THE DETERMINATION OF STRESSES IN MACHINE FRAMES

Thesis for degree of Mechanical Engineer submitted by G. L. Bowles, B. S., N. W. Conner, B. S., and A. A. Williams.

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Introduction

For a number of years strain gages of the Berry type, invented by Professor H. C. Berry of the University of Pennsylvania, have been used in determining the deformation, and the stresses resulting from this deformation, in structures of steel, reinforced concrete, and similar materials, such as bridges, and buildings of various types. Instruments of this kind read elongations of 0.0002 of an inch for each division on the Ames gage head (recording dial), and the gage length over which the elongation is found is usually two inches or greater. Thus, for an instrument measuring in the units mentioned above, the deformation or strain recorded over a length of material of two inches would be 0.0001 of an inch per inch of material under test. Consequently, if the deformation of the material per inch and the modulus of elasticity of the material be substituted in the fundamental relation between unit stress, unit deformation, and modulus of elasticity, the determination of the stress in the material tested involves only a simple arithmetical calculation. Thus,

$$\frac{\text{unit stress}}{\text{unit deformation}} = \text{modulus of elasticity.}$$

That is, the unit stress in the material is the product of the unit deformation or unit strain observed with the strain gage and the modulus of elasticity of the material, or

Unit stress = unit deformation x modulus of elasticity. Therefore, in materials such as concrete, which have comparitively small moduli of elasticity, the stress may be found quite correctly for values as low as 400 or 500 pounds per square inch, and if fractions of divisions on the dial are estimated, smaller stress may be determined with reasonable accuracy. In materials such as structural steel or cast iron, the moduli of elasticity of which are large as compared with that of concrete, stresses as low as several hundred pounds per square inch may be measured if fractional divisions of the dial are read. In reference to estimating the fractions of divisions on the dial, the following statement is found in Materials Testing by Cowdrey and Adams: "Closer estimation than one-half of a scale division should not be used, unless care is taken in the interpretation of the results, because the makers of the dial guarantee them only to the nearest scale division."

Up to the present time, however, little or no application has been made of the strain gage to the finding of stresses in the various parts of machine frames, and it was with the object of determining the applicability of the gage in tests of this nature and of observing, at the same time, the magnitude of the stresses produced in the frame of a single-stage, double-acting, Ingersoll-Sergeant Company (now Ingersoll-Rand Company) air compressor that the following experiment was undertaken.

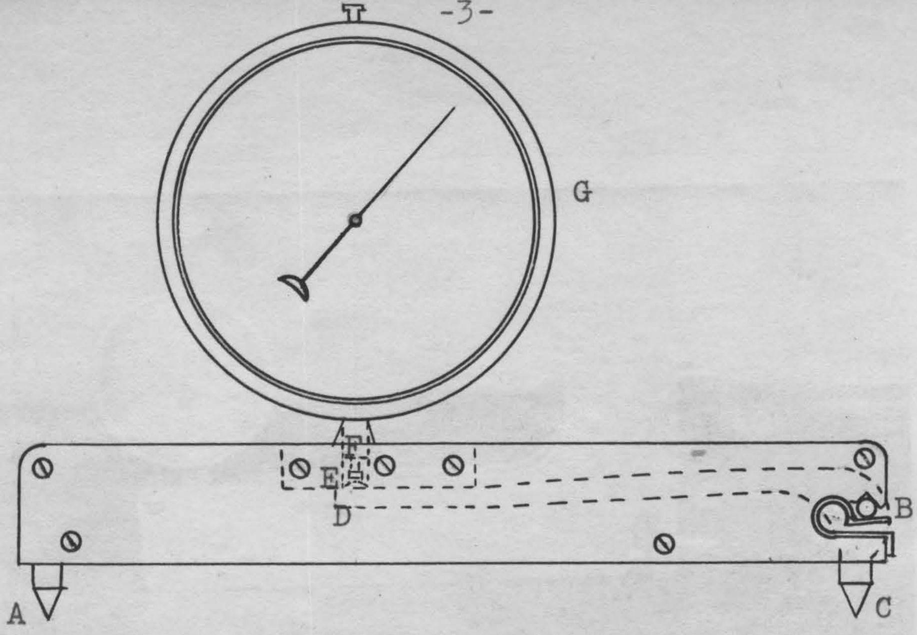


Fig. 1.

BERRY STRAIN GAGE

Operation of the Instrument

The 8-in. type of Berry strain gage is illustrated in Fig. 1. It consists of a frame made of two pieces of steel, into one end of which is securely fastened a conical point, A. The frame is made of Invar steel to minimize the effect of the heat of the operator's hand. The working parts of the Berry strain gage are the lever, CBD, and the Ames dial, G. On one end of the lever is a conical point, C, similar to the one at A. Any movement at A due to a change in length of the gage line is transmitted to the plunger at EF of the Ames dial, through the vertical movement of the arm, BD, which works in a V-shaped bearing at B. The dial is so constructed that one scale division represents a 0.001 inch movement of the plunger, EF. Since the ratio of the length of the arm, BD, to that of the leg, CB, is approximately five to one; each division on the dial represents $\frac{0.001}{5}$, or 0.0002-in. relative movement of the conical points A and C, which are fitted into center punch holes or holes specially drilled

