Arc Quadrupole Design for the SSC

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The two-layer quadrupole design made for the Conceptual Design Report is based on the following requirements:

1. I = 6500 A at B_0 = 6.6T; this allows the quadrupole to be powered in series with the dipoles.

2.

$$\left[\frac{(G/I)_{0.33T} - (G/I)_{6.6T}}{(G/I)_{0.33T}}\right] - \left[\frac{(B_o/I)_{0.33T} - (B_o/I)_{6.6T}}{(B_o/I)_{0.33T}}\right] < 2\%$$

   i.e., The quadrupole will "track" the dipoles within 2%; thus the quadrupole trim coils can easily compensate for saturation effects.

3. Aperture = 40 mm. The total cost must be minimized within the above constraints. A parametric study was made for both one-layer and two-layer quadrupoles with cable having a radial width equal to the dipole 30-strand outer cable, but allowing strand diameter and ratio of copper-to-superconductor to vary while maintaining sufficient copper for quench protection and minimizing the amount of superconductor required (depending on the maximum field at the cable)[1].

   Based on these results an optimum cable design was selected for both one-layer and two-layer cases and a more detailed design was made for each case using the "PARTIALKEYSTONE" optimization code that is used for the dipole. The one-layer design has 9 turns per octant with one spacer wedge for minimizing field distortion and for mechanical

1) Quadrupoles: Preliminary Study, Part 1; R. Meuser, LBL, 11-25-85, SSC-MAG-59.

stability ("Roman arch with no internal support). The cable has 36 strands, 0.0226 inch strand diameter and copper-to-superconductor ratio of 2.5. The operating gradient is 140 T/m and magnetic length is 5.0 m. Thirty-six strands are probably near the maximum practical limit for cable fabrication. The two-layer design has 19 turns per octant with one wedge in the inner layer. The cable is the dipole outer cable, 30 strands, 0.0255 inch strand diameter, and copper-to-superconductor ratio of 1.8. The operating gradient is 212 T/m and magnetic length is 3.3 m. The difference in cost of the two was estimated assuming a mechanical construction method nearly identical to that used in the Tevatron quadrupoles. Cable costs were estimated in detail giving 3.12 $/ft for the single layer design and 3.54 $/ft for the two-layer design (the 36 strand cable requires less superconductor because of lower magnetic field). Without considering interconnections and other per unit costs common to both designs, the cost is about 2500 $/quad higher for the two-layer design. However, the additional 1.7 m of tunnel length would cost about 5200 $/quad*. Therefore the two-layer design was selected for the Conceptual Design. This design has the additional advantage that an optimum cable is already developed for the dipole whereas a different design would be required for the single layer case; thus additional costs of inventory maintenance, procurement, and cable development can be avoided.

There are 1356 regular ARC quadrupoles in the SSC; in addition the Conceptual Design has 256 addition quadrupoles of identical cross section differing from the ARC quadrupole only in length.

The two layer design is described below in greater detail.

* Without EDIA and contingency

An octant of the 19 turn winding cross section is shown in Fig. 1. This was selected after study of several alternatives. There may however be other similar cross sections that have better characteristics and this will be examined.

Calculated field uniformity, expressed in terms of the usual multipoles at a radius of one cm are given in Table I.[2] Transfer function for $\mu = \infty$ is 3.33 T/m-A.

Table I

Multipole Index	B_n/B_1
1	1.0
5	-0.5×10^{-7}
9	-0.66×10^{-6}
13	0.78×10^{-5}
17	-0.16×10^{-5}

Thickness of insulation on the cable, at coil mid-plane, between layers, and between coils and collars is identical to that of the dipole (as described in the Conceptual Design); also, a 0.4 mm protective "shoe" of stainless steel is used between coil package and collar (as in the dipole); 0.4 mm of clearance is allowed between collar O.D and iron; the resulting iron inner radius, for a 10 mm (radial) collar width, is 51.3 mm.

The winding is constrained with interlocking collars, as shown in Fig. 2. The interlocking collar design, as used in the Tevatron, has the following advantages:

1. Inherent mechanical precision of stamped collars.
2. Proven assembly technique.
3. Four-fold symmetry of the assembly process and support structure, thus minimizing introduction of "non-allowed" field distortion.

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2. M. Helm, S. Caspi LBL.

