INSTRUMENTATION AND MEASUREMENT OF SOIL-TIRE CONTACT PRESSURES

Thesis for the Degree of M. S.

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Kay Victor Lask

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INSTRUMENTATION AND MEASUREMENT OF SOIL-TIRE CONTACT PRESSURES

by

Kay Victor Lask

AN ABSTRACT

Submitted to the College of Agriculture of
Michigan State University of Agriculture
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Department of Agricultural Engineering

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KAY VICTOR LASK AN ABSTRACT

The design, development, and mounting of strain gage pressure cells to measure the pressure distribution at the soil-tire interface under a rear tractor tire are described. Two types of cells were constructed. The CST-1 cells were mounted in the lugs of the tire, and the diaphragm cells were mounted in the tire undertread.

The cells were arranged in two general groups in the tire according to the type of data desired. One group was arranged for pressure distribution studies and the other group for traction studies. Several series of data were taken using three different tire pressures. Each series used a different cell arrangement. The diaphragm cells operated more satisfactorily than the CST-1 cells.

The data were tabulated, averaged, and plotted to show pictorially the pressure distribution at the soil-tire interface. Separate curves were plotted for the lug and undertread data. It was found that using three cells per lug did not give a complete picture of the pressure distribution and that at least five cells per lug were necessary. It was also found that the total number of cells needed to obtain the desired information could be reduced to a minimum of twenty. The data confirmed the findings of an earlier investigator that most of the wheel load was carried by the lugs even in a loose soil.

The instrumentation of a tractor for traction studies is described.

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INTRODUCTION

Soil compaction is by no means a recent problem in Agriculture. History provides evidence that soil compaction existed in ancient times (Hovanesian 1958), but only recently has the agricultural worker paid much attention to the problem.

Soil compaction takes place wherever farming is carried on and is dependent on the type of soil, the kind of farming and the machines used. Since farm mechanization began some four decades ago, the problem has become acute and is now of major concern to farmers and soil scientists alike. Edminister (1956) states that the larger and heavier farm machinery and tractors in use today are slowly but surely destroying the structure of some of our best agricultural soils.

Weight alone, however, does not necessarily produce compaction (Vanden Berg 1958). Since changes in the bulk density of the soil are related to changes in the mean stress, the degree of compaction is dependent on how the weight and horizontal forces are transferred to the soil. In the case of a tractor, it depends on the size and shape of the tires which apply not only the weight, but also the wheel torque to the soil. Tests have shown that the tractor tire is compacting the soil (Seaton 1916, Gill 1956) and many people are engaged in trying to find a solution to the problem. Basic data concerning traction and the pressure distribution at the soil-tire interface must be gathered, analyzed, and translated into tire designs before a satisfactory answer will be reached.

While the pressure distribution under a tractor tire has been estimated (Soehne 1953), it has never been accurately measured. Likewise, much theoretical work has been done relative to tractive efficiency (Bekker 1955), but no one knows the actual value of lugs or the effect of pressure distribution on traction. Because of this lack of basic information, little has been done to alleviate the soil compaction problem.

The purpose of this investigation was to supply information concerning the soil-tire interface pressures and the tractive efficiency of a tire. To do this it was necessary to design and construct a pressure transducer which would be capable of measuring the pressure distribution under a tractor tire as it rolls over the soil, and the thrust or pressure on the lug as the tire develops traction in the soil.

It is the author's hope that the development of these transducers will aid in accurately determining the relative merits of the existing tires and that the information gathered now and in the future will lead to the construction of a tractor tire which will reduce soil compaction to a minimum while providing optimum tractive efficiency.

II REVIEW OF LITERATURE

Investigations of tractive efficiency were begun shortly after the appearance of the steam traction engine. Aitkenhead (1920), stated that power was useless without effective traction and that " the search for the wheel of universal utility will lead to a type which successfully lays a plank and rolls on it." He further stated that tractor wheels must be properly designed to operate effectively.

During the twenties investigators such as Blasigame (1922), and Randolph (1926, 1927) studied steel lugged wheels and their relation to traction. Various laboratory and field tests were conducted to determine the best type of lug, width of rim and wheel size.

Josephson (1928) first reported work comparing steel wheels and rubber tires. He found that the tires gave little traction on moist surfaces and were not suitable for plowing. He also stated that rubber tires packed the soil more than steel wheels and that rubber tired front wheels made the tractor hard to steer.

Reed and Berry (1949) reported that the first pneumatic tires used on tractor drivewheels were field tested in April of 1932. These tires were designed for a bomber which crashed on its first flight and rather than let the tires go to waste, the manufacturer decided to test them on a tractor. These field tests looked promising and consequently the first pneumatic tires designed especially for a tractor were made available three to four months later. These early tires were operated at pressures of 50 to 90 psi (Brunner 1933), but in late 1932 and early 1933 a low pressure tire operating at around

12 to 15 psi was introduced. These low pressure tires had a great many advantages over the early steel wheels and their appearance greatly broadened the usefulness of the tractor.

The introduction of these new low pressure tires spurred a wave of investigation into the relative merits of steel lugged wheels and rubber tires. Investigators such as Shields (1933), Hurlbut (1933), Smith (1934, 1935) and others (McCuen 1933, Jones 1934) made extensive comparative tests between the two types of wheels. Some of the tests were similar in nature and some varied widely in their scope, but the reported results were practically all the same. The rubber tired tractors had better fuel economy, greater drawbar horsepower output, they could be operated at higher speeds, and they reduced soil compaction. Other advantages listed were operator comfort, greater versatility of the tractor, and they could be operated on improved roads and in yards and barns. In general the investigations can be summed up in the following statement made by Jones (1934). 'It seems certain . . . . that the field for rubber tires is large enough to warrant continued and intensive engineering study, and to justify vigorous, though discriminating commercial exploitation.'

In early 1934 an editorial in Agricultural Engineering called for an end of the comparative testing of steel wheels and rubber tires. It stated that the tractors then in existence were not built for rubber tires, and that a completely new tractor should be designed to use the new tires. It further stated that an investigation into the engineering properties of rubber tires should be made to provide data for the design of this new tractor. The new tractors were designed and built, but up to this present hour little if any engineering data on tractor tires can be found. In the intervening years from 1934 to the present little was done to gather data on rubber tractor tires with the exception of work done by Reed and Berry (1949) and Reed and Shields (1950).

Soehne (1952), a German Agricultural Engineer, published several papers on soil compaction and related subjects. Two of these papers dealt with the relation of tractor and implement tires to compaction and pressure distribution in the soil, and presented some of the first concrete engineering data and observations on the subject. Soehne found that the average pressure exerted by the lugs of a tractor tire in firm soil is four to five times as large as the average pressure for the entire contact area between the tire and the soil. He also found that the pressure was greater at the edges of the tire rather than at the center due to the stiffness of the tire carcass. This last phenomenon was particularly noticeable at lower tire pressures.

In yielding soils he found that the deeper the tire track the smaller the average surface pressure became and that its distribution was less uniform. Soehne further stated that:

> The softer the soil, the smaller may be the tire pressure. On the other hand the soil deformation, that is the track depth, for equally firm soils is as much smaller as the tire is soft. Two characteristic differences exist between tire and soil deformation. The tire is deformed elastically, that is apart from friction, no energy is lost. The friction loss is very small compared to the total energy involved. The soil deformation on the other hand is essentially a plastic deformation in which the energy involved in deformation is not returned. It is therefore

> important to try to make the elastic deformation of the tire large, by reducing tire pressure in order to minimize the plastic deformation of the soil, which expends rolling energy and produces rolling resistance.

Also in a yielding soil it is conceivable that the soil will deform plastically to such a large extent that only a slight difference in pressure exists between the lugs and the undertread.

By studying the cycloid of a wheel and the slippage of both a powered and unpowered wheel Soehne was able to make some observations about the relation between slippage and soil deformations. He found that for the same amount of slip the soil deformation is greater for larger diameter tires, and that there appears to be a linear increase in the distance of horizontal deformation across the tires as one moves from the front to the back with reference to the tire contact area.

M. G. Bekker (1955) has done a great deal of theoretical work concerning pressure distribution under a tire, tire flotation, and traction. It would be impossible to completely review this work here. Consequently, only a few of his most pertinent observations will be given. He states that tires with a flat tread may be considered better than those having a curved tread from the standpoint of more equal pressure distribution in the soil. However, due to the complexity of pressure distribution and without an analysis of tire deflection in various types of soil, the relative merits of available tire types cannot be determined.

With reference to traction Bekker (1955) stated that theory and experience indicate that lugs clog with soil when in contact with the ground and thus play an insignificant role in developing traction above a definite maximum in homogeneous soil. The main effect of lugs is to increase the wheel diameter and hence the commonly accepted desirability of self-cleaning lugs to provide better traction loses its significance. He further stated that if the soil is not homogeneous, the lug acts as a cutter to help dig the wheel through the soft unstable layers and reach the hard strata where sufficient traction may be developed and when this is accomplished the lug action is the same as described for a homogeneous soil. After considering various theories of lug action, he concluded that the size and form of the loading area as well as the load distribution are the factors of primary importance in wheel performance. Tread design, then, was only important as it affected the stiffness and related geometrical properties of a tire.

Some of the more recent work in the field of soil compaction has not been concerned with tires or traction. Cooper (1956) and Vanden Berg (1956) have developed and used a pressure cell to measure the pressures existing in the soil under tractor and implement traffic. The development of this cell has provided a means for testing the theoretical stress-strain relationship in the soil which has recently been proposed and more recently proven by Vanden Berg (1958). Work has also recently been completed by Hovanesian (1958) which provides an empirical relationship between the mean stress and bulk density in any soil.

III DESIGN AND DEVELOPMENT OF TRANSDUCERS

Since no known devices were suitable for the measurements to be made in this investigation, it was necessary to develop the required instrumentation. Two types of pressure cells (transducers) were designed and constructed. One type, known as the CST-1 cell, was mounted in the face and sides of the lugs. The other type, known as the diaphragm cell, was mounted in the tire body between the lugs (the tire undertread).

Design of CST-1 Cells

Due to the size restrictions placed on the cells by the size of a tractor tire lug, it was decided to build a transducer employing SR-4 strain gages as the sensing element. The transducer was to be able to measure pressures in a range of approximately 10 to 100 psi, and yet be strong enough to withstand a reasonable amount of rough usage. It was to be readily movable from one place to another in the tire and yet small enough to have a minimum effect on the normal lug characteristics.

Two models of the transducer were designed and built. The first design was too large and complicated to be usable, and it was discarded in favor of a simpler design. This second design consisted of a brass body and a steel sensing element on which the strain gages were mounted.

