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FUSION TECHNOLOGY INSTITUTE

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The University of Wisconsin
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Abstract

The problem of magnetic fields outside fusion power reactors and their effects on the environment, on the operation of neutral beam systems and other instruments, on the power handling equipment, and on reactor siting considerations are clearly important. We report here on calculations of the steady state toroidal and poloidal fields outside the University of Wisconsin Conceptual Tokamak Fusion Reactor, UWMAK-I. It is found that, with twelve toroidal field coils, the stray toroidal field is less than 1 gauss outside the reactor building. The poloidal field is larger but becomes less than 1 gauss at distances greater than 500 meters from the nuclear island. For distances larger than 200 meters, the field drops as $1/r^3$, i.e., as a dipole field. The use of 24 toroidal field coils to reduce field bumpiness at the plasma has the concommittant effect of reducing the stray toroidal fields as well. The poloidal field can be reduced by redesign of the transformer system to make the poloidal field fall off as a quadrupole field at large distances. This is under investigation. The fields immediately surrounding the nuclear island can be as high as 10,000 gauss. This is important to the operation of neutral beam systems placed around the reactor. Placement and shielding of these sources is briefly considered. The use of coils to buck out the field near the neutral beam source is under investigation. There are time dependent fields associated with Tokamak operation and the characteristic times are briefly discussed.

The stray fields of UWMAK-I(1) were calculated in two parts, namely, the toroidal field produced by the main toroidal magnetic field coils, and the poloidal field produced by the plasma current, divertor coils and transformer coils. These two fields were calculated separately, and can be superimposed. The toroidal magnets were approximated by 12 circular loops with centers on the circumference of a circle of radius, R_o, equal to 13 meters. The circular loops have a radius of 8.06 meters and are placed at 30° intervals about the torus. The loops approximate the D-shaped coils used in UWMAK-I. These approximations are employed because: (1) the field at large distances is insensitive to the shape of the toroidal field coils and, (2) the D-shaped coils were previously approximated by straight and arc sections(2). With such segmentation, the total field is a sum of the fields calculated from each current section. Different mathematical expressions and numerical schemes(3) are required for each segment and errors can be large at large distances.

Figure 1 shows the contours of constant toroidal field strength on the horizontal midplane through the torus. Figure 2 shows the poloidal fields, which are axisymmetric, on an r-z vertical plane. The dimensions of the building are indicated by dashed lines.

The toroidal field strength outside the reactor building is less than 1 Gauss, which makes it less than or equal to the earth's magnetic field in Wisconsin(4). The poloidal field decreases as a dipole field, namely, as ρ^{-3} beyond 200 meters. (ρ is the polar distance from the center of Tokamak.) The poloidal field at distances greater than 200 meters can be estimated from

$$B_\rho = \left(\frac{200}{\rho}\right)^3 B(\rho=200)$$

This is approximately the dipole field of the net current in the combined plasma, divertor and transformer current systems. The poloidal field drops to less than 1 gauss beyond 500 meters. Although the poloidal field is about the magnitude of the earth's magnetic field (which ranges from 0.6 to 0.7 gauss in the State of Wisconsin), the geological fluctuation of the earth's field is only in the range 0 to 2000 gammas (1 gamma = 10^{-6} gauss). The poloidal field would certainly cause perturbations and create a local anomaly at the reactor site.

Figure 3 shows the extended contour plot of the poloidal field inside the building. The field immediately surrounding the machine is as high as 10 kilogauss. This may impose a problem on the flow of liquid metal coolants.

The magnetic fields shown in Figures 1 and 2 were calculated using a plasma current of 26.2 MA. Two operating points were presented for UWMAK-I, with suggested operation at a plasma current of 20.6 MAmps. The results in Figures 1 and 2 scale down directly since

$$\frac{B^{(1)}}{B^{(0)}} = \frac{I_p^{(0)}}{I_p^{(1)}} \qquad (1)$$

Thus, for UWMAK-I with I_p = 20.6 MA, all the fields given in Figures 1 and 2 are reduced by 19.5%.

