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SOIL STRAIN GAGE INSTRUMENTATION

W. B. Truesdale
R. B. Schwab

IIT Research Institute
Chicago, Illinois

Contract AF29(601)-6410

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TECHNICAL REPORT NO. AFWL-TR-65-207

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AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This report was prepared by the IIT Research Institute (IITRI), Chicago, Illinois, under Contract AF 29(601)-6410. The research was performed under Program Element 7.60.08.01.D, Project 5710, Subtask 13.502, and was funded by the Defense Atomic Support Agency (DASA).

Inclusive dates of research were May 1964 to May 1965. The report was submitted 15 February 1966. Air Force Weapons Laboratory technical monitors were Captain G. Leigh and Mr. F. Peterson (WLDC). Personnel of IITRI who contributed to the program include Messrs. M. Anderson, D. Hampton, R. Schwab, W. Truesdale, J. Van Scoyac, and E. Vey.

This technical report has been reviewed and is approved.

Gerald G. Leigh
GERALD G. LEIGH
Captain USAF
Project Officer
Civil Engineering Branch

F.W. Korbitz, Jr
FREDRICK W. KORBITZ, JR.
Lt Colonel USAF
Chief, Civil Engineering Branch

John W. Kodis
JOHN W. KODIS
Colonel USAF
Chief, Development Division

ABSTRACT

Soil strain gage instrumentation was developed for the measurement of static and dynamic strains when embedded in soil. The gage is suitable for both laboratory and field application. The strain sensor consists of two mechanically uncoupled flat-coil disks which are embedded in the soil in near parallel and concentric orientation. The remainder of the gage comprises an identical set of coils positioned external to the soil as a standard reference, specially designed electronic driving, amplifying, and recording circuitry, and a precision micrometer coil mount. Soil deformations are determined by the resulting change in spacing of the embedded coil disks sensed as changes in mutual coil inductance. The gage is a reliable precise measuring device which is well suited for the measurement of strain in soil.

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SOIL STRAIN GAGE INSTRUMENTATION

I. INTRODUCTION

This report describes gage hardware developed for the measurement of strain in soil. The work was performed for the Air Force Weapons Laboratory under Contract No. AF29(601)-6004. A sufficient range of gage hardware was required to provide capability of strain measurement in both laboratory and field applications under either static or dynamic loading conditions.

The developmental research encompassed a period of 3 years. The efforts in the first 2 years were devoted to the development of a miniature gage for use in laboratory studies.[1, 2] The effort in the third year was primarily concerned with extending the laboratory gage concept to permit measurement of soil strains in the field, but also included investigation of techniques to improve laboratory gage performance.

The gage concept utilized is believed to be well suited for the measurement of strain in soil. The strain sensor consists of two flat-coil disks which are embedded in soil in near parallel and concentric orientation without physical connection between them. The remainder of the gage hardware consists of a second set of coil disks, identical to those used as the strain sensor, and specially designed electronic driving, amplifying, balancing, and recording circuitry. The gage utilizes the differential transformer principle. Soil deformations are measured by the resulting changes in the spacing of the embedded coils which are sensed as changes in the mutual inductance of the coils. The soil strain is computed as the quotient of the change in coil spacing divided by the original coil spacing.

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[1] Truesdale, W. B., Development of a Small Soil Strain Gage, AFWL-TDR-63-3, March 1963.

[2] Keller, R. W. and M. E. Anderson, Development of a Soil Strain Gage for Laboratory Dynamic Tests, AFWL-TDR-64-7, April 1964.

II. PURPOSE AND SCOPE OF RESEARCH

The purpose of the program was to continue the soil strain gage developmental work initiated under Contract No. AF29(601)-5343. In scope the contract had three primary objectives:

(1) Adapt the principle of the laboratory strain gage to the development of a field gage.

(2) Eliminate mutual interference between adjacent gages.

(3) Continue development of the laboratory gage to increase sensitivity and permit use of longer gage lengths.

In accomplishing the first objective, gage instrumentation was developed far superior to that of the laboratory gage with respect to sensitivity and ease of use. To make use of these advantages, objective (3) was accomplished by designing small coils for laboratory use, which could be operated with the field gage instrumentation. The mutual gage interference problem of objective (2) consisted of two effects. The first was a beat frequency mutual interference between gages caused by slight differences in oscillator drive frequencies. The second effect was mutual pickup between gages, i.e., a change in relative positions between gage pairs in close proximity caused a signal voltage to be picked up by each instrument. The gage design provides a means of eliminating the beat interference, but certain restrictions on separation must be imposed to eliminate the problem of mutual signal pick up.

In addition to the above, eight gage units were required as end items on the contract. Three units were delivered to AFWL in October 1964, and five units in April 1965. A field evaluation of the gages was made by IITRI through participation in the May 6, 1965 LDHEST shot co[illegible]ed by AFWL at Kirtland Air Force Base, New Mexico.

III. THE SIGNIFICANCE OF STRAIN MEASUREMENT

Linear strain is defined as the limit of the ratio $\Delta\delta/\Delta L$ as ΔL approaches zero, where ΔL represents the linear separation of two closely spaced points and $\Delta\delta$ represents the change in ΔL under an applied load. Ideally then, exact strain measurement requires a capability of deformation measurement at a point. This is physically impossible. Instead, it is necessary to determine an average strain by measuring the change in spacing of two points a finite distance apart. Only when deformation is uniform over the distance of separation of the points does the measured average strain represent the exact strain. This limitation is most significant in the measurement of strains induced by a transient shock wave. The strains will change most rapidly in the vicinity of the shock front. Therefore, the strain in the region between two points will be non-uniform as the shock front passes from one point to the other. Clearly, from consideration of exact strain measurement, it is desirable to make L as small as possible.

Exact strain measurement at a point in a soil medium, however, is of questionable significance. Soil is an accumulation of solid particles containing a significant portion of void space which may be filled partially or entirely with the water. The major deformations which occur in soil under an applied load are due to interparticle movements and not actual deformations of the individual particles, hence the questionable significance of the concept of point measurement. The desired measurement is the relative movements of a sufficient number of particles to obtain a statistically representative soil strain. To obtain such a measurement it is necessary to measure deformations over a finite distance in the soil.

Presently it is not possible to quantitatively evaluate an optimum length over which a soil strain measurement should be made. The optimum will vary with soil type depending on a number of soil properties, including grain size distribution and shape. In clays, silts and fine sands, gage lengths of only a few tenths of an inch might be desirable. In coarse grained soils and in fine grained soil deposits which contain stones and gravel, gage lengths of several inches might be desirable.

Practical aspects of soil strain measurement introduce additional considerations. The gage must be coupled to the surrounding soil so that it will respond to deformations which occur while offering minimal resistance to these deformations. Coupling and resistance considerations introduce the problem of soil-gage interaction and the effects of gage placement on this interaction. This problem area has been the subject of considerable investigation for several years with respect to stress gage development. However, it has not yet been resolved. The principal controversy which exists concerns gage geometry. It is contended by some that the gage shape should be that of a disk with a diameter to thickness ratio of 10:1 or more,[3] by others that this ratio should be 1:1.* Placement techniques have not been formalized and probably as many techniques exist as gage users.

While the above points do not contribute to the discussion of strain measurement they illustrate that the problem of soil-gage interaction is one of great ambiguity. Obviously it would be desirable that a gage sensor duplicate the properties of the soil it displaces. This is not possible because the stress-strain relationship for soil is not unique, but varies with soil type (and within soil type) with moisture, density, method of compaction, degree of confinement, and even level of stress. A logical method to minimize effects of soil-gage property mismatch is to make the size of the embedded components as small as possible. Discussion of the possible effects of soil gage interaction with respect to the soil strain gage developed on this contract is given in Section IV.

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[3] Selig, E. T., "Shock Induced Stress Wave Propagation in Sand", Unpublished Ph.D. Thesis, Illinois Institute of Technology, January 1964.

* A gage of this shape, purported to hold considerable promise, has been developed by R. E. Lynch at the **E. H. Wang Civil Engineering Research Facility, Kirtland Air Force Base, New Mexico.**

IV. REVIEW OF PREVIOUS WORK

Developmental research on gage instrumentation to measure strain in soil was initiated under Air Force Contract No. AF29(601)-5343 in April 1962.[1] The objective of the program was to design, develop and verify the operation of a small gage intended for laboratory study in small soil samples under either static or dynamic loading conditions. Design criteria specified in the contract were as follows:

(1) The greatest dimension of the gage was not to exceed 1 inch.

(2) The gage was to have a range of measurement of at least ±20 percent of the gage length.

(3) The gage was to offer little resistance to the relative axial movement of the gage ends.

(4) Gage lead wires were to be unshielded, thin, flexible wires covered only with waterproof insulation. Movements of the lead wires during testing were not to affect the signal from the strain sensor.

(5) The gage was to be operable in all types of soils including moist and saturated soils.

To satisfy these criteria a gage was designed to make direct measurement of differential displacement of two gage points which had no mechanical coupling between them. The gage points were determined by wire coils encapsulated in 3/4 inch diameter by 1/16 inch thick disks embedded in the soil in parallel and concentric orientation.

The use of these coil disks as soil strain sensors involved two principles of electrical engineering. First, a current-carrying loop of wire generates a magnetic field which decreases in density as a function of distance from the coil. Second, voltage is induced in another coil placed in near proximity to a current-carrying coil in proportion to the integral of the magnetic field density over the area of the coil. In the soil strain gage application one coil (referred to as a driver coil) is driven with a high frequency AC signal. The AC excitation causes a voltage to be induced in the second coil (referred to as a pickup coil). For a small change in spacing of the coils from L to $L \pm \Delta L$ the voltage induced in the pickup coil is nearly linearly related to L. However, for $\Delta L \ll L$ the percentage change in induced voltage is very small. To isolate this small percentage change in induced voltage, a second set of coils (referred to as the standard coils) were introduced. The circuitry is arranged so that the driver coils are series connected to an AC power source, and the pickup coils are series connected to a receiving circuit. The pickup coils are connected in such a way that the resulting signal is the difference of the individual coil outputs. In this manner the resultant induced voltage output is zero when the coils in each set are equally spaced.

The coils represent the basic elements of the gage. Electronic circuits to amplify, demodulate, indicate signal levels, and maximize sensitivity, and an adjustable micrometer coil mount for positioning the standard coils are also necessary parts of the gage apparatus which were designed specifically for this system.

Figure 1 shows the basic components utilized for the application of a soil strain sensor. The drive-coil circuit comprises a 50-kc oscillator and drive-coil power amplifier. The pickup coils are connected to an amplifier, which in turn is connected to a synchronous detector, filter, and meter. When the spacing of the two sets is different, a small differential voltage appears at the input of the amplifier. Once amplified, the signal of interest is the envelope of this high-frequency carrier. The synchronous detector (a conventional ring demodulator) separates the envelope from the high-frequency carrier. The demodulator output is zero when the carrier input is zero or nulled, and is either positive or negative in polarity when the two pickup coil voltages are not equal. The polarity depends on which coil has the larger voltage, thereby indicating whether the coils embedded in the sample have moved closer together or farther apart. The response time of the gage, defined as the time from 10 percent to 90 percent peak output, was determined experimentally to be approximately 0.01 msec.

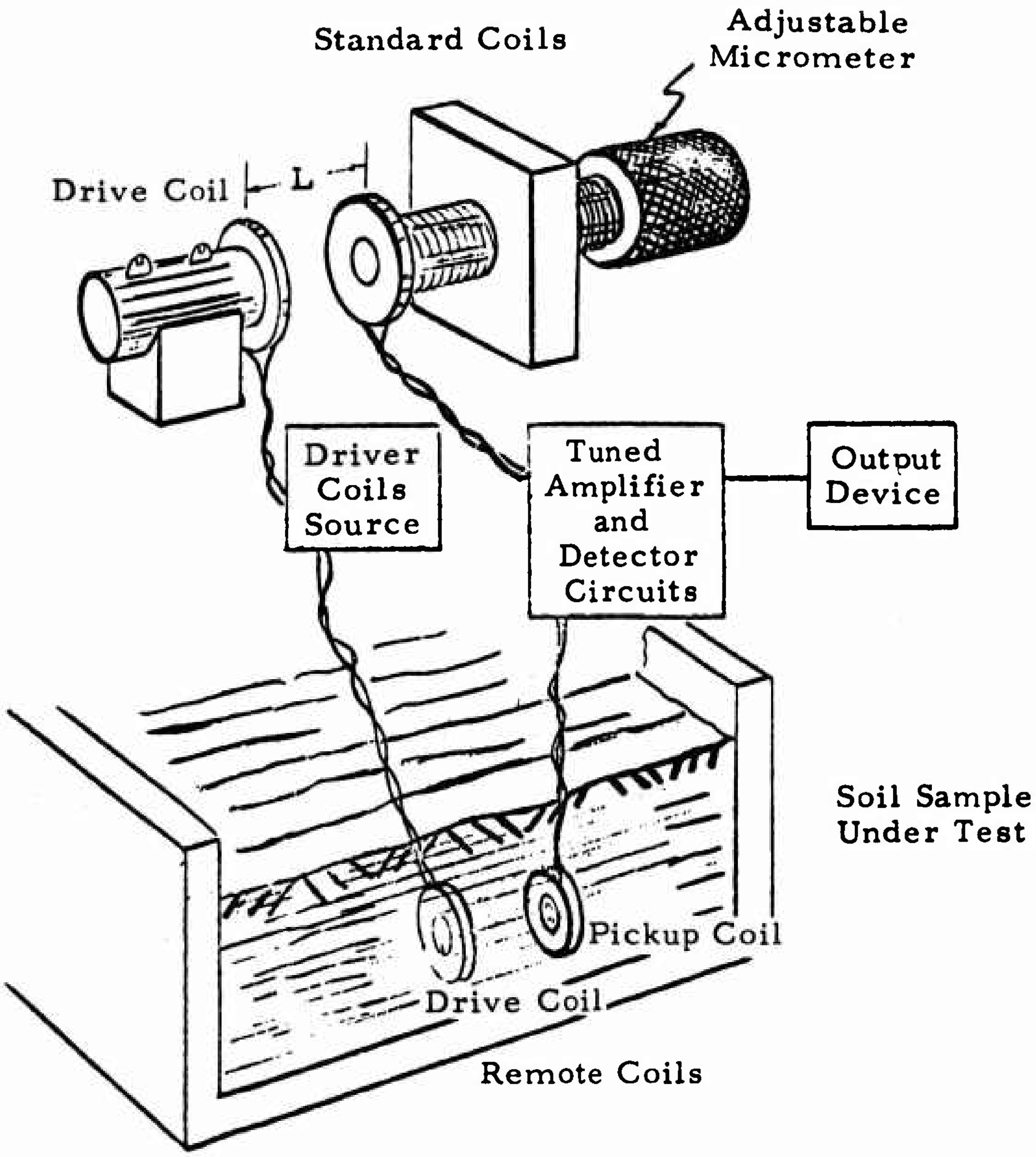

Fig. 1 PICTORIAL DIAGRAM OF SOIL STRAIN GAGE

Figure 2 displays the components which constitute the soil strain gage in its finalized form. These consist of two sets of coils, the adjustable micrometer coil mount and the electronic auxiliaries. The gage satisfied all the specified design criteria and had the following particular advantages which made it well suited for soil strain measurement:

(a) There was not a physical transducer between the driver and the pickup coils embedded in the soil sample. Soil could be placed uniformly within the gage length and actuation of the gage offered no resistance to the movement of the soil. This is a significant improvement over mechanically coupled gages which not only complicate uniform placement of the soil but also require that protection be given to the moving linkage to prevent binding by interference of soil particles.

(b) Precise spacing of the two embedded coils inserted in the soil was not required. The coil spacing could be determined after placement by adjustment of the standard coil spacing to obtain a nulled output.

(c) Calibration of the embedded coils for measurement of transient strains was a quick and simple process performed immediately prior to testing by means of the standard coils. Once the nulled spacing was determined the standard coils could be moved through a series of incremental changes and the corresponding differential output voltages determined. With the standard coils returned to the null position, this served as the displacement-voltage calibration of the embedded coils.

(d) Coil disks were relatively inexpensive (less than $1.00 each) making them expendable.

However, there were also the following drawbacks in the use of the gage:

(a) Minimum resolution was approximately 1 percent change in spacing. The limit on resolution greatly reduced its range of use, particularly in tests where the soil specimen is subjected to a high degree of confinement which frequently limits strains to less than 1 percent.

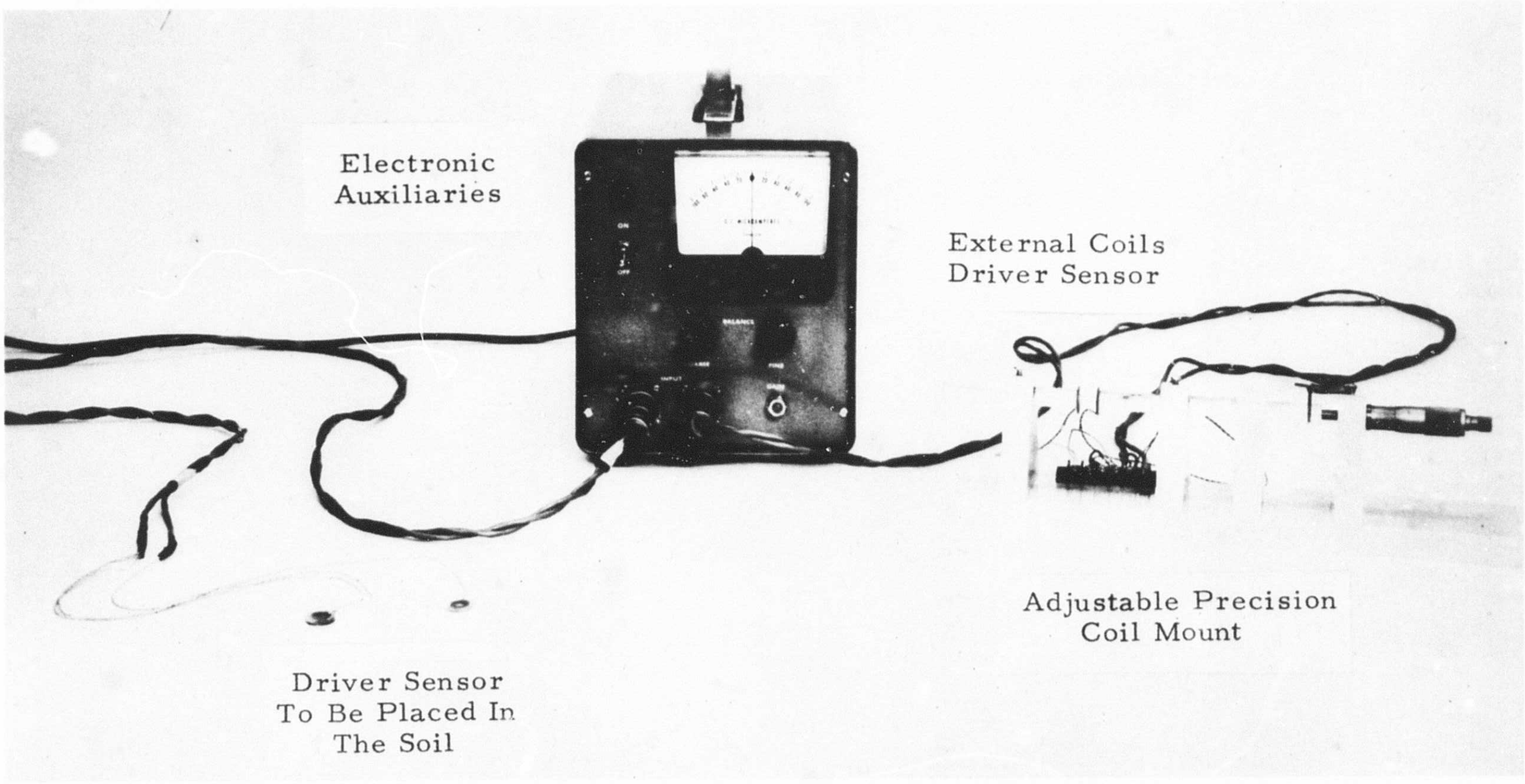

Fig. 2 SOIL STRAIN GAGE

(b) Placement coil alignment tolerances were strict because of effects of lateral misalignment. Figure 3 depicts the coil alignment parameters. While both lateral and rotational misalignment were possible, the effects of rotation were not felt to be critical. Relative coil rotations of 10 degrees resulted in almost negligible error. To reduce sensitivity of the device to lateral misalignments, the driver coils were made larger in diameter than the pickup coils. This was accomplished by winding the driver coils with a greater number of turns and a larger inside diameter. A ratio of two to one was used for both the number of turns and the inside coil diameter. In this manner the area of uniformity of the magnetic field created by the driver coil was greater than the cross-sectional area of the pickup coil. This allowed the pickup coil to move laterally within this uniform area with negligible effect on gage output. The actual amount of movement allowed is dependent on the coil spacing and varies somewhat with the uniformity of coil construction.

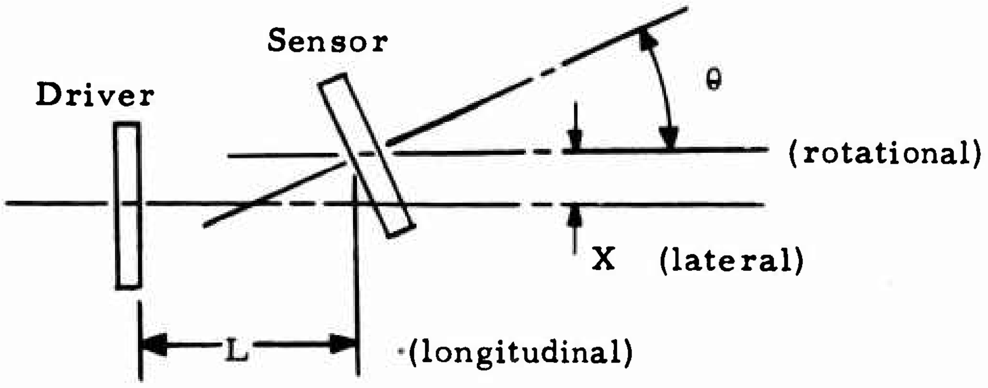

Fig. 3 COIL POSITION PARAMETERS

Even with this provision to reduce lateral misalignment effects, it was required that lateral offset not exceed 10 percent of the coil spacing. Coil spacings were limited to 0.5 inch and less because of sensitivity making this tolerance rather tight. However, experience in working with the gage indicated that the coils could be placed so that error due to misalignment was normally 2 percent or less.

(c) Selecting coil pairs was a laborious process. The principle of operation of the gage relies on the uniformity of the magnetic fields between the embedded and standard coil sets. If the driver and pickup coil in each set are not identical to their counterparts, the coil pairs will not null at equal spacings. Selection of the coils on the basis of a simple electrical measurement was not possible because the small signal levels being measured were quite sensitive to even slight differences in the mutual inductance of the coils. It was necessary to match coil pairs by trial and error selection of the pairs which would produce a near null over a range of equal spacings.

(d) Strain gage electronics were fairly expensive (approximately $1300 each). This limitation could possibly be reduced significantly if the unit were mass produced on a commercial basis.

(e) Gage response was influenced by metallic boundaries. This limitation was not considered severe, since approximately 3 inches clearance was required to reduce this effect to negligible magnitude.

In addition to these drawbacks, there was the unknown effect of soil-gage interaction. The embedded sensor consisted of the two independently placed coil disks. This permitted soil to be placed within the gage length and reduced the volume of soil displaced by the gage to a minimum. A first source of undesirable interaction could be coil disk thickness. Since the coil disk and soil stress-strain relationship necessarily differ, some interaction must occur. To minimize this interaction, special techniques were developed to fabricate coils to an encapsulated thickness of 1/16 inch. Gage length was then chosen as the distance from mid-coil thickness to mid-coil thickness, rather than the clear separation distance of the coils since it appeared most reasonable to assume interaction effects due to coil thickness would be symmetrical. In addition any nonuniform deformation of the disk and surrounding soil should tend to be self-correcting. If the disk is stiffer than the soil, additional load should be transferred to the disk by soil arching action. Conversely if the disk is less stiff than the soil, load should arch around the disk.

Another source of interaction is the cross-sectional surface area of the disk. The effect here is similar to that which occurs in triaxial testing where shearing forces develop between the soil and the end plates. The effect of these shearing forces is to give the soil added stiffness through restraint of lateral expansion. Studies by D. W. Taylor[4] indicated that a specimen height to diameter ratio of 2:1 was required to reduce the effect of end plates on specimen strength to negligible magnitude. It is believed, however, that the restraint of lateral soil movements by the coil disks is less critical. The following facts are offered in support. First the triaxial specimen is enclosed in a rubber membrane which is generally sealed to the end plates by an O-ring in near proximity to the specimen end. This provides added restraint on specimen expansion not present with the embedded sensors. Second, in the triaxial test, soil which expands beyond the edge of the end plate is no longer directly loaded in compression. As such this soil provides additional lateral restraint to that soil which remains under the plate. With the strain gage disk any soil which expands laterally beyond the disk remains under loading due to the surrounding soil. Third, soil arching will tend to self-correct undesirable soil-gage interaction effects. If the soil between the disks exhibits greater stiffness than the surrounding soil, it will incur greater load due to soil arching.

Further, in one-dimensional compression tests, theoretically, no lateral soil strains occur. Practically, at least some small amount of lateral straining does occur, but it is quite probable that the resulting soil-disk surface-area interaction effects would be of negligible influence.

Investigation to determine the influence of soil-gage interaction was carried out by triaxial testing. The desire was to determine if gage measured strains and average specimen strain could be correlated at least during the initial stages of loading. However, using standard triaxial test techniques soil specimens strained so nonuniformly[5] that it was not possible

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[4] Taylor, D. W., Seventh Progress Report on Shear Research to U. S. Engineers, Massachusetts Institute of Technology Publication, 1941.

[5] Truesdale, W. B., Strain Variation in a Triaxial Soil Test, AFWL-TDR-64-47, September 1964.

to draw any definite conclusions about the seriousness of soil-gage interaction. In general gage response appeared to be reasonable, but the possibility of undesirable soil-gage interaction still existed.

Significant information on soil-gage interaction effects was gained during a study of soil stress-strain properties by Januskevicius and Vey.[6] These investigators performed triaxial tests using both standard techniques of preparation and a recently reported technique by Rowe and Barden which greatly reduced end friction restraint effects. With reduced end friction, uniform specimen straining occurred until the specimen approached failure. The soil strain gages developed by IITRI were embedded in 5 inch diameter by 5 inch high specimens of 20-40 Ottawa sand. The average specimen density was 105.4 lb per ft^3 with a maximum variation for all tests of ±1 percent. Ottawa sand at this density has an angle of internal friction of approximately 33 degrees.

The soil strain gages were placed at various locations in specimens at spacings ranging from 0.35 inch to 0.5 inch. Figures 4 and 5 show comparative results of gage measured strain versus total specimen strain. Excellent correlation exists up to 2 percent strain, at which point greater than 80 percent total specimen strength was realized. Hence, it appears likely that the specimens were approaching failure and a nonuniform state of strain was developing. This assumption is supported by measurements made in two tests of specimen lateral expansion (Fig. 6). The specimens underwent uniform lateral expansion over their entire length up to only 3 percent strain. Note also that lateral strains are large with respect to compressive strains. At 2 percent total specimen strain, a 2 percent increase in cross sectional area was realized.

These results verify the ability to measure soil strains which are unbiased by soil-gage interaction with the soil strain gage. The tests were performed in a granular medium where high **frictional stresses could** be generated across the surface area of the gage disks. The disks were closely spaced, approximately one half disk diameter apart. Still the gage

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[6] Januskevicius, C. K. and E. Vey, Stresses and Strains in Triaxial Specimens Using Embedded Gages, ASTM Symposium and Soil Dynamics, June 1965.

