SDC SOLENOID DESIGN

Presented by

Akira Yamamoto

(KEK)

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* to be presented at SDC Technical Review by SSCL on May 5, 92.

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1. General Design

2. Coil Design

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6. Coil Support

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8. Thermal Design and Cooldown Characteristics

9. Diagnostics and Instrumentation

10. Magnet Assembly and Initial Test

Table 5-1
General requirements of SDC solenoid.

Magnet envelope		
Cryostat	Inner radius	1.70 m
	Outer radius	2.05 m
	Total half length	4.389 m
Nominal magnetic field		2 T
Transparency	(η=0)	1.2 X_0
		0.25 λ_I
Cool down time		< 14 days
Quench recovery time		< 4 hr

1. General Design

Design Bases:

The solenoid with B = 2 T and X = 1.2 Xo

to be used with a calorimeter with either a Feromagnetic iron abosrber or with a non-magnetic absorber.

Technical Concerns:

- Strong Electromagnetic Force initiated by B = 2 T
- Thermal Stress after Quench due to thinness of 1.2 Xo

According to recent technical design decision
to take feromagnetic iron abosorber:

Axial Distance b/w Coil and Iron :	47 - 62 cm
Maximum Stress in the Coil:	52 - 54 MPa
Axial Compressive Force:	1100 - 1300 tonnes
Axial Decentering Force:	20 - 15 tonnes/cm

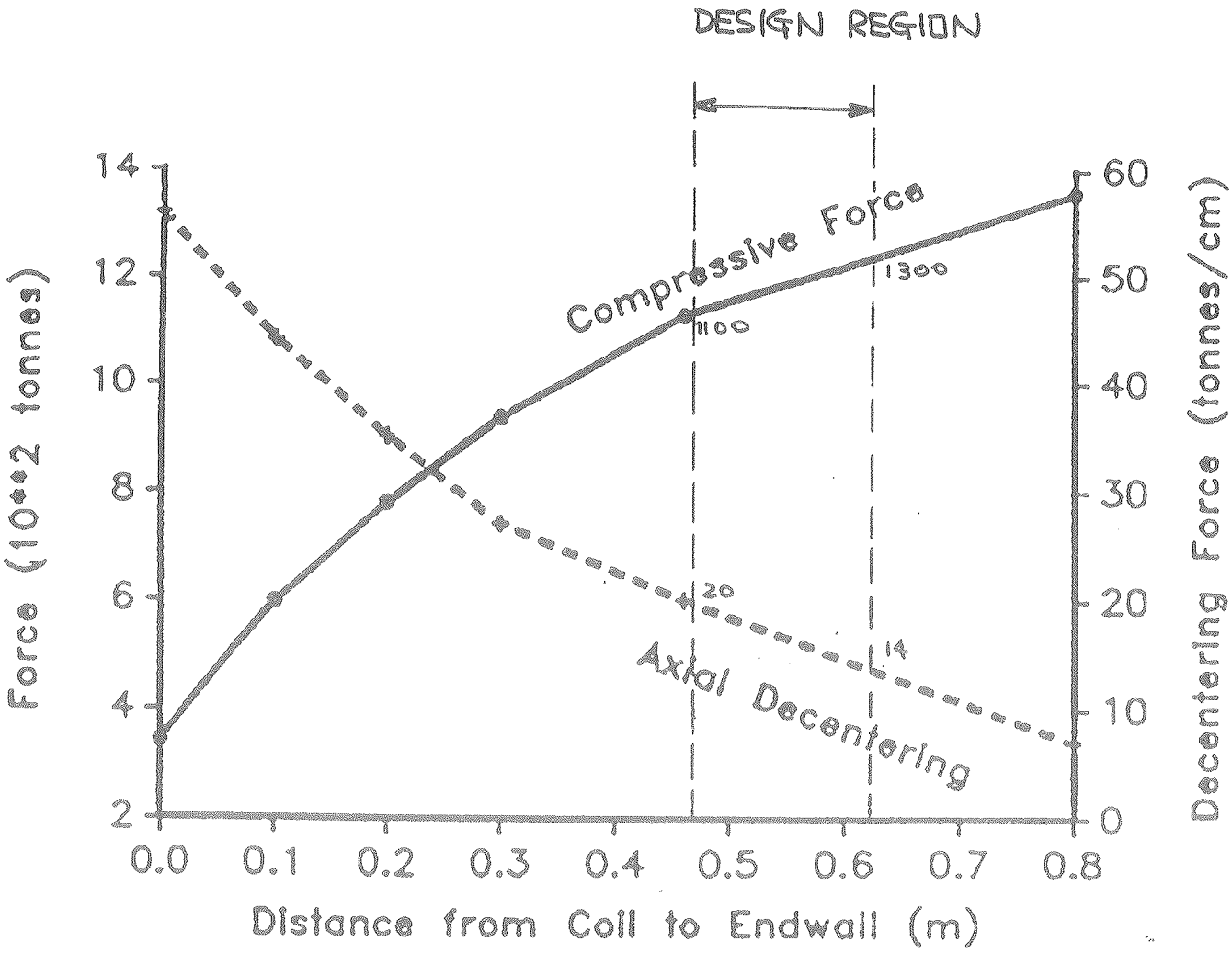


FIG. 5-1. Coil compressive force and axial decentering force as a function of the axial distance between the end of the coil and the iron endcap calorimeter.

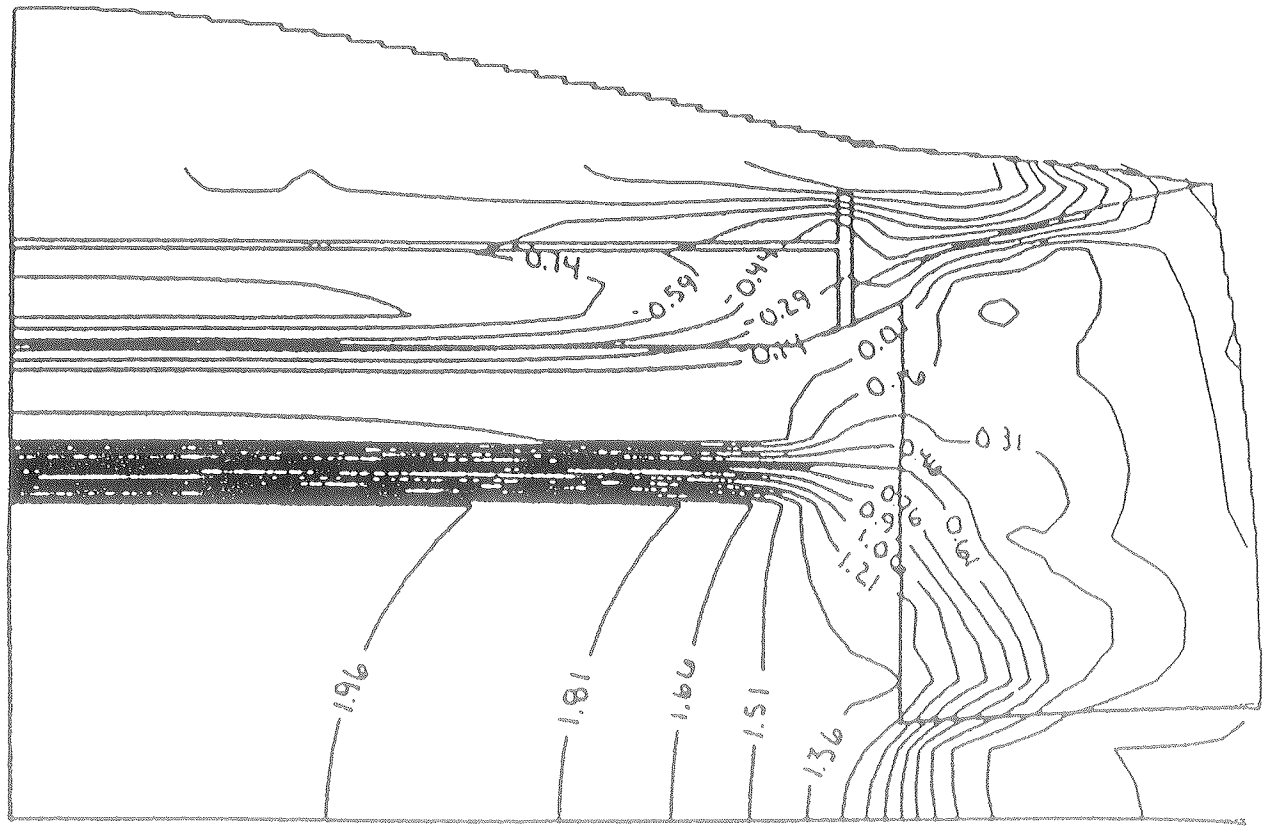


FIG. 5-2. Field contour plot for an axial coil-iron separation of 470 mm. The field is in teslas.

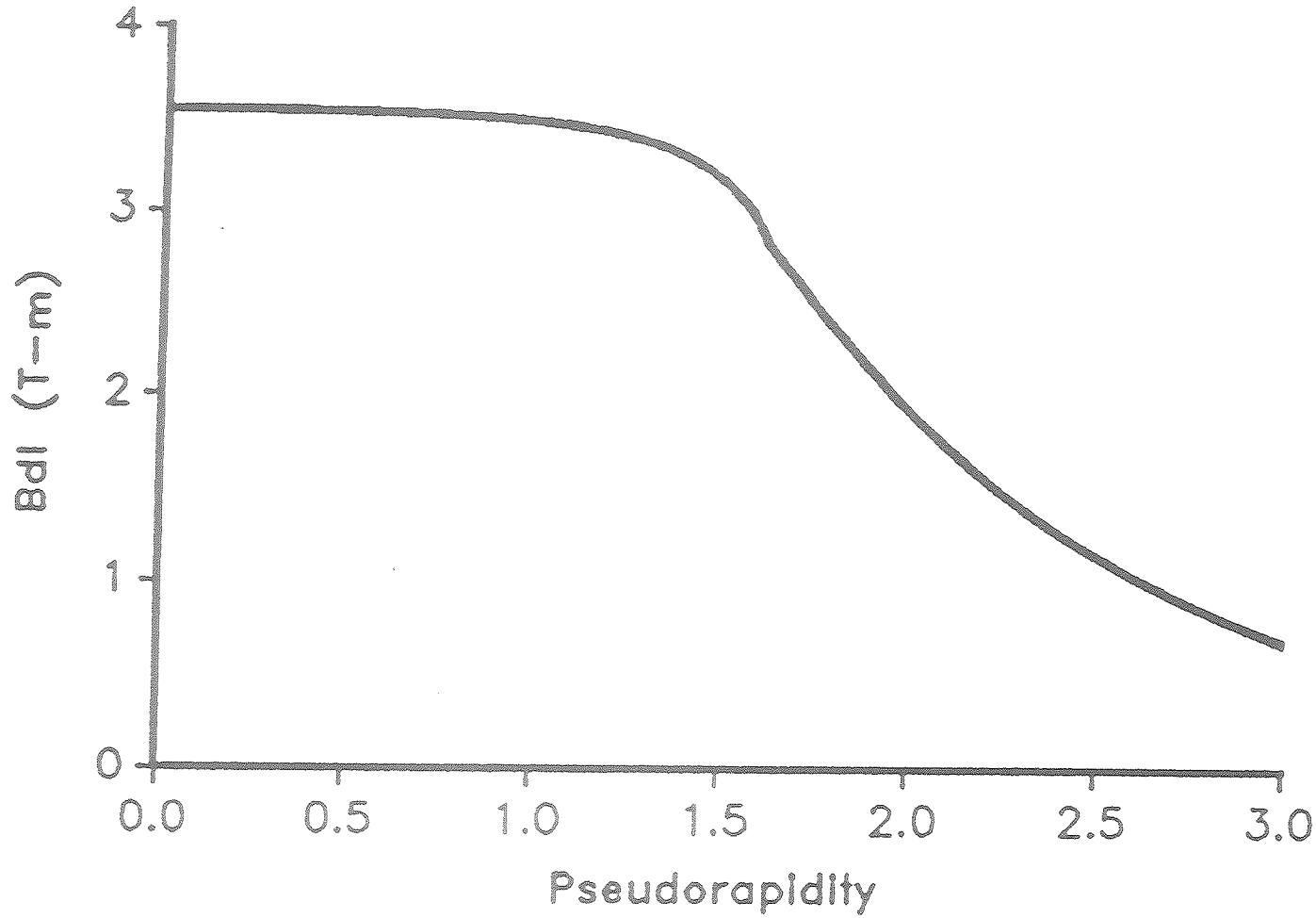
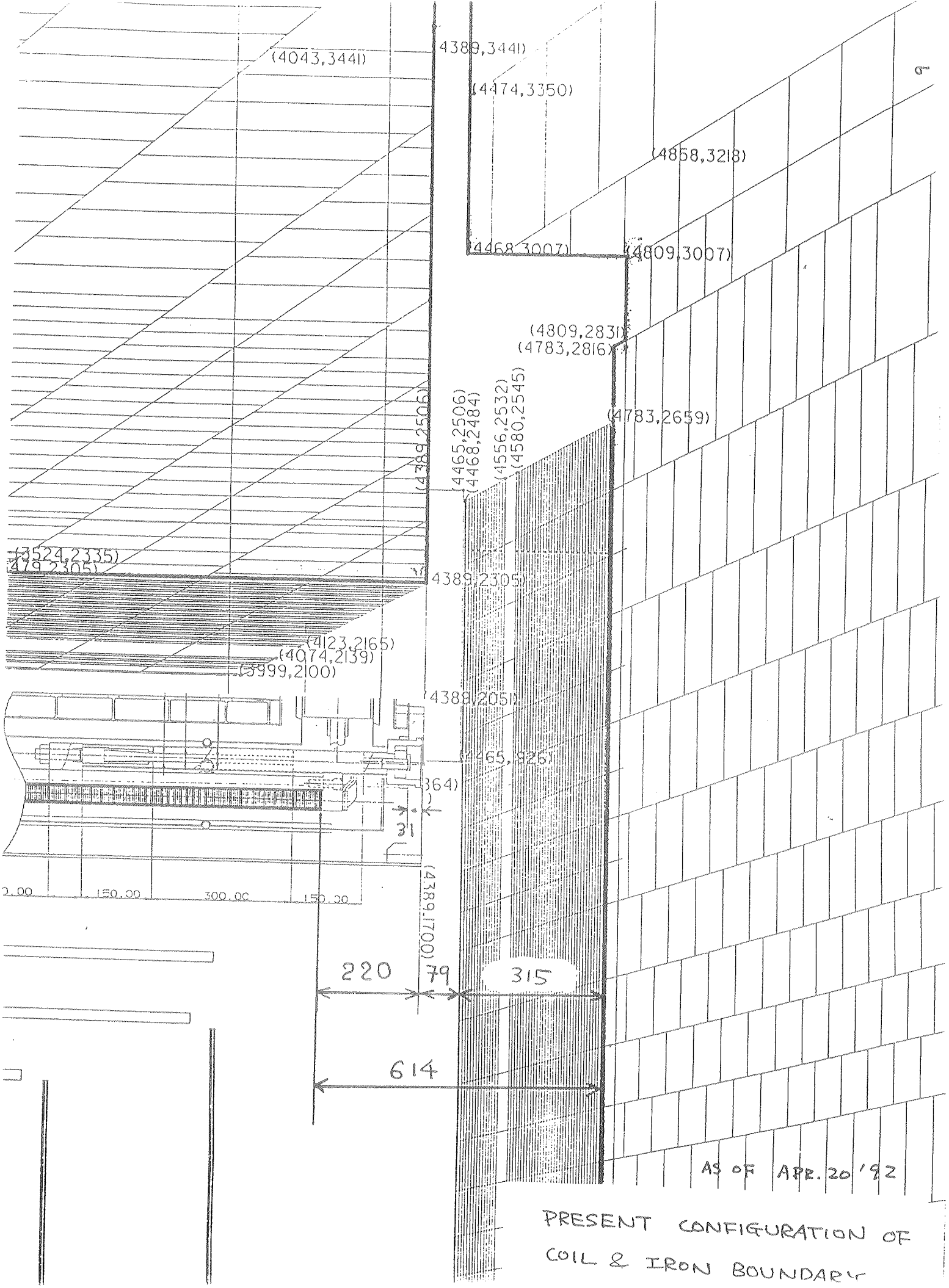