Shielding of the magnetic field has been briefly considered. For a uniform D.C. magnetic field, we can use a spherical shell of high permeability material, mumetal. The field interior to the shell is given by(4)

$$|\delta| = + \frac{9|B_o|}{2\mu(1 - a^3/b^3)} \qquad (2)$$

$$\approxeq + \frac{3|B_o|}{2\mu_o(b-a)} \qquad \text{if } b \approx a$$

where a and b are the inner and outer radii of the spherical shell, μ is the magnetic permeability, and B_o is the field when μ is one. The values of μ for commercial Allegheny mumetal are shown in Figure 4. Taking $\mu = 61{,}000$ for 500 gauss and using $b = 1$ meter and $b-a = 0.01$ meter gives

$$|\delta| \cong \frac{1}{400} |B_o|$$

The shielding efficiency is 99.75%. The difficulty is that the toroidal field is highly nonuniform, as can be seen in Figure 5. In particular, because of the distribution and curvature of the field lines, there is always a large tangential field component to any form of shielding boundary. The required boundary conditions on the normal and tangential fields,

$$B_{no} = B_{ni}$$

and

$$H_{to} = H_{ti} \tag{3}$$

means the effectiveness of any shielding will strongly depend on the field topology in the region to be shielded. Thus, to shield the ion sources and charge exchange cells in the neutral beam system will require locating these sources in a region where the toroidal field is weak and the poloidal field lines are almost parallel. This condition occurs in UWMAK-I at distances greater than 45 meters for the centerline. It appears feasible to shield fields below about 2000 gauss but it may be necessary to operate the neutral beam systems in regions of higher fields. In this case, it will be necessary to use local coils to buck the field down to about 2000 gauss, and use shielding for the remaining reduction. For ion source operation in the neutral beam system, the field should be less than one gauss.

The shielding efficiencies of some commercial materials for 60 c.p.s. a.c. fields are given in Figure 5. These efficiencies are very high. However, the pulsed fields in Tokamaks may have very different characteristic times. The shielding efficiencies are not sensitive to the size and gauge of the material.

The bumpiness in the toroidal field at the plasma produced by the discrete coils may be important to plasma confinement. This bumpiness can be reduced by increasing the number of magnets or extending the outer edge of the magnets. Both these ideas are under study. We have, however, doubled the number of toroidal field coils to 24 and a comparison of the stray fields with the 12 coil system is shown in Figure 7. These field lines are along a radius passing through the center of the magnets rather than between the coils. From the figure, we see that the intensity of the stray toroidal field is considerably reduced with 24 magnets. However, the major field contribution outside the nuclear island is the poloidal field and using 24 toroidal field coils has no effect on this problem. We are presently investigating redesign of the transformer to reduce the poloidal field by balancing the currents. Qualitatively, however, if the divertor field coils were inside the toroidal coils, rather than outside, the poloidal field beyond the nuclear island would be considerably reduced. This was not done in the UWMAK-I because it makes disassembly of the system very difficult. It should also be noted that the transformer system was designed assuming the plasma resistivity is the Spitzer value.(6) If the resistivity is anomalously high by a factor of ~10, as it is in present experiments, the transformer coil currents will be much larger and the poloidal fields outside the system may therefore also be much larger. As noted, one can attempt to design the transformer system to balance the currents such that there is no dipole component at large distances. This would then cause the field to drop off as $1/\rho^5$, i.e., as a quadrupole field. We are presently investigating this possibility.

As a final point, we note that Tokamaks are likely to be pulsed systems with time varying fields associated with the startup and shutdown phases of the cycle. For UWMAK-I(1), we have considered current rise times in the plasma, transformer, and divertor field coils to be in the range of 10 to 100 seconds. The currents will likely depend on time either linearly or as $t^{1/2}$. It may be that impurity problems will limit Tokamak burn times to less than several tens of seconds. In that case, faster current rise times will be required.

References

1. The University of Wisconsin Fusion Feasibility Study Group, "UWMAK-I - A Wisconsin Toroidal Fusion Reactor Design," UWFDM-68.

2. T. F. Yang, "Calculation of Magnetic Fields from a Current Carrying Finite Size Conductor," UWFDM-47 (1973).

3. J. D. Jackson, Classical Electrodynamics, John Wiley and Sons, New York, London, 2nd edition (1962).

4. R. Patenaude, "Regional Aeromagnetic Survey of Wisconsin", Ph.D. Thesis, University of Wisconsin (1967).

5. "Technical Data on Special Steels," Allegheny Ludlum Steel Corporation, Pittsburgh, Pennsylvania.