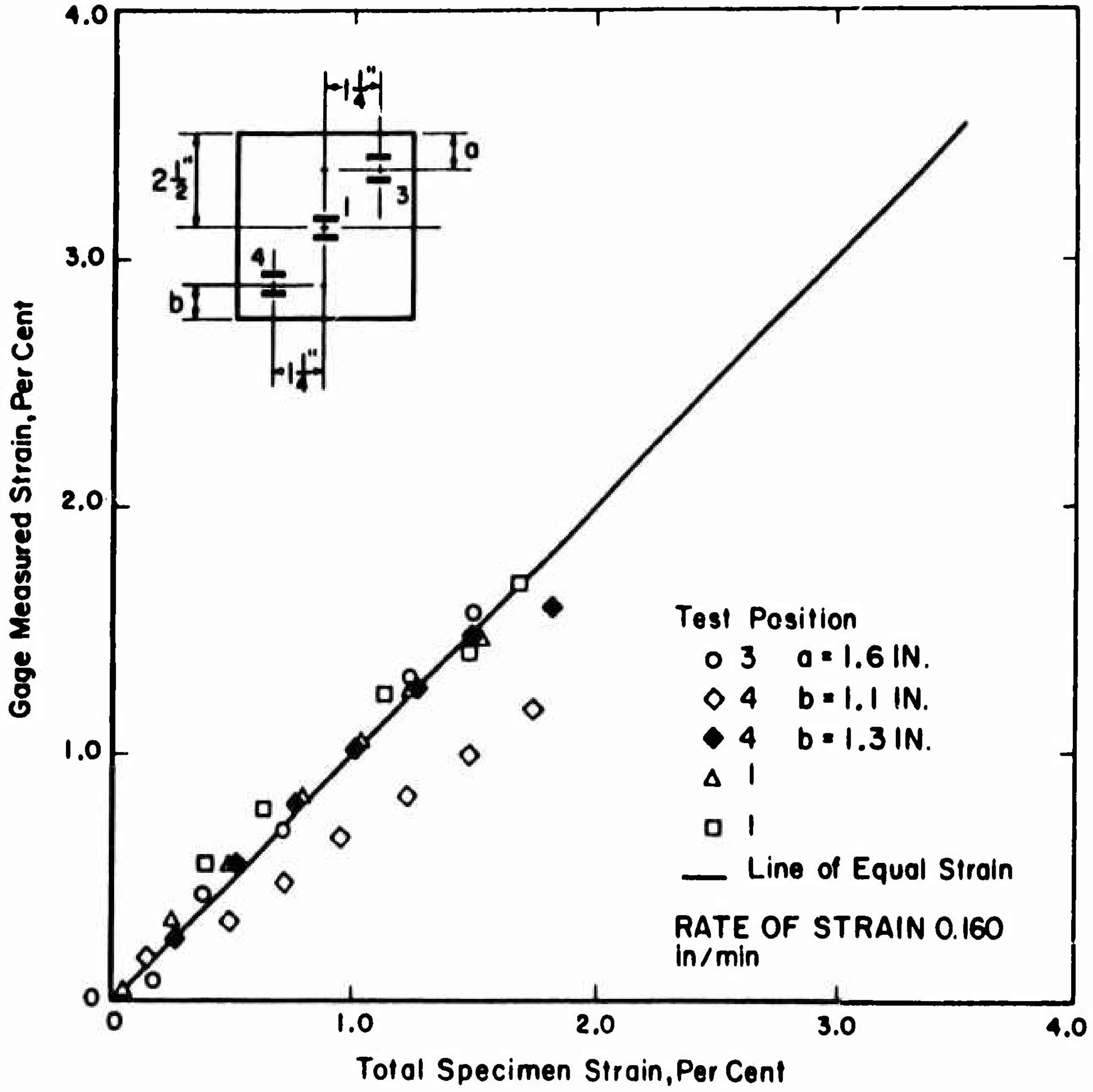


Fig. 4 STRAINS IN FRICTIONLESS END SPECIMENS AT SLOW RATES OF STRAIN (after Januskevicius and Vey)

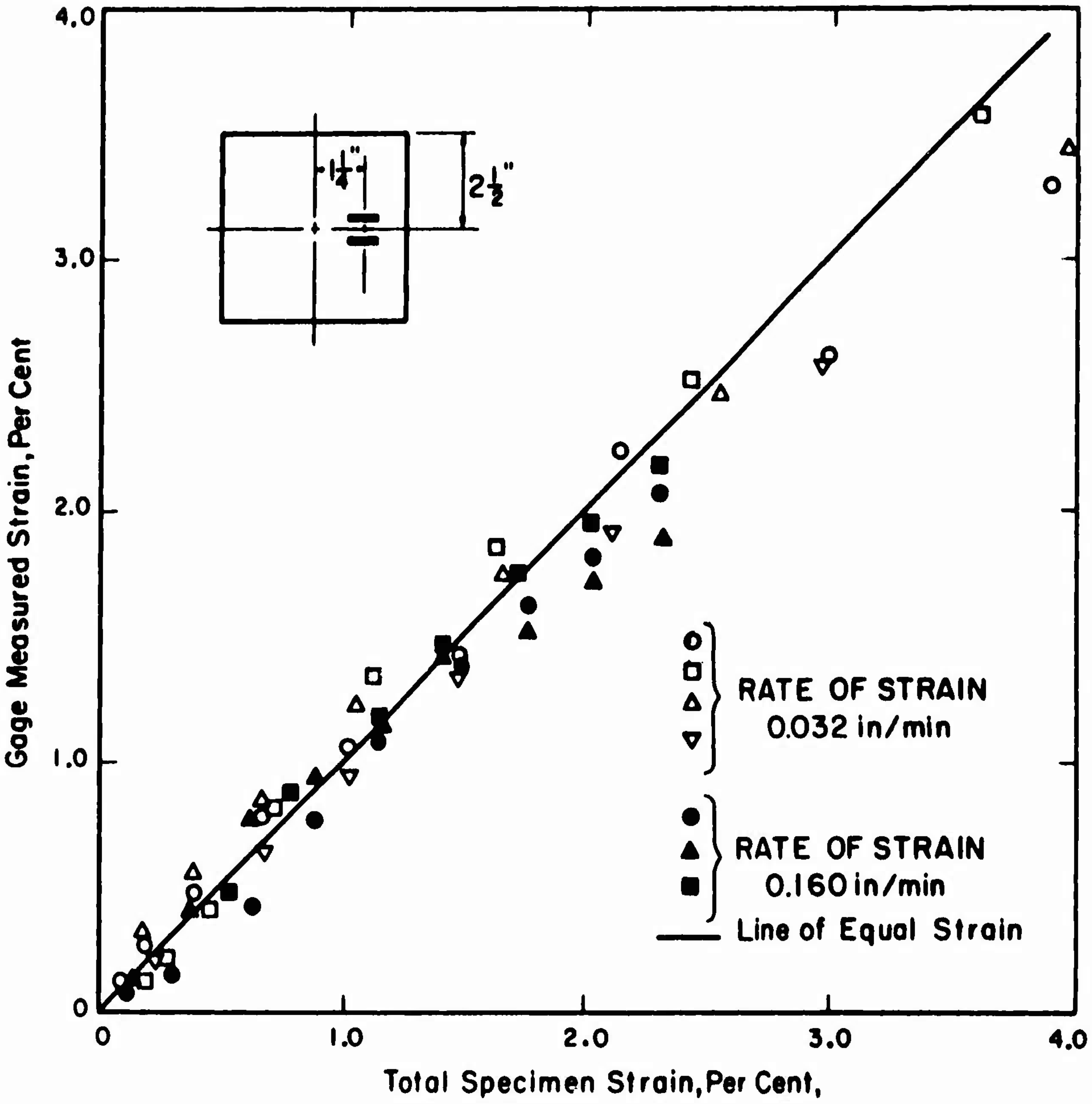


Fig. 5 STRAINS IN FRICTIONLESS END SPECIMENS AT SLOW RATES OF STRAIN (after Januskevicius and Vey)

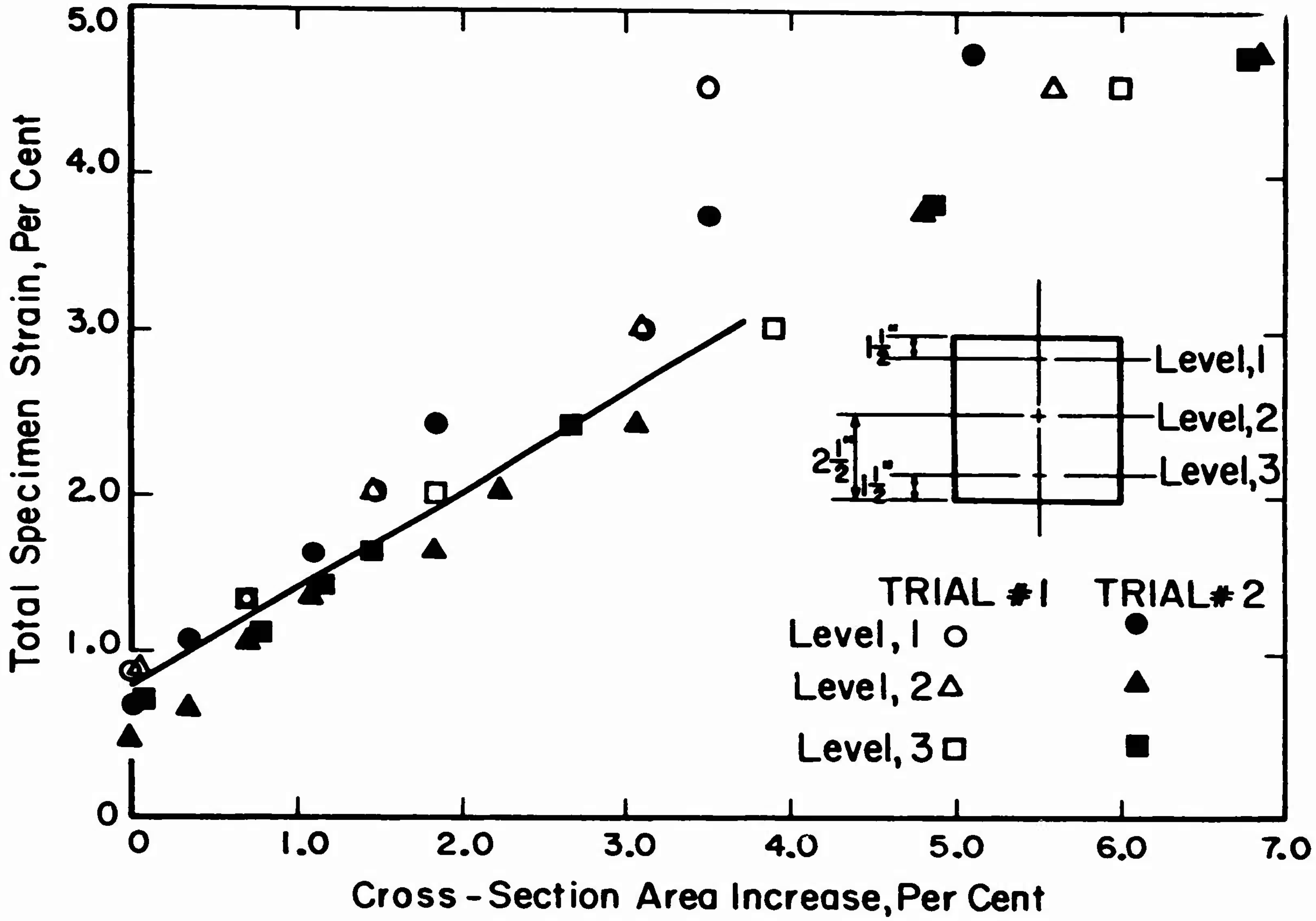


Fig. 6 LATERAL DEFORMATION OF FRICTIONLESS END SPECIMENS (after Januskevicius and Vey)

performed well during that period of testing in which uniform specimen straining can confidently be expected to exist.

In March 1963 the strain gage developmental contract was extended by AFWL to improve the basic gage design and investigate possible development of a gage which would make use of the influence of metal boundaries to permit measurement of relative changes in the position of a coil disk and a metal boundary.

The circuitry of the soil strain gage developed in the first year of work was redesigned to increase sensitivity and facilitate use of the gage by introducing balance controls to compensate for electrical differences in the coils. The changes made in the original system were:

(a) All coils were grounded on one side. This connection allowed for a more uniformly distributed capacity (Fig. 7). Previously, there were uneven capacitances to ground as shown in Fig. 8. With a common ground and approximately equal inductances the stray capacitances were approximately the same. Nulling the bridge was more readily accomplished under these symmetrical conditions.

(b) A 50-kc oscillator was designed by IITRI to replace the earlier commercial module. An improved input waveform to the driver coils was obtained by decreasing the harmonic content transmitted from the oscillator. The isolation between the driver coils and the oscillator was increased and more power was made available for delivery to the drive system.

(c) The input circuit was altered so that the sensing coils made up two legs of a bridge and two balanced resistors make up the other two legs. This eliminated the driver coils from the bridge circuit reducing the requirement for perfectly matched sets of driver and sensor coils.

(d) A continuous gain control was incorporated into the amplifier design ahead of the signal amplifier so that a change in gain would not introduce a phase angle change into the signal amplifier. Previously the gain control was located in a feedback loop in the internal signal amplifier circuitry where a change in gain changed other parameters. This revision enabled a simpler balancing procedure.

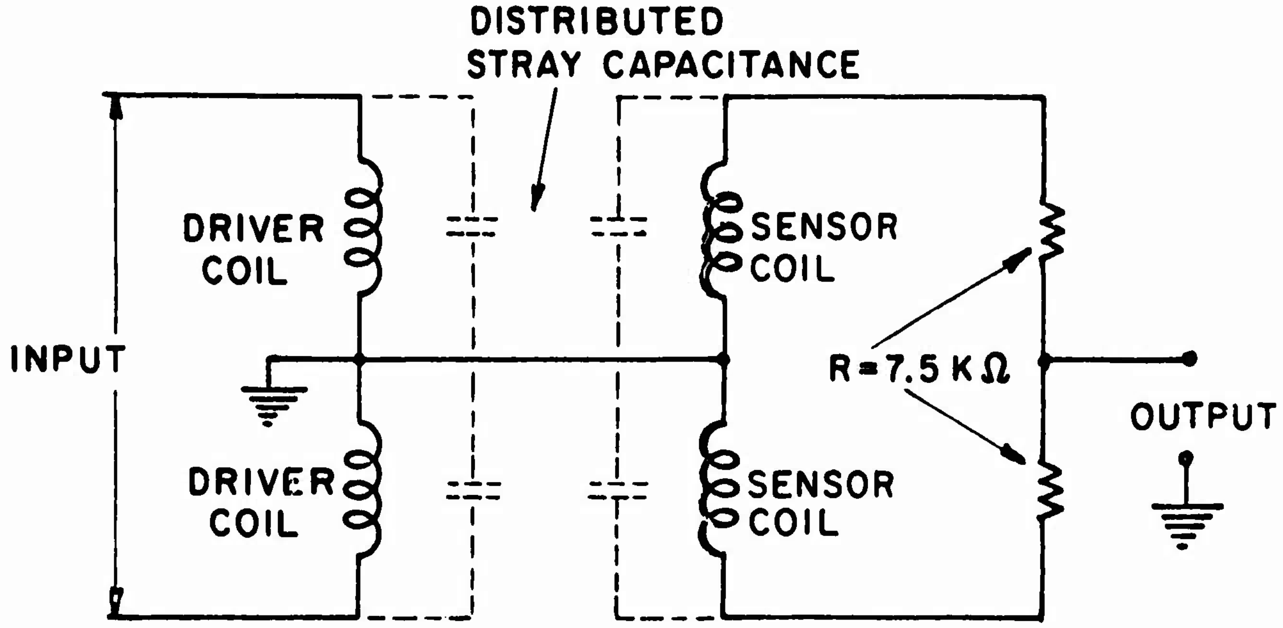


Fig. 7 FINAL BRIDGE CIRCUITRY - COMMON GROUNDING OF ALL COILS

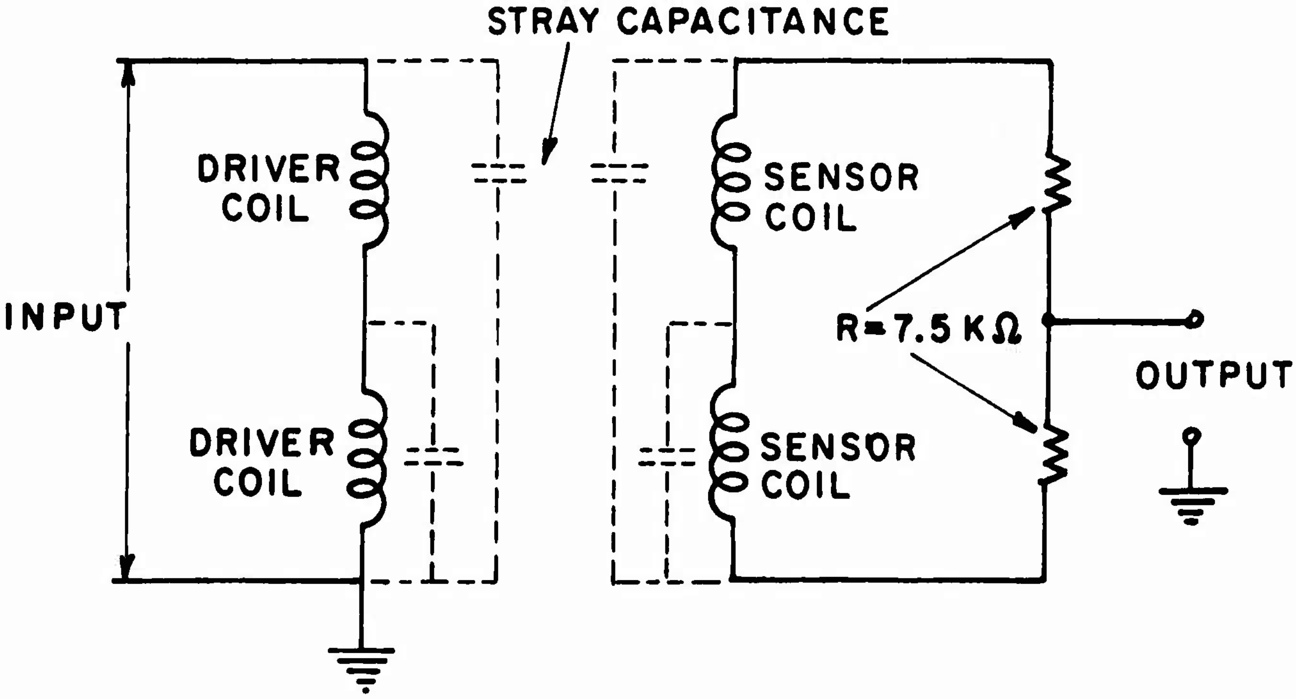


Fig. 8 ORIGINAL BRIDGE GROUNDING - UNEQUAL STRAY CAPACITANCES

(e) The synchronous detector was revised to facilitate detection of the null voltage permitting a more critical balance to be attained.

(f) A power amplifier was introduced into the signal amplifier network to enable the application of stronger signals into the synchronous detector to increase its sensitivity.

(g) Silicon transistors were used throughout the system to increase the stability of the system with temperature changes.

(h) Layout of the components was improved to provide easier accessibility to all the parts, thereby decreasing electronic maintenance problems.

(i) A more precisely regulated power supply was used and thus increased instrument stability.

The increase in sensitivity obtained as a result of these modifications is illustrated in Table 1 by the tabulated comparisons of relative coil displacement required for full scale output for each system.

Table 1

COMPARISON OF SPACING-SENSITIVITY RELATIONSHIPS FOR ORIGINAL AND MODIFIED STRAIN GAGE INSTRUMENTATION

	Differential Movement Required to Produce Full-Scale Meter Deflection	
Coil Separation in.	Original Instrument in.	Modified Instrument in.
0.500	0.123	0.010
0.800	0.315	0.044
1.000	0.450	0.085

With increased gage sensitivity there was found to be a problem of mutual gage interference. Each gage was operated with an independent set of electronics and slight differences in oscillator operating frequencies caused them to beat in opposition to one another when gage sensors from two or more units were placed within a few inches of one another. This effect was temporarily considered to be a limitation on gage use with no attempt made to eliminate the problem on this contract.

To permit measurement of changes in spacing between a coil disk and a conducting metal boundary a bifilar coil configuration was designed. The bifilar coil was a two wire coil winding which achieved a high degree of coupling between the windings. One wire winding served as a driver coil, the other as a pickup coil. To increase effective coil inductance the bifilar winding was inserted in a ferrite pot core as shown in Fig. 9. The ferrite pot core surrounded the coil on all sides except the one which would face a metallic boundary. The magnetic field set up by current through the coil was contained in the low magnetic reluctance path of the ferrite case except for that which fringed out the front face. This fringing flux determined the change in inductance as distance to the metallic boundary varied

The bifilar coil gage concept was the same electronically as the original four-coil system and efforts were directed to make the bifilar coil gage compatible for use with the existing electronic circuitry. Investigation revealed that satisfactory sensitivity was obtained only when the boundary metal was aluminum or copper. However, any boundary material could be made satisfactory by covering a small area opposite the gage with a thin sheet of either aluminum or copper.

Sensitivity of the bifilar gage system was comparable to that obtained with the modified instrumentation of the four-coil gage, but the gage stability proved inadequate. The parameters of the system were responsive to extraneous effects other than the change in distance between the coil and the boundary surface. The gage was not developed to a state which permitted evaluation in soil.

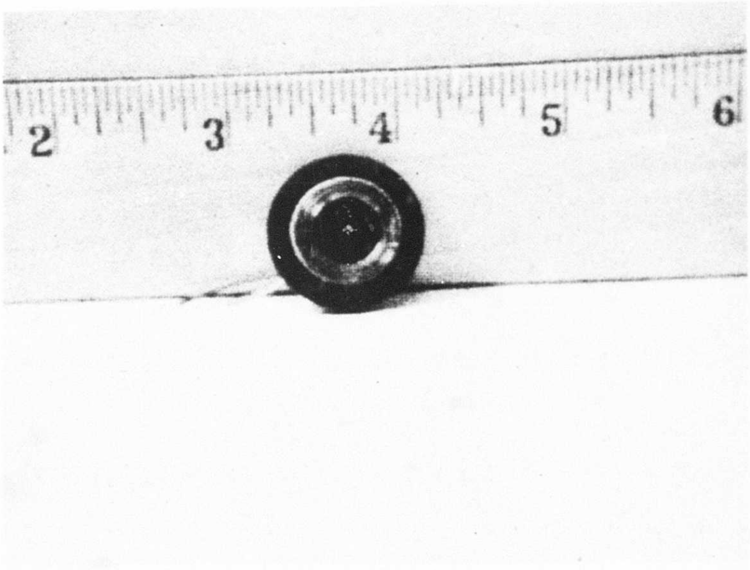


Fig. 9 DIMENSIONS AND CONFIGURATION OF COIL EMBEDDED IN FERRITE CORE

V. GAGE DESIGN

A. Field Gage Design Criteria

The desire was to design the field gage as a modification of the four-coil laboratory gage previously developed. Minimum specifications for the gage outlined in the contract were as follow:

(1) The gage was to operate with coils of from 3 to 6 inches diameter with a coil thickness of approximately 1/4 inch.

(2) The gage was to be operable with gage lengths of at least one coil diameter and preferably of two coil diameters.

(3) The gage was to be capable of accepting lead wires of from 500 feet to 1000 feet in length.

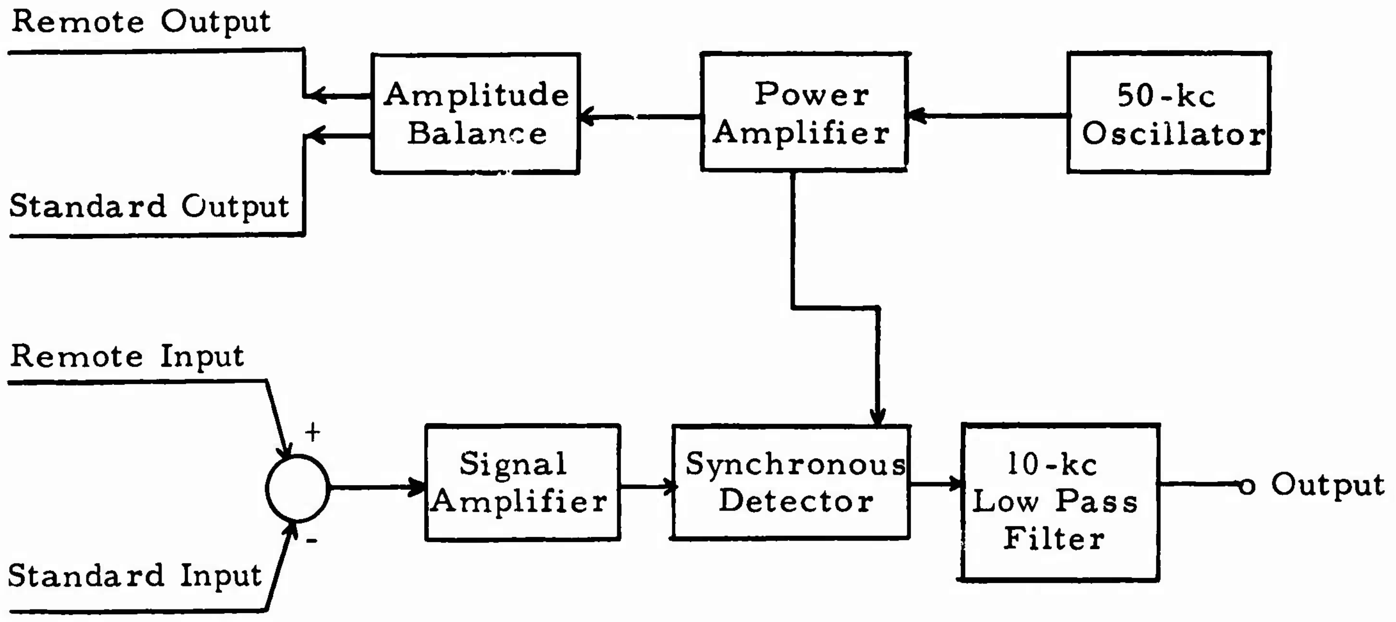
(4) The gage was to have sufficient sensitivity to permit accurate determination of changes as little as 2 percent of the maximum coil spacing.

(5) The gage was to have a frequency response of approximately 1 kc.

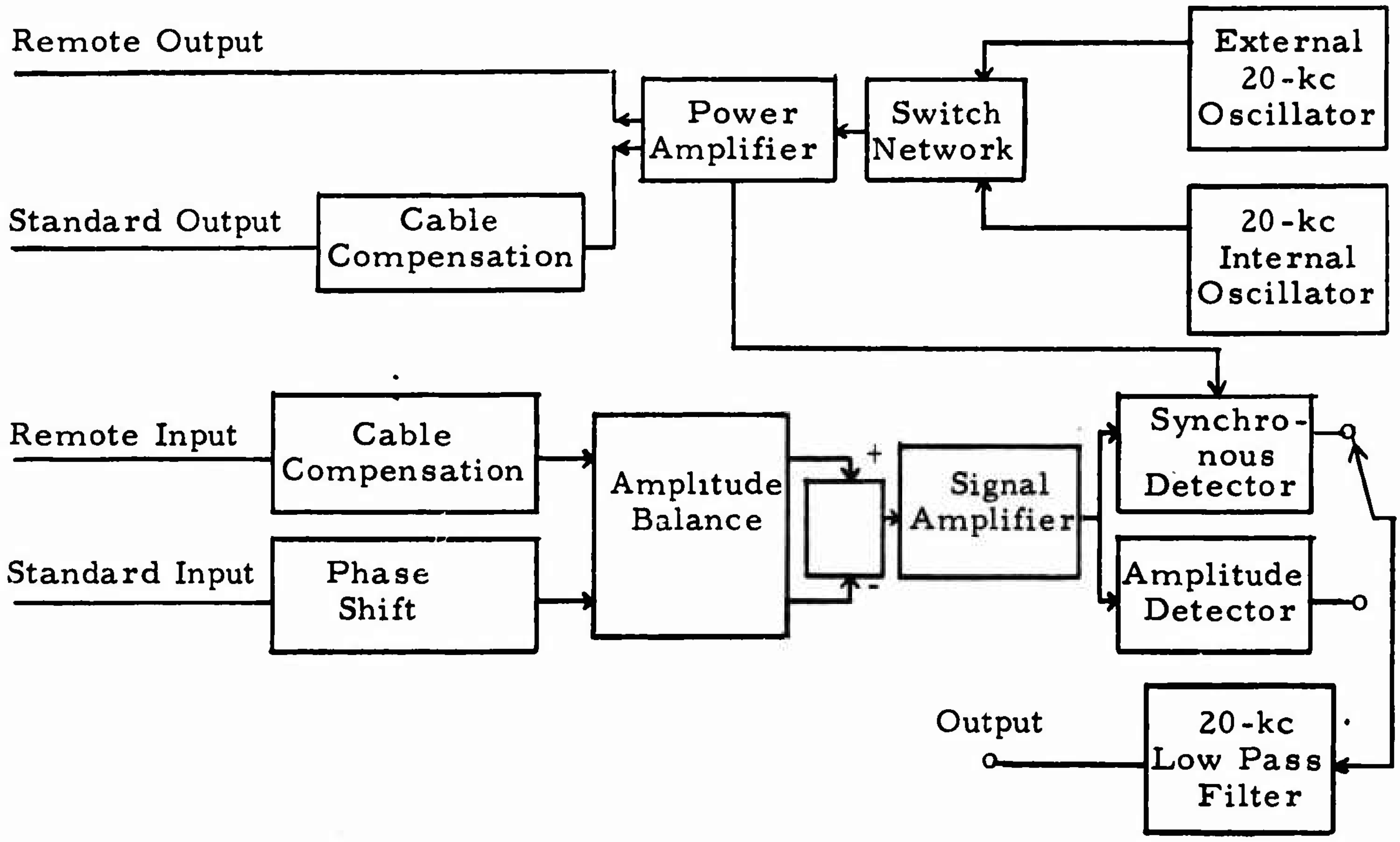
The gage design should satisfy these criteria without major changes from the design of the laboratory instrument electronics. This was not possible, however, because of problems introduced by the long cable length requirements. The changes required are explained with the use of block diagrams of the laboratory and field gage systems shown in Fig. 10.

