MEASUREMENTS ON THE MAGNETIC FIELD OF THE OREGON STATE COLLEGE CYCLOTRON

by

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MEASUREMENTS ON THE MAGNETIC FIELD OF THE OREGON STATE COLLEGE CYCLOTRON

INTRODUCTION

The purpose of this paper is to discuss the measurements made on the magnetic field of the Oregon State College cyclotron, including the design of the necessary measuring equipment and the presentation of the final results. For completeness, a brief history of the magnet construction together with some of the problems relating to its design and operation will also be discussed.

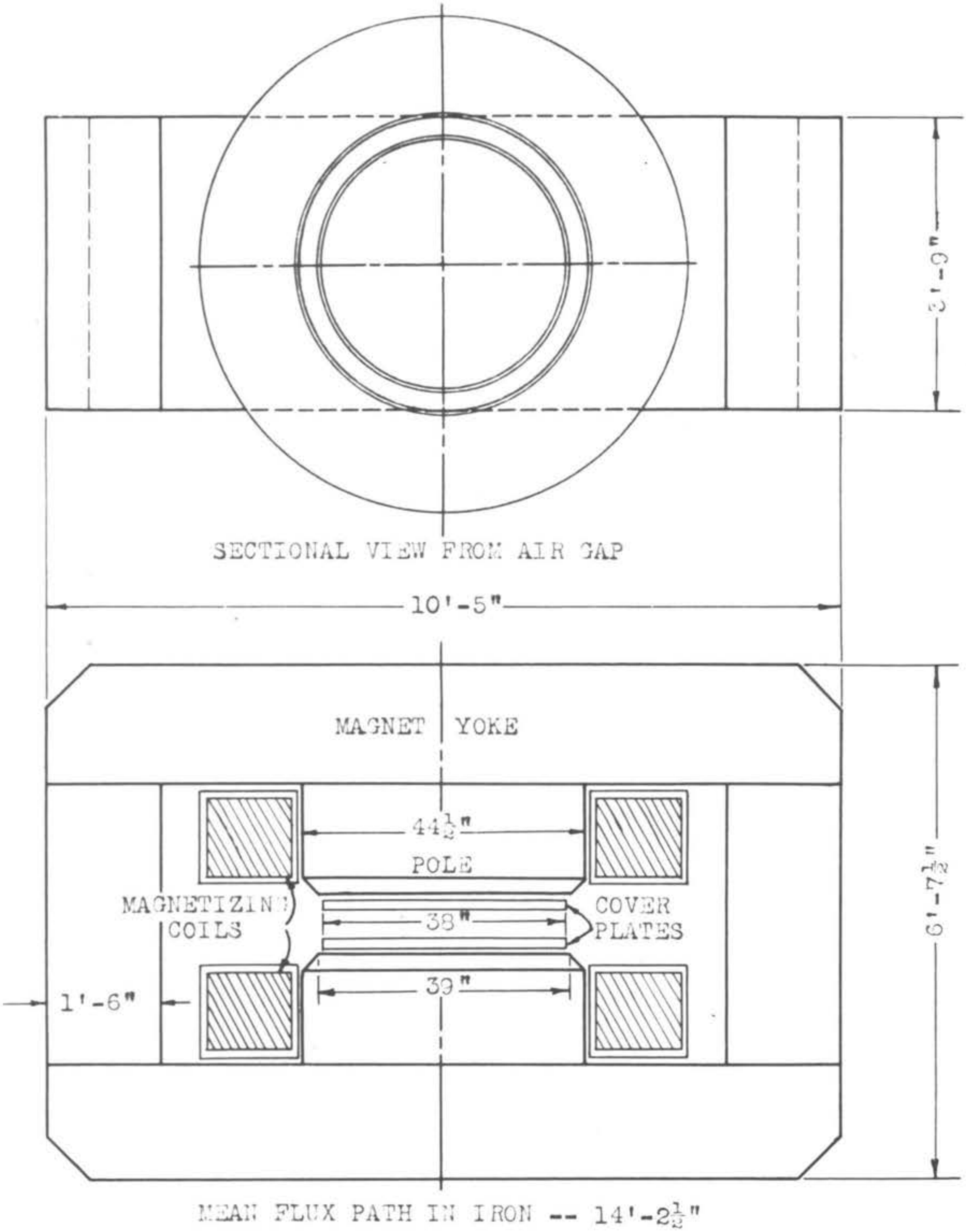
In June, 1950, construction was started on the Oregon State College cyclotron. At that time the concrete slab was laid, upon which the steel sections for the magnet were assembled, and concrete blocks to provide radiation shielding were placed around the magnet to form the cyclotron chamber. Later in 1950, the building housing the cyclotron and its auxiliary equipment was built. In June, 1952, the magnetizing coils and their air-cooling system having been completed, the measurements on the magnetic field were started.

The steel for the magnet, including the castings and machining, was furnished by the Radiation Laboratory of the University of California at Berkeley. The design of the yoke and pole pieces was supervised by Drs. Dempster and Brady, members of the Oregon State Cyclotron Committee.

Previously the Radiation Laboratory had constructed and tested a model of a magnet similar to the present one, and this information was used as a guide in the design of the full scale magnet. Although some data for the general over-all design was available, certain estimates had to be made because of the lack of knowledge of the magnetic properties of the steel. Therefore, the rather detailed measurements described in this paper were absolutely essential before further design of the cyclotron could proceed.

The magnet, drawn in Figure 1, is constructed of approximately 50 tons of steel and $5\frac{1}{2}$ tons of copper. The copper is wound in two coils, each having 9 pancake-shaped layers. Each pancake contains 40 turns of 1 x 1/4 inch strips giving a total of 720 turns. The pancakes are separated by 3/8 inch fiber spacers perforated to allow circulation of the air used in cooling the coils. Between the two pole faces the total air gap is 6 inches; 5 inches separates the two cover plates and $\frac{1}{2}$ inch between each cover plate and pole face serve as shim gaps.

By experiment and by theoretical considerations it has been found desirable to satisfy certain conditions in the design of a cyclotron magnet (1, pp.5-30). It is difficult to build a magnet and expect it to have all the desired properties. If the magnet is carefully designed, on



MEAN FLUX PATH IN IRON -- 14'-2½"

TOTAL AIR GAP -- 6"

DIAGRAM OF OREGON STATE COLLEGE CYCLOTRON MAGNET FIGURE 1.

the basis of general magnetic theory and previous experience, it should produce at least approximately the desired field. After construction, however, the exact field properties must be determined by measurement, and adjustments made to produce the proper field. These measurements are made one at a time in such an order that any adjustments made will have a minimum effect on all previous measurements. This sequence also allows a minimum amount of measurements to be taken. The measurements which are discussed in detail in the following sections of this thesis include: a determination of the absolute value of the magnetic field with its dependence on the magnetizing current; an investigation of the azimuthal homogeneity of the field; a check on the magnetic median surface; and, finally, a set of profile measurements using various shim arrangements in order to obtain a field which could be used for final operation. All important data and calculations are given in the appendix.

INSTRUMENTATION

The simplest and most practical method for the measurement of a magnetic field is obtained by the use of a fluxmeter and search coil. The advantages of this device are simplicity of design and operation, and the usual availability of the necessary equipment. The indicating device, the fluxmeter, is a type of galvanometer whose deflection is proportional to the total charge passing through the moving coil. In all of the described field strength measurements, a Grassot type fluxmeter manufactured by the Cambridge Instrument Company was used. The moving coil in this type of meter is designed to have negligible restoring torque and small moment of inertia. The moving coil is suspended by means of a very thin quartz fiber and the leads are brought out by means of fine silver spirals. The instrument used has a given sensitivity of 14,000 Maxwell-turns per scale division.

Although the suspension had been calibrated at the factory, it was felt that the sensitivity of the instrument should be checked. The sensitivity was checked by two independent methods, first by the use of a standard mutual inductance, and secondly, by quickly removing a search coil of known area from the given field of a pair of Helmholtz coils. By both methods, the former accurate to less than two per cent, the measured sensitivity was found to agree with the factory calibration.

The direct reading scale of the fluxmeter has a total of 120 divisions and is graduated in half scale divisions. With practice the person reading the meter can measure a deflection to within one tenth of a scale division. The meter was checked and found to be linear for deflections in either direction, irrespective of the starting position.

Ideally, with no restoring torque, the fluxmeter deflection is independent of the time during which current is flowing but is proportional only to the total amount of charge passing through the moving coil. In practice, there is a small but noticeable restoring torque. But if the time during which the search coil was flipped were small compared to the period of the instrument, the readings were found to be independent of the flipping time. Since the moving coil has a small moment of inertia, there is minimum damping without any external circuit. But with an external resistance of the order of ten ohms, there is strong electro-magnetic damping that provides a ballistic-like deflection.

A control box, similar to one described in a University of Washington thesis (6, p.12), was built to provide zero positioning and drift control for the fluxmeter. The circuit is shown in Figure 2. The one ohm resistance, R_1,

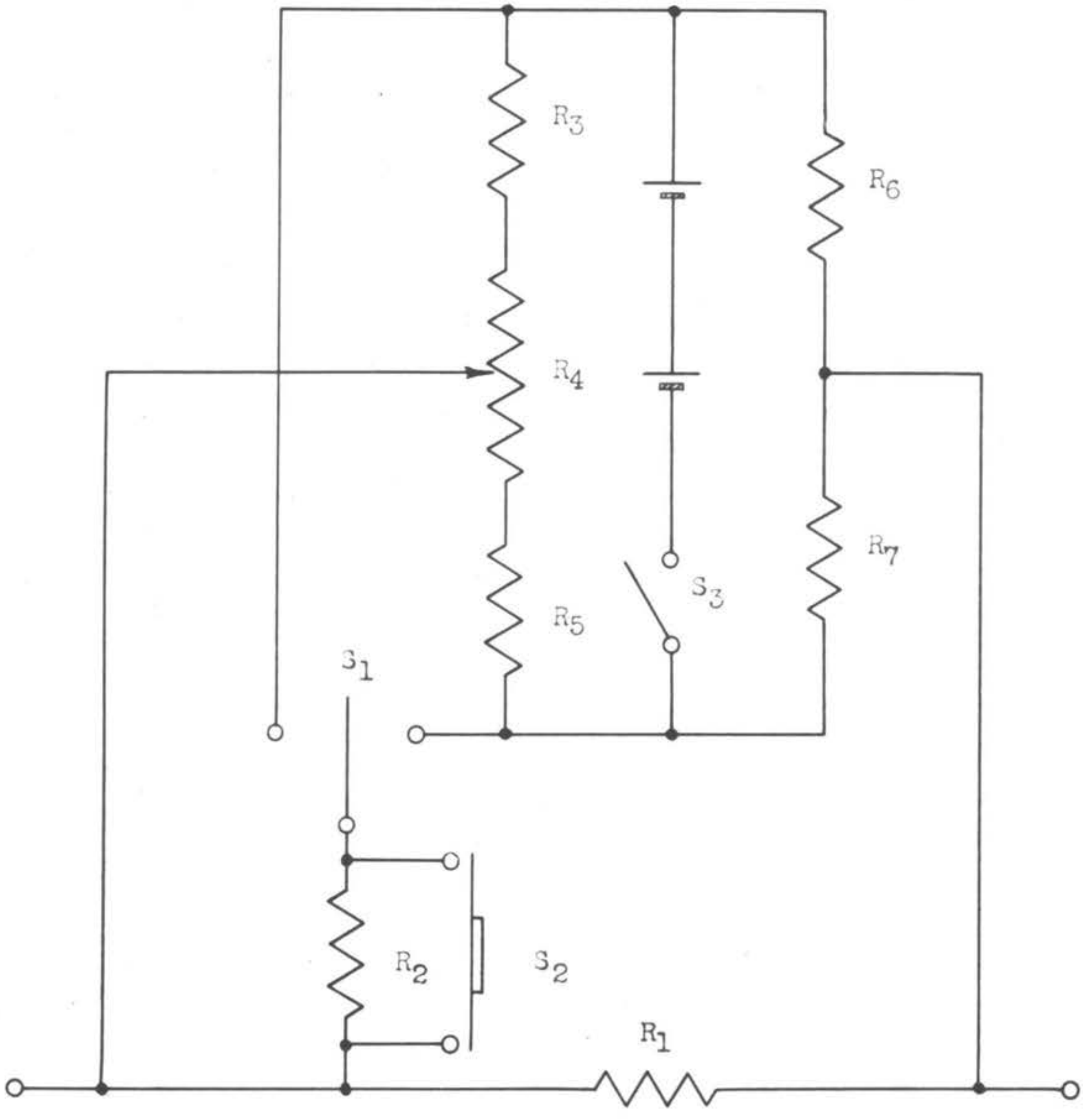


FIGURE 2. FLUXMETER CONTROL CIRCUIT

is connected in series with the fluxmeter and search coil. With the power switch S_3 on, and the movable arm on the variable resistor R_4 in the middle position, there is no current flowing in R_1. An unbalance in R_4 produces an emf across R_1 and thereby causes a small current to flow through the fluxmeter. This current produces a steady torque on the moving coil which is used to control the equilibrium position, or position of zero drift, of the moving coil. By careful adjustment of R_4, the drift could be reduced to an undetectable amount for any zero position. S_1, a double pole momentary contact switch is normally in the open position; moving it to right or left moves the fluxmeter coil to the right or left, respectively. With S_1 closed in either direction, depressing S_2 provides a more rapid motion of the moving coil by shorting out R_2 which is in series with the zero position control.

When one measures a magnetic field with a search coil, the coil either can be held in the field and then quickly moved to a point of zero field, or it can be rotated on a diametrical axis through a given angle. Both of these methods give a measure of the flux density of the field. Since the dimensions of the cyclotron field are so large, it would be very difficult to remove the coil rapidly to a point of zero field; hence, the rotating type of apparatus was used.

The apparatus used for field strength measurements was designed so that the search coil is rotated through 180°, the plane of the coil being perpendicular to the field in the rest positions. There are two important reasons for using 180° rotation instead of 90°. The sensitivity of the measurements is doubled since the flux linking the original area is swept twice. Also, the starting and stopping positions do not have to be located with high precision, because at these positions the coil is cutting minimum lines per degree rotation. Since two different types of flip coil arrangements were used for the absolute and for relative field measurements, details of the instruments are discussed in conjunction with the measurements for which they were used.

ABSOLUTE FIELD MEASUREMENTS

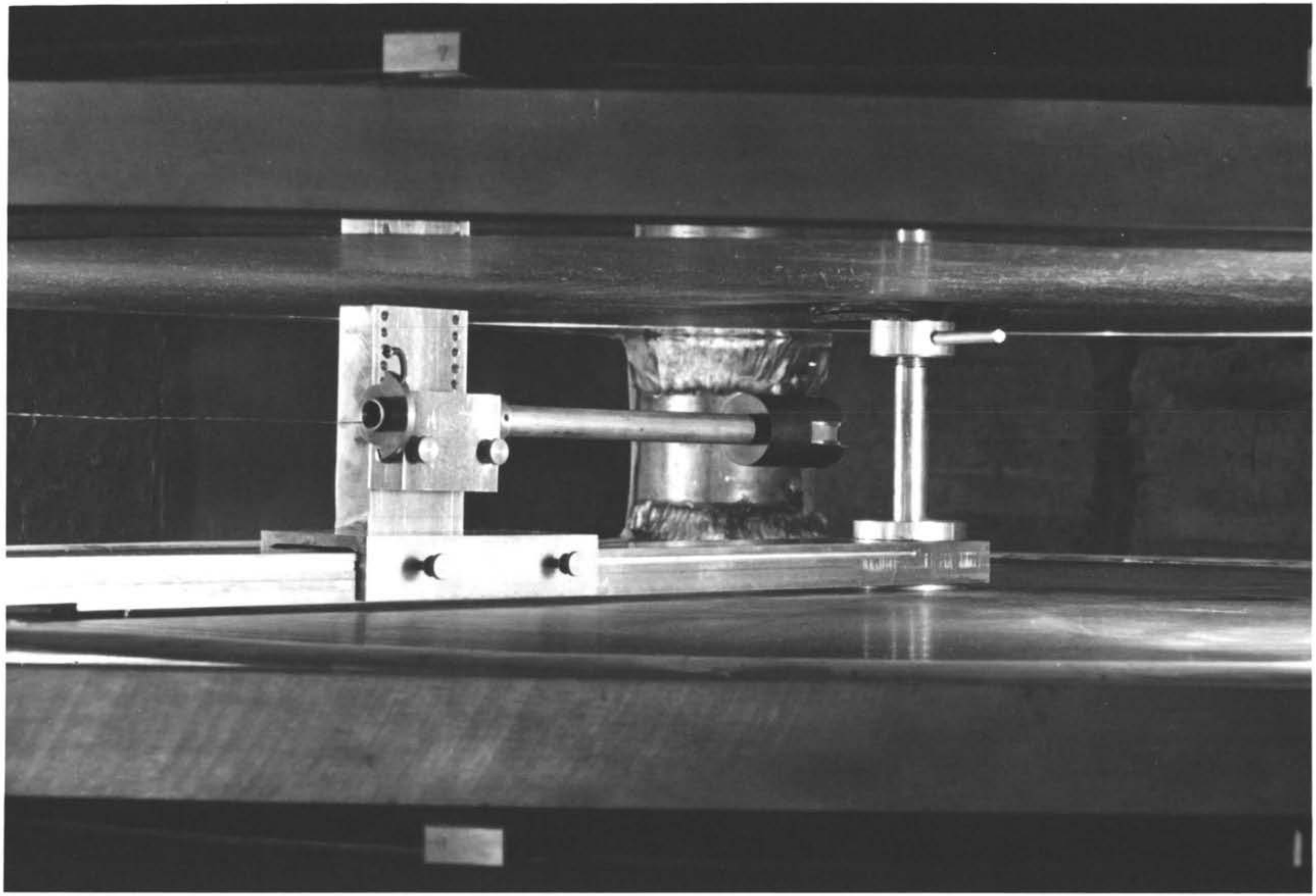
The search coil apparatus used in all absolute field measurements is shown in Figure 3. The coil can be positioned both for height in the gap and distance from the center along any desired radius. The search coil is flipped by hand, the rotation being limited by appropriate stops.

The search coil consists of 7 turns of No. 30 enameled copper wire wound on a lucite spool. The coil has a diameter of 2.25 cm and an effective area of 27.86 cm^2. The leads are brought out of the coil and twisted to eliminate any unwanted pickup. A small loop made by the leads between the coil and twisted pair was formed so as to lie in a plane perpendicular to the plane of the coil. In this position it will not contribute to the effective area of the coil since it contributes zero average emf for 180° rotation.

The twisted leads are brought along the axis of rotation and fastened securely, under slight tension, so the untwisting and twisting during the rotation will be uniform. They are rigidly connected at a terminal strip to the shielded twisted leads from the fluxmeter.

While one person operated the search coil apparatus, it was necessary for another person to read the fluxmeter, which had to be placed outside of the stray field of the

Figure 3. Absolute Field Measuring Apparatus Positioned in the Gap.

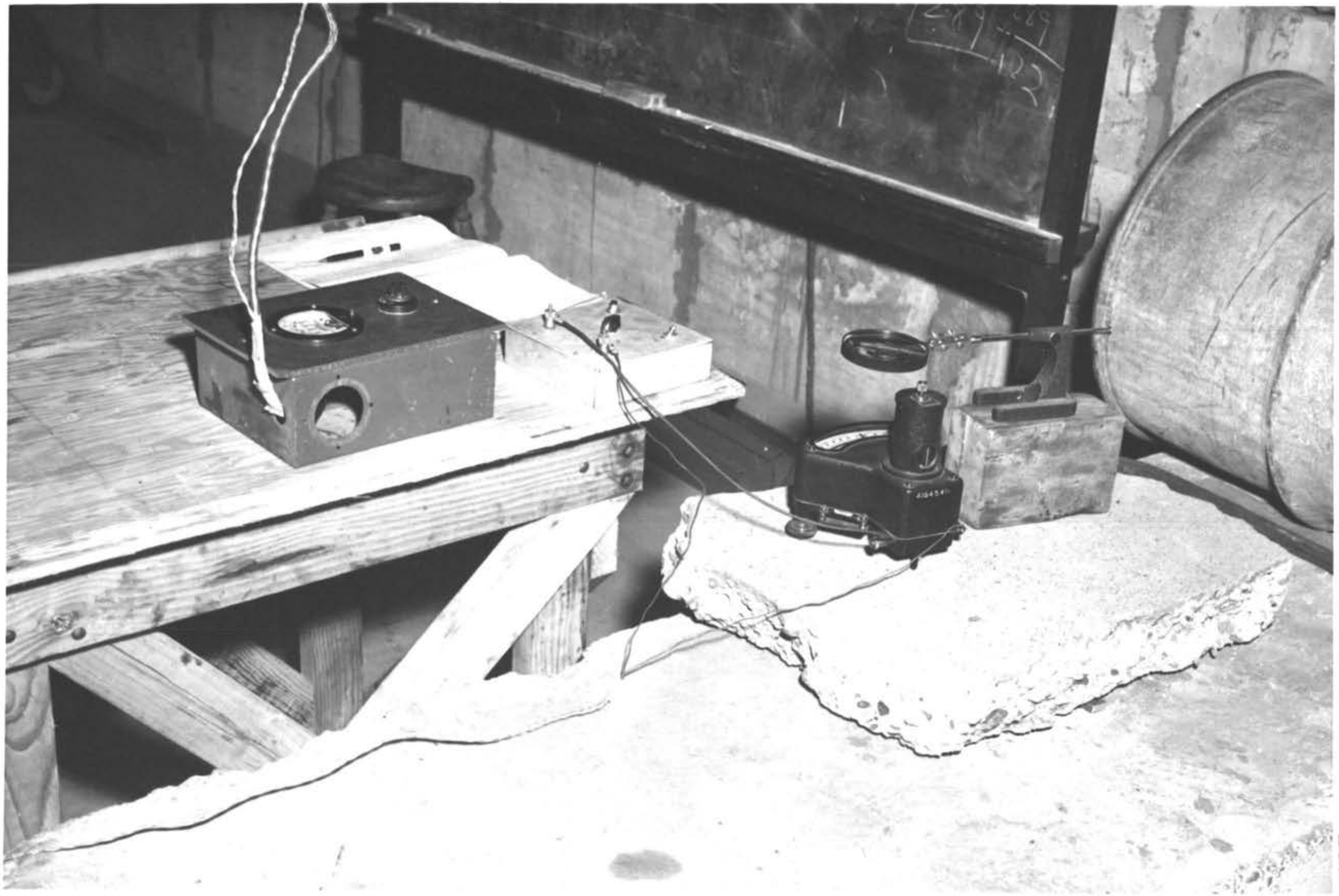


magnet. Figure 4 shows the setup used by the person taking and recording data. In the photograph can be seen the fluxmeter, the leads coming from the search coil apparatus, and the fluxmeter control box connected in the circuit. Also visible on the table is a remote control unit for the magnet regulator. It was placed at this position so the current could be frequently checked and varied when desired.