6. L. Spitzer, Jr., Physics of Fully Ionized Gases, Second Edition, John Wiley and Sons, New York, London, Sydney (1967).

Figure Captions

Fig. 1 - Mapping of $|B|$ of the toroidal field on the midplane. The dashed line indicating the building size.

Fig. 2 - Mapping of $|B|$ of poloidal field on a vertical plane. The dashed lines indicating the building size.

Fig. 3 - Expanded mapping of $|B|$ of poloidal field inside the building which is indicated by the dashed lines.

Fig. 4 - Permeabilities of Allegheny mumetal and low carbon steel in D.C. magnetic fields.

Fig. 5 - Toroidal field lines around the outer edge of the magnets indicating the structure of the stray field. The separatrices are obtained by extrapolation from the closest neighboring field lines.

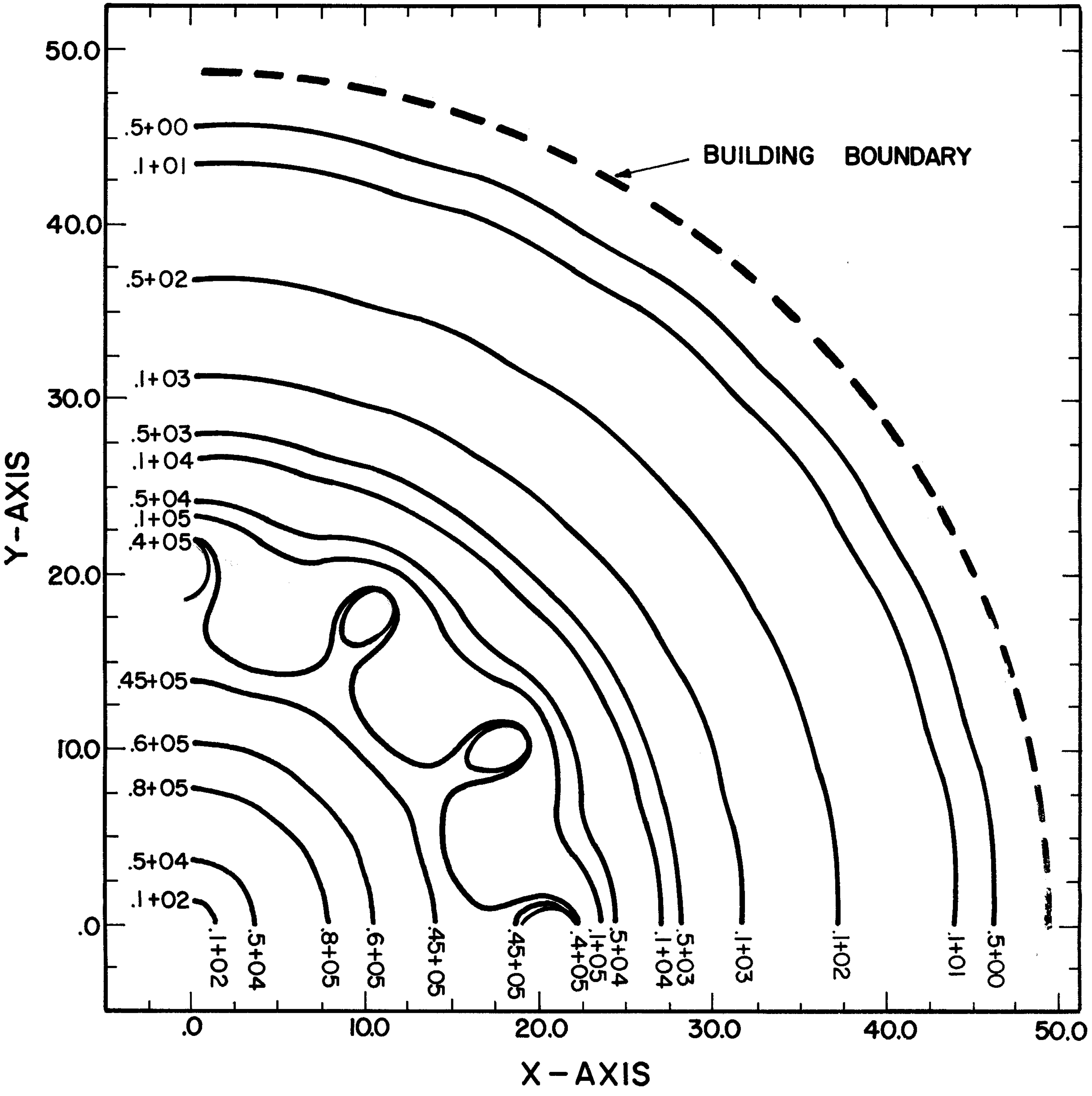
Fig. 6 - Shielding efficiencies of mumetal and steel in 60 cps a.c. fields.