FIG. 5-3. $\int B \times dl$ as a function of pseudorapidity.


(4043,3441)
(4389,3441)
(4474,3350)
(4858,3218)
(4468,3007)
(4809,3007)
(4809,2831)
(4783,2816)
(4783,2659)
(4465,2506)
(4468,2484)
(4556,2532)
(4580,2545)
(4389,2506)
(3524,2335)
(4389,2305)
(4123,2165)
(4074,2139)
(3999,2100)
(4388,2051)
(4465,1926)
31
(4389,1700)
220
79
315
614
AS OF APR. 20 '92
PRESENT CONFIGURATION OF
COIL & IRON BOUNDARY

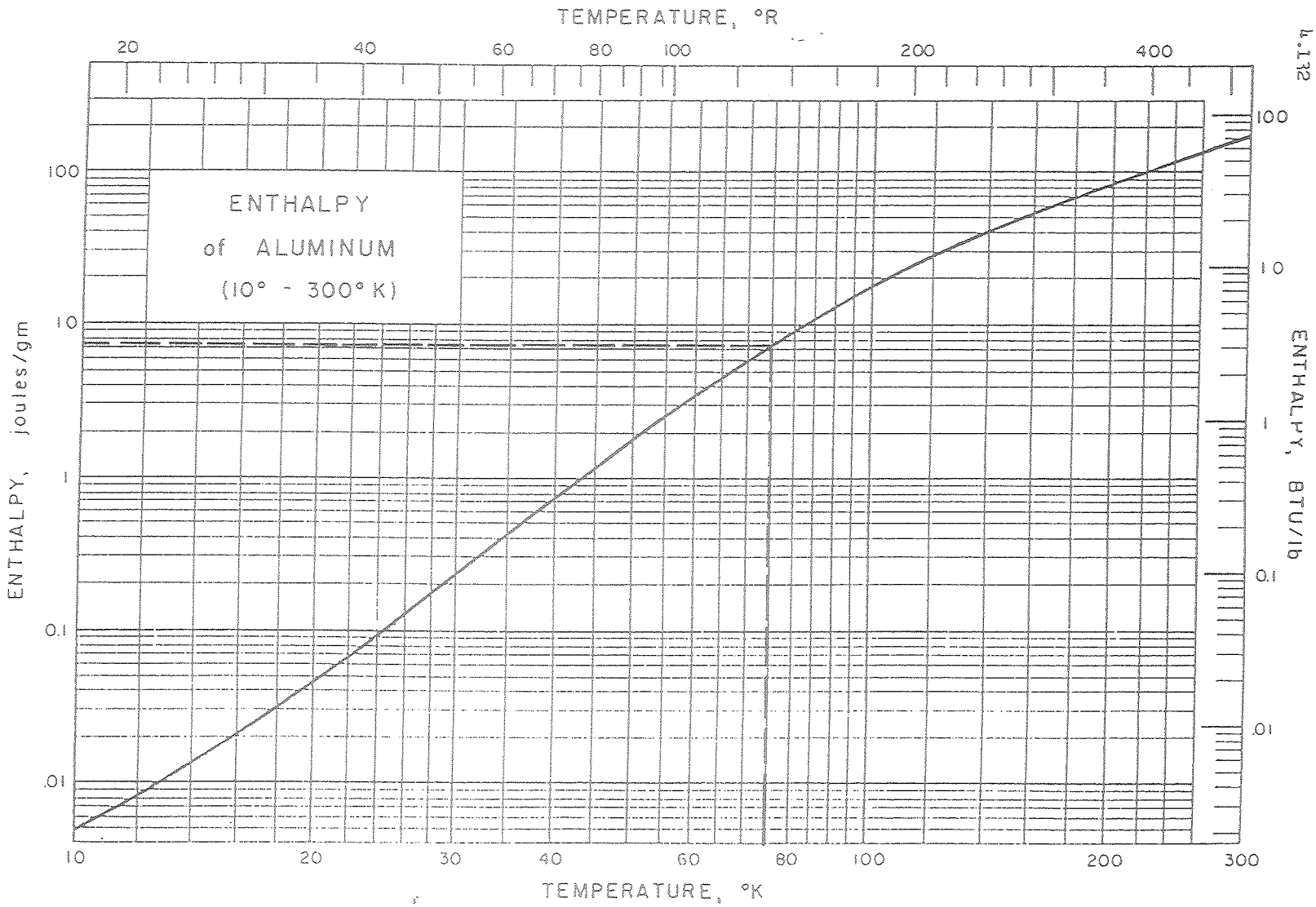
Design Guide Lines:

- In order to have fully elastic design, the stresses in the coil AND outer-support-cylinder cold mass, the mechanical design will limit the strain in the outer support cylinder to <u>0.1 %.</u>

- To eliminate unacceptable thermal stress in the cold mass following a quench, the maximum hot spot temperature will be limited to <u>100 K.</u>

- To optimize transparency of the magnet (1.2 Xo),

$$E/M \text{ Ratio} = H(T2) - H(T1) = 7.5 \text{ kJ/kg}$$



ENTHALPY OF AL V.S. TEMPERATURE

4.132

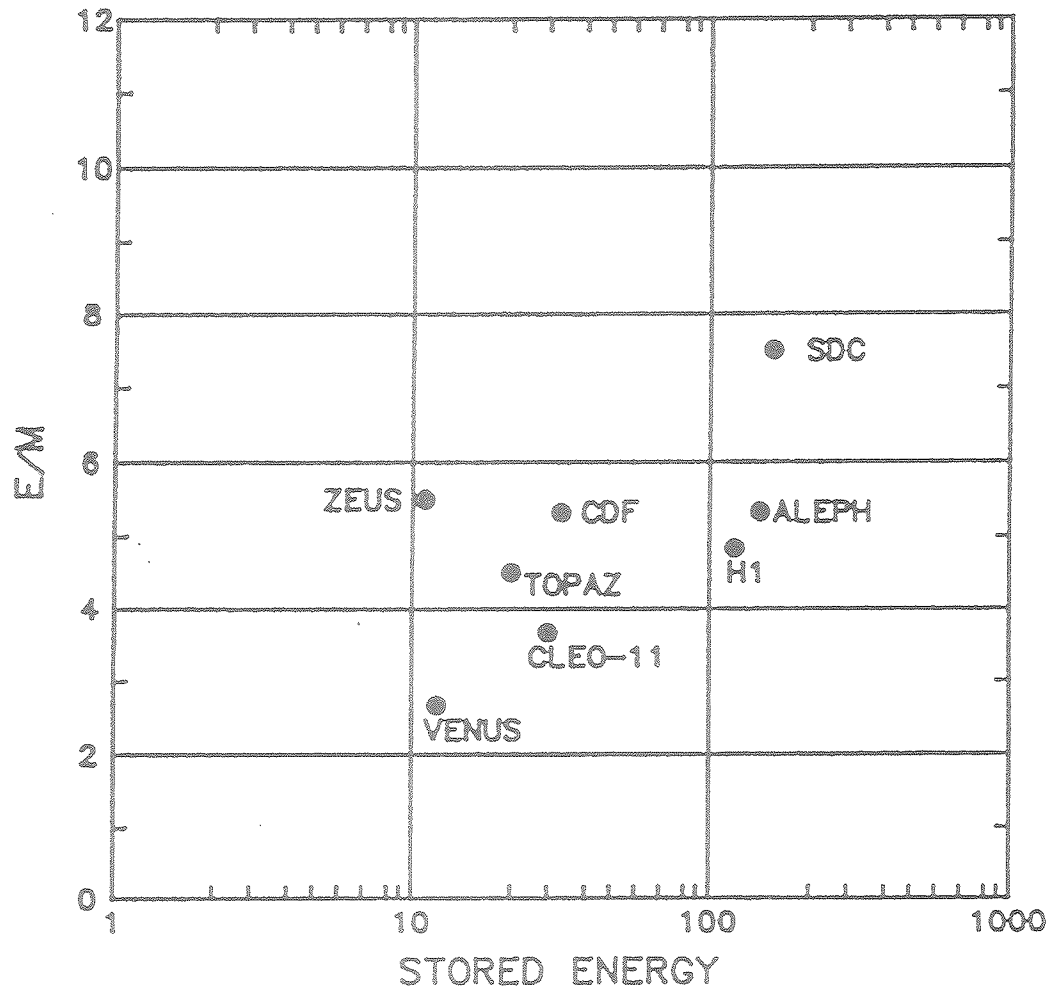
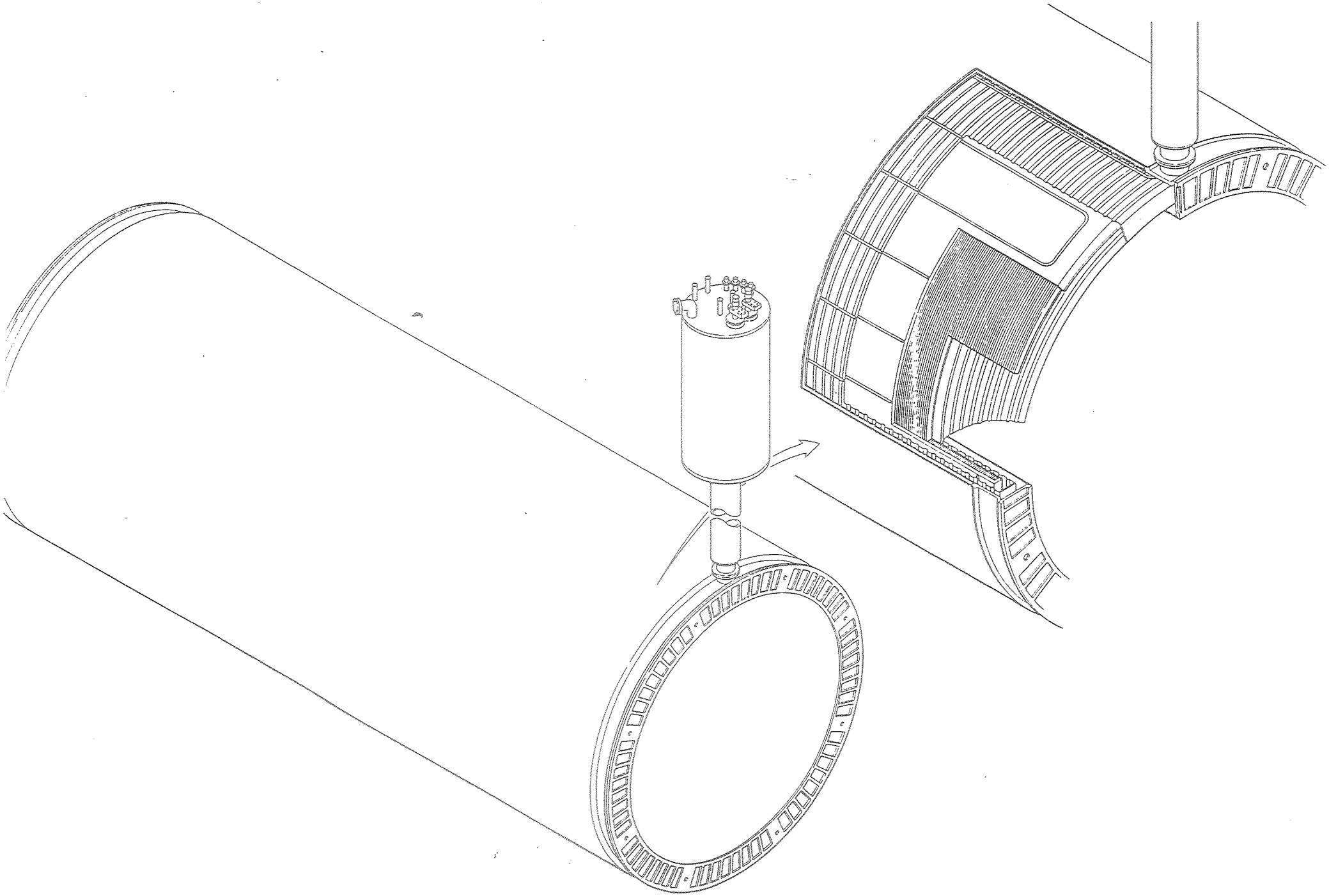


FIG. 5-4. Ratio of stored energy to cold mass for existing thin detector solenoids.