For normal cyclotron operation, it has been found adequate to have the field current regulated to approximately .01%. The electronic regulator which had been built, was designed to regulate the current to within one half of the above value. This regulation was better than required for making absolute field measurements because the accuracy with which the field strength could be determined was not better than to within one per cent. A slight drift in current over a long period of time had to be compensated for by an occasional slight adjustment of the heliopot on the regulator control.

With a field current of 250 amperes, the magnet was designed to produce a central field of approximately 13,000 gauss in a 6 inch gap. It was realized that the actual field value would depend upon the permeability of the magnet steel which was not too well known. When the magnetizing coils and blower system had been completed,

Figure 4. Fluxmeter, Fluxmeter Control Box and Magnet Current Regulator.

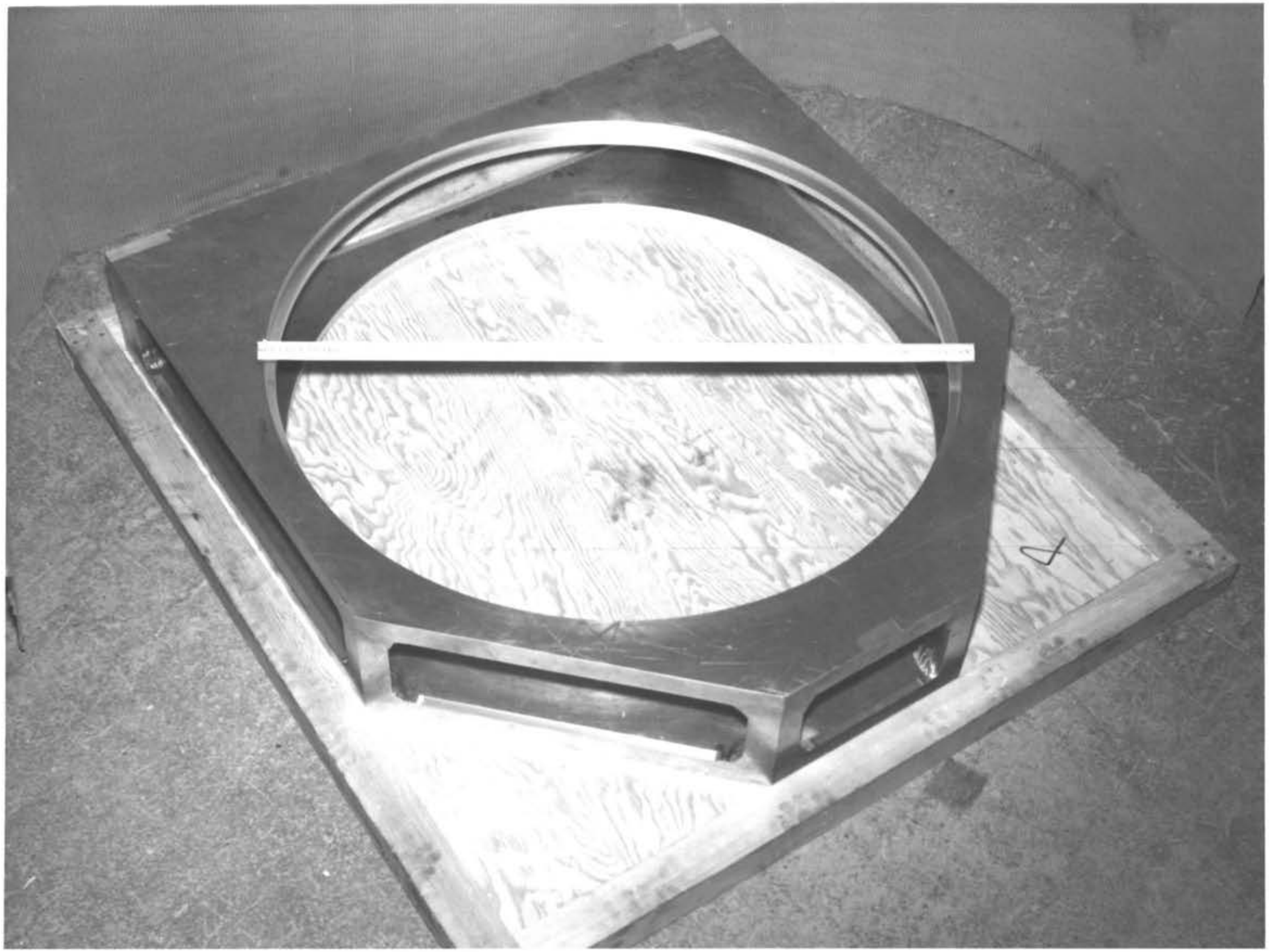


preliminary absolute field measurements were made. The gap, at this time was 9½ inches, since the two 1-3/4 inches thick cover plates had not been completed. Assuming the permeability nearly constant, the field strength in the 6 inch gap should be approximately 1½ times the value produced in the larger gap. With this knowledge we could then predict the field to be expected with the cover plates in the gap.

On April 29, 1952, the first field measurements were taken to determine the central field. It was found to be 8,700 gauss for a magnetizing current of 250 amperes. This indicated that a central field greater than 13,000 gauss should be produced with the cover plates in place.

When the cover plates were completed, it was decided to use the dural vacuum tank skeleton (shown in Figure 5) to hold them in place. The mean distance between the pole faces is 9.530 inches with the field off. With the tank resting on one cover plate and supporting the other, the mean plate separation is 4.964 inches. The thickness of each plate is 1.752 inches. Spacers, approximately .531 inches thick were necessary to separate the pole faces and the cover plates. A set of 24 dural spacers, 12 for each gap, each three inches long and one inch wide were made. These spacers have about .005 in. taper along their length and are about .486 in. thick at the thinner end.

Figure 5. Dural Vacuum Tank Skeleton.



Additional brass shim material was necessary to hold both cover plates snugly in position.

When the field is turned on, the magnetic force pulls the cover plates together about .003 in. This force, calculated to be in excess of 40 tons even without the cover plates in the gap, displaced the poles by bending the horizontal members of the magnet yoke. Since the field increases by one half when the cover plates are inserted, the displacement of the poles should be nearly doubled. If the tank were wedged tightly within the gap before the field was turned on, the pulling together of the poles would squeeze the tank. In order to avoid possible damage the spacers were first set up solid and then about .004 in. of spacer material was removed. Then with the field on, the cover plates are pulled tightly up against the spacers without squeezing the tank. By means of an inside micrometer of non-magnetic material, the plate separation was measured and the thickness of the individual spacers adjusted to bring the plates into parallelism.

Table 1 shows two sets of data taken of the plate separation. The readings in millimeters show only the relative separation, the larger readings corresponding to smaller separations. The readings were taken about 2 inches from the edge of the plates at twelve equally spaced positions numbered consecutively around the

Table 1. Preliminary Plate Separation Measurements (Relative Readings in Millimeters)

Azimuthal Position	Field Off (1)	Field On (1)	Field Off (2)	Field On (2)
1	.695	.695	.680	.695
2	.625	.620	.645	.630
3	.590	.580	.600	.595
4	.620	.610	.625	.615
5	.585	.610	.615	.570
6	.610	.640	.645	.605
7	.660	.670	.650	.640
8	.610	.615	.620	.585
9	.600	.600	.625	.565
10	.645	.630	.655	.615
11	.640	.660	.645	.620
12	.665	.675	.670	.675

circumference. These twelve numbered positions were used throughout all subsequent measurements to define the orientation of the measuring equipment. Positions 1, 4, 7, and 10 were taken due east, north, west, and south, respectively.

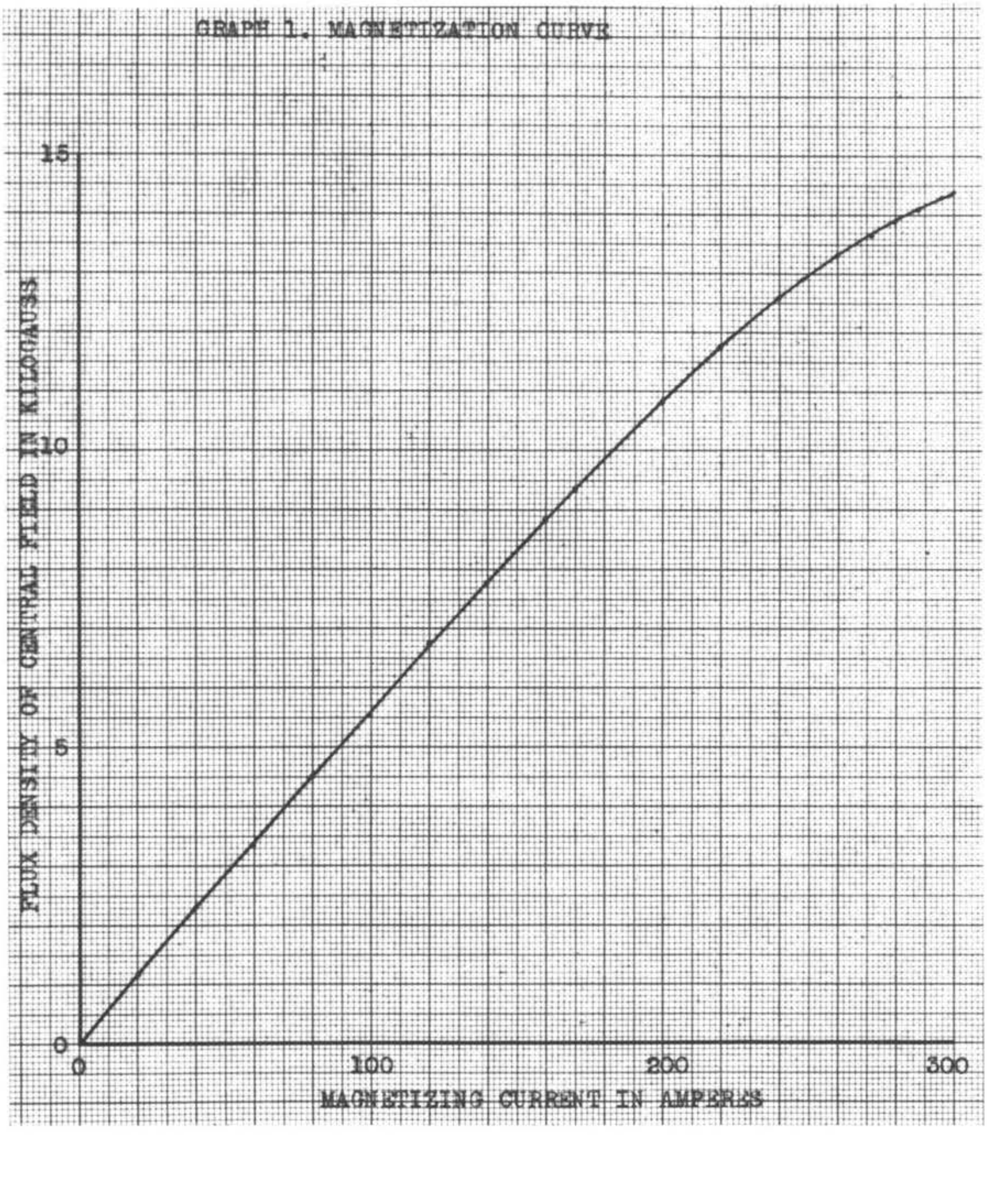
After the plates were centered and made parallel in the gap, the central field strength was found to be 13,050 gauss. Also at this time data for a magnetization curve was taken, but it was felt that another set of data should be taken after the magnet had been operated repeatedly over a long period of time. The combined results are discussed presently.

The magnet cooling system, as originally designed, consisted of two blowers, one blowing air through each coil. It was found that with an incoming air temperature above 25°C, the cooling system was inadequate for field currents higher than 250 amperes. It was felt that, in addition to the original fans, a fan sucking on the exhaust side of the coils would improve the cooling. This new system proved adequate for currents up to 300 amperes for short periods of time, but additional work may have to be done on the cooling system if the cyclotron is to operate at 300 amperes for more than 3 or 4 hours. The upper limit for stable operation of the current regulator was 300 amperes, so no further attempt was made to increase the current. The central field measured at 300 amperes is 14,400 gauss.

The final magnetization curve data was taken after the magnet had been in operation almost daily for a period of about two months. The current was first raised to 300 amperes and measurements taken at various currents as the current was decreased monotonically. The magnetization curve is shown in Graph 1. The preliminary data described earlier had been taken at various currents as the current was raised. No difference was found in the data taken by the two procedures at different times. This indicates the field is constant over a long period of time if the current is kept constant.

Measurements were also taken at this time to determine the radial dependence of the field. Although this could not be determined with a single search coil to the desired accuracy, a rough knowledge of the radial dependence was necessary in the design of the differential search coil apparatus.

From these measurements, it can be concluded that satisfactory values of magnetic field strength are produced by 250 to 300 amperes magnetizing current. It can be seen from the slope of the magnetization curve that the magnet could be very advantageously operated at currents higher than 300 amperes, if the cooling were improved.

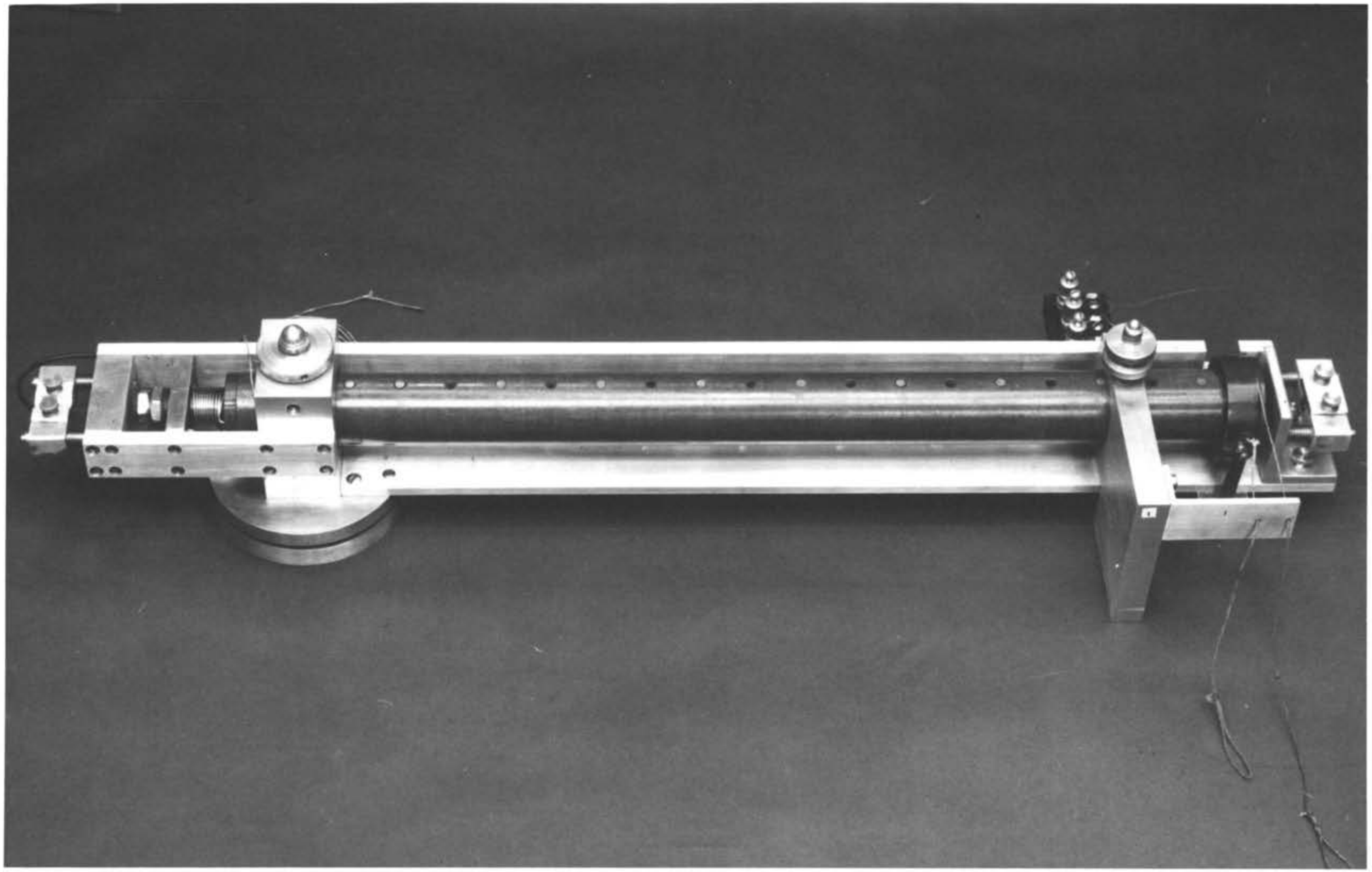

GRAPH 1. MAGNETIZATION CURVE
FLUX DENSITY OF CENTRAL FIELD IN KILOGAUSS
15
10
5
0
0
100
200
300
MAGNETIZING CURRENT IN AMPERES

AZIMUTHAL FIELD MEASUREMENTS

After the initial measurements of the absolute field strength, it was necessary to determine the degree of azimuthal homogeneity in the geometrical midplane of the magnet gap. In order to make the field measurements to the desired accuracy of less than .01%, a differential search coil apparatus was used. In this type of apparatus two search coils are connected in opposition, one being located at the center while the other is moved to different positions within the gap. When the two coils are rotated simultaneously in a uniform field, the two coils will produce emf's in the opposite direction that cancel if the coils have equal areas. Any difference in the fields at the two coils will result in a deflection on the fluxmeter. Hence, the field at any point can be measured by comparing it to the central field.

The condition that both search coils be rotated simultaneously in a common plane is satisfied by mounting the two coils inside a fiber tube and by rotating the entire tube. One coil is held fixed to the tube while the other mounted in a cylindrical fiber cartridge can be positioned at various places along the tube. The tube, whose axis is held fixed in the geometrical midplane, is supported by bearings at either end. This apparatus is shown in Figure 6.

Figure 6. Differential Search Coil Apparatus.



Fitted in one end of the tube, and carrying the spring assembly which provides the torque for rotation, is a fiber plug which furnishes the bearing surface and also has an adjustment to limit the end play of the tube (Figure 7). This end of the apparatus is locked between the cover plates in the center of the gap so the entire apparatus can be rotated in a horizontal plane about this point. A cartridge which holds the fixed coil is pinned rigidly in the tube so it will be positioned accurately in the center of the gap.

At the other end of the apparatus (Figure 8) is the cocking and tripping mechanism. The rotation is limited to 180° by adjustable stops. This end is also locked tightly between the cover plates each time a measurement is taken.

The inside of the tube is keyed by a set of 3/16 inch diameter fiber pins extending 3/16 inch into the tube at two inch intervals, and a keyway is milled into the movable cartridge. This arrangement prevents rotation of the cartridge as it is moved along the tube. The actual positioning is furnished by two spring loaded balls, near the ends of the cartridge, that fit into indexing holes spaced one inch apart along the fiber tube. The movable cartridge and one of the search coils are shown in Figure 9. Strings fastened to the cartridge and extending out of

Figure 7. Differential Search Coil Apparatus Showing Lead Detail of Fixed Coil.

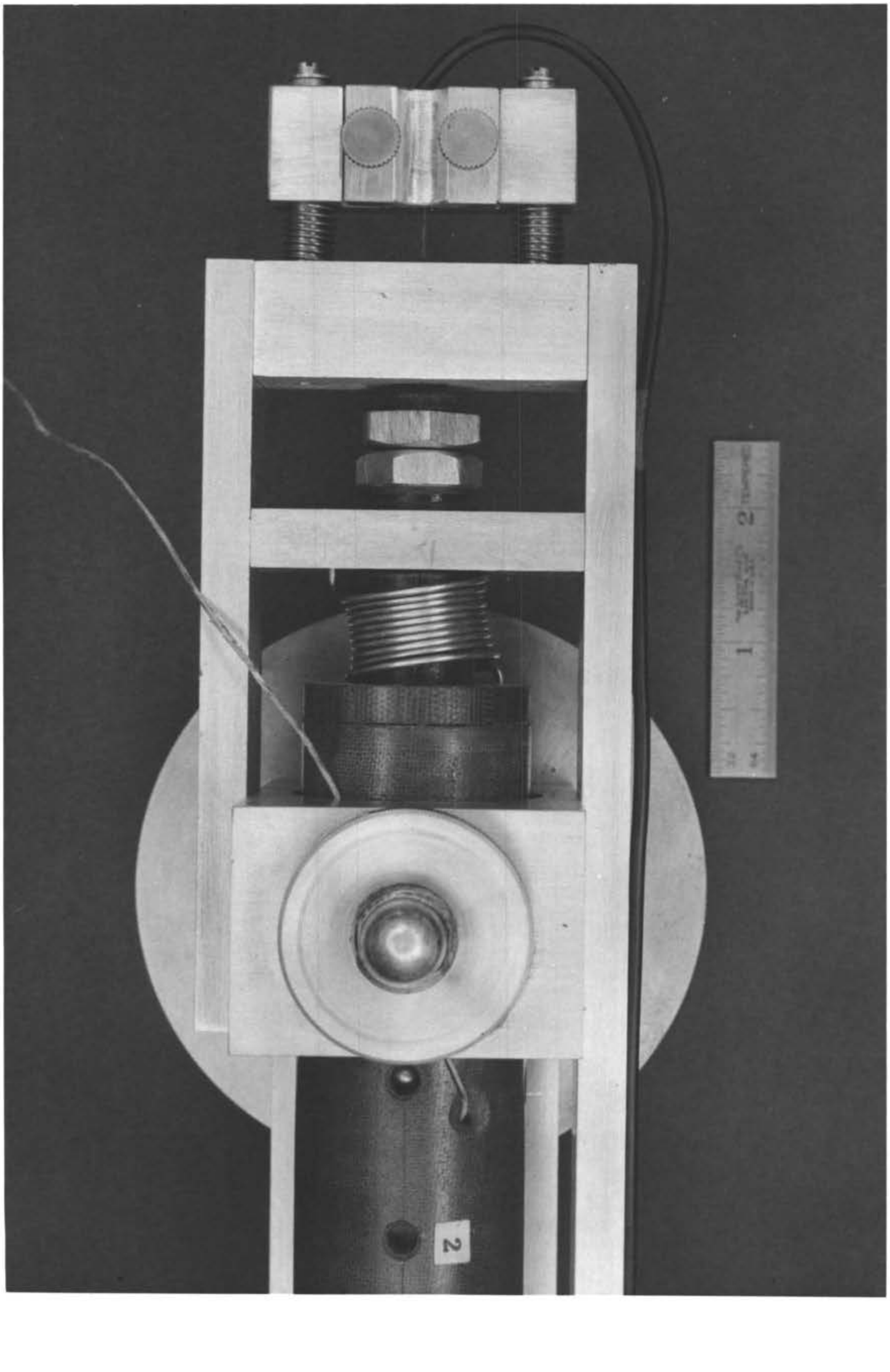


Figure 8. Differential Search Coil Apparatus Showing the Cocking and Tripping Mechanism.

