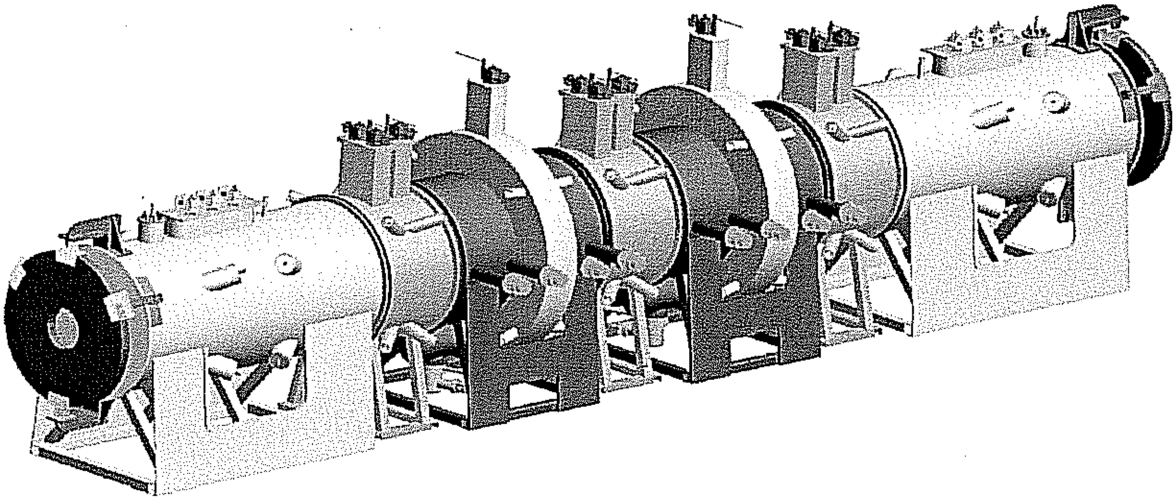
LAWRENCE BERKELEY NATIONAL LABORATORY

FINAL ENGINEERING DESIGN FOR MICE SPECTROMETER SOLENOID MAGNETS
LBL P. O. 6806258



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DATE : September 6, 2006

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Wang NMR, Inc.

550 North Canyons Parkway , Livermore, Ca. 94551

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CHAPTER I

INTRODUCTION TO MICE SOLENOID COIL SYSTEM

The purpose of the MICE spectrometer solenoid is to provide a uniform field for a scintillating fiber tracker, and thus, it is also called tracker solenoid. The uniform field is produced by a long center coil and two short end coils. Together, they produce 4T field with a uniformity of better than 1% over a detector region 1000 mm long and 300 mm in diameter. Throughout most of the detector region, the field uniformity is better than 0.3%.

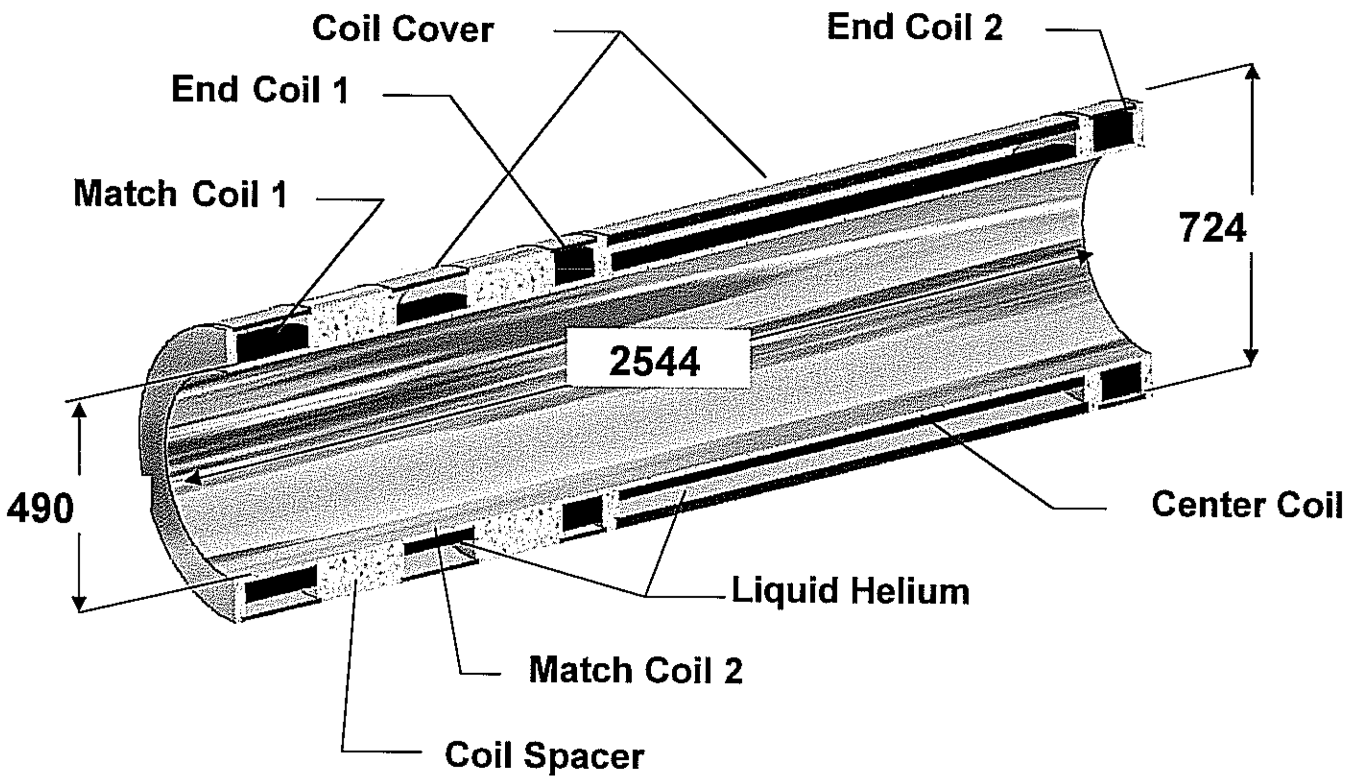
In addition to the uniform field coils, we have match coil 1 and match coil 2. These two coils can be independently adjusted to match uniform field region to the focusing coil field. Figure I-1 shows the tracker solenoid cold mass design. Figure I-2 shows the cold mass support against 50 ton axial load. Figure I-3 shows the cryogen free system with cryocooler, recondenser, and Hi-Tc lead. Figure I-4 shows the vacuum vessel. Finally, Table I-1 shows the list of magnet parameters Drwg MICE- 0000 shows the final design of overall cross section if cryocooler installed in the sleeve. Drwg MICE-0000A shows the overall cross section if cryocooler is directly bolted to cold mass.

Table I-1 Tracker Magnet Parameters

	Coil package length = 2544 mm				
Parameter	**Match 1**	**Match 2**	**End 1**	**Center**	**End 2**
Coil length (mm)	**201.2**	**199.5**	**110.6**	**1314.3**	**110.6**
Coil inner radius (mm)	**258**	**258**	**258**	**258**	**258**
Coil thickness (mm)	**44.7**	**29.8**	**59.6**	**21.3**	**63.9**
Number of layers	**42**	**28**	**56**	**20**	**60**
Number of turns per layer	**120**	**119**	**66**	**784**	**66**
Coil overall current density (A mm^{-2})	**120.06**	**141.13**	**139.84**	**149.04**	**148.64**
Coil current I (A)	**214.2**	**251.8**	**248.9**	**265.3**	**265.3**
Coil self inductance (H)	**17.47**	**9.59**	**15.39**	**51.72**	**16.87**
Coil Stored Energy at I (MJ)	**0.4**	**0.3**	**0.48**	**1.83**	**0.59**
	Separately Powered		**Uniform Field Magnet S**		

*** The uniform field magnet coils in series have a self inductance of 78 H.**

Fig I-1 Tracker Solenoid Cold Mass



The two end coils and the center coil form the spectrometer magnet, which has a field good to 0.3 % in a region 300 mm in diameter and 1000 mm long.