BIRD'S EYE VIEW OF THE SOLENOID

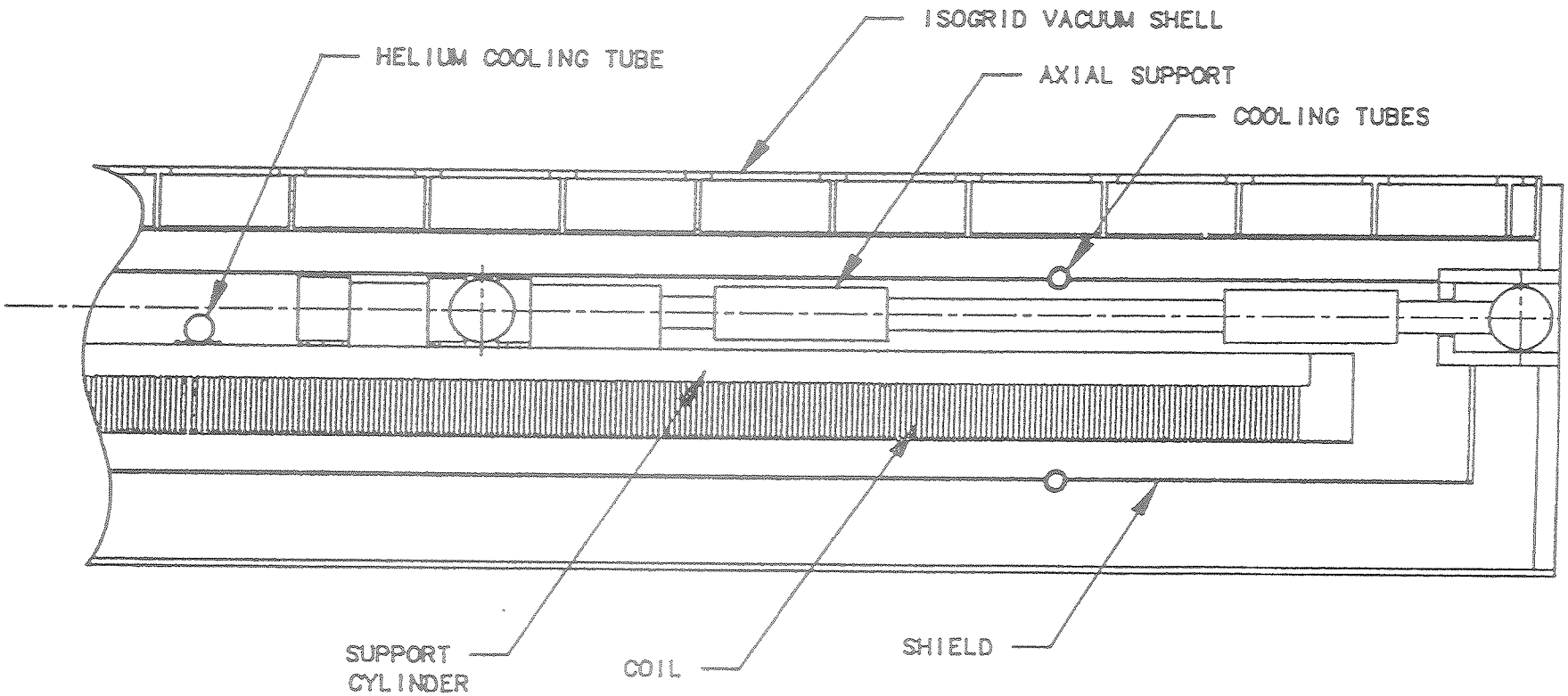


FIG. 5-6. Cross section of the end portion of the detector solenoid.

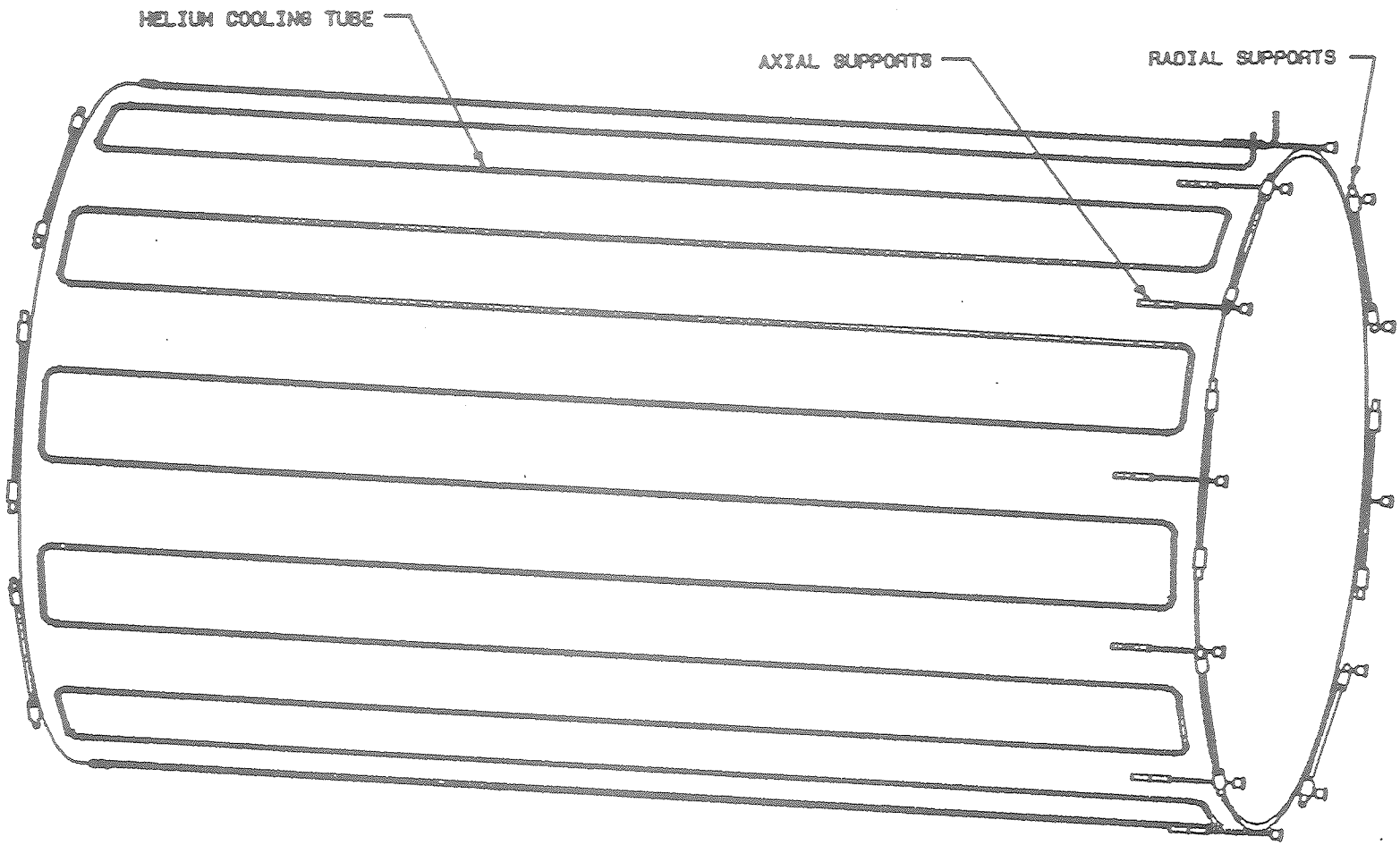


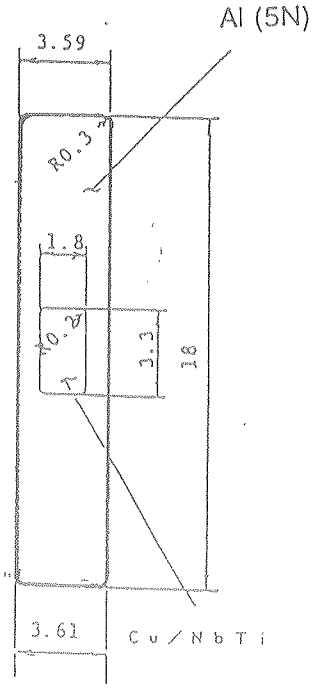
FIG. 5-7. Solenoid cold mass. Radial supports are on both ends, axial supports are on one end only.

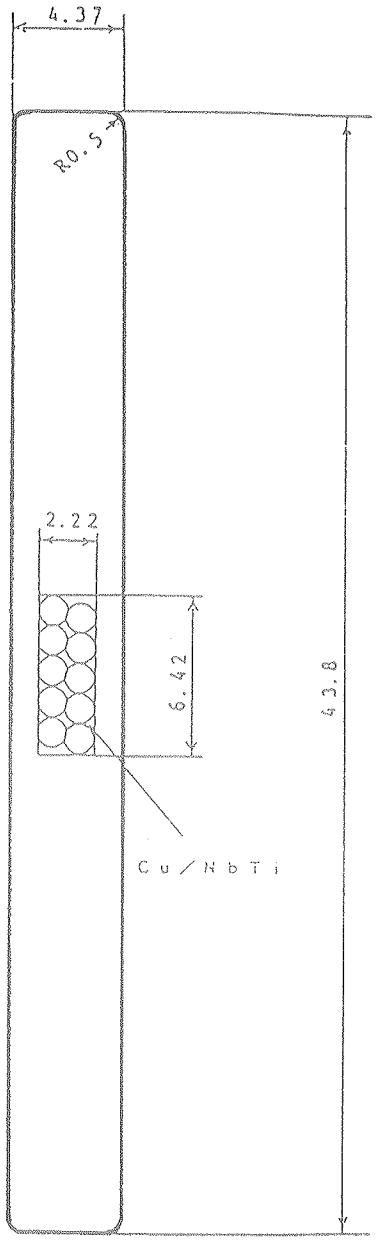
Table 5-2
Baseline design parameters of SDC solenoid.

Dimensions:		
Cryostat	Inner radius	1.70 m
	Outer radius	2.05 m
	Half length	4.389 m
Coil	Effective radius	1.84 m
	Half length	4.12–4.18 m
Conductor	Thickness	44 mm
Outer support cylinder	Thickness	31 mm
Electrical parameters		
Central field		2.0 T
Nominal current		8,000 A
Inductance		4.6 H
Stored energy		146 MJ
Stored energy / cold mass		7.4 kJ/kg
Typical charging time		1 hour
Mechanical parameters		
Effective cold mass		20 tonnes
Total weight		25 tonnes
Radial magnetic pressure		1.6 MN/m^2
Axial compressive force		11 MN (13)

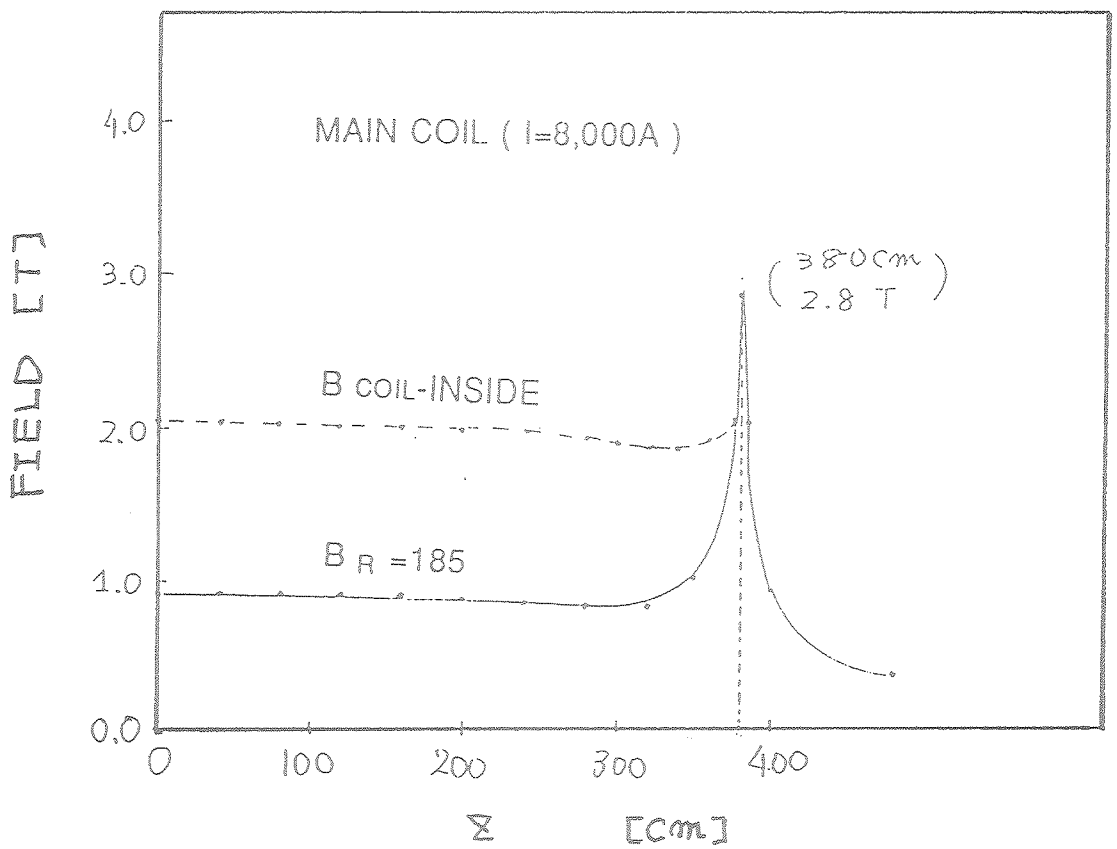
Table 5-5
Design parameters of the SDC superconductor.

