CLAS-NOTE-93-008

Magnetic Fields Surrounding a Shield for the Photomultiplier Tubes in the CLAS TOF.

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1 Introduction

In the CEBAF Large Acceptance Spectrometer (CLAS), three inch diameter photomultiplier tubes will be arranged to form a detector around the main magnet beyond the drift chambers and Cerenkov counters. These three inch tubes will be arranged in a pattern from about 45° from the beam to about 145° from the beam. The photomultiplier tubes form the outer line of detectors shown in *figure 3*. These PMTs will be located in a region subjected to magnetic fields from about 10.0 gauss up to approximately 30.0 gauss. The flux lines of the external field will intersect the PMTs at various angles, however light guides will be used to allow the PMTs to be aligned closer to perpendicular to the magnetic flux lines where the shielding is most effective. To protect these PMTs from the effects of the fields, cylindrical magnetic shields will enclose the tubes. The field in and around the these cylindrical shields were measured at various external field levels.

The magnetic field in and around the 32P80 CO-NETIC shield was plotted to determine the attenuation of the external field inside the shield. The 32P80 shield has dimensions: 3.25 inch in diameter, 8.0 inches long, and a thickness of 0.040 inches. The shields, μ metal cylinders, were purchased from Perfection Mica Corporation. The μ metal is an annealed steel which has a high magnetic saturation. The attenuation was measured in external fields of 10.0 and 30.0 gauss with the axis of the cylinder aligned parallel to, perpendicular to, and at 45° to the flux lines. The magnetic field was measured in two dimensions in one plane with the assumption that it could be extrapolated to three dimensions in a constant field by rotating the result in about the axis of the cylindrical shield or mirroring the field at 45°.

In addition, the effects of a double shield were also measured. Various configurations of the shielding were measured by varying the overlap of the 32P80 shield by the 35P70 shield. The larger shield was 3.5 inches in diameter with a length of 7.0 inches. The overlapped region was varied from 3.0 inches to 7.0 inches. Additionally, the magnetic field around a flat 6 inch by 6 inch plate of μ metal were also determined.

2 Background

Under a 20.0 gauss field, Perfection Mica states that the theoretical attenuation of the field is 2,500 giving an interior field of 0.008 gauss. They also state that this value, 0.008 gauss, is unlikely to be attained under normal working conditions. Although not stated in its description of cylindrical PMT shields, Perfection Mica Corporation, in its description of shields for CRTs states that a shield attenuates the field optimally when the ratio of length to diameter is equal to or greater than 4:1. With a length of 8.0 inches and a diameter of 3.25 inches the ratio for the 32P80 shield is 2.46:1. Thus the expectation was not for optimal shielding. This assumption was confirmed in the procurement catalog for Ad-Vance Magnetics, Inc. In the section dealing with magnetic shielding, the equation for the degree of shielding is

$$g = \frac{H_{out}}{H_{in}} = \frac{\mu}{4}\left(1 - \frac{r_{in}}{r_{out}}\right) \cong \frac{\mu t}{2r}$$

It is pointed out that the equation is valid only when the length to diameter ratio is 4:1 or greater.

In previous work by Elton Smith and Stephen Armstrong in CLAS-NOTE-91-018 measured the magnetic field along the central axis of a cylindrical shield made from μ metal sheets obtained from Perfection Mica Corporation. The cylinder was formed from sheets fabricated from 0.020 inch μ metal. The work showed that in the central portion of 2.0 inch shield attenuated the magnetic field to approximately 1.0 gauss in fields up to 20.2 gauss.

S. P. K. Tavernier et al, in <u>The Design of a Magnetic Shielding for an Array of Photomultipliers in a Strong External Field</u> (Nuclear Instruments and Methods 167 [1979] 391-398) suggested the use of double shields with a 20 mm thick outer shield. The fields used by Tavernier tested designs for 300 to 730 gauss. Their design also included capping the ends with a circular plate with a hole in the end slightly smaller than the inner diameter of the inner shield. This design would seem to accumulate flux lines from the inside of the shield as well as externally, decreasing the internal field near the photocathode of the PMT. The design also kept the PMT totally inside the shield, one diameter from either end of the shield.

3 Apparatus

The total field was determined by making measurements with the axial probe (#1706) and transverse probe (#1561) of the F. W. Bell Model 4048 Gauss/Tesla meter, serial #9110304. Previous measurements of the field in the Helmholtz Coil by Drew Weisenberg were checked using the F. W. Bell Model 4048 Gauss/Tesla meter. The meter has an accuracy of ± 0.1 gauss. An axial probe was used to measure the field parallel to the axis of the shield and a transverse probe was used to measure the field perpendicular to the shield axis. Measurements of the total field indicated a linear relationship between the current and the magnetic field produced by the Helmholtz Coil. This measurement confirmed the original measurements made by Drew Weisenberg to within 1.7%. The graph of measurements made for this experiments are shown in *figure 4*.

The accuracy of the Gauss/Tesla meter and its probes were checked by comparing the readings of the Gauss meter in use for this experiment to a second F. W. Bell Gauss meter, serial #604350, with its own axial probe (#1574) and transverse probe (#1519). The two readings were nearly identical, reporting values within ± 0.2 gauss. The meters were checked in fields up to 50.0 gauss using both the axial and transverse probes from both meters.

4 Heating Effects

The total resistance in a wire is equal to the resistivity times the length of the wire divided by the cross-sectional area. For most metallic conductors, the resistivity increases with temperature. Higher temperatures cause greater molecular vibrations which cause more collisions with the electrons and thus hinder the flow of charge. For the resistivity, ρ, the change is nearly linear for small temperature changes. This change is

$$\rho = \rho_0(1+\alpha\Delta T).$$

The temperature coefficient of resistivity, α, is constant over small temperature ranges. Thus the resistance is

$$R = R_0(1+\alpha\Delta T).$$

where α is a constant for a small temperature range. For copper at 20° C., α is 6.8×10^{-3} $°C^{-1}$. As the temperature in the Helmholtz Coil increased, the resistance in the wire increased. As the resistance increases, the power is dissipated by

$$P = IR^2.$$

Therefore, when the temperature rises, more power is dissipated as heat warming the coil which is cooled only by its contact with the air.

During the course of the experiment, whenever the magnetic field in the Helmholtz Coil was greater than 20.0 gauss, there was noticeable heating in the coil. Heating was dependent on the length of time the coil was in operation. While the coil was set to 10.0 gauss, there was little if any heating noted over periods longer than one hour. At 20.0 gauss, the heating was noticeable in one hour, but then a cooling period was necessary. At 30.0 gauss, measurements requiring periods or a half hour or more either had to completed in pieces or the field had to be readjusted during the experiment.

During the operation of the Helmholtz Coil, there was a temperature change noted in the coils. The temperature always began at room temperature, usually 24° C. During the operation at 30.0 gauss, the temperature was measured up to 32° C. The field was measured to decrease by about 0.5 gauss. After noting this effect, the rate of taking measurements was increased and durations of time were included to allow the coils to cool slightly before resuming measuring the field.

5 Mapping the Field

Measurements in the field were taken by observing the meter as the probe was positioned at the various points marked as the intersections of the lines shown on *figure 1* (points A1..M13). The probe was held in place and when the reading stabilized, it was recorded. Occasionally, this required a half minute to reach a reproducible value. When measurements were made at the edge of the shield, on the surface of the metal, there was difficulty in reproducing the readings requiring rereading the probe values a number of times. These readings required the longest stabilization time.

The Helmholtz Coil had been adapted for use to test the PMTs. A large rotating box had been constructed in the center of the field. Previous measurements of the magnetic field had been made inside the box. To make the measurements in the shield, the box was rotated so the back was horizontal, providing a large flat working surface. The back was marked to plot the field along the plane of the back of the box. Plots of the field were made at 10.0, 15.0, 20.0, 25.0, and 30.0 gauss. The contours show that the field is nearly constant along the center line, varying in some places at the edges of the plotted area by approximately 4% to 5%. The area where the shield was measured varied by smaller amounts, approximately 2% to 3%. Initially, the area plotted was 12 by 18.9 inches. When it was found that the double shield required more space, a larger area of 20.0 inches by 20.0 inches was plotted. The 12 by 18.9 plots are shown in *figures 5 through 9*. The larger 20 by 20 plots show 10.0, 20.0 and 30.0 gauss fields in *figures 10, 11 and 12*. Both plots were centered on the same point. Variations may be noted by comparing the two figures for 10.0, 20.0 and 30.0 gauss fields. Slight differences in the initial settings of the power supply were unavoidable because the amperage setting was only to the nearest whole amp. The voltage setting was to the nearest tenth of a volt.

6 Saturation of the μ-Metal

The saturation of the μ metal was measured by placing the shield in the Helmholtz Coil field. The shield was placed with its axis parallel to the flux lines and the field was increased while the field in the center of the shield was measured. When the external field was increased, the field at the center of the shield was recorded. The field remained at less than approximately 0.7 gauss inside the shield until the external field exceeded 30 gauss. At 35 gauss the internal field increased to about 1.7 gauss. The internal field then rose at a nearly constant rate of 1.08 internal gauss relative to the external field up to the maximum field measured of 105 gauss. The graph of this data is shown in *figure 13*. The measurements show that saturation appears at an external field of about 35 gauss. It is likely that the low length to diameter ratio allowed a higher field to exist internally in the shield and thus caused the saturation effects to occur at this relatively low value. The saturation was also measured at 45° and perpendicular to the flux lines by setting the shield in place and then measuring the internal field. As a check on the data, the field was set at 30.0 to 80.0 gauss and held constant at 5.0 gauss intervals while the shield was rotated in the field and the measurements were taken parallel to at 22.5°, 45°, 67.5°, and perpendicular to the flux lines. Both sets of measurements were taken with both the axial and transverse probes and summed in quadrature using:

$$B_{total} = \sqrt{(B_{axial})^2 + (B_{transverse})^2}$$

The B field seems to be dependent on the square of the sin of the angle measured from the perpendicular to the flux lines.

7 32P80 Shield

When the testing of the 32P80 shield was begun, the shield was set into a foam template which kept it from rotating. It provided support for the cylinder and kept the seam aligned in the same position at all times. There appeared to be no difference in the field on the side where the seam existed and the opposite side. An internal template of polyurethane was constructed which allowed the field to be measured across the interior at units of 0.25 radii. The template allowed the probe to slide into position and be manipulated to the same position for each measurement. A holder was also constructed to keep the probe in the proper position when it was inside the shield.

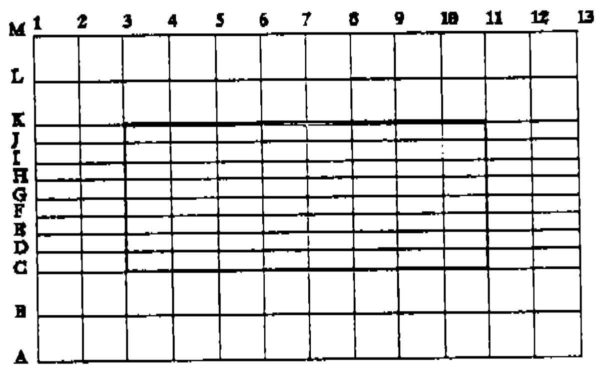


Figure 1

Figure 1 shows the configuration of the template. Measurements were taken at the intersections of the numbered and lettered lines. Letters A, B, & C, and K, L, & M were each one inch apart and outside the shield, shown with a darker line. Lines C, D, E, F, G, H, I, J & K were 0.25 radii apart, or 0.41 inches apart. The numbered lines were all one inch apart. This provided a map over an area 7.25 inches wide and 12.0 inches long.

Since the template was in a nearly constant field, the measurements were made in a single plane. This required the axial and transverse probes to measure the field only in two directions. The symmetry of the shield provided a means to require measurements only in two dimensions. The small variations in the field were not taken into account when plotting the fields around the shield. The fields were measured with the axis of the shield parallel to, perpendicular to, and at 45° to the flux lines formed by the Helmholtz Coils. The two measurements were summed in quadrature.

8 Overlapping Shields

In addition to testing the single 32P80 shield, tests were completed with the 35P70 shield overlapping the 32P80 shield. The first tests varied the overlap from 3 inches to 7 inches. A new template was constructed from the same foam material. *Figure 2* shows the template. This template used the same 1 inch divisions along the numbered edge. Between A, B & C and G, H & I the spacing is 1 inch. The inside measurements from C, D, E. F & G are ½ the radius or 0.81 inches. Shields were kept separated by using the foam packing material which came with the shields.

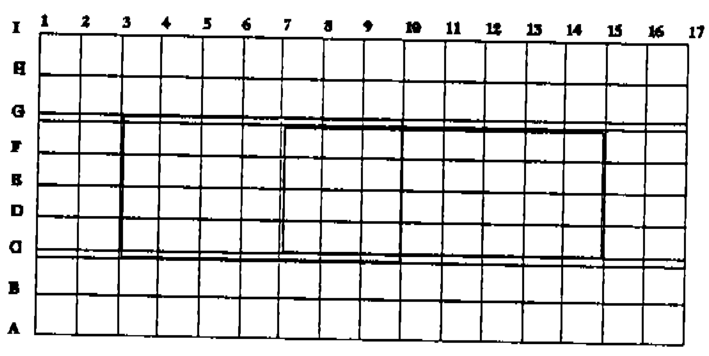


Figure 2

9 Flat Plates

To determine the effect of a flat μ metal plate in a constant magnetic field, a 6 inch by 6 inch plate was placed inside the box on the Helmholtz coil. The field inside the box was closer to constant in all directions. Two directions were tested: having the plate parallel to the flux lines and having the plate perpendicular to the flux lines. To avoid the effects of heating in the coils, the B-field was kept at 20.0 gauss. The points measured were located every inch over an 8 inch by 8 inch region with the plate set at the center.

While the plate was parallel to the flux lines, the edges were kept parallel and perpendicular to the flux lines. The B-field converged on the perpendicular edges and the field at the surface decreased in the central region of the plate. On the north and south edges, the field reached 257 gauss and remained at a value of 135 gauss or higher. The field was drawn into the plate at the north and south edge. The central 4 inches of the plate was lower than the external field. *Figure 30* shows the field at the plate's surface.

When the plate was set perpendicular to the flux lines, there was no large increase measured at the edges. The field over the surface remained very close to the 20 gauss external field over the entire surface of the plate. There was difficulty keeping the plate in the same position durimg the measurements. This problem may have caused the non-symmetry in the plot of the field. There was no expectation for the small field at the edge of the plate. This effect is shown in *figure 31*.

10 Results

The shield becomes saturated at exterior fields ranging from 35 to 70 gauss. When the axis of the shield is parallel to the flux lines, saturation occurs at 35 gauss and at 70 gauss when the axis is perpendicular to the flux lines. There seems to be a direct dependence with the square of the sine of the angle measured from the perpendicular to the flux lines.

At 10.0 gauss, the central 2.0 inches of the shield remained below 0.6 gauss when the field was parallel to the flux lines. This value should be acceptable since the cross-product of the B field and the velocity of the electron between the dynodes of the PMT is close to zero. When the shield was at a 45° angle to the flux lines, the central 2.0 inches remained below 0.6 gauss. The central 2.0 inches of the shield in a 30.0 gauss field remained below 0.45 gauss.

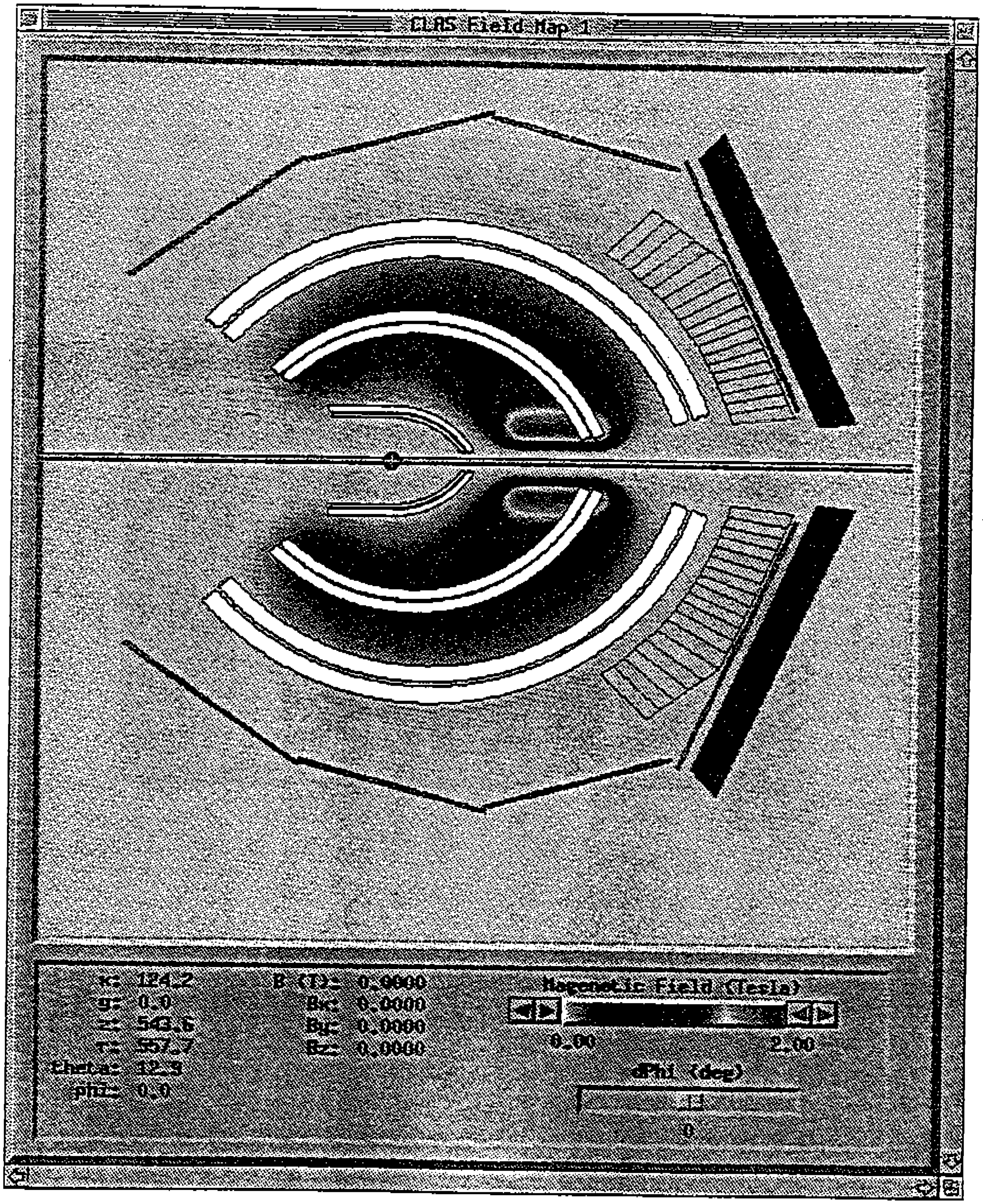
At 30.0 gauss, the central 2.0 inches of the shield remained below 1.4 gauss when the field was parallel to the flux lines. About 2.5 inches of the central portion of the shield remained below 1.4 gauss when the shield was 45° to the flux lines. When the shield was perpendicular to the shield, the central 4.0 inches remained below 0.5 gauss. Since the majority of the PMTs will be placed so they are nearly perpendicular to the flux lines, the most important measurements are those perpendicular to the flux lines. Also, the PMTs can be arranged so the dynodes can provide additional protection for the moving electrons. This may be accomplished by aligning the exterior surface of the dynodes, perpendicular to the flux lines.

Plots of the B-field for 10.0 gauss are shown in *figures 14, 15 and 16*. For the 20.0 gauss field, *figures 17, 18 and 19* display the results. *Figures 20, 21 and 22* show how the field changes in a 30.0 gauss field.

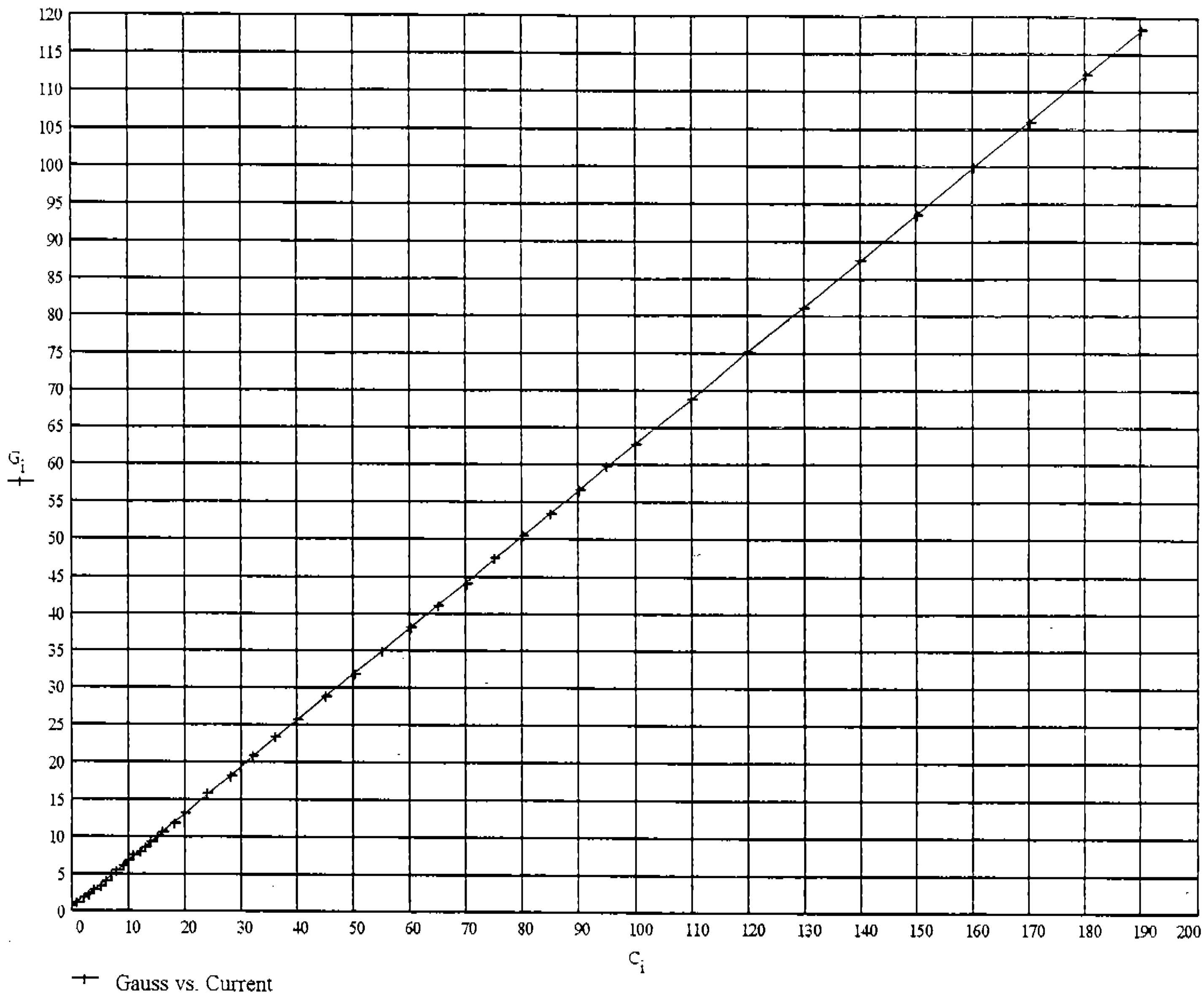
The interior region of the double shield is shown in *figures 23 through 25* while the axis of the shield is parallel to the flux lines for overlaps of 3, 4, and 5 inches in an exterior field of 30.0 gauss. *Figures 26a, 26b and 26c* show the interior B-field with a 6 inch overlap with the shield axis parallel to, at 45°, and perpendicular to the flux lines in an exterior field of 30.0 gauss. *Figures 27a, 27b and 27c* show the interior B-field with a 7 inch overlap with the shield axis parallel to, at 45°, and perpendicular to the flux lines in an exterior field of 30.0 gauss.

In an exterior B-field of 20.0 gauss, *figures 28a, 28b and 28c* show the interior B-field with the shield axis parallel to, at 45°, and perpendicular to the flux lines with a 6 inch overlap. For a 7 inch overlap, the interior B-field is shown in *figures 29a, 29b and 29c* for the shield axis parallel to, at 45°, and perpendicular to the flux lines.

Overall, the 6 and 7 inch overlaps performed the best. From the results of these studies, it appears that the best shielding is a double shield with the outer shield the same size or longer than the inner shield. Also, a 4:1 ratio of length to diameter of the shield would decrease the internal field, enlarging the protected region inside the shield.