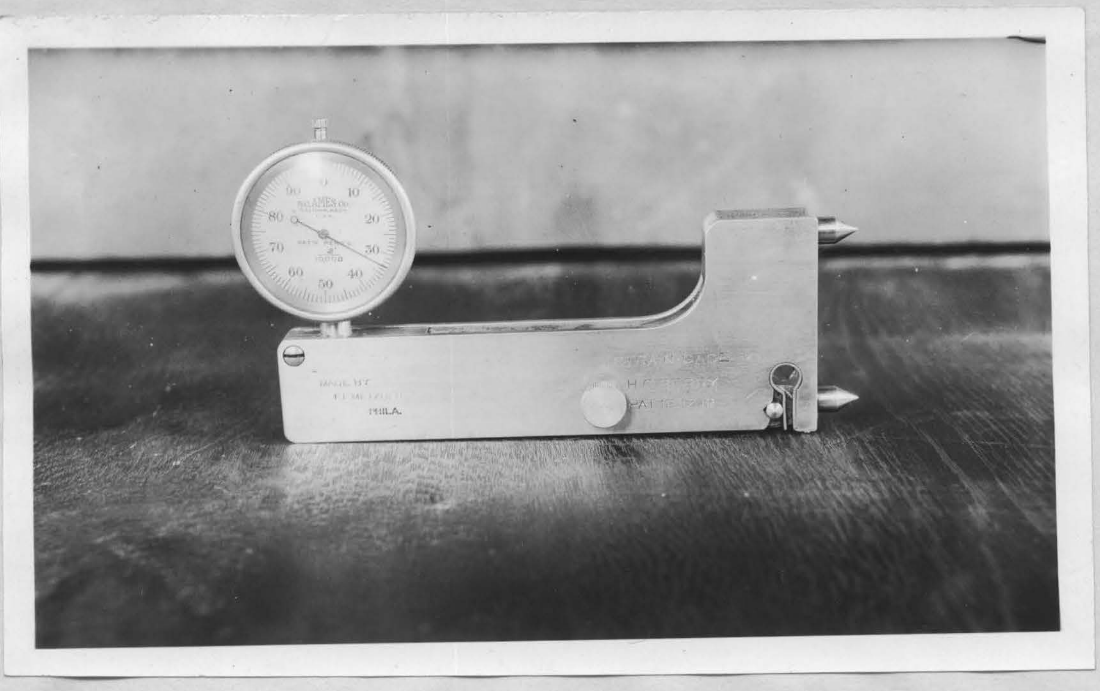


Fig. 2.

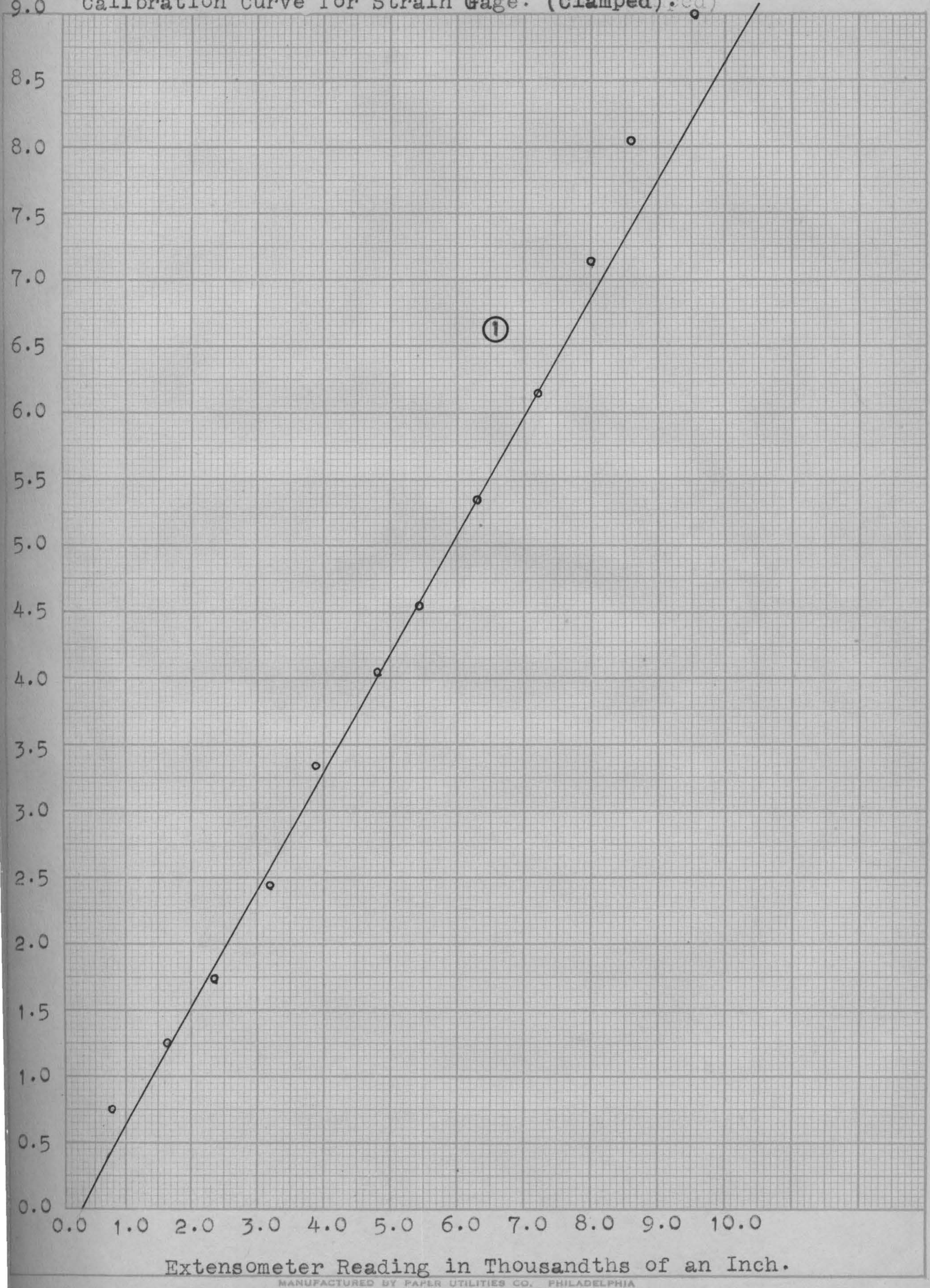
in the specimen. One-half of a scale division represents 0.0001-inch in the gage length used, which is generally either 2 in. or 8 in. In referring to an explanation similar to that presented above, Professor Arthur N. Talbot and Mr. Willis A. Slater of the University of Illinois state on page 26 of Bulletin Number 64 of the Engineering Experiment station entitled Tests of Reinforced Concrete Buildings: "However, this must not be taken to mean that the instrument or extensometer possesses this degree of accuracy in measuring stresses, since some movement of the leg at C is certain to result from variation in the handling of the instrument." On page 35 of the same bulletin the following statement is made: "The ratio of multiplication in the Berry extensometer is not exactly equal to the ratio of the length of the arm to the length of the leg, the error being due to the fact that the plunger of the Ames gage head does not always travel in a line perpendicular to the multiplying lever. However, calculations show that the approximation results in an error in the measurement of steel stresses equal to only one-fourth of one per cent for an extreme case. It may be seen that this error can be neglected."