Figure 1 shows an assembly drawing of the CST-1 cell. The overall length of the cell was 1 1/16 inches and the diameter was 3/4 inch. The steel sensing element was a hollow steel cylinder 1/4

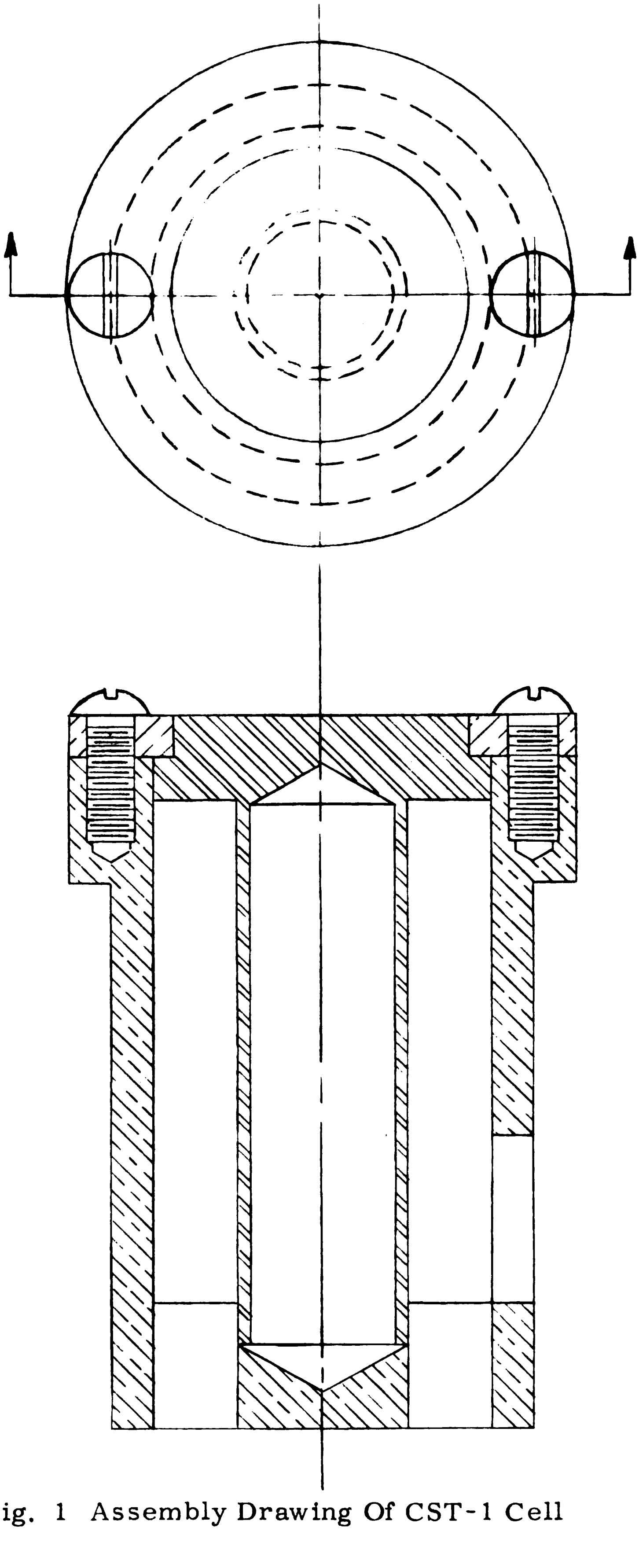


Fig. 1 Assembly Drawing Of CST-1 Cell

inch in diameter with walls 1/64 inch thick. It fitted into a positioning hole in the cell bottom so that it could not become tilted when under load. When assembled the sensing element was held in place by a thin steel ring and two 1/8 inch No. 56 brass screws. An assembled cell is shown in Figure 2a. The cell components are shown in Figure 2b.

Four SR-4, A-18 strain gages were mounted on the steel sensing element. They formed a complete Wheatstone bridge on the element thus giving maximum sensitivity to the cell. This also provided the necessary temperature compensation and canceled out any bending moments which may have been present when the cell was under load. This last point was very important since it was desired to measure the pressures normal to the face of the cell without picking up any extraneous signals. Figure 3 shows a diagram of the gage placement and the Wheatstone bridge circuit.

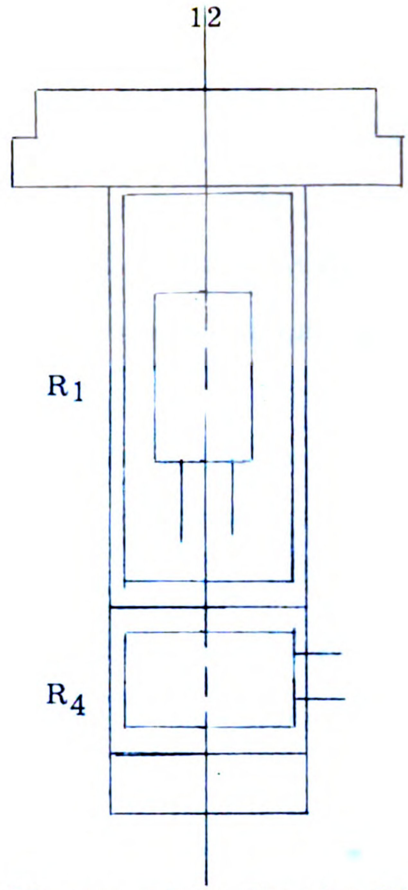
Two 4 foot lengths of 24 gauge, 2 conductor speaker cable were used for the lead wires to each cell. Connecting of the cells to the amplifier circuit was simplified by arranging the lead wires so that it was not necessary to identify each one of the four wires. It was only necessary to connect the two wires in each lead cable to opposite corners of the amplifier bridge circuit.

Design of Diaphragm Cells

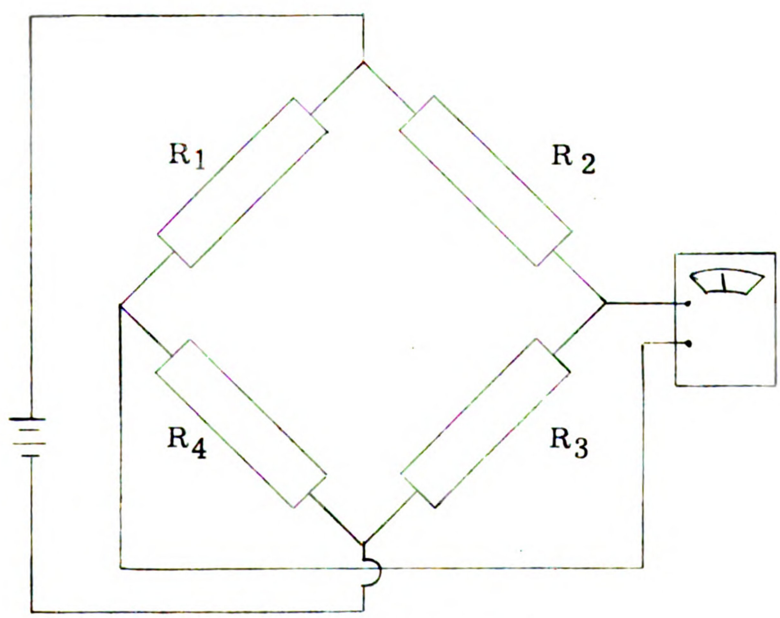
Size limitations prevented the use of the CST-1 cell in the tire undertread. A diaphragm cell meeting the space requirements of the undertread was designed and constructed. The sensitivity range of these cells was from 0 to 15 psi. The cell bodies were 3/4 inch in diameter, 7/16 inch high, and the walls were 1/32 inch thick. A check

Fig. 2a Picture Of Assembled CST-1 And Diaphragm Cell

Fig. 2b Components Of CST-1 Cell



Gage Placement On Sensing Element



Basic Wheatstone Bridge Circuit

Fig. 3 Gage Placement And Wiring Of CST-1 Cell of a theoretical stress-strain curve for a clamped circular diaphragm showed that the diaphragms would have to be 0.005 inch thick to produce the desired sensitivity. Accordingly, a sheet of special stainless steel was obtained for the diaphragms.

Because the cells were small, only one A-18 strain gage was mounted in the center of the diaphragm. Thus the cells did not have temperature compensation. This was not considered serious, however, since the readings were more or less instantaneous and any temperature change would be minimized. This actually proved to be the case during the tests. An assembled cell is shown in Figure 2a.

Calibration of Cells

Both types of cells were calibrated using water pressure. Figure 4 shows the apparatus used to calibrate the CST-1 cells and Figure 5 shows the apparatus used to calibrate the diaphragm cells.

The pressure chamber consisted of a section of large pipe with plates welded to both ends. A 7/8 inch hole was drilled in the top plate. This hole was covered with a rubber diaphragm which was held in place by another plate containing a 3/4 inch hole. The cells were placed upside down on the diaphragm and held in place as shown in Figure 4. The water pressure was supplied from the pressure tank of a home water system.

The CST-1 cells were calibrated from 0 to 80 psi in 10 psi increments. The pressure readings were taken from a large direct reading bourdon gage which had been previously calibrated on a dead weight tester. Three calibration tests were made for each cell,

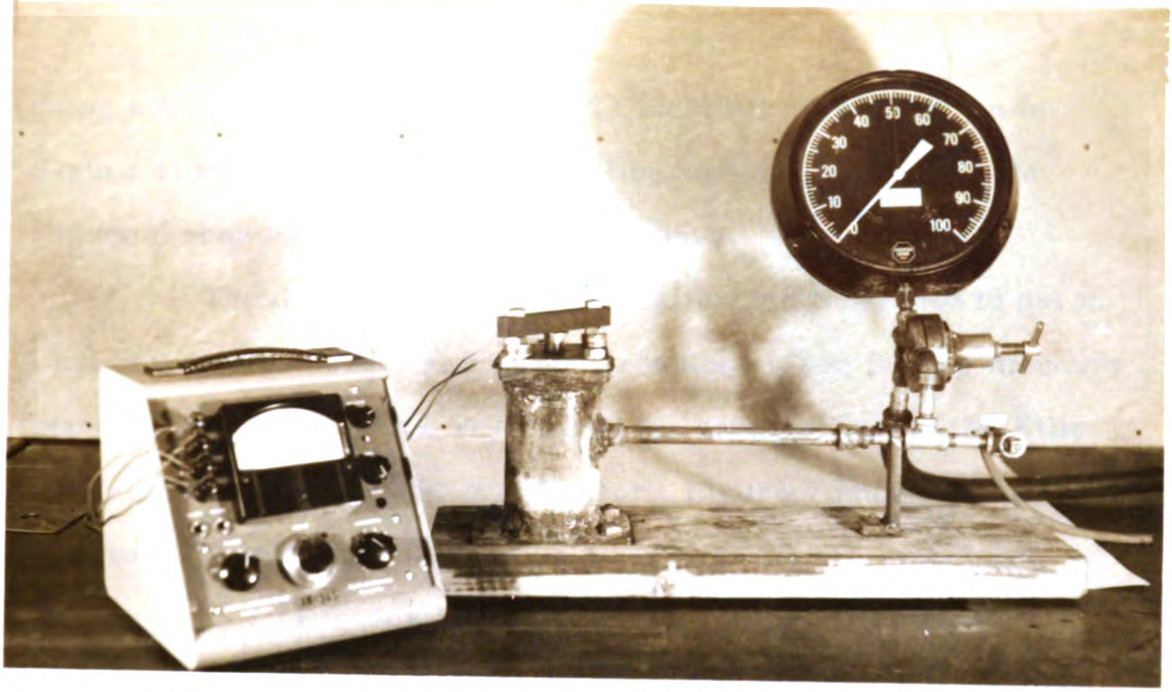


Fig. 4 Calibration Of CST-1 Cells

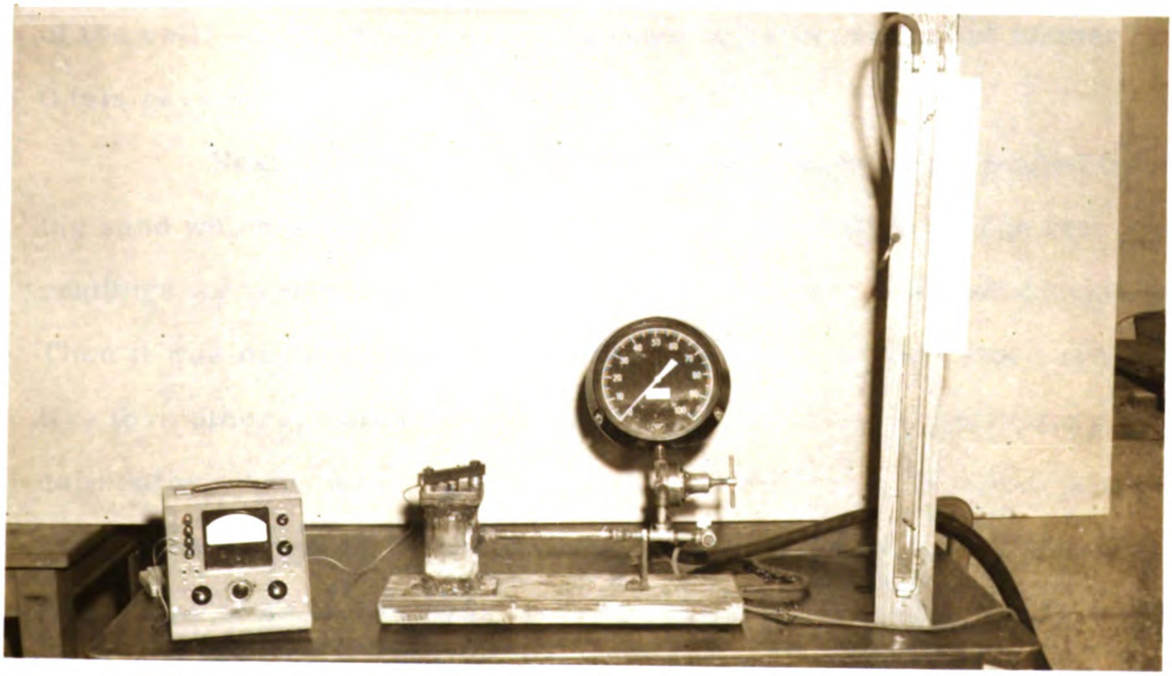


Fig. 5 Calibration Of Diaphragm Cells

using a BL-520 Brush amplifier (not the Ellis BAM-1 shown in Figure 4) and direct recording oscillograph to record the data. Figure 6 shows a sample calibration curve.