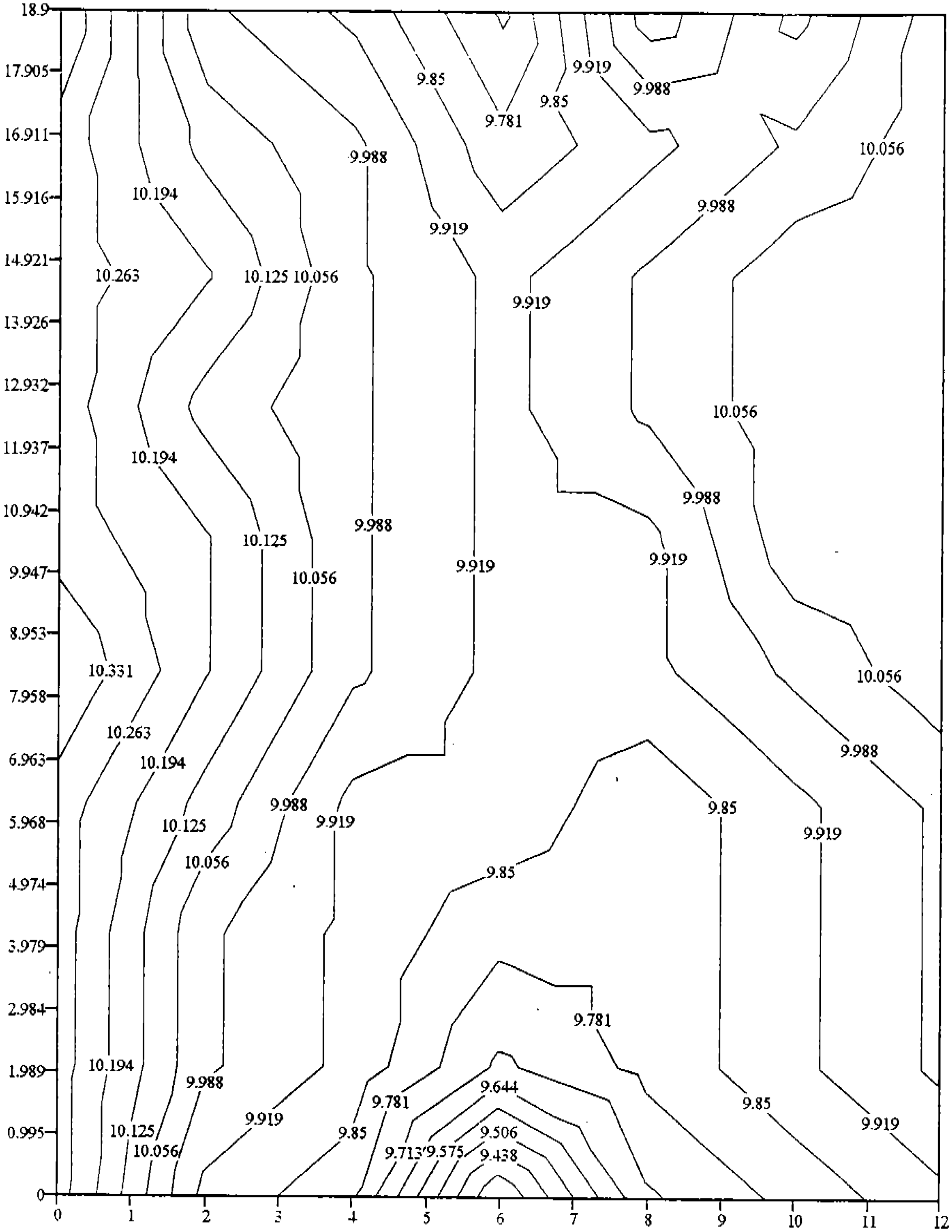

CLAS Field Map 1
y: 0.0
z: 543.6
r: 557.7
theta: 12.3
phi: 0.0
B (T): 0.0000
Bx: 0.0000
By: 0.0000
Bz: 0.0000
Magnetic Field (Tesla)
0.00
2.00
dPhi (deg)
0

<u>*Figure 3*</u>



Plot shows the relationship between the current in the Helmholtz Coil and the magnetic field produced within the interior region.

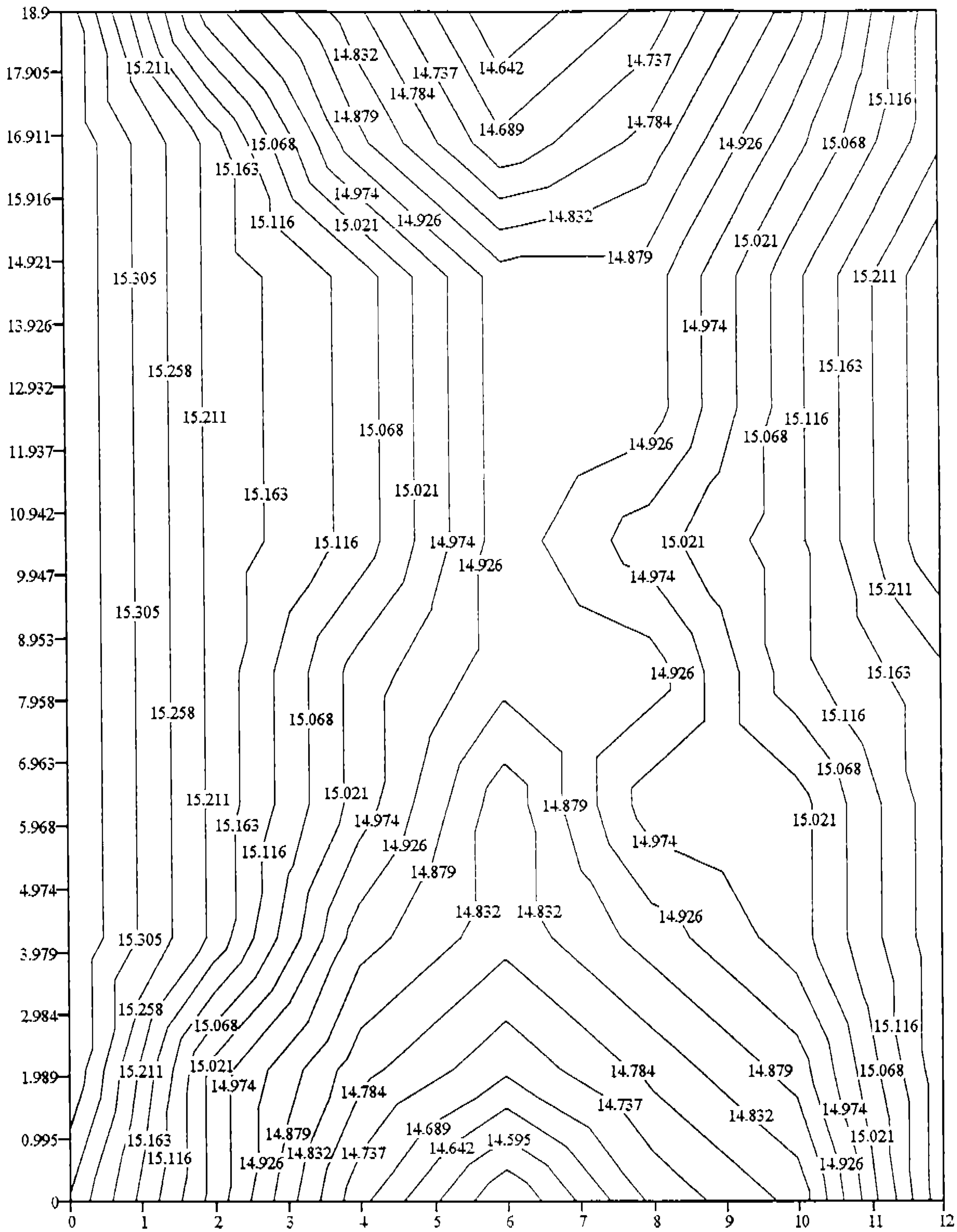
Figure 4



10.3	10.3	10.3	10.3	10.4	10.3	10.3	10.3	10.3	10.4
9.9	10	10	10.1	10.2	10.2	10.1	10.2	10.1	10
9.8	9.9	9.9	9.9	10	10	10	10	10	9.9
9.3	9.7	9.8	9.9	9.9	9.9	9.9	9.9	9.8	9.7
9.7	9.8	9.8	9.8	9.9	9.9	10	10	9.9	10.1
9.8	9.9	9.9	9.9	10	10.1	10.1	10.1	10	9.9
9.9	10	10	10	10.1	10.1	10.1	10.1	10.1	10.1

10.0 Gauss Field

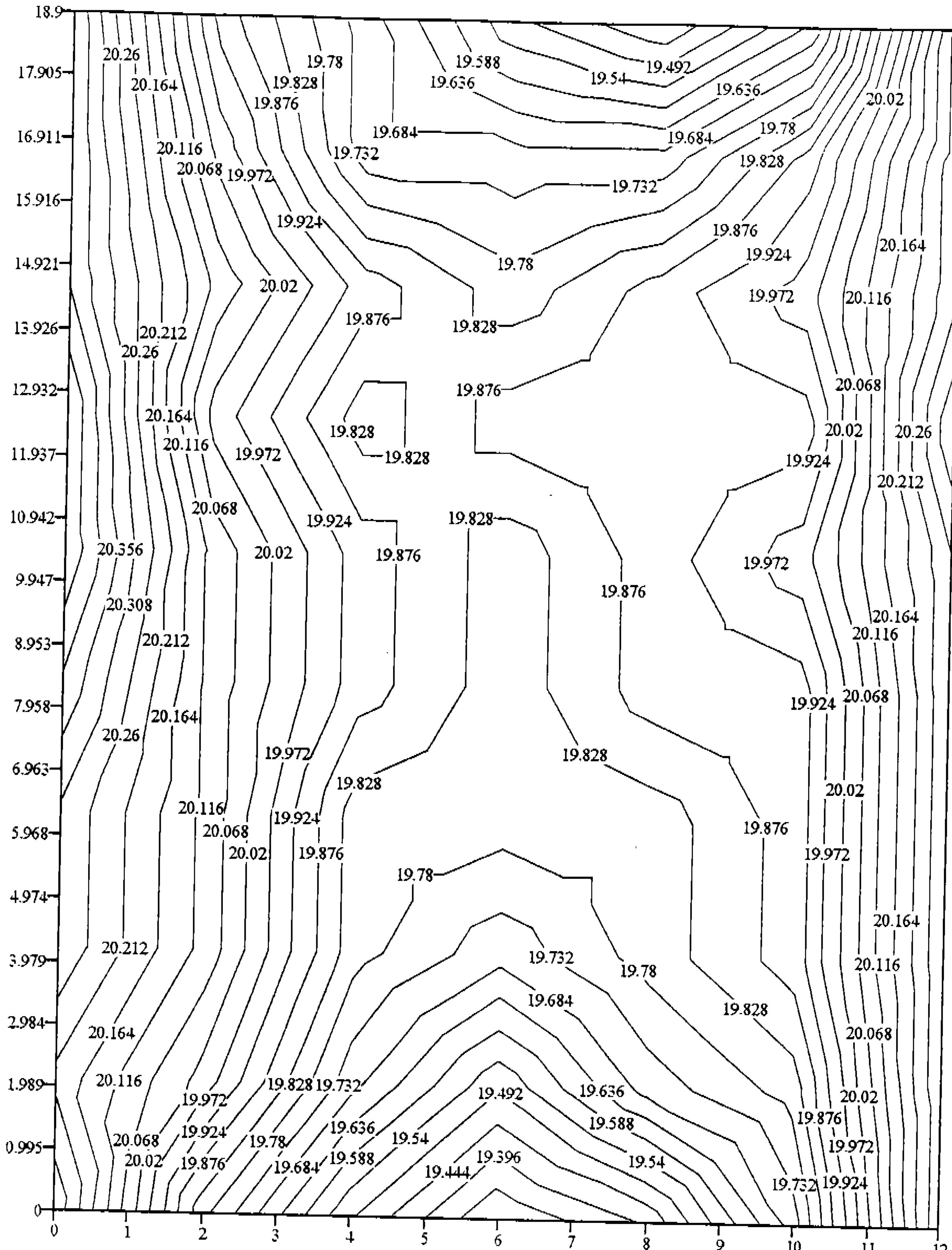
Figure 5



15.3	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
15.0	15.0	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.0
14.7	14.8	14.9	15.0	15.0	15.1	15.1	15.1	14.9	14.8
14.5	14.7	14.8	14.8	14.9	14.9	14.9	14.9	14.7	14.6
14.7	14.8	14.9	15.0	14.9	15.0	14.9	14.9	14.8	14.7
14.8	14.9	15.0	15.0	15.1	15.1	15.1	15.1	15.0	14.9
15.2	15.2	15.2	15.2	15.2	15.3	15.3	15.3	15.2	15.2

15.0 Gauss Field

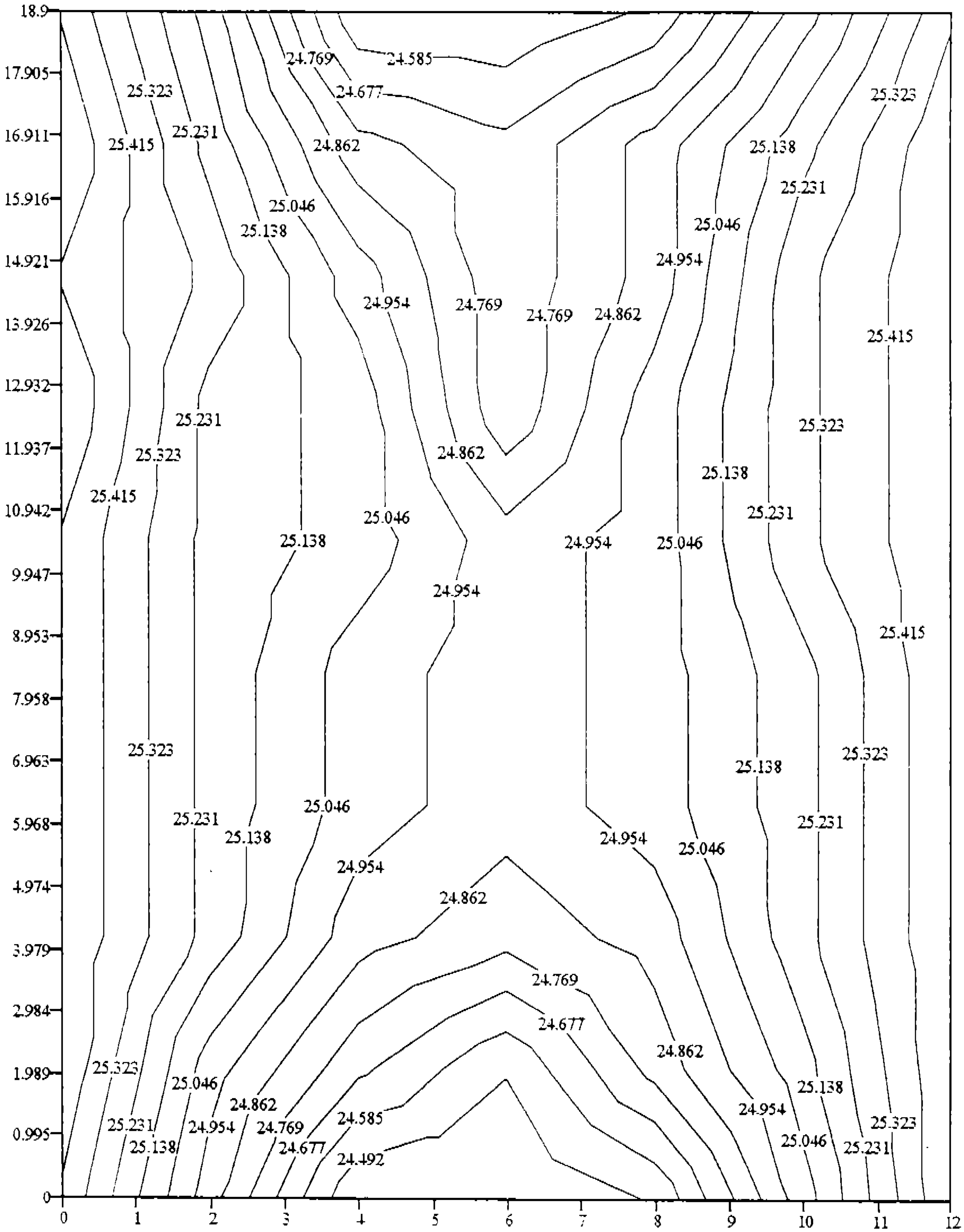
Figure 6



20.3	20.2	20.3	20.3	20.4	20.5	20.5	20.4	20.4	20.4
19.8	20.0	20.1	20.1	20.1	20.1	20.0	20.1	20.0	19.9
19.5	19.7	19.8	19.8	19.9	19.9	19.8	19.9	19.7	19.7
19.3	19.5	19.7	19.8	19.8	19.8	19.9	19.8	19.7	19.5
19.4	19.7	19.8	19.8	19.9	19.9	19.9	19.9	19.7	19.4
19.7	19.8	19.9	19.9	19.9	20.0	19.9	20.0	19.9	19.6
20.3	20.3	20.3	20.3	20.3	20.3	20.4	20.3	20.3	20.3

20.0 Gauss Field

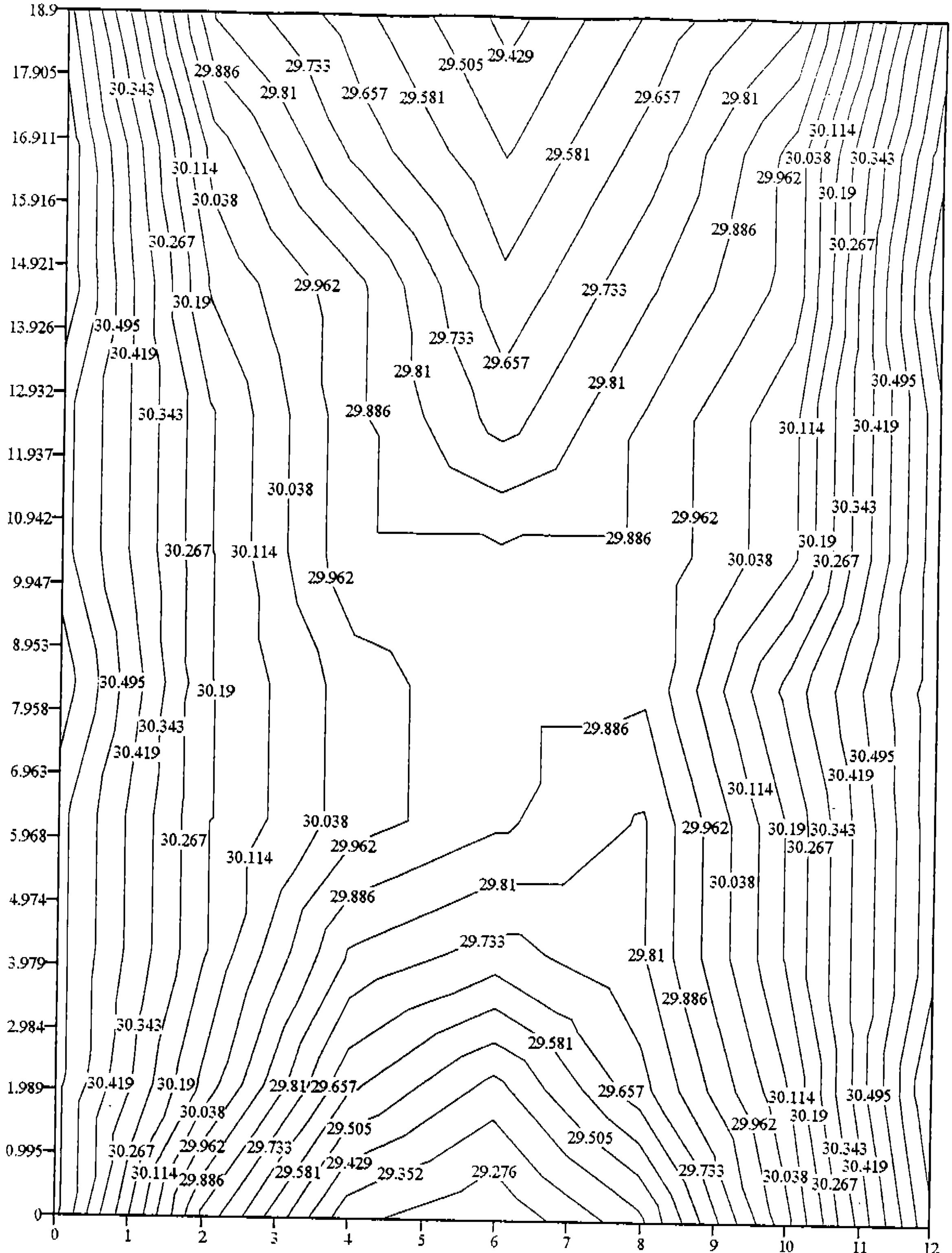
Figure 7



25.4	25.5	25.5	25.5	25.5	25.5	25.6	25.5	25.6	25.5
24.9	25.0	25.2	25.2	25.2	25.2	25.2	25.3	25.2	25.1
24.4	24.7	24.9	25.0	25.0	25.1	25.1	25.0	24.8	24.5
24.4	24.5	24.8	24.9	24.9	24.9	24.7	24.7	24.7	24.5
24.5	24.8	24.9	25.0	25.0	25.0	25.0	24.9	24.9	24.6
25.0	25.1	25.2	25.2	25.2	25.3	25.3	25.3	25.2	25.0
25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.4

25.0 Gauss Field

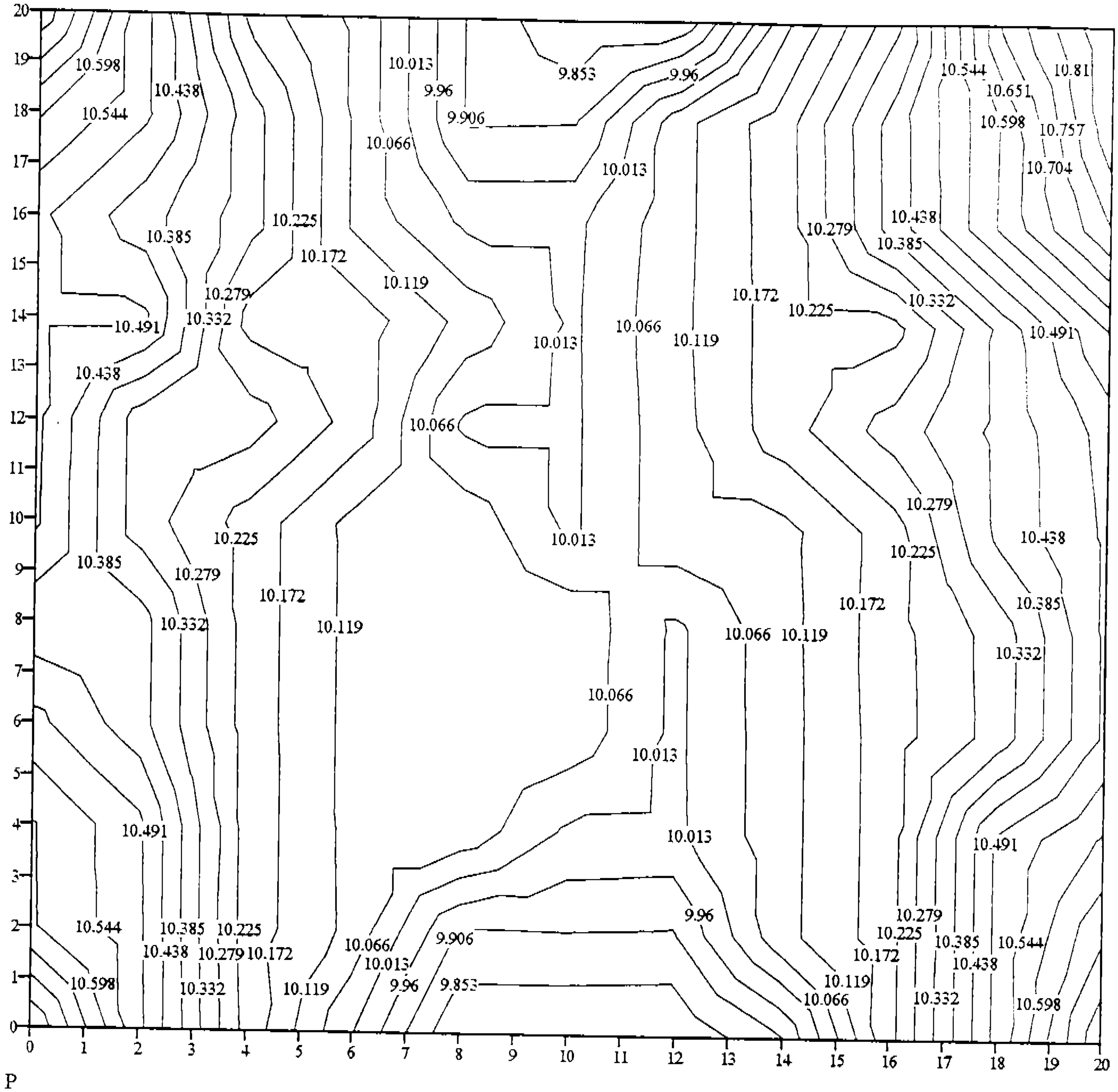
Figure 8



30.6	30.6	30.6	30.6	30.7	30.6	30.6	30.7	30.7	30.6
29.8	30.1	30.2	30.2	30.2	30.2	30.2	30.1	30.0	29.8
29.3	29.6	29.8	30.0	30.0	29.9	29.9	29.9	29.7	29.6
29.2	29.4	29.7	29.9	29.9	29.9	29.7	29.6	29.5	29.4
29.4	29.7	29.8	29.8	29.9	29.9	29.9	29.8	29.7	29.6
30.0	30.1	30.2	30.2	30.3	30.1	30.1	30.0	30.0	29.8
30.7	30.8	30.7	30.7	30.7	30.7	30.7	30.8	30.7	30.6

30.0 Gauss Field

Figure 9

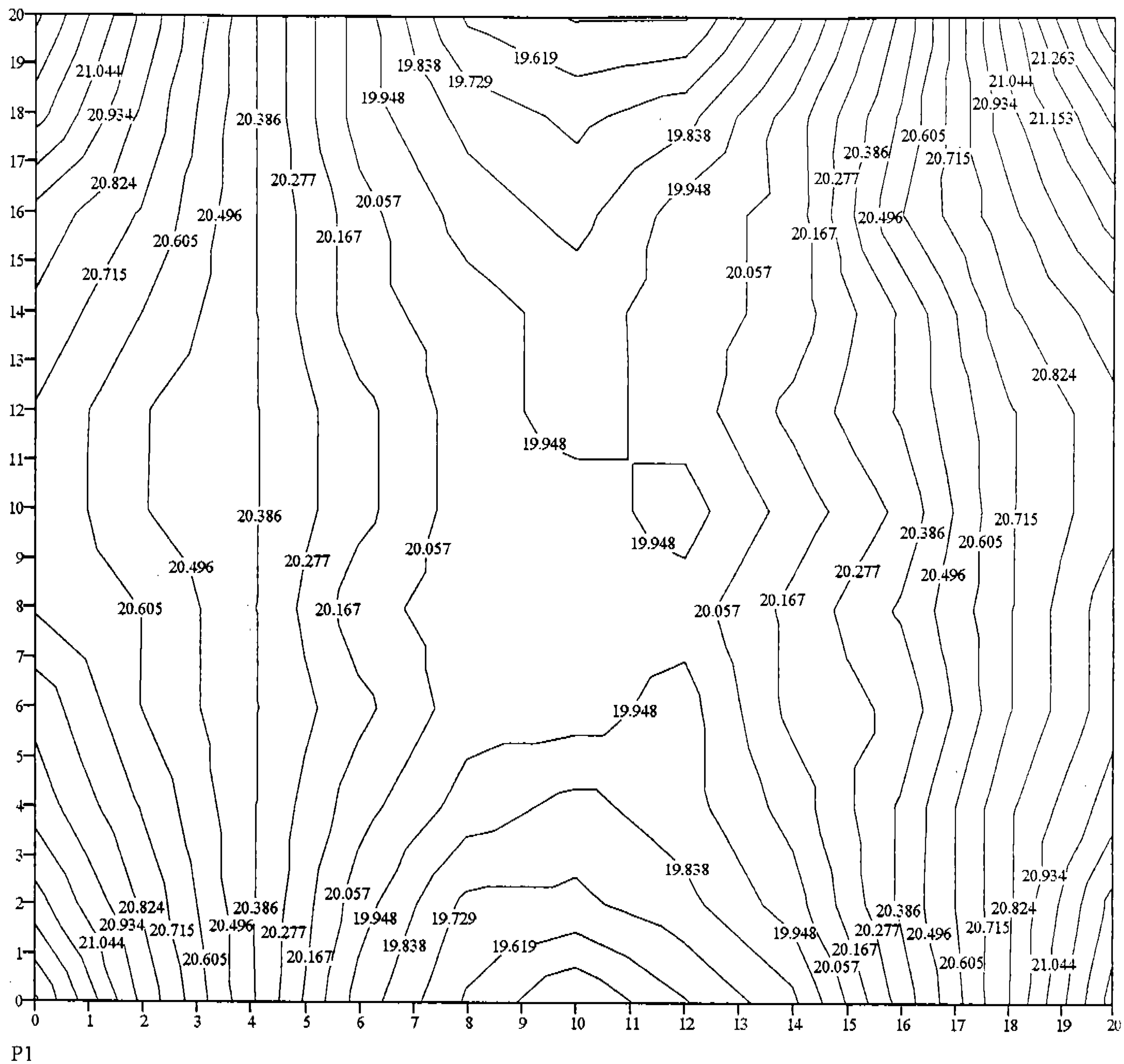


Plot of the 20.0 inch by 20.0 inch surface used for the testing of the 32P80 mu metal shield.

