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Sincerely,

M C Bell

for Paul J. Jacobsmeyer
Chief

Enclosures:
As stated

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NATIONAL DEFENSE RESEARCH COMMITTEE

REPORT No. A-8: SUMMARY REPORT

THE MAGNETIC FIELD MACHINE

A Summary Report on the Design, Construction, Testing and Operation of an Apparatus for the Solution of Magnetic Field Problems, a Project Developed for the Use of the Naval Ordnance Laboratory in Connection with the Protection of Ships Against Magnetic Mines.

by

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Consultant, Section E, Division A

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Approved for submission to Section Chairman

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This report --NDRC No. A-8 -- deals with a problem referred by the U.S. Naval Ordnance Laboratory to the National Defense Research Committee. No project number has been assigned to it by the War Department NDRC Liaison Officer.

The work reported here was done at the National Bureau of Standards by Section E, Division A, National Defense Research Committee. The Committee was responsible for the design, development, construction and testing of the apparatus.

The developmental work was done in part by Bell Telephone Laboratories under the following contract with the NDRC -

Contractor: Western Electric Company; effective date, December 2, 1940; amount $5,700.

The manufacture of the electrical components of the device was carried out by the Western Electric Company under a purchase order for $30,300.

The amount required to cover the two aforementioned contracts was provided by the National Defense Research Committee.

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I. INTRODUCTION

1. General character of magnetic mines

The extensive use of magnetic mines has necessitated the development of means for protecting ships from destruction by them. The magnetic mine ordinarily lies upon the bottom of the body of water where it has been dropped. It is so designed that it becomes armed and ready for destructive action only when a predetermined interval has elapsed after planting. During this interval the mechanism of the mine is automatically levelled and adjusted. Once it is armed the mine can be set off by any appropriate change in the magnetic field in its vicinity, such as might be produced by the passage of a ship above it. At present, mines are constructed so as to be sensitive to changes in the vertical component of the magnetic field only. There is no fundamental reason, however, which prevents the construction of mines sensitive to changes in the horizontal components of the magnetic field as well.

In mines, as constructed at present, the response is essentially produced by the absolute change in the field and not the time rate of that change, at least over wide limits; that is, a mine will be set off if the vertical component H_z of the magnetic field intensity at the place where it is situated changes by more than some limiting increment, ΔH_z.

2. Protection against magnetic mines; degaussing

To protect ships against the hazard of magnetic mines the magnetic field of the ship must be reduced to the least practicable value. The magnetic field of a ship arises, in part, from the permanent magnetization of the steel hull and other ferromagnetic components of the ship's structure and, in part, from the induced magnetization in these materials caused by the field of the earth. The procedure for reducing the intensity of the magnetic field of a ship is called degaussing. This is usually accomplished by providing one or more "belts" of electric wires that lie in a horizontal plane and encircle a part or the whole of the hull. In these wires currents are maintained which are so adjusted that their magnetic fields compensate more or less, the field of the ship itself. Since this compensation cannot be perfect, it is necessary to study with considerable care the magnetic fields both of nondegaussed and degaussed ships. The field of a degaussed ship, while in general much weaker than that of the nondegaussed ship, is also usually much more complicated in its distribution because it is the difference of two nearly but not exactly similar distributions.

3. Methods utilized for studying fields of ships; observation of ship signatures

The magnetic fields of ships are usually studied in a "range" in which flat coils of wire have been laid with their planes horizontal and at uniformally spaced intervals upon the level bottom of a shallow body of water. These coils are usually spaced at distances of 20 ft between adjacent coils in a line extending athwart ship. When the ship under study is propelled slowly over the coils, the total vertical component of the ship's magnetic flux encircled by a given coil changes in magnitude and, in the case of a degaussed ship, even in sign. These changes induce currents in the coil which are recorded automatically upon charts in the form of a curve showing the variation of the vertical component of the magnetic field of the ship at a depth equal to the depth of the coil and along a line in the fore-and-aft direction which may be either directly under the keel or to port or starboard, depending on the athwartship location of the coil responsible for that particular curve. Such a curve showing the variation of the ship's magnetic field along some straight line parallel to the keel is quite appropriately called the ship's magnetic signature. In general, signatures taken along lines situated at different horizontal distances from the keel will be different in shape and will diminish in intensity with increasing distance from the keel. Appreciable intensities will be observed at distances considerably greater than the dimensions of the ship. The magnetic map so formed is usually symmetrical with respect to the keel.

4. Problem of finding the safe depth

Probably the most fundamental problem of protection against magnetic mines arises when we inquire at what depth the magnetic intensity of a degaussed or nondegaussed vessel falls, everywhere in the horizontal plane, below the minimum value $\triangle H_z$ requisite to set off a mine. Since the mine ordinarily lies on the bottom, the determination of this depth gives an indication of the safe depth of water in which the ship may enter without risk.

5. The entire field can be reproduced mathematically or physically everywhere below some plane on which it is known

By providing a very deep range in which the coils for studying the fields of ships are supported at various levels, it is conceivable that these fields could be investigated in all three dimensions and to depths sufficient to give a complete answer to the foregoing problem. However, this expensive and elaborate method is unnecessary, since it can be shown that, if the distribution of the vertical component of the magnetic field intensity of a ship is completely known all over a horizontal plane at any particular depth below the keel, the field of the ship anywhere below this plane is uniquely determined and either can be computed or can be reproduced by a physical model constructed to scale.

6. The magnetic field machine

Both the methods of computation and of the physical model are now in use for the delineation of the fields of ships in three dimensions at greater depths from data obtained in some plane of measurement. Because this problem is so urgent, the method of computation by mathematical means, though slow and tedious, was attempted first before the requisite apparatus for setting up a physical field model had been constructed. The magnetic field machine, which forms the subject of this report, is a device for setting up to scale a physical three-dimensional model of the magnetic field of a ship as it exists below the measured plane in which the ship's signatures were observed on the range.

7. Magnetic maps; in the plane of measurement only the vertical component need be observed

When the vertical component of the magnetic field intensity of a ship has been completely explored in a plane at some definite depth by the method of taking the ship's signature (Sec.3), these results can be combined to form a magnetic map of the vertical component of the ship's field in the measured plane. In an entirely analogous way maps of the distributions of the two horizontal components of the ship's field intensity in the plane of measurement could also be made by placing the plane of each pick-up coil in the appropriate orientation before exploring the signatures. For the complete determination of the field at all greater depths, however, it is sufficient to know the map of the magnetic component normal to the plane of observation; that is, the vertical component 1/. This magnetic map can be represented on paper either by drawing contour lines such that the vertical component of the ship's field has the same value everywhere on a given contour and varies by definite

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1/ The problem here presented falls in a well-known general class in mathematical physics known as boundary value problems. In such problems the behavior of a field of force is described by one or more differential equations, which yield information generally applicable at all points of the field regarding the variation of the field forces from point to point. These differential equations are necessary but not sufficient to establish the field uniquely; it is necessary also to specify the exact distribution of the normal component of the field intensity steps from one contour to the next, or it can be represented more conveniently for the purposes of computation or reproduction as a physical model by a chart ruled off into a large number of rectangles, each rectangle containing a number, positive or negative as the case requires, to represent the magnitude and sign of the mean vertical component of the field intensity in the region covered by that rectangle. Such a representation by numbered rectangles becomes obviously more and more faithful the more finely the map is subdivided into

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everywhere on some surface that encloses the region of space in which the field is to be defined. Only those portions of such a closed surface where the normal component of the field has values different from zero are of interest; the shape of the remainder of the closed surface is unimportant. If sources of the field exist inside the closed surface these must also be completely specified.

In the present case we can regard as part of the closed surface the plane in which the vertical components of the ship's field intensity have been measured. Strictly speaking, we must consideran area in this plane of dimensions sufficient to include all of the field map over which any but an entirely negligible fraction of the total ship's field is distributed. Call this the area of definition. The remainder of the closed surface is then to be thought of as a huge envelope that entirely encloses the region below the measured plane, joining the latter all around the edge of the area of definition. This envelope must be so large that everywhere on it the field is entirely negligible.

In textbooks the fundamental theorems regarding fields and boundary value problems are usually developed for the electric field and are not rediscussed in detail for the closely analogous magnetic field. For a discussion of such problems and of fundamental theorems of uniqueness regarding them see Abraham and Foppol, Theorie der Elektrizitat (B.G. Teubner, Leipzig and Berlin), sec.1, chaps. I and II, pp. 1-92; sec. 3, chap. I, pp. 53-61; Clerk Maxwell, Treatise on electricity and magnetism (Clarendon Press, Oxford), pp. 1-31, also chap. IV, pp. 123-141; J.H. Jeans, Electricity and magnetism (Cambridge Univ. Press, London), chap. VII, especially theorem 187, p. 163.

rectangles. Complicated maps, such as those of degaussed ships, for which the field is rugged with many positive and negative areas, require many rectangles for a faithful delineation.

8. Unique determination of fields from maps of the H_z-component.

Once the distribution of the vertical component of the ship's magnetic field intensity has been completely mapped in the plane of measurement, the special distribution of the entire field below the plane of measurement can be obtained. We can, in fact, forget that the field is that of a ship. Any physical device situated above the plane of the map and capable of setting up in the plane of the map vertical magnetic components having exactly the same distribution as that described by the map will produce in the region below the plane the same magnetic field as that of the ship 2/. Since the measurements from which the map is plotted are always made in a plane only slightly lower than the keel, the field below the measured plane is the one of chief interest to us. Thus, for purposes of determining all field intensities below this plane the magnetic map in the plane of measurement completely replaces the ship.

In a region of space, such as that below the plane of the measured map, where there are no magnets or electric currents of appreciable intensity, the distribution of the field is

2/ This statement is true as regards components of the field parallel to the measured plane save for an arbitrary, additive field which is uniform and constant. In such a field which no ship could produce and which could not trigger a magnetic mine on the approach of a ship we are not interested.

in accordance with a differential equation first given in the eighteenth century by the mathematician, Pierre S. Laplace. This equation is a precise mathematical statement of the condition which must obtain at every point in a region where none of the lines of force either originate or terminate anywhere save on the boundary. A further condition also obtains in this region as a consequence of the absence of magnets and electric currents, namely, that a line of force never closes in upon itself to form an endless closed circuit. It is the fulfillment of these conditions that makes it possible to determine the entire field below the plane of the map once the normal component of the field intensity in that plane is completely established 3/. Using nontechnical language, we may say that, subject to the aforementioned conditions, the entire field below the map plane is a consequence of the field coming through the map plane and is completely determined by the latter. On the contrary, when the space above the map plane includes the ship, the condition of absence of magnets and electric currents is not fulfilled; then a knowledge of the magnetic distribution on the map is insufficient to establish the field distribution in the region everywhere above it. (However, see Appendix E.) But here we are interested in the field below the map plane.

3/ To the nonmathematically disposed reader it may seem incredible on first thought that the distribution of only the normal component of the field intensity over the plane of definition is sufficient to establish, at every point below that plane, the values of all three components of the intensity (save for an additive constant field in some cases). For those who recoil from the complexity of a complete proof, such as is given in the references cited, the discussion in Appendix A, while not a rigorous proof, may serve to make the statement more acceptable. Clearly it is a misnomer to call our solutions "extrapolations."

and, as has already been stated, any physical means of reproducing the magnetic distribution in the map plane will serve as a substitute for the ship and produce a duplicate of the ship's field below the map plane.

9. Magnetic field machine defined

The magnetic field machine is a physical device for reproducing the distribution of the normal component of the magnetic field intensity in the plane of the measured map. It also provides means for exploring the field below this measured plane and for automatically plotting signatures on charts that show the distribution of all three rectangular components of the field intensity below the plane of definition.

Another possible name for the device is the Laplaciagraph; this name is intended to convey the idea that fields satisfying the Laplace equation are set up by the instrument and graphically recorded by it.

II. DESIGN OF THE MAGNETIC FIELD MACHINE

10. Preliminary and general considerations; use of a.c. fields

The construction of the magnetic field machine was first proposed by the United States Naval Ordnance Laboratory to Division A of the National Defense Research Committee early in November 1940. After a brief period of gestation tentative designs were drawn up and rough estimates were made of the probable cost of the entire project. Solution of the problem by various thermal or electrolytic means--for example, an electrolytic bath in which the flow-lines of the current would simulate the magnetic lines of force--were rejected as undesirable or inaccurate for various technical reasons 4/.

It was decided that the model simulate the steady magnetic fields of ships by means of alternating magnetic

4/ In an electrolytic bath it is almost impossible to devise an exploring probe that will not introduce considerable distortion in the field of current flow merely because of the physical shape of the insulated supporting portions of the probe which must be immersed in the electrolyte. Moreover, while it is a fairly simple matter with such a probe to plot either equipotential surfaces or signatures of the variation in potential, it is not this scalar quantity that is desired but rather a vector quantity, the gradient of the potential, or better yet, its three Cartesian components. To get this directly from the electrolytic bath two probes close together are required, thus increasing the chance of distortion of the flow-lines. Another difficulty arises from the necessity for defining the map in the measured plane, not by the potential of the electrolytic solution, but by the current entering it at all points. Moreover, if errors caused by the boundary conditions are to be avoided, it is necessary to employ a bath that is very much larger than the region over which the field has sensible values. None of these difficulties are insuperable, but they are awkward.

fields of some convenient frequency chosen so as not to correspond to any of the harmonics ordinarily present from power lines, and so forth (to reduce the chance of interference).

At any given instant of time (other than the instant when the alternating field is passing through zero), the entire model will have a magnetic field whose intensity at any particular point is proportional in both magnitude and algebraic sign to the field intensity of the ship at the corresponding point below the measured plane. The field in the model will be to smaller geometric scale, and the absolute intensities at corresponding points in the real case and in the model need not be equal. There are thus two entirely arbitrary unrelated constants of proportionality between the model and reality, one for the magnetic intensities and the other for the geometric dimensions. The use of alternating instead of steady magnetic fields in no wise vitiates the similitude between the real case and the model since the instantaneous value of the magnetic field in the model always maintains exact proportionality at every point in the model with the steady intensity at the corresponding point of the real ship's field. Neither the absolute value nor the algebraic sign of the field in the model is of any significance <u>so long as proportionality as to intensity and sign is maintained</u> point by point between the model and reality throughout the entire region occupied by the field.

11. Advantages of alternating over direct fields

The great advantages gained by the use of an alternating magnetic field in the model are two. First, the distribution of such a magnetic field can be studied very conveniently by means of a small exploring search coil. The emf induced in such a coil situated at any point in a sinusoidally alternating field is given by

$$\text{Emf} = 2\pi n a f H_A 10^{-8}, \qquad (1)$$

where n is the number of turns in the search coil, a is the mean area of a turn in square centimeters, f is the frequency in cycles per second of the sinusoidally alternating field; and, if H_A is the root-mean-square value in gauss of the intensity of the component of the magnetic field along the axis of the coil, then Eq. (1) gives the root-mean-square value in volts of the emf induced in the coil. The phase of this induced emf will be in quadrature with that of the magnetic field. A reversal of sign of the phase of the field will, however, produce a reversal of sign of the phase of the induced emf in the coil, and a strict proportionality will always obtain between these two quantities. Thus a recorder can be constructed so as automatically to plot on chart paper a graph, or curve, whose ordinates are proportional to the root-mean-square value of the emf in the search coil and whose algebraic sign (to right or left of the center line of the chart paper) corresponds to the algebraic sign of the phase of the emf in the search coil. Such a device will register curves that delineate component magnetic field distribution axial to the search coil at all points which the search coil is made to explore. Computation showed that, with very moderate and easily realized fields, emf's suitable for the purpose could be obtained.

The second and perhaps more important advantage in the use of alternating magnetic fields is the freedom it affords from interfering disturbances such, for example, as the steady magnetic field of the earth, the local steady magnetic fields produced by the presence of ferromagnetic materials having both permanent and steady induced magnetization and the alternating magnetic fields caused by power lines of frequency different from that used in the magnetic field machine.

12. Choice of the frequency

The frequency of 270 cycle/sec selected for the magnetic field machine was governed by several considerations. First, this frequency does not correspond to any of the prominent harmonics or fundamental frequencies likely to be encountered from power supplies. Second, it can be obtained rather easily by driving an 18-pole alternator directly from the shaft of a standard 4-pole synchronous motor supplied with 60-cycle/sec current. Third, it is not so high a frequency as to introduce certain difficulties in the design of a transformer (Secs. 19 and 60) for use in the magnetic field machine.

13. Method of setting up the field map in the plane of definition by means of solenoids

It was decided to set up the field map in the plane of definition of the magnetic field machine by means of long solenoids consisting of nonmagnetic electrically insulating cores of rectangular cross section, with slightly rounded corners uniformly wound with a single layer of insulated wire. The winding on each core should extend very nearly to one end, and then all of the solenoids so formed should be packed closely together into a dense array with the aforementioned ends of all the windings lying in a common plane normal to the long axes of the coils. The normal component of the magnetic field in the plane of the ends of the coils could then, by appropriate adjustment of the currents in the windings, be given any desired distribution, so as to give to scale a reproduction of any map obtained by observations on a ship to a fidelity limited only by the number of solenoids in the machine and the consequent permissible fineness of subdivision of the map into elementary rectangles. The field map of a ship is naturally much longer than it is wide, and a study of typical maps led to the conclusion that sufficient fidelity could probably be obtained with an array of coils containing 40 coils in length and 20 in width or a total of 800 coils 5/. The relative dimensions of the

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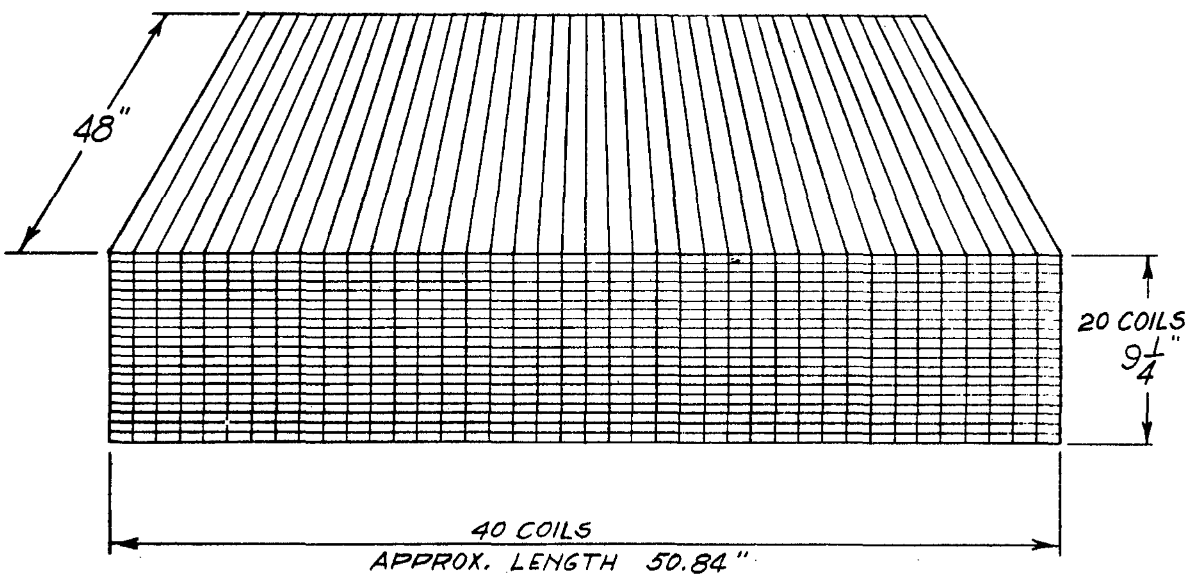
5/ The choice of the total number of coils to be used involved balancing the conflicting requirements of accuracy and economy. It was felt that in a first model it would be unfortunate to run the risk of failure through too great economy on the number of coils. An adequate first model of good generous fundamental design could, on the other hand, serve as a guide to possible saving in the cost of future models. More coils are required than might at first seem necessary because the area of definition of the ship's field should be considerably wider than the plan of the ship, especially if the field is to be studied at considerable depth. The weak field in the outer regions of the area



VIEW OF BOTTOM

FIG. 1. DIMENSIONS AND GENERAL APPEARANCE OF ARRAY OF 800 SOLENOIDS SEEN IN PERSPECTIVE.

rectangular cross section of a coil were fixed so that such a rectangular close-packed array of 20 X 40 coils would have appropriate over-all relative dimensions to accommodate typical magnetic maps of ships. The dimensions thus selected for the cross section of the solenoid cores were $1\frac{1}{4}$ X 7/16 in. After these have been wound, appropriately protected with an insulating cover and packed together, it turns out that the ratio of the mean length to the mean breadth of the rectangular areas defined by the coils is almost exactly as 55 to 20. The general appearance and dimensions of the array of solenoids is shown in perspective in Fig. 1.

14. Magnetic field of a solenoid

The magnetic field intensity of a solenoid, very long in comparison to its cross section, uniformly wound with n turns of wire per centimeter of its length, is uniform in magnitude and axial in direction everywhere inside the solenoid save in a region near its end. At any point inside the coil

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of definition is very important because, in spite of its low intensity, the large area covered represents a large total flux.

It early became evident that a very large fraction of the cost of manufacturing the first model would be expended for supervision, engineering, design, tests, development of manufacturing methods, special tools, jigs, dies and fixtures -- all items independent of the number of coils contemplated in the design. It actually turned out that for an 800-coil model only about 40 percent of the cost was proportional to the number of coils, while the remaining 60 percent was independent of their number. Thus, by cutting the design to only one quarter its present size at the risk of rendering it useless, the cost would still have been more than two-thirds that actually expended.

at a sufficient distance from the ends, the intensity H_i, in gauss, is given by

$$H_i = 4\pi ni/10, \qquad (2)$$

where i is the current, in amperes, in the winding. This magnetic intensity may be thought of as being produced by two equal contributions from the two substantially infinitely long halves of the solenoid extending in either direction from the internal point in question. If one of these halves is removed, therefore, the intensity H_e in the plane of the end of the remaining half-infinite solenoid should be half of the foregoing value, or

$$H_e = 2\pi ni/10. \qquad (3)$$

The transition from the value H_i to the value H_e occurs chiefly in a region near the end that is only a few times as long as the smaller cross sectional dimension of the solenoid.

15. Very long solenoids desirable

Such a solenoid has an external field distribution exactly like a very long and uniformly magnetized magnet with poles situated at the ends. The field distribution in the common plane of the ends of the 800 solenoids of the field machine is, therefore, strictly the resultant of both poles of each solenoid, since the solenoids cannot be made infinitely long. Thus the field machine will in fact set up a field corresponding to two exactly identical maps, in which the fields are at opposite sign, lying in two planes separated by a distance equal to the length of the solenoids. For simplicity of discussion, suppose the axes of the solenoids are vertical and we decide to explore the field set up below the plane established by the lower ends of the solenoids. Then, for distances below this plane small in comparison to the length of the solenoids, the effect of the poles at the upper ends of the solenoids can be neglected because of their remoteness, since the contributions to the field at a given point made by a pole situated at a distance r therefrom diminishes inversely as the square of r. For example, if the solenoid windings are 4 ft long, the effect of one upper pole upon the magnetic field 5 in. below the lower pole is only 1 percent of the effect of the lower pole, and for the purposes of the present device this is completely negligible. To a scale frequently used in the present field machine, 5 in. corresponds to a depth of 200 ft below the plane of measurement of the ship's field. Even at double this depth the disturbance caused by the upper pole would be only 4 percent and a comparatively simple correction could be made for it. The case is considerably more favorable when, instead of the single poles of a solenoid, we consider the effect on a point just below the lower ends of the solenoids of the two completely energized field maps of a degaussed ship, one formed by the lower ends, the other by the upper ends of the solenoids. The fields from such field maps decay in intensity much more rapidly with distance than the inverse square decay of single poles because of the neutralizing effect in such field maps of poles of opposite sign.

From the outset, the manufacture of the 800 long slim, uniformly wound solenoids of accurate dimensions quite obviously constituted by far the most difficult, time consuming and expensive item in the cost of the magnetic field machine. It was clear that special jigs and fixtures would be required to fabricate the cores, and special winding machinery would have to be designed and developed for serving the winding onto the cores (since these must be far too slim and flexible to permit rotating them without many inconvenient intermediate supports). The idea of building the solenoids up out of shorter segments joined together was considered and rejected, as it appeared too difficult to maintain a sufficient uniformity of winding pitch in the region of the joints to avoid dangerous poles at these points. It was evident that the cost of construction would increase very rapidly with the length of the solenoids. The length finally decided upon (4 ft of winding and $4\frac{1}{2}$ ft of core) was the result of an effort to strike a balance between the conflicting requirements of accuracy in the delineation of fields and a design whose dimensions would not be inconveniently large and would not consume a disproportionate fraction of the total cost for this one feature. Another important consideration in arguing against solenoids of too great length is the difficulty arising from thermal expansion and contraction of the cores. The windings must extend very nearly to the working ends of cores of the solenoids so as to permit a search coil to explore the region in the immediate vicinity of the plane of definition (ends of the windings). From this plane the winding must extend without interruption to the other extreme end. Beyond this the core may project any convenient amount, but this projecting end of the core is obviously the only point where it can be securely anchored to supporting structures so as to fix the position of the entire solenoid in space in the axial direction. Furthermore, this fixation must be precise so as to locate the close-wound working ends of all of the solenoids accurately in the common plane of definition. It is obviously unwise to provide this anchorage at a point too far from the plane of definition, else non-uniform temperature distributions throughout the array of cores could by thermal expansion too readily destroy the coplanarity of the working ends of the solenoid windings and introduce very serious inaccuracies. (See Sec. 93 and Appendix F.)

16. Current control and phase angle of solenoids

It is essential, of course, that the phase of the alternating current shall be the same in all the solenoid windings quite independently of the currents of different intensity in them requisite to reproduce the distribution of a given map. It was, therefore, decided to design the coils all with the same resistance, large in comparison to their self-inductive reactance, and to regulate the currents in the coils by connecting them through suitable switching devices to appropriate alternating voltages supplied by the taps of a tap transformer.

17. Coupling between coils

Another important consideration which dictates that the resistance of the coils be large compared to their self-inductive reactances is the necessity for avoiding mutual inductive effects between coils. In the worst imaginable case one coil situated near the center of the rectangular array (map) could have induced in its winding an emf coming from closed alternating magnetic lines of force linking mutually with the coil in question and the entire remaining coils of the array. If these latter coils were all uniformly energized with the same sign and to their maximum intensity, the emf from this mutual coupling would be of the same order of magnitude as the self-inductive emf generated in the one coil in question if it were energized alone. Hence, by keeping the self-inductive reactance of each coil small relative to its resistance, the effect of coupling between coils is certain to be suppressed to a negligible value.

18. Ventilation of solenoids

It seemed highly desirable to provide ventilation ducts for the solenoid windings, not so much because any great dissipation of heat need be expected from them as because the total array of 800 solenoids constitutes a mass of material of large dimensions having very poor thermal conductivity which might be expected to take long periods of time to come to thermal equilibrium with its surroundings. Differences of temperature in different regions of the array of coils would be must undesirable from two points of view. First, the lengths of the cores previously referred to would undergo thermal expansion, thus throwing the positions of the working ends of the solenoid windings out of the plane of definition and introducing large errors in the response of the search coil. It has been found by trial on the present instrument that a change in the distance from the search coil to the end of the solenoid winding of only 0.002 in. is sufficient, when the search coil is close to the plane of definition, to change the response of the search coil by 0.5 percent. Even though uniform temperature were maintained throughout the array of solenoids, a pronounced change in this temperature from that for which the vertical settings of the search coil exploring mechanism were calibrated would necessitate a readjustment.

Accordingly it was decided to provide each solenoid core with longitudinal grooves or ducts in the two large flat faces to permit air to circulate in direct contact with the wire winding. It seemed desirable also to provide for boxing in the nonworking end of the array of solenoids to form a manifold into which conditioned air could be blown so as to give, if necessary, a forced current through these ducts.

19. Considerations in design of tap transformer for controlling currents in solenoids

The tap transformer must be capable of supplying voltages with phases of either positive or negative sign and all values from nothing up to a maximum suitable for the solenoids. The gradation of voltages over this range must be subdivided sufficiently finely to give steps no larger than about one percent of the maximum voltage obtainable. This means a transformer provided with 200 taps -- 100 for positive phases and 100 for negative -- and one tap in the center for the grounded return. Moreover, this transformer must be so carefully designed that, to a high accuracy, the distribution of voltages will be uniform over all taps <u>for any total load whatever from nothing up to the maximum possible when every solenoid is fully energized and also for any distribution of the load over the various taps</u>. These very extraordinary and extreme requirements have been satisfactorily and ably met by the design worked out at the Bell Telephone Laboratories.

20. <u>Switching devices</u>

Switching devices must also be provided to permit <u>each</u> of the solenoids individually to be connected to any desired tap of the tap transformer so as to give in each solenoid winding a current having the phase and intensity required for that particular part of the field map. It seemed desirable also to design these switching devices so that the voltage settings of positive or negative phase selected for the various solenoids in any longitudinal signature on the field map would, when set up, appear both numerically and also as a graphic curve formed by the ends of the adjustable members controlling the voltage of each solenoid on the switching device. It seemed desirable to design these switching devices in such a way that the settings of the voltage selectors for the different solenoids could, if desired, be made by inserting graphs of the signatures plotted to appropriate scale on boards in the switching devices themselves. In this case the sliding voltage selectors would be displaced so that pointers on each would lie on the appropriate ordinate of the plotted signature. Provisions for setting the

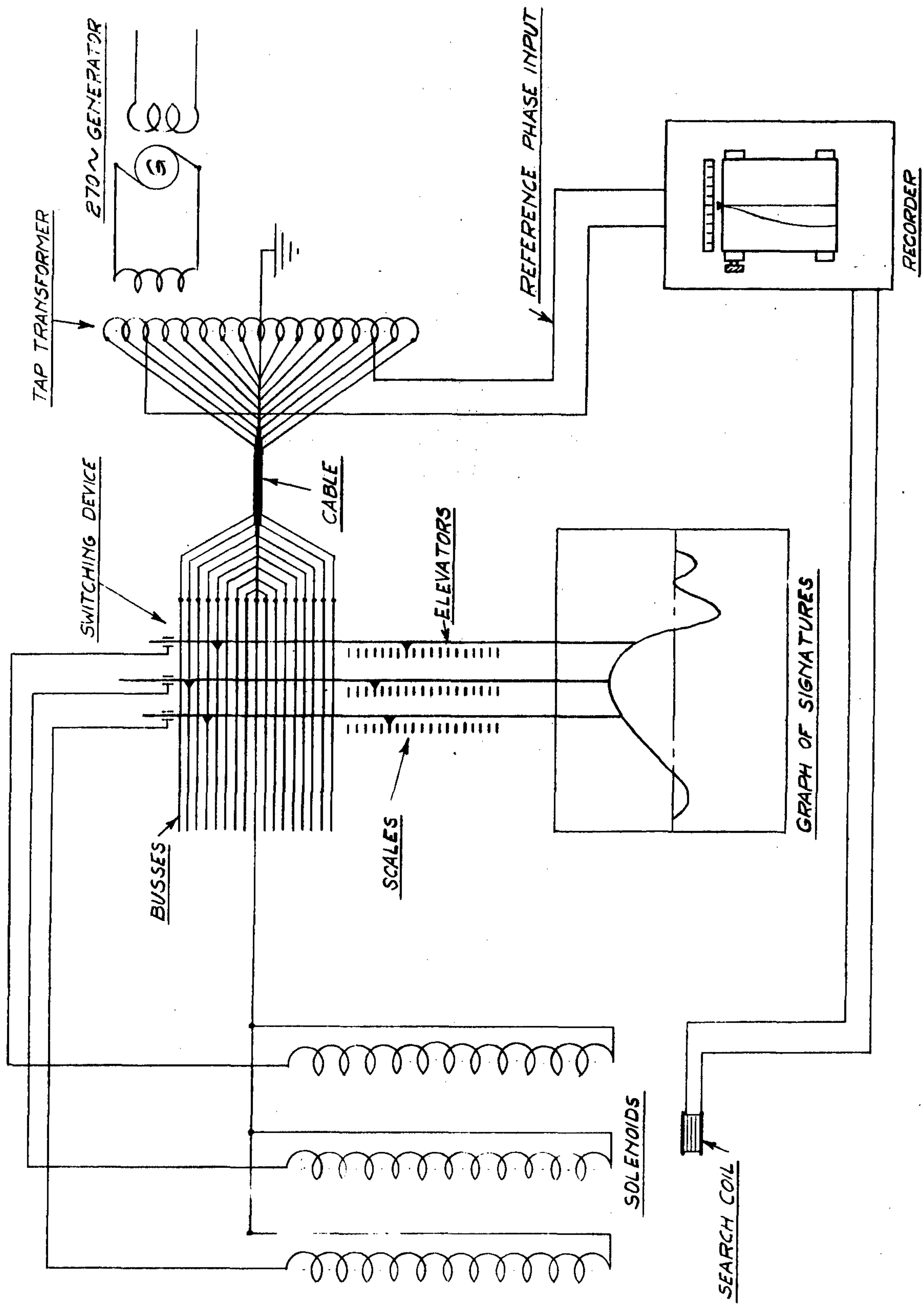


FIG. 2. DIAGRAM OF CONNECTIONS (SIMPLIFIED).

voltage selectors from tabulated numerical data by means of divided scales also seemed desirable.

21. Diagram of hook-up; working ends of solenoids should be grounded

Figure 2 shows the general scheme envisaged for the hook-up of three of the 800 coils through a switching device to the tap transformer. It will be noted that the lower, or working, end of each solenoid has been made the grounded end. Thus the entire plane of definition is at the same electric potential, namely, ground potential, and the danger that either the search coil with which the field is to be explored or one or both of its lead wires may have spurious emf's induced in them by electrostatic induction is completely eliminated.

22. Choice of engineering and manufacturing company; similarity to telephone equipment

From practical considerations of the sort just outlined, tentative designs were established for the physical dimensions of the principal elements of the magnetic field machine and during the first week of December 1940, the project was proposed to engineers of the Bell Telephone Laboratories. This happy choice of a manufacturing company, so amply justified by the splendid cooperation and exemplary speed shown by it in all stages of the work, was at first strongly suggested by the nature of the apparatus to be built. It became evident almost from the start of the design that the apparatus with its switching devices and cabling could not help but resemble closely an automatic telephone exchange. Very little calculation is required to establish the approximate number of cables and soldered joints requisite to connect up the tap transformer, the switching device for connecting each and every one of the 800 solenoid windings to any one of the 201 taps of the tap transformer and the 800 solenoids themselves. In fact, in the present magnetic field machine, about 16,300 soldered joints were made at the factory and more than 6400 were made when the apparatus was installed.

23. Cooperation with Bell Telephone Laboratories and Western Electric Company

Early in December 1940, the problem of designing and constructing the field machine was proposed to engineers of the Bell Telephone Laboratories in New York. Most of the general design considerations already enumerated, with the exception of the choice of frequency, had already been decided by the physicists of the National Defense Research Committee. A great amount of detailed design, however, still remained to be worked out as a collaboration between the representative of the NDRC and research engineers of the Bell Telephone Laboratories and their manufacturing affiliates, the Western Electric Company. Most of these detailed questions were decided in New York and later in Chicago at the Hawthorne plant of the Western Electric Company during the first two weeks of December. Such excellent cooperation was shown on the part of the engineers in the two companies named that it was possible to start production directly after Christmas and to make delivery in Washington, D.C. of the 800 solenoids in their supporting box and all of the switching equipment, together with the 270-cycle/sec generator, during the first week in February. The recording equipment and the tap transformer which were developed and built in New York at the Bell Telephone Laboratories were delivered about a week later, before the installation and wiring of the equipment had been completed.

The principal points of detailed design decided in December will now be discussed.

Since it was desirable to complete in the space of three months a project that normally would take a year or two, every decision was strongly conditioned by the requirements of speedy production. Every effort was made to adapt for use in the field machine, parts designed for other applications and readily available in quantities. Doubtless some slight sacrifice of suitability had to be made at certain points, especially in the switching panels, in order that stock parts could be used, but the great saving in time resulting from this certainly justified the procedure.

24. Choice of the core material for the solenoids

The materials considered for the solenoid cores were wood, plastics, aluminum, wrapped paper and shellac, commonly known as Textolite, and hard rubber. It was desirable to wind the cores with rather fine wire to avoid the necessity of heavy currents at low voltages which could be expected to give contact difficulties in the switching equipment; No. 37 was eventually selected. Such fine wire could easily be loosened or broken by shrinkage or swelling of the cores, an effect which could be expected to occur principally from the absorption of moisture or its loss with changes in atmospheric humidity. This consideration eliminated both wood and all plastics as safe possibilities. Were it not for this, by far the cheapest material is wood, as it can be formed very rapidly and cheaply by planing mill methods. The wire winding could also have been very readily bonded to wood. Paraffined wood was a possibility but considerable time for kiln drying and impregnating is required, and warping probably would have occurred in these processes. All the plastics unfortunately are sensitive to changes in humidity and suffer much larger resulting dimensional changes than we dared to risk. Aluminum cores of such cross sectional shape as to minimize eddy currents were considered and rejected partly because the error from eddy currents seemed likely to be too large and partly because of difficulties in bonding the wire to the core and at the same time insulating the wire without danger of short circuits to the core. The argument against wrapped paper cores was on the basis of time required to work out the process of fabrication. Such material is quite proof against moisture and if further examples of the field machine are to be constructed, when the time factor is less urgent, it would probably be well to spend some research effort upon methods of fabricating cores in this way. Cores of this shellac-bonded paper afford an excellent base to which to bond the wire winding; they would be superior to hard rubber cores in this respect, and probably would be cheaper and much lighter. The problem of anchoring the cores at the end far from the working end and of attaching adequate soldering terminals and anchorages for the ends of the winding would have to be worked out, of course. The final choice of hard rubber in the present case was made because it is not at all subject to dimensional changes with changes in humidity; because, although considerably more expensive to form to the desired shape than other materials, there was not the slightest doubt that this could be done in the required time with the available facilities; because it is an excellent insulator; and, finally, because the Western Electric Company had complete facilities for manufacture of a batch from the original raw rubber sufficient for the entire 850 coils (including the 50 spares), thus insuring a very desirable uniformity of the product as to thermal expansivitity and machinability. The thermal expansivity of hard rubber is unfortunately rather high, 0.00008 per $^{\circ}$C. A change of core temperature of 10°C will thus produce a change in length of the cores of about 1 mm, and a difference of this amount in the position of the working ends of the solenoids with reference to the common plane in which all those ends should be situated would introduce serious errors in the values of the field to be explored close to that plane. However, the problem of maintaining the cores at constant temperature is far simpler than that of maintaining constant dimensions in cores subject to change from humidity variation.

25. Fabrication of the cores

It was decided to form the hard rubber into sheets a little thicker than the smallest dimension of the cores. These sheets were then cut into long strips by a gang of stationary cutting tools in a planer, the sheet being clamped to the moving bed by bars of metal situated between each and every pair of cuts. The strips were then exactly sized and shaped with rounded corners and four grooves were cut, two in each large flat face, for ventilation. These last operations, which took the most time, were performed in a milling machine on which an especial screw feed had to be built on top of the ordinary bed to furnish the abnormally long travel of 54 in. required for the work. Appropriate threaded holes were provided in the top end of the core for the terminal soldering lugs and and one in the center of the working end into which a threaded stud could be screwed by which the core could be fed through the winding machine. Great care was taken in locating three larger holes passing transversely through the core at the top end. Two of these were provided for brass bolts which clamp the cores together (with appropriate spacing washers) in banks of 20, and the third, situated midway between the other two, was taper-reamed after the bank was assembled, so that a long taper dowel pin of nickel silver passing through all 20 cores insured their exact exact alignment. These bolts and the pin also passed through two short hard rubber blocks at the ends of the assembly of 20 solenoids to form shoulders, so that

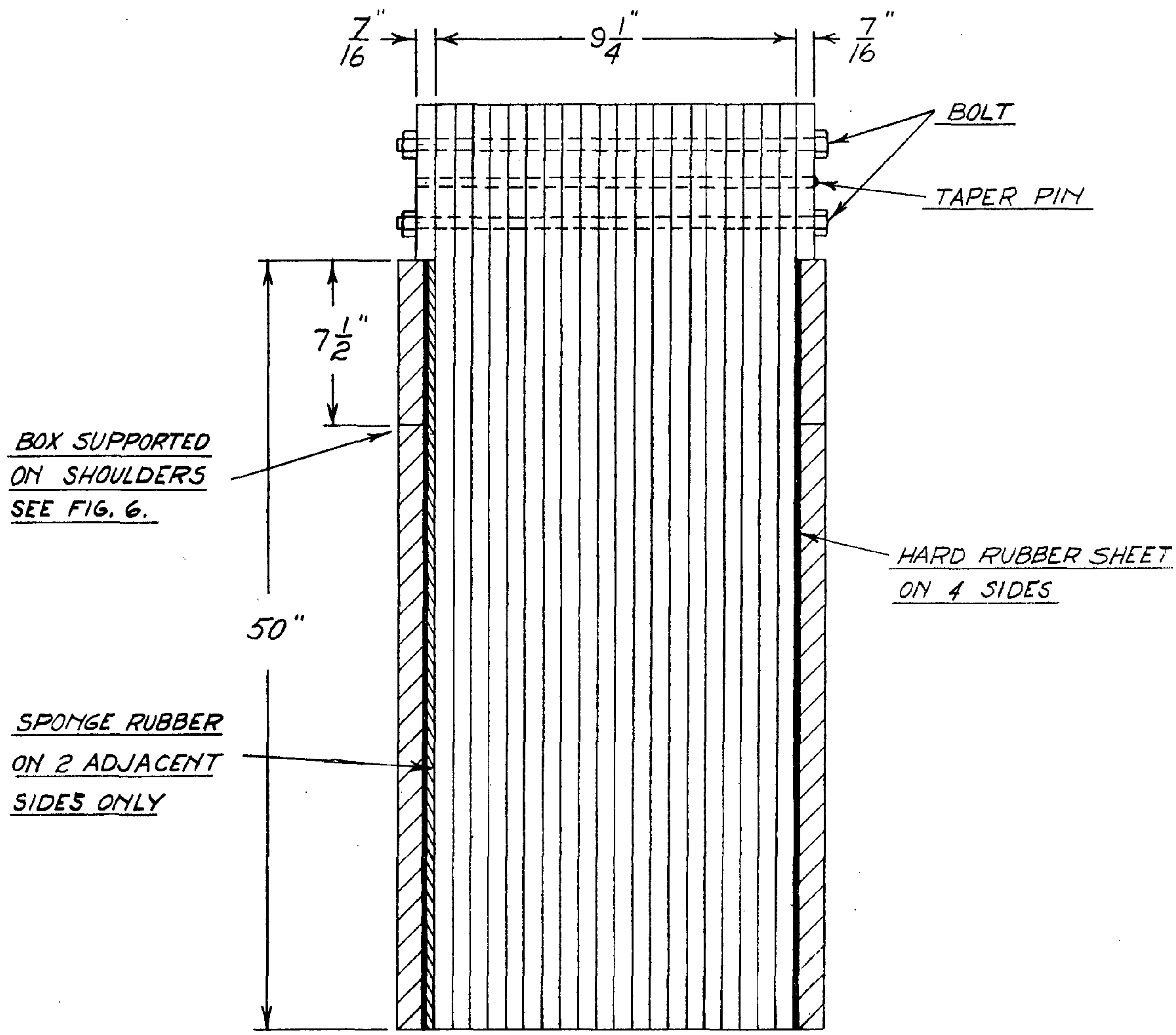


FIG. 3. METHOD OF MOUNTING AND SUPPORTING THE SOLENOIDS IN A BOX IN GROUPS OF TWENTY SOLENOIDS.

the entire assembly could rest on the accurately machined top edges of the Bakelite box designed to contain them (Fig.3). The three holes for the bolts and taper dowel pin were bored and reamed through the unwound projecting ends of the cores of the 20 solenoids and supporting end blocks with these assembled and correctly held in a long steel jig, the working end of the coils being in contact with a guide face on the jig so that the location of the shoulders formed by the blocks with reference to the lower end of the core was uniform to 0.001 in. on all cores. This required maintaining constant temperature on the steel jig while in use and also required having the hard rubber cores in contact with metal at this temperature for several hours before boring the holes to insure that the rubber had assumed the correct temperature.