Fig. 7 - Comparison of the stray fields produced by 12 versus 24 toroidal field coils.

FIGURE 1

|B| PLOT ON X-Y PLANE

|B| IN GAUSS



|B| PLOT ON R-Z, VERTICAL PLANE
|B| IN GAUSS

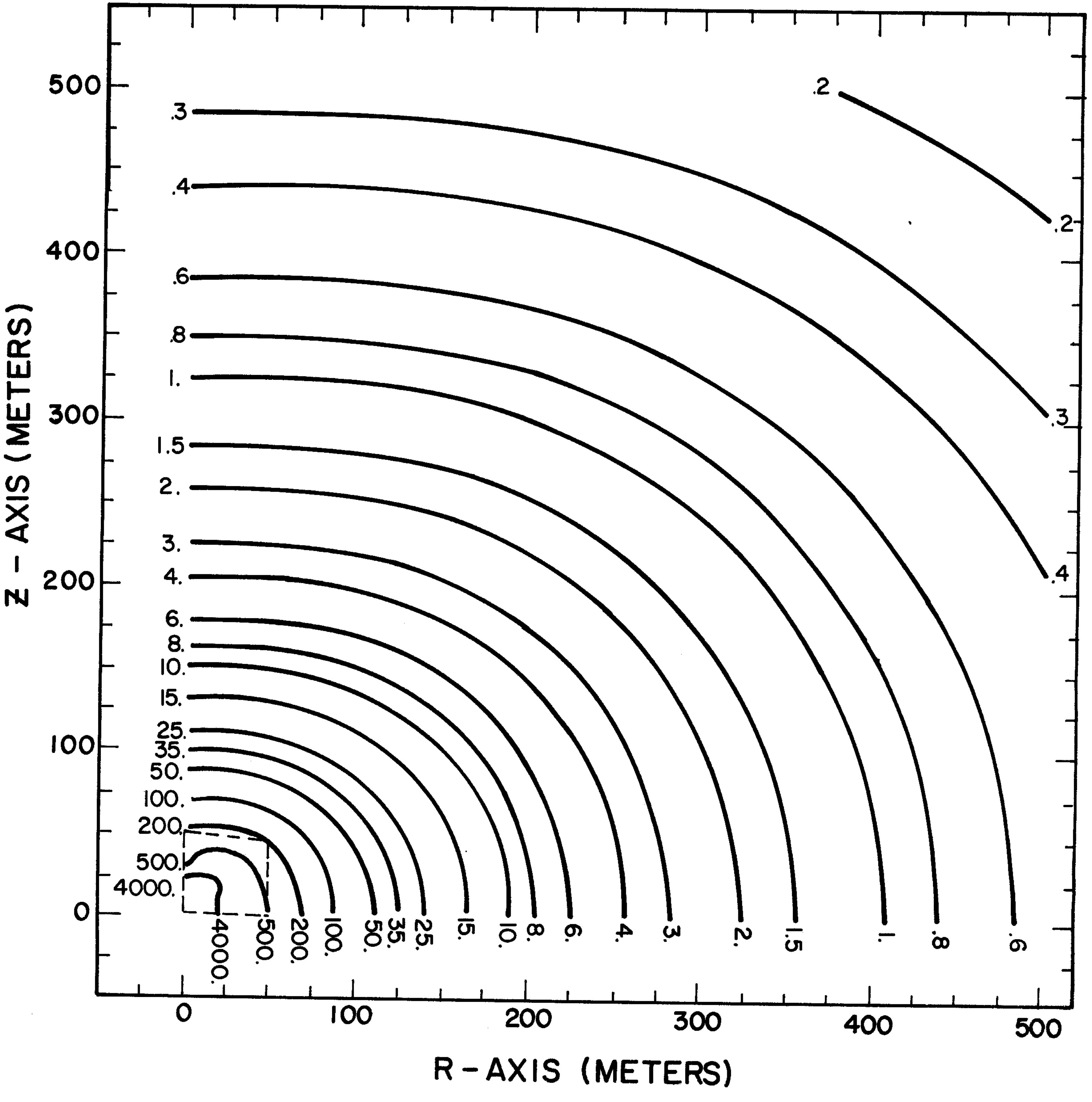
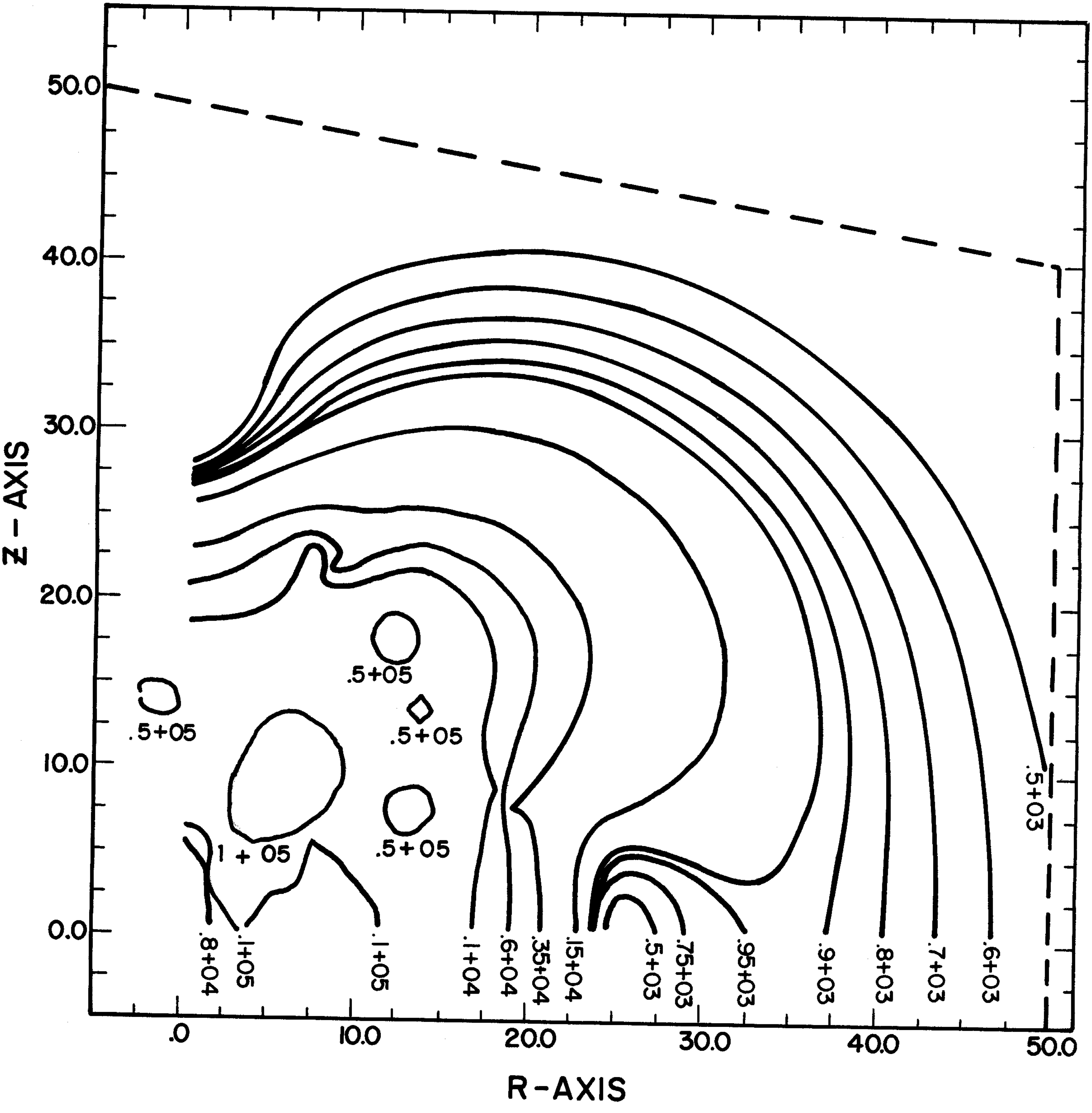