The diaphragm cells were calibrated from 0 to 15 psi in 1 psi increments, with the pressure readings taken from a mercury manometer. Three tests were made for each cell using the Ellis BAM-1 direct reading strain indicator. Figure 7 shows a sample calibration curve.

Proving Of Cells And In-Place Calibration

When the cells were calibrated it was assumed that the calibrations would be valid when the cells were mounted in the tire. This was not the case, however, with the CST-1 cells. After several trial runs had been made and a preliminary series of data recorded, it was found that the results were erratic and questionable. A check of the cells and lead wires showed them to be in order, but further trials gave similar poor results.

Next several trials were made on a bare board placed in the sand which gave more closely controlled conditions. The cell readings were more easily reproducable, but were still not acceptable. Then it was discovered that several of the cells seemed more sensitive than others, which was a contradiction of what the laboratory calibrations had shown. Evidently, the laboratory calibrations had changed and were no longer valid. Despite the precautions taken, a few grains of sand may have lodged between the cell body and sensing element, or the sensing elements may have been loaded in such a way that they were constrained by the cell body, thus giving variable

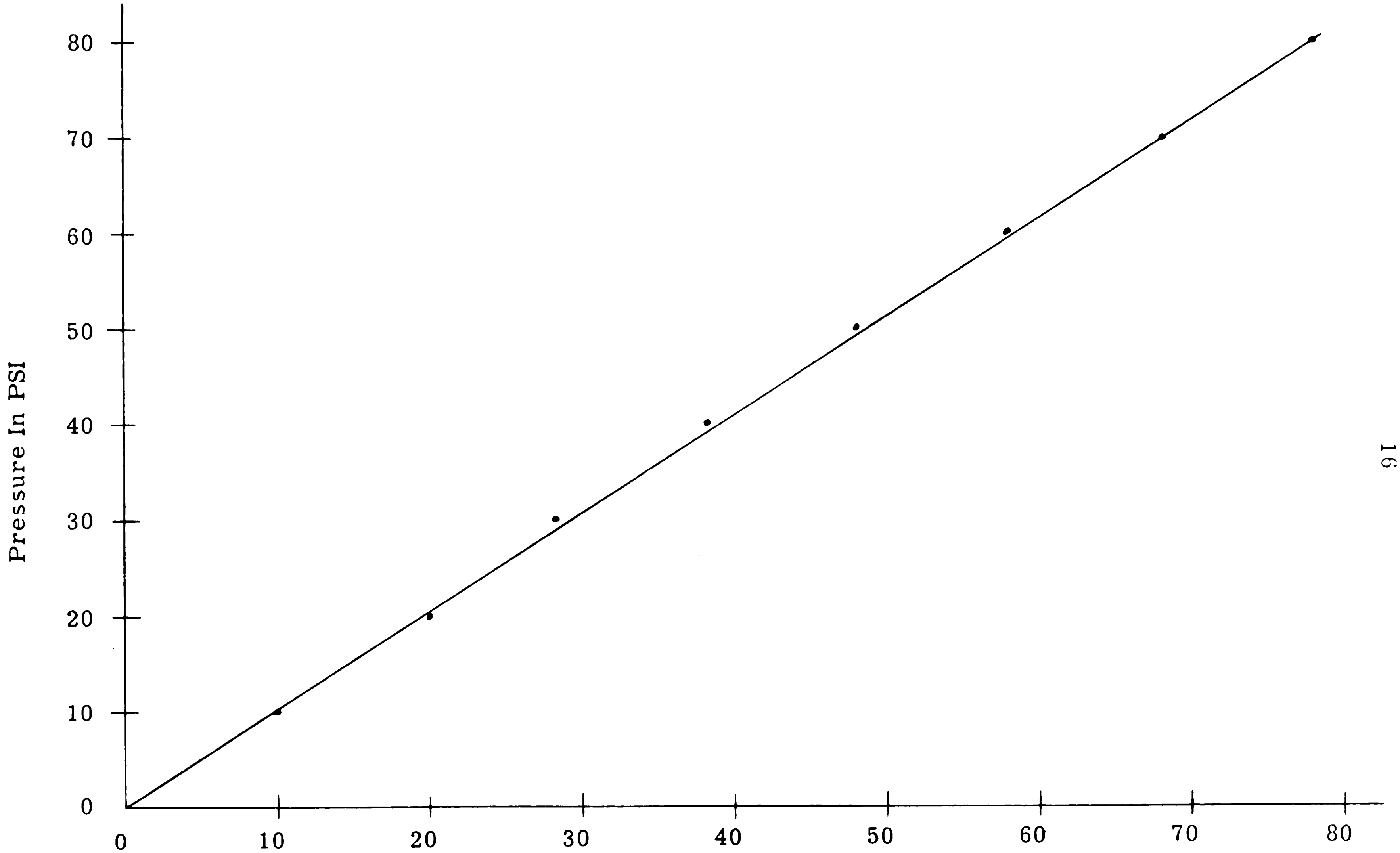


Fig. 6 Sample Calibration Curve For CST-1 Cells (Cell No. 4)

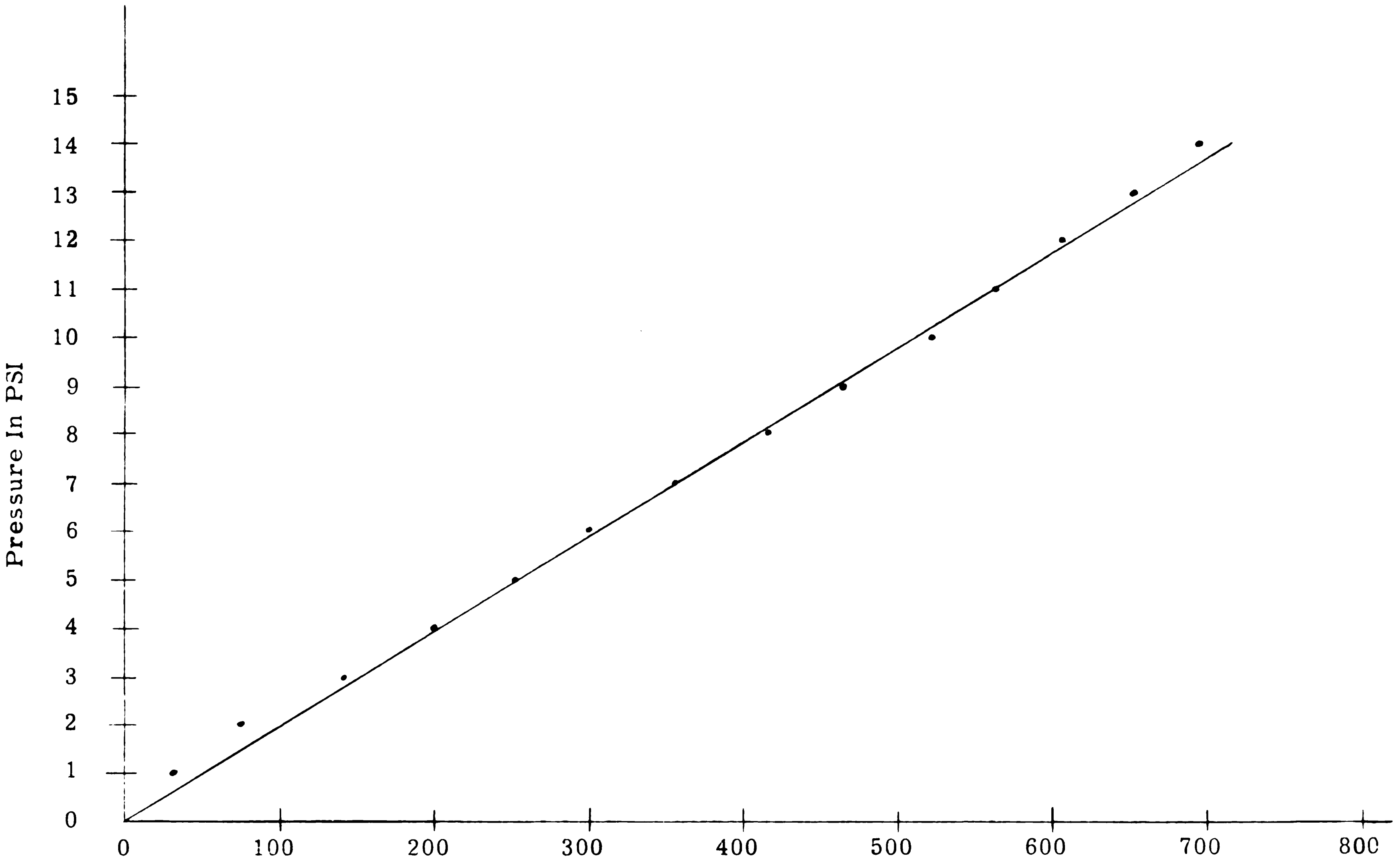


Fig. 7 Sample Calibration Curve For Diaphragm Cells (Cell No. 1)

readings.

It was evident that an in-place calibration device was needed. Therefore the apparatus shown in Figure 8 was assembled. It consisted of a tank of nitrogen, pressure regulator, pressure gage, and a pressure applicator for applying a static pressure to the cells. The pressure was applied by means of a rubber diaphragm which completely covered the cell so that it could be assumed that the gage pressure was actually applied to the sensing element of the cell. Figure 9 shows a general view of the apparatus in use and Figure 10 shows a side view of the pressure applicator in place on a cell.

The cells were calibrated by applying 60 psi (all that a person could hold against the cell) to the sensing element and adjusting the gain on the amplifier so that the pens had a six line deflection on the oscillograph chart. Since the strain and signal amplification were linear in the range used, this gave a direct calibration of 10 psi per line. For all data taken after series 3 the cell calibrations were checked before and after each six runs were made. The data for the runs were either accepted or rejected on the basis of these calibration checks and the author's judgement. This method of calibration proved to be satisfactory with the exception that it is a time consuming process.

To further establish the reliability of the CST-1 cells, two series of data were recorded using a board in the soil. One series of twelve runs was made on a bare board and another series of twelve runs was made on a board covered with approximately two inches of sand. The results of these two series of tests are given in Tables 1

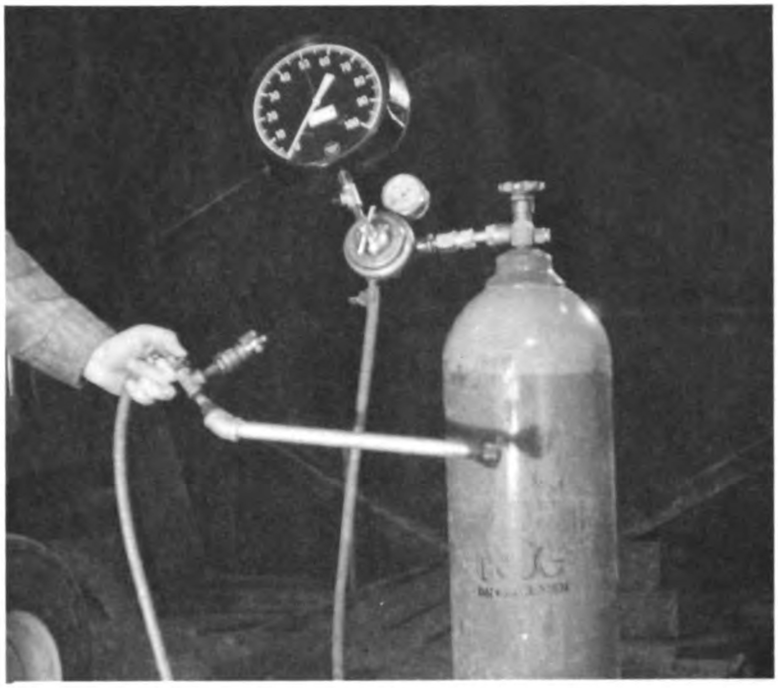


Fig. 8 In Place Calibrator For CST-1 Cells

Fig. 9 In Place Calibration Of Cells

and 2 and show that the readings were relatively consistent from run to run.