Fig. 2 is an illustration of the 2-in. type of the Berry strain gage, which was used in this experiment.

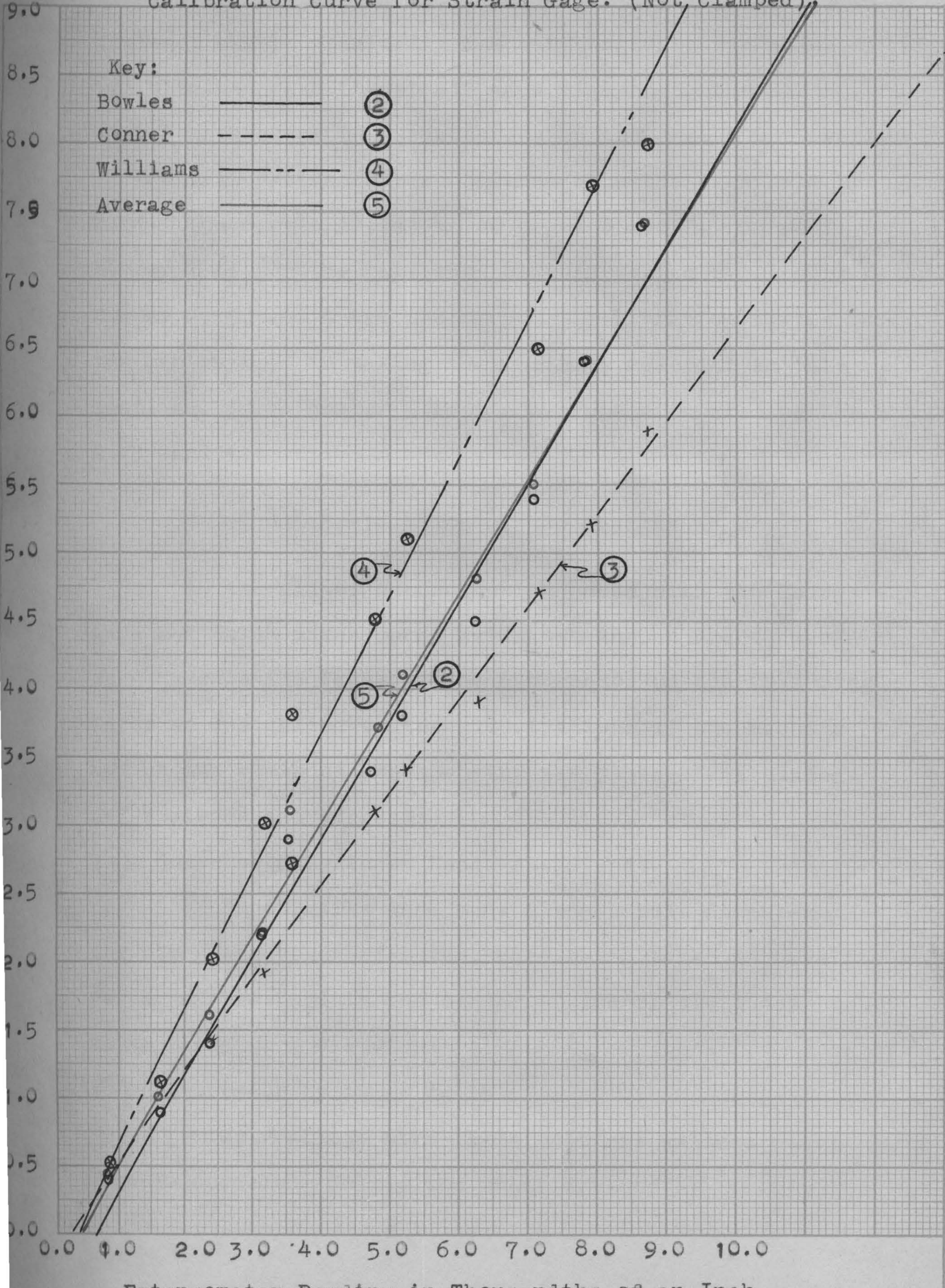
Calibration of the Berry Gage

The Berry strain gage used was calibrated against a Henning micrometer-screw extensometer on a round steel bar of known diameter. Two calibrations were made; one with the instrument held in turn by the men taking the readings, thus obtaining data for the personal calibration curve of each man, and one with the instrument clamped to the steel bar. The average of the personal calibration curves was found, and this curve was used to correct the readings taken in the test since the deflection on each gage line was read several times by each man, and the mean value of all the readings was recorded on the log. It might be said that there were very few cases in which there were any differences in the readings taken by the different men; and that in the few cases that did occur, the differences were so small that they could hardly be detected on the Ames dial. In obtaining the calibration data quite a number of trials were made before any satisfactory results were obtained. This was due to

Calibration Curve for Strain Gage. (Clamped).



Calibration Curve for Strain Gage. (Not Clamped).



the fact that it requires quite a bit of practice in holding and in reading the gage before any degree of proficiency can be obtained. The calibration curve which was obtained with the strain gage clamped to the bar served as a check on the accuracy of the gage and to verify the calibration curves obtained with the gage held by hand. The curves are shown on pages 6 and 7. Curve number 1 is for the gage when clamped to the bar. Curves number 2, 3, and 4 are the personal calibration curves for the men engaged in taking the readings recorded in this test, and curve number 5 is the average of curves number 2, 3, and 4,

