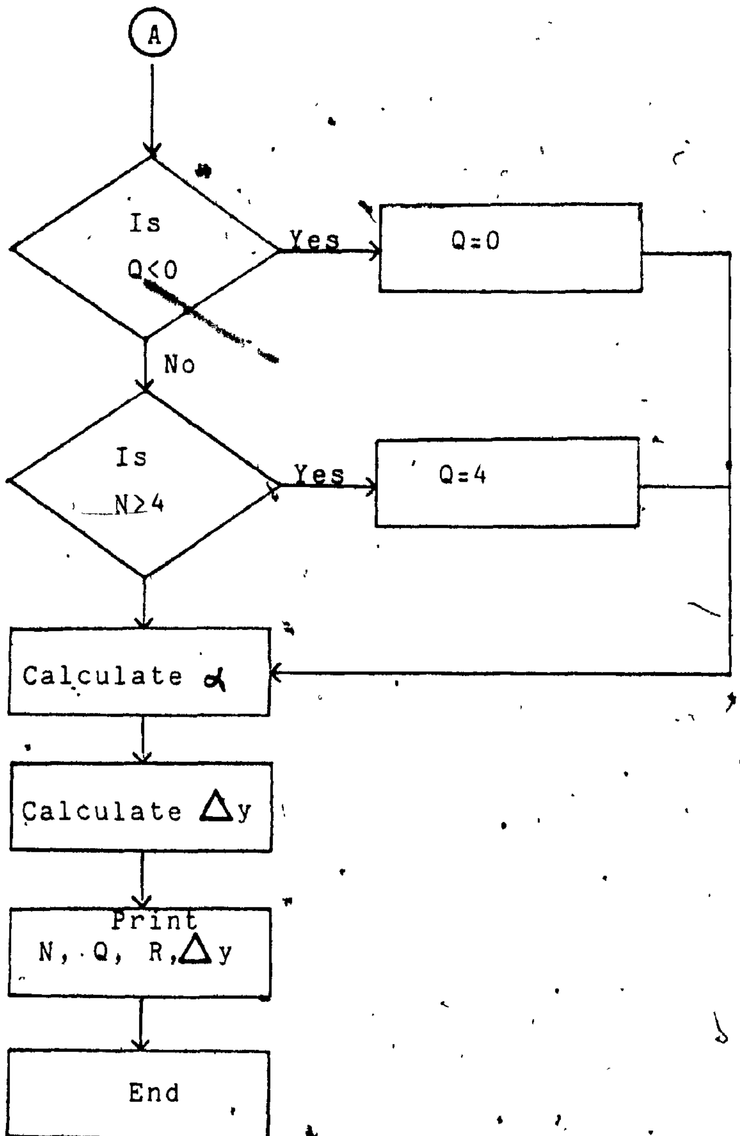
To summarize, the computer program consists of two equations: one for the calculation of angle α and one for the calculation of the permanent deformation Δy, required to straighten the part or section of the part. A complete computer print out of the computer results is included in appendix 4.

5.2 Flowchart

In the preceeding paragraph we have discussed the mathematical approach to the computerized straightening procedure. Let us look at the computer reasonning that allowed us to create a simple program capable of solving the equations. The computer used, was a Radio Shack TRS-80 Model III with 48K of internal memory and two disk drive. The computer language is TRS-80 Basic. The following is the flowchart for the program entitled: "Section straightening program" and gives the graphical representation of our problem.

PROGRAM FLOWCHART





L= Length of Section

D= Distance Between Measurements

T= Half table Length

x= Variable Length

y= Deformation

N= Number of Measurement Points

R= Right Support

Q= Left Support

α = Angle in Radians

Δy = Permanent Deformation Required to Straighten the Section

5.3 Program Listing

From the flowchart of paragraph 5.2, we can derive the following program listing. Again, as mentionned, the language is TRS-80 Basic.

```
100 CLS
104 INPUT "PISTON NUMBER  :  ";P : LPRINT  TAB(15)  "PISTON
    NUMBER : " P
106 LPRINT CHR$(138) : LPRINT CHR$(138)
110      INPUT     "LENGTH,SPACING,HALF    TABLE";L,D,T     :
    LPRINT  TAB(15)"LENGTH  =  "L,  TAB(30)"SPACING  =  "D,
    TAB(45)   "HALF  TABLE  =   "T:LPRINT   CHR$(138):LPRINT
    CHR$(138)
111 DIM X(L/D),Y(L/D),DY(L/D)
112 A$="#.####"
120 FOR X=0 TO L STEP D
125 N=X/D
130  INPUT   "EXCENTRICITY   (T.I.R.)";Y(N):LPRINT   TAB(15)
    "EXCENTRICITY (T.I.R.) = "USING A$;Y(N)
135 X(N)=X
140 NEXT X
141 LPRINT CHR$(138)
142 LPRINT CHR$(138)
147  LPRINT  TAB 15)  "PERMANENT  DEFORMATIONS TO STRAIGHTEN
    PART"
148 LPRINT CHR$(138)
149 LPRINT TAB(15) " N"," Q"," R","  DY"
150 FOR N=1 TO (L/D-1)
160 R=N+T/D
170 IF R>L/D THEN R=L/D
180 Q=N-T/D
190 IF Q<0 THEN Q=0
200 IF N>4 THEN Q=4
210 A=2*Y(N)-(Y(N-1)+Y(N+1))
220 DY(N)=((N-Q)*(R-N)*A/(R-Q))/2
226 LPRINT TAB(15)N,Q,R,:LPRINT USING A$;DY(N)
230 NEXT N
240 END
```

5.4 Comparison of Results

The computer program listed in paragraph 5.3 was, as mentioned earlier, developed several months after the graphical piston straightening procedure. We can recall from chapter 3, that the high areas on the pistons, were found by rotating the pistons on a pair of rollers, using a dial indicator along its longitudinal axis and marking the same high areas so that the load could be applied at that point. Once these measurement were taken the graph was drawn, and the graphical analysis gave a number of location which required straightening. The straightening was done by applying a load on the high areas marked earlier and inducing a known permanent deformation to the piston. As we can recall in chapter 4, the original idea was to calculate the deflection required to attain the yield strength and then add the permanent deformation found on our graph. But, since the annealed strength was different for each piston, it was decided, after a few unsuccessful trials, to apply a load to the piston until the required permanent deformation was attained. The reading was taken directly under the loading cylinder on the opposite side of the high area. It was very easy to obtain the calculated permanent deformation (re. figure 4-1).

Unfortunately, the end result was not recorded due to a time factor. The pistons were inspected after straightening but nothing was recorded if the deflection was within plus or minus 0.025 inch. The pistons were all straight to within plus or minus 0.010 inch, with the majority yielding results of straightness within 0.002 inch. Since the pistons had to be finish-machined after the straightening process, the deflection, after straightening could have been as high as 0.025 inch, since we had to machine 0.100 inch on both the inside and outside diameters after heat treatment. The finished part has tolerances of minus 0.001 inch on the outside diameter, plus 0.002 inch on the inside diameter, a concentricity of 0.002 inch and a perpendicularity of 0.001 inch with the end of the piston.

As previously mentioned, the computer and the graphical methods are similar and should therefore yield the same results. In order to compare the two methods, let us take two pistons, number one and number eleven, and compare the results. The graphical method was redone for the two pistons so as to respect the support points used in the computer method calculation, therefore enabling us to compare the accuracy of the two methods. Also note that the computer method starts from station zero and progresses until the last station is straight.

Piston No 1

Support Stations	Δy Graphical	Δy Computer	Computer Support Stations
0 & 18	0.0035	0.0040	0 & 9
0 & 20	0.0115	0.0112	0 & 10
0 & 22	0.0075	0.0076	0 & 11
0 & 24	0.0140	0.0187	0 & 12
8 & 26	-0.0020	-0.0022	4 & 13
8 & 26	0.0030	0.0031	4 & 13
8 & 26	0.0000	0.0000	4 & 13
8 & 26	-0.0080	-0.0089	4 & 13
8 & 26	0.0000	0.0011	4 & 13
8 & 26	0.0000	0.0010	4 & 13
8 & 26	0.0030	0.0023	4 & 13
8 & 26	0.0000	0.0000	4 & 13

Note: Computer supports are expressed in half graphical supports.

Piston No 11

Support Stations	Δy Graphical	Δy Computer	Computer Support Stations
0 & 18	0.0000	0.0004	0 & 9
0 & 20	0.0190	0.0176	0 & 10
0 & 22	0.0040	0.0044	0 & 11
0 & 24	0.0200	0.0200	0 & 12
8 & 26	0.0030	0.0031	4 & 13
8 & 26	0.0070	0.0062	4 & 13
8 & 26	0.0040	0.0040	4 & 13
8 & 26	0.0040	0.0033	4 & 13
8 & 26	0.0090	0.0089	4 & 13
8 & 26	0.0000	0.0000	4 & 13
8 & 26	0.0000	0.0008	4 & 13
8 & 26	-0.0020	-0.0013	4 & 13

Note: Computer supports are expressed in half graphical supports.

5.5 Accuracy

As can be seen by comparison of the graphical and computer method, the results are very similar. The computer method is certainly more accurate because it calculates the permanent deformation from precise deflection readings and it does not take the best line between three or more points, as was done, in certain cases where the difference in slope was small. The computer method is also more precise because it does not require drawing or reading from a graph. Whereas in the graphical method, the accuracy of the results is directly dependent upon the precision with which the graph is done and the accuracy of reading.On the average, it can be seen that the graphical method can yield results within 0.001 inch accuracy, as compared to the computer method (ref. para 5.4). Recalling the results obtained from the straightening of our twenty-four pistons, it can certainly be said that the graphical method is functional, accurate and most importantly very simple.

CHAPTER 6

CONCLUSION

Straightening of material is an important aspect for many companies involved in the production of parts that require straightness to be within specified tolerances.

The object of this technical report was to introduce a new graphical method which allows straightening of sections by finding, directly on a graph of the section, the load application points and the amount of permanent deformation required to bring the section within prescribed tolerances. The method was however only applied to steel cylindrical tubes with variable or unknown tensile strength having planar deflections. During the first stages of the investigation, the use of the stress formulas to calculate Δ yield and then add Δ correction from the graph was considered, but this route was rapidly abandoned due to its non-practicality.

The method described herein is a simple, yet very practical and useful. It allows anyone who has access to a press to straighten parts to 0.002 inch accuracy or better.

The important factor about this method is that it eleminates guessing as to the amount of permanent deformation required or the location where the straightening load is to be applied. By so doing, the chances of straightening the parts properly is greatly increased. As stated in the introduction, this seems to be the first time that any such work is documented. After working on our pistons, this method was applied to other parts which required straightening and the method was just as successful. Of course, this method was only applied to steel parts, and even though it is highly improbable that it would not apply to other metals, the application of the method to materials different from steel would be of interest.Another field of interest would also be the investigation of the method on parts having bends in different planes.

The computer method developed and described in this report was done three years after the incident. It is a very simple yet useful method. Other computer programs can certainly be developed but one major asset from the computer method is its greater accuracy. The accuracy of the graphical method can be affected by the interpretation of the user.

Computerized methods can be of great help to companies which have bent sections, but no qualified personnel to calculate and straighten them. By simply processing the information, anyone within that company, with a little mechanical skill, would be able to follow a step by step procedure given by the computer print out. One might even go as far as making a scale drawing of the part with all the pertinent data. The time saved and the parts salvaged would certainly offset the price of the computer run. Nevertheless, no matter how complex the program can be made, the end results will be that anyone can have access to an easy and reliable method for straightening bent sections.

Just one word of caution is required. If the work is done on high strength parts, it is recommended to fully inspect them after straightening by a non-destructive method and subsequently to have them stress relieved. The non-destructive inspection is recommended due to the possible appearance of cracks after cold work.