Aluminum stabilized superconductor	
Superconductor material	Nb Ti/Cu
Stabilizer	Al (99.999% +200 ppm Zn)
Area ratio (Nb/Ti/Cu/Al)	1/1/29.8
Conductor size	43.8×4.37 mm^2
Superconductor strand	
Strand diameter	1.277 mm
Nb Ti filament diameter	20 μm
Number of filaments.	4100
Superconductor cable	
Overall size	6.4×2.5 mm^2
Number of cables	10 (2×5)
Cabling pitch	50–60 mm
J_c in Nb Ti (at 5 T, 4.2 K)	2500 A/mm^2
Critical current (at 5 T, 4.2 K)	16,000 A
Characteristics of stabilizer	
RRR (Cu)	100
RRR (Al)	500
Yield Strength of Al (at 77 K)	67 MPa
Shear strength b/w Cu / Al	20 MPa
Conductor welding joint	
Joint resistance (at 4.2 K)	$< 10^{-9}\ \Omega$





CROSS SECTIONS OF (a)
TOPAZ AND (b) SDC SUPERCONDUCTOR


MAIN COIL (I=8,000A)
FIELD [T]
4.0
3.0
2.0
1.0
0.0
B COIL-INSIDE
B R =185
(380cm
2.8 T)
0
100
200
300
400
Z [cm]

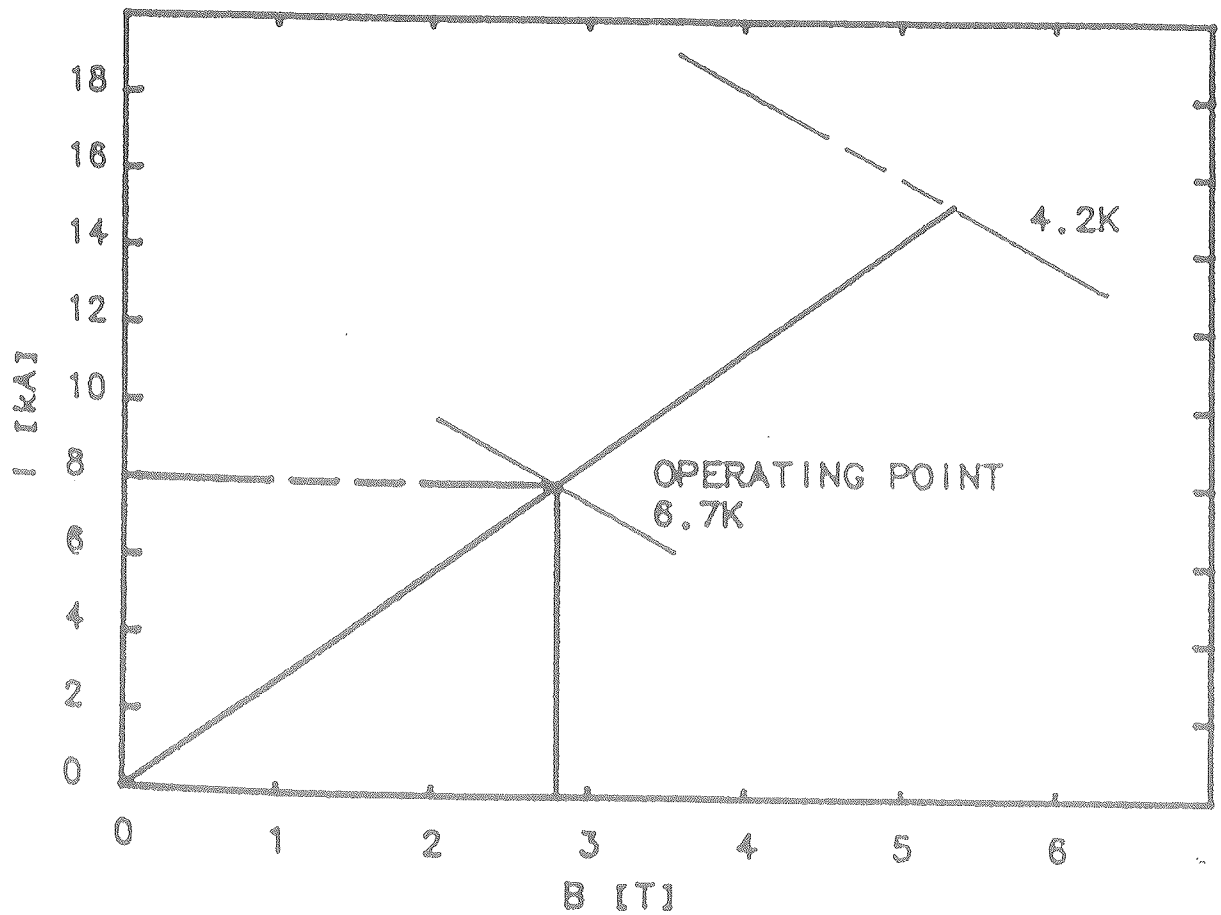


FIG. 5-11. Short-sample characteristics of the SDC conductor and the operating load line.

Table 5-3
Transparency of the solenoid.

Element		Thickness [mm]	X_0	λ_0
Outer vac. wall	(Isogrid)	11	0.138	0.0321
	(Honeycomb)	(7.1)	(0.080)	(0.0180)
Outer rad. shield		2.0	0.022	0.0051
Outer sup. cylinder		31.0	0.348	0.0787
Superconductor				
(Al stab)		39.0	0.438	0.0990
(Nb.Ti/Cu)		2.9	0.181	0.0167
(GFRP)		3.1	0.016	0.0058
(Al Strip)		2.0	0.022	0.0051
Inner rad. shield		2.0	0.022	0.0051
Inner vac. wall		6.0	0.067	0.0152
Super-insulation		2.0	0.007	0.0023
Total	(w/ isogrid)		1.261	0.2651
	(w/ honeycomb)		(1.203)	(0.2510)

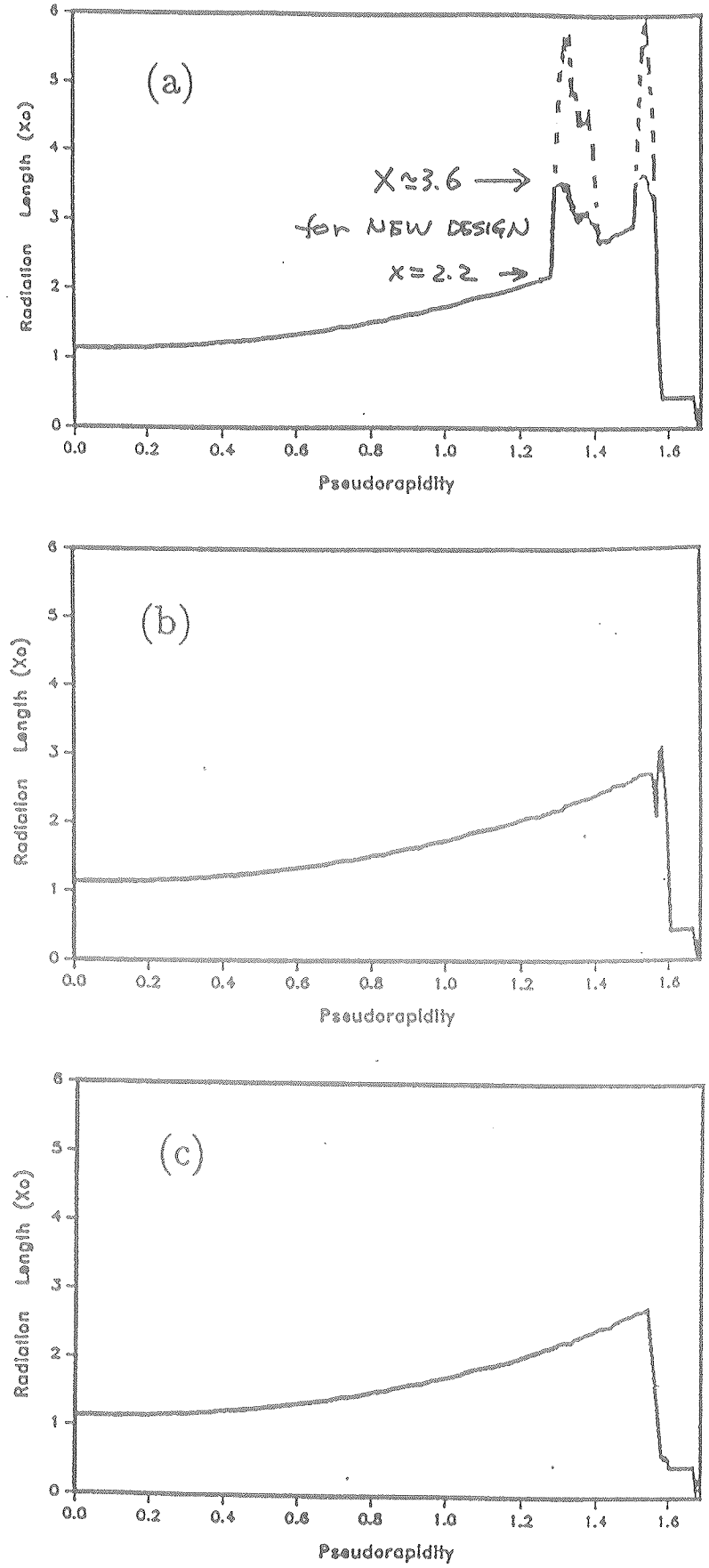


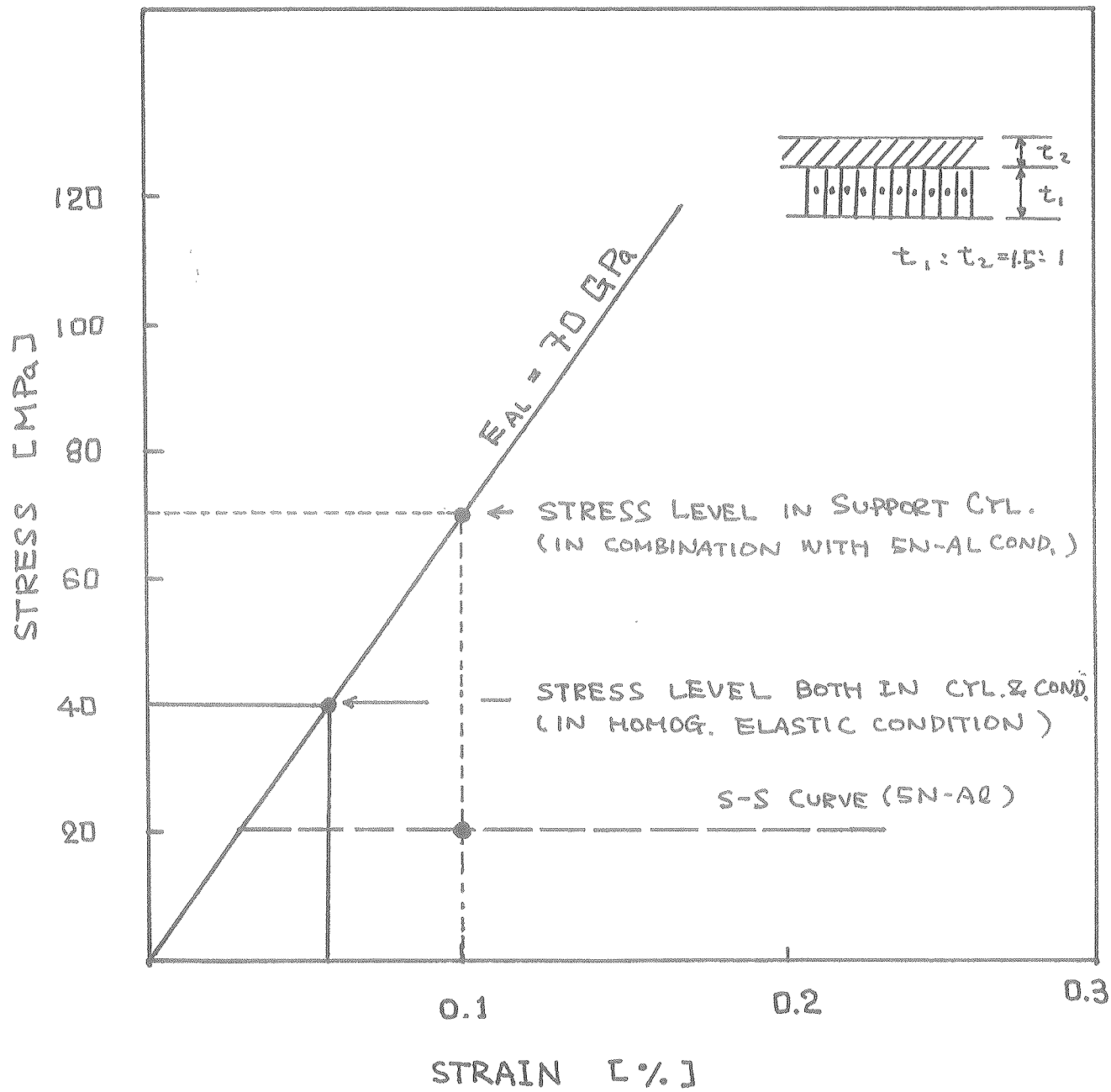
FIG. 5-5. Thickness of solenoid, in radiation lengths, as a function of pseudorapidity. (a) is a path through an axial support and is typical of 6% of the circumference, (b) is through the metallic end fitting of a radial support, 15% of the circumference, and (c) is through the GFRP section of a radial support, 21% of the circumference.

COIL MECHANICAL DESIGN

IMPORTANT ISSUES IN THE SDC MECANICAL DESIGN

1. The combined hoop and axial stress, or stress intensity, in the superconductor during magnet operation in air. This generates a maximum shear stress ($2\tau = s_1 - s_2$) in the pure aluminum, at the axial coil center,
2. The shear stress at the boundary between the coil and the outer support cylinder due to the axial electromagnetic force, which is a maximum at the coil end.

COMPARISON OF RADIAL (HOOP) STRESS AND STARAIN IN CASES OF 5N-AL AND <4N-AL COND.



