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SSC DETECTOR SOLENOID DESIGN NOTE #102

TITLE: Stabilizer and Support Cylinder Thickness for Three SSC Solenoid Geometries Based on Adiabatic Quench and Magnetic Stress Requirements

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Stabilizer and Support Cylinder Thickness for Three SSC Solenoid Geometries Based on Adiabatic Quench and Magnetic Stress Requirments

Bob Wands

Introduction

The conductor stabilizer dimensions and support cylinder thickness of a thin contact cooled solenoid for an SSC detector can be determined by magnetic stresses and/or quench characteristics. The overall radial thickness of such a solenoid must be kept small, due to the placement of calorimetry outside of the field volume, and the possibility of particle interaction within the uninstrumented solenoid mass. The three solenoid designs considered here differ in length and in the manner of flux return. Therefore, the stored energy and magnetic stresses differ between the designs for a given radius and central field. This report illustrate use of a finite element magneto-static analysis and the application of simple adiabatic heating quench models to evaluate overall coil-support cylinder thickness for a range of coil radii from 0.5 to 2.5 meters, and a central field of 1.7T.

Solenoid Geometries

Three geometries were studied. The first, designated FTD1 (for Fast Tracking Detector) is shown in Fig. 1. This design uses an iron return yoke which provides a field-free region for the calorimetry between the coil and the iron. The second design, FTD2, is shown in Fig. 2, and uses calorimetry to provide for the flux return, which allows greater hermeticity but requires the calorimetry to function in a magnetic field. The third design, ACS, is shown in Fig. 3, and is an air-core solenoid whose primary advantages include a nearly crack-free calorimetry configuration about the solenoid and the ability to build and test the coil without regard to the status of other aspects of construction.

The lengths of each geometry remained fixed at those given in Figs. 1-3 during this study, while the radial dimensions were scaled from a minimum coil current sheet radius of 0.5 meters to a maximum of 2.5 meters. Figs. 4-6 show the dimensions used in the 'standard' finite element model of each geometry before scaling.

The conductors in this study were assumed to be of the CDF-type, with a Nb-Ti superconductor embedded in a high purity alumimum stabilizer. Major structural support for the coil is provided by a support cylinder of structural aluminum. This aluminum is unspecified at this time.

Finite Element Models

The geometries were modeled with the ANSYS STIF13 multi-field solid finite element. A b-h curve for 1020 steel, taken from previous work by R. Yamada on the CDF solenoid, was input for the FTD1 and the ACS. FTD2 required a modification of the b-h curve based on the fact that the calorimeter contains only 50% steel, with the remainder being non-magnetic lead. The modification of the b-h curve is discussed in Appendix A.

The coil in each model was coupled radially to a cylinder of STIF61 cylindrical shell elements, which model the external support cylinder. The support cylinder contains endrings of STIF61 elements which can interact with the coil through STIF41 gaps. The support cylinder was connected to the iron in each model with STIF1 spar elements. The features were used in previous work in which the coil was considered to be in two or more modules, with a space at the midplane, and so could produce a net axial force on the support cylinder. In this work, however, the coils are assumed to be one continuous current sheet, and the support cylinder and spar connections are of little importance to the analysis for axial loads, since they are taken by the coil alone in compression.

The analysis also produces forces on the iron, although those are not presented here.

Adiabatic Temperature Rise

The radial thickness of the conductor is a function of the maximum temperature found during a quench. This is most easily and conservatively calculated by assuming that the decay of the current after the opening of the dump switch is dependent on the dump resistance and the coil inductance only (i.e., the resistance of the coil is negligible). If it is also assumed that the

conductor stabilizer does not transfer heat to it's surroundings, so that the total temperature rise can be calculated by equating the energy deposited in a volume of conductor with the change in enthalpy.

A simple Fortran program was written to calculate the adiabatic temperature rise for a range of RRR from 100-30000. This program is described in Appendix B.

Allowable Stresses

The conductor stabilizer is subjected to three stresses:

1. Axial preload stress
2. Hoop magnetic stress
3. Axial magnetic stress

The axial preload occurs when the coil is warm and is preloaded against the support cylinder in an effort to make the coil and cylinder act as a two-springs-in-parallel system against the axial magnetic forces. Appendix C describes the preloading function in more detail.

The hoop and axial magnetic stresses result from the presence of a magnetic field in the current-carrying elements, and is calculated from

$$\vec{J} \times \vec{B}$$

The ANSYS program performs this calculation automatically, and in the case of magneto-structural coupling, applies the resulting force to the structure.

The maximum allowable stress for the cold stabilizer was chosen based on the assumption that the support cylinder and the stabilizer will have the same hoop strain. This strain was limited to 0.1%. The stress-strain curve for a CDF R&D conductor study (Fig. 7) was used to determine that the stabilizer can then be stressed to 3670 N/cm**2 (5300 psi), while the support cylinder at the same strain will have a stress of 9200 N/cm^2 (13000 psi).

The maximum warm stabilizer stress was limited to $0.75S_y$, or 2070 N/cm^2 (3000 psi)

Calculation of Stabilizer Dimensions

The stabilizer axial dimension can be determined from the product N*I, where N is the number of turns in the coil and I is the current in the coil. This product must equal CD*A, where CD is the current density from the ANSYS model and A is the area of the coil assumed in the ANSYS model. (The area assumed in the ANSYS model has no bearing on the conductor dimensions calculated here; it is simply necessary due to program input requirements). Then,

$$t_a = l*i/(cd*a)$$

where

t_a = axial stabilizer dimension
l = length of coil
cd = current density for central field of 1.7T
a = area of coil assumed in ANSYS

The radial stabilizer dimension can be determined from either the adiabatic heating requirements or the axial stress requirements. For axial stress, the thickness is found with

$$t_r = F_a/(2*pi*r*S_s)$$

where

t_r = radial stabilizer thickness
r = radius of coil
F_a = maximum axial compressive force from ANSYS
S_s = maximum allowable stabilizer stress at 0.1% strain

For adiabatic quench requirements, the program described in Appendix B was used, with a correction applied to the axial stabilizer dimension to allow for 0.2 mm thick insulation turn-to-turn in the coil.

The thickness of the support cylinder can be found from the hoop stress requirements.

$$t_{sc} = (F_h - S_s*t_r)/S_{sc}$$

where

t_{sc} = thickness of support cylinder
F_h = maximum hoop force from ANSYS, N/cm
S_s = maximum allowable hoop stress in stabilizer
S_{sc} = maximum allowable hoop stress in support cylinder

Results and Discussion

The conductor stabilizer and support cylinder dimensions for each geometry are given in Tables I-IX. The first table for each geometry calculates the radial thickness of the stabilizer based on the axial stress requirements. The remaining tables calculate the radial stabilizer thickness based on adiabatic quench requirements. All tables calculate the radial support cylinder thickness from the radial stabilizer thickness and hoop stress requirements. It can be seen that the maximum preload for the stabilizer dimensions determined by adiabatic quench requirements are less than the maximum of 2070 N/cm^2, while this value is exceeded in most cases where the dimensions are determined by axial stress requirements.

Figs. 8-10 compare the radial stabilizer thickness as calculated for axial stress and adiabatic quenching requirements. It can be seen that in each case, the radial thickness is determined by quenching rather than stress, although in the case of the ACS the thicknesses are very nearly the same for I=10000 A.

Figs. 11 and 12 show the total radial thickness of stabilizer and support cylinder for 5000 A and 10000 A. The ACS is the thinnest design in each case. This is primarily because as the shortest of the three geometries, it will have the smallest inductance for a given radius, and therefore the smallest adiabatic temperature rise.

Fig. 13 is a plot of the integral

$$\int B_z \; X \; dl$$

along a line running from the center of the solenoid at a constant angle to the inner radius of the coil. The angle has been converted to pseudo-rapidity to allow comparison with physics requirements. This plot shows the more

nearly constant integral value for the FTD1 and FTD2 designs, which show less decrease in axial field toward the end of the solenoid.

Conclusion

This work allows the three geometries to be compared against one another for a wide range of radii for total radial thickness. Future work will focus on a narrower range of radii and more detailed field and force calculations.

Table I. FTD1
Stabilizer and Support Cylinder Thicknesses
for Stress Requirements Only

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)*
0.50	0.48	0.32	0.80	1466.82	
1.00	0.65	0.89	1.53	2123.35	
1.50	0.74	1.58	2.31	2500.07	
2.00	0.81	2.37	3.18	2739.22	
2.50	0.90	3.27	4.17	2874.62	

Table II. FTD1
Stabilizer and Support Cylinder Thicknesses
for Adiabatic Quenching and Stress Requirements
5000 A

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)
0.50	1.45	0.00	1.38	0.00	0.37
1.00	2.88	0.00	2.88	0.00	0.37
1.50	4.32	0.15	4.47	20.51	0.37
2.00	5.76	0.40	6.16	33.21	0.37
2.50	7.22	0.75	7.97	43.29	0.37

Table III. FTD1
Stabilizer and Support Cylinder Thicknesses for Adiabatic Quenching and Stress Requirments 10000 A

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)
0.50	1.00	0.11	1.11	176.80	0.74
1.00	1.90	0.39	2.29	211.19	0.74
1.50	2.97	0.68	3.65	170.70	0.74
2.00	3.69	1.22	4.91	199.79	0.74
2.50	4.96	1.65	6.61	167.23	0.74

Table IV. FTD2
Stabilizer and Support Cylinder Thicknesses for Stress Requirements Only

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)*
0.50	0.56	0.31	0.86	1305.09	
1.00	0.81	0.87	1.67	1899.94	
1.50	1.01	1.51	2.52	2199.11	
2.00	1.23	2.21	3.45	2357.17	
2.50	1.49	3.02	4.51	2459.38	

Table V. FTD2
Stabilizer and Support Cylinder Thicknesses
for Adiabatic Quenching and Stress Requirements
5000 A

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)
0.50	1.21	0.05	1.25	65.65	0.37
1.00	2.39	0.23	2.62	110.55	0.37
1.50	3.56	0.49	4.05	126.07	0.37
2.00	4.75	0.81	5.56	139.08	0.37
2.50	6.13	1.17	7.30	143.03	0.36

Table VI. FTD2
Stabilizer and Support Cylinder Thicknesses
for Adiabatic Quenching and Stress Requirements
15000 A

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)
0.50	0.83	0.20	1.03	477.38	0.74
1.00	1.64	0.53	2.17	443.01	0.74
1.50	2.45	0.93	3.38	417.09	0.74
2.00	3.27	1.40	4.67	415.41	0.74
2.50	4.20	1.94	6.14	411.21	0.72

