national accelerator laboratory

TM-149
0423

COMPUTER DESIGN OF THE MAIN-RING BENDING MAGNETS

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December 23, 1968

The philosophy and procedure for the design of the main-ring bending magnets are as outlined in Report FN-156. The numerical technique and results obtained following that procedure will be discussed in this report.

The computer programs LINDA (written by R. S. Christian of Purdue in collaboration with J. H. Dorst of LRL) and TRIM (written by A. M. Winslow of LRL in collaboration with J. S. Colonias of LRL) were used. For each program a mesh is set up describing the geometry of the magnet. A relaxation calculation is used to calculate the vector magnetic potential at each mesh point. The values of the field and the relative gradient are then calculated. Both programs include the finite permeability of the steel and the current distribution. At the present, TRIM is used on the IBM/360 computer at Argonne and LINDA on the CDC-6600 computer at LRL.

(A) <u>R versus δ Curves</u>

As defined in FN-156, $R \equiv \frac{(NI)_{\text{between poles}}}{(NI)_{\text{total}}}$

is the fraction of total ampere-turn which is in between the poles, and δ is the thickness of the gap between the pole face and the coil conductors. At low field, the field is uniform when R = 1 and the field non-uniformity when R<1 may be compensated by

properly adjusting δ. For each of the magnets B1 and B2 a set of R versus δ curves is computed for various values of the pole width W. These curves are given in Fig. 1 and 2. The shaded band over each curve corresponds to values of (R, δ) for which the relative field gradient $k \equiv \frac{B'}{B}$ is within ±0.5% per meter over the gap up to 0.2 inches of the coil. The relative gradient k is positive above the R versus δ curve and is negative below the curve as illustrated in Fig. 3.

(B) Compensation for the midplane gap

A midplane gap, ε, is also required for turn-to-turn insulation. This lowers the field near the coil and hence can be compensated by increasing the ground gap δ. The effect on k is shown in Fig. 4. If ε is the half-midplane gap, 1.5ε must be added to the value of δ for compensation. This compensation is not perfect and the good-field region is reduced slightly even with the optimum compensation.

(C) Eddy-current effect

The effect of eddy current in the part of the coil which is in between poles has been calculated by assuming a linear current distribution across each coil conductor. At the injection field of 490G the effects on the field of B2 are given in Fig. 5 for the cases of 2 and 4 turns in between poles. As expected the effect for the case of 4 turns is smaller. But even for 2 turns the effect is tolerable.

(D) High-field considerations

For R = 1, saturation of the iron at high field will

cause the field to rise near the coil. For low values of R the field will droop near the coil. For a given pole width and high-field value, there is a point R_{opt} and δ_{opt} on the R versus δ curve for which the k-curve is closest to zero. As a standard high-field value, 18 kG was chosen. For values higher than 18 kG the saturation is so large that when R is adjusted to be optimum for those fields, the field uniformity at intermediate values will not be acceptable. Sets of values of R_{opt} and δ_{opt} have been found for various pole widths as shown by the 18-kG curves of Figures 1 and 2.

Because of the integral number of turns in a coil only discrete values of R are possible. For the B1 magnet with a 12-turn coil they are: $\frac{1}{12}, \frac{2}{12}, \ldots, \frac{11}{12}, \frac{12}{12}$. Likewise, for the B2 magnet with a 16-turn coil the discrete values of R are $\frac{1}{16}, \frac{2}{16}, \ldots, \frac{15}{16}, \frac{16}{16}$. Figures 1 and 2 indicate that a smaller value of R requires a wider pole and hence a lower current density. A wider pole leads to a larger total flux and requires a bigger return yoke. In addition, the B1 and B2 magnets should have the same saturation characteristics. All of these consideration were taken into account in selecting the values shown in Table 1 as the optimum parameters. Three different overall dimensions have been calculated and the resulting saturation characteristics are given in Table 2. One of these "matched pairs" of magnets (case C) has been calculated including the cooling-water holes in coil conductors and insulation around each conductor. Cross sections of the coils are shown in Fig. 6. The shape of the

k-curves are given in Figures 7 and 8. The pole widths have been rounded to 9.30 inch and 8.45 inch.

The authors wish to thank Mr. Gerald J. Bellendir for updating and improving the computer program TRIM, Mr. Jerome K. Wilhelm for preparing the input cards and plotting the results, and Mr. J. H. Dorst and his associates of LRL for their many CDC-6600 computer runs.