BIBLIOGRAPHY AND REFERENCES

1. Sutton, John B. Jr., <u>Modern Straightening Machines for Pipe, Tubes, Bars and sections</u>. Journal of Iron and Steel Engineer, Vol. 54, no. 11, November 1977, p.38

2. Hanson, A. and Parr, Gordon J., <u>The Engineers Guide to Steel</u>. Addison-Wesley Publishing Co. Inc. 1965

3. McGannon, Harold E., editor <u>The Making Shaping and Treating of Steel</u>. United States Steel, Herbick and Held, Pittsburg, Pennsylvania, 1971

4. Bethlehem Steel Corporation <u>Modern Steels and Their Properties</u>. Bethlehem Steel, Bethlehem, Pa. 1967

5. American Society for Metals <u>Source Book on Heat Treating</u>. Vol. 1, The Periodical Publication Department of American Society for Metals, Ohio, 1975

6. American Society for Metals <u>Metals Handbook</u>. 8 ed., Vol. 1 (1961), Vol. 2 (1964)

7. Military Specification MIL-S-5000 Steel, chrome-nickel-molybdenum (E4340) Bars and Reforging Stock.

8. Military Specification MIL-H-6875, Heat Treatment of Steels (Aerospace practice, process for).

9. Oberg, E. and Jones, F.D. — Machinery's Handbook. 17th Edition, The Industrial Press, N.Y. 1964

10. Timoshenko & Young — Elements of Strength of Materials. 5th Edition D. Van Nostrend Co. Inc. New York 1968

11. Timoshenko S.P. Gere J.M. — Mechanics of Materials. D. Van Nostrend Co. Inc. New York 1972

12. Bruhn E.F. — Analysis and Design of Flight Vehicule Structure. Tri State offset Company, Cincinnati, Ohio 1965

13. Fitzgerald, Robert W. — Mechanics of Materials, Addison-Wesley Publishing Co. 1982

14. Horne, M.R. Morris, L.J. — Plastic Design of low rise Frames. Granada Publishing 1981

15. Encyclopaedia Britannica — Heat Treatment. 1972 edition, Vol. 11

APPENDIX ONE

List of references on straightening of sections

COMPUTER SURVEY

1- DA Q7908

RE 0064674

TI Machines for straightening non-circular and thin-walled tubes.

AU Maskileison, A.M.; Rotov, I.S.; Moskalev, V.A.; Kudryashov, B.I.; Levitan, V.YA.

OR All Union Metal Plant Res Inst, USSR

PU Steel USSR V8 N 10 Oct 1978 P574-576

CO SUSRA

KE Rolling mill practice; tubes; manufacture.

SU A535; A632

2- DA Q7803

RE 0021910

TI Modern straightening machines for pipe, tubes, bars and sections. Sutton, John B. Jr.

OR Sutton Eng Co, Pittsburg, PA

PU Iron Steel Eng V54 N 11 Nov 1977 P 38-45

CO IRSEA

KE Straightening machines; rolling mill practice; quality control.

U A535; A601

3- DA Q7702

RE 0013518

TI Pipe straightening machines-2. Selection criteria and design of the most important tube and pipe straightening machines.

AU Fangmeir, Ralf
OR Th. Kieserling & Albrecht, Solingen, Ger
PU Baender Bleche Rohre V 17 N 9 Sep 1976 P 366-372
CO BBROA
KE Straightening machines
SU A535; A601

4- DA Q7701
RE 0006387
TI Straightening machines for tubes and pipes — 1. Straightening principle for conventional cross roll straightening methods for tubes and pipes: origin of the straightening effect.
AU Fangmeir, Ralf
OR Th. Kieserling & Albrecht, Soligen, Ger.
PU Baender Bleche Rohre V 17 N 8 Aug 1976 P 333-337.
CO BBROA
KE Straightening machines; pipe; forming; tubes.
SU A535; A601; A619; A415; A632.

5- DA Q7605
RE 0035390
TI Investigation of the strenghtening of stainless steel tubes in straightening.
AU Vil'yams, O.S.; Ol[illegible]nik, O.V.; Sigal, T.L.
OR Nikopol'South Tubeworks, USSR.
PU Steel USSR V 5 N 6 Jun 1975 P 330-331
CO SUSRA
KE Tubes; Stainless steel
SU A415; A545

6- DA Q7401

RE E003876

TI Selection of cross roll straightening machines for rounds and tubes.

AU Brown, A. N.

OR Bronx Eng Co, Lye, Engl.

PU Iron Steel V 46 N 4 Aug 1973 P 355-360

CO ISTLA

KE Rolling mills; Metal forming; Tubes.

SU 00-A415; 00-A535.

7- DA Q7105

RE E025857

TI Tapered roller bearings set crooked tubes straight.

AU Anon

PU Power Transm Des V 12 N 9 Sept 1970 P 58-9

CO PWTDA

KE Straightening machines; tubes; forming.

SU 00-A601; 00-A619

APPENDIX TWO

Deflection measurements of pistons.

Hardness test of pistons.

PISTON

← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 2" → ← 0.5"

Piston No.														
1	.022	.053	.075	.083	.084	.071	.063	.051	.039	.035	.030	.024	.015	.006
2	.024	.052	.071	.083	.088	.082	.080	.076	.070	.061	.047	.033	.015	.007
3	.022	.051	.086	.103	.123	.133	.148	.142	.142	.124	.103	.070	.037	.008
4	.006	.012	.014	.015	.017	.024	.030	.033	.037	.033	.025	.017	.009	.003
5	.021	.052	.080	.094	.101	.104	.103	.103	.089	.076	.059	.040	.019	.003
6	.025	.054	.061	.103	.117	.123	.123	.119	.109	.096	.074	.052	.027	.005
7	.003	.005	.010	.014	.014	.019	.018	.012	.008	.007	.004	.003	.004	.002
8	.020	.042	.063	.078	.087	.095	.096	.091	.079	.065	.046	.029	.016	.004
9	.020	.047	.069	.079	.083	.085	.083	.084	.078	.068	.057	.040	.022	.006
10	.004	.007	.011	.019	.028	.035	.042	.045	.044	.045	.039	.030	.018	.008
11	.031	.076	.120	.142	.160	.163	.159	.147	.131	.112	.085	.058	.030	.005
12	.027	.070	.104	.124	.134	.131	.123	.108	.089	.071	.044	.029	.015	.005
13	.015	.043	.071	.093	.113	.123	.130	.131	.125	.109	.086	.060	.031	.005
14	.030	.076	.110	.136	.152	.164	.161	.161	.149	.134	.109	.078	.041	.009
15	.013	.034	.047	.055	.053	.047	.037	.026	.023	.015	.011	.009	.007	.001
16	.001	.003	.005	.008	.007	.014	.017	.020	.021	.019	.018	.006	.005	.000
17	.014	.035	.053	.063	.069	.068	.069	.070	.065	.058	.041	.033	.019	.006
18	.008	.017	.029	.042	.053	.060	.065	.068	.065	.060	.047	.034	.018	.006
19	.009	.018	.027	.031	.037	.047	.053	.061	.066	.072	.070	.063	.058	.005
20	.011	.026	.041	.048	.052	.050	.048	.048	.043	.035	.027	.019	.011	.007

Deflection is in inches.

21	.031	.071	.106	.127	.140	.142	.135	.129	.122	.103	.082	.057	.028	.003
22	.011	.027	.043	.055	.061	.060	.062	.063	.064	.058	.045	.035	.021	.005
23	.010	.024	.036	.046	.053	.059	.062	.066	.068	.061	.052	.037	.019	.005
24	.017	.044	.066	.080	.090	.094	.094	.093	.094	.086	.070	.051	.030	.007

Deflection is in inches.

HARDNESS TEST

Piston No.	Rockwell No. ("C" scale)	
1	36	37
2	36	37
3	36	38.5
4	36	35
5	35	38.5
6	32	35.5
7	32	34.5
8	37.5	38.5
9	35.5	33
10	34.5	35.5
11	36	37.5
12	30.5	38.5
13	36	33.5
14	35.5	36
15	33	32
16	34.5	36
17	34.5	37
18	34.5	36
19	40	37
20	36	38
21	38.5	33
22	34.5	36
23	36	35.5
24	36	36

APPENDIX THREE

Graphs of twenty-four pistons showing location, sequence, and amount of permanent deformation required to straighten them.

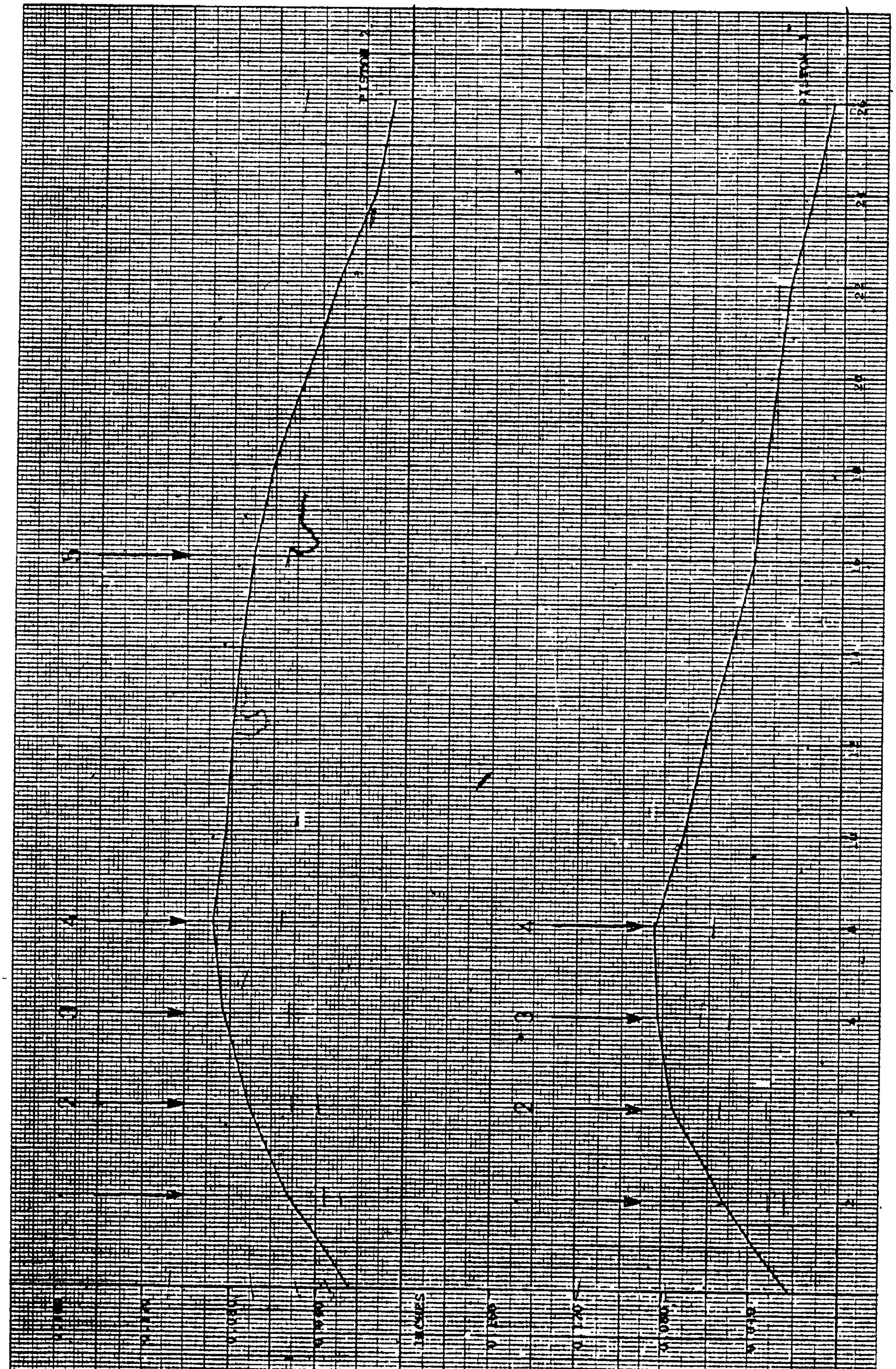
Note: Original size of graph paper was 10" X 15".