Table VII. ACS
Stabilizer and Support Cylinder Thicknesses for Stress Requirements Only

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)*
0.50	0.78	0.16	0.94	623.17	
1.00	1.56	0.38	1.94	722.03	
1.50	2.37	0.69	3.05	824.45	
2.00	3.14	1.20	4.35	1015.16	
2.50	3.97	1.74	5.71	1120.44	

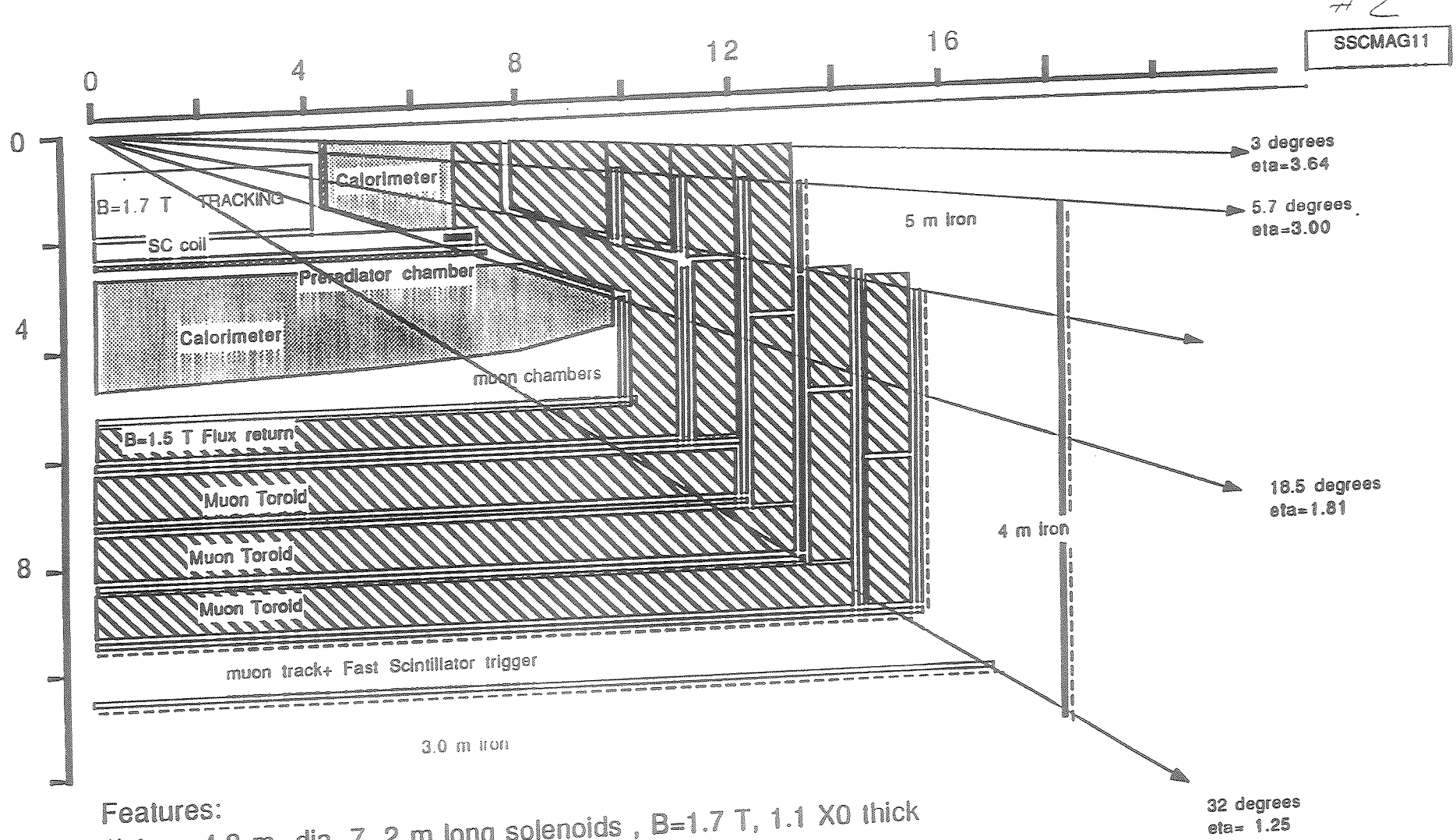
Table VIII. ACS
Stabilizer and Support Cylinder Thicknesses for Adiabatic Quenching and Stress Requirements
5000 A

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)
0.50	1.03	0.06	1.09	163.08	0.37
1.00	2.08	0.17	2.25	210.54	0.36
1.50	3.26	0.33	3.59	244.99	0.35
2.00	4.72	0.57	5.29	264.92	0.33
2.50	6.28	0.82	7.10	268.03	0.32

Table IX. ACS
Stabilizer and Support Cylinder Thicknesses
for Adiabatic Quenching and Stress Requirements
10000 A

Coil Radius (m)	Radial Stabilizer Thickness (cm)	Radial Support Cylinder Thickness (cm)	Total Thickness (cm)	Required Preload Stress (N/cm^2)	Axial Stabilizer Thickness (cm)
0.50	0.71	0.19	0.90	869.75	0.74
1.00	1.43	0.43	1.86	926.94	0.72
1.50	2.24	0.74	2.98	960.19	0.70
2.00	3.30	1.14	4.44	897.86	0.66
2.50	4.30	1.61	5.91	923.28	0.64

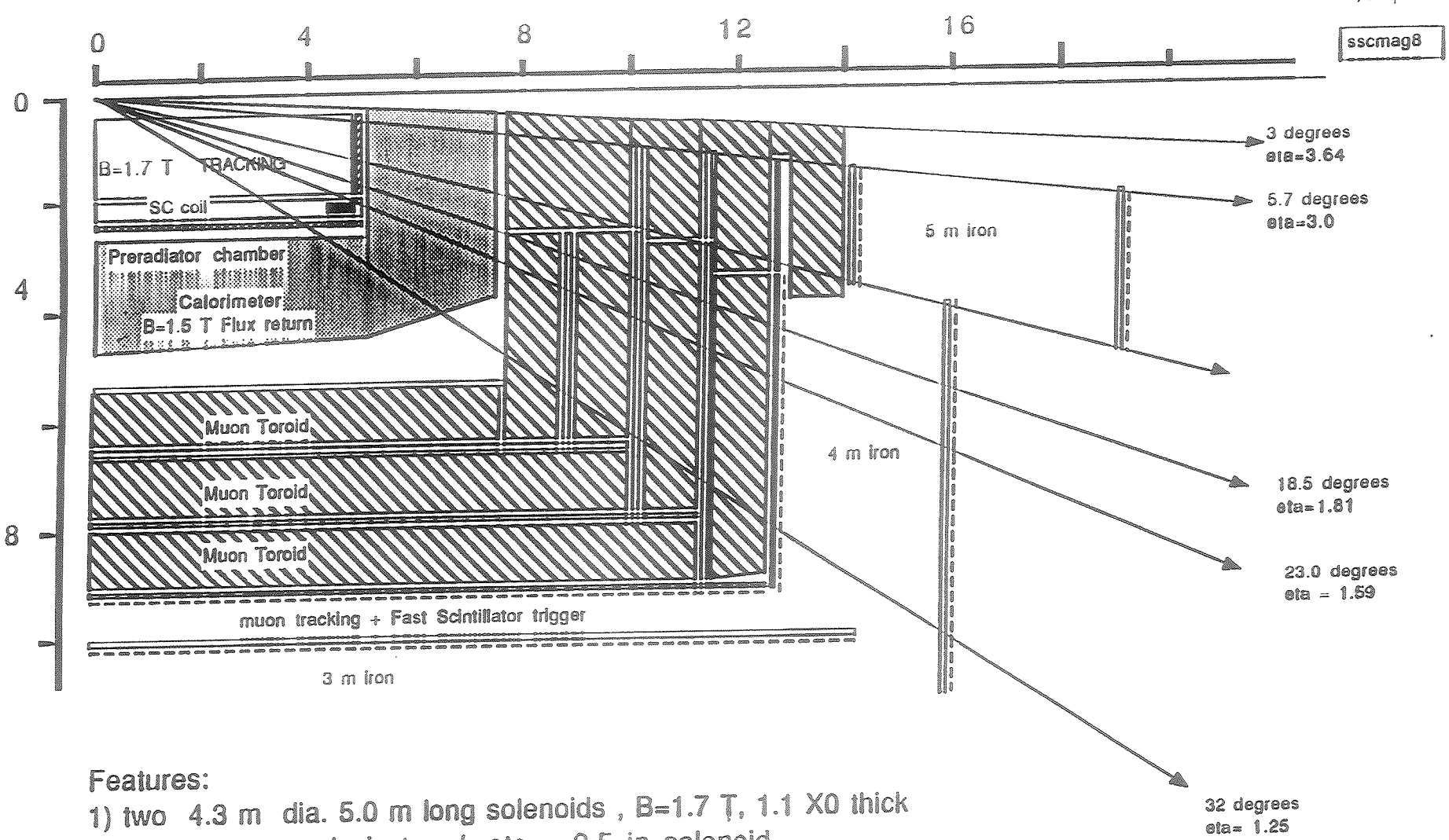
*- axial stabilizer thickness is not determined by stress



Features:

1) two 4.3 m dia. 7 .2 m long solenoids , B=1.7 T, 1.1 X0 thick
2) momentum analysis to +/- eta = 2.5 in solenoid
3) BL**2.5 factor of 2.75 that of CDF
4) Magnetized Iron yoke + muon toroids (44 k tons)
5) muons over +/- eta =3.0, e's over +/- eta=2.5