The plot shows the variation when the center of the area was initially set to measure 10.0 Gauss.

No problems were recorded in the heating of the Helmholtz coils at this setting.

Figure 10

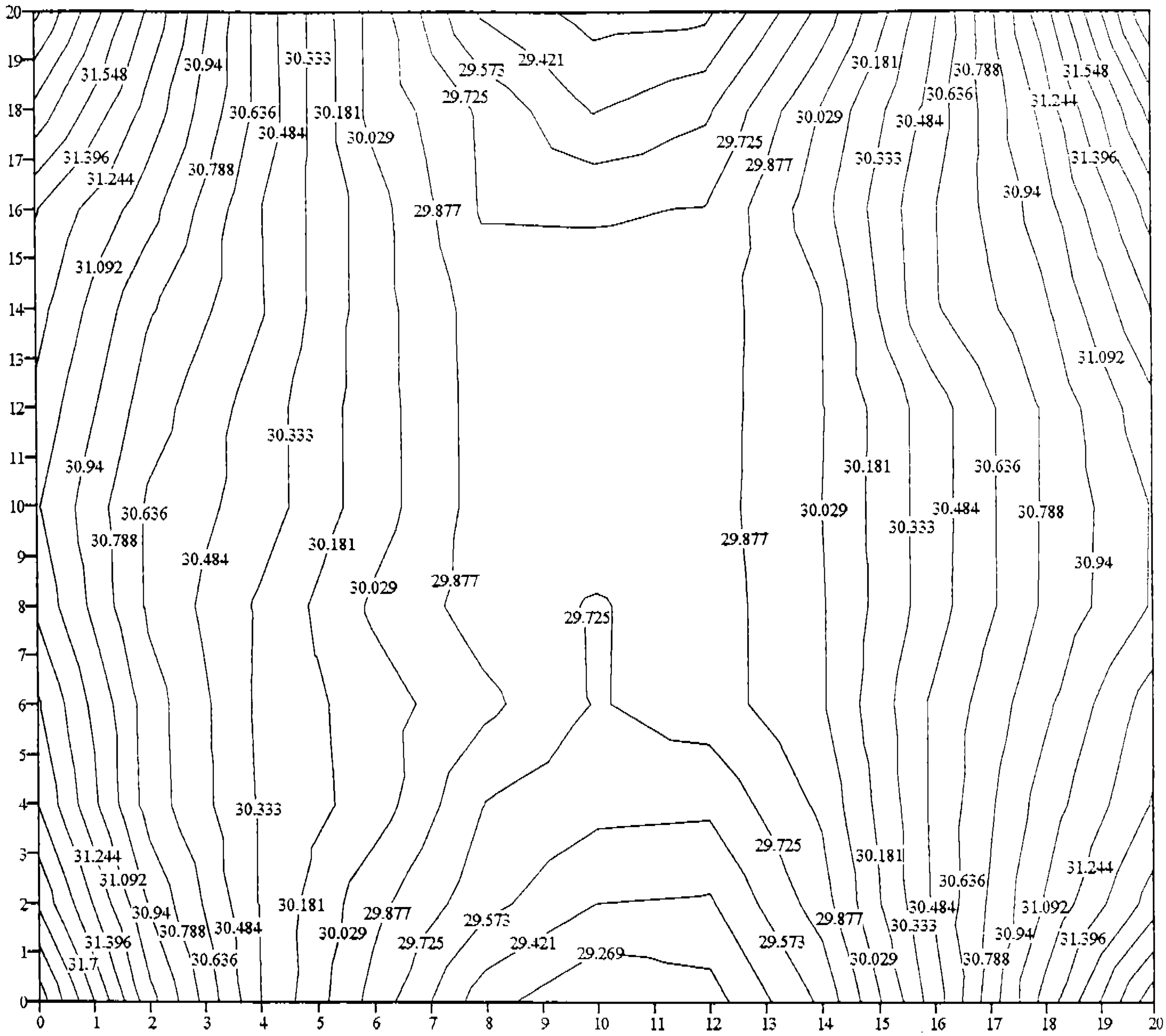


Plot of the 20.0 inch by 20.0 inch surface used for the testing of the 32P80 mu metal shield.

The plot shows the field variation when the center of the area was initially measured to be 20.0 Gauss.

Some heating of the Helmholtz coils was measured during the measurement of this setting. Over a period of an hour the coil was measured to rise in temperature approximately 5 degrees Celsius causing a degradation in the central field intensity of about 0.2 Gauss.

<u>Figure 11</u>



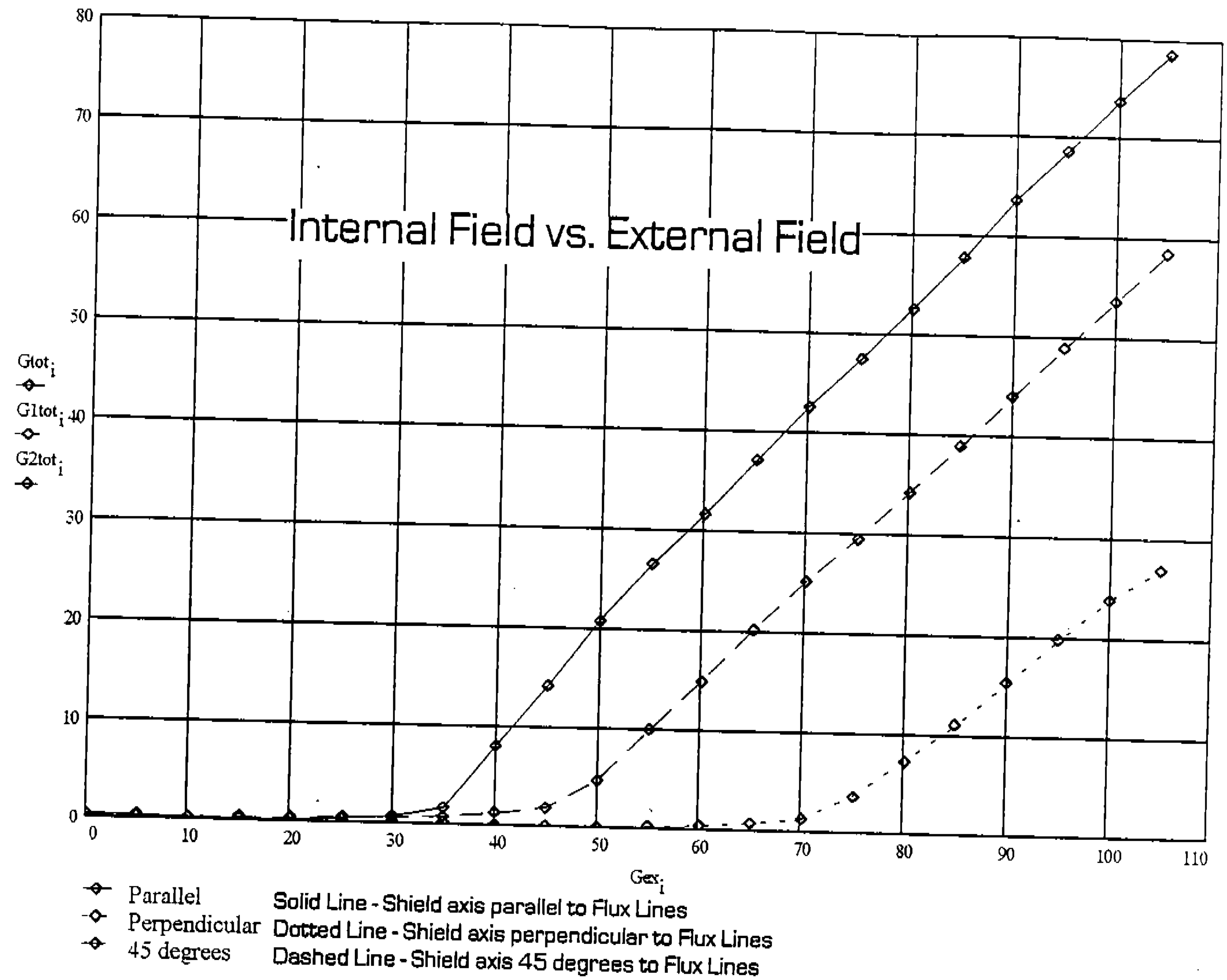
P2

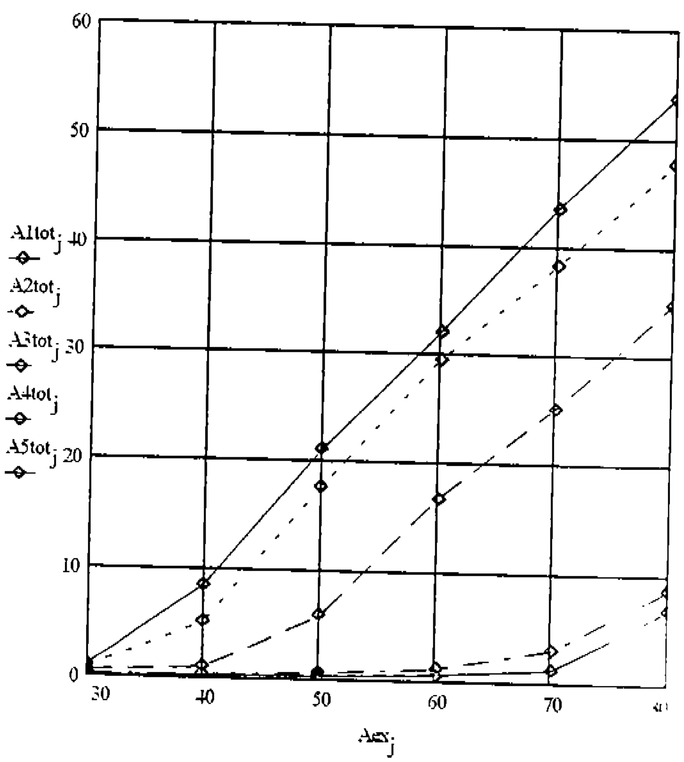
Plot of the 20.0 inch by 20.0 inch surface used for the testing of the 32P80 mu metal shield.

The plot shows the variation when the center of the area was initially set to measure 30.0 Gauss.

Heating of the Helmholtz coil was a problem. The field had to be readjusted during the measurements to maintain a constant external field. The temperature rise over the experiment was 7 degrees Celsius, which without adjustment would have caused the external field to drop 0.5 Gauss.

<u>Figure 12</u>



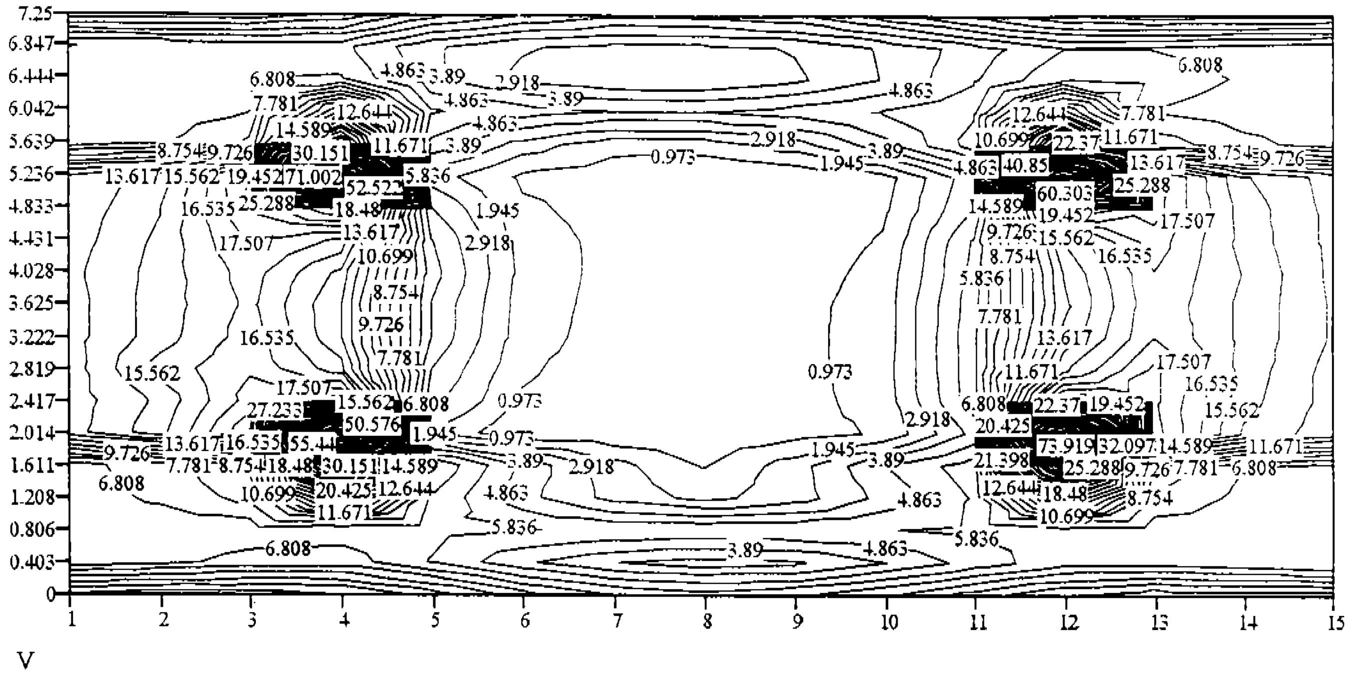


The Graph Above was Measured by Holding the Shield in place and Varying the Field

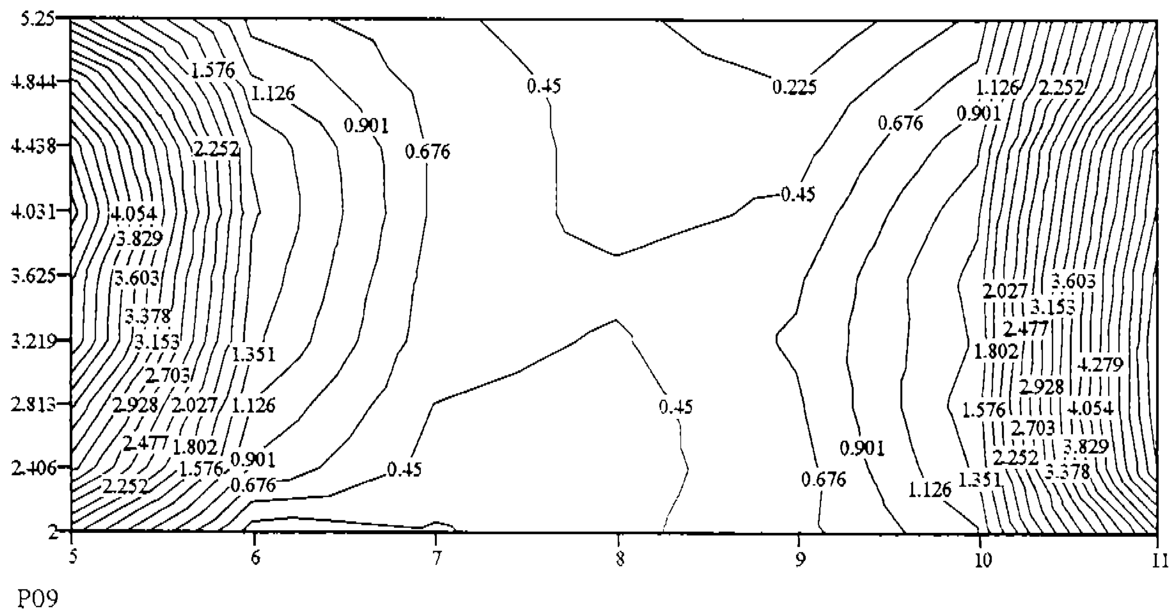
Graph at Left Depicts the Internal Field vs. the External Field Measured by Holding the Field Constant and Measuring the Field as the Shield was Rotated in the Field

Top - Parallel to Flux Lines
Second down - 22.5 degrees from Flux Lines
Third down - 45 degrees from Flux Lines
Fourth down - 67.5 degrees from Flux Lines
Bottom - Perpendicular to Flux Lines

Figure 13



View of the field in and around the shield. The axis of the shield is PARALLEL to the 10.0 Gauss field. The shield is located from (4,2) to (12,5.25).

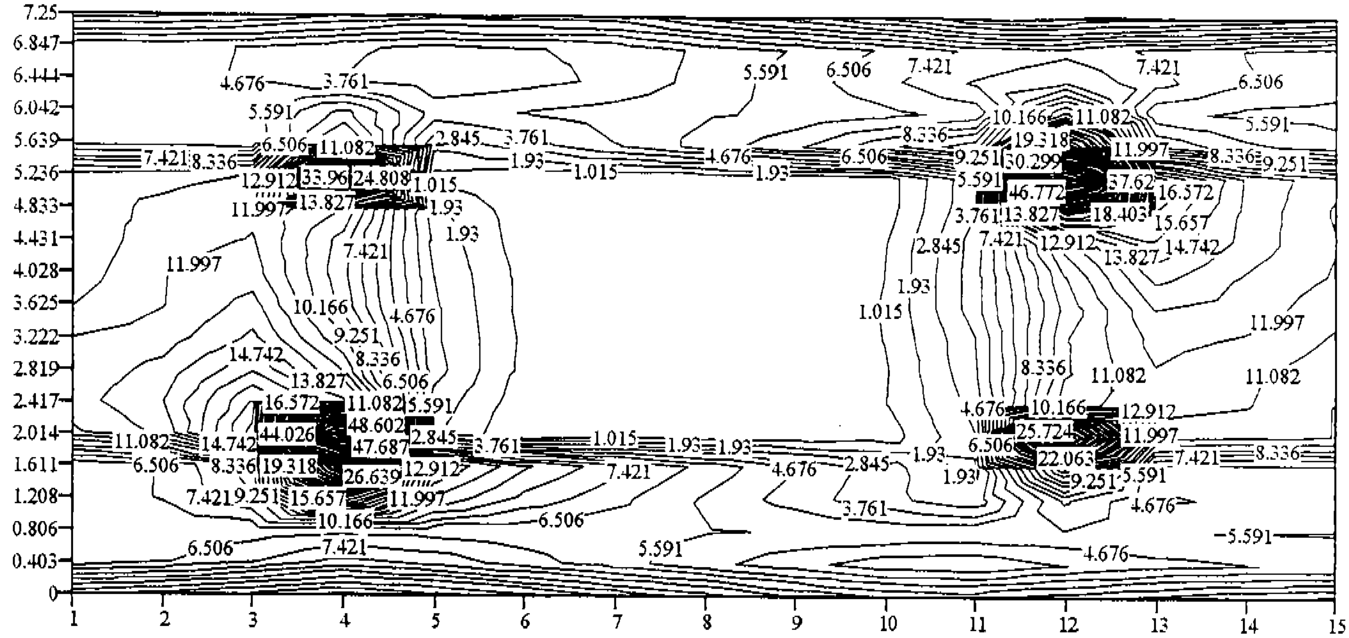


Enlargement of the interior of the shield at 10.0 Gauss.

Figure 14

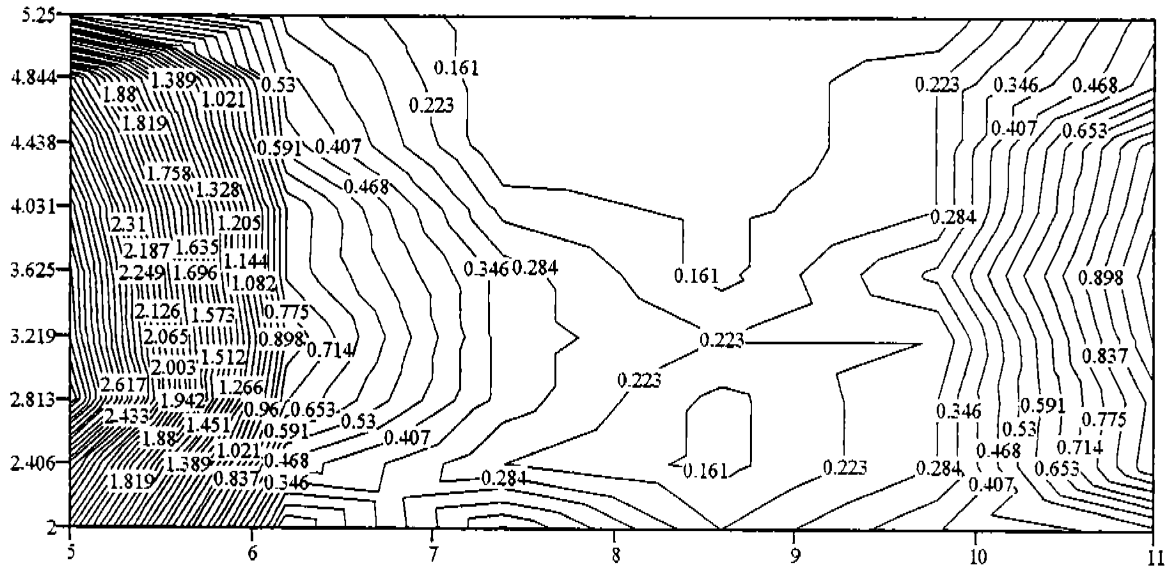
Axis of the shield is PARALLEL to the Flux Lines.

The region shows the central 6 inches of the shield.



V

View of the field in and around the shield. The axis of the shield is 45 degrees to the 10.0 Gauss field. The shield is located from (4,2) to (12,5.25).



P29

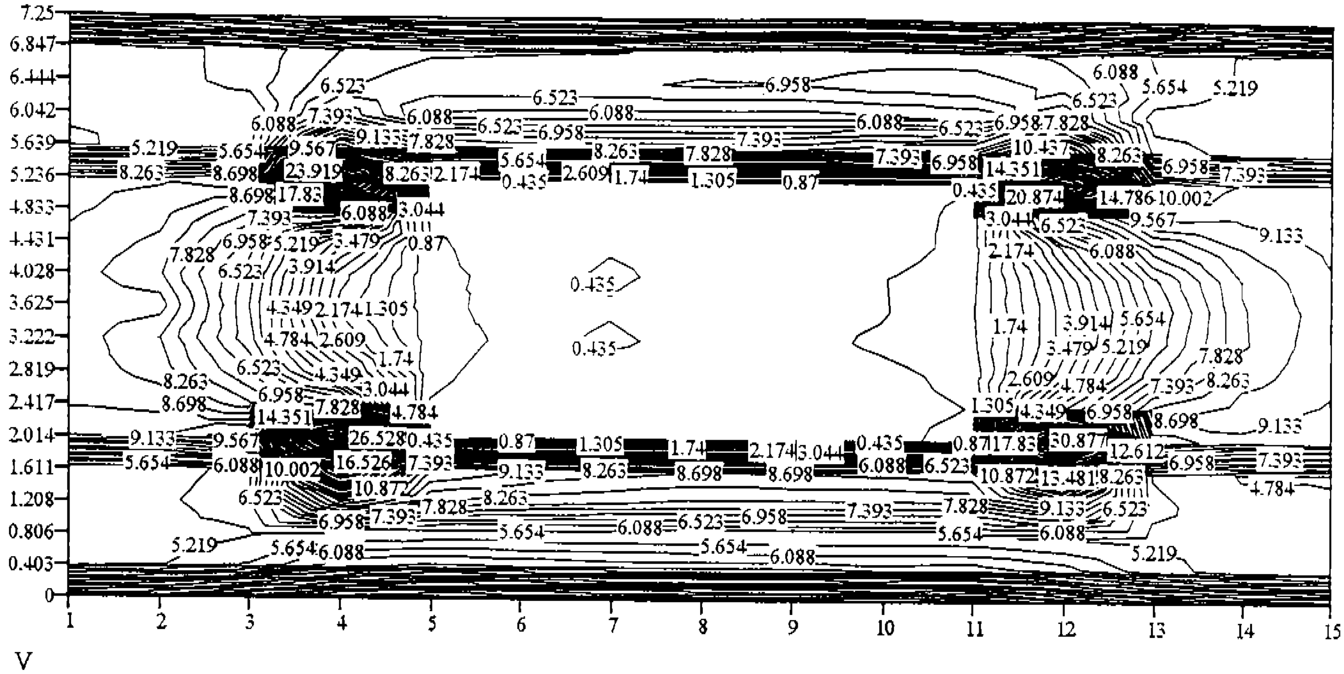
Enlargement of the interior of the shield at 10.0 Gauss.

Axis of the shield is 45 degrees to the Flux Lines

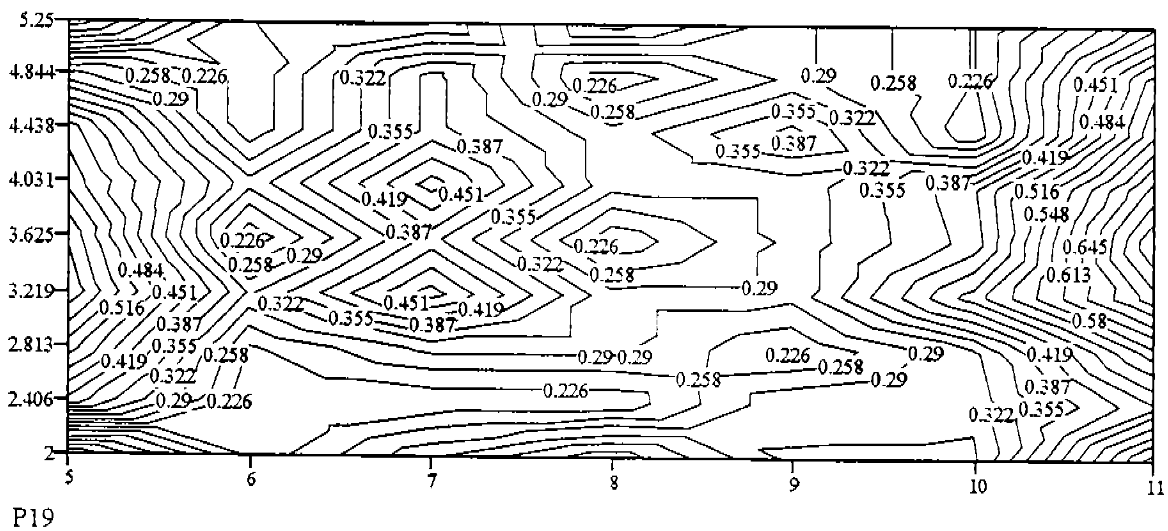
North East is to the left. South West is to the right.