The first difference in the systems is the change in oscillator frequency from 50 kc as was used with the laboratory gage to 20 kc used with the field gage. The reduction in frequency was necessary because of phase shift problems and undesirable effects of standing waves on the drive and pickup cables encountered with long cable lengths at the 50 kc driving frequency. At an operating frequency of 20 kc, phase shift was less critical and standing waves were not troublesome.

A second difference in the systems is the use of cable compensation in the standard drive output circuit and the remote pickup input circuit. These modifications were necessary to eliminate the need for equal length



(a) Laboratory Gage



(b) Field Gage

Fig. 10 BLOCK DIAGRAMS OF LABORATORY AND FIELD GAGE SYSTEMS of connection cables for the standard and remote coil sets. The signal supplied to the drive coil in the remote set, undergoes phase angle shift and amplitude attenuation through the connecting cable. A single Tee section used in the standard drive circuit approximates the phase shift and attenuation of the remote circuit to provide equal drive currents to both the standard and remote driver coils. Compensation in the remote pickup input circuit is accomplished by the addition of a capacitor and resistor across the input circuit. The values of capacitance and resistance are varied depending on cable length to cause the remote and standard circuits to be parallel resonant at 20 kc. Tuning the input circuit to 20 kc is necessary, otherwise cable capacitance would tune the cable to a frequency inversely proportional to the cable length causing other than the desired 20-kc signal to be picked up and amplified.

A third difference between the systems is the addition of a phase shift network in the standard input circuit. This network was required to enable the phase of the standard input voltage wave form to be shifted relative to the remote input voltage wave form so that the system may be balanced with a minimum difference voltage between the remote and standard pickup coil. A small residual signal at balance enabled the use of a higher gain input amplifier than was used in the laboratory gage system, permitting much greater sensitivity to be obtained with the field gage instrument.

The fourth difference in the systems is the use of both synchronous and amplitude detectors in the field gage unit. The required capability of the use of long cables with the field gage makes the balancing process critical. An amplitude detector permits monitoring of the amplitude of the residual balance voltage after amplification. By observing the output of the amplitude detector, successive adjustments of phase and amplitude balance controls can be performed until a unique minimum residual is obtained. The synchronous detector is still used during the recording operation of the gage because it has superior filtering properties which improves the system S/N (signal to noise ratio).

The last difference between the systems is the switch network provision for operation with a remote oscillator. The remote oscillator is used to drive the power amplifiers of several units in parallel in applications where several gages are required. This eliminates beat frequency mutual interference.

Although some of the mentioned modifications represent major changes in the gage electronics, the basic concepts and principle of operation remains the same as for the laboratory gage. Figure 11 displays the components which constitute the field strain gage in its finalized form. As with the laboratory gage these consist of two sets of coils, an adjustable micrometer coil mount, and the electronic instrumentation package.

B. Description of the Circuit

The complete system circuit diagram consists of the input circuit, Fig 12, the detector and output circuit, Fig 13, the power amplifier, Fig 14, and the front and rear sections of the cable length selector switch, Fig 15. The physical positions of these circuits in the unit is shown on Figs 16 and 17. A composite circuit diagram of the strain gage electronics is included in the Appendix.

The 20-kc oscillator has an output of approximately 5 volts rms into a 10Ω load. This signal is amplified by the power amplifier, AMP-3, which consists of a driver transistor, Q1, and an emitter follower power transistor, Q2, which drives the synchronous detector and drive coils with approximately 5 volts rms. The standard pickup coil is tuned to 20 kc with a Q of approximately three by capacitor C-1 and resistor R-3 of Fig 12. The remote pickup coil and length of cable is likewise tuned by an appropriate R-C combination of the front switch, Fig 14. The relative phase between the two pickup voltages is varied via the circuit consisting of the control PHASE, L-1, and C-2, Fig 12. The difference signal from the two pickup coils is then picked up via control AMPLITUDE which may be adjusted for zero output when the standard and remote coils have the same spacing. This difference signal is then amplified at AMP-1 (which is tuned to 20 kc) and AMP-2. The control GAIN at the output of AMP-1 controls the amplification of these two amplifiers and thus the system sensitivity. The output of AMP-2 is applied to the detector and output circuit, Fig 13, through points C and D. At point D the output signal from AMP-2 is rectified by diodes D4 and D5

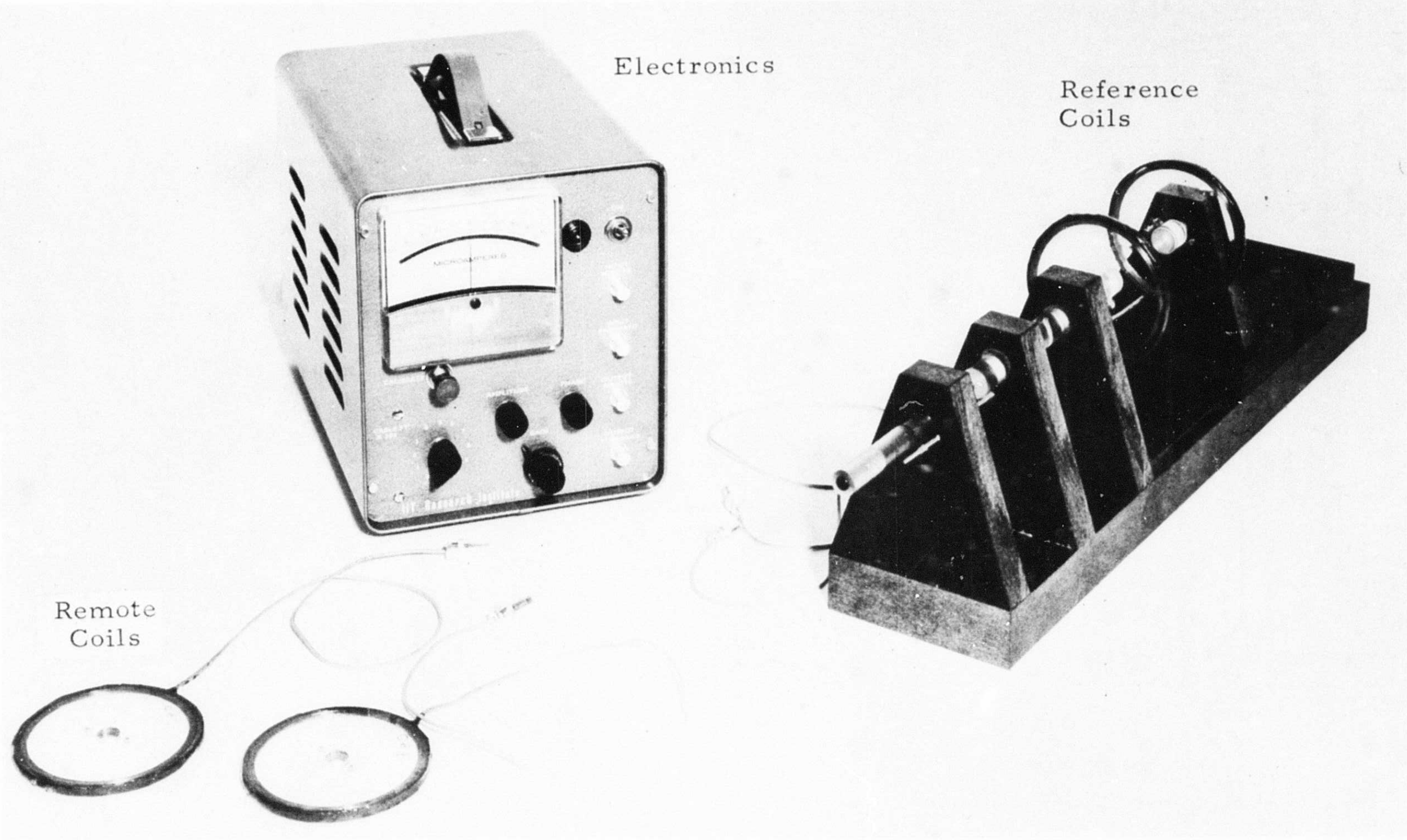


Fig. 11 COMPONENTS OF THE FIELD STRAIN GAGE IN FINALIZED FORM

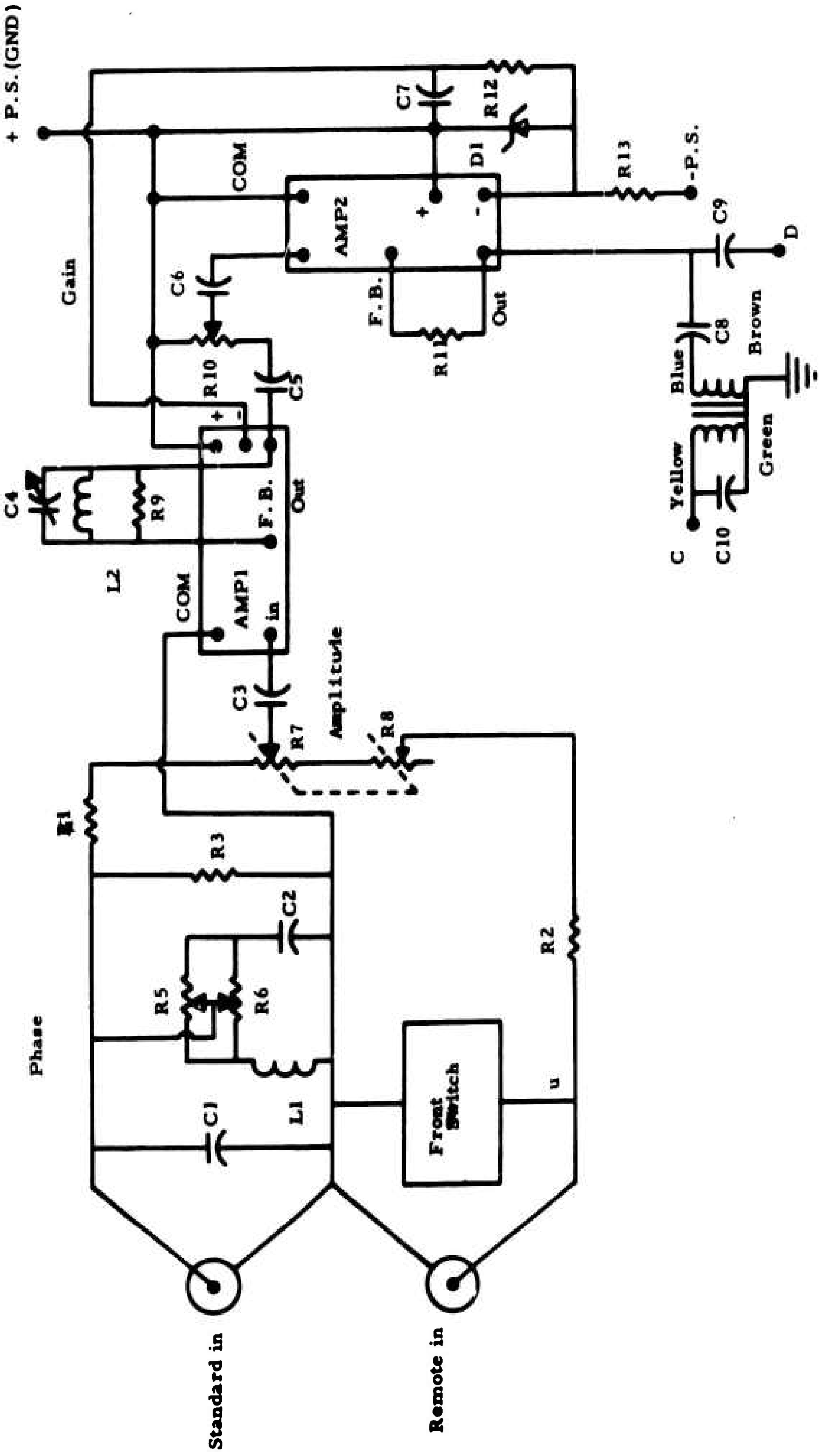


Fig. 12 INPUT CIRCUIT

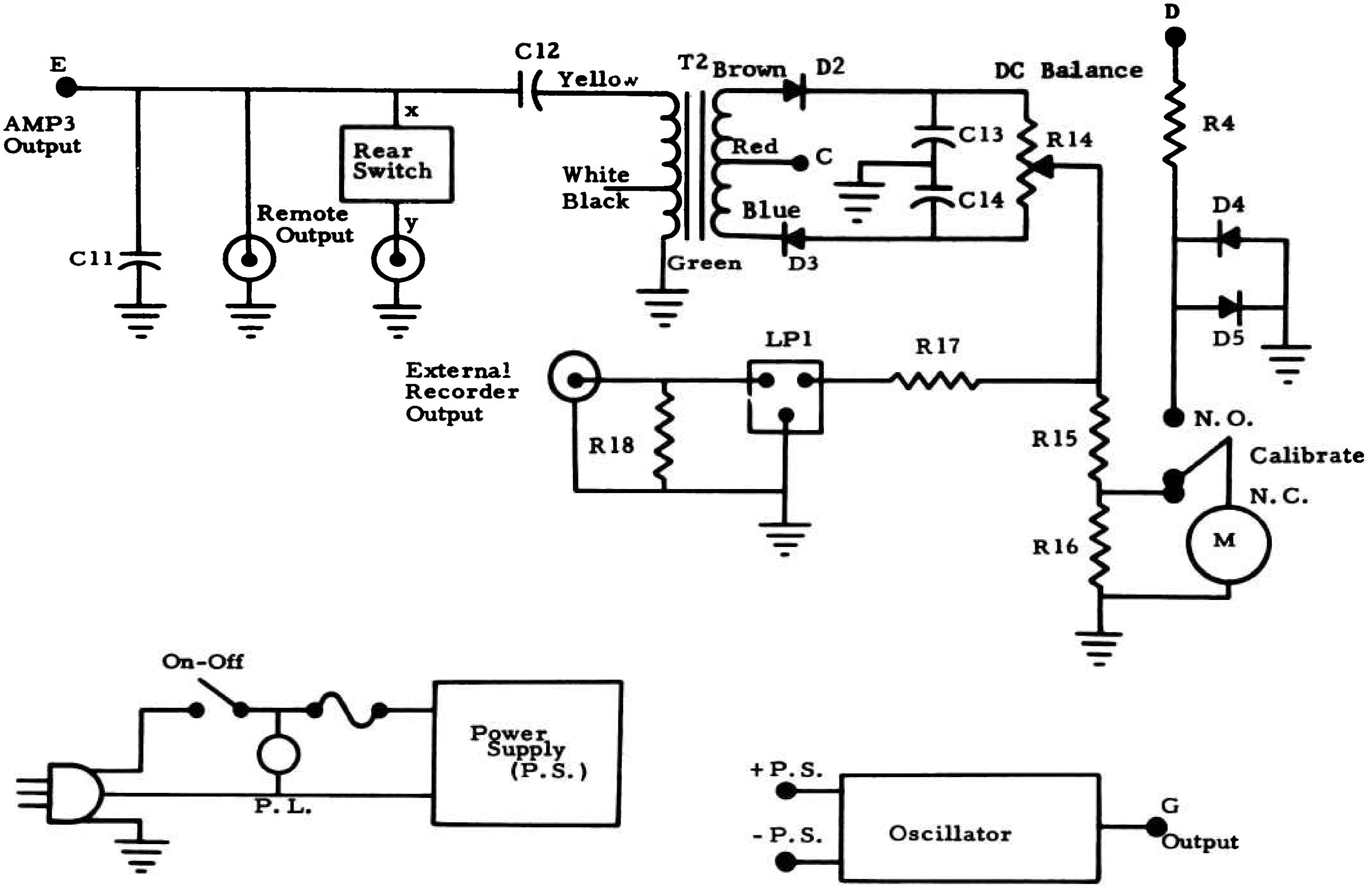


Fig. 13 DETECTOR AND OUTPUT CIRCUIT

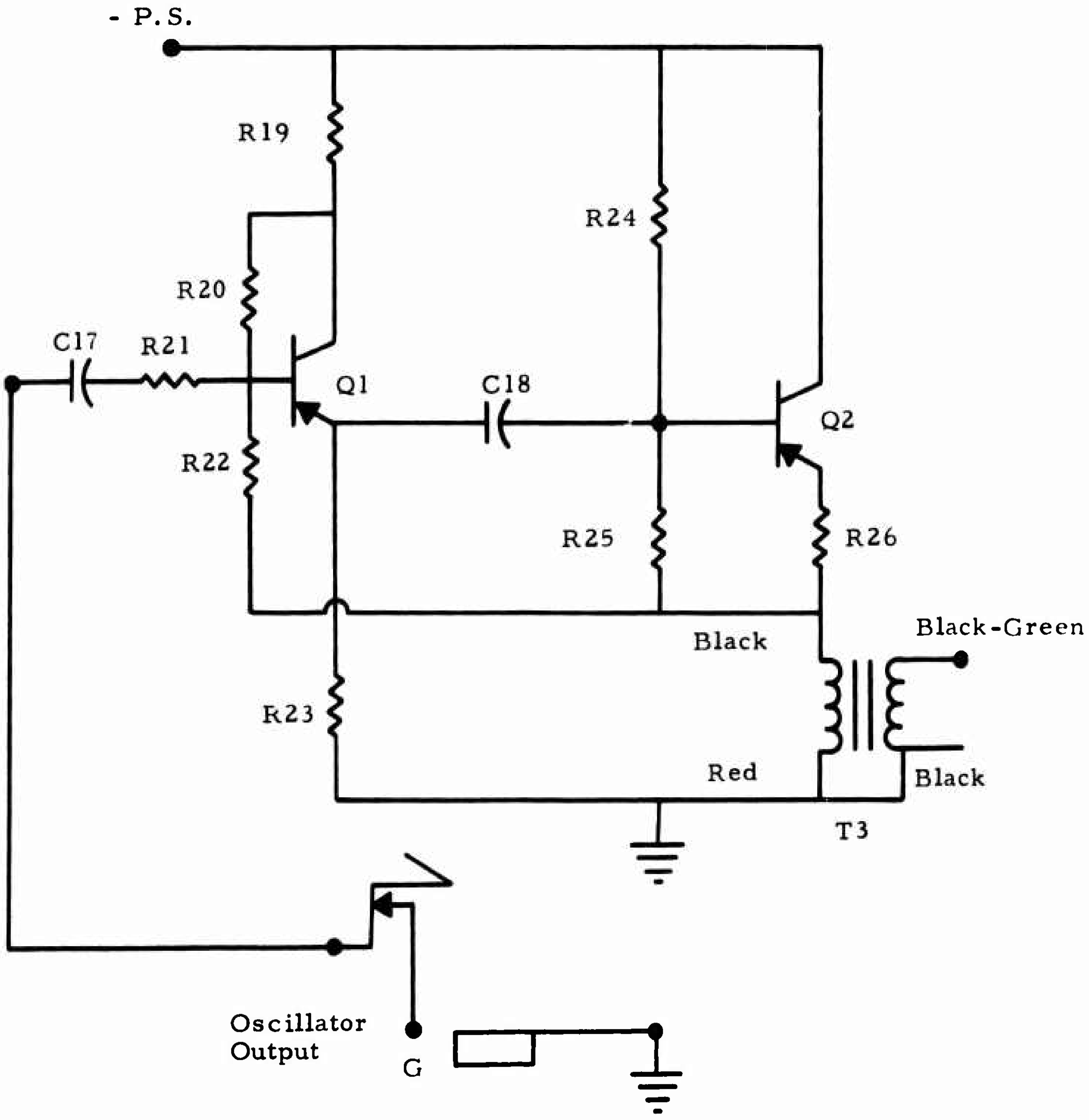
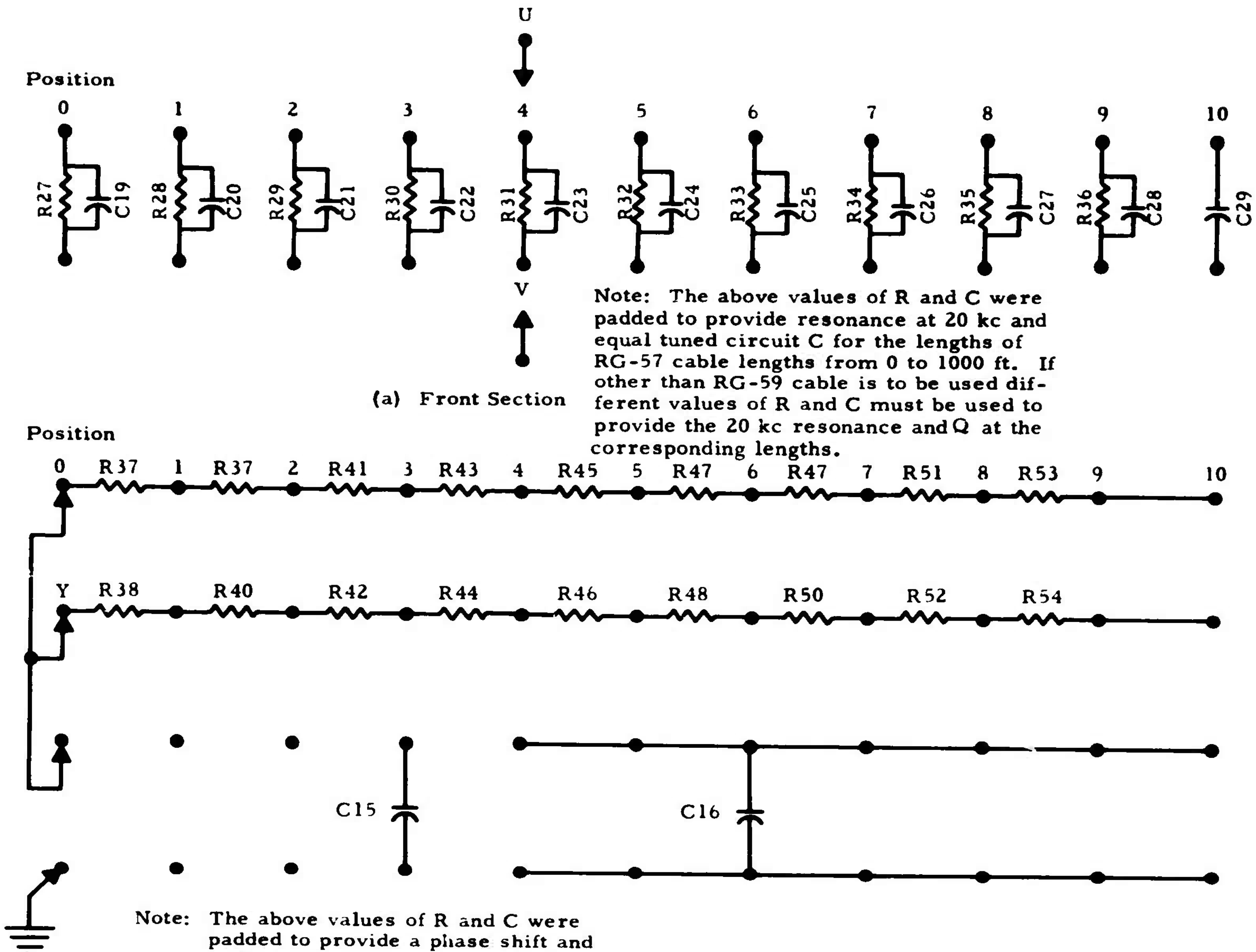


Fig. 14 POWER AMPLIFIER, AMP3



(a) Front Section

Note: The above values of R and C were padded to provide resonance at 20 kc and equal tuned circuit C for the lengths of RG-57 cable lengths from 0 to 1000 ft. If other than RG-59 cable is to be used different values of R and C must be used to provide the 20 kc resonance and Q at the corresponding lengths.

(b) Rear Section

Note: The above values of R and C were padded to provide a phase shift and attenuation approximately equal to that of RG-59 cable lengths from 0 to 1000 ft. If other than RG-59 cable is to be used different values of R and C must be used for that particular cable.

Fig. 15 CABLE LENGTH SELECTOR SWITCH

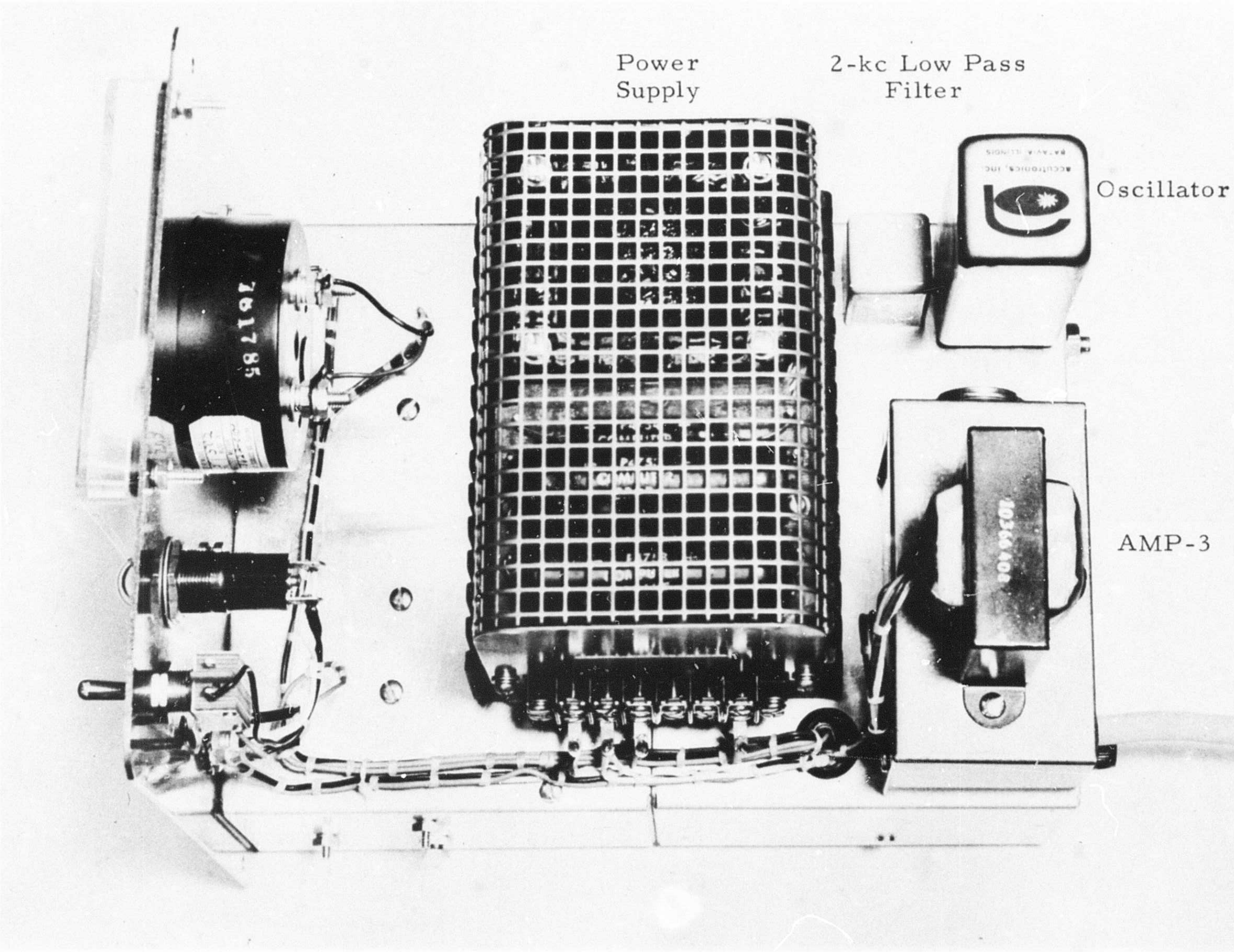


Fig. 16 TOP VIEW OF STRAIN GAGE ELECTRONICS

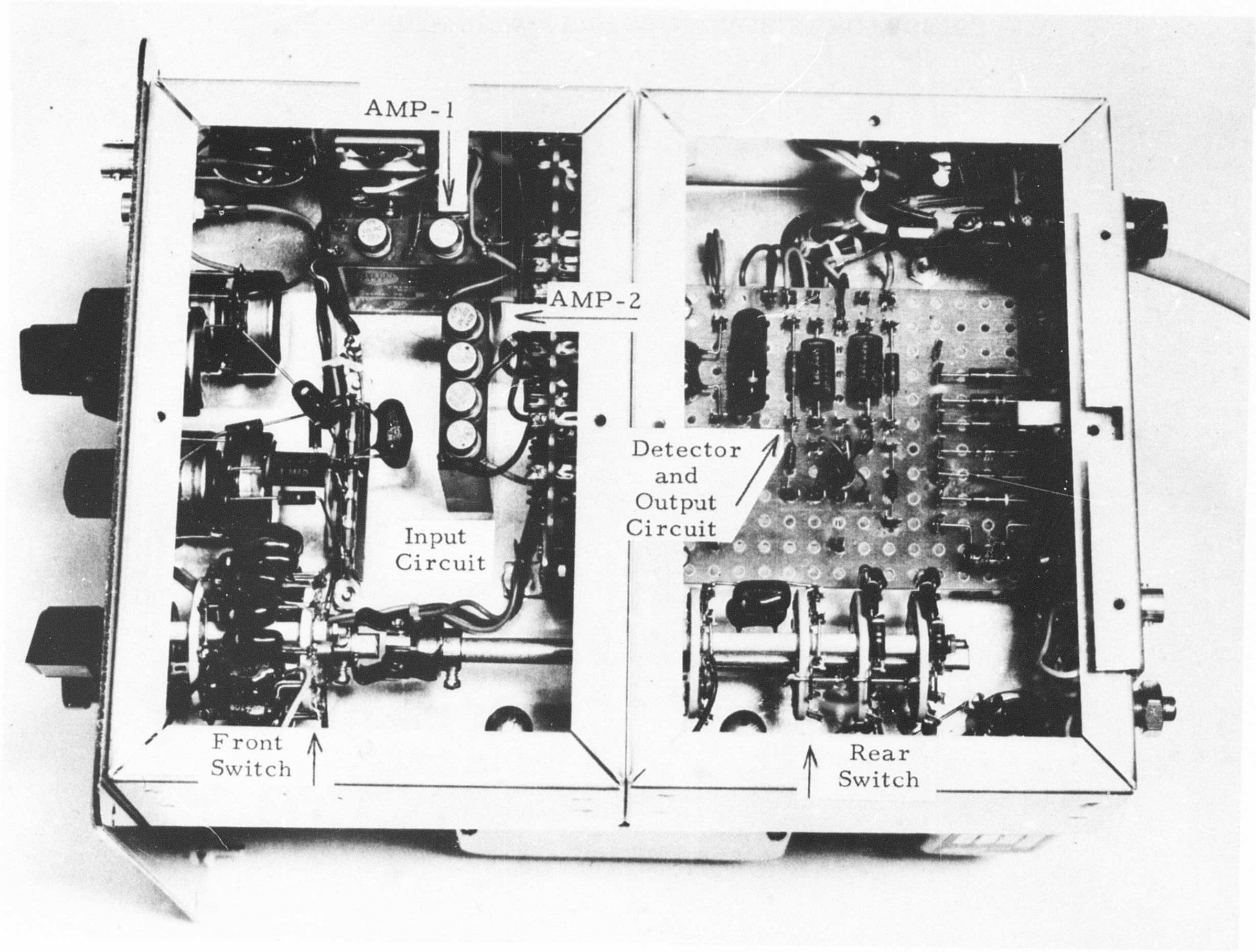


Fig. 17 BOTTOM VIEW OF STRAIN GAGE ELECTRONICS

and applied to the meter by depression of the switch CALIBRATE. The output of AMP-2 is also applied to the synchronous detector via transformer T1, point C, and transformer T2. The reference signal to the synchronous detector is attained from the power amplifier, AMP-3, through point E and capacitor C-12. The synchronous detector output is taken from the potentiometer DC balance and drives the meter and the output jack through the 2-kc lowpass filter LP1.

