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Ejection Septum Concept Design

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Collider Accelerator Department

Brookhaven National Laboratory

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The ejection septum must bend the ejected beam and clear a magnet edge which is 33 cm away in a length of 340 cm. This heavy beam has a rigidity product of 16.7 tesla-meters. Since the beams is vertically diverging it is desirable to make the septum height small at its entrance where the septum edge is thin and increase the height later where the conducting sheet can be made thicker. This has lead to a three section design which I have numbered sequentially as the beam see them.

Table I lists the design parameters of these three septum sections and Fig. 1 shows the cross-sectional concept. The current carring copper edge is restrained from moving outward by a stainless steel plate which is clamped as shown in Fig. 1. Both the copper and stainless steel plate thickness are increased in thickness as the gap height and current are increased. The object is to keep the stresses in these pieces within the fatigue limit of the material and keep the plate resonant frequency higher than the force impulse character. Under these conditions there will be neglectable resonant overshoot.

The major problem in the design of this septum is to find a compromise between the choice of pulse width, iron lamination thickness, energy storage capacitor size and the pulse voltage. The capacitor size considerations pushes the pulse width downward but short pulses lead to thin iron laminations.

Cooling is not a problem and can almost be handled by natural convection. Nevertheless I have shown some small water cooling plates on the top and bottom of the yoke package to reduce thermal stress. With a choosen compromise pulse width (measured across the base of a half sine wave) of 2.5 millisec, the expected temperature rise of the copper septum is only 44°C.

This pulse width compromise was choosen to limit the energy storage capacitor size which is increasing as the square of the pulse width. As shown in Table I the capacitors for this pulse width are .142, .147 and .227 farads respectively for the three septum sections. The energy storage voltage decreases linearly with increasing pulse width and much lower voltages will lead to inefficient use of solid state switches.

This short pulse width forces the use of thin iron laminations determined by the allowable field gradient across the septum width. The pulse width determines the shin depth in the lamination which carries the magnetic flux. This crowding of the flux into a fraction of the lamination width forces up the local flux density and reduces the effective magnetic mu. Typical mu versus flux density for various transformer steels are shown in Fig. 2. Figure 3 shows the relationship between the average flux in the septum gap, the pulse width, the effective mu and the peak flux density in the skin of the iron lamination. The equation used to derive this relationship are also shown. For infinite mu the flux in the gap is uniform across the gap width. All finite values of mu will produce a field gradient. The lower the mu the larger the skin depth and the more effectively the iron is used. But, unfortunately the lower the mu the greater will be the flux gradient. Again a compromise is required.

Figure 3 shows this relationship for only one mu, 300, and one B_{max}. Other plots are required for other magnetic points. Figure 4 shows the same information in different form. For a fixed average flux density in the gap, 10,000 gauss, the relationship between mu, pulse width and lamination thickness is shown. The mu values are choosen to produce the flux gradients indicated using the magnet cross-section shown. Other plots are required for other cross-sectional designs. If the maximum gradient in the gap can be specified then the lamination thickness can be determined. Table II lists the parameters, mu, B_{max} and lamination thickness for three possible flux gradients, 5%, 7.5% and 10%. The choice of flux gradient is left open for further beam optic analysis.

I have assumed that the radiation levels in the vicinity of the septum will be too high to operate a solid state switch, SCR, near the magnet. To move the switch and the energy storage capacitor away from the septum I have included in the magnet inductance the stray inductance of a parallel plate transmission line. This line consists of two 1/4 x 6 inch copper plates 75 feet long spaced apart by kapton or ceramic insulation. This and other circuit details are shown in Fig. 5.