Since the diaphragm cells worked satisfactorily from the beginning, their laboratory calibrations were taken as valid and they were not recalibrated like the CST-1 cells were.

Table 1

Summary Of Series 3 Data *

Run No.	Cell No. 7	Cell No. 9	Cell No. 2	Cell No. 8	Cell No. 4	Cell No. 3
1	40	75	185	215	15	60
2	40	85	—	275	15	60
3	40	105	220	295	20	60
4	20	—	195	280	35	45
5	30	—	235	265	15	60
6	20	100	245	295	35	25
7	25	110	230	330	30	75
8	35	110	235	325	25	70
9	75	90	235	345	25	70
10	50	85	235	340	20	55
11	75	95	230	335	10	70
12	55	—	280	345	20	85
Calibration Check	65	40	35	85	75	55
Average of Runs 1-6	32	91	216	271	23	52
Average of Runs 7-12	53	98	241	337	22	71
Average of All 12 Runs	42	95	230	295	22	61

* Cell readings in psi

Table 2

Summary Of Series 4 Data *

Run No.	Cell No. 7	Cell No. 9	Cell No. 2	Cell No. 8	Cell No. 4	Cell No. 3
1	45	190	155	60	60	20
2	35	205	145	75	20	20
3	55	165	175	60	55	10
4	75	220	160	55	85	25
5	55	230	130	65	70	20
6	65	215	135	65	80	20
Calibration Check	60	140	60	60	80	60
7	50	150	220	75	50	20
8	70	180	150	65	50	35
9	70	175	165	65	40	15
10	55	140	195	65	50	10
11	50	175	170	80	65	15
12	60	180	160	70	60	20
Calibration Check	65	50	60	60	50	60
Average of Runs 1-6	55	204	150	63	62	19
Average of Runs 7-12	60	168	177	70	53	19
Average of Runs 1-12	57	185	163	67	57	19

*Cell readings in psi

IV PLACEMENT AND MOUNTING OF CELLS IN THE TIRE

Twenty-nine CST-1 cell bodies and fourteen diaphragm cells were fabricated and mounted in the tire. Since only six channels of recording equipment were available for use with the CST-1 cells, only six sensing elements for these cells were constructed. These elements were moved to various cell body positions in the tire for the various tests.

Placement Of Cells In The Tire

It was felt that the objectives of the investigation could best be met by dividing the cells into two groups according to the type of data desired. Accordingly, one group of nineteen CST-1 and nine diaphragm cells was arranged primarily for obtaining pressure distribution data and another group of ten CST-1 and five diaphragm cells was located on the opposite side of the tire to obtain data for the traction studies. Figure 11 shows the arrangement of the first group of cells and Figure 12 shows the arrangement of the second group.

The arrangement of CST-1 cells shown on the right hand side of the tire in Figure 11 was used to determine what effect, if any, the cells had on the lug characteristics. It was felt that a comparison of the readings of the cells in these four lugs with respect to the cell position in the lug, and the number of cells per lug would indicate whether the cells themselves were affecting the pressure readings. This arrangement also gave a duplicate set of pressure distribution readings under a lug for one half of the tire.

Fig. 10 Pressure Applicator In Place On A Cell

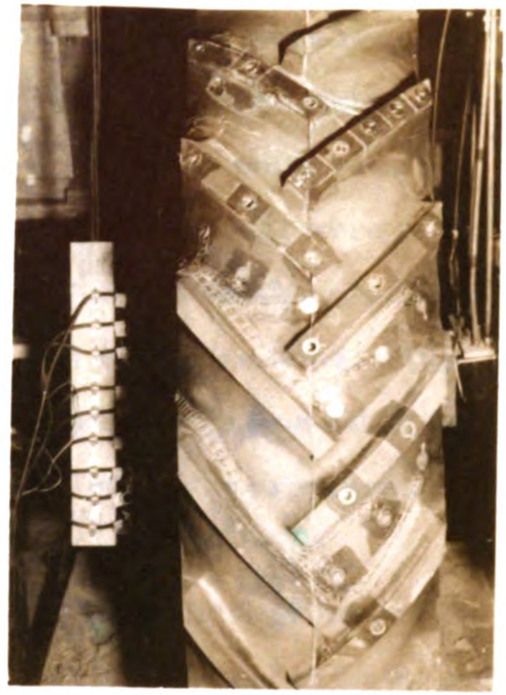


Fig. 11 Group I Cell Arrangement

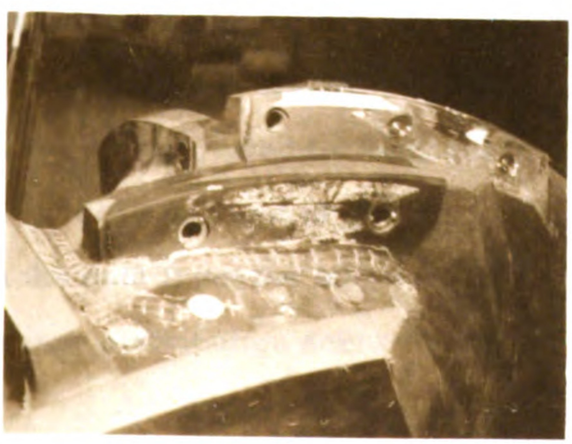


Fig. 12 Group II Cell Arrangement

Fig. 13 Drill For Cutting Cell Holes In Tire

To determine the pressure distribution on the lugs across the width of the tire, the cells mounted in the third lug on the right and first lug on the left were used. The data from these two lugs were compared with the data from the two lugs immediately above them. The two lugs on the left having three cells apiece were intended to check the pressure on the lugs when two lugs were in contact with the ground at the same time. This was not accomplished, however, since the tractor moved too fast during the tests. Two CST-1 cells were mounted in the side of the last instrumented lug on the left, primarily to see if they would effect the pressure readings on the face of the lug.

The nine diaphragm cells used in the first group can be seen in the undertread of the tire. Six cells were placed on the right side of the tire. The other three were placed in the space preceeding the first instrumented lug on the left. The six cells on the right side of the tire were to be used to check the soil-tire interface pressure when two inter-lug spaces were in contact with the ground, but they did not do this because of the tractor speed. The data obtained from these cells were used to study the pressure distribution on the undertread across one half of the tire. They were also used in conjunction with the data from the other three cells in studying the undertread pressure distribution across the tire.

As mentioned earlier, the group of CST-1 cells shown in Figure 12 was arranged primarily for obtaining traction data. Using these cells, it would have been possible to measure the thrust on one lug, two lugs, or two lugs across the width of the tire. However, due to time limitations only one series of data was taken using these cells. It is anticipated that they will be used in future work.

The five diaphragm cells shown in Figure 12 were used to give a more precise picture of the pressure distribution across the undertread on one side of the tire than could be obtained using only three cells.

Mounting The Cells In The Tire

In order to provide favorable operating conditions, the CST-1 cells were vulcanized in place. To the best knowledge of the engineers at the Goodyear Tire Company, this had never been done before and they did a considerable amount of research to produce the desired results.

The preparation of the cells for mounting in the tire entailed several steps as reported by Mr. Robert Carter of Goodyear (1958). First they were pickled to remove any corrosion or foreign matter. Secondly, each cell "was given three coats of natural rubber valve stock No. M45 diluted with gasoline. Each coat was applied with a brush instead of dipping to assure that no slight film of dried rubber was between the green diluted gum and the brass. This was thoroughly dried before the next step" and finally, "a sheet of this natural rubber valve stock No. M45 about 0.040 inches thickness was cut into the proper length and width and wrapped tightly around" the cell bodies.

The cells were mounted in a stock 12-38 rear tractor tire. The cell placement was laid out on the tire and the holes were cut using the special cutter shown in Figure 13. All of the holes were cut while the tire was mounted on a rim and inflated to insure that the holes would be the proper shape.

After the holes were cut the tire was dismounted from the rim and the cells were put in place. Since they were slightly larger than the holes, they were dipped in a can of Texene for two or three seconds to form a thin film of soft rubber which allowed the cells to slip easily into place. Next, the cells were covered with tape to keep out any moisture and the whole tire was put in live steam for 4 1/2 hours at a temperature of 285^{o} F. This treatment vulcanized the cells into the tire and the bond showed no signs of weakening at any time during the tests.

It was not considered necessary to have the diaphragm cells vulcanized into the tire. Therefore, they were mounted after the tire was received at the University. The holes were cut with the above mentioned cutter. The cells were mounted in the tire using Goodyear Pliabond cement and loops of fine wire fastened through the tire casing. It was found that these wires shorted out the strain gages and should not be used in the future.

Placement Of Lead Wires

The CST-1 cells had two sets of lead wire holes in them. The holes in the bottom were used when the cells were mounted in the side of the lug, and the hole in the side was used when they were mounted in the face of the lug. When the cells were mounted in the tire, these lead wire holes were oriented so that the lead wires came out of the back of the lugs. The holes for the lead wires were cut with a 1/4 inch cutter.

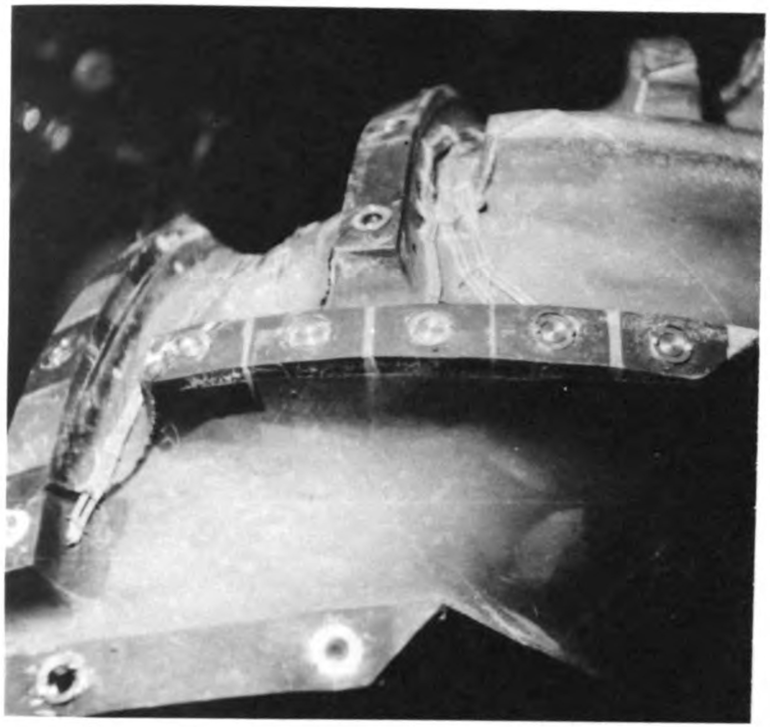


Fig. 14 Lead Wires From CST-1 Cells

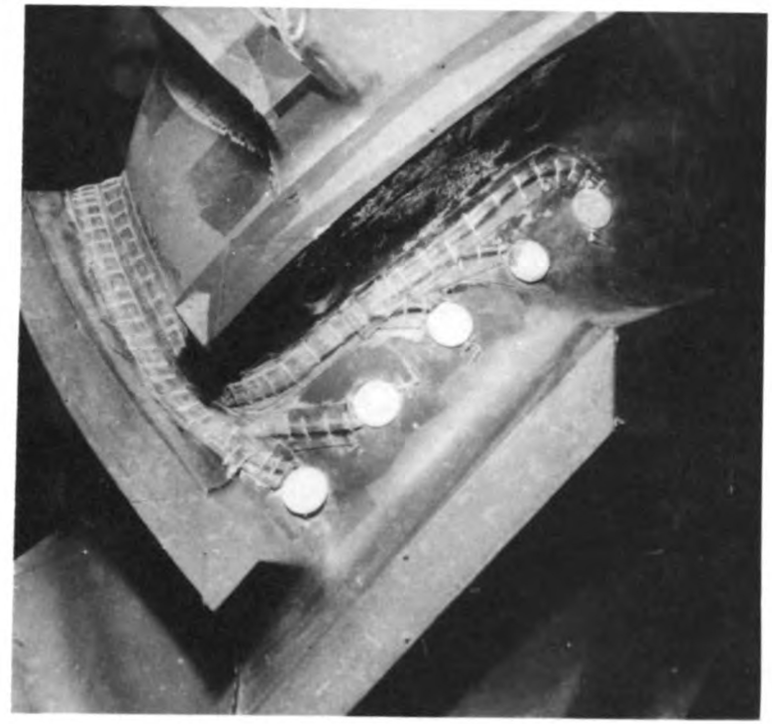


Fig. 15 Lead Wires From Diaphragm Cells

Since the sensing elements of the CST-1 cells were to be moved frequently, the lead wires from these cells were only stapled loosely to the tire as shown in Figure 14. Figure 15 shows how the lead wires from the diaphragm cells were stapled securely to the tire, covered with friction tape, and coated with Pliabond cement.