A complete listing of all parts used in the construction of the strain gage electronics is given in the appendix at the end of this report.

C. Coil Design Parameters

Usually one of the best means of increasing the sensitivity of a measuring system is by increasing the signal level at the output of the sensor. In the case of the soil strain gage there are essentially four interdependent variable coil parameters which contribute to sensitivity. These parameters are:

(1) effective coil diameter,

(2) coil inductance,

(3) number of turns of wire, and

(4) coil resistance.

Because all of the parameters are interdependent they cannot be varied independently and an optimum compromise must be sought. Induced voltage increases with effective coil diameter and number of turns; hence, these quantities should be maximized within the limitations imposed by required performance criteria and physical size requirements.

For soil strain measurement a range of encapsulated coil disk diameters was desired to permit selection of an optimum size for particular applications. Minimim and maximum sizes are primarily dictated by considerations of handling. In the field extremely small disks would be difficult to place with proper alignment and without undesirable disturbance to the soil both between the embedded sensors and in the immediate surrounding area. As the coil diameter increases, alignment problems diminish. However, the problem of embedding the necessarily larger encapsulated disk in the ground can be quite serious, particularly for deep measurements. The decision was that coils of 2- and 4-inch encapsulated diameter would be reasonable sizes to work with and would be satisfactory for most field applications. In the laboratory smaller disk sizes can be tolerated because greater control is possible in test preparation and gage placement. However, greater restrictions on maximum coil size exist because of influence on the sensor output by metal container walls and because in the laboratory it is generally desired to measure strains over smaller gage lengths than in the field.

It is believed that disk sizes of 1 and 2 inches in diameter should be satisfactory for most laboratory applications. The effective coil diameter is maximized for each disk diameter by winding the coil as closely as possible to the edge of the encapsulated disk.

Coil inductance is upper bounded by the requirement that the input to the electronics system be tuned to 20 kc. It is necessary that

$$L < \frac{1}{\omega^2 C}$$

where

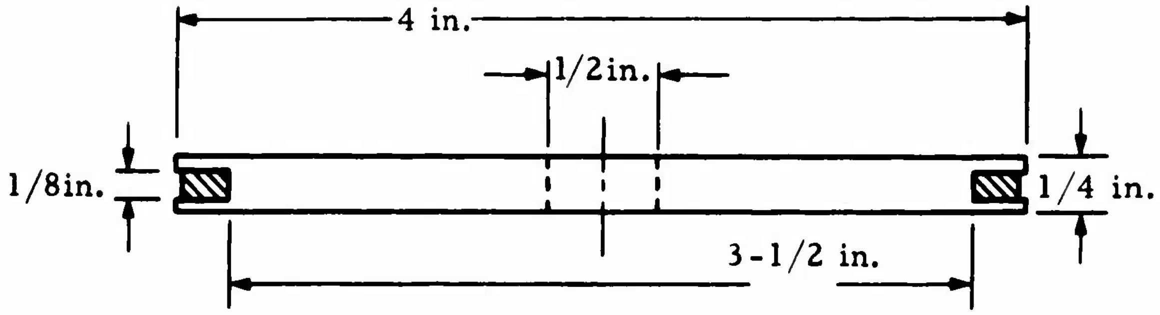
L = coil inductance

ω = 2π 20 kc

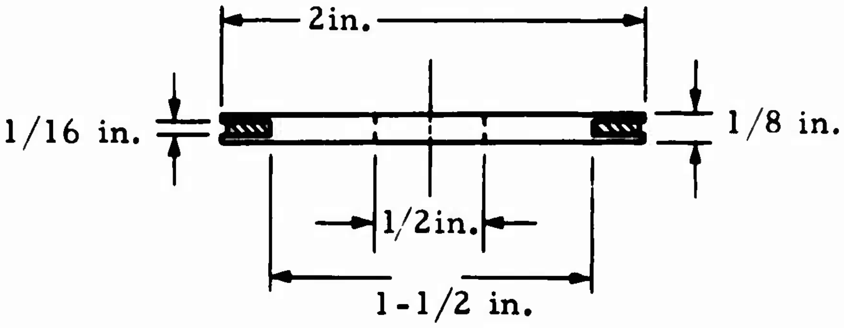
C = maximum cable capacitance of 1000 feet of cable .

A coil inductance of 1.49 millihenrys, approximately one half of that necessary for self resonance with 1000 feet of RG59-U cable, was selected. Capacitance is then added across the cable to tune the circuit to 20 kc. This is preferable to selecting directly the coil inductance necessary for self resonance because it reduces to negligible the effect of small variations in cable capacitance.

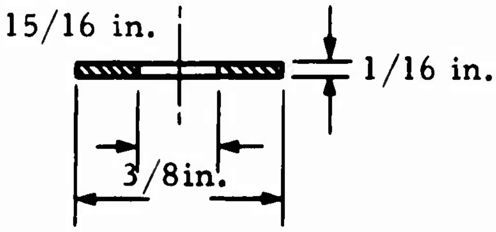
Having selected a desired value of coil inductance the number of turns of wire required for each coil diameter was automatically determined. Figure 18 details the dimensions and number of turns for 1-, 2- and 4-inch diameter coil disk sizes.



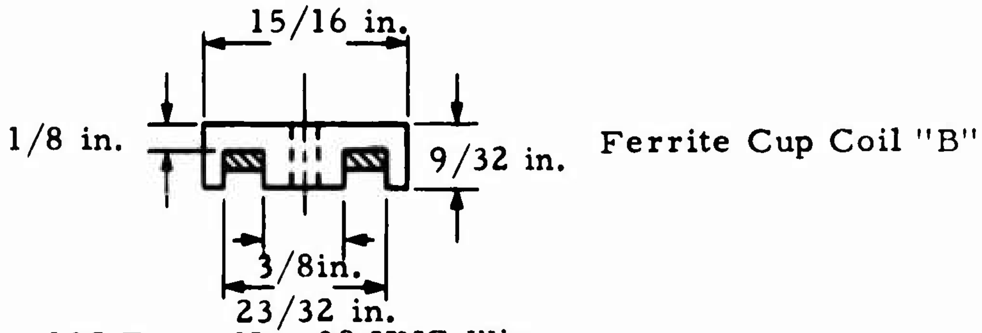
80 Turns No. 28 HNC Wire



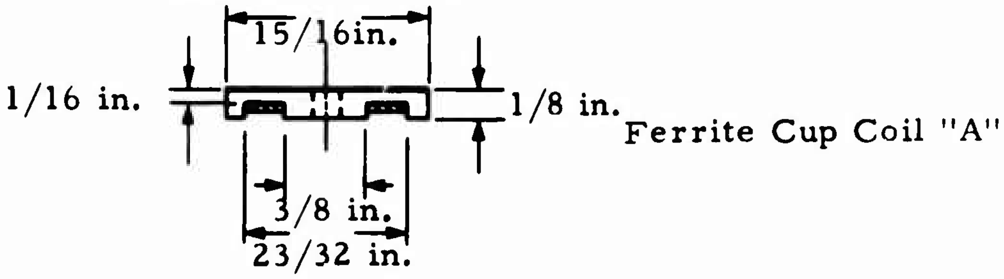
130 Turns No. 32 HNC Wire



235 Turns No. 38 HNC Wire



135 Turns No. 38 HNC Wire



180 Turns No. 38 HNC Wire

Fig. 18 COIL SIZE DETAILS

An additional area of interest to coil design was the influence on gage performance of housing the coil winding in ferrite cup cores. Theoretical evaluation of this influence involves extremely complicated computations therefore coils suitable for experimental evaluation were fabricated by trial and error. The details for these coils are also presented in Fig. 18.

D. Coil Construction

The requirement for tuned input circuits necessitates that the coil be constructed in a manner which ensures that coil inductance or capacitance will not change. In this regard particular attention must be given to ensure that the wire coil is a waterproof, solid mass in which changes in the relative position of the windings cannot occur. Waterproofing of the coil and connecting cable is critical. Moisture changes the capacitance of the circuit and moisture presence in sufficient quantities to cause seepage results in continuous changes causing significant signal output. The following procedures were followed in fabricating the 2- and 4-inch diameter coils:

1. Plexiglass disks were cut to the desired diameters. Disk thickness was chosen as the minimum deemed practical from considerations of ruggedness and workability.
2. A groove was machined into the disk edge to receive the required number of turns of wire. The wire was wound on the disk through a bath of Shell Epon 815 epoxy. This ensured that the wound coil would be a solid mass containing no voids in which moisture might accumulate.
3. A short length of coaxial cable was then soldered to the ends of the winding wire as shown in Fig. 19. The cable was drawn tight into the coil form and soldered in place before the epoxy of step 2 set.
4. The epoxy was then permitted to cure and the remainder of the groove was packed with Scotchcast resin No. 10. This epoxy has good adhesion to plexiglass and is of the consistency of peanut butter, which permitted the groove to be filled without problems of run off.

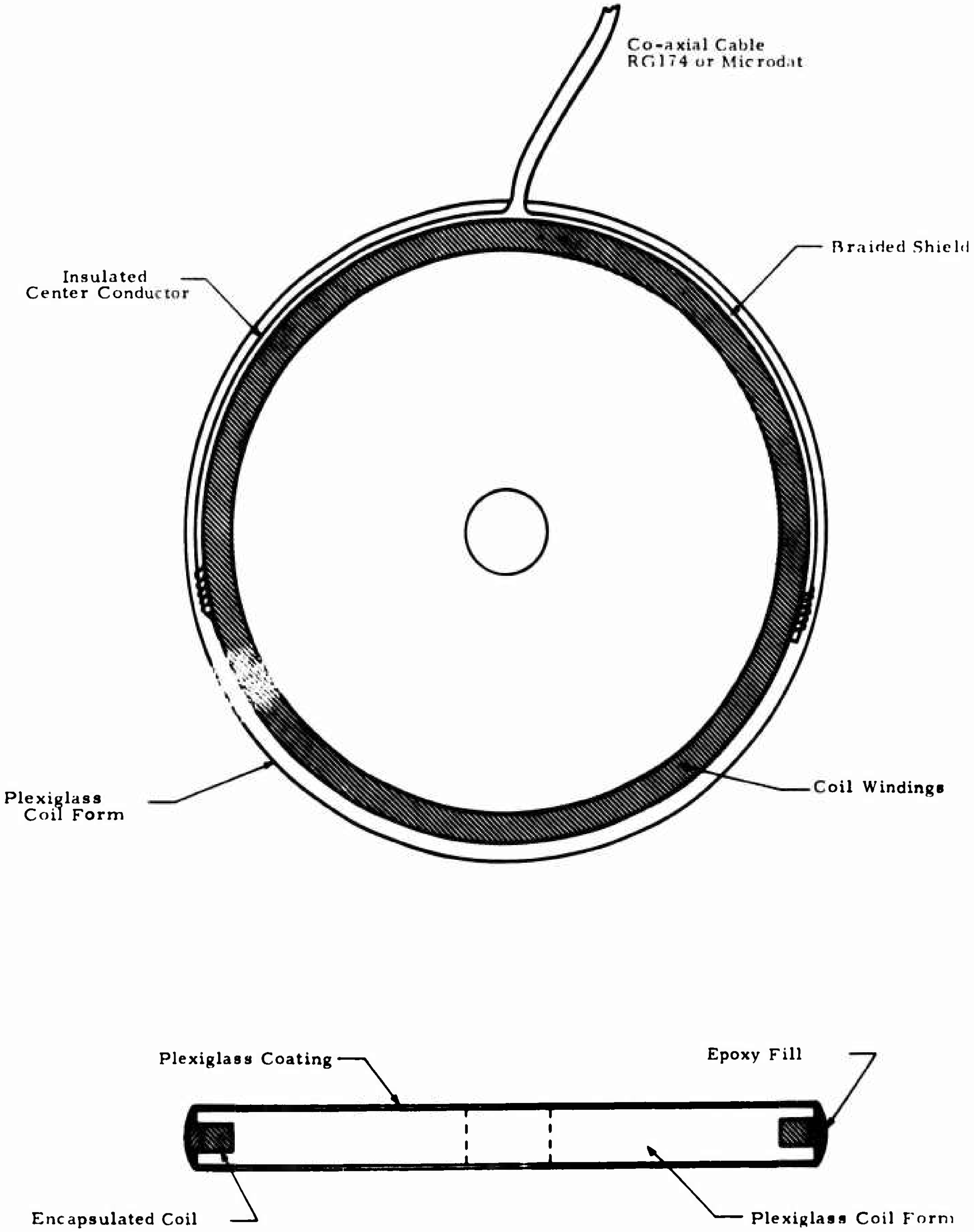


Fig. 19 COMPLETED COIL

(5) After the Scotchcast resin has cured the coil and 1 to 2-inches of lead wire was dipped in solvent Cadco-125 and then in plexiglass glue Acrylite B-7. The solvent cleaned and softened the surface of the plexiglass to ensure that good bonding was obtained with the Acrylite B-7 which served to waterproof the coil and cable connection.

Techniques of ruggedized waterproofed construction were not evolved for the 1 inch diameter or ferrite cup coils. These coils were developed only to a state satisfactory for bench evaluation. The coil windings were turned in a winding chuck and then saturated with molten wax which upon solidifying gave the coils sufficient cohesion to permit limited use.

E. Precision Micrometer Coil Mount

The precision micrometer coil mount (Fig. 20) provides means for accurate determination and adjustment of coil spacing. The mount, with the exception of the micrometer head, was constructed of nonmetallic material to avoid distortion of the magnetic field. The design was made extremely conservative to ensure that mount flexibility would not present any problems.

The coil carriage permits coarse adjustment of coil spacing over wide ranges. Scribe lines marked on the mount base at 1 inch intervals record outside to outside coil spacings with the micrometer set at 1 inch travel.

F. Instrument Adjustment and Calibration

The procedures to be followed in performing the balancing adjustments of the strain gage electronics differ depending on whether single or multiple gage measurements are to be made. The procedure to be followed for single gage measurements is described first and then additional steps required for multiple measurements are presented.

Figures 21 and 22 are front and rear views of the gage electronics unit. In the front view the off-on switch, pilot light, cable connection terminals, amplitude balance control, phase balance control, gain control,

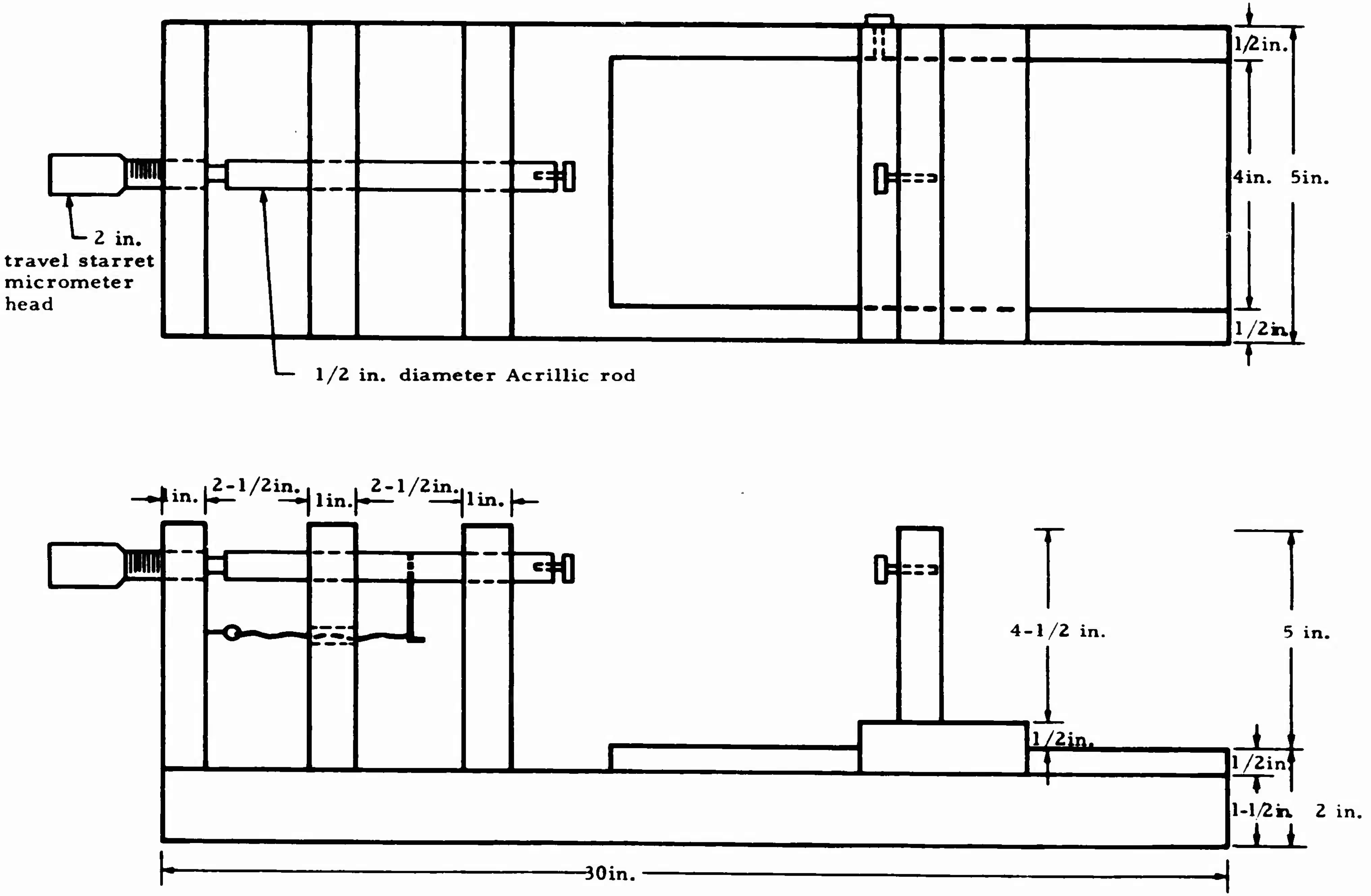


Fig. 20 PRECISION MICROMETER COIL MOUNT

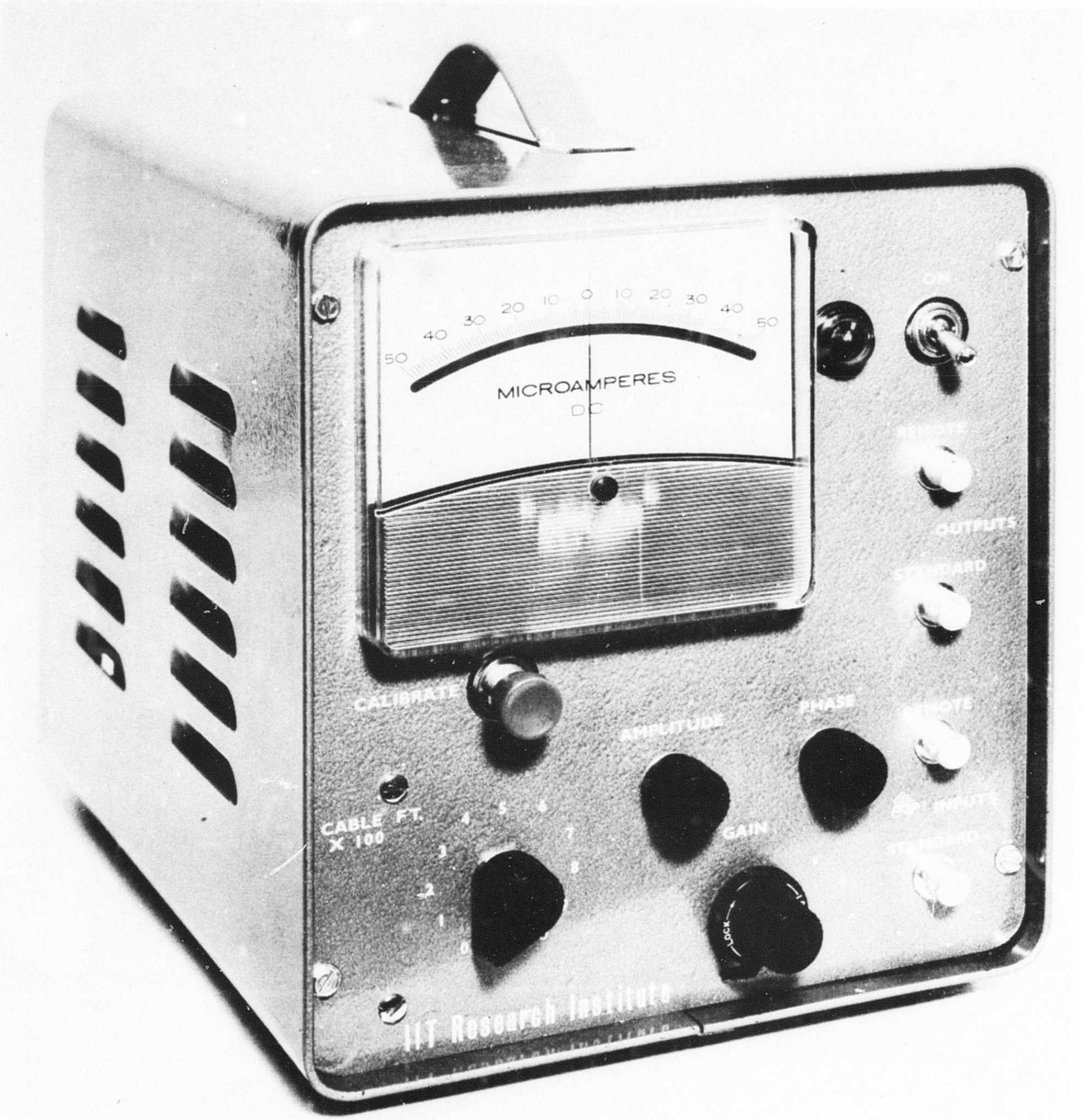


Fig. 21 FRONT VIEW OF STRAIN GAGE ELECTRONICS UNIT

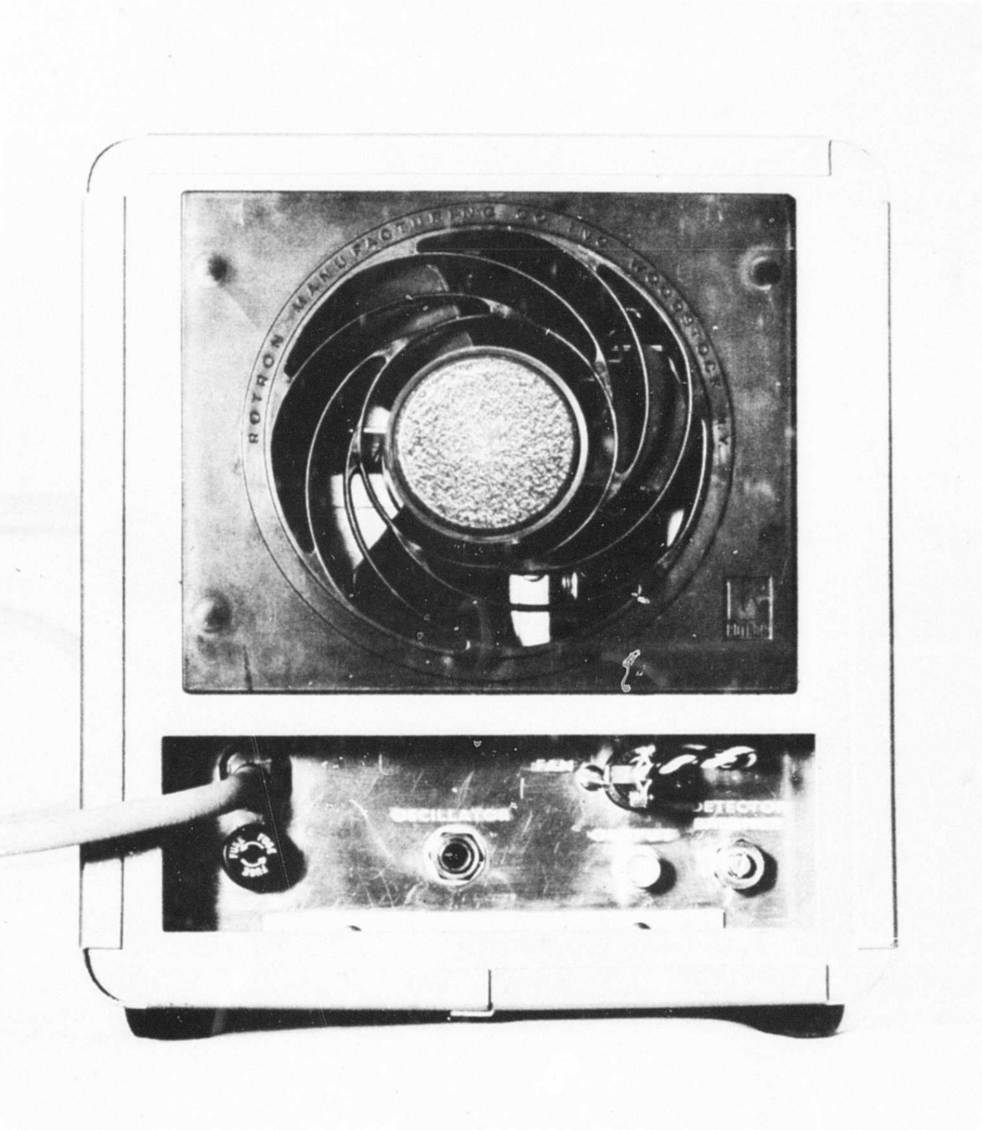


Fig. 22 REAR VIEW OF STRAIN GAGE ELECTRONICS UNIT

calibrate button, cable length selector switch, and meter are included. The rear view shows the fuse location, remote oscillator connection jack, output terminal for connection to a remote recorder, and detector balance adjustment. These steps should be followed in aligning the instrument.