Fig I-2 Tracker Solenoid 50 Ton Longitudinal Force Cold Mass Support System

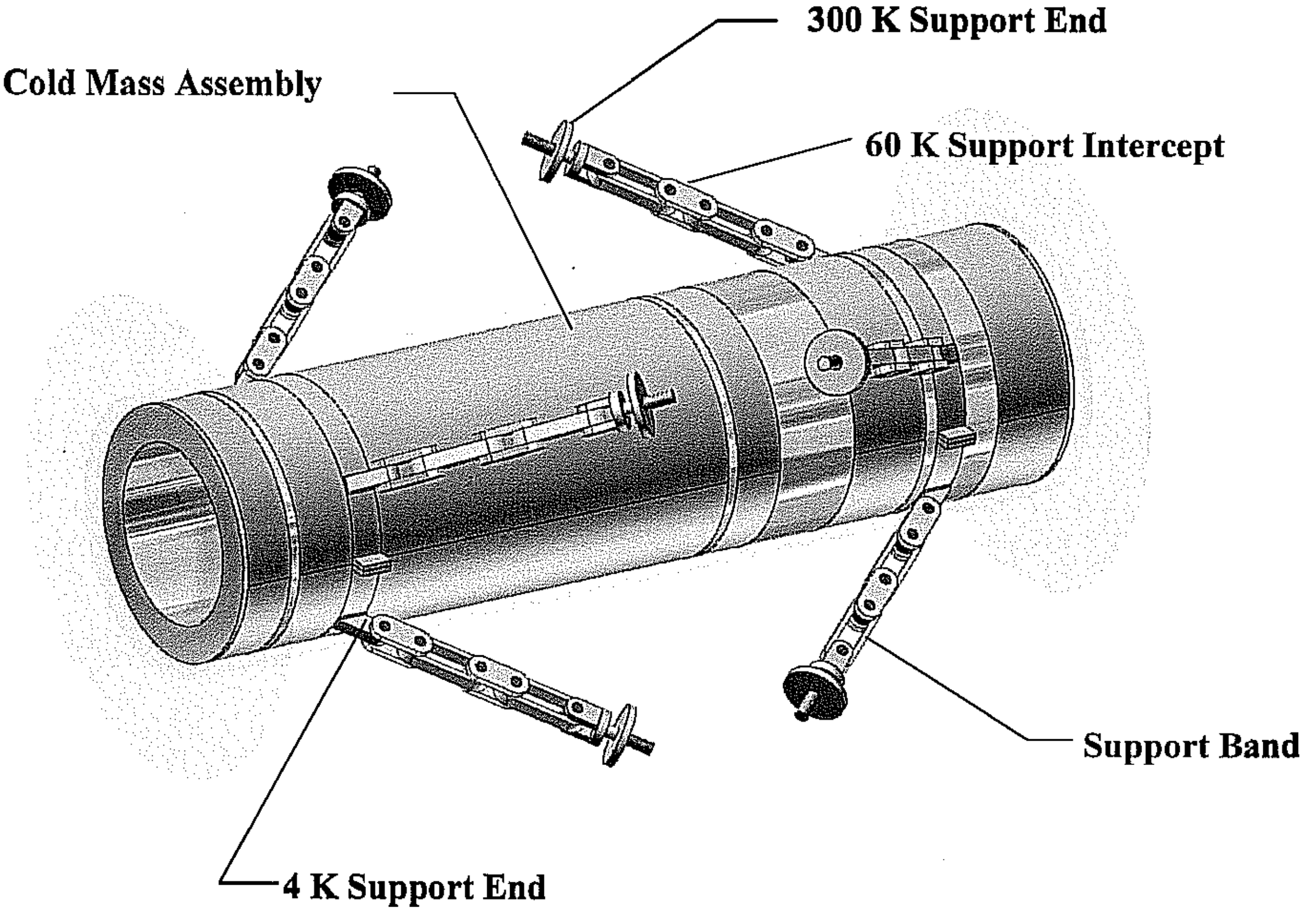


Fig I-3 Tracker Magnet Cold Mass, Coolers