V INSTRUMENTATION OF TRACTOR

In order to carry out this investigation, it was necessary to instrument both the tire and a tractor. A John Deere 620 tractor was instrumented with SR-4 strain gages to measure the torque input to the wheel, the weight transfer of the tractor when under load, the drawbar pull, and the force required to push the front wheels through the soil.

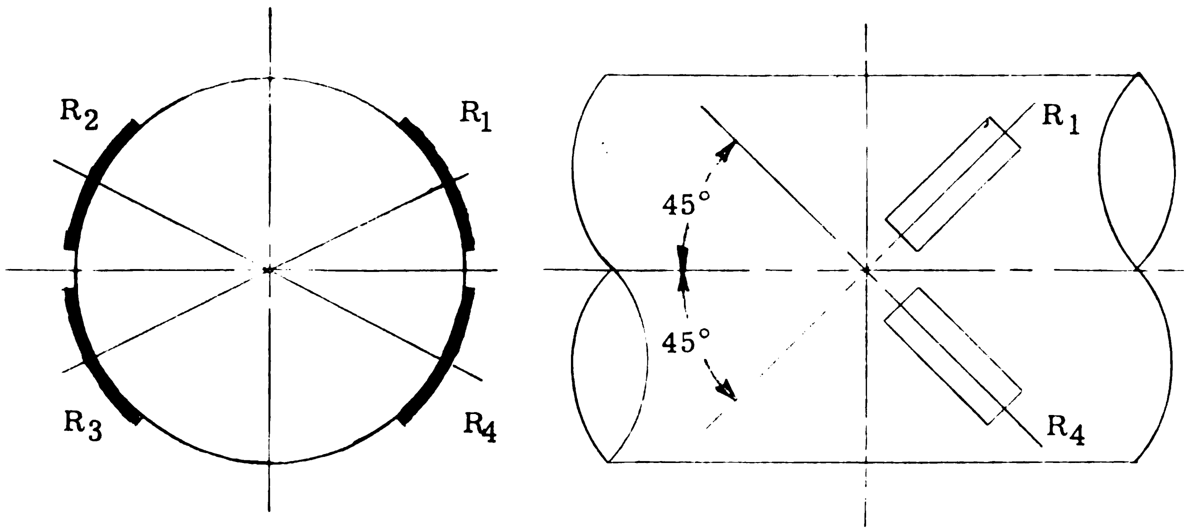
Placement Of Gages On The Tractor

The torque was measured using four A-5 strain gages mounted on the rear axle close to the wheel. Figure 16 shows a diagram of the gage arrangement, which provided a complete Wheatstone bridge on the axle with all of its inherent advantages.

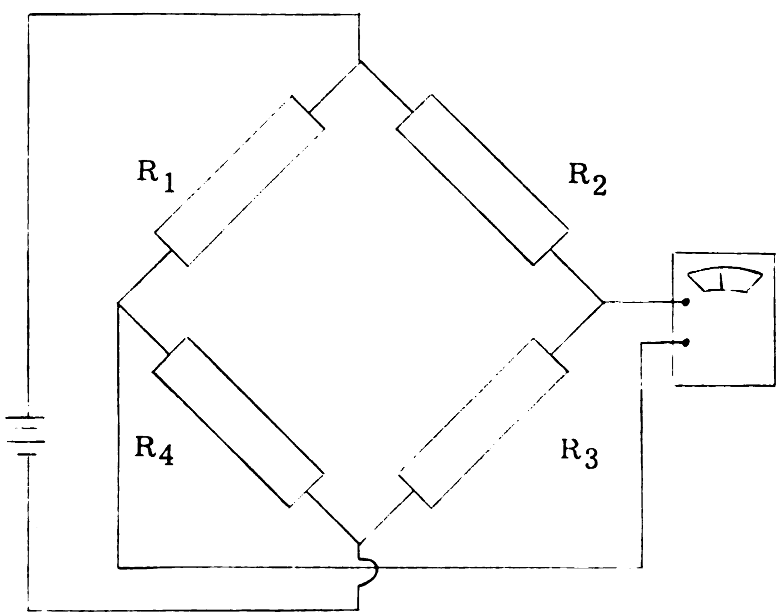
Two A-5 strain gages were mounted to measure the bending of the axle in the vertical plane, and when properly calibrated they gave the weight transfer measurements.

Two other A-5 strain gages measured axle bending in the horizontal plane and when calibrated gave data on the combined effect of drawbar pull and the force on the front wheels. The force on the front wheels was found by subtracting the known drawbar load from the total load as measured by these gages.

The drawbar pull was measured by means of a pulling link constructed using SR-4 strain gages. The link was mounted in the cable between the drawbar and the load and gave a continuous record of drawbar pull whenever the tractor was loaded during the tests.



Gage Placement On Axle



Basic Wheatstone Bridge Circuit

Fig. 16 Diagram Of Torque Measuring Arrangement

Calibration of Gages

The pulling link, torque gages, and weight transfer gages were calibrated using the dead weight method. The pulling link and a weight hanger were hung from a chain fall. Weights from a set of tractor wheel weights were placed on the hanger in approximately 60 pound increments and the strain readings were taken from a direct reading Ellis BAM-1 strain indicator.

The calibration of the weight transfer gages was accomplished by placing the weights on the platform of the tractor, using the same 60 pound increments and the same strain indicator.

To calibrate the torque gages the wheel was raised off the floor and locked in place. The weight hanger was placed on a four foot lever arm and loaded as before. The strain readings were taken with the Ellis BAM-1.

The calibration of the gages to measure the force on the front wheels was done with the tractor in place in the soil box as shown in Figure 20. The loads were applied by means of the loading frame and the weights already described. The strain in the axle gages was read on the Ellis BAM-1 as before, but the load on the drawbar was recorded using the pulling link connected to a Brush BL-520 amplifier and recording oscillograph. In all cases three runs were made for each calibration.

Lead Wires

Figure 18 shows how the lead wires from the gages on the tractor were handled. Due to the large amount of A-C pickup encountered, four-wire shielded cable was used for the lead wires to the

Fig. 17 Loading Frame

Fig. 18 View Of Gages And Lead Wires From Tractor

Fig. 19 Side View Of Wheel Showing Lead Wires

gages on the tractor. Since the tractor traveled less than one wheel revolution, the lead wire from the torque gages was wound around the axle so that it unwound as the tractor traveled forward and wound up as it traveled backward. This arrangement eliminated the need for slip rings.

Figure 19 shows the arrangement which was used to handle the transducer lead wires. The terminal board on the wheel simplified the handling of the lead wires when the sensing elements were moved from place to place in the tire. Four-wire shielded cable was used for the lead wires from the terminal board to the amplifiers.

Experimental Set-Up

An over all view of the set-up used during the tests is shown in Figure 20. All of the work was done in a soil box placed on a concrete floor and filled with approximately eleven inches of mortar sand. Sand was used for the "soil" since it was more homogeneous than field soil and its physical condition was more easily controlled. In order to secure traction without excessive slippage, the sand was kept moist at all times. Since the tractor front wheels tended to bury themselves in the sand, they were operated on a board placed on top of the sand.

The loading frame shown in Figure 17 provided a simple means of obtaining a constant drawbar load. It was approximately 14 1/2 feet high and allowed the tractor to move forward about 12 feet or approximately three fourths of a wheel revolution. The wheel weights mentioned earlier are shown in the left hand corner of the figure, and the loaded weight hanger is shown at the top of the loading

Fig. 20 Overall View Of Experimental Set-Up

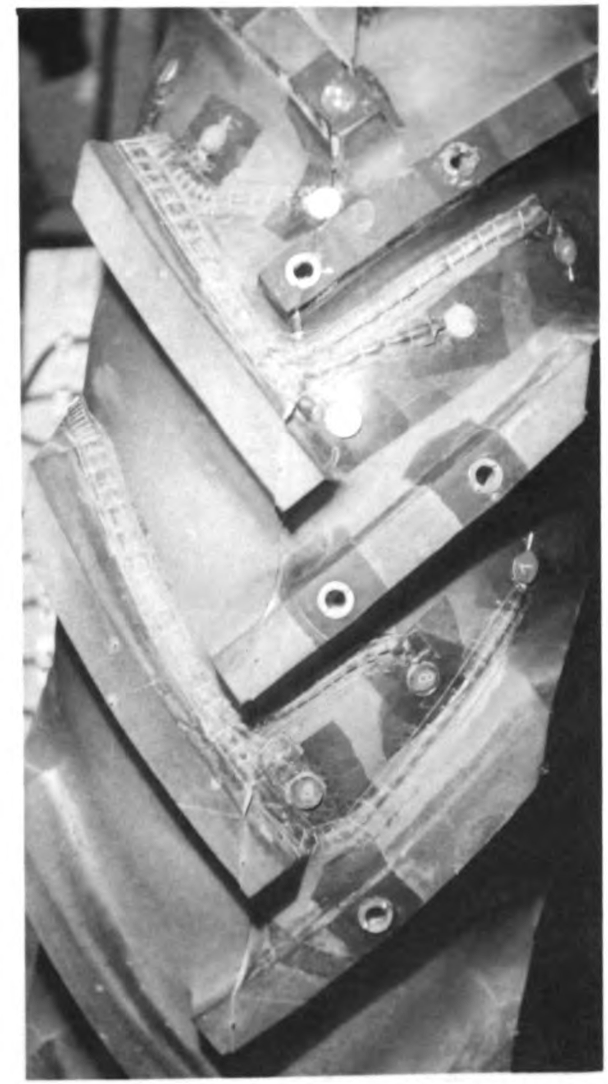


Fig. 21 Arrangement Of Cells For Series 5 And 6

frame.

Figure 22 shows an overall view of the amplifying and recording equipment. The twelve Brush BL-520 amplifiers and the two six channel recording oscillographs used with them are shown. Four other channels of Brush equipment used for the tractor instrumentation are not shown.

Recommendations For Improvement Of Instrumentation

The arrangement used for measuring the weight transfer was not sensitive enough. It would have been much better if at least two or possibly six more gages had been mounted on the axle.

The force on the front wheels could have been measured more easily and accurately by having the gages mounted on the front wheel pedestal rather than on the back axle.

A more sensitive pulling link would have provided larger pen deflections on the oscillograph and would have aided greatly in the ease and accuracy of reading the tape.