Preparation of the Machine

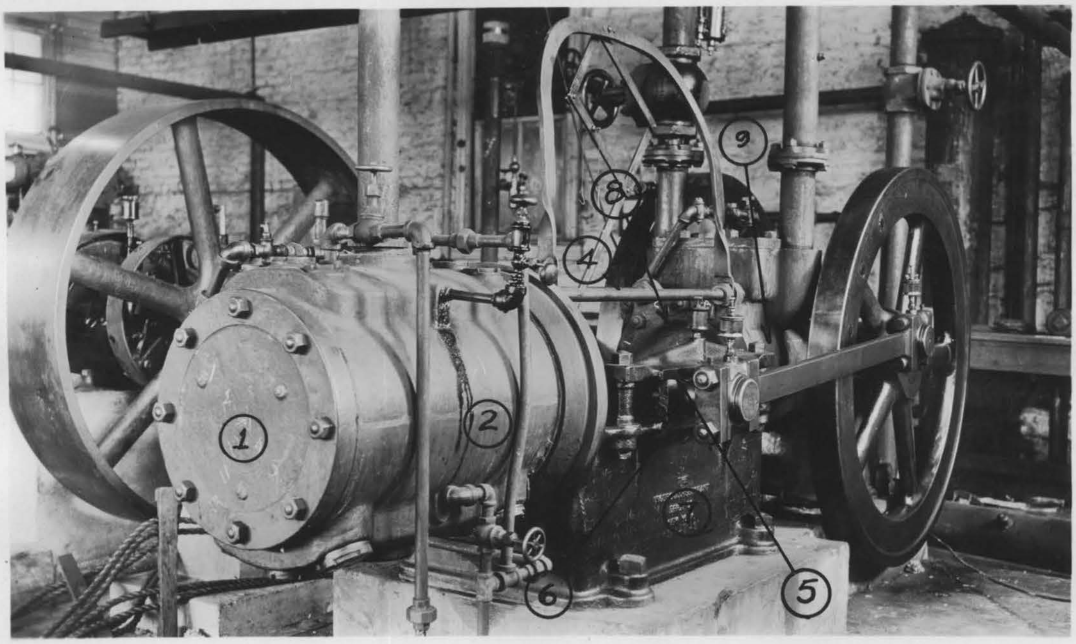
With the aid of a punch which comes with the Berry gage and which makes punch marks two inches apart, marks were made in the frame of the compressor on the following parts as designated on the illustrations of the machine and on the sketches accompanying the pages of tabulated deformations and stresses.

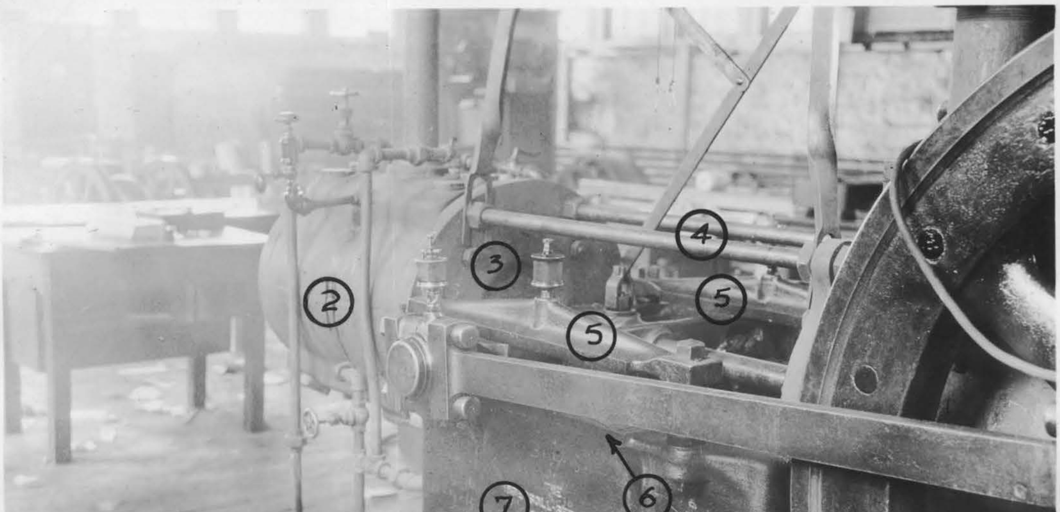
(1) Compressor Cylinder Head (Head End)

Punch marks were made along a bolt diameter and along any other diameter, care being taken to have the center of the head in the center of the middle punch marks along each diameter.

(2) Compressor Cylinder Walls

No readings were taken on these walls as they were inaccessible due to the water jackets.


1
2
4
8
9
6
5


2
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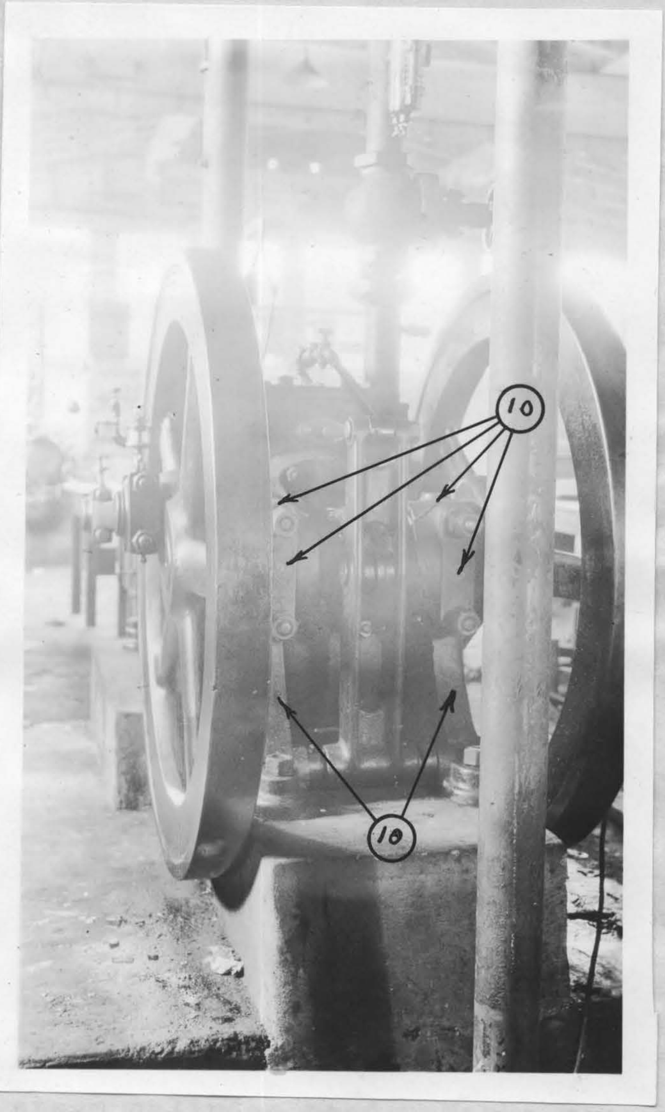

10
10

(3) Compressor Cylinder Head (Crank End)

On account of the shape of this member the punch marks had to be placed at irregular positions on its surface. Marks were placed at one point so that a reading could be taken as near the center of the head as possible.