Table I

Electrical and Mechanical Parameters

Item	1st unit		2nd unit		3rd unit	
Gap height (cm)	2.25		3.5		5.4	
Magnet length (cm)	80		120		120	
Material	Stainless steel	Cu	Stainless steel	Cu	Stainless steel	Cu
Thickness (inches)	.09	.10	.197	.197	.375	.25
I, moment of inertia (in^4)	$6.08x10^{-5}$	$8.33x10^{-5}$	$63.7x10^{-5}$	$63.7x10^{-5}$	$439x10^{-5}$	$130x10^{-5}$
Mass per inch of length (gm)	10.28	12.94	35.07	39.39	102.8	77.6
Mass ($lbs/in\text{-}sec^2$)	$.588x10^{-4}$	$.739x10^{-4}$	$2.00x10^{-4}$	$2.27x10^{-4}$	$5.87x10^{-4}$	$4.43x10^{-4}$
Resonant ω (rad/sec)	$5.70x10^9$		$4.98x1^4$		$3.84x10^4$	
Impulse time $1/\omega$ (μsec)	17.5		20.1		26	
Inductance magnet (μ hen.)	4.47		4.31		2.79	
Inductance 75' transmission line, (μ hen.)	1.0		1.0		1.0	
Stray inductance μ hen.	.75		1.0		1.0	
Total L μ hen.	6.22		6.31		4.79	
B (kilo gauss)	10		11		12	
I (kilo amps)	17.9		30.6		51.6	
Force/inch (lbs)	102		192		353	
Deflection (10^{-3} inches)	.088		.062		.065	
Peak sress (psi)	4900		3100		2700	
h pulse half width (10^{-3} sec)	2.5		2.5		2.5	
Lamination thickness 5% gradient (10^{-3} inches)	6		9		12	
7.5% gradient	10		14		19	
10% gradient	13		19		27	
System resistance (μ ohms)	313		153		78	
Average heating power (watts)	105		149		216	
Storage energy (joules)	715		2020		3715	
Energy storage capacity (farads)	.142		.147		.227	
Capacitor voltage (volts)	101		166		181	
di/dt (A/μsec)	22.5		38.5		64.8	
Radius of curvature (cm)	1670		1518		1392	
Angle of bend (degress)	2.75		4.54		4.98	

Table II

Lamination thickness for 2.5 millisec pulse width

Section	1st unit	2nd unit	3rd unit
Field gradient across gap	5%	5%	5%
Iron mu	580	380	250
B_{max} (gauss)	15200	15900	16600
Lamination thickness (10^{-3} in)	6	9	12
Field gradient across gap	7.5%	7.5%	7.5%
Iron mu	390	250	170
B_{max} (gauss)	15800	16600	17250
Lamination thickness (10^{-3} in)	9.5	14	19
Field gradient across gaps	10%	10%	10%
Iron mu	290	190	125
B_{max} (gauss)	16300	17000	17800
Lamination thickness (10^{-3} in)	13	19	27

