national accelerator laboratory

FN-179
0423

FIELD DESIGN OF A PICTURE-FRAME BENDING MAGNET USING SUPERCONDUCTING COILS

L. C. Teng, National Accelerator Laboratory

and

R. J. Lari, Argonne National Laboratory

January 9, 1969

Iron-core magnets energized by superconducting coils have been used in a few applications and were recently suggested by R. R. Wilson (FN-173) for application to the colliding-beam storage ring. The more immediate and likely application of such magnets in NAL is perhaps as elements in a beam-transport line. The advantage of these iron-core superconducting-coil magnets is the obvious economy in power consumption and the less obvious but true economy in construction cost.

In a bending magnet the high-current density attainable in the superconducting coil permits a simple picture-frame cross section. Unless the entire magnet yoke is cooled to the liquid helium temperature of the coil,which is undesirable for both operation and economy, the coil has to be separated from the yoke by a relatively thick layer of thermal insulation. The magnet cross section, therefore, looks like the one shown in Fig. 1 without the notch.

At low field when the permeability μ of iron is essentially infinity the absence of current above and below the coils causes the field to rise from the center toward the coils. At high field when the yoke iron is partially saturated this rise is even more pronounced because of the shorter flux path through the iron core near the coil compared to that near the center. This is shown in Fig. 2, where the computed relative field gradient $k = \frac{B'}{B}$ is plotted against the horizontal distance x from the magnet center at $\mu = \infty$ and at 20 kG. The cross-sectional dimensions of the magnet are as given in Fig. 1. A good-field region of 1" high by 2.5" wide is desired. With 0.25" thick insulation, the poles (or the top and bottom of the opening in the picture frame) are 1.5" apart. The rough rule-of-thumb of adding one gap height to each side of the required good-field width gives a separation of 2.5" + 1.5" + 1.5" = 5.5" between coils. The magnetic properties of the core iron are assumed to be those of 1010 steel and the stacking factor is taken to be 100%. If one calculates the area under the k-curve from x = o to x = 1.25", namely $\int_o^{1.25"} kdx$ for these two curves one gets the two points on the w = o axis in Fig. 3.

To compensate for the rise of the field toward the coil one can cut notches in the iron as shown in Fig. 1. These act like inverse two-dimensional Rose shims. These notches or inverse shims should be so adjusted as to produce the most uniform possible field between x = -1.25" and x = 1.25" over the range of field from B = 0 to say B = 20 kG. The procedure used in arriving at the optimal size and position of these notches is the following:

(1) The corrective effect depends, to the first order only, on the position d and the area h x w of the notches. The detailed

shape of the notch is not critical. Hence the depth or height h of the notch can be chosen more-or-less arbitrarily provided that the resulting optimal notch width w is reasonable. We have chosen h = 0.25".