PISTON N° 1

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	2"	0.003"
2	0" and 18"	4"	0.011"
3	0" and 22"	6"	0.007"
4	0" and 22"	8"	0.013"

PISTON N° 2

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	2"	0.004"
2	0" and 18"	4"	0.006"
3	0" and 18"	6"	0.007"
4	0" and 22"	8"	0.012"
5	10" and 26"	16"	0.008"

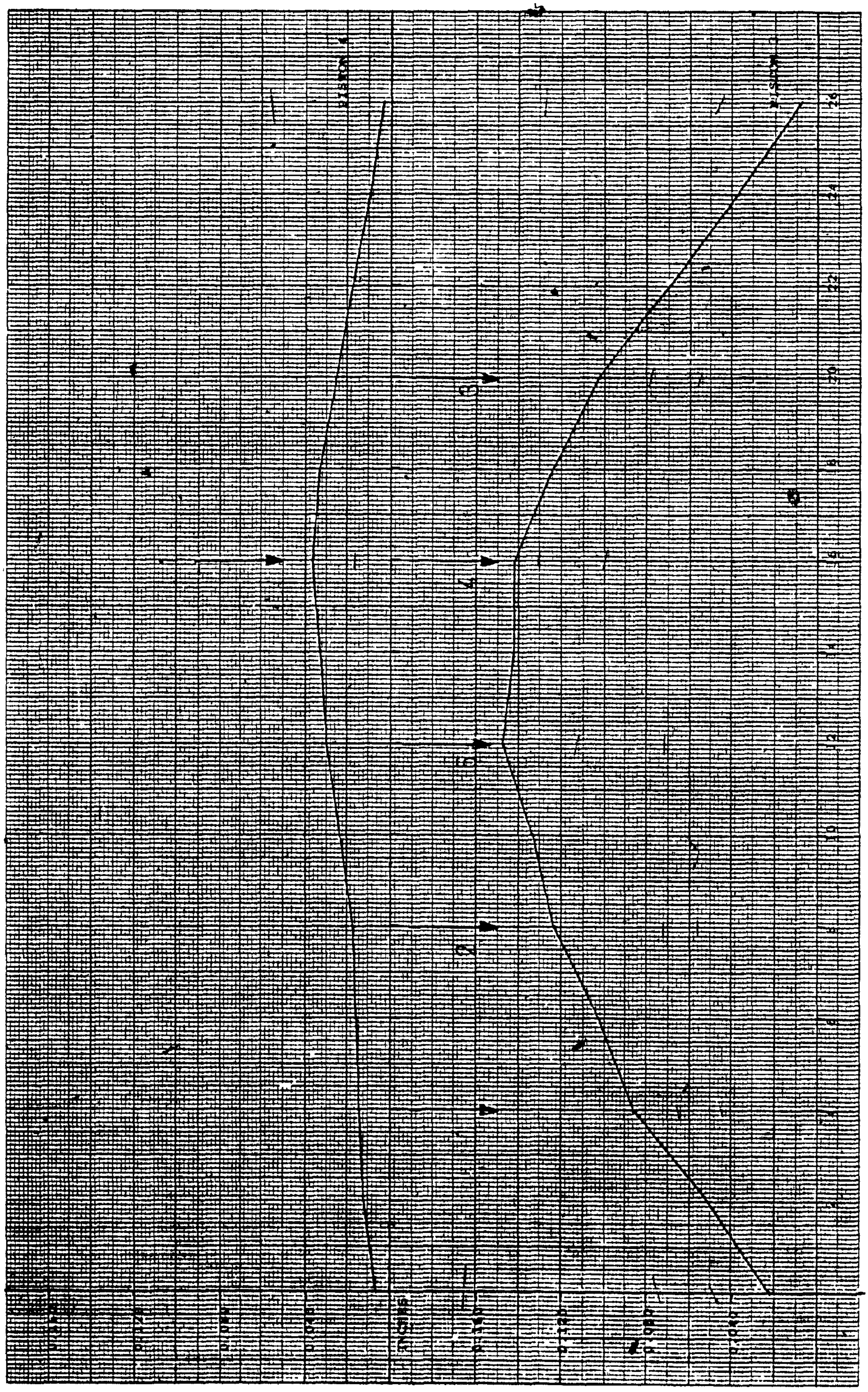


PISTON No 3

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.011"
2	0" and 22"	8"	0.008"
3	10" and 26"	20"	0.011"
4	10" and 26"	16"	0.015"
5	0" and 22"	12"	0.020"

PISTON No 4

Sequence	Support Station	Load Station	Deformation
1	10" and 26"	16"	0.011"

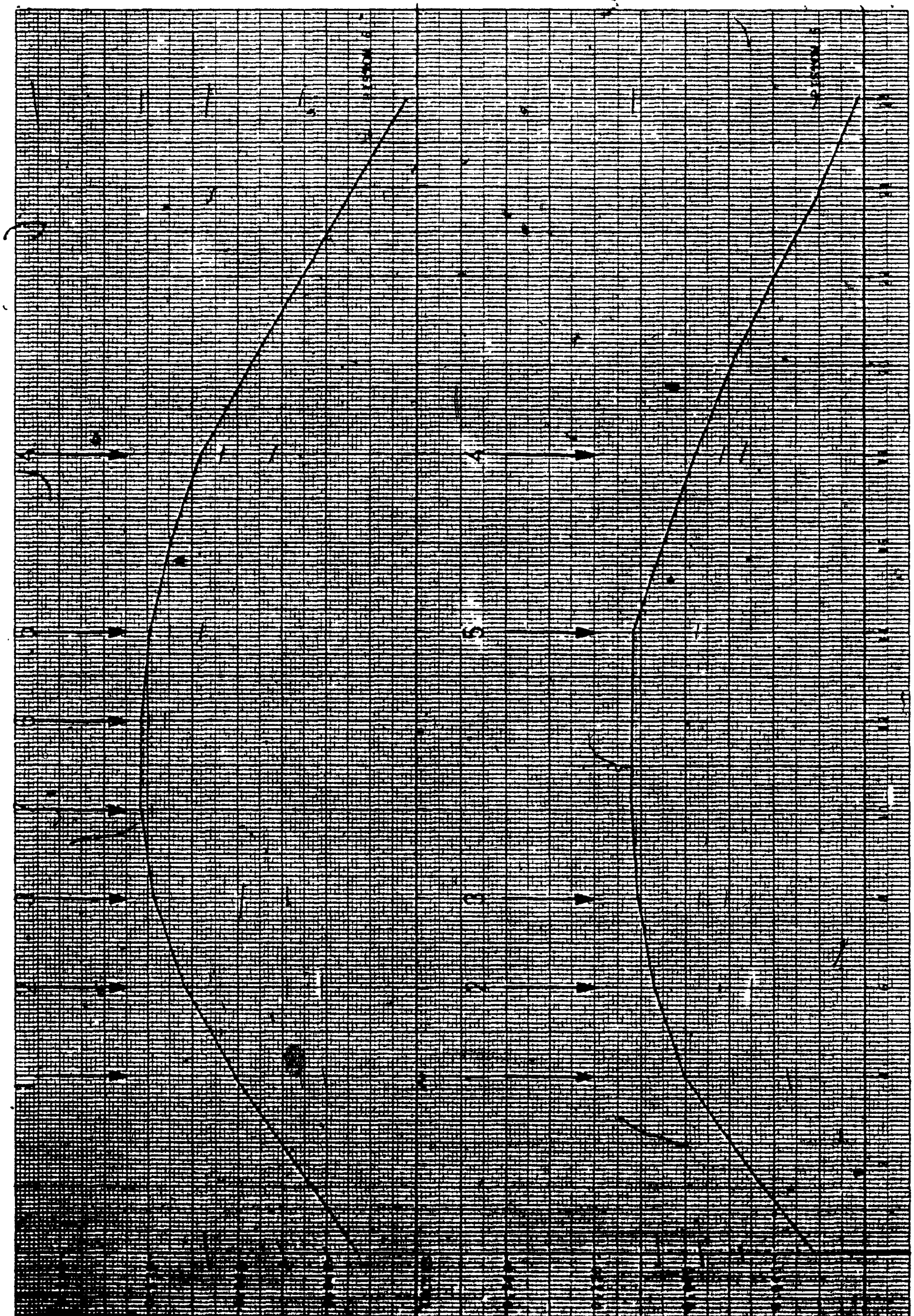


PISTON Nº 5

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.012"
2	0" and 22"	6"	0.008"
3	0" and 22"	8"	0.006"
4	10" and 26"	18"	0.004"
5	8" and 26"	14"	0.014"

PISTON Nº 6

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.005"
2	0" and 22"	6"	0.008"
3	0" and 22"	8"	0.010"
4	10" and 26"	18"	0.011"
5	8" and 26"	14"	0.007"
6	8" and 26"	12"	0.004"
7	8" and 26"	10"	0.002"

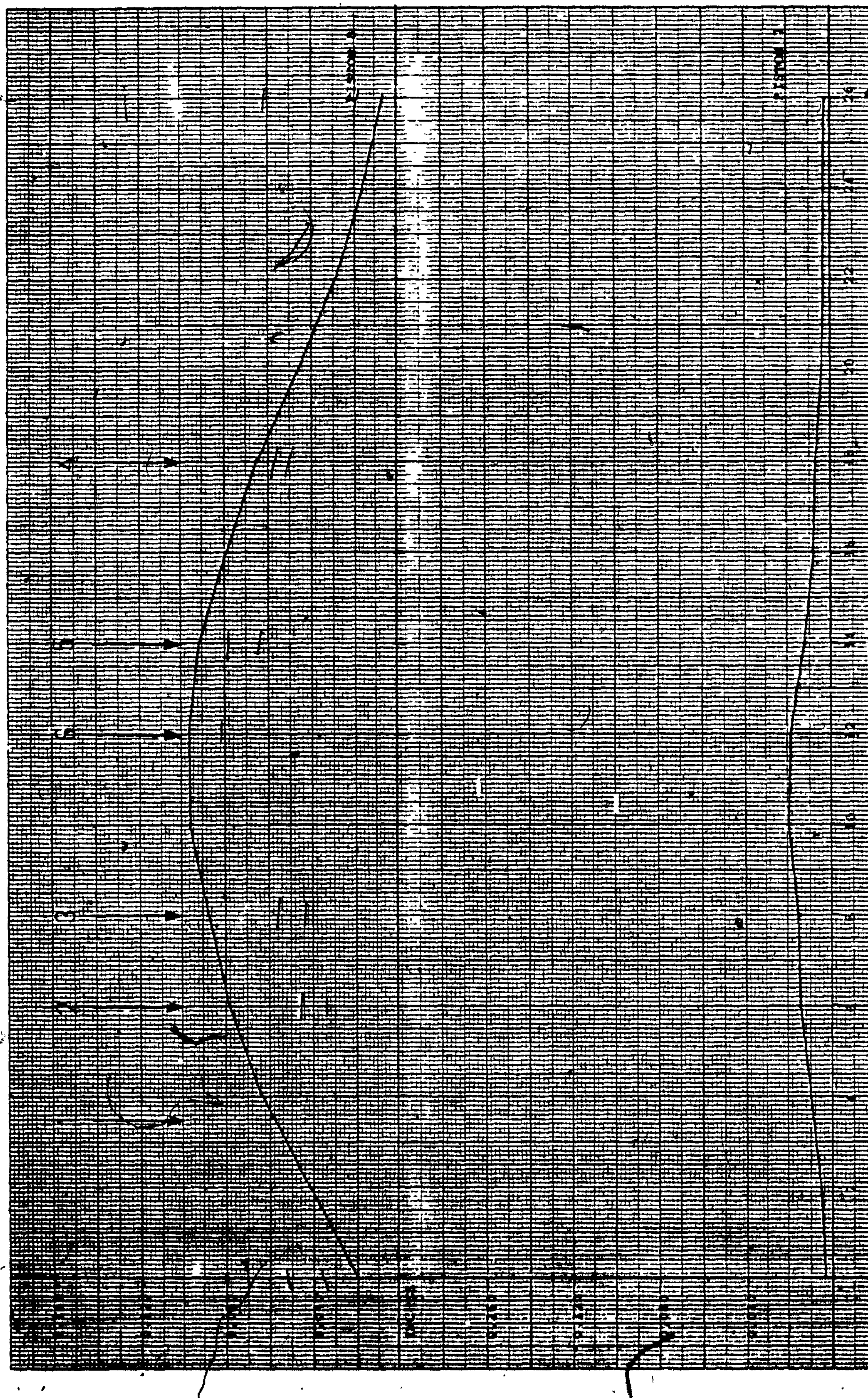


PISTON No 7

Sequence	Support Station	Load Station	Deformation
Use as is.			