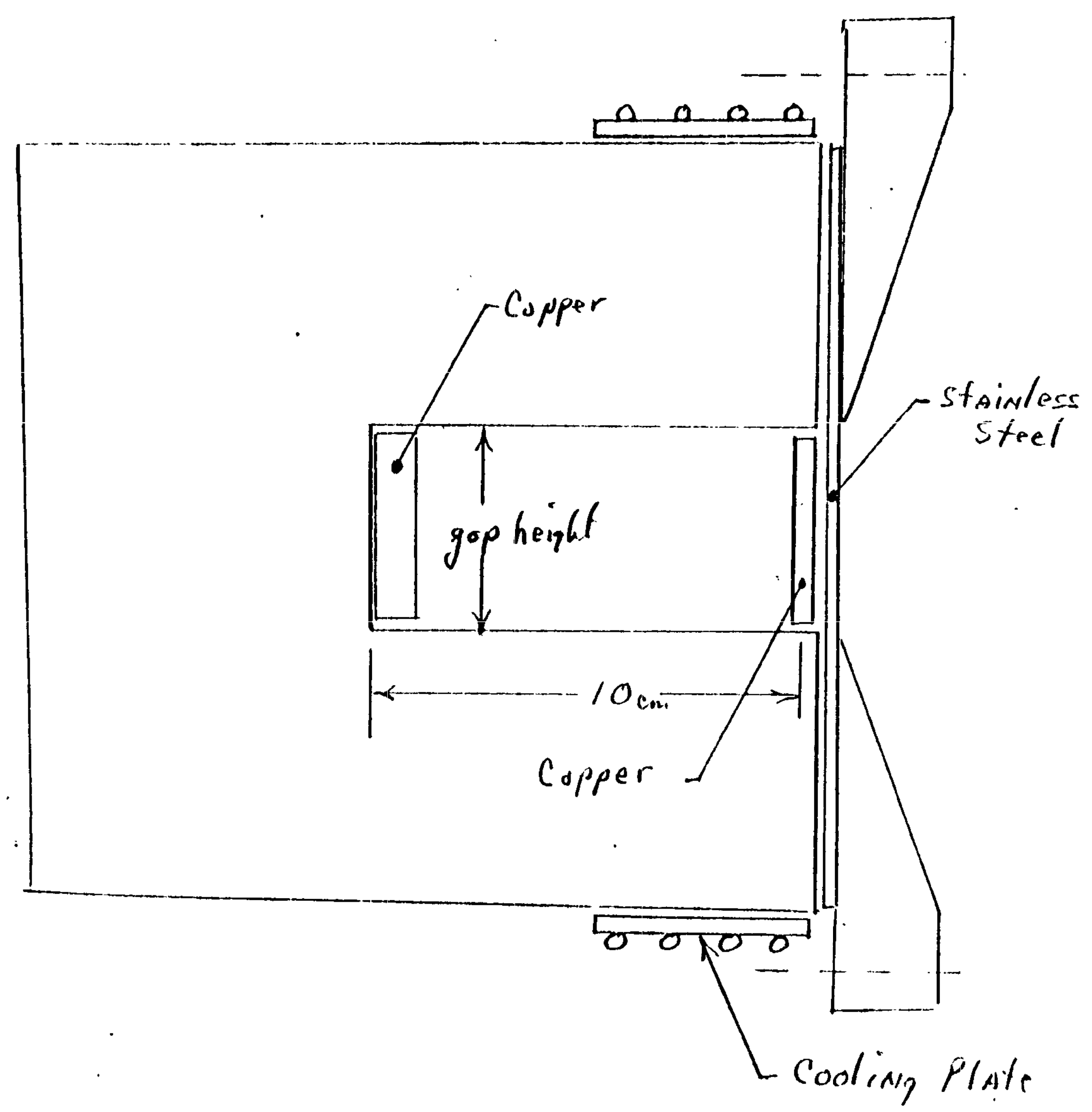