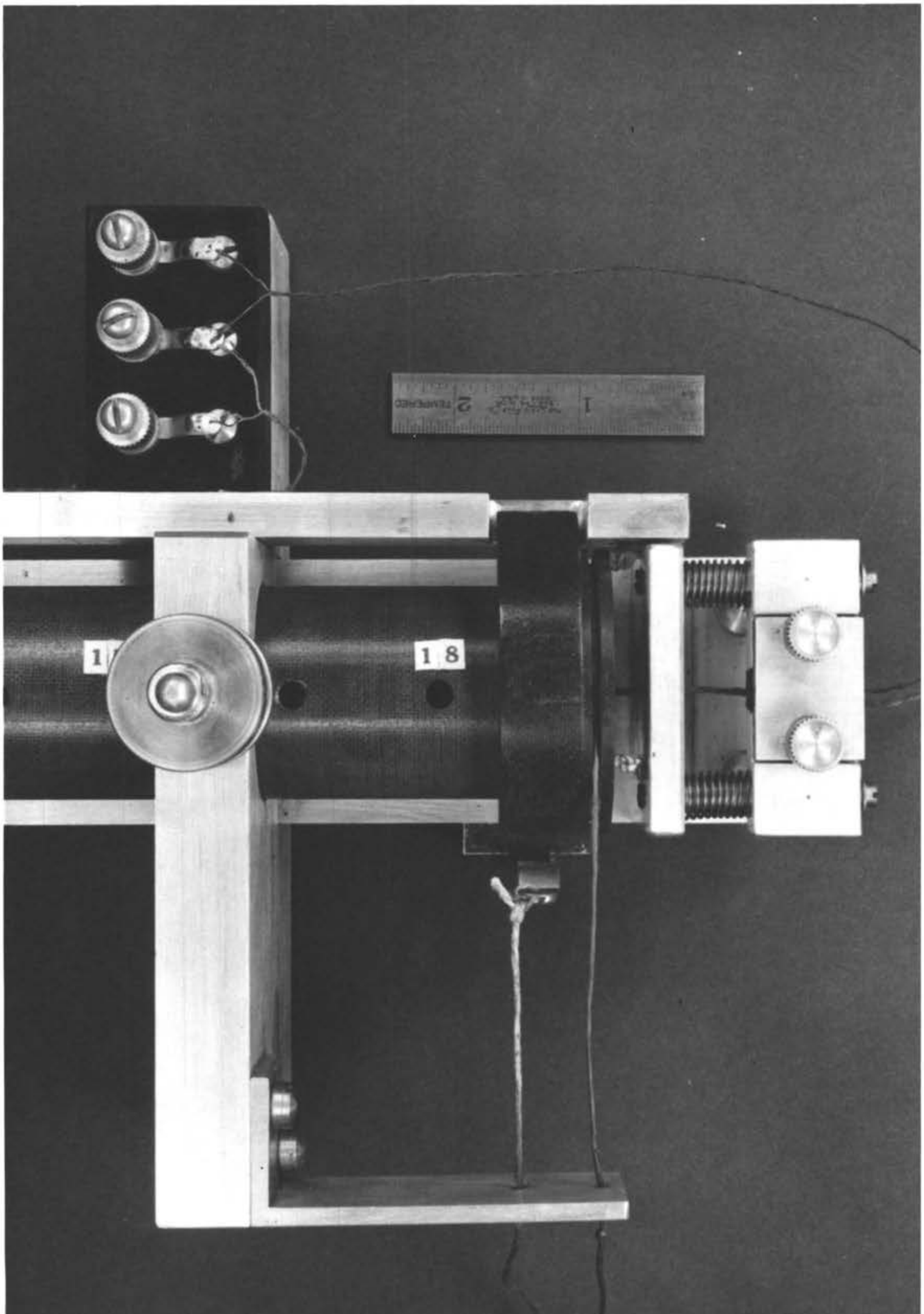
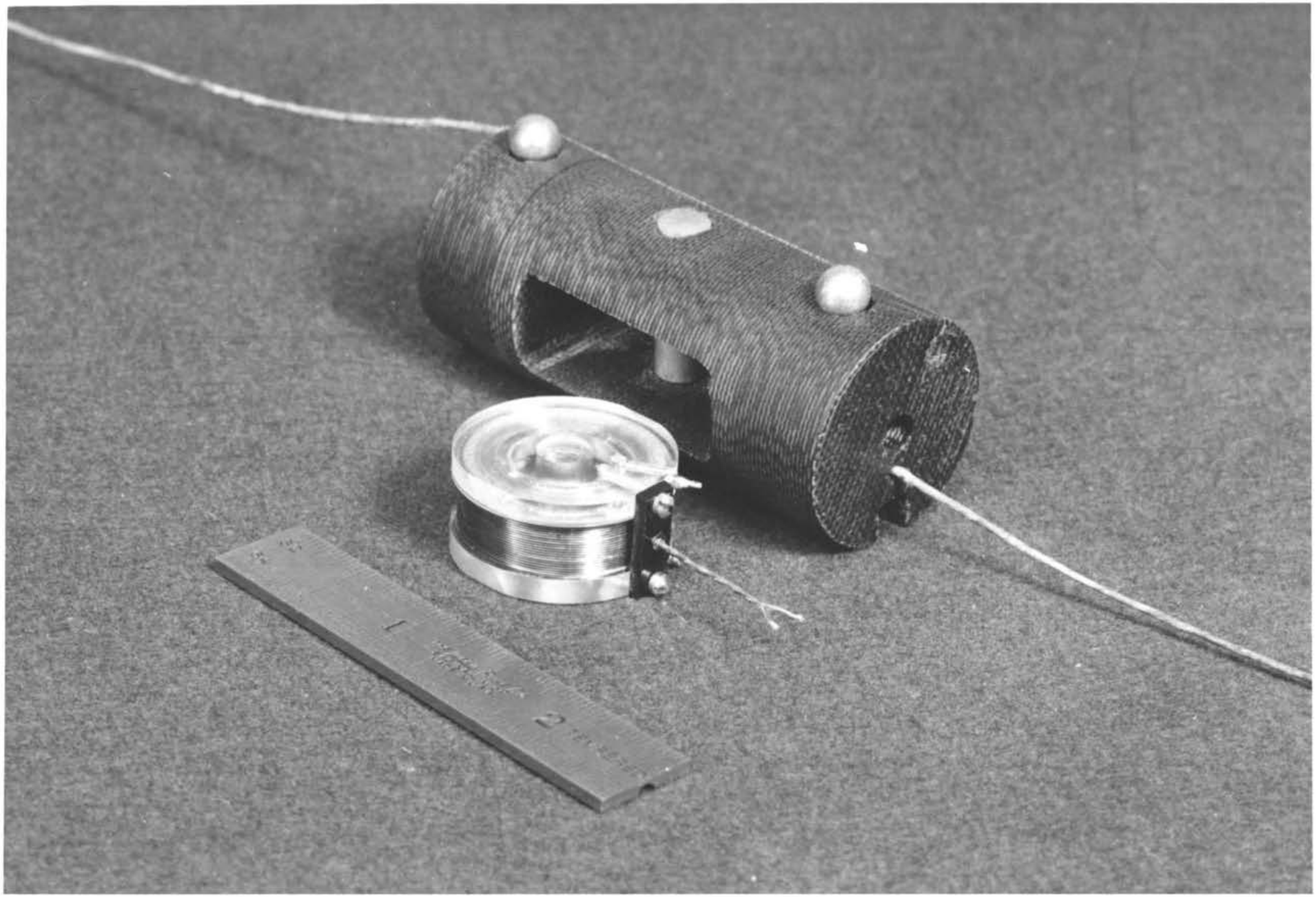

1 8

Figure 9. Movable Cartridge and Search Coil for Differential Search Coil Apparatus.



each end of the tube are used to vary the position of the coil.

The two search coils used in this apparatus were constructed to be as nearly identical as possible. Each one consists of 442 turns of No. 30 enameled wire and has an average diameter of 1.914 cm and an effective area of 1.272 cm^2. In making connections to the leads, similar precautions were taken as used in the construction of the 7 turn coil.

The twisted leads are brought out along the axis of the tube and secured in a simple clamping device. A pair of springs supplies moderate tension to hold the leads on the axis (See Figures 7 and 8). Upon rotation of the tube, there is just a uniform twisting and untwisting of the leads. This type of motion does not introduce any appreciable stray pickup.

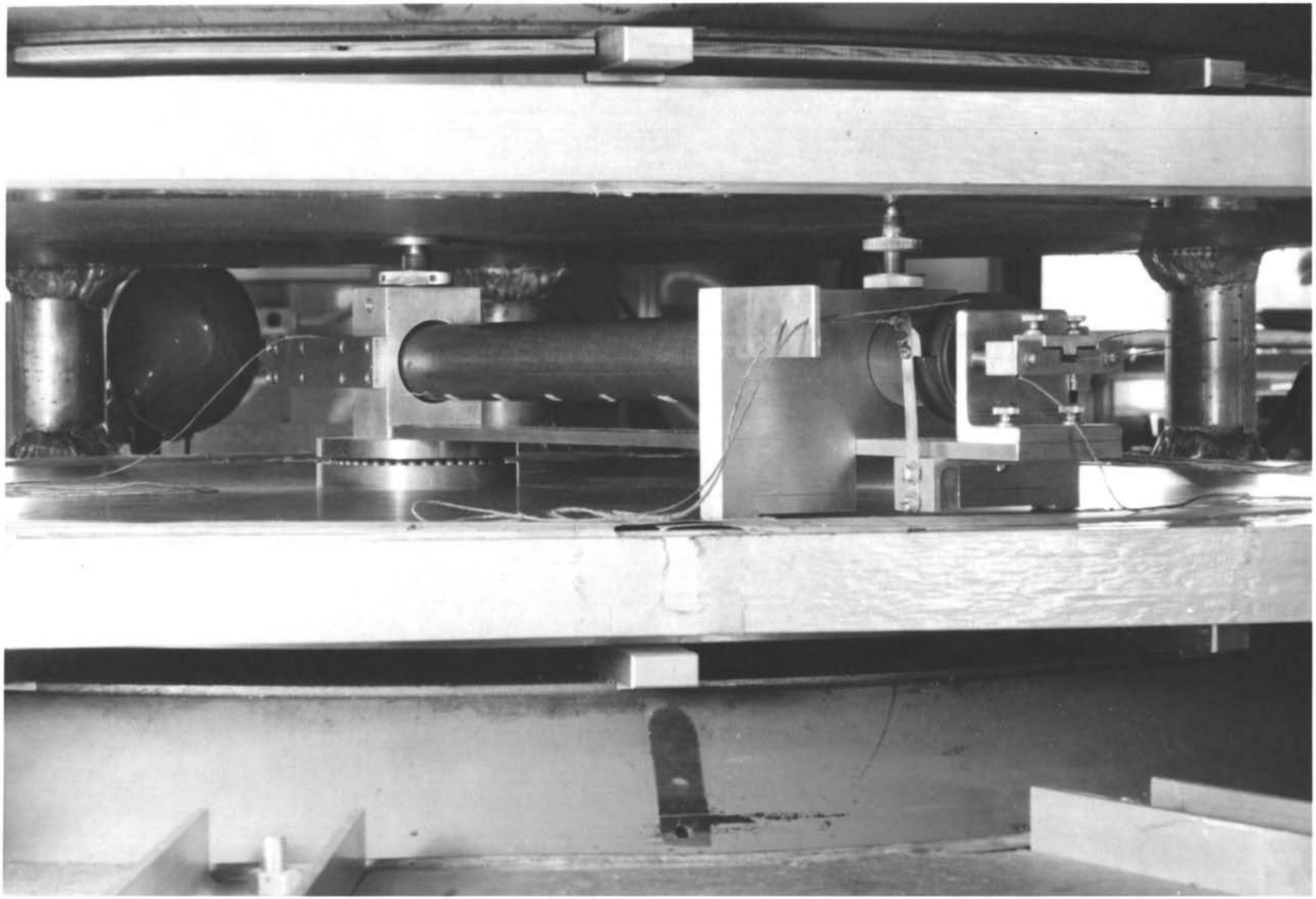
One of the requirements for the field of a cyclotron is that there be no azimuthal variation of field strength. Since the degree of homogeneity of the magnet steel was not known, careful exploration of the entire area in the gap was necessary. The measurements were taken two inches apart, both azimuthally and radially, over the entire area out to and including the 18 inch radius. This entailed making measurements at 252 separate points.

With the field on, the apparatus was first centered within the gap and locked in place. Figure 10 shows the apparatus in position. The movable coil was set at the two inch radial position and measurements were taken two inches apart at 6 positions around the center. Then the movable coil was moved to the four inch radius, where 12 positions were measured, and the process repeated out to 18 inches. Results of these measurements are shown in Graph 2 and will be discussed later.

Although the two coils seemed to be identical, there was an appreciable deflection resulting when both coils were put in positions where the field strength was the same. It was decided not to alter one coil but to find the zero correction factor. This was determined by interchanging the positions of the two coils and reading the deflections in the two cases, the correction being the average of the absolute value of the two readings. This was determined to be 9.6 divisions, and was subtracted from all readings in order to obtain a measure of the true field differences.

It was observed, early in the measurements, that as the tube was cocked the fluxmeter showed a relatively large deflection first in one direction and then in the opposite sense. An investigation of the behavior of the deflection resulting from each individual coil offered a solution. The apparent unbalance of the two coils could

Figure 10. Differential Search Coil Apparatus Positioned in the Gap.

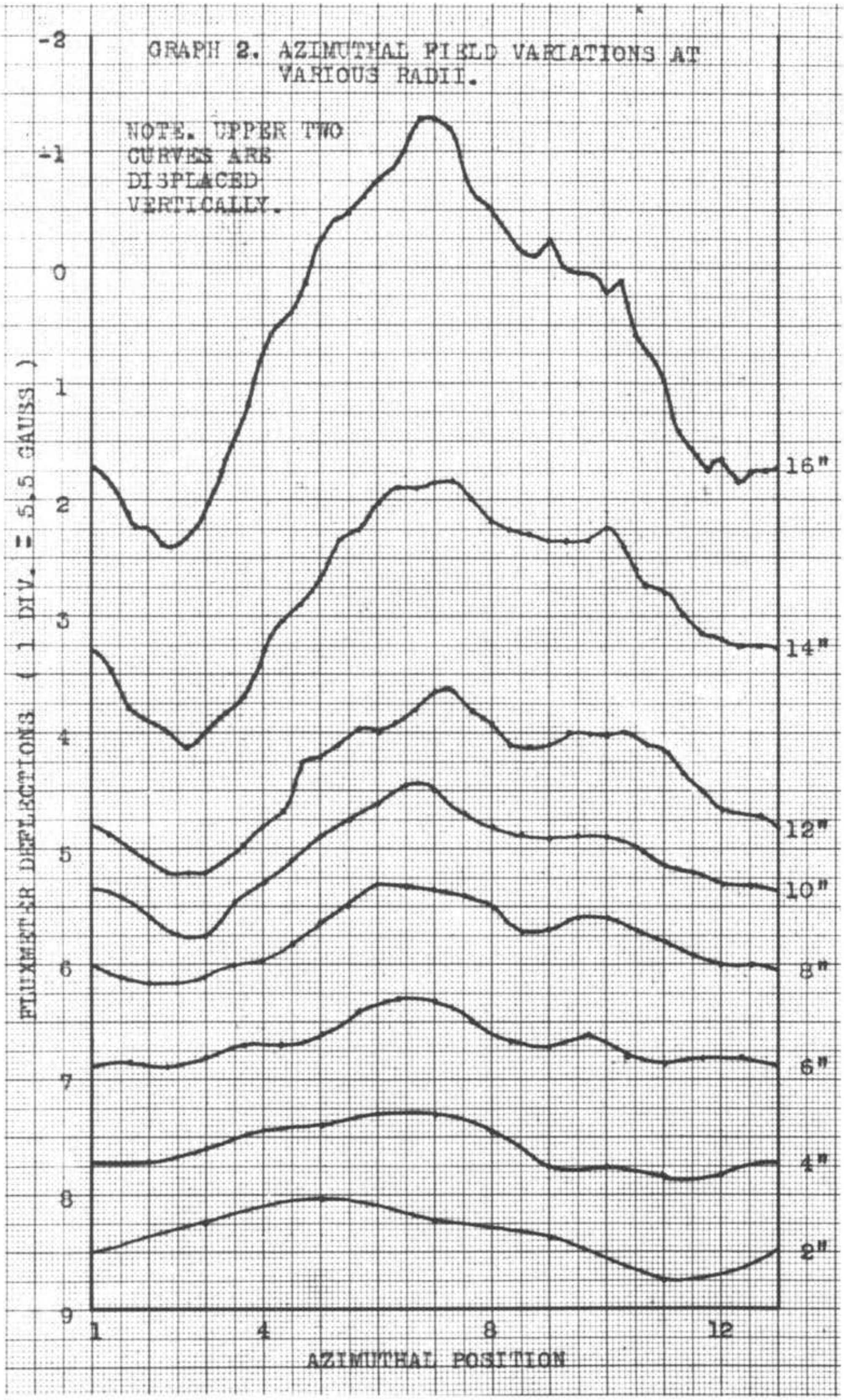


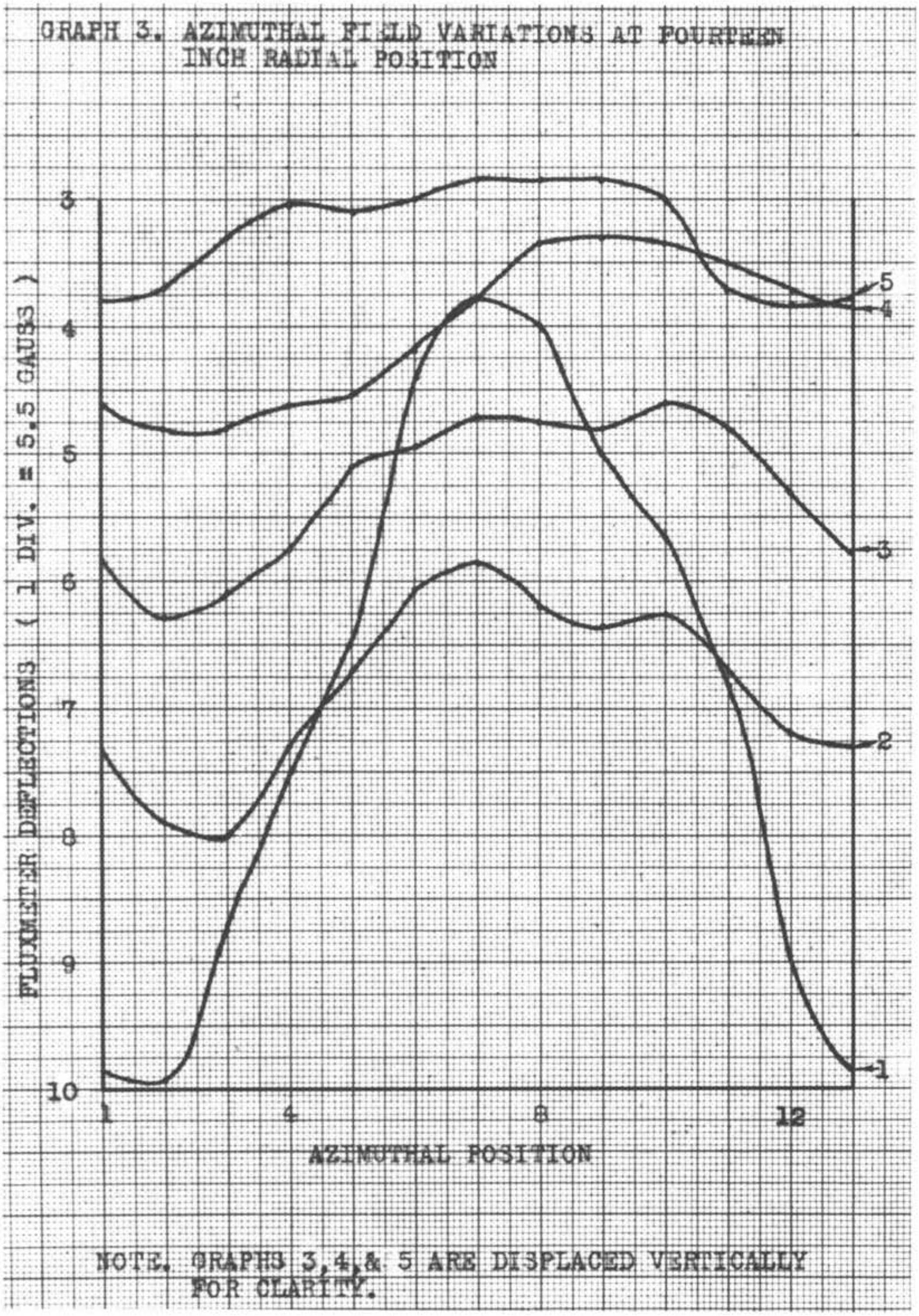
be explained by a very slight angle, of the order of two or three degrees, between the planes of the two coils. As the tube approached the 90° position, one coil would be cutting flux lines at a greater rate than the other, causing a deflection. As the tube proceeded beyond the 90° position, the second coil would be cutting the lines more rapidly, reversing the sense of the deflection. Since for 180° rotation the stationary positions are relatively insensitive, this lack of alignment is not serious. When the tube is flipped, the time of rotation is very short compared to the period of the fluxmeter so that only a smooth deflection in one direction results.

The search coils were designed to give readable deflections at the 16 in. radius with full sensitivity of the meter, but at larger radii the difference in field was large enough to give deflections too great for the meter. There are two convenient methods to handle this problem: either use a larger number of turns on the coil in the smaller field, or reduce the sensitivity of the meter by a shunt. Both of these methods were used but it was decided that the latter method was more satisfactory. Two different types of instrument shunts were used but the best results were obtained by merely putting a resistance in parallel with the meter and measuring the reduction in sensitivity. A 10 ohm resistance was used, reducing the sensitivity by a factor of 3.