The region shows the central 6 inches of the shield.

Figure 15



View of the field in and around the shield. The axis of the shield is PERPENDICULAR to the 10.0 Gauss field. The shield is located from (4,2) to (12,5.25).

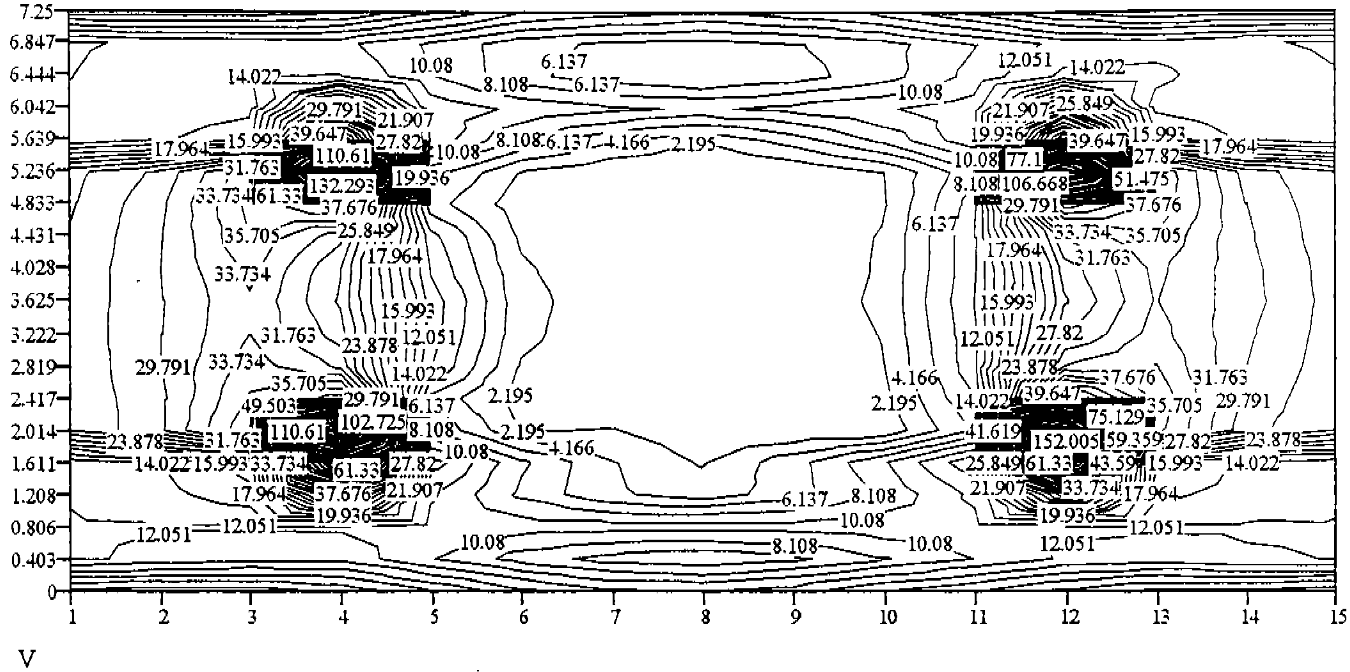


Enlargement of the interior of the shield at 10.0 Gauss.

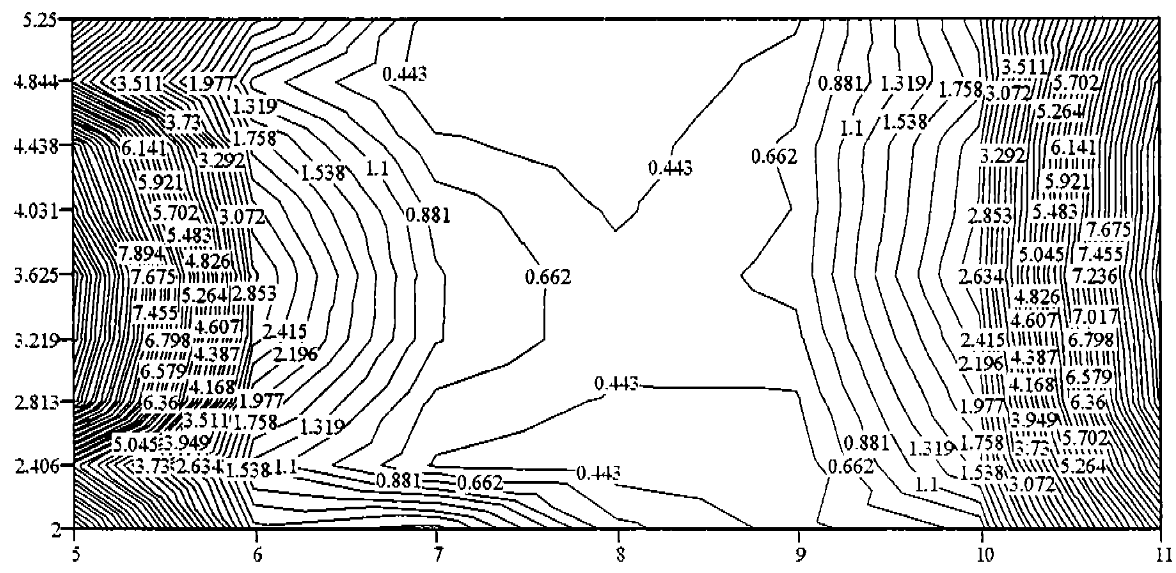
Figure 16

Axis of the shield is PERPENDICULAR to the Flux Lines.

The region shows the central 6 inches of the shield.



View of the field in and around the shield. The axis of the shield is PARALLEL to the 20.0 Gauss field. The shield is located from (4,2) to (12,5.25).

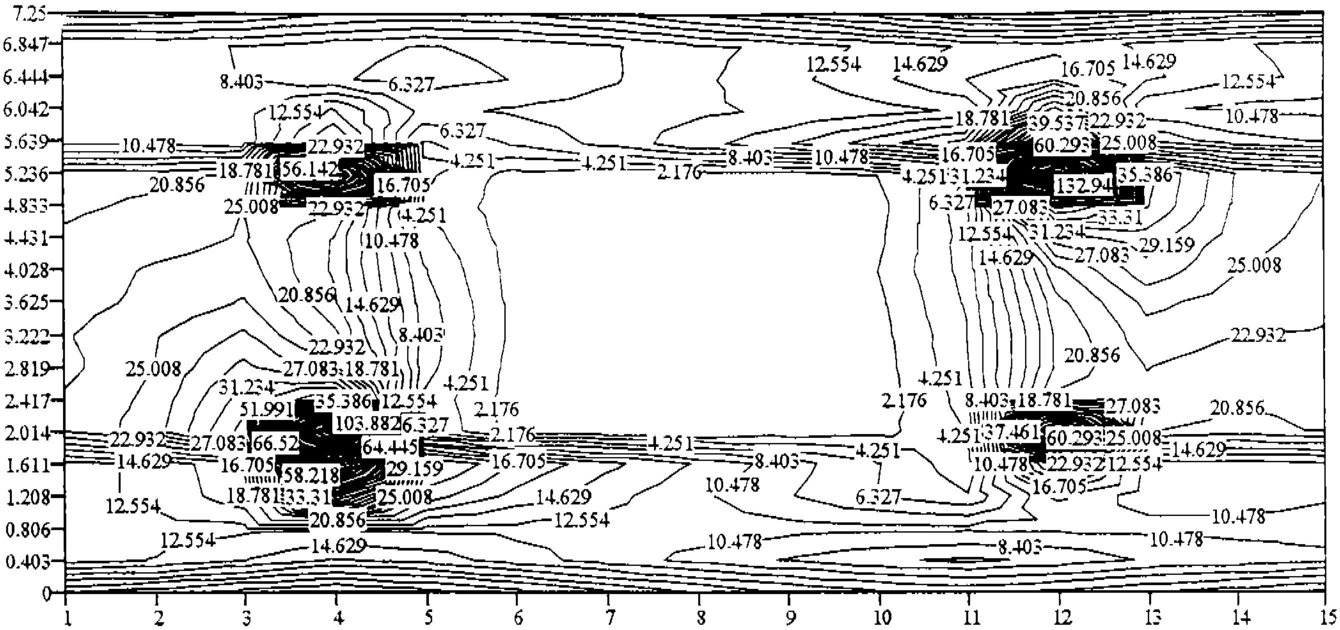


Enlargement of the interior of the shield at 20.0 Gauss.

Figure 17

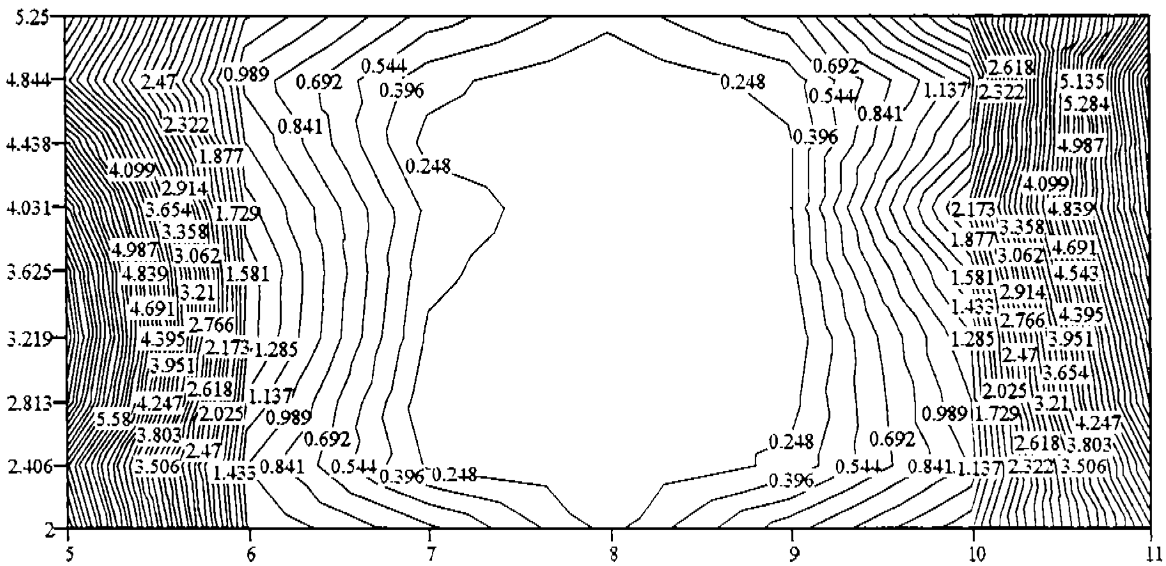
Axis of the shield is PARALLEL to the Flux Lines.

The region shows the central 6 inches of the shield.



V

View of the field in and around the shield. The axis of the shield is 45 degrees to the 20.0 Gauss field. The shield is located from (4,2) to (12,5.25).



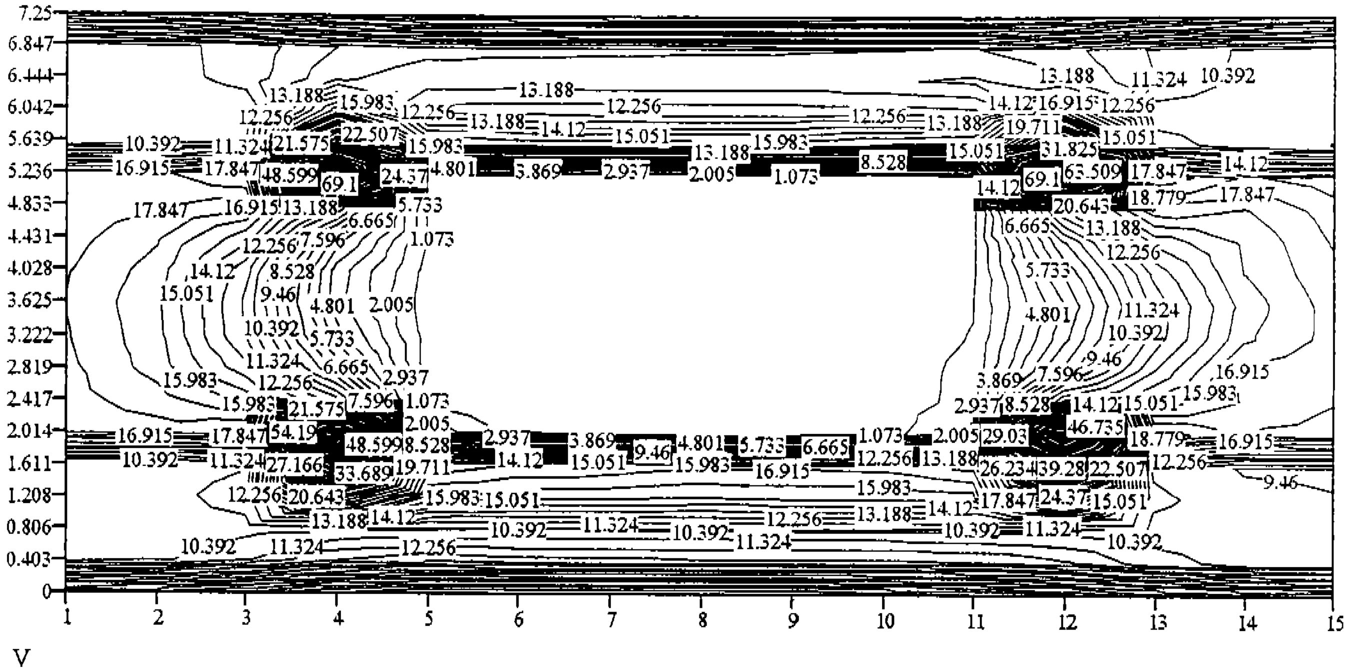
P39

Enlargement of the interior of the shield at 20.0 Gauss.

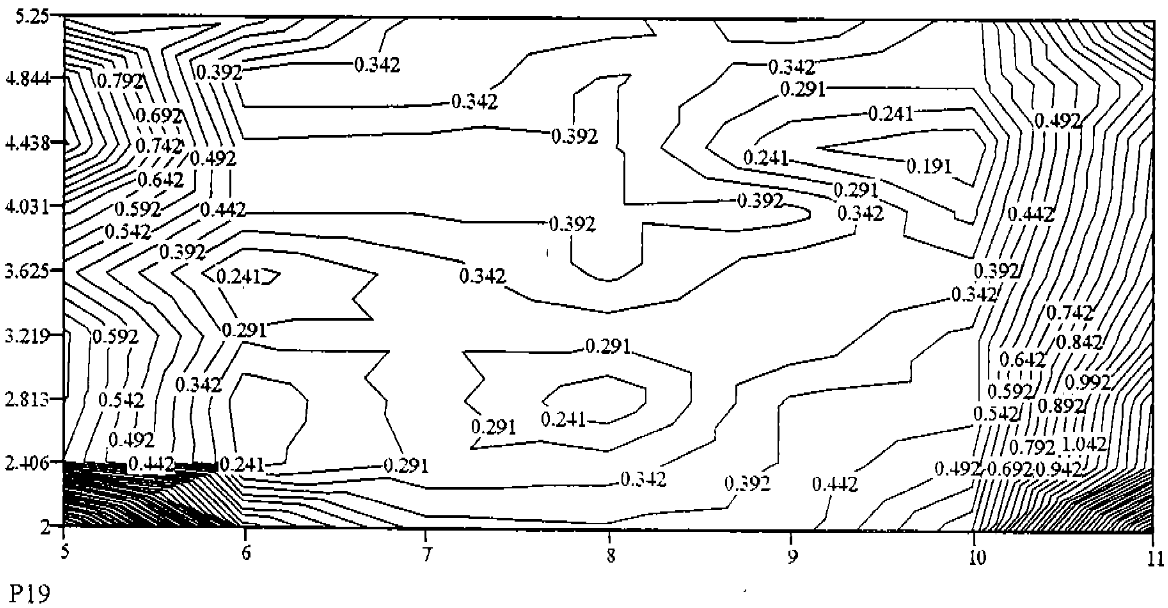
Figure 18

Axis of the shield is 45 degrees to the Flux Lines.

The region shows the central 6 inches of the shield.



View of the field in and around the shield. The axis of the shield is PERPENDICULAR to the 20.0 Gauss field. The shield is located from (4,2) to (12,5.25).

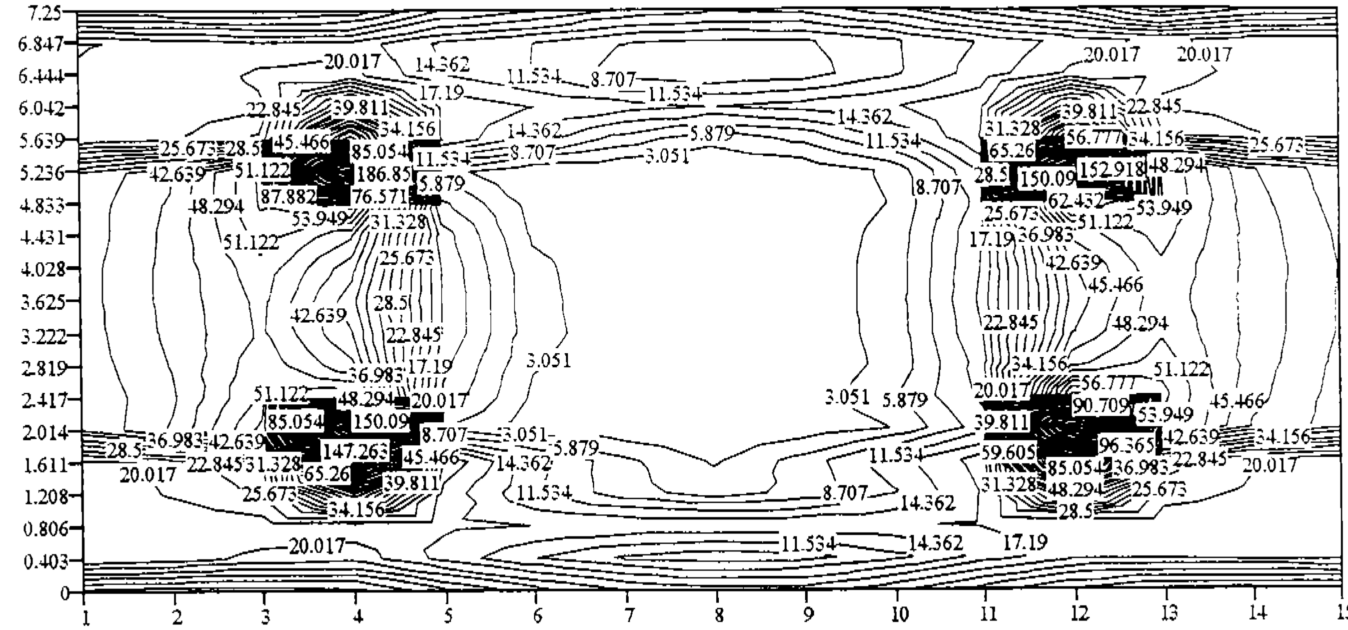


Enlargement of the interior of the shield at 20.0 Gauss.

Figure 19

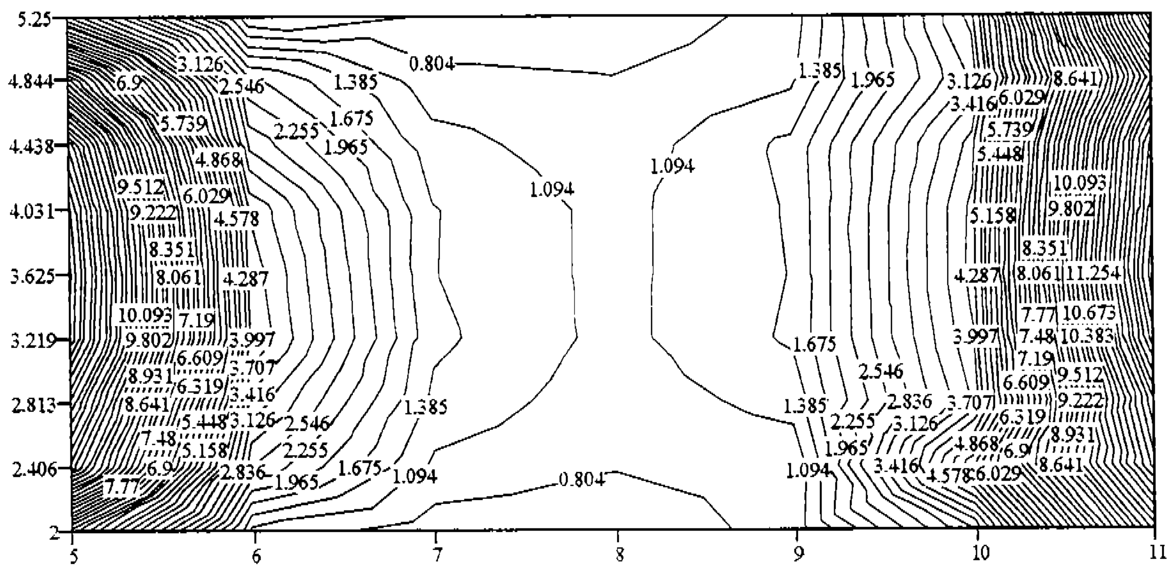
Axis of the shield is PERPENDICULAR to the Flux Lines.

The region shows the central 6 inches of the shield.



V

View of the field in and around the Shield. The axis of the shield is PARALLEL to the 30.0 Gauss field. The shield is located from (4,2) to (12,5.25).



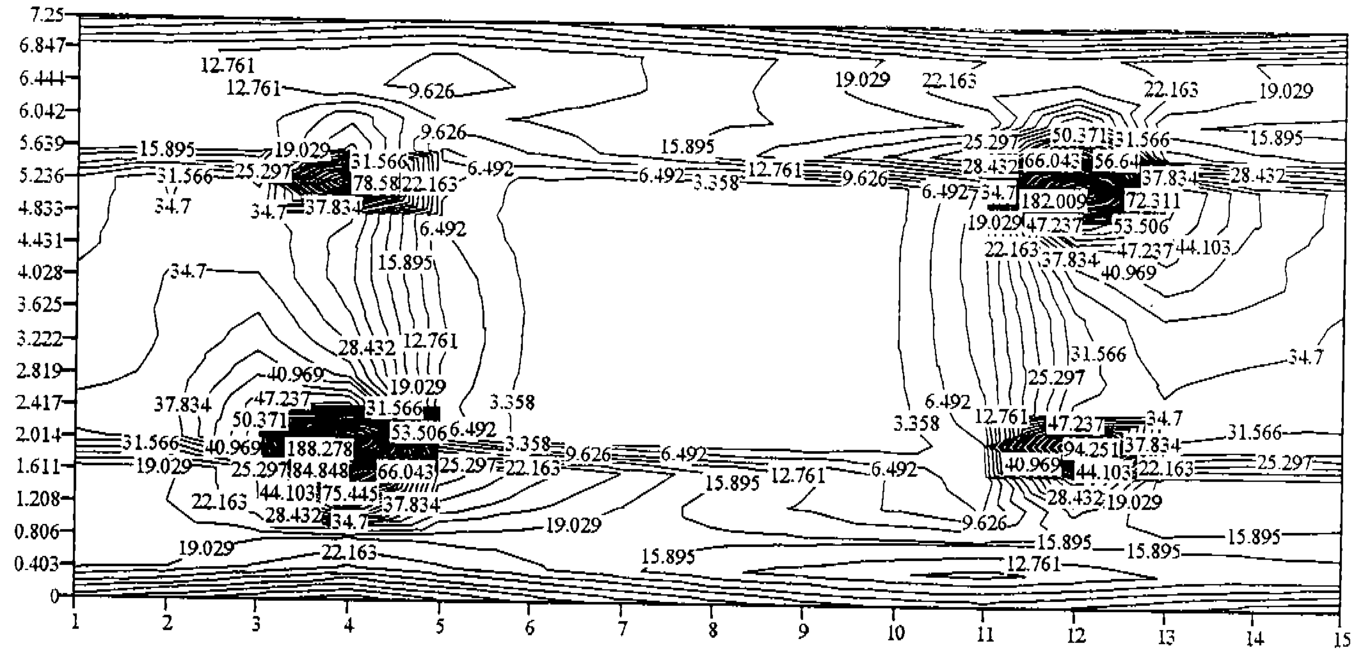
P39

Enlargement of the interior of the shield at 30.0 Gauss.

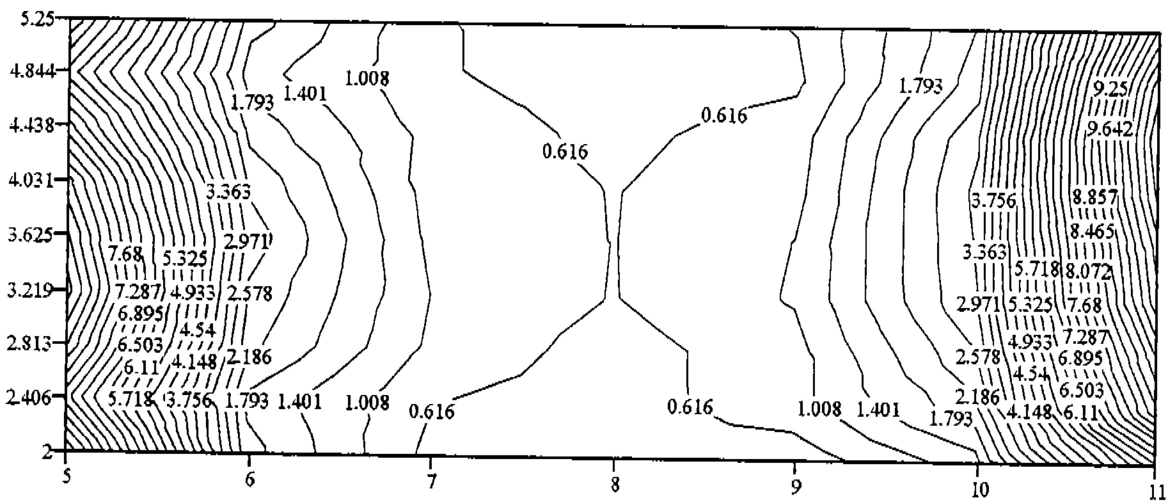
Axis of the shield is PARALLEL to the Flux Lines.