COIL MECHANICAL DESIGN

$$\frac{E}{M} = 7.5 \text{ KJ/kg}$$

$$\Downarrow$$

$$t_{COIL} = \frac{E}{2\pi R \cdot \ell \cdot \rho \, (E/M)} = 0.075 \text{ m}$$

$$\Downarrow$$

$$S_\phi = \frac{R}{t} \times P_R = 39 \text{ MPa}$$

$$\left(\because \; P_R = \frac{B_z^2}{2\mu_0} = 1.6 \text{ MPa} \right)$$

$$S_z = \frac{-F_z}{2\pi R t} = 15 \text{ MPa}$$

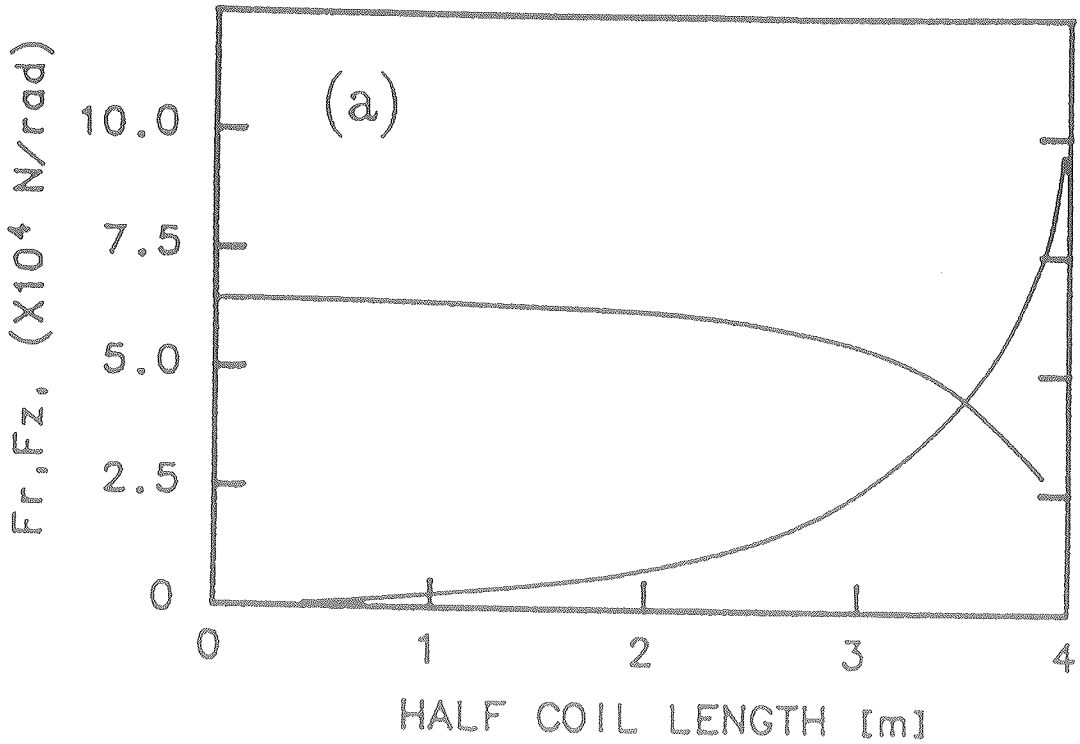
$$\therefore \; 2\tau = S_\phi - S_z = 54 \text{ MPa} \quad (\ll 6.7 \text{ MPa})$$

MAX SHEAR STRESS (STRESS INTENSITY).

Y.S. OF AL ST

Table 5-4
Mechanical stability of the SDC coil.

Element	Material	Yield stress	Anal. model	FEA
Conductor	Pure Al (3N8)	67 MPa	(54) 52 MPa	52 Mpa
Cylinder	A-5083	169 MPa	(54) 52 MPa	< 52 MPa
Cylindrical bonding	Epoxy	(15 MPa)	< 4 MPa	< 1 MPa



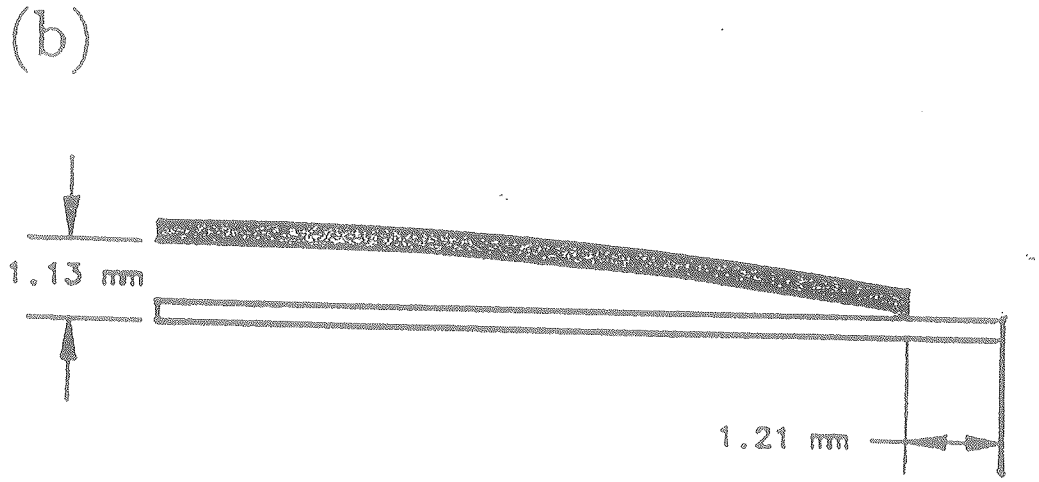


FIG. 5-8. (a) Radial and axial components of the force on the superconducting coil; (b) deformation of the coil under these forces.

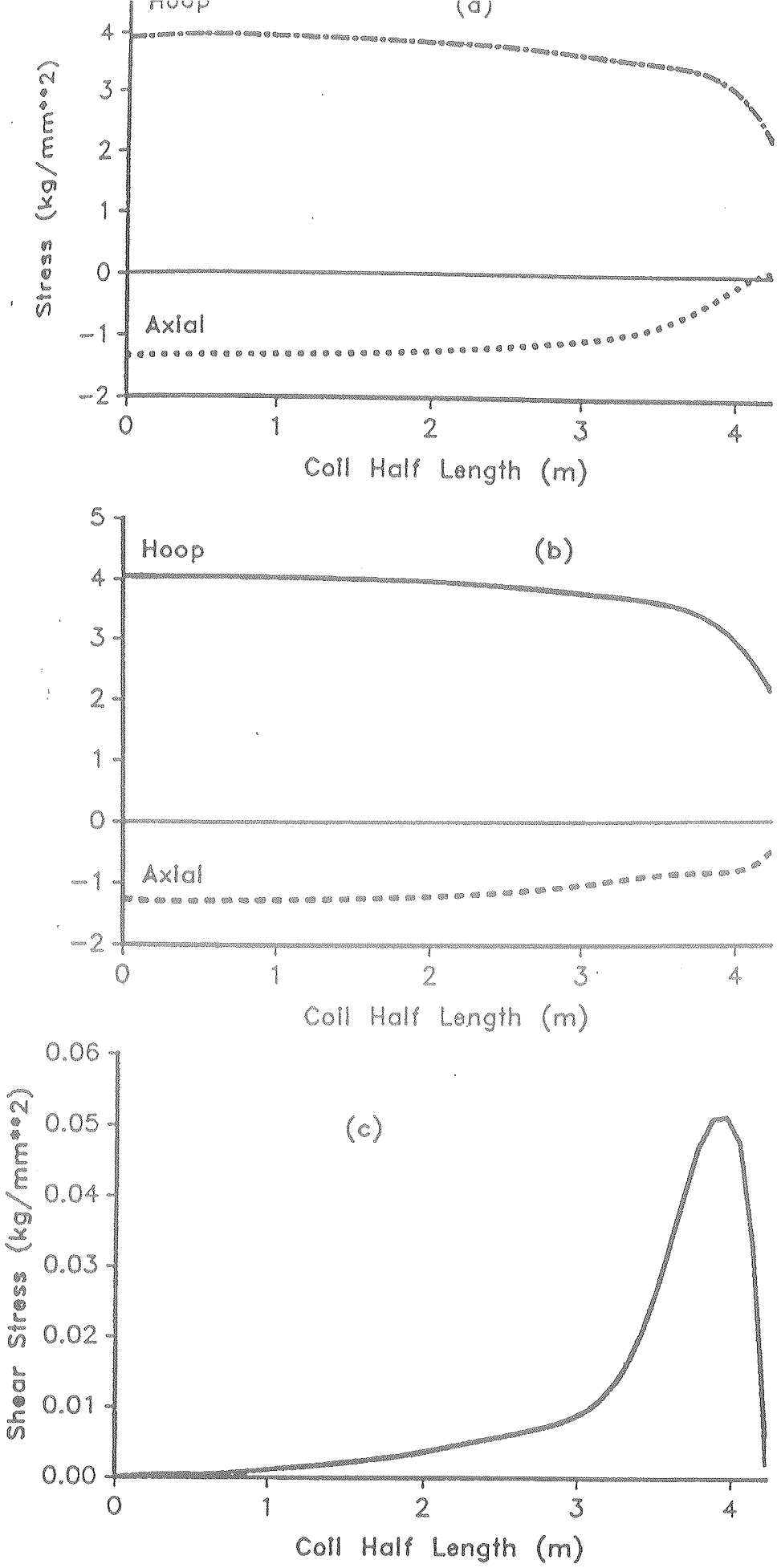


FIG. 5-9. Stresses as a function of axial position (a) on support cylinder, (b) on superconducting coil, and (c) on epoxy joint.

QUENCH PROTECTION

BASIC CONSIDERATION:

- CONDUCTOR STABILITY

  MINIMUM QUENCH ENERGY ..... > 0.1 J

- QUENCH SAFETY

  MAX. TEMP. AFTER QUENCH... 100 K

NEW CONCEPT FOR FAST QUENCH PROPAGATION:

- PURE ALUMINUM QUENCH PROPAGATOR

$$V(\text{phi}) = \frac{J \cdot L_0 \theta_s}{\gamma_c (\theta_s - \theta_0)}$$

$$V(z) = (k_z / k_\varphi)^{1/2} \cdot v_\varphi$$

- AXIAL QUENCH SPEED MAY BE INCREASED INDEPENDENTLY BY USING AXIAL PURE AL STRIP.

QUENCH BEHAVIOR & THERMAL DESIGN

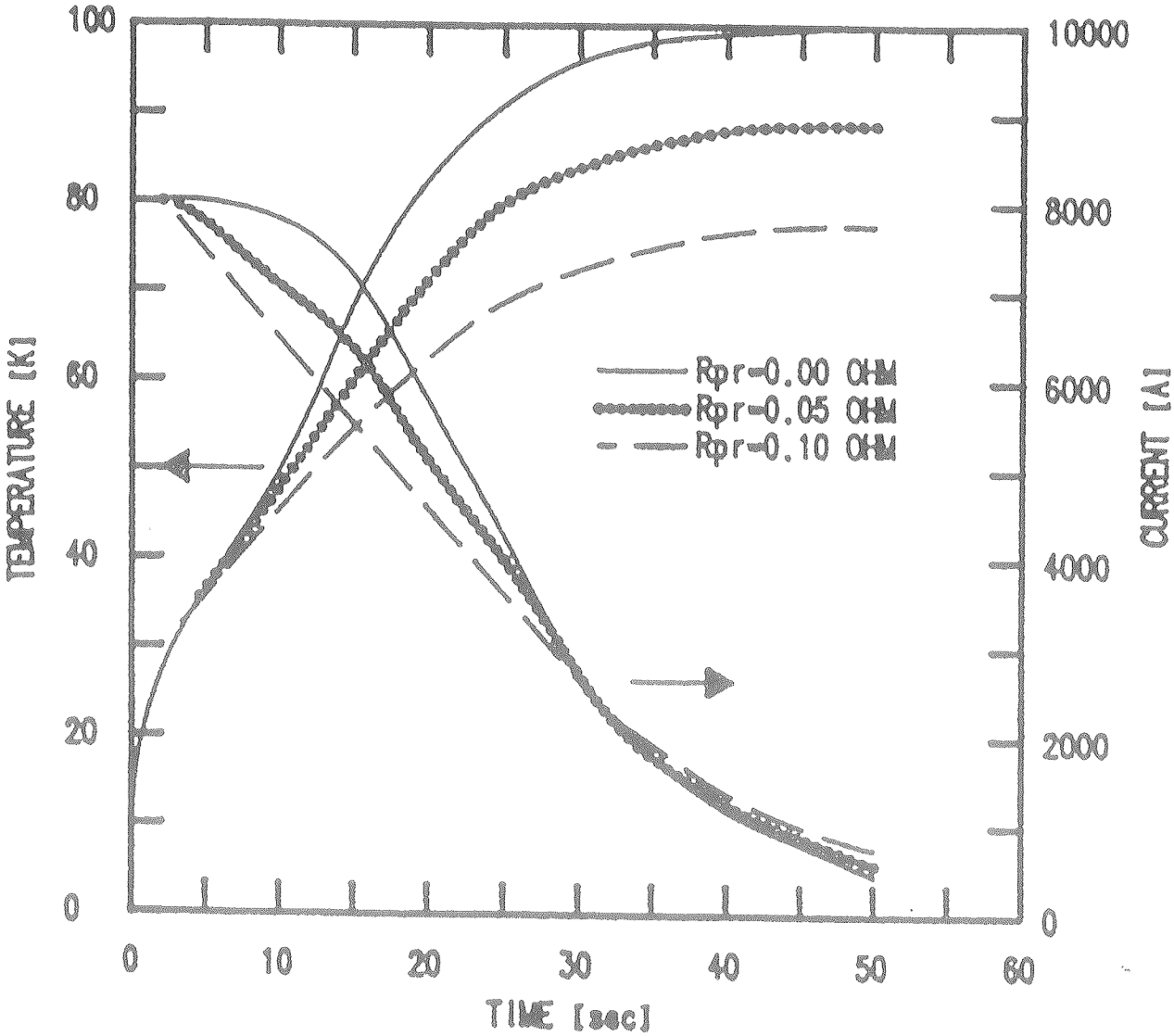
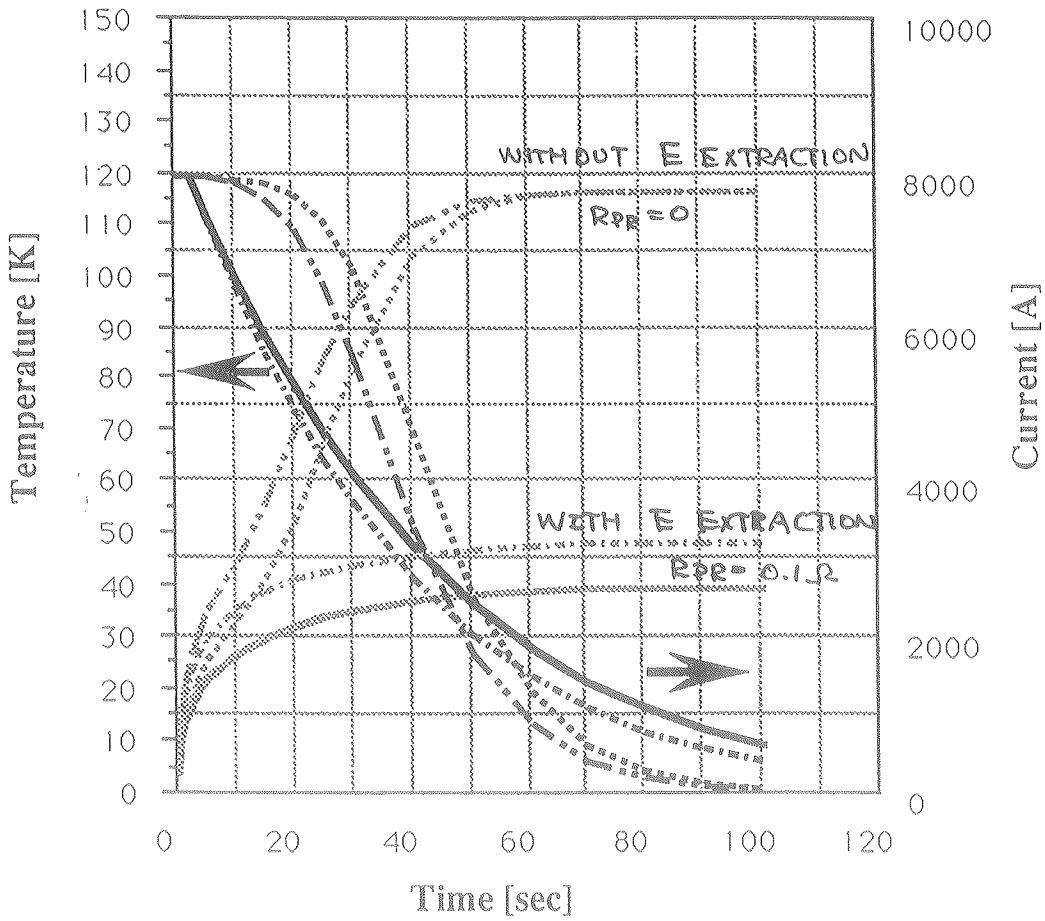