26. Considerations in the design of solenoid windings

It was decided to use a special No. 37 wire of so-called tinsel bronze (a copper-tin alloy) manufactured and stocked by Western Electric Company in large quantities. This alloy has about twice the resistivity of pure copper (not an unfavorable characteristic for this application) and the highly desirable property of very low thermal coefficient of resistivity (only about 1/10 that of pure copper). In addition, the tinsel-bronze wire is much tougher and stronger in tension than copper, a characteristic very favorable to winding on a rectangular core. Very early during the conferences at Chicago a sufficient quantity of the bare wire was enamelled, spooled

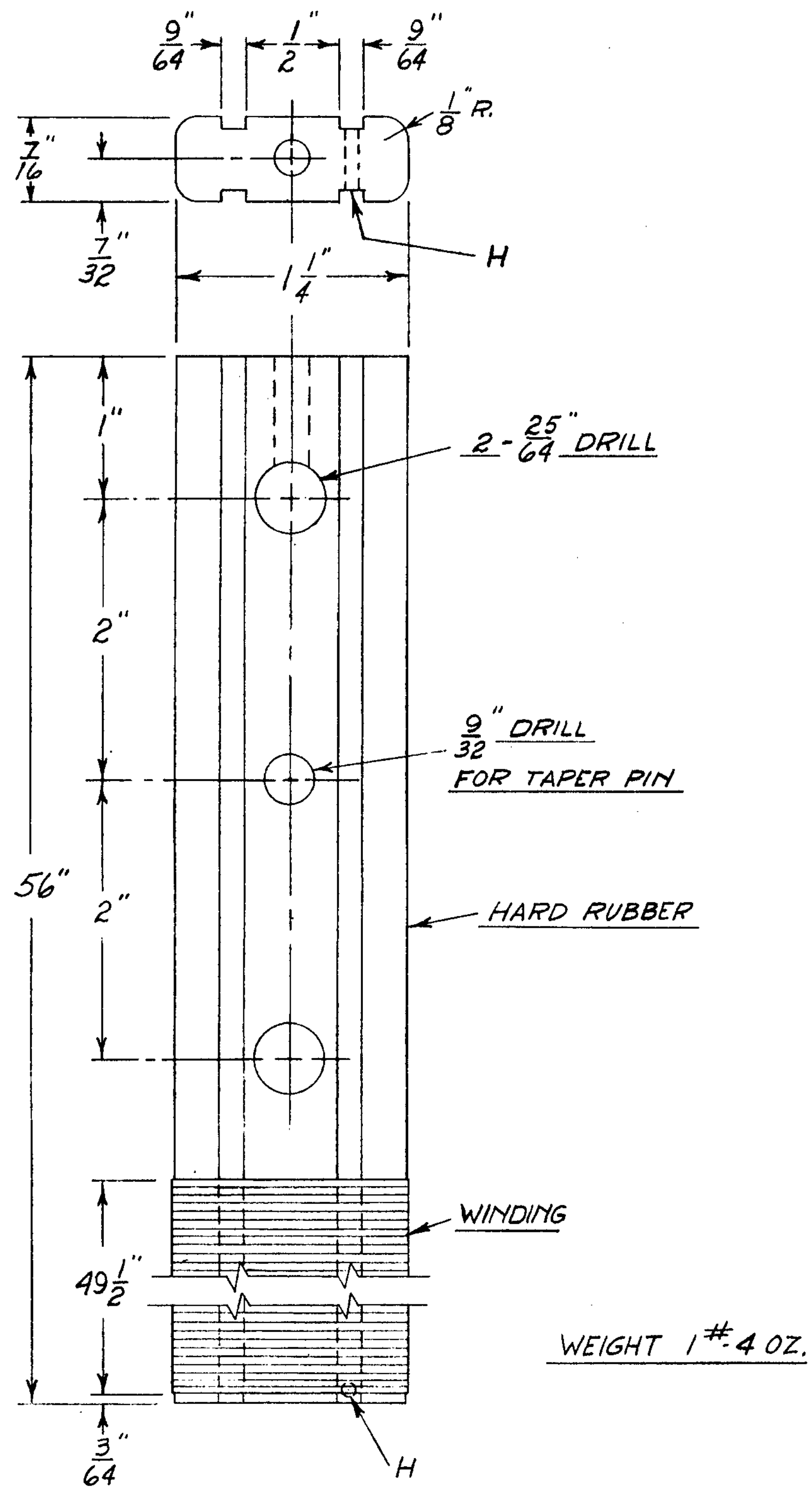


FIG. 4. DETAIL OF SOLENOID (CORE AND WINDING).

and set aside for the job of winding the cores. Measurements showed that the wire exhibited some variability in resistance per unit length, and it was therefore decided to wind the solenoids to a certain length and then add or remove enough turns to bring each solenoid exactly to a standard resistance (about 2200 ohms). This would preclude the necessity of introducing external resistances in series with the coils to balance the currents.

At the close-wound working ends of the solenoids where the winding was started, a small hole H. (Fig. 4) passing from the bottom of one ventilating channel through the thickness of the hard rubber core into the channel on the opposite face was provided with a cellulose acetate sleeve, and the No. 37 wire was anchored in this at the start of winding. A heavier tinned, twisted pair of lead wires was cemented down one corner of the bottom of the ventilating groove into which the No. 37 wire projected. These two conductors were soldered together, the joint being concealed in the groove. Before starting the winding, the core was given a coat of cellulose acetate cement all over the surface to be wound and this was allowed to dry. After the winding was finished another coat of cellulose acetate applied on top of the winding was found to flow very effectively between turns so as to bond with the lower coat. Neither coat adheres very tenaciously to the rubber, but the two coats bond the turns of wire very effectively to each other and adequately prevent slippage of the turns.

After much experimenting at the close-wound end upon methods of securing the end turns from loosening and unravelling from the core, it was finally decided to relax the specification a little regarding the closeness of the beginning of the winding to the end of the hard rubber, and to allow here a space of about 3/64 in. Into this space cellulose acetate strip was tightly wound between a temporary steel end-flange and the start of the wire winding, and this strip was heavily coated with cellulose acetate cement. When the winding was finished the entire solenoid was covered with a layer of acetate sheet 0.002 in. thick extending over the 3/64-in. acetate filled unwound space. This covering was shrunk and sealed closely to the winding by heating it on a steam table. The two ends of the winding (the lower end by means of the tinned twisted pair in the ventilating groove) were connected to small soldering terminals screwed to the flat upper end surface of the mandrel.

The dimensions of the hard rubber core or mandrel are 7/16 X $1\frac{1}{4}$ in., with a cross section as shown in Fig. 4. With the wire and covering in place the mean dimensions of the rectangles occupied by the coils is 0.4615 X 1.271 in. when the coils are compressed into a close-packed rectangular array.

27. Method of making the winding; the winding machine

The diameter of the No. 37 bare wire is 4.453 mils, and a close winding of 198 turns per inch, or a spacing of 5.05 mils, is usually given for enameled No. 37. It was decided to use a spacing for the solenoid windings of 168 turns per inch (a pitch available on the lathes which were to be rebuilt as

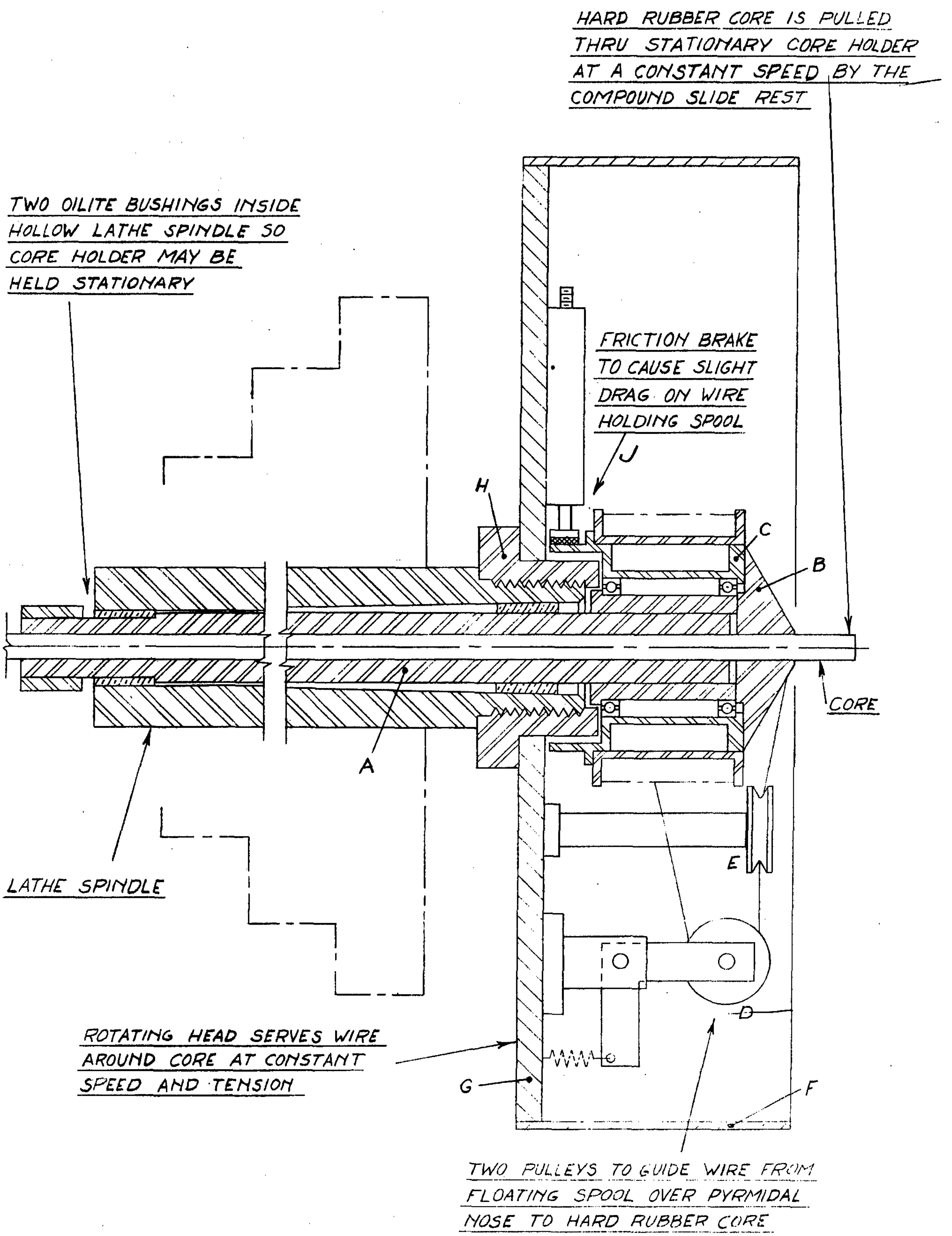


FIG. 5. WINDING MACHINE FOR SOLENOIDS.

winding machines), leaving a space between adjacent turns of about 0.0015 in. (1.5 mils). With a properly designed winding machine, the pitch of a space-wound coil can be maintained much more closely uniform than it can for a close-wound coil. It was of paramount importance to insure high uniformity of pitch since the magnetic field intensity, Eq. (3), depends directly on this.

It was estimated that, with a well-designed winding machine, a solenoid could probably be wound in one-half hour, and this estimate was later on justified by experience. From this, computation showed that with two machines working in three shifts, it would be possible to complete the 800 solenoids and 50 spares in the required time of about four weeks. Two winding machines (Fig.5) were therefore built by remodeling two large lathes as follows. The two lathes were just alike and had holes in the head spindles about 1.5 in. inside diameter. A cylindrical steel quill A was provided to pass through the entire length of the hole in each head spindle and arranged to turn in "oilite" bearing sleeves mounted in the two ends of this hole. This quill was held stationary, by means of a stay bar at the rear end, while the lathe spindle rotated around it. The quill was provided with a long axial hole of rectangular cross section which just fitted the hard rubber cores; the cores were pulled slowly through this hole by the screw cutting feed of the lathe, the drive being actuated by clamping to the lathe carriage a threaded stud screwed into the end of the hard rubber mandrel. A temporary steel flange plate was also screwed

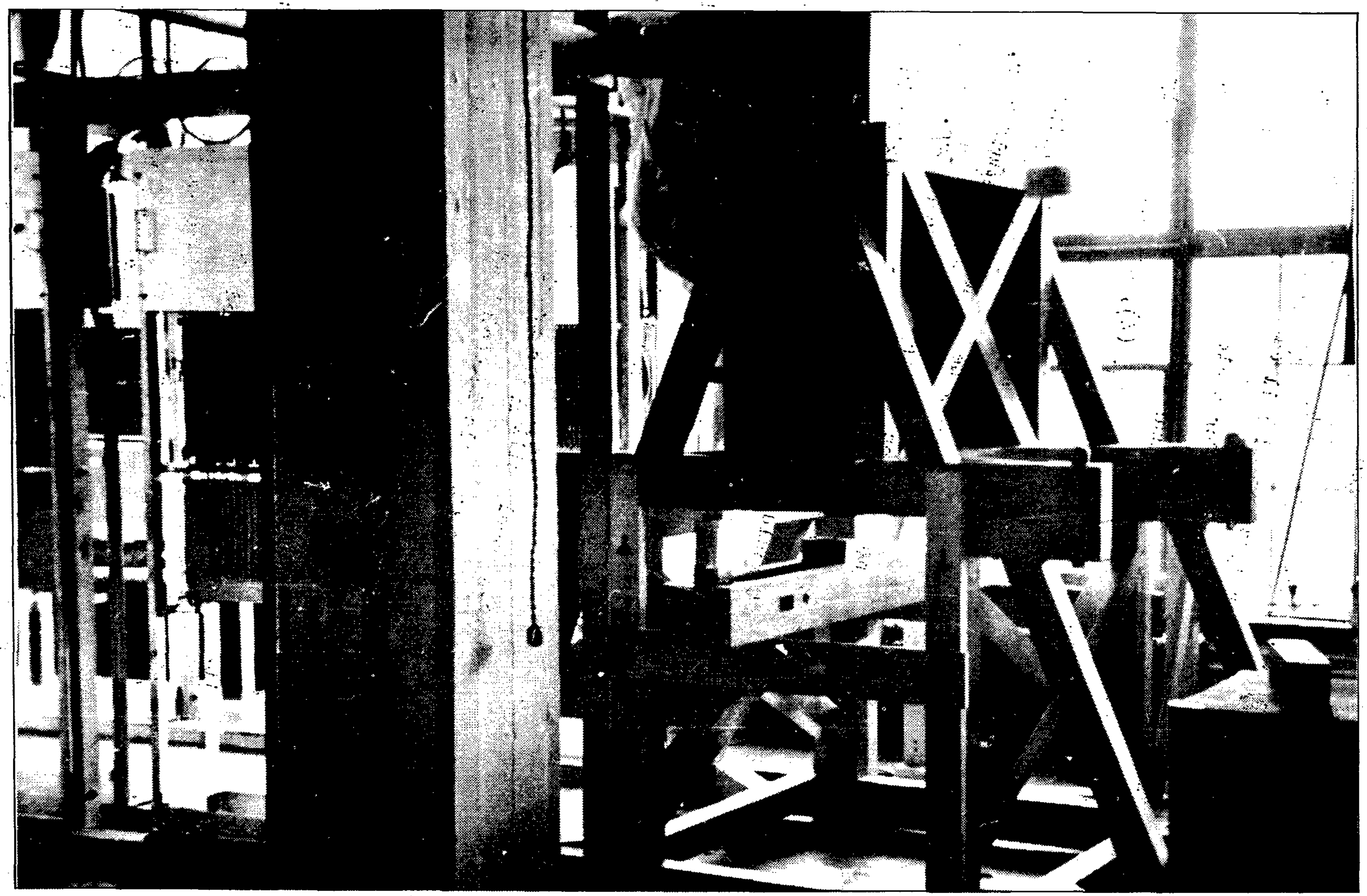


Plate I. General view of coil box and maple frame, exploring device, maple stanchions with peg holes and panel switching devices.

to the beginning end of the mandrel to assist at the start of winding. The forward end of the quill was provided with a hardened and polished pyramidal nose B with smooth rounded surfaces, and it was from this nose that the core gradually and progressively was pulled while the wire was served round and round the core, the winding point being such that the wire was always in contact with the steel nose as a guide. The supply of wire was carried in the winding machine on a spool with large enough central hole to fit on a ball-bearing hub C behind the steel nose B. From this spool the wire passed over two small idler pulleys D and E, one of which was mounted on a spring lever to reduce the tensional shock imparted to the wire as it was wound over the corners of the rectangular rubber mandrel. The entire rotating serving mechanism of pulleys was mounted in a shroud F on a disk G and hub H, which could be screwed to the rotating spindle of the lathe. A friction drag J was provided for the supply spool of wire to determine the appropriate winding tension. The entire rotating system was carefully balanced to eliminate vibration so that the winding could proceed at the rate of about 400 turns per minute.

The parts of these winding machines have been saved and could probably be used again if further solenoids were required.

28. The coil box

It was deemed as important to hold the solenoids in correct position in space as to have each solenoid meet the other necessary geometric specifications. It seemed best to support the solenoids vertically with the fragile working ends down. Below the plane of these working ends the exploring mechanism could then support the search coil on a moving carriage. This admittedly makes the working ends of the solenoids somewhat inaccessible (though readily reached by the search coil) and this was thought to be an advantage since the delicate windings of the solenoids, only 3/64 in. from the exposed ends, might easily be broken by any sharp object inadvertently pushed into the ventilating channels, occasioning serious delay for replacement. The box holding the array of solenoids must maintain them exactly straight with all their axes accurately normal to the common plane in which lie the ends of the windings. Moreover, the total weight of the solenoids (about 1000 lb) is so considerable that the supporting box must be very substantial. To avoid eddy currents which might distort the field no metal of any kind can be used in the box construction with the possible exception of points close to the floor or points high above the working ends of the coils (the brass bolts and nickel silver locating pins for the hard rubber cores). Ferromagnetic materials must not be used, of course,

29. The inner Bakelite coil box

The box therefore was designed in the form of four vertical Bakelite enclosing side walls, or panels, 1 in. thick and 50 in. high, enclosing the rectangular space filled by the coils,

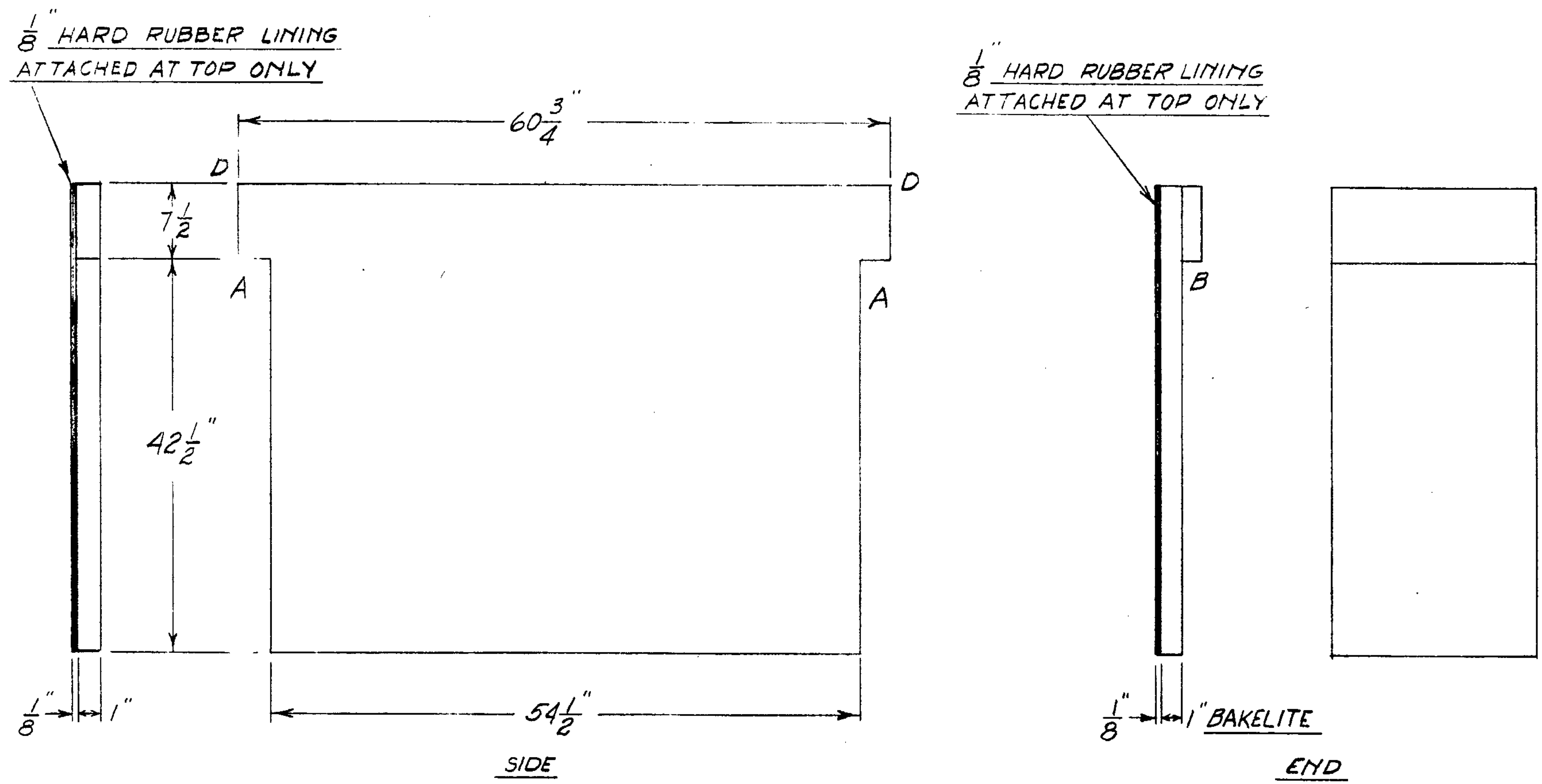


FIG. 6. SIDE WALLS OF BAKELITE BOX.

$9\frac{1}{4}$ X 50.84 in. in plan view dimensions. Dimensional views of these walls are shown in Figure 6. The shoulders _A_ and _B_ rest on Bakelite pads on the top of a heavy maple frame surrounding and enclosing the Bakelite box, this frame being built up of 4 X 4 in. maple beams and cross braces carefully joined by tongue and dowel construction, so as to be extremely rigid. The entire weight of the box and coils is transmitted to the frame by the shoulders _A_. The edges _DD_ are machined very true, straight and parallel to the line of the shoulders _A_, since these edges _DD_, supporting the hard rubber end blocks on the 40 gangs of 20 coils each, entirely determine the vertical positioning of the coils.

30. _Hard rubber lining to prevent shears with thermal changes_

The inner surfaces of all four Bakelite panels of the box are lined with a 1/8-in. sheet of hard rubber _attached to the Bakelite only at the top edge_ and made of the same batch of hard rubber as the coils. Thus when thermal expansion or contraction takes place, this lining follows the movement of the solenoid mandrels exactly and thus precludes the chance of sliding and shearing action that might spoil the delicate covering of the windings.

31. _Adjustments of Bakelite panels_

Two adjacent panels of the box (a side and an end) are fixed and act as reference surfaces against which to push the assembly of coils to insure their correct alignment. These panels bear against many short adjustable wooden screws in threaded holes in the outer maple framework; these are adjusted so that the inner surfaces of the panels are accurately plane, true and square, both with each other and with the lower surfaces of the maple framework, to a high degree as tested at the factory with micrometer gauges against accurate steel surface plates. The short wooden screws have their slotted heads imbedded so deeply in the holes in the 4 X 4 in. maple sticks that there is little danger of their being inadvertently turned. The other two Bakelite panels are movable, and cemented to their hard rubber inner lining is a thick padding of sponge rubber. These panels can be squeezed against the array of coils so as to force them tightly together and in contact with the fixed panels by means of large wooden screws passing through the 4 X 4 in. maple frame beams. These screws are provided with large projecting heads so as to permit tightening by hand. The pressure so produced by hand torque alone is sufficient, and no other means of turning them should be used. These hand screws should be turned up until the resistance is felt to be about equal on all of them. Sheets of cellulose acetate material separate the coils from direct contact with either the hard rubber or the sponge rubber.

32. <u>Adjustable pads to correct, if necessary, for warping</u>

Should any warping or other dimensional change in the outer maple framework ever cause, in course of time, misalignment of the upper edges of the panels of the Bakelite box, this can be corrected by removing the Bakelite pads upon which the shoulders A of these panels rest and then machining off the surfaces of these pads to change their thickness by an amount requisite to correct the mis-alignment.

33. Maple frames and their correct relationships

The maple frame surrounding the coil box proper rests on an under maple frame consisting of two horses joined by a lower framework resting on the floor. Upper and lower frames are joined by four large removable maple dowel pins which are not interchangeable. The upper and lower maple frames must also be superposed in correct relationship to fit accurately. Numbers stamped on the frames and dowel pins indicate this relationship.

34. The ventilating box or manifold

The top ends of the solenoids are completely enclosed in a wooden box which fits tightly at all joints but which can be removed in three pieces by removing eight Bakelite screws. The joints break in such a way as to permit removal of the box without disturbing the cable of 800 conductors which goes inside the box to the row of pyramid-type terminal blocks extending the full length of the coil array. An effort has been made to plug all possible openings with sponge rubber so that, if air is blown into this upper box, it will be forced to pass downward through the ventilating ducts on all the solenoid cores.

35. Ventilation precautions

IT IS STRONGLY URGED THAT A THERMOSTATED SUPPLY OF DRY

DUST-FREE AIR, KEPT COOL IN SUMMER AND WARM IN WINTER, BE BLOWN INTO THIS BOX,AND THROUGH THE COILS SO AS TO MAINTAIN CONSTANT TEMPERATURE TO WITHIN $\pm$ 5°F, OR BETTER, IF POSSIBLE, AT ALL TIMES. BY THIS PRECAUTION ALL ERRORS COMING FROM UNEQUAL EXPANSION AND CONTRACTION OF THE LONG HARD RUBBER CORES WILL BE ELIMINATED. THE QUALITY OF THIS AIR SUPPLY, ITS CLEANLINESS, FREEDOM FROM CORROSIVE FUMES AND DUST, DRYNESS AND CONSTANCY OF TEMPERATURE CAN NOT BE TOO CAREFULLY SAFEGUARDED. THE ACCURACY OF FUNCTIONING OF THE ENTIRE DEVICE AND THE LIFE AND SAFETY OF THE VERY EXPENSIVE ARRAY OF 800 SOLENOIDS DEPENDS ENTIRELY ON THE DILIGENCE WITH WHICH THESE SAGEGUARDS ARE MAINTAINED.

36. Wiring of solenoids

The wiring from the soldering terminals on the tops of the solenoid cores to the pyramid terminal blocks is done with green insulated wire for the "live" upper end connections and with tinned bare wire for the grounded lower end connections. It will be noted that the ground wires strap across transverse banks of 20 solenoids and that they are usually soldered to the left-hand terminal on the top of the hard rubber cores (as one faces the box on the terminal block side). A few exceptions to this rule will be noticed, some of the solenoids appearing to have their "live" and their grounded terminals interchanged; this is because some solenoids were inadvertently assembled incorrectly at the factory.

37. Numbering of coils and signatures for operation of field machine

The end of the heavy maple frame whose corners and dowel pins are marked 1 and 4 is the "working end" at which the operator stands and where the drive and controls of the exploring device are situated. Standing at this end and facing the coil box, the long row, or "signature", of coils on the extreme left is called signature 1, and the other signatures are numbered consecutively from left to right, the 20th signature being the row on the extreme right. With the observer in this position, the terminal blocks are on the left-hand side of the box and the cable enters the box at the end remote from him; the coils in each signature are numbered, starting with coil 1 nearest the observer, or "working end", and ending with coil 40 at the other extreme. This system of numbering coils and signatures is the one that the operator of the machine uses. For his convenience each of the switching panels is numbered on each side according to this system so as to indicate the signature and the coils controlled by the "elevators" on that panel. A different system of numbering was used at the factory for the purpose of wiring and interpreting the color code.

38. Reference scratches for locating alignment of signatures

On the lower edges of the 4 X 4 in. maple sills at both the "working" and the opposite end of the coil box will be found 41 finely scratched lines, alternate lines being longer than the rest. These lines were made during the calibration and testing of the field machine. The 21 short lines are in

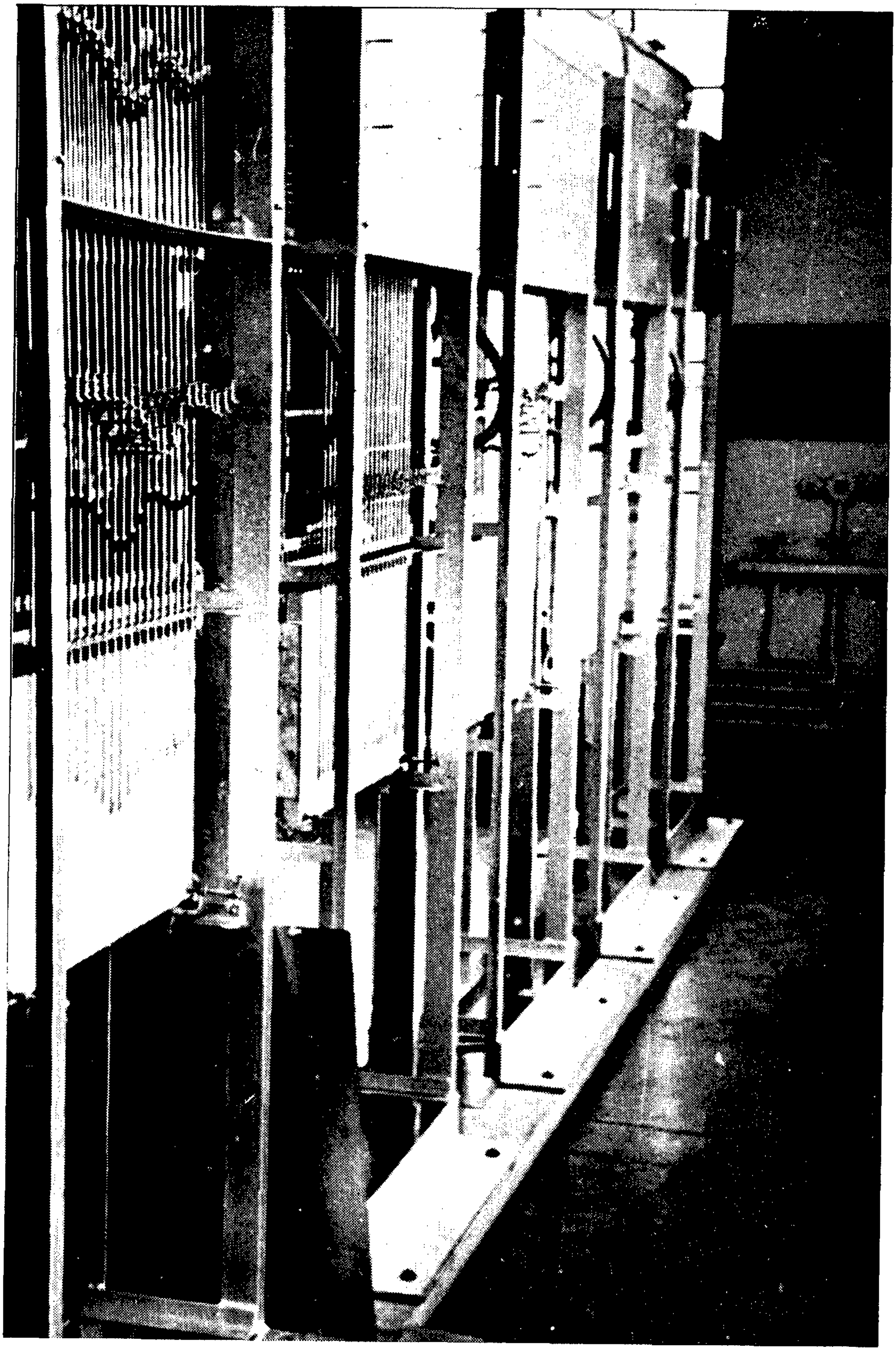


Plate II. The panel switching devices. The nearest one has its dust cover removed so that the bus panel and contact fingers are visible.

close alignment with the surfaces of separation between long rows of solenoids when the array is compressed. These short lines were located by holding a long wooden straight edge against the bottom, or working, ends of the solenoids in contact with the cracks separating the rows and by marking the position of its edge on the vertical face of the maple sill with a knife blade. The long lines were located in the centers of the spaces between short lines and these long lines therefore serve to align a search coil with the center line of a signature. More convenient scales for aligning the exploring mechanism are provided on the transverse supports supplied with it; but, should these be displaced, a check can always be obtained by returning to the scratches on the maple sill.

39. Search coils

While the discussion of the various detailed questions of design were in progress at the Hawthorne works of the Western Electric Company, the fabrication of the small search coils was attempted by one of their most expert winders on a very dimunitive winding machine provided with a microscope. Three entirely satisfactory coils were turned out at the first attempt. Later ten coils beautifully matched as to inductance and resistance were produced. Complete specifications for these are given in Sec. 58.

40. Panel switching devices; contact bridging

The switching devices for setting the magnetic intensities of the solenoids in accord with the intensities, either as

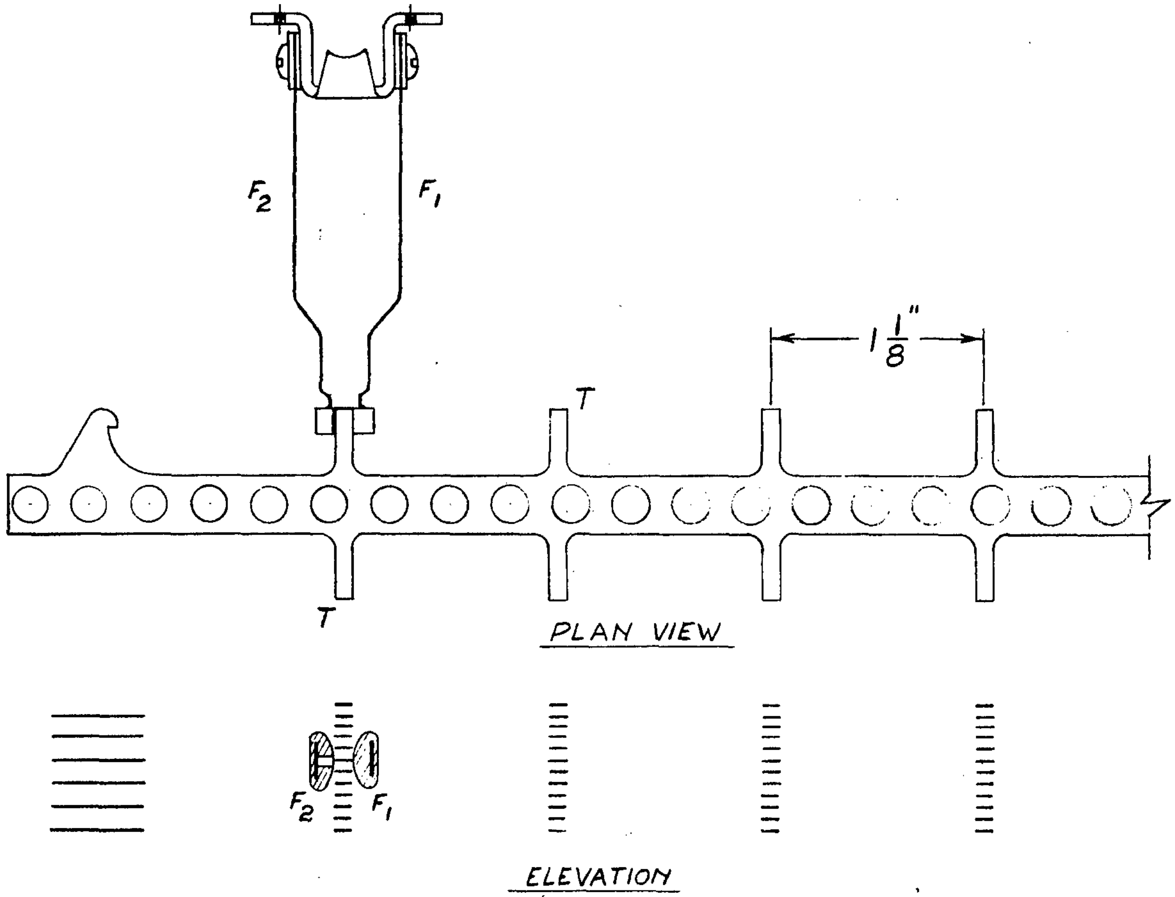


FIG. 7. BUS BAR PUNCHING FOR PANEL SWITCHES.

indicated by a magnetic map or plotted as graphs of the ship's signatures, constitute the bulkiest part of the field machine. Every effort was made to adapt standard telephone exchange parts to the design of these switching panels. They must provide a systematic means of connecting every one of the 800 "live" ends of the solenoids to any one of 201 busses energized from the tap transformer. (See Fig. 2) A standard feature of one type of automatic telephone exchange is a so-called "panel bank" in which a large number of horizontal perforated metal strips are separated by compound impregnated paper insulating strips, the whole being compressed in a metal frame by tie bolts passing through some of the perforations. The punched metal strips are provided with tongues T that project laterally on both sides as indicated in Fig. 7. The tips of the tongues are silver plated. These tongues project beyond the insulating paper and, in the assembled panel, form rows of contacts along which double contact fingers F_1 F_2 can slide. In Fig. 7, F_2 is a conducting contact finger while F_1 has an insulating tip; F_1 merely furnishes the reaction force to the pressure of F_2. In the present design the separation between centers of adjacent busses is 1/16 in., which is only half the standard pitch in use in telephone exchanges. It was found that, with existing equipment, the manufacturing tolerances scarcely permitted the use of two conductive contact fingers; it was too difficult to keep them both accurately aligned so that they always touched the same bus finger. Bridging of two busses is undesirable as this would result in short circuiting part of the tap transformer secondary. No harm results from the momentary bridging of busses when, with the panels energized, the contact fingers are caused to slide up or down a vertical row of bus tongues in the process of setting up a map. The "short circuit" currents that exist momentarily under such conditions are determined by the resistance of the No. 22 wire lines to the tap transformer (about 25 ft long) and by the voltage between taps, which is only 0.3 volt. The tap transformer is designed to have exceedingly good voltage regulation so that this has very little influence in limiting the short-circuit current. However, it would not be desirable to have a large and unknown number of such short circuits, many of which might be on the same taps of the transformer <u>after a magnetic map had been set up</u>, a condition which could readily obtain in the present design if two conductive contact fingers had been used for each "elevator" (as the vertical sliding mechanisms are called). Under such conditions the regulation of the tap transformer might not be sufficiently good to meet the demand for so much current and the consequent unsuspected drop in voltage would produce a large error.

41. <u>Choice of the bus spacing; contact testing with headphones</u>

The decision as to the "pitch" or spacing between adjacent bus tongues to be used had to be made without delay in Chicago during the week spent there just before Christmas or delivery of the complicated and indispensable switching equipment could not have been made on time with the remaining elements of the

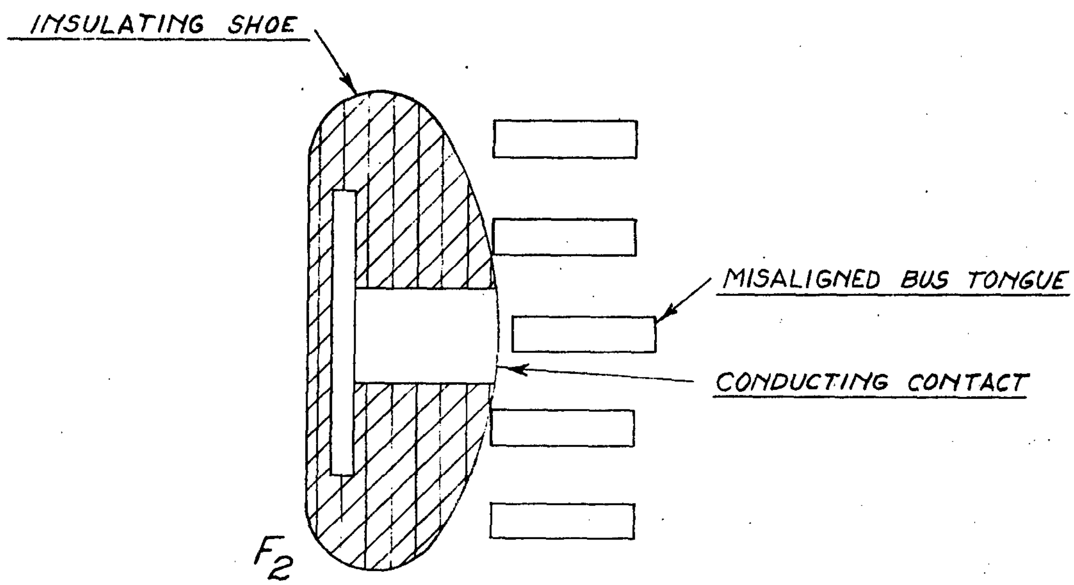


FIG.8. ONE TYPE OF FAULTY CONTACT CAUSED BY SLIGHT MISALIGNMENT OF BUS TONGUE. CAN ONLY BE CORRECTED BY VERY CAREFUL EDGEWISE BENDING OF TONGUE.

wave machine. The specification given the representative of the NDRC was that it must be possible to determine the currents in the solenoids in either positive or negative phase to a precision of 1 percent of the maximum value. This calls for 200 live busses -- 100 for each phase -- which would evidently have filled a panel about 2 ft high and would have given too large a scale on the ordinates of the signatures if the standard telephone exchange spacing of 1/8 in. between centers of adjacent busses had been adhered to. Consideration was given to the deliberate use of bridging contacts designed to have the appropriate current-limiting resistance in order to meet the requirement of 1-percent steps with only 50 busses for each phase. However, such a device was not standard in telephone practice and would have required time consuming research with some uncertainty as to the result; hence it was abandoned in favor of the reduced pitch of 1/16 in. between bus centers. The writer still considers this choice to have been the wisest under the circumstances. If the requirement of 1-percent steps in the adjustment of voltage could be relaxed it would certainly be a slight improvement in design to have the standard 1/8 in. spacing between adjacent busses. One or two isolated instances. have been found (and corrected) on the panels where one slightly misaligned bus tongue (Fig.8) failed to contact the conductive insert in the contact finger. Not all such faults may have been found as yet, despite the careful test, occupying an entire week, of the operating reliability of all elevators at the

Bureau of Standards by the representative of NDRC. Therefore, the recommendation is made in Secs. 98 and 106 that, after a map is set up on the switching devices, the state of contact of all 800 elevators be tested with a telephone receiver; this test can be made quickly and gives complete assurance that no unsuspected open circuits exist.

If the standard 1/8-in. spacing between busses could have been used, the difficulty just referred to would doubtless not have arisen; the standard contact fingers are designed to avoid this for a spacing of 1/8 in.

42. Dead Positions for contact fingers

It seemed wise to provide positions at the bottom of their vertical travel where the contact fingers on each elevator would not be connected to any bus at all, thus leaving the corresponding solenoid in the coil box on open circuit. This is better than to have the live terminals of the coils not in use grounded because, in the latter case, currents by mutual induction might appear. While the design is such (as already stated) that "cross talk" between coils is minimized for individual coils, it is best to avoid having any considerable number of idle coils with closed circuits in which induced currents could exist. The two cooperating fingers on each elevator must not be allowed to leave the row of contact tongues, or some continuation thereof, and come together, as they could not readily be made to open again and engage the row of contact tongues without considerable trouble and loss

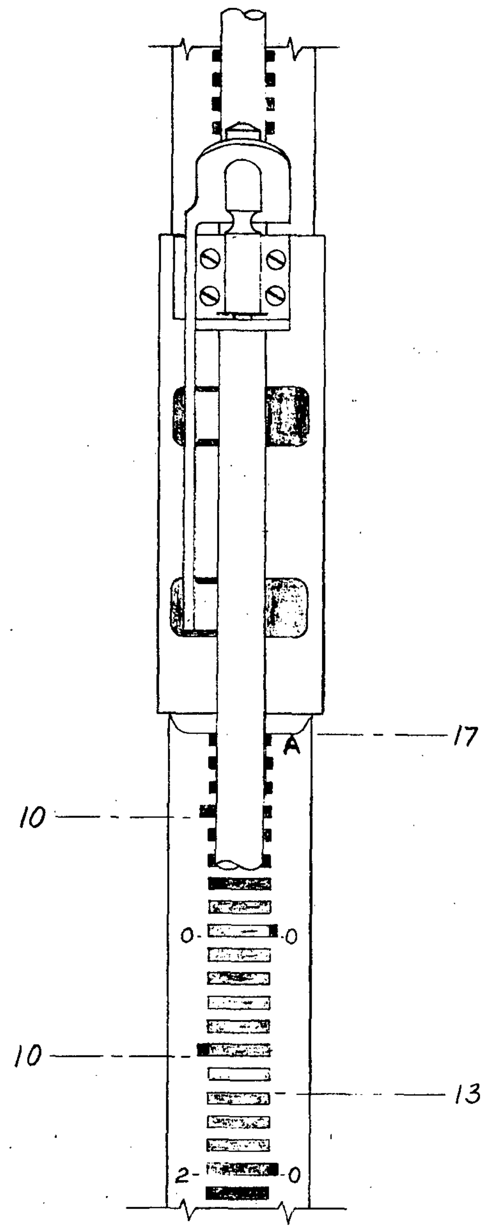


FIG. 9. APPEARANCE OF PAWL CARRIAGE AND RACK SHOWING METHOD OF READING NUMERICAL SCALE.

of time. Guide combs made of Lucite were therefore provided at the bottom of the panel frame so that the teeth of these combs register vertically with the contact tongues and provide an insulating extension on which the contact fingers may rest when in their lowest position. Unfortunately these combs are not standard telephone equipment and had to be made especially for the purpose.