When the azimuthal field measurements were first made it was thought that the centering of the apparatus was not very critical. But it was found that for accurate measurements, in regions where the field gradient is large, it was necessary to center it to within a few thousands of an inch. There was a periodic variation in the readings which was later reduced by careful centering. This variation did not decrease the value of the data since we were primarily interested in determining whether any discontinuities or large inhomogeneities existed in the field. The data, shown in Graph 2, indicates that there are no appreciable defects in the magnet. (Graphs 2 and 3 are drawn so that a higher point on the graph indicates a higher field. The zero correction of 9.6 divisions was not subtracted since only the relative readings in the separate curves are important. The upper two curves in Graph 2 and curves 3, 4, and 5 in Graph 3 have been displaced vertically for clarity.)

After it became evident that careful centering was important, another set of data was taken at the 14" radius. The improvement can be seen by comparing curves 2 and 3 in Graph 3; curve 2 is plotted from the original data while the data for the latter curve was taken after more careful centering.


GRAPH 2. AZIMUTHAL FIELD VARIATIONS AT VARIOUS RADII.
NOTE. UPPER TWO CURVES ARE DISPLACED VERTICALLY.
FLUXMETER DEFLECTIONS (1 DIV. = 5.5 GAUSS)
-2
-1
0
1
2
3
4
5
6
7
8
9
1
4
8
12
AZIMUTHAL POSITION
16"
14"
12"
10"
8"
6"
4"
2"


GRAPH 3. AZIMUTHAL FIELD VARIATIONS AT FOURTEEN INCH RADIAL POSITION
FLUXMETER DEFLECTIONS (1 DIV. = 5.5 GAUSS)
3
4
5
6
7
8
9
10
1
4
8
12
AZIMUTHAL POSITION
5
4
3
2
1
NOTE. GRAPHS 3,4,& 5 ARE DISPLACED VERTICALLY FOR CLARITY.

Since the degree of parallelism of the plates was known to affect the azimuthal homogeneity of the field, it was decided to tilt the top plate slightly to determine the effect on the field. The plate was tilted by varying the amount of shim material in the individual spacers. The amount of tipping is shown by plate separation measurements taken before and after the plate was tipped. The data is shown in Table 2, Columns 1 and 2, respectively. There was a little bending of the plate due to an uneven taper of the various shims but the total amount of tipping was about .018 in. The azimuthal field measurements taken with the plate tilted are shown in Graph 3, curve 1. After tilting, the cover plates were again made parallel.

It was found that the cover plates could be made parallel to within .002 in. by careful adjustment of the spacer thickness. Due to a slight unevenness in the surfaces of the cover plates, this figure could not easily be improved. It was then desirable to find what effect this unevenness had upon the field. It was decided that a rotation of the top cover plate through 90° would indicate whether the field was dependent upon the angular orientation of the plates. For this purpose a jack was built to raise the top plate so that it could be rotated. Before the rotation, its axis was displaced about .010 in. from the axis of the bottom cover plate. After rotation, the

Table 2. Relative Readings in Millimeters

Azimuthal Position	1*	2*	3*	4*	5*
1	.515	.075	.485	.490	.500
2	.480	.075	.455	.475	.485
3	.490	.240	.460	.480	.475
4	.530	.270	.485	.503	.510
5	.505	.310	.465	.460	.480
6	.520	.440	.485	.475	.480
7	.500	.525	.505	.485	.510
8	.500	.485	.470	.475	.490
9	.490	.370	.470	.490	.490
10	.515	.300	.470	.490	.510
11	.520	.260	.490	.465	.500
12	.520	.130	.490	.470	.485
Extreme Variation (in inches)	.002	.018	.002	.0018	.0014

*1. Cover plates in original position.
2. Top cover plate tilted.
3. Plates made parallel after tilting.
4. Top plate rotated through 90°.
5. Tank centered in gap.

two cover plates were made coaxial by displacing the top plate. The field measurements taken before and after the rotation are shown in Graph 3, curves 3 and 4, respectively. No large effect can be seen due to the rotation but there seems to be a slight improvement that is probably due to better centering of the cover plates.

When the magnet was assembled, the two poles were not made exactly parallel or coaxial, the pole faces being out of parallel by .008 in. and not coaxial by 0.1 in. These dissymmetries created a problem in lining up the cover plates. When the tank and cover plates were first placed in the gap, they were centered with respect to the bottom pole. It was then desirable to know if a position could be found that would improve the azimuthal homogeneity. With the tank in the original position, there was a slight periodic variation in the field which could not be eliminated by the other corrections. It was decided to center the plates with respect to neither pole but to split the difference. This resulted in a small but significant improvement in the field as can be seen in curve 5, Graph 3. Some variation is still present, undoubtedly due to poor pole positioning, but this variation is very small. By making the various adjustments discussed, the azimuthal variation at 14" was reduced from about 9 gauss to less than 5 gauss, or a final variation of less than .04%.

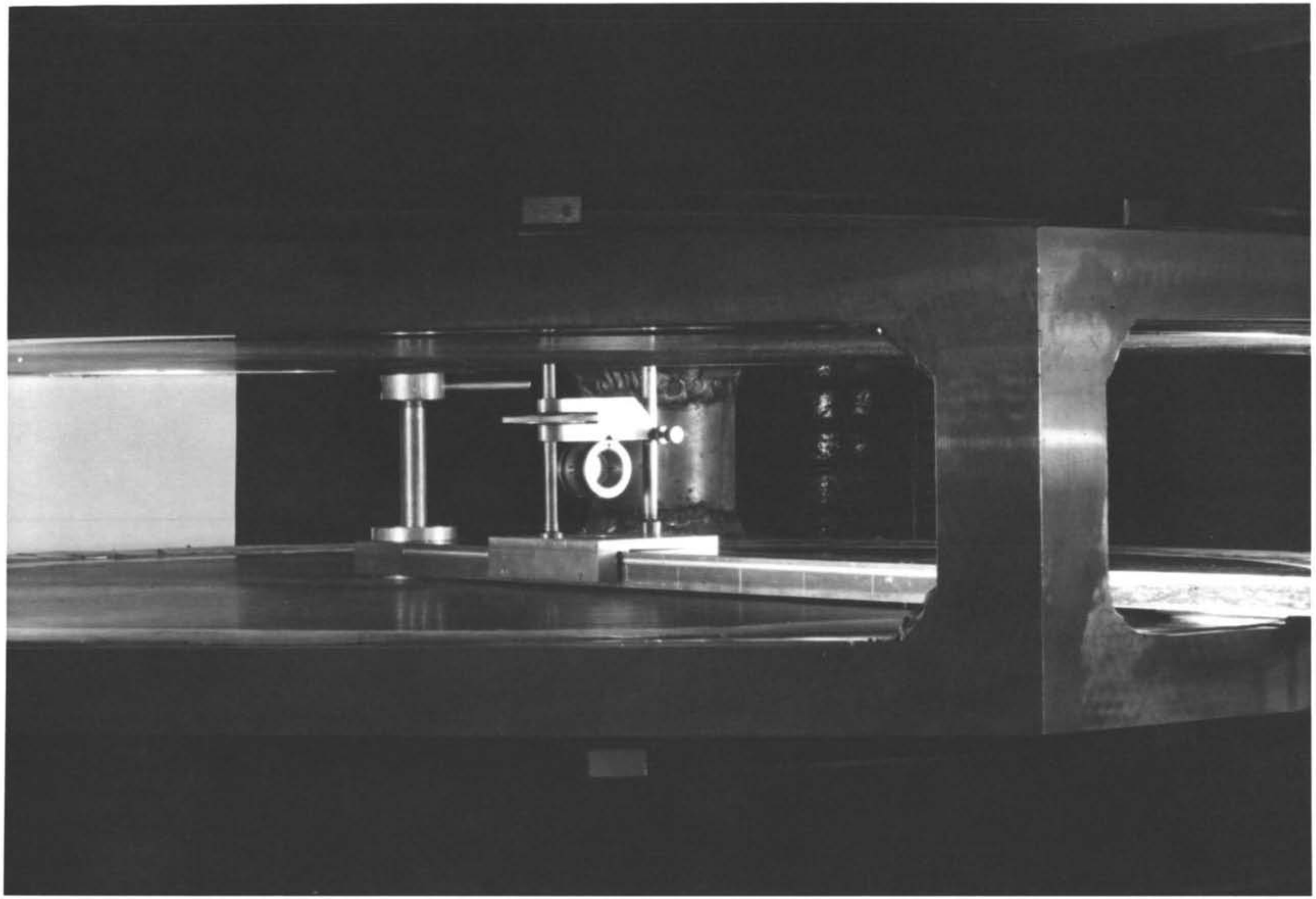
Qualitatively these measurements indicate the factors which affect the azimuthal homogeneity of the field. Quantitatively they indicate with what care the cover plates must be aligned and also the degree of homogeneity that can be expected. It was found that by tipping the plates about .018 in. the variation was increased from 9 to 34 gauss. The corrections in alignment reduced the variation to 5 gauss. When the plates are finally positioned for operation of the cyclotron, care must be exercised to insure adequate parallelism and centering.

MEDIAN SURFACE MEASUREMENTS

The magnetic median surface can be defined as the locus of points where the radial component of the field is zero. Thus, a charged particle moving in a path along this surface is subject to no vertical electro-magnetic forces. The beam will tend to travel on or near this surface, thereby making a knowledge of its location important. In particular, it is desirable that the magnet median surface coincide with the geometrical midplane of the gap.

Since the lines of force are vertical everywhere in the median surface, a soft iron dip needle can be used to find its location at various points. The needle used was 3/4 in. long and 1/16 in. in diameter. The needle is tapered at both ends, so that it will produce minimum distortion of the field. Because of the continuity of the tangential component of H, the magnetic intensity, the value of H within the tapered needle will nearly equal that in the air gap. (5, p.75) A small front surface mirror was fastened approximately parallel to the needle so that the inclination of the needle could be determined by means of an optical lever. The dip needle was mounted so it could be moved up and down and also radially along a dural rail clamped in the gap. The dip needle apparatus is shown positioned in the gap in Figure 11.

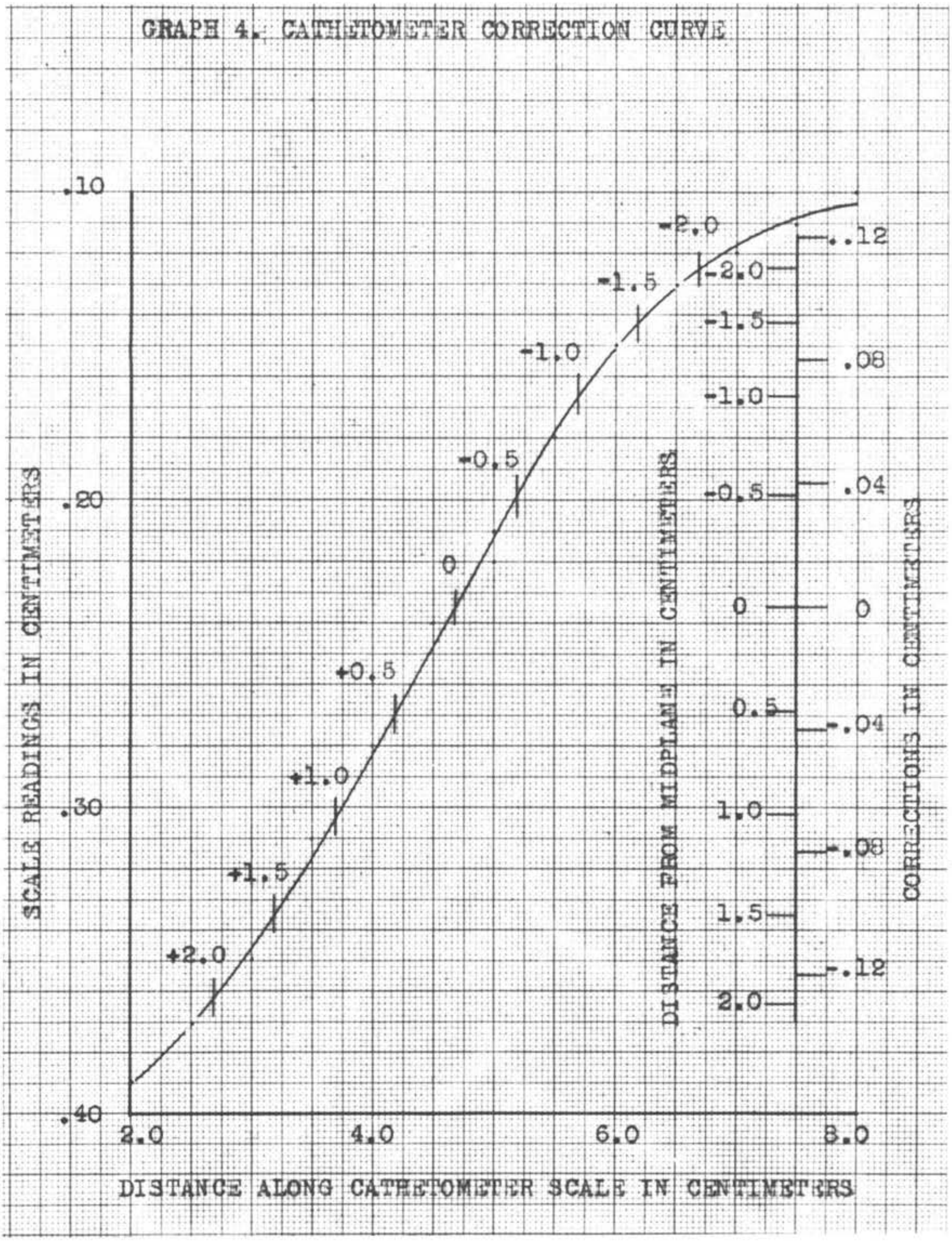
Figure 11. Dip Needle Apparatus Positioned in the Gap.



A cathetometer is used to measure the height of the pivot axis of the dip needle, and the cathetometer telescope, with a vertical scale attached to it, was used to determine the inclination of the needle. This apparatus is shown being used to take median surface measurements in Figure 12. Initially, the geometric midplane is determined and the telescope cross-hairs set on that level. Then the needle assembly is placed in the center of the gap and the pivot of the needle set at the same height as the cross-hairs. The telescope is then focused on the image of the scale and the scale reading noted. Since the flux lines are vertical in all probability at the center of the gap, this reading can be used as a reference for finding the median surface at any position. Thus, in principle, points on the median surface are located by finding those points where this reading can be reproduced. All inclination measurements, of course, must be made with the cross-hairs and needle pivot at the same height. This simple exploratory procedure was found unsuitable due to a number of factors arising both in the dip needle apparatus and the cathetometer. It was found necessary to take systematic sets of readings above and below the midplane, and then by making certain necessary corrections in the data, an interpolation could be made to find the height of the median surface.

Figure 12. Measuring the Magnetic Median Surface with a Dip Needle and Modified Cathetometer.

One of the correction factors arose from purely instrumental reasons. The cathetometer telescope was mounted in a micrometer movement which was designed to be used with the telescope vertical, the weight of the traveling mount being used to hold it against the ways. With the telescope horizontal, it was necessary to hold the mount against the ways by some other means. This was done by attaching a heavy stretched rubber band to the traveling mount. But as the mount was moved along the ways, the direction and magnitude of the tension varied, tilting the axis of the telescope slightly. To determine the amount of tilting at various positions, a large front surface mirror of high quality was placed in the gap and scale readings taken at 5 mm intervals along the vertical path of the telescope. Two sets of data were taken, one with the mirror in the center of the gap, and the other with it at the 8 inch radius. The location of the cathetometer was fixed so the optical lever arm changed when the position of the mirror was changed. With the mirror in the center of the gap, the lever arm was 247 cm, while at the 8" radius it was 227 cm. Graph 4 shows the scale readings, observed through the telescope, plotted as a function of the vertical position of the cathetometer telescope. The mirror to scale distance was 247 cm. If there had been no instrumental errors, the scale reading


GRAPH 4. CATHETOMETER CORRECTION CURVE
SCALE READINGS IN CENTIMETERS
.10
.20
.30
.40
DISTANCE ALONG CATHETOMETER SCALE IN CENTIMETERS
2.0
4.0
6.0
8.0
+2.0
+1.5
+1.0
+0.5
0
-0.5
-1.0
-1.5
-2.0
DISTANCE FROM MIDPLANE IN CENTIMETERS
-2.0
-1.5
-1.0
-0.5
0
0.5
1.0
1.5
2.0
CORRECTIONS IN CENTIMETERS
.12
.08
.04
0
-.04
-.08
-.12

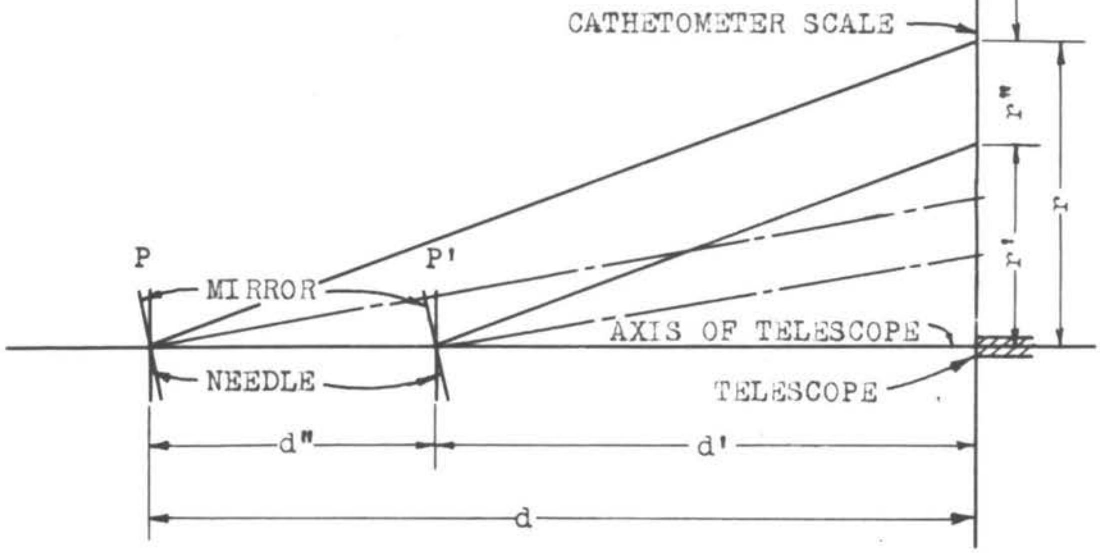
would be independent of the vertical position of the telescope. The curve plotted shows that a correction must be applied to the data which is a function of the telescope position. These corrections are shown on the scale at the right-hand side of the graph, where the telescope positions at 0.5 cm intervals above and below the geometrical midplane are also indicated. These measurements were repeated and the readings found to be reproducible. The sets of data taken for the two lever arms were also found to be compatible so that interpolations could be made in the necessary corrections for dip needle readings taken at various radii. In most cases, though, the correction was relatively so small that interpolation was not necessary. The corrections that were applied to most of the data are tabulated in Table 3.

The readings also had to be corrected for a slight lack of parallelism between the needle and its mirror. Since the horizontal position of the telescope is fixed, as the needle is moved along a radius, the lever arm changes. This effect is illustrated by Figure 13 in which the lack of parallelism is greatly exaggerated. The error, r", is directly proportional to d", the distance of the dip needle from the original position. Because of the linear nature of the error, the corrections can easily be determined by inverting the needle and taking another set

Table 3. Cathetometer Corrections From Graph 4

Distance From Midplane (in cm)	Correction (in mm)
2.0	-1.2
1.5	-1.0
1.0	-0.7
0.5	-0.4
0	0
-0.5	0.4
-1.0	0.7
-1.5	0.9
-2.0	1.1