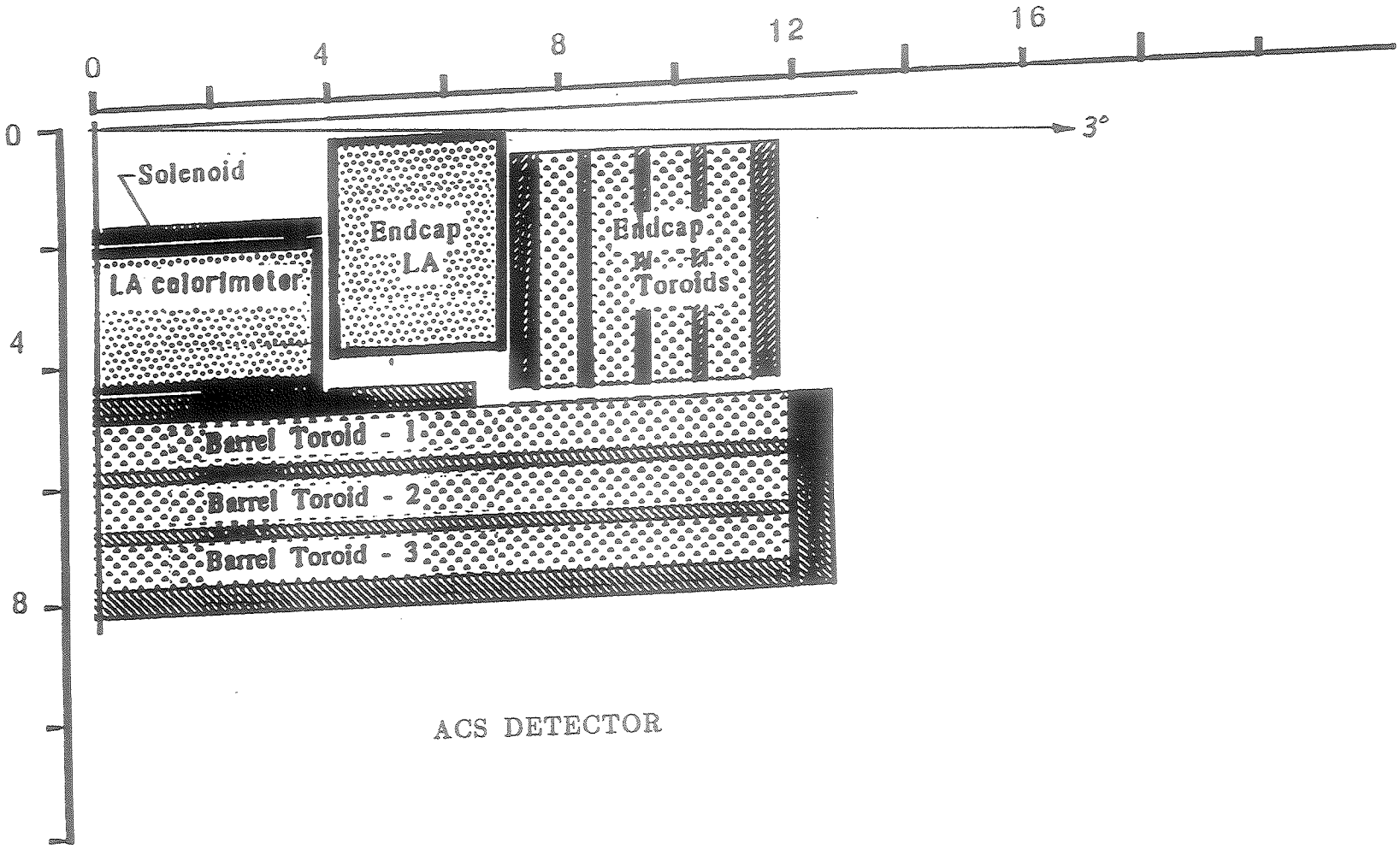
FIG. 1. GEOMETRY OF FTD1 (IRON FLUX RETURN)



Features:

1) two 4.3 m dia. 5.0 m long solenoids , B=1.7 T, 1.1 X0 thick
2) momentum analysis to +/- eta = 2.5 in solenoid
3) BL**2.5 factor of 2.75 that of CDF
4) Magnetized Iron toroid muon system (31K tons)
5) muons over +/- eta =3.0, e's over +/- eta=2.5

FIG. 2. GEOMETRY OF FTD2 (CALORIMETER FLUX RETURN)

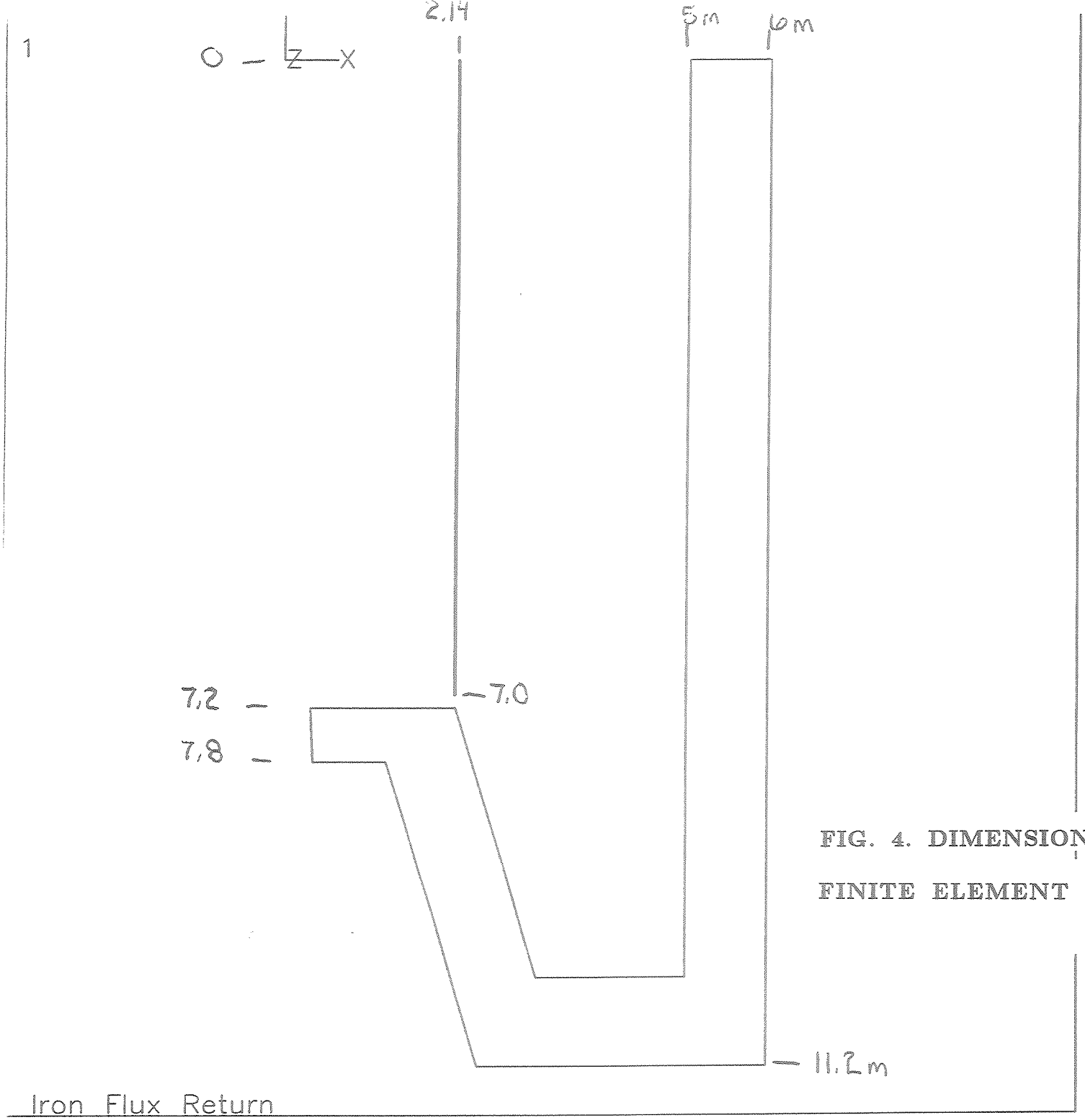


ACS DETECTOR

Features:

1) One, 3.6 m diameter x 7.3 m long air core solenoid
2) B = 1.7 T, 0.9 X0 thick
3) Magnetized iron toroid muon system (approx. 30 k tons)

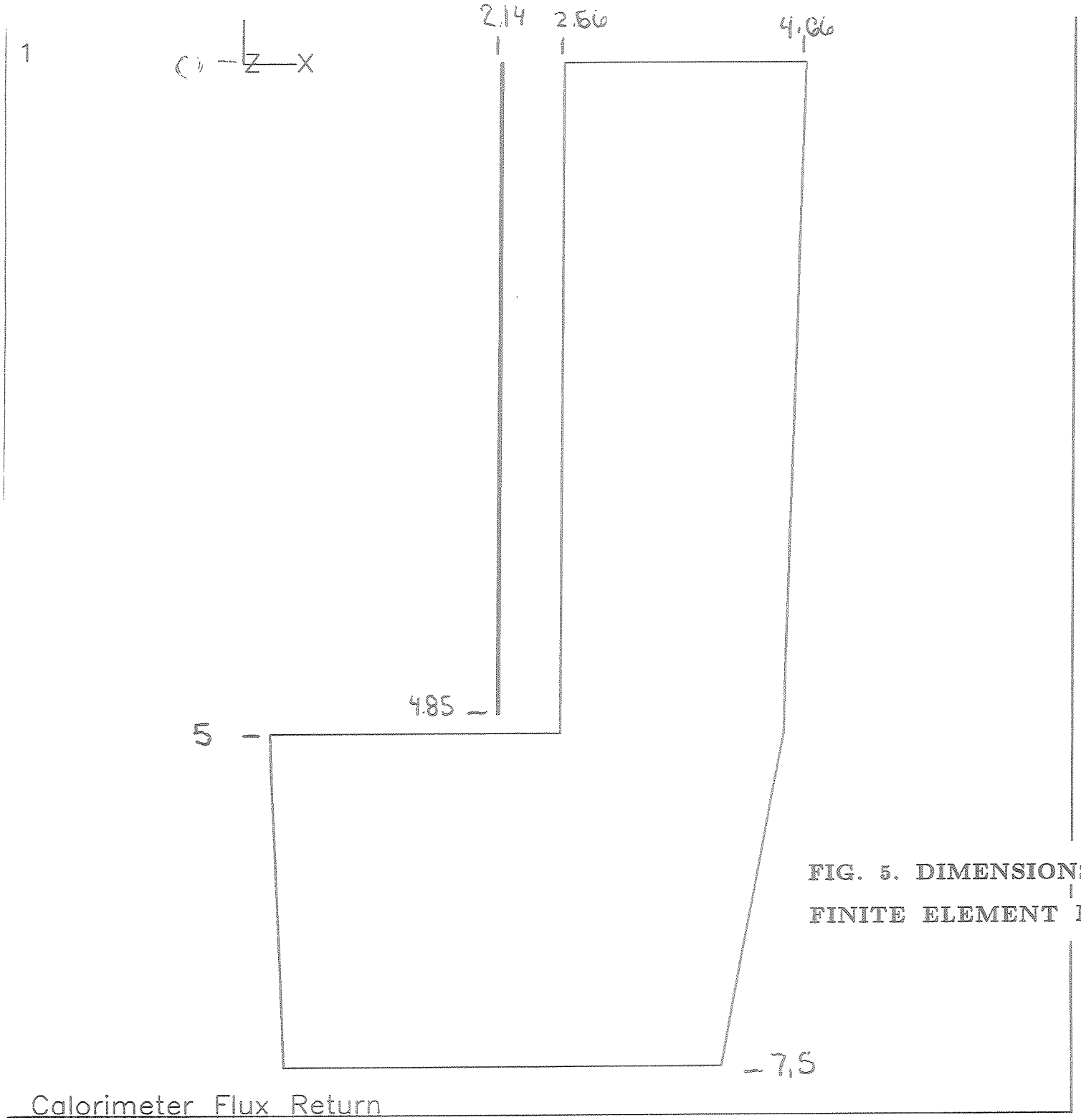
FIG. 3. GEOMETRY OF ACS (AIR CORE SOLENOID)