43. Racks and double pawl systems; reading of numerical scales

To insure that when the elevators are set, the conductive contact fingers will always stop on a bus tongue and never bridge between two tongues, a "rack" is provided which consists of a strip of hard alloy copper punched with slots 1/16 in. wide spaced 1/8 in. between centers; this is standard equipment in automatic telephone exchange mechanisms. To give stopping points along such a rack at intervals of 1/16 in. rather than 1/8 in., a cooperating carriage provided with two pawls had to be specially designed. One pawl engages a slot in the rack while the other pawl is half way between slots. Numbers are provided stamped on the rack so that numerical as well as graphical settings can be made. In Fig. 9, which shows the front of the pawl carriage and rack, the carriage is set on +17. Several other settings and the numerical readings that correspond to them are also shown. The line A, which coincides with the surface (seen on edge) on the lower pawl that contacts the top of the slot in the rack, is the one to be used as the reading index. Both top and bottom edges of each slot in the rack must be counted as division lines. Note that every fifth slot, or every tenth division, is indicated by cutting the slot a little longer than its neighbors. It is well to remember that, if the numerical setting is an <u>even</u> number, solid copper will be seen directly below the line <u>A</u>, while, if it is an odd number, a slot will appear there.

The exact register of the entire elevator mechanism relies on gravity to keep the system at the lowest point permitted by the engagement of the pawl in any particular slot of the rack. A few isolated instances of elevators that worked a little too stiffly to insure this positive gravity action were corrected by adding small cylindrical lead weights which can be clamped in two halves by means of screws around the vertical elevator shafts. An ample supply of such lead weights is furnished with the machine in case other similar corrections should be needed.

44. <u>Adjustment of register of contacts</u>

An adjustment may be occasionally necessary to improve the accuracy of register between the stopping points of the carriages and elevators, on the one hand, and the contact fingers and bus tongues, on the other hand. The easiest way to do this is to remove the dust cover from the front of the panel bank and loosen the single small cadmium plated hexagonal bolt which clamps the contact finger support to the brass sleeve. Do not loosen the two slotted screws. Then, with the pawl carriage set on -100 near the bottom end of the rack, adjust the height of the contact finger support on the brass sleeve until the metallic contact can be seen to be in good alignment with the lowest bus tongue. Tighten the hexagon nut; a special flat wrench furnished in the kit of tools will be found most convenient for this operation. If the register is well set at this lowest point it ususlly will be found to be good on all other bus tongues. Occasionally a panel may be found in which the pitch of the busses fails slightly to correspond to the pitch of the punched rack; if such is the case, a compromise adjustment at several points should be made.

An even less frequent type of maladjustment which should be checked occasionally is revealed when the lower taper-pointed indicating end of the brass elevator rod fails to coincide with the zero line on the wooden chart board, although the pawl carriage is set exactly on the zero mark on the rack. This can be corrected only by readjusting the position of the pawl carriage on the brass elevator rod. After such a readjustment the register of the contact fingers and bus tongues must, of course, be readjusted.

In making these various adjustments care should be taken never to set the contact finger supports so high on its brass sleeve that, when the hexagon bolt is tightened, the clamping action bears on the split end of the brass sleeve so as to clamp it to the rod on which the sleeve should slide freely. If this seems to be required to obtain correct register, adjustment of the pawl carriage is probably necessary, or some other clamped settings in the elevator structure may have slipped and a general check and comparison with correctly adjusted elevators should be made. Always mark a defective or maladjusted elevator with chalk until it is completely corrected; then erase the mark.

45. Sensitivity of panel switches to temperature

Any change in the register or, worse yet, in the pitch of the bus tongues away from the exact correspondence with the punched racks clearly is serious. The impregnating compound in the insulating paper separators between the bus strips is purposely designed to be very slightly plastic. Thus, when the panel frames are assembled and the bolts pulled down, this compound squeezes out into the holes perforated in the busses and locks the entire structure into a solid rigid mass incapable of loosening through vibration. On the other hand, if thermal expansion and contraction of the panel bus frame occur, there may be both temporary or permanent deformations in this plastic compound which can spoil the aforementioned register of contacts in a way that might be difficult to correct. Differential thermal expansion of various elements in the mechanical structure (elevator rods, angle iron frame, and so forth) can also temporarily spoil the register of contacts. IT IS THEREFORE STRONGLY RECOMMENDED THAT THE WHOLE ROOM IN WHICH THE WAVE MACHINE IS TO BE USED SHOULD BE CONTINUOUSLY MAINTAINED WITHIN A REASONABLE TEMPERATURE RANGE, SAY $\pm$ 20° F.

46. Plan of association of panel switches with solenoid coils

To avoid confusion, the panel switching devices have their

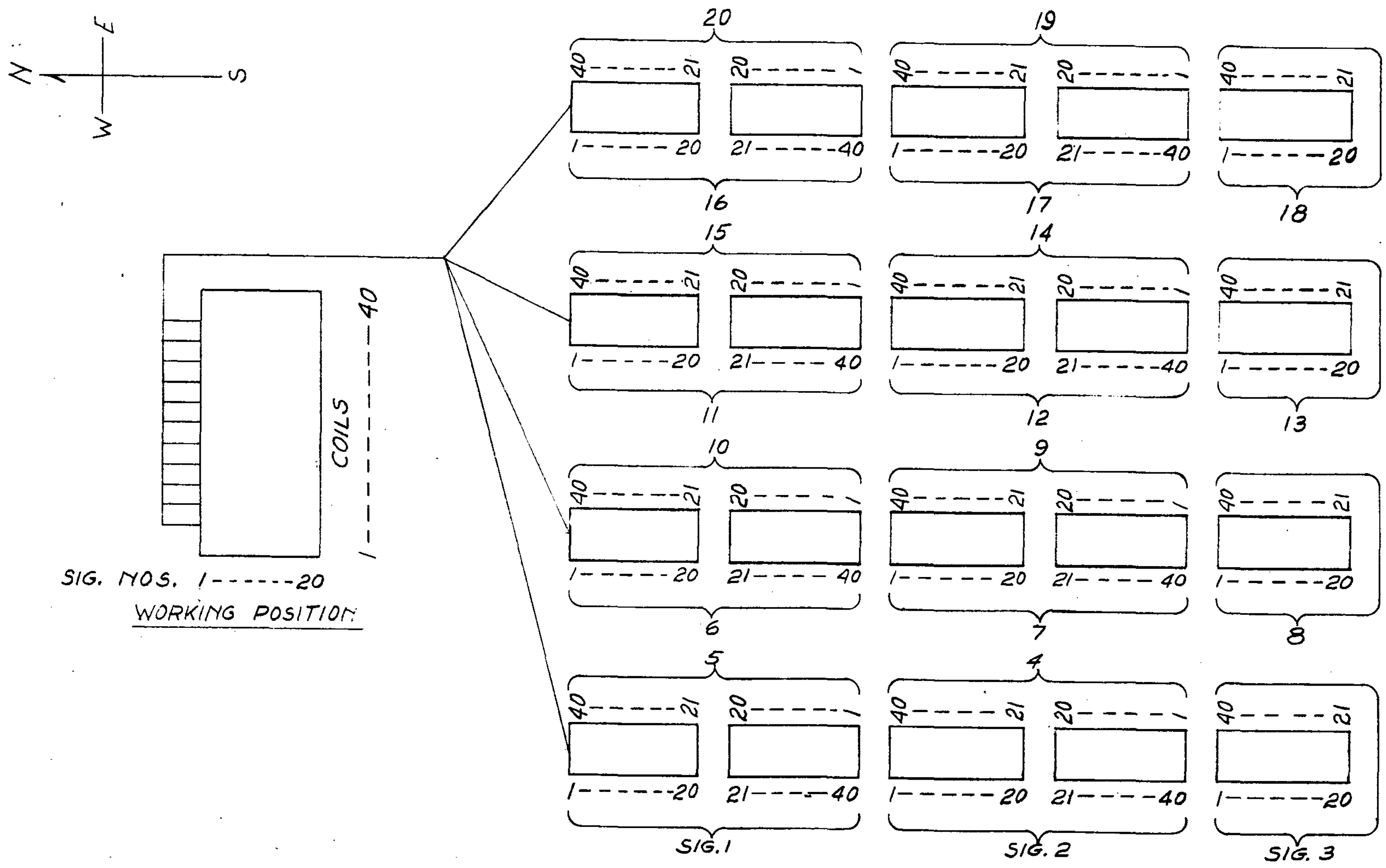


FIG. 10. LAYOUT OF ASSOCIATION BETWEEN COILS IN COIL BOX AND PANEL SWITCHING DEVICES.

elevators wired to the solenoid coils in the coil box so that, as one faces the panel switching device, the numbers of the coils connected to each elevator increase from left to right. Since standard panel switches and bus punchings with provision for more than 30 elevators were not obtainable, it was impossible to associate one complete signature of 40 coils with each side of a panel. The panels therefore were designed with 20 elevators, or half a signature, on each side of each panel. To make the intensity curve for complete signatures easy to inspect, the the 40 elevators on one side of two adjacent panel switches are associated from left to right in order of increasing numbers with the coils of a given signature in the coil box. The same rule of numbers increasing from left to right applies on both sides of the panels, the observer always facing the panel on which he is working. The plan view of Fig. 10 shows the system adopted. Since, for a compact arrangement, it is necessary to have five panel switches in a row (and four rows), the fifth panel switching device in a row is exceptional in that it has one complete signature of 40 coils associated with the elevators on both of its sides. However, the rule of numbers increasing from left to right as one faces that board still holds here.

47. The phase-sensitive recorder to record the emf generated in the search coil

The design and construction of this all important element in the field machine was entirely the work of Bell Telephone Laboratories engineers. It is not a deflection-type instrument, but is an a.c. potentiometer bridge recorder in which the rectilinear motion of the pen across the moving chart-paper is produced by two small d.c. servo-motors. The pen carriage carries a contact finger which wipes over a rheostat as the position of the pen is displaced. This rheostat is supplied with a 270-cycle/sec. a.c. voltage of appropriate phase to correspond with the phase of the emf generated in the search coil, the total drop across the rheostat being only about 2 mv (that is,the maximum range of emf's from maximum value in negative to maximum in positive phase to be expected from the search coil). The potential difference between the center of this rheostat and the point of contact of the sliding finger is placed in series with the output of the search coil; and the algebraic sum of these two is applied to the grid of a vacuum tube, the first element in an amplifying chain which sends an amplified signal that determines the ignition of one of two mercury-vapor filled gas tubes. These gas tubes control currents that determine the rotation of the pen-carriage servo-motors. These two small motors, which are built in a single frame, tend to drive a common shaft in opposite senses. Each motor is controlled by one of the gas tubes. The pen carriage is moved by a fish line belt which wraps around a small pulley on the shaft of the motors. When the sliding contact finger on the pen carriage picks up a potential that exactly balances the emf delivered by the search coil, no signal is sent such as to cause either servo-motor to rotate; the pen carriage then remains stationary. Any unbalance, however, results in motion of the pen carriage until a new balance is established

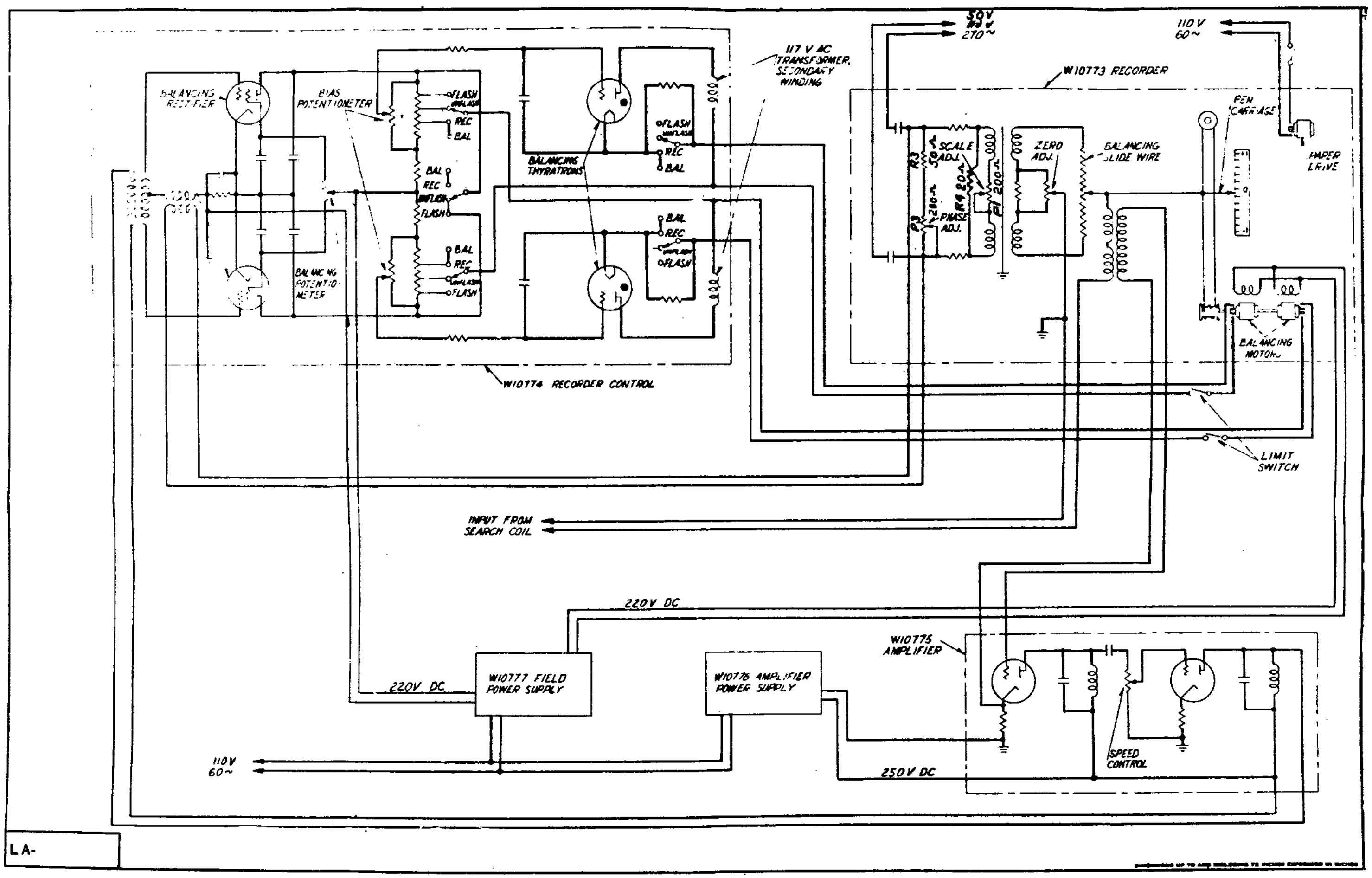


FIG. 11 SIMPLIFIED DIAGRAM OF RECORDER CIRCUITS
(BELL TELEPHONE LABORATORIES, INC. ESO-779982)

by moving the sliding contact finger to the appropriate position on the rheostat. Thus the position of the pen carriage is a reliable indication both as to phase (+ or -) and magnitude of the emf output of the search coil. Since this output is in series with the grid of a vacuum tube in the recorder having an impedance of the order of 10^4 ohms, the currents demanded are very minute. The leads from search coil to recorder and the low voltage circuits connected to them inside the recorder must evidently be very thoroughly shielded. However, this arrangement of balancing the emf of the search coil directly against the reference emf on the slider of the recorder pen carriage without intermediate amplification has the great advantage of liberating the entire system from all unreliable fluctuations which might come from variations in the amplification factor of an amplifier. The thing amplified is thus only the signal that directs the motors which way to move the pen carriage. How far the carriage shall move and where it shall stop depends in no way on the amplifier.

Figure 11 is a simplified diagram of the circuits of the recorder. It is clear from this diagram that the deflections of the pen carriage are proportional to the quotient of the emf of the search coil by the emf of the 270-cycle/sec reference supply to the recorder from the tap transformer; for this latter determines the total alternating potential difference across the slide wire rheostat over which the pen carriage contact finger explores for a balance and therefore determines the search coil emf which will balance the pen carriage at full-scale deflection.

48. Recorder deflections unaffected by slight fluctuations in 270-cycle/sec generator voltage

An important advantage results from the foregoing arrangement. Since the deflections of the recorder pen are proportional to the search coil emf divided by the 270-cycle/sec reference supply voltage, which is taken directly from the tap transformer, the accuracy of the entire system is unaffected by slight fluctuations in the voltage of the 270-cycle/sec, 110-volt, generator; for a slight diminution in generator voltage diminishes at one and the same time and in the same proportion the intensities of the fields set up by the solenoid coils, and therefore diminishes the emf of the search coil, on the one hand, and the 270-cycle/sec reference supply voltage to the recorder, on the other hand. The quotient of the last two quantities is therefore unchanged. This valuable property will not hold if the generator voltage falls by too large an amount because, for a reason explained below, the deflections of the recorder pen become erratic if the 270-cycle/sec reference supply voltage to the recorder falls much below 50 volts. It is well to bear constantly in mind this fact that the recorder measures the ratio of the search coil emf to the 270-cycle/sec reference supply (or to the secondary voltage on the tap transformer). It means that our standard unit of measurement on the recorder is not 1 volt or 1 mv, but rather is the voltage of the tap transformer. The recorder does, of course, change slightly as to the deflection it gives for a given value of the ratio which it is designed to measure, probably partly because of temperature changes in the slide wire resistance. Therefore, to standardize the recorder deflections one should have available a low 270-cycle/sec voltage (of appropriate phase and about 1 mv) <u>which is constant, not in absolute value, but as to its value relative to the tap transformer secondary voltage</u>. The standardizing millivolt box for this purpose is described in Secs. 76 and 78.

49. <u>Deflection scale control on recorder</u>

Thus, within certain quite restricted limits, the sensitivity of the recorder can be <u>increased</u> by <u>decreasing</u> this 270-cycle/sec reference voltage. However, a decrease of this reference input much below ± 25 volts (50 volts total) results in erratic behavior of the recorder. The reason lies in the fact that this reference voltage is used inside the recorder in two ways: (1) to energize the slide wire rheostat over which the pen carriage explores; (2) as a part of the grid biasing voltage on the rectifier tubes (the other part of this grid biasing voltage being the amplified signal from the amplifier). It is the second of these two uses that sets a lower limit at present to the reference voltage input which will work satisfactorily. A more fundamental limitation would enter, of course, if a very large increase in sensitivity were attempted, such that the level of the input voltage from the search coil(and on the slide wire of the pen carriage) approached the fundamental noise level resulting from the particle, or electronic, nature of electricity (Shot effect).

The sensitivity of the recorder thus is controlled at present in two ways, both of which vary the total potential difference across the slide wire rheostat over which the pen carriage explores. One of these sensitivity controls is in the form of a dial placed at the top of the recorder panel. This gives about a 25-percent variation of the deflection scale. More variation, if required, can be had by changing the alligator clips at the tap transformer which connect the reference supply voltage to the recorder, care being taken not to go much below 20 or 25 volts on either side of grounnd. <u>These alligator clips must be attached to positive and negative taps symmetrically situated above and below the grounded center tap of the tap transformer</u>.

Complete instructions for starting, balancing and operating the recorder are given in Secs. 103-105.

III. COMPLETE SPECIFICATIONS OF THE PHYSICAL DIMENSIONS AND CHARACTERISTICS OF THE ELEMENTS SUPPLIED BY THE BELL TELEPHONE LABORATORIES AND THE WESTERN ELECTRIC COMPANY

50. <u>800 solenoids and 50 spares</u>

These coils are wound on hard rubber (W.E. Co., Grade No. 1024) mandrels, each 56.1 in. long and 1-1/4 X 7/16 in. cross section, with corners rounded to 1/8 in. radius. Each mandrel has two longitudinal ventilating slots on each side, approximately 5/32 in. wide and 1/8 in. deep, and running the full length of the mandrel. The winding is of No. 37 gauge bronze alloy (W.E. Co., No. 36 tinsel alloy) varnish enameled and wound 168 turns per inch. The winding length is between 48 in. mimimum and 51-1/2 in. maximum. The d.c. resistance at 70° F is adjusted by removal of excess turns to within ± 1/4 percent of the mean value for all the coils.

At the starting end of the winding, adjustment is made by removing a few end-turns under a microscope to bring the finished end of the winding exactly to a common distance from the end of the mandrel for all coils. This leaves a bare space (3/64 in.) which is then filled with a cellulose acetate strip wound to the level of the wire winding and cemented in place.

The adjusted coils are given a coat of cellulose acetate lacquer over the winding and are then covered with a layer of acetate sheet (0.002 in.) cemented to the winding and extending at the close-wound end over the 3/64-in. acetate filled unwound space. At the opposite end two soldering terminals connected to the winding are fastened to the flat end surface of the mandrel.

Resistance of each coil: (2175 ± 3) ohms.

Appendix C gives the resistance of all solenoids, including the spares, and also the length of the winding on the core.

Maximum voltage to be used on each coil: 30 volts, rms, at 270 cycle/sec.

Maximum current in each coil: 14 ma, rms, at 270 cycle/sec.

Reactance of each coil: 40 ohms at 270 cycle/sec.

Phase angle of coil: 1°.

Maximum axial component of magnetic field at end of coil: 0.521 gauss, rms; 0.738 gauss, peak.

Maximum power dissipated per coil: about 0.4 watt.

51. Coil assembly

Adjusted coils are placed in groups of 20 in a steel jig with flat surfaces adjacent and close-wound ends pressing against a straight steel face plate. Hard rubber pieces having the same sections as the mandrels and corresponding in length to the nonwound portions of the coils are placed on each side of the group of 20 with flat end-surfaces gauge spaced from the face plate. While clamped in this position a line of holes on a common axis above the wound portions of the mandrels is taper reamed through the entire group including the side pieces. Thus a tapered nickel silver pin driven into these reamed holes serves to keep the mandrel ends in a common plane and at a fixed distance from the ends of the side pieces. The 20 coils of the group are clamped together by two threaded brass rods, one on each side of the taper pin. Washers are placed between the adjacent coils and over the clamp rods to keep the pressure from being applied to the windings.

Forty of the coil groups are assembled side by side with long axes vertical and are supported by resting the ends of the group side pieces on the straight horizontal edges of two side panels of 1-in. phenol fiber. These panels and also two end panels are in turn supported in a substantial doweled frame of hard maple. Side and end members of the frame are provided with large screws made of wood which bear at their ends on one side and one end panel and serve to clamp the whole lot of coils snugly together. A sheet of 1/2-in. sponge rubber, acetate lined, is placed against the inner surface of a side and end panel to cushion the coils against the pressure.

In the plane of the top end of the assembled coils and 3 in. from one of the long sides are mounted terminal strips (W.E. Co.) that carry 960 two-ended soldering terminals arranged in 6 rows of 160 terminals per row. The terminals of the top row are all connected together and to each of the winding terminals connecting to the close-wound ends. Each of the other winding-ends of the first 20 coils is connected in a regular order to the first block of 20 terminals (5 rows by 4 terminals lengthwise), the second 20-coil group to the next adjacent block, and so on for the 40 groups of 20 coils each.

A wood cover encloses the upper end of the coil assembly and the terminal strips. This cover has a removable section that exposes the terminal strips for connecting the outgoing cables. Openings in the cover for these cables and for the ventilating apparatus are not provided at the factory; they can best be cut during installation.

Exterior surfaces are cleaned of dirt and pencil marks and are given a mahogany stain finish. A pair of strongly braced under-supports of all wood construction are furnished. When erected, the coil assembly will be held with the lower end-plane of the coils 4 in. above the floor. An overall floor area of 90 X 70 in. is required. The overall height is 112 in.

52. Switching panels

Twenty switching panels are provided.

53. Panel bank

Each panel bank has 201 feeder strips, each having 20 horizontally projecting contact members on each side, front and back. These feeder strips are rigidly assembled in 1/16-in. centers so that the projecting contact tongues are in straight vertical rows. At the bottom of the frame in which the strips are clamped are mounted "guide combs" made of Lucite. The "teeth" of these combs register vertically with the contact tongues and provide an insulated, or dead, position for the contact brushes.

One panel bank is mounted at the top of a steel angle supporting frame approximately 90 in. in vertical height.

54. Racks

Immediately below the panel bank in each frame there are mounted on each side, 20 elevator racks (W.E.Co.), one for each of the vertical rows of contact tongues. The racks are provided with 101 slots accurately spaced on 1/8-in. centers. A black, phenol fiber faced panel is placed between the front and back sets of racks; it provides a firm and true surface to keep the racks accurately in position.

55. Brushes and rods

In line with each row of contact tongues and corresponding rack is a vertically movable rod that carries at its upper end a contact brush and over the rack a handle provided with a pair of spring actuated pawls. These pawls are mounted vertically one above the other and are spaced 1/16-in apart. Thus they engage the rack slots alternately and so provide for a succession of 1/16-in. movements of the rod assembly in a vertical direction. The pawls engage the rack slots only against downward motion; motion upward is therefore relatively free, the pawls clicking from slot to slot.

To permit rapid restoration to the bottom position, each pawl set is provided with a retracing lever projecting just above the rod handle by means of which the pawls are withdrawn from the rack slots and held in the withdrawn position by a latch post. The latch post is readily disengaged by the thumb or finger of the operator when holding is desired.

The brush at the upper end of the rod makes sliding contact with the contact tongues of the feeder strips. It also is connected to a thin walled tube sliding on a fixed rod to which electric connection to a cable connecting terminal is made. The lower end of the brush rod is cut to a rounded point and this travels over a chart board removably fastened to the frame.

The weight of the brush rod and the frictional components affecting its motion are adjusted so that each rod falls to the lowest position permitted by the pawls when they are engaging the slots and to a position bringing the brush on the guide comb when the pawls are held in the disengaged position.

56. <u>Chart boards</u>

Two chart boards of white pine, 1-7/32 in. thick and with rabbeted cross brace at each end, are provided for each switching unit. These boards are supported at their upper and lower edges by means of side plates and are clamped in the frame by thumb screw swinging bolts which, when released, permit removal of the boards in a downward direction. When in the frames, the top edges of the boards are 48 in. above the base of the frame.

57. <u>Frame and cabling</u>

The frames are of welded steel angle construction, 12 X $31\frac{1}{2}$ in. in horizontal dimensions except at the base, where 6- in. angles project front and back, making the base 24 X $31\frac{1}{2}$ in. Dust protecting covers are placed over the brushes and bank. Terminal strips are attached near the top on one narrow side

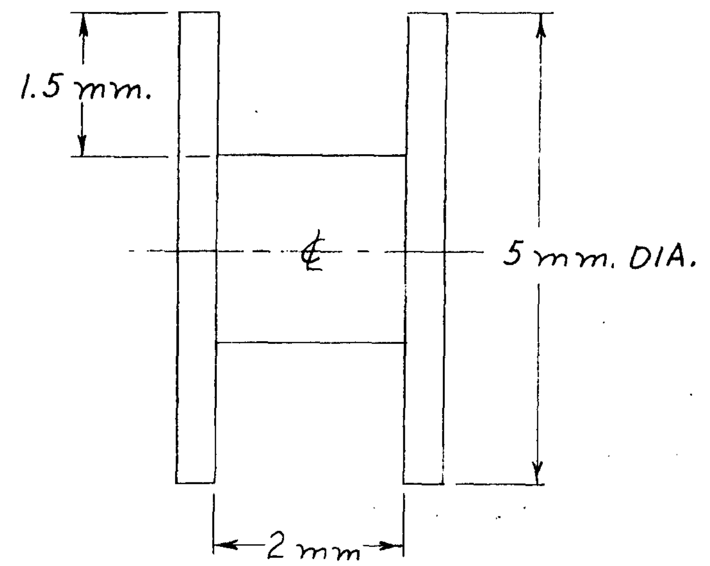


FIG. 12. DIMENSIONS OF SEARCH COILS.

for cabling feeder strips of adjacent switching units together, and on the other narrow side for cabling to the coil assembly. Factory-connected cables for these purposes are supplied. These cables have No. 22 gauge, cotton and lacquer insulated copper conductors.

58. Search coils (ten) (See Fig. 12)

Search Coil No. 23, for example, has these characteristics: 2905 turns: diameter of wire, 0.001 in. (enameled); cellophane between layers; inductance, 17.81 mh (reactance at 270 cycles/sec, 32 ohms); resistance, 1019.6 ohms at 26°C.

Ten such coils exist, including three now in use. All ten have self-inductances that differ from the mean of the set by less than 1.0 percent; hence the sensitivities to fields differ by less than 0.5 percent.

59. Motor generator set

A 270-cycle/sec motor generator set with the following specifications is furnished.

The generator shall have an output voltage of 120 volts, 270 cycle/sec at 1800 rev/min, with an output capacity of 3 Kva at 120 volts and unity power factor. The supplier shall furnish a 13-in. Ward-Leonard rheostat, front of board mounted, front of board operated, with the rheostat manufacturer's standard handwheel for adjusting the generator voltage. The regulation of the generator shall not exceed ± 10 volts from 120 volts under conditions of constant normal line voltage and frequency on the motor, from no load to full load and cold to hot.

The motor shall be a 230-volt, 3-phase, 60-cycle/sec synchronous motor with self-contained field resistor adjusted for unity power factor at full load.

The set shall be excited by a direct-connected exciter of suitable capacity for both the motor and generator, and shall be permanently connected through a suitable resistor to the motor field.

The Electric Products Company shall also furnish the following motor starter: G.E. Co. CR-1034, 230-volt, 3-phase, 60-cycle/sec, 10-hp starter, catalog No. 2019014G3, with CR-2824TC121 temperature overload relay, catalog No. 2019557G19. When installed, the leads to the motor should be No. 8 gauge and shall be fused at 70 amp.

60. Tap Transformer

Electrical features: Primary voltage, 120 volts; secondary voltage, 60 volts; frequency 270 cycle/sec; secondary full load, 300 watts at practically unity power factor.

Secondary winding to have center tap and a tap every 0.3 volt each side of center.

With primary voltage of 120 volts, the tap voltages at any load (up to full load) shall be within ± 2.5 percent of nominal values except that this tolerance shall not be less than ± 0.075 volt.

Full load current for 30-volt tap to be 5 amp and, for 0.3-volt tap, 0.1 amp, with outputs for intermediate taps in straight line proportion.

Ambient temperature to be normal room temperature.

61. Mechanical features

The transformer is to be housed in a sheet steel case, approximately 10 in. cube. It will be mounted on a rectangular angle-iron framework approximately 20 X 23 in.

Adjacent to one long edge of the framework will be 5 vertical terminal arrangements, each consisting of 2 Western Electric Company 101-B Terminal Strips and carrying 40 terminals. Each terminal will have 4 multipled soldering lugs for outside connections.

The 200 secondary taps (excepting center tap) will be brought to these terminals, which will be marked with their voltages from the center tap. The center tap will be brought out to a separate terminal mounted on the framework.

The primary leads will be brought out as a rubber covered cord and plug.

The transformer case and the metal framework will be given an aluminum lacquer finish.

62. 270-cycle/sec potentiometer recorder

A potentiometer recorder is to be built to meet the following requirements:

1. It shall record the component of a voltage ranging from about -1 to +1 mv which is in quadrature with a 110-volt, 270-cycle/sec supply. The frequency of the supply is to be maintained to ±1 percent.

2. The accuracy of recording shall be ± 0.01 mv.

3. The scale range should be adjustable within ± 25 percent.

4. The record should be made with ink on paper 9-7/8 in.

wide at a maximum speed of about 1 mv/sec on sudden unbalance.

The unknown voltage is fed in series with the voltage output of a potentiometer into an amplifier (Fig. 11). When the vector sum of the unknown and the potentiometer output is not zero, the amplifier output operates either one or another of two gas tubes, depending on the sign of the sum, which tube actuates a motor that changes the potentiometer setting in such a direction as to reduce the amplifier input. When the vector sum of the two voltages is zero the system is in equilibrium and the unknown emf is equal and opposite in phase to the potentiometer output. Therefore the potentiometer setting which is recorded on a moving strip of paper indicates the unknown voltage.

The recording system comprises the following panels:

1. The potentiometer circuit panel, comprising the potentiometer, with its input network, the balancing motors, the chart drive motor, the paper drum and the pen mechanism. It will have, in addition to the paper drive switch, a scale range adjustment control, a zero setting control and a switch for short circuiting the unknown, for scale zero adjustment. The available paper speeds will be 18, 6 and 2 in/min. The same numbers of inches per hour can also be obtained as speeds. (A "microphone" type plug has been added to this panel by which the control of the paper drive can be plugged to a switch provided for the purpose on the exploring device.)

2. The tuned amplifier panel, comprising a high gain amplifier tuned to 270 cycle/sec. The gain of this amplifier will be adjustable, as it determines the speed of response of

the recorder.

3. The control circuit panel, where the amplifier output is rectified in a balanced circuit which causes the proper gas tube to flash. This panel will have a control for adjusting the bias on the Thyratron tubes.

4. The power supply panel, which will furnish all of the 60-cycle/sec and d.c. voltages used in the circuit. It will have a d.c. voltage adjustment.

The potentiometer circuit panel and the tuned amplifier panel will be housed together in one table cabinet, 42 X 22 in., 18 in. deep. In another cabinet of these same dimensions, the control circuit panel and the power supply panel will be housed together. It may be found to be desirable to keep the two units separated by several feet, in order to avoid inductive effects.

IV. DESIGN CONSTRUCTION AND TESTS AT THE NATIONAL BUREAU OF STANDARDS

63. Secrecy precautions

One essential element, the exploring device, was not constructed by the Bell Telephone Laboratories or the Western Electric Company but was designed by the representatives of the NDRC and built at the National Bureau of Standards, where also the entire equipment was assembled and tested. This arrangement made possible the maintenance of adequate provisions for secrecy; no unauthorized person has seen all essential elements of the equipment or their manner of functioning together. All tests were made at the National Bureau of Standards under excellent conditions of secrecy.

64. The exploring device; requirements

The function of the exploring device is to move the search coil rectilinearly along signatures (fore and aft) in the magnetic field set up by the solenoids while holding the search coil with its axis in the appropriate orientation to pick up the component of the magnetic field which is being explored. The position of the search coil in depth below the plane of definition (ends of the solenoid windings) and in the direction athwartship must be capable of being accurately defined, and the motion fore and aft must synchronize appropriately with the motion of the chart paper in the phase-sensitive recorder. It is desirable to be able to move the search coil in very close proximity to the ends of the solenoid windings so as to be able to explore as close an approximation as possible to the actual field in the plane of definition. (This ideal we were unable to realize as well as we had hoped.) Means must be provided, while the search coil is in motion through the field, to keep its terminals connected to the recorder through a cable which will permit as little inductive pick-up from the field as possible. All parts of the exploring device closer to the magnetized region than 3 ft must be nonmetallic.

The complete exploration of a field involves having the search coil make many trips to and fro over the magnetized region. It seemed desirable not to have the search coil operative upon the recorder during return trips, to avoid the possibility of confusion in interpreting the records, as well as geometric errors from mechanical "backlash". To save time, therefore, the mechanism was designed with a "quick return motion". By means of mechanical clutches, reversal of the drive automatically throws another train of gears into action; thus, when the motion is in the nonrecording direction, the speed is higher. The operator stands at the "working end" of the exploring device where the synchronous motor drive with its gears and control switches is located. The recording is done with the search coil moving <u>away</u> from the operator.

65. <u>Definition of coordinates and units for geometry of exploration</u>

A point in the model magnetic field is located by giving its rectangular coordinates $\underline{x}$, $\underline{y}$, $\underline{z}$. The unit of length employed for the model field is the <u>width of a solenoid coil</u>

(or spacing between centers of adjacent signatures in the coil box); namely, 0.4615 in. This very frequently corresponds to 20 ft of the ship's field, though other scales can also be adopted, of course. The _x_-coordinate always refers to measurements fore and aft (direction of exploration). The _y_-coordinate refers to measurements athwartship; the vertical plane through the keel is usually situated at $y = 0$. The _z_-coordinate refers to depth below the measured plane (plane of definition). As the measured plane is at some depth (frequently 50 ft or $2\frac{1}{2}$ coils) below the water line, this constant difference must be added to _z_ in order to obtain actual depths in the water.

As previously stated, any scale ratio of magnetic intensities in the ship's field to magnetic intensities in the model is permissible, and any _single_ geometric scale ratio between the coordinates describing the ship's field and those describing the field of the model is permissible. Only one restriction must be observed. The geometric scale ratio adopted between the dimensions of the ship's field and the dimensions of the model field _must_ be identical for the three coordinates _x_, _y_, _z_. This is a consequence of the interrelatedness of the rates of variation of the magnetic intensity along the three coordinates alluded to in Appendix A-- a fundamental Law of electromagnetism from which there is no escape. Thus the scale ratio for depth measurements is immediately and automatically fixed the moment a scale ratio has been selected for representing the ship's magnetic map in the plane of definition.

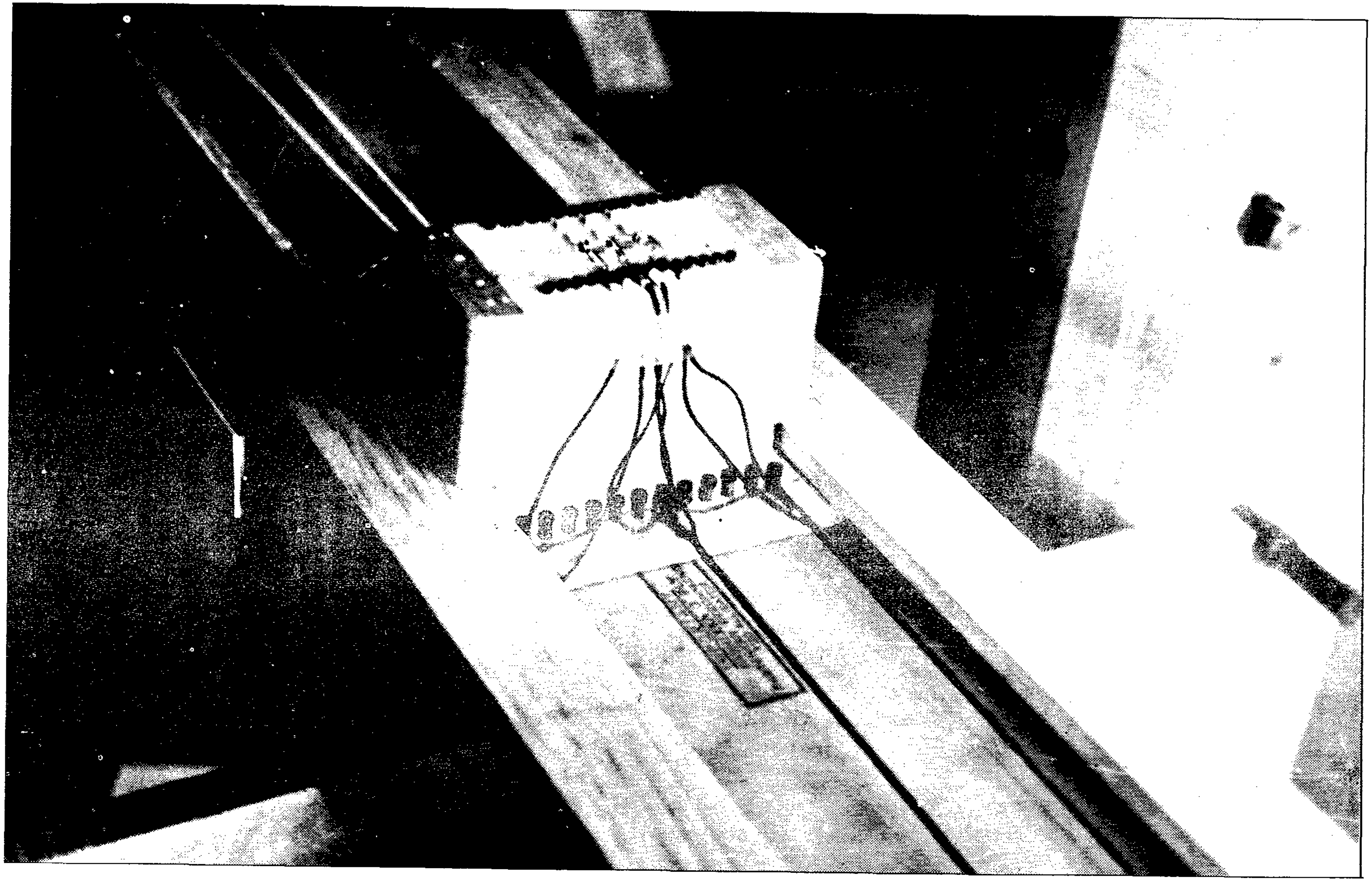


Plate III. The search coil carriage. Three search coils, with their "Hearing Aid" cables, are shown mounted to explore H_x, H_y and H_z.

66. Description of exploring device

Three search coils are at present mounted on the top of the traveling carriage in appropriately designed cavities in an inlaid Lucite block to give their axes the directions of the x-y-and z coordinates, respectively. They are held in these cavities by Lucite fingers and Lucite screws which exert on the coils a downward clamping pressure. The cavities are so designed as to hold the geometric centers of all three coils at the same value of z (height). The centers of adjacent coils are separated by just the width of one solenoid coil, 0.4615 in.

The search coil carriage is driven along guides in a long wooden (sugar pine) box (joined entirely with dowels, ship lap joints and glue) by means of a cotton fabric endless belt, 6 in. wide and 0.05 in. thick, impregnated with rubber for protection against moisture. The joint on this belt is effected by means of a short piece of the same belting lapping over the nearly adjoining ends of the belt proper and permanently vulcanized thereto. This lap joint is concealed beneath the carriage.

The driving belt passes over two nearly cylindrical pulleys which have slightly tapered ends to make the belt "track" in their centers. The travel of the belt is never sufficient to cause its joint to run over either pulley. At the end where the driving mechanism is situated and which is far enough from the magnetized region to permit the use of metal, the belt pulley is of brass, but at the other end the pulley is of hard wood with maple journals turning in hard (dogwood) bearing blocks. Provision is made for separate adjustment in the x-direction of all four bearing--on the wooden pulley by means of wedges and on the brass pulley by special screw-controlled slide motions designed into the ball bearing housings. These have been adjusted to put the belt under correct tension and to keep it running truly centered.

67. Removal of inner structure of exploring device and its disassembly

The belt and pulleys, together with the driving mechanism and the mechanism for taking up the variable excess length of search coil cable in the space underneath the belt, form a separate structure which can be drawn out of the long box or housing forming the main frame of the exploring device (as a drawer is withdrawn). To do this one has only to pull on the brass cross partition of the drive mechanism while exerting a reaction on the outer wooden box structure, being careful, however, to remove beforehand the search coil cable lugs where they are connected to the terminal posts on the lower black Bakelite switchboard and all three of the black Bakelite screw plugs (on the sides of the box) which control the limit switching mechanism for the motion of the belt. When the inner system has been withdrawn, the entire driving mechanism can be removed as a unit. First, however, the two 1/8-in. brass push rods which actuate the Mercoid switches should be detached from the brass blocks that project up through the slots on either side of the belt. The driving unit can now be removed by removing eight screws, four on each side, which fix the two prongs of each fork on the brass sideframe of the driving unit to the brass frame supporting the ball bearings of the brass belt pulley. With the driving mechanism removed, the entire remaining structure may be carefully inverted with the working side of the belt down on a long board or support. Then the search coil cables should be removed from their grooves in the bottom board (now on top) and the four Bakelite and two brass threaded studs which hold the lower tray (now on top) to the upper framework should be taken out. (A special brass wrench is provided in the folding cloth pocket of tools for turning the Bakelite nuts.) The white cotton cords are now to be detached from the Bakelite pins on the bottom tray on the nonmetallic end. Now the bottom tray can be lifted off. These cords loop around the grooved wooden roller (now for the first time visible) round which also loop, from the other direction, the slack length of the search coil cables. As the exploring carriage approaches the driving end of the device in its normal return motion, the increasing slack length of exploring coil cable is taken up in the loop under the belt around the wooden roller. The white cotton cords keep this loop taut because they are taken up an equal amount by the motion of the carriage to which their ends are attached on the side opposite the search coil cables. The axis of rotation of the roller moves at half the speed of the belt just above it, but the upper surface of the roller in contact with the belt moves at the same speed as the latter. The travel of the roller is thus only half the travel of the carriage and belt.

Note that when this point of disassembly has been reached there is no obstruction to prevent slipping the belt sideways off the pulleys, if so desired.

The ribbed frame structure on which belt and pulleys are mounted is long and somewhat fragile and should be handled carefully. It contains the rocking lever arms and push bar of the mechanism for operating the limit switches which control the travel of the belt. These are completely accessible only afrer the belt has been slipped off the pulleys. However, holes are cut in the working side of the belt to permit inspection of the limit mechanisms.

68. <u>Guiding of carriage</u>

That the motion of the carriage be rectilinear is of great importance if accurate results are to be obtained. This is insured as far as vertical deviations are concerned by the overhanging lip of the outer box. The block and base of the carriage embrace this lip on both sides, and four Bakelite screws in the four corners of the carriage base are set with their slotted ends at such a height that this embracing action permits only just enough vertical play to insure against friction. Horizontal deviations from rectilinear motion are precluded by means of a long true slot in the wooden table surface on which the belt slides. Two Bakelite rollers whose diameters fit this slot accurately are mounted with axes vertical on the bottom of the carriage. These engage the slot through holes in the belt. In this way the belt motion in no sense determines the rectilinearity of the carriage motion. The belt merely drags the carriage and does so by means of a Bakelite disk permanently pinned to the belt by Bakelite pins passing through the lap joint in the belt. This disk engages in an oval slot in the bottom of the carriage, the slot giving the disk lateral clearance so that the only motion or force transmitted to the carriage by the belt is in the *x*-direction.