FIG. 5-10. Quench behavior of the SDC solenoid with pure aluminum strips. Quench back in the outer support cylinder is not included in this calculation and the mass of the outer support cylinder is neglected.



Rpr = 0 ohm w/o Cylinder (RRR = 200)

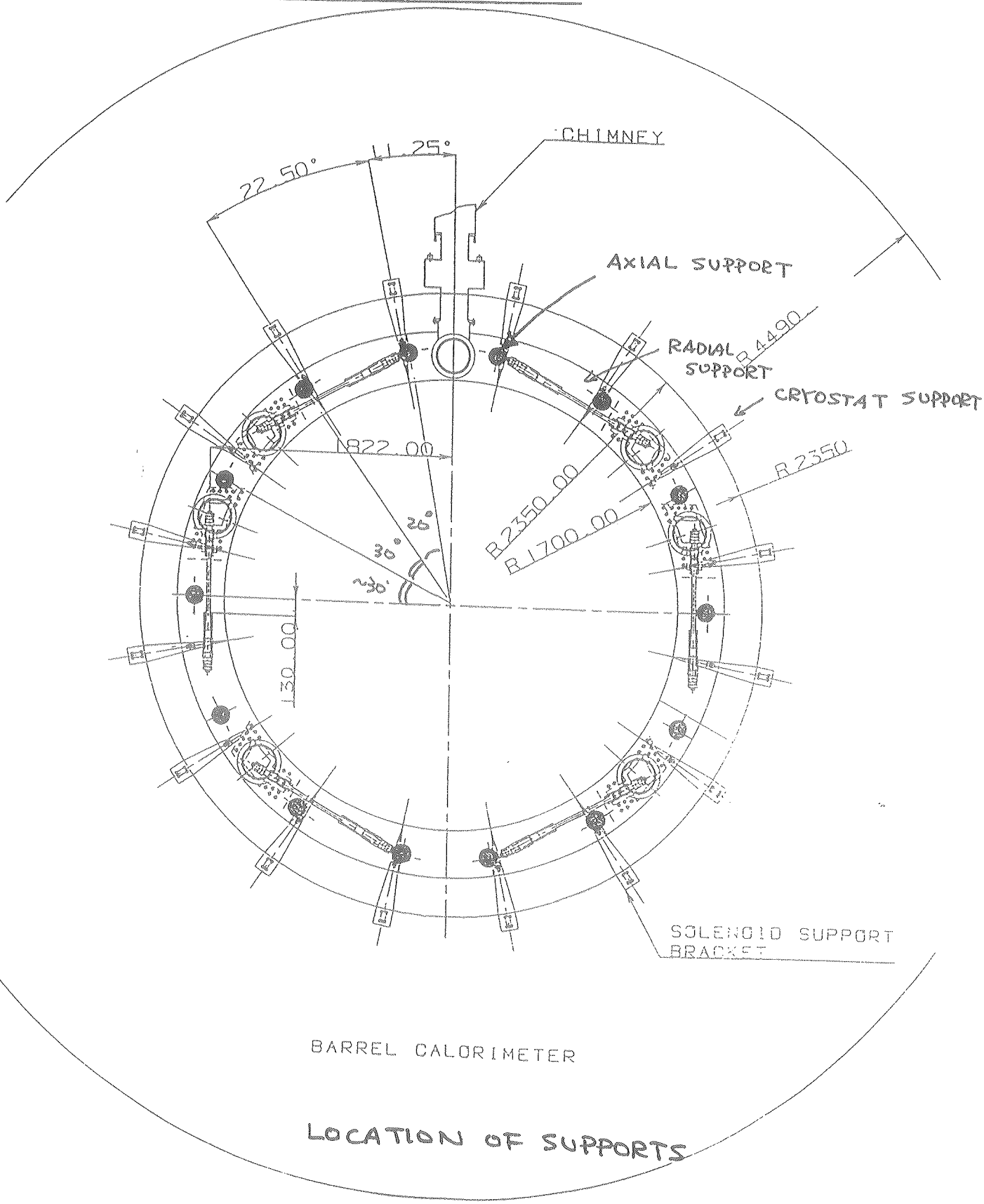
Rpr = 0 ohm w/o Cylinder (RRR = 500)

Rpr = 0.1 ohm with Cylinder (RRR = 200)

Rpr = 0.1 ohm with Cylinder (RRR = 500)

QUENCH BEHAVIOR IN MOST PESIMISTIC AND OPTIMISTIC CASES.

COIL SUPPORT DESIGN

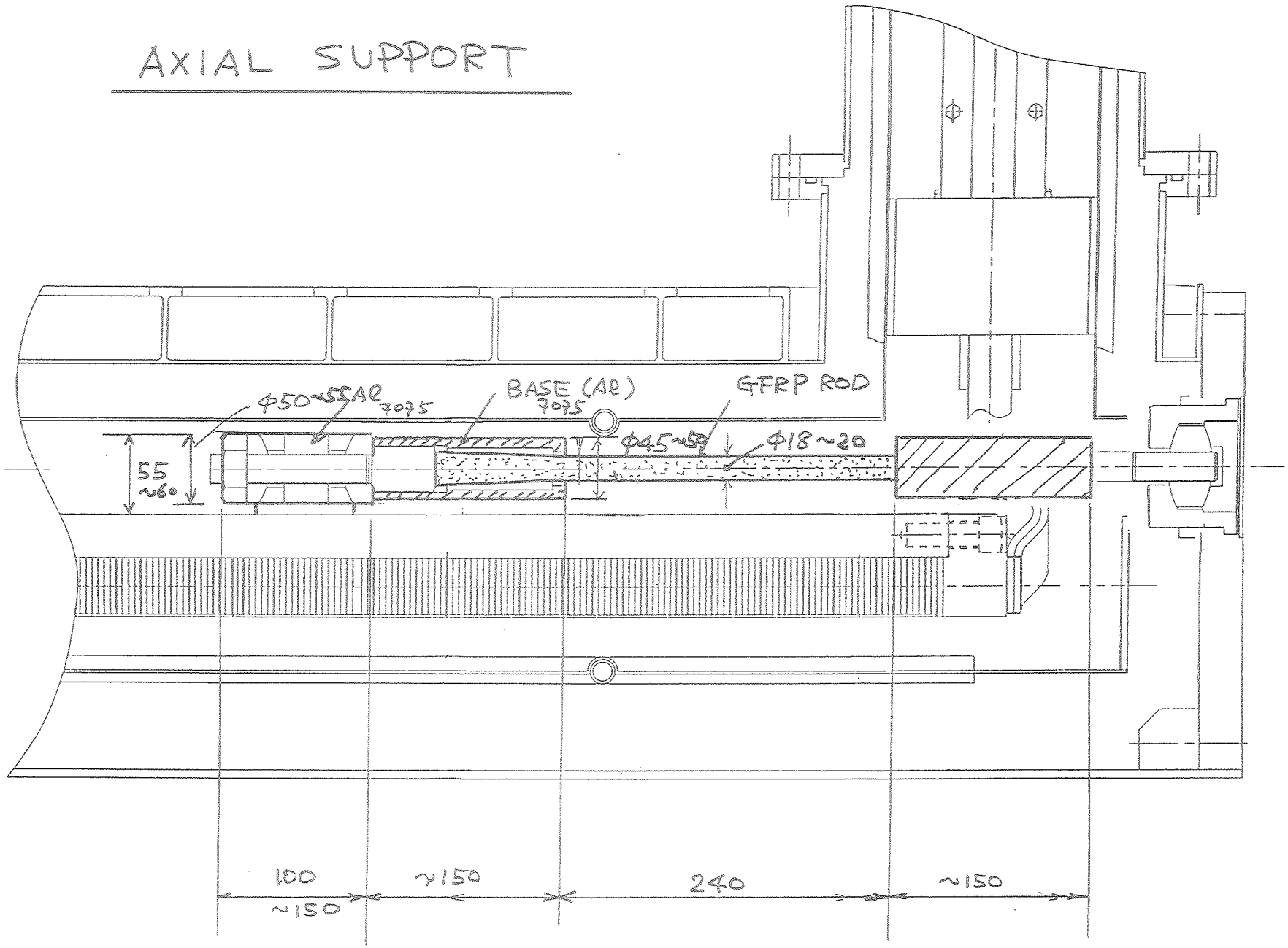


LOCATION OF SUPPORTS

Table 5-8
Design load of the coil support system. (RADIAL SUPPORT)

Function		Upward	Downward	Left/right	F/B-ward
Global force					
Coil weight	(ton)	−20	20		
Applied load	(ton)	40	40	40	40
Design load	(ton)	20	60	40	40
Force constant	(t/mm)	2	2	2	2
Support stiffness	(t/mm)	>10	>10	>10	>10

AXIAL SUPPORT



DESIGN OF AXIAL SUPPORTS OF THE COIL

	TDR	RE-REVISED (APRIL 28)
MATERIAL FOR SUP.	GFRP	GFRP
TYPE	SINGLE	SINGLE
DIA. OF SUPPORT	ϕ20mm	ϕ20mm (18)
EFFECTIVE LENGTH	300mm	300mm (240)
MATERIAL FOR BASE	Ti-Alloy	Al-Alloy(7075)
DIA. OF BASE	ϕ50mm	ϕ50mm
LENGTH OF BASE	~150mm	~150mm
# OF AXIAL SUPPORT	14	14
TENSILE FORCE/14RDS.	$\geq$300tonnes	$\geq$300tonnes
BUCKLING FORCE/14RDS.	100tonnes	100tonnes
THERMAL LOADS/14RDS.	~600mW	~600mW
BUMP IN TRANSPARENCY	3.7	1.4
(MAX) at η=1.4	at tR=60mm	(tR=60mm)

