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THE DESIGN OF A PRESSURE TRANSDUCER
FOR MEASURING SILAGE PRESSURES

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Woi-wen Yu

1960

This is to certify that the

thesis entitled

**"The Design of a Pressure Transducer
For Measuring Silage Pressures"**

presented by

Wei-Wen Yu

has been accepted towards fulfillment
of the requirements for

M. S. degree in Agricultural Engineering

James D. Boyce
Major professor

Date 8/18/60

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**THE DESIGN OF A PRESSURE TRANSDUCER
FOR MEASURING SILAGE PRESSURES**

by

Wei-wen Yu

AN ABSTRACT

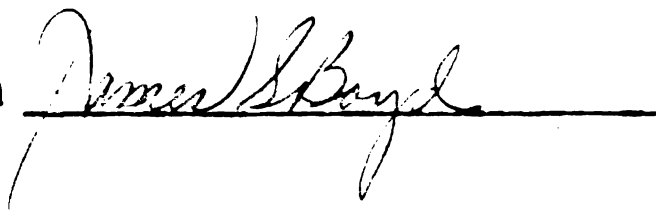
**Submitted to the Colleges of Agriculture and Engineering
of Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of**

MASTER OF SCIENCE IN AGRICULTURAL ENGINEERING

Department of Agricultural Engineering

1960

Approved

A handwritten signature in cursive script, appearing to read "James S. Boyd", is written over a horizontal line.

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The importance of silo structures has been recognized for years in cattle and livestock farming. The size of silo has changed greatly. The investigation of structural phases of vertical silos was insufficient to keep up with the change in size of silo.

In the past five years more than ten silos have failed. The reasons for silo failures were investigated but most of them were left unverified.

Various methods have been used to measure pressure. The transducer using wire strain gages was suitable for multiple point pressure measurement.

Pressure transducers made of SR-4 A-18 gages were built and checked. The gages were cemented to the back of a thin stainless steel diaphragm which was rigidly clamped to a brass body. The transducer was calibrated against known hydraulic pressure up to 36 psi; its stability observed with and without loading; calibrated against known pressure under different temperatures; calibrated against known pressure with silage in contact with the transducer diaphragm.

Thirty-one transducers were made and installed in the wall and on the bottom of a 30' x 60' silo.

The characteristics of transducers were summarized as follows:

1. The curves obtained from the hydraulic pressure calibration were excellent. They were reproduced

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with high accuracy in successive runs.

2. The output of the transducer was insensitive to a change in temperature.
3. The output measured with the silage in direct contact with the transducer diaphragm was found correct below 5 psi and 9 per cent higher at 10 psi than that measured from the hydraulic pressure calibration.
4. Stability without loading was observed for six transducers over a period of two months. Four of them had a change less than 90 micro inches per inch in two months. The other two tended to creep. One transducer remained unloaded for 180 days and the strain readings observed continuously. The maximum variation in zero pressure readings was found to be 360 micro inches per inch over 180 days and was considered too high. Stability of a transducer under constant pressures of 10 and 20 psi is satisfactory. Change in readings tended to approach a constant decrease in output of 150 micro inches per inch. Measuring strains at a constant pressure as high as 30 psi was found unsatisfactory.

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INTRODUCTION

It is well recognized that the storage silo is one of the most important structures in cattle farming. For over 80 years, silos have played an important and necessary part in livestock farming. The first silos were merely rectangular walled pits. Stone, brick, and concrete were commonly used. James Neilson of New Brunswick (5) erected one of the first vertical silos of chestnut posts in 1881. The structure was 40 feet long, 20 feet wide, and 18 feet high. In spite of the increase in sizes of silos, investigation of structural phase were unfortunately very limited.

In the past five years, more than ten silos from 14' by 50' to 30' by 70' in size have collapsed. According to the remarks made by the National Silo Association, failures were due to inadequate hooping, improper filling, and improper site selection, yet the exact causes of failure for the most of them are unknown.

OBJECTIVES

The objective of this investigation was to develop a device for measuring pressures exerted by silage in silos.

REVIEW OF LITERATURE

J. R. McCalmont (5) formulated silo design data from his experimental results obtained from the full scale silo in 1946. He used a calibrated bar as the sensing element. The deflection due to the pressure exerted by the silage in the silo was measured. The pressure panel was built of two layers of 1- by 6- inch lumber as an ordinary silo door. To this were attached vertically two steel 3-inch T-sections 12 inches apart. Each panel was supported on two 5/8-inch round alloy steel bars that passed through holes in the T-sections and were secured in corresponding channels along each side of the doorway. The panels were hung in each door opening in column and the measurements taken from the outside. His results show that the diameter of the silo affects the unit lateral pressure exerted on its wall. The formulas calculated from these experimental results recognize the critical relationship between diameter and pressure as follows:

Design pressures for the silos 14 feet and less in diameter:

$$P_h = \frac{d h^{1.90}}{2.65 h^{1.42}}$$

Design pressures for silos 16 feet and more in diameter:

$$P_h = \frac{d h^{1.45}}{5}$$

where, P_h = Horizontal pressure, pounds per square foot

d = Diameter, feet.

h = Depth of the silage, feet.

Density measurements were carried out by Otis and Pomroy (7) to evaluate silage pressure. They used the layer method, the surface sampling method, and the horizontal core sampling method at various elevations. The density was measured and the curves drawn. The samples used for the density measurement were placed in airtight plastic bags and brought into the laboratory. A portion of each sample was placed in a cylinder and compressed to the density in the silo at the time the core sample was taken. Comparison of the pressure and density diagram (7) showed good agreement with high density material located in high pressure area.

During 1940 in connection with the construction of silos in France and Algeria, a large scale investigation of pressure in silos was initiated. The results of investigations have been published by Reimbert (1954), Caquot (1957), and Despeyroux (1958). They found that, in grain silos, when filling, the wall pressure was almost in accordance with the Janssen-Konen formula and with Caquot's modified formula. Reimbert carried out an experiment on a steel silo 13-feet 6-inch square and 33-feet in height. The pressures were determined by measuring the strains in the walls at various depth with electric wire strain gages.

Bergau (1951-1952) made two test arrangements for measuring grain silo pressures, one in a reinforced concrete

silos he used hydraulic earth pressure cells developed by Kallstenius and Bergau, to make the measurement. The hydraulic earth pressure cell has built-in electrical contacts for checking cell compression. In 1951, he obtained one complete cycle of pressure measurements and found that during emptying the pressure of the grain was almost twice as large as that during filling. He suggested further investigation be made as the above results were merely from one point measurement and doubtful as being representative of the distribution of pressures over the entire surface. For the steel silo, similar results were found by using electrical wire strain gages. The strain gages were cemented on the steel plate in pairs both horizontal and vertical. The compensation circuit was also employed by placing the dummy gages on an angle profile fixed between the points of measurement.

Pressure cells have been successfully used in measuring soil pressures. The United States Waterway Experimental Station report (11) gives a complete description of types of soil pressure cells developed for measurements of pressure in the soil under walls, footings, and tunnels. They considered it very probable that the criteria established for cells mounted in a rigid wall were as follows. The ratio of the diameter to the projection of the cell must be greater than 30 and the ratio of the diameter to the deflection must be greater than 1000. The ratios do provide the limit within which the cells indicate approximately the

pressures which act on the wall in their absence. The WES soil pressure cell consists of a circular face plate welded at its perimeter to a thicker base plate. The face plate has a peripheral slot which forms a flexible joint between two plates. A diaphragm is formed in the base plate by a lathe. A connecting cable enters the gage chamber through a packing gland at the side of the base plate. The thin disc chamber between the face and base plate is filled with oil (recently modified cells are filled with mercury). Pressure applied to the face plate is averaged and transmitted by the oil to the diaphragm. The radial strain produced in the diaphragm by the pressure is measured by SR-4 electric wire strain gages. A linear relation between applied pressure and resistance change can be obtained with appropriate connection of gages to give the complete temperature compensation.

Cooper (2) developed another type of pressure cell which had two SR-4 electric wire strain gages cemented on the underside of the 0.025-inch thick circular stainless steel plate. The circular plate was rigidly soldered to a brass body. The strain gages used were 1/8-inch in gage length, 120-ohm in resistance and had a gage factor of 1.73. Two gages of the same lot were cemented to the side of the brass body to complete the Wheatstone Bridge as well as perfect temperature compensation. The cells were placed at various depths in the soil perpendicular to the direction of travel, and pressures were measured. The results were very satisfactory.

THEORY AND DESIGN OF PRESSURE TRANSDUCERS

The electric wire strain gage was adopted in designing pressure transducers. The gages will be cemented on a stainless steel diaphragm firmly clamped on the cell body. The theory related to this design will be discussed here.

Wheatstone Bridge

The output of the wheatstone bridge in Figure 1 can be found by the following equations.

$$\delta = \frac{\Delta R_1}{R_1} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_2}{R_2} - \frac{\Delta R_4}{R_4}$$

where δ = total output of the bridge.

R_1, R_2, R_3 and R_4 = resistances of the gage 1, 2, 3, and 4.

$\Delta R_1, \Delta R_2, \Delta R_3$ and ΔR_4 = changes of resistances in gage 1, 2, 3, and 4.

If the gages of the same resistance were used, the equation becomes,

$$\delta = \frac{1}{R} (\Delta R_1 + \Delta R_3 - \Delta R_2 - \Delta R_4)$$

As from the relation between strain and resistance change of gages

$$\epsilon = \frac{\Delta L}{L} = \frac{\sum \frac{\Delta R}{R}}{F} = \frac{\delta}{F}$$

the change in resistance can be measured by a strain meter directly in strain (micro inches per inch). In order to get the maximum output by Wheatstond Bridge, gage 1 and gage 3

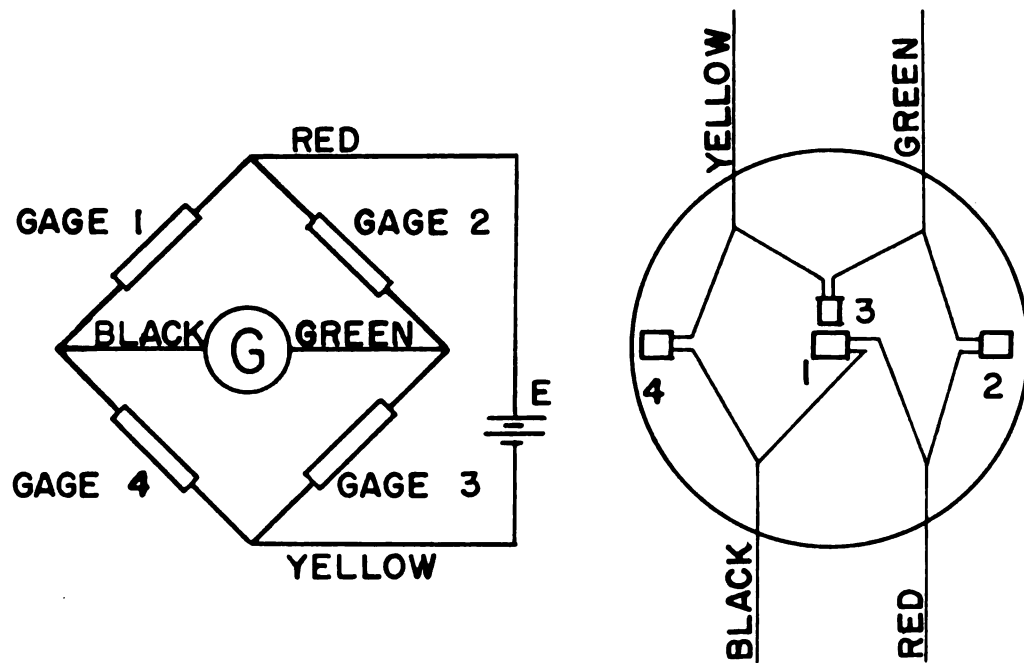


FIGURE 1. WHEATSTONE BRIDGE

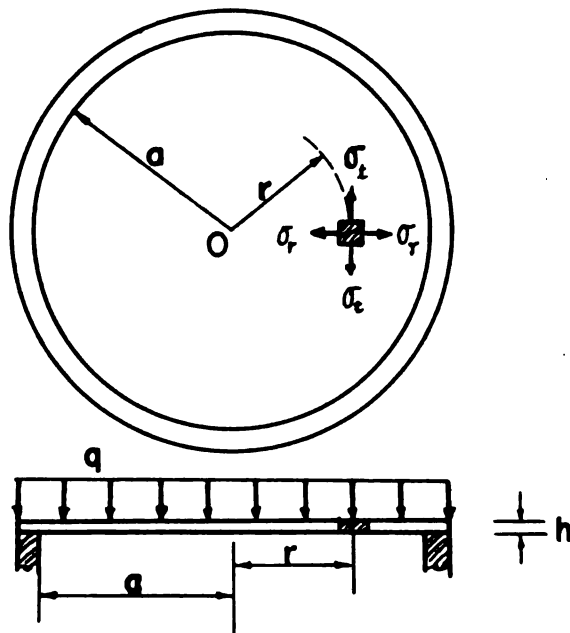


FIGURE 2. A CIRCULAR PLATE CLAMPED AT THE EDGES WITH UNIFORMLY DISTRIBUTED LOAD

should be cemented at a point subject to tension and gage 2 and 4 should be cemented at a point subjected to compression.

Stress and Strain

For a circular plate clamped all around the edges with uniformly distributed load of intensity q pounds per square inch applied, the radial and tangential moment, stress and strain can be calculated from the following formulas (Fig. 2).

$$M_r = \frac{q}{16} [a^2(1+\nu) - r^2(3+\nu)]$$

$$M_t = \frac{q}{16} [a^2(1+\nu) - r^2(1+3\nu)]$$

$$\sigma_r = \frac{6M_r}{h^2} = \frac{3q}{8h^2} [a^2(1+\nu) - r^2(3+\nu)]$$

$$\sigma_t = \frac{6M_t}{h^2} = \frac{3q}{8h^2} [a^2(1+\nu) - r^2(1+3\nu)]$$

$$\epsilon_r = \frac{1}{E} (\sigma_r - \nu \sigma_t)$$

$$\epsilon_t = \frac{1}{E} (\sigma_t - \nu \sigma_r)$$

where,

M_r, M_t = radial and tangential moment, in pound-inch

σ_r, σ_t = radial and tangential stresses, in pound per square inch

ϵ_r, ϵ_t = radial and tangential strain, in micro inches per inch

q = unit uniform load, in pound per square inch

h = thickness of the diaphragm, in inch

E = Young's modulus of elasticity, in pound per square inch

ν = Poisson's ratio

a, r = radii of the diaphragm, in inch

Design Procedure

Diameter of diaphragm. General consideration should be given to the nature of the silage and the situation during pressure measurements. The transducers were calibrated against hydraulic pressure, while during the field measurement, the diaphragm was in direct contact with silage. Because of silage cut size and its non-homogeneous property, a diameter sufficiently large as to avoid possible concentrated loading was selected. On the other hand, from the technique in strain gage application the diameter of the diaphragm will directly affect the thickness of the diaphragm as well as its sensitivity. Silage stored on Michigan farms, usually was chopped from $3/8$ to $5/8$ inch in length. Hence, a diameter of 2 inches was selected for this study.