Cryogenic Distribution System

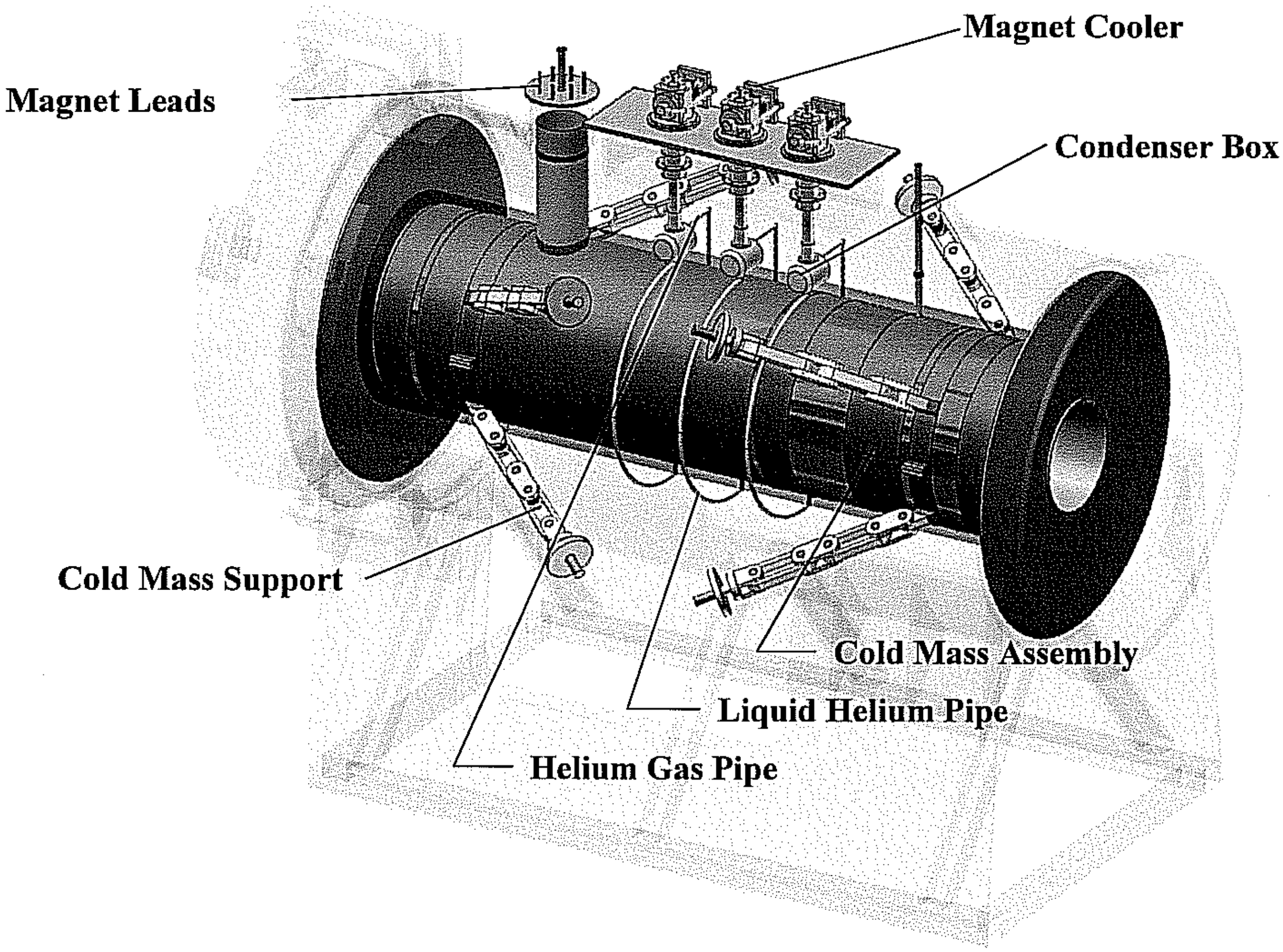
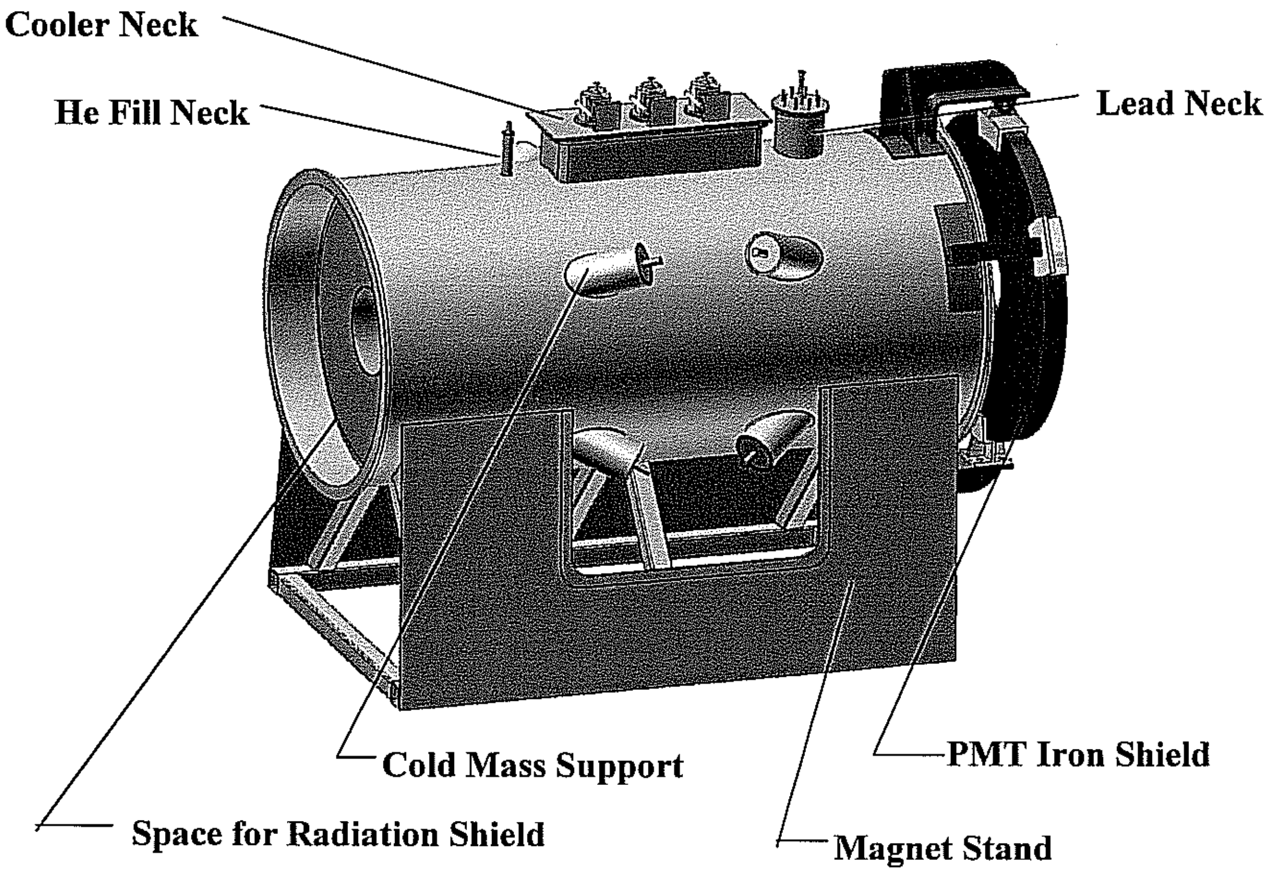
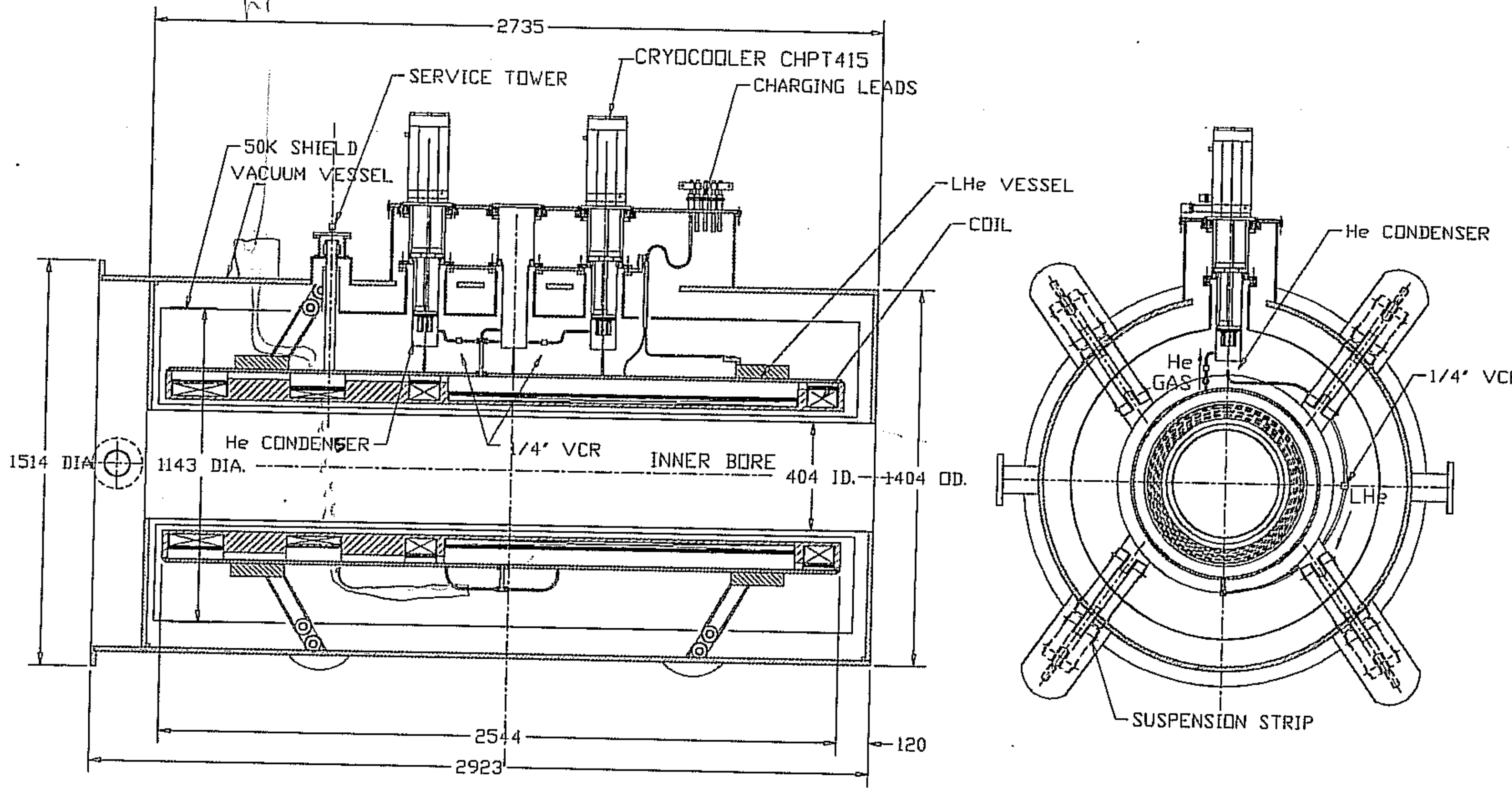