The region shows the central 6 inches of the shield.

Figure 20



View of the field in and around the Shield. The axis of the shield is 45 degrees to the 30.0 Gauss field. The shield is located from (4,2) to (12,5.25).



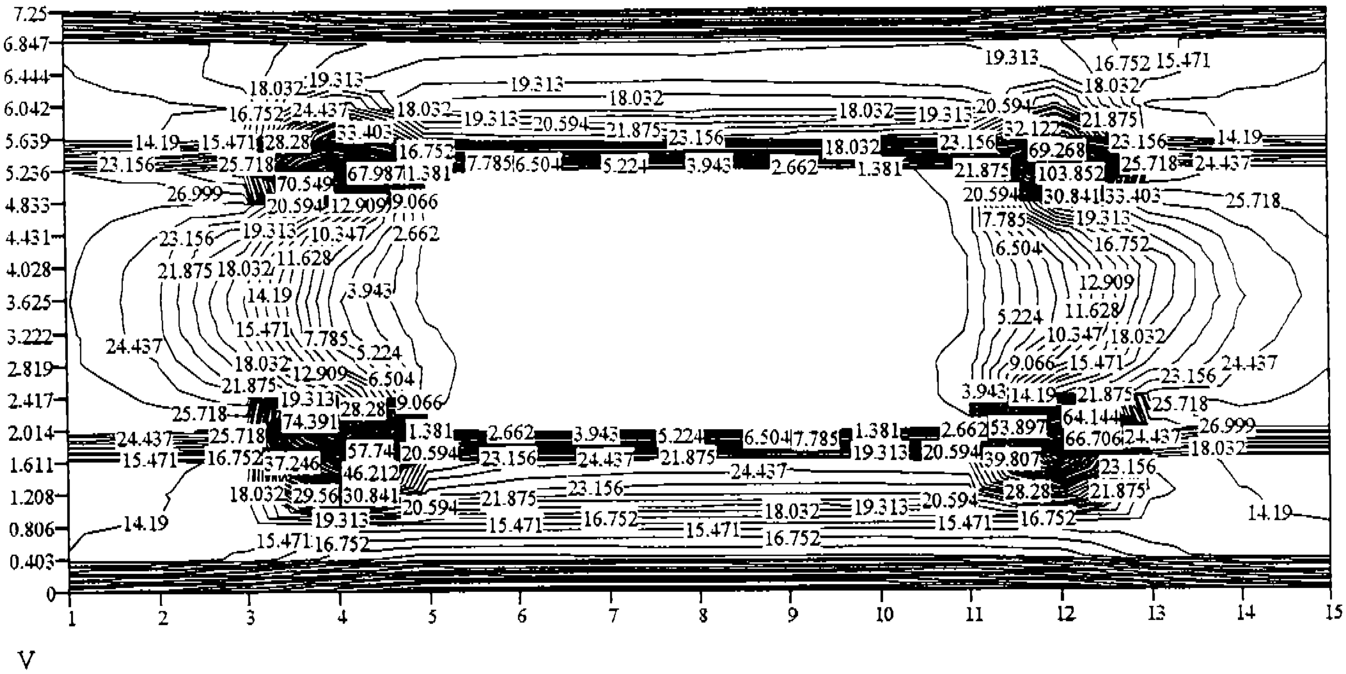
Enlargment of the interior of the shield at 30.0 Gauss.

Axis of the shield is 45 degrees to the Flux Lines.

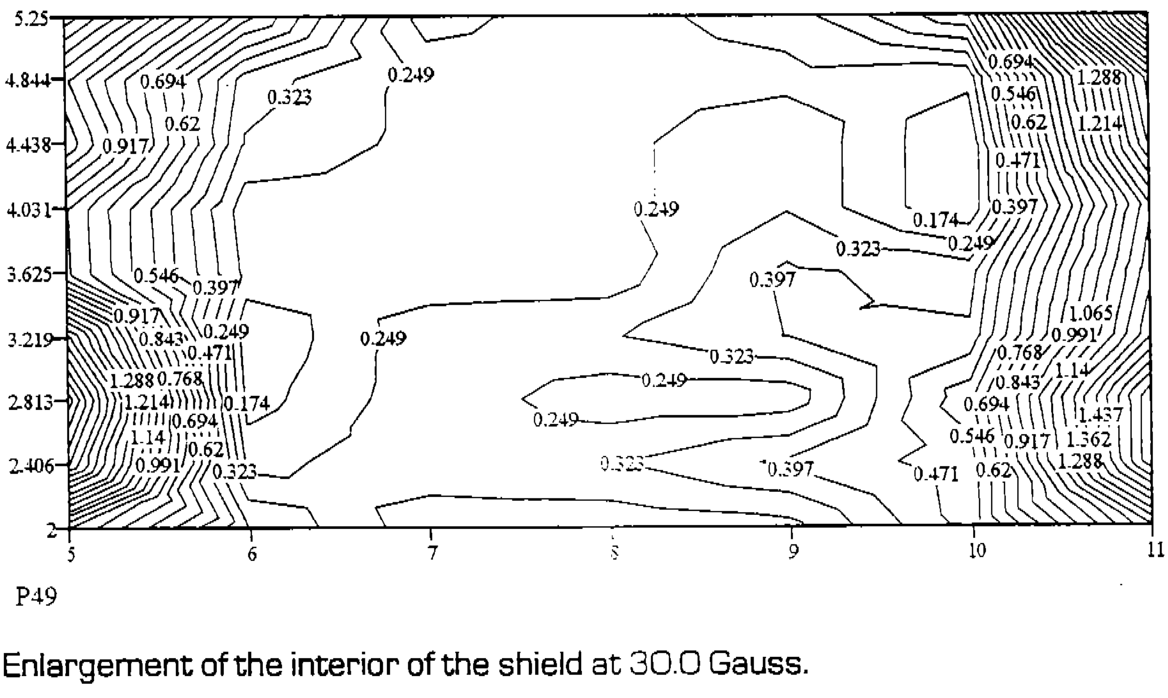
Figure 21

North East is to the Left. South West is to the Right.

The region shows the central 6 inches inside the shield.



View of the field in and around the shield. The axis of the shield is PERPENDICULAR to the 30.0 Gauss field. The shield is located from (4,2) to (12,5.25).

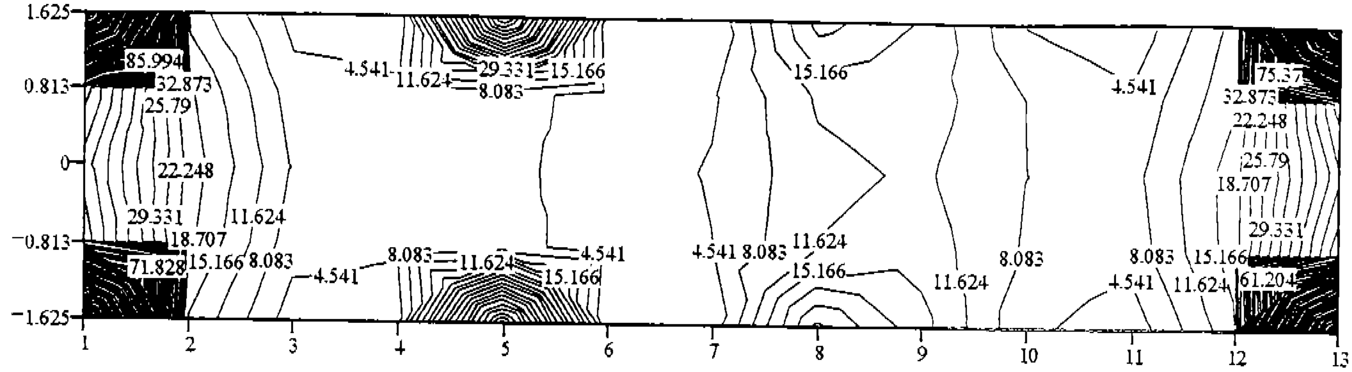


Enlargement of the interior of the shield at 30.0 Gauss.

Axis of the shield is PERPENDICULAR to the Flux Lines.

Figure 22

The region shows the central 6 inches of the shield.

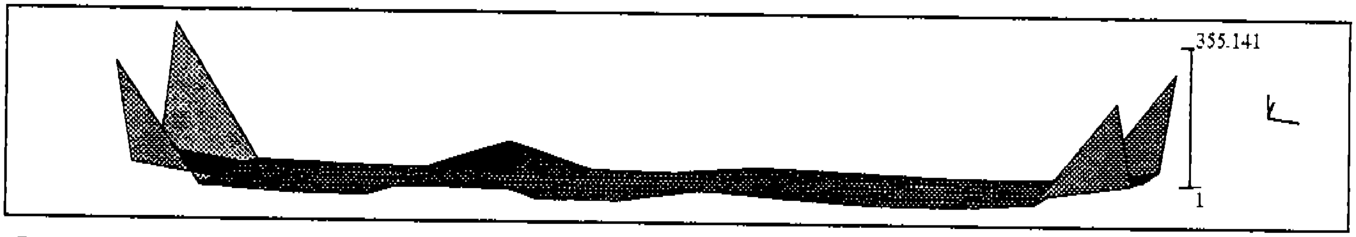


P

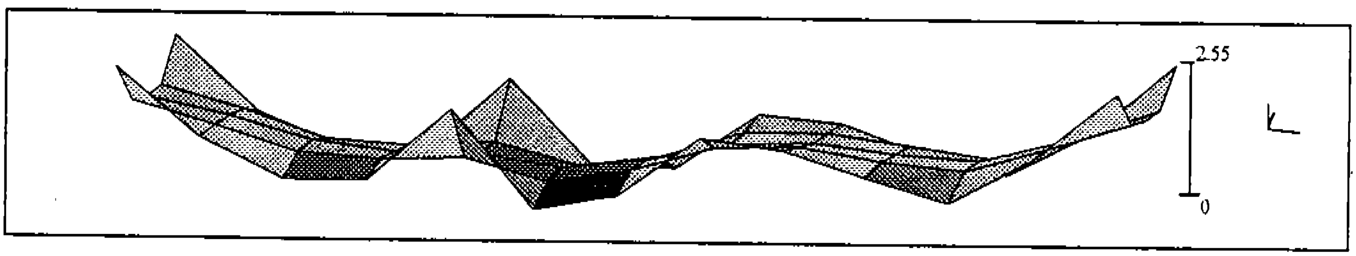
Contour Plot is shown Above.

Diagrams show the magnetic field in shields with a 3 inch overlap between 4 and 7 inches on the horizontal scale. The field is 30.0- gauss with the shield axes parallel to the flux lines.

Surface Plot is shown Below.

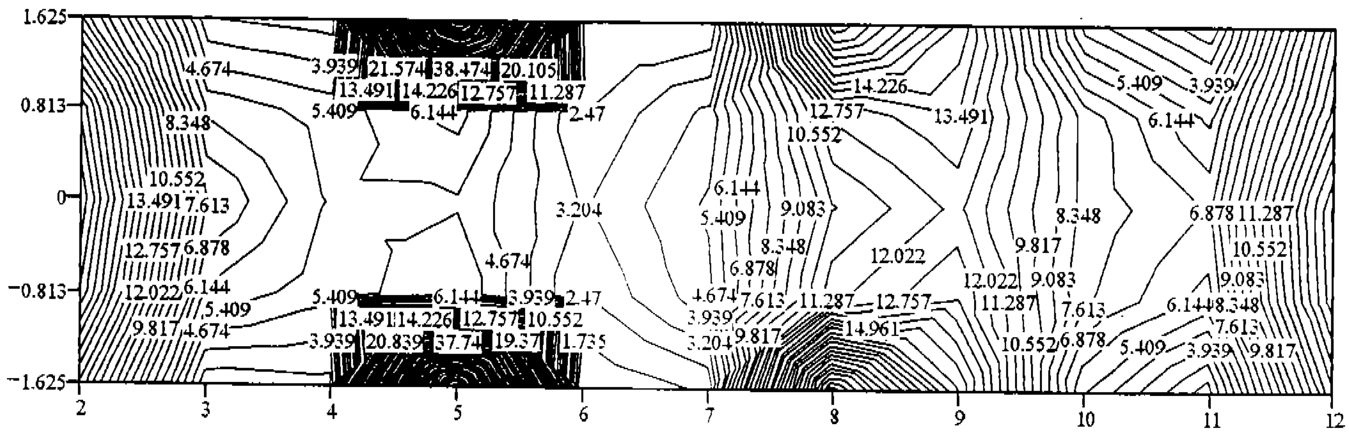


P



Q

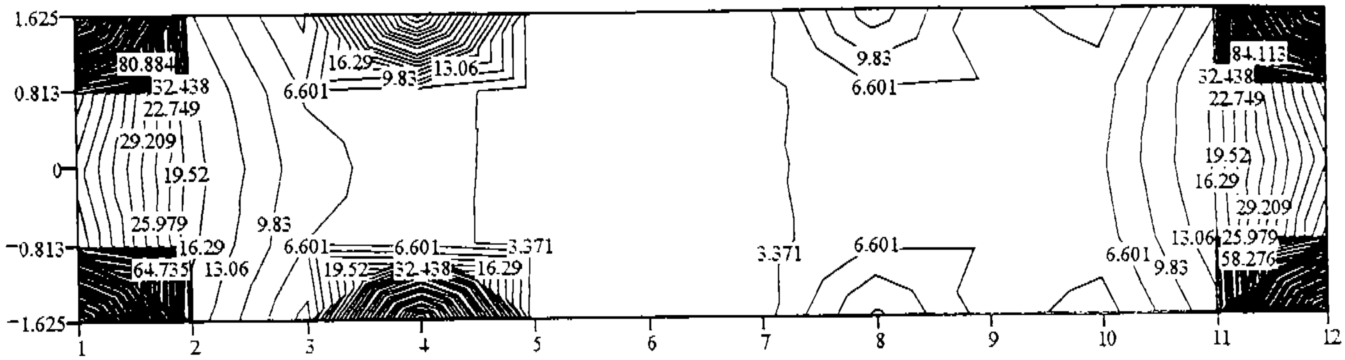
Above is a surface plot of the interior of the shield, but the vertical scale is a logarithmic plot of the data.



Q1

The region above depicts the interior of the 3 inch overlapping shields. The 1.0 inch region at the end of the double shield is not shown.

Figure 23

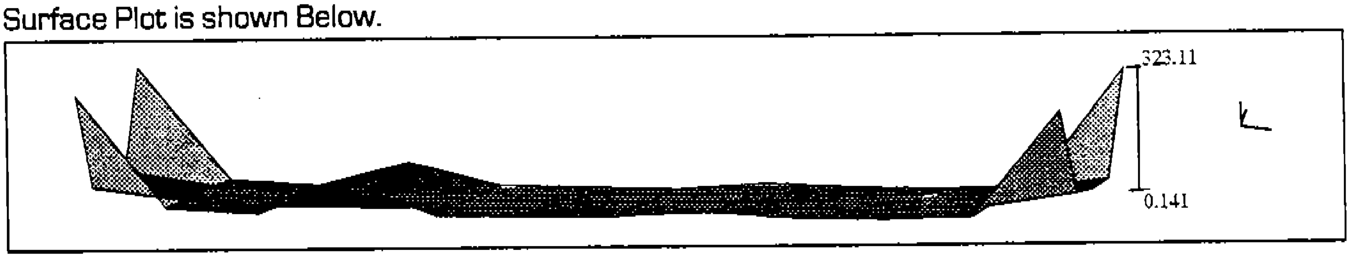


P

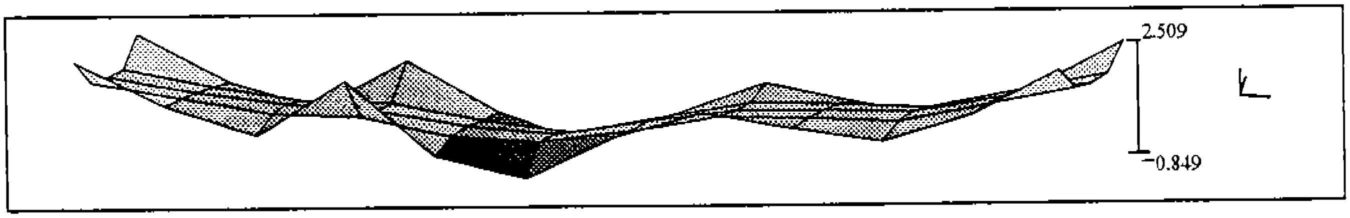
Contour Plot is shown Above.

Diagrams show the magnetic field in shields with a 4 inch overlap between 3 and 7 inches on the horizontal scale. The field is 30.0 gauss with the shield axes parallel to the flux lines.

Surface Plot is shown Below.

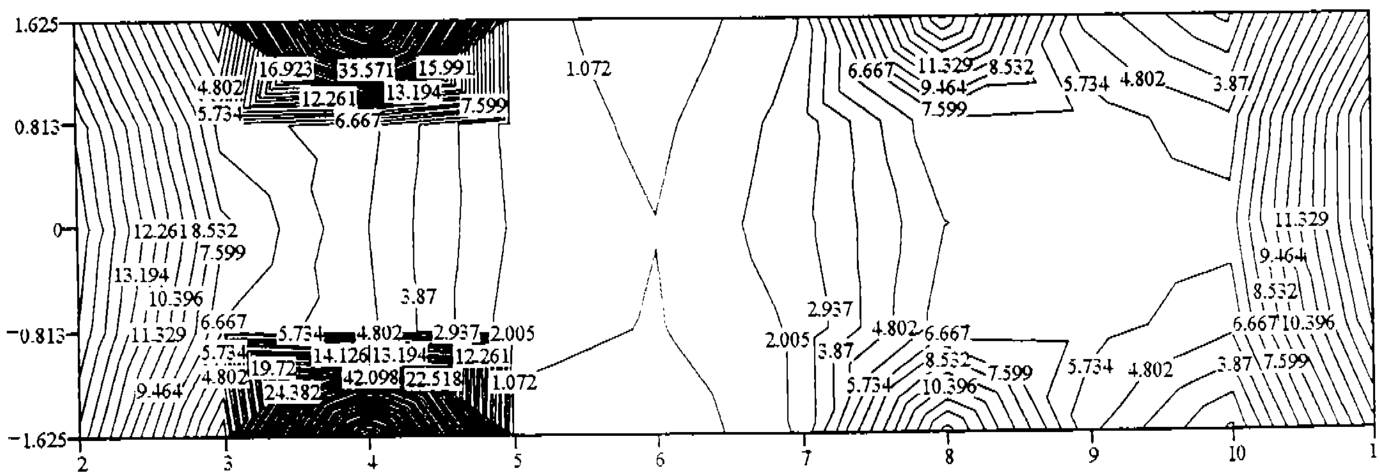


P



Q

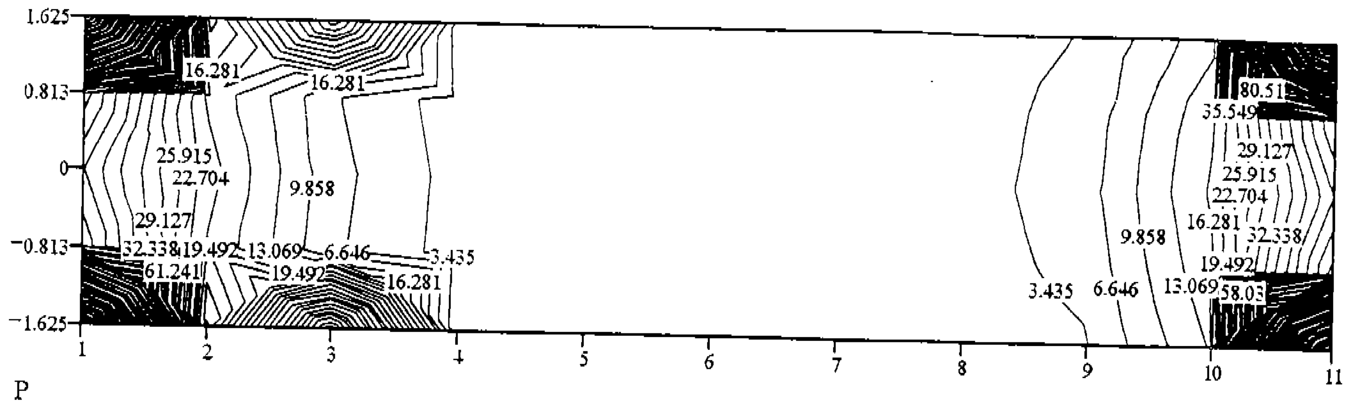
Above is a surface plot of the interior of the shield, but the vertical scale is a logarithmic plot of the data.



Q1

The region above depicts the interior region of the 4 inch overlapping shields. The 1.0 inch region at the ends of the double shield is not shown.

Figure 24

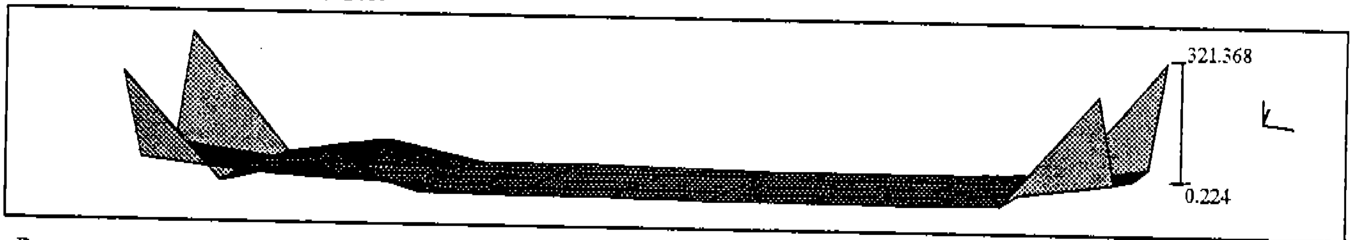


P

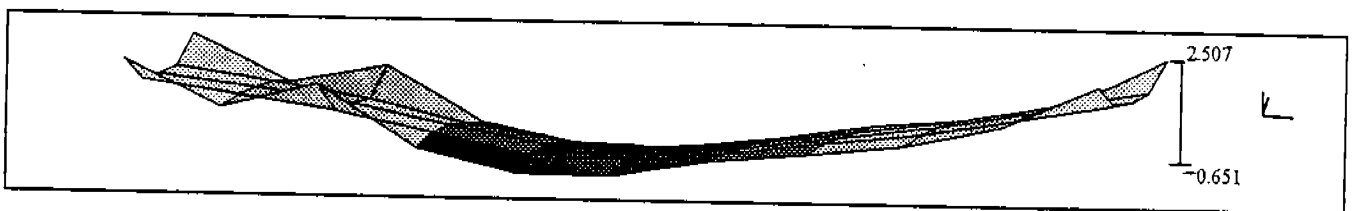
Contour Plot is shown Above.

Diagrams show the magnetic field in shields with a five inch overlap between 2 and 7 inches on the horizontal scale. The field is 30.0 gauss with the shield axes parallel to the flux lines.

Surface Plot is shown Below.

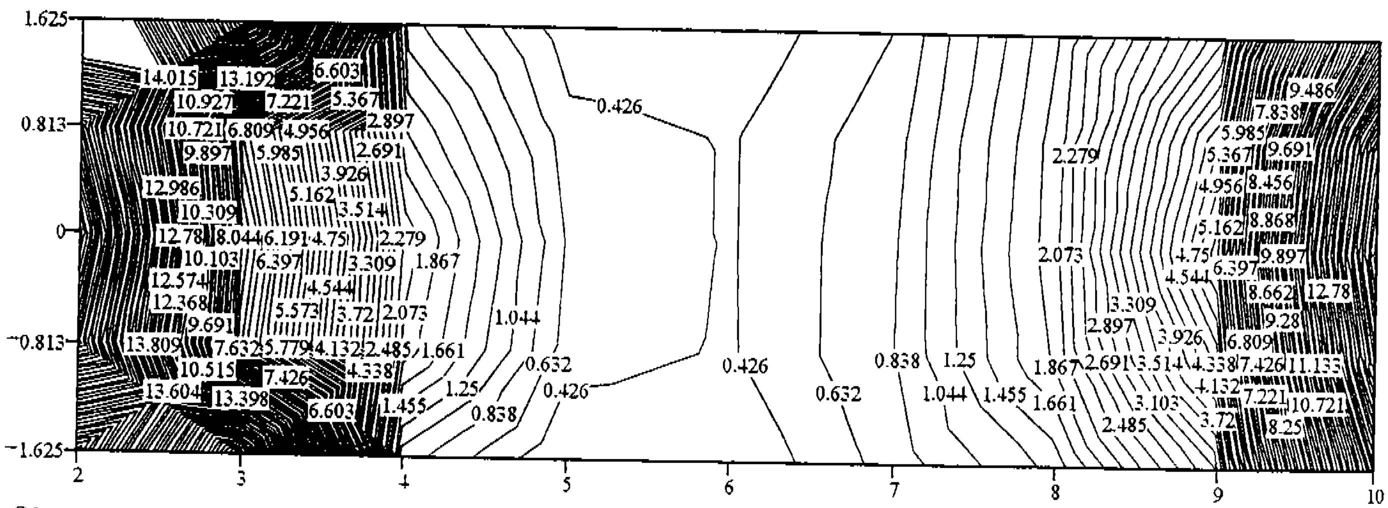


P



Q

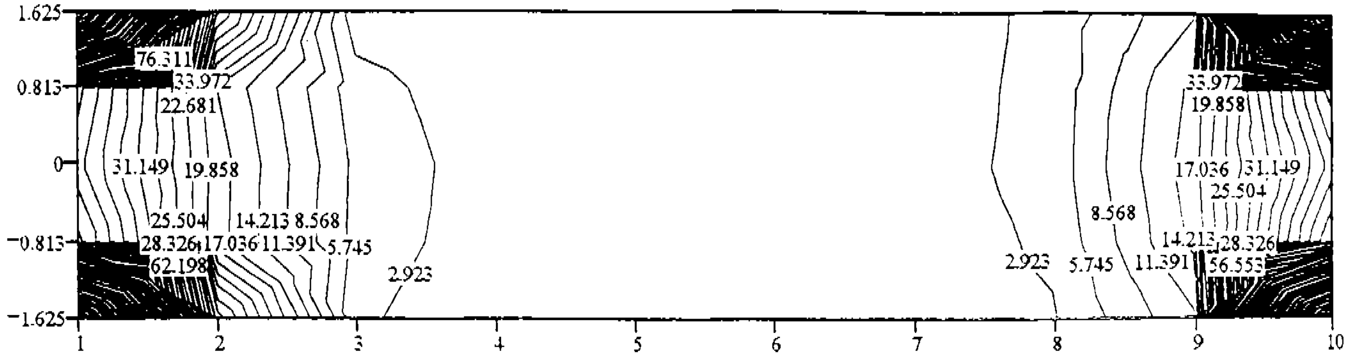
Above is a surface plot of the interior of the shield, but the vertical scale is a logarithmic plot of the data.