PISTON No 8

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.007"
2	0" and 22"	6"	0.006"
3	0" and 22"	8"	0.006"
4	10" and 26"	18"	0.003"
5	8" and 26"	14"	0.007"
6	8" and 26"	12"	0.007"

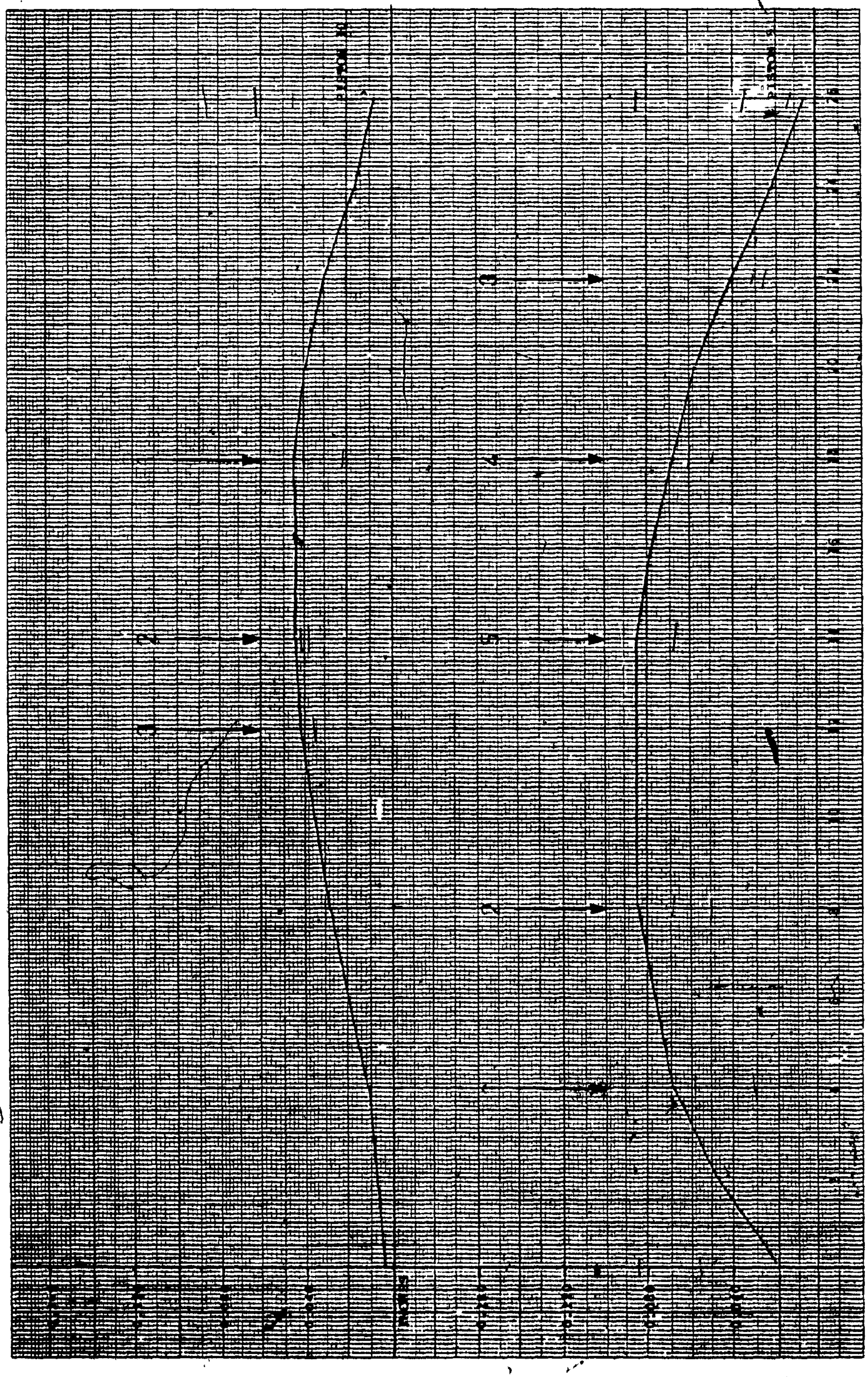


PISTON Nº 9

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.013"
2	0" and 22"	8"	0.010"
3	10" and 25"	22"	0.003"
4	10" and 26"	18"	0.005"
5	8" and 25"	14"	0.008"

PISTON Nº 10

Sequence	Support Station	Load Station	Deformation
1	10" and 25"	18"	0.009"
2	10" and 26"	14"	0.002"
3	8" and 26"	12"	0.003"

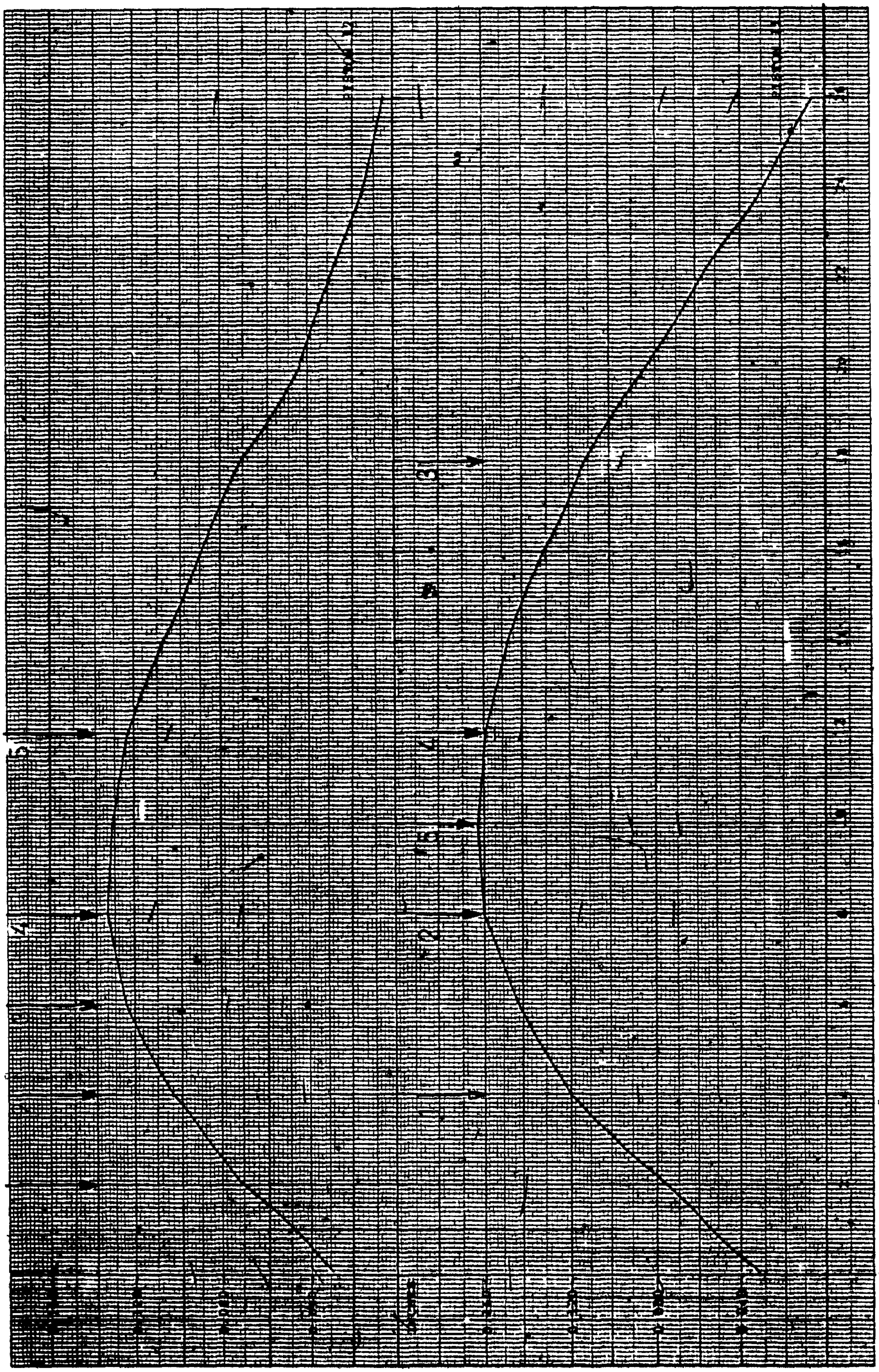


PISTON No 11

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.019"
2	0" and 22"	8"	0.022"
3	8" and 26"	18"	0.009"
4	8" and 26"	12"	0.006"
5	0" and 18"	10"	0.010"

PISTON No 12

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	2"	0.004"
2	0" and 18"	4"	0.011"
3	0" and 22"	5"	0.010"
4	0" and 22"	8"	0.020"
5	8" and 26"	12"	0.009"

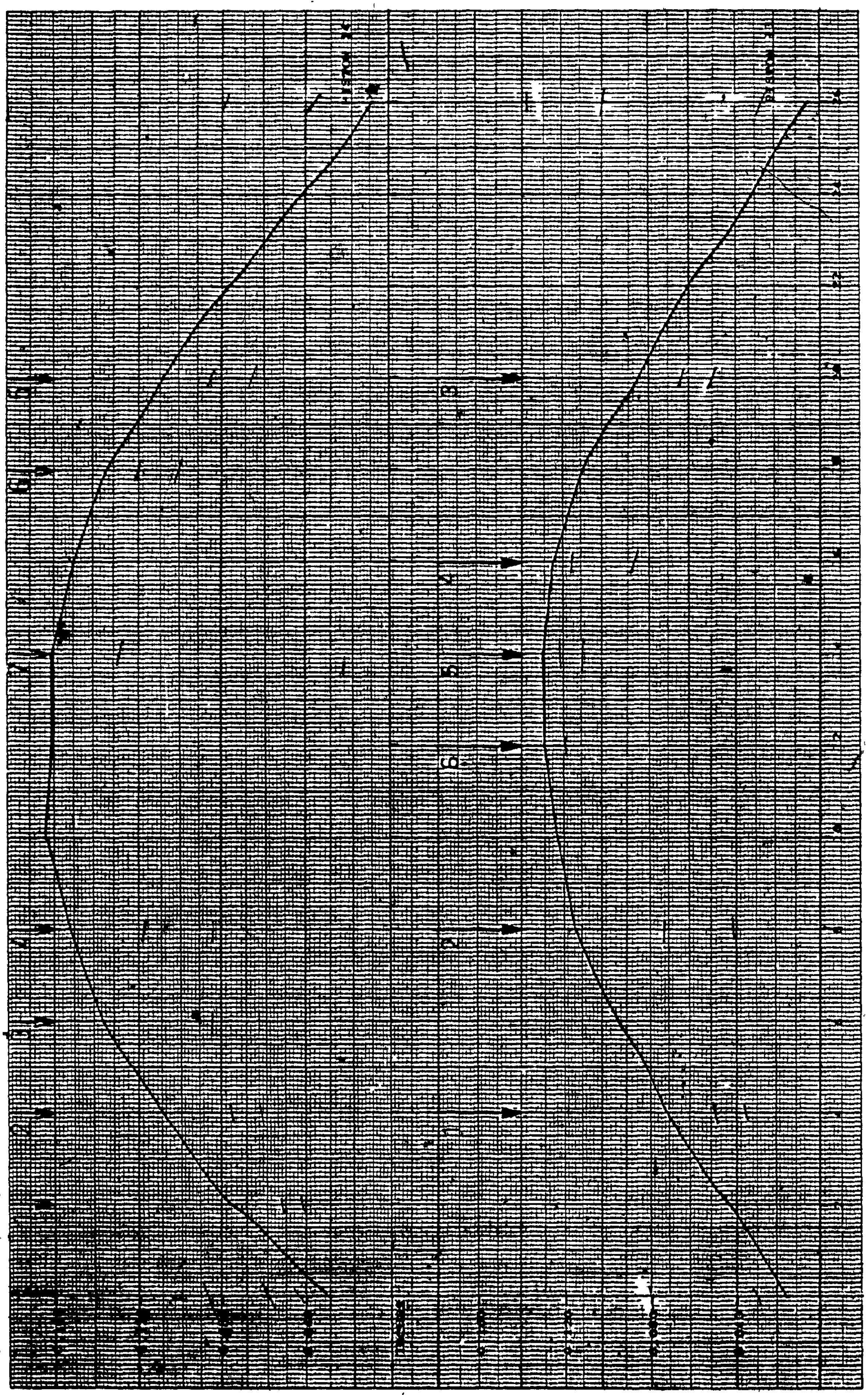


PISTON No 13

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.005"
2	0" and 22"	8"	0.015"
3	10" and 26"	20"	0.007"
4	10" and 25"	16"	0.013"
5	8" and 25"	14"	0.005"
6	8" and 26"	12"	0.006"