Fig I-4
Tracker Magnet Vacuum Vessel and Iron Shield





NOTES:
1) DIMENSIONS ARE IN mm

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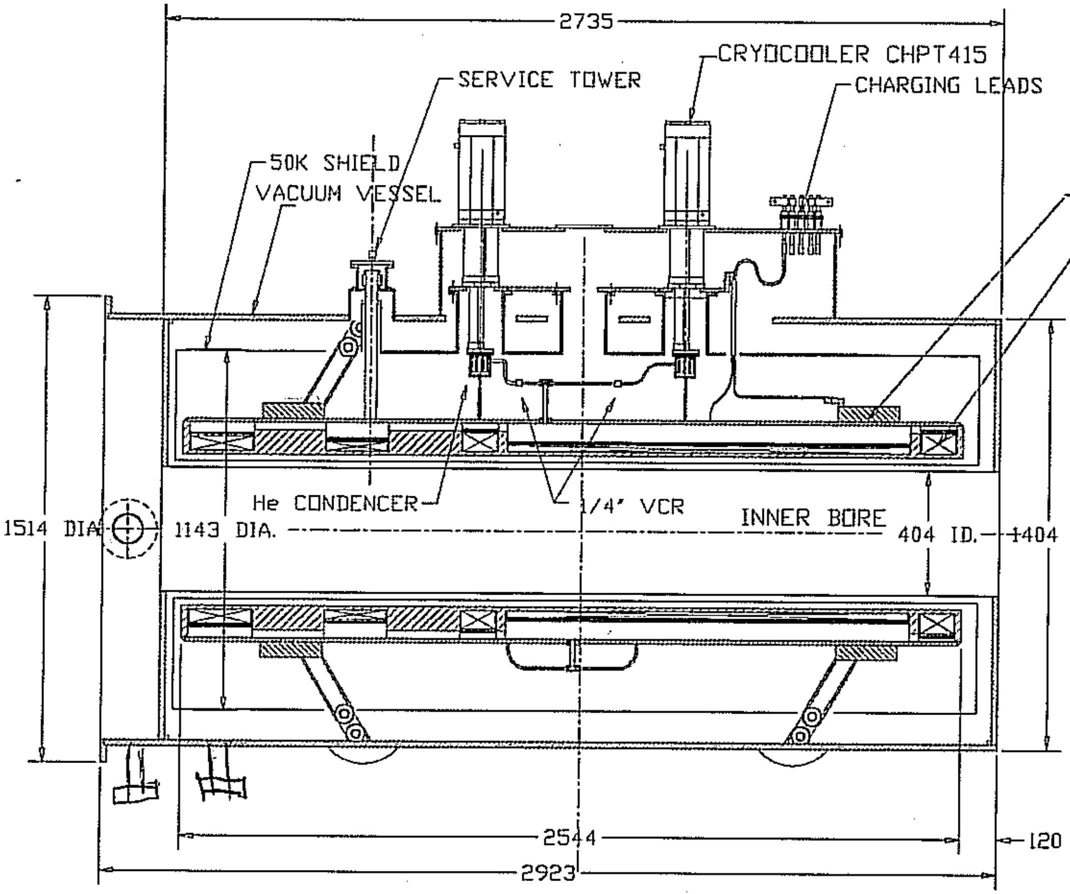
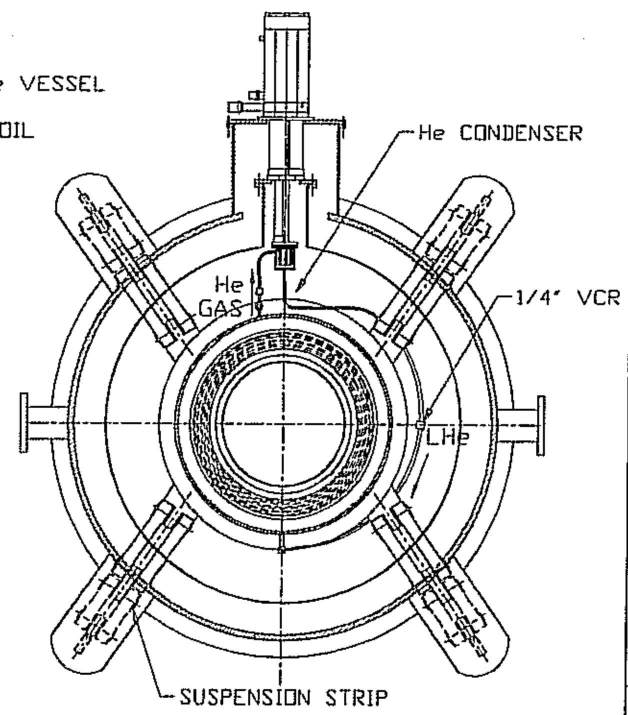
MICE TRACKER MODULE
4.5T TRACKER
SOLENOID MAGNET

D MICE-0000





NOTES:
1) DIMENSIONS ARE IN mm

WANG NMR, INC.

MICE TRACKER MODULE
4.5T TRACKER
SOLENOID MAGNET

D MICE-0000 A

CHAPTER II

MICE Detector Spectrometer Solenoid Coil Assembly Design

Engineering design drawing for coil assembly is shown in Appendix II-1

II-1. Five Coil Design, on-axis Field Profile and Peak Field on Conductor

The solenoid consists of five coils; match coil 1 (M1), match coil 2 (M2), the end coil 1 (E1), the center coil (C), and the end coil 2 (E2). The end coil 1, the center coil, and the end coil 2 are connected in series and form the spectrometer solenoid. The end coil 1 and the end coil 2 can be fine-tuned and adjusted to ensure spectrometer solenoid field uniformity of 1% over detector volume of 300 mm diameter by 1000 mm long. On the other hand, match coil 1 and match coil 2 are each an independently-adjustable coil. These match coils will be tuned to match muon beam between spectrometer coil set and the focusing coil set.

The magnet design is shown in Table II-1-1.

The central field profile is shown in Figure II-1-1. The peak field on conductor in each coil is shown in Table II-1-1 and Fig II-1-2.