An analysis was made to select the minimum collar thickness required for structural support so that the iron inner diameter is minimum, thus maximizing gradient. As functions of iron radius, Fig. 3 shows the gradient in T/m, Fig. 4 shows saturation effect presented as

$$1 - \frac{(G/I)_{6.6T}}{(G/I)_{\mu=\infty}} ,$$

and Fig. 5 shows design "margin" J_o/j_c* for a current of 6500 A. Magnetic fields are computed using the program POISSON with 97.5% iron packing factor.[2]

A collar with 10 mm minimum radial thickness was selected and analyzed.[3] Although additional analysis and detailed design is required, this thickness appears to be sufficient and resulting stresses are similar to those incurred in present dipole models. Maximum stress conditions occur during room temperature assembly. (Additional analysis is required to refine details of keyway, tabs, etc.) The resulting iron inner radius is 51.3 mm giving a gradient of 212 T/m, j_o/j_c = 1.36 (for the same cable in the dipole, j_o/j_c = 1.28) and 1.5% decrease in G/I due to saturation effects at 6.6 T thus nearly matching the dipole (for the dipole, B/I decreases about 2%.

The outer diameter of the iron was determined in a preliminary way from the parametric study[1] by selecting the minimum iron thickness required to keep the flux density below 2T; an additional 25 mm in radial thickness was added to provide space and support for high-current busses, trim leads, helium flow passages, etc. Detailed POISSON calculations must be done to optimize the iron design.

* J_o is operating current density in the NbTi and j_c is the strand critical current density at maximum field.

3) Design and Analysis of SSC Arc Quadrupole, Steve Marks, LBL, LBID 1126, 3-5-86.

For the Conceptual Design, the cryostat was chosen to be nearly identical to the dipole cryostat for simplicity and ease of making magnet-magnet interconnections; it could of course be slightly reduced in diameter but the cost of additional development and more complex transition pieces would probably not result in a cost savings.

The two-layer quadrupole design appears to satisfy the SSC requirements of matching the dipole current and saturation behavior; in addition, it uses the 30 strand dipole cable in an optimum way. The cost is minimized by the higher gradient two-layer design mainly because shorter quadrupoles (and therefore a shorter tunnel) is needed compared to a one-layer, lower gradient design. Additional structural analysis of collars and optimization of iron yoke are necessary before proceeding with building of models.

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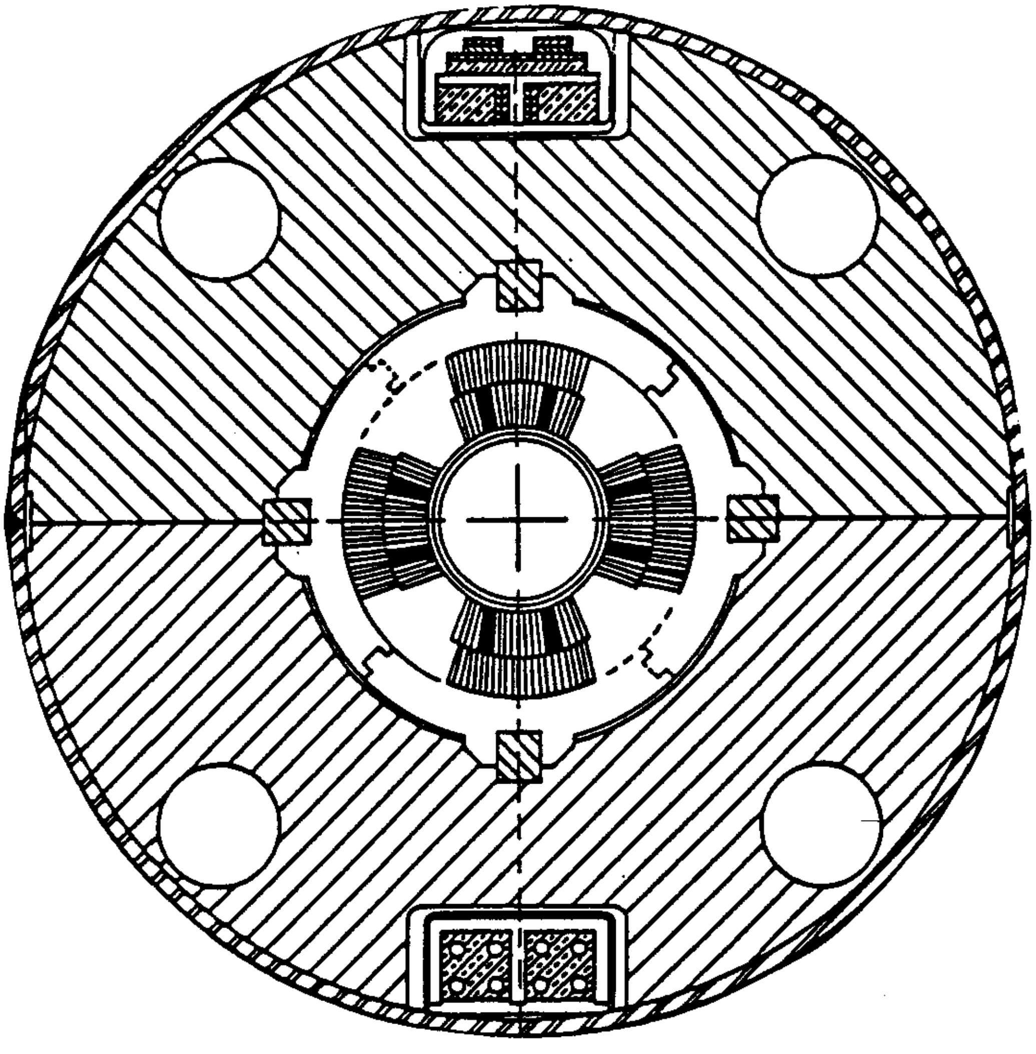