ANSYS 4.4
NOV 15 1989
17:00:30
PLOT NO. 1
POST1 ELEMENTS
TYPE NUM

ZV =1
DIST=6.16
XF =2.98
YF =-5.6
EDGE

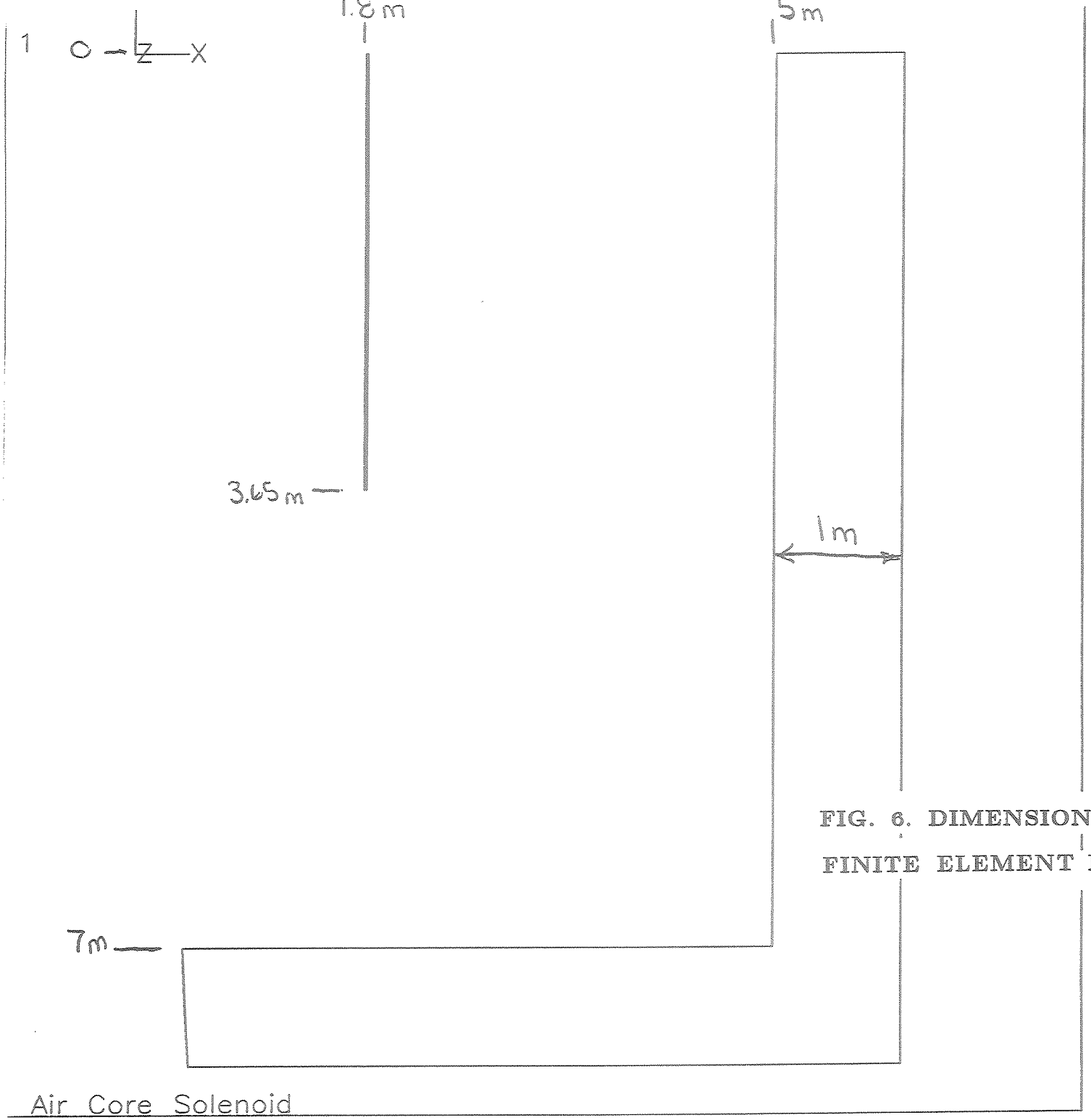
FIG. 4. DIMENSIONS USED IN STANDARD FINITE ELEMENT MODEL OF FTD1



ANSYS 4.4
NOV 15 1989
16:59:26
PLOT NO. 1
POST1 ELEMENTS
TYPE NUM

ZV =1
DIST=4.125
XF =2.3
YF =-3.75
EDGE

FIG. 5. DIMENSIONS USED IN STANDARD FINITE ELEMENT MODEL OF FTD2



ANSYS 4.4