TABLE 1

	B1	B2
Gap dimensions	1.5"x5.0"	2.0"x4.0"
Coil window dimensions	4.0"x2.0"	4.0"x3.0"
Pole width W	9.29"	8.43"
R_{opt}	0.25	0.25
δ_{opt}	0.0006"	0.0068"
Total coil turns	12	16
Coil turns in between poles	3	4

TABLE 2 Relative Excess Ampere-Turns Due to Saturation of Yoke
(Numbers in Parentheses are Overall Dimensions of Yoke)

Field (Kilogauss)	Case A B1 (23"x13.6")	Case A B2 (23"x13.0")	Case B B1 (24"x14.4")	Case B B2 (24"x13.5")	Case C B1 (with Holes & Insulation) (25"x16.0")	Case C B2 (with Holes & Insulation) (25"x14.0")
9.0	0.50%	0.37%	0.47%	0.37%	0.45%	0.25%
15.0	1.59%	1.85%	1.06%	0.93%	0.85%	0.73%
18.0	9.37%	9.36%	5.64%	5.61%	3.55%	3.69%
19.5	-----	-----	-----	-----	6.87%	7.33%
21.0	28.31%	29.91%	19.46%	17.93%	13.64%	13.35%

FIGURE 1

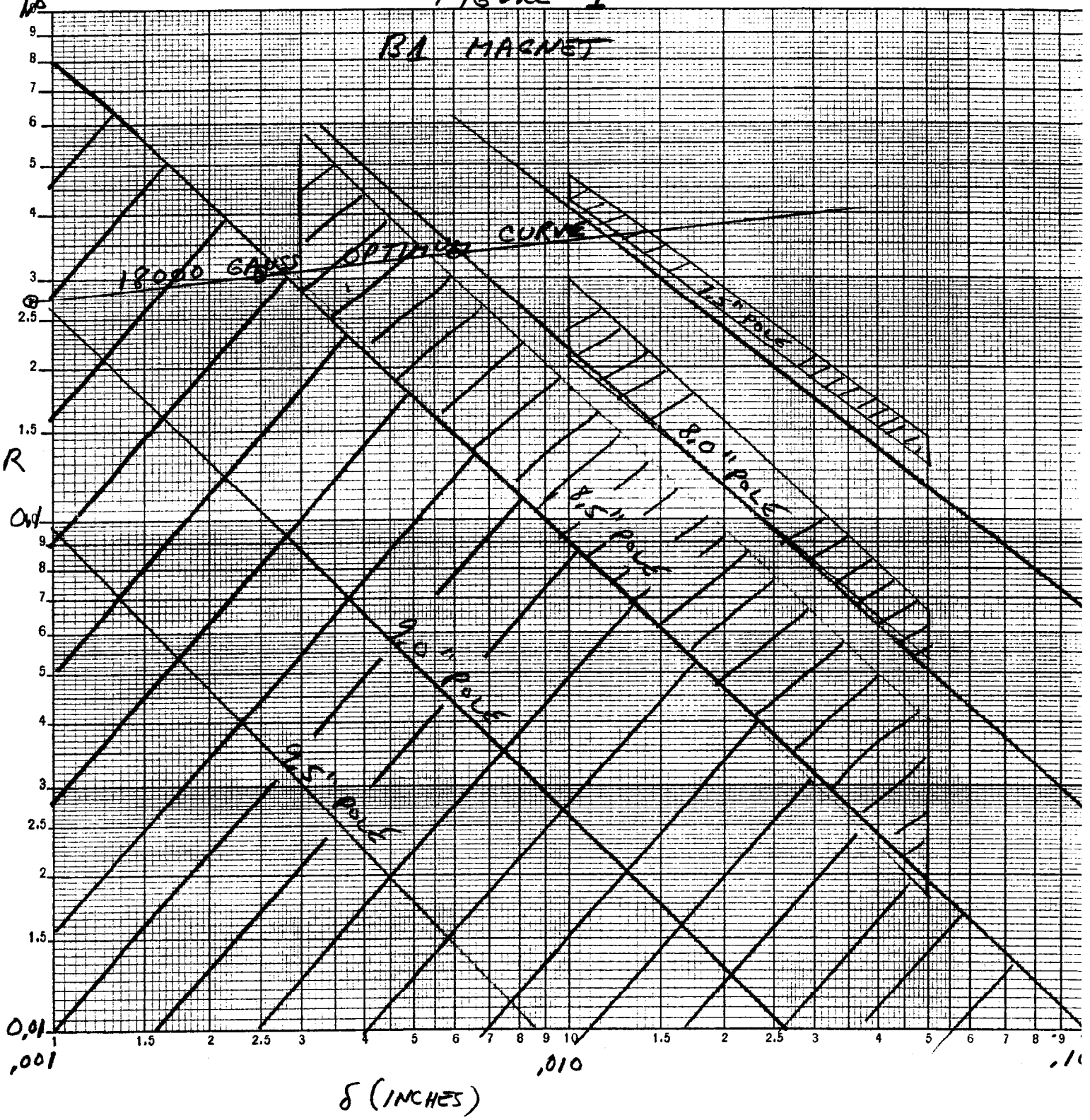
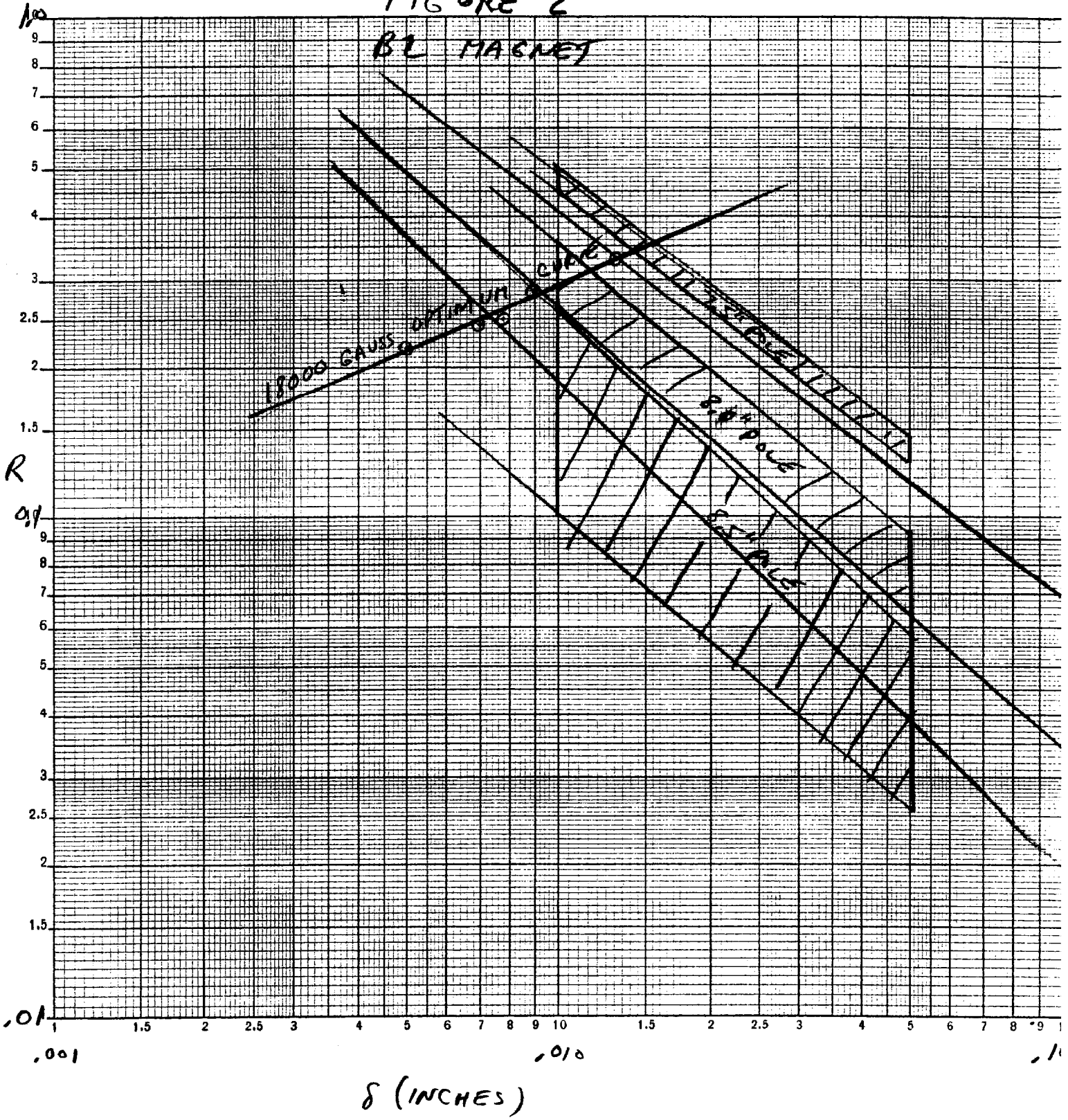