(a) Place both remote and standard coil sets on adjustable micrometer coil mounts and position the coils at equidistant spacings. Connect the long cable lead wires from the cables to be embedded in the ground to the remote connection terminals and the cable from the other coil set to the standard connection terminals. All coils are identical, hence, no care need be taken as to which coil in each set is connected to an input or output terminal.

(b) With the unit off, adjust the meter to read zero using the black screw adjustment located just below the meter face at mid scale.

(c) Adjust the control GAIN, full counterclockwise and turn the off-on switch to the "on" position. Observe the pilot light. If it fails to light insure that the unit is plugged in and then check the fuse located at the rear of the instrument. Allowing approximately 15 minutes warmup time, if meter output has deviated from zero, adjust the control DETECTOR BALANCE on the back of the unit to renull the meter.

(d) Set the selector switch CABLE FT. x 100 to the position corresponding to the remote coil cable length in hundreds of feet.

(e) Depress the button CALIBRATE and turn the control GAIN clockwise until near full scale deflection appears at the meter.

(f) With the CALIBRATE button depressed, alternately adjust the controls PHASE and AMPLITUDE to obtain a minimum meter reading. NOTE: If adjustment of the controls has little effect and a near zero meter reading cannot be obtained check to insure the remote and standard coils are connected to the proper terminals. If proper connections exist one coil in either set must be turned over.

(g) Repeat step (f) until a minimum meter reading is obtained with the control GAIN turned full clockwise.

(h) Release the switch CALIBRATE and adjust the meter output to zero with the control AMPLITUDE.

(i) The balancing procedure is now complete and the control GAIN should be returned to the full counterclockwise position. The remote coils may then be removed from their micrometer mount for test placement. taking care to maintain the face to face orientation established during instrument adjustment.

(j) After the coils are embedded in the soil adjust the control GAIN clockwise until near full scale meter deflection is attained. The position of the standard coils should then be adjusted to renull the meter. Full gain should then be applied and the position of the standard coils again adjusted to renull the meter. The spacing of the embedded coils is now determined by that of the standard coils.

(k) Move the standard coils through a relative displacement equal to the greatest expected displacement anticipated during testing. Decrease instrument gain until a full-scale meter deflection is obtained. Return the standard coils to the null position.

(ℓ) Connect the external recording unit to the output terminal on the rear of the instrument.

(m) Displace the standard coils in a series of incremental steps over the range of deformation expected during the test, recording the incremental differential displacements and corresponding output. The results obtained serve as the calibration for the embedded coils, but are of opposite phase to the signal which will be received from the remote coils during testing. The calibration should be linear beyond the range of full scale meter deflection. Deterioration from linearity before full scale meter deflection suggests poor alignment conditions exist in the placement of the embedded coils.

(n) Return the standard coils to null position. The instrument is now ready to record.

When several gage measurements are to be made steps (a) through (j) should be followed as before with only the unit worked with being turned on. It is not necessary that all 10 steps be accomplished with one unit before proceeding to another. Convenience would probably dictate performing all steps but (i) and (j). It is necessary, however, that only a single unit be on at one time. Once all remote coils are placed and their embedded positions determined, all units should be connected to the external oscillator (Fig. 23). The following procedure should then be followed.

(1) Turn on the external oscillator and all units, with gains set full counterclockwise.

(2) Balance each unit following steps (a) through (h) outlined for single unit operation. (However, all units should now be on).

(3) Perform steps (k) through (n) outlined for single unit operation for each gage.

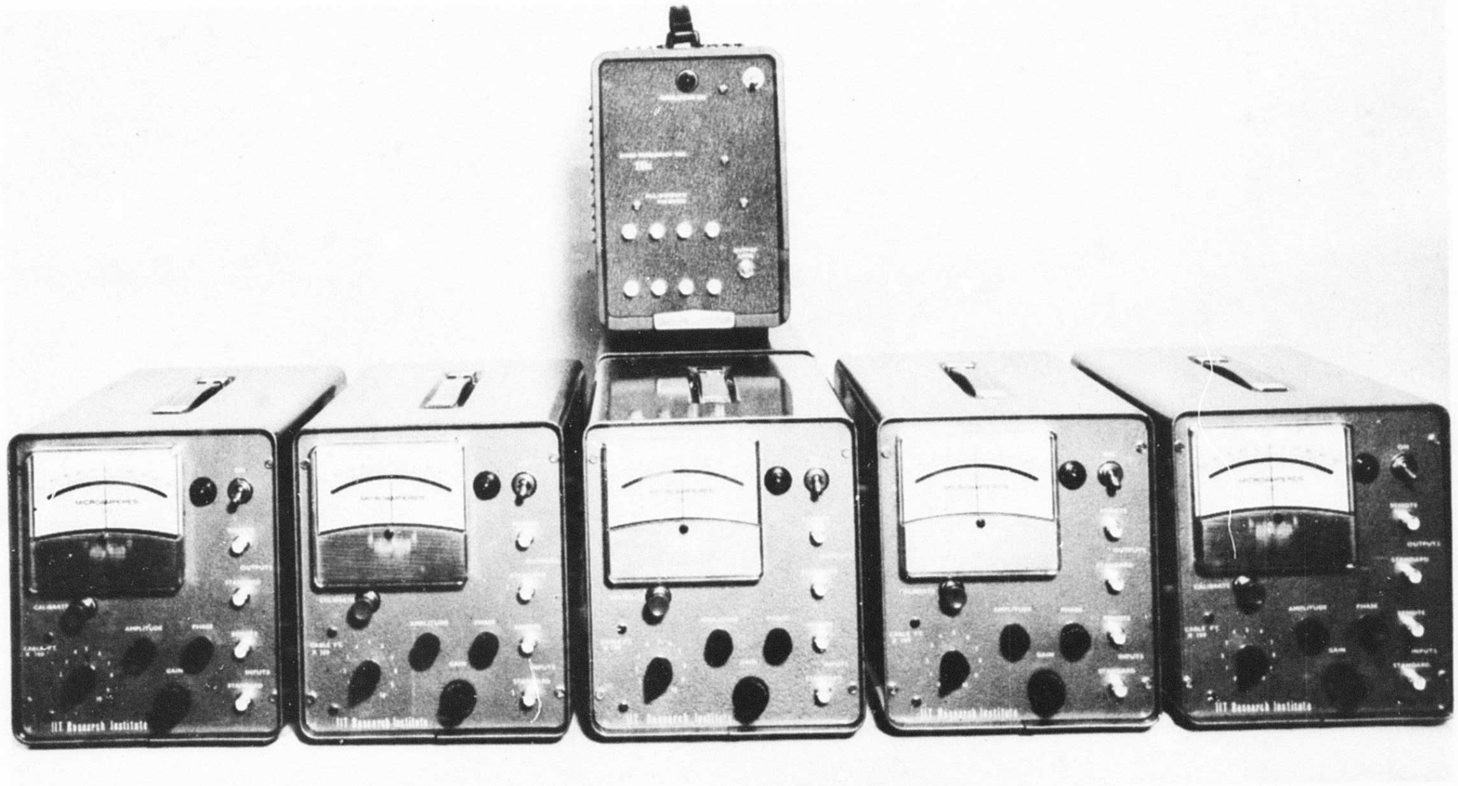


Fig. 23 REMOTE OSCILLATOR FOR USE WITH SOIL STRAIN GAGES

VI. GAGE PERFORMANCE CHARACTERISTICS

A. Dynamic Response

The dynamic response time of the strain gage system was determined by simulating electrically an instantaneous differential displacement of the gage coils. The gage electronics were balanced with both remote and standard coils placed on micrometer coil mounts. An open loop of wire was placed in the magnetic field of one coil set as shown below.

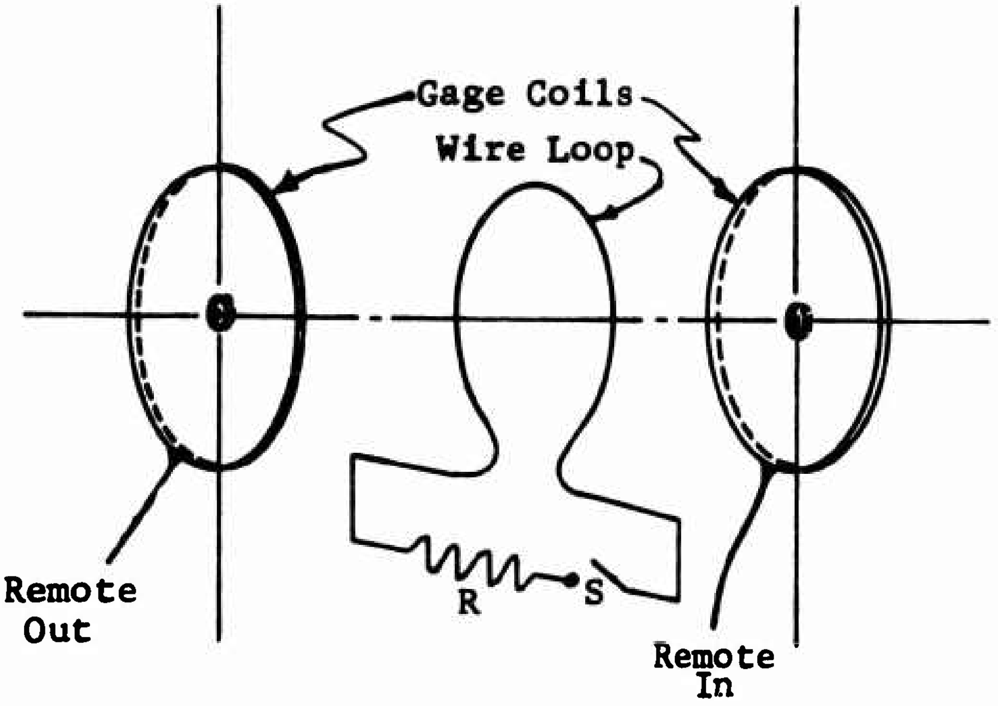


Fig. 24 EXPERIMENTAL SETUP USED TO DETERMINE GAGE RESPONSE TIME

Depression of switch S closing the wire loop to resistance R causes energy to be absorbed by the loop inducing a virtually instantaneous input to the gage system equivalent to that caused by moving the coils apart. The value of R was adjusted to provide a static full scale meter output when the switch was closed.

The output response of the gage to the induced input is presented on Fig 25. Rise time, defined as time between 10 percent and 90 percent full scale output, is 0.30 msec.

The dynamic respones of the gage is presently limited to the 0.30 msec rise time by three factors.

(1) the 2-kc low pass filter at the output
(2) the tuning of Amp 1
(3) the use of a tuned input circuit.

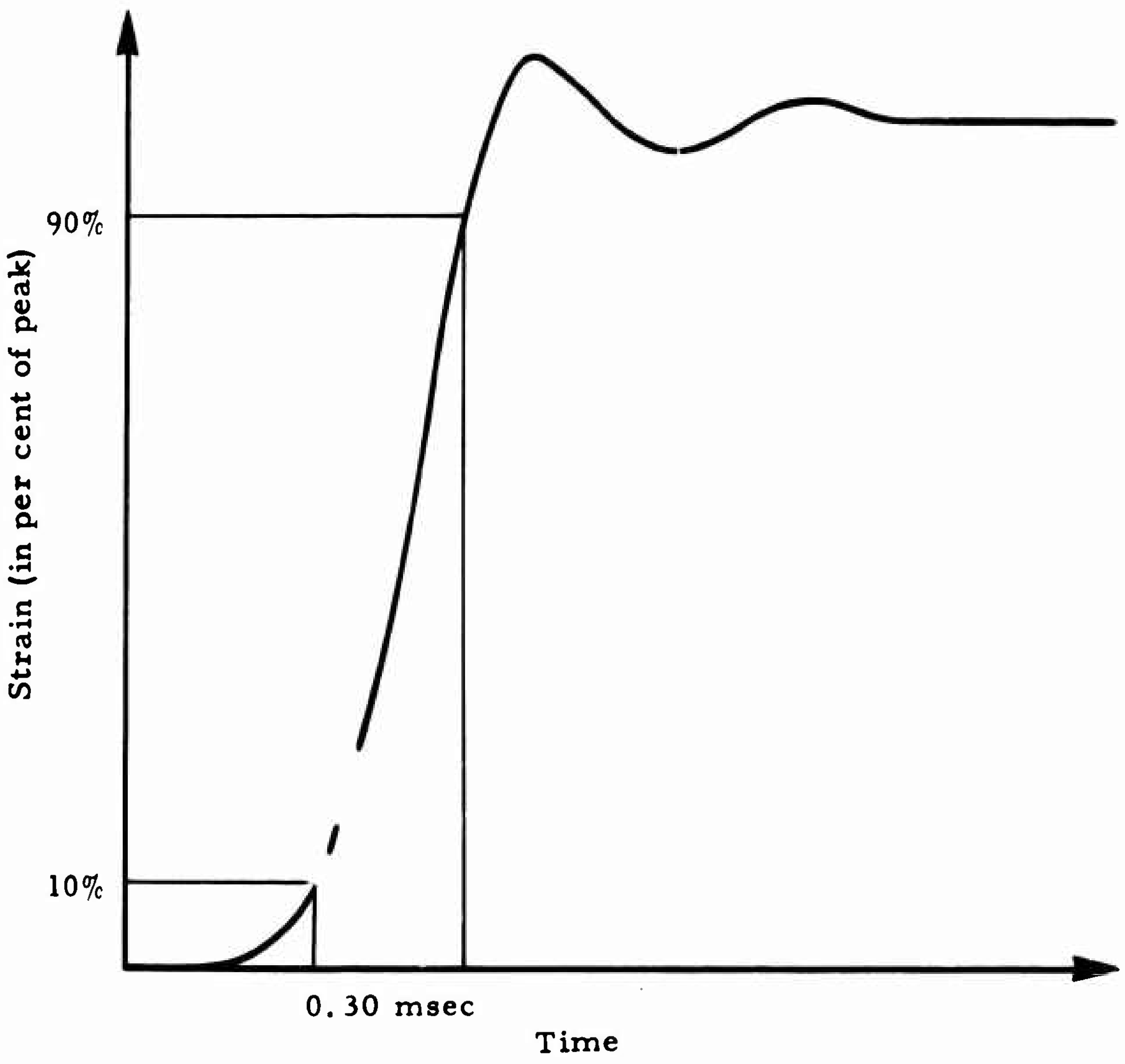


Fig. 25 DYNAMIC RESPONSE OF GAGE TO STEP PULSE INPUT

These measures were taken to reduce the adverse S/N problems introduced by long cable lengths. For laboratory applications the need for long cables and the associated problems would be eliminated. Minor circuit changes should then permit reduction in rise time by a factor of 3 to 5 with only slight degradation in the output S/N.

B. Sensitivity and Linearity

Factors affecting the soil strain gage sensitivity and limitations on the linearity of the system are discussed with the aid of Fig. 26 and 27. The DC output voltage for an incremental change in coil spacing may be expressed as

$$E_o = K \frac{dE_i}{dL} \qquad (1)$$

where E_o = DC output voltage,
K = input amplifier gain,
E_i = coil pickup voltage, and
L = coil spacing,

Figure 26 shows the variation of coil pickup voltage as a function of coil spacing for the 4-inch diameter coil. From Eq. (1), system sensitivity is directly proportional to the slope of the curve. Thus it is seen that sensitivity will decrease quite rapidly with increased coil spacing out to about 7-inches. Thereafter the slope of the curve decreases less rapidly.

The linearity of the system is related to d^2E_i/dL^2, the rate of change of the slope. The rate of change of slope decreases as coil spacing increases, resulting in improvement in the range of linear operation of the system with increased spacing. The effects of d^2E_i/dL^2 on linearity is also shown in Fig. 27. The system was balanced with the 4-inch diameter coils at 8-inch center to center spacing. The output of AMP-1 is first concave upward and then concave downward in the range from 0 to 2.5-inch differential displacement of the coils. If the system gain were reduced from 0.018-inch to 2.5-inch for full scale output, the graph of AMP-1 would be compressed 2500/18 and this nonlinearity of the AMP-1 output would be reflected in the system output. Also seen in Fig. 27 the output of AMP-1 limits above 2.5-inch of differential displacement. This determines the maximum compressive strain measurable

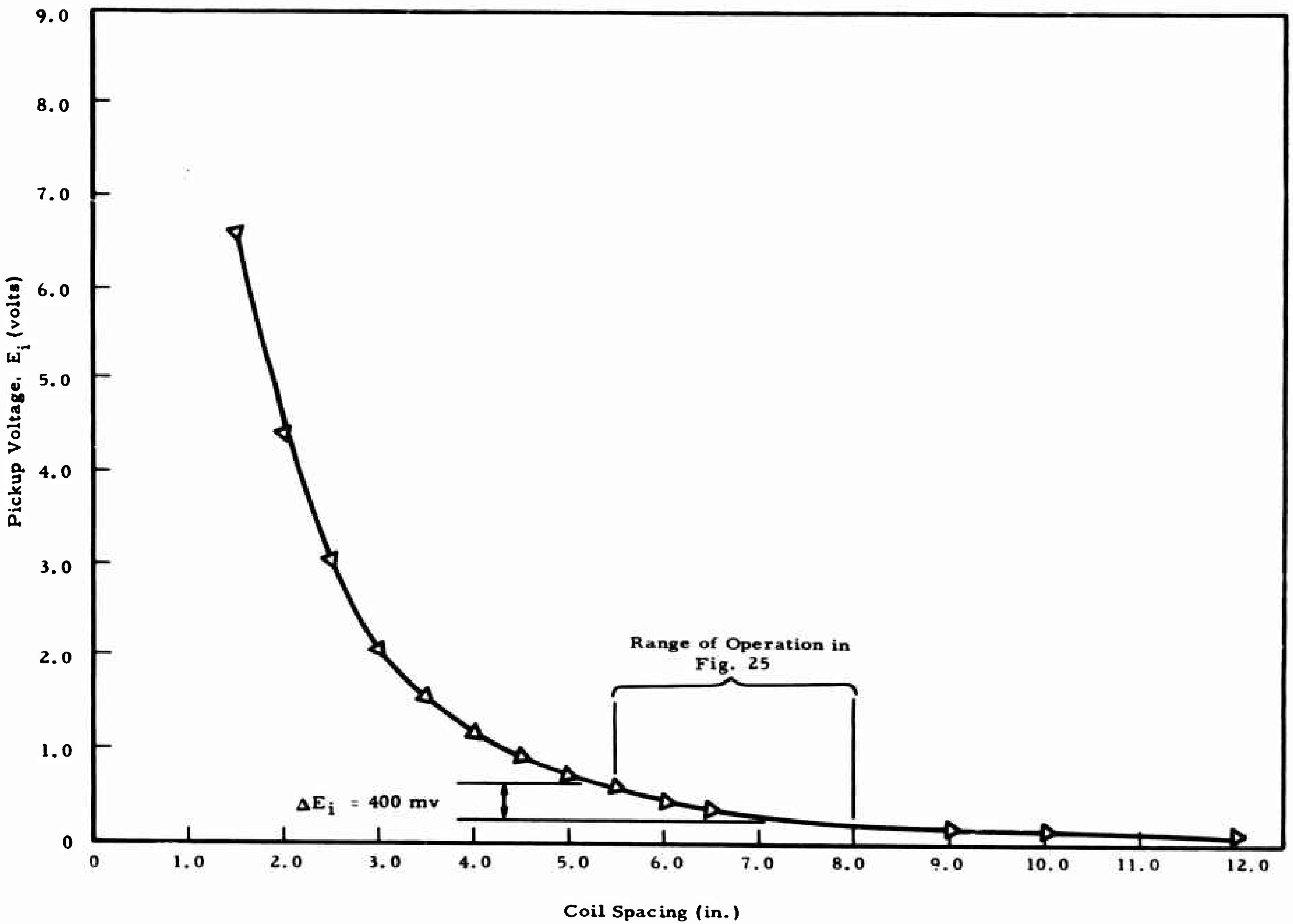


Fig. 26 COIL PICKUP VOLTAGE VS. COIL SPACING FOR 4 IN. DIAMETER COILS

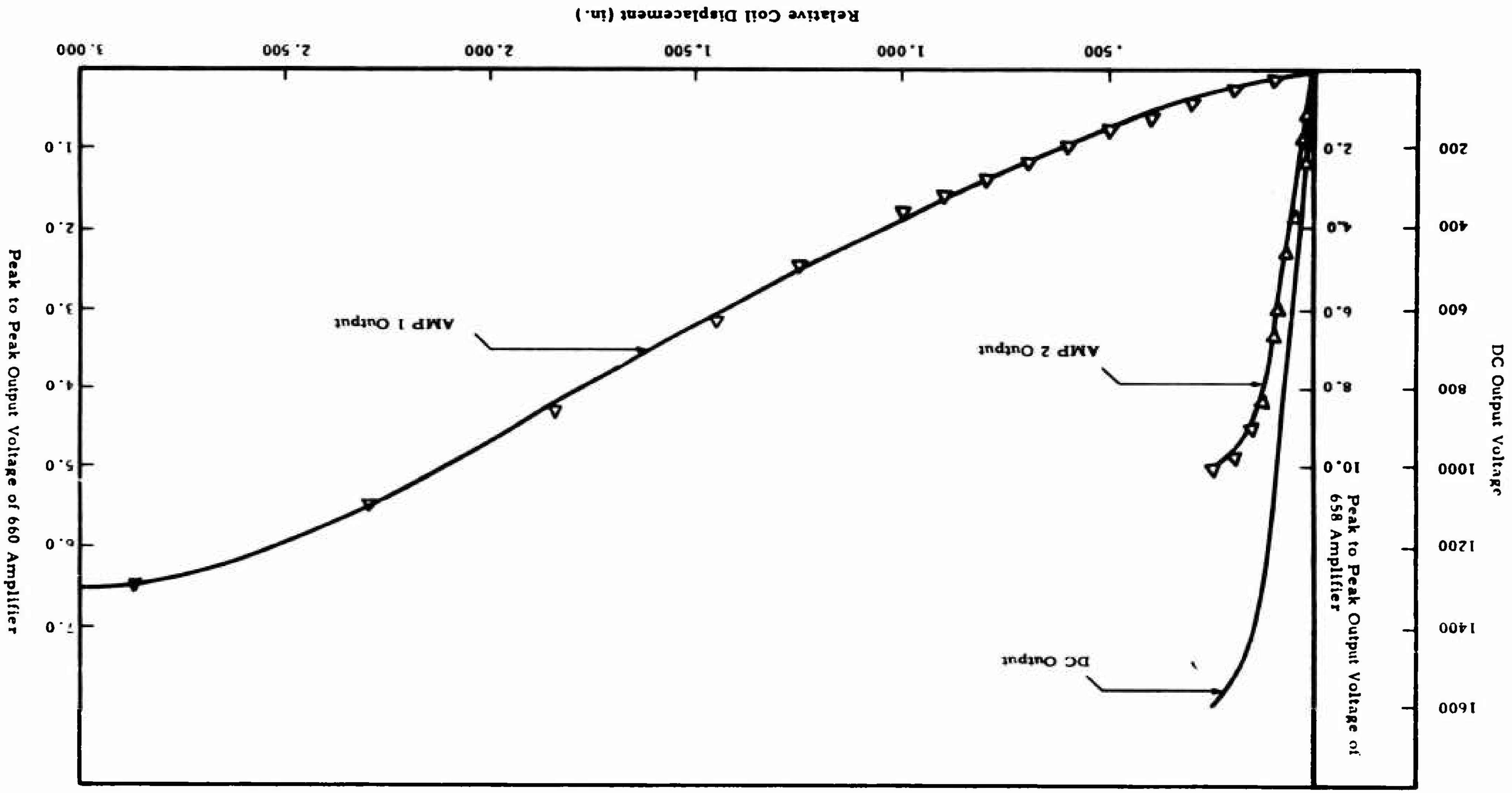


Fig. 27 SYSTEM LINEARITY VS. DISPLACEMENT FOR 18 MILS FULL SCALE SENSITIVITY USING 4 IN. DIAMETER COILS AT 8 IN. SPACING

at the 8-inch center to center spacing. On Fig. 26 this corresponds to a ΔE_i of 400 mv. To determine the maximum measurable strain at spacings other than 8 inches one need only mark off the ΔE_i = 400 mv at that coil spacing and measure the corresponding ΔL.

Figure 28 compares the effect of coil spacing on system sensitivity for the various size coils developed. The tabulated data of Table 1 for the modified laboratory instrument and results obtained using a 2-inch diameter coil with the laboratory instrument are also presented. Sensitivity is compared in terms of the percentage change in coil spacing required to cause full scale meter deflections for various ratios of coil spacing to coil diameter. From the figure the following observations are made.

(a) The sensitivity of the field gage instrument is vastly greater than that of the laboratory gage.

(b) Increasing the gage sensor diameter increases sensitivity. This increase is realized because as the coil size increases fewer turns of wire are required to obtain the desired coil inductance enabling the wire to be wound closer to the edge of the disk. As such the effective coil diameter increases at a greater rate than the increase in disk diameter. The effect is evident with both the laboratory and field gage systems; however, little additional benefit is gained when the disk diameter is increased beyond 2 inches.

(c) Excellent sensitivity is obtained for all size sensors used with the field gage unit at a spacing of one coil diameter. Good sensitivity is obtained for all but ferrite cup coil B at a spacing of two coil diameters and adequate sensitivity exists for the 1-, 2-, and 4-inch diameter coils at a spacing of three coil diameters.

(d) The use of a ferrite cup to constrain the magnetic field of the coil results in rapid loss of sensitivity as the coil spacing increases beyond one coil diameter.