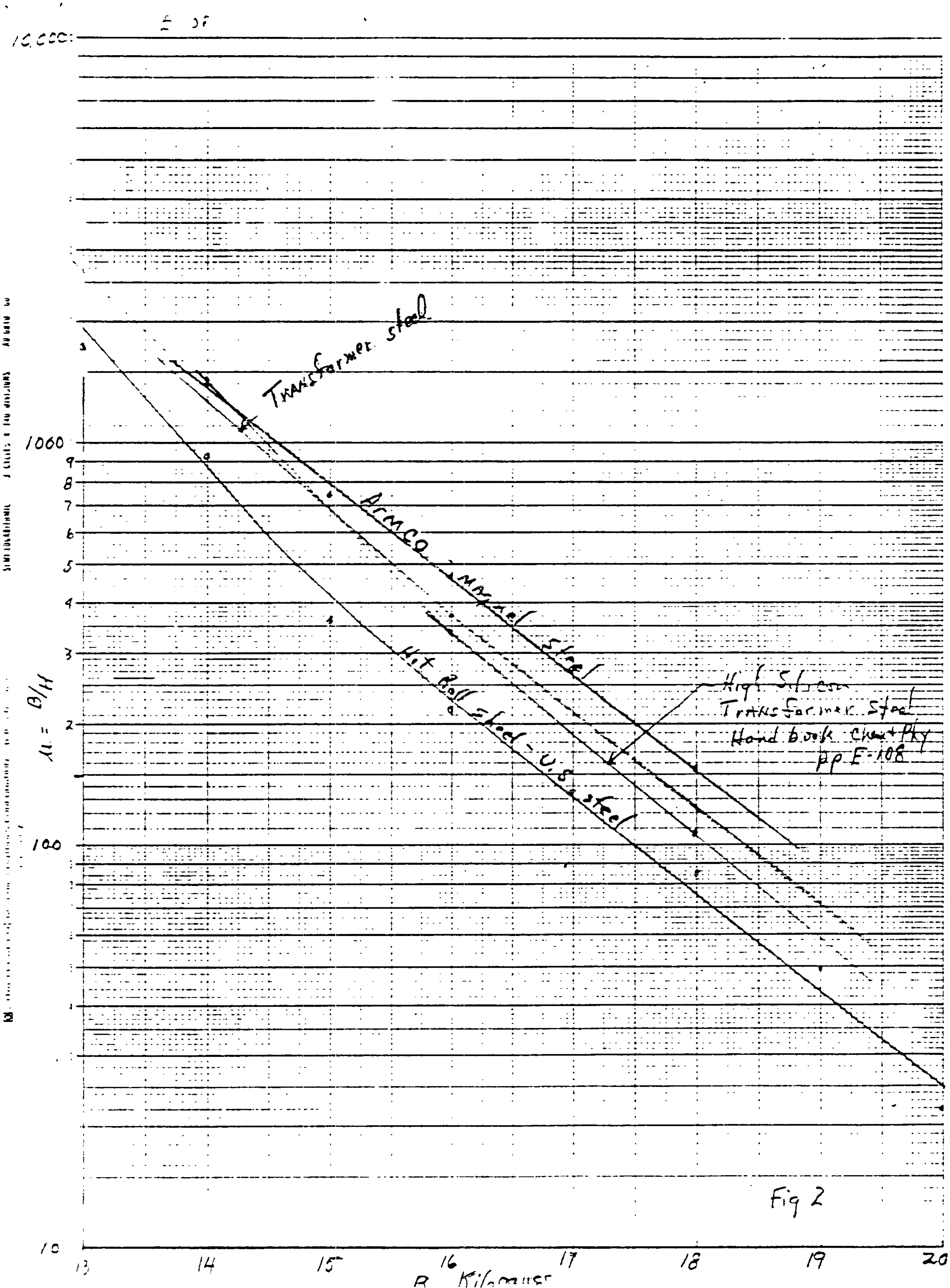