FIGURE 3

|B| PLOT ON R-Z, VERTICAL PLANE

|B| IN GAUSS



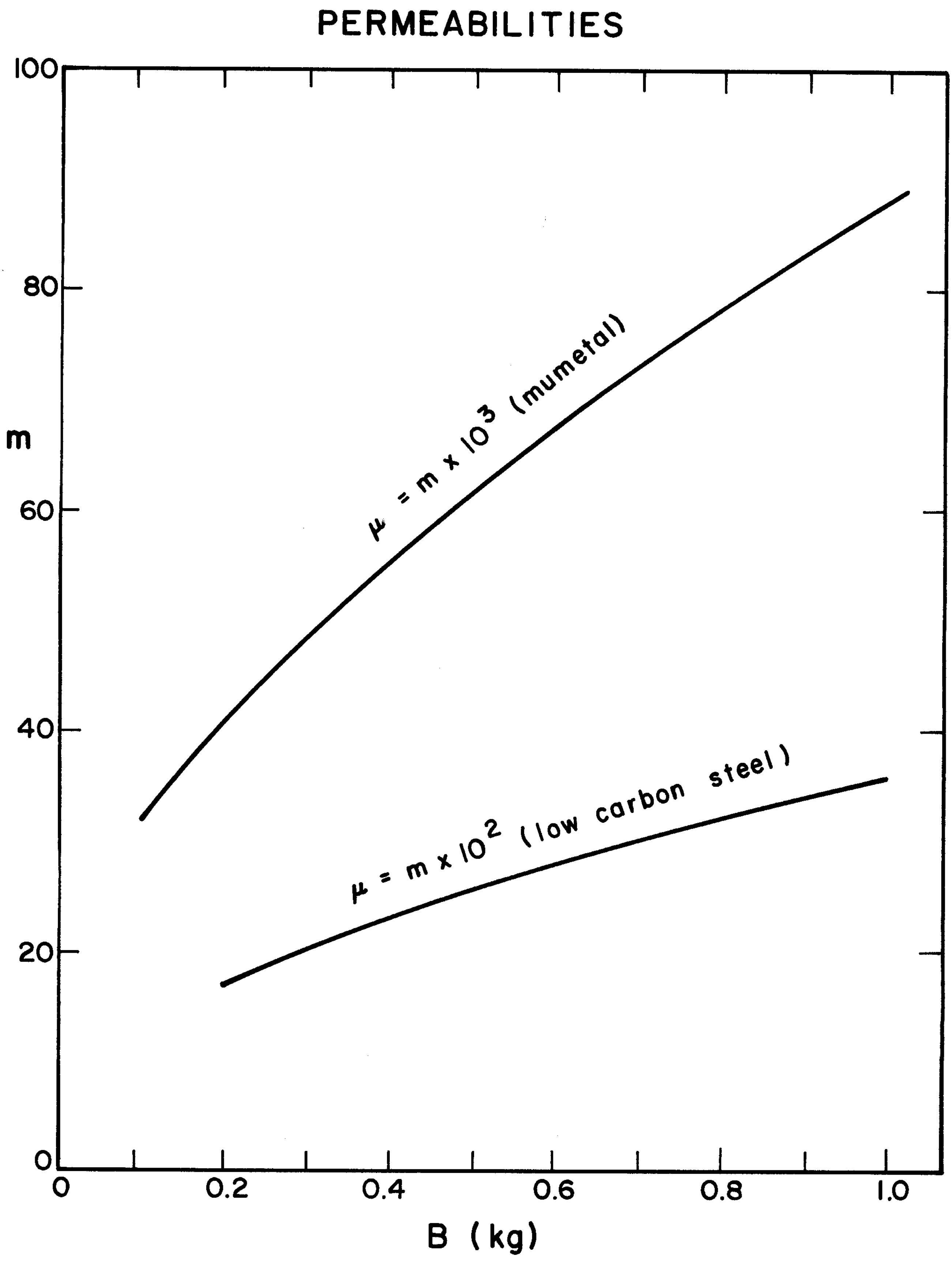

PERMEABILITIES
m
B (kg)
0
20
40
60
80
100
0
0.2
0.4
0.6
0.8
1.0
μ = m x 10^3 (mumetal)
μ = m x 10^2 (low carbon steel)