Thickness of diaphragm. After the diameter of the diaphragm was determined, the limiting factor was the diaphragm thickness. As the thickness of the diaphragm was inversely proportional to its extreme fiber stresses, a thin diaphragm was more desirable for sensitivity. The high reproductibility and stability would provide the lower limit for the design of its thickness. For a circular diaphragm clamped all around the edges with uniform loading, the outer edge has the higher fiber stress and remains as the reference point for the chosen working stress in design.

Sensitivity. After the diameter and thickness of the diaphragm were determined, the total output of the transducer

could be calculated by formulae in terms of the strain. The smallest gradient of Young's Strain Indicator is 10 micro inches per inch and the strain reading can be estimated accurately to 5 micro inches per inch. The best design would be to make the diaphragm of such a thickness to give the desired sensitivity at the smallest gradient of the Strain Meter.

Design

It was required to design the transducer for the measurement of the wall pressure in a silo with silage out 3/8 to 5/8 inches in length. Use stainless steel plate as the diaphragm material.

Working stress = 20,000 psi

Maximum load = 20 psi

Poisson's ratio = 0.3

Modulus of elasticity = 30×10^6 psi

Diameter of diaphragm. D = 2 inches

Thickness of diaphragm. (h)

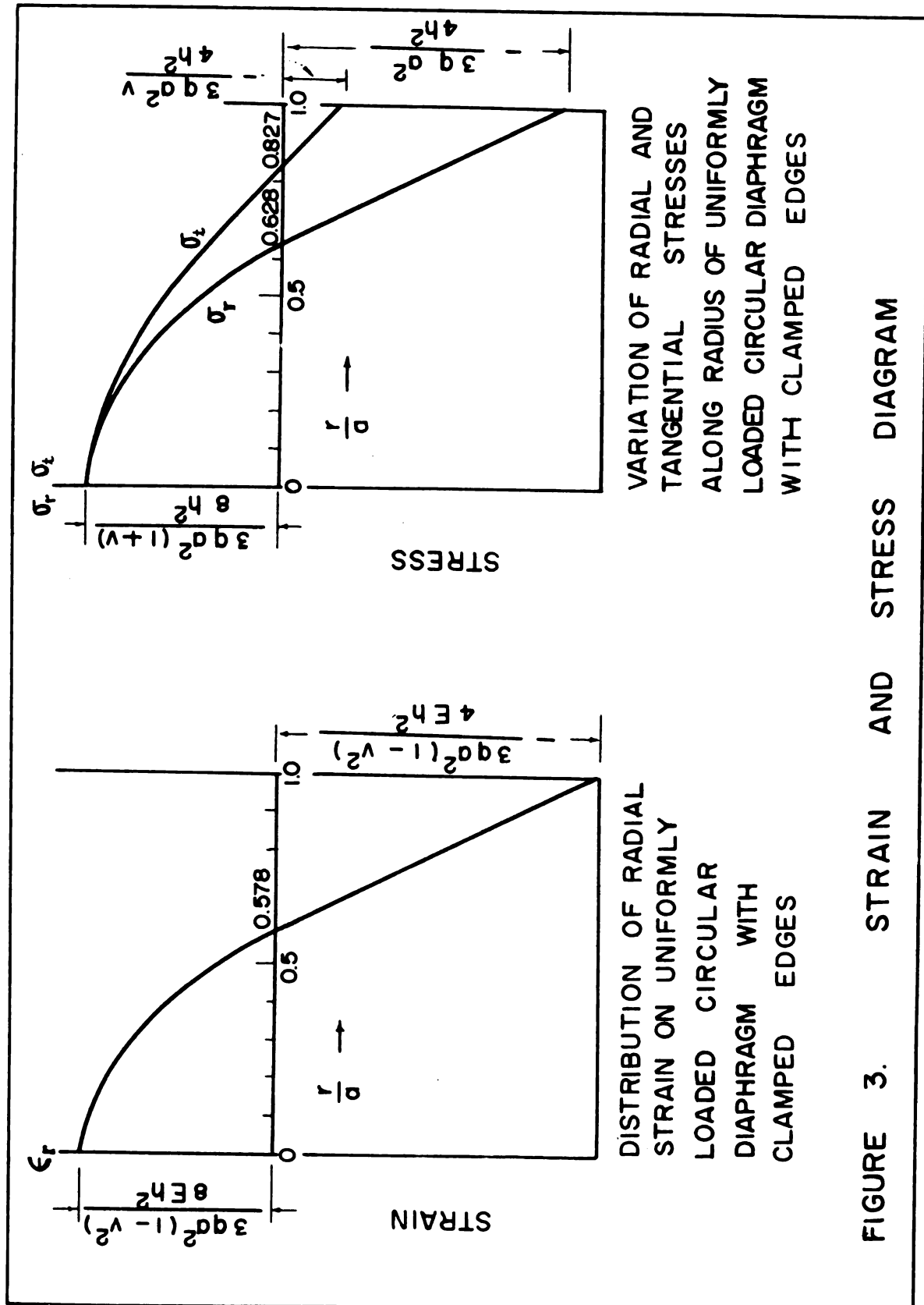
From the formulae for the maximum radial stresses in Figure 3. Thickness required at the center of diaphragm

$$h = \sqrt{\frac{3(1+\nu) a^2 q}{8 \sigma_w}} = 0.022 \text{ inch}$$

Thickness required at the edge of diaphragm

$$h = \sqrt{\frac{3 a^2 q}{4 \sigma_w}} = 0.027 \text{ inch}$$

So, choose h = 0.025 inch plate (corresponding to 22 gage plate).



Sensitivity. Sensitivity implies the output of the pressure transducer due to the uniform load of unit intensity. The total output can be calculated by summing the output of four gages.

Gage 1: $r = 0$; $a = 1''$; $h = 0.025''$; $\nu = 0.3$; $q = 1 \text{ psi}$
 $E = 30 \times 10^6 \text{ psi}.$

$$\sigma_r = \frac{3q}{8h^3} [a^2(1+\nu) - r^2(3+\nu)] = \frac{3}{8 \times (0.025)^3} [1.3] = 780 \text{ psi}$$

$$\sigma_t = \frac{3q}{8h^3} [a^2(1+\nu) - r^2(1+3\nu)] = \frac{3}{8 \times (0.025)^3} [1.3] = 780 \text{ psi}$$

$$\epsilon_r = \frac{1}{E} (\sigma_r - \nu \sigma_t) = 18.2 \times 10^{-6} \text{ inches per inch}$$

Gage 3: $r = 3/16'' = 0.1875''$

$$\sigma_r = 710.7 \text{ psi} \qquad \sigma_t = 740.1 \text{ psi}$$

$$\epsilon_r = 16.3 \times 10^{-6} \text{ inches per inch}$$

Gage 2 and 4: $r = 7/8'' = 0.875''$

$$\sigma_r = 735.9 \text{ psi} \qquad \sigma_t = 92.8 \text{ psi}$$

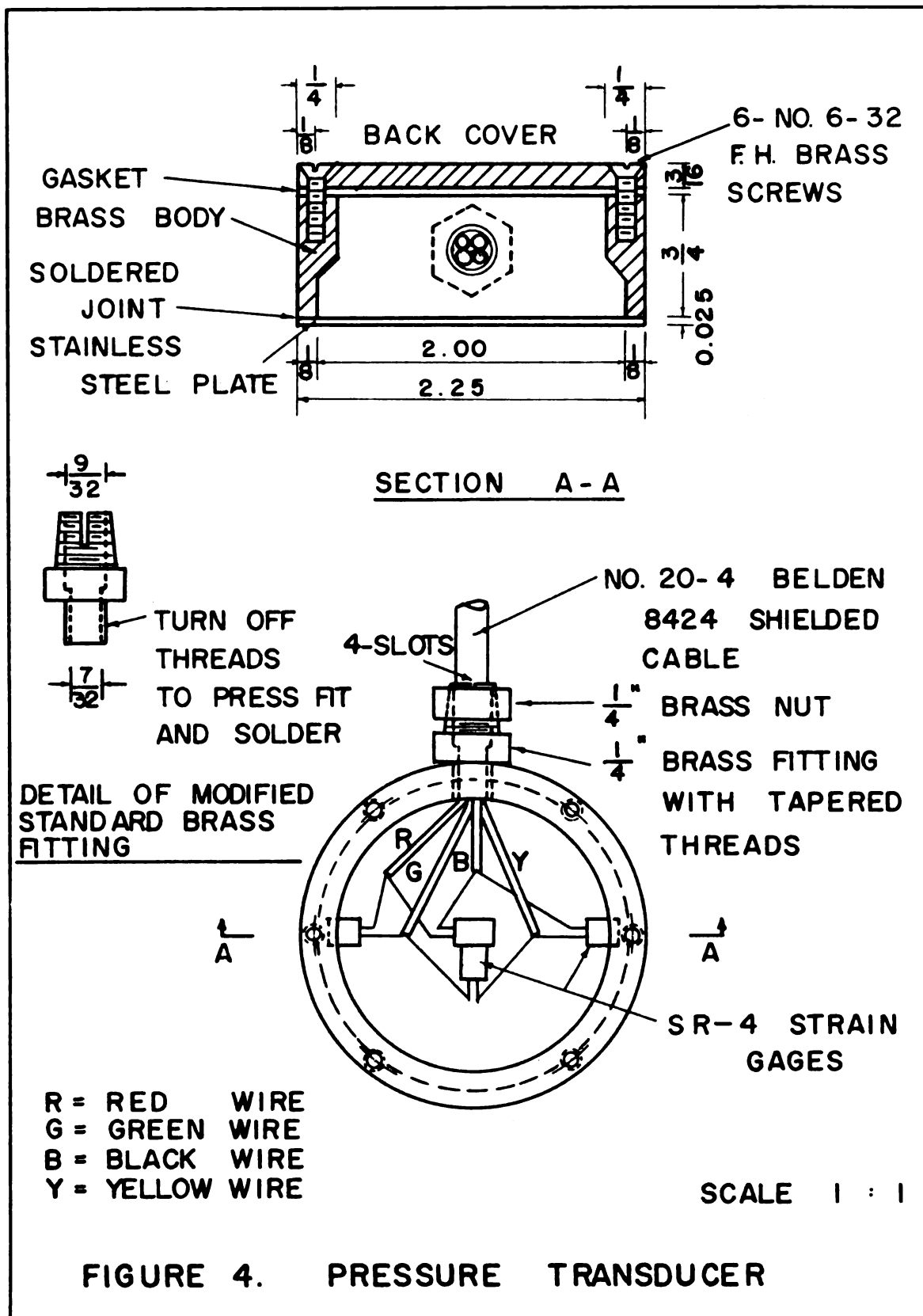
$$\epsilon_r = 23.6 \times 10^{-6} \text{ inches per inch}$$

$$\begin{aligned} \text{Sensitivity} &= \sum \epsilon_r = (18.2 + 16.3 + 23.6 + 23.6) \times 10^{-6} \\ &= 81.7 \text{ micro inches per inch per psi.} \end{aligned}$$

DESCRIPTION OF EQUIPMENT

Pressure Transducer

Strain gage transducers were built to make silage pressure measurements. Each transducer had four SR-4 A-18 electric resistance wire strain gages cemented to the underside of the stainless steel plate 0.025 inches in thickness and 2.25 inches in diameter. Two gages were cemented at the center of the circular plate perpendicular to each other and the other two gages were cemented close to the fixed edge in the radial direction. The four gages were connected so as to compose a wheatstone bridge with all four gages active and providing a complete temperature compensation. A-18 gages were 1/8 inch in length 120 ohms in resistance and had gage factors of $1.80 \pm .3$. Dupont No. 5458 Cement and Petrosene Wax were used for cementing and moisture-proofing the gages. Belden 8424 four lead rubber shielded cable was used for the connection of the transducer to the strain indicator. Each transducer was made water tight with a brass back cover screw-fastened to the body. A special gasket made of the tube patch and aluminum foil was used in sealing. The design of the transducer is shown in Figures 4 and 7.



Young's Strain Indicator

The type A M strain indicator was used to measure the change in resistance of electric strain gages. The indicator was calibrated to interpret those resistance changes directly in micro inches of strain. The indicator was useable both for two arm bridges and four arm bridges. The gage should have a resistance of 60 to 500 ohms to use this indicator. The wiring diagram of the transducer and indicator is shown in Figure 5.

Calibration Equipment

The apparatus for calibrating the transducer against the hydraulic pressure is shown schematically in Figures 6 and 8. The calibration equipment consists of a constant hydraulic pressure tank, Bourdon tube pressure gage, regulator valve, pressure chamber, transducer fastener, and a release valve. At the upper part of the pressure chamber an entrapped air-release valve was installed to obtain more stable and uniform pressure on the transducer diaphragm. The Bourdon Tube pressure gage was calibrated with the Ashcroft dead weight tester. Each transducer was calibrated separately up to a gage pressure of 36 pounds per square inch.