69. Removal of carriage

The parts described in Sec. 68 are normally concealed but may be inspected by throwing out of action the appropriate limit mechanism (as explained below) and running the carriage backward almost to the end of travel until it just fails to reach the brass blocks actuating the limit switches which project through slots in the wood on either side of the belt. In this region the overhanging lips of the outer box are cut away so that the carriage can be lifted free of the belt (the white cotton cords and the search coil cables should first be detached from the carriage by removing the pins from the holes in the case). Care must be taken not to operate the belt with the carriage removed because the search coil cable roller and white cotton cords will become fouled under the belt so as to require complete disassembly. When the carriage is replaced and the belt is run forward into its normal working position, the carriage must be guided a little to see that it engages properly over the lip of the outer box until it is entirely beyond the cut-away portion of the lip.

70. Search coil cables

The search coil cables are made in the form of a central conducting core of very light flexible conductor completely surrounded by and insulated from a cylindrical shielding conductor. These cords are the same as are supplied by the Western Electric Company for its "Hearing Aids" (manufactured for amplifying sounds in cases of deafness). They were chosen to minimize the inductive stray pick-up by the cable from both electric and magnetic fields. These cables are bifurcated at both ends and are provided with lugs. That one of the pair of conductors that is distinguished by the red tracer woven into its cover is invariably the inner, or core, conductor. This should be so connected as to lead to the white rubber covered member of the twisted pair of rubber covered conductors in the cable going to the recorder. Ten spare Hearing Aid cables, beside the three now mounted on the exploring device, are supplied with the equipment.

71. Differential speeds of cables and belts; frictional drag

Provision is made on the carriage and on the slack-take up roller under the belt for the installation of a maximum number of ten search coil cables. However, actual trial has shown that so large a number of cables as ten does not operate very satisfactorily as regards the take-up mechanism. Because of the finite through small diameter of the search coil cable,

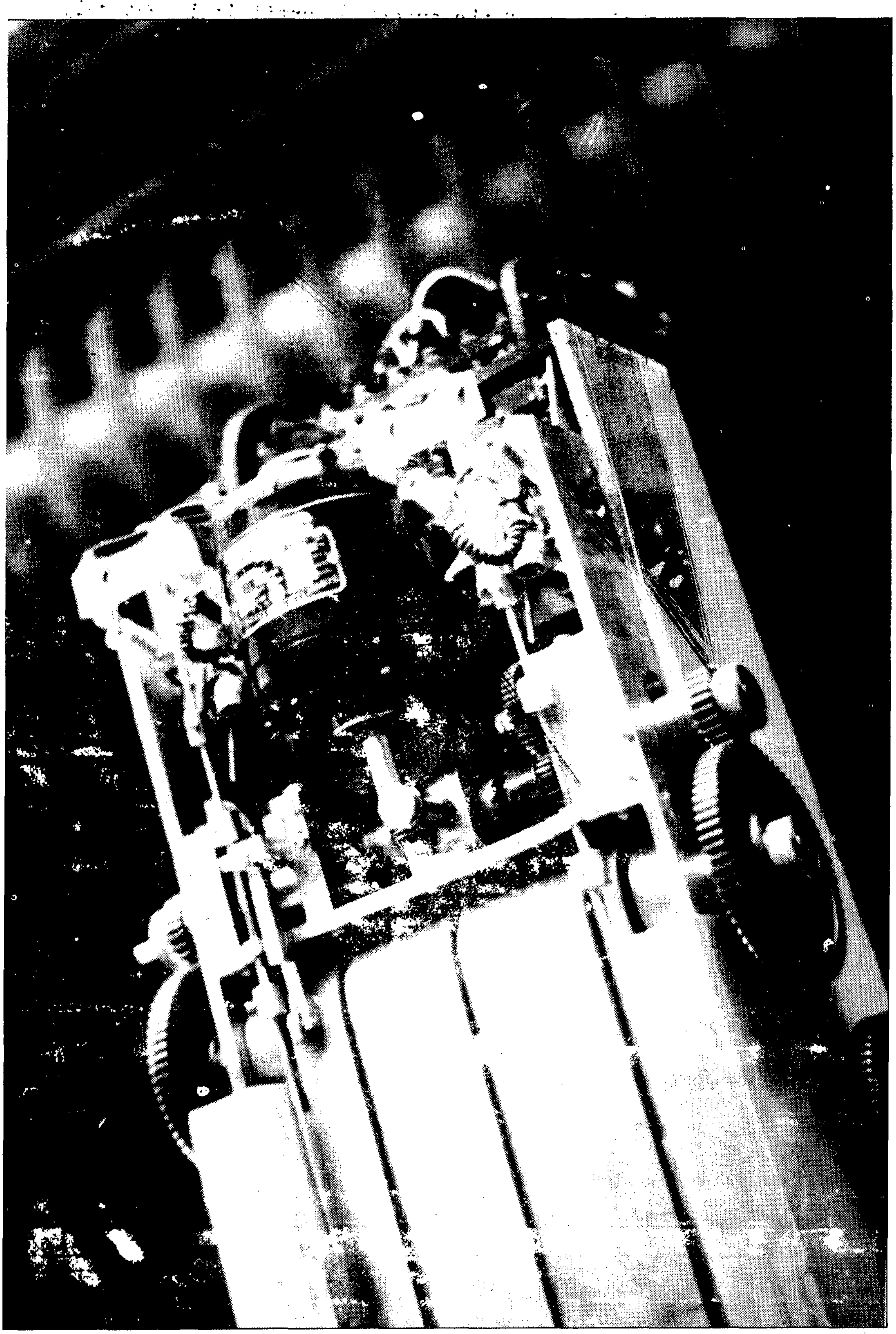


Plate IV. Explorer driving mechinism. The fiducial marking cam, the brass blocks on either side of the belt, and the brass push rods to operate the Mercoid switches are visible.

its mean radius of curvature where it wraps around the half turn of the belt over the pulleys is appreciably larger than the mean radius of the belt. But, since the linear speed of cables and belt must be the same (both are attached to the carriage), a certain amount of slippage is required between cables and belt where they bend around the pulley. However, this is the point where tension in the cable produces normal pressure and hence frictional drag between cables and belt. The "capstan" effect on the half turn of this cable emphasizes this frictional drag so much that the total force required to drag ten cables against the friction puts an inordinate load on the carriage and the white cotton cords. It should be noted that the diameter of these latter has been expressly chosen so as to match the diameter of the cables in order to equalize this differential speed effect.

Should it ever become necessary to mount a larger number of search coil cables on the exploring mechanism, it would probably be wise to provide two separate gangs of small pulleys at each end so that the cables and cords could make the 180°-turn round the belt pulley without lying in contact with the belt at the turn.

72. Explorer driving mechanism and speeds

A small 1/50-hp, single phase, 60-cycle/sec Bodine synchronous motor drives a 50-tooth bronze worm wheel through a single-thread hardened steel worm. The speed of the worm wheel after this 1/50 reduction is 36 rev/min. A system of two sawtooth crown gears coupled by two splines working axially in keyways in the worm wheel shaft permits the motion at 36 rev/min to be locked to either one of two sleeves on the right and left of the worm wheel. (It is here assumed that the operator faces the driving end of the exploring device and looks toward the other end.) The selection of the sleeve to be locked to the driving mechanism is automatically determined by the direction of rotation of the driving worm wheel and crown sawtooth gears. This is accomplished by means of a screw slot in the hub of one of the latter into which projects a pin fixed on the inner surface of a sleeve turning with adjustable friction drag in a housing. When the driving shaft reverses its direction of rotation, the friction sleeve does not turn until the action of the pin in the screw slot has thrown the crown wheels into position for driving the sleeve on the opposite side. The drive is locked into the right-hand sleeve when the direction of rotation is such that the carriage is making its quick return-trip, and the right-hand pair of outboard change gears then determines the speed. (A table of gears and speeds is given in Table I.) The exploring device as delivered to the N.O.L. has a speed reduction of 3 to 1 on these right-hand outboard change gears, so that on the quick return motion the belt pulley rotates 12 rev/min; and its diameter is such that the linear speed of the return motion of the belt is about 80 in./min. It is recommended that this speed of return be left unchanged. The drive is locked into the right-hand sleeve when the direction of rotation is such that the carriage is on its forward or exploring trip. In this case a compound train of four brass spur gears further reduces the speed of the left-hand outboard countershaft on which the driving change gear is mounted by a factor of 4 to 1. This driving change gear thus has a speed of 9 rev/min. With 3-to-1 reduction on the change gears at this point, the speed of the belt in forward exploring motion is approximately 20 in./min. This is the speed which will be used most frequently in operation. When this speed is used in conjunction with one of 18 in./min for the recorder paper, <u>the ratio of speeds of exploring carriage and recorder paper is the same as the ratio of the distance in the x-direction between adjacent solenoid coils in the coil box to the distance between adjacent elevator rods on the chart boards of the panel switching devices</u>. This relationship was expressly provided so that, without any replotting, the curvilinear graphs could be removed from the recorder and would have the correct scale in the *x*-direction if placed directly on the chart boards of the panel switches. In this way a magnetic map traced out by the recorder with search coil at any given level can without delay be reinserted directly into the machine and set up as a new magnetic distribution in the plane of definition. By this method, with change of scale of the magnetic intensities at each step, a field can be projected downward in several successive steps, if necessary, considerably farther than the sensitivity of the recording system would permit in a single step. The original idea was to use this particular speed ratio also for a rapid check as to whether the field in the plane of definition was correctly set up by matching it directly with the elevator settings. As will be explained in Chap. IV, however, it has turned out that the search coils, because of their dimensions and because of the projecting ends of the hard rubber solenoid mandrels, cannot be brought close enough to the plane of definition to give a close replica of the distribution in that plane, especially in the case of the complicated magnetic maps of degaussed ships; hence, only a rather rough check of this type can be made.

Careful measurements with an electric stop clock show that the nominal speed of 20 in./min is in reality 20.28 in./min, while the speed of the recording paper, when set nominally at 18 in./min, is 17.96 in./min. This is a ratio of 1.129 to 1. On the other hand, the exact mean distance in the *x*-direction between adjacent solenoids in the coil box is 1.271 in., and

Table I. Nominal speeds and gears for exploring device.

Number of Teeth on Left-hand Change Gears		Nominal Forward Belt Speed (in./min)	Remarks
On Driver Shaft	On Driven Shaft		
24	72	20	Recommended for most work; gives x-scale to fit chart boards and elevators
48	48	60	
72	24	180	
22	74	18	Gives scale of *x* on record nearly identical with *x* on model field.

the exact mean distance between adjacent elevators on the panel frame is 1.125 in. This is also a ratio of 1.129 to 1, which is in much better agreement with the previous ratio then the requirements demand.

Attention is called to the last set of gears in Table I. These provide a means, if it should ever be desired, of drawing on the chart paper a graph whose x-coordinate scale is nearly identical with the actual x-coordinates in the model field under the solenoids.

In changing gears care must be taken not to lose the small spline or key whose engagement in the slots prevents the gear from turning on its shaft.

The extra gears, when not in use, are kept on a stud provided for the purpose on the left-hand side of the exploring device.

73. Switching controls, and limit mechanisms on exploring device

The synchronous driving motor is energized through four wire leads, two black and two green. The motor operates normally with one wire of each color connected to each terminal of the 110-volt, 60-cycle/sec power supply. To reverse the direction of rotation of the motor, it must be allowed to come to rest, and then a pair of leads of one color must be reversed relative to the other pair and both pairs reconnected to the lines. This is accomplished automatically by four Mercoid switches. In the normal cycle of operations during a field exploration, these reversals must occur at the end of every travel both forward and back. It is undesirable from several points of view, however, to have the reverse motion start without delay as soon as the travel in one direction is completed. A much safer arrangement has therefore been made so that, by means of the two tilting Mercoid switches, the limit mechanism at the end of travel in either direction throws off the power and also reverses one pair of motor leads to prepare for the direction of motion next to be used. At the end of each travel, then, the limit mechanism brings the carriage to rest. A small two-way tumbler switch in the middle of the upper switchboard of the exploring device must then be thrown to the other side (marked "Forward" or "Reverse", whichever the next operation is to be) in order to set the carriage in motion again. If, for some reason, it is desired to reverse the motion of the carriage by hand (rather than by the automatic action of the limit mechanisms), the Mercoid switches can be tilted by pushing on the brass blocks on either side of the belt which command the motion of the two 1/8-in. brass push-rods coupled to the Mercoid switches 6/. The tumbler switch on the extreme right of the upper switchboard turns off the motor driving power altogether. Two "little" fuses on the back of this board protect the entire 110-volt, 60-cycle/sec motor driving circuit. A switch on the left-hand side of the upper switchboard provides remote control for starting

6/ It is best to do this with both hands, one pushing (or pulling) on each of the push rods or blocks; otherwise, the concealed part of the limit mechanism is likely to jam from friction.

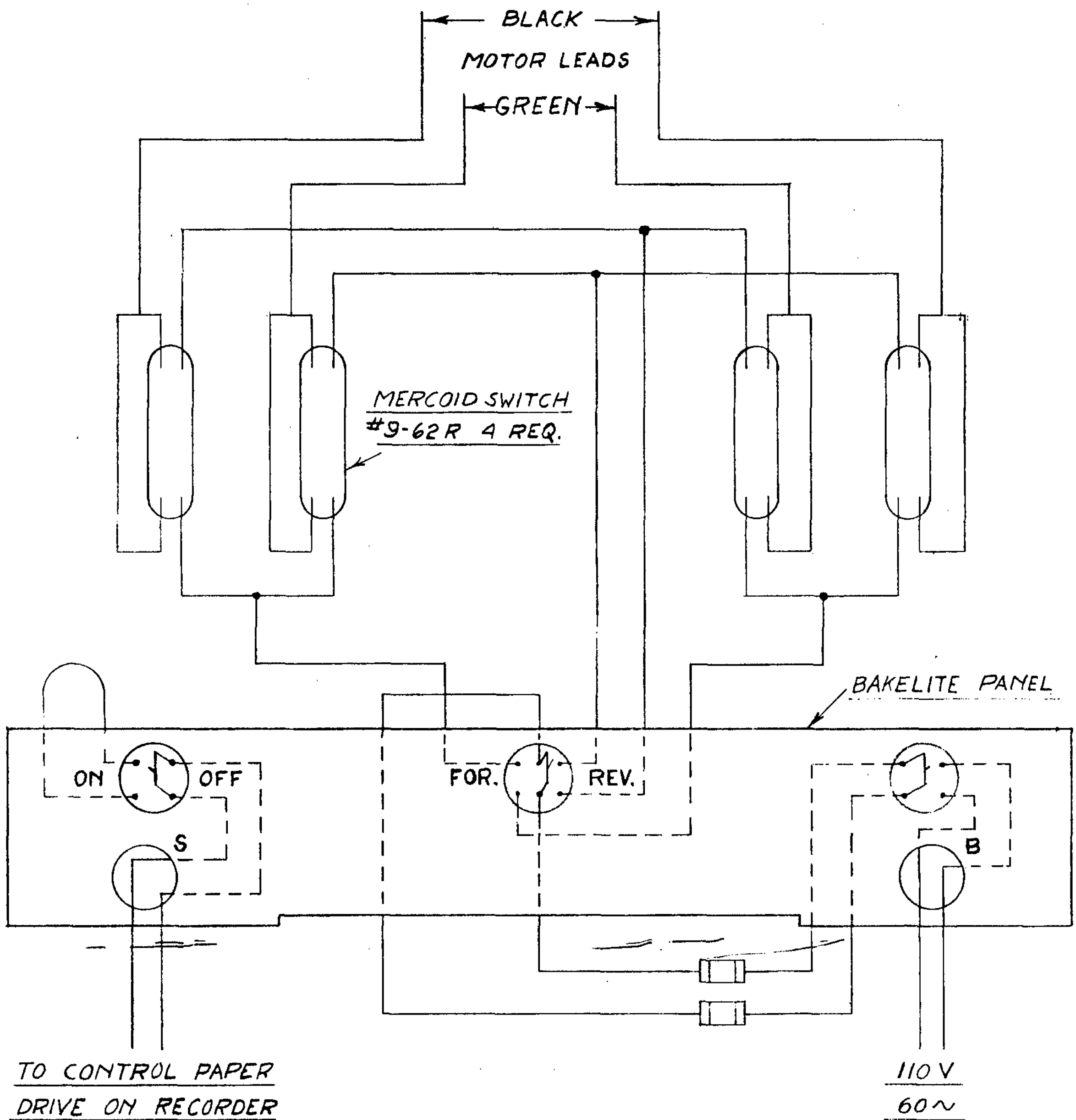


FIG. 13. DIAGRAM OF CONNECTIONS FOR DRIVING MOTOR ON EXPLORING DEVICE. (UPPER SWITCHBOARD).

the motion of the paper chart in the recorder. Flexible leads and "microphone-type" couplings are provided for the power supply on the right and for the recorder paper drive on the left, the correct association of couplings being insured by matching the colors painted on their male and female members. Figure 13 shows how the motor is connected through the reversing Mercoid switches and the switchboard.

The Mercoid switches for reversing the motor stand on tilting tables with counterweights adjusted so that a center of gravity high above the tilting pivots insures a strong tendency for them to remain tilted in either of two positions. Other counterweights increase the moment of inertia so that the tilting action, once it is initiated by a sufficient elongation of the springs coupling the tables to the 1/8-in. brass push rods, will surely continue past the center. The push rods are moved by means of a brass coupling yoke which is between the upper and lower sides of the belt and this, in turn, partakes of the motion of a long flat stick of wood to which it is screwed. This long flat stick of wood lies with a smooth sliding fit in slots provided for it in the cross ribs of the long inner wooden frame to which the belt pulleys are attached. Four maple rocking arms pivoted on maple shafts below the long flat stick project upward through rectangular holes in the latter to such a height that their ends can be engaged by a Bakelite pin. This pin projects below the belt under the center of the carriage into a long slot provided for it in the table top on which the belt slides. When this pin in its travel encounters a rocker arm, the latter is tilted over so as to displace the long flat stock longitudinally, thus operating the Mercoid switches. The rocker arm can, however, be thrown out of line with the pin on the belt so that it becomes inoperative as a limit mechanism. This is done by screwing a Bakelite screw plug into the right-hand hole provided for it in the outer lateral surface of the long box. This plug, when screwed down to the end of travel, pushes on the end of the maple pivot shaft to which the rocker arm is permanently attached and causes the rocker arm to slide transversely to the long axis of the box into a position out of line with the travel of the pin under the belt. This particular arm is thus rendered inoperative. No such provision is made for rendering inoperative the last rocker arm at the extreme end of travel far from the driving mechanism, as there is never any reason for permitting the carriage to pass this point. Thus there are four points provided in the travel of the carriage where stoppage and reversal of the motor connections is effected automatically, if desired, and three of these points can be rendered operative or inoperative at will. To restore a rocker arm to operation as a limit mechanism, the screw plug is merely removed from the hole in the right-hand side of the box and screwed all the way into the opposite hole in the left-hand side. When the two extreme rocker arms are the only ones operative, the travel of the carriage is about 70 in. When the other two are limiting the carriage motion, the travel is about 50 in.

The exploring device is located on its supports in such a way that both these travels have their center points under the center of the solenoid coil array. Two travels are provided because, when the exploration is at a deep level below the plane of definition, the outward spreading characteristic of magnetic fields calls for wider latitude of exploration, while at levels immediately under the coils, such a long travel might be a waste of time.

It is not necessary to use the automatic limit mechanism, of course, but if it is rendered inoperative, one must not forget to exercise manual control; if the driving power continues when the carriage reaches the end of its travel, damage can occur to the mechanism.

74. Cam mechanism for exploring device for making a fiducial mark on the chart record

A means is needed for making a fiducial reference point on the recorder chart paper, corresponding to the point on the exploring device where the search coil always passes one and the same value of x (relative to the coil box). What value of x is so indicated is unimportant, so long as it is always quite reproducibly the same. Such fiducial marks on all the signatures taken on the recorder serve to line these up correctly in the x-direction relative to one another.

This is accomplished on the exploring device by means of a bell-crank-lever cam fitted with a wheel on its extreme end which rolls on the belt. The wheel is made to bear firmly on the belt by means of a tension spring, the bearing point being directly over the brass belt pulley. A rectangular hole is cut in the belt and, when the wheel on the cam falls into this hole, the right angled arm of the bell-crank-lever strikes the button of a <u>microswitch</u>; this switch then performs the function of a single-pole double-throw switch by opening the normally grounded member of the pair of conductors connecting the search coil to the recorder and introducing in series with this conductor at the open point a 270-cycle/sec voltage of the order of 1 mv and having the same phase as that of the search coil. The source of this special voltage supply is the standardizing millivolt box described in Secs.76-78. The depth of the hole (equal to the thickness of the belt) into which the lever wheel drops is amply sufficient to actuate the microswitch. The brass bracket on which the bell-crank-lever pivot is mounted is adjustable on the bearing cap to which it is screwed so that it can be adjusted to give operation of the microswitch in the correct way when the wheel falls in the hole and yet allow the microswitch to be in its normally closed position when the wheel is rolling on the belt. The hole in the belt is very short in the $\underline{x}$-direction so that the insertion of the 270-cycle/sec voltage into the line to the recorder lasts only a small fraction of a second, a time indeed sufficient for the recorder pen carriage to give the full response required by the applied impulse. The motion of the pen is so rapid, however, that the peak drawn is very sharp indeed. Tests were made of the reproducibility of this fiducial marking device by cutting another similar hole in the belt at a second point not likely to be frequently used. The roller was allowed to drop successively into both holes and the separation between resulting peaks on the recorder chart was measured for repeated trials. No variability could be detected of the order of 0.01 in.

75. <u>The second or lower switchboard on the exploring device</u>

The board provides convenient terminals -- 10 pairs of binding posts -- for all the search coil cables that are ever likely to be required. Any one of these can thus be selected for connection to the recorder or, if one wishes, weighted averages of the emf output of several search coils exploring at once can be formed by hooking up the search coils with appropriately designed transformers at this switchboard 7/. Designate any such unknown emf which one desires to connect to the recorder by the symbol *x*. Then *x* should be connected to the binding posts +*x* and -*x* in the two extreme lower corners of this lower board. The cables to the recorder are to be connected to the binding posts marked "Recorder + and -." The algebraic signs are not a matter of indifference; they must be so chosen that the white rubber covered lead in the twisted pair of the recorder cable goes to the same algebraic sign on its binding post as the red tracer lead

7/. This provision makes it possible to apply a method of interpolation so as to plot on the recorder, graphs of unknown signatures situated between other signatures which have been given. The interpolation can be made of higher order than a merely linear variety. See Appendix B.

(or core) of the search coil. This is the "live" or unground lead. The black rubber covered lead is the other member of the twisted pair while the black silk covered lead is merely connected to the shield in the recorder cable. The calibrating millivolt box output is to be connected to the binding posts marked "Calibrating voltage + and -". With these connections made, the tumbler switch on the lower left may be snapped to the side marked "Rec," in which case the emf x from the search coils is connected to the recorder; or this switch may be snapped to the side marked "Cal," in which case the recorder input is not connected to the unknown emf x but may be either supplied with the calibrating voltage from the calibrating millivolt box or shorted to test the zero position of the recording pen. The choice of these two possibilities is made with the tumbler switch on the lower right marked on one side "Short" and on the other side "Cal.V."

It is found advisable to test the zero of the recorder at the start and end of every travel of the explorer carriage. It is also well to throw the calibrating voltage on the recorder frequently. The standardizing deflection thus obtained can be used as a reliable correction for any slight changes (temperature, and so forth) which may vary the deflection response of the recorder. The absolute value of this calibrating voltage may indeed change, since it comes from the same supply (the 270-cycle/sec M.G. set) as the supply for the solenoids and the 270-cycle/sec standardizing supply to the recorder. However, as we have already explained,

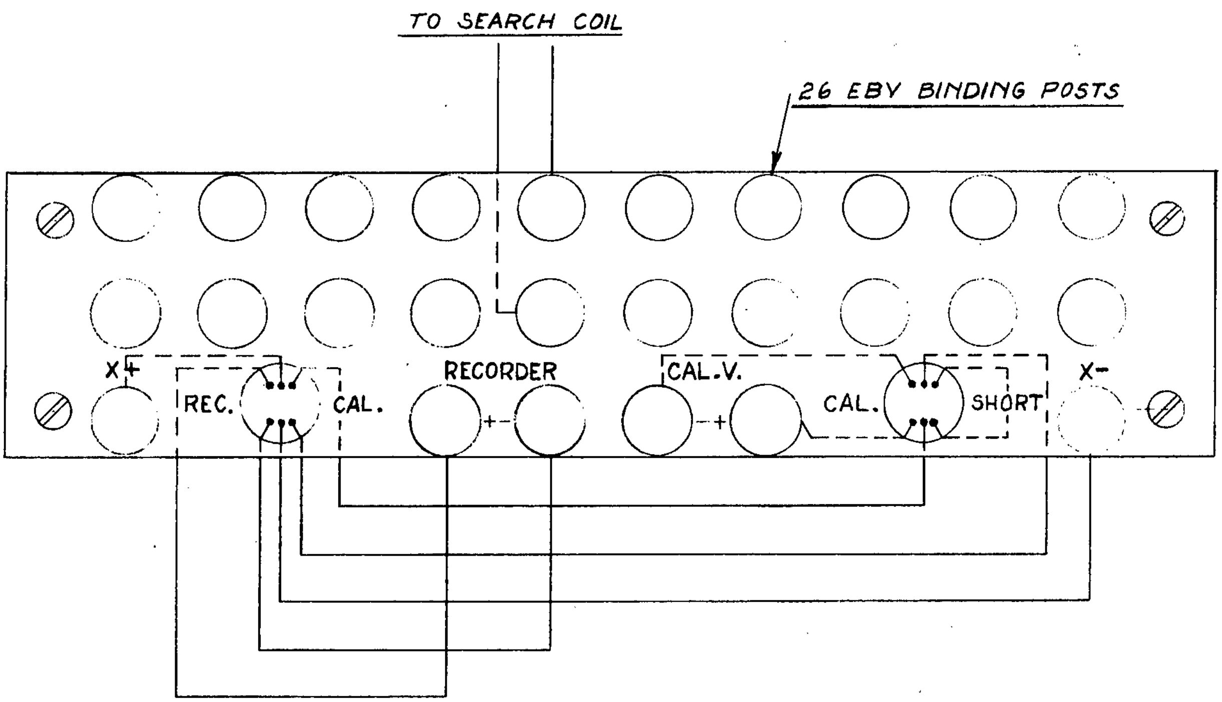


FIG. 14. LOWER SWITCHBOARD ON EXPLORING DEVICE AND DIAGRAM OF ITS CONNECTIONS.

we are interested in recording, not absolute voltages from the search coils, but the ratio of the search coil voltage to the voltage applied to the solenoids; so the calibrating millivolt box furnishes exactly what is needed.

Figure 14 shows the appearance of the lower switchboard on the exploring device and a diagram of its connections.

76. The calibrating millivolt box; requirements

Evidently all that is needed to check the deflection scale of the phase sensitive potentiometer recorder is a means of substituting for the search coil emf a low 270-cycle/sec voltage of order 1 mv which shall always be strictly proportional to the secondary voltage on the tap transformer and shall have the appropriate phase. Clearly this phase should be almost exactly in "quadrature" (at one-quarter cycle phase displacement) with the phase of the tap transformer because the potentiometer recorder is provided with a phase shifting network adjusted to bring about a coincidence of phase between the emf of the search coil and the potential difference across the potentiometer slide wire resistor over which the pen carriage wipes. It will be recalled that these two voltages are to be algebraically added (in series) and the sum used as a signal through the amplifier, so as eventually to command the pen carriage driving motors. If, however, these voltages cannot add algebraically for the reason that they are not exactly in phase (or in phase opposition), they will never be able to balance each other exactly at any point on the slide wire.

A slight residual voltage will always remain, even at the point where balance is most nearly obtained, this residual being in fact the quadrature component of the search coil voltage (relative to the slide wire voltage) which remains after the in-phase component of the search coil voltage has been balanced out.

77. Phase relationship discussed

It is clear that the search coil voltage is very nearly in quadrature with the tap transformer voltage because the instantaneous value of the search coil voltage is proportional to the time rate of change of that part of the magnetic flux from the solenoids which links with the turns of the search coil. This instantaneous emf, in volts, is in fact given by the equation

$$e = 10^{-8} \frac{dH_A}{dt} \cdot na, \qquad (4)$$

where H_A is the average axial component of the magnetic field intensity in the region of the search coil, n the number of turns of the search coil and a the average area of a turn. Equation (1) is directly derived from Eq. (4) on the assumption that the alternating voltage is sinusoidal, and, on this assumption, Eq. (4) requires the phase of H to differ from the phase of e by one-quarter cycle. But the phase of H closely coincides with the phase of the secondary voltage of the tap transformer because, as previously stated, the ratio of reactance to resistance in the solenoid windings

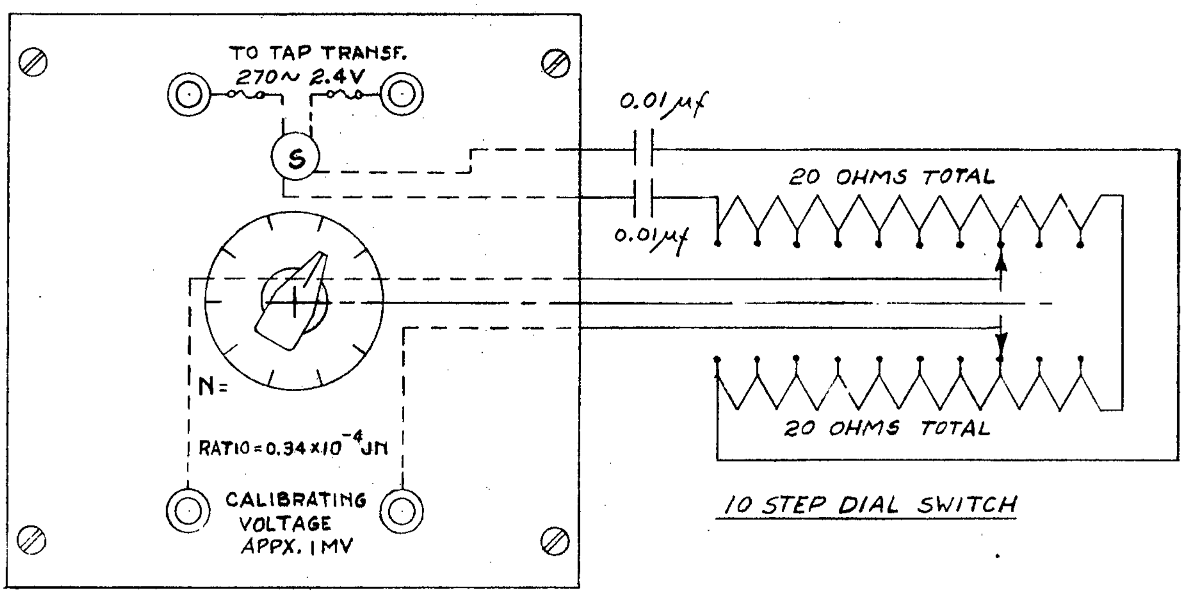


FIG. 15. COVER OF CALIBRATING MILLIVOLT BOX AND DIAGRAM OF CURCUIT.

is purposely very low, giving a phase displacement between the current and applied voltage in those windings of less than 1° (1/360 cycle).

78. Calibrating millivolt box design

Figure 15 shows the appearance of the cover and the diagram of the calibrating millivolt box. It seemed desirable to provide a means of obtaining, not only one standardizing voltage, but a series of such voltages, (1) because different deflection scale ranges (sensitivities) on the recorder will perhaps require the use of different calibrating voltages, and (2) as a means of checking linearity of scale on the recorder. Accordingly, ten voltages increasing by uniform increments from 1/10 of full output to full output are made available by means of the dial switch. The ratio marked on the cover, 0.34×10^{-4} *JN*, is the factor by which the input voltages (on the terminals marked "To Tap Trans.") must be multiplied to obtain the much smaller voltages appearing at the terminals marked "Calibrating Voltage". Here *N* is the number of the step set on the dial switch and *J* is the electrical engineering symbol for a change of phase of one-quarter cycle. The maximum calibrating voltage obtainable is clearly 0.34×10^{-3} *JNV*, where *V* is the voltage selected on the tap transformer for connection to the calibrating millivolt box. Suppose *V* is 2.4 volts, as obtained by connecting the alligator clips on the end of the long rubber covered cable provided with the calibrating millivolt box to the +1.2 and -1.2 volt taps, respectively (eight taps of the tap transformer contiguously and symmetrically disposed about the grounded center point). The impedance in the circuit(which is almost entirely due to the capacitances of the two 0.01 μf condensers) is 1.18 X 10^5 ohms at 270 cycle/sec. The resulting current through the resistors is closely in quadrature with the tap transformer voltage and will produce a quadrature potential difference of 0.814 mv across all of them in series. The range of the millivolt box can be further extended, of course, by appropriate choice of the taps on the tap transformer. To save expense, only moderately accurate resistors were used in the millivolt box; better ones can readily be substituted for them if greater precision becomes desirable.

79. General requirements for y- and z-adjustments on exploring device

Early tests of the exploring device were made with rudimentary supports consisting of straight horizontal sticks clamped to the vertical posts at the two ends of the supporting under-frame of the coil box by means of all-wooden cabinet makers' clamps. As a unit of length for settings of the coordinates *y* and *z*, it is convenient to adopt the mean distance between adjacent signatures or rows of coils (0.4615 in.). As already stated, this frequently is taken to represent 20 ft, the distance between adjacent search coils on the range where the ship's field is explored in the measured plane. This unit will usually be referred to as 1 coil-width. Scales in terms of this unit were laid out, for *y* on the transverse

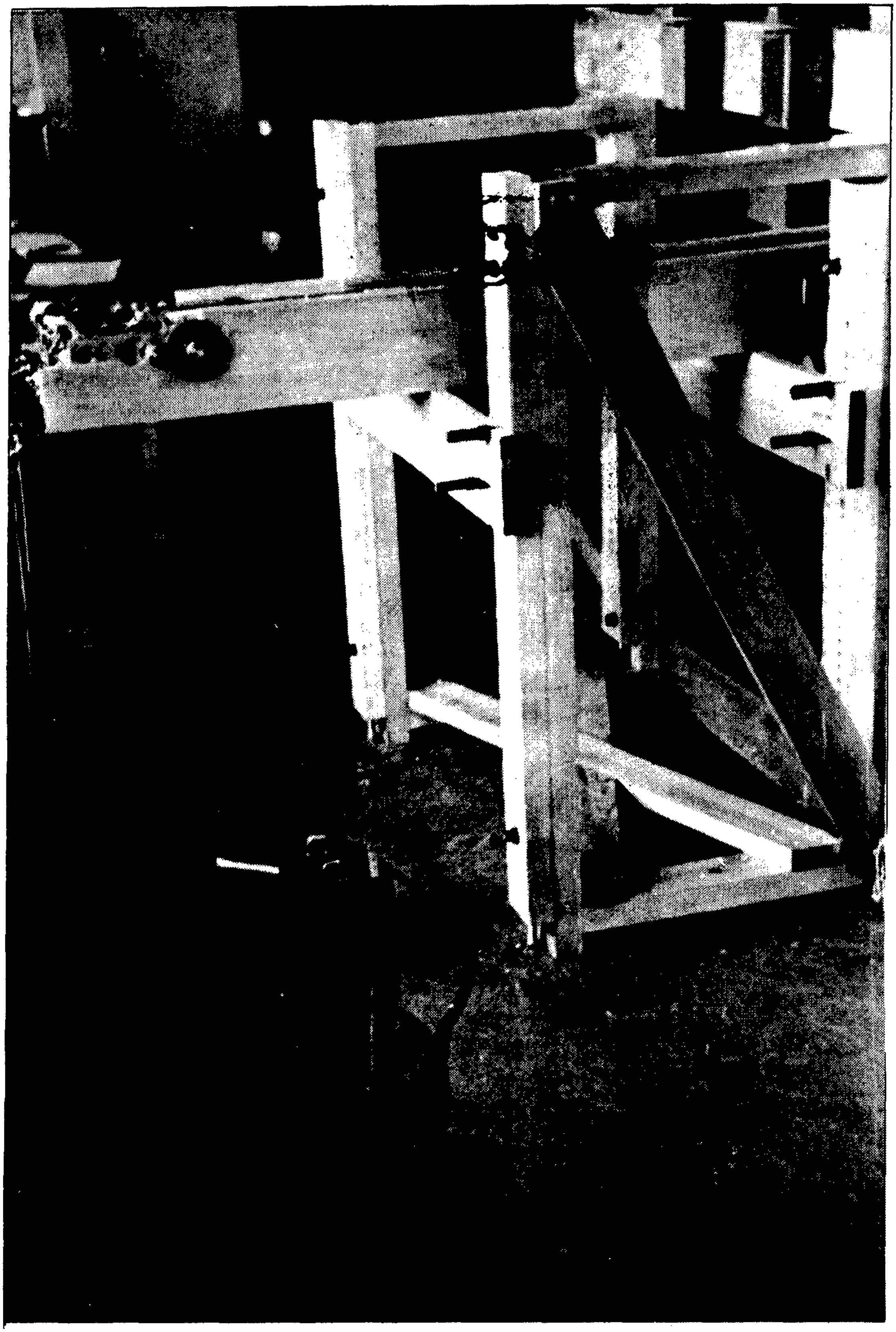


Plate V. The outboard structure, showing the adjustable vertical stanchions, maple cross bars, exploring device and millivolt box.

horizontal sticks, for *z* on the vertical posts supporting the coil box. After considerable work had been done, so that a clearer notion of the requirements had been secured, more convenient, precise and permanent facilities for adjusting the *y*-and *z*-coordinates of the exploring device were designed and installed.

80. Weight distribution and provisions for support of exploring device; Bakelite carriages for y-adjustment

The weight of the driving mechanism of the exploring device throws the center of gravity of the latter to a point only about one-quarter of the total length away from the working or driving end. If, then, the exploring device in its requisite *x*-position rests only on two horizontal sticks located at the ends of the coil-box supporting frame, the overhanging heavy end of the exploring device makes it unstable. Therefore, a horizontal supporting stick has been provided about 2 ft out from the supporting under-frame of the coil box (nearer the driving mechanism). This last horizontal bar is itself supported upon an outboard structure consisting of two well-braced rectangular frames of maple that rest on the floor and are attached to the main under-frame of the coil box by heavy countersunk Bakelite screws. In spite of the bracing, however, the rigidity of this outboard structure, while excellent in the vertical direction, is insufficient in the horizontal direction to serve with absolute certainty to hold the position of a scale of *y*-displacements relative to the coil box if it were marked on the horizontal supporting stick nearest the driving mechanism with the precision that our tests showed was required in some cases. Bracing adequate to insure such required rigidity would have decreased the accessibility of the exploring device, and so it was decided to index the *y*-position of the exploring device at the operator end, with a scale located on a transverse stick which is carried close to the heavy under-frame support of the coil box, and which has just enough clearance below the bottom of the exploring device so that it carries none of the weight of the latter. Thus there are three transverse supports: one far from the operator, carried close to the under-frame of the coil box which supports little weight and is provided with a *y*-scale; one intermediate in position, also carried close to the under-frame of the coil box which supports no weight and is provided with the other *y*-scale for locating the exploring device; and one near the operator, carried on the outboard structure, supporting most of the weight of the exploring device, but not provided with a scale for *y*-settings. The exploring device does not rest directly on these horizontal supports but on Bakelite carriages fitted to slide easily on the horizontal supports and provided with screw driven slow motion slides built into their tops. The exploring device is pinned to the top of that Bakelite carriage which is nearer the operator by means of a ball-ended pin on the sliding top of the carriage engaging an accurately fitting Bakelite-lined cylindrical socket on the bottom of the exploring device. The top of that carriage which is farther from the operator is equipped with a pin having a swivelling square Bakelite head which engages an elongated maple lined slot in the bottom of the exploring device. This elongated slot allows the exploring device, without danger of jamming the carriages, to lie as obliquely as it ever might be placed beneath the coil box in the process of adjusting its position. Thus, when the settings of both *y*-scales have been made correctly, the exploring device lies parallel to the *x*-axis *and has an invariable position in the x-direction* imposed by the ball pin in the cylindrical socket. The exploring device is readily disengaged from the ball pin and square swivel pin merely by lifting it upward (care being taken to see that the search coil carriage is so located that the delicate search coils cannot possibly be hit). Accurate settings of the exploring device on the two *y*-scales are greatly facilitated by the slow-motion screw-driven slides on the Bakelite carriages. A rough *y*-setting of the exploring device is first made by sliding the carriage as a whole on the transverse stick. Then the precise setting is made by means of the slow-motion screw which slides the top of the carriage (on which the exploring device rests) with respect to the bottom. This motion can have an amplitude of about 2 in. No index is provided on the exploring device for the *y*-scale nearer the operator; instead, the left-hand edge of the exploring device itself can be aligned very reliably with the divisions of the scale, since there is no carriage on that stick. The upper sliding member of the carriage on the horizontal stick far from the driving end of the exploring device is, however, provided with an index which is to be matched with the scale on that stick in making *y*-settings. This index can be adjusted to correct an additive constant error by loosening the two Bakelite screws that clamp it to the Bakelite carriage. The Bakelite carriage nearer the operator is also provided with a similar index which is not at present used but which has been supplied in case later changes should require it. Slot sockets and screw holes for attaching these indexes to either side of each carriage are also provided to meet the requirements of possible future modifications. The *y*-scales and indexes can always be checked by running the exploring coil carriage to such an *x*-position that the *y*-position of the search coil can be compared with the scratches on the heavy horizontal maple sill of the coil box frame. In this connection, note the remark at the end of Sec. 81.

81. After making y-settings at far end, the exploring device must be clamped or wedged to remove a slight warp

The geometric accuracy of the exploring device, which is made entirely of glued wood with no metal, was a difficult problem. Permanent straightness as regards the long axis seems to have been attained successfully and no changes of this sort have been observed. However, it is much more difficult to obtain the necessary rigidity against a slight torsional warp over the entire length (the two ends twisted in opposite senses around the long axis) and, unfortunately, such a warp of the order of half a degree (at one extreme relative to the other) occurred during or shortly after gluing and varnishing. Over a subsequent period of months, in February, March and April, no change in this warp was observed. <u>Therefore, after every y-setting has been made at the end far from the driving mechanism, a block and wedge should be inserted between the exploring device and the maple sill of the coil box bearing down on the extreme left-hand edge of the exploring device</u> ("left" as one faces the coil box when standing at the "far" end) to remove this slight twist. No such wedging is necessary at the driving end because the weight of the mechanism insures correct seating there. It is hardly necessary to point out that, when the <u>y</u>-index and scale is checked against the search coil position relative to the scratches on the maple sill, <u>this must be done with the exploring device wedged down to remove this slight warp</u>.

82. <u>The vertical or z-settings of the exploring device</u>

These settings are accomplished by raising or lowering the three horizontal maple cross bars on two of which the Bakelite carriages slide. The heights of these cross bars are adjustable in steps of 1 coil-width over a total range of 52 coil-widths and in steps of $\frac{1}{4}$ coil-width over a range of 8 coil-widths, the latter being for depths close to the plane of definition. The maple cross bars are pinned to vertical maple stanchions by means of Bakelite pins having tapered ends which pass through the cross bars into taper holes accurately located by jig boring in the maple stanchions.

The straight shanks of the pins fit accurately through straight-bored holes in the maple cross bars which locate in every case the left-hand ends of these bars. The Bakelite pins pass through horizontally elongated slots in the cross bars to locate the heights of their right ends, however. In this way the two vertical stanchions with their holes need not be located with extreme precision in the _y_-directions, and slight dimensional changes in them and in the cross bar do not interfere with pushing the taper pins "home" in their taper holes. Beside these pins which locate the height of the cross bars, Bakelite screws passing into threaded holes in the stanchions serve to clamp the maple cross bars closely to the stanchions to fix their _x_-locations definitely. These pass through U-shaped notches in the edges of the cross bars. Four of the holes in each stanchion serve the double purpose of both taper pin holes and threaded screw holes, the maple cross bars being at different heights, however, when the two different applications of these holes occur. The threads near the bottom of the taper hole are sufficient in number for strength and do not interfere with the reliability of location obtained from the remainder of the tapered portion. When assembling the apparatus, the Bakelite screws for this purpose can be distinguished from those for attaching the stanchions permanently to the frame of the coil support structure by the fact that the former have long heads of square section for convenient manual turning, whereas the latter have short square heads (which should be turned only with a socket wrench).

The steel jig with its accurately located holes, which was used for guiding the drill in boring the holes in the maple stanchions, is furnished with the equipment in case future checking, warping or wear of these stanchions should necessitate duplicating them. Some spare stanchions, already jig bored, are also furnished. Four sleeves fitting the holes in the steel jig go with it. Two of these are, respectively, for guiding the preliminary and final drill sizes for the taper holes, while the other two perform the same function for the tapped holes. It was found necessary to drill all holes to a preliminary diameter slightly undersize and let the stick stand a few days until it had adjusted itself before finishing the holes.