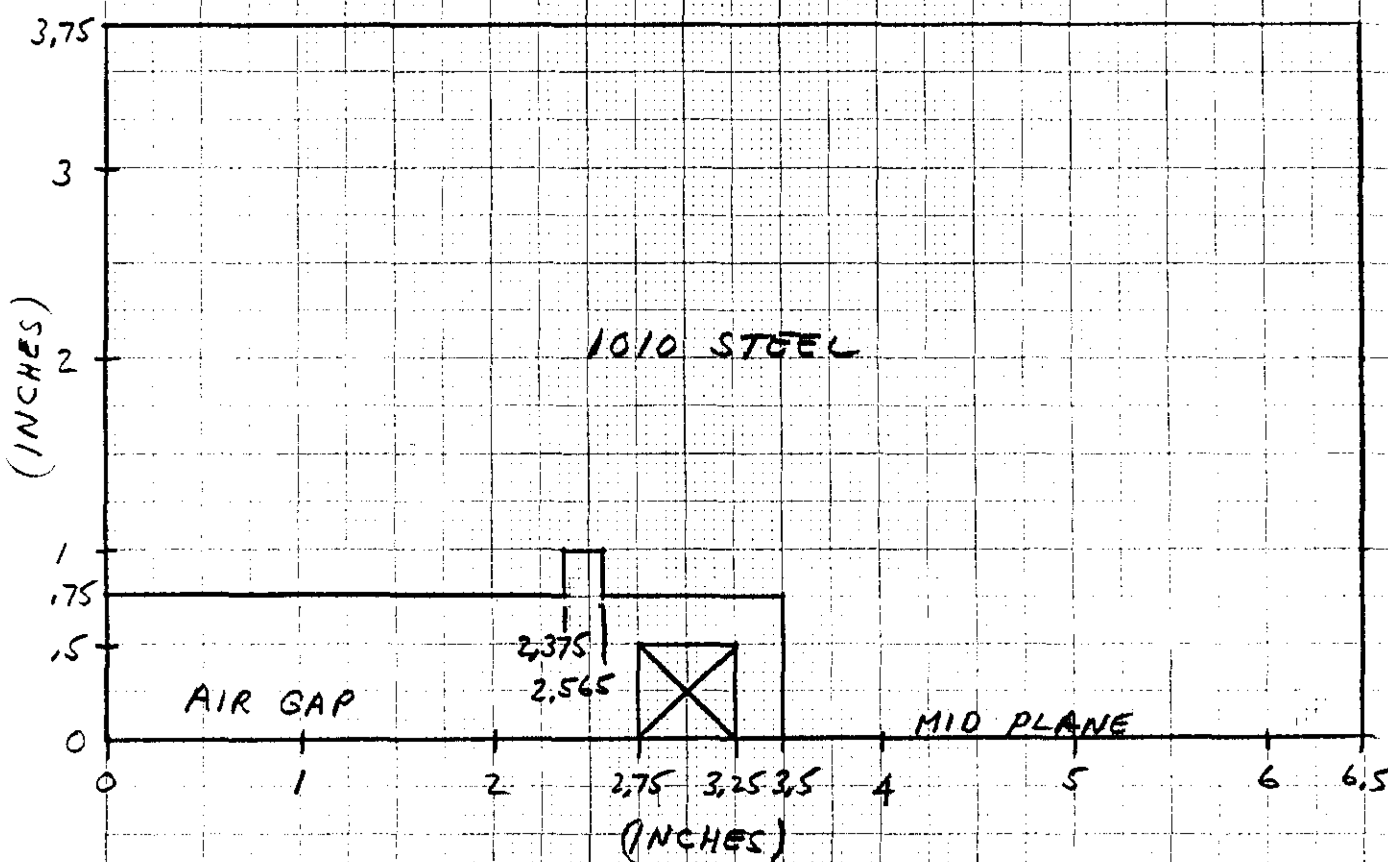
(2) With a given position, say, $d = d_A = 2.25"$ and various values of w we can compute two $a = \int_0^{1.25"} k dx$ versus w curves one for $\mu = \infty$ and one for some high field, say, B = 20 kG. These are shown as curves I and II in Fig. 3. These two curves intersect at point A, corresponding to notch width $w = w_A$. This means that with w_A and d_A the notches will produce k-curves at $\mu = \infty$ and at 20 kG deviating equally from k = 0 on the average. And, in this case, the deviation is negative as indicated by the fact that the point A lies below the a = 0 axis.

(3) With a second given position, say, $d = d_B = 2.5"$ similar curves III and IV give an intersection at B ($w = w_B$) lying above the axis. We, then, interpolate between d_A and d_B to find the optimal position d_{opt} for which the intersection of the two curves lies on the a = 0 axis at $w = w_{opt}$. The position d_{opt} and width w_{opt} are clearly optimal in the sense that they produce k-curves with minimum deviation from k = 0 between x = 0 and x = 1.25" at both low field ($\mu = \infty$) and high field (B = 20 kG), at least as far as can be accomplished with one set of notches with height h = 0.25".

For the specific example we obtained $d_{opt} = 2.375"$ and $w_{opt} = .190"$. The k-curves at $\mu = \infty$, B = 20 kG, and some intermediate field values are plotted in Fig. 4. We see that over the required aperture of $x < 1.25''$ k is within ± .005 m^{-1} all the way from B = 0 to B = 20 kG. The same procedure can be followed to obtain the optimal position and size of a second set of notches to further improve the field uniformity and this process can be continued ad infinitum. However, as we have seen, the correction produced by one set of notches is already quite adequate and additional notches will only make the fabrication of the magnet yoke more complicated and costly.

The program TRIM on the IBM/360 computer was used throughout this work. Mr. Jerome K. Wilhelm, Argonne, prepared the input cards, submitted the runs and plotted the results.