B1 MAGNET
18000 GAUSS OPTIMUM CURVE
7.5" POLE
8.0" POLE
8.5" POLE
9.0" POLE
9.5" POLE
R
δ (INCHES)
,001
,010

FIGURE 2



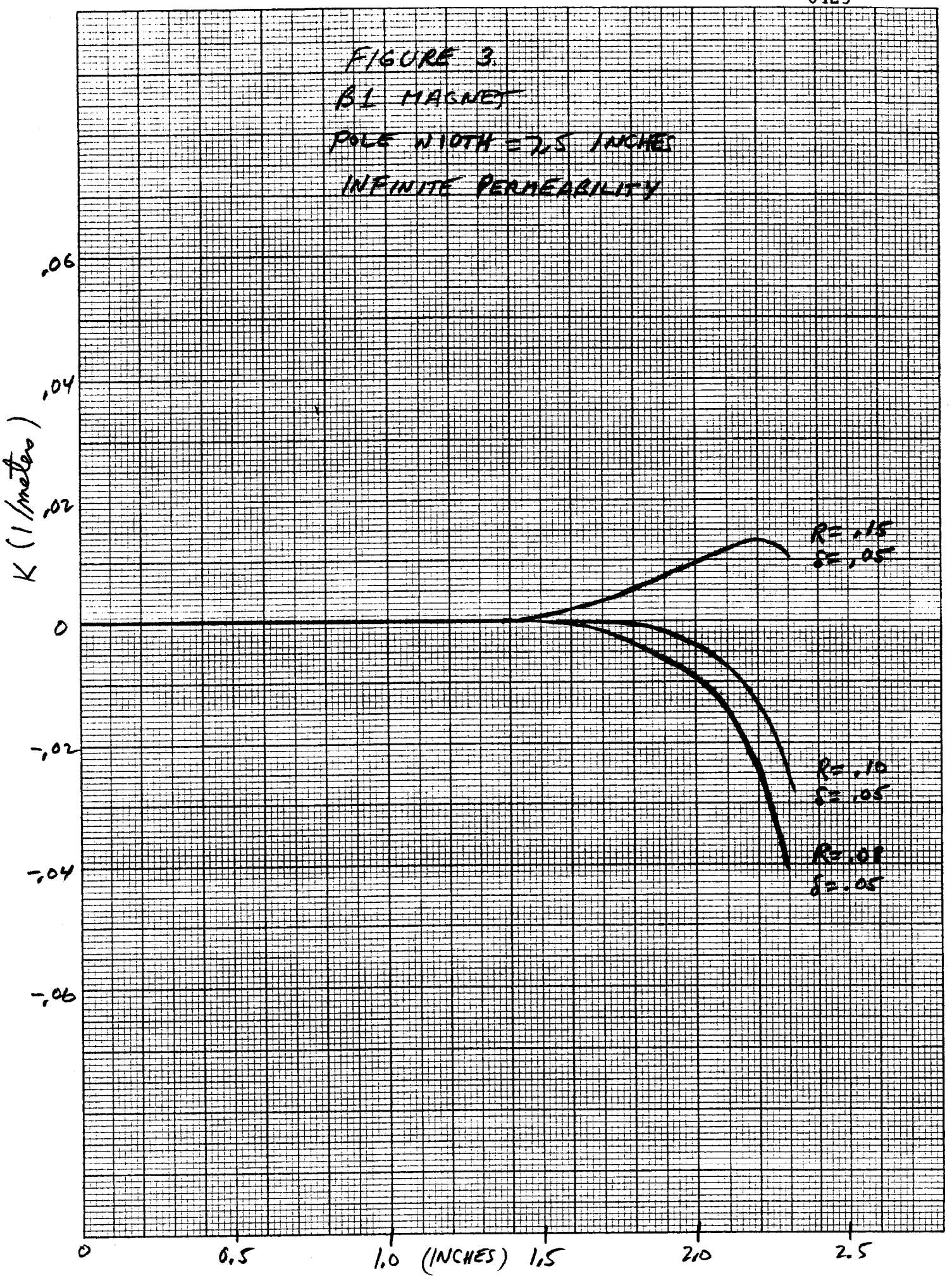


FIGURE 3.
B1 MAGNET
POLE WIDTH = 2.5 INCHES
INFINITE PERMEABILITY
K (1/meter)
.06
.04
.02
0
-.02
-.04
-.06
R= .15
δ= .05
R= .10
δ= .05
R= .05
δ= .05
0
0.5
1.0
(INCHES)
1.5
2.0
2.5