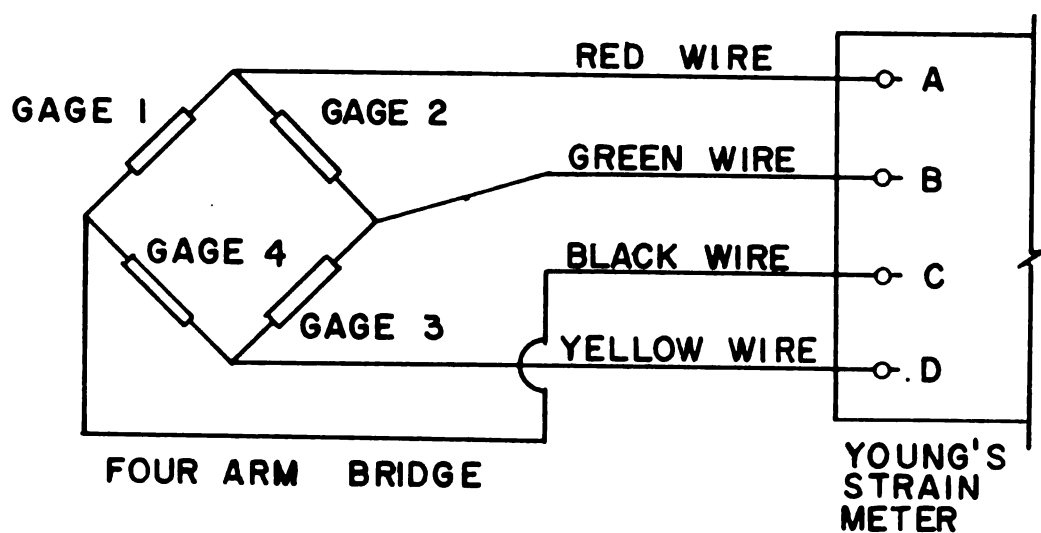


FIGURE 5. TRANSDUCER WIRING DIAGRAM

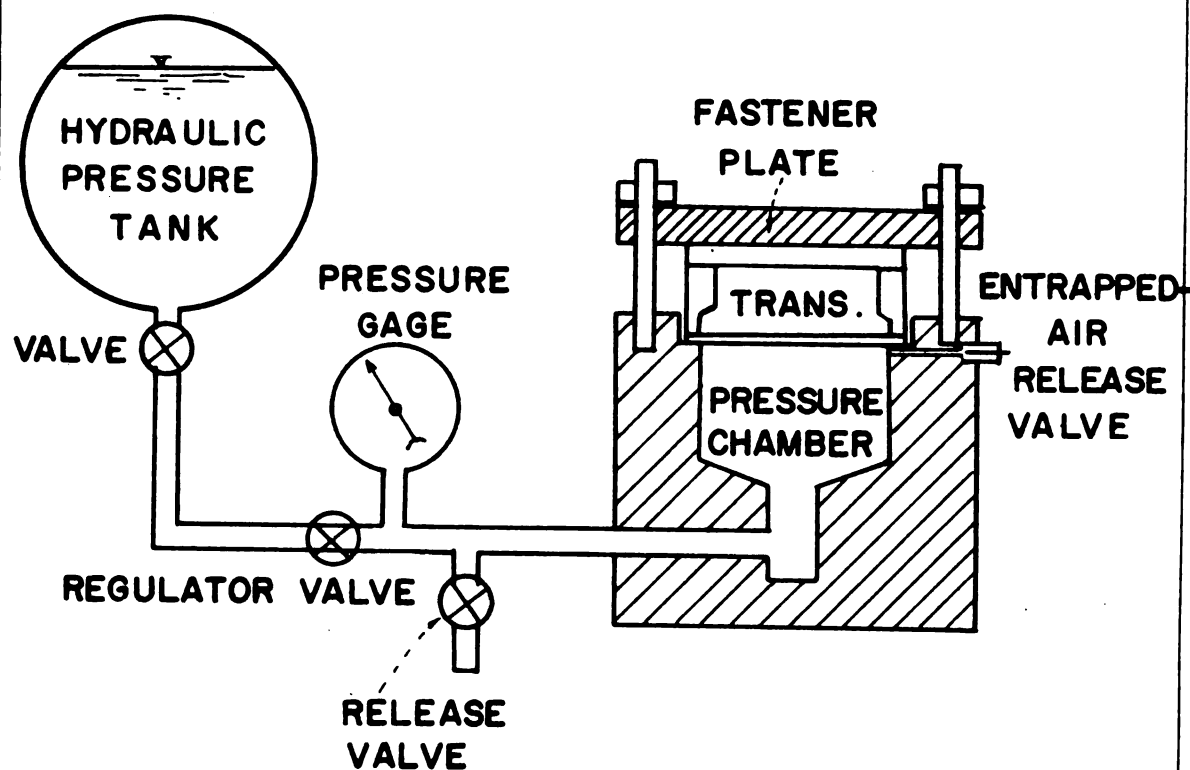


FIGURE 6. SKETCH OF CALIBRATION EQUIPMENT



Figure 7. Pressure transducer before the back cover sealing.

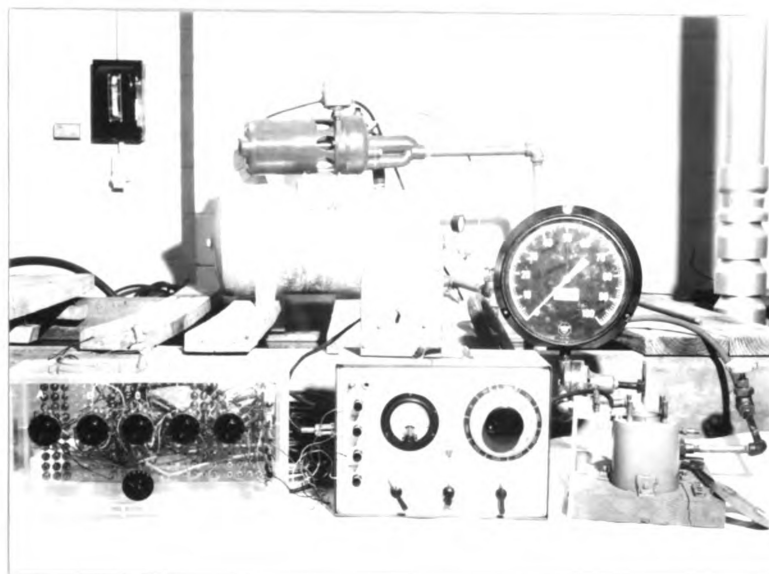


Figure 8. Pressure transducer calibration apparatus

CALIBRATION PROCEDURES AND THE RESULTS

Hydraulic Pressure Calibration

Each transducer was placed on the calibration apparatus and calibrated against the known hydraulic pressure indicated by the Bourdon Tube pressure gage. The pressure was first applied to about 30 psi and released from the valve to eliminate entrapped air. Loading and unloading was then repeated several times before the data were taken. The strain output was taken for each 2 psi pressure increment up to 36 psi.

Typical calibration curves are shown in Figure 9 and 10. Theoretically the curve should be a straight line yet it has a slight curvature with an increase of applied pressure. The calibration results were excellent, and were reproducible without error in successive runs. Sensitivity of the transducers ranged from 100 to 140 micro inches per inch per psi. The difference in sensitivity was due to the variation in diaphragm thickness and inexact alignment of the gages.

Stability of the Transducers

Stability without loading. Six transducers were placed in the laboratory after they were calibrated. The zero pressure readings were taken continuously for two months