PISTON No. 14

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	2"	0.005"
2	0" and 18"	4"	0.006"
3	0" and 22"	6"	0.010"
4	0" and 22"	8"	0.018"
5	10" and 26"	20"	0.008"
6	10" and 26"	18"	0.010"
7	8" and 25"	14"	0.017"

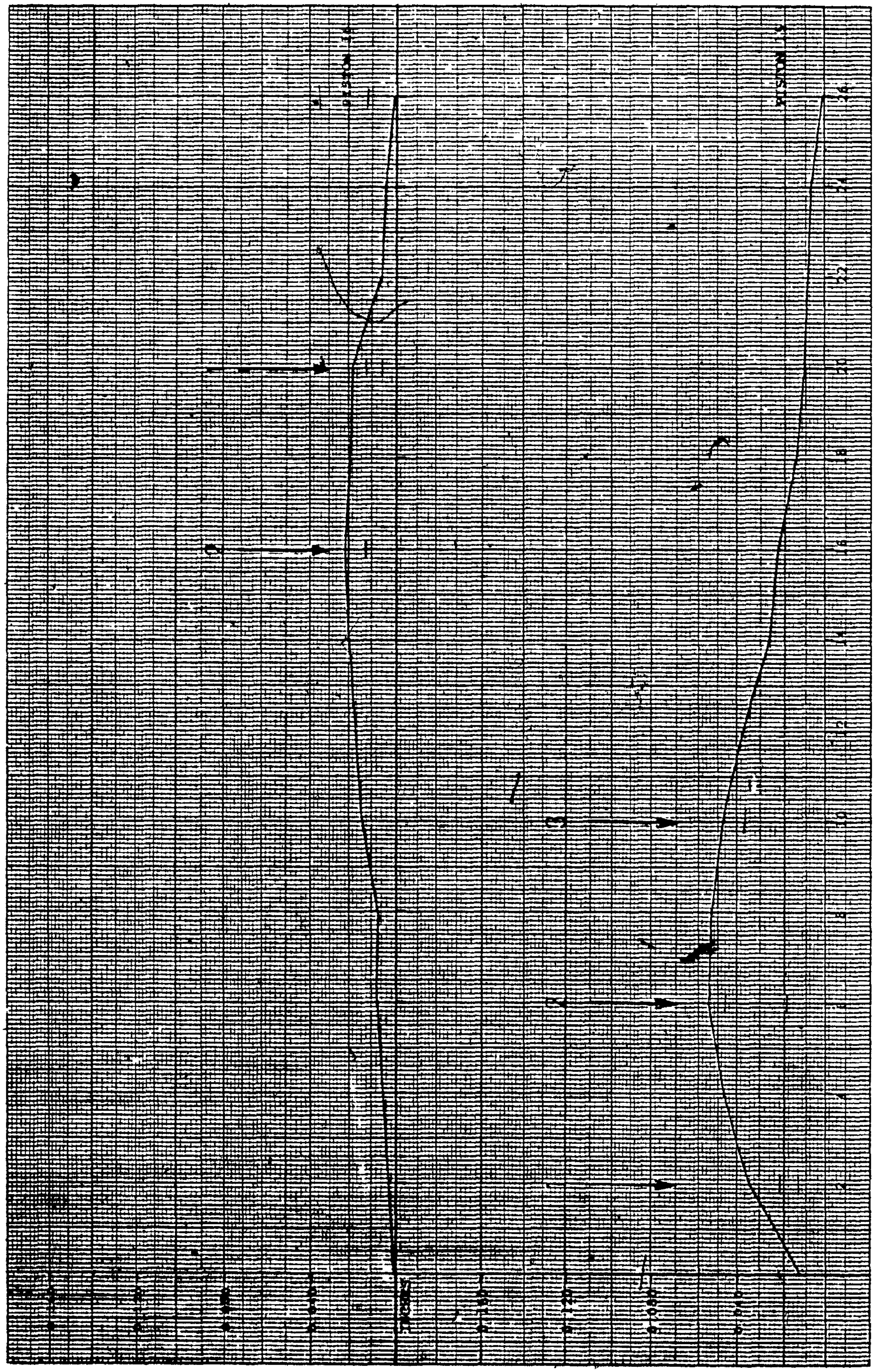


PISTON No 15

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	2"	0.004"
2	0" and 22"	5"	0.013"
3	0" and 22"	10"	0.005"

PISTON No 16

Sequence	Support Station	Load Station	Deformation
1	10" and 25"	20"	0.003"
2	10" and 25"	16"	0.005"

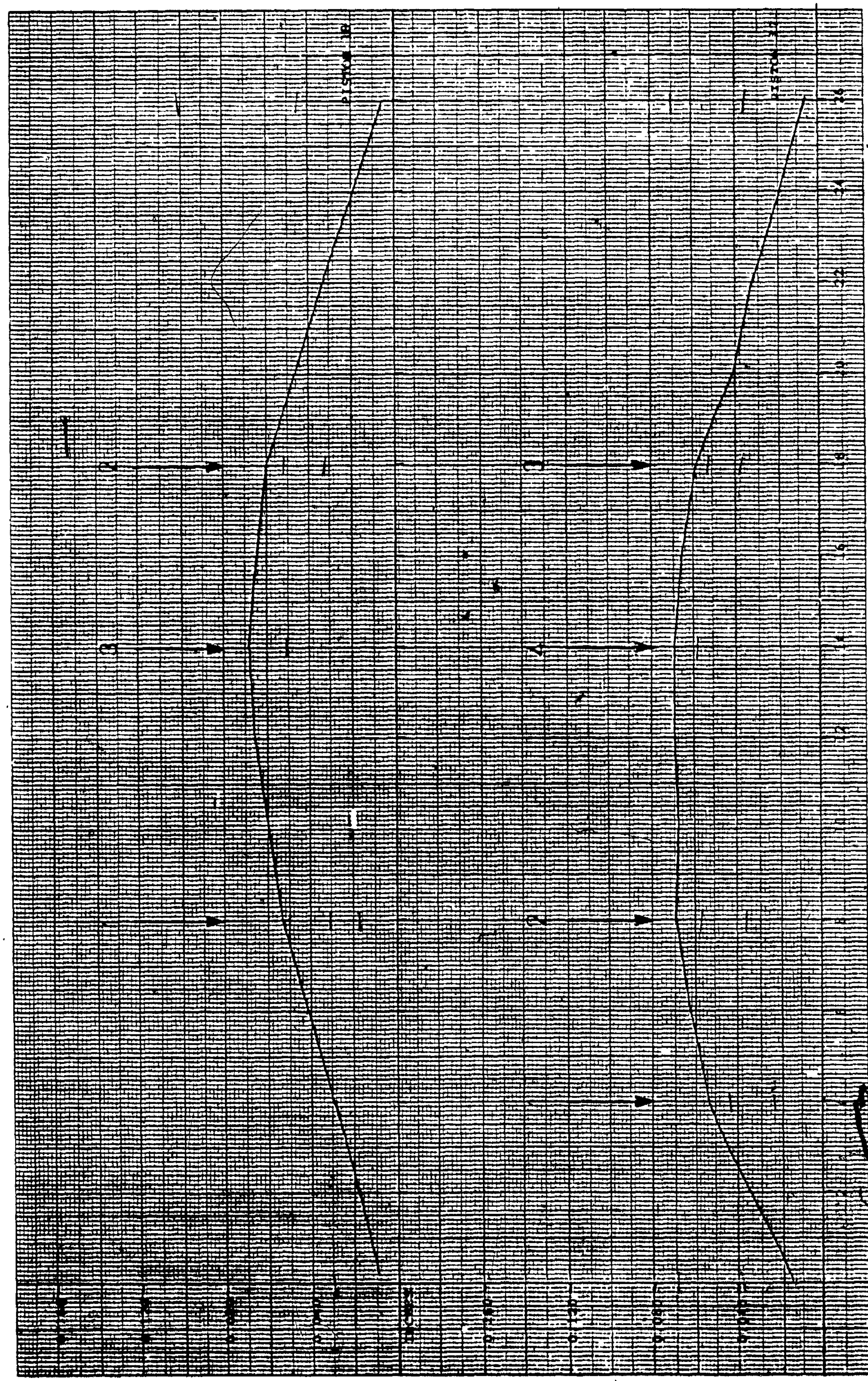


PISTON Nº 17

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.010"
2	0" and 22"	8"	0.010"
3	10" and 25"	18"	0.007"
4	8" and 26"	14"	0.006"

PISTON Nº 18

Sequence	Support Station	Load Station	Deformation
1	0" and 22"	8"	0.008"
2	10" and 26"	18"	0.010"
3	8" and 26"	14"	0.008"

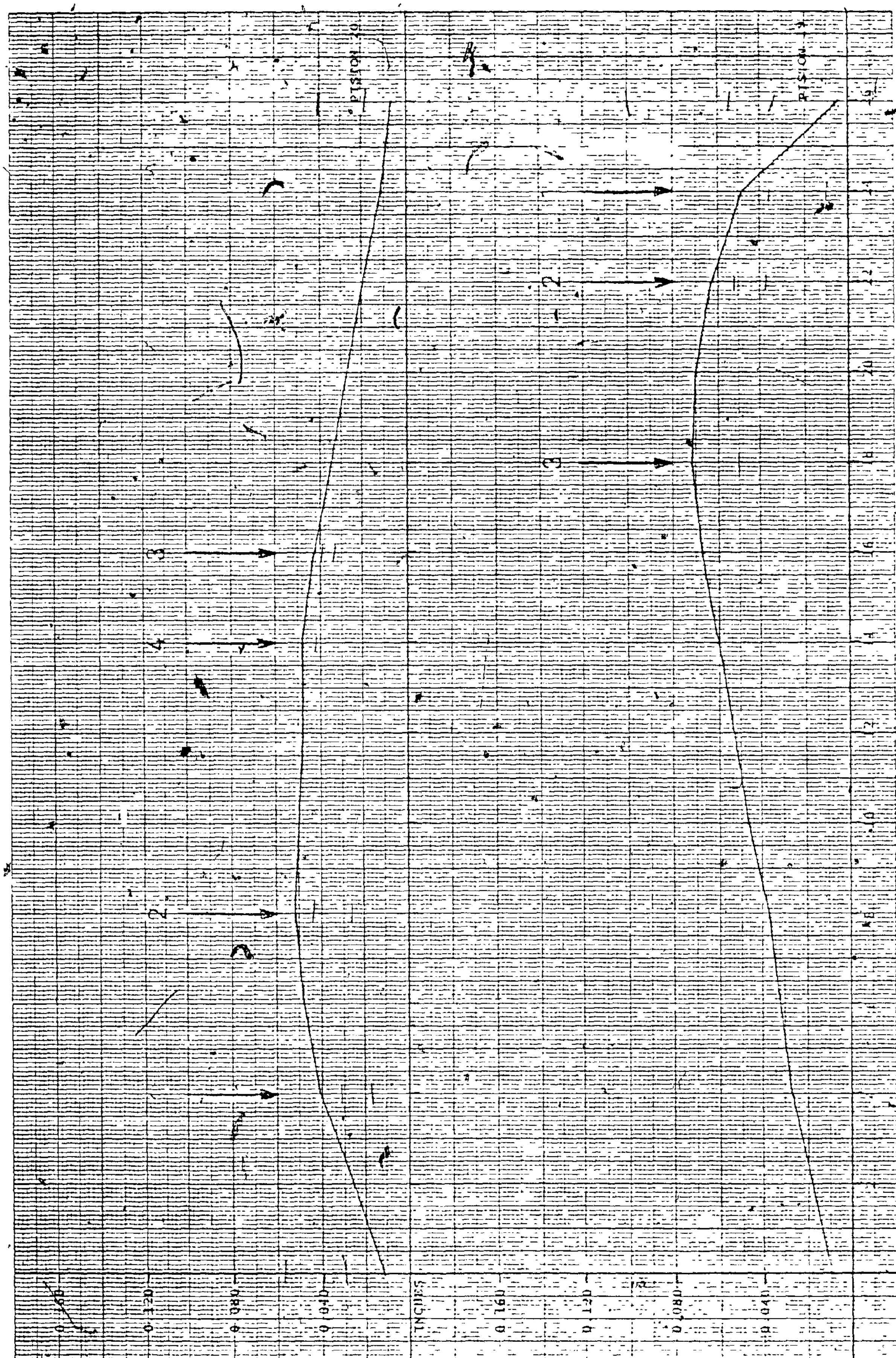


PISTON Nº 19

Sequence	Support Station	Load Station	Deformation
1	10" and 26"	24"	0.013"
2	10" and 26"	22"	0.007"
3	10" and 26"	18"	0.011"