NOV 15 1989
17:01:22
PLOT NO. 1
POST1 ELEMENTS
TYPE NUM

ZV =1
DIST=4.675
XF =3.552
YF =-4.25
EDGE

FIG. 6. DIMENSIONS USED IN STANDARD FINITE ELEMENT MODEL OF ACS

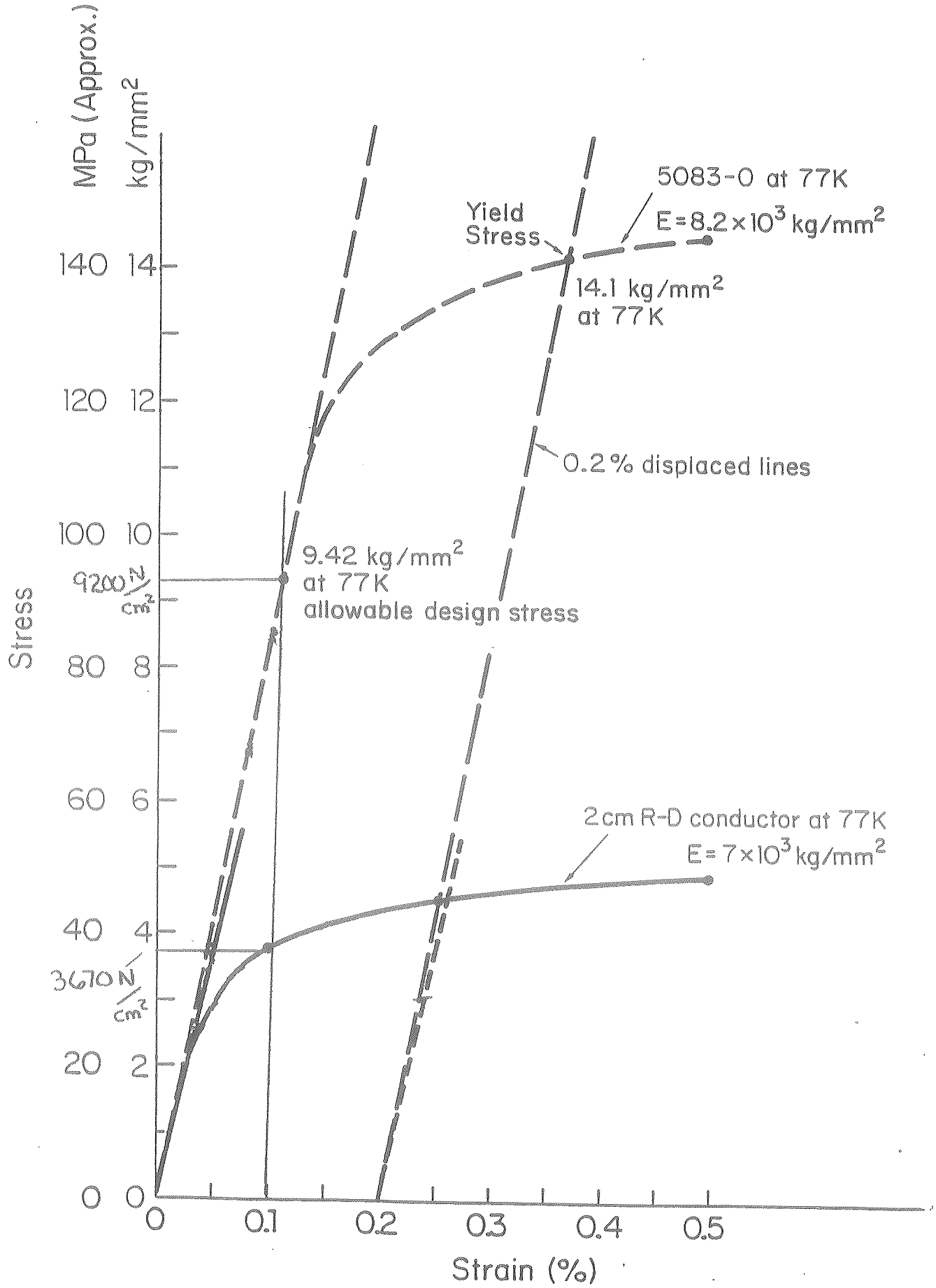


FIG. 7. STRESS-STRAIN CURVE USED TO DETERMINE MAXIMUM STRESSES

FIG. 8. RADIAL STABILIZER THICKNESS FOR FTD1

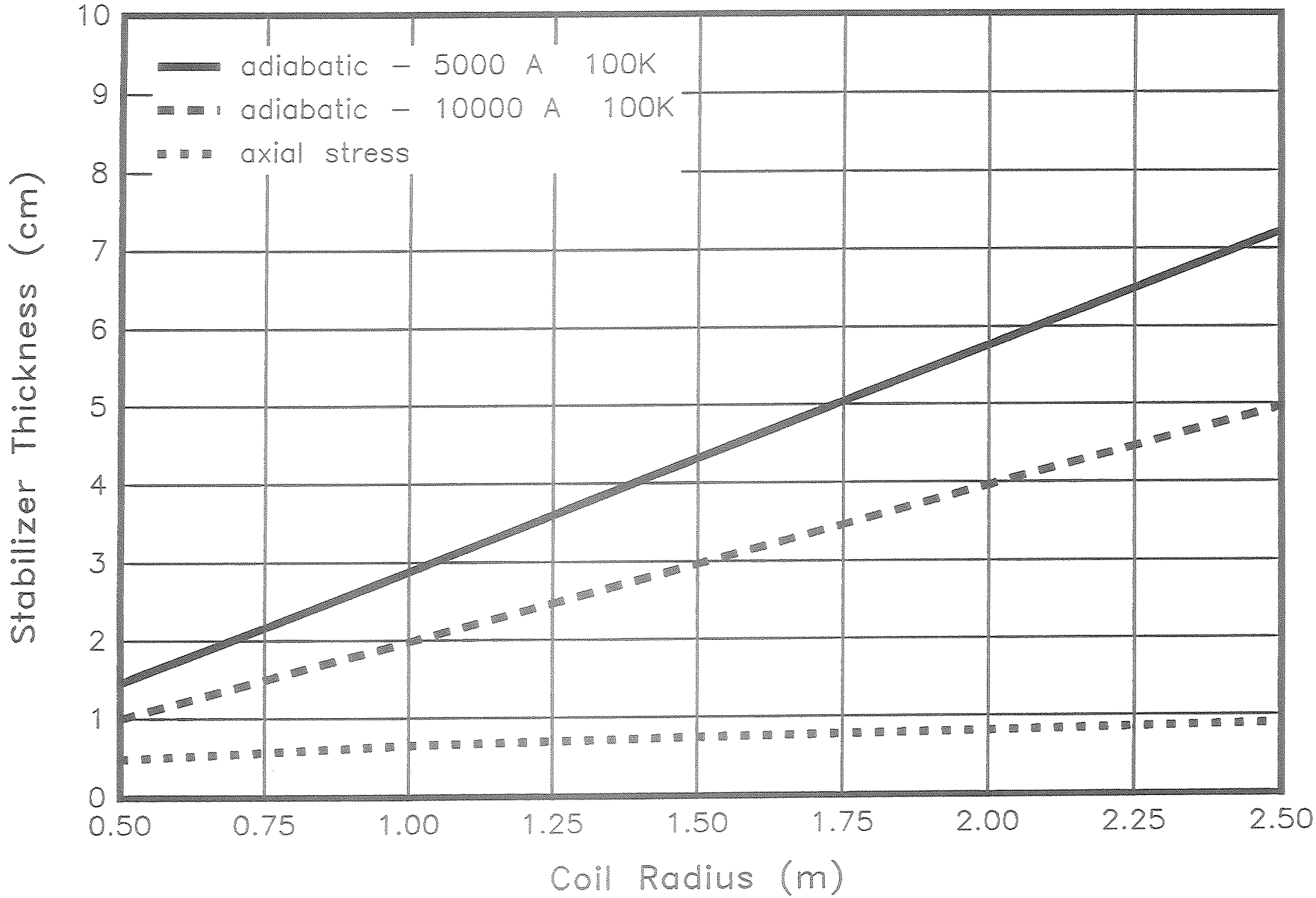


FIG. 9. RADIAL STABILIZER THICKNESS FOR FTD2