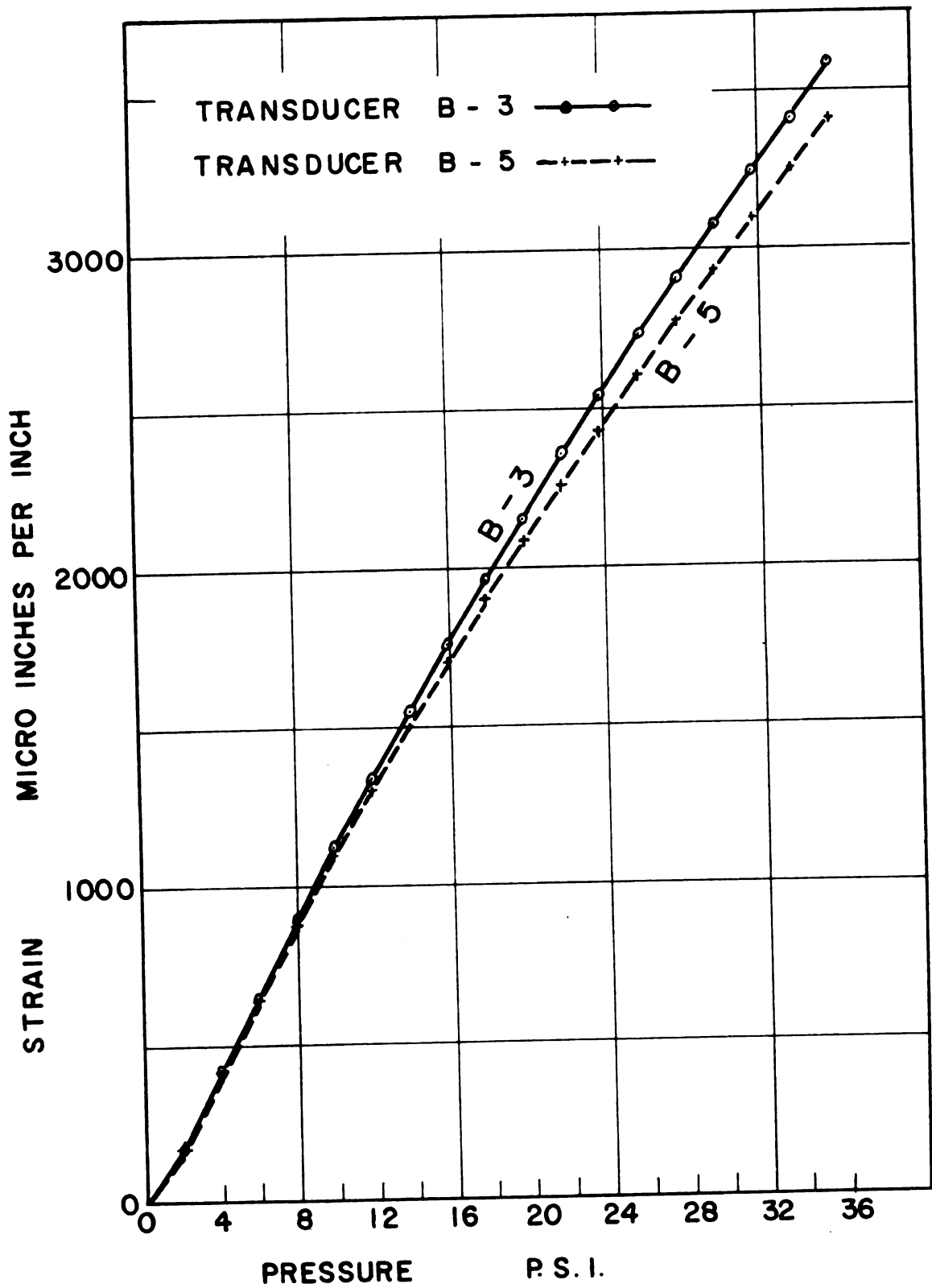


FIGURE 9. CALIBRATION CURVES

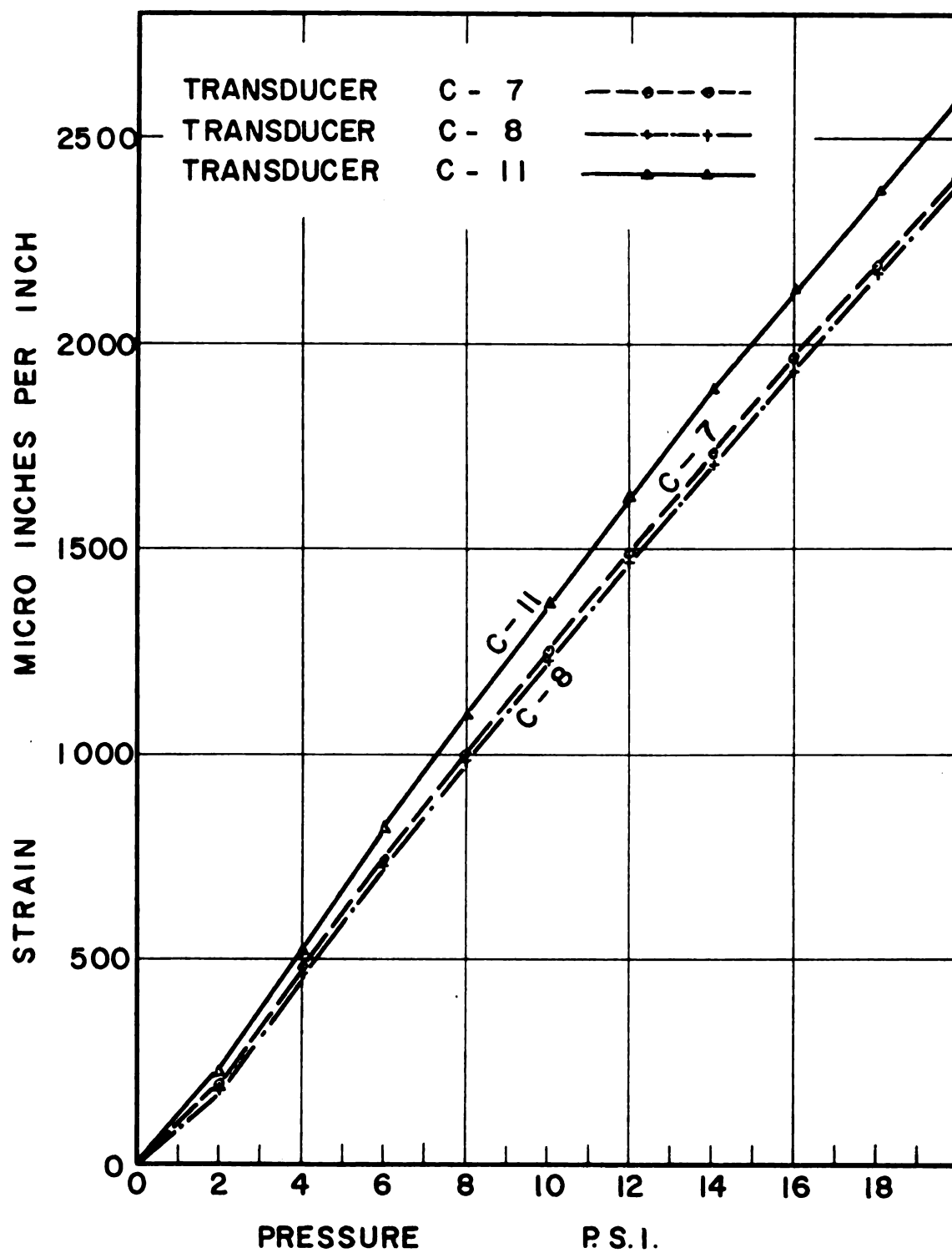


FIGURE 10. CALIBRATION CURVES

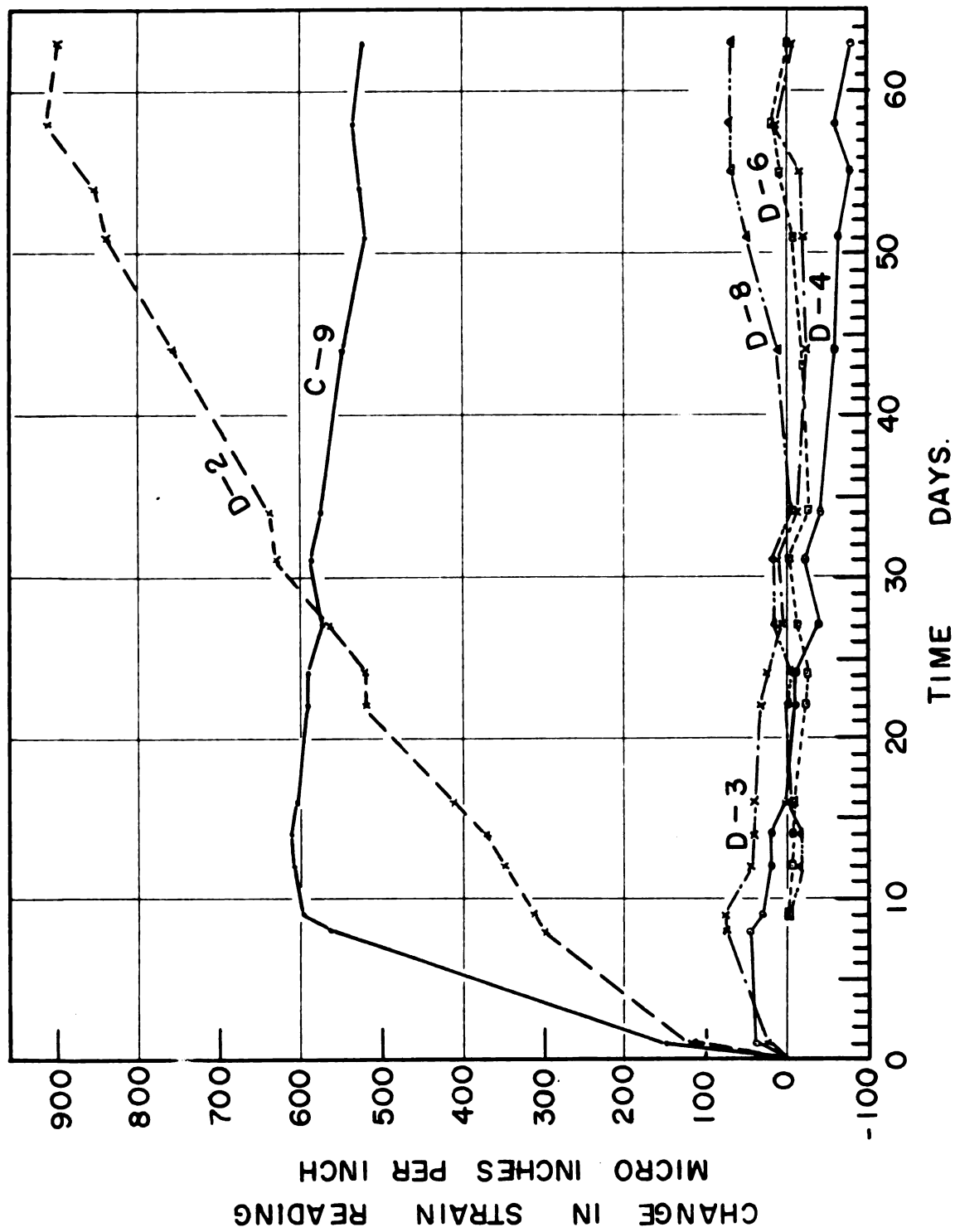


FIGURE 11. STABILITY OF TRANSDUCERS

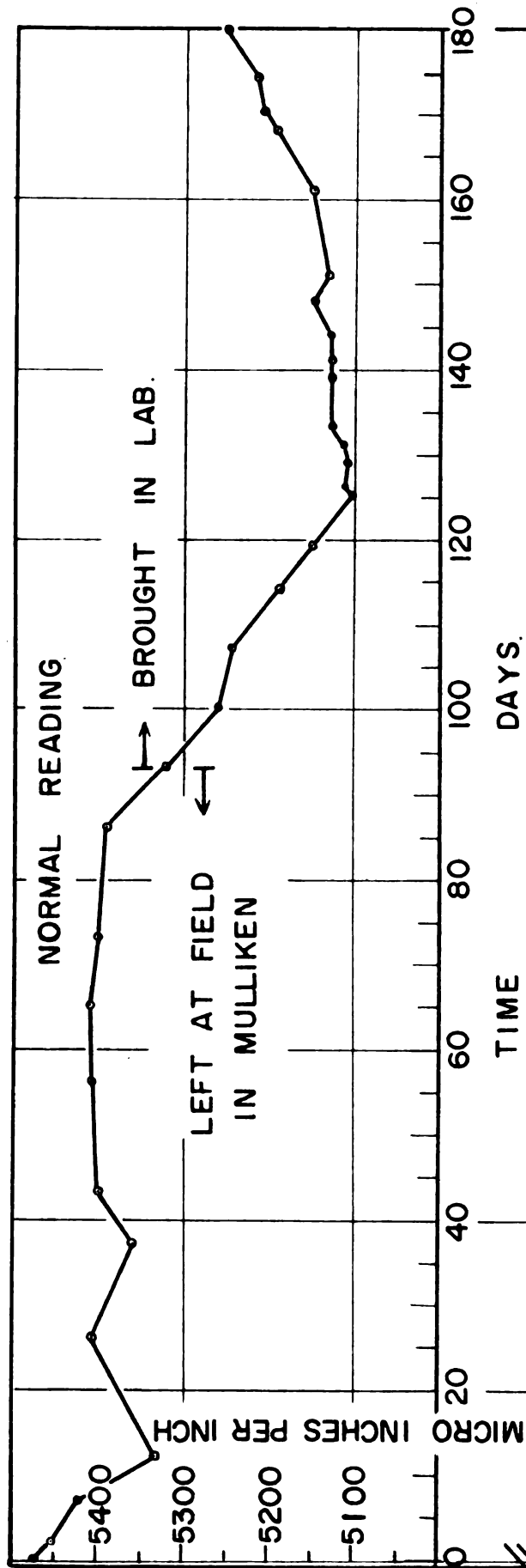
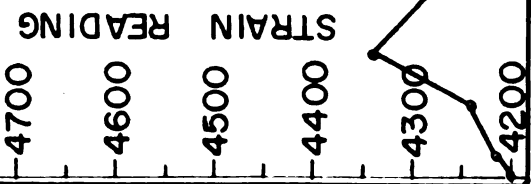


FIGURE 12. STABILITY OF THE PRESSURE TRANSDUCER WITHOUT LOADING (D - 4)



and results shown (Figure 11). It was found that four of the transducers had a limited range of change (70 micro inches per inch) in output while unstressed. Two transducers were found unsatisfactory. The failure of two transducers was attributed to poor moisture-proofing.

Transducer D-4 was also checked for long-time stability. This transducer was left at the W & B Farm in Mulliken, Michigan for three months and then brought to the laboratory completely unloaded. The change in strain readings was continuously observed for six months. The results, both normal and reversed readings, were shown in Figure 12. It indicates that the variation in strain readings was not due to zero drift or temperature effect (this will be verified later) but from creep and other unknown sources. The maximum range of this variation was 360 micro inches per inch which would correspond to 3.0 psi of calibrated sensitivity. This variation was considered too high.

Stability with constant loading. One transducer was used for testing the effects due to constant loading. The transducer was assembled on the hydraulic pressure calibration apparatus and pressures of 10, 20, and 30 pounds per square inch were applied separately over a period of 25 days. The change in strain readings was continuously observed. This result was shown in Figure 13. It was found that for pressure up to 20 psi, the change was small and tended to approach the constant decrease in output of 150 micro inches

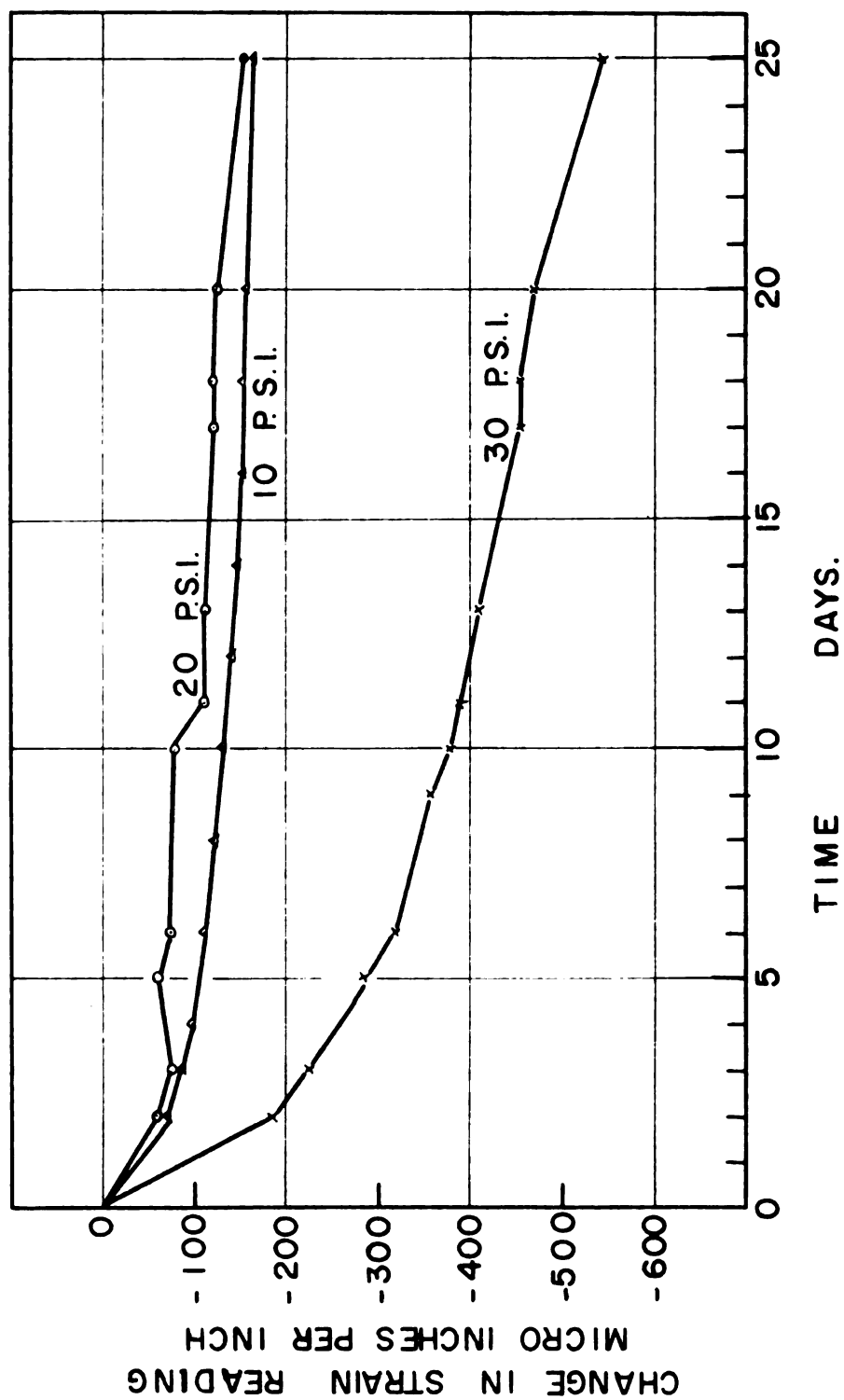


FIGURE 13. A TRANSDUCER UNDER CONSTANT PRESSURES

per inch after 25 days of continuous loading. From the constant pressure of 30 psi the strain reading decreased rapidly during the first few days and then decreased almost constantly at the rate of 10 micro inches per inch per day after sixth day of loading. The reason for this variation might be due to the relaxation of the bond of the cement between the gages on the diaphragm.

Effects Due to the Change in Temperature

The same hydraulic pressure calibration apparatus was used in this test except that the temperature of the water was changed. The setup of this test was shown in Figure 14 and 15. The temperature of the water was measured by a thermocouple placed under the diaphragm in the pressure chamber and indicated by a potentiometer. Both a two arm bridge and a four arm bridge were calibrated under water pressure with changes in water temperature. The result from the four arm bridge transducer was shown in Figure 16. The designed transducer proved to be insensitive to changes in temperature.

Effects Due to the Materials in Contact with the Diaphragm

As silage is a non-uniform, non-homogeneous material, the relation between hydraulic pressure calibration and silage in direct contact with the diaphragm was desired. The test apparatus is shown in Figure 17. Six transducers were firmly placed at the bottom of the circular tank. The inner tube of a 4 x 8 inch trailer tire was placed on the

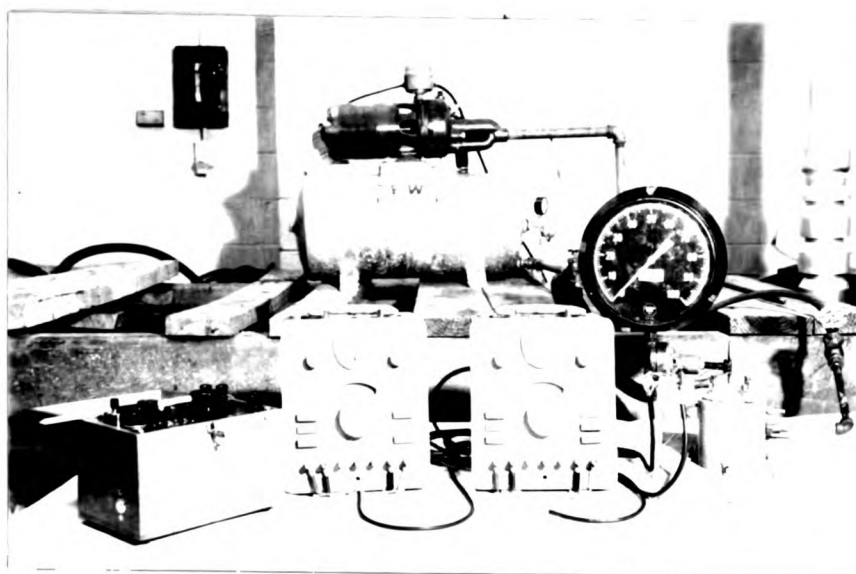


Figure 14. Calibration set up for temperature effect on output of transducers with two-arm bridge.

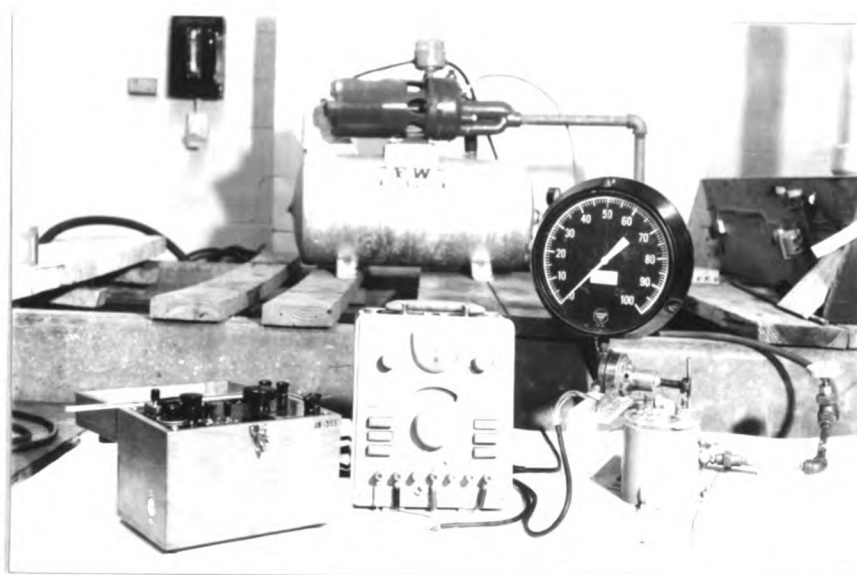


Figure 15. Calibration set up for temperature effect on output of transducers with four-arm bridge.