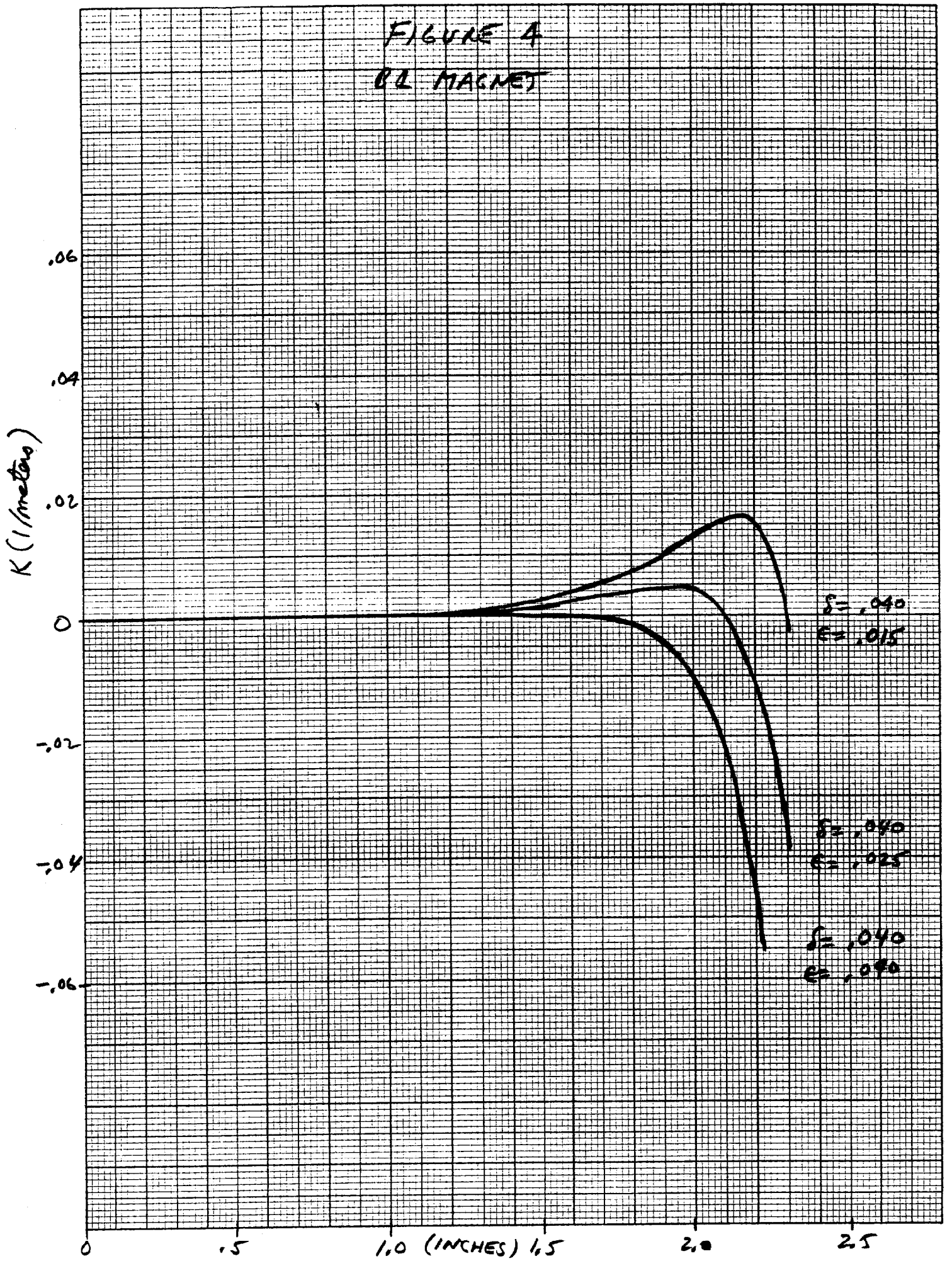


FIGURE 4
Q1 MAGNET
.06
.04
.02
0
-.02
-.04
-.06
K (1/meters)
0
.5
1.0 (INCHES) 1.5
2.0
2.5
δ= .040
ε= .015
δ= .040
ε= .025
δ= .040
ε= .040