Table II-1-1 MICE MAGNET DESIGN

PARAMETER	MATCH1	MATCH2	END1	CENTER	END2
LBL ORIGINAL SPEC.					
R1 (MM)	258	258	258	258	258
COIL THICKNESS (MM)	46.2	30.8	61.6	22	68.2
R2 (MM)	304.2	288.8	319.6	280	326.2
MID-Z POSITION	124	564	964	1714	2464
COIL LENGTH (MM)	198	197	110	1294	110
Z1(MM)	25	465.5	909	1067	2409
Z2(MM)	223	662.5	1019	2361	2519
# OF LAYER	42	28	56	20	62
# OF TURN PER LAYER	120	119	66	784	66
WANG NMR DESIGN: (MM)					
CONDUCTOR INSUL THK	1.0000	1.0000	1.0000	1.0000	1.0000
CONDUCTOR INSUL WIDTH	1.6500	1.6500	1.6500	1.6500	1.6500
LAYER THICK(+2.5 MIL)	1.0643	1.0643	1.0643	1.0643	1.0643
TURN WIDTH (+ 1 MIL)	1.6764	1.6764	1.6764	1.6764	1.6764
SP	56.0499	56.0499	56.0499	56.0499	56.0499
DESIGN CURRENT	214.2	251.8	249.5	265.9	265.2
COIL THICK NESS	44.699	29.799	59.599	21.285	65.984
COIL LENGTH	201.168	199.492	110.642	1314.298	110.642
B PEAK (T)	4.43	4.01	5.90	4.19	6.37
MID R POSITION (LBL)	281.10	273.40	288.80	269.00	292.10
MID R POSITION (Wang)	280.35	272.90	287.80	268.64	290.99
Delta Mid-R (mm)	0.75	0.50	1.00	0.36	1.11
DESIGN COIL DIMENSION (MM)					
R1(MM)	258.000	258.000	258.000	258.000	258.000
R2	302.699	287.799	317.599	279.285	323.984
Z1	23.416	464.254	908.679	1056.851	2408.679
Z2	224.584	663.746	1019.321	2371.149	2519.321
SIDE WALL INSULATION (.125" G-10 + KAPTON)				3.2 MM	
COIL MANDREL INSULATION				1.0 MM	
(2 LAYERS G-10 0.015" + 2 LAYERS KAPTON 0.005")					
BOBBIN DESIGN:					
R1(MM)	257	257	257	257	257
R2					
Z1	20.22	461.05	905.48	1053.65	2405.48
Z2	227.78	666.95	1022.52	2374.35	2522.52
COIL BOBBIN DESIGN IN INCH					
R1(INCH)	10.118	10.118	10.118	10.118	10.118
R2					
Z1	0.796	18.152	35.649	41.482	94.704
Z2	8.968	26.258	40.257	93.478	99.312

Fig II-1-1

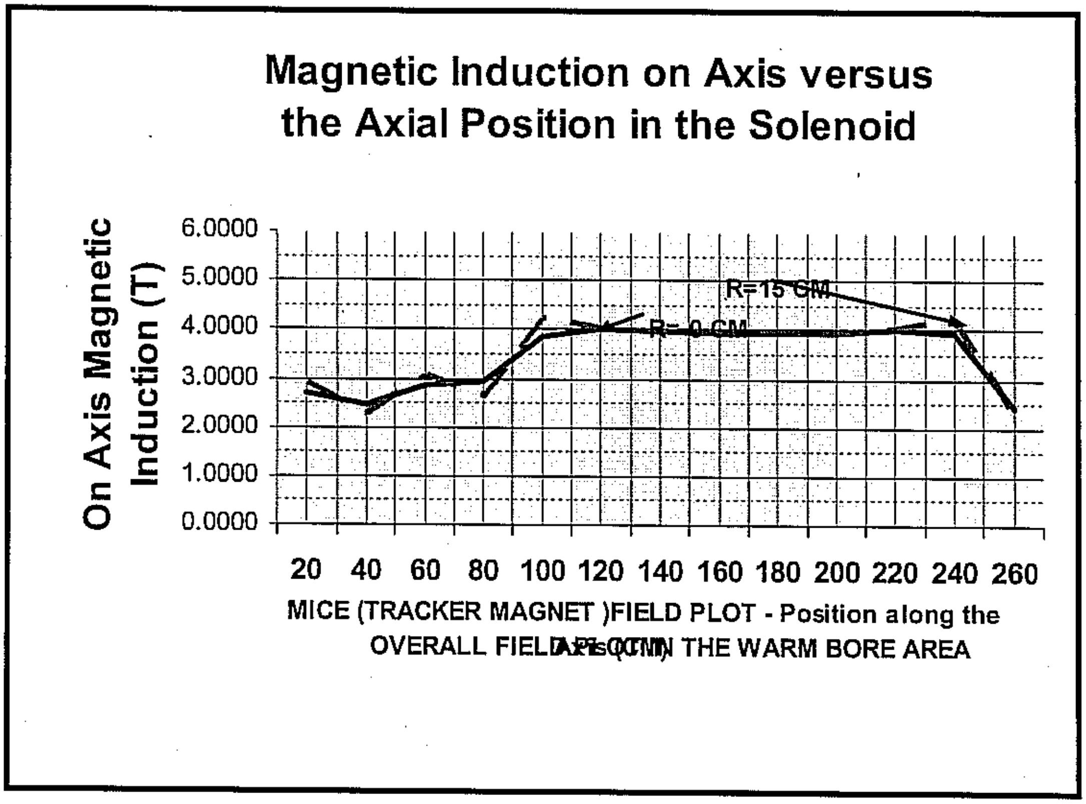
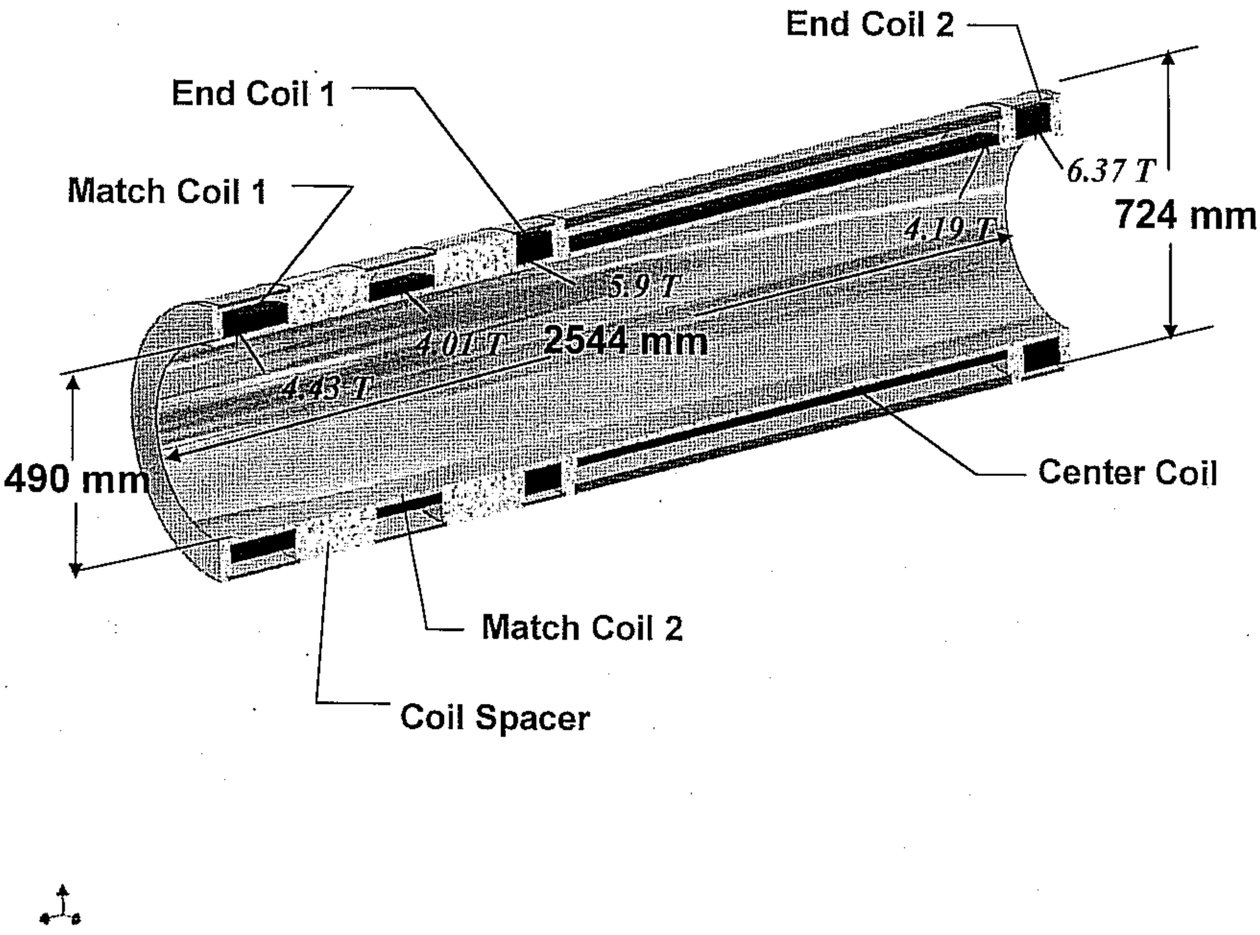