The effect of range of differential displacement measurement (controlled by gain employed at any particular coil spacing) is illustrated by typical gage calibration curves presented on Fig. 29, 30 and 31. At full gain the calibrations are linear for differential displacements two to three

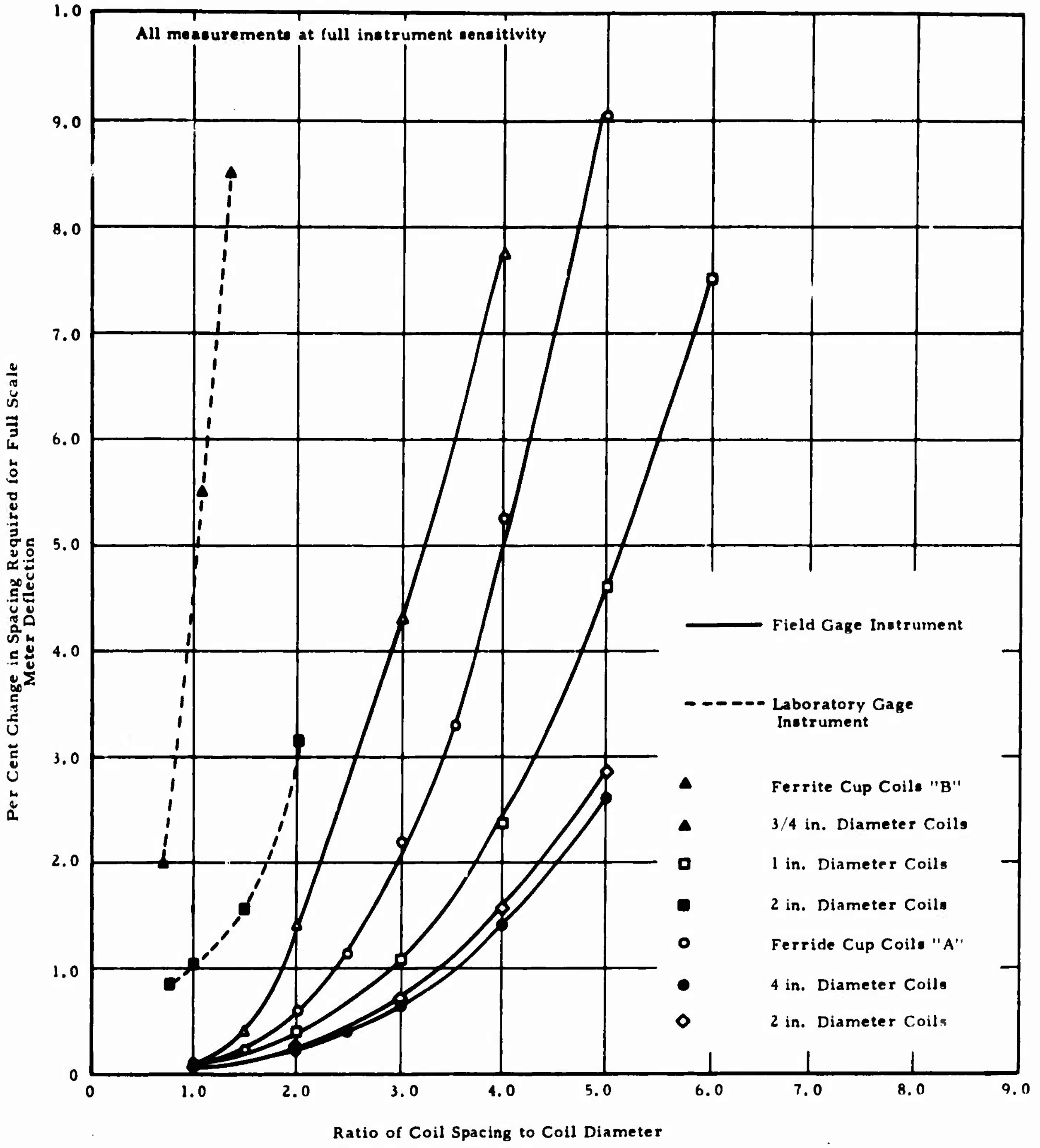


Fig. 28 EFFECT OF COIL SPACING ON SENSITIVITY

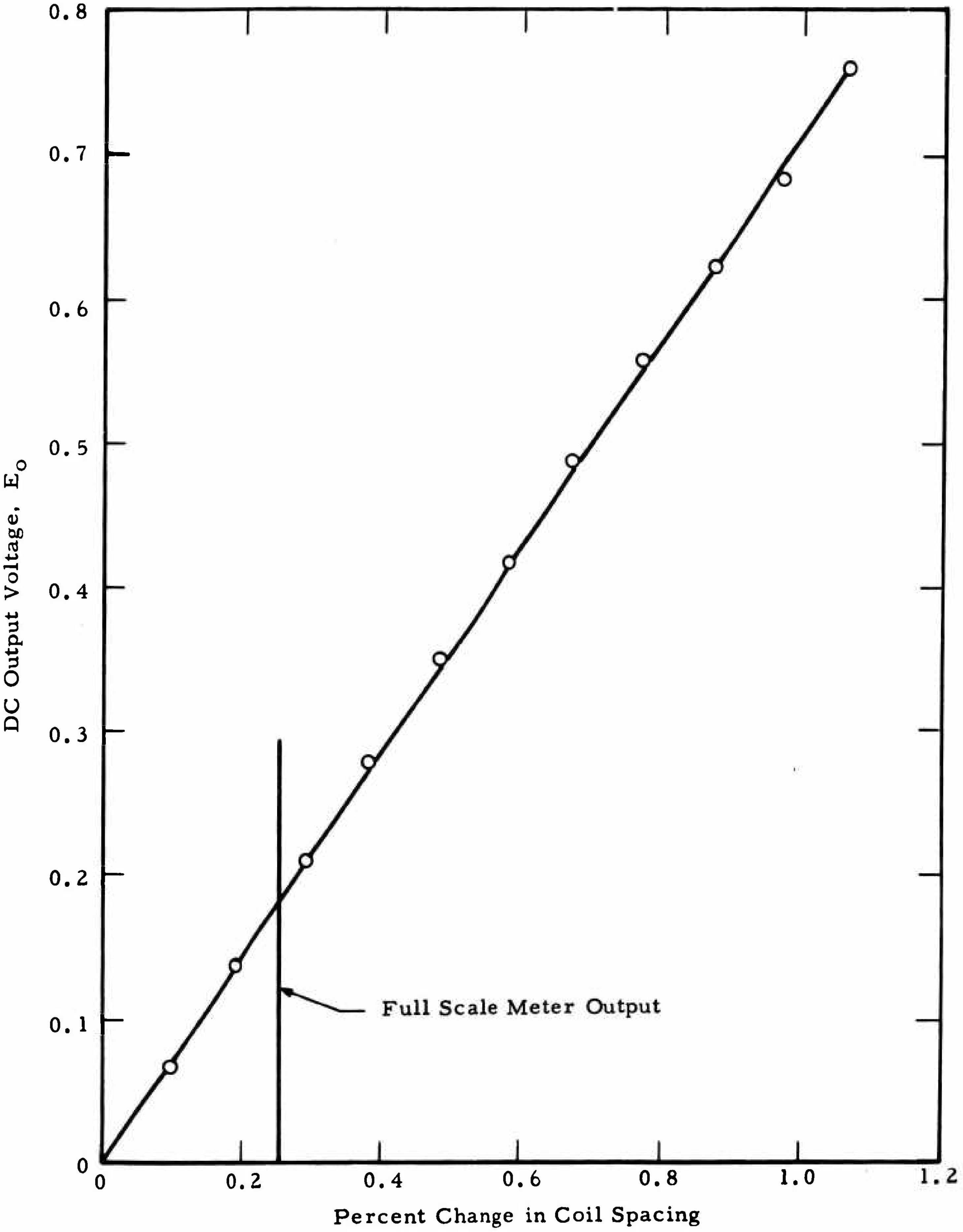


Fig. 29 CALIBRATION CURVE FOR 2-IN. DIAMETER COIL AT 4-IN. SPACING, FULL SENSITIVITY

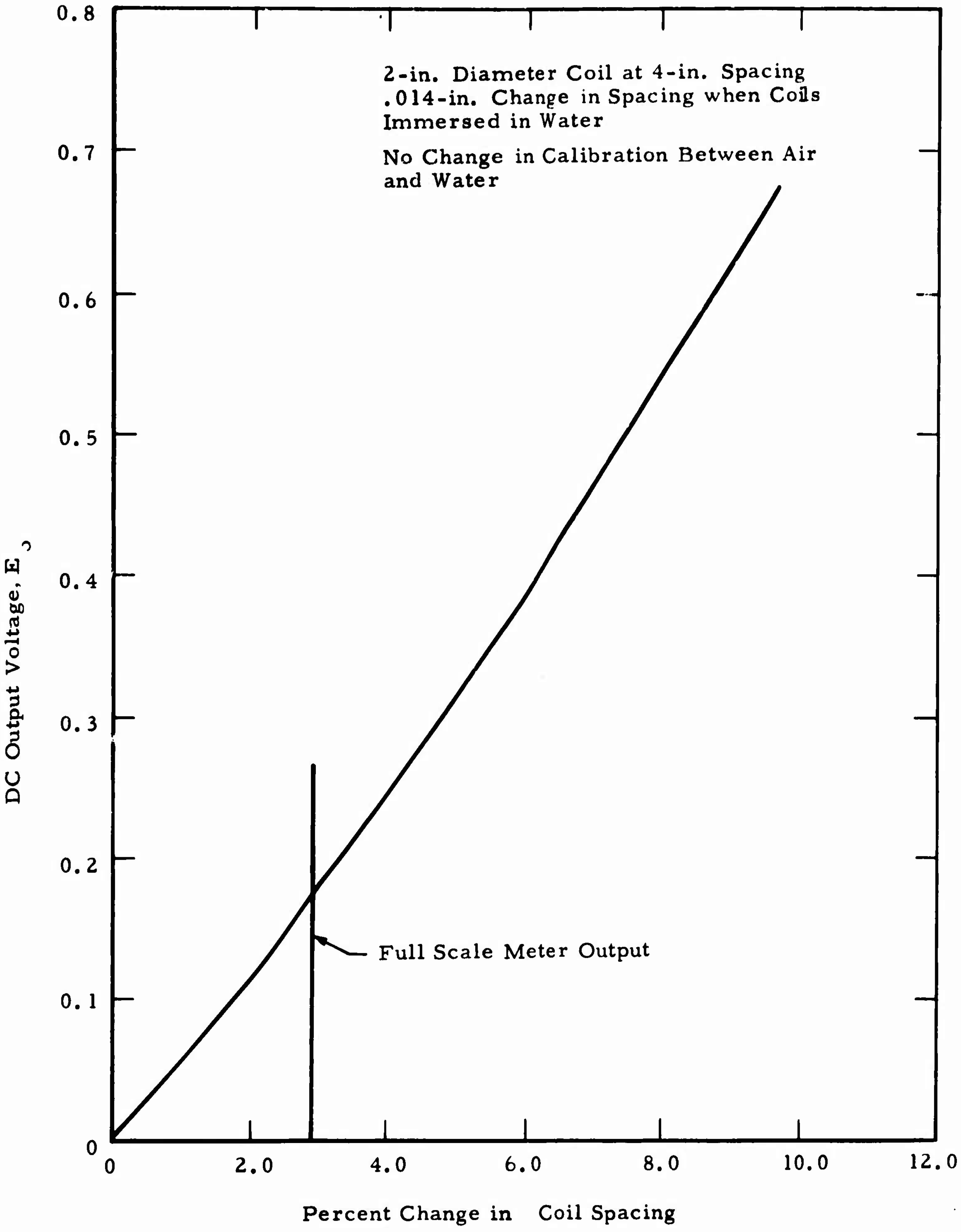


Fig. 30 CALIBRATION CURVE FOR 2-IN. DIAMETER COIL AT 4-IN. SPACING, REDUCED SENSITIVITY

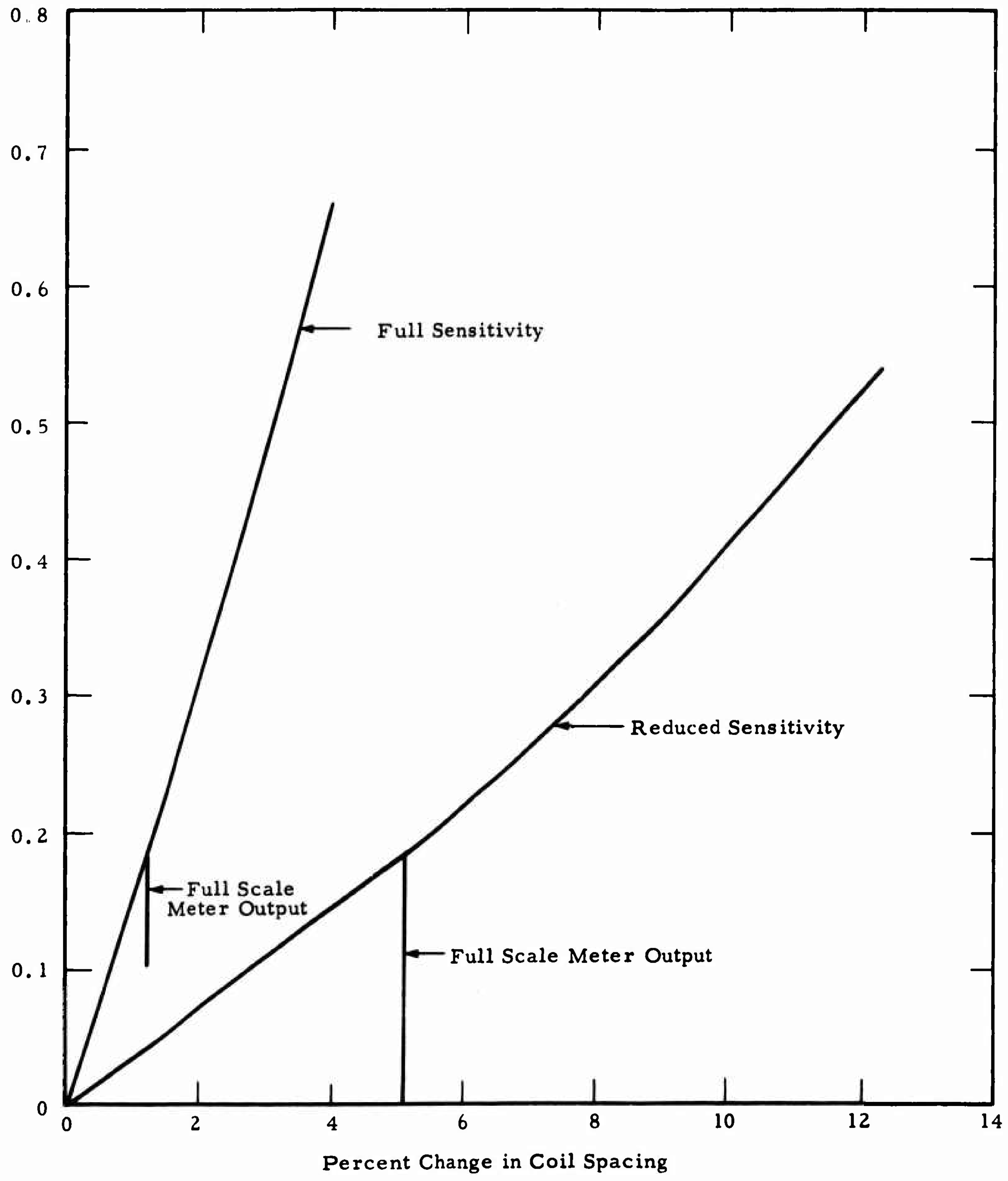


Fig. 31 CALIBRATION CURVES FOR FERRITE COILS A AT 2-IN. SPACING

times that necessary to cause full-scale meter output. When gain is reduced to increase the range of measurement, the calibration becomes nonlinear for differential displacements in excess of that which causes full-scale meter output. Continued decrease of gain to increase range of measurement would further decrease the range of sensitivity with respect to full scale output. These results illustrate the discussion of Fig. 26 and 27.

C. Mutual Interference of Gages

The operation of several gages in near proximity to each other causes mutual interference problems resulting in low frequency oscillations in gage outputs and induced signals due to changes in relative positions of gage sensors. The solution to these problems may be sought in three ways.

(a) Oscillator frequencies differing by greater than 2 kc may be used. In this case the interfering signal would be attenuated by the band-pass tuning of the input circuitry and by the 2-kc low pass filter at the output since the difference frequency at the output of the synchronous detector would be greater than 2 kc. This technique would not eliminate entirely effects of relative position changes between gage sensors and has the objection of requiring that each unit have slightly different circuitry.

(b) Ferrite materials may be used on the drive and pickup coils to restrict the magnetic field. This technique was found to be objectionable, however, because sufficient isolation can not be attained without undesirable increases in coil thickness and decreases in gage sensitivity at coil spacings greater than one coil diameter.

(c) A common oscillator may be used to drive all gages. As with the first method outlined, this technique eliminates only low frequency oscillations. However, considering factors of cost and overall gage performance it was selected as the best means of interference reduction. The effect of relative changes in position of gage sensor coils dictates minimum permissible separation between coil sets. The worst case of mutual interference occurs when gages are placed coaxially. Guide lines as to required separation distances of gages may be gained from Fig. 32. Two sets of 2-inch diameter coils at 4-inch center to center spacing were placed at a distance D apart. Both gages were adjusted to give full scale meter output for 0.65 percent

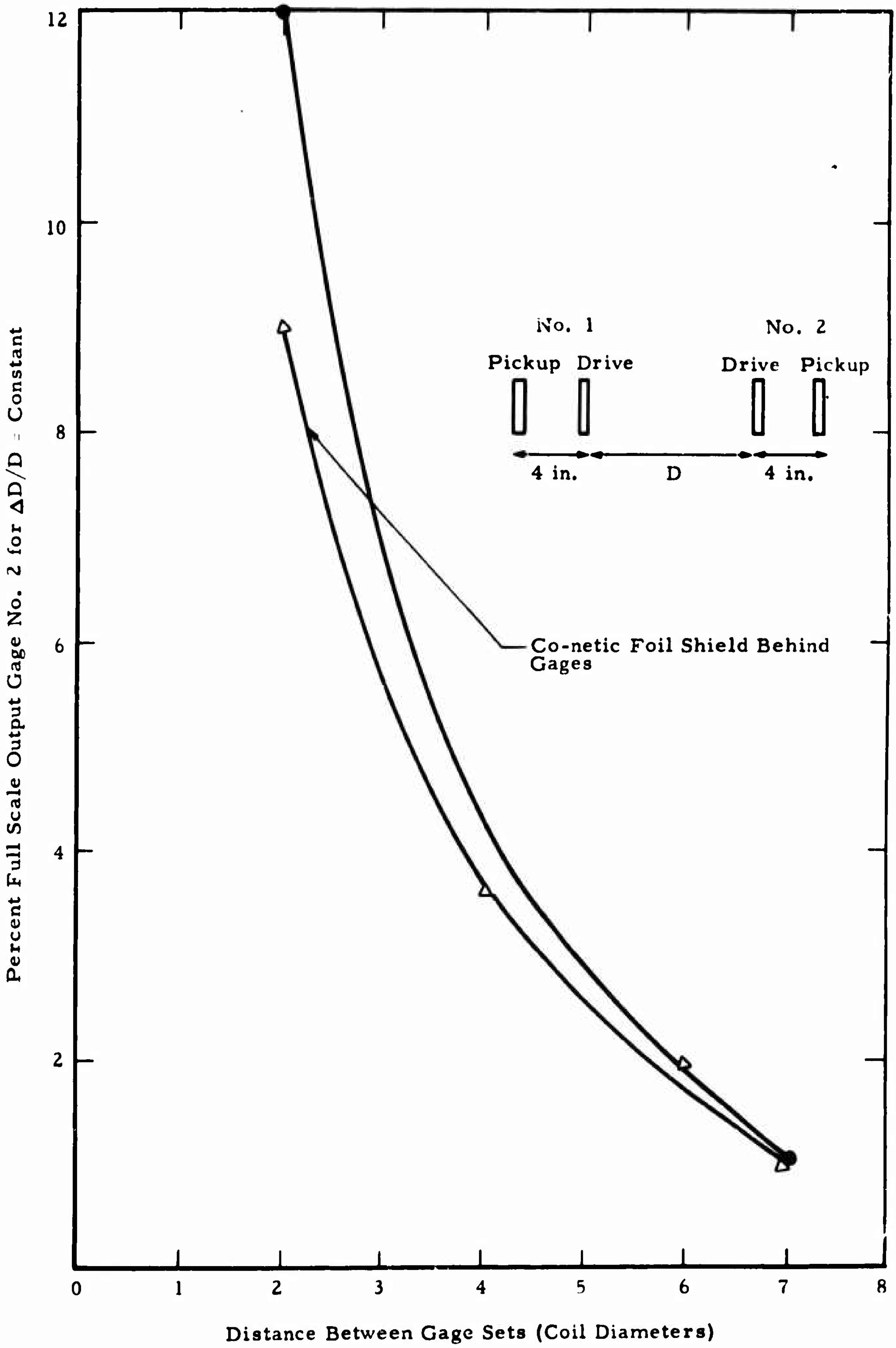


Fig. 32 EFFECT OF SEPARATION ON MUTUAL INTERFERENCE OF 2 IN. DIAMETER GAGE SETS

change of the distance between gages as D was increased. Thus $\Delta D/D \times 100$ was maintained equal to the percentage change in coil spacing required to cause full scale output of gage No. 2 operating alone. At seven coil diameters separation between gages, changes in gage separation have only 1 percent the effect of changes in the individual gage center to center coil spacing. Investigation was then made to determine if interference could be further reduced by placing a thin foil shield on the back of the coils. Results showed negligible improvement.

D. Effects of Sensor Coil Misalignment

The embedded strain sensor consists of the two physically independent remote coil disks. These coils should be placed in the soil as closely aligned as possible to the same axis in a parallel orientation. However, perfect control over placement cannot realistically be expected in any situation and often only limited control may be possible. Such conditions of sensor coil misalignment as depicted on Fig. 3 may be encountered.

The strain-voltage output calibration of the embedded remote coil set is determined with the use of the standard coil set which is positioned on a micrometer coil mount. Investigation was carried out to study how accurately the calibration obtained with the standard coil set represents the true calibration of the remote coil set when poor conditions of alignment exist. Figures 33 through 39 present results of percent change in coil spacing versus voltage output of both standard and remote coils for various sensor sizes and conditions of misalignment. In all cases the instrument was first balanced with both standard and remote coils aligned at equal spacings. The alignment of the remote coils was then distorted and the position of the standard coils adjusted to renull the system. The standard coils were then moved through a series of incremental changes and the corresponding voltage output recorded. The system was then renulled and the procedure repeated with the remote coils.

It is evident that with coil spacings of two diameters or more, significant misalignment can be tolerated before errors as large as 10 percent are encountered. As was the case with the previously developed laboratory instrument negligible errors are encountered if the gage coils are placed with less than 10 degrees relative rotation and with lateral offset less than 10 percent of the coil spacing. For coil spacings in excess of 2 inches these should be reasonable tolerances to hold.