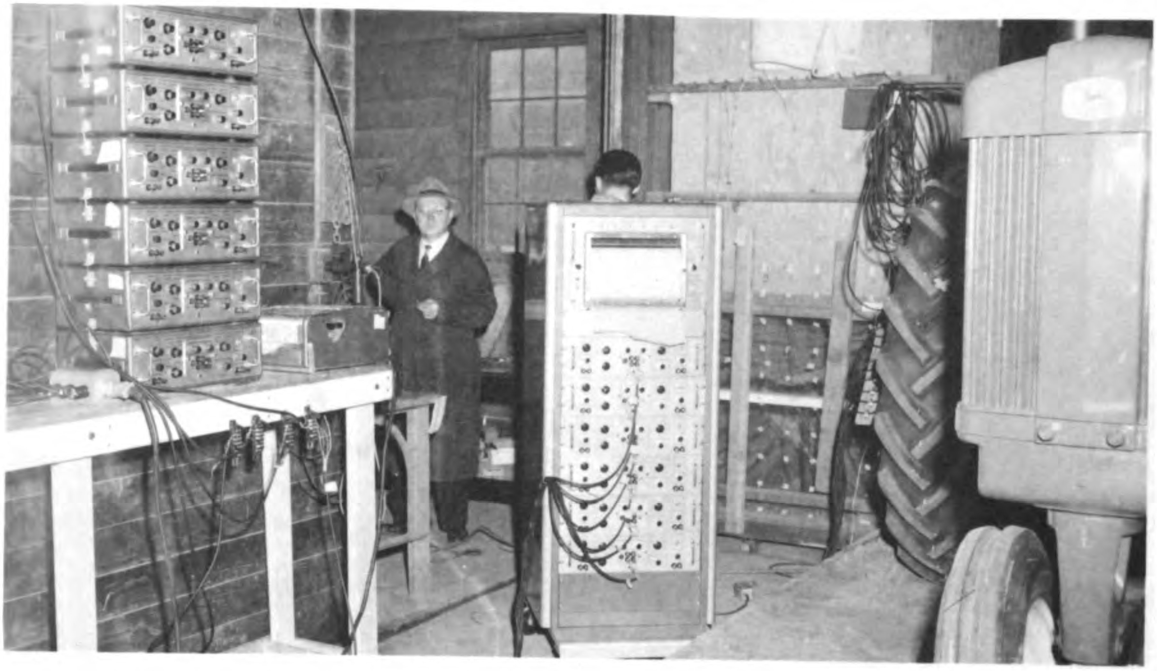


Fig. 22 View Of The Twelve Brush Amplifiers And Two 6-Channel Recording Oscillographs

Fig. 23 Demonstration Of Equipment For A Class In Experimental Stress Analysis

VI PROCEDURE

Nine series of data were taken during the course of this investigation. Series No. 3 and 4 have already been described. The data in Series Nos. 5, 6, 7, 9, and 10 were taken in three parts with six runs each. A run consisted of driving the tractor forward in 1st gear, with the engine idling and then backing it up in a similar manner. Data were recorded for both the forward and backward pass. With the exception of Series No. 10, part 1 of each series was run with a tire pressure of 14 psi, part 2 was run at 10 psi, and part 3 at 18 psi. In Series No. 10, part 1 was run at 18 psi, part 2 at 14 psi, and part 3 at 10 psi. Cell calibration was checked and adjusted before and after each part of each series.

Figure 21 shows the arrangement of cells used for the data in Series Nos. 5 and 6. The data of Series No. 5 were obtained using the six CST-1 cells in the three lugs on the right along with the six diaphragm cells between these lugs. These data were used to determine the effect of the cells on lug characteristics. In Series No. 6, the six CST-1 cells in the two lugs at the top of the figure and the six diaphragm cells just below them were used to measure the pressure distribution across the tire.

The data in Series No. 7 were taken with the diaphragm cells shown in Figure 15, and were used to give a better picture of the pressure distribution across one side of the tire than could be obtained with only three cells.

Only CST-1 cells were used in obtaining Series Nos. 9 and

10 data. The data of Series No. 9 were obtained using the six cells in the two lugs shown in the left and top half of Figure 14 and were used to supplement earlier data. The five cells shown in the middle of Figure 14 were used to obtain the data of Series No. 10. These data gave a better picture of the pressure distribution across one lug than was obtained earlier with only three cells per lug.

Two series of data were taken for use in the traction studies. These data were of a preliminary nature and are not included in this thesis. Hence, they will not be discussed further.

An attempt was made to keep the physical condition of the sand under the test wheel as uniform as possible throughout all of the tests. It was kept moist at all times, and spaded to the bottom of the box before each series of data was taken. Before each run it was raked and leveled off. The sand in front of the other wheel was loosened and leveled only as often as necessary to keep the tractor approximately level.

In tabulating the data from the data tapes, only the maximum values of pressure were recorded for each run. All of the curves were plotted using these maximum values. In cases where there were data from several series for the same cell position, an average of all of the values was used in plotting the curves.

VII RESULTS AND ANALYSIS OF DATA

The data of Series Nos. 3 and 4 presented in Tables 1 and 2 in part 3 of this thesis were used to determine the reliability of the CST-1 cells. As mentioned earlier, these data were taken using a board in the soil in order to eliminate as many variables as possible. This fact partly accounted for some of the differences between the two series. Series No. 3 was run using a bare board, but Series No. 4 was run using the board covered with two inches of sand which gave a more homogeneous surface and thus more uniform data. Another cause of the differences was the fact that the calibration of the cells was checked and adjusted more often during Series No. 4 than during Series No. 3.

The data showed that the cell calibrations changed during the tests. It was decided, however, that the data obtained would be acceptable for the purposes of this investigation. Though they operated satisfactorily, the CST-1 cells were not as reliable as expected and for this reason it would have been better if diaphragm cells had been used for all of the tests.

Effect Of Number Of Cells Per Lug

It was assumed that the more cells per lug the higher the pressure readings would be; since the more cells per lug the more rigid the lug becomes causing it to penetrate more deeply into the soil. The author now knows that this assumption was not entirely correct, and it was not confirmed by the data.

Table 3 shows a summary of the data of Series Nos. 5 and

Table 3

Summary Of Data For The Pressure Distribution Across A Lug*

Series Of Data	Cell Position Across The Lug				
	Center of Tire		Center of Lug		Shoulder of Tire
18 psi Tire Pressure					
10	90°	55°	12°	42	28
5	112°	--	204	--	74
5	--	22	--	75	--
5	--	--	76	--	--
14 psi Tire Pressure					
10	49°	48	14	60	40
5	151°	--	180	--	54
5	--	18°	--	48	--
5	--	--	70	--	--
10 psi Tire Pressure					
10	20	23	18	50°	54°
5	235	--	143	--	33
5	--	12	--	52	--
5	--	--	65	--	--

* Cell readings in psi
° Calibration changed during test

10 with respect to the cell position in one lug. If the assumption were completely true the cell readings in Series No. 10 would have been the highest since there were five cells in one lug. This was not the case, however since most of the readings were lower than the readings of Series 5 where there were fewer cells per lug. The data of Series No. 5 also showed higher readings with three cells per lug than with either five, two, or one cell per lug. The readings with one cell per lug were higher than with two cells per lug. It was certain that the presence of the cells affected the lug rigidity, but it appeared that the differences between the cells themselves and the various series of data were more obvious than any effect the cells may have had on the lugs. Thus it was concluded that the affect of the cells on the lugs could be neglected.

Pressure Distribution Across A Lug

The data of Series No. 10, as plotted in Figure 24, showed the effect of tire pressure on the pressure distribution across a lug. At 18 psi tire pressure, the tire carcass was relatively rigid and maintained most of its radial shape under load. This caused the greater part of the wheel load to be carried on the center third of the tire. At 14 psi tire pressure, the carcass was less rigid, which allowed a somewhat more uniform distribution of pressure. The peak pressure was greatly reduced and had shifted to a position in the outer one third of the tire. Despite the reduced peak pressure the average pressure was reduced only 6 1/2 percent from 45.5 to 42.5 psi. At 10 psi tire pressure, the tire carcass buckled under the load and the sidewalls rather than the tread area were carrying the largest share

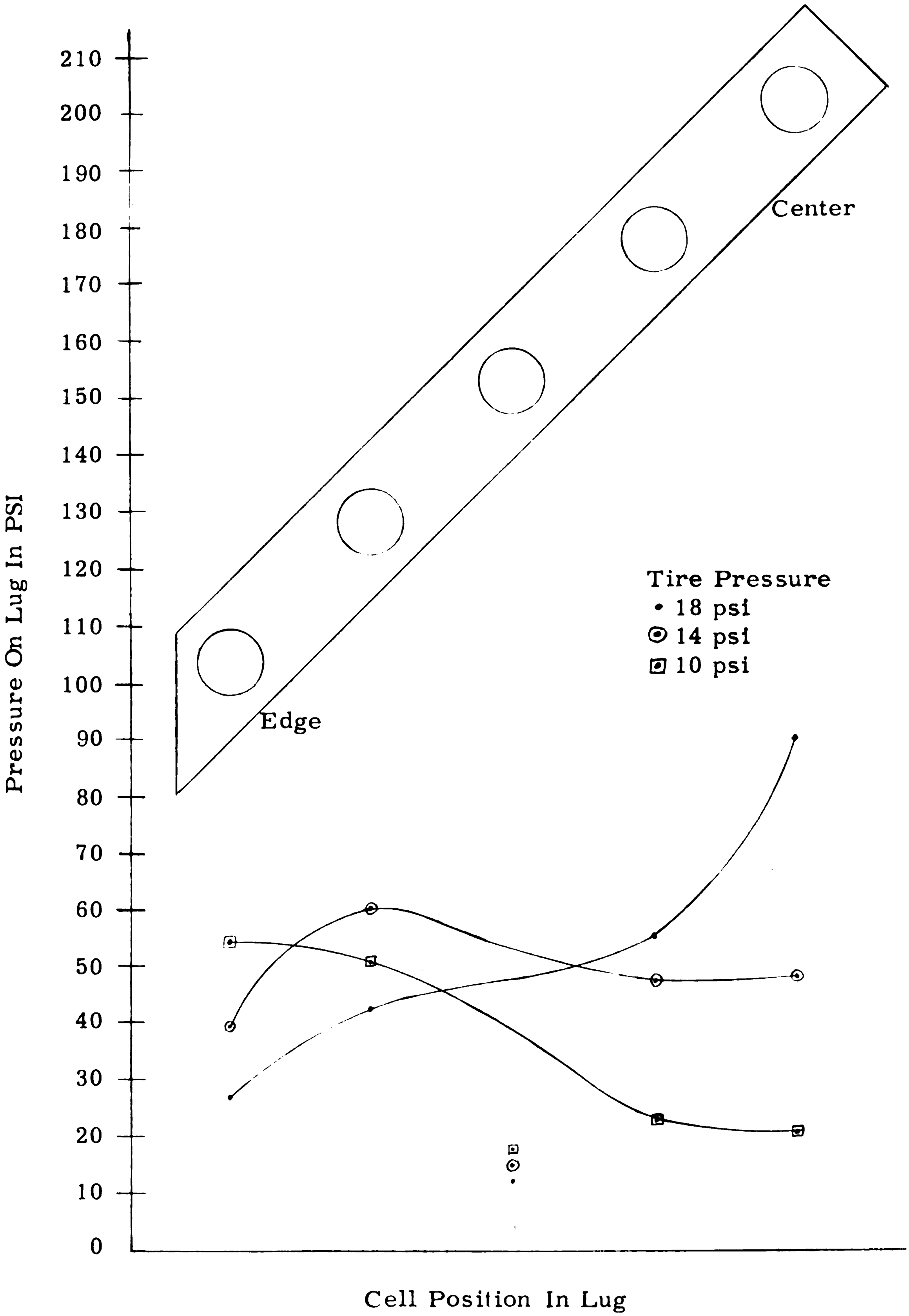


Fig. 24 Pressure Distribution Across A Lug As Given By Five Cells Per Lug

of the wheel load. Not only was the peak pressure reduced by the lower tire pressure, but the average pressure over the lug was reduced by 22 1/2 percent from 42.5 to 33 psi. This was a significant reduction in the soil-lug interface pressure and in itself was desirable. But, it cannot be concluded that lower tire pressures alone are the answer to the soil compaction problem. More data must be collected and evaluated and coordinated with the work of Bekker (1955), Soehne (1952), and Vanden Berg (1958), and a complete study and analysis of traction must be made before any reasonable answer can be obtained.

The readings of the cell in the center of the lug were not included in the curves of Figure 24 since it was felt that these data were in error on the basis of the surrounding readings.

Figures 25 and 26 show two different plots of the data summarized in Table 4. The curves of Figure 25 were drawn for the average of all the data taken with respect to the three cell positions shown and included data from both halves of the tire. This was done to get the best possible picture of the pressure distribution over a lug when only data from three cells were used. Figure 26 was plotted to give a picture of the pressure distribution on the lugs across the width of the tire. In this case the average of the data for each half of the tire was plotted seperately.