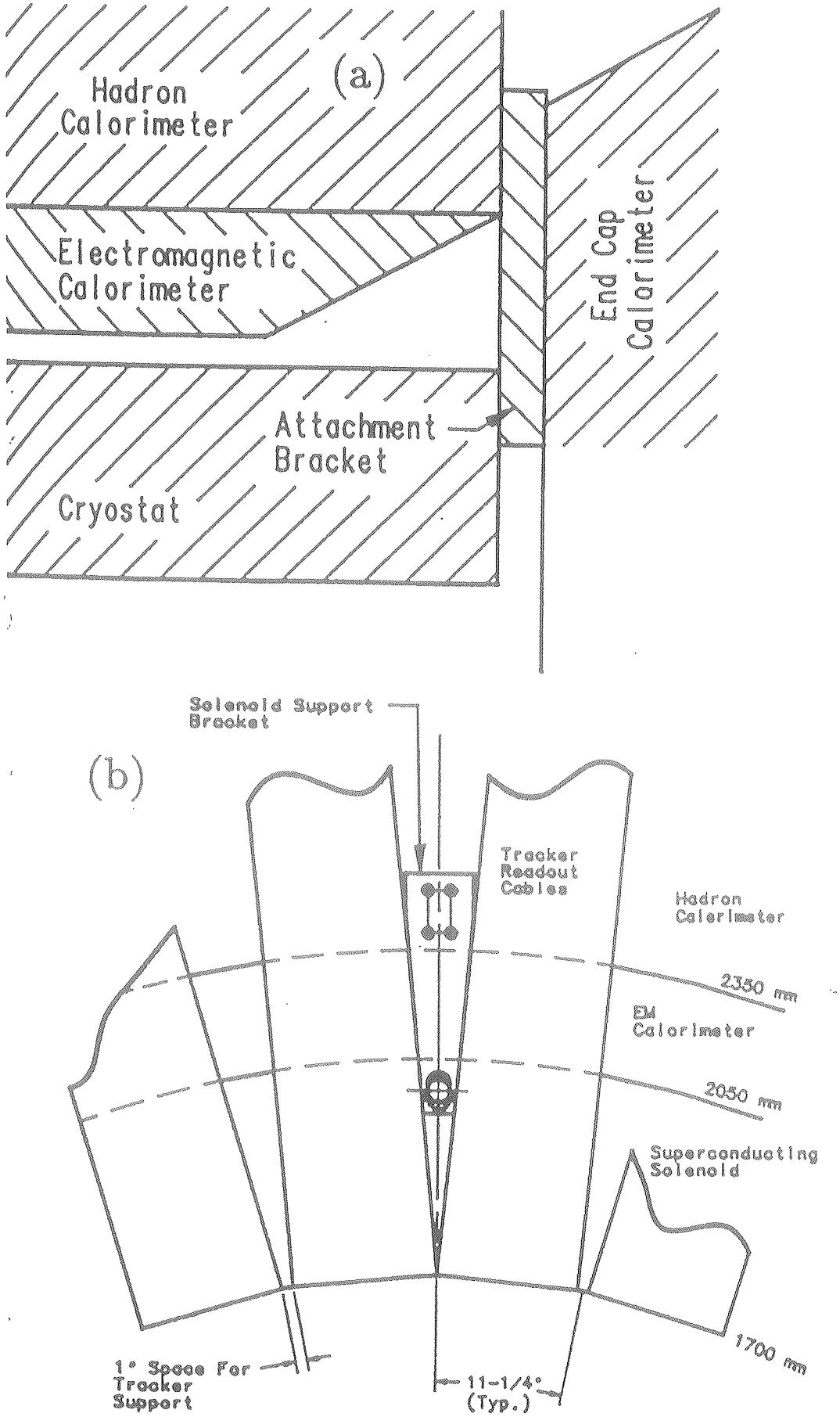
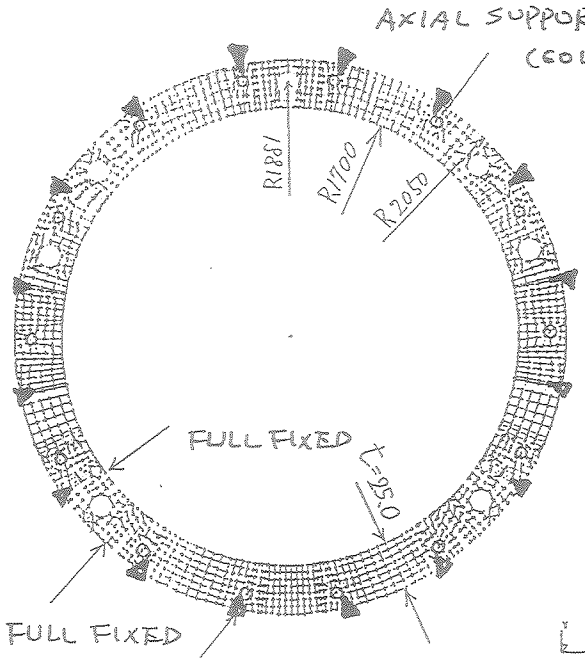


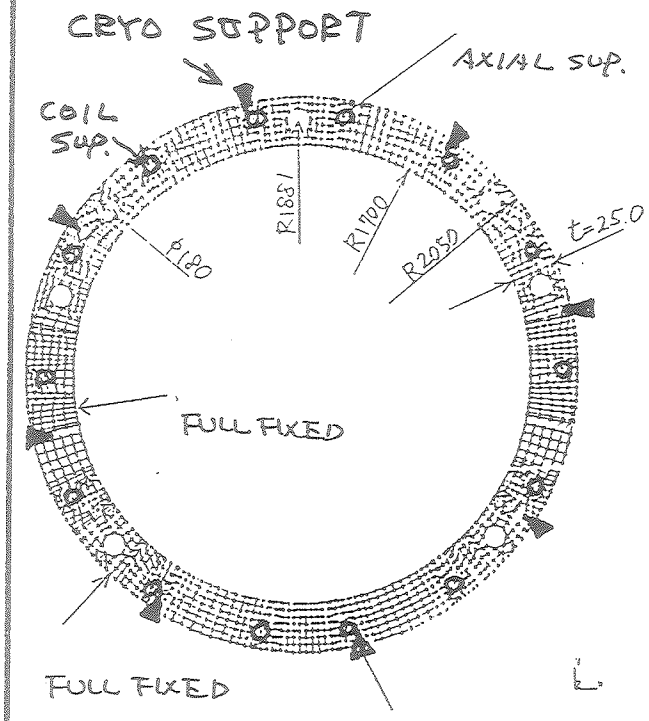
FIG. 5-13. Cryostat attachment to the barrel hadron calorimeter, (a) section view, (b) enlarged end view.

SUPPORT FOR CRYOSTAT &BULKHEAD STRESS ANALYSIS

	16 FOLD SYMMETRY		8 FOLD SYMMETRY	
	MAX STRESS	DISPLACE-MENT	MAX STRESS	DISPLACE-MENT
1 ATM. (-40T)	0.65 kgf/mm2 [6.5 MPa]	0.04 mm	0.78	0.04
1 ATM+Fz(40ton)	3.1	0.16	3.1	0.16
1 ATM-Fz(-40T)	4.4	0.23	5.1	0.23



16 FOLD SUPPORT

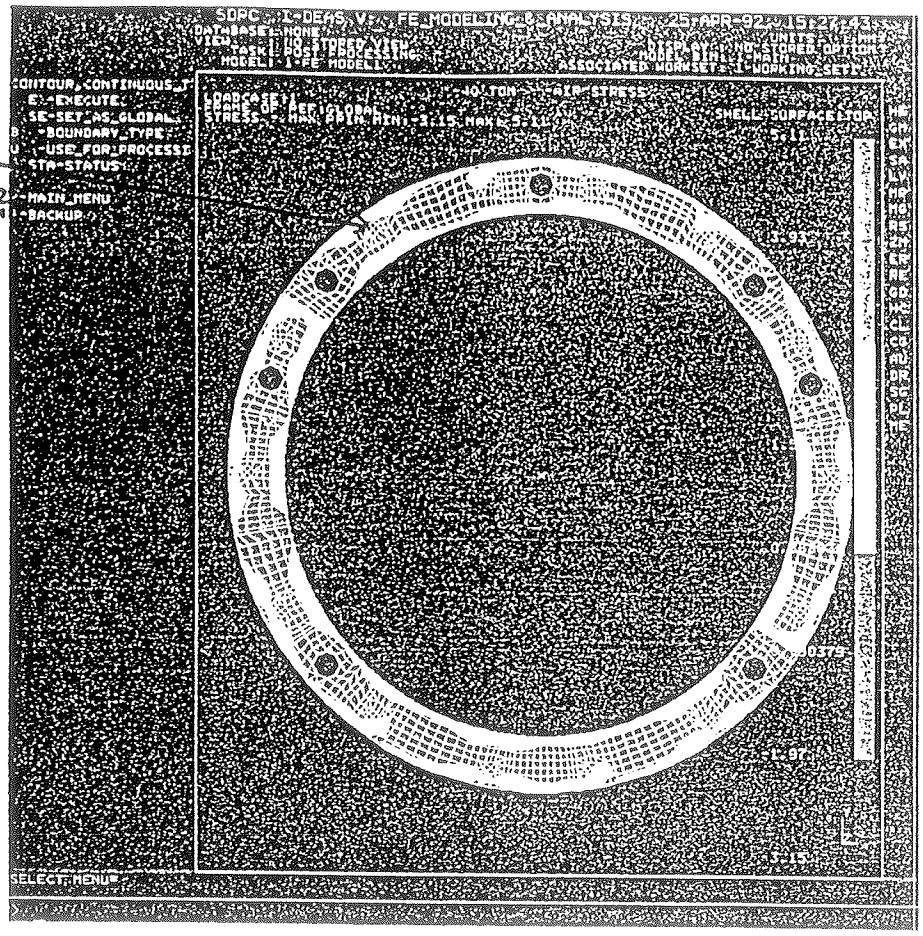


8 FOLD SUPPORT

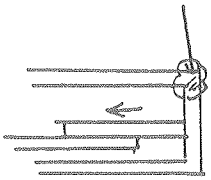
ANALYS MODEL FOR BULKHEAD IN STRESS & DISPLACEMENT DUE TO AXIAL ELECTROMAGNETIC DECENTERING FORCE OF (I 40tonnes) and 1ATM LOAD.

σ_{max}

$= 5.1\ kgf/mm^2$



STRESS MAX



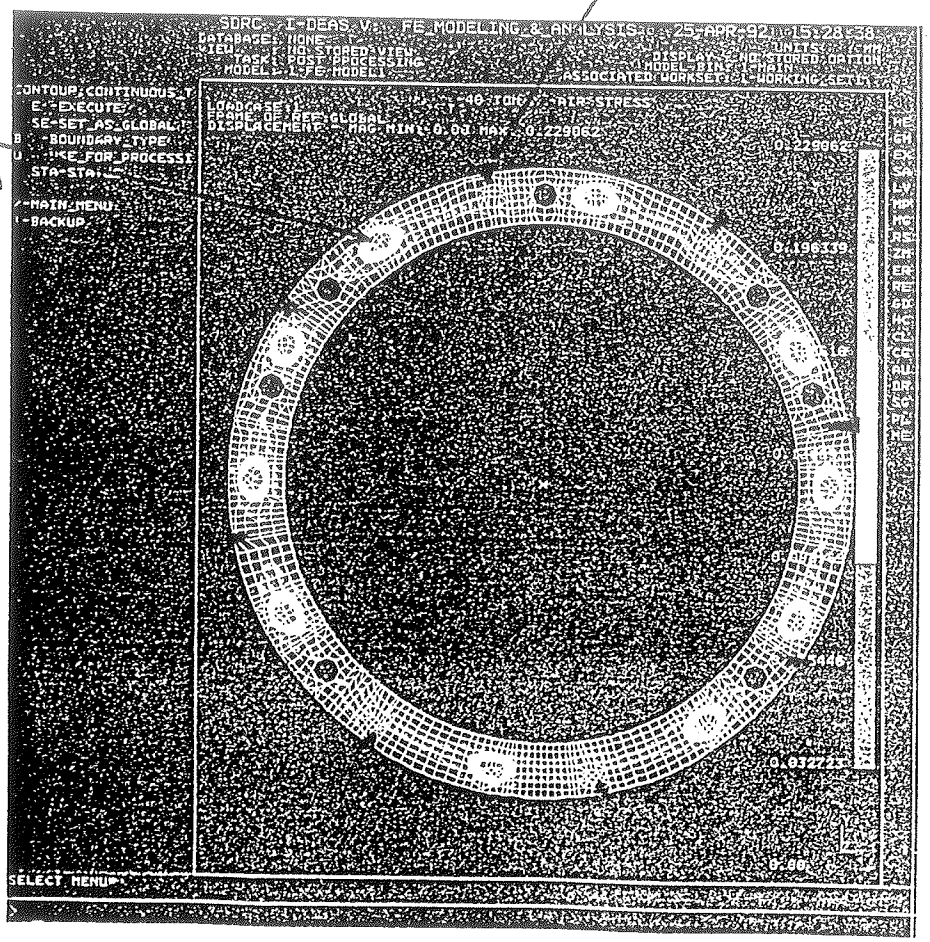
STRESS

[8 FOLD SYM.

CRYOSUPPORT

δ_{max}

$= -0.23\ mm$



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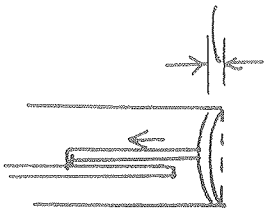

DISPLACEMENT

[8 FOLD SYM

CRYOSTAT VACUUM WALL DESIGN

Table 5-6
Outer vacuum shell requirements.

Vacuum load	1 atm radial and axial
Design standard	
Radial collapse pressure	> 2 atm
Axial buckling load	> 2 atm
Allowable stress	Based on ASME press. vessel code
Material	Aluminum alloy
Construction	Welded joints

CONSIDERATION ON CRYOSTAT VAC. WALL

Table 5-7
Comparison of solid, isogrid, and honeycomb outer vacuum shells.

	Solid	Isogrid	Brz. honeycomb
Aluminum alloy	5083	5083-H32	6951/4045-T6
Total thickness (mm)	27	46	46
Skin thickness (mm)	—	4.0	3.0 + 3.0
Skin layers	—	single	double
Node configuration	—	triangle	hexagon
Effective thickness (mm)	27	11	7
Weight reduction ratio	1	1/2.5	1/3.9
Radiation thickness (X_0)	0.303	0.123	0.079
Maximum size of plate (m × m)	2 × 6.4	2.2 × 4.3	1.2 × 4
Units to be welded	8 (= 2 × 4)	12 (= 3 × 4)	21 (= 3 × 7)

THERMAL LOAD AND COOLING CHARACTERISTICS

Table 5-9
An estimate of steady state thermal loads for the SDC solenoid.

Component	300 to 77 K	77 to 4.2 K	300 to 4.2 K
Thermal radiation	300	30	—
Conduction			
Coil support rods ($n = 24$–36)	24	2.5	—
Shield support rods ($n = 12$)	3	—	—
Chimney and service port	36	4.5	—
Current leads (8 kA pair)	—	—	30
Total thermal load	363 W	37 W	30 L/hr

Table 5-10
Cooling design parameters in the initial cool down.

Boundary conditions	
Coil cold mass (aluminium)	20 tons
Radiation shield mass (aluminium)	1 ton
Temperature difference in coil during cool down	<50 K
Coil cooling	
Initial cooling speed	1 K/hr
GHe mass flow required	21 g/s
Initial cooling power	4.4 kW
Initial inlet pressure	0.7 MPa A
Pressure drop in cooling pass (25 mm $\phi \times 250$ m)	0.2 MPa
Shield cooling	
Initial cooling speed	1 K/hr
GHe mass flow required	1.2 g/s
Initial cooling power	250 W
Initial inlet pressure	0.7 MPa A
Pressure drop in cooling pass (15 mm $\phi \times 400$ m)	<0.035 MPa

Table 5-11
Cooling design parameters in steady state operation.