FIGURE 5

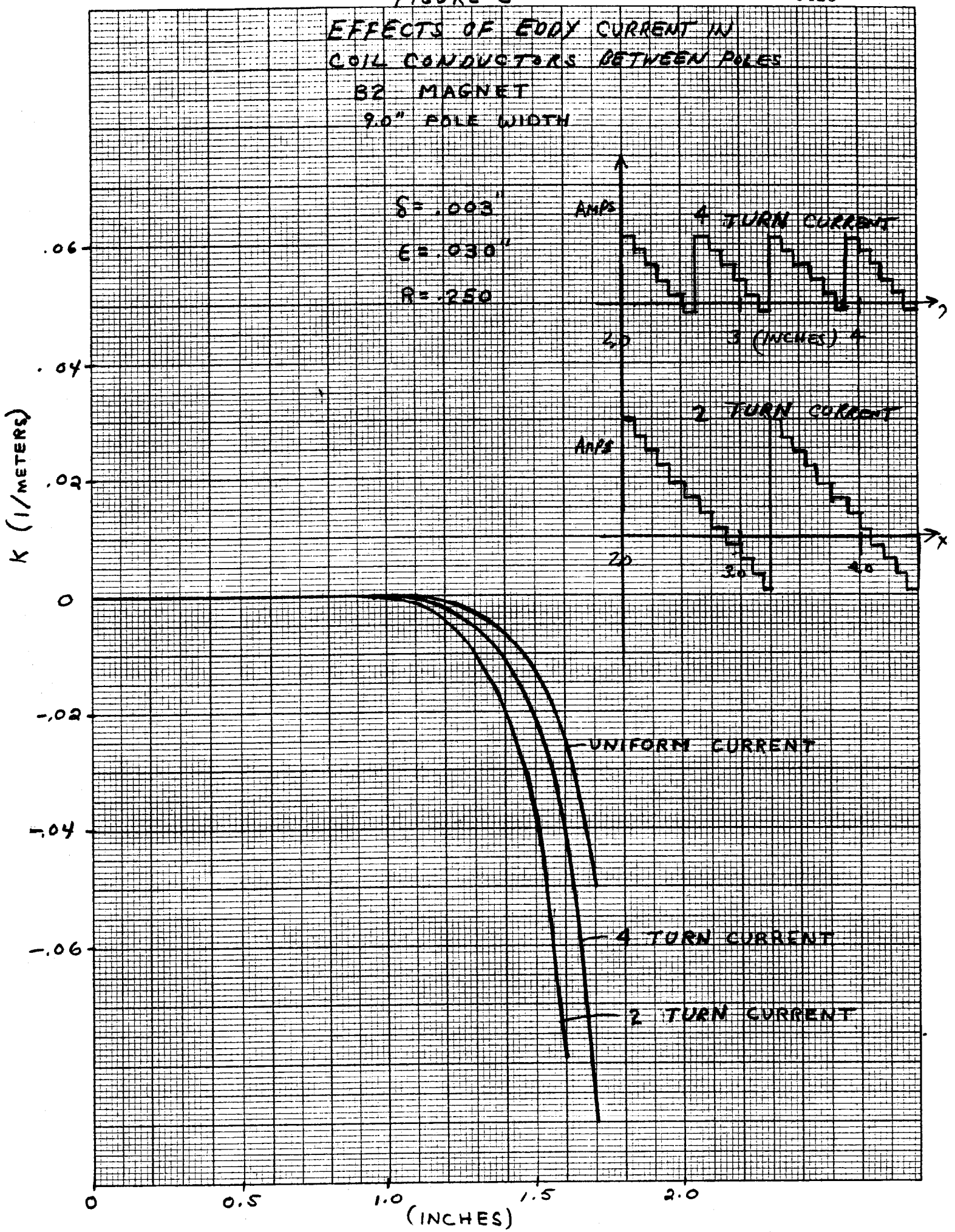
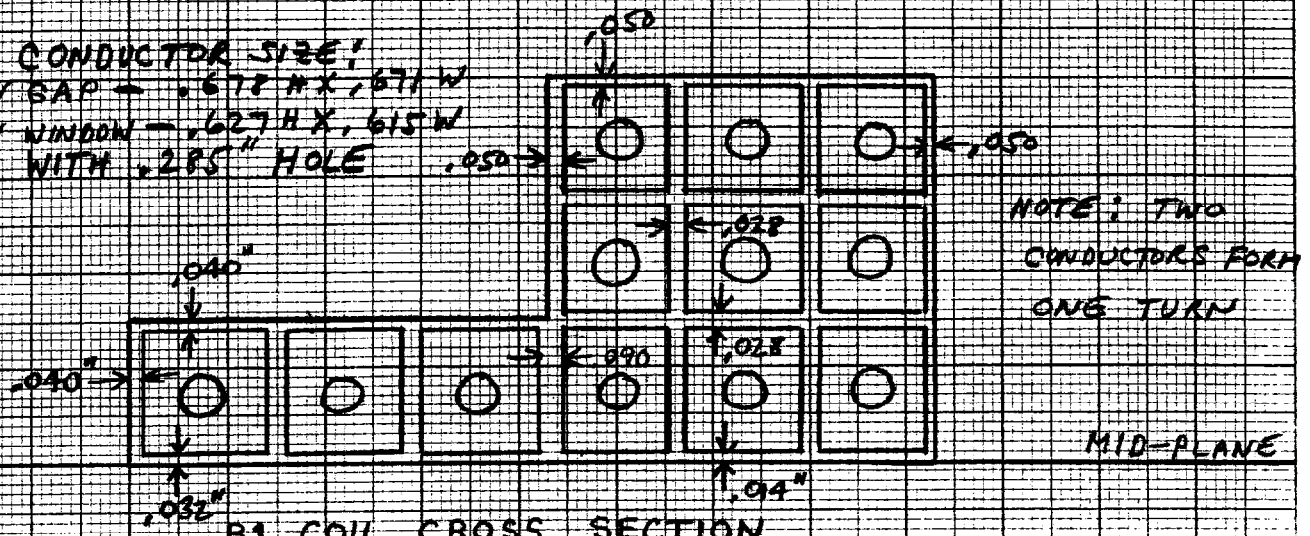

EFFECTS OF EDDY CURRENT IN
COIL CONDUCTORS BETWEEN POLES
B2 MAGNET
9.0" POLE WIDTH
δ = .003"
ε = .030"
R = .250
AMPS
4 TURN CURRENT
2.0
3 (INCHES) 4
2 TURN CURRENT
AMPS
2.0
3.0
4.0
x
.06
.04
.02
0
-.02
-.04
-.06
K (1/METERS)
UNIFORM CURRENT
4 TURN CURRENT
2 TURN CURRENT
0
0.5
1.0
1.5
2.0
(INCHES)