Magnetic Induction on Axis versus the Axial Position in the Solenoid
On Axis Magnetic Induction (T)
6.0000
5.0000
4.0000
3.0000
2.0000
1.0000
0.0000
R=15 CM
R= 0 CM
20 40 60 80 100 120 140 160 180 200 220 240 260
MICE (TRACKER MAGNET)FIELD PLOT - Position along the OVERALL FIELD PLOT IN THE WARM BORE AREA
Axis (CM)

Fig II-1-2

Tracker Solenoid Peak Field



II-2. Conductor Design, Ic-Bc, Operating Current and Load Line (LBL task)

(A) Conductor Design

LBL has designed and procured a rectangular conductor with formvar insulation (dimension: 1.0 mm by 1.65 mm). Its copper to superconductor ratio is 3.9±0.4. The number of filaments is 222. The filament diameter is 41 μ. The filament twist pitch is 19±3 mm. The conductor crossection is shown in Figure II-2-1. Six spools of MICE conductors were delivered to LBNL in May 2006. The QC on the mechanical properties are shown in Table II-2-1. It will be delivered to Wang NMR Inc. in July 2006.

(B) Ic-Bc

The Ic-Bc electrical specification of the superconductor is > 760A at 4.2K and 5T. The QC test on each spool is shown in Table II-2-2. A typical short sample test is shown in Figure II-2-2, which is further plotted in Figure II-2-3.

(C) Operating Current, Load Line, and Temperature Margin

As shown in Figure II-2-3, the load lines for each of five coils in spectrometer solenoid are shown to have temperature margin of more than 2K.

Fig II-2-1 Conductor Cross-section

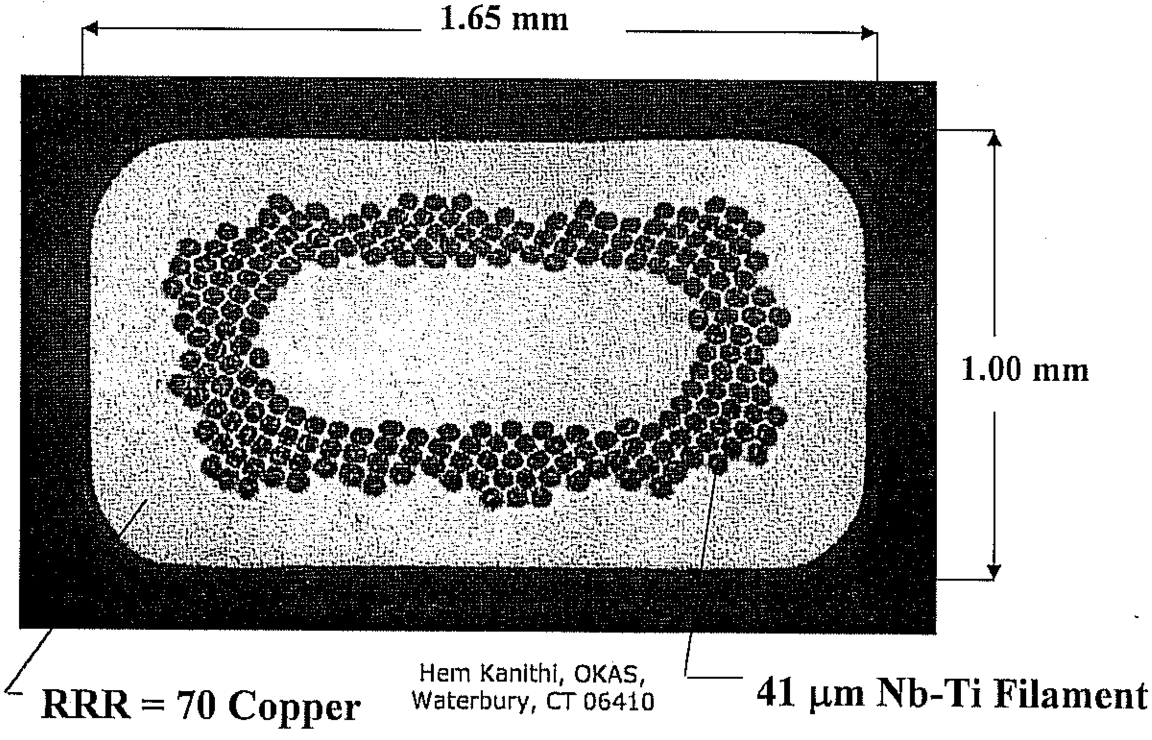


Table II-2-1
Conductor Mechanical Characteristics

Both tests look for filament breakup and defects in the filament bundle.

Piece ID	Length, meters	Weight, kgs	Insul Thk	Insul Width	Bend test	Eddy current
Spec.			0.97-1.00	1.62-1.65	pass	Pass
36680	32964	393.7	0.995	1.644	pass	pass
36679	33140	396.5	0.996	1.645	pass	pass
36761-1	27363	329	0.994	1.646	pass	pass
36761-2	5366	64.7	0.994	1.646	pass	pass
36760-1-1	15218	182.2	0.994	1.644	pass	pass
36760-1-2	7440	89.2	0.994	1.645	pass	pass
Total	**121491**	**1455**				

Hem Kanithi, OKAS,
Waterbury, CT 06410

The dimensions are acceptable.

Table II- 2-2
Conductor Electrical Characteristics

Piece ID	End A Cu/Sc	End A Ic(5T)	End A n(5T)	End B Cu/Sc	End B Ic(5T)	End B n(5T)	Billet RRR
Spec.	3.5-4.3	>760	>35	3.5-4.3	>760	>35	~80
36680	3.90	826	50	3.74	955	57	75
36679	3.55	868	54	3.70	826	51	71
36761-1	3.65	867	49	3.83	872	49	91
36761-2	3.83	872	49	3.83	826	51	91
36760-1-1	3.84	793	56	3.71	824	57	73
36760-1-2	3.71	824	57	3.72	837	60	73