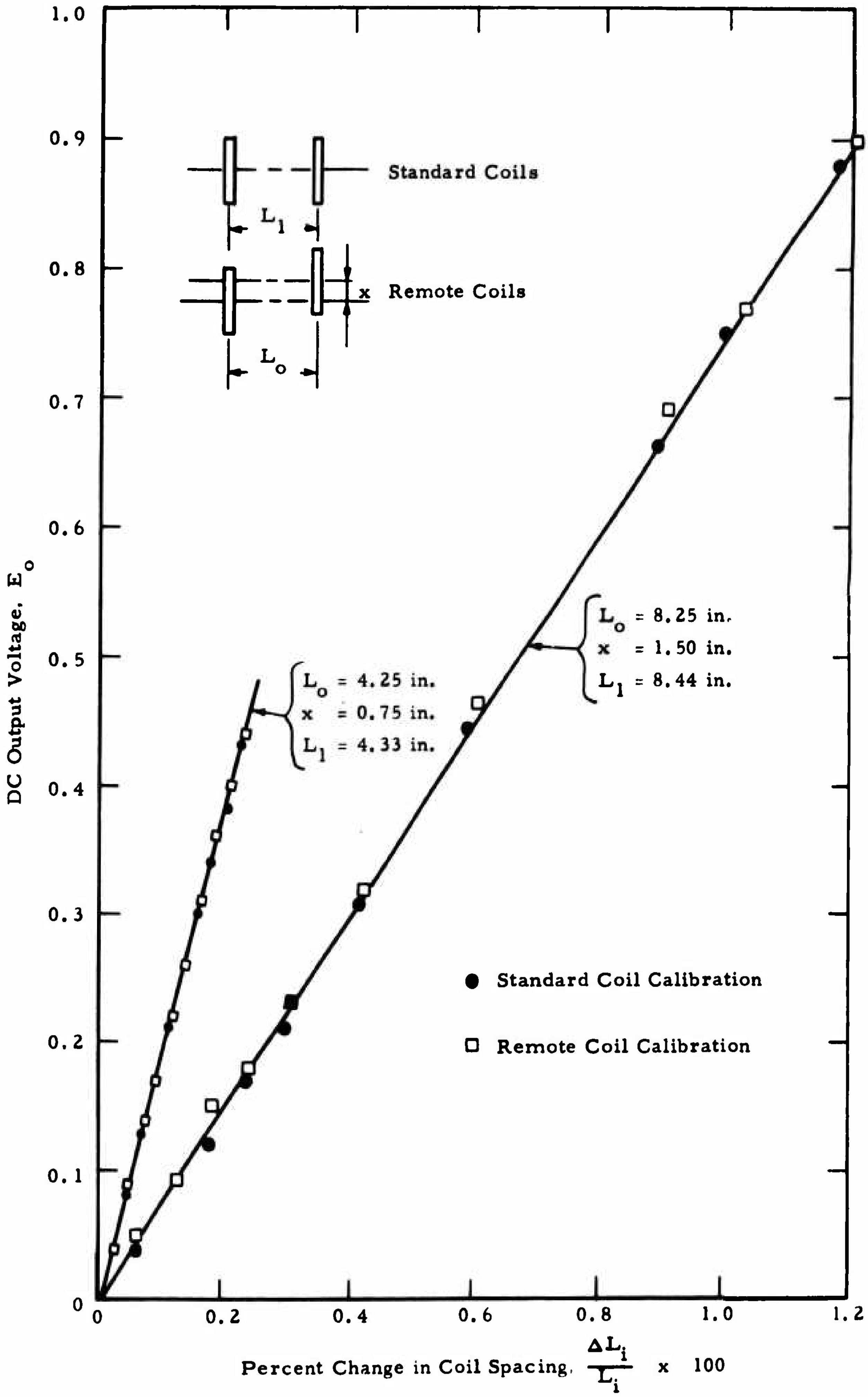


Fig. 33 EFFECT OF LATERAL MISALIGNMENT ON GAGE CALIBRATION OF 4 IN. DIAMETER COILS, FULL SENSITIVITY

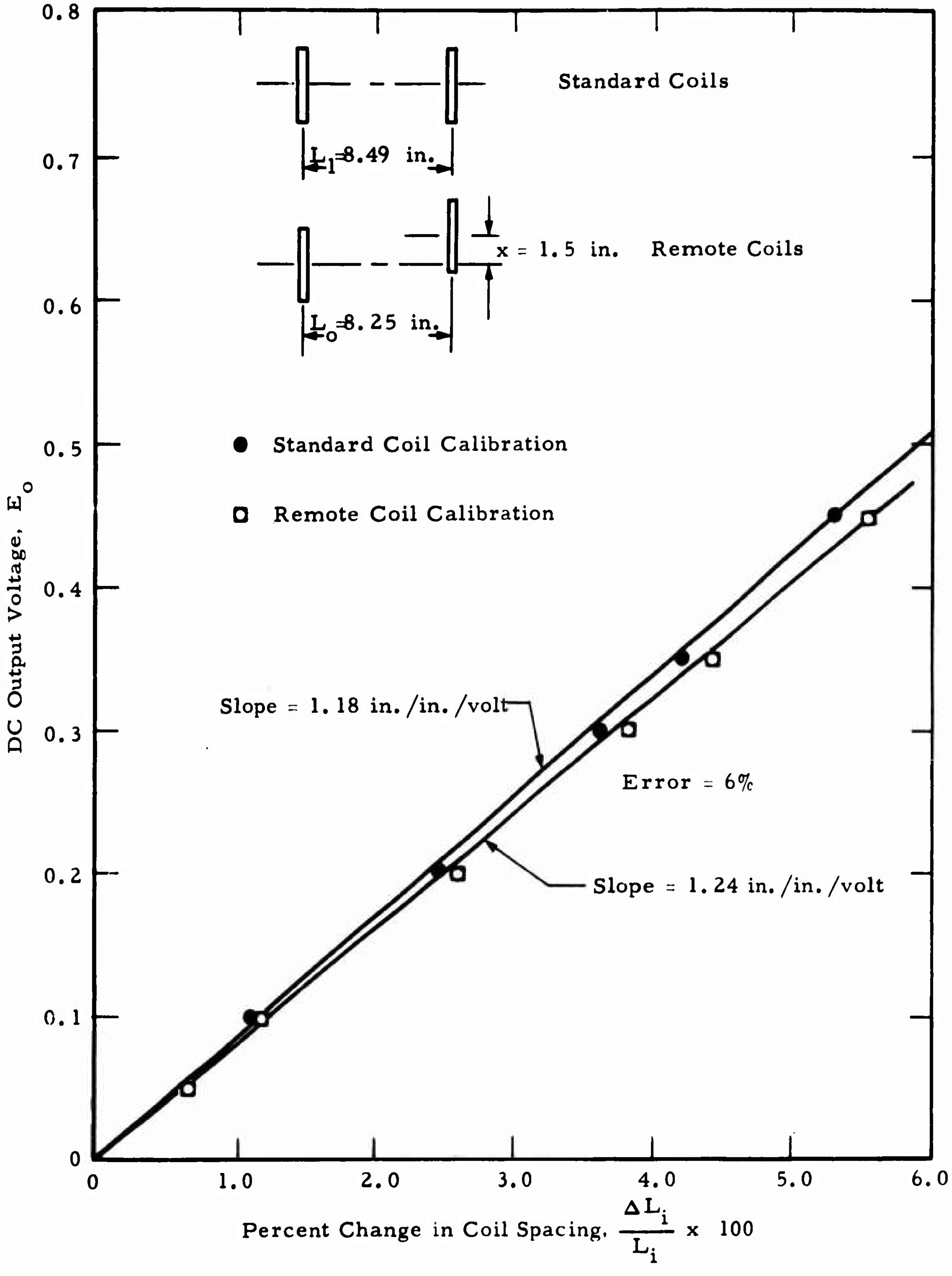


Fig. 34 EFFECT OF LATERAL MISALIGNMENT ON GAGE CALIBRATION OF 4-IN. DIAMETER COILS, REDUCED SENSITIVITY

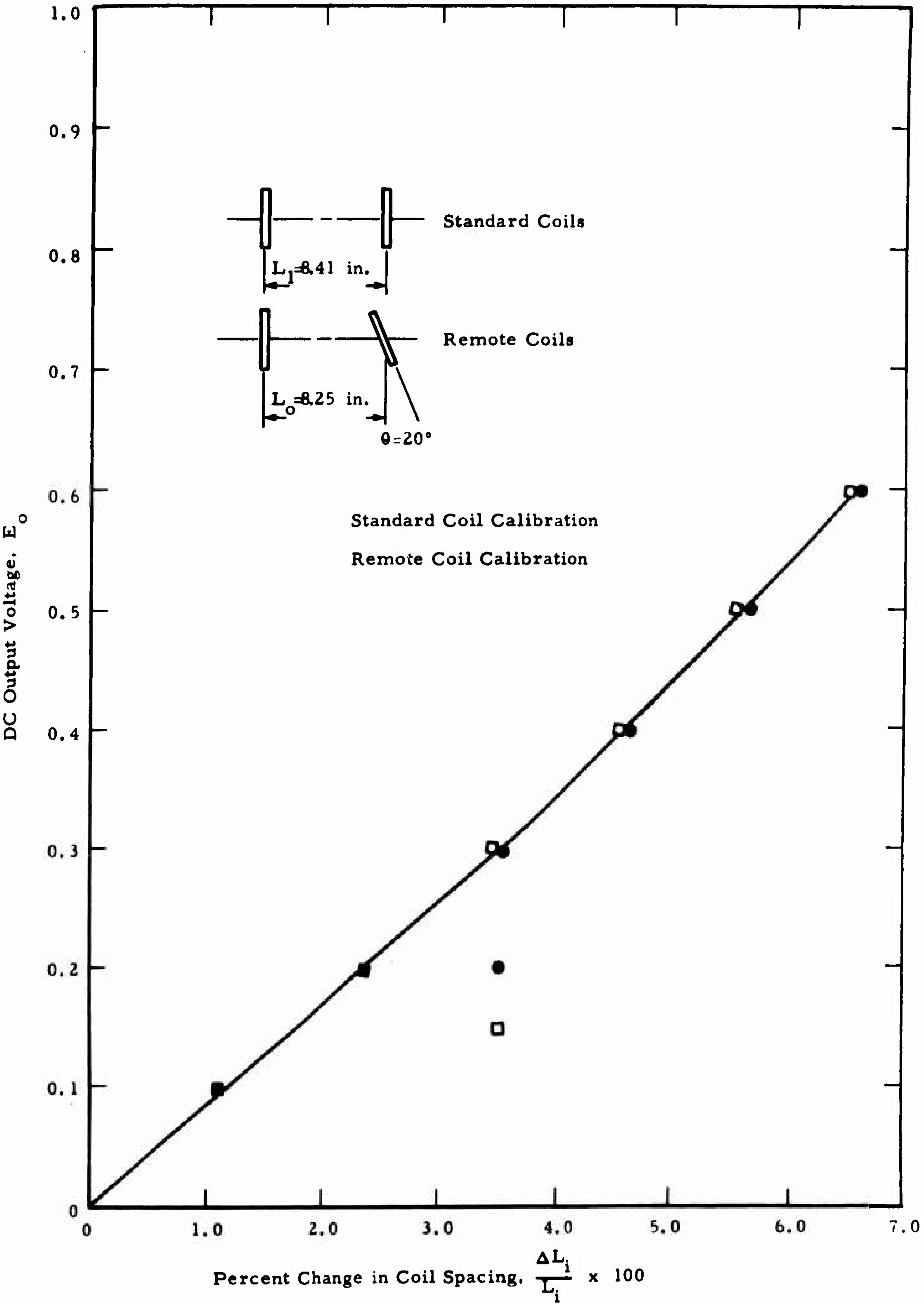


Fig. 35 EFFECT OF ROTATIONAL ALIGNMENT ON CALIBRATION OF 4 IN. DIAMETER COILS, REDUCED SENSITIVITY

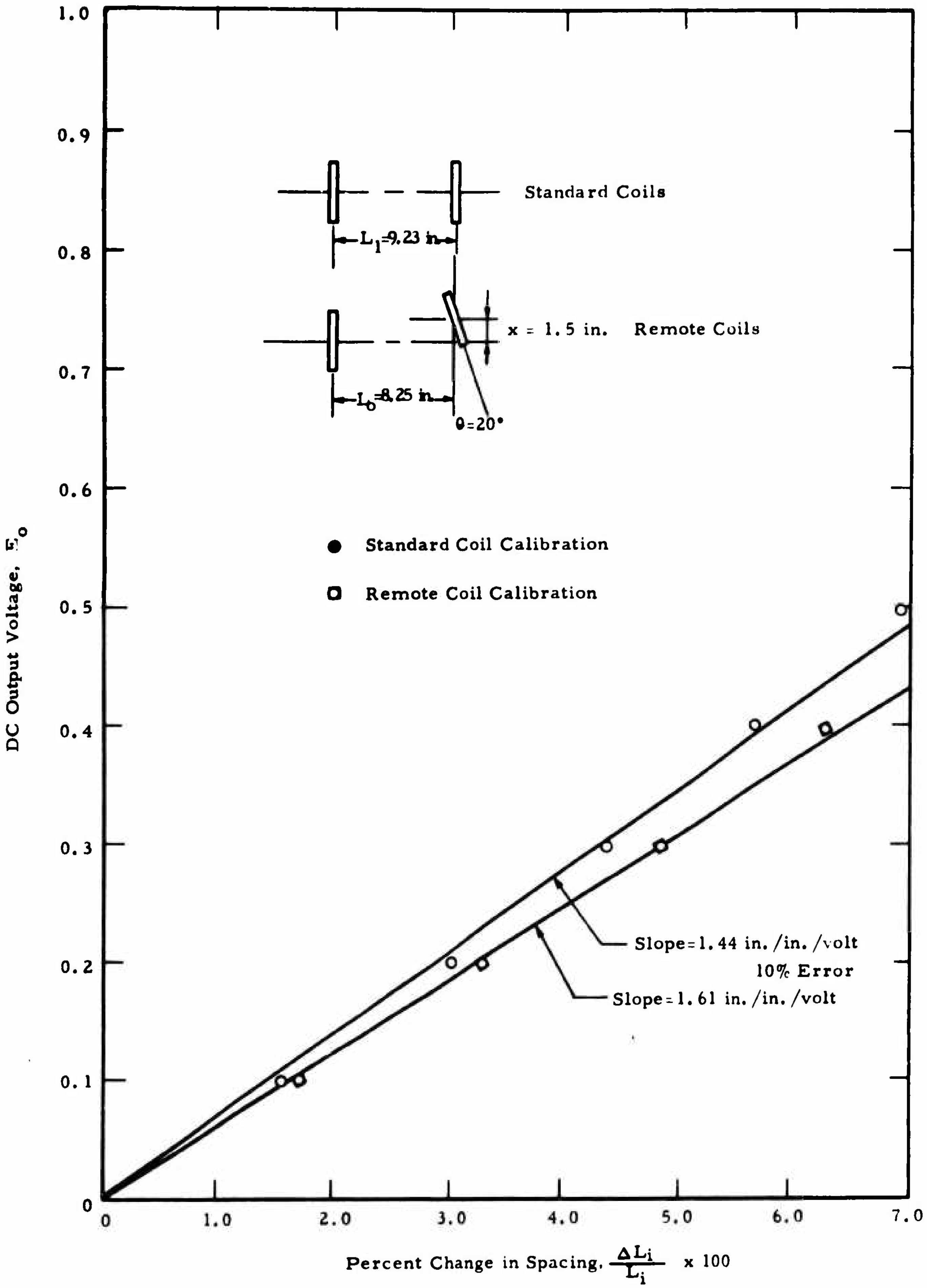


Fig. 36 EFFECT OF LATERAL AND ROTATIONAL MISALIGNMENT ON CALIBRATION OF 4 IN. DIAMETER COILS

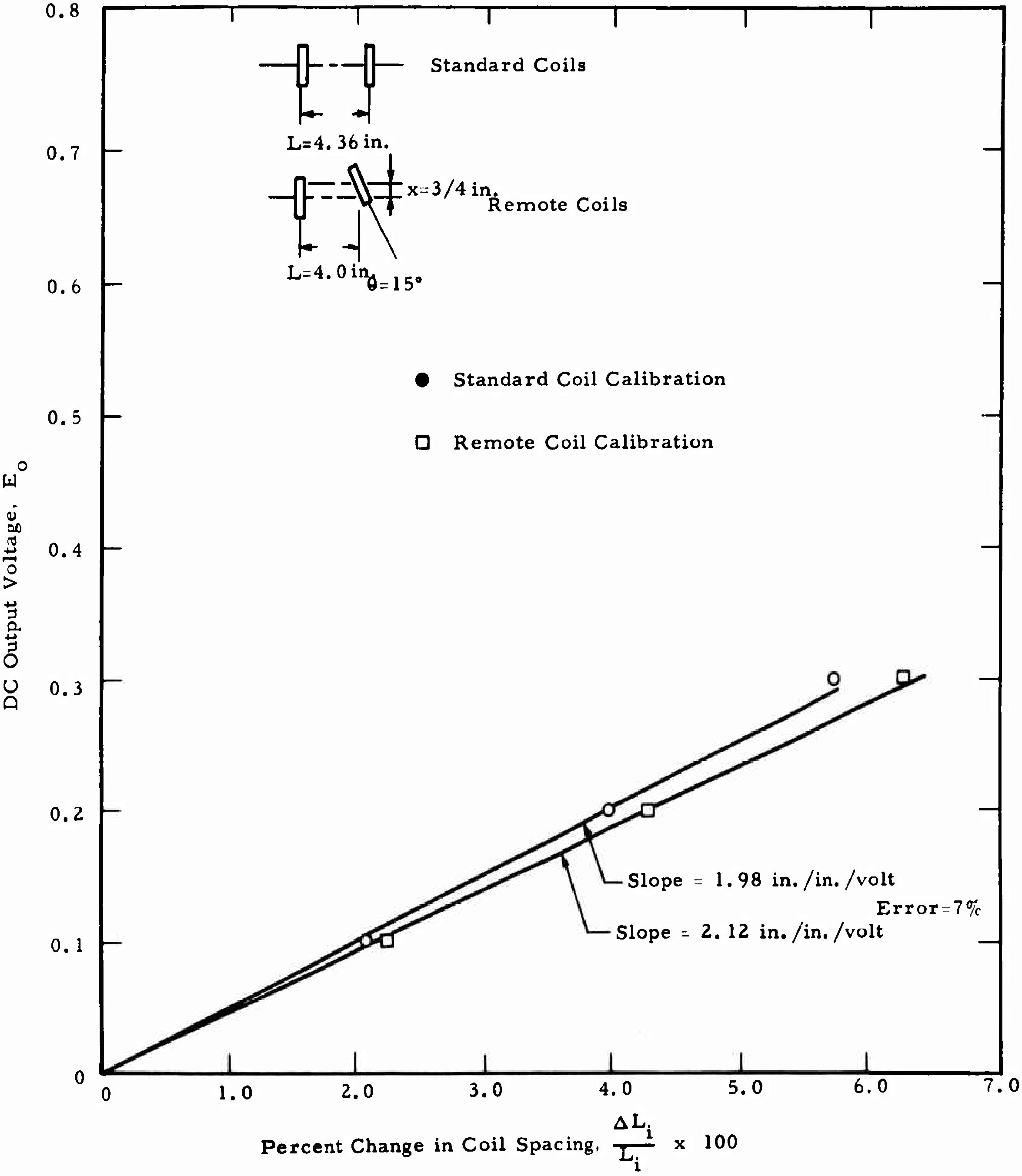


Fig. 37 EFFECT OF LATERAL AND ROTATIONAL MISALIGNMENT ON CALIBRATION OF 2-IN. DIAMETER COILS

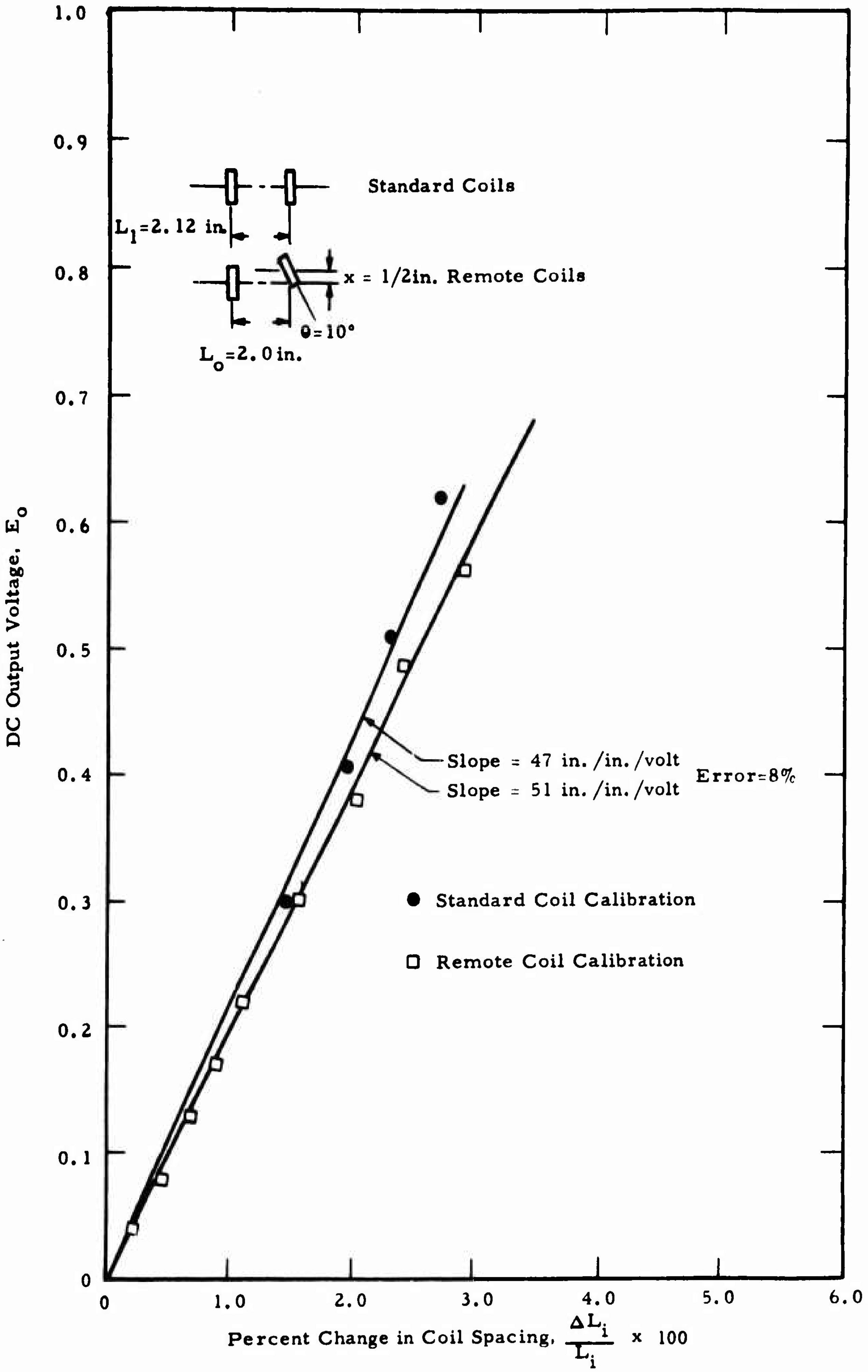


Fig. 38 EFFECT OF LATERAL AND ROTATIONAL MISALIGNMENT ON CALIBRATION OF 1 IN. DIAMETER COILS

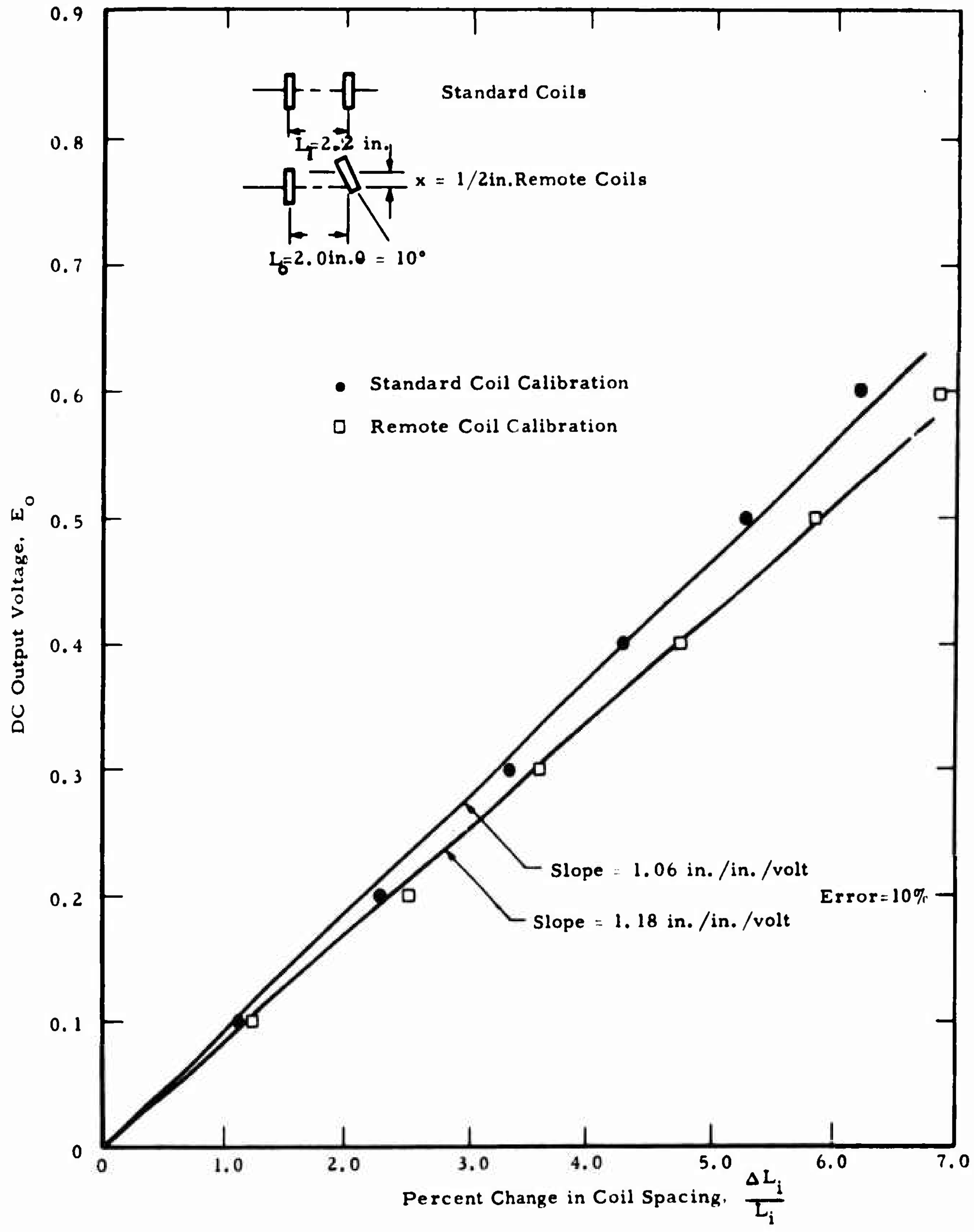


Fig. 39 EFFECT OF LATERAL AND ROTATIONAL ALIGNMENT ON CALIBRATION OF FERRITE CUP COILS B

E. Effects of Operational Environment

The operation principle of the soil strain gage relies on the exact uniformity of the magnetic fields between the two sets of coils; one set placed in the soil, the other placed on a precision micrometer coil mount. Soil of itself (unless it contains deposits of materials which have magnetic properties) has no influence on gage performance. Water and salts which soil may commonly be expected to contain may, however, cause greatly different conditions of conductivity to exist in the areas between the standard and remote embedded coils. The following test was performed to determine the seriousness of possible soil conductivity on the balance and sensitivity of the gage.

Two sets of 4-inch diameter coils were positioned on coil mounts at 8-inch center to center spacing. The strain gage electronics were balanced and the gain set to full sensitivity. The remote coil set was then submerged in a glass container of distilled water which had conductivity of 2.8×10^5 ohms/inch^3. This caused the system to be slightly out of balance and the standard coil position had to be adjusted to a spacing of 8.041-inches to renull the system. The required differential change in coil spacing to cause full scale meter output was then separately determined for the remote and standard sets. These were identically equal to 0.019-inch. A salt was then mixed with the water and conductivity increased to 2.5×10^2 ohms/inch^3 with negligible effect on the balance and sensitity of the system. It is believed that the range of conductivity of 2.8×10^5 ohms per cubic inch to 2.5×10^2 ohms per cubic inch encompasses the complete range of conductivity which may be encountered in soil.

The most logical cause for the initial off-balance of the system when the remote coils were immersed in water was that eddy currents were set up slightly changing the pattern of the magnetic field. This effect was relatively independent of conductivity over the range of interest. The tests indicate that only a small error, of the order of 1/2 percent, may be expected in determining the spacing of the remote coils when embedded in moist soil.

Use of the gage in the laboratory introduces an additional environmental influence, that of the test chamber on the magnetic field of the coils. The significance of the effect will depend to a large extent on the size of the test chamber in relation to the size of sensor coils being used. The effect is most critical when the chamber provides a continuous electrical and magnetic path around the coils. When this condition exists even small deflections of the chamber during test loading will effect strain gage response. Another source of chamber influence is the existence of slight capacitance between the sensor coils and each point of the chamber walls and ends. Differential changes in spacing between the coils and each point on the interior of the chamber as the chamber deflects under loading can effect gage response. The influence of any particular point is small but integrating the effect over the entire interior surface area can be significant.

To study these effects 2-inch diameter coils were placed in an 8-inch square by 30-inch long steel pressure tube as shown on Fig. 40. The gage coils were submerged under water to reduce the volume of the tube which had to be pressurized and to ensure that temperature changes could not contribute to the results. The strain gage electronics were balanced and set to full gain. Full scale meter output was obtained for a 0.4 percent change in spacing of the standard coils.

Pressure was gradually applied until full-scale meter output was obtained at 15 psi. The pressure was then relieved and the tube cover removed. The bolt holes were lined with electrical tape, and plastic washers were inserted between the nuts and tube cover breaking the electrical and magnetic path around the coils. The tube cover was then re-tightened. Pressure was gradually applied to 150 psi, the limit of the test tube, at which point 40 percent full scale meter output was obtained. The tube was then grounded to eliminate effects of capacitance differences between the coils and the interior of the tube. Gage response then decreased to 10 percent full scale meter output which corresponds to 0.04 percent change in spacing. The phase of the output signal was indicative of increased coil spacing, hence, no portion of the output can be attributed to compression of the acrylic rod upon which the coils were positioned.

The tube chamber used in the above tests was relatively small for use with 2-inch diameter coils but these tests indicate evaluation of chamber effects should be made before using the soil strain gage in the laboratory. This is especially necessary if the chamber head can not be isolated electrically from the body of the chamber.

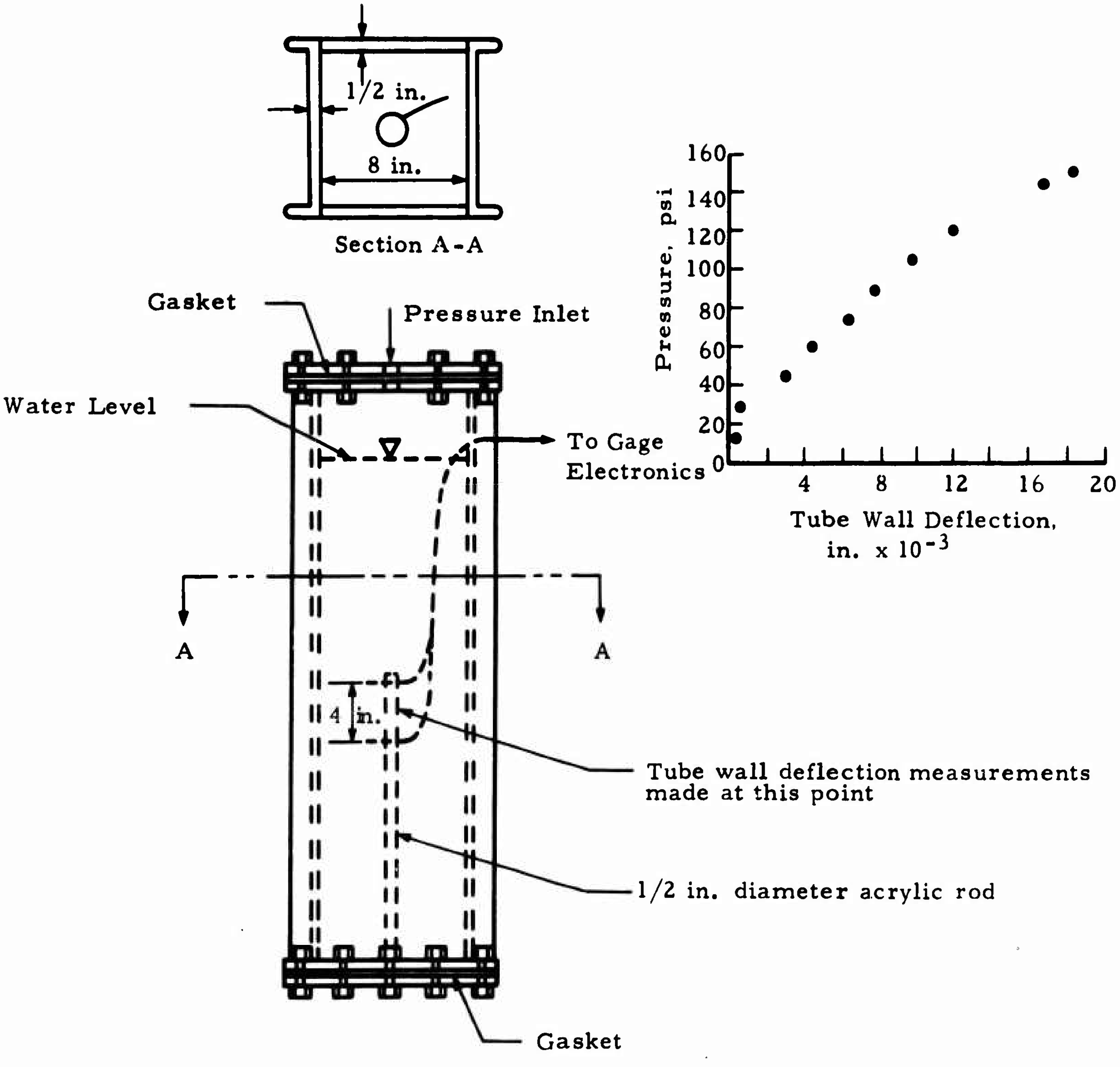


Fig. 40 TEST SETUP FOR STUDY OF TEST CHAMBER EFFECTS

F. Measurements With Respect to Metal Boundaries

Investigation was made to determine if bifilar wound coils could be used with the field gage electronics to enable measurements to be made with respect to metal boundaries. As was the case with the laboratory gage instrument the system was found to have insufficient stability; reproducible results could not be obtained from set-up to set-up. Considerable refinement of the gage electronics will be required to develop this gage concept to a useful state.

The possibility does exist, however, of making measurements against boundaries with the present gage system. Tests were performed with 4-inch diameter coils and ferrite cup coils B with one coil in each set mounted on a 12-inch square by 1/16-inch thick steel plate. The 4-inch diameter coils showed a decrease in sensitivity by a factor of two at an 8-inch spacing, but accurate tracking existed between the remote and standard coil sets. The ferrite cup coils showed only slight loss in sensitivity and also evidenced accurate tracking of remote and standard coil sets.

While the tests indicate that measurements can be made with respect to boundary materials it is recommended that thorough evaluation of test chamber effects on gage response be made first.

G. Recommended Gage Placement Techniques

A particular advantage of the soil strain gage is the fact that the embedded sensor coils have no physical coupling between them. This permits the coils to be placed independently and facilitates matching the soil conditions within the gage length to that of the surrounding soil. Thus it is desirable to take advantage of this feature whenever possible.

When the gage is used in a prepared test bed, the coils can be placed as the bed is formed. This is particularly effective when a raining sand-placement technique is used. The tolerances on gage alignment for coil spacings of a few inches or more give confidence that the coils can be placed without great trouble. When the test bed is to be prepared by compaction, some method of stabilizing coil position when compacting near the gage will be necessary. Experience in working with the laboratory gage indicates a thin rod through the center of the coils is satisfactory for this purpose.

Placement in natural soil deposits, as will often be required in the field, will be more difficult. It is recommended in these instances that in cohesive soils the gage coils be inserted in prepared slots. A small chain saw could easily be adapted to the purpose of carefully cutting the required grooves in hard soils, while hand tools should serve satisfactorily in soft soils. This technique would leave the soil between the gage coil disks essentially undisturbed. In cohesionless soils and for measurements at depths inconvenient to permit use of the above techniques other methods of placement must be sought.

Placement in cohesionless soils will require excavation, gage placement, and replacement of soil. The problem is quite similar, but possibly on a larger scale, to laboratory test-bed preparation and gage placement. .

For deep measurements gage coils may be placed in prepared cores and lowered into a drilled hole. The cores may be prepared by compaction with cohesive soils or by freezing with saturated cohesionless soils. A technique of this type was used to place gage coils for the field evaluation of the gage described in Section VII-A.

VII. FIELD EVALUATION OF GAGE

A field test of the IITRI strain gage was performed in the LDHEST shot conducted by the Air Force Weapons Laboratory at Kirtland Air Force Base, New Mexico on May 6, 1965. This was a high-explosive field test in which soil strain gage instrumentation played only a minor role. Description of the test is limited to that information pertinent to the strain gage measurements. Complete test results and detailed particulars will be reported by AFWL.

The test site was a large pit, approximately 88 feet wide by 102 feet long. The surface of the pit was laced with primacord which was then covered with 8 feet of sand fill. Detonation of the primacord generated a transient pressure pulse over the pit surface. The peak pressure realized was approximately 600 psi.