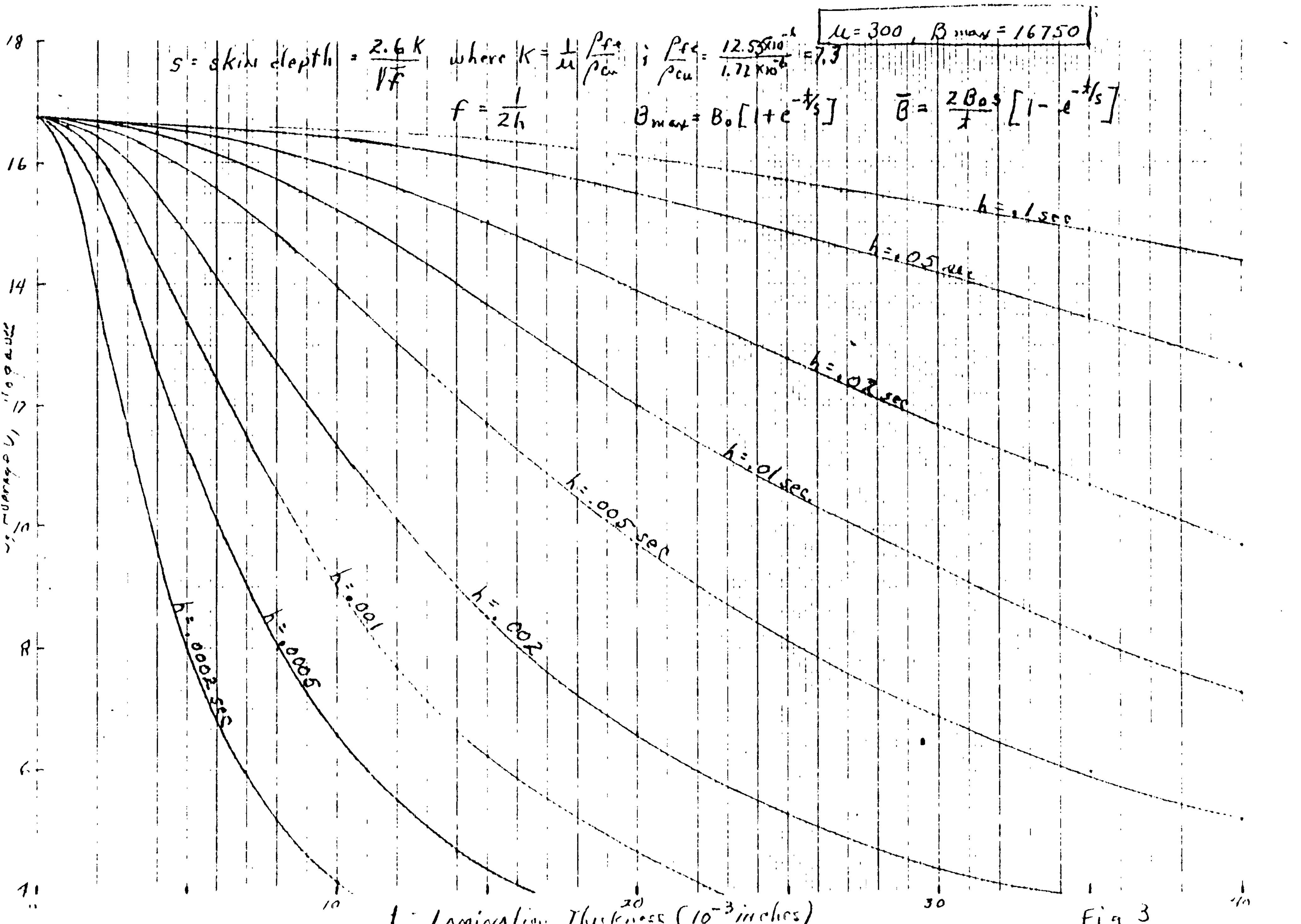