(4) Tie Rods

On the tie rods on each side of the machine punch marks were made for three readings.

(5) Upper Crosshead Guides

The whole length of the upper corsshead guides were punch-marked at intervals of two inches.

(6) Lower Crosshead Guides

The lower crosshead guides were marked in a number of places on each side of the center where it was beleived the greatest stresses would occur.

(7) Bed Plate

Punch marks were made in a large number of positions over both sides of the bed plate and on the legs through which the machine was bolted to the foundation.

(8) Steam Cylinder Head (Crank End)

Various positions were chosen for the punch marks on the steam cylinder head. Marks were made, however, as near the center of the head as possible and along the "ears", which can be seen to deflect when the compressor is in operation.

Because of the motion of the valve rod it was virtually impossible to obtain readings of the deformation in the steam cylinder head on the head end.

(9) Steam Cylinder Walls

Both sides of the steam cylinder walls were punch marked near the crank end. Readings could not be taken on other portions of the cylinder wall because of the rotation of the flywheel.

(10) Bearing Pedestals and Covers

These member were marked at regular intervals of two inches for the entire distance along the tops of the bearing covers and along the ends of the pedestals. Marks were also made on the lugs where the pedestals were bolted to the foundation.

In all cases the marks were made, wherever possible, in several similar positions so that the reading at one position would serve as a check on the reading at a corresponding position, as well as the reading on one side of the machine would be a check on the corresponding on the opposite side, in the case of the cylinder walls, tie rods, and so forth.

Testing

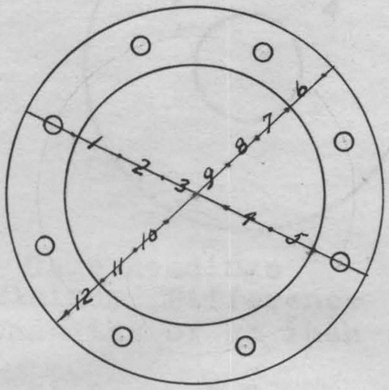
Whenever observations were made on the compressor in operation, it was allowed to run for about an hour to insure the uniform heating of the parts and as constant condition as possible throughout the entire mechanism.

The compressor was run during the test at an average speed of about 129 R. P. M. and with an average air pressure in the receiver of about 66 pounds per square inch.

To obtain the stresses in the various parts the maximum and minimum deflections of the Berry gage was noted while the machine was running. In this process, the gage was held by hand in the punch marks in as constant a position as possible while consecutive readings were recorded. Whenever any doubt as to the reading of the gage was experienced, several readings were taken and the average reading recorded. The number of corresponding readings which were obtained by the method employed in punch-marking the machine should, however, give the assurance of fairly accurate results.

Tabulated Results

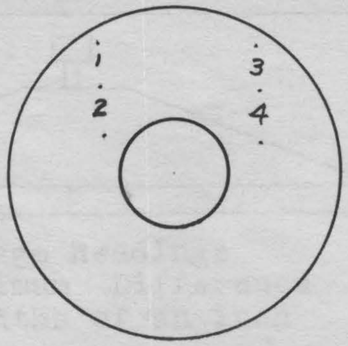
(1) Compressor Cylinder Head (Head End)



No.	Gage Readings Maximum	Minimum	Difference	Corrected	Stress
	Ten-thousandths of an inch			inches	lbs./sq. in.
1	15.0	15.0	0.0	0.000000	0
2	8.2	8.0	0.2	0.000063	945
3	33.7	33.0	0.7	0.000123	1845
4	20.2	20.0	0.2	0.000063	945
5	11.0	11.0	0.0	0.000000	0
6	20.1	20.0	0.1	0.000050	750
7	23.0	23.0	0.0	0.000000	0
8	30.1	30.0	0.1	0.000050	750
9	21.6	21.0	0.6	0.000111	1665
10	34.2	34.0	0.2	0.000063	945
11	34.0	34.0	0.0	0.000000	0
12	25.1	25.0	0.1	0.000050	750

Maximum stress in compressor cylinder head (head end) equals 1845 lbs. per sq. in.

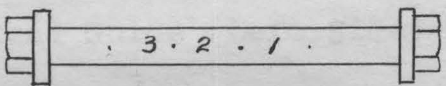
(3) Compressor Cylinder Head (Crank End)



No.	Gage Readings Maximum	Minimum	Difference	Corrected inches	Stress lbs./sq. in.
	Ten-thousandths of an inch				
1	54.0	54.0	0.0	0.000000	0
2	12.2	12.0	0.2	0.000063	945
3	22.0	22.0	0.0	0.000000	0
4	94.2	94.0	0.2	0.000063	945

Maximum stress--------------945 lbs. per sq. in.

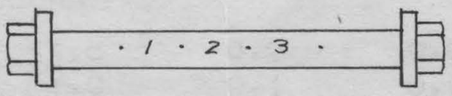
(4) Tie Rods (Right Side)

Steam End  Air End

No.	Gage Readings Maximum	Minimum	Difference	Corrected inches	Stress lbs./sq. in.
	ten-thousandths of an inch				
1	11.4	11.0	0.4	0.000087	2610
2	25.4	25.0	0.4	0.000087	2610
3	19.3	19.0	0.3	0.000075	2250

Maximum stress------------2610 lbs. per sq. in.