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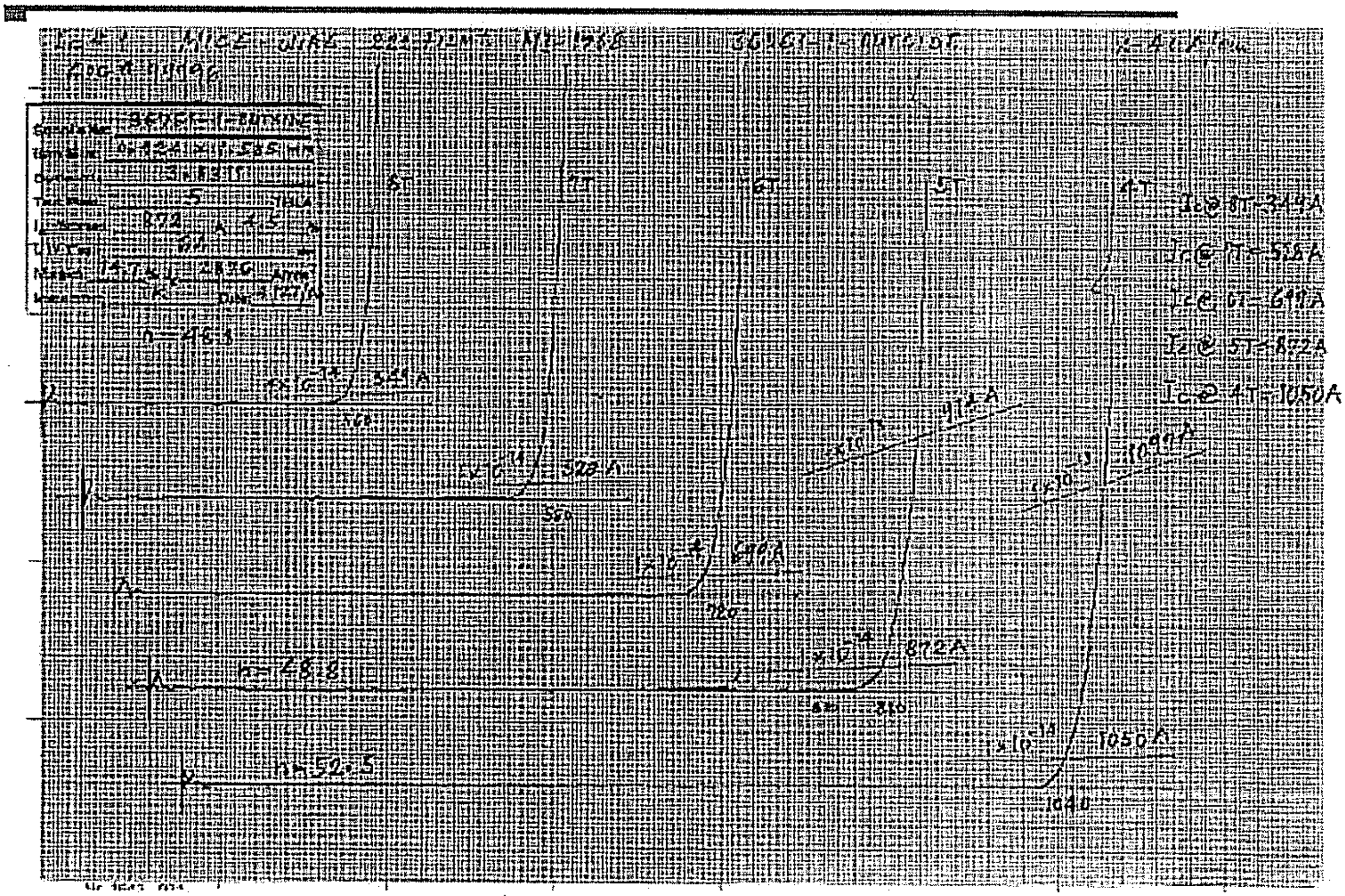
The specified conductor critical current is >760 @ 4.2 K and 5 T.
The specified conductor n value is >35.
The specified conductor copper to S/C ratio is 3.9 ± 0.4.
The RRR values for the conductor copper are acceptable.

Fig II- 2-2

Typical OKAS Short Sample Test Plot



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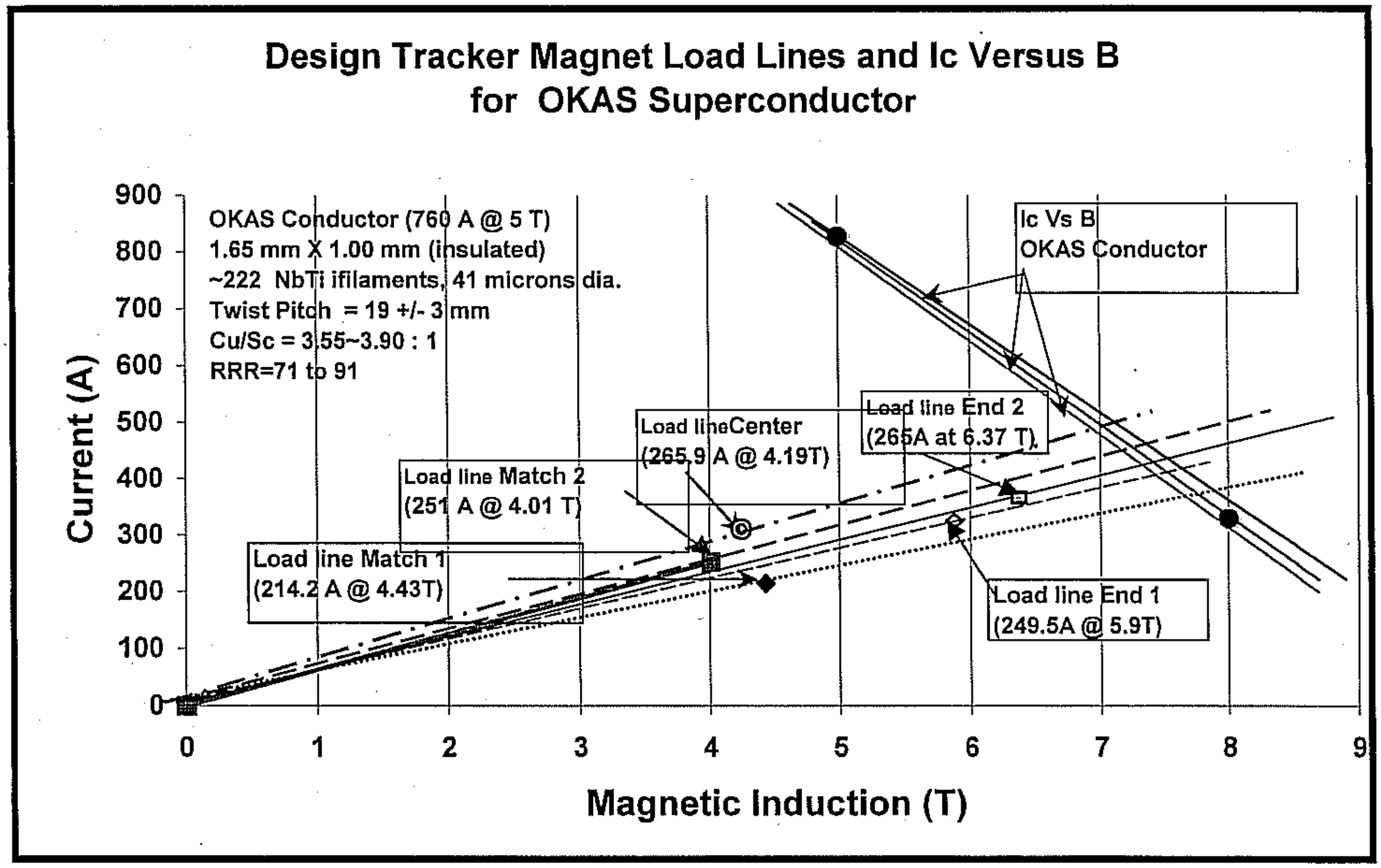
Waterbury, CT 06410

Fig II- 2-3


Design Tracker Magnet Load Lines and Ic Versus B
for OKAS Superconductor
OKAS Conductor (760 A @ 5 T)
1.65 mm X 1.00 mm (insulated)
~222 NbTi ifilaments, 41 microns dia.
Twist Pitch = 19 +/- 3 mm
Cu/Sc = 3.55~3.90 : 1
RRR=71 to 91
Ic Vs B
OKAS Conductor
Load lineCenter
(265.9 A @ 4.19T)
Load line End 2
(265A at 6.37 T)
Load line Match 2
(251 A @ 4.01 T)
Load line Match 1
(214.2 A @ 4.43T)
Load line End 1
(249.5A @ 5.9T)
Current (A)
Magnetic Induction (T)

II-3 Insulation Design of Conductor, Turn-to-Turn, Layer-to-Layer, and of Coil to Ground

(A) Conductor insulation

The superconducting composite shall be insulated with formvar (0.001" or 0.025 mm thick) per NEMA standard MW-1000 section 18-C poly-vinyl formal resin/ class 10J/ heavy build. The insulated overall dimension of conductor is 1.00 mm by 1.65 mm, with corner radii in the range of 0.2 mm to 0.475 mm.