83. The "zero adjustment" of z

The stanchions are clamped to the maple supporting frame by Bakelite cap screws passing through elongated and countersunk slots in the stanchions, so that they can be adjusted as to height. These cap screws should be loosened preparatory to the adjustment only just enough to allow vertical sliding of the stanchion with no looseness. The z-adjustment is made by turning a brass screw at the bottom end of each of the stanchions. This screw bears on the floor and supports the weight of the exploring device. It is threaded into a brass sleeve secured in the bottom of the stanchion. The use of metal at this point close to the floor is permissible.

The initial zero adjustment of the stanchions is made as

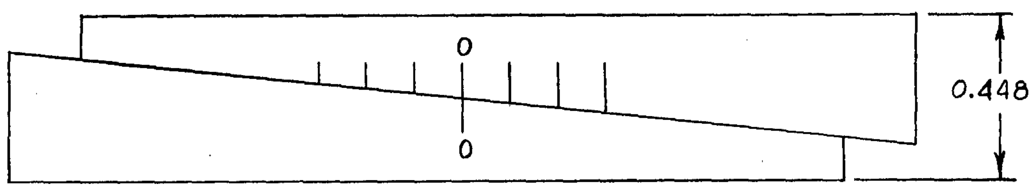


FIG. 16. WEDGE GAUGE FOR ZERO ADJUSTMENT OF Z
EACH DIVISION IS 0.010"

follows. The taper pins are inserted so as to locate the maple cross bars at the nominal value $z = 1$ coil-width. (See below for the arrangement of pins and holes.) The heights of the stanchions are then adjusted by means of the brass screws at their lower ends so as to bring the whole assembly of cross bars, carriages, exploring device and search coil to such a position that, for all x-and y-settings under the array of coils, the center of the search coil is just 1 coil-width, or 0.4615 in., below the ends of the solenoid windings. By measuring the dimensions of search coils and taking into account the length of hard rubber core projecting beyond the first turn of the solenoids, it was determined that, when the aforementioned setting obtains, the distance from the plane of the ends of the hard rubber cores to the plane surface of the top of the exploring carriage should be just 0.448 in. A pair of small cooperating maple wedges were accordingly prepared to serve as a thickness gauge to test this clearance (Fig.16). These are supplied with the apparatus. When the index (marked 0) on one wedge is aligned with the zero of the scale on the other wedge, the thickness of the pair has the required value. The other marks on one of the wedges represent successive deviations above and below this correct setting in successive steps of 0.010 in. each. The adjustments are preferably made in four locations, with the carriages and exploring device set so as to bring the search coil carriage successively under the four extreme corners of the array of solenoids. The search coil carriage should be near the corner, but far enough from the boundary of the array to permit the wedges to seat truly on the flat surface formed by the ends of the hard rubber cores without touching anything else save the top of the exploring coil carriage. The wedge gauge should not be read until the exploring device has had its warp removed in the manner explained in Sec. 81. The error, or deviation from correct clearance, is then read on the wedge gauge for all four corners and appropriate adjustment of the stanchions is made to correct this. A little geometric calculation is advisable 8/ to determine how much each of the stanchions must be moved vertically because the stanchions are not located under the corners of the array of solenoid coils but must be spread much wider apart to afford necessary clearances. When this has been done, it will also be found helpful to observe the actual correction made in the height of the stanchion and

8/. The following formulas for computing the required adjustments apply to the dimensions of the present framework. Let e_1, e_2, e_3 and e_4 be the errors (positive or negative) at each of the corners of the array of coils, the measured points being at the corners of a rectangle centered with the array and of dimensions 8 X 43 in. Then, if the adjustments to be made on the four stanchions are a_1, a_2, a_3, and a_4,

$$a_1 = 3.5e_1 - 1.5e_4 - 0.5\,(e_2 + e_3),$$

$$a_2 = 3e_2 - 2e_3, \quad a_3 = 3e_3 - 2e_2,$$

$$a_4 = 3.5e_4 - 1.5e_1 - 0.5(e_2 + e_3).$$

In each case the subscripts refer to the same numbering as is used to designate the four corners of the maple framework; this is stamped on the maple sills. All the quantities and operations in these formulas are algebraic.

to regulate it to the desired value by means of a machinst's dial depth-indicator. This indicator may be conveniently mounted on a machinist's surface gauge, the base or block of the latter being placed on the top of the maple sill of the coil box supporting frame at the far end of the coil box and on the maple outboard structure at the working end, while the push-pin of the dial indicator contacts the top of the stanchion to be adjusted. A rational quantitative procedure such as this will save much time and will permit correct adjustment to within two or three thousandths of an inch at all four corners in the first or second attempt. Needless to say, it is the two most distantly separated pairs of stanchions that must be thus accurately adjusted in height, since these are the ones that support the exploring device. The third pair of stanchions, which only supports the cross bar bearing the nearer of the two _y_-scales, need only be adjusted later so that the cross bar does not quite touch the bottom of the exploring device in any _y_-position.

All these adjustments will be facilitated if the coil-box supporting frame has first been carefully leveled by adjusting a number of double maple wedges between it and the floor. This frame is quite rigid and true so that a test of the levelness of any of the horizontal members of the frame is a fairly reliable indication that the surface formed by the lower ends of the hard rubber solenoid cores is level. This surface itself can, however, be directly tested with a level by preparing a block of wood of the shape shown in

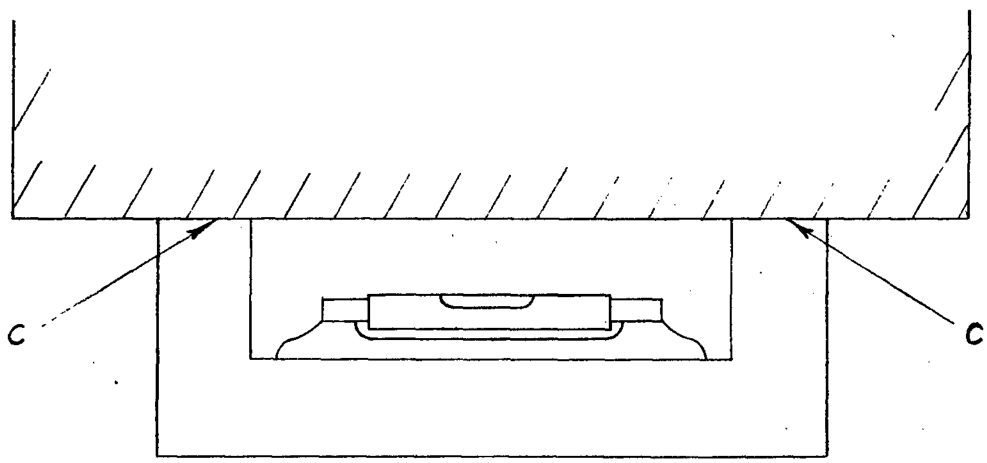


FIG. 17. METHOD OF LEVELING LOWER SURFACE FORMED BY ENDS OF SOLENOIDS.

Fig. 17 to support an ordinary level. The parallelism of the contact surfaces C of the block with the axis of the level can be tested by the well-known method of reversals. If this leveling of the under surface of the solenoid core ends has been done, a check on the adjustment of the heights of the stanchions can be made by seeing if the top surfaces of the two extreme maple cross bars lie in the same level plane. It may be found possible to establish a somewhat more exact parallelism between the x y-plane defined by the exploring device and the under surface of the hard rubber solenoid core ends by leveling than by the wedge gauge. The latter, however, affords the only method of establishing the zero of the z-scales correctly.

84. Sealing wax witnesses

When the heights of the vertical maple stanchions have been correctly set, the Bakelite cap screws clamping them to the maple framework should be tightened down with a socket wrench. It is also a good precaution, at this point, to melt a large drop of sealing wax at the point of contact between the brass height-adjusting screw of the stanchion and the floor, applying enough heat to obtain adherence to both. This serves as an indicator that the brass screw has not been accidently disturbed or turned so as to falsify the zero adjustment of z. Similar sealing wax "witnesses" on the maple wedges supporting the entire coil box structure are a good precaution.

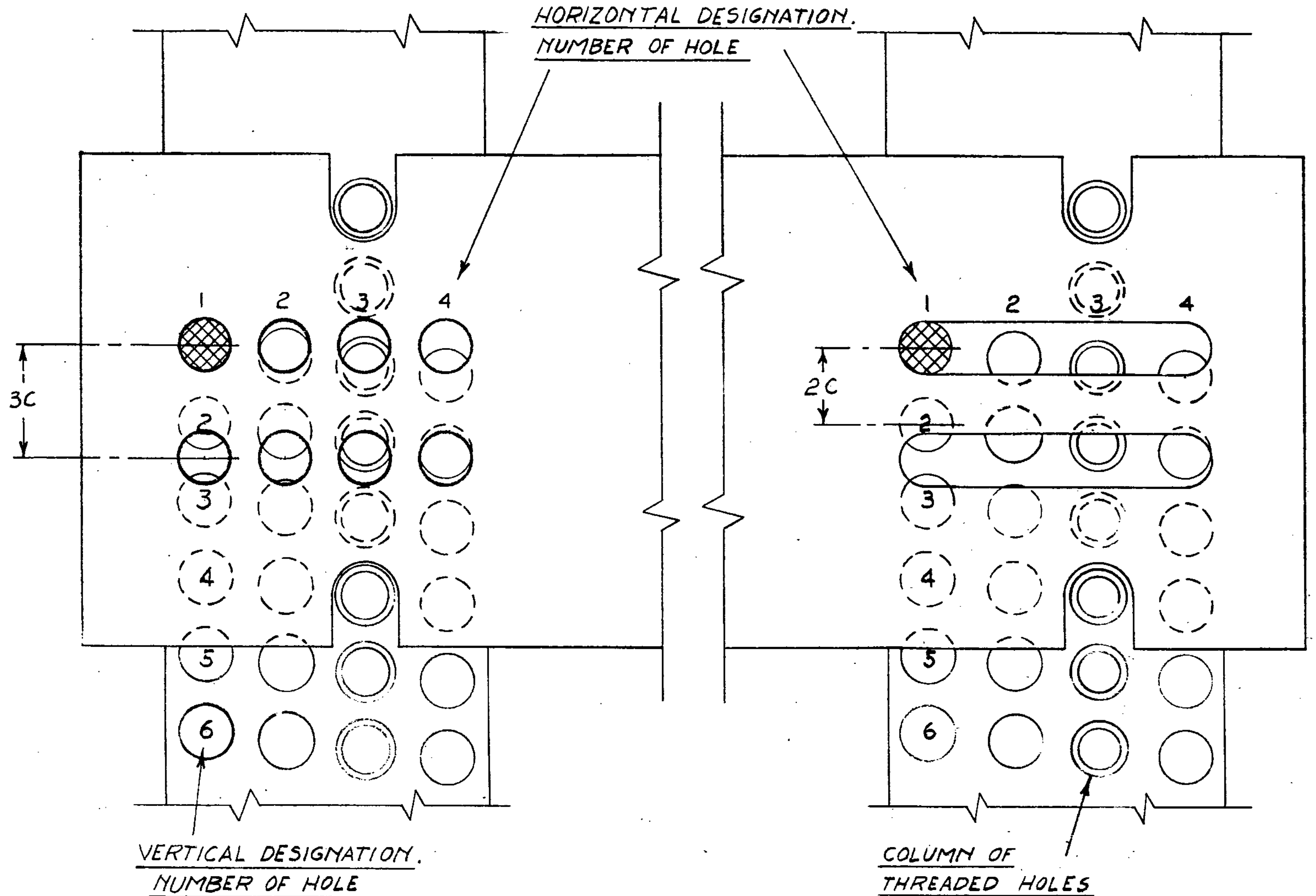


FIG. 18. ARRANGEMENT OF PINS AND HOLES FOR Z SETTINGS OF CROSS BARS. THE NUMBERS IN THE HOLES AND ON THE VERTICAL ROWS OF HOLES REFER TO THE "DESIGNATION NUMBERS" OF THE HOLES IN THE "TABLE OF PIN SETTINGS FOR Z ADJUSTMENT" AND ARE NOT VALUES OF Z.

85. <u>Precaution: the zero of z must always be readjusted if new cross bars are substituted for old ones</u>

This precaution is so obvious that little comment is needed. The relationship between the holes and the upper guiding edges of the cross bars cannot be relied upon to be reproducible in all cross bars.

86. <u>Method of setting the cross bars for various values of z</u>

Figure 18 shows the appearance of the holes in the stanchions with a cross bar in place. The pin location is shown with a black circle. In order to have room for pins of adequate strength and still provide the requisite fineness of height adjustment, it was necessary to have a choice of two heights (in the form of eight holes on one end and two horizontal slots on the other) for insertion of the pin through the maple cross bar in addition to the array of holes in the stanchion. The upper and lower rows of four holes on one side of each cross bar and the upper and lower slots on the other side are each separated by a difference in height of 3 coil-widths. In Fig. 18 the pins and cross bars are shown in the position which gives $\underline{z} = 1$ coil-width. Table II indicates the way of obtaining $\underline{z}$-settings below this one more readily than it can be explained in words. The system can be quickly learned, however, and then the table need not be used. Scales are provided on the stanchions (indexed for the upper edges of the cross bars) so that it is very easy (after the pins are inserted) to consult these scales and see if the $\underline{z}$-setting is correct.

Table II. Pin settings for z-adjustment (See Fig.18).

	Position of Pin in Cross Bar			Position of Pin in Stanchion	
	Desired z-Settings	Vertical Designation of hole	Horizontal Designation-No. of hole	Vertical Designation-No. of hole	Horizontal Designation-No. of hole
Settings in steps of $\frac{1}{4}$ coil-width	1	Upper row	1	1	1
	$1\frac{1}{4}$	Upper row	2	1	2
	$1\frac{1}{2}$	Upper row	3	1	3
	1-3/4	Upper row	4	1	4
	2	Lower row	1	3	1
	$2\frac{1}{4}$	Lower row	2	3	2
	$2\frac{1}{2}$	Lower row	3	3	3
	2-3/4	Lower row	4	3	4
	3	Upper row	1	2	1
	$3\frac{1}{4}$	Upper row	2	2	2
	$3\frac{1}{2}$	Upper row	3	2	3
	3-3/4	Upper row	4	2	4
	4	Lower row	1	4	1
	$4\frac{1}{4}$	Lower row	2	4	2
	$4\frac{1}{2}$	Lower row	3	4	3
	4-3/4	Lower row	4	4	4
	5	Upper row	1	3	1
	$5\frac{1}{4}$	Upper row	2	3	2
	$5\frac{1}{2}$	Upper row	3	3	3
	5-3/4	Upper row	4	3	4
	6	Lower row	1	5	1
Settings in steps of 1 coil-width	7	Upper row	1	4	1
	8	Lower row	1	6	1
	9	Upper row	1	5	1
	10	Lower row	1	7	1
	11	Upper row	1	6	1
	12	Lower row	1	8	1

87. Rules for setting pins

Examination of Table II will show that, for odd whole number values of z the upper holes (or slots) in the cross bar are always used while for even whole number values of z the lower holes (or slots) are used. Also, if only whole number values of z are considered, the left-hand vertical column of holes in the stanchion is used exclusively and z equals 1 in the top hole of this column, while the rule for increasing z is "down two holes" "back up one hole" "down two more" "back up one", and so forth. The fractional values of z derive from the integer values in an obvious way.

88. Tests carried on at the National Bureau of Standards

After delivery of the equipment during the first week of February 1941 at the National Bureau of Standards, some time was occupied in leveling the apparatus, building cable supporting structures, wiring, and connecting the cables between the tap transformer, the switching panels and the coil box. Adjustment and physical tests were started March 1; this was the first day on which the entire equipment had been made to function as a unit.

89. Tests of individual solenoids and elevators

By means of the exploring device the search coil was placed successively under the center of each and every solenoid with about 1/8 in. clearance below the end of the hard rubber solenoid mandrel, and the correct "elevator" on the panel switching device was slowly raised and lowered through its full travel while carefully watching the motion of the pen on the recorder. The objects were to check for: (1) possibly reversed or otherwise misconnected solenoids; (2) condition of contact of the elevator contact fingers; (3) uniformity of response of the search coil and recorder to different solenoids when these were equally energized (on same tap of tap transformer).

By this essential but rather tedious procedure, occupying more than a week for the 800 solenoids, four serious faults were found in the total array. Coils 21 and 25 in signatures 10 and 7 were found to have their windings connected so as to be reversed relative to the others. In signatures 11 and 12 the adjacent coils numbered 39 were found to have a connection between their windings at points roughly in the middle of their length. A similar trouble was found for the adjacent coils number 1 in signatures 8 and 9. This was first detected by noting that these coils gave incorrect maximum response on the recorder. Investigation then also showed that, when only one of the pair was energized, the other coil nevertheless was giving a field. Because of the possibility of further faults of this kind, an exhaustive test for such shorts from coil to coil was made (Sec. 90).

90. Tests for interconnections between solenoids

On the switching devices, signatures 2 to 20 inclusive (all except No. 1,which was left dead) were fully energized. An exploration along $\underline{x}$ was then made with the search coil centered directly under signature 1. The stray field from the adjacent live signatures could be observed as a constant deflection of about 1/5 maximum value. However, had any coil in signature 1 been connected to any coil in the entire remaining array, this would have shown up as an abnormal response in the vicinity of the first-mentioned coil. Next, signature 2 was explord with signatures 1 and 2 dead and signatures 3 to 20, inclusive, fully energized, looking always for abnormal response under signature 2. By the same process each signature was explored, with it and the signatures on its left-hand dead but the remaining signatures to right-hand fully energized. This gives an exhaustive test for shorts between signatures. No other shorts were found.

91. Correction of shorted coils

The representative of the Bell Telephone Laboratories, upon request, made a special trip to Washington. On his arrival the coil box was opened and the two banks of 20 coils, each of which contained one of the shorted pairs, were removed. It was found that a minute speck of metal, perhaps a chip or a filing, had become lodged between the solenoids in the case of each pair and, under the clamping pressure exerted on them by the walls of their containing box, had cut through the cellulose acetate covers on the coils. (The tests just described, however, cover the more general possibility that coils at some distance apart might be interconnected through some fault in the cables or in wiring and soldering the connections.) The coils were reassembled with strips of condenser paper placed between the pairs which had been shorted. Before closing the coil box the reversed coils were also corrected by reversing the wiring to them in the top of the coil box. Like several others so corrected at the factory, these coils had been supplied with top terminals incorrectly connected or else inadvertently assembled incorrectly in the box.

92. Contact finger faults in switching panels

The tests of individual solenoids and elevators were prolonged by the fact that an effort was made to correct all faulty contact fingers encountered as the test proceeded. A few such faults may still remain -- insufficient spring pressure, springs bent so as to hold the insulating rather than the conducting parts of the contact shoe against the projecting bus bar tongues, bent or displaced bus bar tongues, failure of register relative to positions defined by the rack and pawl, and so forth. Some of the less flagrant examples, it appears, do not always become evident on a first trial; and, as there has been no exhaustive exploration of all contacts on all elevators save the first one just described, it is advisable to observe future vigilance in locating and rectifying any such faults as make their appearance.

93. Fluctuations in solenoid intensities

It was observed that the different solenoids did not give quite the same deflection on the recorder, although care was taken to see that they were all energized from the same tap on the transformer. It seems impossible to ascribe these fluctuations from coil to coil to the very small differences in the resistances of the coils. The differences are observable only when the search coil is very close to the ends of the solenoid cores. To make this test more precise, a search coil was mounted firmly in a Lucite container provided with a surface which could be held in contact with the lower ends of the hard rubber cores. A cylindrical boss on this Lucite surface was provided, to engage the hole in the center of the end of each hard rubber core. The search coil was so mounted inside the Lucite as to be very close to the hard rubber end surface of the solenoids. A hand exploration of several signatures made with this device established that the fluctuations of intensity from coil to coil were real and very reproducible. They were of the order of 2 or 3 percent, with an infrequent deviation as high as 5 percent. Insertion of a mica shim only 0.002 in. thick between the Lucite and the hard rubber core end was sufficient to reduce the intensity 1/2 percent. Thus even the 5-percent fluctuations could be explained by assuming that these coils had the ends of their windings displaced only 0.02 in. from the common plane of the ends of the majority of coils. Such manufacturing variations do not seem at all unlikely and it is probable that the fluctuations in coil intensities can be ascribed to them. These fluctuations of magnetic intensity with the height of the end of the solenoid winding are in good accord with theory as shown in Appendix F. They diminish rapidly with the depth $\underline{z}$ of the search coil. The labor of readjusting the exact height of 800 solenoids seemed unwarranted, however, especially since the present fluctuations from coil to coil become completely indistinguishable at $\underline{z} = 3$ coil-widths and are not even very marked at $\underline{z} = 2$ coil-widths.

94. Exploration of the field of a single solenoid

The vertical component H_z of the field of coil 1 in row (or signature) 1, fully energized, was explored at depths $\underline{z} = \frac{1}{2}$, $1\frac{1}{2}$ and $2\frac{1}{2}$ coil-widths below the plane of definition. At each depth signatures were taken at various values of $\underline{y}$, starting with $\underline{y} = 0$ and extending as far off center as $\underline{y} = 4$ coils. The effects of varying the amplification factor (of the amplifier in the recorder) on the speed of response and stability, or hunting, of the pen were studied. The effects of variation of the 270-cycle/sec reference voltage input to the recorder were also tried. For comparison, some records were also made for the field of coil 20 in signature 1, to see if the proximity of other coils or their hard rubber cores could have any distorting effects on the field. This last-named test revealed no observable distortion. As for the reference voltage, the recorder was found to be noticeably and objectionably erratic when it was reduced from the recommended 50.4 volts to 25.2 volts. The pen would fail to return to zero satisfactorily. On further reduction to 12.6 volts this was greatly exaggerated, the pen failing to return to zero by as much as 22 percent of maximum deflection 9/.

9/ Full scale deflection, it must be recalled, is one-half the total travel of the pen carriage across the chart paper because the zero is in the middle of travel to permit deflections of both algebraic signs.

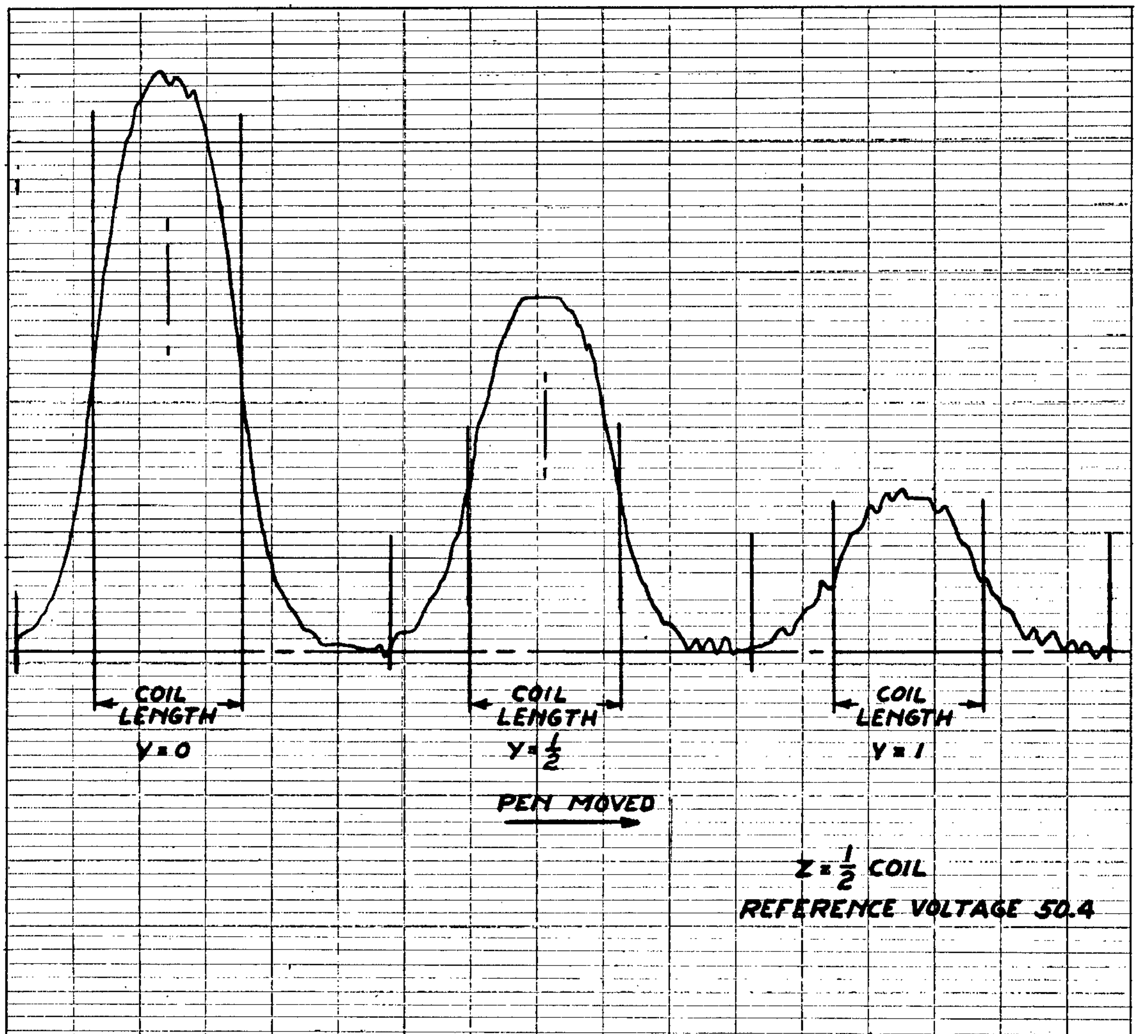


FIG. 19. SIGNATURES OF COIL 1 IN ROW 1 AT VALUES OF Y AND Z INDICATED.

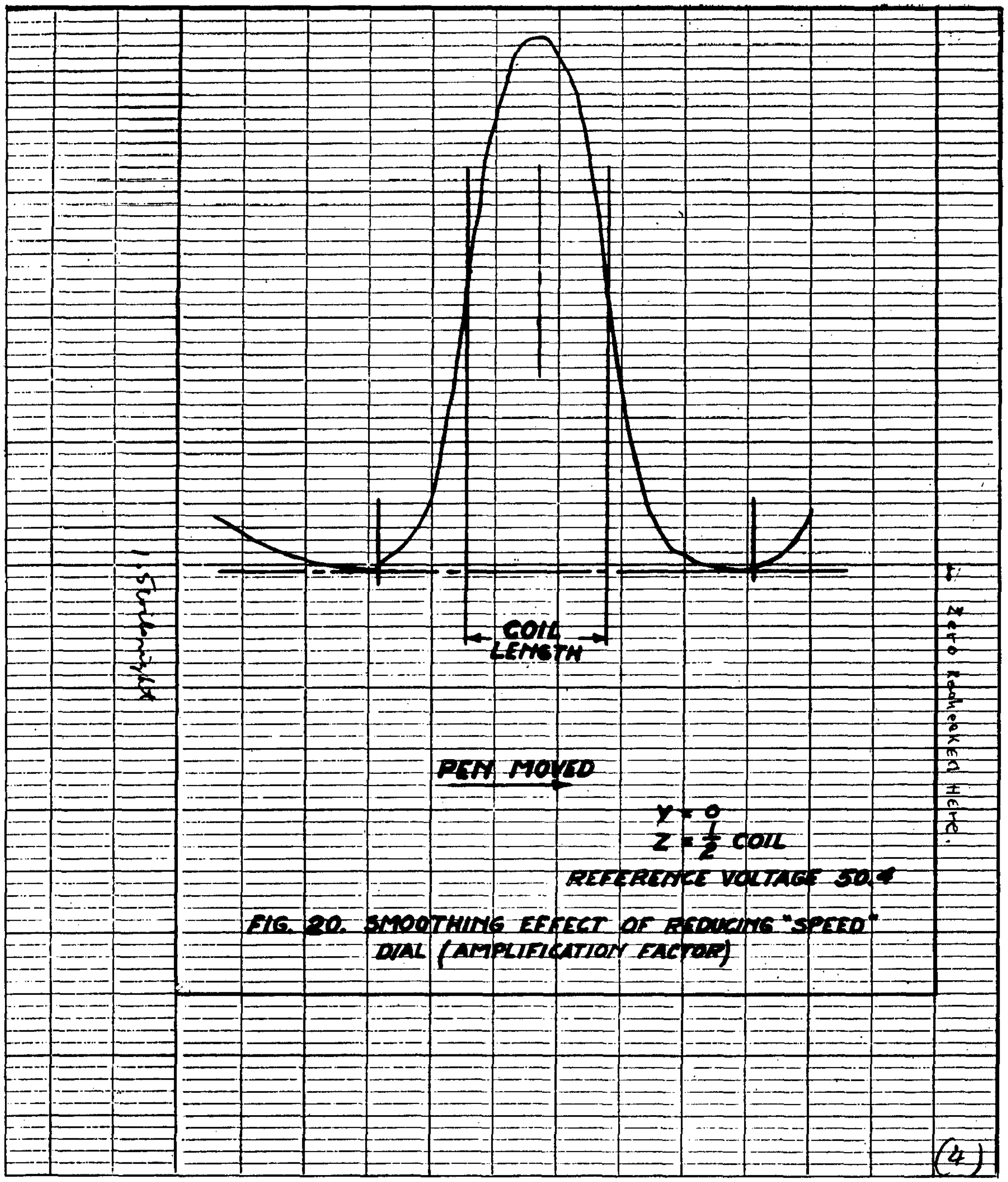


FIG. 20. SMOOTHING EFFECT OF REDUCING "SPEED" DIAL (AMPLIFICATION FACTOR)

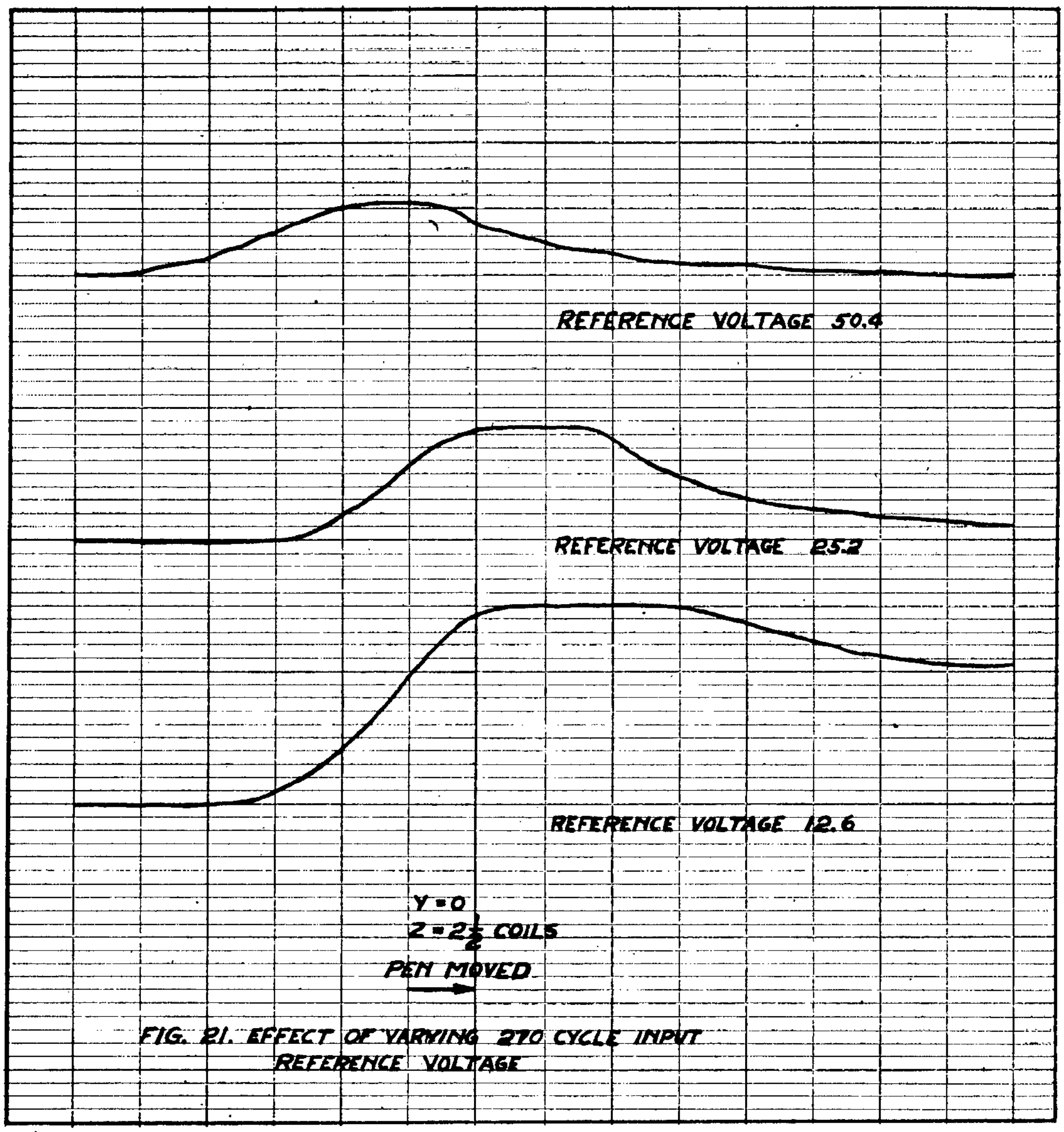


FIG. 21. EFFECT OF VARYING 270 CYCLE INPUT REFERENCE VOLTAGE

Figure 19 shows three signatures of coil 1 in row 1 taken at a depth of $\underline{z} = \frac{1}{2}$ coil-width and at values of $\underline{y} = 0$ (under center of coil), $\underline{y} = \frac{1}{2}$ coil to left, and $\underline{y} = 1$ coil to left. The amplification had been set nearly to its highest value so that some hunting of the pen is shown. The length of the solenoid is plotted to correct scale on each curve. The smoothing effect of reducing the amplification is shown in Fig.20, which was made (save for this reduction) under the same conditions as the first curve of Fig.19. Figure 21 shows the effect of varying the 270-cycle/sec input reference voltage. Failure of the pen to return to zero in the 12.6-volt case is very marked.

A great many curves were taken in these preliminary studies of the field of a single solenoid which need not be reproduced here. The conclusions reached were that the field from single solenoids is satisfactorily symmetrical and unaffected by the position of the solenoid in the coil box. The spatial distribution of the field is entirely in accord with theoretical expectations also.

95. Exploration of the field of a uniformly energized array of solenoids

It was deemed advisable to subject the equipment to a more rigorous and quantitative test than the foregoing one. For this purpose a magnetic distribution in the plane of definition was selected, whose field could readily be computed theoretically for comparison with the results of the recorder. This consisted of a uniformly energized rectangular array of coils, 5 coils

FIGS. 22, 23, 24. - SIGNATURES OF A UNIFORMLY ENERGIZED ARRAY OF SOLENOIDS 5 COILS WIDE AND 20 COILS LONG TAKEN RESPECTIVELY AT DEPTHS 5, 10 AND 15 COIL WIDTHS BELOW THE PLANE OF DEFINITION. THE DOTS ARE THE COMPUTED VALUES.

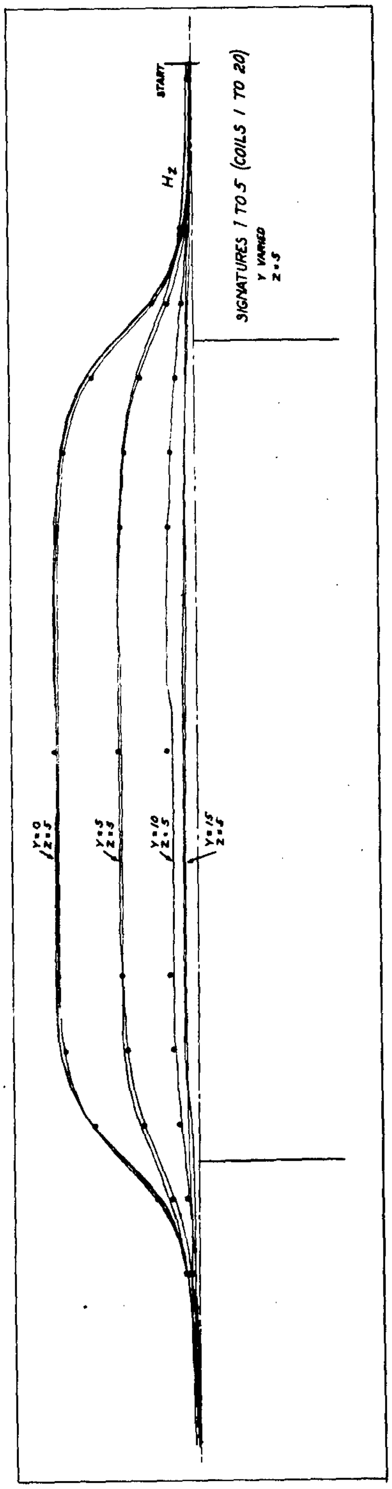


FIG. 22

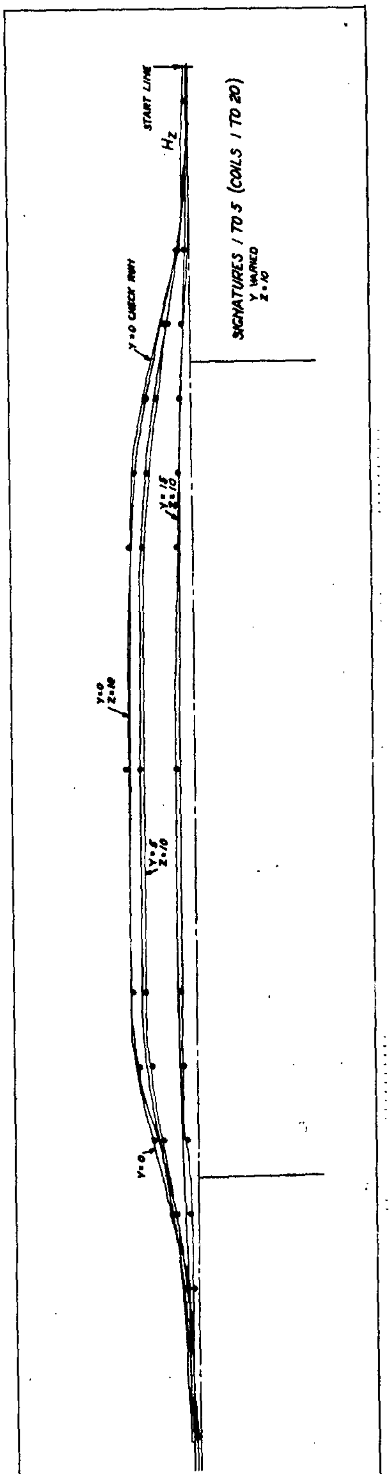


FIG. 23

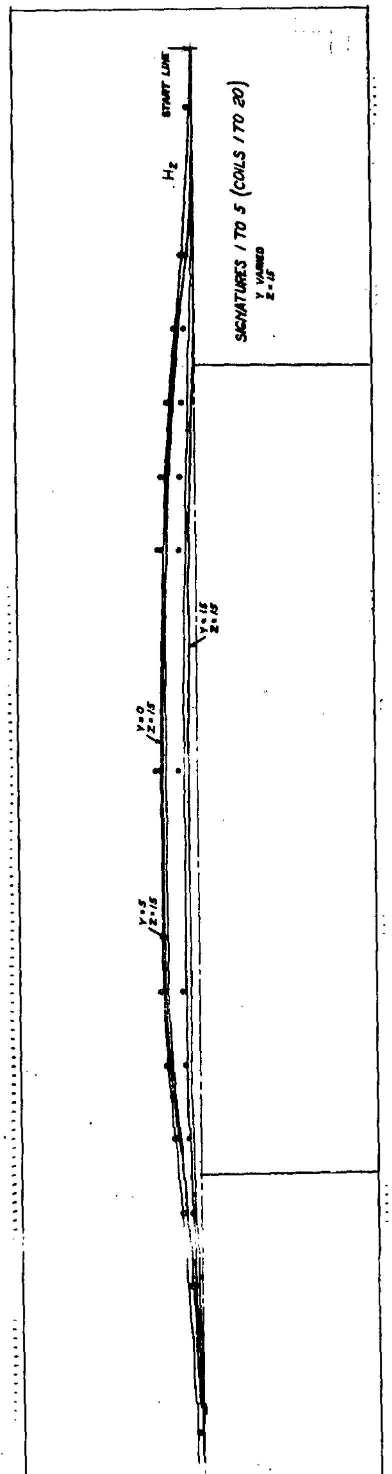


FIG. 24

wide in the y-direction and 20 coils long in the x-direction, constituting one-eighth of the entire coil box. The actual dimensions of this rectangle are 2.3 X 25.4 in. Four such rectangles in the four extreme corners of the array of coils were explored as to H_z. The rectangle in corner No. 1 was explored in a variety of y- as well as z- positions, while the other rectangles were explored only for $y = 0$ (in the vertical plane directly under the center of the energized array) and at $z = 5$ and 15 coil-widths. Reproductions of these curves are shown in Figs. 22 to 27, inclusive. In these figures the heavy dots represent the theoretically computed points, and the curves are those drawn by the recorder. The curves for negative and positive values of y are plotted on the same sheet in Figs. 22, 23 and 24; they are seen to coincide nearly, if not quite exactly, in all cases. The lack of coincidence is in part ascribable to errors in setting the exploring device at precisely symmetrically disposed values of y, but in most cases it represents the limiting uncertainty of the recorder response (Sec.96). This is an absolute amount (about 2 percent of maximum deflection) for all deflections and is not proportional to the deflection. Therefore, it constitutes a larger error relative to the deflection when the deflections are small.

It will be noted that the agreement between the plotted curves and the theoretically computed points is generally good. Only one adjustable constant multiplier was used to fit the scale of plotted magnetic intensities to the theoretical

FIGS. 25, 26, 27.- SIGNATURES OF THREE OTHER UNIFORMLY ENERGIZED ARRAYS OF SOLENOIDS EACH 5 COILS WIDE AND 20 COILS LONG. EACH IS TAKEN AT Y = 0 FOR DEPTHS OF 5 AND 15 COIL WIDTHS BELOW THE PLANE OF DEFINITION. THESE ARRAYS OCCUPIED EXTREME CORNERS OF THE COIL BOX. THE DOTS ARE THE COMPUTED VALUES.