FIGURE 13. DIAGRAM ILLUSTRATING ERROR CAUSED BY LACK OF PARALLELISM BETWEEN DIP NEEDLE AND MIRROR

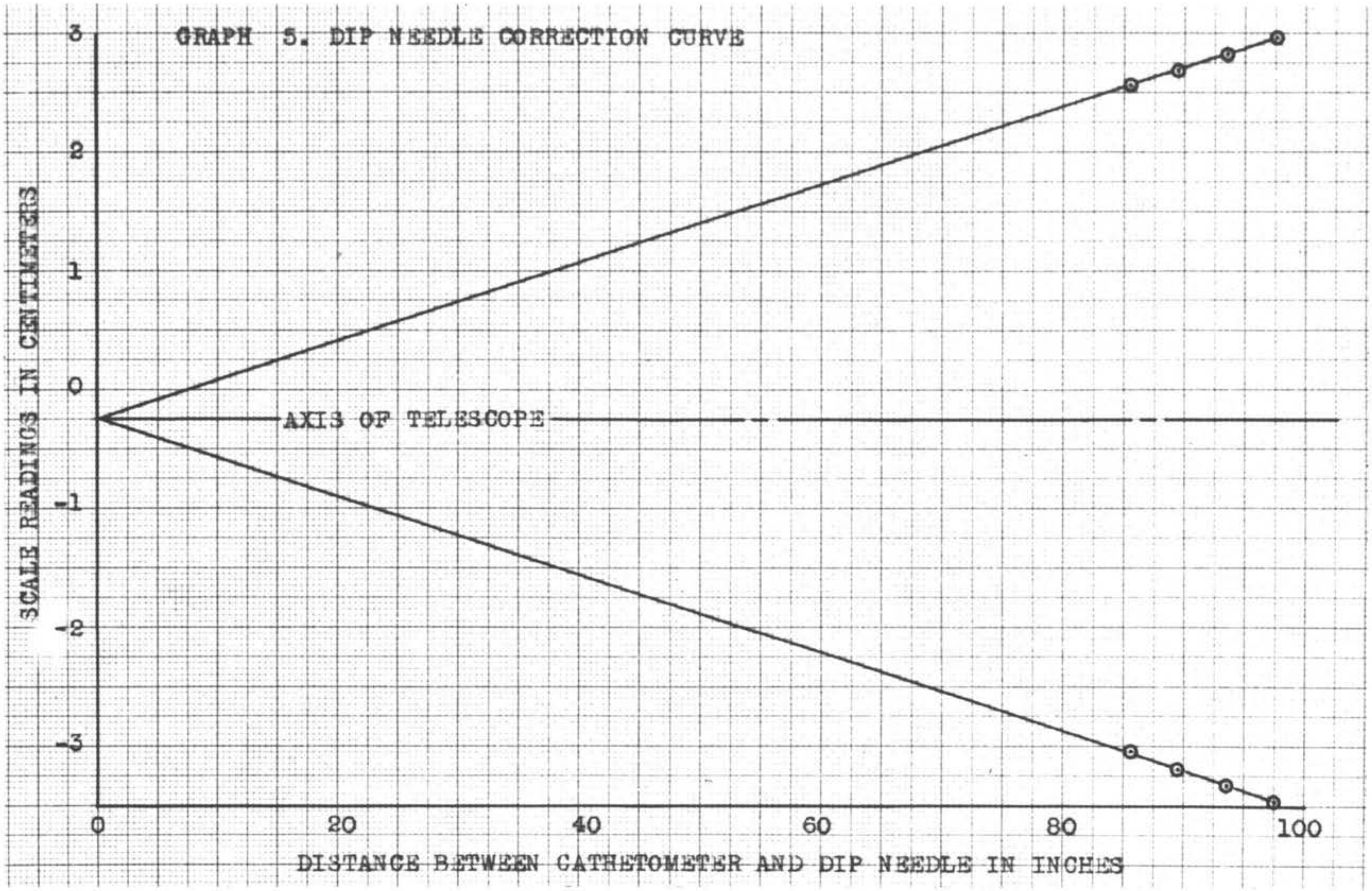


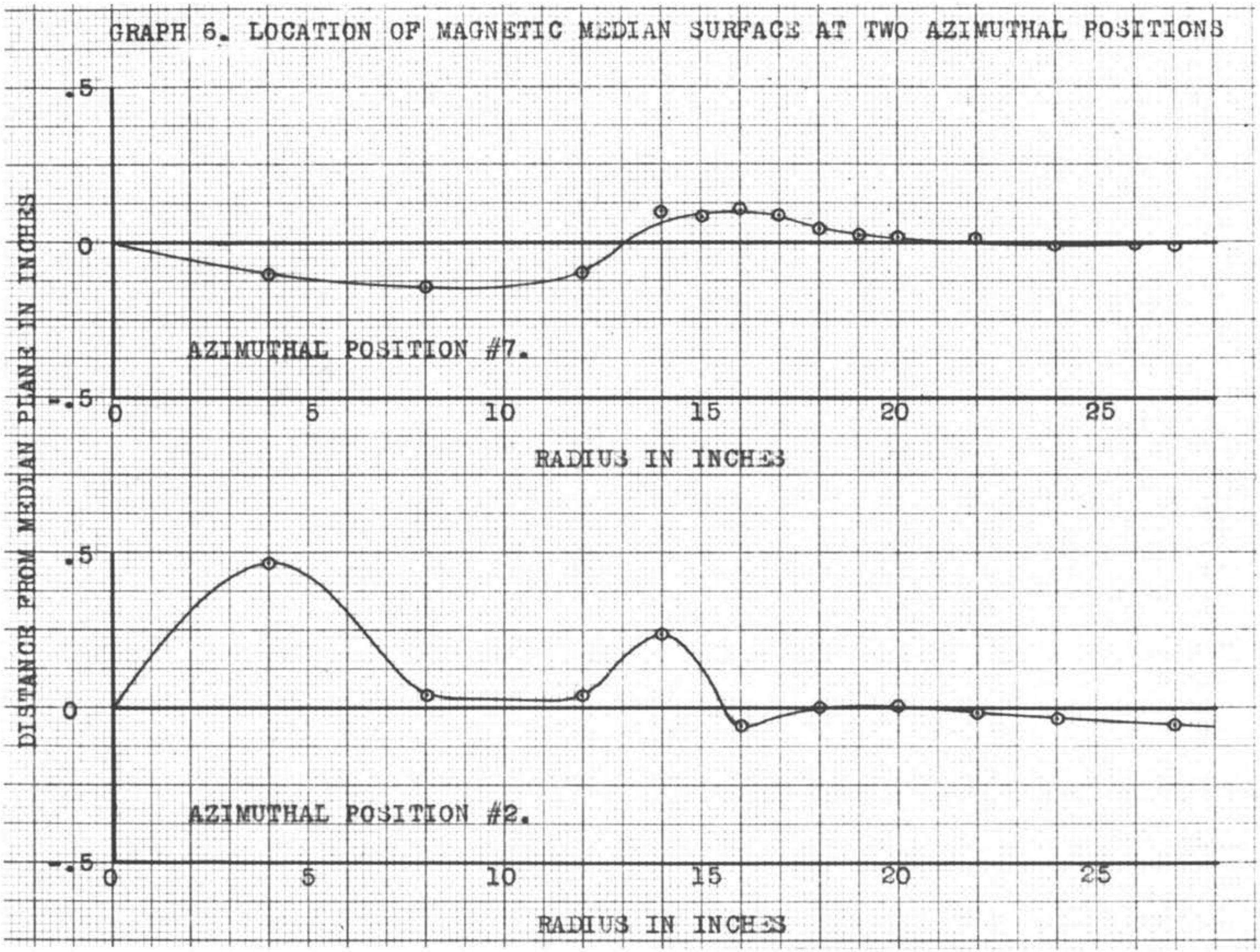
NOTE: VERTICAL SCALE IS EXAGGERATED

readings. Graph 5 shows two curves, one taken with the needle in its original position and the other with the needle inverted. The scale readings which are plotted for various needle to telescope distances are taken with the magnetic field on, and, therefore, are plotted for only the smaller radii. Data taken at radii greater than 6 inches departed from the straight lines shown due to the deviation of the magnetic median surface from the geometrical midplane. However, the graph is not intended to show these deviations, but, instead, it illustrates a simple geometric effect. By extending the curves to zero distance between mirror and telescope it can be seen that they converge at a scale reading of -.251 cm, the scale reading at the height of the cross-hairs.

For measurements taken at radii greater than 13", it was found unnecessary to use the corrections just mentioned because of the large curvature of the flux lines. By applying these corrections wherever appropriate, the median surface could be located with fair reliability. Graph 6 shows the results of the measurements for two different azimuthal positions.

The median surface at position No. 7 seems to lie very close to the midplane for all radii but at the No. 2 position there appears to be a much larger deviation for the 4" radius. This apparent deviation is not very


GRAPH 5. DIP NEEDLE CORRECTION CURVE
AXIS OF TELESCOPE
SCALE READINGS IN CENTIMETERS
3
2
1
0
-1
-2
-3
0
20
40
60
80
100
DISTANCE BETWEEN CATHETOMETER AND DIP NEEDLE IN INCHES



GRAPH 6. LOCATION OF MAGNETIC MEDIAN SURFACE AT TWO AZIMUTHAL POSITIONS

serious at such a small radius. Since the curl of the magnetic field is zero in the gap, in cylindrical coordinates we have $\frac{\partial B_z}{\partial r} = \frac{\partial B_r}{\partial z}$ where B_r is the so-called radial field and B_z is the vertical field. As will be discussed in the next section, the magnitude of $\frac{\partial B_z}{\partial r}$ was found to be 3 gauss per inch at the point of interest. With the median surface displaced $\frac{1}{2}$ in. upward, the radial field on the midplane is probably less than 2 or 3 gauss, or about .02% of the central field. Hence, it can be seen that in this region the location of the median surface is not very critical. For radii greater than about 14 inches the median surface could be determined to within less than .05 in. For smaller radii it was estimated that the accuracy was to within approximately .25 in.

These measurements, while not extremely accurate for the smaller radii, allowed the median surface to be located with fair reliability. It was found to nearly coincide with geometric midplane except for localized variations. Therefore, no attempt was made to correct these variations.

MAGNETIC FIELD PROFILE MEASUREMENTS

The final set of magnetic field measurements, after the azimuthal homogeneity and vertical symmetry had been established, consisted of a study of the radial dependence, or profile, of the field. In general, a certain degree of homogeneity is necessary to provide a near-"resonant field" while a certain degree of inhomogeneity is important for focusing of the ion beam.

The "resonant field" condition, in a constant frequency cyclotron, involves maintaining a constant phase relationship between the accelerating voltage applied to the dees and the accelerated ion beam throughout its entire path within the dee chamber. The ideal profile for this condition, neglecting relativistic effects, is a perfectly homogeneous field out to the exit radius, where the field suddenly decreases to zero to allow the ions to escape from the dee chamber.

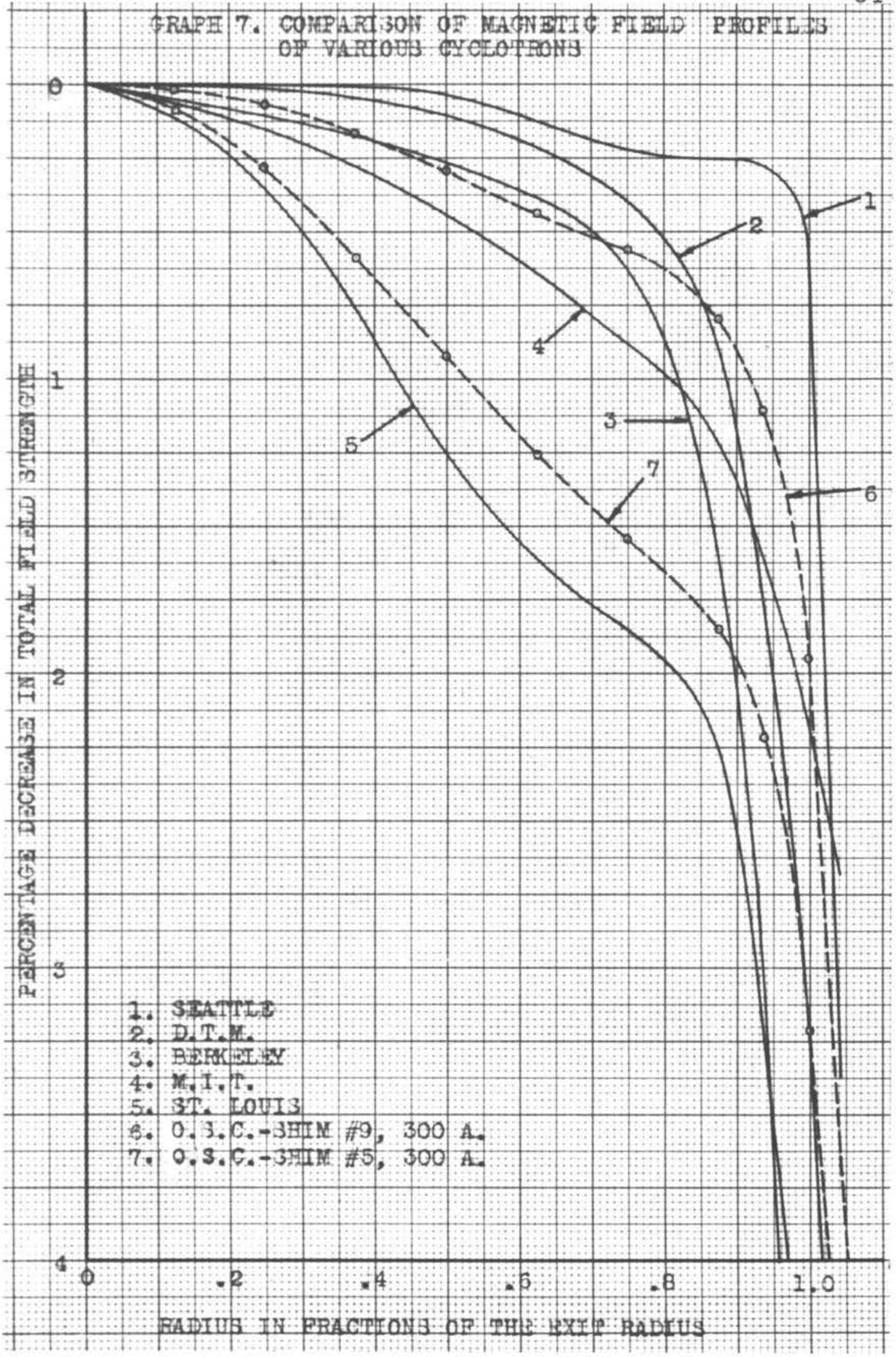
Since the ions usually leave the source in random directions, large focusing forces are needed to produce a beam having a small cross-sectional area at the exit slit. These focusing forces must be supplied by the crossed electric and magnetic fields. Although the time dependent electric field supplies phase focusing during the first few accelerations of the ions, it supplies negligible vertical focusing. (3, p.396) The latter must then be supplied by proper adjustment of the magnetic field profile.

When a particle, with a charge q, moves in a magnetic field $\overline{B}$, with a velocity $\overline{v}$, it experiences a force $\overline{f}$, at right angles to its motion, given by the vector expression $\overline{f} = q(\overline{v} \times \overline{B})$. The vertical component of the field serves to circulate the ions in the dee chamber, allowing them to be accelerated repeatedly in the dee gap, while the radial component provides vertical forces on the ions. If the flux lines are concave inward, that is, if there is a negative field gradient, then these vertical forces are directed toward the median surface and increase with the distance from it. But if there is a positive field gradient over even a small region, the de-focusing forces will cause nearly all the beam to be lost. Foss (1, pp.5-30) has found that the following condition must be fulfilled: the field should decrease with increasing radius such that for radii less than the exit radius, $0 < \text{"n"} = -(\frac{r}{B})(\frac{dB}{dr}) <$ 0.2, and at the exit radius the value of "n" should be 0.4. Since the magnitude of the radial field increases as the vertical field decreases, the focusing forces increase as the radius increases. These forces are proportional to $\frac{d \log B_z}{d \log r}$ (3, p.398), where B_z is the vertical field.

It is obvious that the profile chosen must represent some compromise between the two basic requirements for resonance and focusing. Moreover, in practice the optimum shape of the field profile is also a function of other parameters such as the design of the ion source, the magnitude of the dee voltage, and the working pressure in the dee chamber. The solid lines in Graph 7 (2, p.6) show a wide variation of profiles used in some of the constant frequency cyclotrons in this country. For a quantitative comparison, the focusing forces in the St. Louis cyclotron are over 1000 times greater than in the Seattle machine.

The problem of obtaining the desired profile by the use of magnetic shims is discussed in detail by Rose (4, pp.715-719). The proper shim for a certain profile can be predicted to a certain extent by mathematical analysis, but it is sometimes found more satisfactory to insert certain shims and then measure their effect on the field.

Since the final design of many components of the cyclotron had not been completed, it was requested by the cyclotron committee that a catalog of shims be made up in order that a profile of any desired shape could quickly be obtained. Consequently, a fairly comprehensive study was made of various profiles which might be desired. Measurements were first made of the profile without shims, and then with thirteen different shim arrangements. Seven of these were repeated at three different magnet currents


GRAPH 7. COMPARISON OF MAGNETIC FIELD PROFILES OF VARIOUS CYCLOTRONS
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
0
1
2
3
4
0
.2
.4
.6
.8
1.0
RADIUS IN FRACTIONS OF THE EXIT RADIUS
1. SEATTLE
2. D.T.M.
3. BERKELEY
4. M.I.T.
5. ST. LOUIS
6. O.S.C.-SHIM #9, 300 A.
7. O.S.C.-SHIM #5, 300 A.

while two others were taken at two currents. By interpolation it is possible to predict the approximate profiles resulting from different shim arrangements.

The profile measurements were taken along an arbitrarily chosen radius with the differential search coil apparatus. Graph 8 shows the profile without shims for three different values of magnet current. The percentage decrease in total field strength relative to the field at the center is plotted as a function of the radius in inches. Since the saturation effects in the tapered pole pieces are greater near the edge of the field, the central field is greater in proportion at the higher currents. Therefore, the highest profile curve on the graph is produced at the smallest current, although the magnitude of the central field is smaller. The central field values are noted on the graph. Even at the highest current the field without shims has a positive gradient over most of its length and thus it is clear that shims are necessary in order to satisfy the conditions set forth by Foss.

The shims were made in pairs of galvanized iron disks of various radii. The shims were centered in the external shim gaps between the cover plates and the pole faces. They were placed in the gap so that they would lie symmetrically about the midplane. A list of the shims is shown in Table 4.

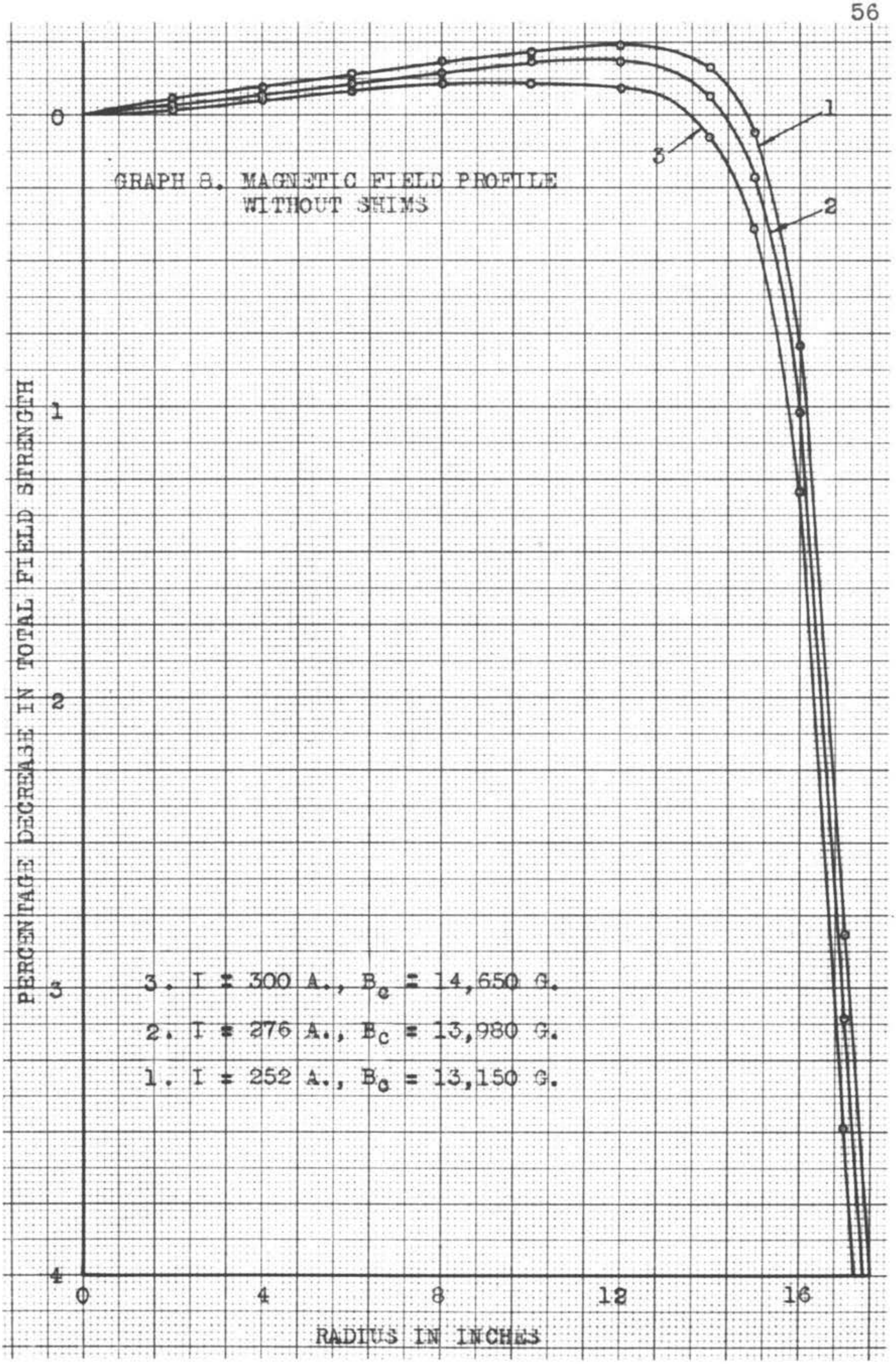
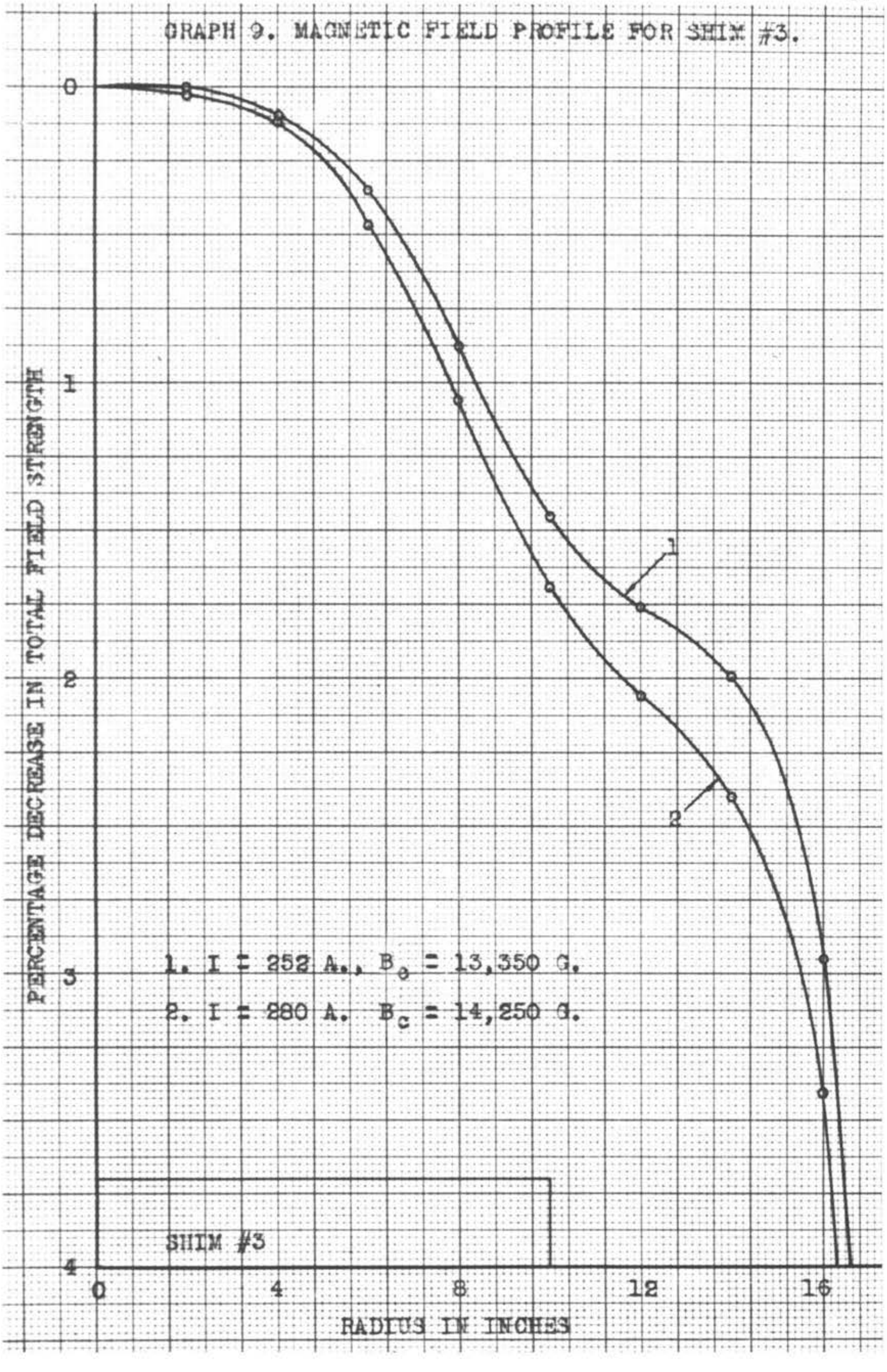

GRAPH 8. MAGNETIC FIELD PROFILE
WITHOUT SHIMS
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
0
1
2
3
4
RADIUS IN INCHES
0
4
8
12
16
1
2
3
3. I = 300 A., Bc = 14,650 G.
2. I = 276 A., Bc = 13,980 G.
1. I = 252 A., Bc = 13,150 G.