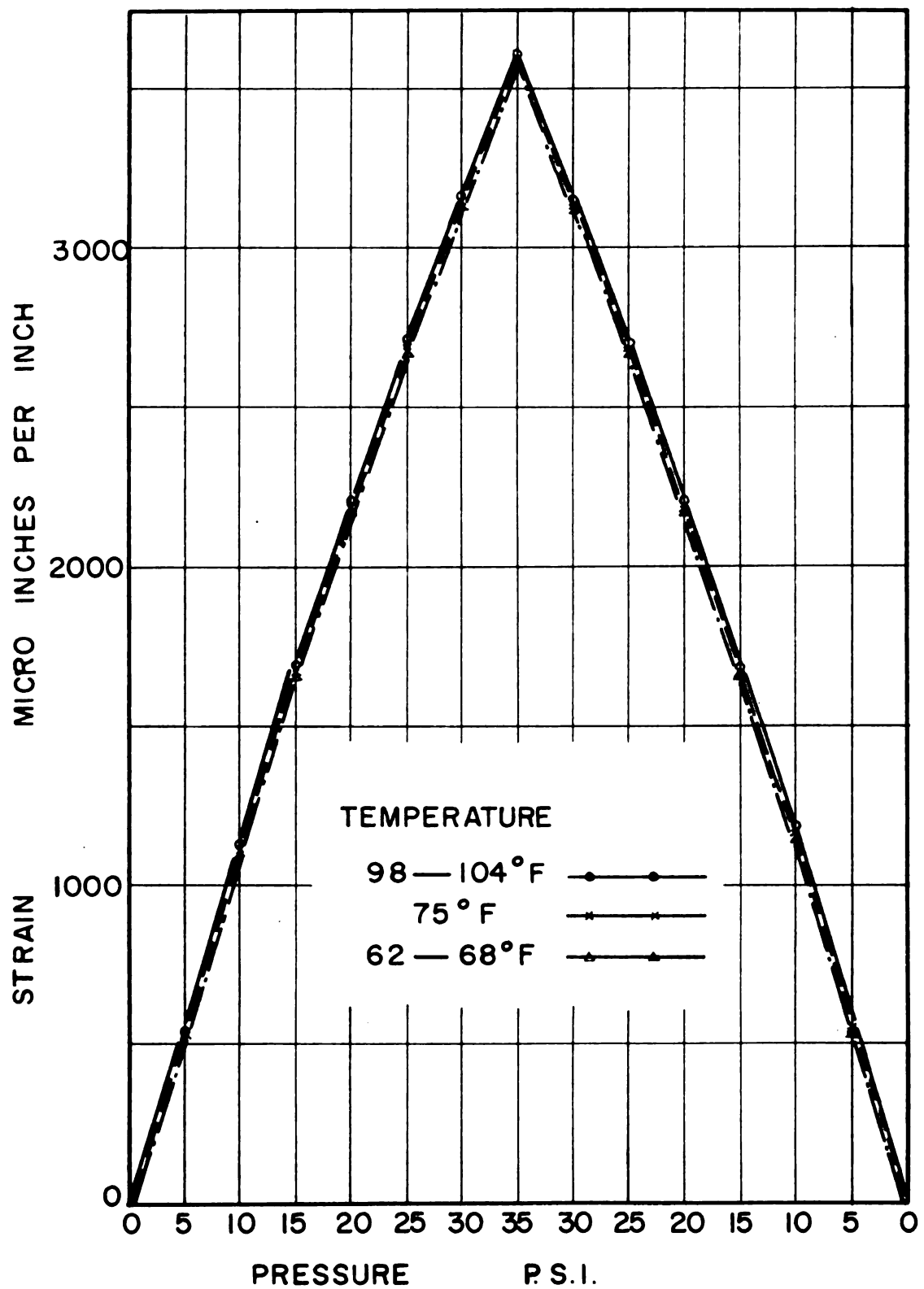
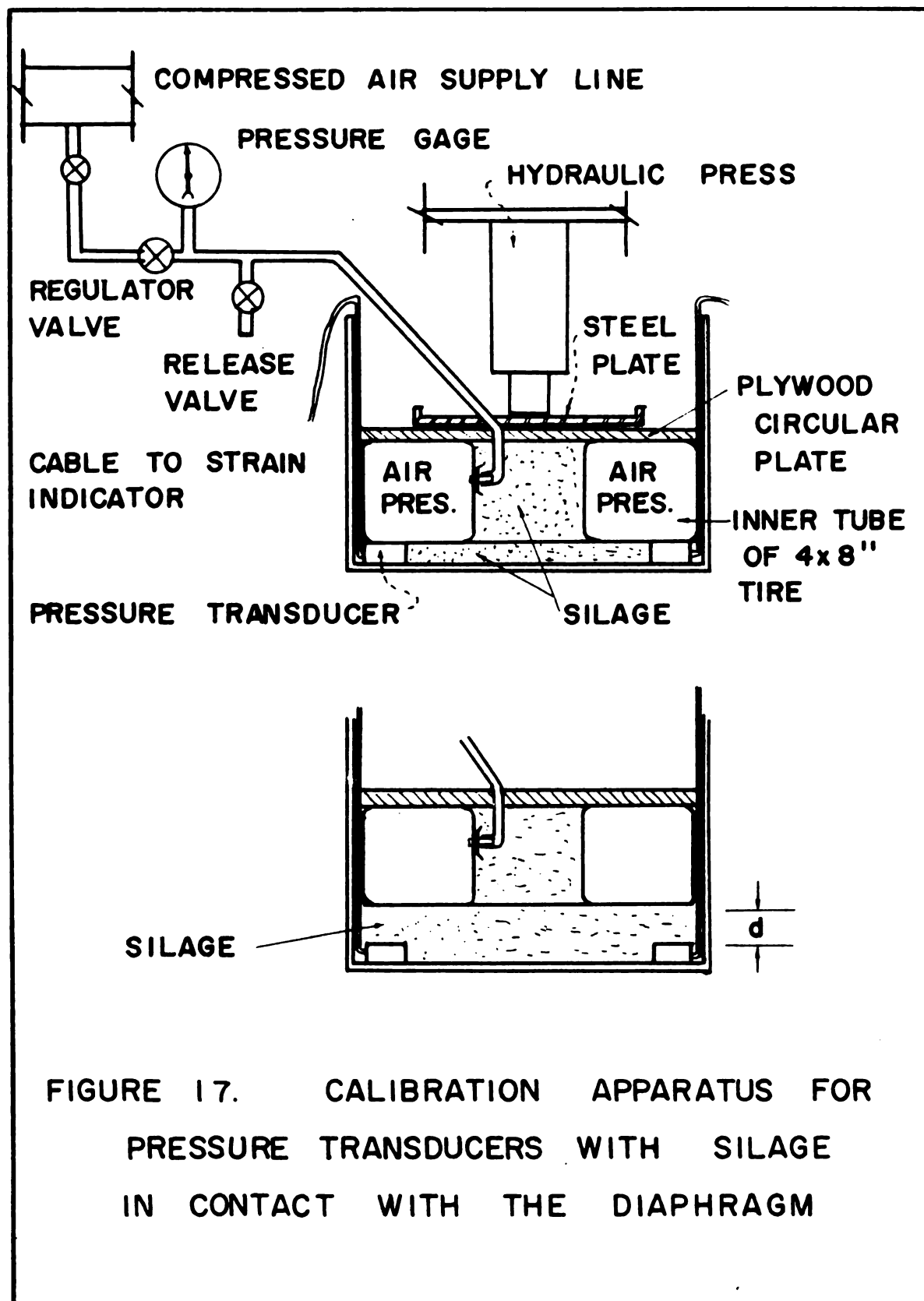


FIGURE 16. TEMPERATURE EFFECT



transducers under the circular plate held firmly in place by the hydraulic press. Silage was placed in all the open spaces, before the circular plate was put on. Different depths of corn and grass silage between the diaphragm and the tube was tested. A known pressure was applied to the tube from the compressed air supply line, and the strain was measured. The results were shown in Figure 18 and 19. It was found that the slope of the curve was greater than that of the hydraulic pressure calibration, for silage of one inch depth was placed between the diaphragm and the pressure source. When the depth of the silage was increased, the strain output decreased. This was due to the fluffy condition of the silage, which continued to condense without much pressure transmitted to the diaphragm of the transducer at first. It was found that the output of the pressure transducer with corn or grass silage of one inch depth in contact with the diaphragm was higher than that without them. The comparison of the calibration curves obtained from the hydraulic pressure calibration and the calibration with silage in contact with the diaphragm was shown in Figure 20.