Coil		
Typical coil temperature		4.4 K
Quality of two phase helium	Inlet	0.8
	Outlet	0.5
He mass flow required		7 g/s
Pressure drop in cooling pass		small
Current leads mass flow		1–2 g/s
Radiation shield		
Max. shield temperature		< 70 K
Inlet He gas temperature		60 K
Helium gas mass flow required		15 g/s
Heat exchange efficiency		0.5
Pressure drop in cooling pass		small

Table 5-12
Cooling parameters in excitation and after quench.

Excitation of the coil		
Static heat-in-leakage		37 W
Eddy current loss in support cylinder	(@ 1 mT/s)	88 W
Quality of two phase helium	Inlet	0.8
	Outlet	0.5
He mass flow into cooling pass required		23 g/s
He mass flow into current leads	$(2 \times 8,000$ A)	1 g/s
Quench recovery in coil		
Energy dumped into coil		88 MJ
Recovery time assumed		4 hr
Cooling power required		6.2 kW
Cooling efficiency assumed		0.8
Liquid (two phase) helium flow required		28 g/s (830 L/hr)
Total liquid helium for recovering		3,300 L

5.3.9. Diagnostics and instrumentation

A substantial amount of instrumentation is required to monitor the cooldown and steady-state operation of the magnet and to provide diagnostic data. The monitoring and diagnosis functions include:

- Maintaining the appropriate cool-down rate, allowable temperature distribution, mechanical stress and thermal contraction.
- Monitoring the magnet during excitation and operation by measuring the temperature of the cold mass, thermal shields and support intercepts; the stress in the outer support cylinder and supports; the magnet current and voltage; and the magnetic field.
- Monitoring the magnet during and after a quench to verify the safety of the system. Current, voltage, temperatures, pressures and stresses will be measured as a function of time.

Table 5-13
Diagnostic instrumentation in the SDC solenoid.

Element	Coil	R/S	Support	V/V	Chimn.
Voltage taps (short pair tap)	13				4
Quench heater	3				
Temperature sensors					
Pt-Co (300 K–4.2 K)	24	24	4	4	6
CGR (high resol. @4.2 K)	17				
Strain gauge (pair of ϕ, z)	12	8	36	16	4
Position sensor (r, ϕ)	8				8
(z)	4				4
Pressure	3				
Total	83	32	40	20	26

Table 5-14
General requirements on the cryogenics for the SDC solenoid.

Typical refrigeration capacity	1,500 W at 4.4 K
Liquid helium transfer rate	750 L/hr (after quench)
Liquid helium storage capacity	5,000–10,000 L
Cold gas helium mass flow at 60 K	12 g/s

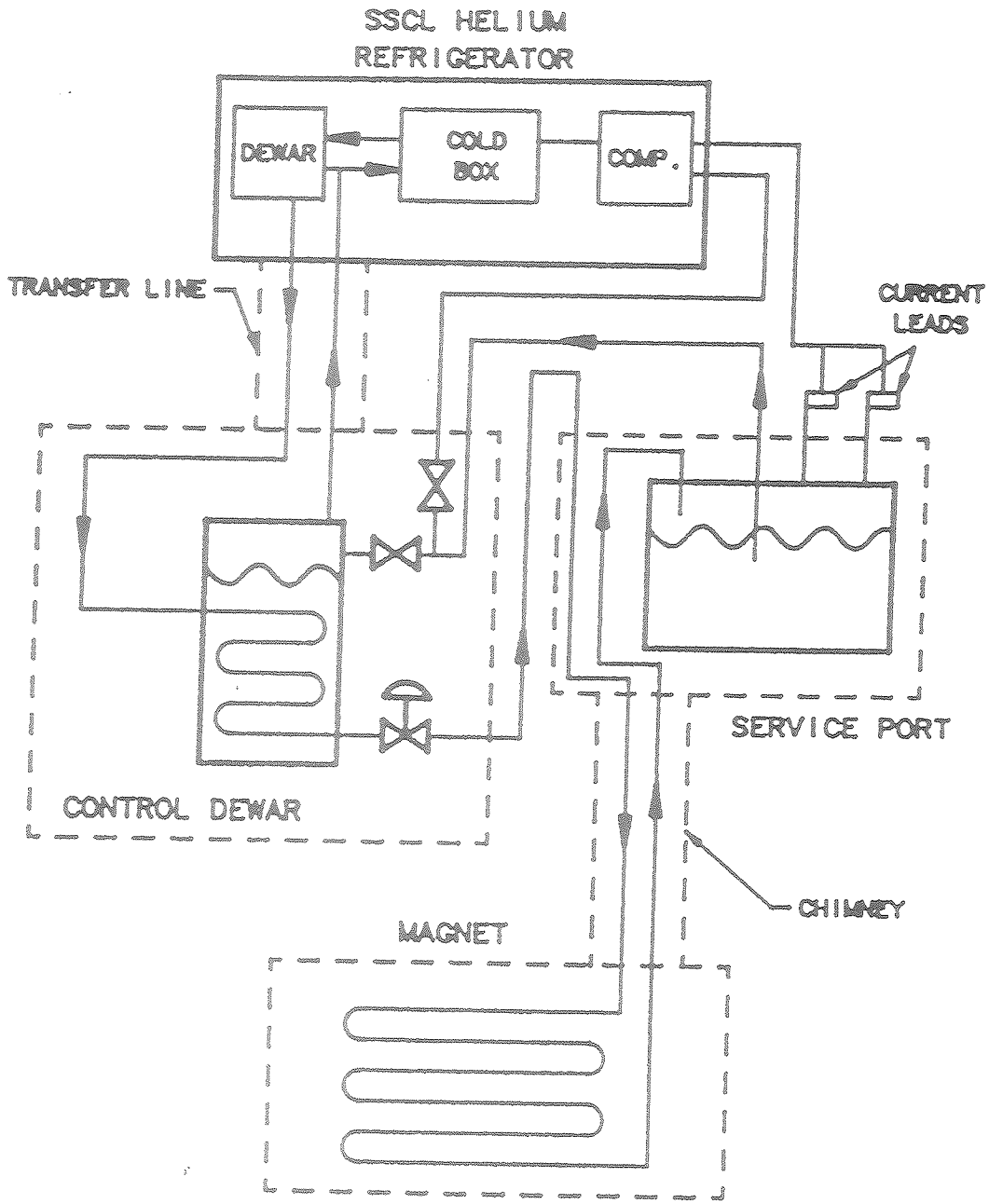

FIG. 5-14. Flow schematic of the cryogenic system for the SDC solenoid.

Table 5-15

General requirements for the SDC electric power system.

Maximum current	10,000 A
Nominal operation current	8,000 A
Regulation	$< \pm 1 \times 10^{-4}$
Inductive voltage (@1 mT/s)	± 17 V
Bus-bar voltage drop	10 V
Ramp rate	1–10 A/s
Fast discharge time const.	45 s
Slow discharge time const.	500 s
DC switching time	< 1 s

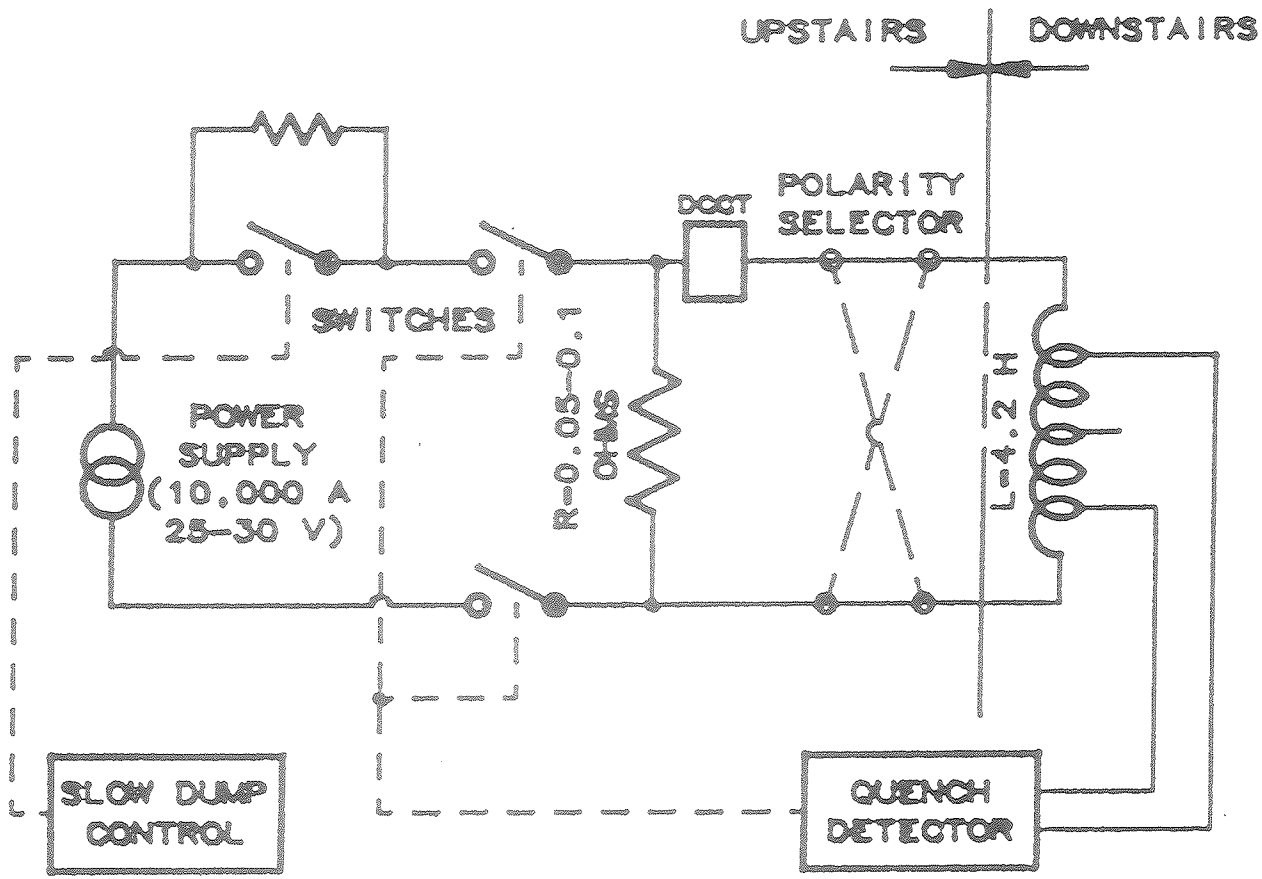

FIG. 5-15. Schematic of DC circuit for SDC solenoid.

Table 5-17

Overall schedule for the prototype solenoid and the production solenoid. The Japanese fiscal year begins April 1 of the year indicated.

JFY1991	Prototype Magnet Development
	—Superconductor fabrication
	—Winding machine development
	—Outer support cylinder fabrication
	—Isogrid vacuum wall development
JFY1992	—Coil winding
	—Cryostat element fabrication
JFY1993	—Assembly of the magnet
	—Cool-down and excitation in air
JFY1994	Production Magnet Fabrication
	—Superconductor fabrication
	—Cryostat element fabrication
JFY1995	—Coil winding
	—Magnet assembly
JFY1996	—Magnet assembly continued
	—Cool-down and excitation test in air
	—Transportation to SSCL
JFY1997	—Cool-down and excitation in iron
	—Field mapping

PARAMETERS IN PHYSICS AND ENGINEERING

Requirements from Physics	Engineering Parameters important
	<u>Coil</u>
- Magnetic Field	- Mechanical Safety at 2 T
$Bc = 2$ T	Max. Stress ($2\ \tau$) < 60 MPa
$Fz = 1300$ tonnes	(@ $Y.S._{0.2\%} = 6.7$ MPa)
- Tranparency	- Stability in Superconductivity
$X = 1.2\ Xo$ (@$\eta = 0$) $< 3.0\ Xo$ (@$\eta = 1.5$)	MQE $= 0.27$ J
	- Thermal Safety after QUENCH
$\lambda\iota = 0.25\ \lambda\iota$ (@ $= 0$)	Tmax < 100 K $\Delta\varepsilon < 0.05$ %
	<u>Cryostat (Vacuum Wall)</u>
	- Stability against Buckling
	$P_{bkl} > 2$ atm

Summary

1. THE SDC SOLENOID DESIGN HAS BEEN OPTIMIZED TO PROVIDE:

   B = 2 T
   V = 3.8 m dia x 8.8 m
   1.2 λ_r (at $\eta = 0$)
   0.25 λ_i

2. TO MINIMIZE MATERIAL IN THE SOLENOID , THE FOLLOWING TECHNICAL CONCEPTS HAVE BEEN INCLUDED IN THE SOLENOID DESIGN:

   - HIGH E/M RATIO OF 7.5 KJ/KG WITH HIGH SPEED QUENCH PROPAGATION USING PURE AL-STRIP QUENCH PROPAGATOR TO SUPPRESS LOCAL TEMPERATURE RISE.

   - HIGH STRENGTH PURE ALUMINUM STABILIZER (Y.S.> 65 MPa) HAS BEEN DEVELOPED WITH RRR = 500.

   - HONEYCOMB OR ISO-GRID OUTER VACUUM WALL FOR CRYOSTAT

3. OVERALL COIL SAFETY PARAMETERS SUCH AS SUPERCONDUCTOR STABILITY, TEMPERATURE RISE AFTER QUENCH, MECHANICAL STRESSES, ETC. ARE SIMILAR TO OTHER SUCCESSFUL SOLENOIDS IN OPERATION.

4. MATERIAL CORRESPONDING TO 0.6 λ_r CAN BE SAVED ; 0.4 λ_r IN THE COIL AND 0.2 λ_r IN THE OUTER VACUUM WALL

5. AN EXTENSIVE R&D PROGRAM IS IN PROGRESS

- PROTOTYPE SOLENOID WITH HIGH E/M RATIO IS BEING BUILT.
- TEST OF AL-STRIP QUENCH PROPAGATORS IN PROTOTYPE COIL
- HIGH STRENGTH AL-STABILIZED CONDUCTOR (Y.S. > 67 MPa)
- TESTS OF COIL WINDING AND BONDING TO OUTER SUPPORT CYLINDER
- TESTS OF HONEYCOMB AND ISO-GRID OUTER VACUUM WALL
- 1/4 LENGTH FULL DIAMETER PROTOTYPE MAGNET TESTED BY 1993