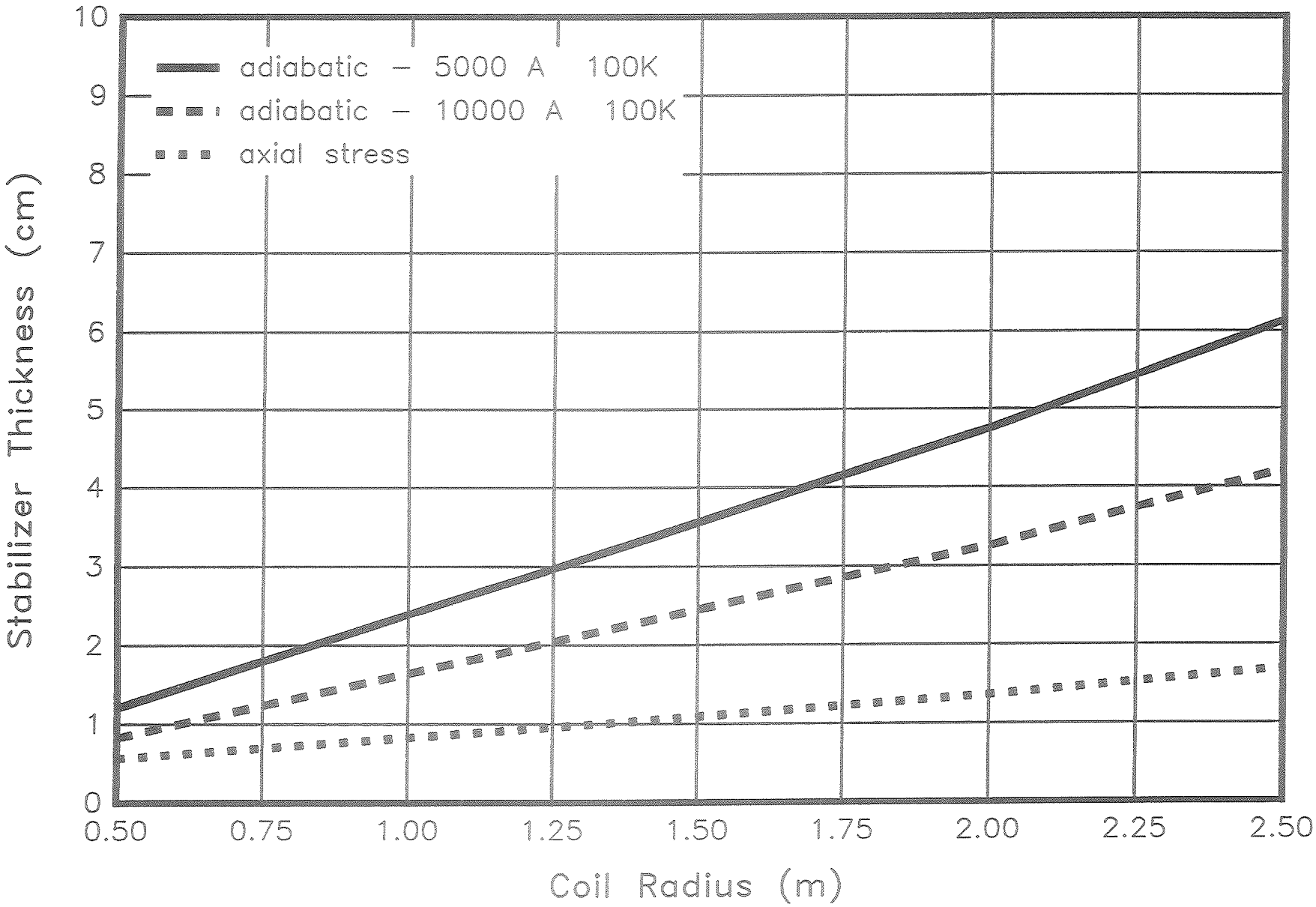


FIG. 10. RADIAL STABILIZER THICKNESS FOR ACS

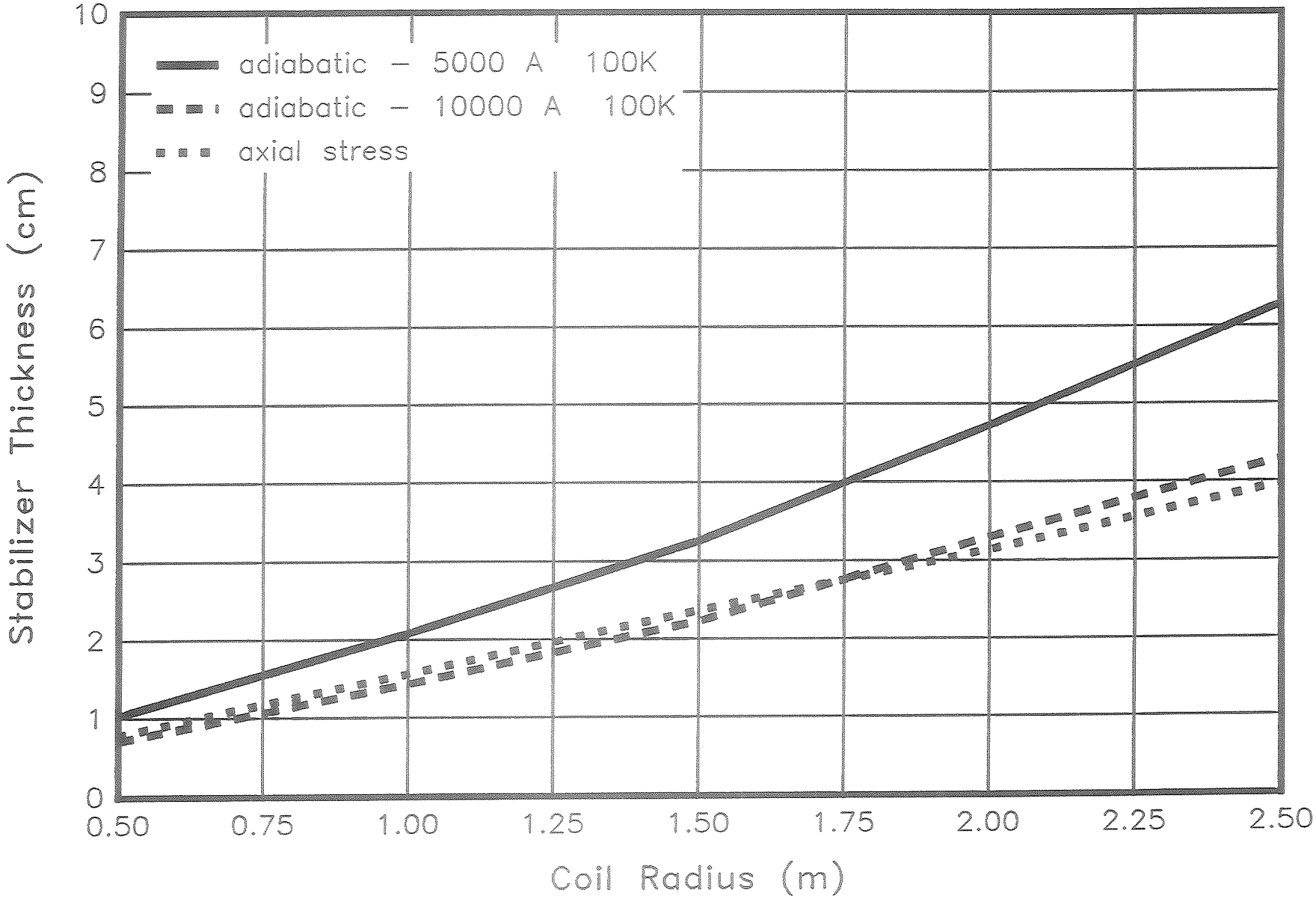


FIG. 11. TOTAL RADIAL THICKNESS FOR 5000 A AND 1.7T

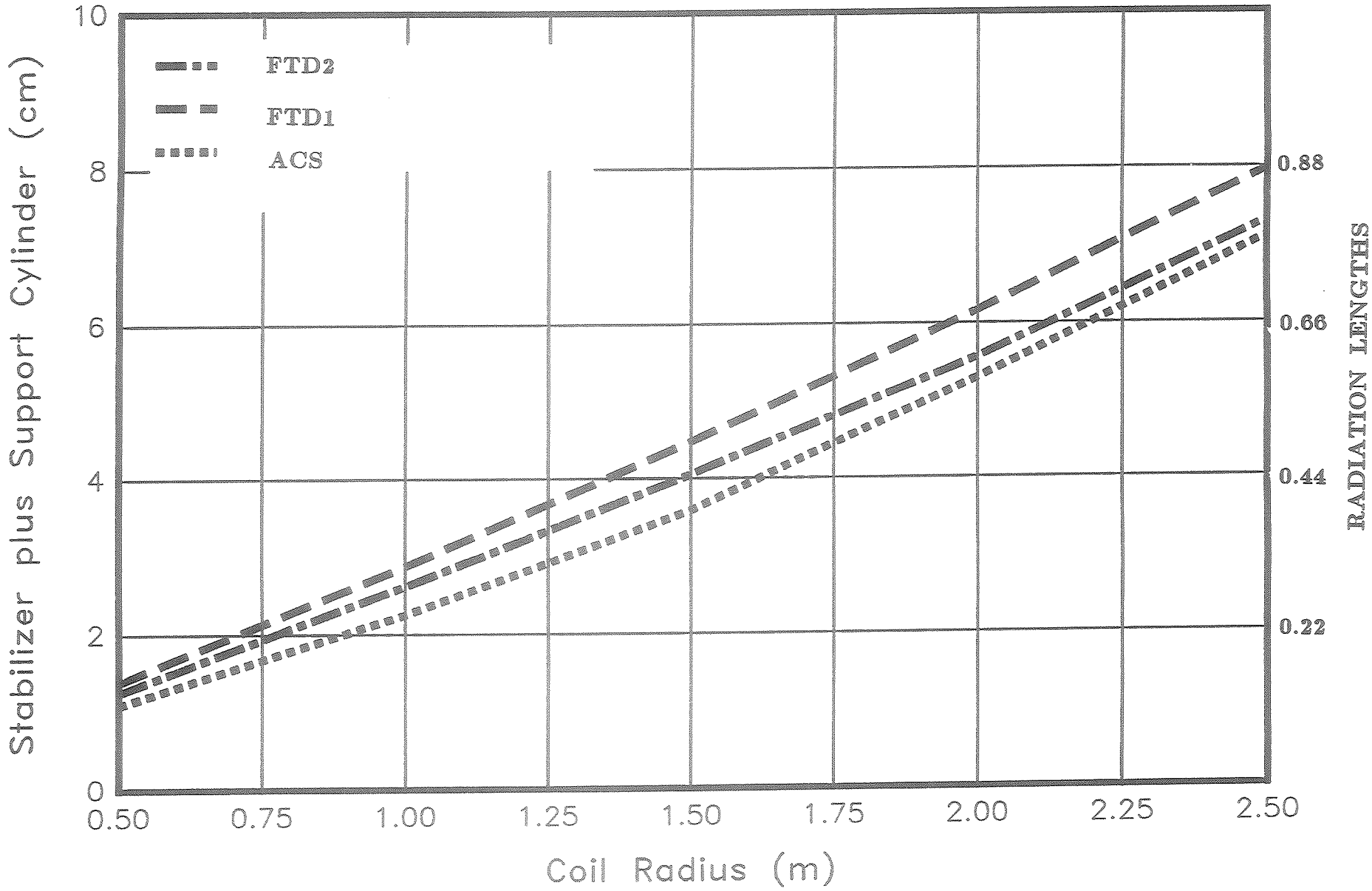


FIG. 12. TOTAL RADIAL THICKNESS FOR 10000 A AND 1.7T

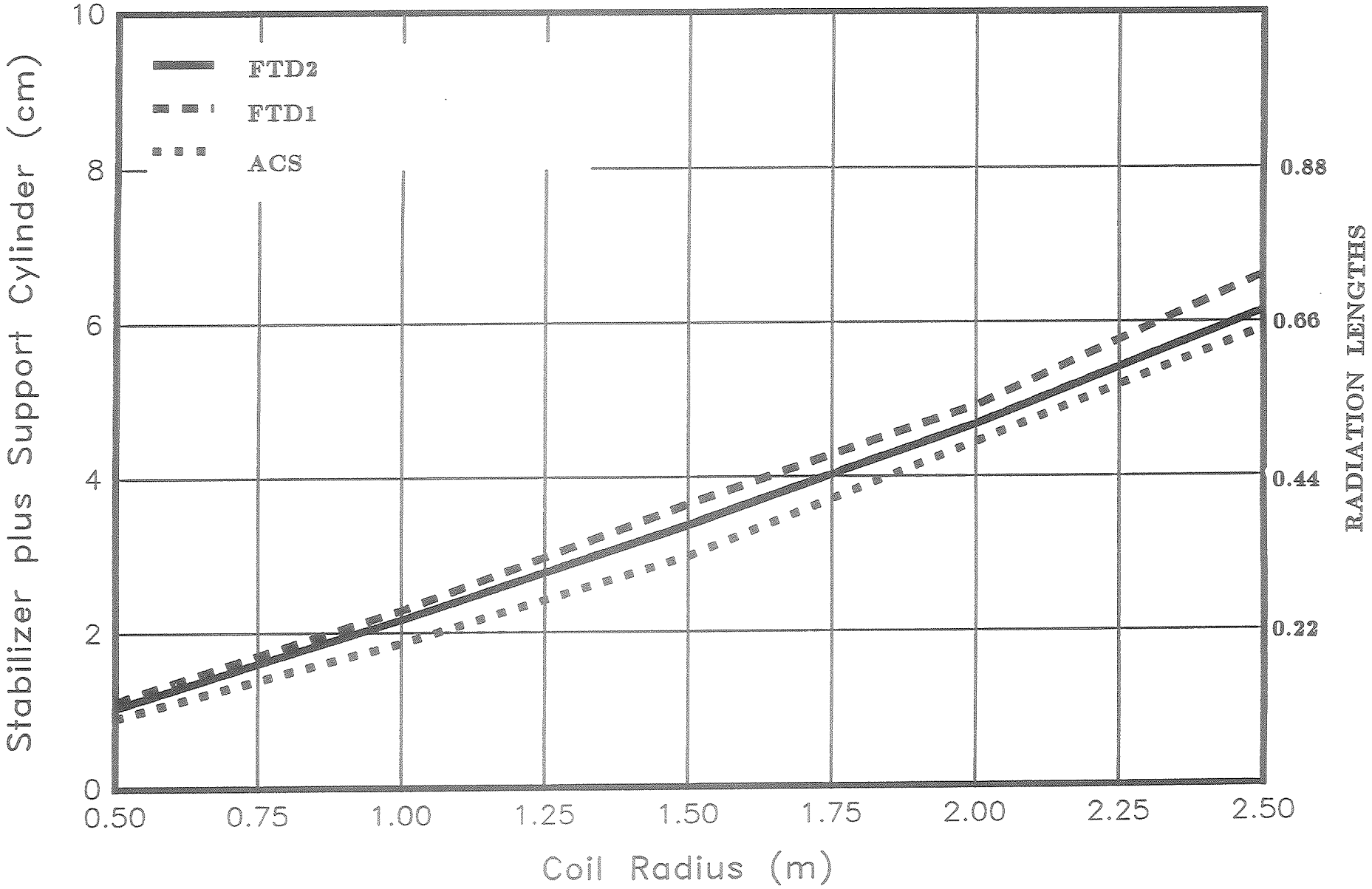
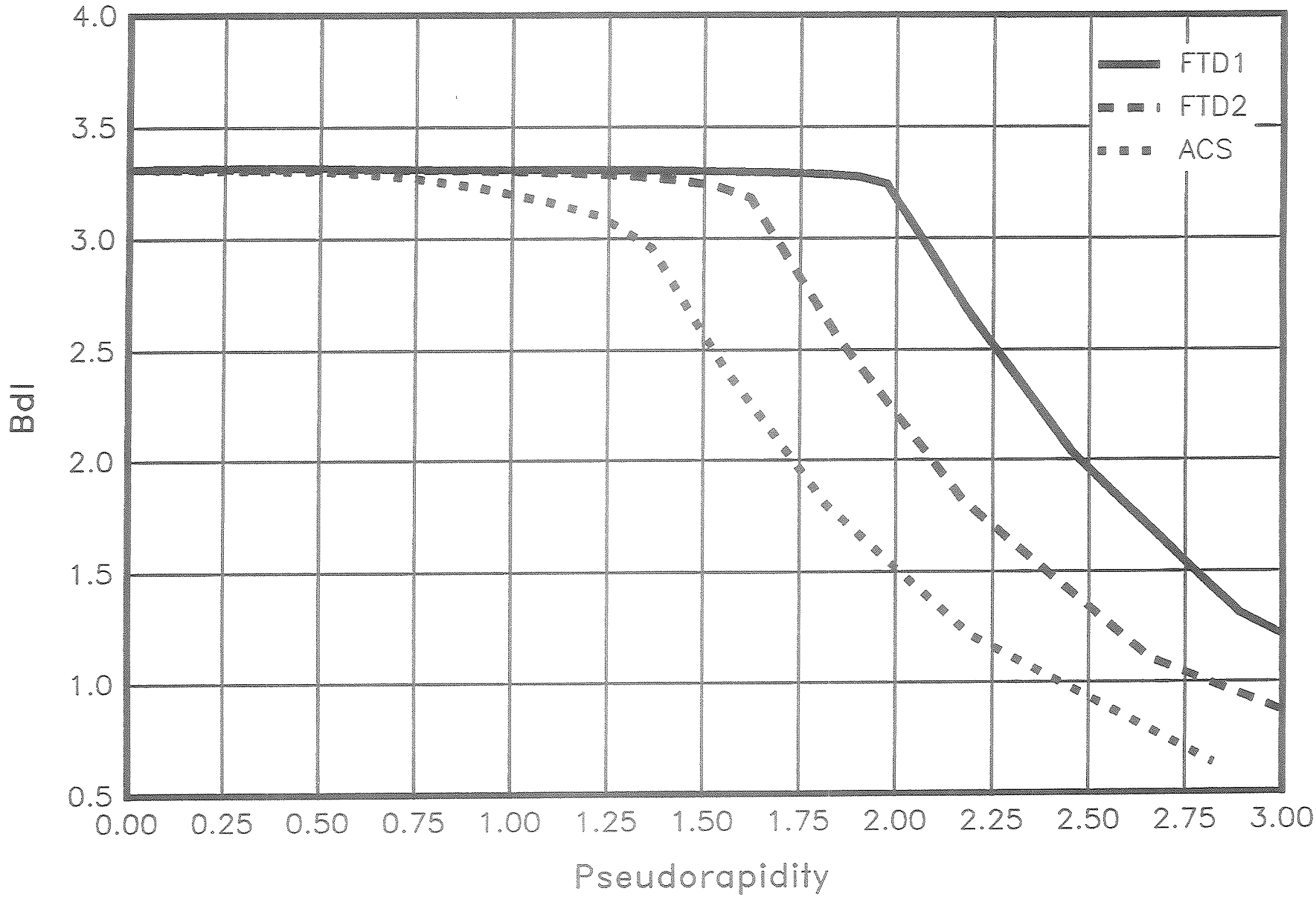
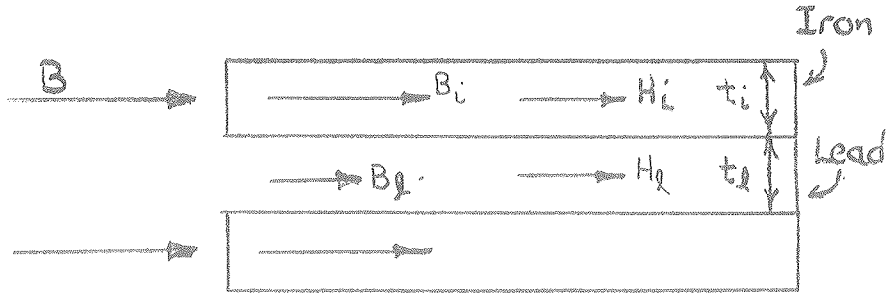