Q1

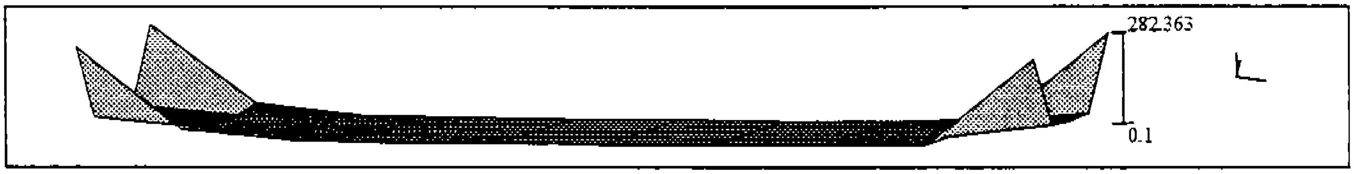
The region above depicts the interior region of the 5 inch overlapping shields. The 1.0 inch region at the ends of the double shield is not shown.

Figure 25

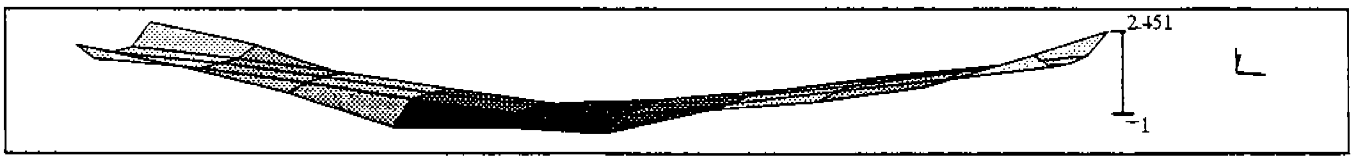


P

Contour Plot of the Inside of the Shield is shown Above.
Diagram of the magnetic field in shields with a 6 inch overlap between 2 and 8 inches on the horizontal scale. The field is 30.0 gauss with the shield axes parallel to the flux lines.
Surface Plot of the Inside of the Shield is shown Below.



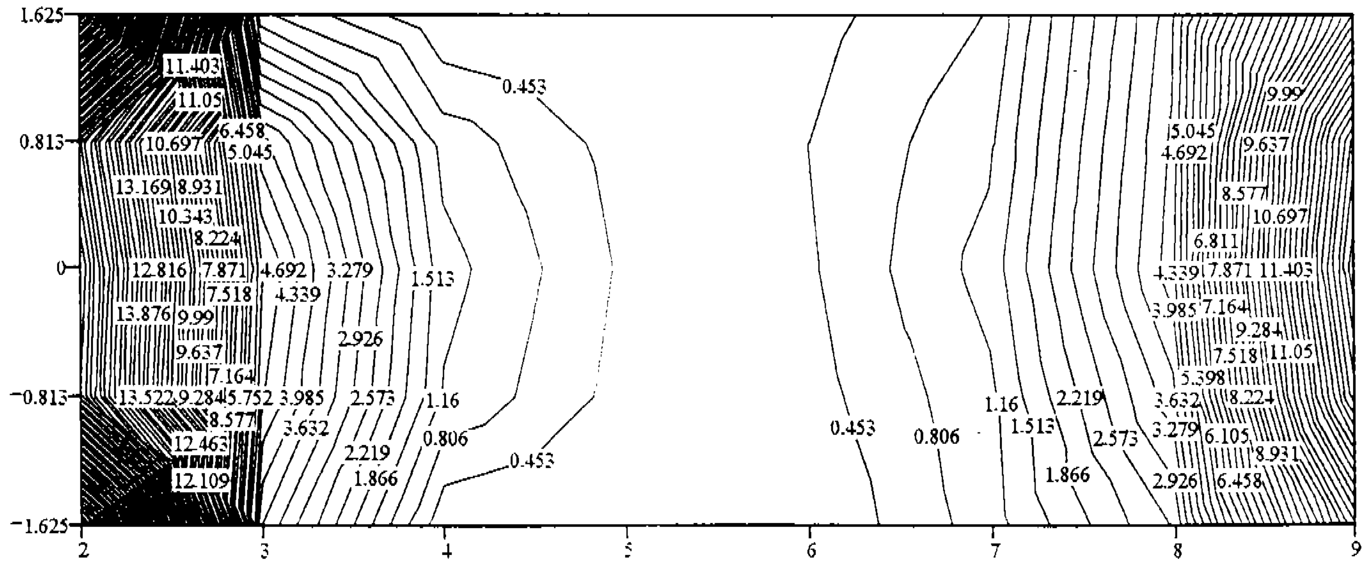
P



Q

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot.

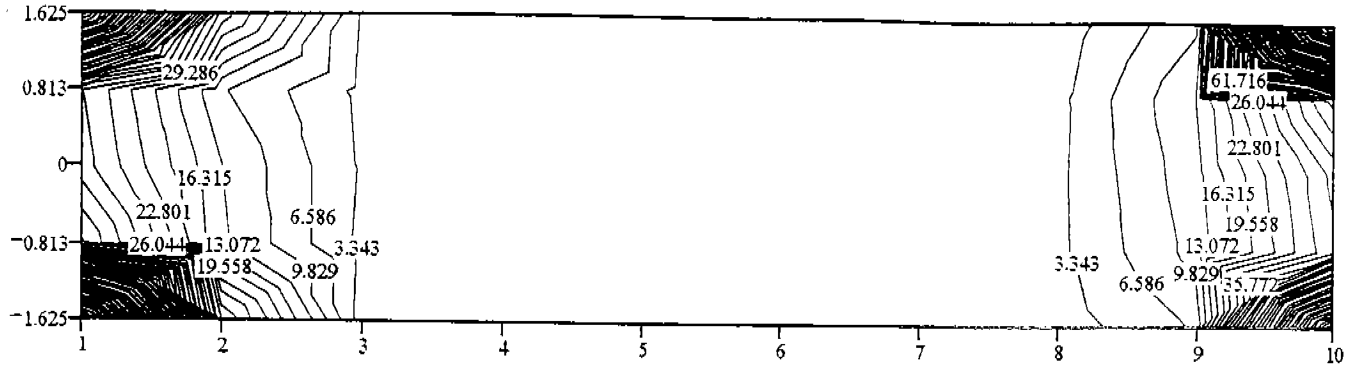
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 6.0 inches. This means the inner shield ends 1.0 inch from the left end of the plot and the outer shield ends 2.0 inches from the right end of the plot. The total length of the pair is 9.0 inches.



QI

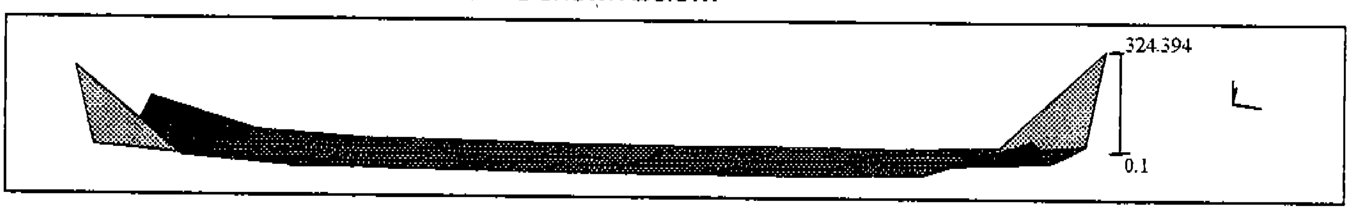
The diagram above depicts the interior region in the overlapping shields at 30.0 gauss. The overlap is 6 inches.

Figure 26a

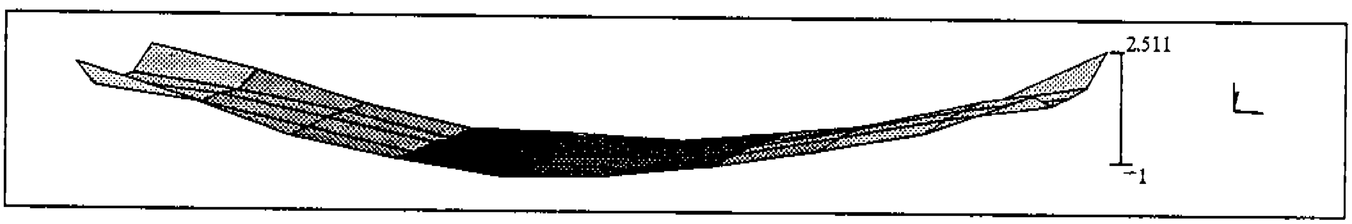


P2

Contour Plot of the Inside of the Shield is shown Above.
Diagrams show the magnetic field in shields with a 6 inch overlap between 2 and 8 inches on the horizontal scale. The field is 30.0 gauss with the shield axes 45 degrees to the flux lines.
Surface Plot of the Inside of the Shield is shown Below.



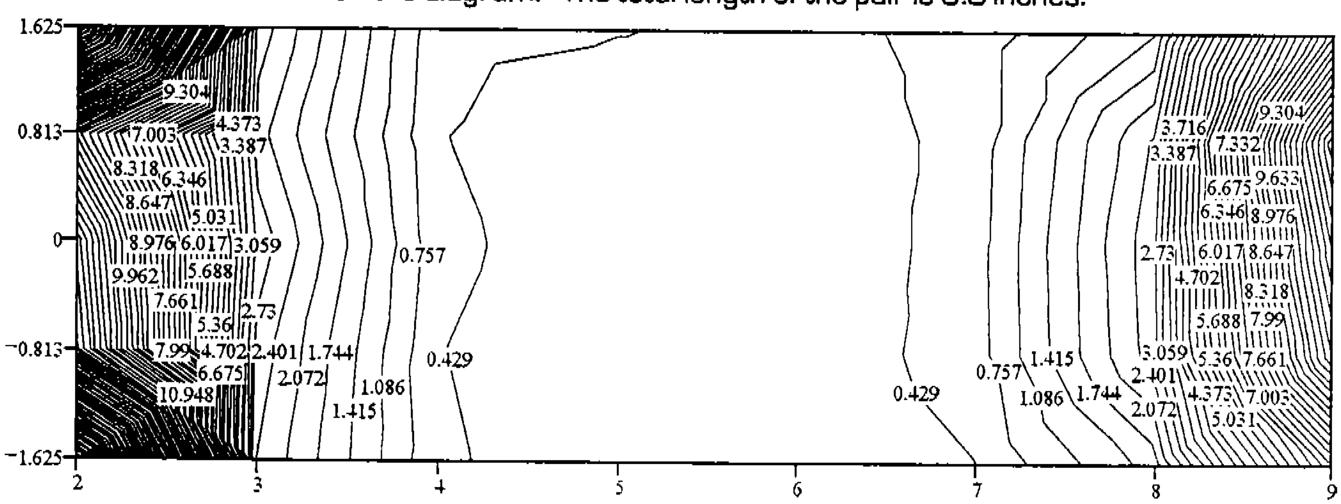
P2



Q2

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 30.0 gauss.

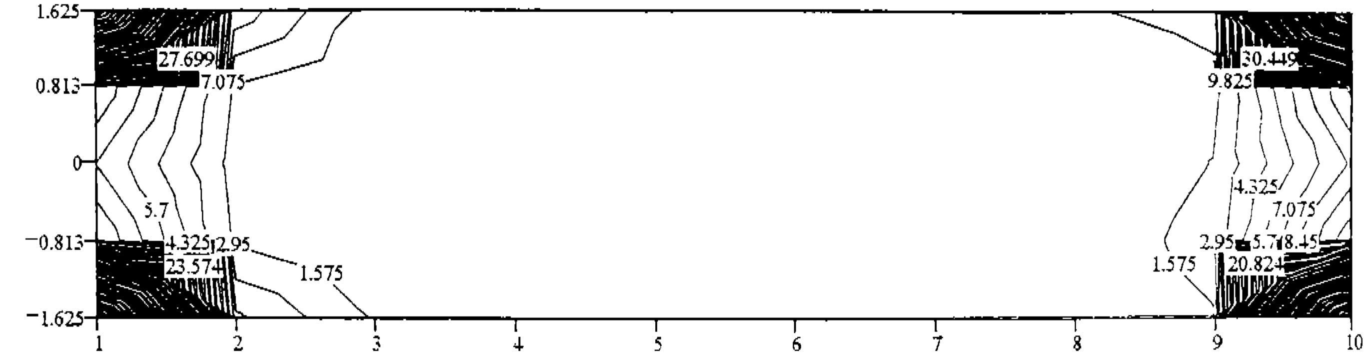
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The shield overlap is 6.0 inches from 2 to 8 on the diagram. The total length of the pair is 9.0 inches.



Q1

The region above depicts the central portion of the double shield without the 1.0 inch regions at either end. The exterior B-field is 30.0 gauss.

Figure 26b

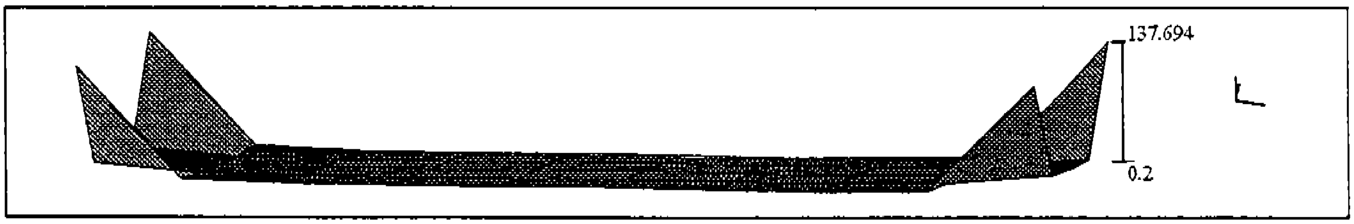


P1

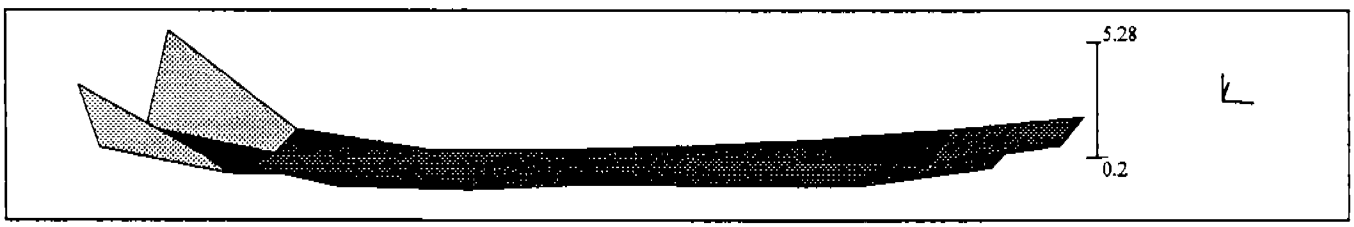
Contour Plot of the Inside of the Shield is shown Above.

Diagrams show the magnetic field in shields with a 6 inch overlap between 2 and 8 inches on the horizontal scale. The field is 30.0 gauss with the shield axes perpendicular to the flux lines.

Surface Plot of the Inside of the Shield is shown Below.

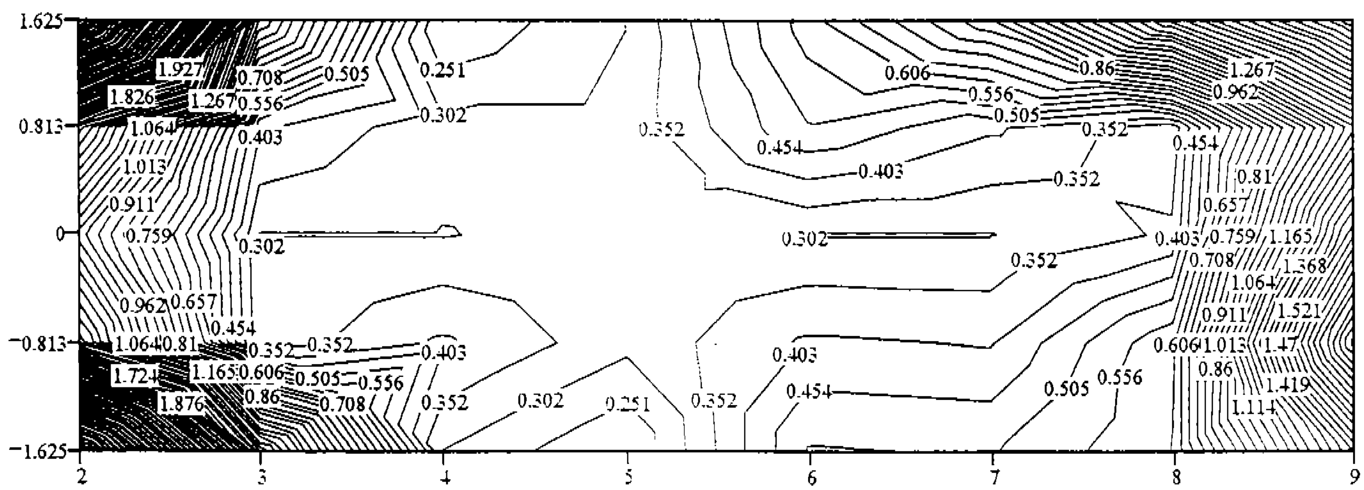


P1



Q1

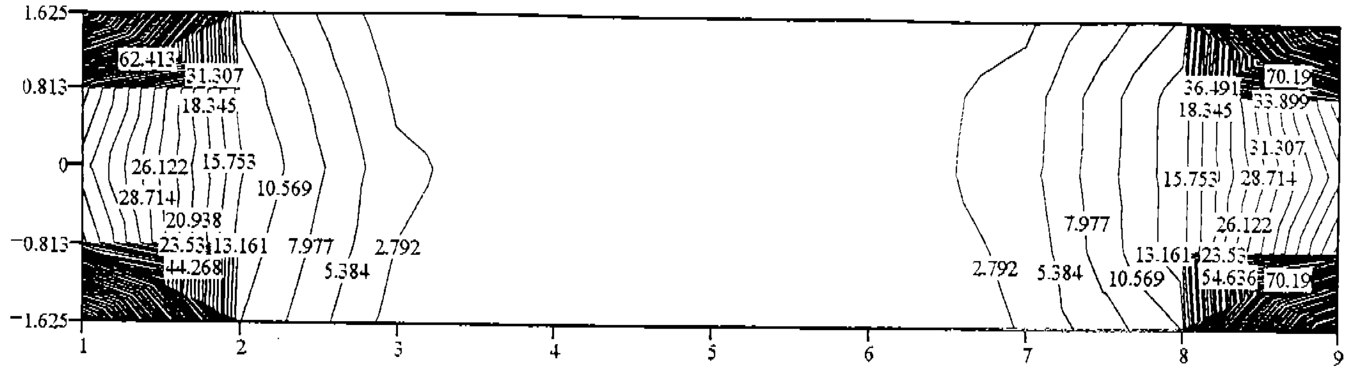
Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 30.0 gauss.



Q1

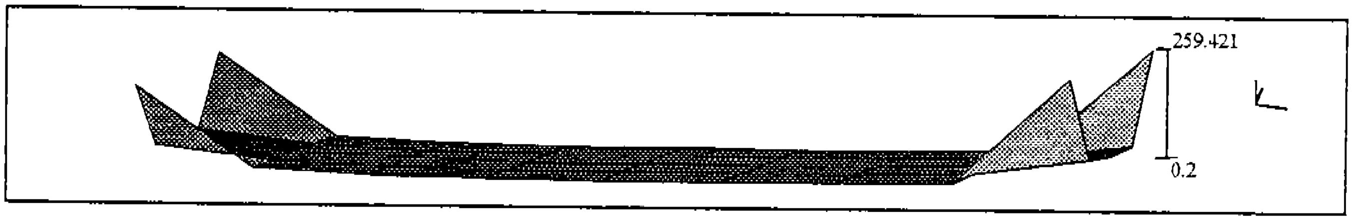
The plot above depicts the interior of the double shield without a 1.0 inch section at either end of the shields.

Figure 26c

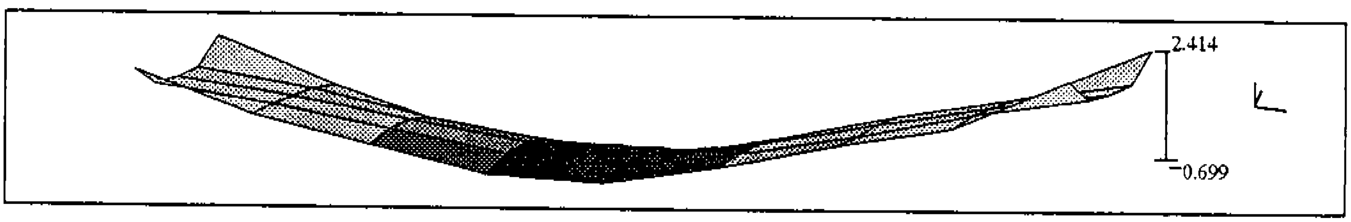


P

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 30.0 gauss. The overlap is 7.0 inches from 1 to 8 inches on the diagram.
The axes of the shields are parallel to the Flux Lines.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



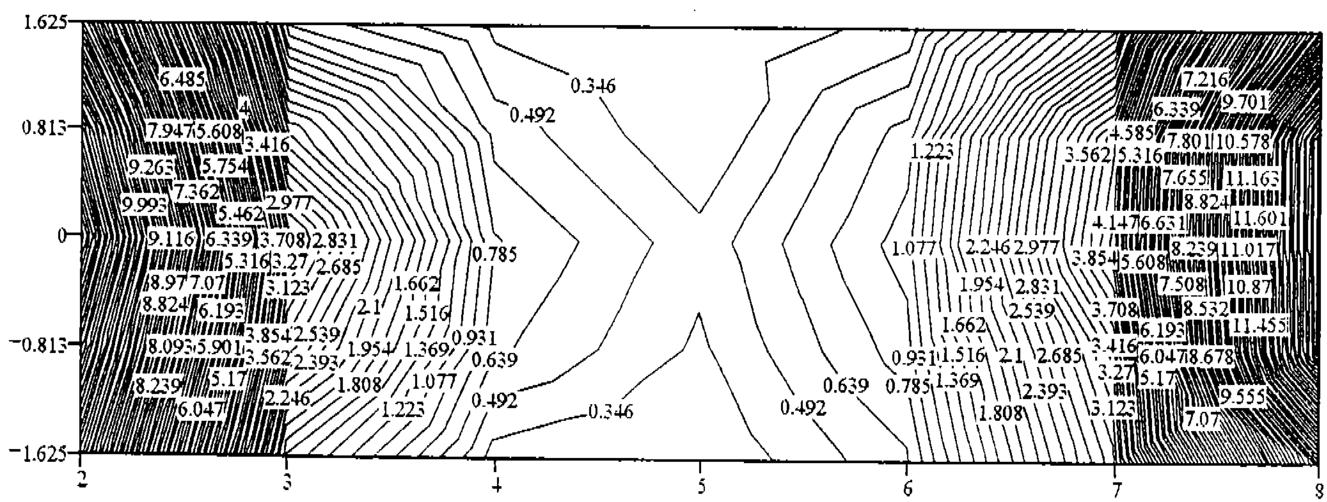
P



Q

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 30.0 gauss.

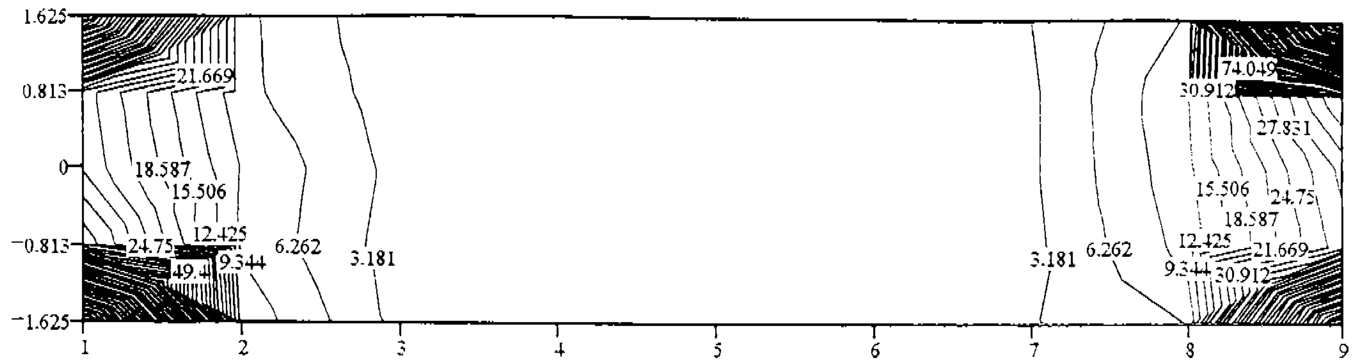
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 7.0 inches. Both shields end at the left end of the plot. The outer shield ends 1.0 inch from the right end of the plot. The total length of the pair is 8.0 inches.