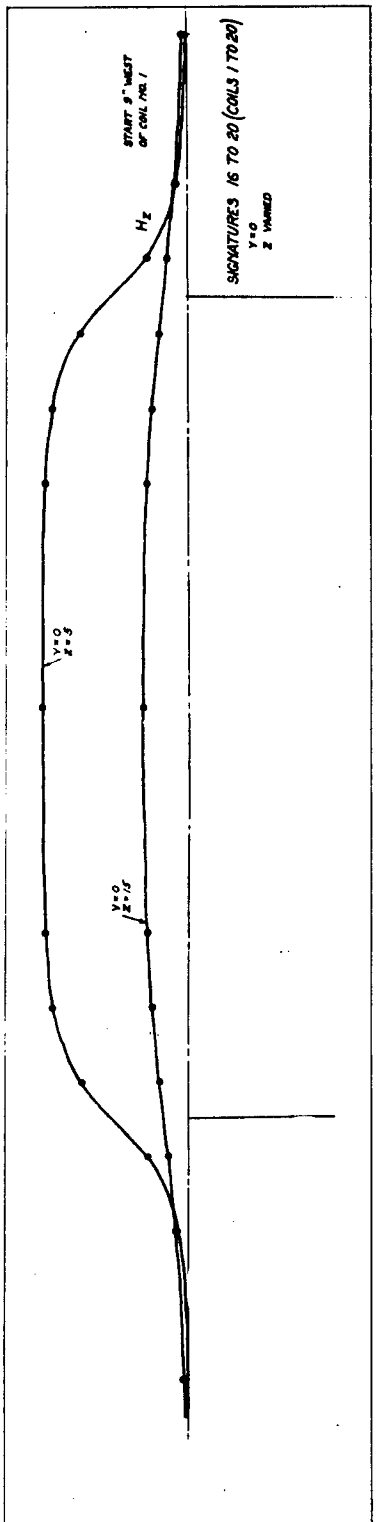


FIG. 25

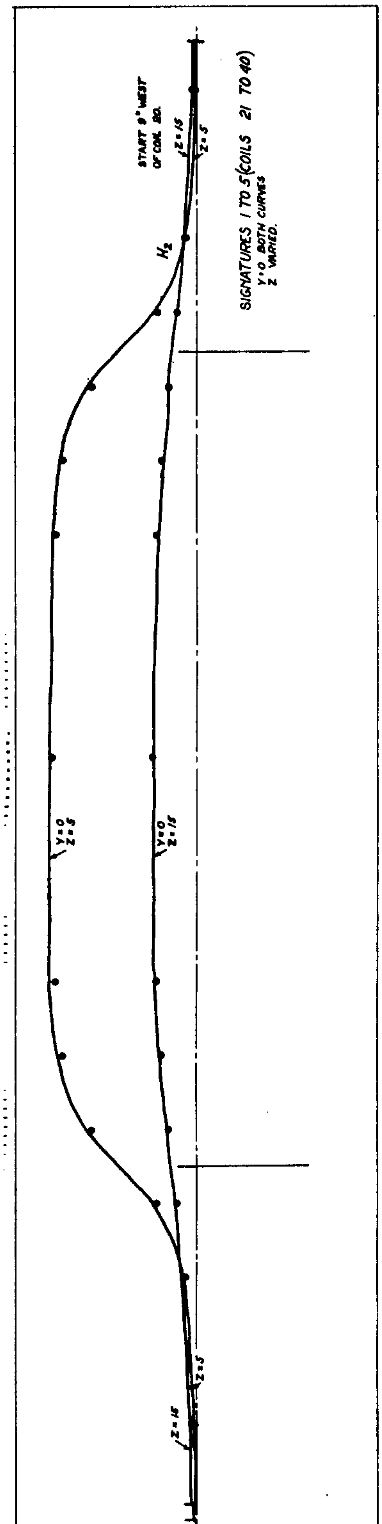


FIG. 26

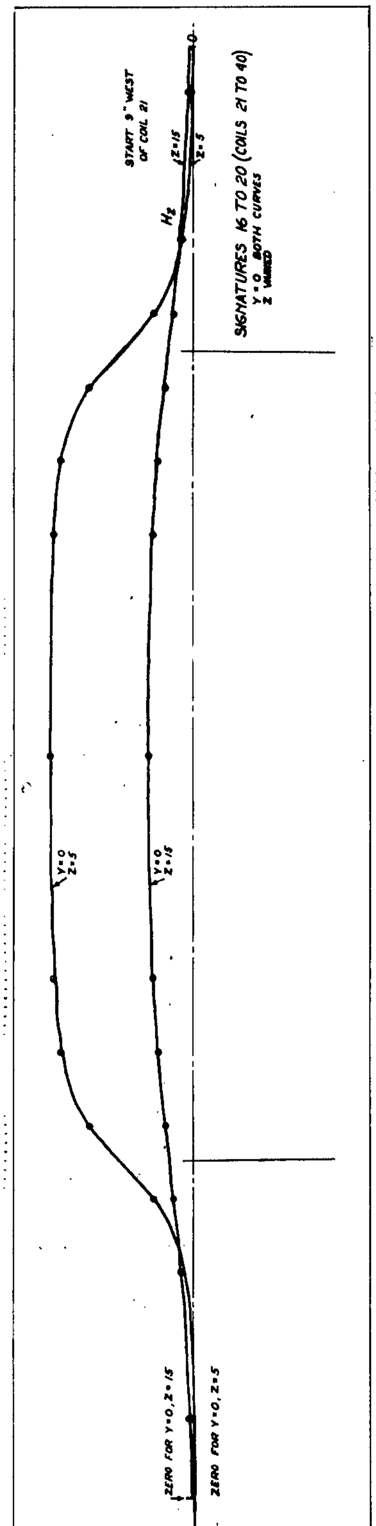


FIG. 27

computations. Thus the entire functional dependence of H_z on x, y and z is subjected to test and comparison with theory. These tests give assurance that there are no serious disturbances from metal (or other causes) which might distort the field. It is interesting to note (Figs. 25, 26 and 27) that, at extreme values of x beyond the ends of the array, the instrumental curves agree with theory in giving a greater intensity for H_z at $z = 15$ than at $z = 5$ coil-widths. The length to scale of the energized array of coils is indicated on this chart. Note that, in the signatures taken at $z = 5$, $y = 0$, the intensity H_z falls off to half its maximum value quite precisely at the values of x marking the boundaries of the energized array. This is to be expected from theory, since the array is long enough in the x-direction relative to the depth $z = 5$ to be regarded as a half-infinite array when the search coil is at one end or as an infinite array when the search coil is near the middle.

96. The limiting uncertainty of the recorder; adjustment of thyratron; warming up precaution

It was found in these tests that a certain minimum increment, or "quantum", of increased emf from the search coil was required before the recorder would respond. This is usually about 2 percent of maximum deflection, but it differs somewhat on different days and depends to some extent on the care with which the bias voltages on the Thyratrons have been adjusted. Since these Thyratrons are mercury vapor tubes, their behavior is quite sensitive to their operating temperature and it was found that reliable results could scarcely be expected during the first hour in the morning while the tubes were warming to their equilibrium running temperature. It was found advisable, therefore, to start the entire set, including the 270-cycle/sec generator (which is also somewhat temperature sensitive), an hour before beginning work in the morning and then an hour or two later to recheck the bias voltage adjustments on the Thyratrons. Every effort should be made to get these so that one Thyratron lights as soon as the other goes out. Possibly some slight improvement could be effected by an adjustment of phase shift in the recorder as described under servicing and operating instructions. The magnitude of the recorder uncertainty can be tested roughly by turning the projecting pulley on the driving motors of the recorder pen carriage with thumb and finger. The maximum displacement of the pen produced in this way before the Thyratrons light to return it to its position of equilibrium is a measure of the recorder uncertainty.

97. Exploration of the field of a ship which had previously been theoretically computed

The magnetic map of a ship (designated as Tu 12) was next set up on the panel switches from numerical values furnished by the N.O.L. As soon as this was ready the exploring device was set with the search coil at $\underline{z} = \frac{1}{2}$ coil-width and an exploration was made directly under the center of signature 10 to compare the curve so obtained with the profile of the elevator points on the corresponding panel switch. The scale of deflections of the recorder was purposely adjusted at a point of maximum deflection so as to match the scale of the elevator settings on the panel switch. It had been hoped that by such a scheme the fidelity of reproduction of the field map set up in the plane of definition could be checked as a routine procedure preparatory to exploration of the field at greater depths. It turned out, however, that at the depth $\underline{z} = \frac{1}{2}$ coil-width the field distribution was already appreciably different (on Tu 12) from the distribution in the plane of definition ($\underline{z} = 0$). Tu 12 was a degaussed ship and, in the athwart ship direction, the field varied steeply from large positive to large negative values in rather short distances. In consequence, even though the center of the search coil is only $\frac{1}{2}$ coil-width below the ends of the solenoid windings, its response is not due solely to the row of solenoids under which it is exploring but is in part contributed from the adjacent rows. This was plainly to be seen by comparing the curve at $\underline{z} = \frac{1}{2}$ coil-width under signature 10 with the corresponding curve set-up in the plane of definition. In every case the deviations of the former from the latter were in the direction that the influence of neighboring rows of solenoids would lead one to expect. To test this more thoroughly, however, the explorations at $\underline{z} = \frac{1}{2}$ coil-width were repeated (always directly under signature 10), but in the first instance with the adjacent signatures 8, 9, 11 and 12 "dead" and in the next instance with signatures 6, 7, 8, 9, 11, 12, 13 and 14 "dead". The last-named exploration gave a surprisingly perfect copy of the profile set up in the plane of definition (on the panel elevators), while the one just preceding it gave a better approximation than the one with the entire map energized. One should add that, in order to obtain the perfect check in the last instance, it was naturally necessary to readjust the deflection scale of the recorder after cutting out the four adjacent rows of solenoids on either side of row 10.

98. Use of headphones to check that all contacts are good

When it became evident that no reliable check of a field map could very readily be made, even with the search coil set to explore in the closest practicable proximity to the ends of the hard rubber cores, it became advisable to find a substitute method so as to be sure, at least, that no coils in the array were dead because of faulty contacts. The method adopted was to provide a pair of headphones (supplied with the present equipment) with an appropriately chosen series resistance, so that the 270-cycle/sec current produced a clearly audible, though faint, note at 0.3 volt (the lowest available voltage on the tap transformer) and a response not unpleasantly loud at the maximum voltage of 30 volts. One terminal of this head set was clipped at the terminal block to the grounded center terminal of the switching panel to be tested. The other terminal of the head set was then run rapidly over the projecting ends of the live brass slider rods where they protrude through the bottom of the dust cover of the bus bar bank. If a "dead" rod was found it was necessary to ascertain whether the setting of that elevator was on zero. If not, then the "dead" rod

FIGS 28, 29 SAMPLE SIGNATURES TAKEN FROM THE FIELD OF A SHIP (TU 12) WHICH HAD ALREADY BEEN SOLVED BY COMPUTATIONS. THE DOTS ARE THE COMPUTED POINTS.

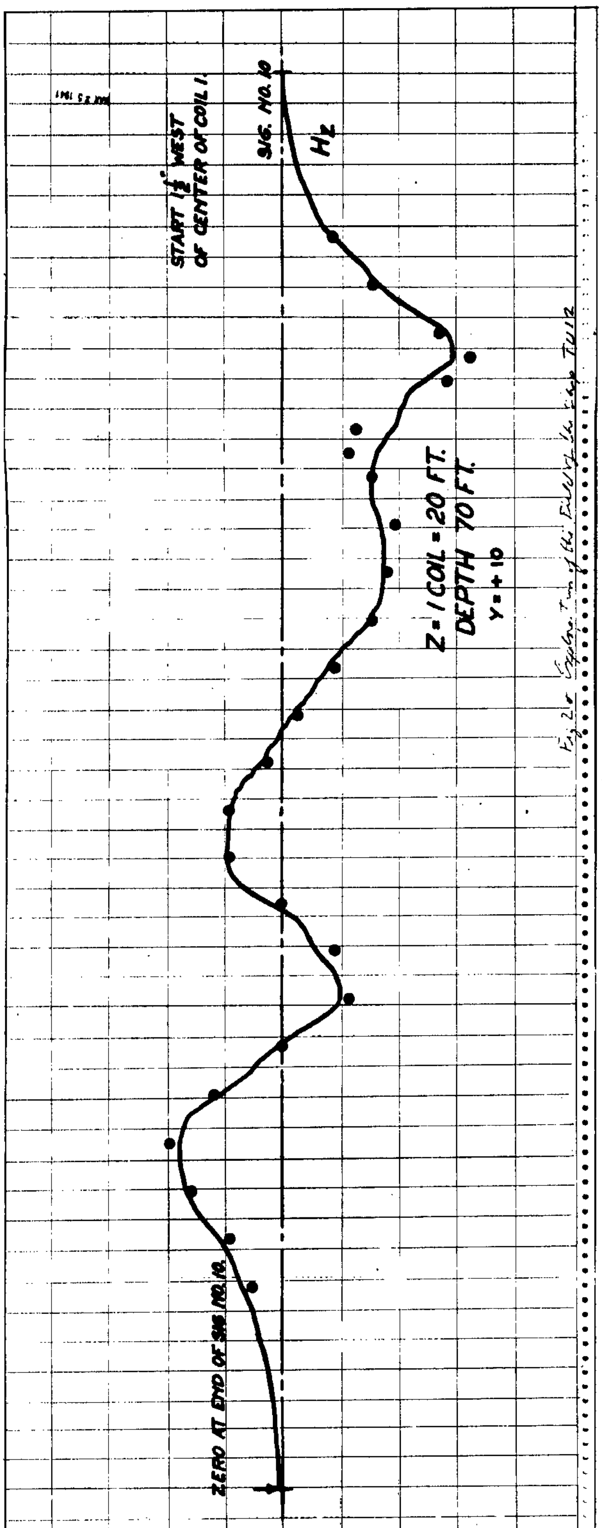


FIG. 28

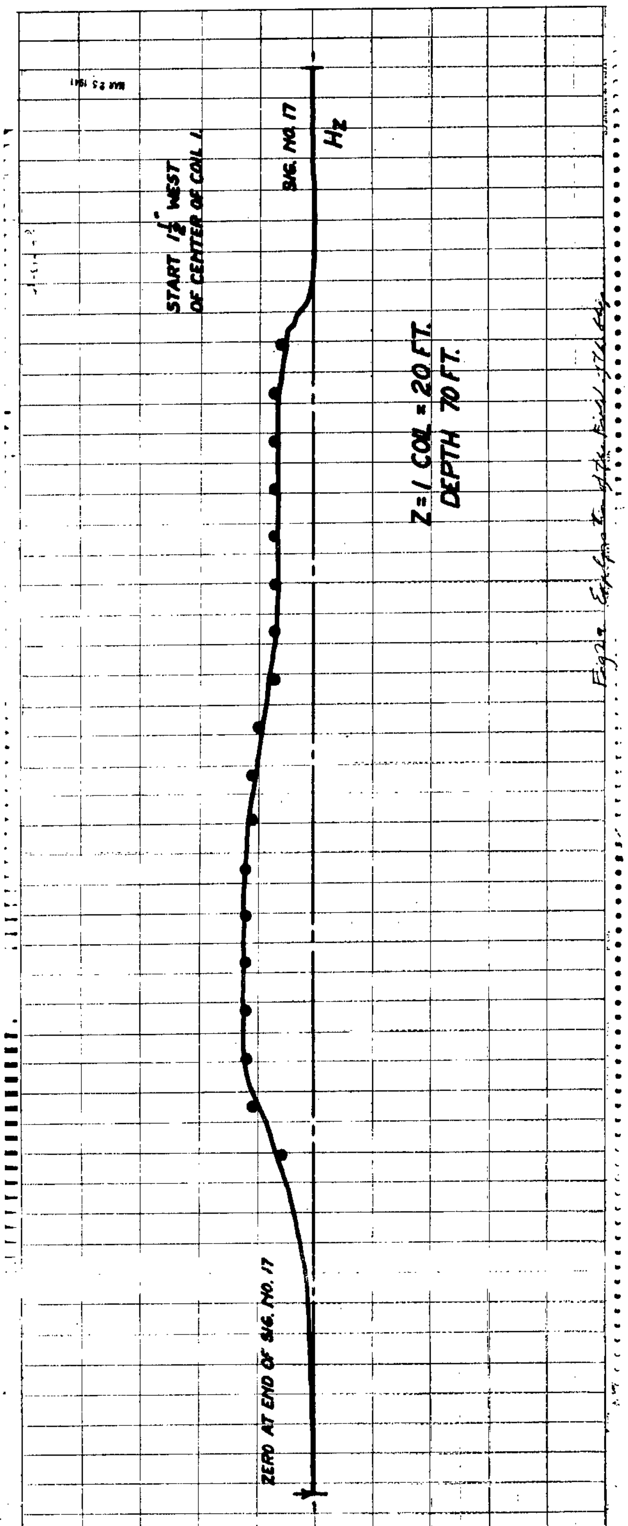


FIG. 29

was evidently caused by a real fault of contact and this was corrected immediately.

In point of fact, this headphone check for reliability of contacts is far quicker and easier to make than the originally contemplated exploration just below the plane of definition, and it gives a reliable answer to the only type of fault in setting up a map that is likely to occur (other than sheer errors in setting elevators that are rather easily detected by inspection, especially if graphs of the signatures set up are available). <u>The headphone check should be made an invariable part of the routine of setting up a map.</u>

99. <u>The results of exploration of the field of Tu 12</u>

Only two of the charts, or signatures, of the field of the ship Tu 12 are reproduced in this report. Both were taken at $\underline{z}$ = 1 coil-width (20 ft) below the plane of definition. This corresponds to a depth of 70 ft below the water line because the depth of the coils on the range was 50 ft. The two curves (Figs. 28 and 29) were taken, respectively, at $\underline{y} = +10$ and $\underline{y} = -130$ ft to starboard and to port of the vertical plane through the keel. These two curves are fairly representative of those taken at a high level. The dots are the computed magnetic intensities. The recorder, it will be noted, tended here to plot a curve somewhat less rugged than the theoretical computations lead one to expect. Small rugosities are, as it were, averaged out. At lower levels the field becomes smoother and, the lower the level, the better the recorder curves agree with the computed points. We tend to believe that the deviations at higher levels between the physical and mathematical results are not entirely the fault of the physical equipment. In order to facilitate computation, discrete poles are taken to replace the magnetic areas which the ends of the solenoids define in the physical case. At high levels close to the plane of definition which, in the mathematical case, is dotted with these discrete poles, one would expect a somewhat more rugged result by computation than is obtained from the smoother physical set-up. In point of fact, the real field is smoother than either one, since even our physical set-up defines uniform areas with discontinuous variation of intensity at the boundaries, whereas the real field map in the plane of definition is a smooth continuous function of position. This would lead one to expect that, at high levels near the plane of definition, the physical method gives a closer approximation to the true field than does the mathematical method, if only discrete poles are assumed in the latter. However, this conclusion omits one consideration. The mathematical method, even if only discrete poles are assumed, admits of indefinite flexibility regarding the number-density of these poles in regions of the plane of definition, where the field to be described is complicated and full of detail. In subsequent work with other ships it frequently becomes obvious that not all of the details of the signature curves set up on the switching panels can be faithfully reproduced by the solenoids because the elevators are not spaced closely enough to avoid missing features which occur between adjacent elevators. The remedy for this difficulty, of course, is to change the scale of representation, and this has been done in several instances with good results. However, such a change of scale frequently requires making only a part of the map of a ship at one time. The explored results of two or more physical set-ups must then be combined algebraically by computation. In general, it has been found that the present design, while adequate perhaps as to the number of coils fore and aft, does not have an entirely adequate number of coils in its athwartship dimensions. The fields of degaussed ships are found to have very rugged profiles in this transverse cross section; furthermore, these fields extend far out beyond the dimensions of the hull itself, with lower intensities, it is true, but over such wide areas that the total flux is not negligible in its effects, especially at great depths.

In one instance, not here reproduced, a deviation between the recorder graph and the computed points was such as to indicate that the difficulty was due to a fault in making the _y_-setting of the exploring device. At the time when the work on Tu 12 was done, the facilities for making these settings (slow motion screws and Bakelite carriages) were not yet available, and it seems probable that small errors of a fraction of a coil width may easily have been made. In regions where the field varies steeply in the athwartship direction, such errors of setting would easily account for the observed deviations.

The conclusions drawn from an examination of all the curves of Tu 12 were very favorable to the physical method of determining the field and to the successful nature of the present equipment. At the deeper levels, not here reproduced, the check between the recorder graphs and theoretical computations were exceedingly satisfactory.

100. Saving in time by physical method

The results of work of the kind just described lead to the conclusion that the ratio of over-all time required for the solution of ship's fields by the two methods -- mathematical and physical -- is between 10 to 1 and 20 to 1 in favor of the physical method.

101. Formal exhibit of the equipment and its results

A formal exhibit of the entire physical equipment for setting up and exploring ship fields was made on April 10,1941. Representatives from the Naval Ordnance Laboratory, the National Defense Research Committee and the National Bureau of Standards were present. Allen G. Shenstone, of the National Research Council of Canada, was also present.

V. OPERATING AND SERVICING INSTRUCTIONS

102. Recommendations on locating, wiring, setting up and starting the equipment the first time

The room where the equipment is installed should have a very solid floor, free from vibration 10/. It should be partitioned from intruders and provided with one or more desks and a number of locked files for storing data.

The room should preferably be air conditioned so as to maintain low and constant humidity, and to hold the temperature, winter and summer, within a range of, say, $\pm$ 20°F. It is almost imperative that conditioned air, regulated by thermostat to within a range of $\pm$ 5°F, be blown through the manifold above the coil box and through the coils. In this connection reread Secs. 15, 18, 24, 34, 35, 45.

In addition to the manifold cabling which connects the tap transformer, the panel switching banks and the solenoid coil box, the following wiring in the room, preferably all in conduits, is indispensable:

(1) A well-shielded pair of No. 14 wires leading the output of the 270-cycle/sec generator to a receptacle conveniently located near the tap transformer (preferably coming through a conduit from the ceiling, since the transformer should be located on top of the cable supports above the panel switches and near the center of the plan of their array). The receptacle

10/ Both the contacts on the panel switches and the behavior of the recorder and its power control cabinet are sensitive to vibration. Vibration of elements, tubes and contacts in the two last-named devices can produce erratic behavior of the pen carriage and thus falsify the curves obtained.

or outlet should, of course, be adapted to the plug furnished on the primary connection cord of the tap transformer. This line should be run in such a way that there may be installed in it on the wall, not inconveniently far from the working end of the coil box, a thermal relay or cut-out and also a switch for, respectively, protecting and controlling the primary supply to the tap transformer. The total primary current with all coils fully energized on the tap transformer, a most improbable condition in practice, would be only of the order of about 3 amp. As a rule, field maps should require less than 1 amp. Protection of the tap transformer against all types of secondary overloading is almost impossible, but the limited protection afforded by a thermal circuit breaker in the primary is worth while.

(2) A well-shielded three-wire circuit (No. 14) must be run from a point near the tap transformer to a conveniently located polarized wall outlet near the recorder cabinet, the receptacle being of a type adapted to the plug on the cord from the recorder provided jointly for the 270-cycle/sec standardizing input and for the ground connection. One of these three wires connects the grounded midpoint of the tap transformer to the ground lead of the recorder; this wire must be tied to a good water pipe ground as well. The other two wires are for the 270-cycle/sec reference voltage to be supplied to the recorder; each should be provided at the tap transformer end with a generous length of flexible rubber covered cable terminated with convenient small "alligator"

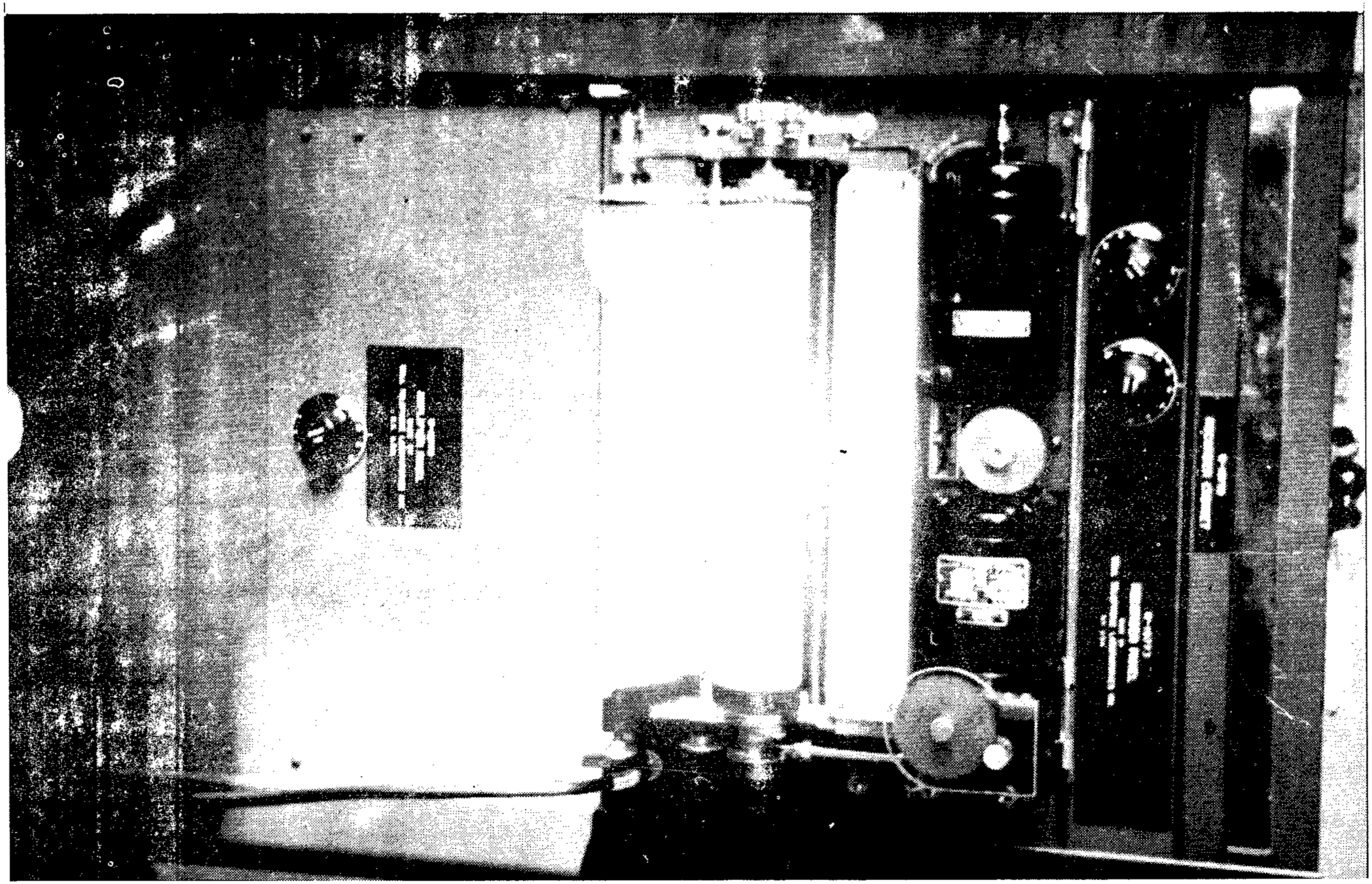


Plate VI. The recorder with cover removed. The dials for scale and zero adjustments (above) and the dial for "speed" of pen carriage response (below) are visible. Note cable for remote paper drive control.

type clips for making connection to any desired secondary taps on the tap transformer.

(3) A 110-volt, 60-cycle/sec supply outlet should be furnished on the wall conveniently near the recorder power supply cabinet, with the receptacle adapted to the plug for the main power supply to the latter.

(4) Appropriate wiring and protective and starting equipment for the motor generator set must be furnished. It is recommended that this set be located in another room or building, on account of the noise, most of which is of a very audible high pitch from the 270-cycle/sec. field. If this is done, it is preferable to have lines for starting and stopping of the generator by remote control from the room where the apparatus is installed.

It is urged that expert, trained telephone switchboard installers of the Western Electric Company (the manufacturers of the equipment) make the manifold cabling connections at the place of installation. Knowledge and experience with the "color code" for identifying wires in cables is required.

When all wiring is tested and ready, the voltage of the 270-cycle/sec primary supply to the tap transformer should be set at 110 volts by regulating the field rheostat of the generator. A good dynamometer-type voltmeter should be used here and preferably a correction made for the reactance of the meter, which is usually calibrated to read more nearly correctly at 60 cycle/sec.

The recorder and its power supply should now be made ready as described in Sec. 103. It must not be forgotten that until the 270-cycle/sec reference voltage from the tap transformer is supplied to the recorder the pen carriage of the latter will drift erratically and no balance can be obtained.

103. Engineering description and operating instructions for the W-10768, 270-cycle/sec potentiometer recorder

(a) Principle of operation recapitulated.-- The W-10768, 270-cycle/sec potentiometer recorder is designed to measure and record an emf that is 90° or 270° out of phase with a balanced-to-ground 270-cycle/sec, 50-volt supply adjustable by selection of taps on the power supply transformer. The unknown emf, ranging from -0.001 to +0.001 volt, is connected in series with the output voltage of a potentiometer deriving its voltage from the 270-cycle/sec supply. The difference between the two voltages is amplified and made to actuate a mechanism that sets the potentiometer so that its output is equal and opposite in phase to the unknown emf. The position of the potentiometer brush is recorded on a strip of paper with a suitable scale.

(b) Description of apparatus.--The recorder is housed in two cabinets, the W-10779 recorder cabinet and the W-10780 power cabinet.

The W-10779 recorder cabinet contains three panels: the W-10773 recorder panel; the W-10775 amplifier panel; the W-10778 amplifier power panel.

The W-10780 power cabinet contains three panels: the W-10774 recorder control panel; the W-10776 power distribution

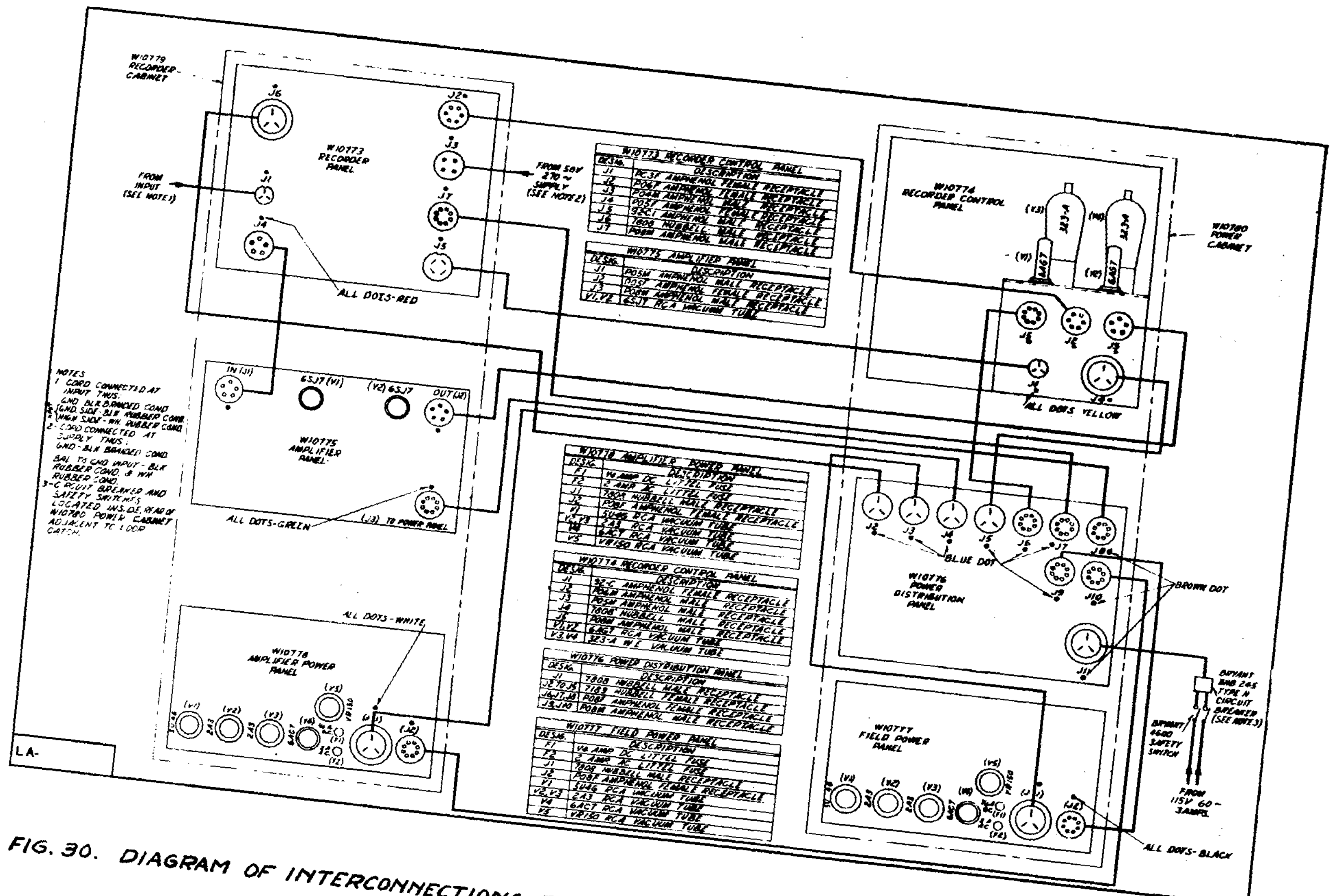


FIG. 30. DIAGRAM OF INTERCONNECTIONS BETWEEN PANELS OF POTENTIOMETER RECORDER SYSTEM

(BELL TELEPHONE LABORATORIES, INC. ESO-779149) panel; the W-10777 field power panel.

The interconnections between the panels are shown schematically in Fig. 30.

(c) Operating instructions.-- (1) Connect all the plugs and insert the tubes as shown in Fig. 30. The plugs and the jacks are marked in color to facilitate the connections:

Panel	Color of Plug
Recorder	Red
Amplifier	Green
Amplifier power	White
Recorder control	Yellow
Power distribution	Blue and brown
Field power	Black

(2) Set the control switch on the recorder control panel to FLASH, and the MAIN SWITCH on the power distribution panel to OFF. Connect the 60-cycle/sec 115-volt supply. Set the DRIVE switch on the recorder panel to ON, the paper switch to OFF and the third switch to ADJ.

NOTE...If the 323-A tubes have been removed from their sockets and kept in any but the vertical position, they should be replaced in the sockets with the filament voltage on (MAIN SWITCH on) for 15 min and the plate caps disconnected before proceeding with the adjustments.

(3) Set the circuit breaker in the back of the power cabinet and the MAIN SWITCH on the power distribution panel at ON, and close the cabinet door which operates the door switch. Wait approximately 1 min until a click indicates that the time-delay relay has operated in the recorder control panel. Adjust the field power voltage to 220 volts and the amplifier power

voltage to 250 volts. Adjust the LEFT and RIGHT BIAS controls until both tubes flash with a blue glow. Set the control switch to UNFLASH and adjust the RIGHT and LEFT BIAS controls until the blue glow disappears in both. Repeat the last two operations until both tubes glow on FLASH and are extinguished on UNFLASH.

(4) Set the control switch on the recorder control panel to balance and adjust the BALANCE control until neither tube glows. Set the switch on the recorder control panel to RECORD and readjust the BALANCE control until the pen settles at zero with the ADJ. ZERO CONTROL on the recorder panel at 50. This equalizes the space currents in the rectifier tubes. Set the ADJ. SPEED control on the amplifier panel until a displacement of the ADJ. ZERO on the recorder panel in either direction by 25 divisions or less causes the pen to move. If the pen oscillates, reduce the setting of the ADJ. SPEED control. The ADJ. SPEED control adjusts the gain of the amplifier.

(5) Set the switch on the recorder panel to RECORD. This connects the unknown voltage.

(6) The length of the scale is adjustable by means of the ADJ. SCALE control on the recorder panel.

The 270-cycle/sec supply cord connecting the recorder to the transformer and the input, or search coil, cord are shielded cords, the black braided conductor being the shield and the rubber conductors being the twisted pair. The shields form the only way of grounding the whole recording system and should be connected to the center of the 270-cycle/sec supply transformer secondary. It is also suggested that the center tap of the transformer be connected to actual ground, if such is available in the room, or, at least, to the water pipe.

The black rubber conductor of the cord going to the exploring apparatus should be connected to the outer conductor of the concentric cord from the search coil, the white wire being connected to the inner conductor, which is the one designated by the red tracer woven into the terminals of the search coil Hearing Aid cables. The rubber conductors of the 270-cycle/sec reference supply cord to the recorder should be connected to the secondary of the power supply transformer so that there is approximately 50 volts or more across them, balanced to ground; that is, one should be connected to +25 volts and one to -25 volts. Interchanging these conductors will reverse the direction of motion of the recorder.

Since the voltage across the recorder potentiometer is proportional to the voltage across these conductors, this voltage may be changed to change the range of the recorder, if the range of the ADJ. SCALE dial on the recorder is not sufficient. The deflection of the pen for a given search coil input varies inversely as the reference supply voltage to the recorder.

104. <u>Maintenance and adjustments on the W-10773 recorder panel</u>

(a) <u>Cover</u> -- The cover is normally held in place by the catches at the lower part of the two sides and the hinges at the top. These hinges are of the loose-joint type, and the cover may be removed by lifting it <u>vertically</u> approximately 3/8 in.

and then pulling it straight forward. It may also be opened on its hinges and held in the open position by means of the stay joint on the right-hand side of the panel. It will probably be found most convenient to remove the cover completely while making charts as this allows simultaneous access to the paper rolls, pen and adjustment dials.

(b) Paper drive.-- The chart paper is driven by an 1800-rev/min motor mounted in the upper right-hand corner of the panel which is connected to the paper drive sprocket through gearing. Paper speeds of 2, 6 and 18 in./min and 2, 6 and 18 in./hr are available. To change from inches per minute to inches per hour, loosen the thumb screw which holds a small pivoted bracket directly behind the vertical worm shaft and shift this bracket to the left as far as it will go; then tighten the thumb screw. The change from 2 to 6 or 18 in. per minute or hour is accomplished by changing the spur gears which face toward the front. The additional gears required are carried on a post mounted between the chart drive motor and the balancing motor. The position of these gears on the upper and lower spindles for the various speeds is as follows:

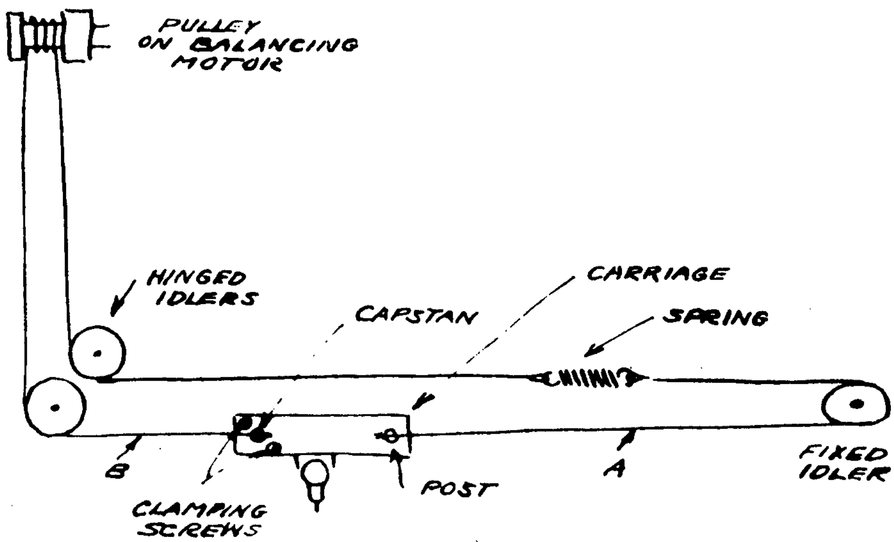
Speed	Upper Gear	Lower Gear
18 in.	$1\frac{1}{4}$ in. (stamped 18)	$1\frac{1}{4}$ in. (stamped 18)
6 in.	5/8 in.(stamped 6)	1-7/8 in.(stamped 6)
2 in.	$\frac{1}{4}$ in. (spindle)	$2\frac{1}{4}$ in. (stamped 2)

(c) Chart paper.-- A chart paper suitable for use with this recorder and providing 100 divisions full scale is the Leeds and Northrup Company No. 489 chart paper. In addition to the longitudinal ruling, this paper has horizontal ruling at 1/2-in. intervals.

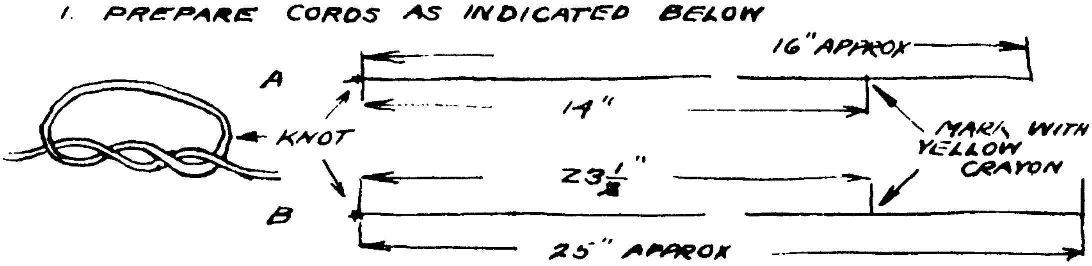
The paper supply roll is inserted between the fixed hub at the left-hand side of the frame and the retractible hub at the right-hand side. The paper should be led from the top of the supply roll under the 5/16 in. longitudinal bar, which is below the paper drive sprocket, and thence around the sprocket. Care should be taken that the paper fits properly on the sprocket teeth and that the supply roll is in proper alignment with the chart drive sprocket. If it is not, it may be adjusted laterally by means of the knurled adjusting nut on the outside end of the left-hand spindle. If the re-roll is to be used, a red cardboard spool should be placed on the takeup spindles between the drive hub at the left hand and the retractible hub at the right. The paper should then be clipped to the spool at two points with the phosphor bronze clips furnished with the recorder. Even though the take-up is not being used, it is advisable to place a take-up spool on the take-up spindles so that the flange guide at the right-hand side of the take-up mechanism will not place a drag on the supply roll.

Both the paper drive sprocket and the take-up spindle are driven through friction clutches which will normally require no adjustment. However, if either shows a tendency to slip, adjustments are provided for changing the tension. The paper drive sprocket clutch is adjusted by loosening the lock nut at the extreme right-hand end of the shaft and tightening or loosening the inner nut after which the lock nut is again tightened in place. The take-up clutch may be adjusted by changing the position of the hexagon nut on the left-hand end of the take-up spindle.

When making routine exploration charts of fields, it is most convenient to dispense with the take-up spindle entirely and to let the paper on which the chart has been drawn hang freely from the paper drive sprocket. Before each signature is started the operator at the recorder writes the designating notations on the chart, using the paper drive sprocket as a hard backing. From time to time scissors may be used to cut off lengths of the chart. A light pull should be applied to the short end of the paper while it is starting to feed off the sprocket, either by hand or by attaching a weight made of a light piece of wood to the end of the paper by means of Scotch tape. The weight of a yard or more of the paper is sufficient in itself to insure close adherence to the drive sprocket roller and good register on the sprockets. By thus letting the paper hang freely in front of the recorder, the entire signature can be inspected while it is being drawn, so that, if there are indications for a repetition, it may be made immediately. It will also be found convenient to stand the recorder on a stout box or stand of such height that the pen is about on a level with the eyes when the operator is standing. The free end of the paper can then be allowed to fold loosely into an open box on the floor provided for the purpose.



1. PREPARE CORDS AS INDICATED BELOW



2. INSERT CORDS A AND B BY THREADING THEM THROUGH THE HOLES IN THE POST AND CAPSTAN AS INDICATED.

3. DOUBLE EACH CORD EXACTLY AT THE YELLOW MARK AND MAKE LOOP AS INDICATED

4. ENGAGE LOOPS WITH HOOKS ON SPRING, THREAD OVER IDLER PULLEYS AND WRAP THREE TIMES AROUND PULLEY.

5. UNCLAMP CAPSTAN AND TURN CLOCKWISE UNTIL HINGED IDLER BRACKET LIFTS APPROX 1/8" OFF STOP. CLAMP CAPSTAN.

FIG. 31. ILLUSTRATING METHOD OF RENEWING SILK CORD FOR PEN CARRIAGE DRIVE.

(BELL TELEPHONE LABORATORIES, INC. ES779170)

(d) Pen drive. -- The pen and contact carriage slides on a longitudinal bar along which it is moved by a silk cord which runs over idler pulleys to a pulley on a shaft of the balancing motor. The two idler pulleys at the left-hand side of the mechanism are mounted on a hinged bracket which tends to be pulled downward by a tension spring. This arrangement has two functions: (1) to maintain a suitable tension in the silk drive cord; (2) to permit the cord to slip on the pulley if the carriage comes to an abrupt stop. This occurs when the recorder tends to go off scale and the carriage comes against the limit switches or the end bumpers. The limit switches consist of two microswitches placed at opposite ends of the scale and so arranged that the current to the balancing motor is cut off approximately one scale division before the end of the scale.

If replacement of the silk cord should be necessary, the instructions in Fig. 31 should be carefully followed.

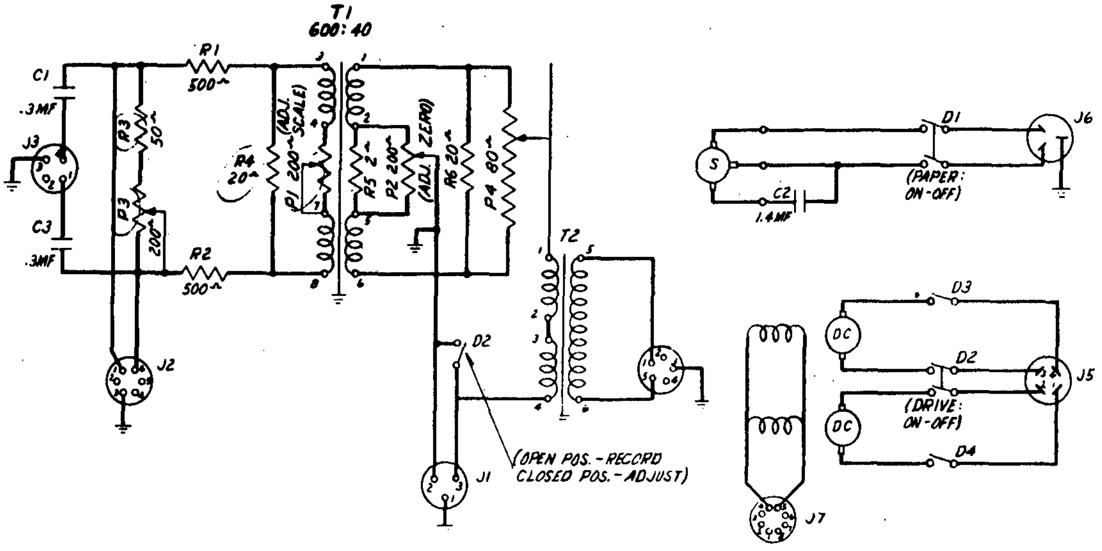
(e) Pen. -- In handling the pen be careful not to bend the point. The recorder should not be shipped with ink in the pen.

To fill the pen, remove it from the holder and, using the dropper furnished, fill the bulb portion approximately half full. Use only the Leeds and Northrup recorder ink furnished. To force the ink into the capillary tip, blow gently in the opening in the tube until a drop of ink is expelled. Insert the pen into the holder with the tip in the guide slot. The point should project sufficiently beyond the slot so that the guide will be raised approximately 1/32 in. above the surface of the paper.