An examination of the curves of Figures 24, 25, and 26 and the data of Tables 3 and 4 showed some large variations in pressure readings for the same cell position from one series of data to another, and some large variations in the readings for the same cell position

Table 4

Summary Of Lug Pressure Distribution Data Across The Width Of The Tire*

Series Of Data	Cell Position Across The Tire					
	Left Hand Side			Right Hand Side		
	Shoulder of Tire	Center of Lug	Center of Tire	Center of Tire	Center of Lug	Shoulder Of Tire
			18 psi Tire Pressure			
10	---	---	---	90°	12°	27
5	---	---	---	112°	204	74
6	---	---	---	75	172	64
9	21	54	58	----	----	---
9	12°	38°	63	---	----	----
Average	16	46	60	92	129	55
			14 psi Tire Pressure			
10	---	---	---	48°	14	39
5	---	---	---	151°	180	53
6	---	---	---	130°	176°	72
9	24	24	45	---	---	---
9	15	37°	35°	---	---	---
Average	20	31	40	110	123	54
			10 psi Tire Pressure			
10	---	---	---	20	18	54°
5	---	---	---	235	143	33
6	---	---	---	201	137	33
9	31	33°	26°	---	---	---
9	41°	49	20	---	---	---
Average	36	41	23	152	99	40

*Cell readings in psi

°Calibration changed during tests

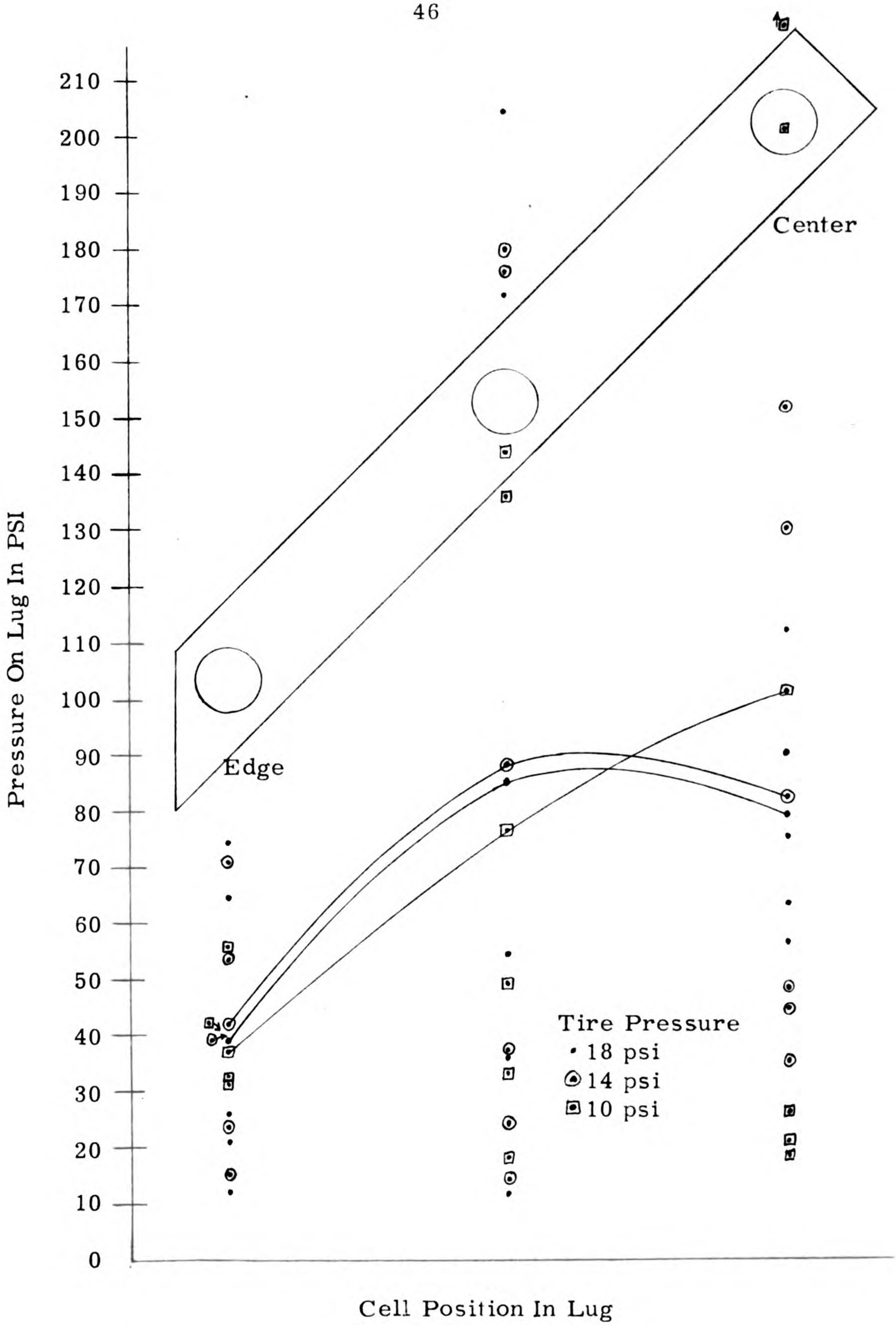


Fig. 25 Pressure Distribution Across A Lug As Given By Three Cells Per Lug

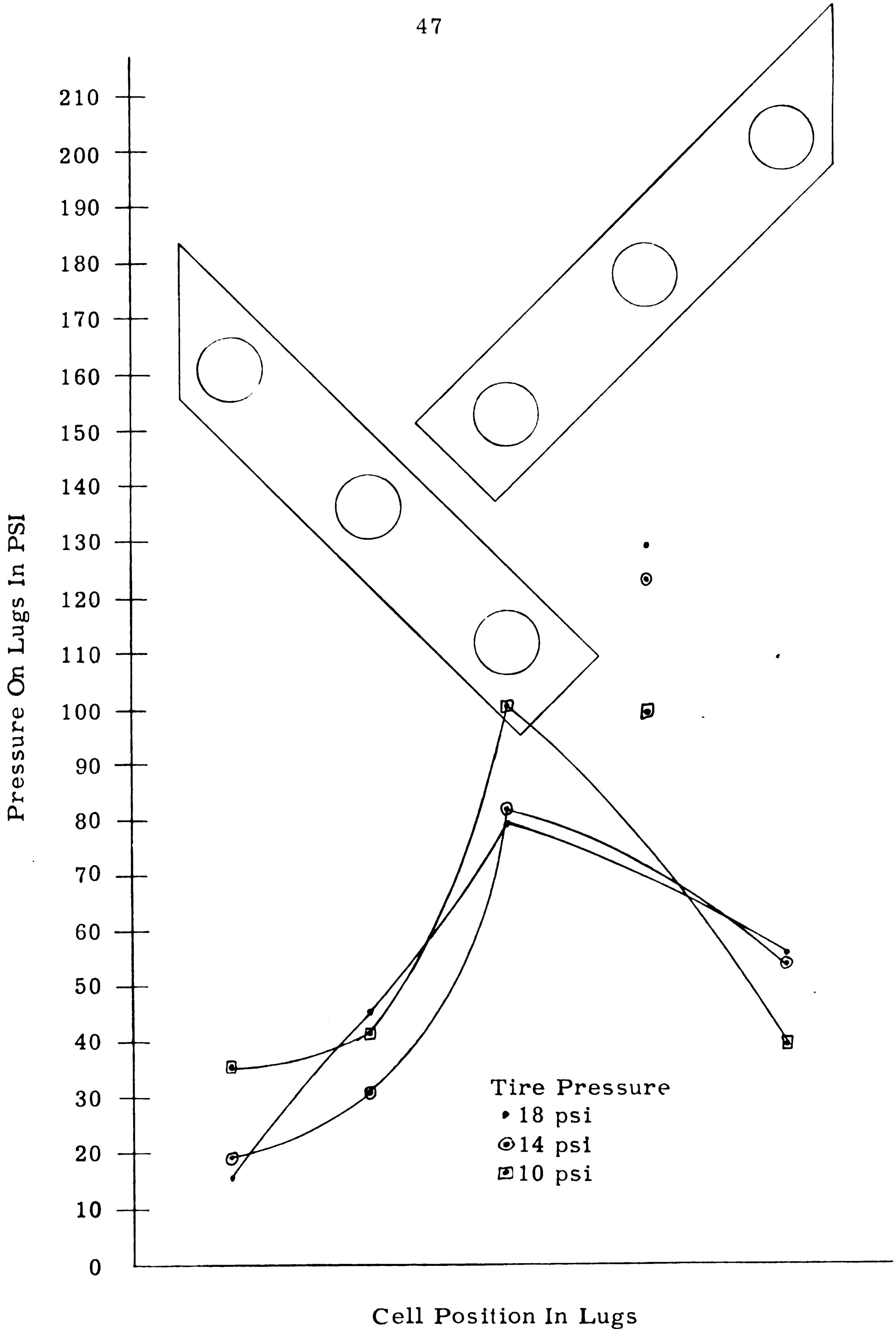


Fig. 26 Pressure Distribution Across The Width Of The Tire As Given By Three Cells Per Lug

from one series of data. It was felt that one major cause of these variations was the changing calibration of the cells. Although the calibration check showed little or no change in calibration, the fact that there was a change at all raised the question of whether or not more than one change had taken place. It may have been that the calibrations were in error during part of the runs and yet were correct when checked after the last run.

Another thing which may have caused the readings to vary was the moisture content of the sand. A change of 2 or 3 percent in the moisture content of sand is the difference between moist and dry sand. The data were collected over a period of about 3 months and the sand had to be wet down several times during this period. Thus the data were collected over a wide range of moisture contents. Also, the sand was probably not in the same state of compactness for every run.

A phenomenon which could have accounted for the variations of readings between the cells in the same series of data was brought to my attention by Mr. Harris Gitlin of the Ford Motor Company. It was discovered that the scale weight of the rear wheels of a tractor could be varied by as much as 200 pounds depending on which lug supported the tractor weight while on the scales. If it was supported by a lug in front of the axle the scale read heavier, and if the weight was supported by a lug in back of the axle the scale read lighter. This phenomenon of the changing lever arm, probably accounted for the variations of pressure readings in the Series No. 9 data.

The differences in the pressure readings from one half of the tire to the other may have been due to the tractor not being level at all times, but it was felt that this could not completely account for the large differences recorded in the data. It was suspected that this difference in pressure distribution from one half of the tire to the other, may exist at all times. It was hoped to have shown this during this investigation, but more data are necessary before any definite conclusions can be drawn.

In conclusion, it was felt that Figure 24 more closely represented the actual pressure distribution existing at the soil-lug interface, and that the curves of Figures 25 and 26 are only crude approximations. More data are necessary, and they should be taken using at least five cells per lug before any definite statements can be made concerning the absolute magnitude of the existing pressures. The data presented here should be taken only as representative of the range of pressures existing, and not as absolutely correct.