FIGURE 1


3,75
3
2
1
,75
,5
0
(INCHES)
1010 STEEL
2,375
2,565
AIR GAP
MID PLANE
0
1
2
2,75
3,25
3,5
4
5
6
6,5
(INCHES)

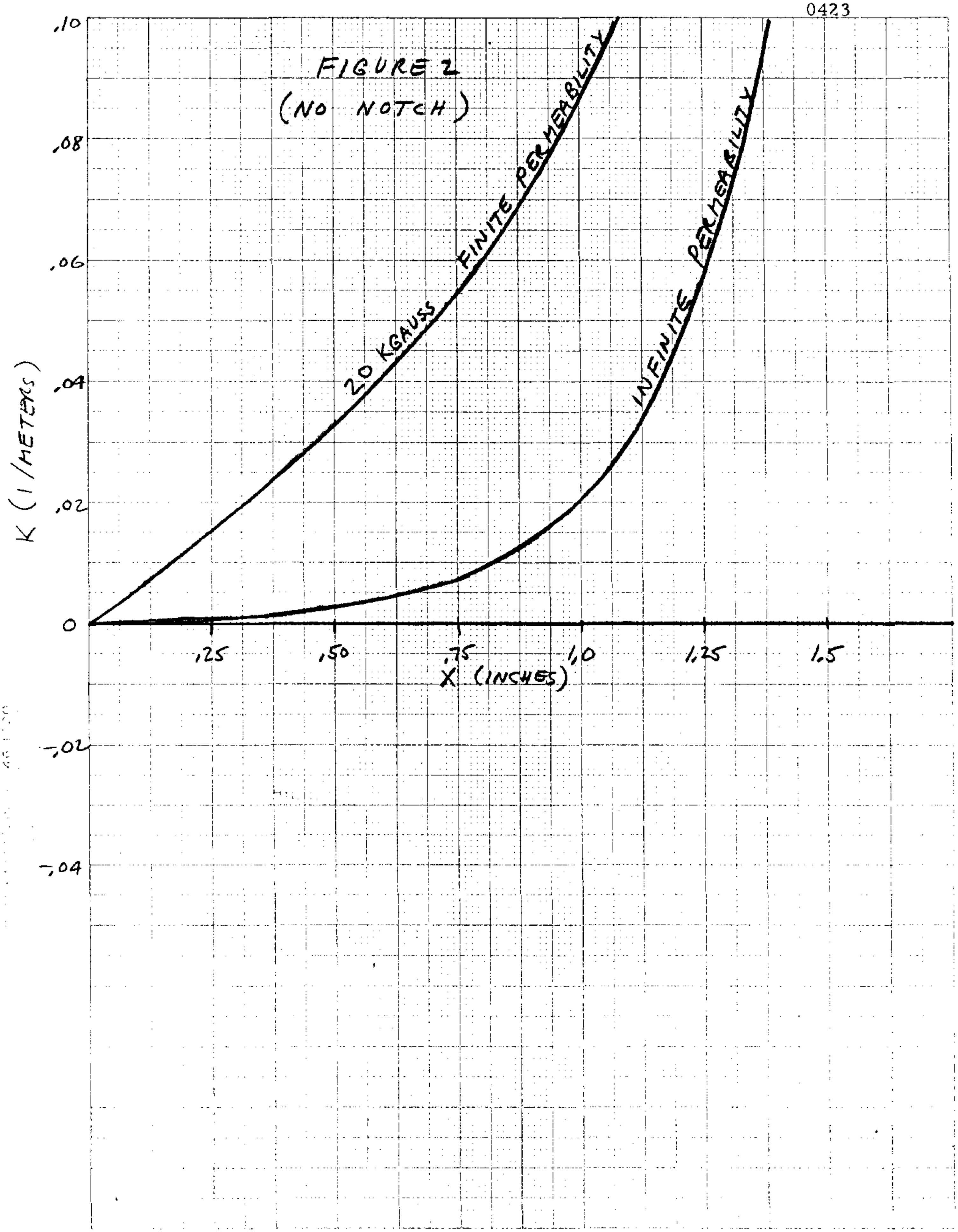


FIGURE 2
(NO NOTCH)
20 KGAUSS FINITE PERMEABILITY
INFINITE PERMEABILITY
K (1/METERS)
X (INCHES)
.10
.08
.06
.04
.02
0
-.02
-.04
.25
.50
.75
1.0
1.25
1.5