If the pen fails to ink properly, moisten a finger-tip and draw it across the pen point. If this procedure fails, remove the pen from the carriage and blow through it as previously directed. If the ink still does not flow, clean the tip with one of the fine wires supplied for this purpose in the maintenance kit. If the recorder is not to be used for some time, the ink should be emptied from the pen and the pen cleaned with alcohol before allowing it to dry. It is estimated that a pen which is half full will have ample ink for any normal type of recording on a 40-yd length of chart paper.

(f) Lubrication. -- Both the chart drive and balancing motors have ball bearings and are not expected to require lubrication. The following points where there is open mechanism should be lubricated as indicated; a small can containing a suitable light machine oil will be found in the tool kit.

Item	Lubrication
Horizontal and vertical worm shafts	Light machine oil
Worms and worm gears (3)	Light grease
Friction clutches	None
Chart supply roll spindles	Light machine oil
Paper drive sprocket spindle	Light machine oil
Takeup spindles	Light machine oil
Carriage guide rod	Light machine oil
Idler ball bearings	Light machine oil (use sparingly)
Slidewire and collector bar	Unmedicated vaseline (use sparingly)



DESIG.	DESCRIPTION
C1, C3	.3MF COND. D77647
C2	1.4 MF COND. CORNELL DUBILIER PC1489
D1, D2	HART & HEGEMAN S.T.D.P. SWITCH
D3, D4	LIMIT MICRO SWITCH
J1	SP-PC3F AMPHENOL FEMALE RECEPTACLE
J2	PO6F AMPHENOL FEMALE RECEPTACLE
J3	PO4M AMPHENOL MALE RECEPTACLE
J4	PO5F AMPHENOL FEMALE RECEPTACLE
J5	92C1 AMPHENOL MALE RECEPTACLE
J6	7808 HUBBELL MALE RECEPTACLE

DESIG.	DESCRIPTION
J7	PO8M AMPHENOL MALE RECEPTACLE
P1, P2, P3	200Ω POT. TYPE 301 GR
P4	80Ω POT. L&N SLIDEWIRE IND. WOUND
R1, R2	500Ω RES. TYPE 106A
R3	50Ω RES. TYPE 106A
R4, R6	20Ω RES. TYPE 106A
R5	2Ω RES. TYPE 106A
T1	111A REPEATING COIL
T2	285E INPUT TRANS.

FIG. 32. SCHEMATIC DIAGRAM OF CONNECTIONS IN RECORDER PANEL SHOWING PROVISIONS FOR PHASE ADJUSTMENT.

(BELL TELEPHONE LABORATORIES, INC. ESL-779033)

105. Supplementary information on the recorder

(a) Phase adjustment and "sensitivity", or uncertainty of response. -- See Secs. 47, 48, 49, 62, 77; also Fig. 11, the general diagram of the recorder. In Fig. 32, which is a schematic diagram of the various elements and adjustments on the recorder panel proper, the variable resistance P3 is the phase adjustment that makes it possible to bring the phase of the potential difference on the slide wire of the pen carriage into coincidence with the phase of the emf of the search coil.

If this adjustment is not correct, the potentiometer cannot balance the unknown voltage completely. A residual voltage will remain which will be a minimum at the equilibrium position of the slide wire, but the sensitivity,11/ and hence the accuracy, will be reduced by an amount which is a function of the phase unbalance.

To verify whether there is a residual voltage at balance, a telephone receiver or an amplifier voltmeter such as a Ballantine Model 300A may be connected to terminals 1 and 5 of J2 on the W-10775 amplifier (Fig. 30), after removing the plug.

11/ In this report the word sensitivity unfortunately is used with two meanings which will, however, be amply clear from the context. Meaning (1) refers to the amount of deflection of the pen carriage for a given input emf from the search coil; this is also referred to as the scale adjustment. Meaning (2) refers to the uncertainty of response of the pen carriage-- its least quantum of input emf from the search coil required to elicit response. It is the second sense which is used here.

CAUTION. Terminals 1 and 5 are both approximately 200 volts d.c. above ground. Terminal 1 is at a.c. ground potential. With the drive switch off, balancing may be accomplished by hand and the loss in sensitivity observed directly.

To correct for the phase shift, the resistance P3 (Fig.32) in the rear of the W-10773 recorder panel should be adjusted for minimum amplifier output at balance. If the range of P3 is insufficient, the value of R3 may be changed. These adjustments will alter the range of the recorder and, in order to bring the range back to its original value, P1 (ADJ. SCALE) should be readjusted. If the range of P1 is inadequate for this purpose, the 270-cycle/sec supply voltage may be altered and, this failing, R4 may be changed. The efficiency of any P3 adjustment should be evaluated only after the range is readjusted because this affects both the phase and amplitude of the slidewire voltage.

If there is any 270-cycle/sec pickup into the amplifier as set up in a particular location, the foregoing procedure is not satisfactory. It would then be best to operate the recorder in the normal way and vary P3 and P1 simultaneously so as to keep the range constant and check the sensitivity for each pair of resistance values; the final pair of values to be used should be the one that gives maximum (or sufficient) sensitivity.

The relative sensitivity may be measured under operating conditions by the amount of manual displacement of the motor pulley in both directions as indicated on the recorder scale which is necessary to cause the control circuit to react. To facilitate all these tests the amplifier speed control may be set higher than normally.

(b) Grounding. -- The grounding of the whole system has been connected together and requires an external ground connection at only one point. For convenience, this physical ground connection may be made either to the search coil input cord shield or to the 270-cycle/sec supply cord shield, preferably the latter.

If local conditions are such that excessive ground current pick-up is encountered, experimentation is necessary to determine the optimum set-up. Grounding of the cabinets, omission of all ground connections and isolation of the equipment from the 60-cycle/sec supply lines by a shielded transformer are possible alternatives.

106. Setting up the map on the panel switches

(a) Choice of scales for setting up data. -- The magnetic map may have been prepared either in the form of numerical data, in which case the average magnitudes of the vertical components of the field intensity associated with the various equal rectangular areas of the chart will appear as numbers in the rectangles, or it may have been prepared in the form of graphic curves representing the signatures of the ship in the measured plane. In the first case it may be advisable to multiply all the numbers by some constant factor so that the largest one of them is just 100 or slightly less. This procedure insures making the fullest use of the scale range of the panel boards and gives the greatest accuracy of setting. It is essential that the rectangles into which the ship's map is divided shall have dimensions in the ratio of 20 to 55 to coincide with the solenoid coil dimensions. In the second case care should be taken that the plotted signatures have no ordinates on either the positive or negative side of the zero line that exceed the travel of the elevators (6¼ in.); otherwise, a complete change of the scale of ordinates must be made. It is advisable that the largest ordinate on any signature to be set up should be about 6¼ in., or a little less, to take maximum advantage of the available accuracy of setting. It is <u>most important</u> not to overlook the following precaution as to the abscissa scale on the graphic signatures to be inserted on the panel boards for setting the elevators. <u>If the signatures are set up on adjacent rows of solenoid coils in the coil box, then the scale of the graphs for the panel boards must be such that the abscissa interval on the graph equal to the distance between adjacent elevators (which is 1-1/8 in.) must stand for a fore-and-aft measurement on the ship's map which bears the ratio 55 to 20 compared to the distance between adjacent signatures on the map. This essential fact resulting from electromagnetic laws must never be forgotten -- that a magnetic field can be truly reproduced to scale only if the same geometric scale ratio is used on all three coordinates x y and z. It must be borne in mind also that, though the x-spacing of solenoids in the coil box is 1¼ in., the elevator rods are spaced 1-1/8 in.</u>

(b) <u>Precautions; attaching sheets and setting elevators.</u>-- First remove the dust covers from all bus panels so that these are accessible in case contact finger faults arise. Before setting up the graphic signatures (unless one is already absolutely certain), make a rapid check to see if all elevator points coincide with the penciled zero line on the chart boards when the pawl carriages are set at zero on the racks. Also, if any doubt exists, release all elevators and set them on the rack position -100 at the bottom of their travel and check all contact fingers to see that they register with the lowest bus tongue. Next, if graphic signatures are used for setting up, release the pawl levers on all elevators so that the "click" is on, and raise them to their highest point to get them out of the way while attaching the chart sheets. Take care to set the chart sheet zero line in exact register on the penciled zero line on the chart boards. <u>On each chart sheet some fiducial point must be marked that defines the same value of x for all charts; and the chart must be fastened to the board so that this point coincides with the elevator having the same solenoid coil number for all signatures of the total coil array.</u> The charts may be attached to the boards at the corners with short diagonal strips of Scotch tape. The elevator pawls are now all to be released by depressing the pawl levers so they all drop to the bottom of their travel and then the "click" should again be set preparatory to setting the elevator points on the chart curve. In raising the elevator either to set its point on a graphic curve or on a numbered rack setting, it will be found most convenient to grasp the elevator rod near its pointed end with the thumb and forefinger of the right hand. The upward motion can then be conveniently controlled, especially when the exact desired position is being approached, by the frictional reaction of the other fingers against the board. This leaves the left hand free to uncatch the pawl and reset it if a slight error of over-travel is made in the first attempt. If the settings are being made numerically, it is a good idea to sight roughly at the desired position on the rack while the elevator carriage is down at the bottom of travel. Then, as the carriage is raised, one can, with a little experience, halt the motion a few slots short of the exact setting even though this is now covered by the carriage. The exact setting can then be adjusted with care "one click at a time". Elevators whose settings call for "zero" are best left at the bottom of travel with the contact fingers on the insulated point rather than on the zero bus position. This is especially true if there are many such elevators set on zero, as frequently occurs if the entire length of the coil box is not being employed. Sections 40 to 46 inclusive, which describe the panel switches, may profitably be reread at this point.

(c) Headphone contact check.-- As soon as all elevators are set, make a complete check for contact continuity with the headphone as explained in Sec. 41 and, more especially, Sec.98. When all faults so disclosed have been corrected, replace the dust covers on the bus panels. The equipment is now ready for exploration of the model magnetic field.

107. Exploring the field

Reference should here be made to Secs. 64 to 78, inclusive, which describe the entire exploring device, and especially to

Sec. 73, on the travel limit mechanisms and switching controls, to Sec. 75, on the explorer lower switchboard and to Sec. 76, on the standardizing millivolt box. Sections 79 to 87, which explain the facilities for setting the exploring device in different y and z positions, should also be reread, and Table II, Sec. 86, should be understood. Working instructions for the recorder appear in Sec. 103.

Above all, it is a waste of time to start recording signatures unless the recorder and its power cabinet and the motor generator set and tap transformer have been operating for at least an hour and preferably two hours to bring them to temperature equilibrium. A rough preliminary balance adjustment which should have been made at the start on the Thyratrons must now be carefully readjusted, and the recorder should be checked for zero and for "speed" of response and hunting of the pen carriage. The uncertainty of balance ("sensitivity") should be tested by rotating the pulley on the pen carriage driving motors slightly with thumb and fore-finger to see how much it can be displaced before the signal acts through the Thyratrons to restore the carriage.

Turn the driving motor switch on the exploring device to "Off". See that the 110-volt power cable (green microphone cable connector) is coupled so as to supply power to the explorer driving motor, See also that the other cable (with black microphone cable connector) is connected from the exploring device to the receptacle at the lower right-hand corner of the recorder panel to control the starting and stopping of the paper drive on the recorder from the switch on the exploring device. Connect the two rubber covered conductors of the shielded recorder input cable to the binding posts on the lower explorer switchboard marked "Recorder". The black silk covered conductor in this cable is the shield and need not be grounded if ground on the recorder has been otherwise defined. (See end of Sec. 103, however.) Couple the search coil to be used (or a combination of them if this is desired) to +<u>x</u> and -<u>x</u> on the lower explorer switchboard by means of short jumper wires; <u>remember</u> that the red tracer on the search coil cable goes to the white rubber covered wire in the recorder input cable. The + and - signs on the switchboard are provided to facilitate this polarity check. If the wrong polarity is connected the response of the recorder may be extremely erratic. Now connect the low-voltage output of the standardizing millivolt box to the posts on the lower switchboard of the exploring device marked "Cal. Voltage" by means of the special cables with colored "banana" plugs, and also connect the supply cable of the millivolt box to two symmetrically located taps on the tap transformer above and below ground by means of the "alligator" clips supplied with the long rubber covered cable for this purpose. (±1.2 volts will be found convenient.) The millivolt box automatically supplies not only a standardizing source available by switching but also the low voltage to "kick" the pen on the recorder for making the fiducial mark on the scale of <u>x</u>. The latter is always connected in for use.

It is recommended that two operators be used in recording signatures. The use of two men is especially helpful in making the y-and z-settings of the exploring device. While recording, one of the men, here called No. 1, stands near the recorder; the other, No. 2, stands at the working end of the exploring device.

The limit mechanisms on the exploring device should now be set so as to permit (or define) a travel of the search coil carriage conveniently adapted to the field to be explored. The engraved plaques on the sides of the device indicate where to screw in the Bakelite plugs to throw into or out of action the corresponding limit levers.

Operator No. 2 now sets the lower left-hand switch on the lower switchboard of the explorer to "Cal." and the lower right-hand switch to "short". This permits operator No. 1 to check the "zero" of the pen carriage and adjust it, if necessary, with the dial marked "zero adjustment". Operator No. 2 now sets the lower right-hand switch to "Cal.V", and No. 1 rotates the knob on the paper drive sprocket slightly by hand so as to make the pen in its deflected position mark a short indication on the chart paper showing the calibration voltage deflection. No. 2 now switches back to "short", returning the pen to zero. After No. 1 has recorded on the chart the date (a dating stamp is convenient), the job designation, the values of the y-and z-settings of the exploring device, and any other pertinent notes, such as the taps on the transformer for the reference voltage and the taps used to supply the millivolt box, he checks to see if the recorder pen is writing properly by inserting a small slip of paper under the pen which is then made to trace a line by sliding the paper under it. (It is a good idea while the chart paper is not feeding to leave this slip of paper under the pen; this prevents soaking the chart paper in one spot with an excess of ink.) Operator No. 1 now signals to No. 2 that all is ready. No. 2 now switches the lower left-hand switch on the lower explorer switchboard to "Record". (A most frequent mistake is to overlook this.) The search coil carriage is now presumably at its "near" end of travel. If it has operated the limit mechanism, the Mercoid switches will be tilted toward the operator. If they are not in this position, No. 2 can set them there by sliding the brass blocks projecting up on either side of the belt (or the 1/8-in. brass slide rods) toward himself. No. 2 now sets the right-hand switch on the upper switchboard to turn on the 110-volt supply for the driving motor, first seeing that the motor control switch in the center of the upper board is set to the right-hand side marked "Rev." He now throws both the center switch and the left-hand switch (motor control and recorder paper drive switches) to the left hand so as to start the explorer and the recorder simultaneously. It is well to check and see that the fiducial marker operates the recorder pen carriage. When the search coil carriage has reached the limit lever which was set to stop it, the Mercoid switches will be thrown automatically and the explorer carriage will stop. At this time operator No. 2 throws off the left-hand switch on the upper switchboard and stops the paper on the recorder. He now throws the lower left-hand switch on the lower switchboard to "Calibrate" and the lower right-hand switch on the same board to "Short"; and then he throws the center switch on the upper switchboard back to the right ("Rev."), which starts the driving motor of the exploring carriage in the reverse direction. The limit mechanism will stop the carriage automatically when it has returned to the "near" position. One entire cycle of exploring-recording operations is now completed and all switch settings are ready for an identical repetition.

Should operator No. 2 desire to move the search coil carriage by hand, he can do this by manually turning the worm shaft on the driving motor in the right direction to uncouple one of the crown clutches without going far enough to engage the other. The exploring carriage and belt can now be moved by turning the gears on the brass belt pulley shaft.

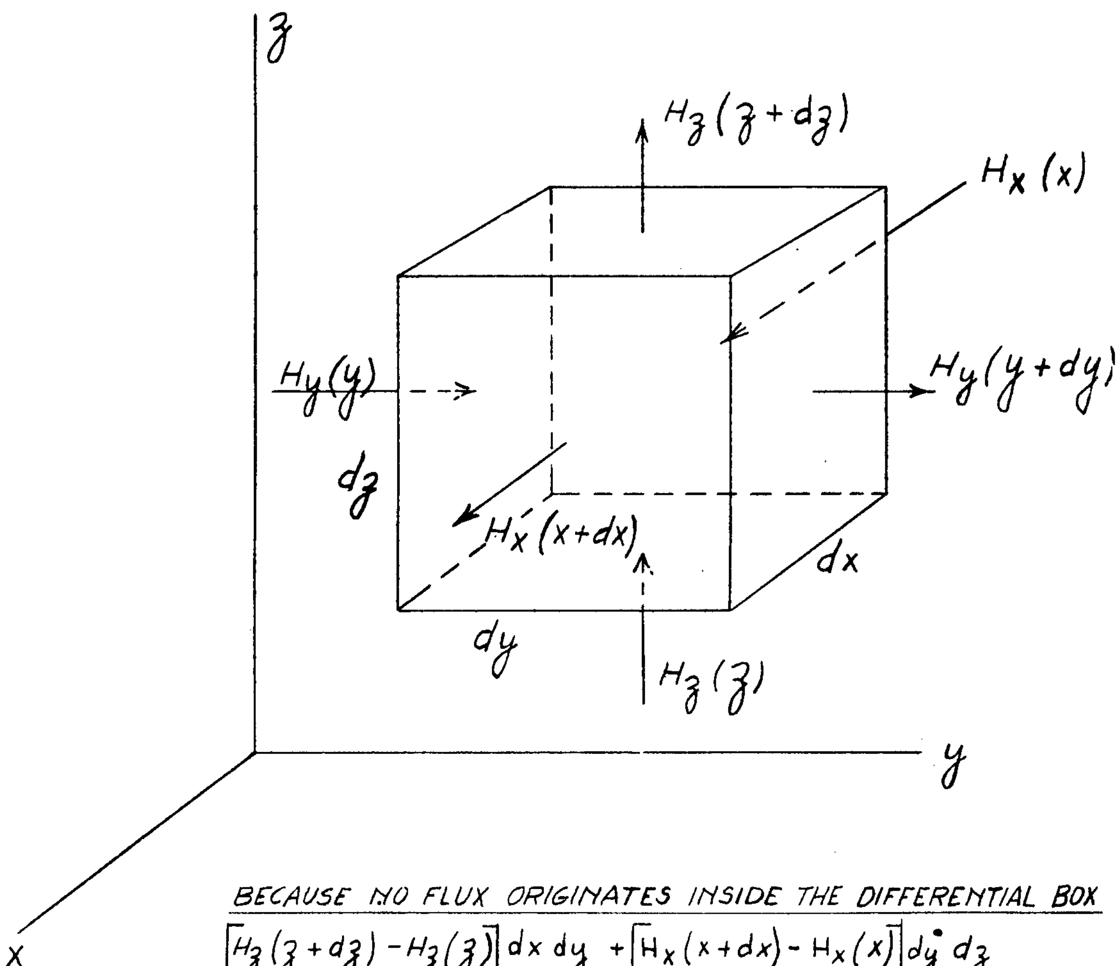
The method of changing _y_-and _z_-settings has already been explained in Secs. 79 to 87, inclusive. The most frequent error to guard against here is to set the two ends of the explorer box on different values through a misunderstanding on the part of the two operators. _Do not forget to block and wedge the far end of the explorer box to remove the warp._

APPENDIX A

Fundamental Relationships between Components and their Derivatives in Fields of Force

A field of force is a region of space at every point of which some particular type of test-particle is subject to a force that generally varies in magnitude and direction from point to point. In the case of a magnetic field the test-particle is an ideal object, the unit magnetic pole. While a single isolated unit magnetic pole cannot be physically realized, its behavior can be inferred from the behavior of small magnets having two poles, of opposite sign and equal strength, separated by a small distance. The concept of the unit pole has the advantage of being easy to grasp. The strength of such a pole is defined by saying that unit poles of like sign placed unit distance apart (1 cm in the cgs system) repel each other with unit force (1 dyne in the cgs system). Unit poles of unlike sign attract each other, the magnitudes being similar. The magnetic force on a unit pole at any point in a magnetic field may be described completely by giving the magnitudes and signs of its three components along the three mutually rectangular axes, X, Y, Z, of a Cartesian coordinate system. Let these three components be denoted by H_x, H_y and H_z. All three are functions of the coordinates x, y, z. Their vector sum, or resultant, is vector field intensity H. The situation can be visualized if we think of the space as filled with small arrows, each having the direction of the intensity at the point where it is situated and a length proportional to the magnitude of that intensity.

If, as frequently occurs, the variation of such a field from point to neighboring point occurs in a slow continuous manner, continuous lines can be drawn -- known as lines of force -- that have at all points of their length the same direction as the field intensity H. A tube that has lines of force as the elements of its bounding walls is called a tube of force. The product of the average field intensity in such a tube and the cross-sectional area of the tube taken normal to the lines of force is called the flux of magnetism in the tube. The positive sense, or direction, along a line or tube of force is arbitrarily defined as the direction in which a north-seeking magnetic pole is urged. Lines or tubes of force originate from magnetic poles and spread out in all directions therefrom. If no poles exist in the volume enclosed by a given closed boundary surface, then as much flux or force must pass out through some regions of the closed boundary as passes into the remaining regions, and the inward-drawn normal component of the magnetic field averaged over the closed surface is zero. The Laplace equation,



BECAUSE NO FLUX ORIGINATES INSIDE THE DIFFERENTIAL BOX

$$\left[H_z(z+dz)-H_z(z)\right]dx\,dy+\left[H_x(x+dx)-H_x(x)\right]dy\,dz+\left[H_y(y+dy)-H_y(y)\right]dx\,dz=0$$

SINCE

$$H_z(z+dz)-H_z(z)=\frac{\partial H_z}{\partial z}dz$$

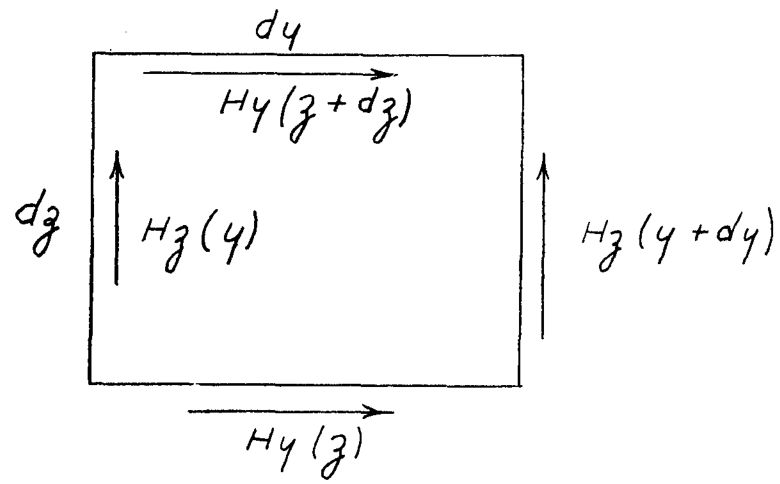
$$H_x(x+dx)-H_x(x)=\frac{\partial H_x}{\partial x}dx$$

$$H_y(y+dy)-H_y(y)=\frac{\partial H_y}{\partial y}dy$$

SUBSTITUTING ABOVE ONE OBTAINS

$$\left[\frac{\partial H_x}{\partial x}+\frac{\partial H_y}{\partial y}+\frac{\partial H_z}{\partial z}\right]dx\,dy\,dz=0$$

FIG. 33. TO ILLUSTRATE HOW LAPLACES' EQUATION EXPRESSES THE FACT THAT THERE ARE NO SOURCES OF FLUX IN ANY SMALL ELEMENTARY RECTANGULAR BOX.



$$H_z(y+dy) - H_z(y) = \frac{\partial H_z}{\partial y}\, dy$$

$$H_y(z+dz) - H_y(z) = \frac{\partial H_y}{\partial z}\, dz$$

$\therefore$ WORK GOING CLOCKWISE AROUND CIRCUIT IS W :-

$$W = \left[H_y(z+dz) - H_y(z)\right] dy - \left[H_z(y+dy) - H_z(y)\right] dz$$

$$= \frac{\partial H_y}{\partial z}\, dz\, dy - \frac{\partial H_z}{\partial y}\, dy\, dz$$

$$W = \left[\frac{\partial H_y}{\partial z} - \frac{\partial H_z}{\partial y}\right] dy\, dz$$

Q.E.D.

FIG. 34. TO ILLUSTRATE HOW THE VANISHING OF THE "CURL" OR "CIRCULATION" OF A FIELD MEANS THAT NO WORK IS DONE WHEN A MAGNETIC POLE IS CARRIED AROUND A SMALL ELEMENTARY CLOSED CIRCUIT.

$$\frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y} + \frac{\partial H_z}{\partial z} = 0, \qquad \text{(Condition A)}$$

is the statement of this condition for an infinitesimal volume (the box in Fig. 33).

A further condition that obtains in a region of space where there are no electric currents, moving electric charges or magnets is expressed by the three equations,

$$\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} = 0 \quad \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = 0 \quad \text{and} \quad \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = 0. \quad \text{(Condition B)}$$

Each of these equations states that the line integral of the magnetic field intensity around a small closed circuit in the field is zero; in other words, that the work done by or on a magnetic pole moving round and round in a closed circuit in the field is zero. It can readily be seen, for instance, that the left-hand member of the first equation of Condition B represents the work required to carry a unit pole round a vanishingly small rectangle whose plane is normal to the <u>x</u>-axis and whose sides are the elements of length <u>dy</u> and <u>dz</u> divided by the area <u>dy dz</u> of the rectangle. (See Fig. 34.) The three equations of Condition B are usually subsumed in the single statement that the <u>circulation</u>, or <u>curl</u>, of the field is zero.

Conditions A and B are the two that obtain below the measured plane in a ship's field. Condition A asserts that, in every elementary cube of this space, any component of magnetic flux entering one face of the cube and failing to leave the opposite face in equal amount must be compensated for by similar but opposing discrepancies in the normal components through the other pairs of faces.

Condition B says that, if the normal component of the field in the measured plane varies from point to point <u>in that plane</u>, then this variation must be compensated by balancing variations in the two components of the field <u>parallel</u> to the measured plane for displacements of position <u>normal</u> to that plane. It thus becomes more reasonable to expect that the spacial variations in the distribution of the <u>normal</u> component of the magnetic field intensity at the plane of measurement can exert a determining influence on the other two components.

APPENDIX B

On a Physical Method for Determining and Tracing Unknown Signature Curves at y-Positions Intermediate to Given Signatures by Interpolation of Higher Order than the First

1. General considerations and ideas regarding interpolation and order of interpolation

Suppose that, from a field map, a certain number of complete signatures, all equally spaced in the y-direction, are known, let us say in the form of plotted curves representing the magnetic field intensity as a function of x. For the purpose of greater fineness and fidelity of delineation of the field, suppose we wish to set up these known signatures as intensities of alternate rows of solenoids in the coil box and we wish to set the solenoids in the intervening rows at intensities whose values are smoothly interpolated between the given neighboring values. If we think of a surface with hills and valleys distributed so that the heights h represent the field intensities while the other two coordinates are the x-and y- coordinates of our field map, then the given signatures are the profiles of this map as cut by vertical planes in the x-direction. Vertical planes in the y-direction will also cut out curvilinear profiles of the map on which ordinates corresponding to various values of y will appear. For simplicity of discussion, let us suppose that the known ordinates of the latter transverse curves (at the intersections of the transverse vertical planes with the known and given signatures) occur at

$$y = 10,\ 9,\ 8,\ 7,\ 6,\ 5,\ 4,\ 3,\ 2,\ 1,\ 0,\ -1,\ -2,\ -3,\ \text{etc.}$$

Consecutive integers are taken for y here for subsequent mathematical simplicity, although it was previously stated that only alternate rows of coils are energized. This change of units for y introduces no ambiguity.

Let us represent the intensities along this curve at the various values of y as $h(y)$; that is,

$$h(10),\ h(9),\ h(8)\ \ldots\ldots\ h(0),\ h(-1),\ h(-2)\ldots\ldots$$

Interpolation between these values may be made in a number of ways. If adjacent given ordinates h are joined by straight lines, then ordinates erected half way between the given ones will have values defined where they meet these straight line segments. These values we shall call linearly interpolated values, and the process of obtaining them we shall call linear, or first order, interpolation. A parabolic, or second order, interpolation is obtained as follows. Take three given ordinates, say $h(-1)$, $h(0)$ and $h(+1)$, and trace a curve whose general equation is that of a parabola,

$$h = ax^2 + bx + c,$$

with the three constants a, b and c so determined that the curve passes through the three points h(-1), h(0) and h(+1). Then an ordinate erected at the point $y = \frac{1}{2}$, for example, will have a definite value where it meets this curve, and this value is said to be parabolically interpolated. It is clear that, in this case, an ordinate can also be parabolically interpolated at $y = -\frac{1}{2}$ in the same way. Further, it is clear that any parabolically interpolated ordinate, say $h(-\frac{1}{2})$, having two known ordinates on each side of it, say h(-2), h(-1), h(0), h(+1), can be obtained in two ways, either by using the three ordinates h(-2), h(-1), h(0) or by using the other three ordinates, h(-1), h(0), h(+1). The results of these two ways of interpolating may not be quite the same, but in either case $h(-\frac{1}{2})$ will lie on a smooth curve through three neighboring ordinates.

Clearly, by taking n adjacent given ordinates in the same way, a curve of degree (n - 1) may be adjusted to pass through them and we shall be able to interpolate (n - 1) ordinates between the given ordinates. Also, given (n - 1) known ordinates on both sides of an unknown ordinate, there are (n - 1) ways of determining a value for it by interpolation of order (n - 1).

Extrapolation may also be similarly effected, the only difference being that this term applies only to the determination of ordinates outside the array of given ordinates.

The whole process of interpolation or extrapolation involves the assumption that the unknown curve on which the known ordinates lie can be represented by an algebraic expression of some finite degree. In many cases where the physical conditions insure smoothness in the function, the method is fairly reliable; but it must, of course, be used with caution. Extrapolation is less reliable than interpolation.

The problem of interpolating signatures here proposed may be solved either by repeated curvilinear interpolation along transverse profiles taken in the y-direction, as just described, or, more elaborately still, by two-dimensional interpolation, so that the ordinate is made to lie on a surface of degree n passing through the terminii of $\frac{1}{2}(n + 1)^2 + \frac{1}{2}(n + 1)$ ordinates arranged at various positions (x, y) of the plane of definition. The aforementioned number of given ordinates requisite to determine the parameters of a two-dimensional algebraic equation of degree n is never a perfect square. However, if it is desired to use the entire square array consisting of known ordinates, m^2 in number, surrounding a point where it is desired to interpolate the unknown ordinate, the $\frac{1}{2}m^2 + \frac{1}{2}m$ parameters of a surface of degree $(m - 1)$ may be determined so that the surface fits the m^2 ordinates as best it may according to the well-known criterion of least squares.

2. Interpolated values may always be found by taking appropriately weighted arithmetic averages of adjacent known values

It will soon become clear that any value h which we desire to obtain by interpolation to a specified degree from other given values at neighboring points (disposed either in one dimension or in two dimensions) can always be expressed as a weighted average of the given values at the neighboring points. The weights to attach to the neighboring values depend on the degree of interpolation, the positions of the points, and on whether the interpolation is in one dimension or in two.

For example, in the simple case of linear interpolation in one dimension, the value $h(\frac{1}{2})$ at the point intermediate to the given values $h(0)$ and $h(1)$ is obviously given by the simple average

$$\overline{h(\tfrac{1}{2})} = \tfrac{1}{2}h(0) + \tfrac{1}{2}h(1).$$

In the case of a one-dimensional parabolic interpolation let the given values be $h(-1)$, $h(0)$ and $h(+1)$, and let the values to be found by interpolation (or extrapolation, as the case may be) be $h(-3/2)$, $h(-\frac{1}{2})$, $h(+\frac{1}{2})$, $h(+3/2)$. Then a system of three linear equations in the three unknown parameters a, b, c of the general equation $h = ay^2 + by + c$ can be set up in which each equation is written for one of the known values of h and the corresponding value of y. This system gives a, b and c in terms of $h(-1)$, $h(0)$ and $h(+1)$. By substitution then of $y = -3/2$, $-\frac{1}{2}$, $+\frac{1}{2}$ and $+3/2$ successively into the quadratic equation with determined coefficients, one can obtain the following formulas for the desired interpolated values in terms of the given values:

$$h(+3/2) = (15/8)h(+1) + (3/8)h(-1) - (5/4)h(0), \quad (7)$$
$$h(+\tfrac{1}{2}) = (3/8)h(+1) - (1/8)h(-1) + (3/4)h(0), \quad (8)$$
$$h(-\tfrac{1}{2}) = -(1/8)h(+1) + (3/8)h(-1) + (3/4)h(0), \quad (9)$$
$$h(-3/2) = (3/8)h(+1) + (15/8)h(-1) - (5/4)h(0). \quad (10)$$

Here again we see that each of the interpolated values is a simple weighted average of the given values. In general, it is clear that the more closely adjacent a given value is to the desired unknown value, the greater the weight it receives in the formula. Clearly, symmetry should and does exist between the coefficients, or weights, for the interpolated values on the two sides of the array if the sign of y is reversed. It is, therefore, really only necessary to calculate the coefficients for one-half of the positions.

The formulas for third degree interpolation in one dimension where the given ordinates are $h(-3/2)$, $h(-\frac{1}{2})$, $h(+\frac{1}{2})$, $h(+3/2)$ are:

$$h(0) = -(1/6)h(-3/2) + (9/16)h(-\tfrac{1}{2}) + (9/16)h(+\tfrac{1}{2}) - (1/16)h(+3/2), \qquad (11)$$
$$h(+1) = (1/16)h(-3/2) - (5/16)h(-\tfrac{1}{2}) + (15/16)h(+\tfrac{1}{2}) + (5/16)h(+3/2), \qquad (12)$$
$$h(+2) = -(5/16)h(-3/2) + (21/16)h(-\tfrac{1}{2}) - (35/16)h(+\tfrac{1}{2}) + (17/16)h(+3/2). \qquad (13)$$

The values for $h(-1)$ and $h(-2)$ can be obtained by a symmetrical reflection of these formulas. Here again the appropriately weighted average gives the desired result and, from the mode of derivation of these formulas (by means of a simultaneous linear set of equations to determine the coefficients in the type form), it is evident that this rule is quite general.

We shall also work out, as an example of two-dimensional interpolation, the case of a quadratic surface having the equation

$$ax^2 + by^2 + cxy + dx + ey + f = h(x,y). \qquad (14)$$

This surface has six parameters to be determined in such a way as to give the best fit (according to the criterion of least squares) to a set of nine ordinates located in a square array in the _x_, _y_-plane as follows:

$$\begin{array}{cccc} h(-1,1) & h(0,1) & & h(1,1) \\ h(-1,0) & h(0,0) & h(\tfrac{1}{2},0) & h(1,0) \\ h(-1,-1) & h(0,-1) & & h(1,-1). \end{array} \qquad (15)$$

The tenth ordinate, $h(\frac{1}{2},0)$, is the ordinate to be found by interpolation. The nine ordinates at the nine points (_x_, _y_) lead, in the terminology of least squares, to nine linear observation equations in the six unknowns _a_, _b_, _c_, _d_, _e_, _f_. From these, in the classical way, six normal linear equations are formed which are solved for the unknown coefficients. Upon substitution of the values $x = \frac{1}{2}$, $y = 0$ into the quadratic in two variables with determined coefficients, one obtains the expression for the desired ordinate, $h(\frac{1}{2},0)$. For compactness we give below merely the weights by which the known ordinates must be multiplied and summed to give the ordinate to be interpolated:

$$\begin{array}{ccc} -11/72 & 10/72 & 1/72 \\ 13/72 & 34/72 \;\bullet & 25/72 \\ -11/72 & 10/72 & 1/72 \end{array}$$

The dot indicates the position of the unknown ordinate which the weights are adapted to give.

It is interesting to compare this result with the previously calculated weights for the analogous case of interpolation between three points in a line. For comparison we again write down only the weights

$$-1/8 \quad 3/4 \cdot 3/8 \qquad (17)$$

Here again the dot indicates the position of the unknown ordinate which the weights are adapted to give. Note that the coefficients in formula 17 are merely the sums of the columns of the coefficient in the previous two dimensional formulas.

3. Physical method of interpolation making use of the foregoing law of weighted averages

It should now be amply clear that, if the solenoid coil box has alternate rows of coils energized to represent a set of given signatures and the remaining rows are simply "dead", an array of search coils appropriately disposed on the exploring carriage might be made to explore the field very close to the plane of definition, and a weighted average of the emf's generated in these search coils could be made up physically by means of small transformers (with adjustable ratios to represent the weights) and continuously supplied to the recorder so that the latter would draw a curve giving the interpolated value of any one of the desired intermediately situated signatures. Any desired degree of refinement is obviously possible since the array of exploring search coils can have extension fore and aft as well as athwart ship. The transformers would have their secondary windings connected in series so that the total of all secondary emf's would be fed to the recorder. The primaries would be connected to the search coils. These transformers should be provided with several decade dials so that their ratios could be set with some precision (say to two or three significant figures). They would be coupled to the search coil cables at the search coil binding posts on the lower switchboard of the exploring device. The total emf (in series) from the secondaries would be thus connected to +x and -x. The transformers would require special design to insure accuracy of ratio and they should have a sufficiently high no-load input impedance to demand negligible current from the search coils. Such transformers have not as yet been built, but engineers of the Bell Telephone Laboratories have considered designs for them and have submitted quotations.

In the opinion of the writer a cubic interpolation in one variable y of the type for which the coefficients in Eqs. (11), (12) and(13) have been obtained would be quite sufficiently refined for all practical purposes. In the majority of cases interpolation would be made for a position at the midpoint of the four given, equally spaced signatures using only Eq. (11). Only at the edges of the entire coil box array would be be necessary to deviate from this arrangement and to use Eqs. (12) and (13).

4. Graphs so interpolated can be set up immediately on panel switches without replotting

As has been pointed out (Sec.72), the ratio of speeds between recorder and exploring device can be chosen so that the correct abscissa scale is plotted directly by the recorder to fit the 1-1/8 in. spacing of the elevators on the panel banks. If the system of interpolation here contemplated is adopted, the ordinate scale of magnetic field intensities on the recorder should also be adjusted to coincide with the ordinates set up on the chart boards. This could be determined by comparing the recorder deflection from a single search coil with the ordinates on the chart board responsible for the deflection in question.

5. Method of correcting for the fact that the search coil cannot explore in the plane of definition but must be a small distance below it for clearance

The results described in Sec.97 with a completely energized field map show that the necessary clearance of only $\frac{1}{2}$ solenoid-coil-width between the center of the search coil and the plane of definition (ends of solenoid windings) already makes the field picked up by the search coil markedly different from the field in the plane of definition. 12/. At first sight this would seem to render the entire scheme of physical interpolation described in this appendix inapplicable, since the method envisages up to this point that each search coil shall truly explore the signature under which it stands.

In point of fact, however, this difficulty can be corrected by a mere modification of the weights to be set up on the transformers. For clearly, if a given search coil picks up the field of adjacent solenoids as well as the field of the solenoid under which it is placed, a weighted average of an array of search coils can be made to correct for this effect. In the first place, the fact that, at worst, only alternate rows of solenoids are energized when interpolation is required, means that the nearest energized solenoids are at least 2 coil-widths away in the y-direction. Thus the correction for the effect of these adjacent rows is small, and the correction for the effect of the rows next to them is

12/This difference is unfortunately not a mere proportional diminution but an actual change in the distribution of intensities caused chiefly by the effect of superposition of the fields of neighboring rows of coils upon the field of the row being explored.

completely negligible. We may, therefore, use the outputs of search coils under adjacent rows to correct the output of the search coil in question so that the corrected result will be a better approximation to the output that would be obtained if that search coil were in the plane of definition instead of being $\frac{1}{2}$ coil-width lower down. This verbal statement of the method is not intended to be an accurate description; it is offered merely as an introduction to the more precise mathematical treatment which follows.

Let us first consider how rapidly the vertical component of the magnetic field intensity of a solenoid of unit width decays at depth $z = \frac{1}{2}$ for increasing values $y = 0, 1, 2,$ etc. If the solenoid is long in the x-direction in comparison to its width, the answer is given by the following figures for $z = \frac{1}{2}$:

$$\begin{array}{rll} \text{At } y = 0, & \text{if } H_z = 1.000, \\ \text{then at } y = 1, & H_z = 0.346, \\ y = 2, & H_z = 0.078, \\ y = 3, & H_z = 0.033, \\ y = 4, & H_z = 0.018, \\ y = 5, & H_z = 0.010. \end{array}$$

Thus the effect of the "live" row of solenoids at $y = 2$ is less than 8 percent of the effect of the row immediately above the search coil while the next "live" row at $y = 4$ has an effect of less than 2 percent, which can be completely neglected for our purposes.

From this point on, the discussion is facilitated by the use of operational methods. Our dependent variable is the vertical component of the magnetic intensity which, for brevity, we shall call simply h. We think now of the curve or profile $h_{\frac{1}{2}}(y)$; this is the transverse cross section of our field map at $z = \frac{1}{2}$ which we are able to observe, the observation being made at $y = 0, \pm 2, \pm 4,$ etc. The thing we would like to obtain, however, is the curve $h_0(y)$, namely, the transverse cross section of our field map in the plane of the ends of the solenoids.

Consider an operation E_Δ, defined so that $f(y)$ when operated upon by E becomes $f(y + \Delta)$. In works on the calculus of finite differences it is shown that this operator has all the properties of an algebraic quantity, provided that certain very mild conditions limit the type of function f. This operator E can appear in infinite series (and other limiting processes) and the results, so long as the series is convergent, will be entirely reliable. The restrictions upon f do not exclude the functions of interest for our present purpose.

E_Δ^2 obviously changes f($\underline{y}$) into f(y + 2$\underline{\Delta}$), and E_Δ^{-1} changes f(y) into f($\underline{y - \Delta}$).

Now the situation which we face can be expressed in this notation as follows:

$$h_{\frac{1}{2}}(y) = A(aE_\Delta^{-1} + aE_\Delta + 1)\ h_o(y). \qquad (18)$$

Here a = 0.078 and A = 0.586 for the particular case in hand, while Δ = 2 coil-widths. In words, this says that, at z = $\frac{1}{2}$ coil-width below a given coil, the contribution of that coil to the intensity there is 0.586 of the coil's intensity at z = 0, while the contribution of the "live" coils 2 coil-widths to the right and left hands is 0.078 of their intensities at z = $\frac{1}{2}$ (which latter are also 0.586 of their intensities at z = 0).

However, the quantity desired is h_o (y), given $h_{\frac{1}{2}}(y)$, so we must "solve" the foregoing operational equation. This, the calculus of finite differences teaches us, we can do quite fearlessly as follows:

$$h_o(y) = A^{-1}\ (aE_\Delta^{-1} + aE_\Delta + 1)^{-1} h_{\frac{1}{2}}(y) \qquad (19)$$

$$= A^{-1}\left[1 + a(E_\Delta^{-1} + E_\Delta)\right]^{-1} h_{\frac{1}{2}}\ (y). \quad (20)$$

Expanding the bracket by the dinomial law, we get

$$h_o(y) = A^{-1}\left[1 - a(E_\Delta^{-1} + E_\Delta) + a^2(E_\Delta^{-1} + E_\Delta)^2 + \ldots\right] h_{\frac{1}{2}}\ (y). \qquad (21)$$

Because of the smallness of $\underline{a}$, this alternating infinite series evidently is very rapidly convergent, and it is clear that, if the term in the second power is neglected, the error in h_o ($\underline{y}$) will be only a little more than $\frac{1}{2}$ percent, hence negligible for our purposes.

We must now recall that our final object is not the determination of h_o(y) but rather the interpolated value to be obtained from a weighted mean of several such ordinates. For definiteness let us take the case of one-dimensional interpolation of third order (with four given, equally spaced ordinates) in which the ordinate to be found is in the midpoint of this array (Eq. 11). Call this ordinate to be found, h_o' ($\underline{y}$). Then the formula for finding it, given h_o($\underline{y}$), may be expressed in terms of our operator as follows:

$$h_o'(y) = \left[b(E_\Delta^{\frac{1}{2}} + E_\Delta^{-\frac{1}{2}}) + c(E_\Delta^{3/2} + E_\Delta^{-3/2})\right] h_o\ (y). \qquad (22)$$

Here b = 9/16 and c = -1/16 (see Eq. 11) and no inversion is necessary since the operational equation is already solved for the desired quantity. We can now combine the two operators into one and obtain

$$h_o'(y) = \Big[b(E_\Delta^{\frac{1}{2}} + E_\Delta^{-\frac{1}{2}}) + c(E_\Delta^{3/2} + E_\Delta^{-3/2}) - ab(E_\Delta^{-\frac{1}{2}} + E_\Delta^{-3/2} + E_\Delta^{3/2} + E_\Delta^{\frac{1}{2}}) - ac(E_\Delta^{\frac{1}{2}} + E_\Delta^{-5/2} + E_\Delta^{5/2} + E_\Delta^{-\frac{1}{2}})\Big] A^{-1} h_{\frac{1}{2}}(y). \tag{23}$$

The last parenthesis in the bracket can be dropped because of the smallness of its coefficient, ac. Collecting the remaining terms, we have

$$h_o'(y) = \Big[b(1 - a)(E_\Delta^{\frac{1}{2}} + E_\Delta^{-\frac{1}{2}}) + (c - ab)(E_\Delta^{3/2} + E_\Delta^{-3/2})\Big] A^{-1} h_{\frac{1}{2}}(y). \tag{24}$$

6. Normalization or adjustment of the deflection scale of the recorder

From Eq. (24) it is now clear that, by slightly modifying the weights in the interpolation formulas from the values b and c to the values b(1 - a) and(c - ab),we can correct for the difficulty introduced by our inability to explore exactly in the plane of definition. The constant multiplier A^{-1} is a matter of no great concern since this will be taken care of in adjusting the scale of the recorder. This adjustment may best be made by setting up in alternate rows a uniformly energized set of signatures with the intermediate signatures dead. The combined weights designed both to interpolate and to correct for the z-displacement are then to be set up on the transformers, and the scale adjustment on the recorder is adjusted so that the pen carriage deflections obtained are identical to the settings of the elevators controlling the live signatures. When the real interpolation problem is then set up, the recorder will automatically draw curves to appropriate scale to be used directly on the panel switches for setting up the intermediate interpolated signatures.