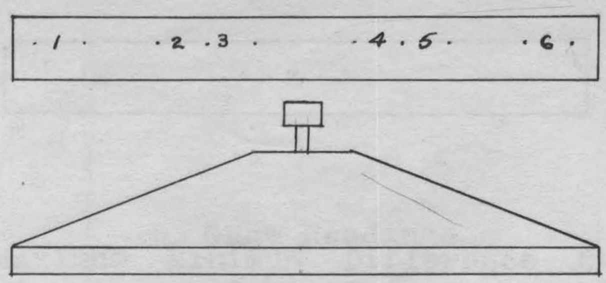
(4) Tie Rods (Left Side)

Air End  Steam End

No.	Gage Readings Maximum	Minimum	Difference	Corrected inches	Stress lbs./sq. in.
	ten-thousandths of an inch				
1	26.3	26.0	0.3	0.000075	2250
2	12.3	12.0	0.3	0.000075	2250
3	46.4	46.0	0.4	0.000087	2610

Maximum stress------------2610 lbs. per sq. in.

(5) Top Crosshead Guide (Right Side)

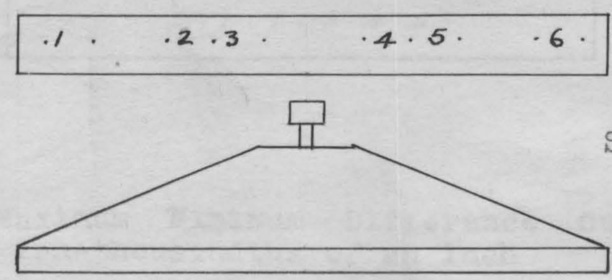


Air End Steam End

No.	Gage Readings Maximum	Minimum	Difference	Corrected	Stress
	ten-thousandths	of an inch		inches	lbs./sq. in.
1	85.0	85.0	0.0	0.000000	0
2	65.0	65.0	0.0	0.000000	0
3	81.0	81.0	0.0	0.000000	0
4	80.0	80.0	0.0	0.000000	0
5	77.0	77.0	0.0	0.000000	0
6	75.0	75.0	0.0	0.000000	0

Zero stress in top crosshead guides (right side).

(5) Top Crosshead Guide (Left Side)



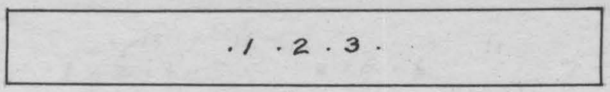
Air End Steam End

No.	Maximum	Minimum	Difference	Corrected	Stress
	Ten-thousandths	of an inch		inches	lbs./sq. in.
1	54.0	53.8	0.2	0.000063	945
2	61.1	61.0	0.1	0.000050	750
3	79.1	79.0	0.1	0.000050	750
4	94.1	94.0	0.1	0.000050	750
5	91.2	91.0	0.2	0.000063	945

Maximum stress-----------945 lbs. per sq. in.

(6) Lower Crosshead Guide (Right Side)

Steam End



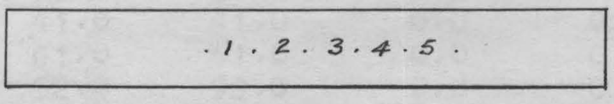
Air End

No.	Maximum	Minimum	Difference	Corrected	Stress
	Gage Readings				
	ten-thousandths of an inch			inches	lbs./sq. in.
1	10.1	10.0	0.1	0.000050	750
2	41.0	41.0	0.0	0.000000	0
3	86.0	86.0	0.0	0.000000	0

Maximum stress-----------750 lbs. per sq. in.

(6) Lower Crosshhead Guide (Left Side)

Air End



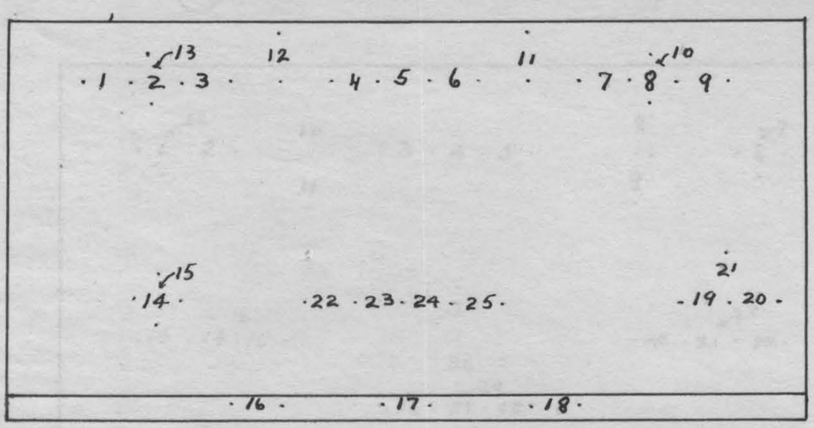
Steam End

No.	Maximum	Minimum	Difference	Corrected	Stress
	ten-thousandths of an inch			inches	lbs./sq. in.
1	11.5	11.5	0.0	0.000000	0
2	1.1	1.0	0.1	0.000050	750
3	96.1	96.0	0.1	0.000050	750
4	95.1	95.0	0.1	0.000050	750
5	97.0	97.0	0.0	0.000000	0

Maximum stress------------750 lbs. per sq. in.

(7) Bed Plate (Right Side)