PISTON Nº 20

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.008"
2	0" and 22"	8"	0.009"
3	10" and 26"	16"	0.003"
4	10" and 26"	14"	0.003"

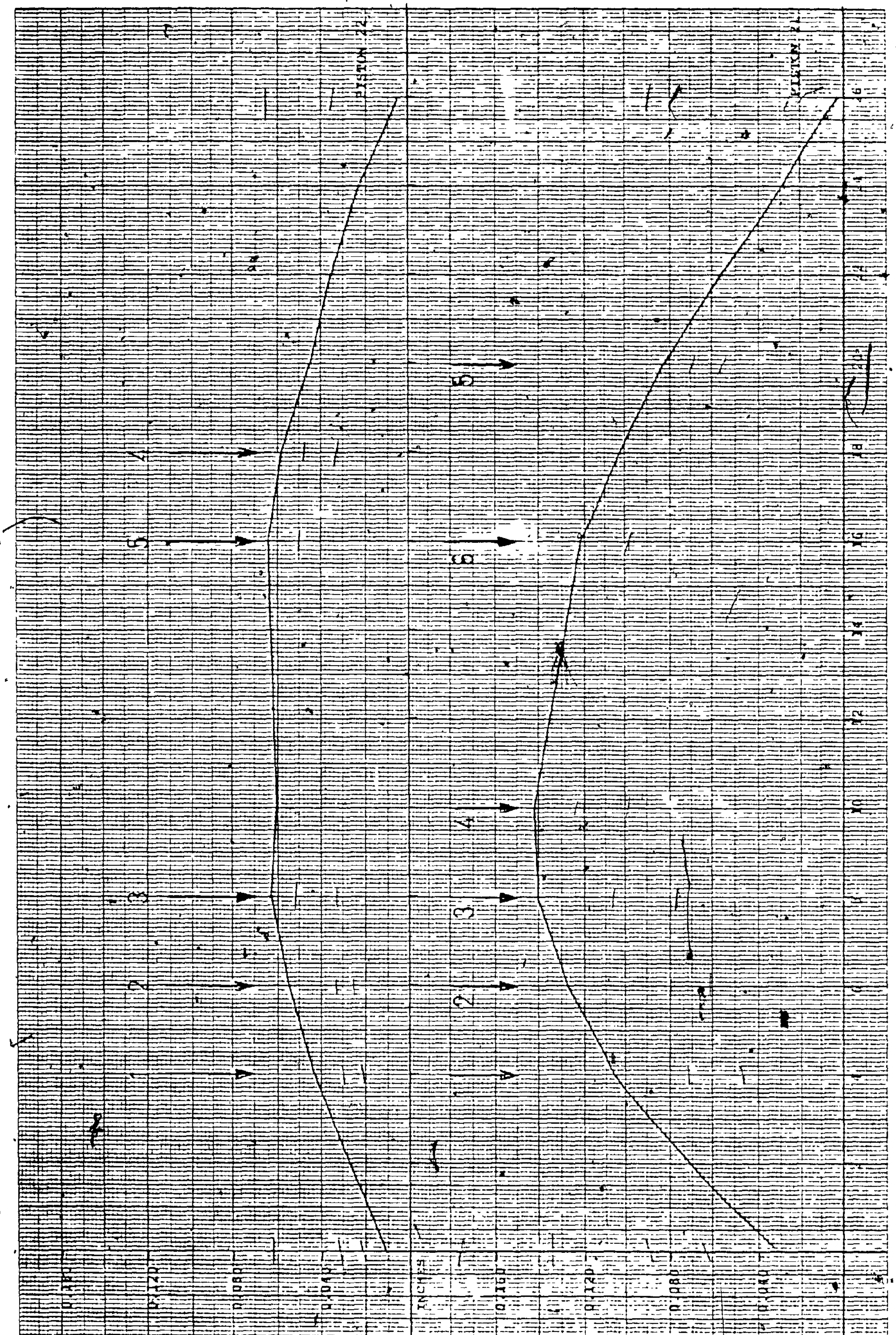

PISTON
PISTON
INCHES
0.160
0.120
0.080
0.040
0.160
0.120
0.080
0.040

PISTON Nº 21

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.013"
2	0" and 22"	6"	0.009"
3	0" and 22"	8"	0.014"
4	0" and 22"	10"	0.013"
5	10" and 25"	20"	0.005"
5	10" and 25"	16"	0.012"

PISTON Nº 22

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.003"
2	0" and 22"	6"	0.004"
3	0" and 22"	8"	0.010"
4	10" and 25"	18"	0.007"
5	10" and 25"	15"	0.007"

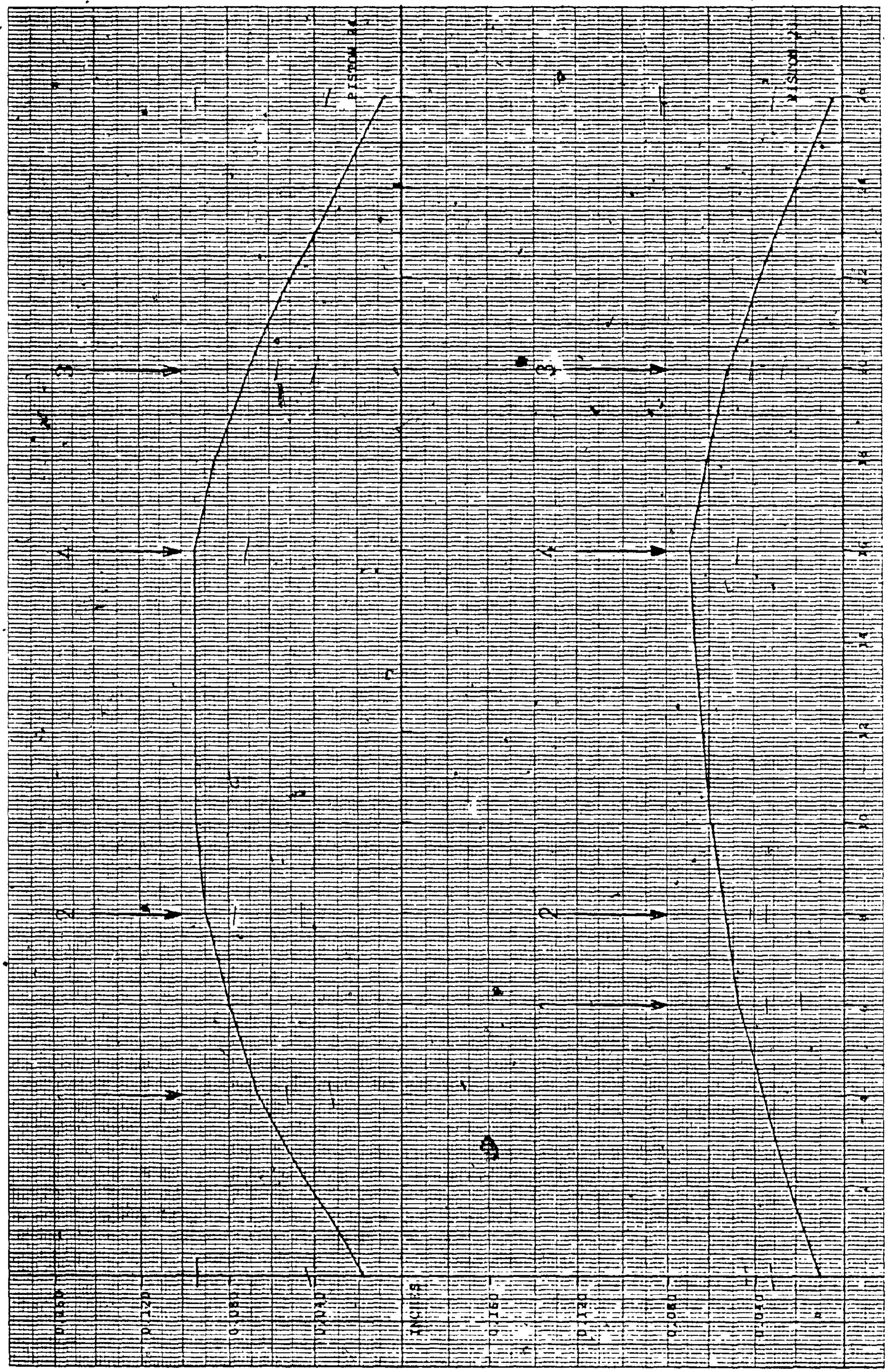


PISTON No 23

Sequence	Support Station	Load Station	Deformation
1	0" and 22"	6"	0.008"
2	0" and 22"	8"	0.004"
3	10" and 25"	20"	0.008"
4	10" and 25"	15"	0.010"

PISTON No 24

Sequence	Support Station	Load Station	Deformation
1	0" and 18"	4"	0.010"
2	0" and 22"	8"	0.015"
3	10" and 25"	20"	0.008"
4	10" and 25"	15"	0.012"


0.160
0.120
0.080
0.040
INCHES
0.160
0.120
0.080
0.040

APPENDIX FOUR

Computer print out of results using the computer method.

PISTON NUMBER : 1

LENGTH = 26   SPACING = 2   HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0220
EXCENTRICITY (T.I.R.) = 0.0530
EXCENTRICITY (T.I.R.) = 0.0750
EXCENTRICITY (T.I.R.) = 0.0830
EXCENTRICITY (T.I.R.) = 0.0840
EXCENTRICITY (T.I.R.) = 0.0710
EXCENTRICITY (T.I.R.) = 0.0630
EXCENTRICITY (T.I.R.) = 0.0510
EXCENTRICITY (T.I.R.) = 0.0390
EXCENTRICITY (T.I.R.) = 0.0350
EXCENTRICITY (T.I.R.) = 0.0300
EXCENTRICITY (T.I.R.) = 0.0240
EXCENTRICITY (T.I.R.) = 0.0150
EXCENTRICITY (T.I.R.) = 0.0060

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0040
2	0	10	0.0112
3	0	11	0.0076
4	0	12	0.0187
5	4	13	-.0022
6	4	13	0.0031
7	4	13	-.0800
8	4	13	-.0089
9	4	13	0.0011
10	4	13	0.0010
11	4	13	0.0023
12	4	13	0.0000

PISTON NUMBER : 2

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0240
EXCENTRICITY (T.I.R.) = 0.0520
EXCENTRICITY (T.I.R.) = 0.0710
EXCENTRICITY (T.I.R.) = 0.0830
EXCENTRICITY (T.I.R.) = 0.0880
EXCENTRICITY (T.I.R.) = 0.0820
EXCENTRICITY (T.I.R.) = 0.0800
EXCENTRICITY (T.I.R.) = 0.0760
EXCENTRICITY (T.I.R.) = 0.0700
EXCENTRICITY (T.I.R.) = 0.0610
EXCENTRICITY (T.I.R.) = 0.0470
EXCENTRICITY (T.I.R.) = 0.0330
EXCENTRICITY (T.I.R.) = 0.0150
EXCENTRICITY (T.I.R.) = 0.0070

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0040
2	0	10	0.0056
3	0	11	0.0076
4	0	12	0.0147
5	4	13	-.0018
6	4	13	0.0016
7	4	13	0.0020
8	4	13	0.0033
9	4	13	0.0056
10	4	13	-.0000
11	4	13	0.0031
12	4	13	-.0044