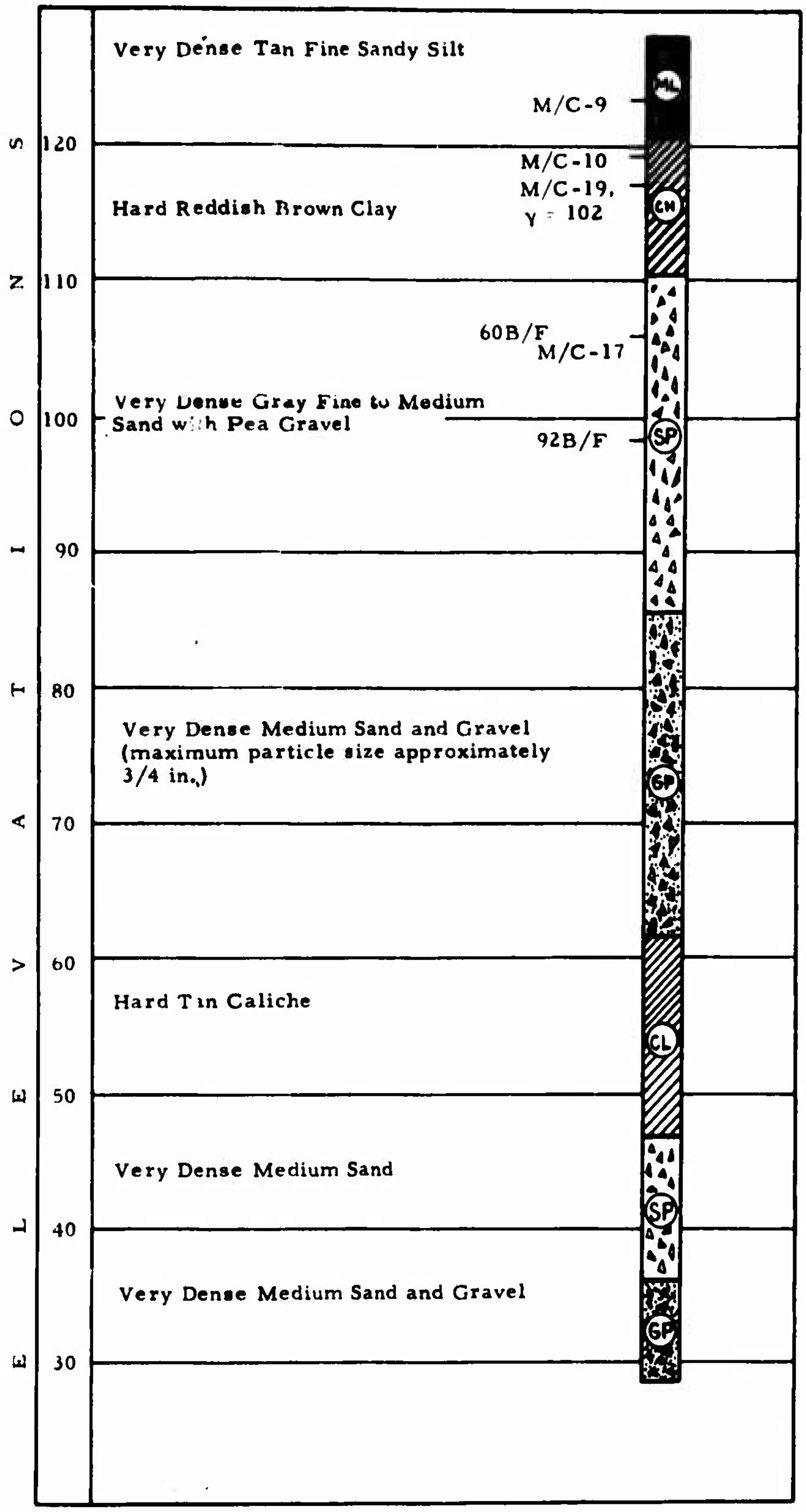
Eight 4-inch diameter soil strain gages were placed at intervals of 1, 5, 10, 20, 40, 60, 80, and 100 feet below the floor of the test pit. The gages were placed in a single hole located toward the firing end of the pit, approximately 25 feet from the front and side walls. All gages were oriented to measure strain in the vertical direction.

A. Gage Placement

A drill hole 9 inches in diameter and 105 feet deep was provided by AFWL for gage installation. Figure 41 presents a boring log from the center of the test site. This log is from a soil profile of the site prepared by Spencer J. Buchanan and Associates, Inc., Bryan, Texas. Overall inspection of the profile indicated this log should be representative of the soil profile at the test hole.

The gages were placed at the test site during the period of March 22 through 26, 1965 using the following procedure:

Sand fill material provided by AFWL at the test site was passed through a Number 4 sieve. The material passing the sieve was intimately mixed with water to a moisture content of approximately 15 percent. The soil was then compacted into eight molds 8 inches long and 5 inches in diameter. The soil was compacted in 6 layers using 50 tamps with a 1/2-inch-diameter aluminum rod. Gages were placed in the molds at 1 inch from each end as the soil was



Note: Elevations for soil profile referenced to topographic map of site of project "Gasbag", Phase II by William A. Pettit, August 1964.

Legend

M/C = Moisture content, dry weight basis in percent.

γ = Dry unit weight of soil in pounds per cu ft

B/F - Blows per foot, standard penetration test.

Sympols for soil strate conforms with Corps of Engineers standards for unified system of soil classification.
The classification shown is by visual methods and not based on test determinations.

Fig. 41 BORING LOG FROM CENTER OF TEST SITE compacted. The wet density of the compacted soil in all molds was within ± 2 percent of 101 pounds per cubic foot.

Following compaction the molded specimens were placed in a freezer for a period of 2 days. At the end of this time the soil-water-gage system was frozen into a solid mass. The specimens were then removed from the freezer and packed in dry ice for transportation to the test site.

At the test site, the molds were stripped off the specimens, the cable leads connected to the microdot cable leads from the gages, and the gages lowered into the hole to the appropriate depth. It should be noted that prior to connecting the cable leads the elevation of the bottom of the hole was raised to the proper level by backfilling. The resistance of the cables was determined with and without the gage in the circuit.

Once the gage was resting on the bottom of the hole, backfill was placed around it. The backfill soil consisted of the same soil as was placed between the gages. It was in an air-dry condition and was placed by the "raining" technique. Following completion of the backfill operation for each gage the electrical systems were again checked and in all cases were found to be functioning satisfactorily. Pertinent data on gage placement are given in Table 2.

Table 2

DEPTH TO BOTTOM

Gage No.	Depth Of Gage Below Pit Floor	Center to Center Spacing
1	1'0"	7"
2	5'10"	6"
3	10'2"	6"
4	20'2"	6"
5	40'6"	6"
6	60'6"	6"
7	80'4"	6"
8	100'6"	6"

B. Event Recording

Recording instrumentation was set up and checked out 3 days prior to the test. The standard coil set for each embedded gage was positioned at the corresponding spacing from Table 2. All strain gage units were then connected to the remote oscillator and balanced. This assumed that the spacing of the embedded coils had not changed as the frozen soil specimens used for placement thawed out during the six-week interval between placement and the test. The assumption was necessary because no way of checking final embedded spacing existed, and was felt to be reasonable because tests indicated that at 6-inch spacing of the standard coils the remote coils could be misspaced 1/2 inch before introducing a 10 percent calibration error.

Gage calibration was performed the morning of the test. A CEC recorder with 1-kc frequency response was used to record the transient strain. The recorder was turned on 1 second prior to test detonation on an audible countdown signal. The one second interval enabled the recorder to reach a preset recording speed of 128 inches per second.

Although all gages appeared to be functioning properly and satisfactorily, two adverse effects were noted in the pretest checkout period. First, considerable drift was noticed with all instruments. All instruments were final balanced within 5 minutes of firing time and hence, drift is not felt to be of any significance with respect to the transient strain measurements. But the existence of drift was of considerable surprise because the gages had proved quite stable in the laboratory. The variable temperature, bad dust conditions, and approximately 600 feet of lead cable exposed to the sun probably all contributed to instrument drift. The second effect noted was a deviation in the S/N from that observed in the laboratory. In addition to the above conditions, pickup from other instrumentation may have been a partial cause of this problem.

C. Results

The data recorded by each of the strain gages are shown in Fig. 42. Unfortunately, the pressure-time history at the ground surface is not available. As a result, the difficulty of interpreting the strain gage data is increased significantly.

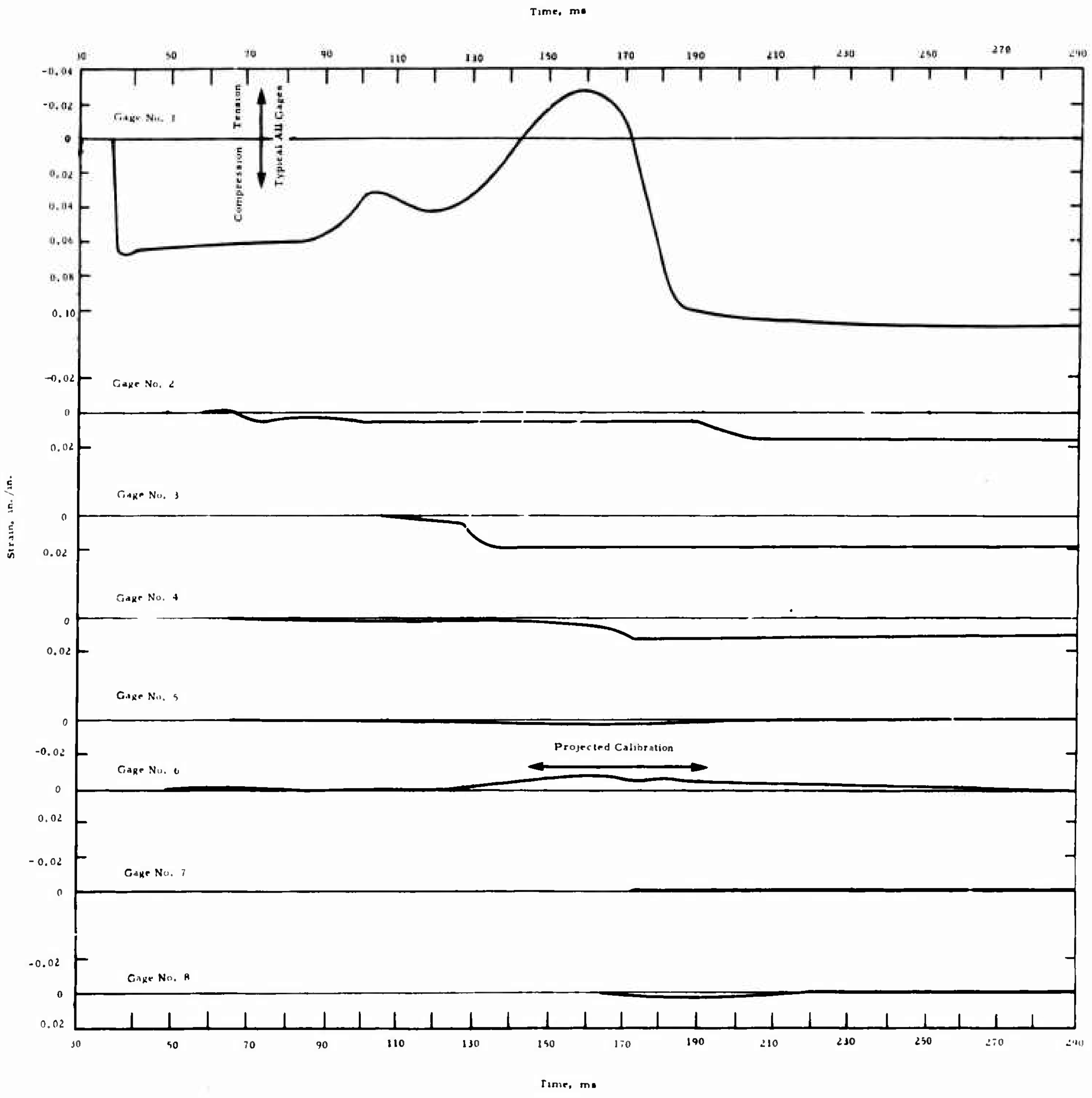


Fig. 42 STRAIN GAGE RECORDS FOR LDHEST SHOT, MAY 6, 1965

It is anticipated that the overpressure-time curve would have a microsecond risetime to peak load followed by a relatively rapid decay. It is also assumed that the peak overpressure was approximately 600 psi.

The data from all eight soil strain gages placed in the field (Fig. 42) are shown as plots of strain versus time. As aforementioned, it is difficult to ascertain the credibility of the measured gage response without knowledge of the overpressure-time history.

Based on previous experience, the strain time data recorded by the 8 gages, in general, appear satisfactory. With the exception of the uppermost gage, all gages were still operating satisfactorily after the test. There was an abrupt break in this gage record approximately 350 msec after detonation and beyond this time the record is of doubtful credibility. The main areas of doubt in overall gage performance are the facts that the two gages closest to the ground surface have a second compressive strain peak which is larger than the first and some of the gages indicate tensile strain during a portion of their recorded history. For the overpressure-time history assumed, as well as the overpressure-time history normally known to be associated with high energy air blast phenomena, the presence of a second compressive strain peak of greater intensity than the initial peak is not feasible, i.e., a precursor wave of significant magnitude would be required. Consequently, the presence of a second compressive strain peak is, at present, of doubtful validity and will not be given further consideration at this time. The strain peak significance cannot be satisfactorily evaluated until a later date when information on the overpressure-time history becomes available.

The explanation of the tensile strains is not accurately known. It is probably associated with cable squeeze under loading and/or the coils may have been displaced laterally by the direct induced shock wave. With the exception of the uppermost gage the magnitude of the tensile strains are small and can be neglected.

Based on previous discussion, data analysis will be confined to compressive strain - in particular, the strain-time relationship associated with the first compressive peak. The maximum compressive strain measured was obtained from gage No. 1 which was located approximately 1 foot below the loaded surface. The magnitude of this maximum strain is 6.7 percent with risetime to peak strain of about 3 msec.

The attenuation of peak strain is quite rapid with depth. At a depth of approximately 5 feet the peak strain is only about 7 percent of the strain at a depth of 1 foot. However, the strain at the 10 feet depth of burial was 27.4 percent and at 20 feet depth of burial 18.8 percent of the strain at 1 foot depth of burial. The reason for the strain at 5 feet being less than that at 10 and 20 feet is not precisely known. It is possible that at depths of burial of 10 and 20 feet the air-induced stress wave and the blast-induced stress wave significantly reinforce each other, but based on the time intervals involved, this is not probable.

Assuming that the principal direction of wave propagation in the column of soil containing the gages is vertical, wave propagation velocities were computed from the difference in time of arrival of the compression at the first three gage stations. The wave propagation velocity between the gages at 1 and 5 feet was approximately 1300 fps and between the gages at 5 and 10 feet approximately 1200 fps. These values are within reason.

The data below a depth of embedment of 20 feet are not considered to be of any consequence. The magnitude of the positive strain is too small to be of importance, i.e., the magnitude of the measured positive strain could be associated with air blast phenomena, e.g., pressure on the cables or stretching of the cables. Some such effect is evidenced, to a certain extent, by the fact that the measured time of arrival at these lower gages does not increase as a function of depth. As a result, the data obtained from the gages at 40, 60, 80, and 100 feet should be considered invalid.

The gages at 20 feet appear to respond too soon, in relation to its depth of burial. This is probably due to the aforementioned effects of air blast phenomena on the gage leads.

It must be recognized that the data obtained from the LDHEST shot cannot be used to completely evaluate the IITRI strain gage. The reason is the small amount of data obtained from the single shot--much more data are required for a comprehensive evaluation of the gage. Local apparent inconsistencies appear, e.g., the gages measuring tension, but this does not detract from the overall soundness of the data. Based on the information available, overall the output from the gages is believed to be quite reasonable.

The method of placement of the gages in the ground was not such as to provide for a good coupling between the soil surrounding the gage. Consequently it is not to be expected that the strain measured by the gages would be the true free-field strain. Instead, it is a strain uniquely related to the artificial conditions established during gage placement. Consequently, the data obtained from the strain gages cannot be used as a quantitive measure of the free-field strains which occurred during the test, but only as an aid in evaluating gage performance.

D. Summary

The IITRI strain gage was used to measure strains occurring in a soil column as a result of a contained high-energy explosion. Based upon the data obtained, conclusive evaluation of gage performance cannot be made. The response of the uppermost gages, in general, seems to have a degree of credibility. Unfortunately, the overpressure-time history is not available for comparison.

The data indicate an increase in rise time with depth of penetration of the stress wave as well as a rapid attenuation of peak strain with depth. Below a depth of 20 feet no significant strain was measured.

There are certain anomalies in the data, e.g., peak compressive strain occurring approximately 250 msec after the blast (for the gage closest to the surface), gages indicating an initial tension phase, and the arrival times at the gages not being completely consistent with depth of burial. The significance of these factors can be ascertained only through controlled use of the gages over a period of time.

VIII. CONCLUSION

The primary objective of this research program was to modify the small soil strain gage developed on Contract AF29(601)-5343 to extend its use to the field with larger size sensors and long lengths of lead wires. Accomplishing this objective required major redesign of the electronics of the laboratory gage system. As a result of this redesign a vastly improved gage was obtained which achieved secondary program objectives of increased sensitivity over greater gage lengths. Gage features include:

(1) Gage coil size may be selected to most readily adapt to the specific application.

(2) Lead wire lengths from a few feet to 1000 feet may be used.

(3) Phase and amplitude balance controls permit a precise null balance to be obtained compensating for electrical differences in gage coils. The problem of finding matched coil pairs for accurate operation is of negigible magnitude.

(4) Gage lengths of up to three coil diameters may be used while maintaining sufficient sensitivity to cause full scale output for a 1 percent change in gage length.

(5) Provision for use of several gages with an external oscillator permits use of up to eight gages in near proximity without mutual beat frequency interference

(6) The gage system has a response rise time of 0.3 msec from 10 percent to 90 percent full-scale output.

(7) At gage spacings of two coil diameters tolerances on embedded sensor alignment are sufficiently broad to permit placement of gage coils with only reasonable care.

Increased gage sensitivity, greater permissible gage length and corresponding increases in alignment tolerances, and ease of selecting matched coil pairs makes the field gage instrument desirable for laboratory use. In laboratory applications where long lead wires are not required minor modifications to the circuitry would permit gage response time to be reduced from 0.3 msec by a factor of three or more. However, use of the gage in the laboratory does necessitate evaluation to be made of possible effects of the test chamber on gage response.

The performance of the gage in the field was highly encouraging but the varying temperature conditions and blowing sand and dust problems encountered in the field indicate a need for greater temperature stability and a dust proof instrument console. The response of the eight gages tested appeared, in general, to be reasonable, but some extraneous influence, quite possibly cable squeeze, was evidenced in the gage records. On the basis of a single test it is not possible to draw detailed conclusions as to the seriousness of these extraneous effects. They are probably negligible with respect to strain measurements of 2 percent or more and of significance with respect to strain measurements of 1/2 percent or less.

Studies by others [6] indicate that soil-gage interaction may not be a serious problem with the soil strain gage. Although the referenced work deals with only one soil type and fairly small strains, the excellent correlation between strain gage measurements and the uniform strain applied proves the ability of the soil strain gage to record true soil strains.

IX. Recommendations

A comprehensive evaluation of the soil strain gage should be conducted under both laboratory and field applications. The limited evaluation permitted during gage development indicates problems exist in the laboratory due to container effects and in the field due to loading effects on the cable leads. These problem areas should be thoroughly investigated. In addition to the above the following specific recommendations are made:

(1) The coil sensors (all sizes) should be fabricated by molded encapsulation of the coil windings, as per the previously developed 3/4 inch diameter coil disks used with the laboratory gage. This can best be accomplished by a commercial firm which specializes in transformer and coil windings.

(2) The strain gage electronics should be mounted in a dust proof package more suitable for use in the field.

(3) The field strain gage electronics should be modified to increase frequency response to 5 or 6 kc when used with short lead cables.

(4) Investigation should be made of multiple-channel gage design using a common oscillator, power amplifier, power supply, and output meter, and replacing the standard coil sets with small-size packaged controls.

(5) Additional study should be made of soil-gage interaction. The experimental research, "Stresses and Strains in Triaxial Specimens Using Embedded Gages," should be expanded to a greater range of test conditions and several soil types.

APPENDIX

PARTS LIST

Designation	Description
R1	8.2KΩ
R2	8.2KΩ
R3	2KΩ
R4	4.7KΩ
R5, R6	Allen-Bradley Dual Vernier pot, Coarse 1K, Fine 5K
R7, R8	Allen-Bradley Dual Vernier pot, Coarse 5K, Fine 1K
R9	30 KΩ
R10	50 KΩ linear pot
R11	30 KΩ
R12	10 KΩ
R13	330Ω
R14	1 KΩ linear locking pot
R15	3.3KΩ
R16	1.5KΩ
R17	6.8KΩ
R18	10 KΩ
R19	470Ω
R20	15 KΩ
R21	15 KΩ
R22	22 KΩ
R23	2.2KΩ
R24	10 KΩ
R25	4.7KΩ
R26	39Ω 5W
R27	910Ω
R28	910Ω
R29	1 KΩ
R30	1.2KΩ
R31	1.4KΩ
R32	1.6KΩ
R33	2.1KΩ
R34	3.3KΩ
R35	5 KΩ
R36	5 KΩ
R37	2.7Ω
R38	2.7Ω
R39	2.7Ω
R40	2.7Ω
R41	2.7Ω
R42	2.7Ω
R43	6.8Ω
R44	6.8Ω
R45	4.7Ω
R46	4.7Ω

PARTS LIST (Cont'd)

Designation	Description	
R47	2.7Ω	
R48	2.7Ω	
R49	4.7Ω	
R50	4.7Ω	
R51	4.7Ω	
R52	4.7Ω	All resistors 1/2 μ - 5% unless other wise specified
R53	4.7Ω	
R54	4.7Ω*	
C1	0.054	
C2	0.004	
C3	0.1	
C4	ARCO type 304 100-550 μμf	
C5	0.1	
C6	0.1	
C7	100	
C8	10	
C9	0.02	
C10	0.03	
C11	0.15	
C12	0.025	
C13	0.1	
C14	0.1	
C15	0.03	
C16	0.06	
C17	0.1	
C18	0.1	
C19	0.044	
C20	0.041	
C21	0.039	
C22	0.037	
C23	0.034	
C24	0.031	
C25	0.029	
C26	0.026	
C27	0.023	
C28	0.020	
C29	0.020	
L1	5 millihenry toroidal inductor	
L2	100 millihenry toroidal inductor	

---

*Pad value to obtain 0 phase shift between standard and remote inputs when Pot PHASE is at center of range and range switch is at position 0.

PARTS LIST (Cont'd)

Designation	Description
T1	UTC DO-T-42
T2	UTC DO-T-43
T3	TRIAD TY-29X
D1	IN3027B
D2	IN457
D3	IN457
D4	IN457
D5	IN58
Q1	2N398A
Q2	2N174A
AMP1	Allison Labs Model 660 preamplifier
AMP2	Allison Labs Model 658 amplifier
LP1	UTC I 000 2KC Low pass filter

PARTS LIST (Cont'd)

Miscellaneous Parts

Items per Unit	Description
1	Octal socket
1	4"x2 1/4"x2 1/4" Bud Minibox
2	5"x7"x3" Chassis
2	5"x7" Chassis Bottom Plates
1	12"x8"x9" Bud Portalab Cabinate
5	UG 109410 BNC Connectors
1	Wipter fan W/grill
1	API 502-1 Taut Band Meter
1	D.P.ST. Toggle Switch
1	Con Avionics HT 28-0.65 Power Supply
1	Accutronics 20KC 0.1% Oscillator
2	Centralab PA-301 Switch Shaft Assm
6	Centralab PA-1 Ceramic Switch Section
1	Shaft Coupling
1	S.P.D.T. Push Button Switch
2	Raytheon 70-2-2G Knobs
1	Raytheon 70-4-2G Knobs
1	Raytheon 70-1LK-2G Knobs
1	Raytheon KL-701G Knob lock
1	Phone Jack with Break Contact
1	Fuse Assembly
1	Pilot lamp assembly
3	Terminal strips
1	Line cord
1	Line cord strain relief
1	Cinch jenec male 202 connector
1	Cinch jenec female 202 connector

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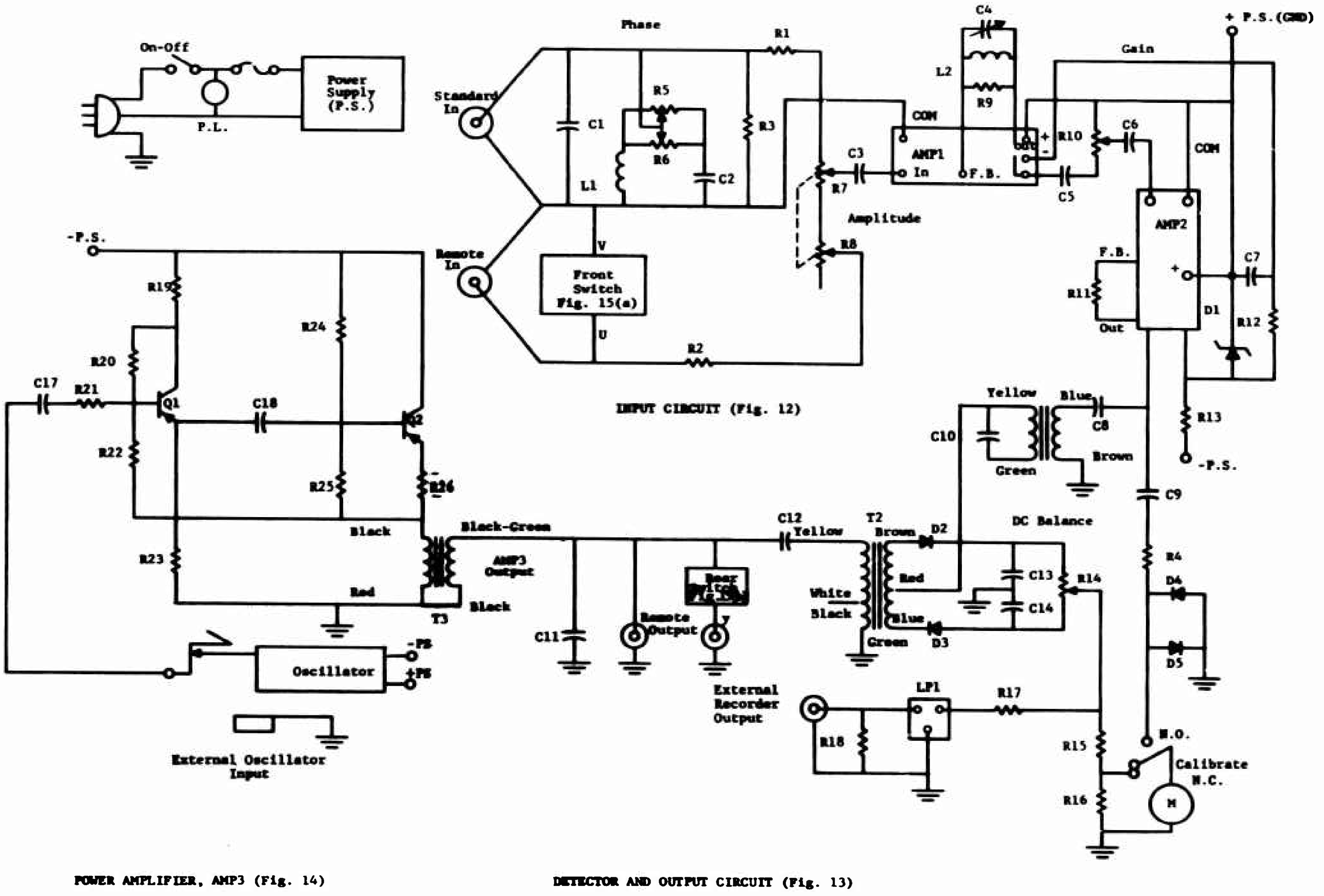

Fig. 43 SCHEMATIC DIAGRAM FOR SOIL STRAIN GAGE

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13. ABSTRACT

Soil strain gage instrumentation was developed for the measurement of static and dynamic strains when embedded in soil. The gage is suitable for both laboratory and field application. The strain sensor consists of two mechanically uncoupled flat-coil disks which are embedded in the soil in near parallel and concentric orientation. The remainder of the gage comprises an identical set of coils positioned external to the soil as a standard reference, specially designed electronic driving, amplifying, and recording circuitry, and a precision micrometer coil mount.
Soil deformations are determined by the resulting change in spacing of the embedded coil disks sensed as changes in mutual coil inductance. The gage is a reliable precise measuring device which is well suited for the measurement of strain in soil.

DD FORM 1 JAN 64 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Soil strain						
Dynamic soils testing						
Soil strain instrumentation						

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