Steam End



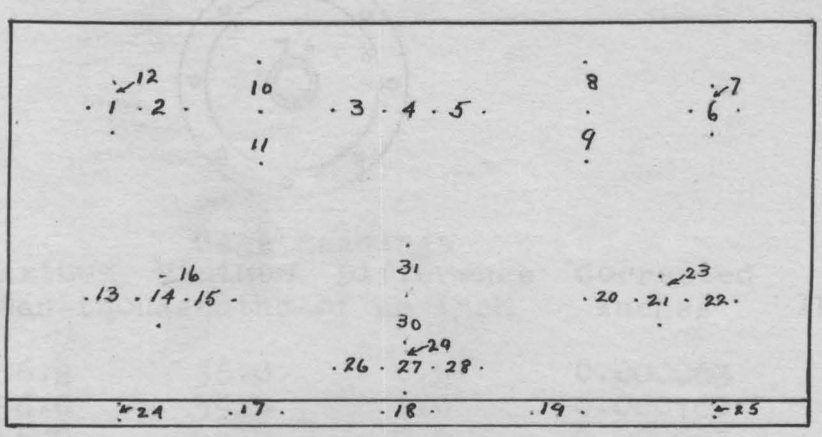
Air End

No.	Maximum	Minimum	Difference	Corrected	Stress
	ten-thousandths of an inch			inches	lbs./sq. in.
1	32.2	32.1	0.1	0.000050	750
2	32.0	32.0	0.0	0.000000	0
3	70.1	70.0	0.0	0.000050	-750 Compression
4	25.0	24.8	0.2	0.000063	-945
5	62.2	62.0	0.2	0.000063	945
6	53.0	52.8	0.2	0.000063	945
7	56.1	56.0	0.1	0.000050	750
8	56.0	56.0	0.0	0.000000	0
9	55.0	54.8	0.2	0.000063	945
10	41.0	41.0	0.0	0.000000	0
11	41.0	41.0	0.0	0.000000	0
12	92.0	92.0	0.0	0.000000	0
13	43.0	43.0	0.0	0.000000	0
14	55.1	55.0	0.1	0.000050	-750
15	60.1	60.0	0.1	0.000050	750
16	65.0	65.0	0.0	0.000000	0
17	68.1	68.0	0.1	0.000050	750
18	62.0	62.0	0.0	0.000000	0
19	18.0	18.0	0.0	0.000000	0
20	15.0	15.0	0.0	0.000000	0
21	25.0	25.0	0.0	0.000000	0
22	29.0	29.0	0.0	0.000000	0
23	40.0	40.0	0.0	0.000000	0
24	30.0	30.0	0.0	0.000000	0
25	36.0	36.0	0.0	0.000000	0

Maximum stress------------------945 lbs. per sq. in. tension
-945 lbs. per sq. in. compression

(7) Bed Plate (Left Side)

Air End

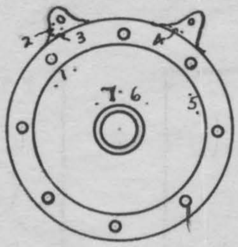


Steam End

No.	Gage Readings Maximum	Minimum	Difference	Corrected	Stress
	ten-thousandths of an inch			inches	lbs./sq. in.
1	17.0	17.0	0.0	0.000000	0
2	13.0	13.0	0.0	0.000000	0
3	4.2	4.0	0.2	0.000063	945
4	14.2	14.0	0.2	0.000063	945
5	91.1	91.0	0.1	0.000050	750
6	18.0	18.0	0.0	0.000000	0
7	27.0	27.0	0.0	0.000000	0
8	81.0	81.0	0.0	0.000000	0
9	51.2	51.0	0.2	0.000063	945
10	87.0	87.0	0.0	0.000000	0
11	74.2	74.0	0.2	0.000063	945
12	99.0	99.0	0.0	0.000000	0
13	19.0	19.0	0.0	0.000000	0
14	19.0	19.0	0.0	0.000000	0
15	15.0	15.0	0.0	0.000000	0
16	26.0	26.0	0.0	0.000000	0
17	17.0	17.0	0.0	0.000000	0
18	97.05	97.0	0.05	0.000045	675
19	97.05	97.0	0.05	0.000045	675
20	97.0	97.0	0.0	0.000000	0
21	7.0	7.0	0.0	0.000000	0
22	87.05	87.0	0.05	0.000045	675
23	24.0	24.0	0.0	0.000000	0
24	98.0	98.0	0.0	0.000000	0
25	64.0	64.0	0.0	0.000000	0
26	93.0	93.0	0.0	0.000000	0
27	89.0	89.0	0.0	0.000000	0
28	83.0	83.0	0.0	0.000000	0
29	85.0	85.0	0.0	0.000000	0
30	50.0	50.0	0.0	0.000000	0
31	84.4	84.4	0.0	0.000000	0

Maximum stress-----------------945 lbs. per sq. in. tension

(8) Steam Cylinder Head (Crank End)

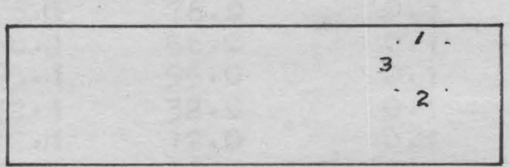


No.	Maximum	Minimum	Difference	Corrected	Stress	
	Gage Readings ten-thousandths of an inch			inches	lbs./sq. in.	
1	36.2	36.0	0.2	0.000063	945	
2	56.0	55.0	1.0	0.000160	-2400	Compression
3	46.2	46.0	0.2	0.000063	-945	
4	91.0	90.0	1.0	0.000160	-2400	
5	82.2	82.0	0.2	0.000063	945	
6	82.0	82.0	0.0	0.000000	0	
7	75.4	75.4	0.0	0.000000	0	

Maximum stress------- 945 lbs. per sq. in. tension
2400 lbs. per sq. in. compression

(9) Steam Cylinder Walls (Right Side)

H. E.



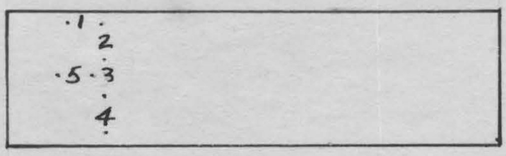
C. E.