PISTON NUMBER : 3

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0220
EXCENTRICITY (T.I.R.) = 0.0510
EXCENTRICITY (T.I.R.) = 0.0860
EXCENTRICITY (T.I.R.) = 0.1030
EXCENTRICITY (T.I.R.) = 0.1230
EXCENTRICITY (T.I.R.) = 0.1330
EXCENTRICITY (T.I.R.) = 0.1480
EXCENTRICITY (T.I.R.) = 0.1420
EXCENTRICITY (T.I.R.) = 0.1420
EXCENTRICITY (T.I.R.) = 0.1240
EXCENTRICITY (T.I.R.) = 0.1030
EXCENTRICITY (T.I.R.) = 0.0700
EXCENTRICITY (T.I.R.) = 0.0370
EXCENTRICITY (T.I.R.) = 0.0080

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	-.0027
2	0	10	0.0144
3	0	11	-.0033
4	0	12	0.0133
5	4	13	-.0022
6	4	13	0.0163
7	4	13	-.0060
8	4	13	0.0200
9	4	13	0.0033
10	4	13	0.0120
11	4	13	0.0000
12	4	13	-.0018

PISTON NUMBER : 4

LENGTH = 26 SPACING = 2 . HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0060
EXCENTRICITY (T.I.R.) = 0.0120
EXCENTRICITY (T.I.R.) = 0.0140
EXCENTRICITY (T.I.R.) = 0.0150
EXCENTRICITY (T.I.R.) = 0.0170
EXCENTRICITY (T.I.R.) = 0.0240
EXCENTRICITY (T.I.R.) = 0.0300
EXCENTRICITY (T.I.R.) = 0.0330
EXCENTRICITY (T.I.R.) = 0.0370
EXCENTRICITY (T.I.R.) = 0.0330
EXCENTRICITY (T.I.R.) = 0.0250
EXCENTRICITY (T.I.R.) = 0.0170
EXCENTRICITY (T.I.R.) = 0.0090
EXCENTRICITY (T.I.R.) = 0.0030

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0018
2	0	10	0.0008
3	0	11	-.0011
4	0	12	-.0067
5	4	13	0.0004
6	4	13	0.0023
7	4	13	-.0010
8	4	13	0.0089
9	4	13	0.0044
10	4	13	0.0000
11	4	13	0.0000
12	4	13	-.0009

PISTON NUMBER : 5

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0210
EXCENTRICITY (T.I.R.) = 0.0520
EXCENTRICITY (T.I.R.) = 0.0800
EXCENTRICITY (T.I.R.) = 0.0940
EXCENTRICITY (T.I.R.) = 0.1010
EXCENTRICITY (T.I.R.) = 0.1040
EXCENTRICITY (T.I.R.) = 0.1030
EXCENTRICITY (T.I.R.) = 0.1030
EXCENTRICITY (T.I.R.) = 0.0890
EXCENTRICITY (T.I.R.) = 0.0760
EXCENTRICITY (T.I.R.) = 0.0590
EXCENTRICITY (T.I.R.) = 0.0400
EXCENTRICITY (T.I.R.) = 0.0190
EXCENTRICITY (T.I.R.) = 0.0030

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0013
2	0	10	0.0112
3	0	11	0.0076
4	0	12	0.0053
5	4	13	0.0018
6	4	13	-.0008
7	4	13	0.0140
8	4	13	-.0011
9	4	13	0.0044
10	4	13	0.0020
11	4	13	0.0016
12	4	13	-.0022

PISTON NUMBER : 6

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0250
EXCENTRICITY (T.I.R.) = 0.0540
EXCENTRICITY (T.I.R.) = 0.0810
EXCENTRICITY (T.I.R.) = 0.1030
EXCENTRICITY (T.I.R.) = 0.1170
EXCENTRICITY (T.I.R.) = 0.1230
EXCENTRICITY (T.I.R.) = 0.1230
EXCENTRICITY (T.I.R.) = 0.1190
EXCENTRICITY (T.I.R.) = 0.1090
EXCENTRICITY (T.I.R.) = 0.0960
EXCENTRICITY (T.I.R.) = 0.0740
EXCENTRICITY (T.I.R.) = 0.0520
EXCENTRICITY (T.I.R.) = 0.0270
EXCENTRICITY (T.I.R.) = 0.0050

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0009
2	0	10	0.0040
3	0	11	0.0087
4	0	12	0.0107
5	4	13	0.0027
6	4	13	0.0031
7	4	13	0.0060
8	4	13	0.0033
9	4	13	0.0100
10	4	13	0.0000
11	4	13	0.0023
12	4	13	-.0013

PISTON NUMBER : 7

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0030
EXCENTRICITY (T.I.R.) = 0.0050
EXCENTRICITY (T.I.R.) = 0.0100
EXCENTRICITY (T.I.R.) = 0.0140
EXCENTRICITY (T.I.R.) = 0.0140
EXCENTRICITY (T.I.R.) = 0.0190
EXCENTRICITY (T.I.R.) = 0.0180
EXCENTRICITY (T.I.R.) = 0.0120
EXCENTRICITY (T.I.R.) = 0.0080
EXCENTRICITY (T.I.R.) = 0.0070
EXCENTRICITY (T.I.R.) = 0.0040
EXCENTRICITY (T.I.R.) = 0.0030
EXCENTRICITY (T.I.R.) = 0.0040
EXCENTRICITY (T.I.R.) = 0.0020

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	-.0013
2	0	10	0.0008
3	0	11	0.0044
4	0	12	-.0067
5	4	13	0.0027
6	4	13	0.0039
7	4	13	-.0020
8	4	13	-.0033
9	4	13	0.0022
10	4	13	-.0020
11	4	13	-.0016
12	4	13	0.0013

PISTON NUMBER : 8

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0200
EXCENTRICITY (T.I.R.) = 0.0420
EXCENTRICITY (T.I.R.) = 0.0630
EXCENTRICITY (T.I.R.) = 0.0780
EXCENTRICITY (T.I.R.) = 0.0870
EXCENTRICITY (T.I.R.) = 0.0950
EXCENTRICITY (T.I.R.) = 0.0960
EXCENTRICITY (T.I.R.) = 0.0910
EXCENTRICITY (T.I.R.) = 0.0790
EXCENTRICITY (T.I.R.) = 0.0650
EXCENTRICITY (T.I.R.) = 0.0460
EXCENTRICITY (T.I.R.) = 0.0290
EXCENTRICITY (T.I.R.) = 0.0160
EXCENTRICITY (T.I.R.) = 0.0040

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0004
2	0	10	0.0048
3	0	11	0.00[illegible]5
4	0	12	0.0013
5	4	13	0.0031
6	4	13	0.0047
7	4	13	0.0070
8	4	13	0.0022
9	4	13	0.0056
10	4	13	-.0020
11	4	13	-.0031
12	4	13	-.0004

PISTON NUMBER : 9

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0200
EXCENTRICITY (T.I.R.) = 0.0470
EXCENTRICITY (T.I.R.) = 0.0690
EXCENTRICITY (T.I.R.) = 0.0790
EXCENTRICITY (T.I.R.) = 0.0830
EXCENTRICITY (T.I.R.) = 0.0850
EXCENTRICITY (T.I.R.) = 0.0830
EXCENTRICITY (T.I.R.) = 0.0840
EXCENTRICITY (T.I.R.) = 0.0780
EXCENTRICITY (T.I.R.) = 0.0680
EXCENTRICITY (T.I.R.) = 0.0570
EXCENTRICITY (T.I.R.) = 0.0400
EXCENTRICITY (T.I.R.) = 0.0220
EXCENTRICITY (T.I.R.) = 0.0060

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0022
2	0	10	0.0096
3	0	11	0.0065
4	0	12	0.0027
5	4	13	0.0018
6	4	13	-.0023
7	4	13	0.0070
8	4	13	0.0044
9	4	13	0.0011
10	4	13	0.0060
11	4	13	0.0008
12	4	13	-.0009

PISTON NUMBER : 10

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0040
EXCENTRICITY (T.I.R.) = 0.0070
EXCENTRICITY (T.I.R.) = 0.0110
EXCENTRICITY (T.I.R.) = 0.0190
EXCENTRICITY (T.I.R.) = 0.0280
EXCENTRICITY (T.I.R.) = 0.0350
EXCENTRICITY (T.I.R.) = 0.0420
EXCENTRICITY (T.I.R.) = 0.0450
EXCENTRICITY (T.I.R.) = 0.0440
EXCENTRICITY (T.I.R.) = 0.0450
EXCENTRICITY (T.I.R.) = 0.0390
EXCENTRICITY (T.I.R.) = 0.0300
EXCENTRICITY (T.I.R.) = 0.0180
EXCENTRICITY (T.I.R.) = 0.0080

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	-.0004
2	0	10	-.0032
3	0	11	-.0011
4	0	12	0.0027
5	4	13	0.0000
6	4	13	0.0031
7	4	13	0.0040
8	4	13	-.0022
9	4	13	0.0078
10	4	13	0.0030
11	4	13	0.0023
12	4	13	-.0009

PISTON NUMBER : 11

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0310
EXCENTRICITY (T.I.R.) = 0.0760
EXCENTRICITY (T.I.R.) = 0.1200
EXCENTRICITY (T.I.R.) = 0.1420
EXCENTRICITY (T.I.R.) = 0.1600
EXCENTRICITY (T.I.R.) = 0.1630
EXCENTRICITY (T.I.R.) = 0.1590
EXCENTRICITY (T.I.R.) = 0.1470
EXCENTRICITY (T.I.R.) = 0.1310
EXCENTRICITY (T.I.R.) = 0.1120
EXCENTRICITY (T.I.R.) = 0.0850
EXCENTRICITY (T.I.R.) = 0.0580
EXCENTRICITY (T.I.R.) = 0.0300
EXCENTRICITY (T.I.R.) = 0.0050

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0004
2	0	10	0.0176
3	0	11	0.0044
4	0	12	0.0200
5	4	13	0.0031
6	4	13	0.0062
7	4	13	0.0040
8	4	13	0.0033
9	4	13	0.0089
10	4	13	-.0000
11	4	13	0.0008
12	4	13	-.0013

PISTON NUMBER : 12

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0270
EXCENTRICITY (T.I.R.) = 0.0700
EXCENTRICITY (T.I.R.) = 0.1040
EXCENTRICITY (T.I.R.) = 0.1240
EXCENTRICITY (T.I.R.) = 0.1340
EXCENTRICITY (T.I.R.) = 0.1310
EXCENTRICITY (T.I.R.) = 0.1230
EXCENTRICITY (T.I.R.) = 0.1080
EXCENTRICITY (T.I.R.) = 0.0890
EXCENTRICITY (T.I.R.) = 0.0710
EXCENTRICITY (T.I.R.) = 0.0440
EXCENTRICITY (T.I.R.) = 0.0290
EXCENTRICITY (T.I.R.) = 0.0150
EXCENTRICITY (T.I.R.) = 0.0050

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0040
2	0	10	0.0112
3	0	11	0.0109
4	0	12	0.0173
5	4	13	0.0022
6	4	13	0.0054
7	4	13	0.0040
8	4	13	-.0011
9	4	13	0.0100
10	4	13	-.0120
11	4	13	-.0008
12	4	13	-.0018

PISTON NUMBER : 13

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0150
EXCENTRICITY (T.I.R.) = 0.0430
EXCENTRICITY (T.I.R.) = 0.0710
EXCENTRICITY (T.I.R.) = 0.0930
EXCENTRICITY (T.I.R.) = 0.1130
EXCENTRICITY (T.I.R.) = 0.1230
EXCENTRICITY (T.I.R.) = 0.1300
EXCENTRICITY (T.I.R.) = 0.1310
EXCENTRICITY (T.I.R.) = 0.1250
EXCENTRICITY (T.I.R.) = 0.1090
EXCENTRICITY (T.I.R.) = 0.0860
EXCENTRICITY (T.I.R.) = 0.0600
EXCENTRICITY (T.I.R.) = 0.0310
EXCENTRICITY (T.I.R.) = 0.0050

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0000
2	0	10	0.0048
3	0	11	0.0022
4	0	12	0.0133
5	4	13	0.0013
6	4	13	0.0047
7	4	13	0.0070
8	4	13	0.0111
9	4	13	0.0078
10	4	13	0.0030
11	4	13	0.0023
12	4	13	-.0013