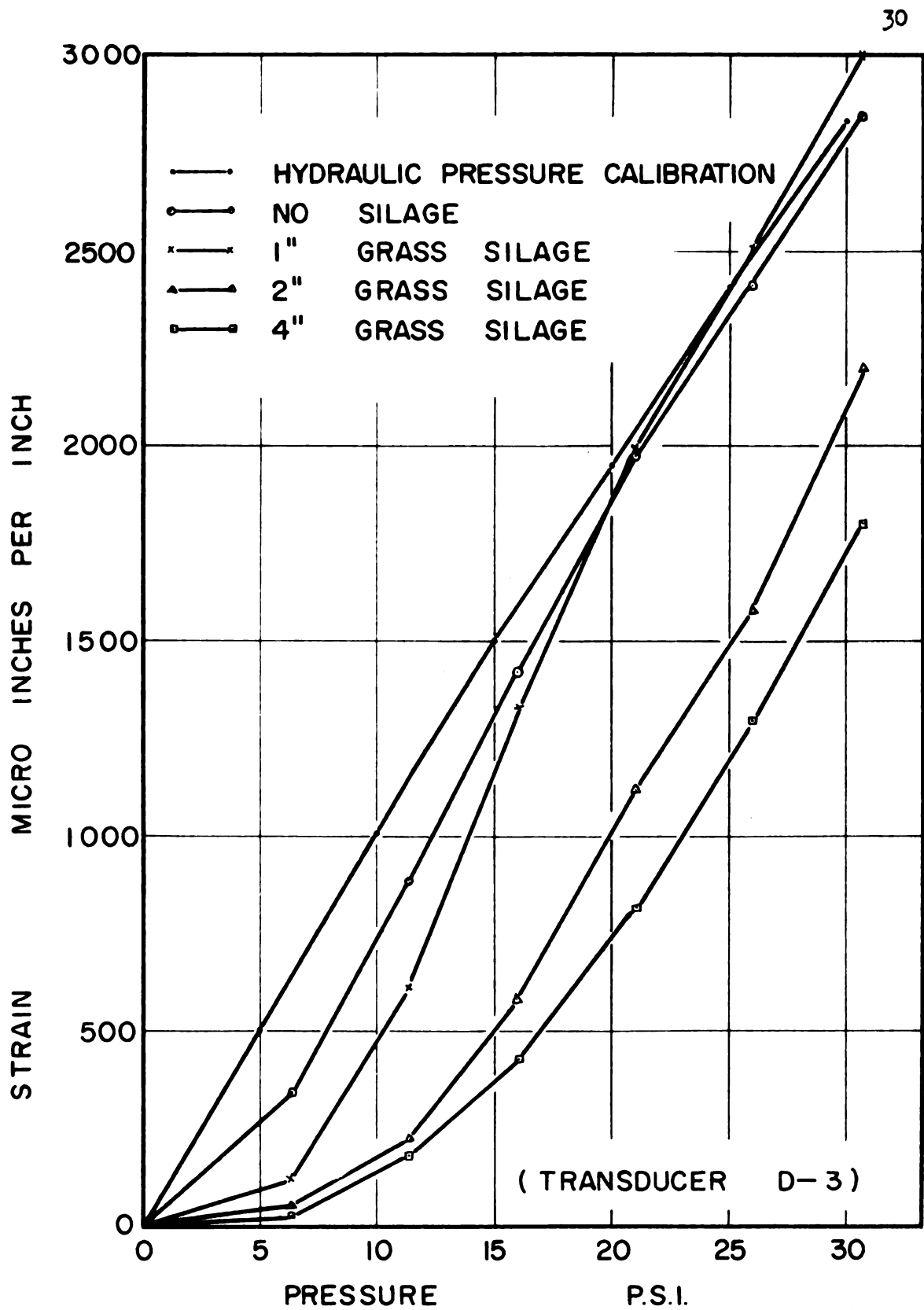


FIGURE 18. CALIBRATION CURVES WITH DIFFERENT DEPTH OF SILAGE IN CONTACT WITH TRANSDUCER

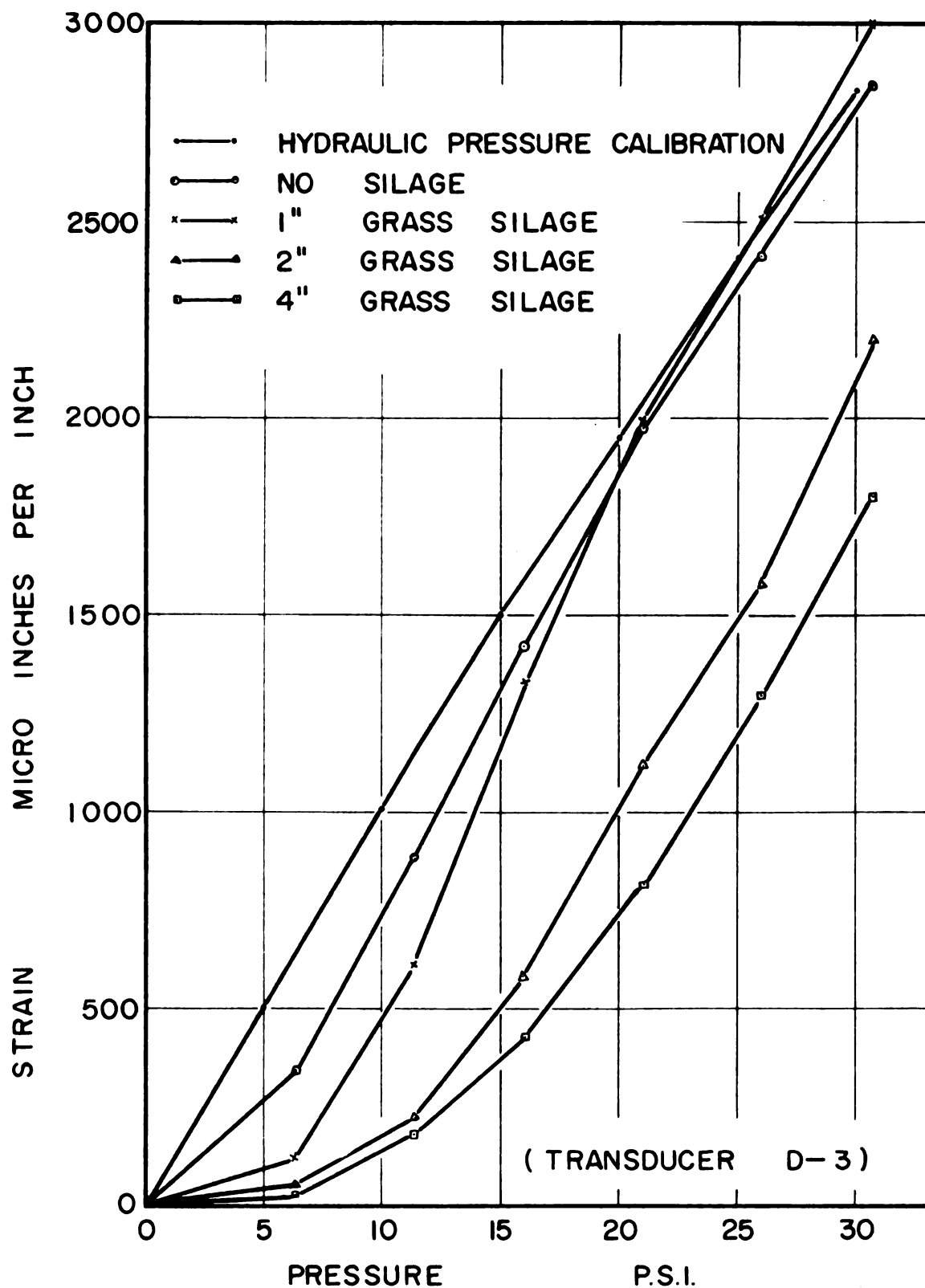


FIGURE 18. CALIBRATION CURVES WITH DIFFERENT DEPTH OF SILAGE IN CONTACT WITH TRANSDUCER

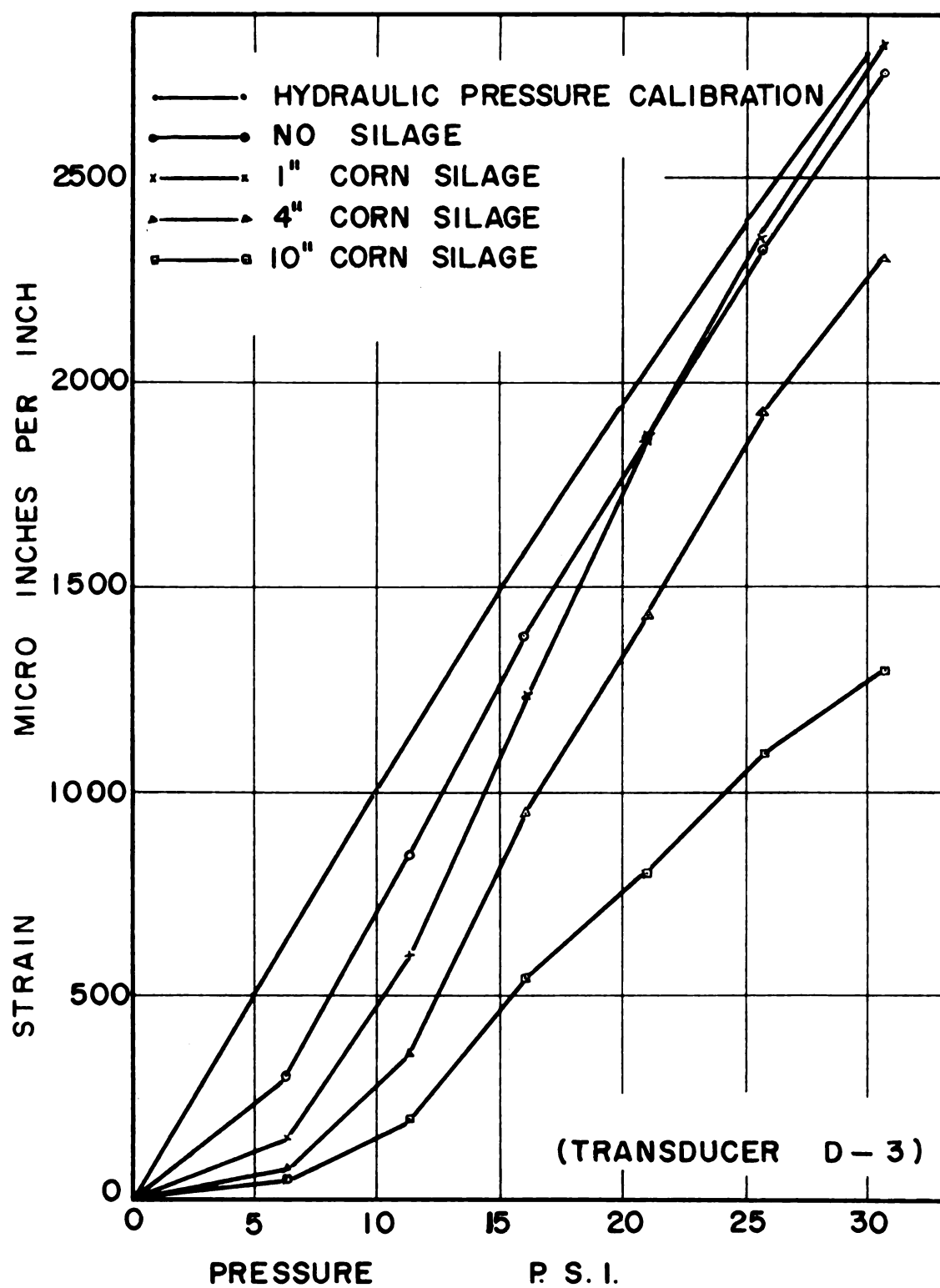


FIGURE 19. CALIBRATION CURVES WITH DIFFERENT DEPTH OF SILAGE IN CONTACT WITH TRANSDUCER

TRANSDUCER D-3

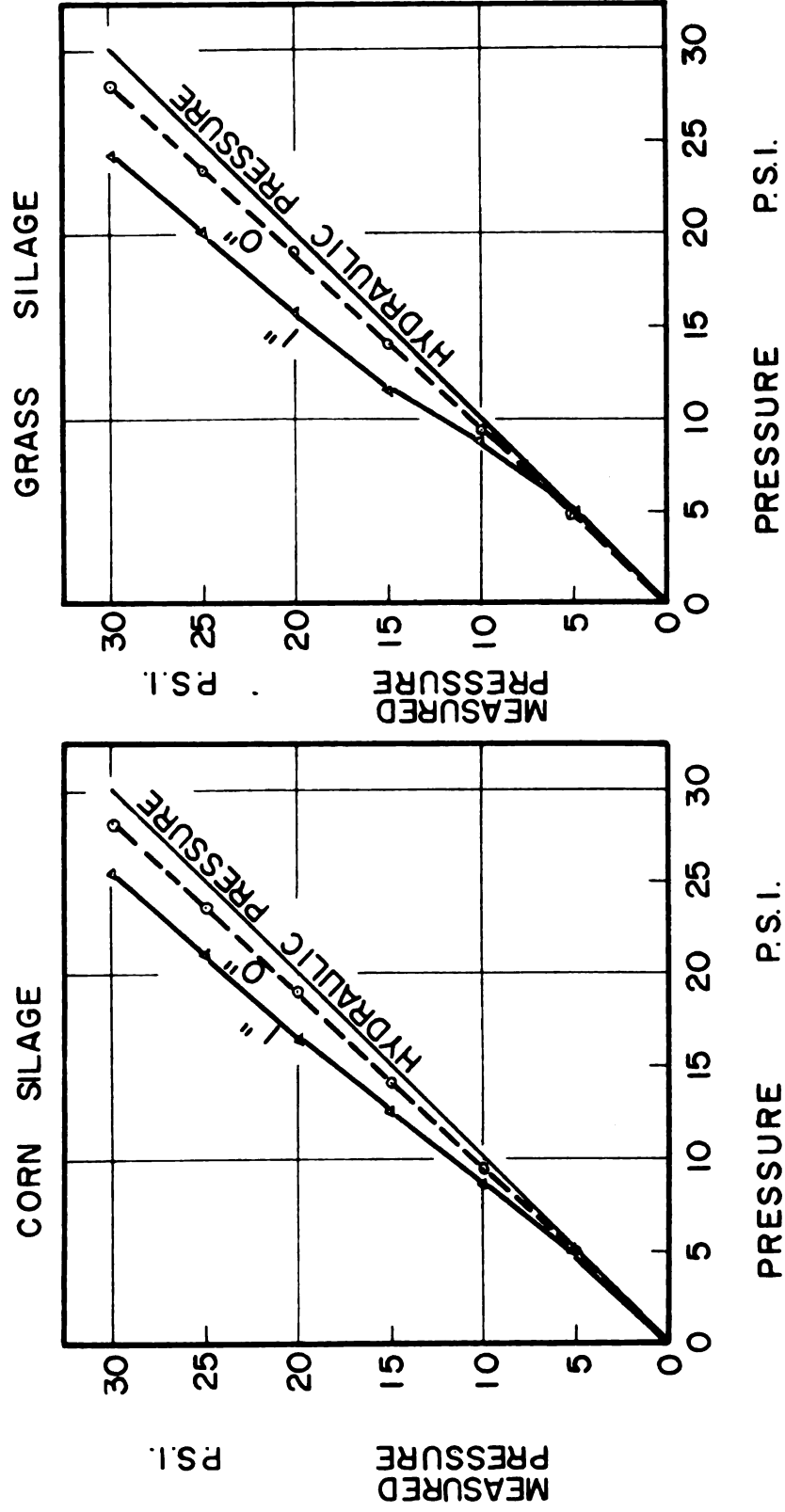


FIGURE 20. CALIBRATION CURVES WITH SILAGES IN CONTACT WITH DIAPHRAGM COMPARED WITH HYDRAULIC PRESSURE CALIBRATION

APPLICATION OF PRESSURE TRANSDUCERS TO MEASURING SILAGE PRESSURES

Thirty-one transducers of the type described in the previous chapters were built for the measurement of silo pressures during the Summer in 1959. Owing to the limit in the harvesting time of corn silage, those pressure transducers were installed in the silo right after they were calibrated against the known hydraulic pressure. The excellent calibration curves were obtained and reproduced in successive calibrating runs. Those pressure transducers were installed in the wall at 0', 2.5', 5', and 10' in four projections, with one at 20' and one at 30' above the bottom of the silo. The silo was 30' x 60' in size and located at B & W Farm, in Mulliken, Michigan. Transducers were embedded in the corrugated concrete staves with their diaphragm surfaces flush with the inside face of the staves. The new staves were installed in place of old staves. As there was 2.5 feet corn silage left in the silo, the silage was dug out to install the transducer at 0' elevation and refilled again after the transducer was installed. Another 13 transducers were installed on the top surface of the corn silage in the silo along two diameters perpendicular to each other and 5' apart. All the leads were brought out of the silo into a shelter and connected to the Young's Strain Indicator.

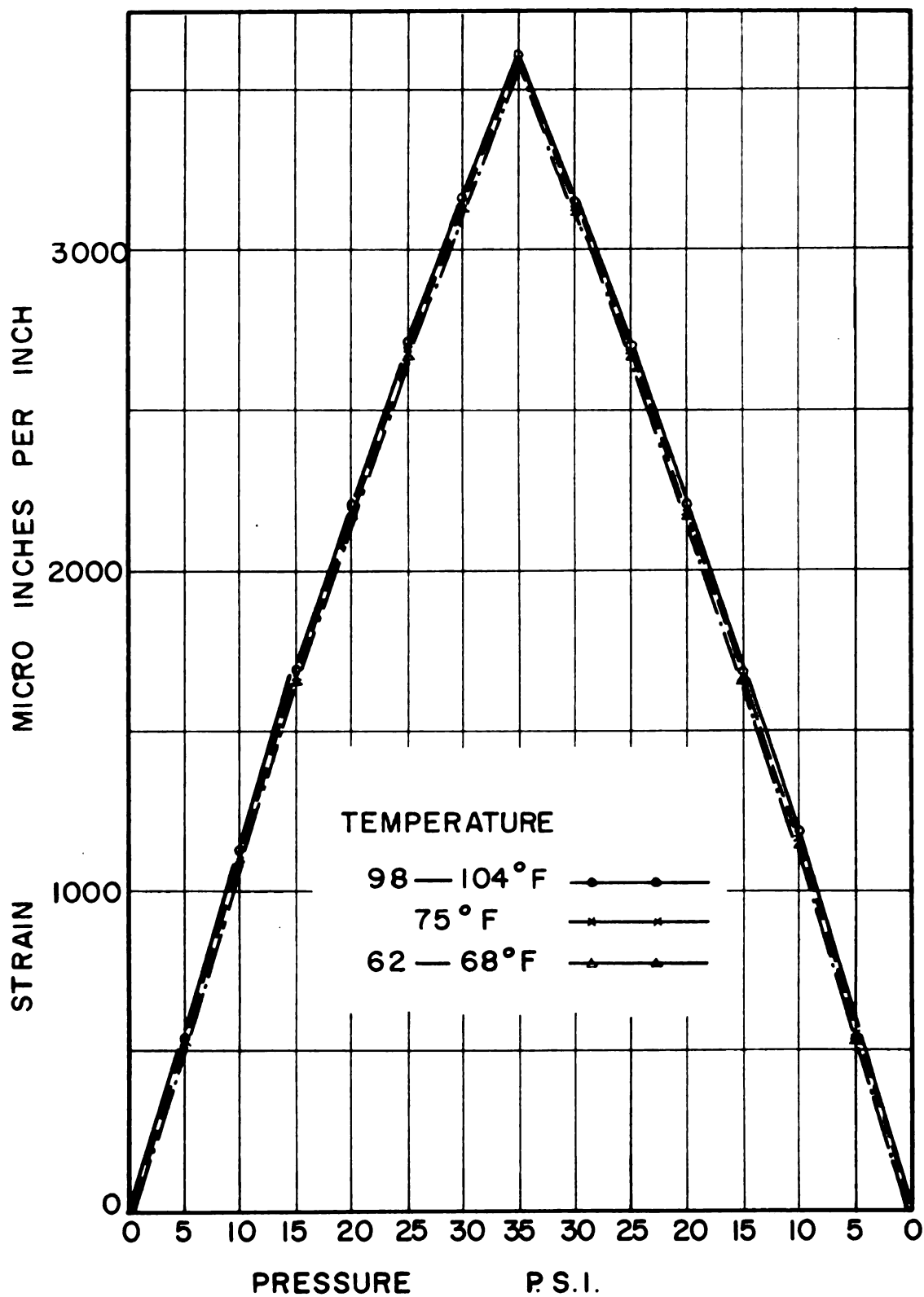
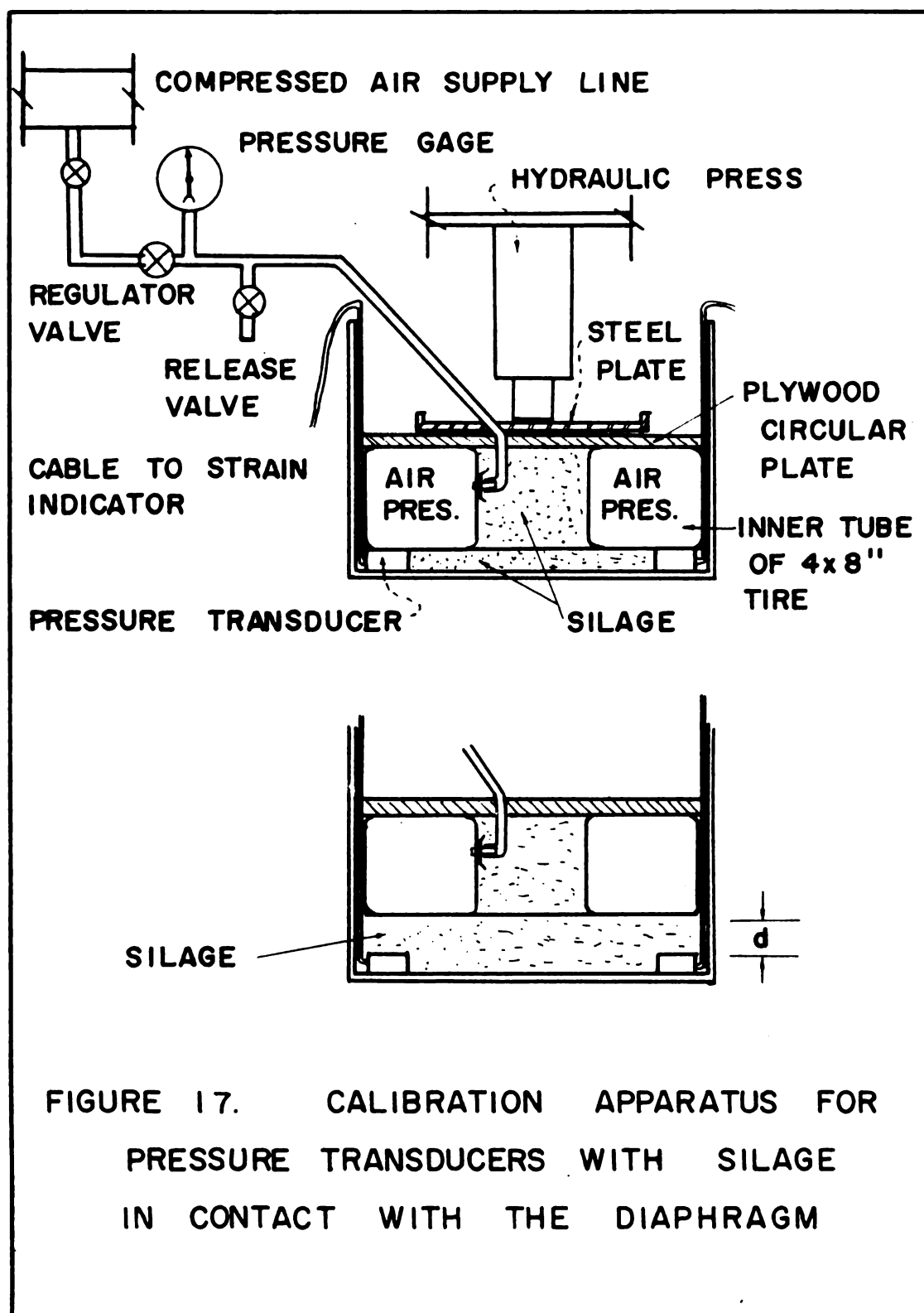