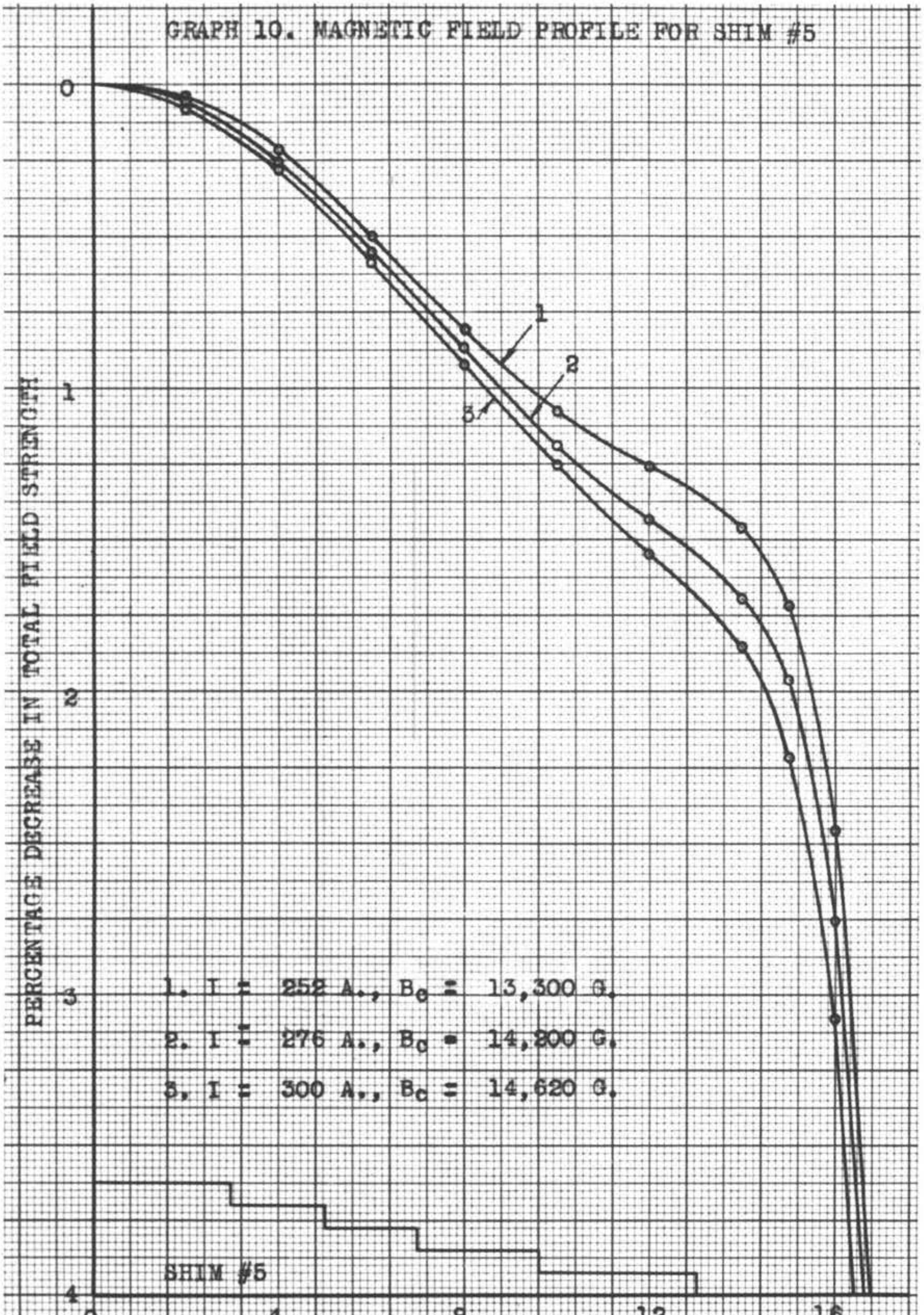
Table 4. List of Shims

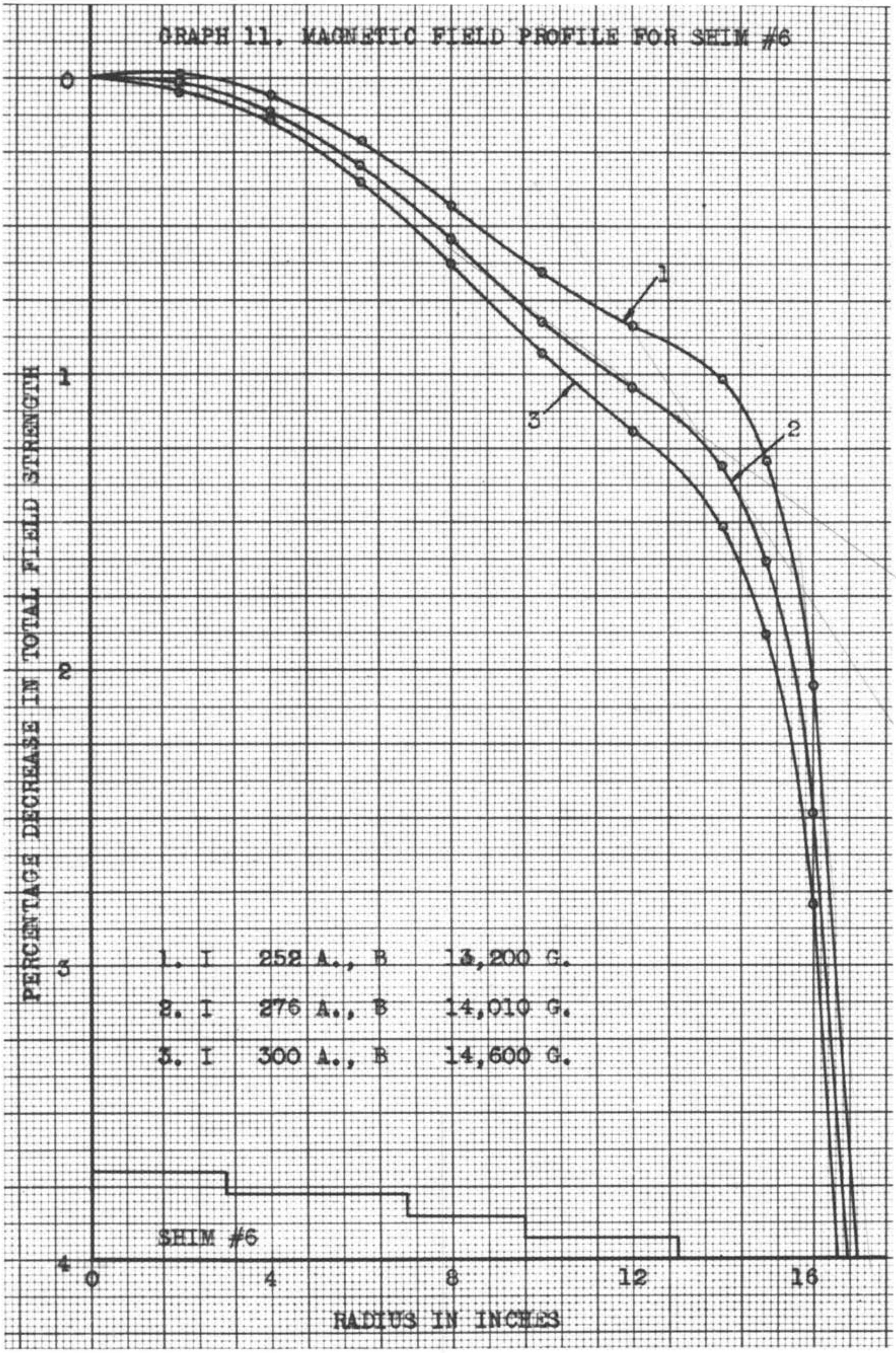
Shim Stack Number	Disks per Stack	Diameter (inches)	Thickness (inches)
1	1	10	.048
2	1	26	.048
3	1	20	.1875
4	2	20	.048
5	1 each	6, 10, 14, 20, 26	.048
6	1 each	6, 14, 12, 26	.048
7	1 each	6, 20, 26	.048
8	1 each	6, 10, 20	.048
	2	4	.015
9	1 each	6, 10, 20	.048
	1 each	26, 30	.015
	2	4	.015
10	1 each	4, 6, 10, 14, 26, 30	.015
	1	20	.048
11	1 each	2, 4, 6, 8, 26, 30	.015
	1	20	.048
12	1 each	2, 4, 6, 8, 10, 14, 26, 30	.015
	1	20	.048
13	1 each	6, 8, 26, 30	.015
	2	4	.015
	3	2	.015
	1	20	.048

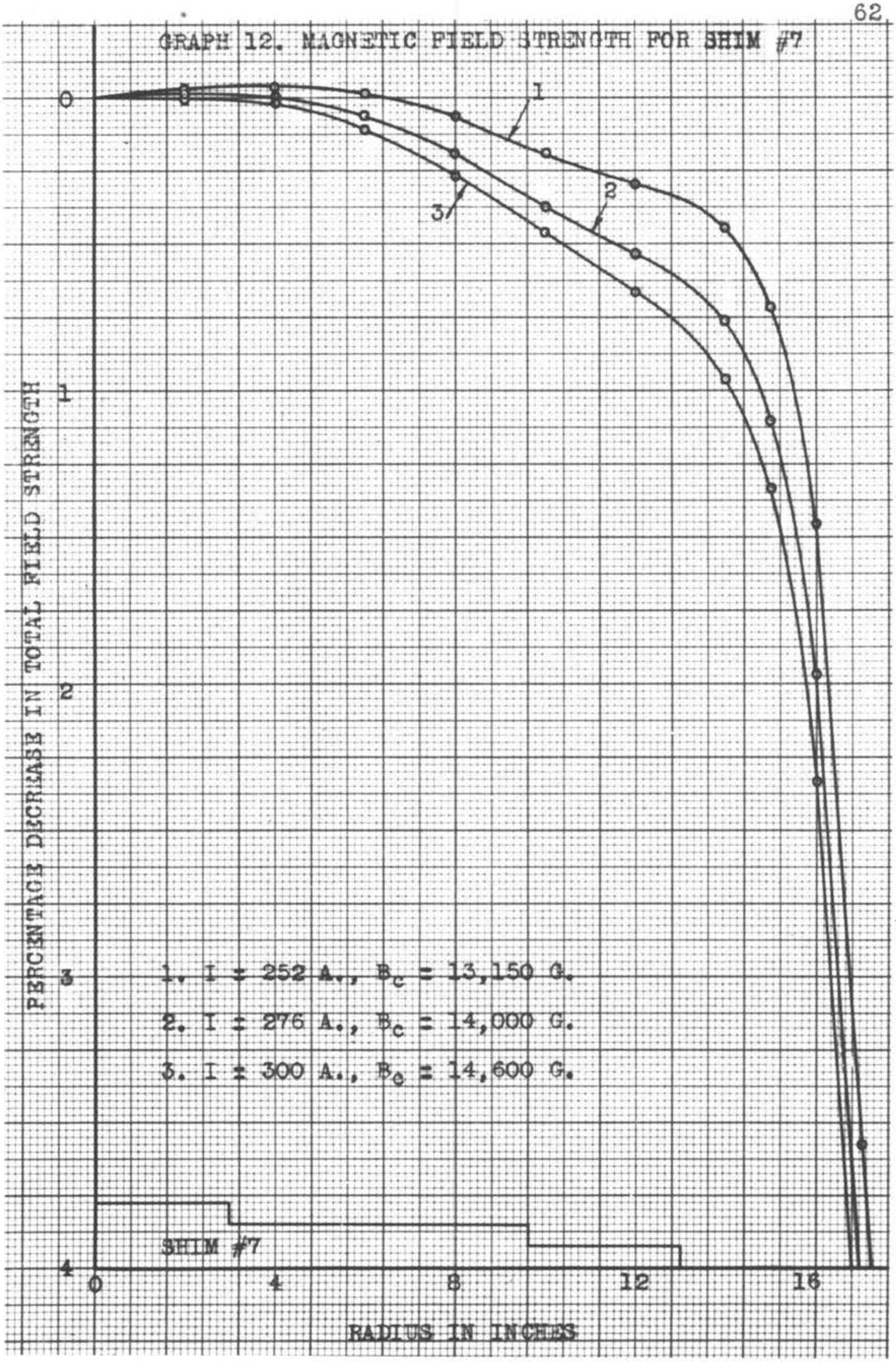
Graphs 9 through 15, inclusive, show the profiles for the major shim arrangements. At the bottom of each graph is drawn a profile of the shim stack. The vertical scale of the shim stack has been greatly exaggerated, with 1 small division equal to approximately .015 inch of shim thickness. Comparisons of the field profiles produced by some of the different shims are shown in Graphs 16 through 20, inclusive.

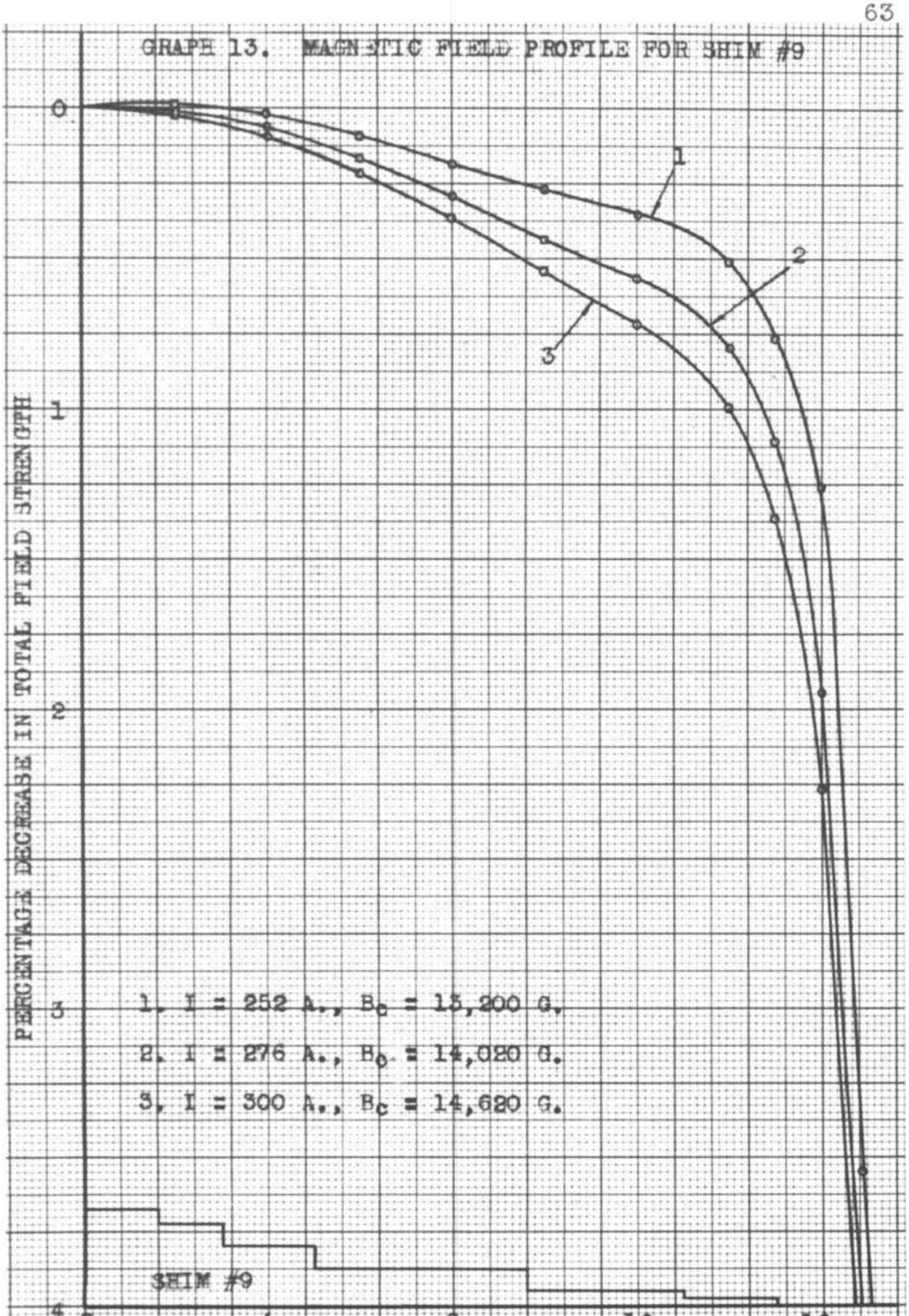
Graph 7 shows two of the Oregon State profiles compared with profiles of various other cyclotrons. The curves are normalized by plotting the radius in fractions of the exit radius. The exit radius of the Oregon State machine was tentatively assumed to be 16 inches. None of the shims used seems to provide a sufficiently rapid decrease in field at the exit radius to satisfy the Foss condition. If this drop-off is not adequate, excessively high deflector voltages are needed. It has been suggested by members of the Cyclotron Magnet Group of the University of California Radiation Laboratory that internal ring shims, or the so-called Rose shims be used to increase the drop-off in field strength at the exit radius. Although the ring shims necessary to produce the desired profile can be estimated fairly accurately from the profile data and the magnet dimensions, there are certain advantages in not using ring shims. An alternate method would be to

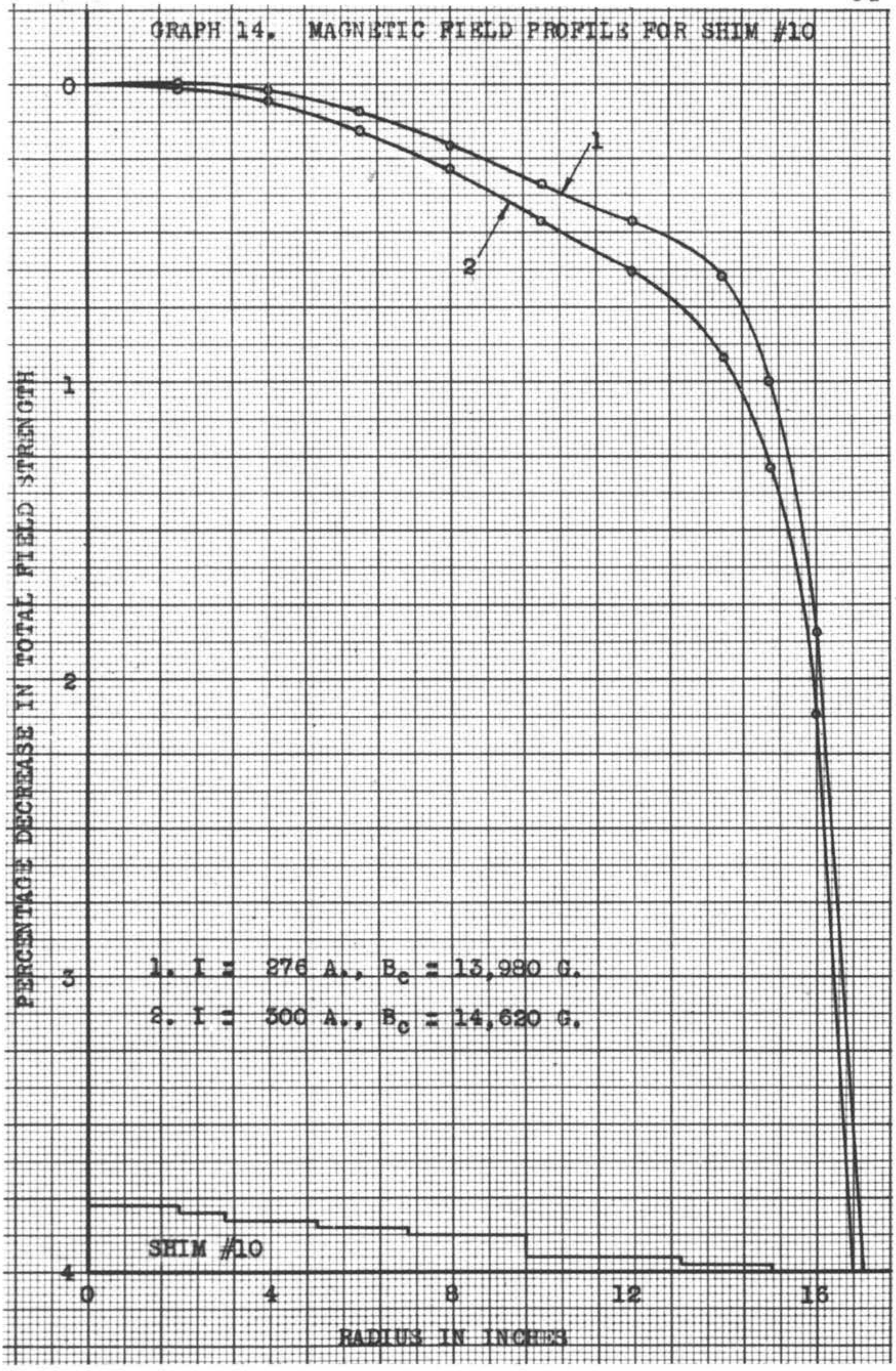

GRAPH 9. MAGNETIC FIELD PROFILE FOR SHIM #3.
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
RADIUS IN INCHES
0
1
2
3
4
0
4
8
12
16
1
2
1. I = 252 A., B_o = 13,350 G.
2. I = 280 A. B_c = 14,250 G.
SHIM #3