Q1

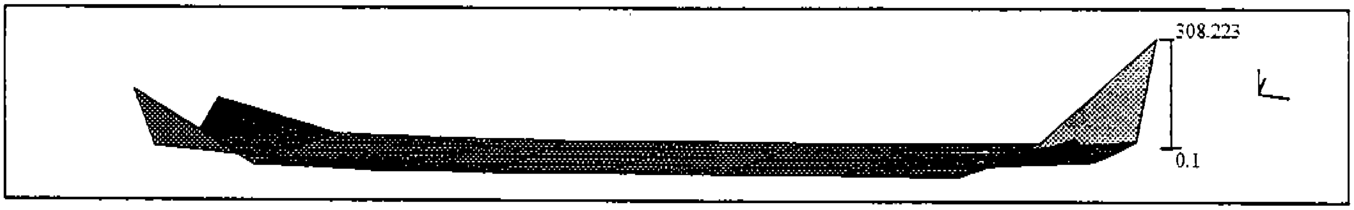
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 27a

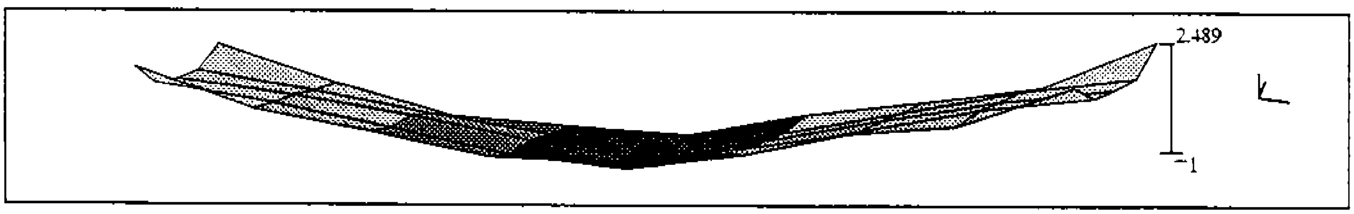


P2

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 30.0 gauss. The overlap is 7.0 inches from 1 to 8 inches on the diagram.
The axes of the shields are 45 degrees to the Flux lines.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



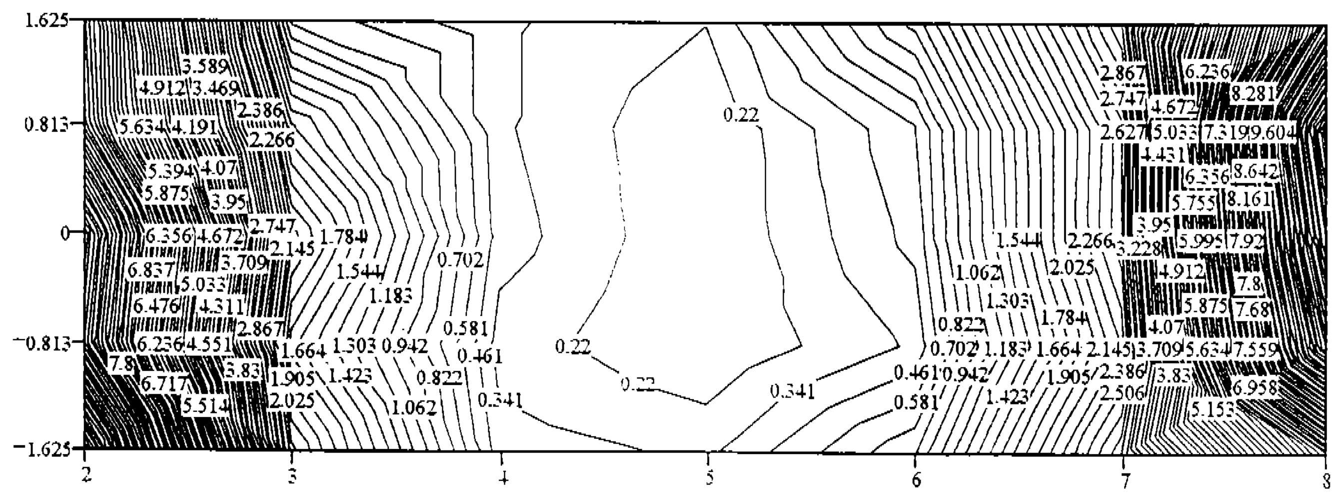
P2



Q2

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 30.0 gauss.

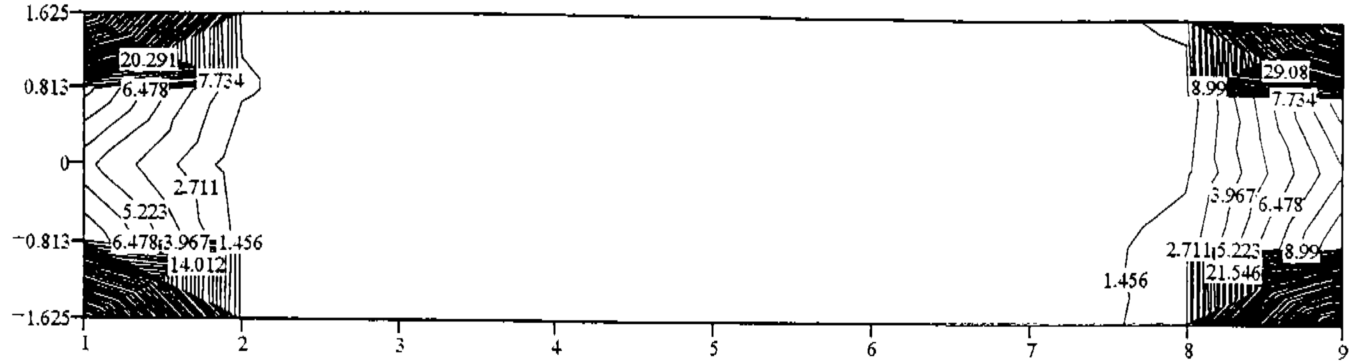
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 7.0 inches. Both shields end at the left end of the plot. The outer shield ends 1.0 inch from the right end of the plot. The total length of the pair is 8.0 inches.



Q1

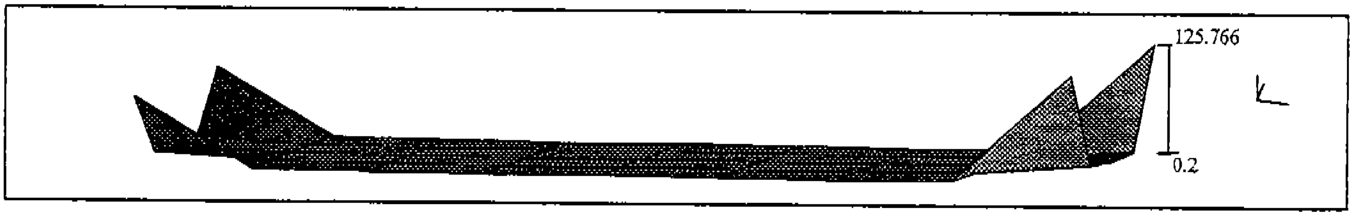
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 27b

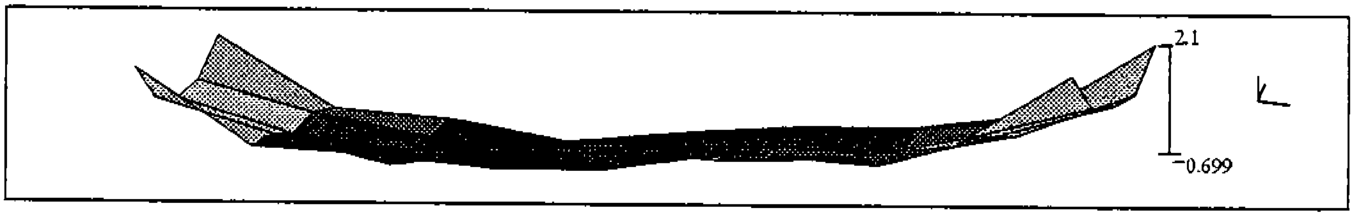


P1

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 30.0 gauss. The overlap is 7.0 inches from 1 to 8 inches on the diagram.
The axes of the shields are perpendicular to the Flux lines.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



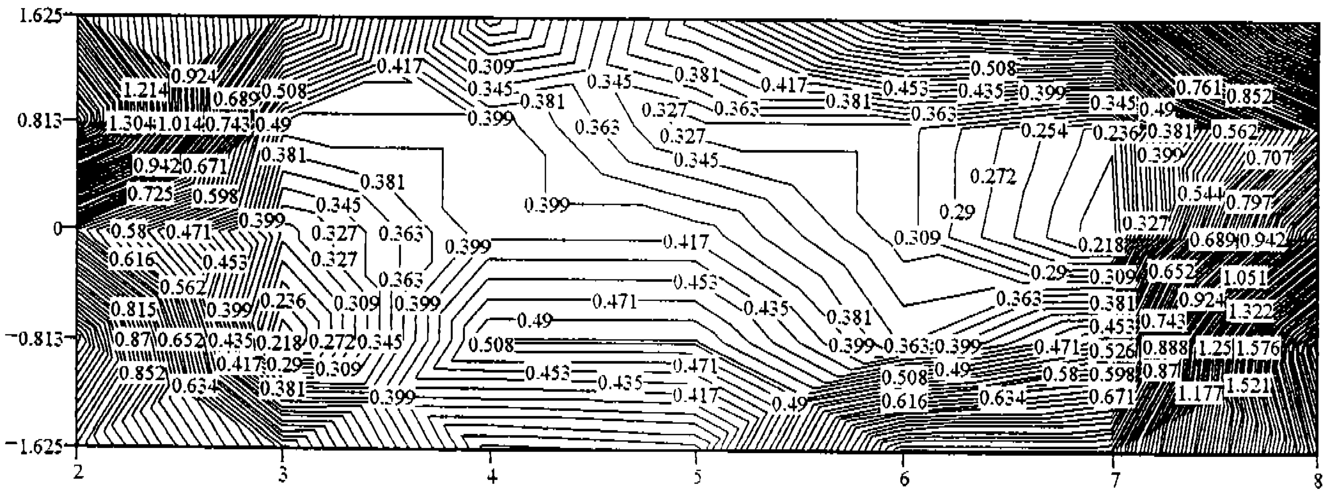
P1



Q1

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 30.0 gauss.

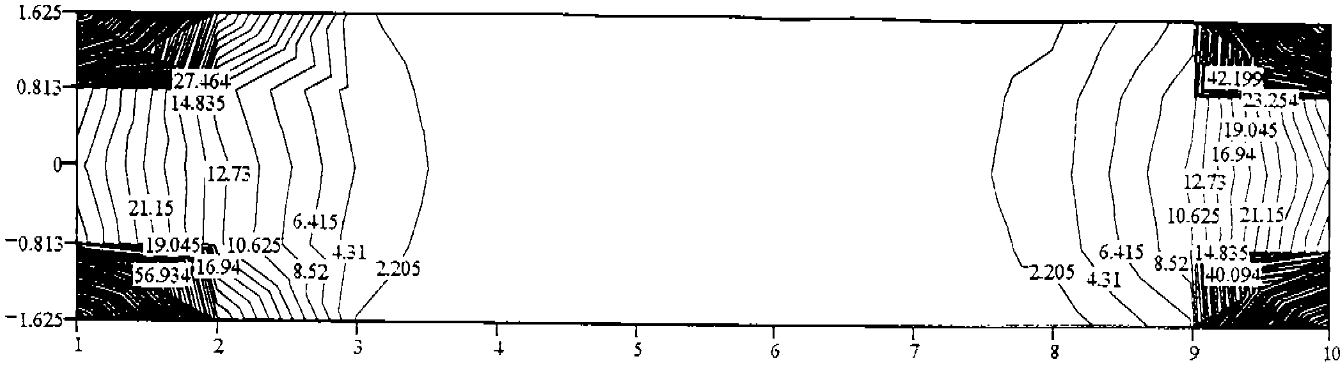
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 7.0 inches. Both shields end at the left end of the plot. The outer shield ends 1.0 inch from the right end of the plot. The total length of the pair is 8.0 inches.



Q2

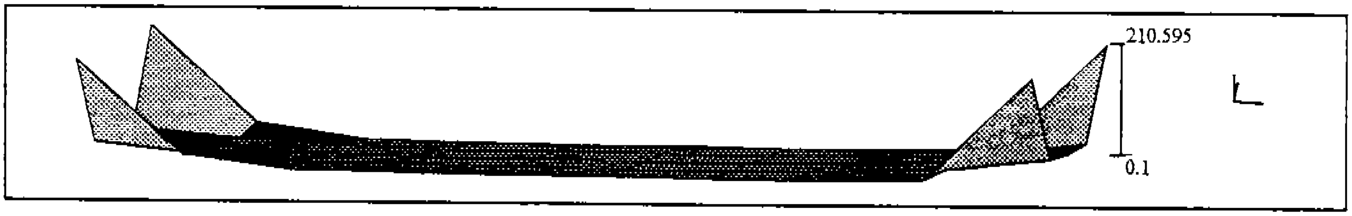
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

<u>Figure 27c</u>

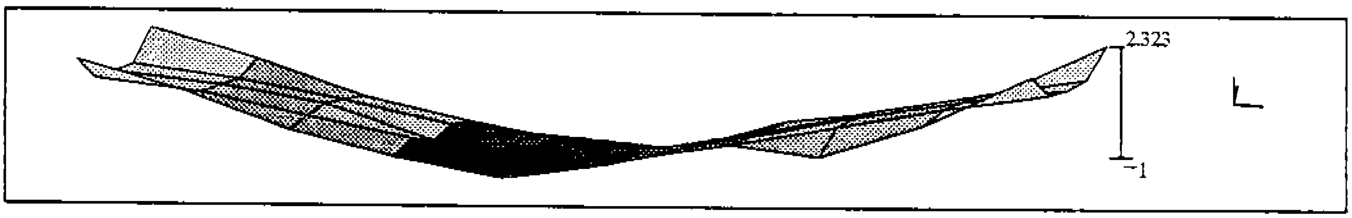


P

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 20.0 gauss. The axis of the shield is aligned parallel to the flux lines.
The overlap is 6.0 inches from 2 to 8 inches on the diagram.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



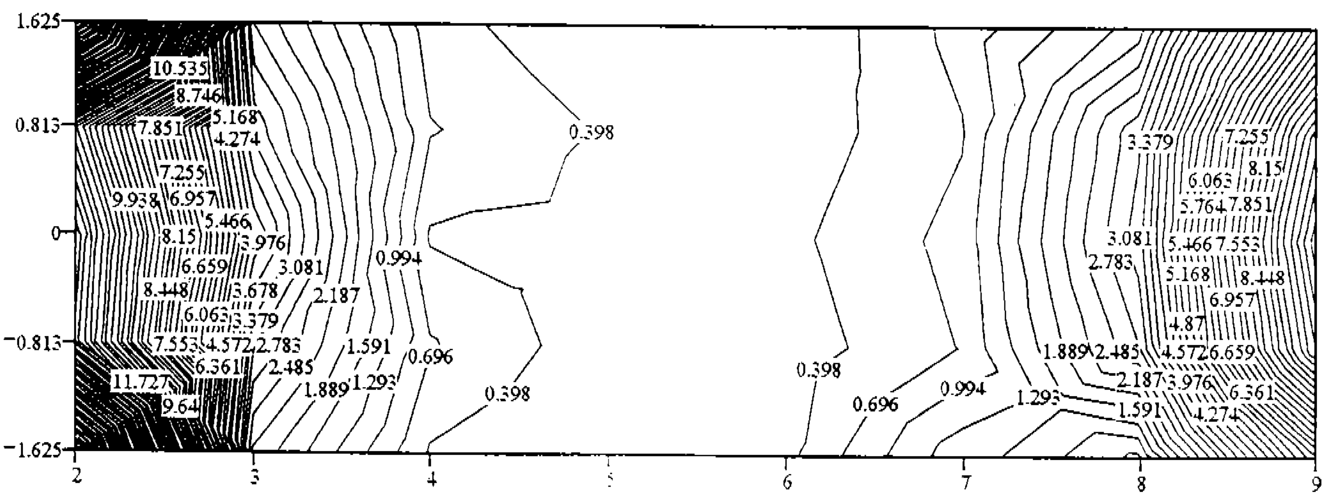
P



Q

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 20.0 gauss.

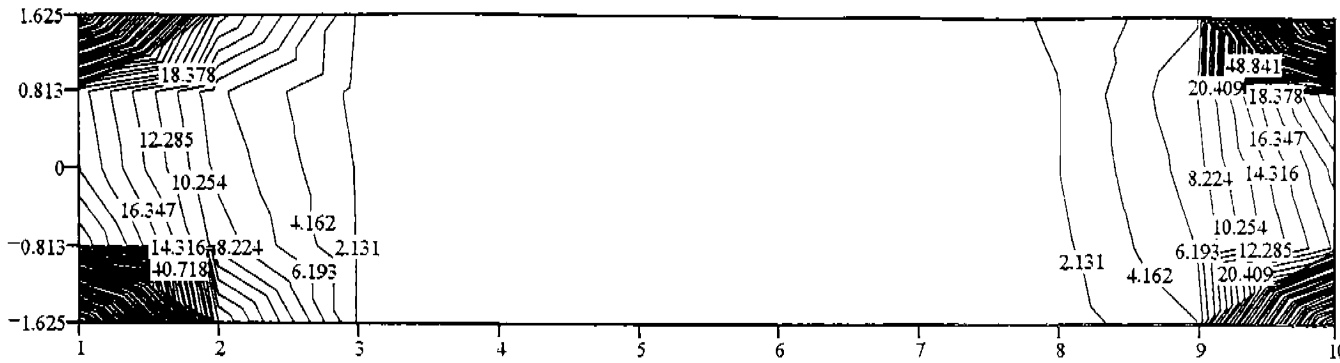
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 6.0 inches. The overlap is from 2 to 8 inches. The total length of the pair is 9.0 inches.



Q1

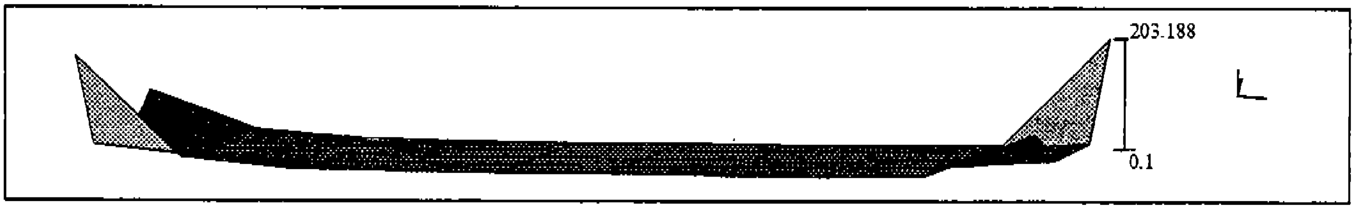
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 28a

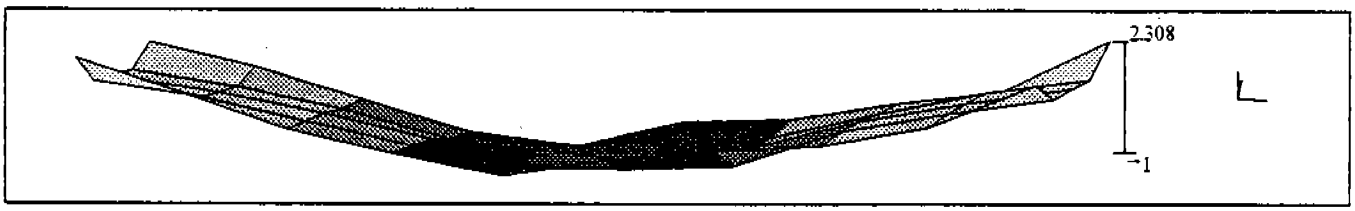


P2

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 20.0 gauss. The axis of the shield is aligned 45 degrees to the Flux lines.
The overlap is 6.0 inches from 2 to 8 inches.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



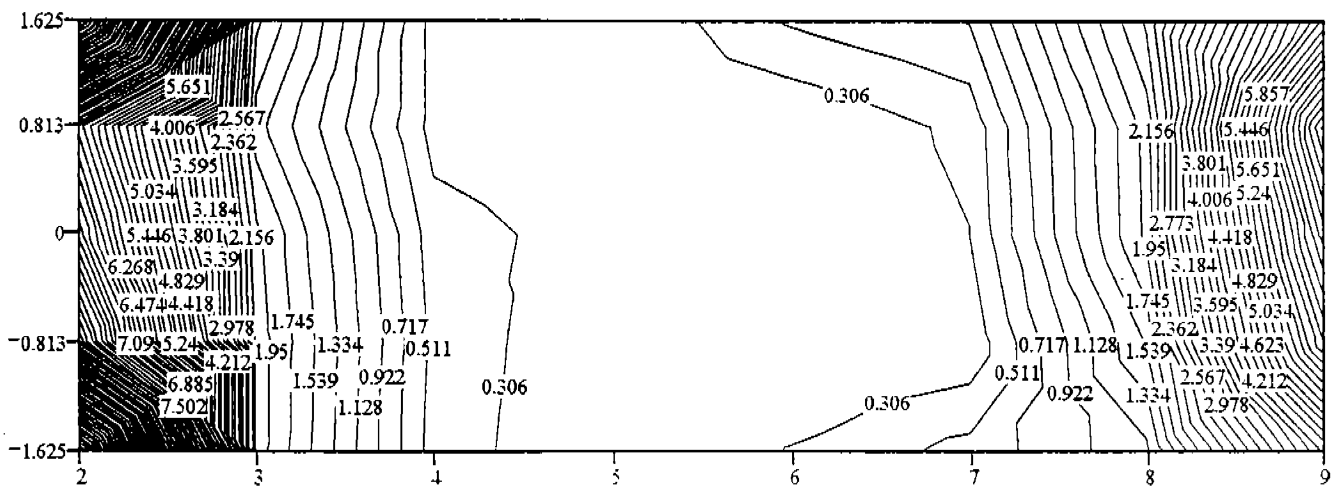
P2



Q2

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 20.0 gauss.

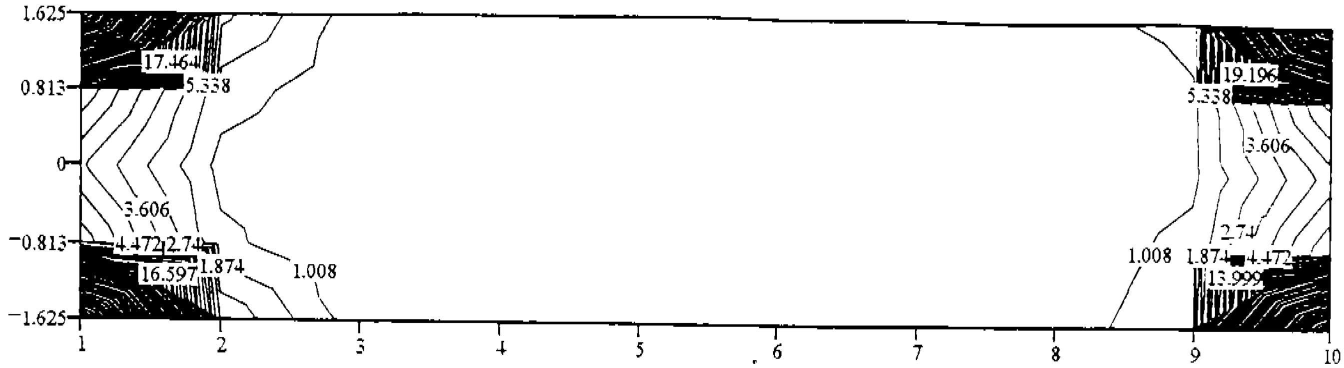
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 6.0 inches. The shields overlap from 2 to 8 inches. The total length of the pair is 9.0 inches.



Q1

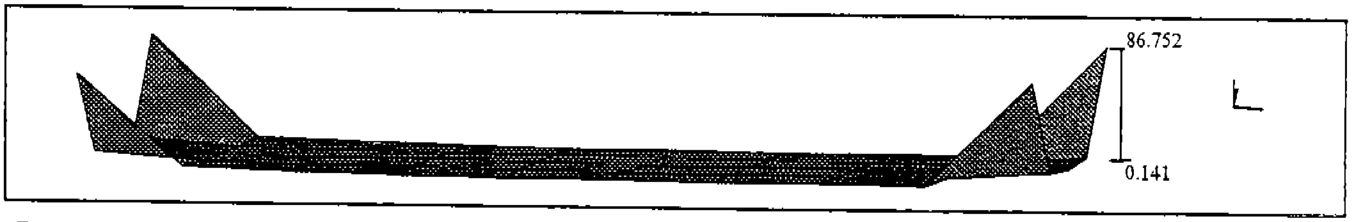
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 28b

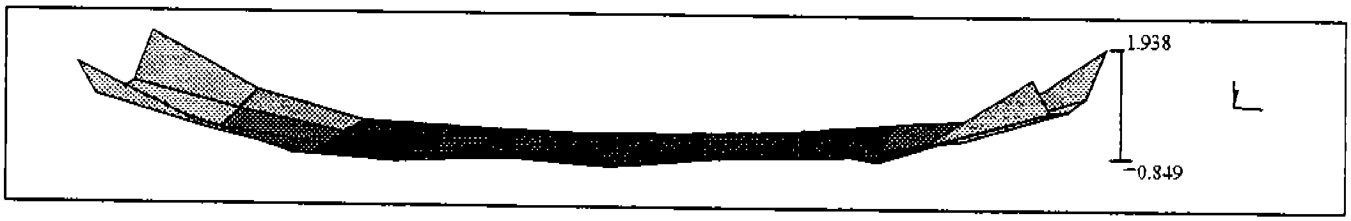


P1

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 20.0 gauss. The axis of the shield is perpendicular to the Flux lines.
The overlap is 6.0 inches from 2 to 8 inches on the diagram.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



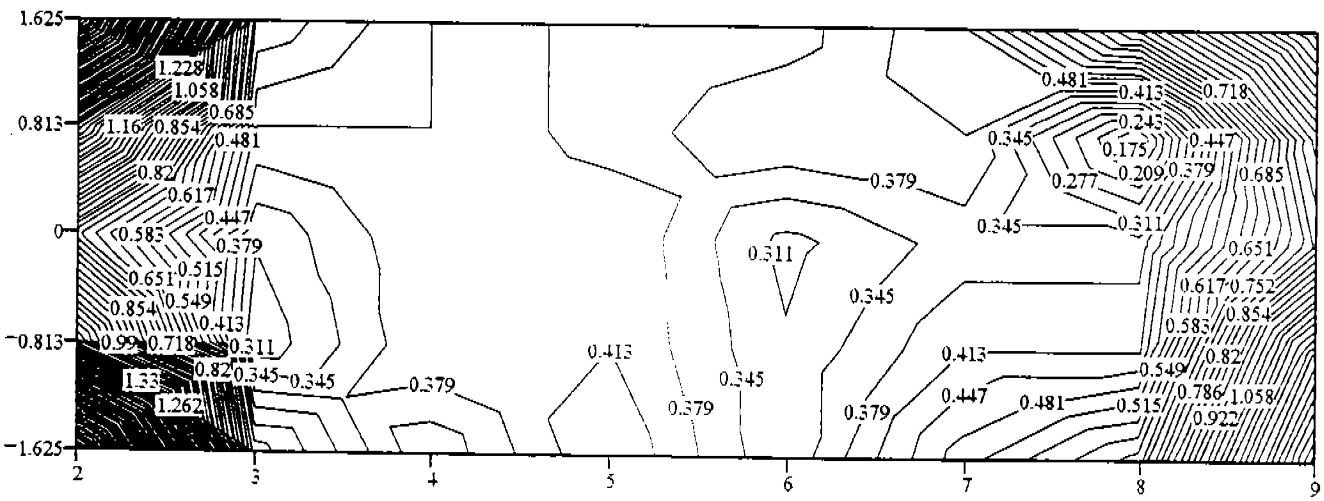
P1



Q1

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot.