Figure 4

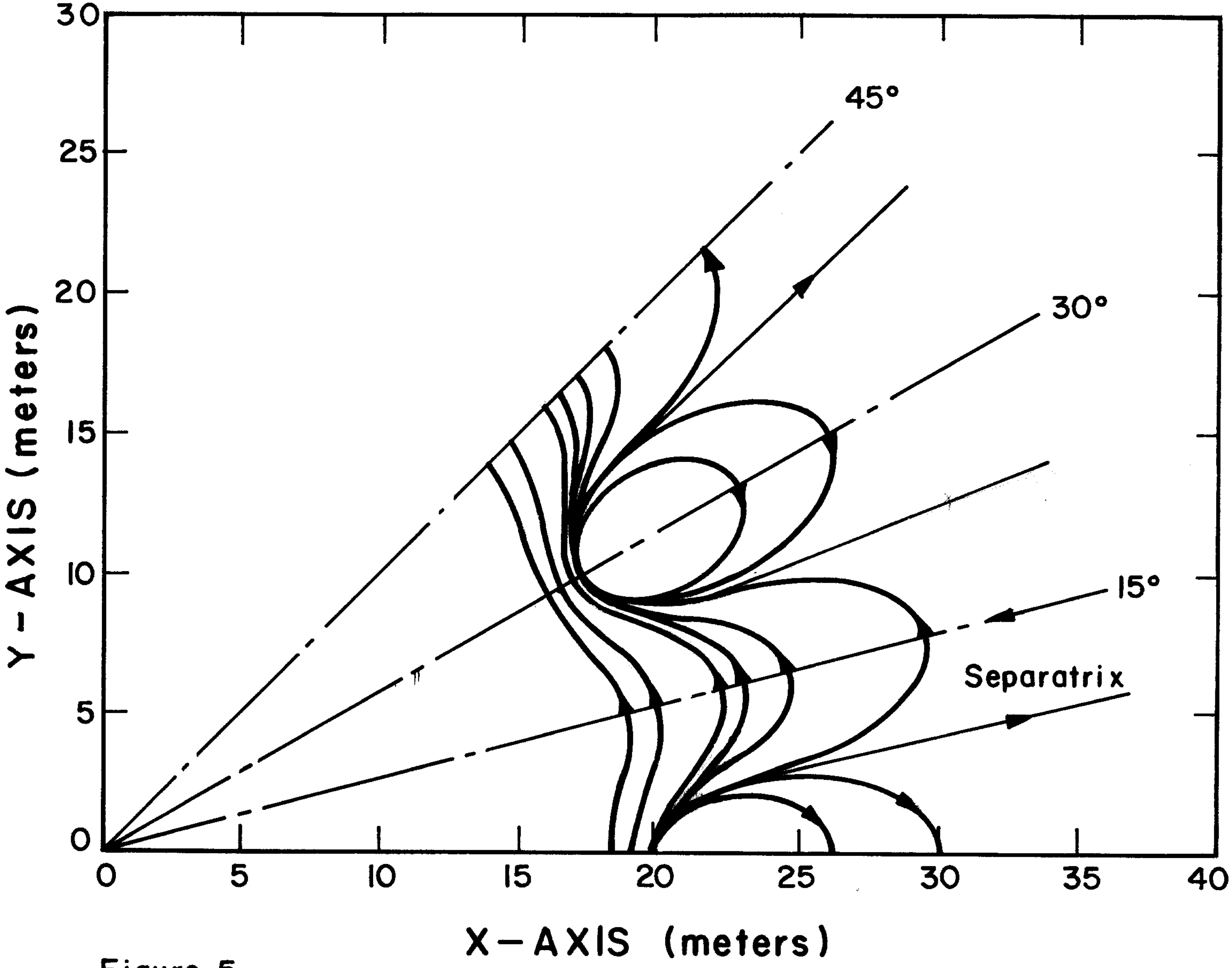
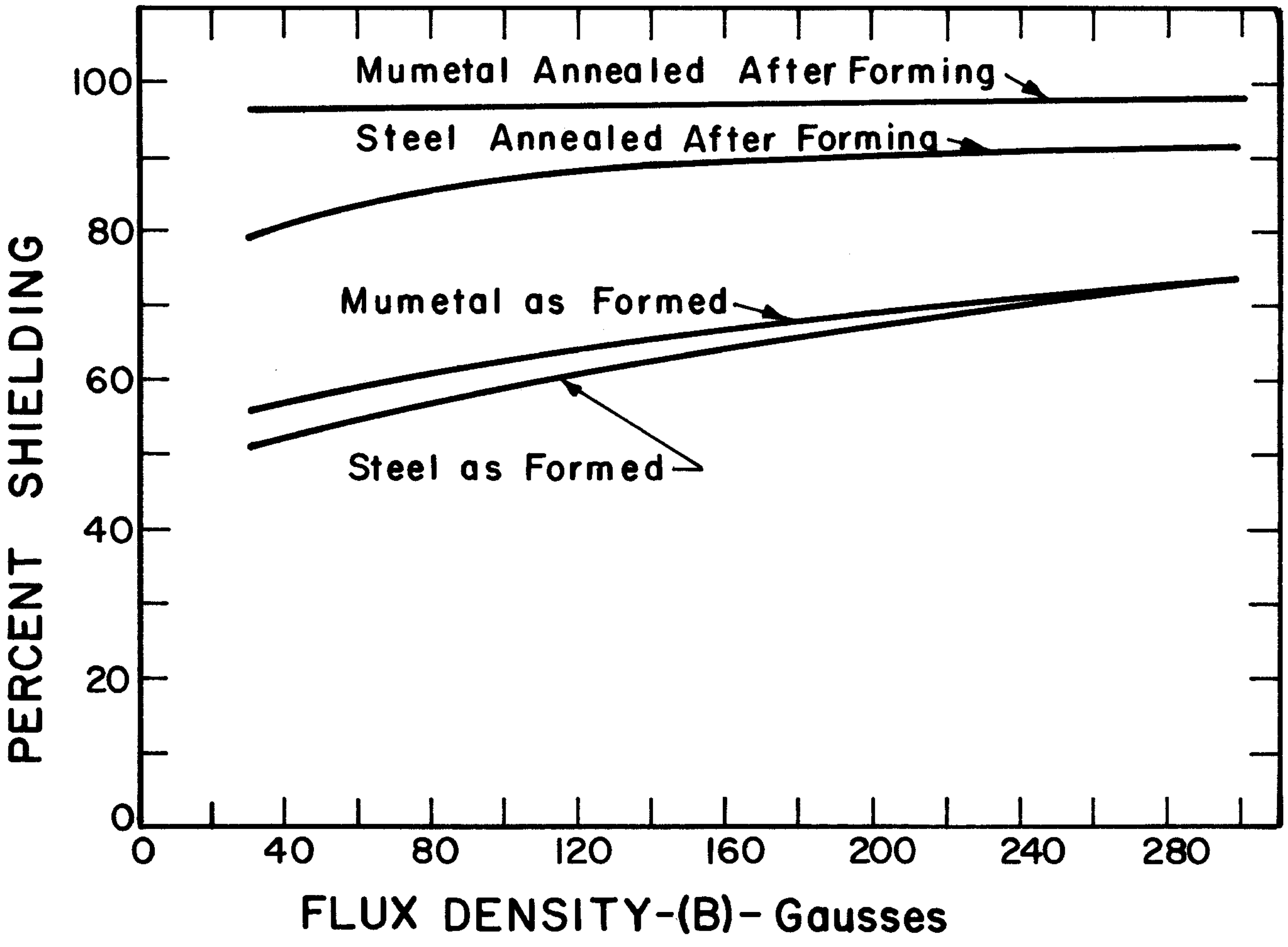

30
25
20
15
10
5
0
Y - AXIS (meters)
0
5
10
15
20
25
30
35
40
X - AXIS (meters)
45°
30°
15°
Separatrix

Figure 5



Mumetal Annealed After Forming
Steel Annealed After Forming
Mumetal as Formed
Steel as Formed
PERCENT SHIELDING
100
80
60
40
20
0
0
40
80
120
160
200
240
280
FLUX DENSITY-(B)- Gausses

Figure 6