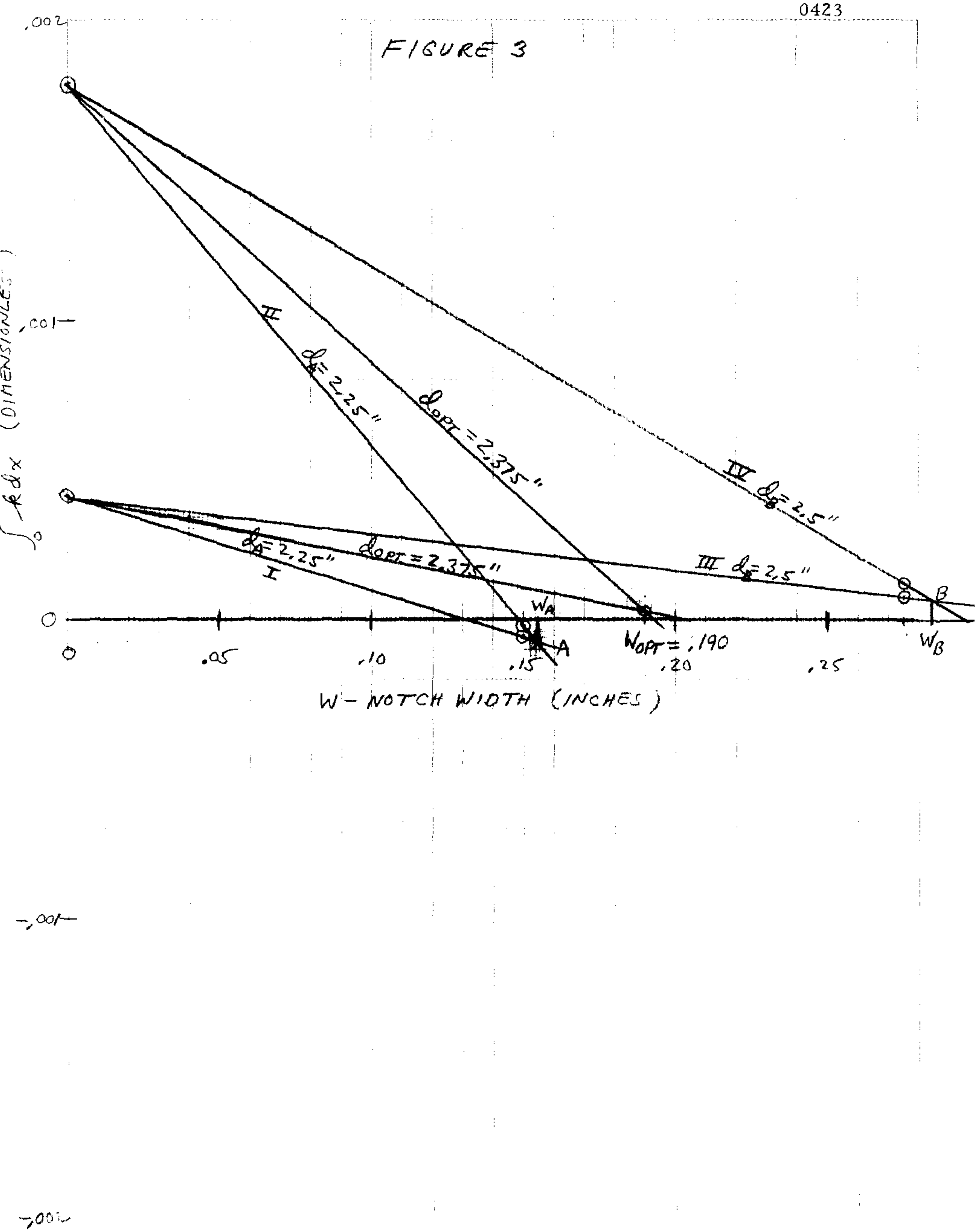
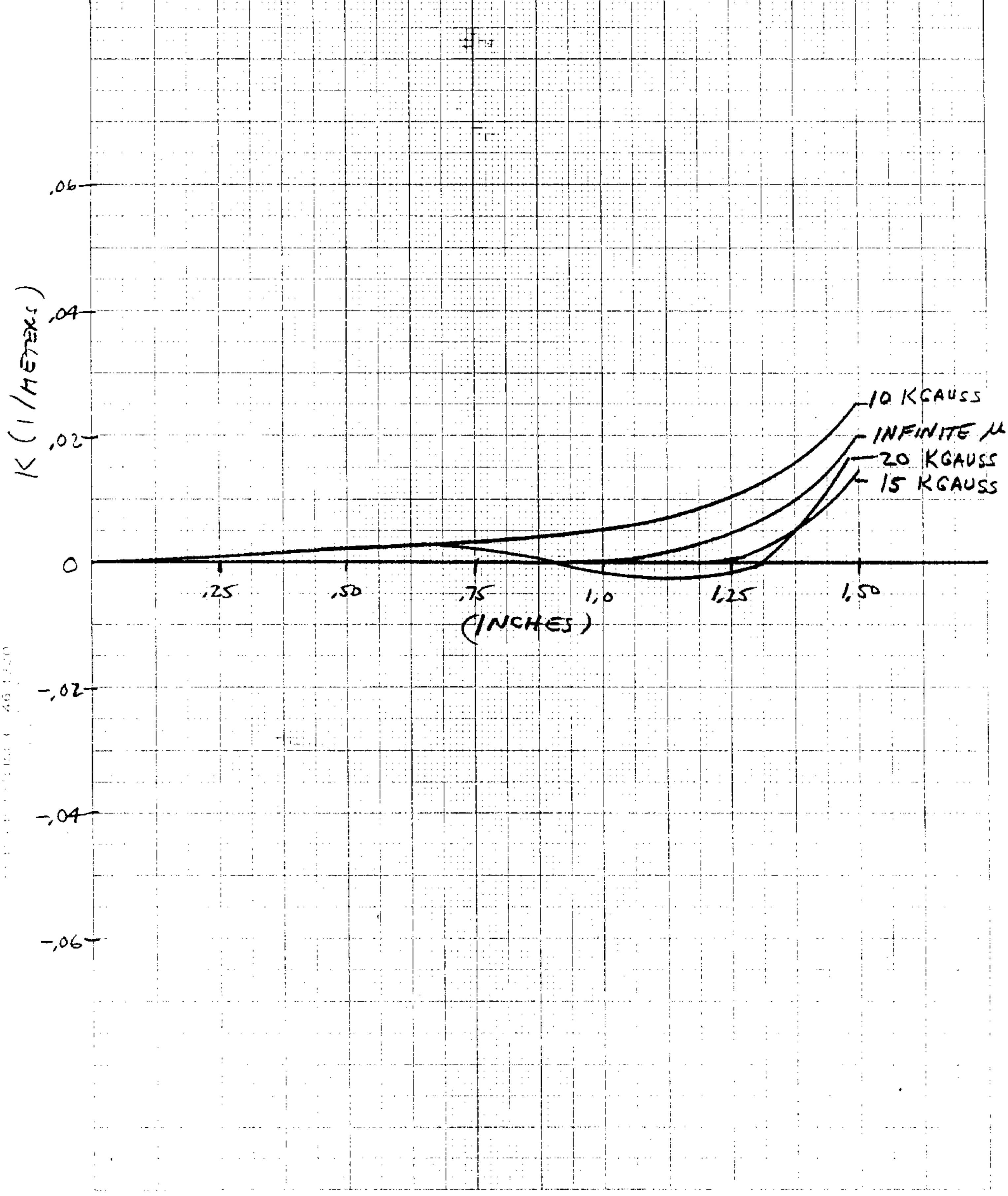


FIGURE 3
.002
.001
0
-.001
-.002
$\int_0^{1.25} k\, dx$ (DIMENSIONLESS)
II
$d_A = 2.25''$
$d_{OPT} = 2.375''$
IV $d_B = 2.5''$
I
$d_A = 2.25''$
$d_{OPT} = 2.375''$
III $d_B = 2.5''$
W_A
A
$W_{OPT} = .190$
B
W_B
0
.05
.10
.15
.20
.25
W - NOTCH WIDTH (INCHES)

FIGURE 4


.06
.04
.02
0
-.02
-.04
-.06
K (1/METERS)
.25
.50
.75
1.0
1.25
1.50
(INCHES)
10 KGAUSS
INFINITE μ
20 KGAUSS
15 KGAUSS