FIGURE 16. TEMPERATURE EFFECT



transducers under the circular plate held firmly in place by the hydraulic press. Silage was placed in all the open spaces, before the circular plate was put on. Different depths of corn and grass silage between the diaphragm and the tube was tested. A known pressure was applied to the tube from the compressed air supply line, and the strain was measured. The results were shown in Figure 18 and 19. It was found that the slope of the curve was greater than that of the hydraulic pressure calibration, for silage of one inch depth was placed between the diaphragm and the pressure source. When the depth of the silage was increased, the strain output decreased. This was due to the fluffy condition of the silage, which continued to condense without much pressure transmitted to the diaphragm of the transducer at first. It was found that the output of the pressure transducer with corn or grass silage of one inch depth in contact with the diaphragm was higher than that without them. The comparison of the calibration curves obtained from the hydraulic pressure calibration and the calibration with silage in contact with the diaphragm was shown in Figure 20.

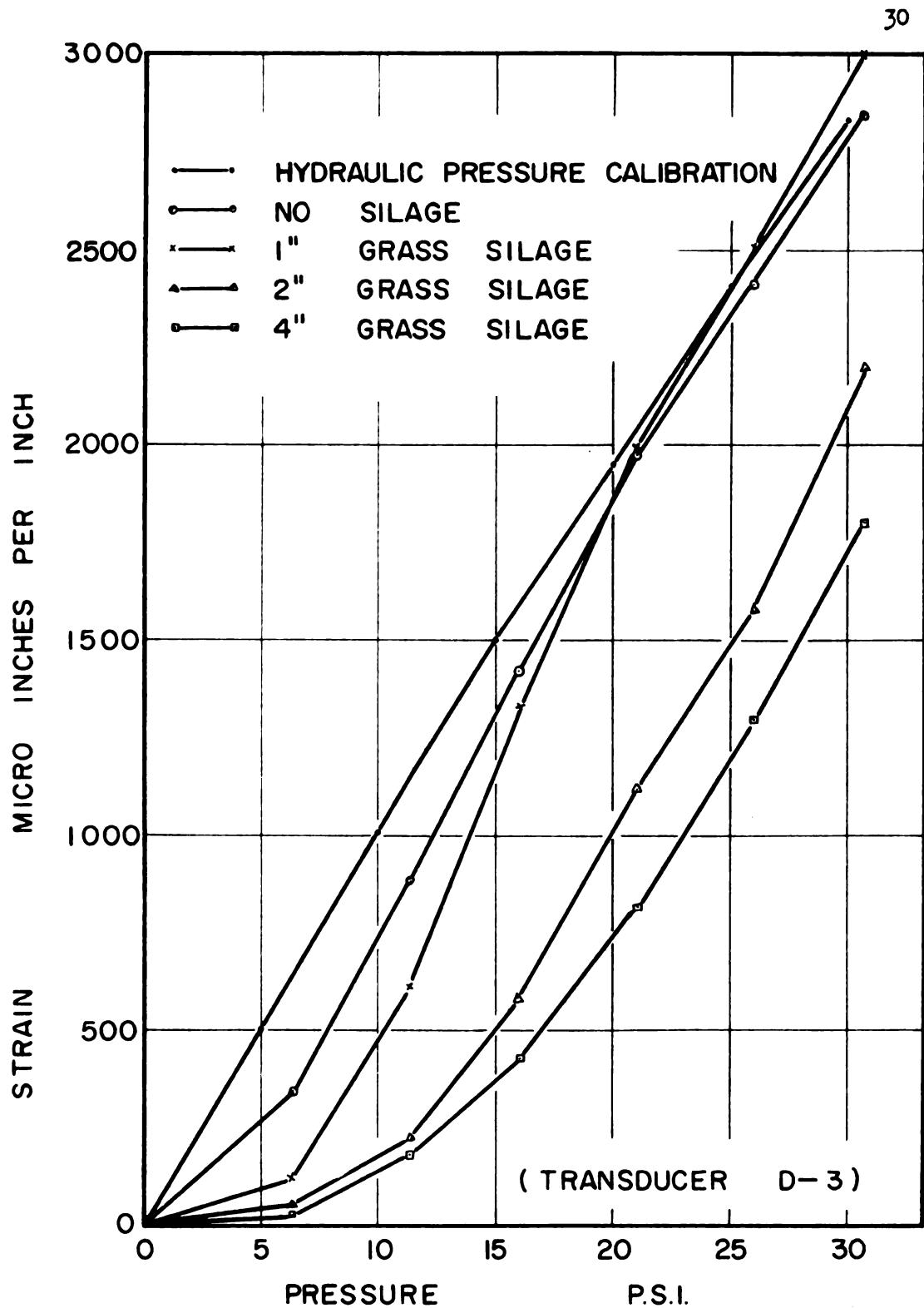


FIGURE 18. CALIBRATION CURVES WITH DIFFERENT DEPTH OF SILAGE IN CONTACT WITH TRANSDUCER

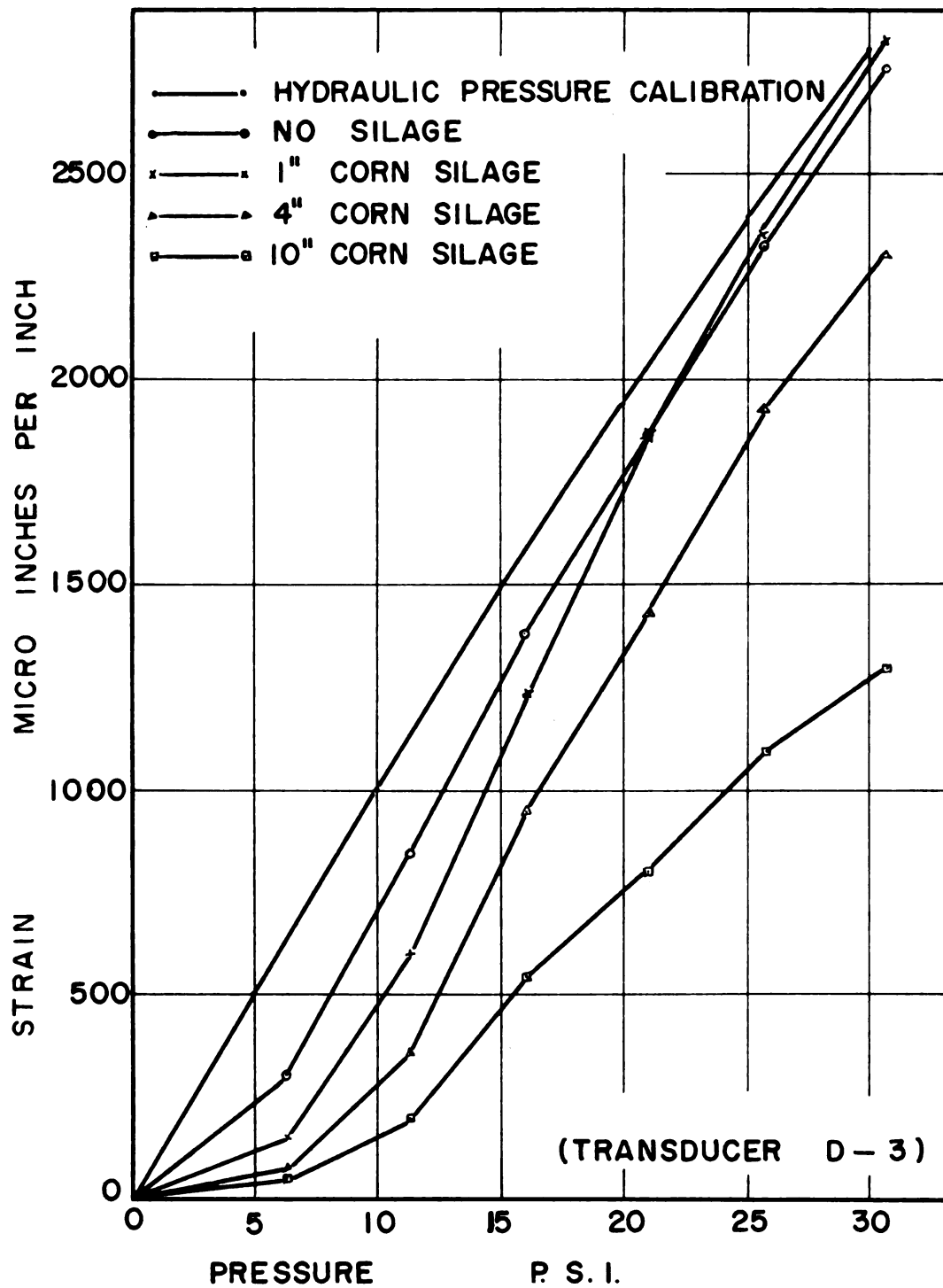


FIGURE 19. CALIBRATION CURVES WITH DIFFERENT DEPTH OF SILAGE IN CONTACT WITH TRANSDUCER

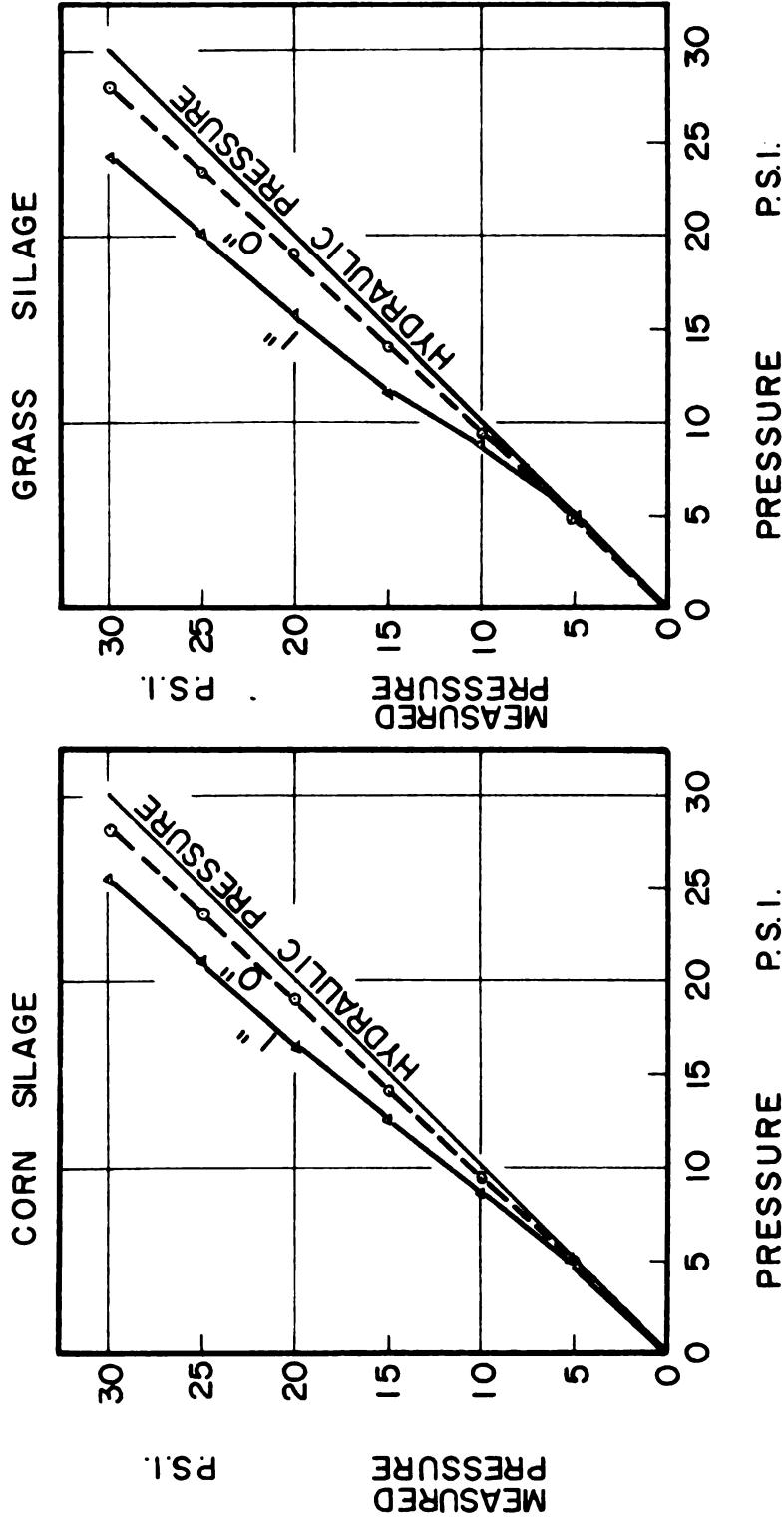


FIGURE 20. CALIBRATION CURVES WITH SILAGES IN CONTACT WITH DIAPHRAGM COMPARED WITH HYDRAULIC PRESSURE CALIBRATION

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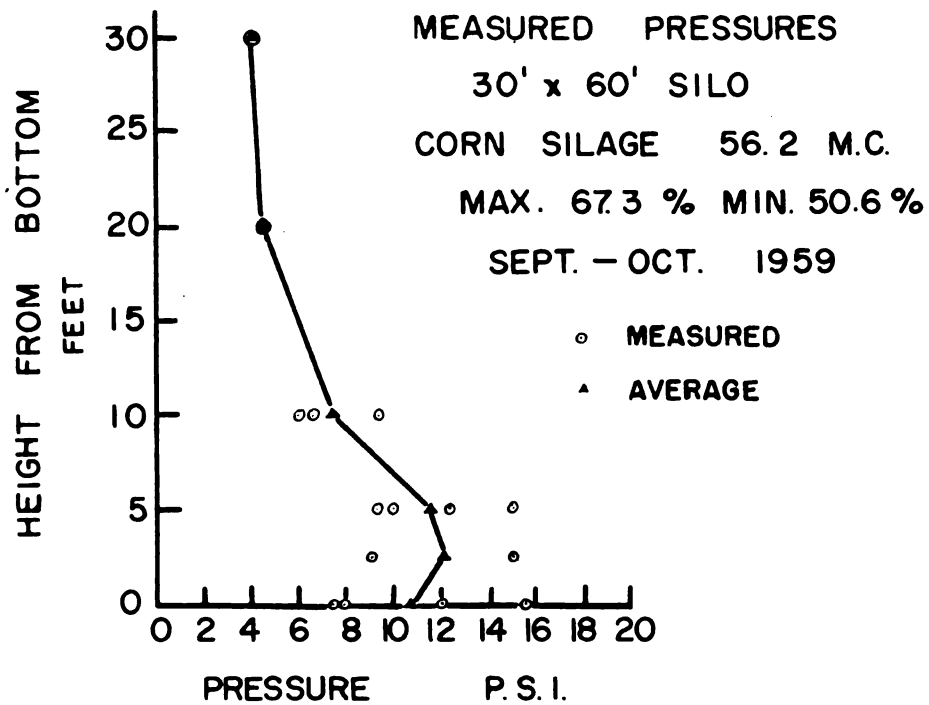


FIGURE 21. HORIZONTAL PRESSURE

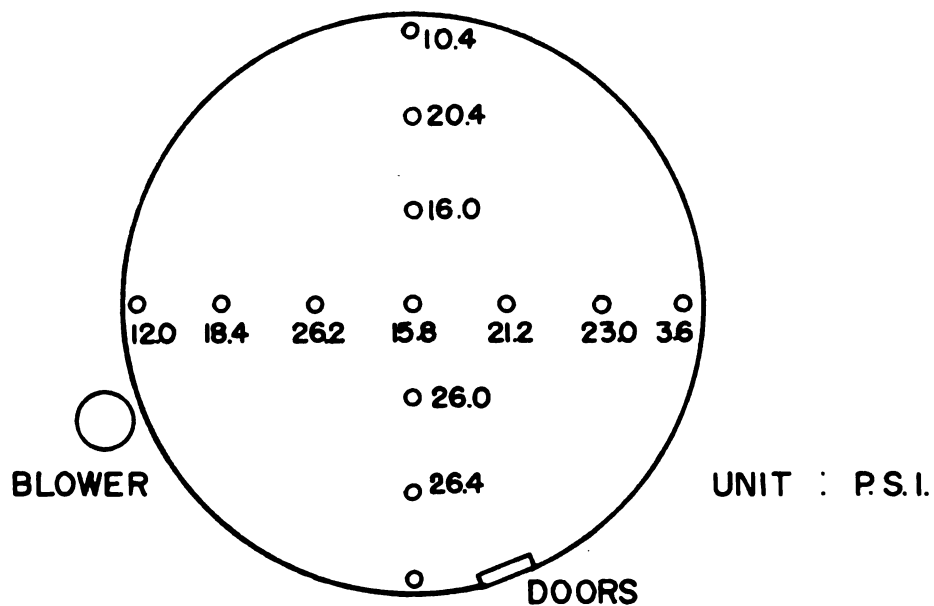


FIGURE 22. VERTICAL PRESSURE

The pressure, both on the wall and on the bottom, was measured during filling and emptying.

During the filling period the pressure increase was found hard to plot against the increase in depth of silage due to its settlement. The pressure distribution, when the silo was full to the height of 60', was shown in Figure 22 and 21. It was found that the horizontal pressure at 0' was lower than that at 2.5' and 5'. This could be due to the effect of soft backfill during the installation of the transducers. The pressure on the bottom showed an interesting distribution. By using an Even-flo Distributor, silage was found to be fairly well distributed in the silo and formed an inverse cone at the center of the silo. The pressure on a ring area five feet from the wall was higher than the pressure at the center or at the wall.

The pressure was continuously observed during the feeding out period. After the silo was emptied seven transducers tended to creep and failed to give reliable results. The data from the good transducers was summarized and shown on Figure 23 and 24. The pressure at each depth of silage has a wide range of variation and does not follow the uniform distribution. From the irregular distribution of the pressure in the silo, transducers will remain as the best means for this type of pressure measurement as long as the stability over a long period of time could be assured. The mathematical mean pressure was calculated and shown on Figure 24. It read 6 psi at 60' of corn silage, and had fairly smooth distribution against the depth of the silage.