FIG. 13. BDL VS. PSEUDORAPIDITY



Appendix A
Modification of B-H Curve for FTD2

The FTD2 uses the calorimetry for flux return. Iron plates within the modules are oriented radially, such that once flux has entered the plate, it will encounter air gaps only between modules, and not within modules. The flux path with a module is



From Maxwells fourth relation it can be shown that $H_i = H_l$. Then $B_i = \mu H_i$ and $B_l = \mu_0 H_l$. The average B field is then

$$B_{AVG} = \frac{B_i t_i + B_l t_l}{t_i + t_l}$$

or, in terms of B_i and H_i,

$$B_{avg} = \frac{B_i t_i}{t_i + t_l} + \frac{\mu_0 H_i t_l}{t_i + t_l}$$

Then an approximate B-H curve can be generated for this case from $B_i - H_i$, resulting in retaining H_i and substituting B_{avg} for B_i

Appendix B
Calculation of Stabilizer Thickness from Adiabatic Quench Requirements[1]

Consider a heat balance on a unit volume of stabilizer

$$J^2(t)\rho(T)dt = \gamma C(T)dT$$

where J = current density

γ = mass density

ρ = resistivity

C = specific heat

t = time

T = temperature

Rearranging and integrating

$$\int_0^\infty J^2(t)dt = \int_{T_0}^{T_{max}} \gamma \frac{C(T)}{\rho(T)} dT$$

The LHS is a decaying exponential for the case of protection by an external dump resistor. If the dump resistance is much greater than the stabilizer resistance during the current decay then

$$\int_0^\infty J^2(t)dt = \frac{I^2}{A^2}\frac{\ell}{2R_d}$$

where ℓ = inductance $\quad$ I = current

R_d = dump resistance $\quad$ A = area of stabilizer

Then, if the RHS can be integrated numerically, A can be found. Knowing the axial conductor dimension t_a allows t_r to be solved for.

A program, MAXTEMP, was written to numerically integrate the RHS and solve for t_r (see attached). Parameters were

$T_{max} = 100$ K

$T_0 = 4.2$ K

RRR = 750

$R_d = 0.1\ \Omega$ @ 5000 A

$R_d = 0.05\ \Omega$ @ 10000 A

l = from ANSYS

t_a = from required NI

The values of RRR were taken from <u>Handbook on Materials for Superconducting Machinery</u>, Metals and Ceramics Information Center, Batelle-Columbus Laboratories, 1977. The values from RRR = 100-3000 were interpolated with a B-spline fit using an IMSL routine. Magnetoresistivity was not included

```
c*****************************************************************
c
c       This program calculates the maximum temperature rise in
c       a superconducting wire during a quench.
c
c       Require input is:
c
c       l = total inductance of magnet, Henrys (array)
c       rd = dump resister resistance, ohms
c       rr = residual resitivity of aluminum stabilizer, unitless
c       ta = axial width of conductor (array)
c
c*****************************************************************
        program maxt
        real l5000(5,3)/.7076,2.778,6.181,10.98,17.25,1.026,4.049
     1  ,9.104,16.15,25.35,.513,1.999,4.606,8.516,14.11/
c
        real ta(5,3)/.0037,.0037,.0037,.0037,.0036,.0037,.0037,.0037,.0037,
     1  .0037,.0037,.0036,.0035,.0033,.0032/
c
        real ta2(5,3)/.0074,.0074,.0074,.0074,.0072,.0074,.0074,.0074,.0074,
     1  .0074,.0074,.0072,.0070,.0066,.0064/
c
        real l10000(5,3)/.1769,.6946,1.545,2.745,4.313,.2566,1.012,2.276,
     1  4.038,6.336,.1282,.4997,1.151,2.219,3.526/
c
        real tr(5,3)
c****
        open(unit=1,file='cptemp.dat',status='new')
        open(unit=2,file='rhotemp.dat',status='new')
        open(unit=3,file='results.dat',status='new')
c
c       input the insulation thickness and call subroutine adjusta to
c       adjust the axial thickness arrays ta and ta2
c
        tin=0.0002
        call adjusta(ta,ta2,tin)
c
c****
c
        rr=750.
        rd=.1
        tmax=100.
c
c       call calcu to calculate radial widths
c
        cc=5000.
        call calcu(l5000,ta,rr,rd,tmax,tr,cc)
c
        write(3,3100)cc,rd,rr,tmax
 3100   format(' current=',f7.0,' dump resistance= ',f3.2,' RRR= ',f5.0,
     1  ' tmax=',f5.0)
c
c       print l
c
        write(3,3000)
        do 10 i=1,5
 10     write(3,1000)(l5000(i,j),j=1,3)
c
```

```
c       print tr
c
        write(3,2000)
 1000   format(3g20.5)
 2000   format(/,' Radial Thickness (meters)',/)
 3000   format(/,' Inductance (henries)',/)
 4000   format(/,' Axial Thickness (meters)',/)
        do 5 i=1,5
 5      write(3,1000)(tr(i,j),j=1,3)
c
c       print ta
c
        write(3,4000)
        do 15 i=1,5
 15     write(3,1000)(ta(i,j),j=1,3)
        write(3,3200)
 3200   format(///)
c       call calcu to calculate radial widths
c
        rd=.05
        cc=10000.
        call calcu(l10000,ta2,rr,rd,tmax,tr,cc)
c
        write(3,3100)cc,rd,rr,tmax
c
c       print l
c
        write(3,3000)
        do 100 i=1,5
 100    write(3,1000)(l10000(i,j),j=1,3)
c
c       print tr
c
        write(3,2000)
        do 35 i=1,5
 35     write(3,1000)(tr(i,j),j=1,3)
c
c       print ta
c
        write(3,4000)
        do 25 i=1,5
 25     write(3,1000)(ta2(i,j),j=1,3)
c
        stop
        end
c
c*****************************************************************
c******** Subroutine calcu takes in the array of inductance in, the
c******** array of axial widths, ta , the maximum desired temperature
c******** tmax, the dump resistance, the rrr of the stabilizer, and
c******** returns the array tr, the radial width of the conductor
c*****************************************************************
        subroutine calcu(l,ta,rr,rd,tmax,tr,cc)
c
        real l(5,3),ta(5,3),tr(5,3)
c
c
        do 10 i=1,5
        do 10 j=1,3
```

```
c       print tr
c
        write(3,2000)
 1000   format(3g20.5)
 2000   format(/,' Radial Thickness (meters)',/)
 3000   format(/,' Inductance (henries)',/)
 4000   format(/,' Axial Thickness (meters)',/)
        do 5 i=1,5
 5      write(3,1000)(tr(i,j),j=1,3)
c
c       print ta
c
        write(3,4000)
        do 15 i=1,5
 15     write(3,1000)(ta(i,j),j=1,3)
        write(3,3200)
 3200   format(///)
c       call calcu to calculate radial widths
c
        rd=.05
        cc=10000.
        call calcu(l10000,ta2,rr,rd,tmax,tr,cc)
c
        write(3,3100)cc,rd,rr,tmax
c
c       print l
c
        write(3,3000)
        do 100 i=1,5
 100    write(3,1000)(l10000(i,j),j=1,3)
c
c       print tr
c
        write(3,2000)
        do 35 i=1,5
 35     write(3,1000)(tr(i,j),j=1,3)
c
c       print ta
c
        write(3,4000)
        do 25 i=1,5
 25     write(3,1000)(ta2(i,j),j=1,3)
c
        stop
        end
c
c*****************************************************************
c******** Subroutine calcu takes in the array of inductance in, the
c******** array of axial widths, ta , the maximum desired temperature
c******** tmax, the dump resistance, the rrr of the stabilizer, and
c******** returns the array tr, the radial width of the conductor
c*****************************************************************
        subroutine calcu(l,ta,rr,rd,tmax,tr,cc)
c
        real l(5,3),ta(5,3),tr(5,3)
c
c
        do 10 i=1,5
        do 10 j=1,3
```

```
      Call intg(tmax,l(i,j),rd,rr,tot)
c
c     Solve for appropriate jo
      a=(l(i,j)/(2*rd))
      jocor=sqrt(tot/a)
c
c     solve for radial thickness of conductor
c
      tr(i,j)=(cc/(jocor*ta(i,j)))
 10   continue
      return
      end
c*****************************************************************
c********* subroutine writer1 asks for inductance, dump resistance
c********* residual resistivity, and current density
c*****************************************************************
      subroutine writer1(l,rd,rr,ta)
      real ta,l
      print *,' enter inductance, dump resitance, rrr, and axial thickness:'
      read *,l,rd,rr,ta
      return
      end
c*****************************************************************
c********* subroutine writer2 asks for trial tmax
c*****************************************************************
      subroutine writer2(tmax)
      print *,' enter trial tmax:'
      read *,tmax
      return
      end
c*****************************************************************
c********* subroutin intg does the numerical integration of the
c********* integral gamma*cp(t)/rho(t) between tmax and 4.2k
c*****************************************************************
      subroutine intg(tmax,l,rd,rr,tot)
      real rhotemp(500),cptemp(500)
      tend=tmax
      tstart=4.2
      tinc=1.
      gamma=2770.
      call prop(rr,tstart,tend,tinc,rhotemp,cptemp)
      tot=0
      tottemp=tstart
      do 5 i=1,600
      write(1,1000)tottemp,cptemp(i)
      write(2,1000)tottemp,rhotemp(i)
 1000 format(f6.2,5x,g20.6)
      cptemp(i)=4.1868e3*cptemp(i)
      tot=tot+(gamma*cptemp(i)/rhotemp(i))*tinc
      tottemp=tottemp+tinc
      if(tottemp .gt. tmax)goto 10
 5    continue
 10   continue
      return
      end
c*****************************************************************
c********* subroutine prop fills the arrays rhotemp and cptemp with
c********* resistivity and specific heat as functions of temperature
c********* requires starting temperature, ending temperature, and inc
```