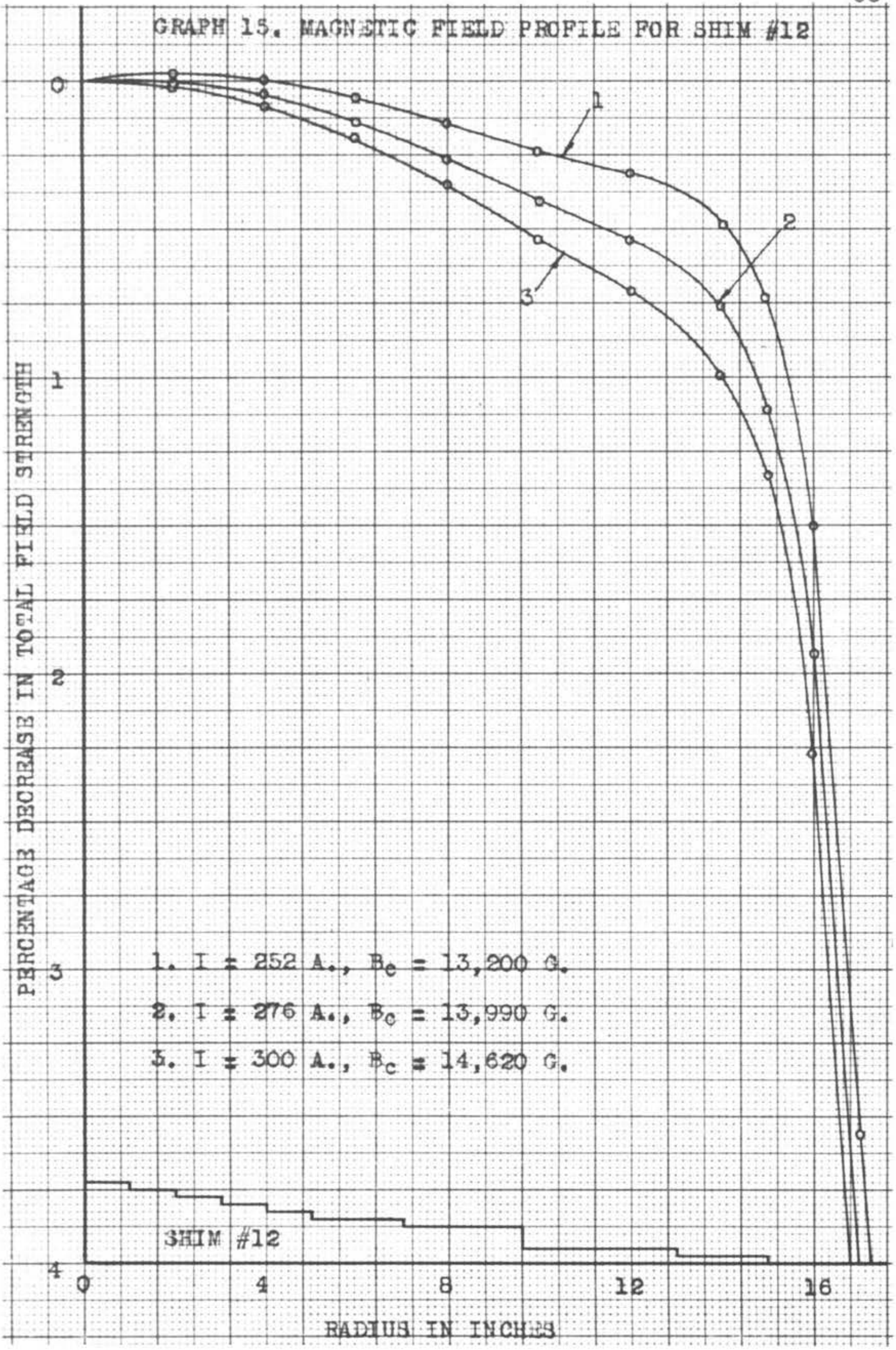

GRAPH 10. MAGNETIC FIELD PROFILE FOR SHIM #5
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
0
1
2
3
4
1
2
3
1. I = 252 A., Bc = 13,300 G.
2. I = 276 A., Bc = 14,200 G.
3. I = 300 A., Bc = 14,620 G.
SHIM #5
0
4
8
12
16
RADIUS IN INCHES

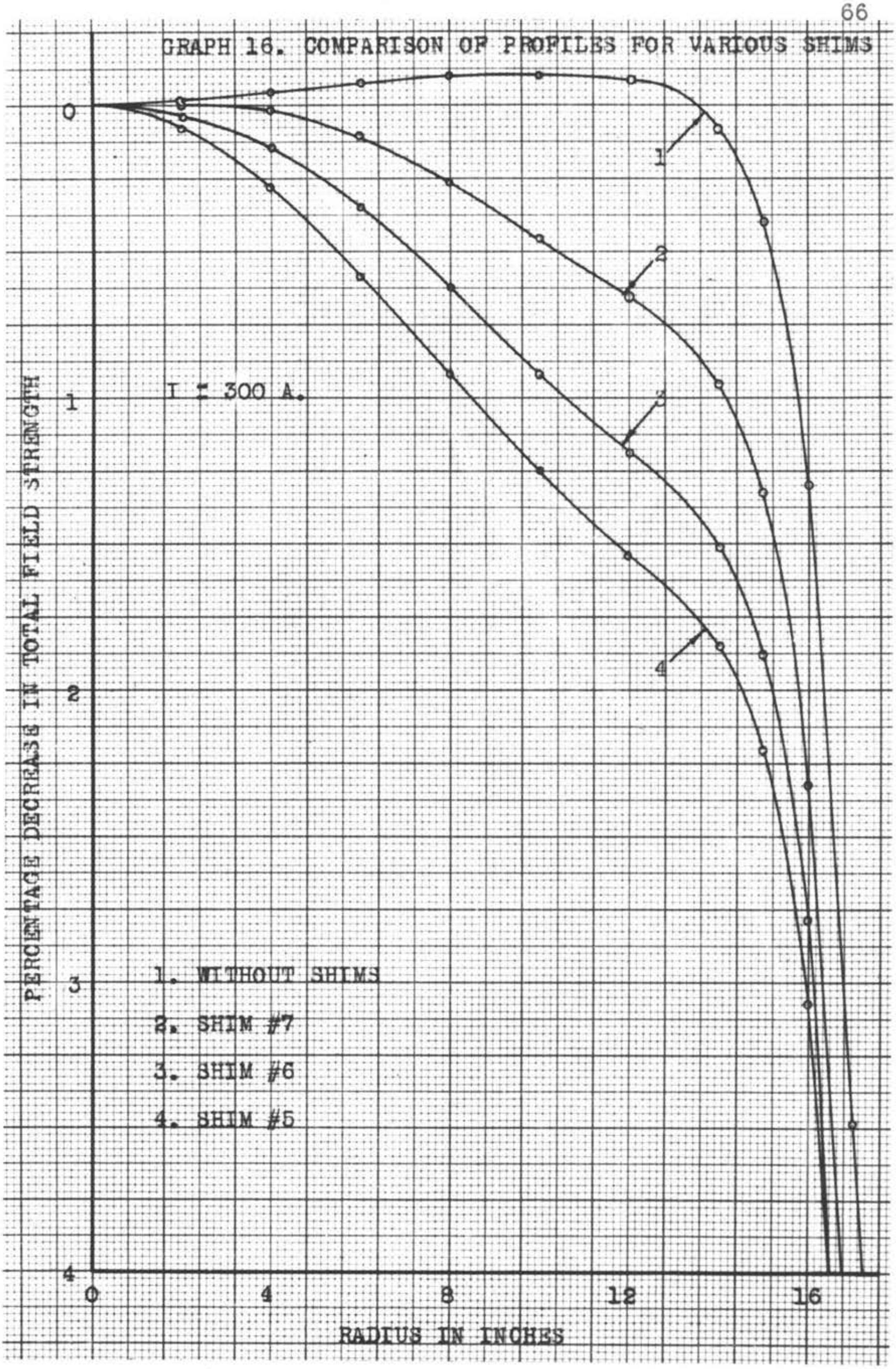

GRAPH 11. MAGNETIC FIELD PROFILE FOR SHIM #6
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
0
1
2
3
4
RADIUS IN INCHES
0
4
8
12
16
1
2
3
1. I 252 A., B 13,200 G.
2. I 276 A., B 14,010 G.
3. I 300 A., B 14,600 G.
SHIM #6

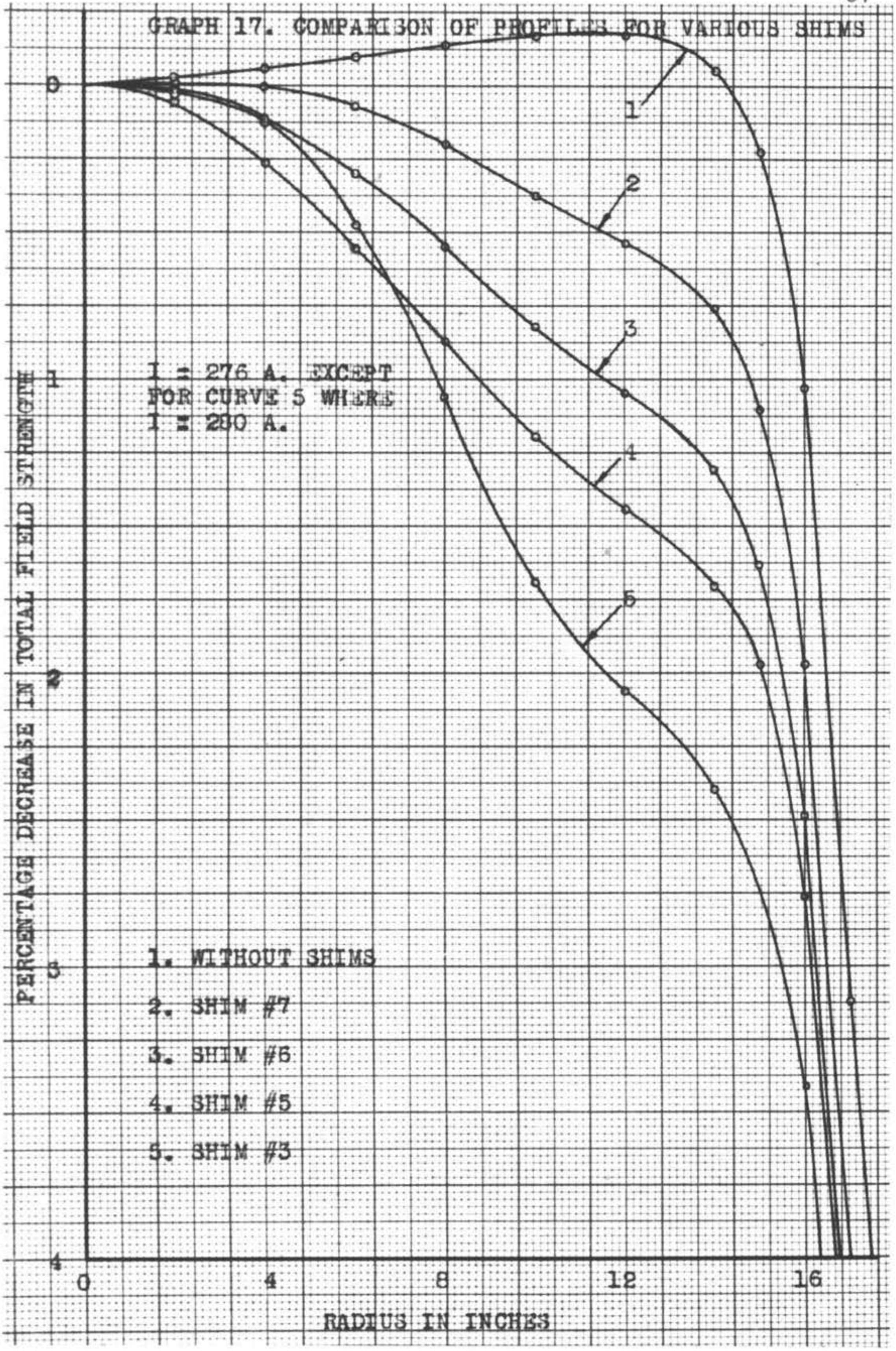

GRAPH 12. MAGNETIC FIELD STRENGTH FOR SHIM #7
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
0
1
2
3
4
1
2
3
1. I = 252 A., B_c = 13,150 G.
2. I = 276 A., B_c = 14,000 G.
3. I = 300 A., B_c = 14,600 G.
SHIM #7
0
4
8
12
16
RADIUS IN INCHES

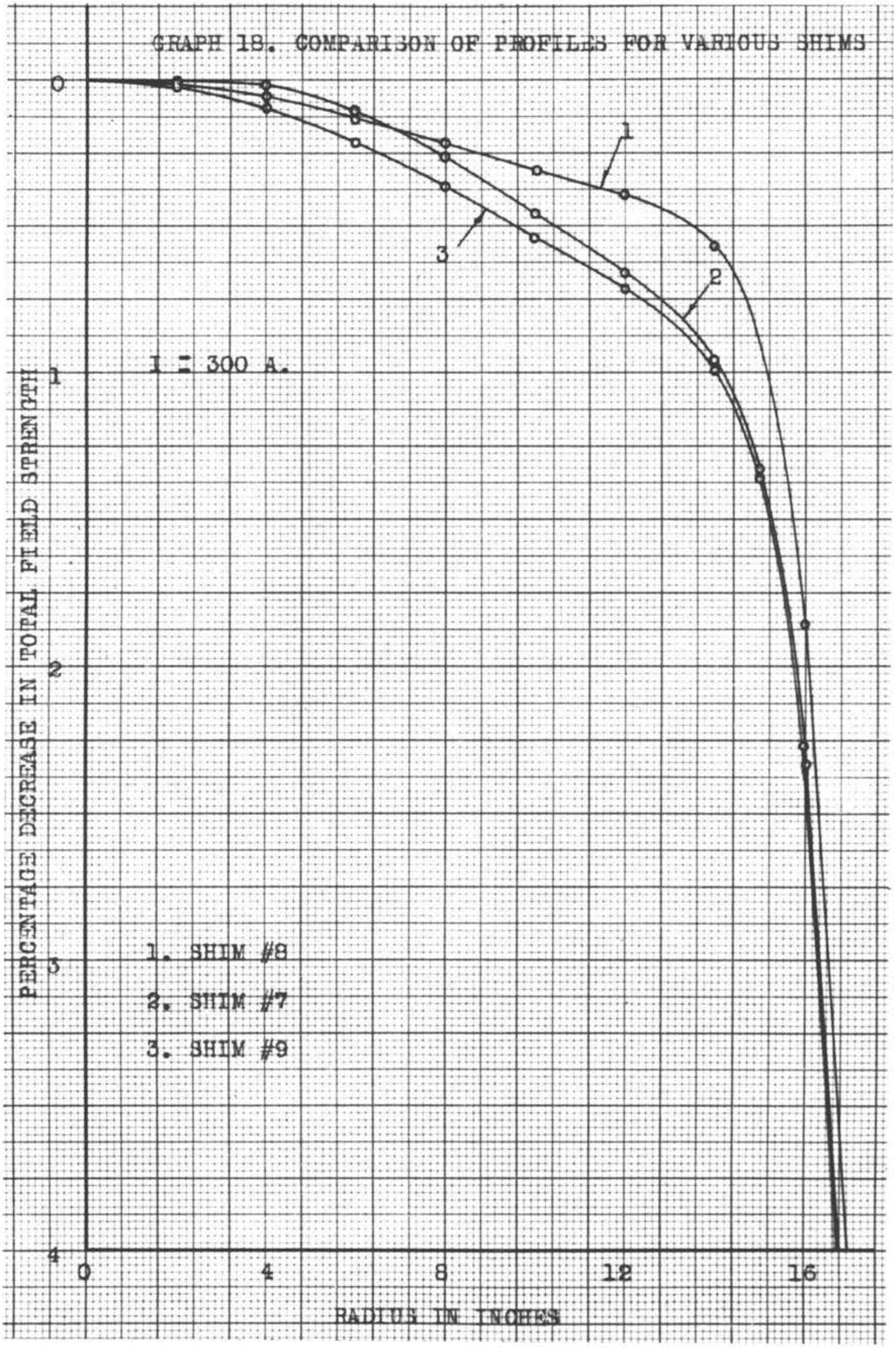

GRAPH 13. MAGNETIC FIELD PROFILE FOR SHIM #9
0
1
2
3
4
1
2
3
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
1. I = 252 A., Bc = 13,200 G.
2. I = 276 A., Bc = 14,020 G.
3. I = 300 A., Bc = 14,620 G.
SHIM #9
0
4
8
12
16
RADIUS IN INCHES

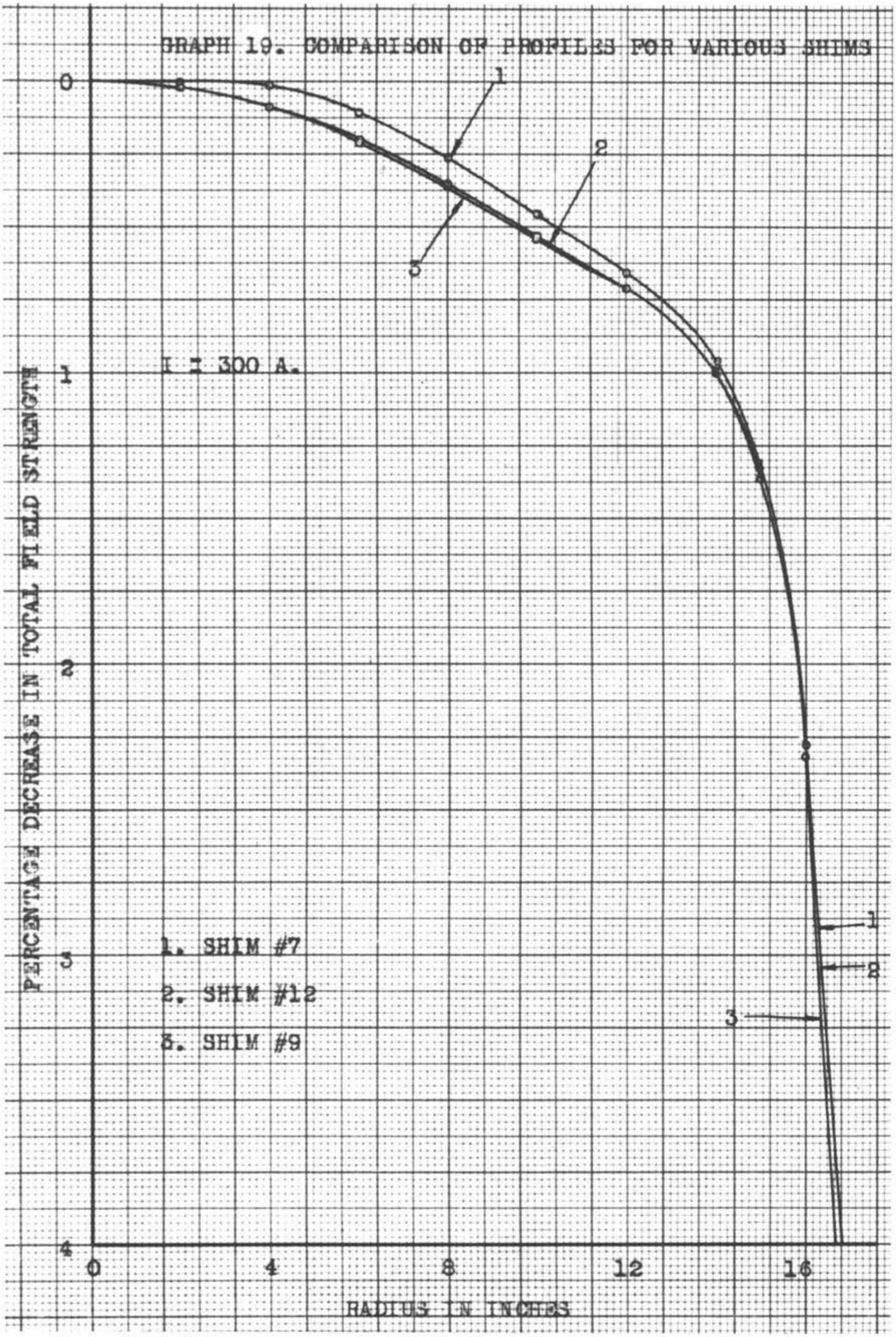

GRAPH 14. MAGNETIC FIELD PROFILE FOR SHIM #10
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
0
1
2
3
4
1
2
1. I = 276 A., B_c = 13,980 G.
2. I = 300 A., B_c = 14,620 G.
SHIM #10
0
4
8
12
16
RADIUS IN INCHES


GRAPH 15. MAGNETIC FIELD PROFILE FOR SHIM #12
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
0
1
2
3
4
1
2
3
1. I = 252 A., Bc = 13,200 G.
2. I = 276 A., Bc = 13,990 G.
3. I = 300 A., Bc = 14,620 G.
SHIM #12
0
4
8
12
16
RADIUS IN INCHES

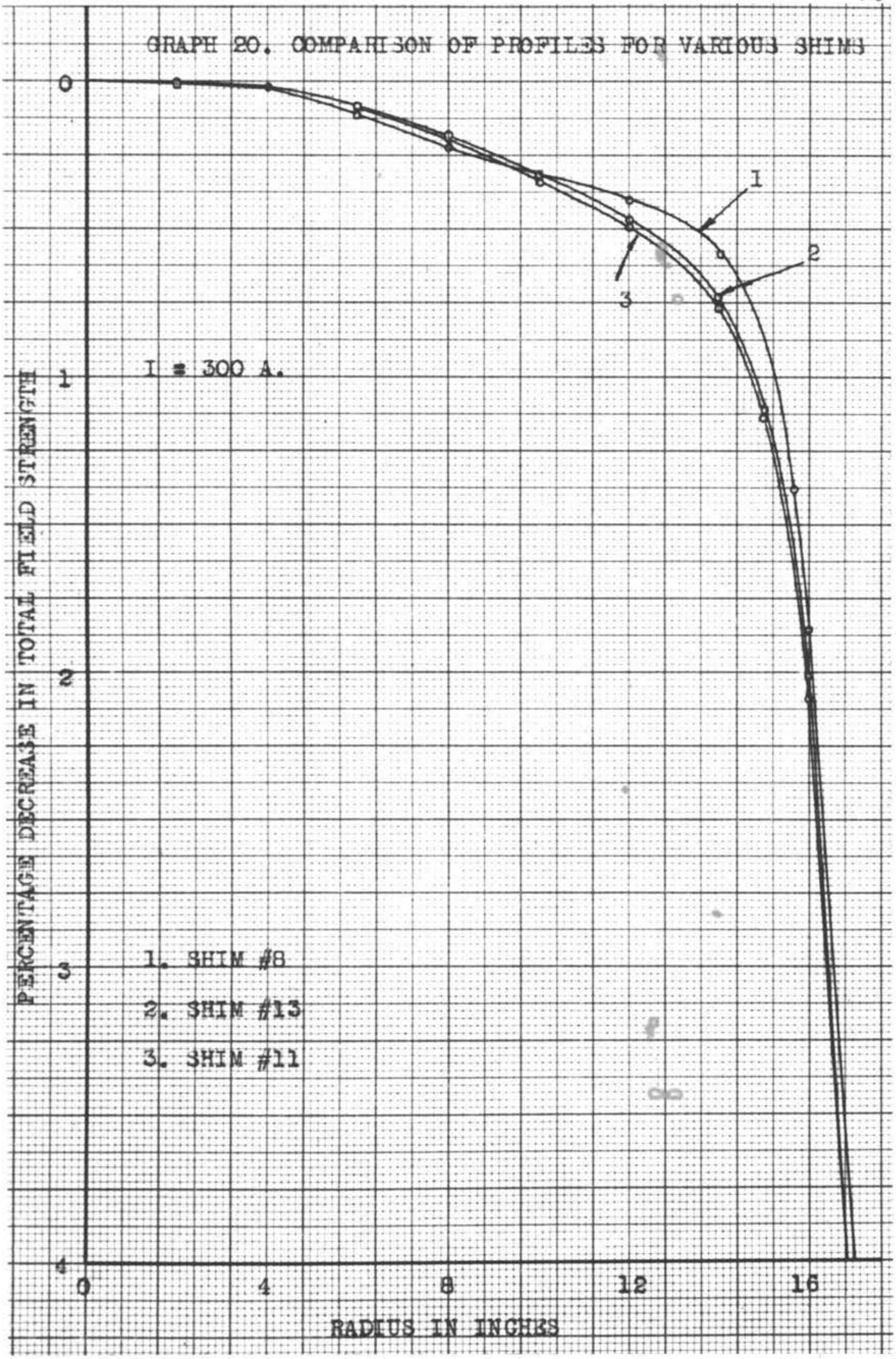

GRAPH 16. COMPARISON OF PROFILES FOR VARIOUS SHIMS
I = 300 A.
1. WITHOUT SHIMS
2. SHIM #7
3. SHIM #6
4. SHIM #5
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
RADIUS IN INCHES
0
1
2
3
4
0
4
8
12
16
1
2
3
4