No.	Maximum	Minimum	Difference	Corrected	Stress	
	Gage Readings ten-thousandths of an inch			inches	lbs./sq. in.	
1	70.2	70.0	0.2	0.000063	945	
2	65.4	65.0	0.4	0.000087	1305	
3	80.1	80.0	0.1	0.000050	-750	Compression

Maximum stress------- 1305 lbs. per sq. in.tension
750 lbs. per sq. in. compression

(9) Steam Cylinder Walls (Left Side)

C. E.

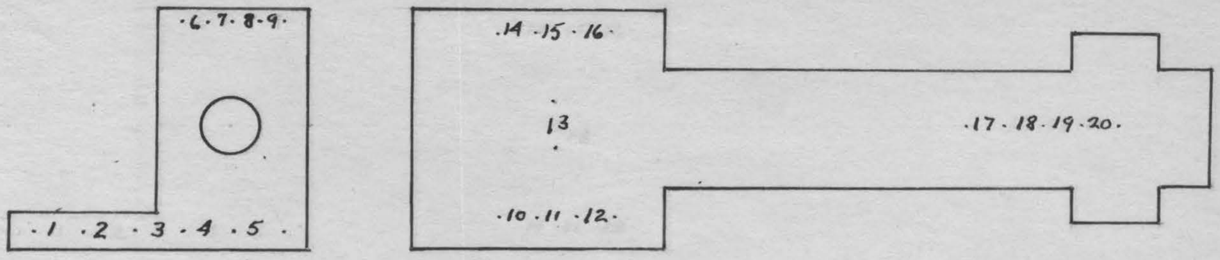


H. E.

No.	Maximum	Minimum	Difference	Corrected	Stress
	Gage Readings ten-thousandths of an inch			inches	lbs./sq. in.
1	46.1	46.0	0.1	0.000050	750
2	57.1	57.0	0.1	0.000050	750
3	52.0	52.0	0.0	0.000000	0
4	69.1	69.0	0.1	0.000050	750
5	52.4	52.0	0.4	0.000087	1305

Maximum stress--------1305 lbs. per sq. in. tension

(10) Bearing Pedestals and Covers (Right Side)

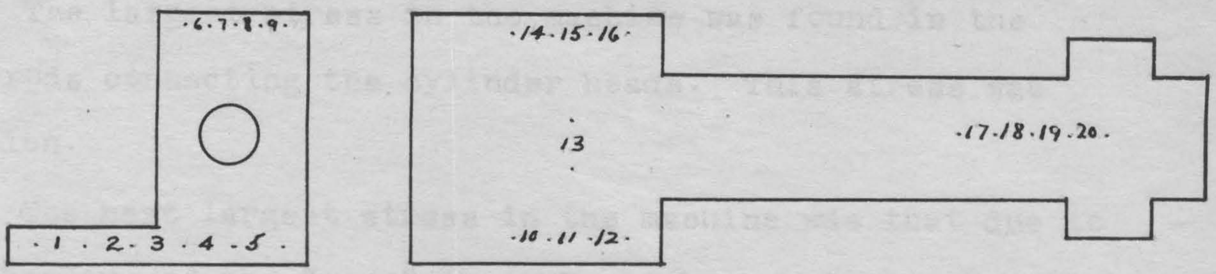


Top End

No.	Gage Readings Maximum	Minimum	Difference	Corrected	Stress
	ten-thousandths of an inch			inches	lbs./sq. in.
1	32.2	32.0	0.2	0.000063	945
2	54.3	54.0	0.3	0.000075	1125
3	64.5	64.0	0.5	0.000100	1500
4	46.2	46.0	0.2	0.000063	945
5	37.1	37.0	0.1	0.000050	750
6	89.1	89.0	0.1	0.000050	750
7	76.1	76.0	0.1	0.000050	750
8	56.1	56.0	0.1	0.000050	750
9	95.1	95.0	0.1	0.000050	750
10	32.1	32.0	0.1	0.000050	750
11	12.1	12.0	0.1	0.000050	750
12	31.2	31.0	0.2	0.000063	945
13	9.2	9.0	0.2	0.000063	945
14	29.1	29.0	0.1	0.000050	750
15	51.1	51.0	0.1	0.000050	750
16	61.1	61.0	0.1	0.000050	750
17	99.1	99.0	0.1	0.000050	750
18	67.1	67.0	0.1	0.000050	750
19	88.0	88.0	0.0	0.000000	0
20	45.0	45.0	0.0	0.000000	0

Maximum stress-----------1500 lbs. per sq. in. tension

(10) Bearing Pedestals and Covers (Left Side)



Top End

No.	Gage Readings Maximum	Minimum	Difference	Corrected	Stress
	ten-thousandths of an inch			inches	lbs./sq. in.
1	89.5	89.0	0.5	0.000100	1500
2	74.5	74.0	0.5	0.000100	1500
3	50.5	50.0	0.5	0.000100	1500
4	35.2	35.0	0.2	0.000063	945
5	79.1	79.0	0.1	0.000050	750
6	7.5	7.0	0.5	0.000100	1500
7	52.2	52.0	0.2	0.000063	945
8	22.2	22.0	0.2	0.000063	945
9	33.2	33.0	0.2	0.000063	945
10	47.1	47.0	0.1	0.000050	750
11	93.1	93.0	0.1	0.000050	750
12	45.2	45.0	0.2	0.000063	945
13	55.2	55.0	0.2	0.000063	945
14	25.1	25.0	0.1	0.000050	750
15	6.2	6.0	0.2	0.000063	945
16	15.2	15.0	0.2	0.000063	945
17	96.2	96.0	0.2	0.000063	945
18	8.1	8.0	0.1	0.000050	750
19	85.0	85.0	0.0	0.000000	0
20	20.0	20.0	0.0	0.000000	0

Maximum stress----------1500 lbs. per sq. in. tension

CONCLUSION

The largest stress in the machine was found in the tie rods connecting the cylinder heads. This stress was tension.

The next largest stress in the machine was that due to the bending of the "ears" through which the tie rods are connected to the cylinder heads. Each "ear" acts as a cantilever beam subjected to a concentrated load, and if observed closely, it could be seen to deflect. This stress was compression because the strain was observed on the inside fibers subjected to bending.

It is apparent, as one might expect, that the maximum stress in the cylinder head of the head end of the compressor is in the center of the load. It can also be seen from the data that the readings for corresponding points along both diameters are approximately the same.

No deformation could be detected on the top crosshead guide (right side). Only a small deformation could be detected on the top crosshead guide (left side) and on both of the lower guides.

As stated before, all stresses were calculated from the fundamental relation

unit stress = unit deformation x modulus of elasticity.

The modulus of elasticity of the steel tie rods was taken as 30,000,000 pounds per square inch, while the modulus of elasticity of all cast iron members of the machine was taken as 15,000,000 pounds per square inch.

Since accepted values for the allowable stress in steel is 16000 pounds per square inch and in cast iron 3000 pounds per square inch, it may be seen that all parts of the compressor which were tested are far within the limit of safety.