FIG. 1

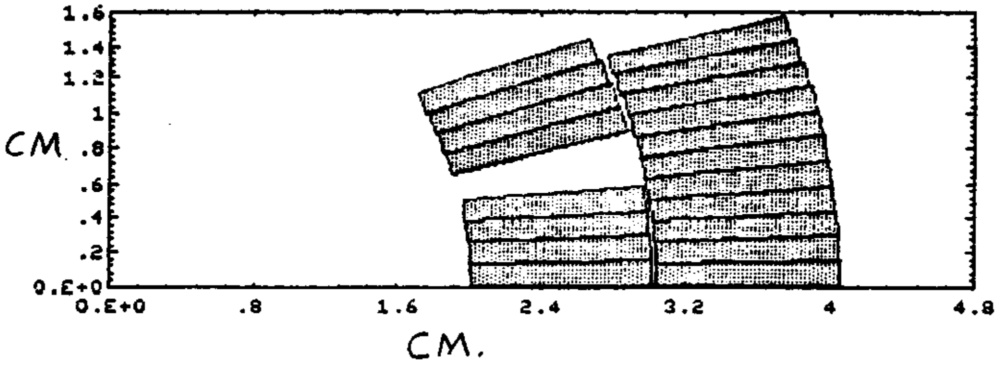

FIG. 2