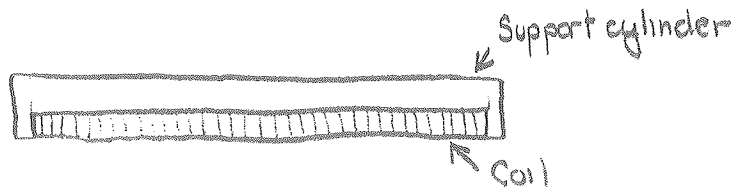
```
c*********************************************************************
      subroutine prop(rr,tstart,tend,tinc,rhotemp,cptemp)
      real cscoef(4,6),rhot,break(6)
      real cscoef1(4,24),break1(24),rhotemp(500),cptemp(500)
c****
c****
c****
c****   call subroutine to interpolate rho vs t for rint, do spline
c****   fit and return info necessary to determine rho for any t
c****
      call rrr(rr,cscoef,break)
c****
c****   call subroutine to do spline fit of cp vs t and return info
c****   necessary to determine cp for any t
c****
      call cpe(cscoef1,break1)
c****
c****   fill arrays rhotemp and cptemp
c****
      t=tstart
      do 5 i=1,1000
      nintv=5
      rhotemp(i)=csval(t,nintv,break,cscoef)
      nintv=23
      cptemp(i)=csval(t,nintv,break1,cscoef1)
      t=t+tinc
 5    if(t .gt. tend)goto 10
c****
 10   continue
      return
      end

c*********************************************************************
c*********************************************************************
      subroutine rrr(rint,cscoef,break)
c***
c***   This subroutine finds the resistivity of aluminum over the
c***   temperature range from 4k to 273k, for rrr's from 100 to
c***   30000. Data is interpolated from 'Handbook on Materials for
c***   Superconducting Machinery'
c***
c***   Declare array for handbook tables and initialize
c***
c***   Vectors of temperatures and rrr
c***
      real temp(6)/273,100,50,20,10,4/
      real rratio(6)/30000,10000,3000,1000,300,100/
      real rint,rhorrr(6),cscoef(4,6),break(6)
      parameter (ndata=6)
c***
c***   Array of resisitivity
c***
      real rho(6,6)/2.43e-8,2.43e-8,2.43e-8,2.43e-8,2.44e-8,2.45e-8,
     1 4.6e-9,4.6e-9,4.61e-9,4.63e-9,4.68e-9,4.85e-9,
     1 4.96e-10,4.97e-10,5.03e-10,5.19e-10,5.76e-10,7.4e-10,
     1 7.02e-12,8.64e-12,1.43e-11,3.05e-11,8.74e-11,2.52e-10,
     1 1.e-12,2.62e-12,8.29e-12,2.45e-11,8.14e-11,2.45e-10,
     1 8.15e-13,2.43e-12,8.1e-12,2.43e-11,8.12e-11,2.45e-10/
c****
```

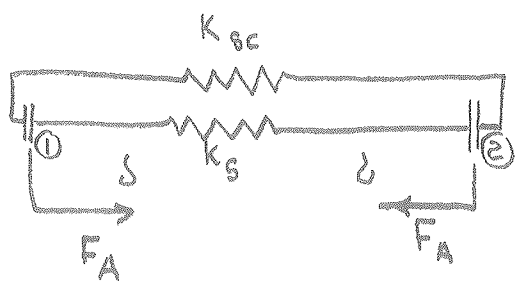
```
c****
c****   Call subroutine for calculating six values of resistivity at
c****   the six temperatures
c****
        Call crrr(rint,temp,rratio,rho,rhorrr)
c****
c****   Call subroutine to calculate coefficients from trrr and temp
c****
        Call cspline(rhorrr,temp,cscoef,break,ndata)
c****
        return
        end
c*******************************************************************
c*******************************************************************
c************* Subroutine crrr
c*************
c************* This subroutine calculates the six values of rho at
c************* the six temperatures in the array temp by linearly
c************* interpolating the values in rho
c*******************************************************************
        subroutine crrr(rint,temp,rratio,rho,rhorrr)
        real rint,temp(6),rratio(6),rho(6,6),rhorrr(6)
c******
c****** find the two values of rratio that rint lies between
c******
        do 5 i=1,5
        if(rint .eq. rratio(i))goto 25
 5      if(rint .lt. rratio(i) .and. rint .gt. rratio(i+1))goto 10
 10     lb=i
        ub=i+1
c******
c****** The interpolation will occur between row b1 and row b2 in the
c****** array rho. i.e., rho(b1,j) and rho(b2,j)
c******
c****** Interpolate for temp(i)
c******
        do 15 i=1,6
        f1=rint-rratio(lb)
        f2=rho(ub,i)-rho(lb,i)
        f3=rratio(ub)-rratio(lb)
 15     rhorrr(i)=(f1*f2/f3)+rho(lb,i)
        goto 35
 25     do 30 j=1,6
 30     rhorrr(j)=rho(i,j)
 35     continue
        return
        end
c*******************************************************************
c*************  Subroutine cspline interpolates rhorrr and temp data
c*******************************************************************
        Subroutine cspline(rhorrr,temp,cscoef,break,ndata)
        real cscoef(4,ndata),break(ndata)
        call csakm (ndata,temp,rhorrr,break,cscoef)
        return
        end
c*******************************************************************
c*********** Subroutine cpe initializes cp-temp arrays, calls
c*********** spline fit routine cspline, and returns cscoef and break
c*******************************************************************
```

```
      subroutine cpe(cscoef,break)
      parameter (ndata=24)
      real cscoef(4,ndata),break(ndata)
c*****
c***** initialize cp vector
c*****
      real cp(24)/6.768e-5,9.826e-5,1.245e-4,2.567e-4,4.133e-4,
     1 6.067e-4,8.918e-4,1.398e-3,1.958e-3,
     1 3e-3,9e-3,1.94e-2,4.88e-2,6.13e-2,
     1 6.96e-2,9.21e-2,1.135e-1,1.389e-1,1.628e-1,
     1 1.816e-1,1.932e-1,1.993e-1,2.065e-1,2.109e-1/
c*****
c***** initialize temp vector
c*****
      real temp(24)/4.072,5.093,6.003,8.426,10.479,12.185,
     1 14.713,17.121,19.280,22.67,31.61,40.68,58.59,65.79,70.52,
     1 84.,97.97,119.74,148.5,178.45,204.92,225.75,253.32,273.03/
c*****
c***** Call cspline and get back cscoef,break
c*****
      Call cspline(cp,temp,cscoef,break,ndata)
      return
      end
c*****************************************************************
c*********** subroutine adjusta reduces the axial thickness
c*********** of the conductor by the amount of the insulation
c*********** thickness tin
c*****************************************************************
      subroutine adjusta(t1,t2,tin)
      real t1(5,3),t2(5,3),tin
      do 5 i=1,5
      do 5 j=1,3
      t1(i,j)=t1(i,j)-tin
 5    t2(i,j)=t2(i,j)-tin
      return
      end
c*****************************************************************
```

Appendix C
Calculation of Coil Preload

The purpose of preloading the coil against the support cylinder is to force the two components to act together in resisting the axial magetic force. This analysis uses a simple two spring model





If there is no contact at 1 and 2, Then the displacement due to F_A is

$$\frac{F_A}{2K_s} = \delta$$

with to coil compression of

$$\delta_t = 2\delta = \frac{F_A}{K_s}$$

If sufficient preload exists to maintain contact at 1 and 2, Then

$$\frac{F_A}{2(K_s+K_{sc})} = \delta$$

$$\delta_t = \frac{F_A}{K_s+K_{sc}}$$

The minimum preload is the preload that results in the support cylinder having a tensile stress of zero when F_A is applied - in otherwords, the preload tensile stress in the support cylinder is totally relieved under F_A, and the coil carries the full load. This can be calculated from $\delta_t = \frac{F_A}{k_s + k_{sc}}$, since the force relieved in the cylinder for

This displacement must be the preload force, F_p. So,

$$F_p = \frac{k_{sc} F_A}{k_s + k_{sc}}$$

for identical coil and support cylinder materials and nominal axial dimensions

$$\boxed{F_p = \frac{t_{sc} F_A}{t_s + t_{sc}}}$$