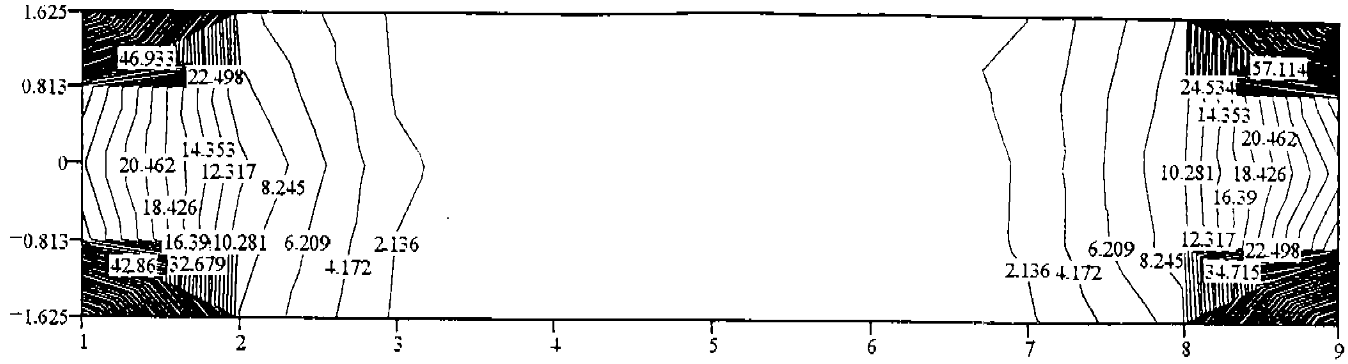
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 6.0 inches from 2 to 8 inches in the diagram. The total length of the pair is 9.0 inches.



Q2

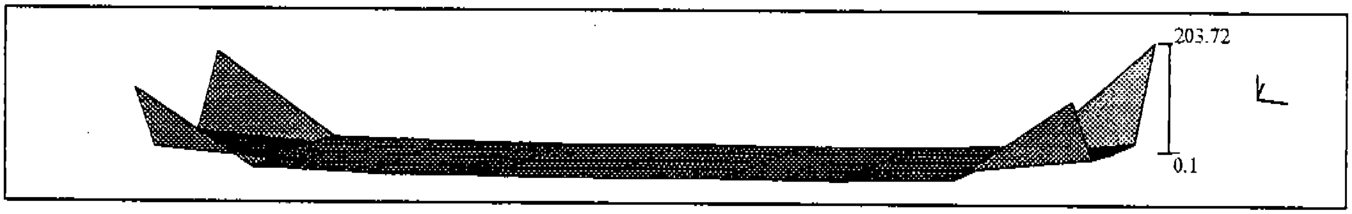
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 28c

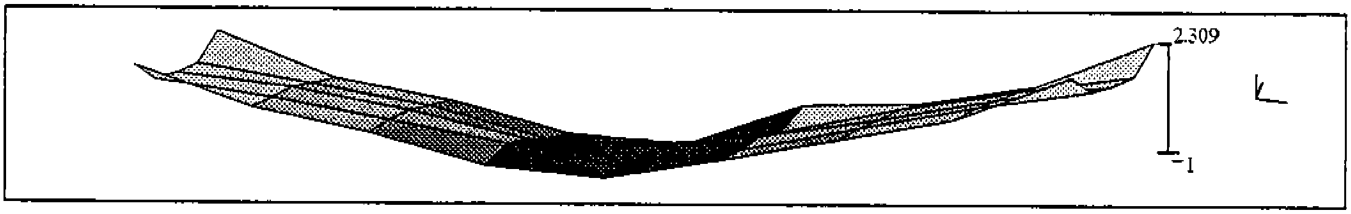


P

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 20.0 gauss. The overlap is 7.0 inches from 1 to 8 inches on the diagram.
The axes of the shields are parallel to the Flux lines.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



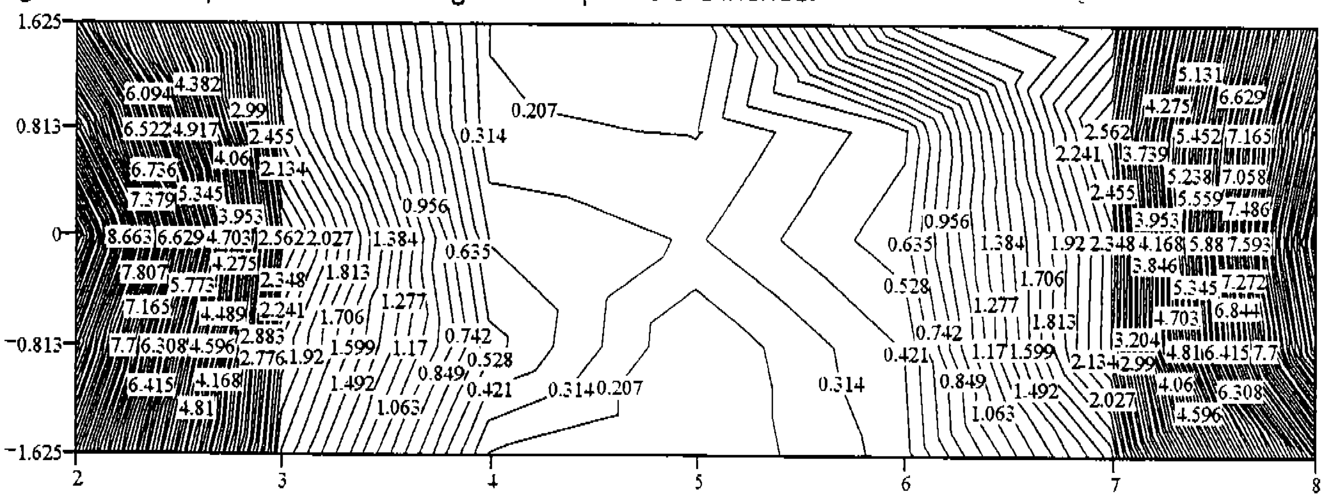
P



Q

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot. The B-field is 20.0 gauss.

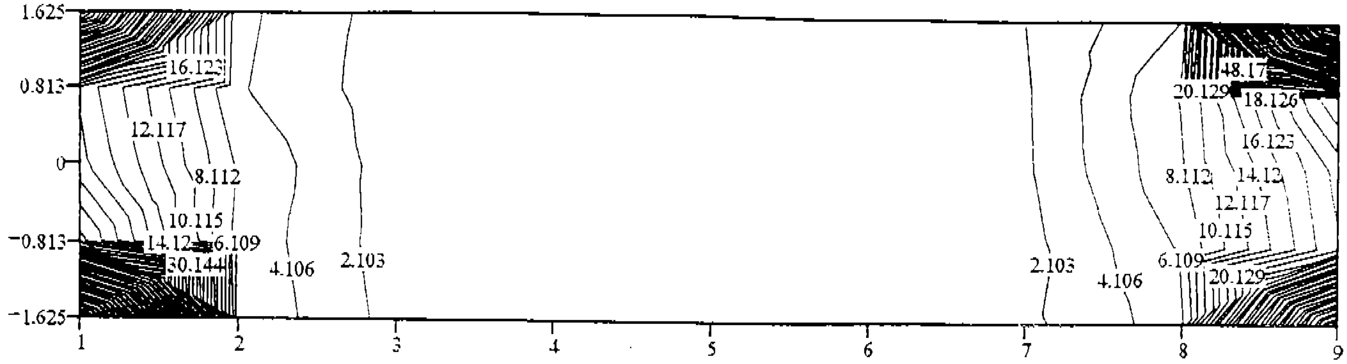
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 7.0 inches. Both shields end at the left end of the plot. The outer shield ends 1.0 inch from the right end of the plot. The total length of the pair is 8.0 inches.



Q1

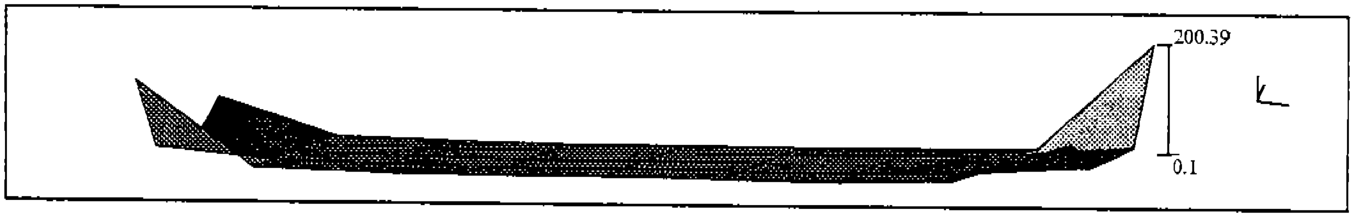
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 29a

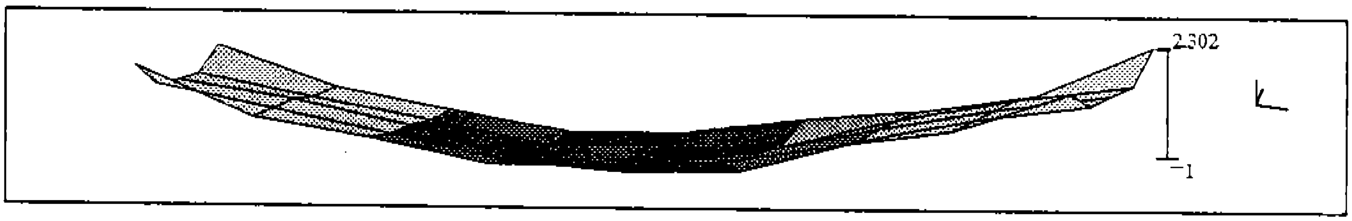


P2

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 20.0 gauss. The overlap of the shields is 7.0 inches from 1 to 8 on the diagram. The axes of the shields are 45 degrees to the Flux lines.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



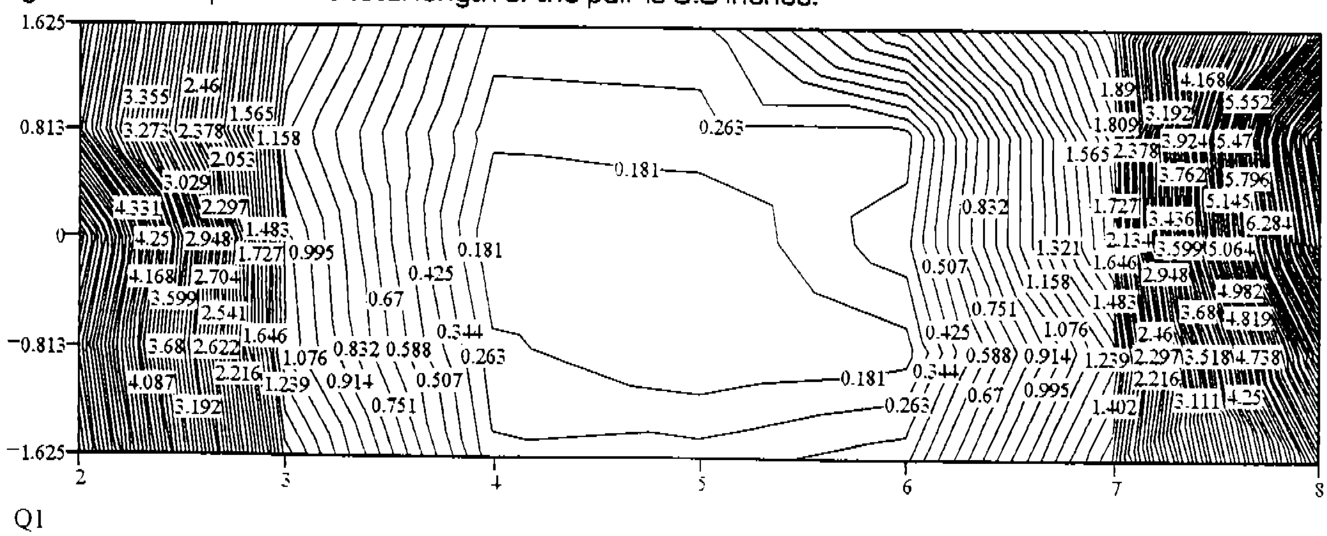
P2



Q2

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot.

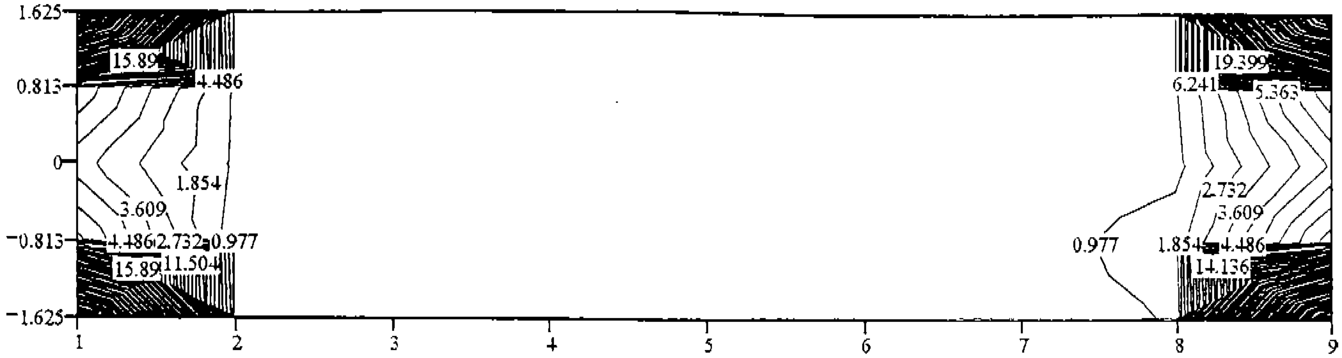
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 7.0 inches. Both shields end at the left end of the plot. The outer shield ends 1.0 inch from the right end of the plot. The total length of the pair is 8.0 inches.



Q1

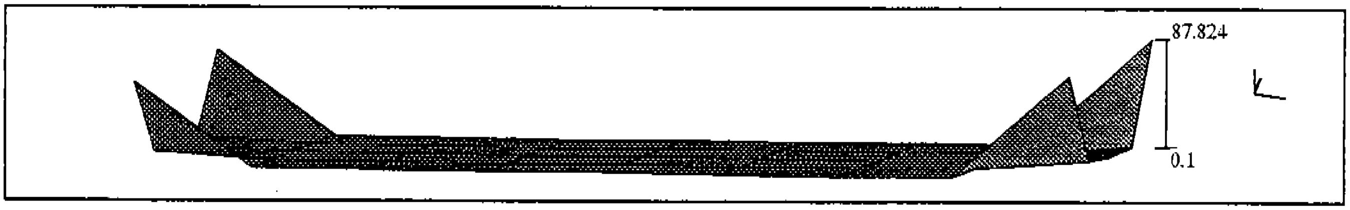
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 29b

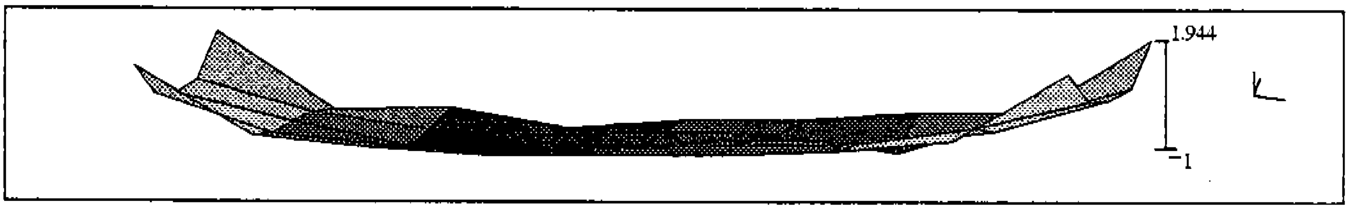


P1

Contour Plot of the Magnetic Field Inside the Shield is shown Above.
The B-field is 20.0 gauss. The overlap of the shields is 7.0 inches from 1 to 8 inches on the diagram. The axes of the shields are perpendicular to the Flux lines.
Surface Plot of the Magnetic Field Inside the Shield is shown Below.



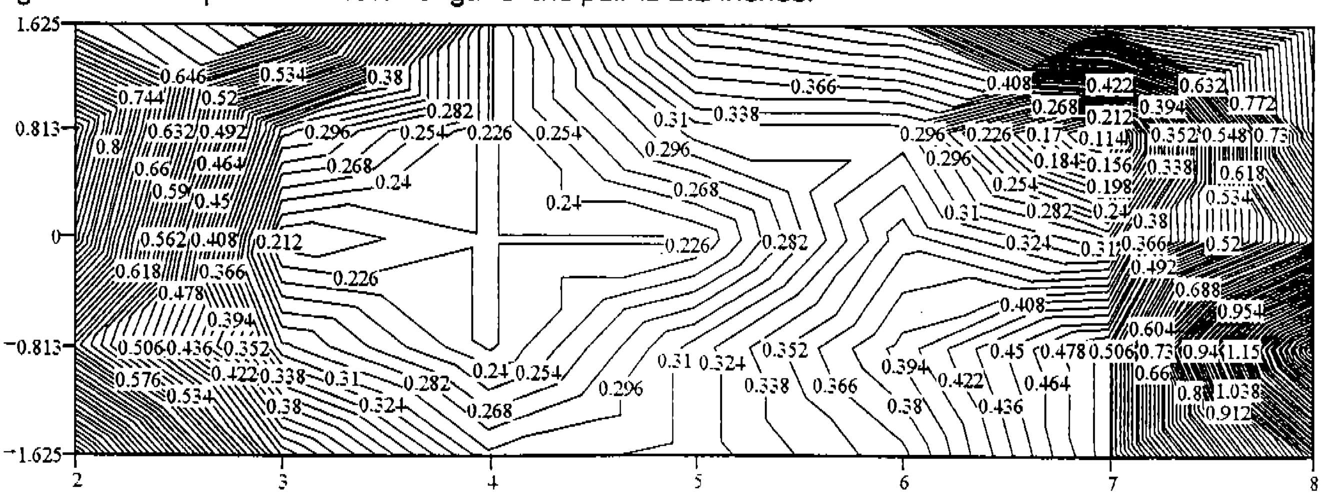
P1



Q1

Above is a surface plot of the interior of the shield. The vertical scale is a logarithmic plot of the data. The lowest points are easier to find in this plot.

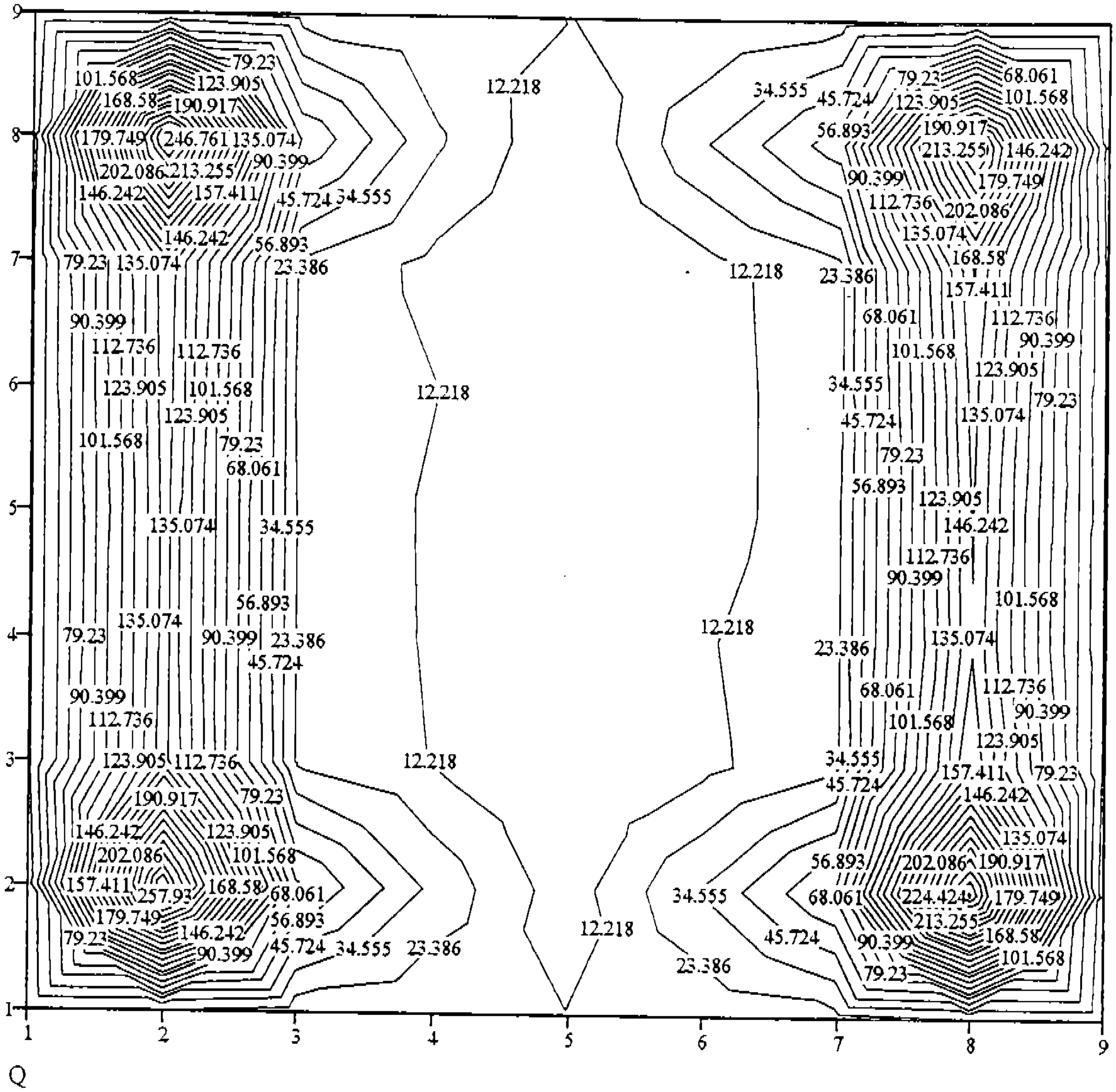
The outer shield (7.0 inches long) overlaps the left end of the inner shield. The overlap is 7.0 inches. Both shields end at the left end of the plot. The outer shield ends 1.0 inch from the right end of the plot. The total length of the pair is 8.0 inches.



Q2

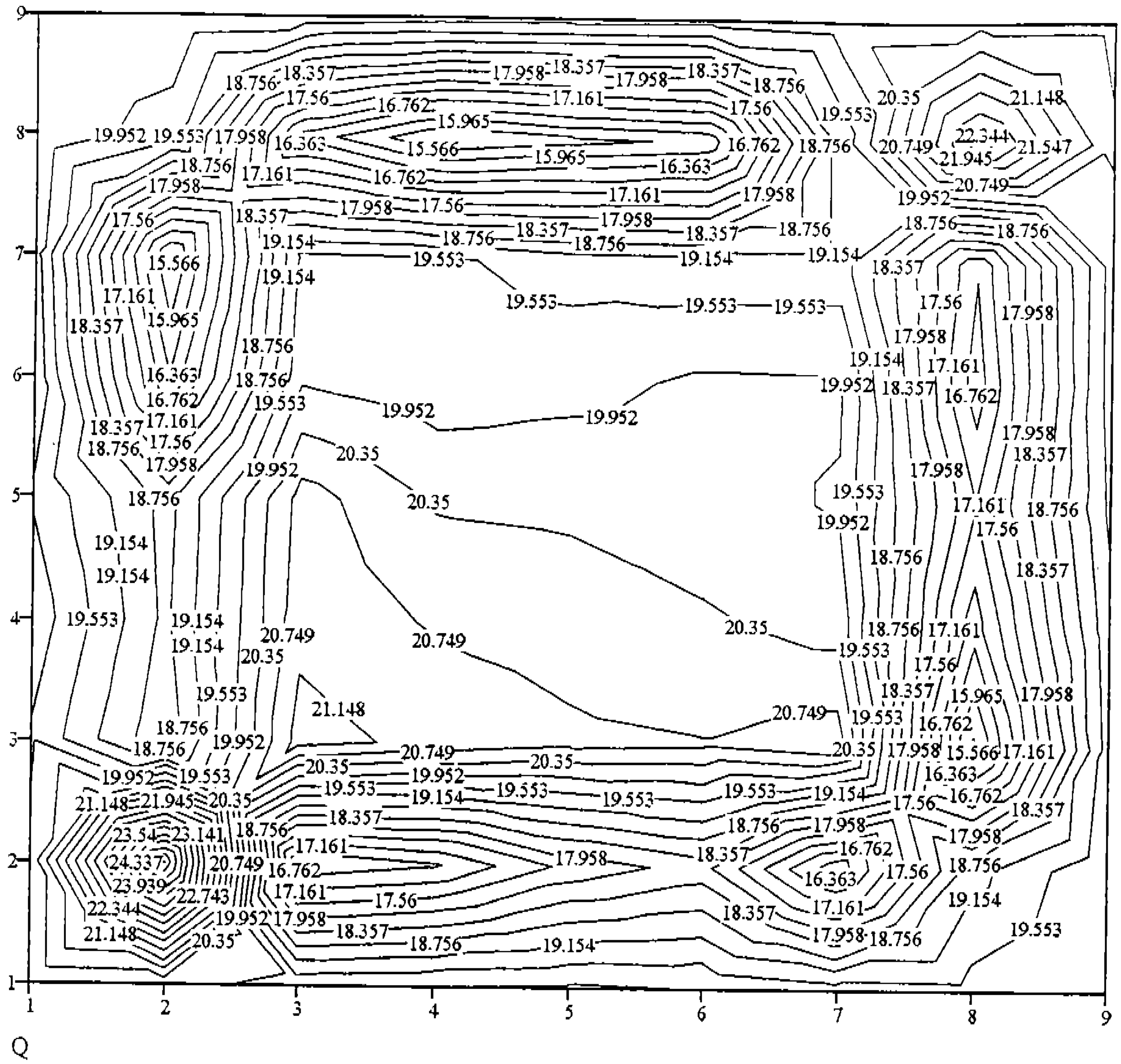
The plot above depicts the interior of the shield without a 1.0 inch section at either end of the double shield.

Figure 29c



Flat Plate, 6 inches by 6 inches, oriented parallel to the flux lines with North on the left side of the diagram.
The plate is located from (2,2) to (8,8).
The B-field is 20.0 gauss.

Figure 30



Flat Plate, 6 inches by 6 inches, oriented perpendicular to the flux lines with North inside the sheet of paper.
The plate is located from (2,2) to (8,8).
The B-field is 20.0 gauss.

<u>Figure 31</u>