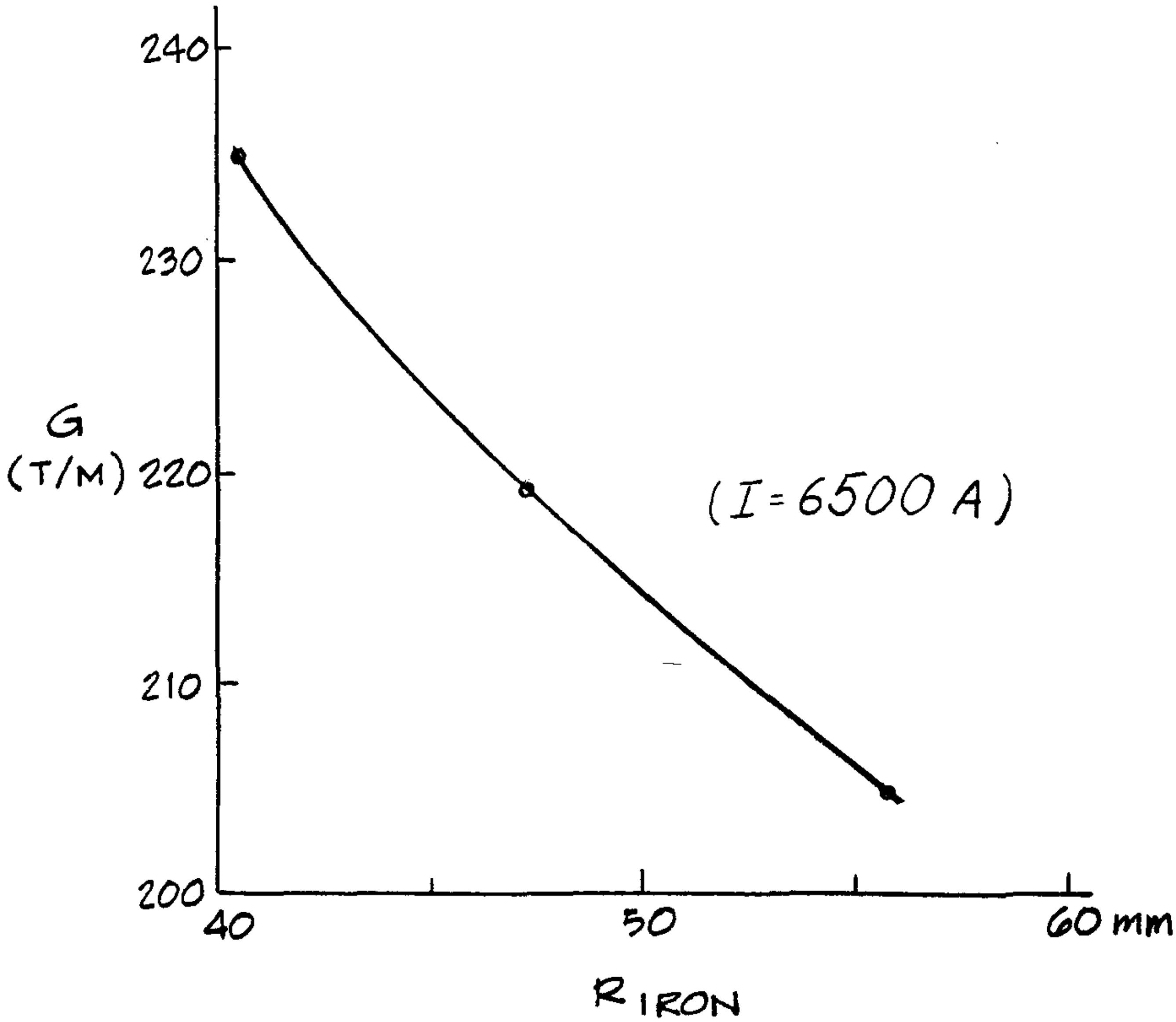

FIG. 3

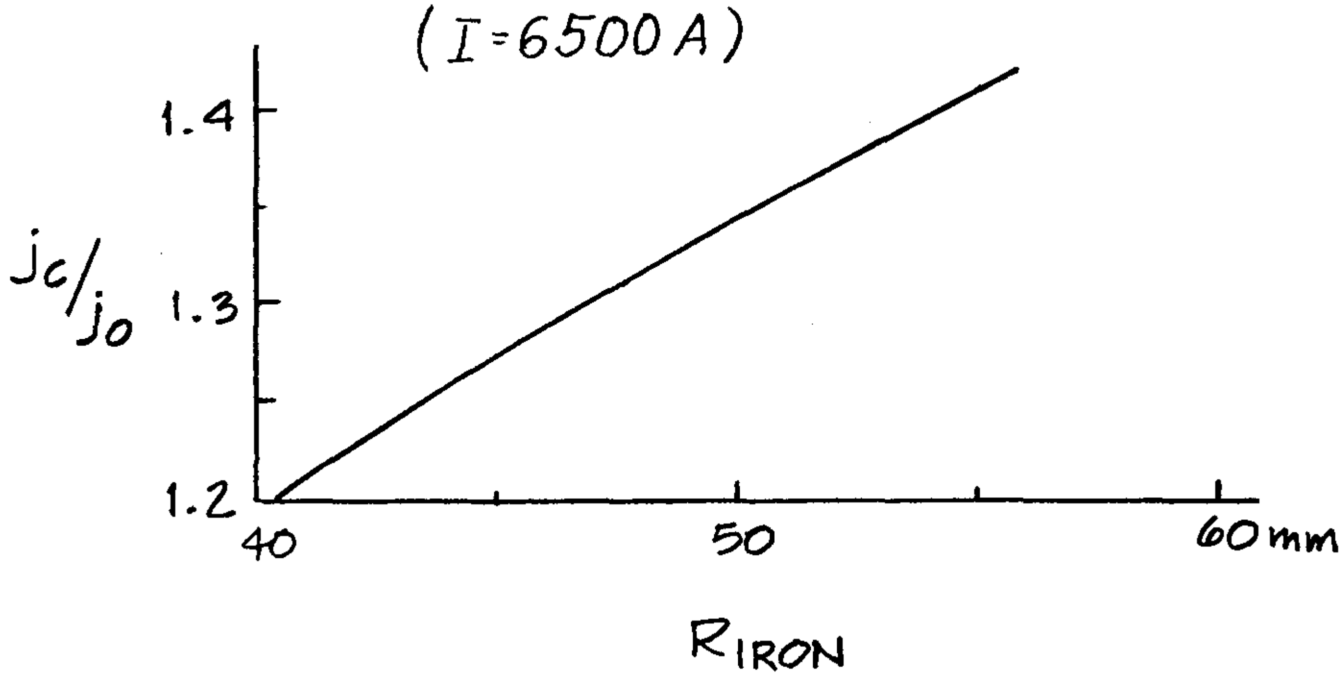