The foregoing exposition is offered merely as an example of the methods that might be used. The possibilities are too extensive to be explored exhaustively in this report. It should be clear, however, that the equipment here described opens up many possibilities for the physical solution of difficult or tedious mathematical situations. For example, an array of search coils whose outputs are properly weighted by means of transformers can be made to explore a field so as to approximate a product integral or, again, can be used as a "solving kernel" in solving integral equations.

One more example of the use of a weighted array of exploring search coils is given in Appendix E.

APPENDIX C

Resistances of Solenoid Coils at 68°F

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
A-1	2176	48-7/16	C-1	2175	48-3/4
-2	78	49-3/16	-2	75	48-9/16
-3	78	48-3/8	-3	76	48-1/2
-4	74	48-5/8	-4	74	48-11/16
-5	73	48-3/4	-5	77	48-13/16
-6	75	48-5/8	-6	76	49-5/16
-7	74	48-15/16	-7	76	49-5/16
-8	75	48-5/16	-8	77	48-7/8
-9	77	49-1/8	-9	74	49-5/16
-10	74	48-15/16	-10	75	49-3/4
-11	74	48-1/2	-11	75	48-13/16
-12	76	48-3/4	-12	75	48-1/2
-13	74	48-7/8	-13	75	48-13/16
-14	75	48-13/16	-14	76	48-7/8
-15	76	49	-15	75	48-5/16
-16	73	48-9/16	-16	75	48-13/16
-17	74	48-7/8	-17	77	48-5/8
-18	77	48-1/16	-18	77	48-3/16
-19	74	49-3/16	-19	75	49-1/4
-20	74	48-15/16	-20	74	48-3/16
B-1	2177	49-1/2	D-1	2175	48-11/16
-2	76	48-3/4	-2	76	48-1/8
-3	76	49	-3	74	49-1/4
-4	77	49-1/4	-4	75	48-15/16
-5	77	48-1/2	-5	76	49-3/16
-6	75	49	-6	76	49-7/16
-7	75	49-5/16	-7	76	48-15/16
-8	76	48-15/16	-8	74	49-1/8
-9	78	49	-9	75	48-15/16
-10	75	49	-10	76	49-1/16
-11	77	49-1/8	-11	77	48-13/16
-12	75	48-7/8	-12	76	49-1/4
-13	77	48-9/16	-13	76	48-5/8
-14	76	48-3/8	-14	76	49-7/16
-15	80	49-1/8	-15	76	49
-16	78	48-11/16	-16	77	49-7/16
-17	80	48-1/8	-17	75	48-13/16
-18	77	49	-18	75	48-15/16
-19	78	49-1/8	-19	75	48-7/16
-20	76	48-9/16	-20	76	48-9/16

Resistances of Solenoid Coils at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
E-1	2174	49-3/16	G-1	2175	49
-2	75	49-1/2	-2	78	48-11/16
-3	76	48-9/16	-3	75	48-13/16
-4	73	48-13/16	-4	76	48-15/16
-5	75	48-7/8	-5	75	48-11/16
-6	76	48-3/8	-6	76	49-1/8
-7	75	48-5/8	-7	76	49-1/8
-8	74	48-13/16	-8	76	48-5/8
-9	75	48-11/16	-9	74	49
-10	75	49-1/2	-10	76	49-1/8
-11	75	48-3/4	-11	76	49
-12	75	48-3/16	-12	76	49-3/16
-13	75	48-1/4	-13	75	48-15/16
-14	75	48-1/4	-14	76	49-5/16
-15	75	48-5/16	-15	77	49-3/16
-16	75	49-1/4	-16	76	49-3/8
-17	75	48-1/4	-17	76	48-13/16
-18	76	48-11/16	-18	76	48-9/16
-19	76	48-5/8	-19	75	48-1/16
-20	76	48-9/16	-20	74	48-1/2
F-1	2172	48-7/8	H-1	2175	48-7/16
-2	71	48-7/16	-2	76	49
-3	71	48-11/16	-3	76	49-1/16
-4	71	48-3/4	-4	75	49-5/16
-5	74	49-3/8	-5	71	48-15/16
-6	70	48-13/16	-6	73	48-9/16
-7	71	48-9/16	-7	73	49
-8	73	48-5/8	-8	74	48-1/2
-9	72	48-1/16	-9	76	49-1/4
-10	72	49-1/16	-10	71	48-3/4
-11	71	49-3/16	-11	71	48-13/16
-12	72	48-11/16	-12	71	48-5/8
-13	72	48-1/2	-13	75	48-5/8
-14	72	48-3/8	-14	73	48
-15	72	48-15/16	-15	70	49-1/4
-16	72	48-9/16	-16	71	49-1/16
-17	70	49-1/4	-17	71	48-5/16
-18	70	48-1/16	-18	71	48-5/16
-19	71	48-9/16	-19	70	48-3/4
-20	71	49-3/16	-20	73	48-11/16

Resistances of Solenoid Coils at 68°F (Continued)

Coil	Res. (Ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
J-1	2173	48-7/16	L-1	2176	48-9/16
-2	74	48-3/8	-2	76	48-3/16
-3	76	49	-3	75	49-3/16
-4	76	48-7/8	-4	76	48-7/8
-5	74	49-1/16	-5	76	48-15/16
-6	76	48-3/4	-6	76	49-1/16
-7	73	48-7/16	-7	76	49-3/16
-8	73	48-7/16	-8	76	48-15/16
-9	76	49	-9	73	48-13/16
-10	76	48-5/16	-10	74	48-15/16
-11	76	48-13/16	-11	76	48-3/16
-12	76	49-1/8	-12	76	48-15/16
-13	76	49-3/8	-13	75	49-5/8
-14	75	48-9/16	-14	75	49-3/8
-15	76	48-1/2	-15	75	49-5/8
-16	76	48-7/16	-16	76	48-15/16
-17	76	48-3/4	-17	75	48-11/16
-18	76	48-5/8	-18	75	49-1/16
-19	76	48-9/16	-19	76	49-3/8
-20	75	49	-20	75	49-1/16
K-1	2175	48-1/8	M-1	2176	48-9/16
-2	76	48-9/16	-2	73	48-5/8
-3	76	48-5/8	-3	76	48-11/16
-4	75	48-7/16	-4	76	48-15/16
-5	75	48-7/8	-5	76	48-5/16
-6	76	48-11/16	-6	76	48-5/16
-7	75	49-1/8	-7	76	48-5/8
-8	76	49-7/16	-8	75	48-15/16
-9	76	48-13/16	-9	75	48-7/8
-10	74	49-9/16	-10	76	48-7/8
-11	75	48-15/16	-11	76	48-9/16
-12	76	48-3/4	-12	76	49-3/16
-13	76	48-7/16	-13	76	49-3/16
-14	75	48-11/16	-14	77	48-1/8
-15	76	48-7/16	-15	74	48-3/8
-16	76	49	-16	76	48-15/16
-17	76	48-1/16	-17	75	48-3/8
-18	76	48-1/8	-18	76	48-11/16
-19	76	49	-19	76	48-1/4
-20	75	49-5/16	-20	76	49-1/4

Resistances of Solenoid Coils at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
N-1	2176	49-3/16	P-1	2177	48-3/16
-2	76	49-1/4	-2	76	49-1/8
-3	76	49-1/4	-3	76	49-1/4
-4	76	49-3/16	-4	75	49-5/8
-5	77	48-1/16	-5	74	49-1/4
-6	76	48-15/16	-6	75	49-3/4
-7	77	48-7/16	-7	73	49-3/8
-8	78	48-1/2	-8	76	48-15/16
-9	78	48-9/16	-9	76	49-5/8
-10	75	48-3/8	-10	77	48-3/4
-11	76	49-3/16	-11	75	48-15/16
-12	76	48-11/16	-12	76	48-3/8
-13	77	48-15/16	-13	74	49-3/8
-14	78	49-3/16	-14	76	49-1/16
-15	76	49-3/16	-15	76	49-1/16
-16	76	48-13/16	-16	74	49-9/16
-17	76	48-13/16	-17	76	49-15/16
-18	76	48-7/8	-18	76	49-11/16
-19	77	48-5/8	-19	76	49-11/16
-20	77	48-1/4	-20	76	49-11/16
O-1	2176	48-7/8	R-1	2175	48-5/16
-2	76	49-1/8	-2	76	48-1/8
-3	76	48-11/16	-3	73	48-1/2
-4	76	48-3/16	-4	76	49-7/8
-5	77	48-1/16	-5	76	48-15/16
-6	76	48-7/8	-6	76	49-5/8
-7	75	49-1/4	-7	76	49-3/16
-8	74	49	-8	76	49-5/8
-9	76	49-7/16	-9	75	48-13/16
-10	76	49-1/16	-10	75	48-3/16
-11	74	49	-11	74	48-11/16
-12	74	49	-12	75	48-5/8
-13	75	49-7/16	-13	75	49-1/4
-14	75	48-9/16	-14	76	48-5/16
-15	75	48-7/8	-15	76	48-3/8
-16	75	49-9/16	-16	76	48-3/8
-17	76	49-7/8	-17	77	48-1/4
-18	75	49-1/4	-18	70	49-15/16
-19	75	48-5/16	-19	74	48-1/8
-20	76	48-11/16	-20	76	48-1/16

Resistances of Solenoid Coils at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
S-1	2179	48-3/16	V-1	2176	49-13/16
-2	75	48-15/16	-2	76	49-3/16
-3	76	49	-3	77	49-3/16
-4	75	48-1/8	-4	76	48-1/4
-5	76	49-5/8	-5	76	48-1/2
-6	76	48-3/16	-6	76	49-1/4
-7	76	49-7/16	-7	75	49-1/8
-8	74	48-15/16	-8	74	49-3/4
-9	76	48-5/16	-9	76	48-13/16
-10	76	49-3/16	-10	73	48-11/16
-11	75	48-5/16	-11	75	49-3/16
-12	74	48-1/8	-12	76	49-3/4
-13	74	48-1/4	-13	77	49-11/16
-14	76	48-1/4	-14	75	49-1/2
-15	76	48-9/16	-15	76	49-13/16
-16	75	48-1/4	-16	77	48-13/16
-17	75	49-1/8	-17	77	48-11/16
-18	75	49-3/16	-18	77	48-5/8
-19	76	49-1/4	-19	76	48-7/8
-20	76	48-9/16	-20	74	49-3/8
T-1	2176	49-1/8	W-1	2177	48-7/16
-2	75	49-3/4	-2	76	49-5/16
-3	76	48-5/8	-3	78	48-5/16
-4	75	49-1/8	-4	76	49-1/16
-5	75	48-3/4	-5	77	48-9/16
-6	76	49-3/16	-6	77	48-11/16
-7	75	49-3/16	-7	76	49
-8	76	49-1/2	-8	77	49-5/16
-9	75	48-3/4	-9	76	48-15/16
-10	76	48-3/16	-10	76	48-1/8
-11	76	49-7/8	-11	75	48-11/16
-12	76	49-7/16	-12	76	49-1/4
-13	76	49-1/8	-13	76	48-1/8
-14	75	48-3/4	-14	75	48-7/8
-15	76	48-1/4	-15	76	49-5/16
-16	77	49-7/16	-16	75	49-1/4
-17	76	49-7/16	-17	75	48-1/2
-18	76	48-1/16	-18	76	48-5/8
-19	76	49-1/8	-19	75	48-15/16
-20	75	48-3/8	-20	76	48-1/2

Resistances of Solenoid Coils at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
X-1	2177	49-3/8	Z-1	2175	48-9/16
-2	76	49-3/16	-2	76	49-3/16
-3	76	49-3/8	-3	75	48-5/16
-4	76	48-15/16	-4	75	49-1/2
-5	76	49-1/4	-5	76	48-7/16
-6	75	49-7/16	-6	73	48-1/2
-7	75	49-1/4	-7	75	48-3/8
-8	76	49-1/16	-8	77	48-1/2
-9	76	49-1/8	-9	76	48-9/16
-10	75	48-3/16	-10	76	48-1/16
-11	75	49-5/16	-11	75	48-7/8
-12	75	48-7/8	-12	74	48-1/8
-13	75	48-7/16	-13	74	49-7/16
-14	76	48-1/16	-14	75	48-3/16
-15	76	48-3/16	-15	75	48-1/4
-16	76	48-13/16	-16	76	49-1/8
-17	76	49-9/16	-17	75	48-9/16
-18	75	48-15/16	-18	75	48-3/8
-19	76	49-15/16	-19	75	48-5/8
-20	73	48-7/16	-20	76	48-3/8
Y-1	2176	48-1/2	A-1	2175	49-5/8
-2	75	48-7/8	-2	75	49-5/8
-3	76	48-7/16	-3	74	48-7/8
-4	76	49-5/16	-4	75	48-9/16
-5	75	49-3/16	-5	76	49
-6	75	49-7/16	-6	74	49
-7	75	48-7/16	-7	75	48-9/16
-8	76	49-3/4	-8	75	49-1/4
-9	75	48-9/16	-9	74	49-1/2
-10	75	48-15/16	-10	75	48-1/2
-11	73	48-11/16	-11	75	48-3/16
-12	76	48-1/8	-12	75	48-1/2
-13	76	48-3/16	-13	76	48-15/16
-14	75	49-13/16	-14	76	48-11/16
-15	75	48-5/16	-15	75	49-11/16
-16	75	49-9/16	-16	76	49-1/16
-17	76	48-3/16	-17	77	48-7/16
-18	76	49-1/8	-18	77	49-1/16
-19	75	49	-19	75	48-15/16
-20	76	48-5/16	-20	75	48-3/8

Resistances of Solenoid Coils at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
BB-1	2174	49-1/4	DD-1	2175	48-5/16
-2	75	48-15/16	-2	74	49-3/8
-3	75	49	-3	75	49-3/16
-4	75	48-3/4	-4	74	49
-5	75	48-7/8	-5	74	49-1/16
-6	75	49-1/8	-6	75	49
-7	75	49-1/16	-7	75	49-1/2
-8	74	49	-8	76	49-1/8
-9	75	49-3/16	-9	75	48-15/16
-10	75	49-3/16	-10	75	49-1/4
-11	76	49-1/8	-11	74	48-15/16
-12	73	49-1/8	-12	75	49-3/16
-13	75	49-5/16	-13	75	49-1/16
-14	75	48-7/8	-14	75	49-3/16
-15	75	49-7/16	-15	74	49-5/8
-16	75	49-1/8	-16	75	49-1/16
-17	76	48-15/16	-17	75	48-5/16
-18	74	49-1/16	-18	75	49-1/8
-19	75	49-5/16	-19	75	48-5/16
-20	75	48-1/16	-20	75	48-3/16
CC-1	2177	48-3/8	EE-1	2175	48-7/16
-2	75	49-1/16	-2	75	49-1/16
-3	75	49	-3	71	48-9/16
-4	75	48-3/16	-4	75	48-3/4
-5	75	48-1/16	-5	74	48-1/8
-6	74	49-1/16	-6	75	48-13/16
-7	74	48-7/8	-7	75	48-7/16
-8	74	49	-8	75	49-5/16
-9	73	49-5/16	-9	75	48-5/16
-10	75	48-15/16	-10	75	48-7/16
-11	74	49-1/4	-11	74	48-5/16
-12	75	48-15/16	-12	75	48-3/16
-13	75	49-1/16	-13	75	49-1/16
-14	75	49-5/8	-14	75	48
-15	76	49	-15	75	49-7/16
-16	75	48-15/16	-16	75	49-1/8
-17	75	49-1/16	-17	75	48-1/2
-18	76	49-1/8	-18	75	49-1/8
-19	76	49-11/16	-19	75	49-11/16
-20	75	48-1/8	-20	74	48-11/16

Resistance of Solenoid Coils at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
FF-1	2175	49-3/8	HH-1	2175	48-3/8
-2	75	49-3/16	-2	75	48-3/8
-3	74	48-1/8	-3	75	49-5/16
-4	74	49-15/16	-4	75	48
-5	75	48-1/4	-5	76	49-1/2
-6	74	50	-6	75	48-1/16
-7	75	48-5/16	-7	75	49-1/4
-8	74	48-3/16	-8	75	48-5/16
-9	74	48-1/16	-9	75	49-5/8
-10	74	49-1/8	-10	76	48-3/16
-11	75	48-5/16	-11	75	49-3/4
-12	74	49-7/16	-12	75	49-1/2
-13	71	49-9/16	-13	75	48-3/4
-14	74	48-5/16	-14	75	48-5/16
-15	74	49-3/16	-15	75	48-7/8
-16	75	48-1/16	-16	75	48-3/4
-17	75	48-3/16	-17	75	49
-18	75	49-9/16	-18	74	49-1/16
-19	75	48-1/4	-19	74	49-1/16
-20	75	48-1/2	-20	76	49-1/16
GG-1	2175	48-1/8	JJ-1	2176	48-3/16
-2	75	48-3/8	-2	76	48-1/8
-3	75	48-15/16	-3	76	49-7/16
-4	75	48-5/8	-4	77	49-5/16
-5	75	49-3/8	-5	76	48-13/16
-6	75	49-3/16	-6	76	48-5/8
-7	74	48-15/16	-7	77	48-5/8
-8	74	48-1/8	-8	77	49-1/8
-9	75	49-1/16	-9	76	48-9/16
-10	75	48-3/8	-10	77	48-15/16
-11	74	49-13/16	-11	76	49-3/16
-12	74	49-9/16	-12	75	49
-13	75	49-13/16	-13	76	48-9/16
-14	75	48-7/16	-14	75	48-7/16
-15	75	48-3/16	-15	76	48-1/2
-16	75	48-1/2	-16	76	49
-17	75	48-3/8	-17	76	49-5/16
-18	76	48	-18	75	48-1/4
-19	75	49-3/16	-19	77	49-3/16
-20	74	49-3/8	-20	75	49-1/2

Resistances of Solenoid Coils at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
KK-1	2174	48-1/8	NN-1	2174	48-1/8
-2	74	49-3/16	-2	76	48-1/8
-3	75	49-7/16	-3	74	49-1/16
-4	76	49-7/8	-4	75	48-7/8
-5	75	48-1/2	-5	74	48-7/16
-6	75	49-1/4	-6	73	48-1/16
-7	75	49-13/16	-7	75	49-1/4
-8	75	48-11/16	-8	76	48-7/16
-9	75	48-11/16	-9	75	48-3/8
-10	76	48-13/16	-10	76	48-3/4
-11	75	49-5/8	-11	75	48-1/2
-12	75	48-3/16	-12	76	48-3/4
-13	70	49-13/16	-13	76	48-3/8
-14	76	48-5/16	-14	73	49-9/16
-15	76	48-3/16	-15	76	48-1/4
-16	76	49-7/8	-16	78	48-1/2
-17	77	49-13/16	-17	77	48-11/16
-18	73	49	-18	76	49-1/8
-19	73	48-1/4	-19	73	49-15/16
-20	74	48-5/16	-20	75	48-1/8
LL-1	2174	48-5/8	OO-1	2175	48-15/16
-2	72	49-1/16	-2	76	48-5/16
-3	74	48-3/16	-3	75	49-1/2
-4	75	48-13/16	-4	75	48-11/16
-5	75	48-4/16	-5	75	49-3/8
-6	73	48-5/16	-6	75	48-3/8
-7	76	48-7/16	-7	74	49-9/16
-8	74	48-15/16	-8	75	48-1/2
-9	75	49	-9	75	49-3/8
-10	73	48-3/16	-10	75	48-7/16
-11	74	49-3/16	-11	76	49-11/16
-12	75	48-1/16	-12	74	48-7/8
-13	75	48-13/16	-13	75	49-3/16
-14	75	48-1/16	-14	76	49-1/16
-15	74	48-7/8	-15	75	48-7/16
-16	74	48-5/8	-16	75	49-9/16
-17	75	49-9/16	-17	75	49-11/16
-18	77	49-5/16	-18	75	49-1/16
-19	77	48-7/8	-19	75	49
-20	75	48-1/16	-20	75	48-1/2

Resistances of Solenoid Coles at 68°F (Continued)

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
PP-1	2175	48-5/16	TT-1	2175	49-3/16
-2	76	49	-2	75	49-1/8
-3	74	49-1/16	-3	75	49-1/16
-4	77	48-15/16	-4	76	49-3/16
-5	75	48-3/8	-5	76	48-3/16
-6	75	48-1/16	-6	73	48-5/16
-7	75	48	-7	73	49-1/8
-8	77	48-1/16	-8	73	48-3/16
-9	73	48-3/16	-9	74	48-1/16
-10	75	48-7/8	-10	75	48
-11	73	49-1/16	-11	75	49
-12	74	48-1/2	-12	75	49-1/8
-13	74	48-1/4	-13	75	49-5/16
-14	74	48-13/16	-14	74	48
-15	78	48-1/16	-15	75	48-15/16
-16	75	48-3/16	-16	75	48-1/2
-17	74	48-13/16	-17	75	49-5/16
-18	76	48-1/8	-18	75	49
-19	74	48-5/16	-19	73	48-1/4
-20	74	48-1/8	-20	73	48-1/4
SS-1	2174	49-1/16	XX-1	2175	48
-2	74	49-5/16	-2	74	48-3/4
-3	75	48-3/4	-3	75	48-1/16
-4	73	49-1/4	-4	72	49-1/16
-5	73	48-5/16	-5	74	49-7/16
-6	75	49	-6	73	49-1/16
-7	74	48-5/16	-7	74	49-3/8
-8	74	48-1/16	-8	76	48-5/8
-9	73	48-1/2	-9	75	49-3/8
-10	75	48-3/16	-10	75	49-1/8
-11	73	48-1/8	-11	75	49
-12	76	48	-12	75	48-15/16
-13	74	48-3/16	-13	71	49-3/8
-14	74	49-1/4	-14	75	48-9/16
-15	74	48-9/16	-15	74	49-3/16
-16	73	48-1/8	-16	75	48-1/8
-17	74	49-3/16	-17	75	48-7/8
-18	74	49	-18	75	48-13/16
-19	74	49-1/8	-19	75	49
-20	75	48	-20	75	49-3/8

Resistances of Spare Solenoid Coils at 68°F

Coil	Res. (ohms)	Wdg. Length (in.)	Coil	Res. (ohms)	Wdg. Length (in.)
1	2174	48-7/16	26	2175	49-1/4
2	76	49	27	74	48-1/4
3	75	48-7/16	28	76	48-7/16
4	76	48-1/2	29	76	49-3/16
5	75	49-7/8	30	74	49-13/16
6	75	49-11/16	31	74	49-1/8
7	76	49-7/8	32	76	49-5/8
8	75	49-1/8	33	76	49-5/16
9	75	49-3/8	34	75	49-7/8
10	76	49-5/8	35	75	49-3/16
11	75	49-13/16	36	74	48-3/4
12	76	48-7/8	37	74	48-7/8
13	76	49-3/8	38	75	49-1/2
14	75	49-7/16	39	74	49-5/8
15	75	48-1/2	40	75	48-5/8
16	74	49-1/2	41	75	48-3/4
17	75	48-1/4	42	74	48-1/16
18	74	49-1/2	43	74	49-13/16
19	75	49-1/16	44	74	49-1/16
20	74	49	45	75	49-1/8
21	75	49-3/4	46	75	49-1/2
22	75	49-1/4	47	73	48-7/8
23	75	49-5/16	48	75	49-1/4
24	74	49-1/2	49	73	48-1/8
25	75	49-3/16	50	74	48-3/16

Appendix D

Inventory of Accessories and Extra Parts for Naval Ordnance Laboratory Field Machine

I. <u>Parts for exploring device</u>

1. 7 Search coils, 16 mh each, beside the three on the carriage of the device.

2. 10 Hearing Aid cables, concentric type, 12 ft long.

3. Gears as follows (mounted on spare pin of recorder):
   1, 22-teeth; 2, 48-teeth; 1, 74 teeth (beside 2, 72-teeth and 2, 24-teeth on recorder).

4. 7 spare Lucite holding fingers and 8 Lucite screws for search coils.

5. Cable, rubber covered, for power supply to synchronous motor of exploring device with "microphone plug" connector (painted green).

6. Cable, rubber covered, for control of recorder paper motion from switch on exploring device with two "microphone plug" connections (painted black).

7. 2 cables, rubber covered, one short to lead from exploring device to standardizing millivolt box, one long to lead from latter to tap transformer with "banana plug" terminals and alligator clips.

8. Standardizing millivolt box.

9. 2 Bakelite micrometer screw slide adjusting carriages for adjusting and supporting exploring device on cross bars.

10. 2 extra Bakelite adjusting screws and 2 extra Bakelite fillister machine screws, 3 extra Bakelite pins and one extra Bakelite set screw for fiducial index, all for above screw slide adjusting carriages.

11. 6 Bakelite taper pins for locating height of cross bars supporting exploring device.

12. 7 Bakelite screws with elongated square heads for hand adjustment to hold cross bars in place (one is a spare).

13. 19 Bakelite screws with short square heads for holding vertical stanchions on framework (three are spares).

14. 6 vertical maple stanchions with taper and threaded locating holes for locating cross bars by means of taper pins and provided with vertical calibrated scales and brass adjusting screws and sleeves at bottom ends.

15. 2 similar vertical maple stanchions (spares) without scales or brass adjusting screws.

16. 3 maple cross bars fitted to Bakelite slide carriages (Item 9), two provided with calibrated scales for setting exploring device transversely.

17. 3 similar spare maple cross bars not so fitted or provided with scales.

18. 1 steel templet and 4 steel sleeves for same, for boring accurately located holes in vertical stanchions.

19. 2 diagonally braced rectangular maple frames provided with appropriate holes for cross bar supports and one X-brace for these frames, all to go on working end of coil box.

20. 1 wood cover to protect mechanism of exploring device from dust when not in use.

21. 2 wood covers for gears on exploring device.

II. Accessories for recorder and switching panels

22. Kit of tools in cloth pocket holder containing 2 small oil cans, 1 pair tweezers, 4 small flat wrenches of graduated sizes, 1 small "meter type" screw driver, 1 "angle" type screw driver, 2 larger wood handle screw drivers, 1 short nosed cutting plier, 1 long nosed cutting plier, 1 close side cutting plier, 3 Allen-type screw drivers for set screws in exploring device.

23. One pair headphones with leads and jumper, with alligator clips for testing contacts on switching panels.

24. 2 bottles recorder pen ink.

25. One dropper for filling ink in recorder pen.

26. 2 recorder pens (one in recorder).

27. 2 sets of mounted fine steel wires for cleaning recorder pen.

28. One spare cord for pen carriage drive on recorder.

29. One spare No. 1075 fuse extractor posts for recorder.

30. 6 No. 1264 3AG 1/4 amp Slo Blo little fuses.

31. 2 spare No. 323A Western Electric Thyratrons.

32. Small bag of screws for recorder cabinet.

33. 2 large boxes of lead counterweights for elevators on switching panels, to be used, if desired, to insure falling of elevators when released.

34. Large box of extra contact fingers (some of insulated and some of conducting type) for panel switching devices.

35. Box of cable clasps.

36. 3 spare paper rollers for recorder and one phosphor bronze clip for same.

37. One hand exploring coil mounted in support block provided with Hearing Aid cable for exploring by hand. (Seems to have an open circuit in it.)

38. Two boxes assorted maple wedges for levelling coil box and other purposes.

39. One pair calibrated maple wedges for adjusting zero on vertical stanchions by inserting the wedges between top of exploring carriage and bottom ends of hard rubber cores on coil box.

40. One box assorted shingles for leveling panel switching frames.

41. One bottle of oil for recorder and exploring device.

42. Bag of screws and parts for panel switching device.

APPENDIX E

On a Physical Method of Determining the Magnetic Map at a Higher Level (Nearer the Source) from the Magnetic Map at a Lower Level

Let h be the vertical component of the magnetic field. Designate by h_1 (x, y) the values of h in a horizontal plane in which search coils can explore and, by h_o (x,y), the values of h in some other horizontal plane higher (nearer the source of the magnetic field) than the first.

The field at a point (x, y) in the lower plane can be regarded as the sum of the effects of the magnetic field intensities at many points in the upper plane. We shall represent the real continuous magnetic distributions in both planes by an approximation consisting of discrete concentrated points located at the intersections of a rectangular grid whose squares for simplicity we shall take as having sides of unit length. Each point thus replaces a small magnetized surface and all these surfaces are of equal area. We shall describe the positions of such points in the x,y-plane by means of the complex quantity, $a + ib$, in which a and b may assume any integral values and either algebraic sign.

Suppose, for the moment, we consider the magnetic field at some point P in the lower plane and call this point our origin of complex values. We shall describe the positions of points in the upper plane with exactly the same complex numbers as those directly (vertically) below them in the lower plane. Then it is clear that the field at P is a weighted sum of effects from fields at many points in the upper plane. The contribution from the point directly above P will have the greatest weight and contributions from points having the same radial distance from the origin will have equal weights, which will diminish with increasing distance. These weights will depend upon the distance between the two planes and the unit separation between points in the planes.

The weights may be computed by means of the inverse square law, as though the field were the result of charges concentrated in points. A slightly better approximation may be obtained by computing weights as though the charges were uniformly spread over the square area to be associated with the point in question. In the present treatment the weights will be left in literal form to permit substitution of any desired values to suit each problem.

The choice of the unit distance between grid points $a + ib$ must be governed by the field map, so as to give a reasonably faithful delineation of its features to the accuracy required in the solution. If the distance between the two planes is large relative to this unit, we shall be obliged to regard the field in the lower plane as the resultant of the field at a large number of points of the upper plane in order to have an accurate result, because all points must be included which lie inside a circle of such radius that on it and outside it the weights become negligible. As the number of points to be considered increases, the complexity of the method increases rapidly. The conclusion is, therefore, that the method here described is limited to upward extrapolation over "small" distances, that is, distances not too large in comparison to the detailed features of the field map.

It now becomes of interest to classify the points $a + ib$ in our square checkerboard array into groups such that, in each group, all members have the same distance from the origin and so that these distances form an increasing sequence. Each group will have the same weight attached to all of its members to express the contributing power of unit field at those points in the upper plane for producing field at the origin in the lower plane. These weights we shall represent by the lower-case letters, a, b, c, etc. The largest weight, a, corresponds to the group of points nearest the origin whose positions are described as $+1$, -1, $+i$, $-i$. The next nearest group of points is $1+i$, $-1+i$, $-1-i$, $1-i$, and its weight we call b. Below are tabulated 13 such groups, with the letters designating their weights, the number of members in each group and the common distance of the members of the group from the origin (in the same plane as the group).

Table of net point groups.

Order No.	Weight	No. of points	Distance from origin
1	a	4	1
2	b	4	$\sqrt{2} = 1.414$
3	c	4	2
4	d	8	$\sqrt{5} = 2.24$
5	e	4	$2\sqrt{2} = 2.828$
6	f	4	3
7	g	8	$\sqrt{10} = 3.16$
8	h	8	$\sqrt{13} = 3.6$
9	i	4	4
10	j	8	$\sqrt{17} = 4.11$
11	k	4	$3\sqrt{2} = 4.24$
12	l	8	$2\sqrt{5} = 4.46$
13	m	12	5

The diagram which follows shows the spatial locations of the members of the various groups of net points, the members of each group being designated by the letter standing for the weight of that group. Such a diagram gives a more compact way of describing the groups than would the formulas for the complex numbers describing their positions. The 12 points having the weight m, for example, have the formulas (5), (4 + i3), (3 + i4), (i5), (-3 + i4), (-4 + i3), (-5), (-4 - i3), (-3 - i4), (-i5), (3 - i4), (4 - i3).

```
                m
          m l j i j l m
        m k h g f g h k m
        l h e d c d e h l
        j g d b a b d g j
      m i f c a · a c f i m
        j g d b a b d g j
        l h e d c d e h l
        m k h g f g h k m
          m l j i j l m
                m
```

Since the purpose at present is merely to explain the method, the calculations will not be extended to cover a very wide array of points.

Let us now define an operator E such that, when $E^{a + ib}$ operates on $h(x, y)$, it changes that function into $h(x+a\Delta, y+b\Delta)$, where Δ is the unit chosen above for our checkerboard array of net points. We shall handle this operator in every respect as though it were an algebraic quantity. That this can be done is proved in the calculas of finite differences for such an operator in the case of functions of a single variable; and there seems little reason for doubting an extension of this property to the present case, for it is quite clear that, if h is a single valued function of x and y, the commutative and distributive laws must apply when successive two-dimensional shifting operations occur.

We now express the relationship between the known magnetic distribution $h_1(x,y)$, and the distribution above it to be found, $h_0(x,y)$, in the following symbolic way:

$$h_1(x,y) = \left[1 + a(E + E^{i} + E^{-1} + E^{-i}) + b(E^{1+i} + E^{1-i} + E^{-1-i} + E^{1-i}) + \ldots\right] X \cdot h_0(x,y). \quad (1)$$

Here X is merely a numerical coefficient less than unity whose value depends on the distance between the two horizontal planes.

Each of the parentheses in the bracket consists, it will be noted, of a group of operators having the same weight coefficient. Only the first two groups have been written above, but it will be clear from the preceding table and diagram of net points how the other groups of operators are to be formed. We shall now designate by capital letters, A, B, C, etc., a set of operators equal to the sums of the operators in the respective parentheses; the capital letter for the operator will thus correspond to the lower-case letter for its weight. Thus we shall have

$$A = E + E^{i} + E^{-1} + E^{-i}, \qquad (2)$$

$$B = E^{1+i} + E^{1-i} + E^{-1-i} + E^{1-i}, \qquad (3)$$

etc.,

and we can write in the more abbreviated form,

$$h_1(x,y) = \left[1 + aA + bB + cC + \ldots\right] X \cdot h_o(x,y). \qquad (4)$$

This we can solve for $h_o(\underline{x},\underline{y})$ as follows:

$$h_o(x,y) = \left[1 + aA + bB + cC + \ldots\right]^{-1} X^{-1} \cdot h_1(x,y). \qquad (5)$$

Our task now is to obtain the inversion of the polynomial in the bracket. Since the weights have been purposely classified in descending order of magnitude and are all less than unity, it clearly will be a simple matter, at least in principle, to expand this bracket in a convergent series. This expansion will evidently contain powers and products of the operators A, B, C, etc., and it will therefore be convenient to work out a multiplication table for these operators. Such a table can be worked out either by actual multiplication of the analytic expressions, such as Eqs. (2) and (3) for the different operators, or much more conveniently and quickly from the preceding space diagram, since multiplication is effected by addition of the complex exponents.

Multiplication table

	A	B	C	D
A	4+2B+C	2A+D	A+D+F	2B+2C+2E+G
B		4+2C+E	2B+G	2A+2D+2F+H
C			4+4E+I	2A+D+H+J
D				8+2B+2C+2G+2I+2K+L

By the application of such a table it is easy also to work out third-degree terms such as

$$A^3 = 9A+3D+F, \qquad B^3 = 9B+3G+K,$$

$$AB^2 = 6A+3D+2F+H, \qquad A^2B = 8+6B+4C+2E+G.$$

It is also clear that the compound operators A, B, C, and D, as well as the simple operators E^{a+ib} from which they are formed, are members of an infinite closed set for the operation of multiplication between them; that is to say, no product of such operators can lead to a result which is not a member of the infinite set. It was to obtain this valuable property that the original elementary magnetized areas were chosen in a regular array (rather than being defined by some system of polar coordinates, for example).

We shall suppose that the weights, $\underline{a}$, $\underline{b}$, $\underline{c}$, $\underline{d}$, etc., decrease consecutively in such a way that we can neglect terms multiplied by $\underline{e}$ and all weights beyond. We shall also suppose that we can neglect terms with coefficients less than $\underline{c}^2$, $\underline{d}^2$, $\underline{a}^4$, $\underline{b}^4$ or terms of equivalent smallness.

We now proceed to expand the bracket of Eq.(5), retaining therein only five terms and rejecting in the result negligible terms as just defined:

$$\left[1+aA+bB+cC+dD\right]^{-1} = 1-aA-bB-cC-dD+a^2A^2+b^2B^2+2abAB+2acAC+2adAD$$

$$+2bcBC+2bdBD-a^3A^3-b^3B^3-3ab^2AB^2-3a^2bA^2B. \qquad (6)$$

If we next make use of our multiplication table to reduce the right-hand member and collect its terms, there results the following expression for the inverted operator:

$$(1+4a^2+4b^2-24a^2b) + (-a+4ab+2ac+4bd-9a^3-18ab^2)A$$

$$+ (-b+2a^2+4ad+4bc-9b^3-18a^2b)B+ (-c+a^2+2b^2+4ad-12a^2b)C \qquad (7)$$

$$+ (-d+2ab+2ac+4bd-3a^3-9ab^2)D + (b^2+4ad-6a^2b)E +(2ac+4bd-a^3-6ab^2)F$$

$$+ (2ad+2bc-3b^3-3a^2b)G + (2bd-3ab^2)H - b^3K.$$

This is the operator which, operating on our known values $h_1(\underline{x},\underline{y})$, gives us the desired values $h_o(\underline{x},\underline{y})$. The parentheses are to be evaluated as numerical coefficients from the known weights $\underline{a},\underline{b},\underline{c},\underline{d}$. The operator directs us to find the magnetic field intensity at a point in the upper plane by weighting the intensities at the designated groups (A, B, C, etc.) of points in the lower plane. This we propose to do physically by arranging search coils in an appropriate array on the exploring carriage and connecting these search coils together through transformers in such a way that the final output shall represent the weighted sum of expression (7). It is clearly necessary to have only as many transformers as there are groups of points in the array, since all search coils in the same group receive the same weight. For the solution of such a problem, special search coils wound on hollow rectangular frames might be used, and these could have their turns so adjusted as to furnish the correct weights without the use of transformers. However, such an arrangement evidently could be used for upward extrapolation over one interplanar distance only. It is clear that, if the weighted sum of the outputs of these search coils is connected to the recorder, profiles or "signatures" of the magnetic map in the upper plane will automatically be drawn. Thus the method here proposed eliminates all time consuming computations for individual problems. On the other hand, much more lengthy computations than those given here are to be recommended for the initial establishment of the weights because the present computations have not been carried out to cover any large number of points. They are offered here merely as an illustration of the method.

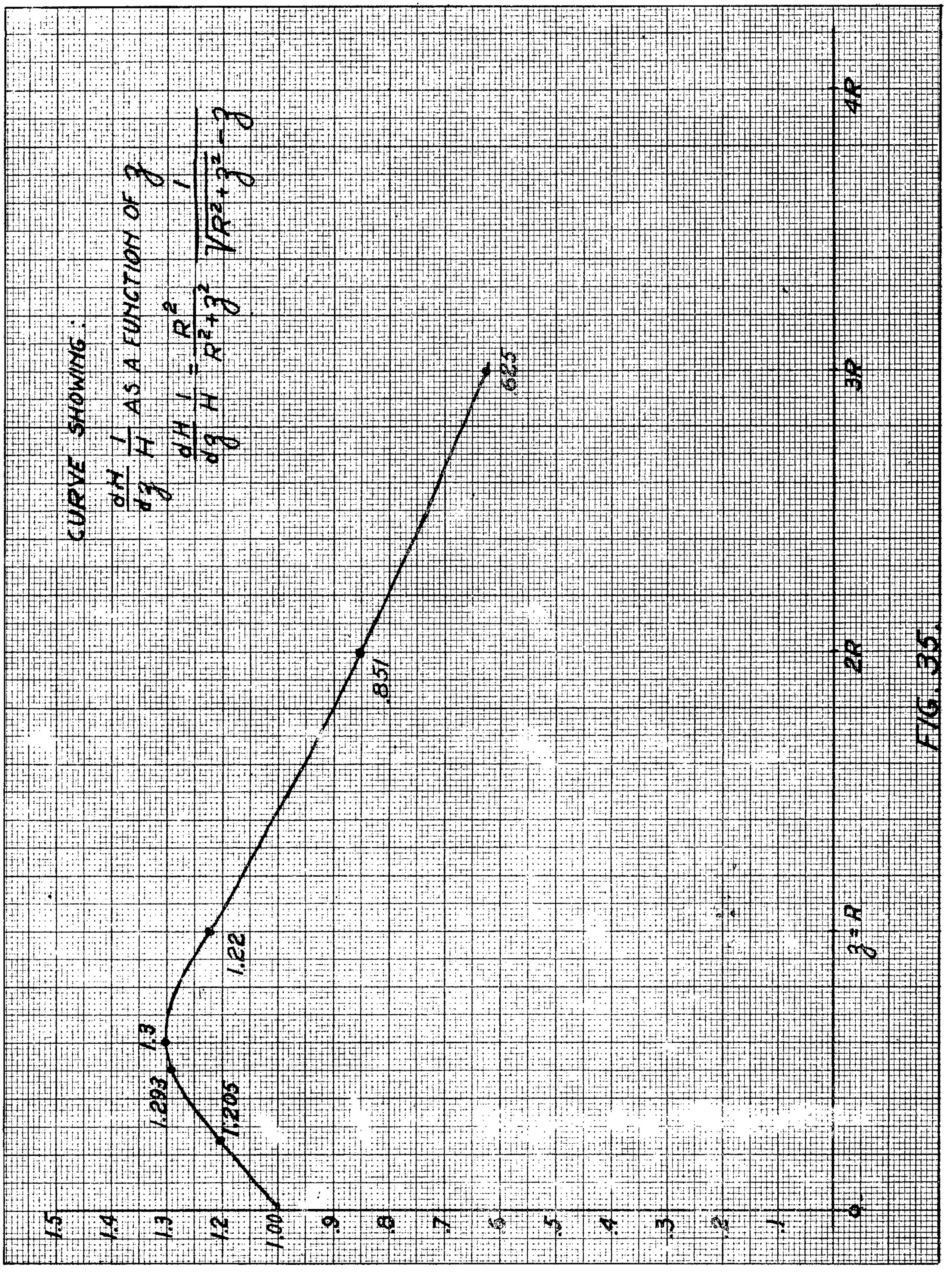

CURVE SHOWING:
$\frac{dH}{dz}\frac{1}{H}$ AS A FUNCTION OF z
$\frac{dH}{dz}\frac{1}{H} = \frac{R^2}{R^2+z^2}\frac{1}{\sqrt{R^2+z^2}-z}$
1.205
1.293
1.3
1.22
.851
.625
1.5
1.4
1.3
1.2
1.00
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
$z=R$
2R
3R
4R

FIG. 35.

APPENDIX F

The Axial Field Outside the End of a Long Cylindrical Solenoid

Consider a circular cylinder of great length compared to its radius R. For convenience of discussion, suppose the axis is vertical and that at the bottom end, the cylinder is terminated by a plane base normal to its axis. This cylinder is wound with n turns of wire per unit length, the winding terminating exactly at the end of the cylinder. The turns are supposed to be spaced sufficiently close to each other so that the angularity of the helix can be neglected and each turn can be treated as substantially circular. Consider a point P on the axis of the cylinder at a distance z below the plane of the end of the winding. According to the law of Biot and Savart, one finds that the magnetic field intensity at P produced by the entire half-infinite solenoid is

$$H = 2\pi ni\left[1 - \frac{z}{(R^2 + z^2)^{\frac{1}{2}}}\right]. \text{ (i in absolute emu.)} \qquad (1)$$

Let us inquire as to the relative rate of variation of this field with depth at different depths z:

$$\frac{dH}{dz}\frac{1}{H} = \frac{R^2}{R^2 + z^2} \cdot \frac{1}{(R^2 + z^2)^{\frac{1}{2}} - z} \,. \qquad (2)$$

At depth $z = 0$ this relative rate of variation is $1/R$. This means that a 1-percent variation of R along z results in a 1-percent change in H. The relative rate of variation [13] at first increases slightly as z increases but clearly vanishes as $\frac{1}{2}z^{-1}$ for great depths.

By plotting the curve of $(dH/dz)(1.H)$ as a function of z/R, one finds a maximum for this curve at $z = 0.6R$, approximately, the maximum value being $1.3/R$.

At $z = 1$ coil-width (or 2R), $(dH/dz)(1/H) = 0.851/R$; thus at a dpeth of 1 coil-width, a 1-percent variation in field intensity will result from a change in height of only a little more than 0.002 in.

In Fig.35, $(dH/dz)(1/H)$ is shown plotted as a function of z/R.

13/Namely, $(dH/dz)\ (1/H)$.