PISTON NUMBER : 14

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0300
EXCENTRICITY (T.I.R.) = 0.0760
EXCENTRICITY (T.I.R.) = 0.1100
EXCENTRICITY (T.I.R.) = 0.1360
EXCENTRICITY (T.I.R.) = 0.1520
EXCENTRICITY (T.I.R.) = 0.1640
EXCENTRICITY (T.I.R.) = 0.1610
EXCENTRICITY (T.I.R.) = 0.1610
EXCENTRICITY (T.I.R.) = 0.1490
EXCENTRICITY (T.I.R.) = 0.1340
EXCENTRICITY (T.I.R.) = 0.1090
EXCENTRICITY (T.I.R.) = 0.0780
EXCENTRICITY (T.I.R.) = 0.0410
EXCENTRICITY (T.I.R.) = 0.0090

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0053
2	0	10	0.0064
3	0	11	0.0109
4	0	12	0.0053
5	4	13	0.0067
6	4	13	-.0023
7	4	13	0.0120
8	4	13	0.0033
9	4	13	0.0111
10	4	13	0.0060
11	4	13	0.0047
12	4	13	-.0022

PISTON NUMBER : 15

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0130
EXCENTRICITY (T.I.R.) = 0.0340
EXCENTRICITY (T.I.R.) = 0.0470
EXCENTRICITY (T.I.R.) = 0.0550
EXCENTRICITY (T.I.R.) = 0.0530
EXCENTRICITY (T.I.R.) = 0.0470
EXCENTRICITY (T.I.R.) = 0.0370
EXCENTRICITY (T.I.R.) = 0.0260
EXCENTRICITY (T.I.R.) = 0.0230
EXCENTRICITY (T.I.R.) = 0.0150
EXCENTRICITY (T.I.R.) = 0.0110
EXCENTRICITY (T.I.R.) = 0.0090
EXCENTRICITY (T.I.R.) = 0.0070
EXCENTRICITY (T.I.R.) = 0.0010

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0036
2	0	10	0.0040
3	0	11	0.0109
4	0	12	0.0053
5	4	13	0.0018
6	4	13	0.0008
7	4	13	-.0080
8	4	13	0.0056
9	4	13	-.0044
10	4	13	-.0020
11	4	13	-.0000
12	4	13	0.0018

PISTON NUMBER : 16

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0010
EXCENTRICITY (T.I.R.) = 0.0030
EXCENTRICITY (T.I.R.) = 0.0050
EXCENTRICITY (T.I.R.) = 0.0080
EXCENTRICITY (T.I.R.) = 0.0070
EXCENTRICITY (T.I.R.) = 0.0140
EXCENTRICITY (T.I.R.) = 0.0170
EXCENTRICITY (T.I.R.) = 0.0200
EXCENTRICITY (T.I.R.) = 0.0210
EXCENTRICITY (T.I.R.) = 0.0190
EXCENTRICITY (T.I.R.) = 0.0180
EXCENTRICITY (T.I.R.) = 0.0060
EXCENTRICITY (T.I.R.) = 0.0050
EXCENTRICITY (T.I.R.) = 0.0000

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0000
2	0	10	-.0008
3	0	11	0.0044
4	0	12	-.0107
5	4	13	0.0018
6	4	13	0.0000
7	4	13	0.0020
8	4	13	0.0033
9	4	13	-.0011
10	4	13	0.0110
11	4	13	-.0086
12	4	13	0.0018

PISTON NUMBER : 17

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0140
EXCENTRICITY (T.I.R.) = 0.0350
EXCENTRICITY (T.I.R.) = 0.0530
EXCENTRICITY (T.I.R.) = 0.0630
EXCENTRICITY (T.I.R.) = 0.0690
EXCENTRICITY (T.I.R.) = 0.0680
EXCENTRICITY (T.I.R.) = 0.0690
EXCENTRICITY (T.I.R.) = 0.0700
EXCENTRICITY (T.I.R.) = 0.0650
EXCENTRICITY (T.I.R.) = 0.0580
EXCENTRICITY (T.I.R.) = 0.0410
EXCENTRICITY (T.I.R.) = 0.0330
EXCENTRICITY (T.I.R.) = 0.0190
EXCENTRICITY (T.I.R.) = 0.0060

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0013
2	0	10	0.0064
3	0	11	0.0044
4	0	12	0.0093
5	4	13	-.0009
6	4	13	-.0000
7	4	13	0.0060
8	4	13	0.0022
9	4	13	0.0111
10	4	13	-.0090
11	4	13	0.0047
12	4	13	-.0004

PISTON NUMBER : 18

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0080
EXCENTRICITY (T.I.R.) = 0.0170
EXCENTRICITY (T.I.R.) = 0.0290
EXCENTRICITY (T.I.R.) = 0.0420
EXCENTRICITY (T.I.R.) = 0.0530
EXCENTRICITY (T.I.R.) = 0.0600
EXCENTRICITY (T.I.R.) = 0.0650
EXCENTRICITY (T.I.R.) = 0.0680
EXCENTRICITY (T.I.R.) = 0.0650
EXCENTRICITY (T.I.R.) = 0.0600
EXCENTRICITY (T.I.R.) = 0.0470
EXCENTRICITY (T.I.R.) = 0.0340
EXCENTRICITY (T.I.R.) = 0.0180
EXCENTRICITY (T.I.R.) = 0.0060

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	-.0013
2	0	10	-.0008
3	0	11	0.0022
4	0	12	0.0053
5	4	13	0.0009
6	4	13	0.0016
7	4	13	0.0060
8	4	13	0.0022
9	4	13	0.0089
10	4	13	-.0000
11	4	13	0.0023
12	4	13	-.0018

PISTON NUMBER : 19

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0090
EXCENTRICITY (T.I.R.) = 0.0180
EXCENTRICITY (T.I.R.) = 0.0270
EXCENTRICITY (T.I.R.) = 0.0310
EXCENTRICITY (T.I.R.) = 0.0370
EXCENTRICITY (T.I.R.) = 0.0470
EXCENTRICITY (T.I.R.) = 0.0530
EXCENTRICITY (T.I.R.) = 0.0610
EXCENTRICITY (T.I.R.) = 0.0660
EXCENTRICITY (T.I.R.) = 0.0720
EXCENTRICITY (T.I.R.) = 0.0700
EXCENTRICITY (T.I.R.) = 0.0630
EXCENTRICITY (T.I.R.) = 0.0580
EXCENTRICITY (T.I.R.) = 0.0050

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	-.0000
2	0	10	0.0040
3	0	11	-.0022
4	0	12	-.0053
5	4	13	0.0018
6	4	13	-.0016
7	4	13	0.0030
8	4	13	-.0011
9	4	13	0.0089
10	4	13	0.0050
11	4	13	-.0016
12	4	13	0.0213

PISTON NUMBER : 20

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0110
EXCENTRICITY (T.I.R.) = 0.0260
EXCENTRICITY (T.I.R.) = 0.0410
EXCENTRICITY (T.I.R.) = 0.0480
EXCENTRICITY (T.I.R.) = 0.0520
EXCENTRICITY (T.I.R.) = 0.0500
EXCENTRICITY (T.I.R.) = 0.0480
EXCENTRICITY (T.I.R.) = 0.0480
EXCENTRICITY (T.I.R.) = 0.0430
EXCENTRICITY (T.I.R.) = 0.0350
EXCENTRICITY (T.I.R.) = 0.0270
EXCENTRICITY (T.I.R.) = 0.0190
EXCENTRICITY (T.I.R.) = 0.0110
EXCENTRICITY (T.I.R.) = 0.0070

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	-.0000
2	0	10	0.0064
3	0	11	0.0033
4	0	12	0.0080
5	4	13	0.0000
6	4	13	-.0016
7	4	13	0.0050
8	4	13	0.0033
9	4	13	0.0000
10	4	13	0.0000
11	4	13	-.0000
12	4	13	-.0018

PISTON NUMBER : 21

LENGTH = 26   SPACING = 2   HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0310
EXCENTRICITY (T.I.R.) = 0.0710
EXCENTRICITY (T.I.R.) = 0.1060
EXCENTRICITY (T.I.R.) = 0.1270
EXCENTRICITY (T.I.R.) = 0.1400
EXCENTRICITY (T.I.R.) = 0.1420
EXCENTRICITY (T.I.R.) = 0.1350
EXCENTRICITY (T.I.R.) = 0.1290
EXCENTRICITY (T.I.R.) = 0.1220
EXCENTRICITY (T.I.R.) = 0.1030
EXCENTRICITY (T.I.R.) = 0.0820
EXCENTRICITY (T.I.R.) = 0.0570
EXCENTRICITY (T.I.R.) = 0.0280
EXCENTRICITY (T.I.R.) = 0.0030

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0022
2	0	10	0.0112
3	0	11	0.0087
4	0	12	0.0147
5	4	13	0.0040
6	4	13	-.0008
7	4	13	0.0010
8	4	13	0.0133
9	4	13	0.0022
10	4	13	0.0040
11	4	13	0.0031
12	4	13	-.0018

PISTON NUMBER : 22

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0110
EXCENTRICITY (T.I.R.) = 0.0270
EXCENTRICITY (T.I.R.) = 0.0430
EXCENTRICITY (T.I.R.) = 0.0550
EXCENTRICITY (T.I.R.) = 0.0610
EXCENTRICITY (T.I.R.) = 0.0600
EXCENTRICITY (T.I.R.) = 0.0620
EXCENTRICITY (T.I.R.) = 0.0630
EXCENTRICITY (T.I.R.) = 0.0640
EXCENTRICITY (T.I.R.) = 0.0580
EXCENTRICITY (T.I.R.) = 0.0450
EXCENTRICITY (T.I.R.) = 0.0350
EXCENTRICITY (T.I.R.) = 0.0210
EXCENTRICITY (T.I.R.) = 0.0050

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0000
2	0	10	0.0032
3	0	11	0.0065
4	0	12	0.0093
5	4	13	-.0013
6	4	13	0.0008
7	4	13	0.0000
8	4	13	0.0078
9	4	13	0.0078
10	4	13	-.0030
11	4	13	0.0031
12	4	13	0.0009

PISTON NUMBER : 23

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0100
EXCENTRICITY (T.I.R.) = 0.0240
EXCENTRICITY (T.I.R.) = 0.0360
EXCENTRICITY (T.I.R.) = 0.0460
EXCENTRICITY (T.I.R.) = 0.0530
EXCENTRICITY (T.I.R.) = 0.0590
EXCENTRICITY (T.I.R.) = 0.0620
EXCENTRICITY (T.I.R.) = 0.0660
EXCENTRICITY (T.I.R.) = 0.0680
EXCENTRICITY (T.I.R.) = 0.0610
EXCENTRICITY (T.I.R.) = 0.0520
EXCENTRICITY (T.I.R.) = 0.0370
EXCENTRICITY (T.I.R.) = 0.0190
EXCENTRICITY (T.I.R.) = 0.0050

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0009
2	0	10	0.0016
3	0	11	0.0033
4	0	12	0.0013
5	4	13	0.0013
6	4	13	-.0008
7	4	13	0.0020
8	4	13	0.0100
9	4	13	0.0022
10	4	13	0.0060
11	4	13	0.0023
12	4	13	-.0018

PISTON NUMBER : 24

LENGTH = 26 SPACING = 2 HALF TABLE = 16

EXCENTRICITY (T.I.R.) = 0.0170
EXCENTRICITY (T.I.R.) = 0.0440
EXCENTRICITY (T.I.R.) = 0.0660
EXCENTRICITY (T.I.R.) = 0.0800
EXCENTRICITY (T.I.R.) = 0.0900
EXCENTRICITY (T.I.R.) = 0.0940
EXCENTRICITY (T.I.R.) = 0.0940
EXCENTRICITY (T.I.R.) = 0.0930
EXCENTRICITY (T.I.R.) = 0.0940
EXCENTRICITY (T.I.R.) = 0.0860
EXCENTRICITY (T.I.R.) = 0.0700
EXCENTRICITY (T.I.R.) = 0.0510
EXCENTRICITY (T.I.R.) = 0.0300
EXCENTRICITY (T.I.R.) = 0.0070

PERMANENT DEFORMATIONS TO STRAIGHTEN PART

N	Q	R	DY
1	0	9	0.0022
2	0	10	0.0064
3	0	11	0.0044
4	0	12	0.0080
5	4	13	0.0018
6	4	13	0.0008
7	4	13	-.0020
8	4	13	0.0100
9	4	13	0.0069
10	4	13	0.0030
11	4	13	-0.0016
12	4	13	0.0069