FIGURE 6

CROSS-SECTION OF COILS FOR CASE C

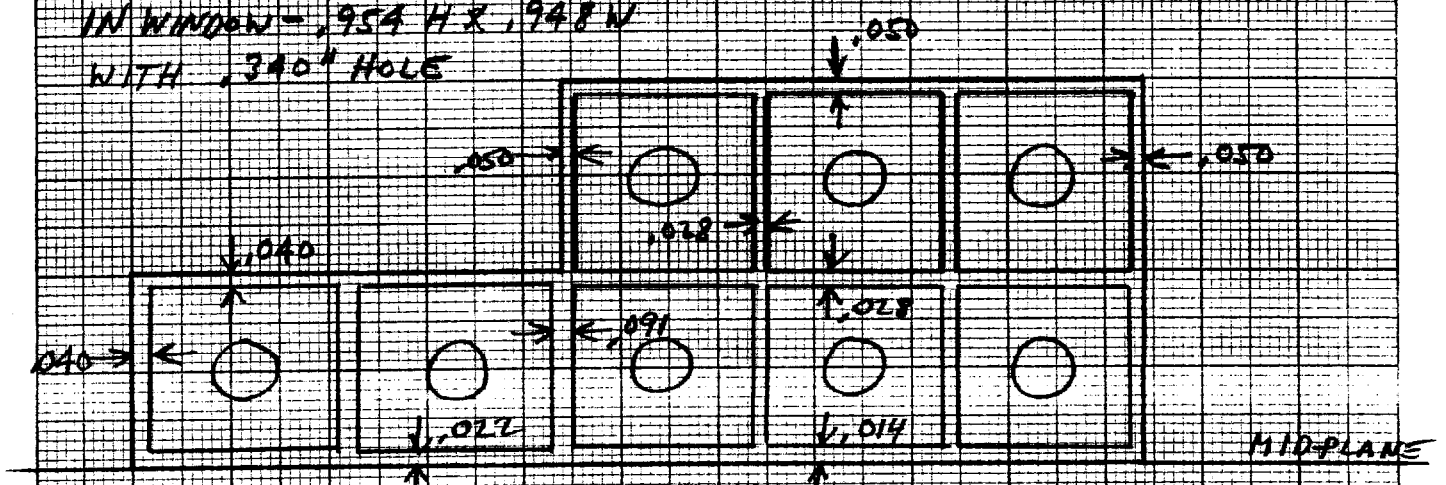
CONDUCTOR SIZE:
IN GAP — .678 H X .671 W
IN WINDOW — .627 H X .615 W
WITH .285" HOLE