Pressure Distribution Across The Tire Undertread

The data taken with the diaphragm cells were summarized in Table 5 and plotted in Figures 27 and 28. Figure 27 shows a plot of the pressure distribution at the soil-tire interface across one half of the undertread as measured with five diaphragm cells. These curves show a shift of pressure from the center to the edge of the tire with decreasing tire pressure for the same reasons that are mentioned earlier in connection with the lugs. However, since these pressures are considerably lower, the shift is much smaller than that observed under the lugs. With only one exception, all of the pressure

Table 5

Summary Of Undertread Pressure Distribution Data
Across The Width Of The Tire*

Series Of Data	Cell Position Across The Tire					
	Left Hand Side			Right Hand Side		
	Shoulder of Tire	Center of Under-tread	Center of Tire	Center of Tire	Center of Under-tread	Shoulder of Tire
	18 psi Tire Pressure					
7	---	---	---	11.2	5.55	0.4
5	---	---	---	9.54	3.86	0.0
5	---	---	---	15.76	5.28	2.08
6	---	---	---	9.56	---	0.0
6	0.08	6.7	12.3	---	---	---
Average	0.08	6.7	12.3	11.45	4.89	0.62
	14 psi Tire Pressure					
7	---	---	---	11.0	4.2	0.53
5	---	---	---	7.1	5.01	0.08
5	---	---	---	11.27	4.77	0.84
6	---	---	---	6.99	2.56	0.0
6	0.38	5.93	12.1	---	---	---
Average	0.38	5.93	12.1	9.09	4.14	0.36
	10 psi Tire Pressure					
7	---	---	---	10.3	4.67	0.68
5	---	---	---	3.51	2.71	0.25
5	---	---	---	8.46	4.61	1.63
6	---	---	---	5.94	5.54	0.5
6	1.0	4.3	7.18	---	---	---
Average	1.0	4.3	7.18	7.05	4.83	0.77

* Cell readings in psi

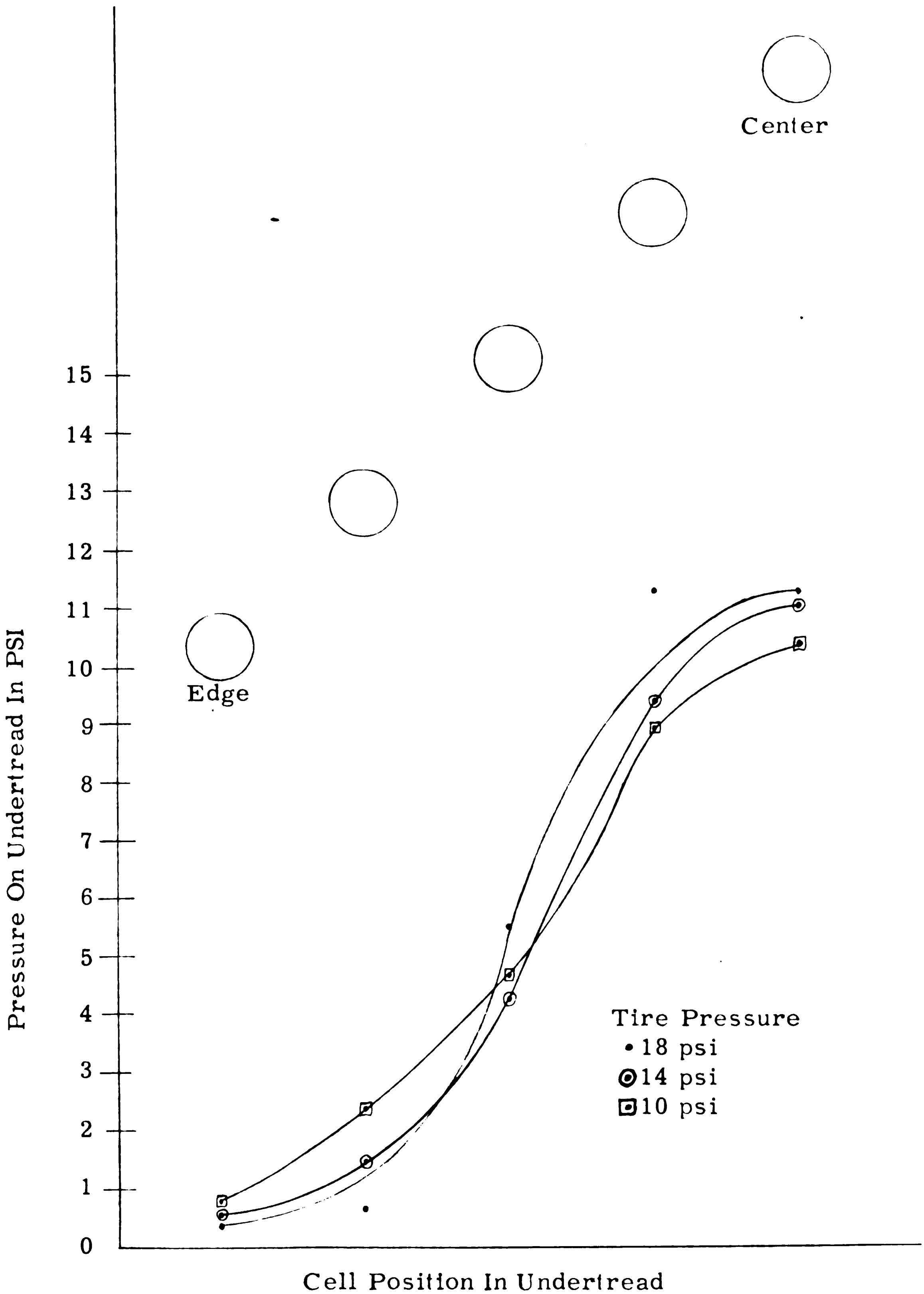


Fig. 27 Pressure Distribution Across One Half Of The Tire Undertread As Given By 5 Cells

readings were lower than the tire pressure used for that particular series of data, and all of the pressures were approaching the range where their effect on soil compaction would be minimized.

The curves of Figure 28 show the pressure distribution across the entire width of the tire undertread as measured by only three cells in each half of the tire. These curves can be considered as a general representation of the pressure distribution, but five cells in each half of the tire would be required to give an exact picture. These curves have indicated, however, that the pressure distribution on the undertread across the width of the tire was more uniform than for the lugs.

It is felt that the data taken with the diaphragm cells is reliable and can be accepted as is. Thus Figure 27 was accepted as a true representation of the undertread pressure distribution over one half of the tire. All future data should be taken using at least five cells in each half of the tire.

The diaphragm cells used in this investigation were a little more sensitive than necessary, but their over all performance was excellent. It is felt that they can be made to operate satisfactorily for obtaining the lug pressures, and the author suggests that properly designed diaphragm cells be used in all future work for both lug and undertread pressure distribution measurements.

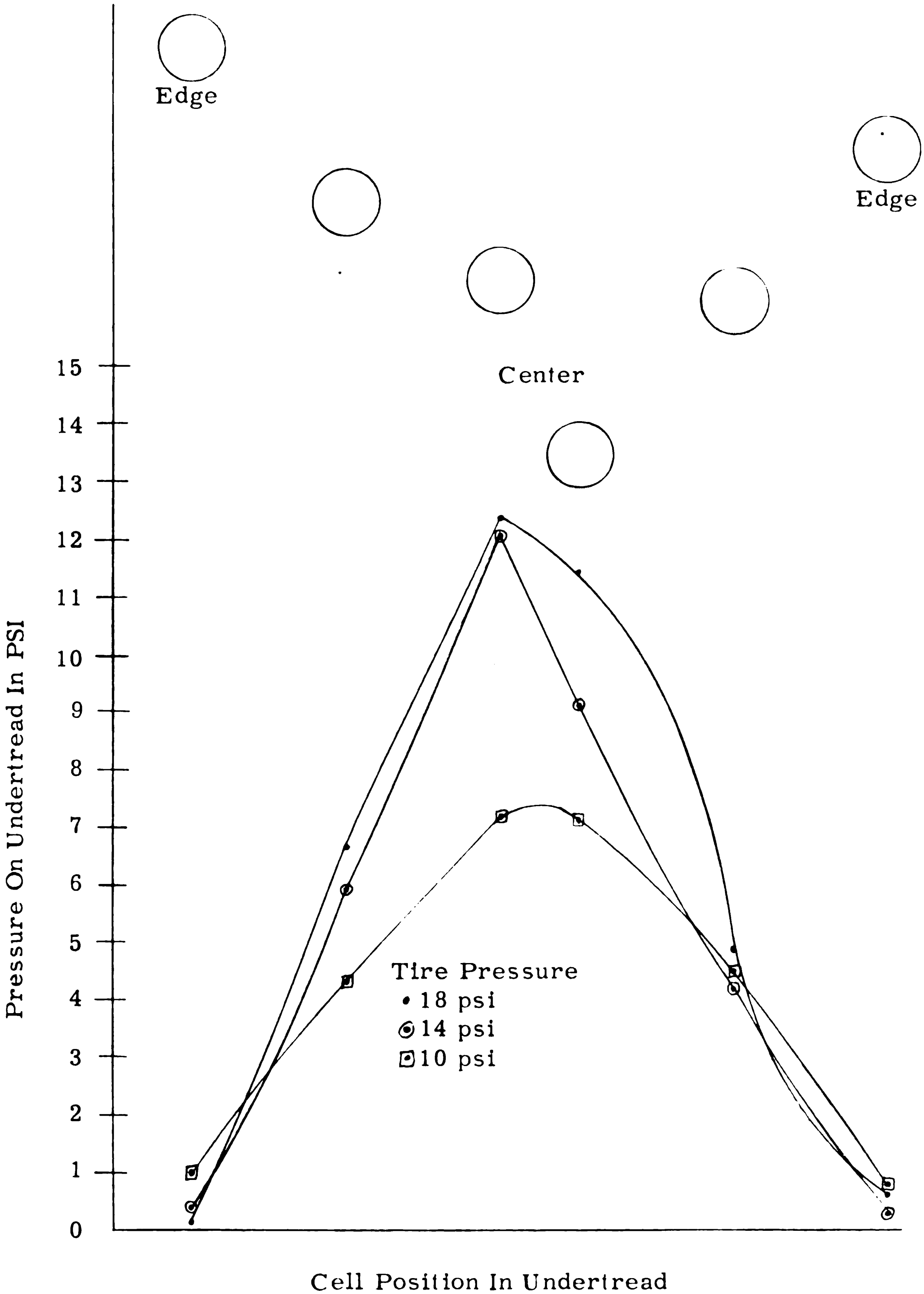


Fig. 28 Pressure Distribution Across The Width Of The Tire Undertread As Given By Three Cells In Each Half Of The Tire

VIII SUMMARY

Two types of strain gage pressure transducers were built and tested in a rear tractor tire. The CST-1 cells were mounted in the lugs of the tire to measure the pressure distribution at the soil-lug interface and the thrust on the lugs as the tire develops traction in the soil. The diaphragm cells were mounted in the undertread of the tire to measure the pressure distribution existing there.

Both types of cells were calibrated using water pressure before they were mounted in the tire. The CST-1 cells did not operate as well as expected and an in-place method of calibration was developed in an effort to overcome some of the difficulties. The new calibration method improved the reliability of the cells, but did not solve all of the problems.

While the diaphragm cells provided accurate readings they were more sensitive than necessary. On the basis of the performance of these cells it is recommended that any further work be done using diaphragm cells exclusively in both the lugs and the undertread of the tire.

Data were taken with both types of cells and when analyzed and plotted gave a picture of the pressure distribution existing at the soil-tire interface. It was felt that the data from the diaphragm cells gave a reliable picture of the existing pressure distribution, whereas the data from the CST-1 cells were not considered completely correct.

The purpose of this investigation was to establish the pressure distribution existing at the soil-tire interface under a rear tractor tire. However, this purpose was not completely accomplished since it was necessary to design and construct the transducers used in the experiment. Also, one set of transducers did not function properly. The greatest accomplishment of this investigation has been the design and development of a transducer which can be used in making further investigations. The collecting and analyzing of completely reliable data must be left for future investigators.

IX CONCLUSIONS

1. Strain gage pressure cells can be used effectively to measure the pressure distribution under a tractor tire.

2. The CST-1 cells can be made to work satisfactorily, but are not the best type of cell to use.

3. Diaphragm cells should be used in place of the CST-1 cells.

4. At least five cells are necessary to give an accurate picture of the pressure distribution existing over one half of the tire.

5. The number of cells required to give the necessary amount of data in any further tests can be reduced to a minimum of twenty; ten cells in the lugs and ten in the undertread.

6. Tire pressure has very little effect on the pressure applied to the soil by the undertread of the tire.

7. Tire pressure has a great influence on both the maximum pressure and the pressure distribution existing under the lugs.

8. Lower tire pressures give a more even and favorable pressure distribution under the lugs.

9. The lugs of the tire carry the greatest part of the wheel load even in sand.

X RECOMMENDATIONS FOR FURTHER STUDY

1. Design and develop a diaphragm cell to take the place of the CST-1 cells in future work.

2. Make comparative readings with the new diaphragm cells and the CST-1 cells in the present tire.

3. Collect more data to accurately determine the pressure distribution under the lugs of the present tire in the sand box.

4. Collect and evaluate field data on the present tire using the new diaphragm cells.

5. Accurately determine the effect of drawbar load on the pressure distribution across the lugs and undertread of the tire.

6. Determine the force distribution across the side of the lug as it develops traction in the soil at various drawbar loads.

7. Determine the effect of lug height, shape, angle and size on tractive efficiency.

8. Test the relative merits of other tires with respect to the above mentioned things.

9. Develop a theory of traction which will take into account the findings of the above investigations and be useful in designing more efficient tractor tires.

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