FIG. 4

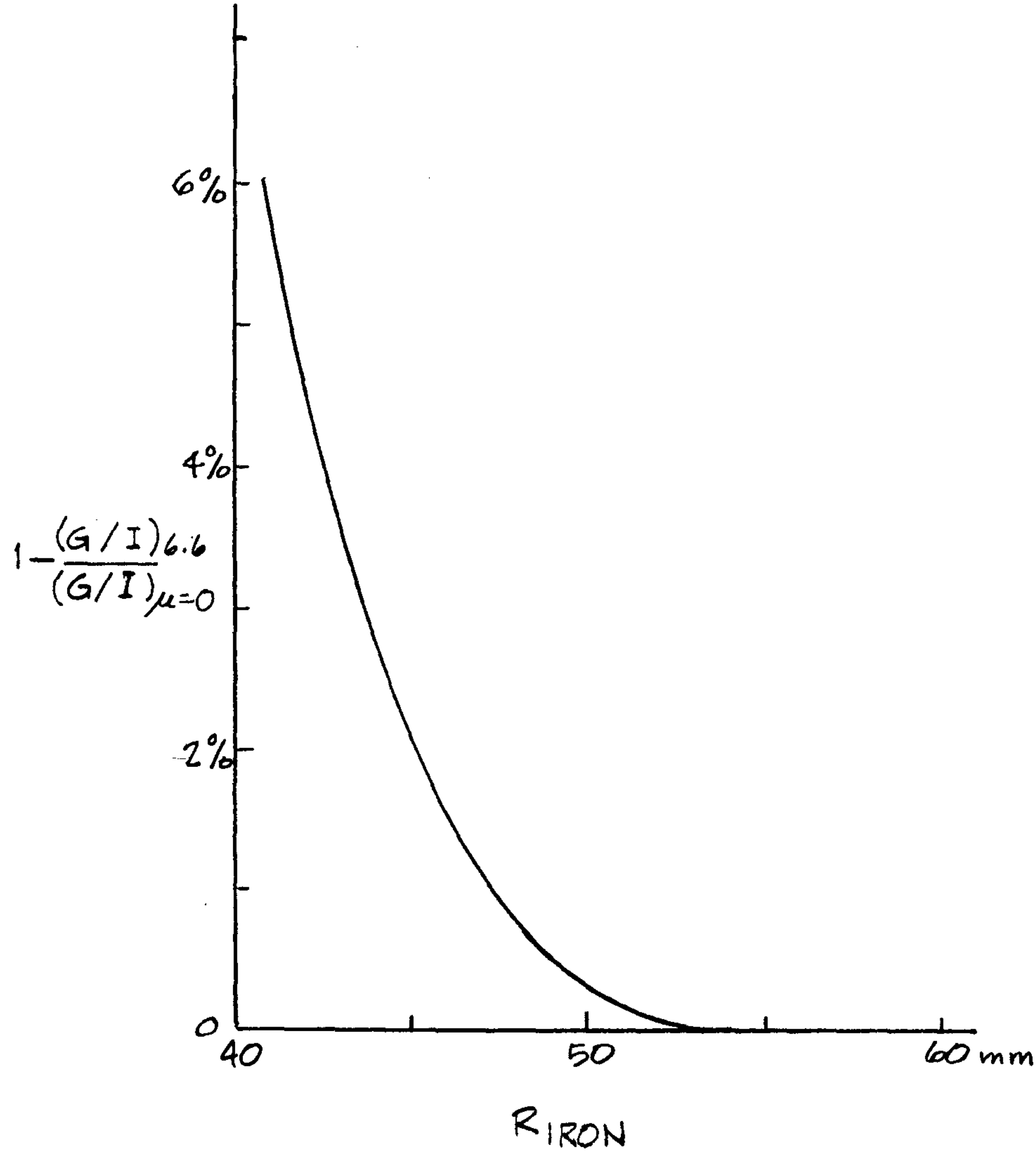

FIG. 5