NOTE: TWO CONDUCTORS FORM ONE TURN

B1 COIL CROSS SECTION

CONDUCTOR SIZE:
IN GAP — .938 H X 1.058 W
IN WINDOW — .954 H X .948 W
WITH .340" HOLE



B2 COIL CROSS SECTION

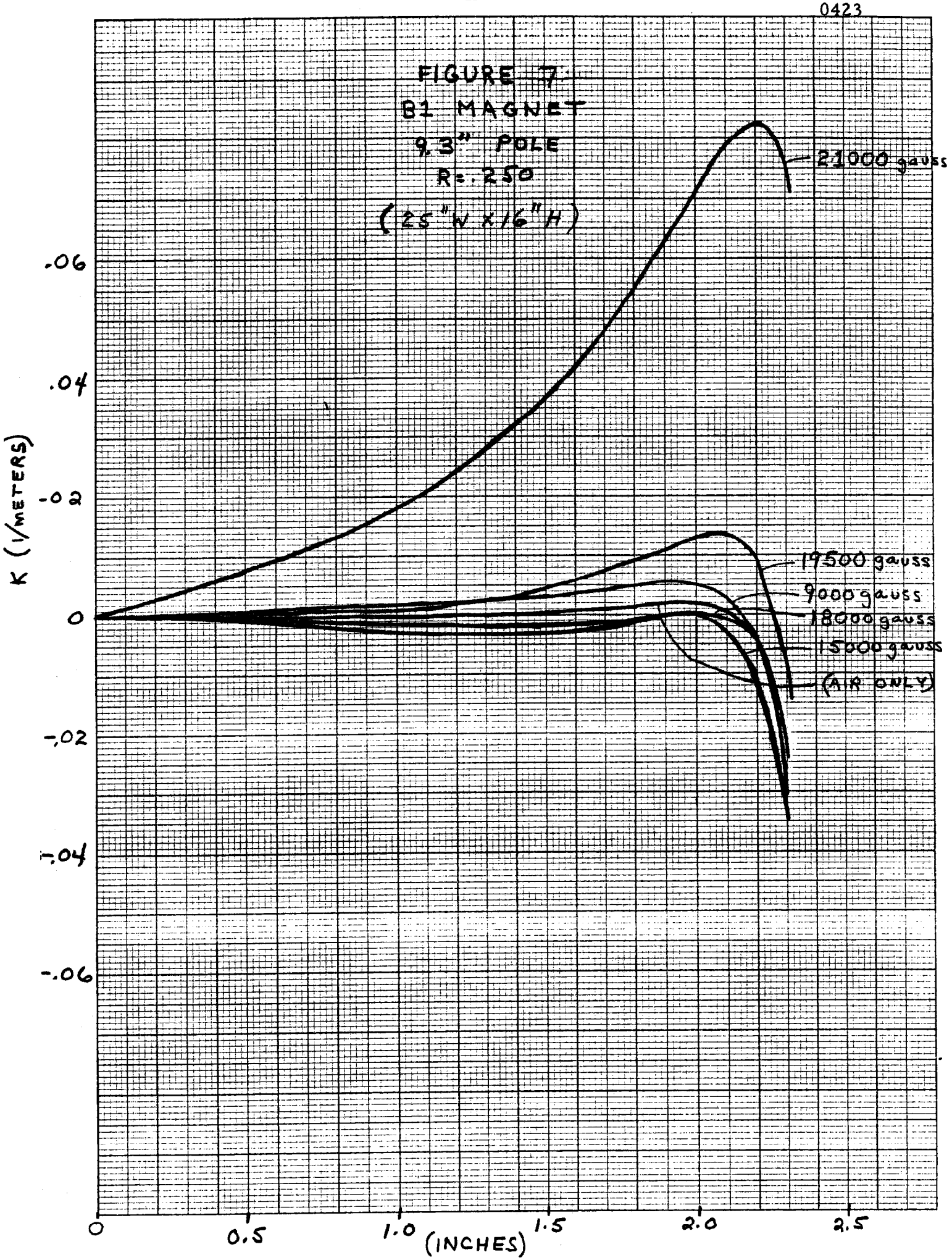


FIGURE 7
B1 MAGNET
9.3" POLE
R=.250
(25"W x 16"H)
21000 gauss
19500 gauss
9000 gauss
18000 gauss
15000 gauss
(AIR ONLY)
K (1/METERS)
.06
.04
.02
0
-.02
-.04
-.06
0
0.5
1.0
1.5
2.0
2.5
(INCHES)

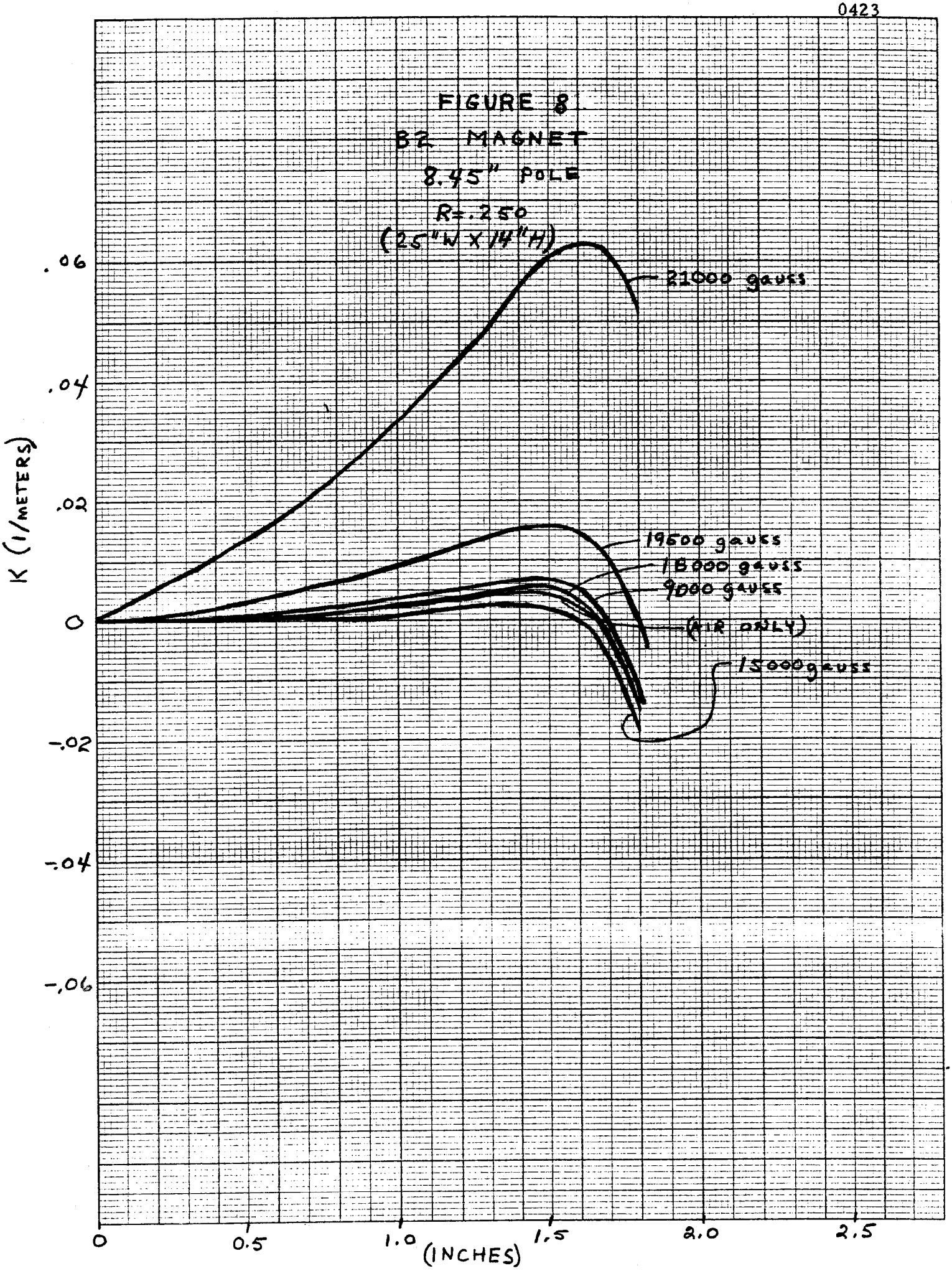


FIGURE 8
B2 MAGNET
8.45" POLE
R=.250
(25"W X 14"H)
21000 gauss
19600 gauss
18000 gauss
9000 gauss
(AIR ONLY)
15000 gauss
K (1/METERS)
.06
.04
.02
0
-.02
-.04
-.06
0
0.5
1.0
1.5
2.0
2.5
(INCHES)