Copper
stainless
Steel
gap height
10cm
Copper
Cooling Plate

Fig 1



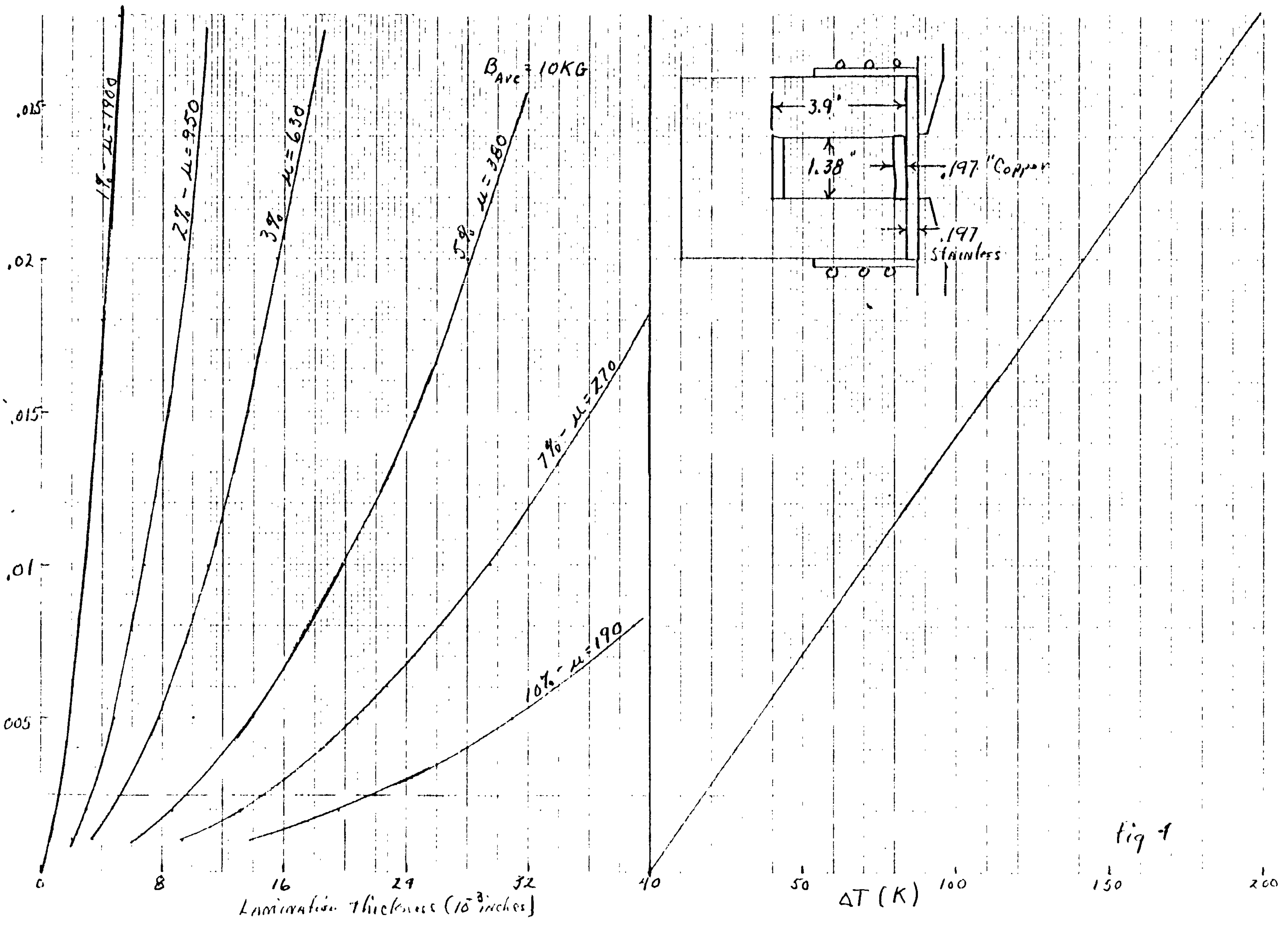
10,000
1000
9
8
7
6
5
4
3
2
100
10
$\mu = B/H$
Transformer steel
Armco Ingot Steel
Hot Roll Steel - U.S. Steel
High Silicon Transformer Steel Hand book Chem+Phy pp E-108
13
14
15
16
17
18
19
20
B Kilogauss