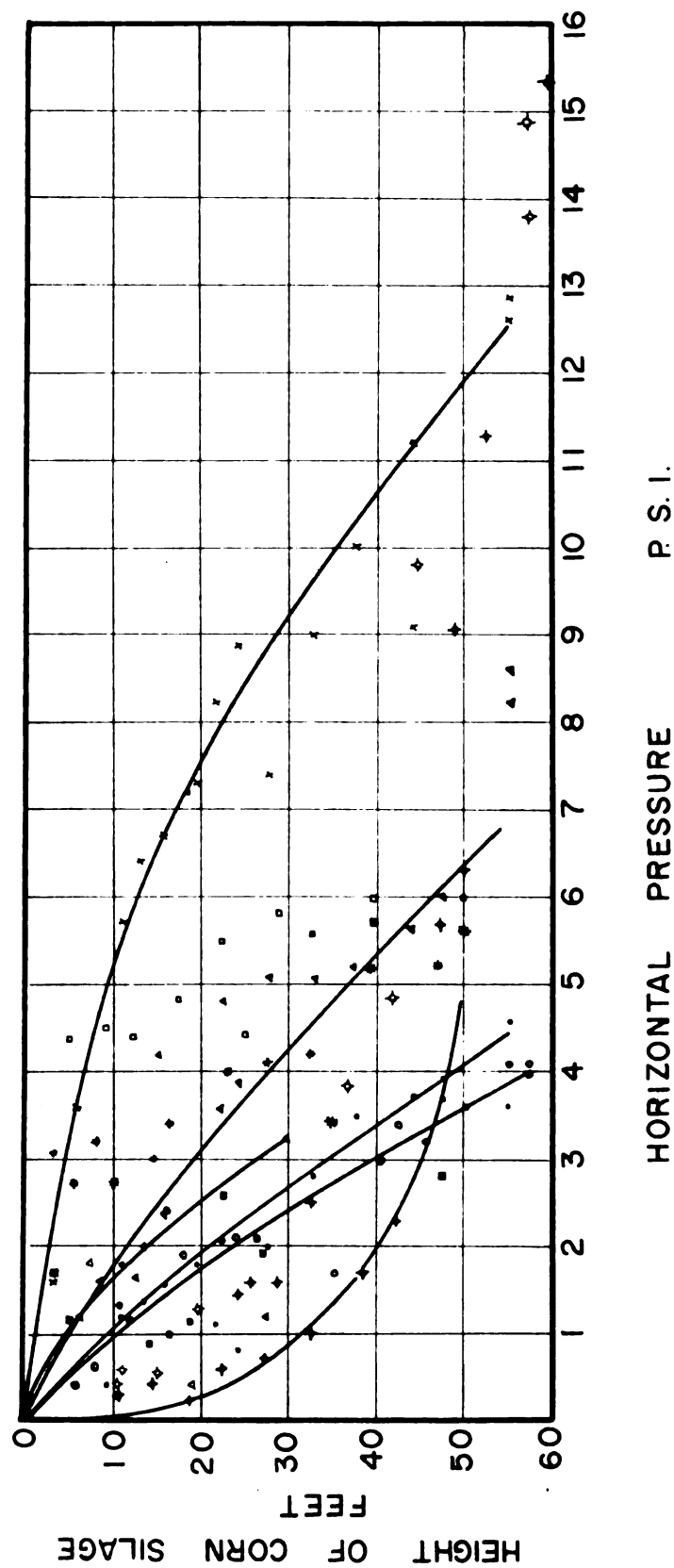


FIGURE 23. HORIZONTAL PRESSURES MEASURED ON THE WALL OF
30' X 60' SILO WITH CORN SILAGE

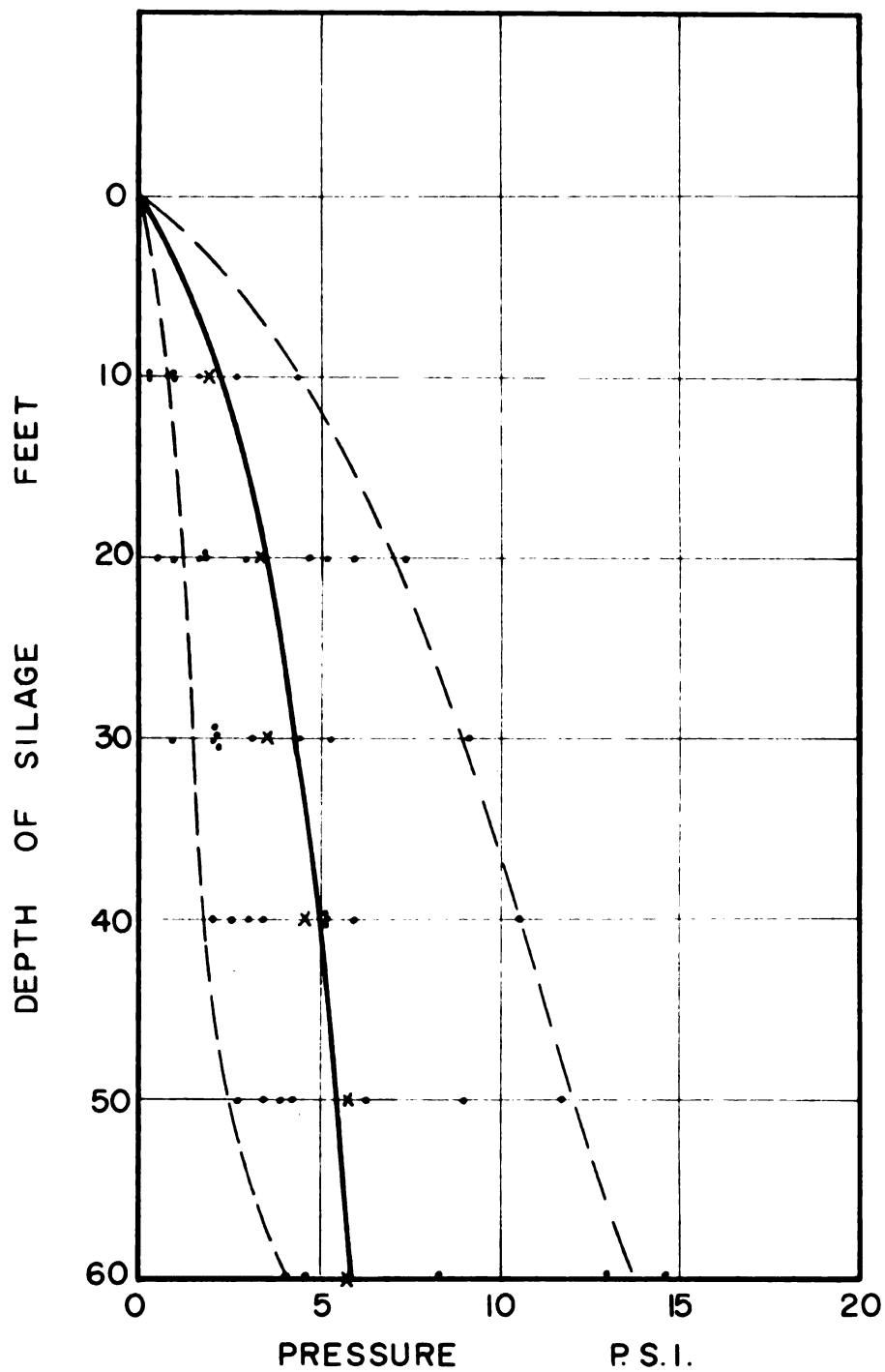


FIGURE 24. SUMMARY OF HORIZONTAL PRESSURE MEASURED ON THE WALL OF 30' X 60' SILO WITH CORN SILAGE

SUMMARY AND CONCLUSION

In view of the non-homogeneous and non-uniform property of silage stored in silos, multiple point measurement of pressure is desired. In addition to this, high sensitivity and facilities for remote control is required.

The pressure transducer made of SR-4 A-18 strain gages was built and checked. Gages were cemented to the back of a thin stainless steel diaphragm rigidly clamped on a brass body. The transducer was calibrated against known hydraulic pressure up to 36 psi; its stability observed with and without loading; calibrated against known pressure under different temperatures; calibrated against known pressure with silage in contact with the transducer diaphragm.

Thirty-one transducers were made and installed in the wall and on the bottom of a 30' x 60' silo.

The characteristics of transducers were summarized as follows:

1. The curves obtained from the hydraulic pressure calibration were excellent. It was reproduced with high accuracy in successive runs.
2. The output of the transducer was insensitive to a change in temperature.
3. The output measured with silage in direct contact with the transducer diaphragm was found correct

below 5 psi and 9 per cent higher at 10 psi than that measured from the hydraulic pressure calibration.

4. Stability without loading was observed for six transducers over a period of two months. Four of them had a change less than 90 micro inches per inch in two months. The other two tended to creep. One transducer remained unloaded for 180 days and the strain readings observed continuously. The maximum variation in zero pressure readings was found to be 360 micro inches per inch over 180 days and was considered too high. The stability of a transducer under constant pressures of 10 and 20 psi was satisfactory. Change in readings tended to approach a constant decrease in output of 150 micro inches per inch. Measuring strains at a constant pressure as high as 30 psi was found unsatisfactory.

RECOMMENDATIONS FOR FURTHER STUDIES

1. Diaphragm gages should be studied to replace the paper based gages.
2. Bakelite type gages as well as bakelite type cement should be investigated in building the transducers.
3. Stability of the transducers should be reviewed more thoroughly by using different glues in cementing the gages.
4. The complete moisture-proofing should be investigated.
5. Other remote controlled pressure measurement devices should be reviewed.

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