GRAPH 17. COMPARISON OF PROFILES FOR VARIOUS SHIMS
I = 276 A. EXCEPT
FOR CURVE 5 WHERE
I = 280 A.
1. WITHOUT SHIMS
2. SHIM #7
3. SHIM #6
4. SHIM #5
5. SHIM #3
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
RADIUS IN INCHES
0
1
2
3
4
0
4
8
12
16
1
2
3
4
5


GRAPH 18. COMPARISON OF PROFILES FOR VARIOUS SHIMS
I = 300 A.
1. SHIM #8
2. SHIM #7
3. SHIM #9
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
RADIUS IN INCHES
0
1
2
3
4
0
4
8
12
16
1
2
3



GRAPH 19. COMPARISON OF PROFILES FOR VARIOUS SHIMS
I = 300 A.
1. SHIM #7
2. SHIM #12
3. SHIM #9
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
RADIUS IN INCHES
0
1
2
3
4
0
4
8
12
16
1
2
3

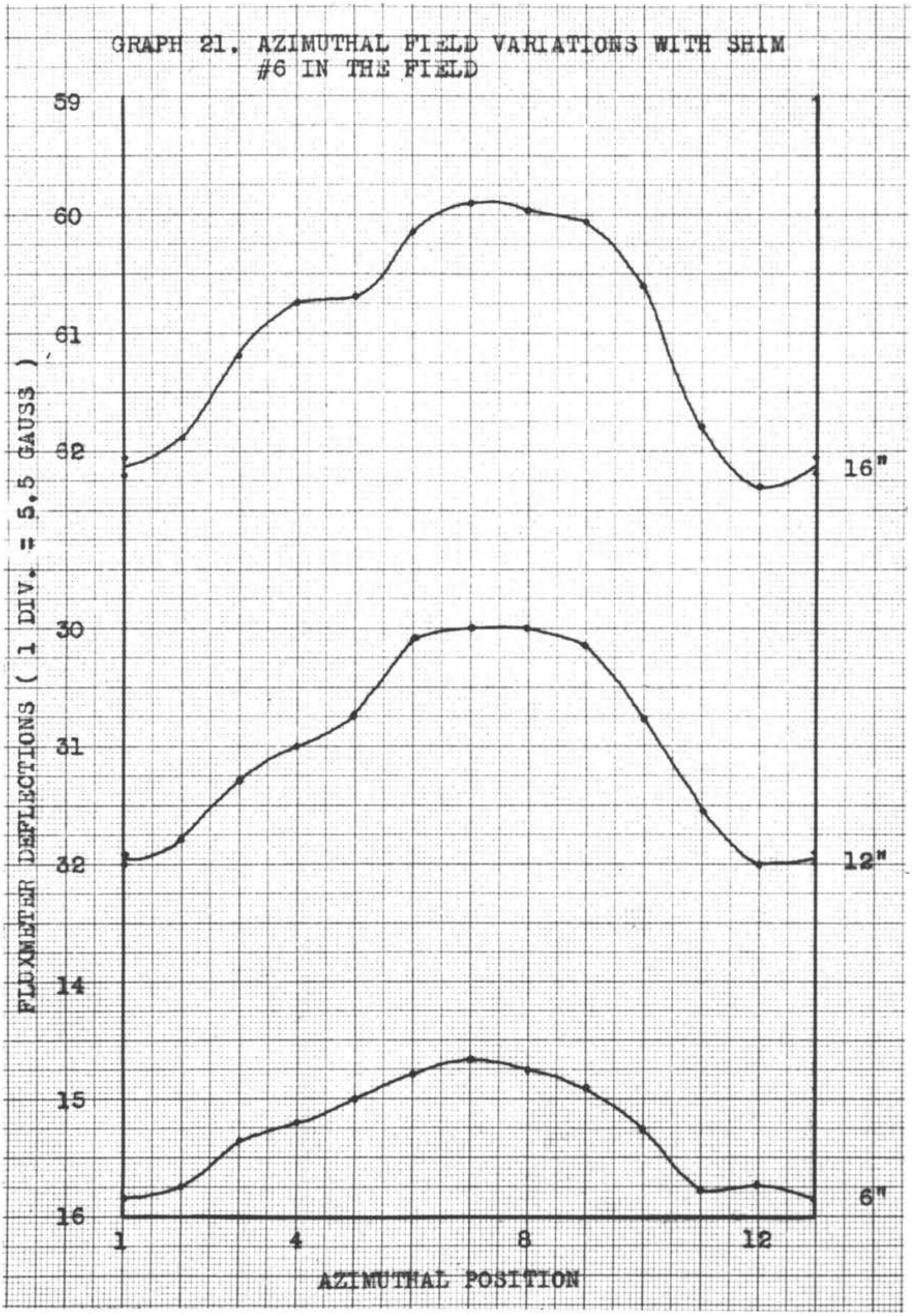

GRAPH 20. COMPARISON OF PROFILES FOR VARIOUS SHIMS
I = 300 A.
1. SHIM #8
2. SHIM #13
3. SHIM #11
PERCENTAGE DECREASE IN TOTAL FIELD STRENGTH
RADIUS IN INCHES
0
1
2
3
4
0
4
8
12
16
1
2
3

increase the exit radius slightly and use the necessary disk shims to obtain the desired profile. Increasing the exit radius alone would provide the required drop-off in field, but then the magnitude of the field at the exit radius would be too low. Adding the required large diameter disks would increase the field at the exit radius without appreciably affecting the drop-off, although quite possibly the drop-off would be increased. Since the construction and testing of the full-size dees and r.f. system has not been completed, it might be possible to increase the exit radius. Increasing the exit radius would have the additional advantage of allowing higher energy ions to be produced in the cyclotron.

By observing the modifications in the field profile produced by the various shims, certain general statements can be made. It was found that the central field was increased by the addition of shims. The greater apparent decrease in field with increasing radius, caused by the addition of shims, is due to an increase in the central field. If the diameters of the disks are not less than about 6 inches, this increase in field is nearly proportional to the decrease in air gap at the center of the magnet. For smaller disks, the increase in field is proportionately smaller. This effect is illustrated in Graph 18. Although the total thickness in Shim #8 is greater than in Shim #7, the increase in central field due to the latter is larger. Hence, it is shown that the field at one point cannot be altered without affecting the field at other points. Thus, to increase the central field, the peripheral field must also be increased proportionately by combining larger disks with the smaller ones. At first glance, Graph 16 appears to illustrate the opposite effect. Curves 3 and 4 result from adding first a 14 in. and then both a 14 in. and a 10 in. disk, respectively, to the shim producing curve 2. But curve 2 already has a relatively large field gradient at the larger radii. Also the effect of the 10 inch disk was not as pronounced as that of the 14 inch disk.

Although the shimming was meant to be symmetric about the geometric midplane, the individual disks were rather uneven and it was difficult to center the shims to within less than 1/8 inch. Therefore, it was desirable to determine the degree of azimuthal homogeneity and the location of the median surface with shims in place.

The azimuthal field was measured at three different radii and was found to be fairly acceptable (Graph 21). The total variation at the 12 in. radius is 10.7 gauss and at 16 in. is 12.3 gauss, or a total variation at 16 in. of less than .09%. The variation has then been approximately doubled by the addition of the shims, but it still

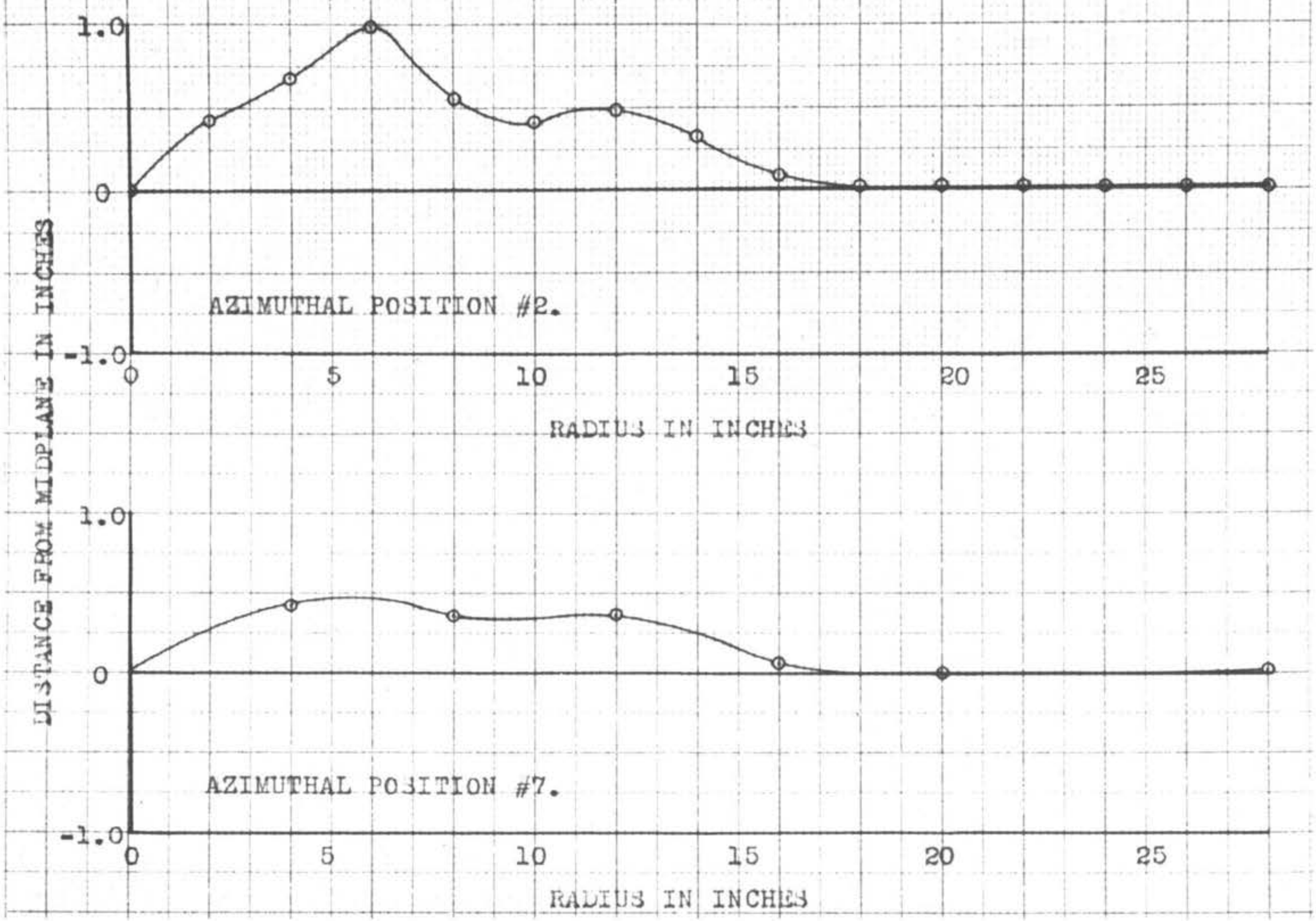

GRAPH 21. AZIMUTHAL FIELD VARIATIONS WITH SHIM #6 IN THE FIELD
FLUXMETER DEFLECTIONS (1 DIV. = 5.5 GAUSS)
59
60
61
62
30
31
32
14
15
16
16"
12"
6"
1
4
8
12
AZIMUTHAL POSITION

is not excessive. The University of Washington cyclotron field shows up to 0.1% variation, and other cyclotron groups report even larger ones.

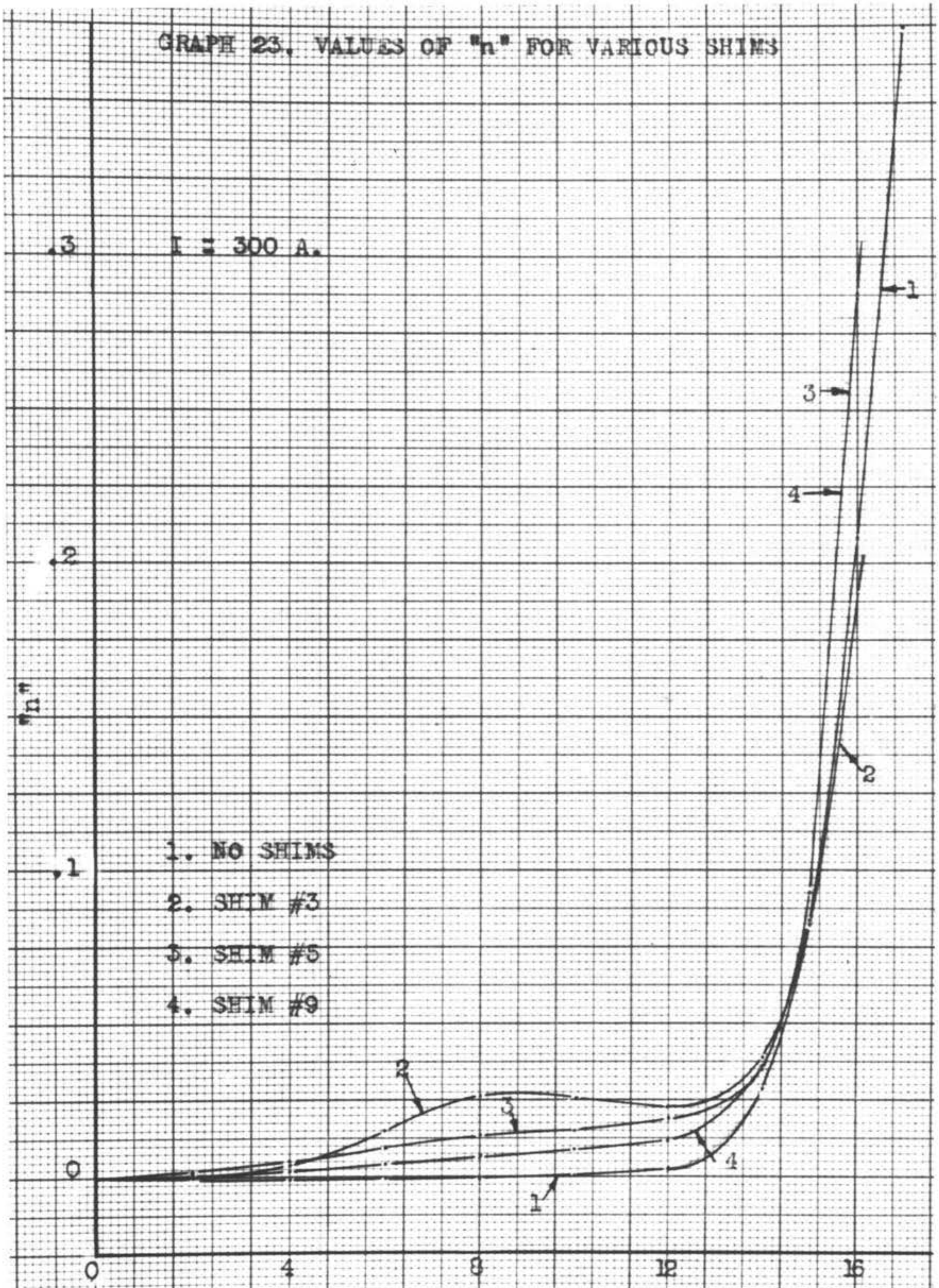
The median surface was measured at the two previously measured positions and its location is shown in Graph 22. At the No. 2 position, the deviation of the median surface from the midplane is nearly 1 inch at the 6 inch radius. This variation is quite large since the radial field, due to the shims, is at least 20 gauss at a distance of 1 inch from the magnetic median surface. Hence, the location of the median surface is more critical with the shims in the gap. Although it was felt that the radial field is larger than the mentioned value, time did not permit direct measurements. The magnitude of the radial field could be measured by rapidly moving a search coil from the center of the gap to the point in question.

Graph 23 shows values of "n" for various shims plotted as a function of the radius. These curves are more useful than the profiles for evaluating the radial dependence of the field. Although the condition that "n" must satisfy, for radii smaller than the exit radius, is rather broad, the value of "n" at the exit radius should be about 0.4. It can be seen that the greatest calculated value of "n" at the exit radius is .286, which indicates the drop-off

GRAPH 22. LOCATION OF MAGNETIC MEDIAN SURFACE AT TWO AZIMUTHAL POSITIONS
SHIM #6 INSERTED IN EXTERNAL SHIM GAP



GRAPH 23. VALUES OF "n" FOR VARIOUS SHIMS



in field is not large enough at the exit radius.

A variety of shims have been tested in order to obtain possible desired profiles and the results were quite satisfactory. The median surface and azimuthal field have been measured and the results indicate that the final shims should be accurately constructed and positioned in the gap. Thus, it is felt that the azimuthal field and median surface variations will not necessarily be increased by the final shims.

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APPENDIX

Table 5. Magnetization Curve
(Data for Graph 1)

Data of August 4		Data of July 7	
Current (amps)	Central Field (kilogauss)	Current (amps)	Central Field (kilogauss)
20	1.19	50	2.96
40	2.31	75	4.35
60	3.36	100	5.80
80	4.52	125	7.09
100	5.57	150	8.38
120	6.75	175	9.71
140	7.78	200	10.90
160	8.84	225	12.05
170	9.35	250	13.08
200	10.80	275	13.75
220	11.73		
240	12.58		
248	12.90		
260	13.32		
272	13.68		
280	13.90		
288	14.11		
296	14.31		
300	14.40		

Table 6. Azimuthal Field Homogeneity at the 14 Inch Radius
(Data for Graph 3)

Azimuthal Position	1*	2*	3*	4*	5*
	(Readings in fluxmeter divisions, without correction)				
1	7.3	6.8	9.95	6.65	6.8
2	7.9	7.3	8.95	6.45	6.7
3	8.0	7.1	6.8	6.0	6.3
4	7.3	6.75	5.65	5.35	6.05
5	6.7	6.1	5.0	5.3	6.1
6	6.05	5.95	4.0	5.35	6.0
7	5.85	5.7	3.8	5.8	5.85
8	6.2	5.75	4.9	6.2	5.85
9	6.35	5.8	6.6	6.55	5.85
10	6.25	5.6	7.5	6.6	6.0
11	6.8	5.8	8.75	6.8	6.7
12	7.2	6.3	9.95	6.8	6.8
Total Variation (divisions)	2.15	1.7	6.15	1.5	.95
Total Variation (gauss)	11.8	9.35	33.8	8.25	5.22

*1. Plates in original position, search coil apparatus poorly centered.
2. Plates in original position, search coil apparatus centered.
3. Top plate tilted.
4. Top plate rotated.
5. Vacuum tank centered.

Table 7. Location of Magnetic Median Surface
(Data for Graph 4)

Radius (inches)	Azimuthal Position No.7 Distance from Midplane (inches) 1*	2*	Azimuthal Position No.2 Distance from Midplane (inches) 1*
0	0	0	0
4	-.1		.47
8	-.14		.04
12	-.1	-.1	.04
14		.1	.24
15		.08	
16	.1		-.059
17		.08	
18	.04		0
19		.02	
20		.012	0
22		.012	
24		-.0008	-.031
27		-.002	-.063

*1. Needle in original position.
2. Needle inverted.

I. Sensitivity of Field Strength Measuring Apparatus

A. Calculation of Sensitivity of Fluxmeter used with 7-turn Coil.

Given the following data:

1. Sensitivity of the fluxmeter, $S = 14{,}000$ Maxwell-turns per division

2. Effective area of 7-turn coil, $A = 27.86\ \text{cm}^2$

Then the sensitivity s, of the apparatus, expressed in gauss per scale division is:

$$s = \frac{14{,}000 \text{ Maxwell-turns}}{2 \times 27.86 \text{ cm}^2 \text{ division}}$$

$$s = 251.3 \text{ gauss per division}$$

The factor of 2 in the denominator enters because of the 180° angle of rotation of the search coil.

B. Calculation of Sensitivity of Fluxmeter with 442-turn coil.

Given:

1. $A = 1272\ \text{cm}^2$

In a similar manner, the sensitivity of the differential field measuring apparatus is:

$$s = \frac{14{,}000}{2 \times 1272} = 5.5 \text{ gauss per division}$$

C. Calibration of Fluxmeter Sensitivity

1. A standard mutual inductance was constructed with the following dimensions:

a. Primary:

Length, 2L	19.56 in.
Radius, R	1.40 in.
Number of turns, N	364

b. Secondary:

Length, 2l	1.41 in.
Radius, r	1.40 in.
Number of turns, n	118

2. The sensitivity of the fluxmeter may be calculated from the following approximate formula:

   Sensitivity, $S = \frac{4 \quad Nn\,Ai}{20 \quad L^2 \quad R^2}$ (Maxwell-turns per division)

   where i is in amperes per division, determined by taking the slope of a graph of the primary current, I, as a function of the deflections resulting when the circuit is interrupted

   $$\text{Then } S = \frac{(15.56)(364)(118)(39.6 \text{ cm}^2)(.336 \text{ amps/div.})}{20(24.9^2 \quad 3.56^2)\ \frac{1}{2} \text{ cm}}$$

   $$= 14{,}200 \text{ gauss / div.}$$

This agrees to within slightly more than one per cent, with the factory calibration, and since no greater accuracy is claimed, the latter figure of 14,000 Maxwell-turns per division has been used throughout. Only a two per cent variation in sensitivity is observed when the 7-turn coil and the two 442-turn coils are used due to their different resistances.