Fig 2



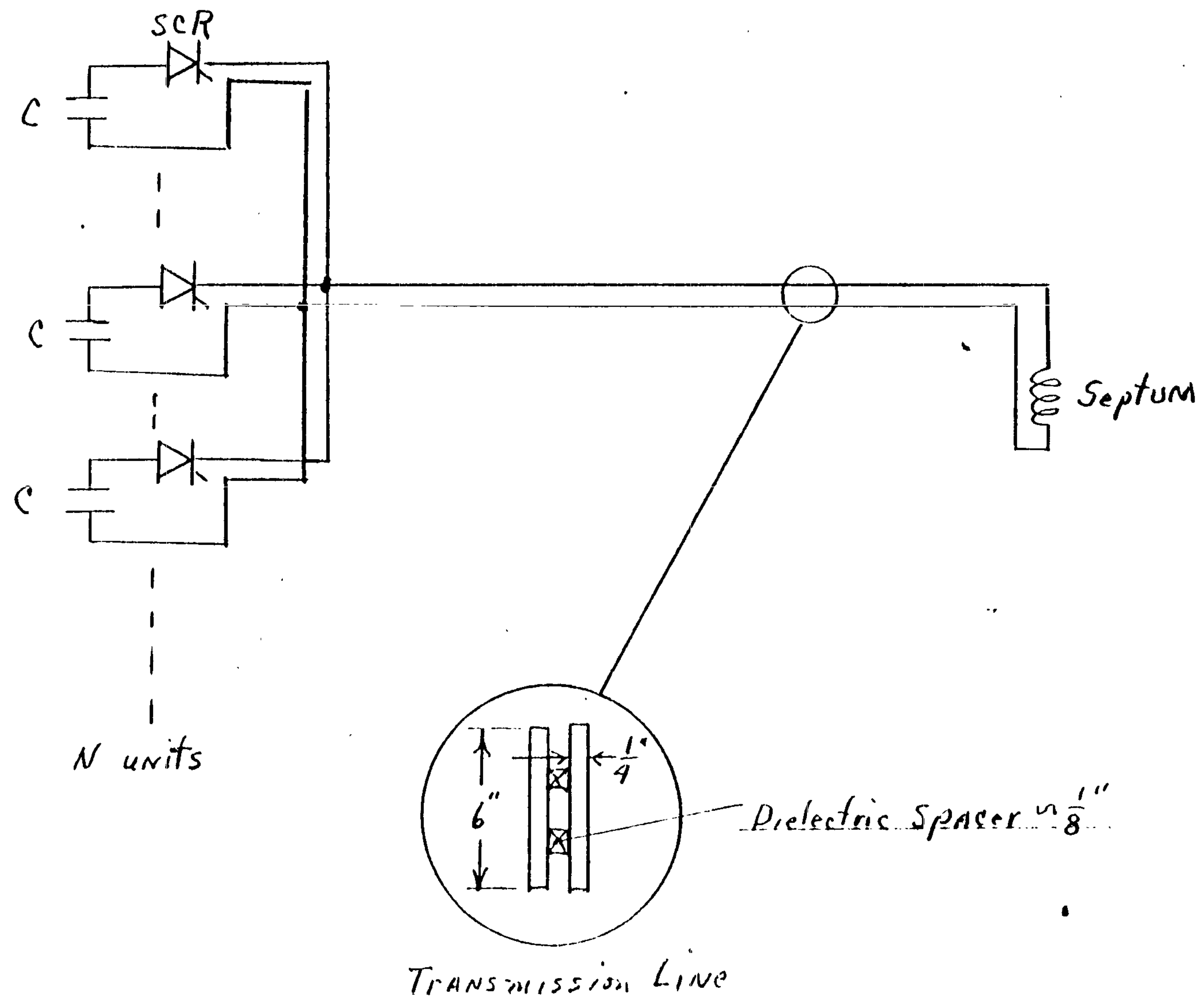
s = skin depth = 2.6 K / √f   where K = 1/μ · ρfe/ρcu ; ρfe/ρcu = 12.55×10⁻⁶ / 1.72×10⁻⁶ = 7.3
μ = 300 , B max = 16750
f = 1/2h
Bmax = B₀ [1 + e^(-t/s)]
B̄ = 2B₀s/t [1 - e^(-t/s)]
h = .1 sec
h = .05 sec
h = .02 sec
h = .01 sec
h = .005 sec
h = .002
h = .001
h = .0005
h = .0002 sec
18
16
14
12
10
8
6
10
20
30
40
t - Lamination Thickness (10⁻³ inches)

Fig 3



B_{Ave} = 10KG
1% - μ = 1900
2% - μ = 950
3% - μ = 630
5% - μ = 380
7% - μ = 270
10% - μ = 190
3.9"
1.38"
.197 "Copper
.197 Stainless
.025
.02
.015
.01
.005
0
8
16
24
32
40
50
100
150
200
Lamination thickness (10⁻³ inches)
ΔT (K)

fig 1



SCR
C
C
C
N units
Septum
6"
1/4"
Dielectric Spacer ~ 1/8"
Transmission Line

Fig 5