(B) Turn-to-Turn Insulation

The turn-to-turn insulation including gap will be 0.050 mm (0.002") thick formvar.

(C) Layer-to-Layer insulation

The layer-to-layer insulation will be 0.0625 mm (2.5 mil) thick fiberglass cloth (E glass) plus 0.050 mm (0.002") formvar.

(D) Coil-to-ground insulation

Coil to mandrel will be insulated with 2 layers of Kapton (0.002" x 2) and two layers of G-10 sheets (0.018" x 2). Coil to the coil former side wall will be insulated with 0.125" G-10 and 0.002" Kapton.

These insulation design will be meggered test to satisfy 5 kV and 200 μA leakage current requirement.

II-4. Coil Winding Pack Design and Design of Coil Former

(A) Control winding density

During each layer winding, winding density (# of turn per cm) will be controlled to assure field uniformity.

(B) Coil layer and potting epoxy

2.5 mil thick fiberglass will be used for layer to layer winding. Stycast 2850 FT will be used to wet wind each coil layer.

(C) Aluminum Coil Banding to Support Coil Force

Outer most coil layer will be insulated with one layer kapton and two layers G-10 totaling 1 mm thick. A high strength aluminum alloy 6061T6 banding will be used to band each coil. This will provide additional hoop force support and will ensure coil is tightly packed when it is cool-down.

(D) Conductor Joints and Voltage Tap

After banding, conductor joints will be made by lapping joints over at least 24" long. All joints will be carefully insulated, supported, and epoxy potted in a G-10 supporting plate. Heating due to conductor joints must be as small as possible to keep overall refrigerator load within cryocooler capability. If necessary, superconducting joints will be made to eliminate the heating due to joints. Voltage taps will be made at each joints.

(E) Coil leading superconductors

In the helium space, each coil leading conductors (in and out) will be soldered with at least three times superconductor/ copper to avoid burn out due to vapor locking. In the vacuum space, each coil leading conductors will be soldered with at least five time superconductor/ copper to avoid burn out. The leading conductor lengths should be kept as short as possible. All leading conductor must be well-insulated and well-supported.

(F) The inner coil radius (R1)

The inner coil radius of all coils will be 258 mm or 10.158" (R1).

(G) The turn-to-turn width

Adding a turn-to-turn gap of 0.001" to conductor width 1.65 mm (0.065"), the design turn-to-turn width will be 0.001" + 0.065" = 0.066".

(H) The layer-to- layer thickness

The layer-to-layer insulation will be 0.0025" fiberglass cloth, thus layer-to-layer thick will be 0.0025"+0.0394" = 0.0419".

The winding build ($\Delta R \times \Delta Z$), the number of layer, L, and the number of turns per layer, N are shown in Table II-4-1.

Table II-4-1 COIL DESIGN PARAMETERS

COIL	MATCH 1	MATCH 2	END 1	CENTER	END 2
# of layer (L)	42	28	56	20	62
# of turns/ layer (N)	120	119	66	784	66
Radial Coil Build (ΔR)	1.7598"	1.1732"	2.3464"	0.838"	2.5978"
Axial Coil Build (ΔZ)	7.92"	7.854"	4.356"	51.744"	4.356"
Inner Coil Radius (R1)*	10.158"	10.158"	10.158"	10.158"	10.158"
Outer Coil Radius (R2)*	11.917"	11.331"	12.504"	10.996"	12.755"
Mean Coil R* (mm) (Current Center)	280.35 mm	272.9 mm	287.8 mm	268.65 mm	290.94 mm
Mean Coil Z** (mm) (Axial Current Center)	124±1	564±1	964±1	1714±1	2464±1
Coil Inner Z1** (mm) (inch)	23.4 (0.921")	464.25 (18.278")	908.7 (35.776")	1056.85 (41.608")	2408.7 (94.831")
Coil Outer Z2** (mm) (inch)	224.6 (8.843")	663.75 (26.132")	1019.3 (40.130")	2371.15 (93.352")	2519.3 (99.185")

* Radial dimensions are measured from the magnetic axis.
** Axial dimensions are measured from cold mass cryostat end of match coil 1.

(I) <u>Coil winding structure, coil former design, and coil axial groove width design</u>

As shown in Figure I-1 and Table I-1, the coil former will have an inner radius of 245 mm (9.646") and an overall coil former length (cold mass length) of 2544 mm (100.157"). Since all five coils shall have a G-10 sidewall thickness of 0.125", the longitudinal (axial) distance of each coil winding pack is calculated as shown in Table II-4-1.

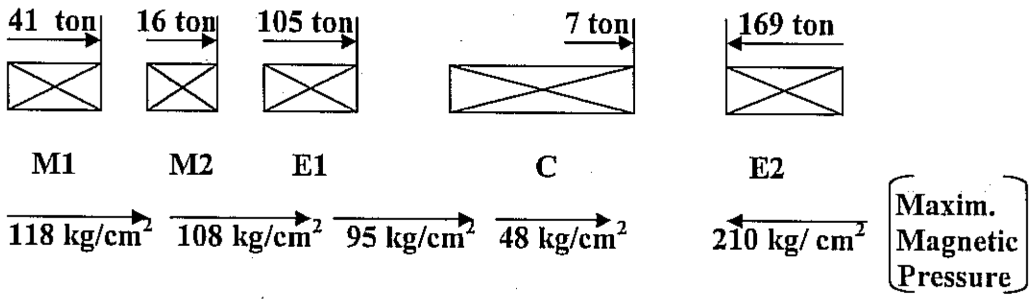
(J) <u>Coil radial groove depth design</u>

As shown in Table II-4-1, each coil shall have enough radial groove depth to allow for: (i) coil to mandrel insulation 0.040", (ii) coil radial build, (iii) banding and its insulation (0.250"), and (iv) 0.75" space reserved for precool line, or intercoil connection. In addition, the center coil has the thinnest build, we plan to install coil protection system (2.5" radial build) on the surface of center coil banding, as shown in Figure II-4-1. Thus, the outer radius of each winding groove will be 11.25" + 2.5" = 13.75" R. The coil former design is shown in drawing MICE-C001.

II-5. Calculation of the Axial Forces and Axial Magnetic Pressure

Radial field component, Br, generate axial magnetic force and pressure. Figure II-5-1 tabulates the total axial forces and maximum axial magnetic pressure for each coil.

Figure II-5-1. Axial Coil Force & Maximum Axial Pressure



Therefore, E2 coil has maximum axial magnetic pressure of 210 kg/ cm^2.

II-6. Finite Element Stress Analyses for Coil and Reinforcement Rings

The coil forces consists of hoop forces and axial compressive forces. To set up finite element analyses and to compute hoop force and axial forces, we have computed the magnetic field component Bz and Br within the winding. The coil is divided into 25 axial-symmetric elements. The reinforcing cylinder is divided into 90 solid elements. Detail of finite element stress analyses are shown in Appendix II-6-1. The conductor stress in each coil is shown in Table II-6-1.

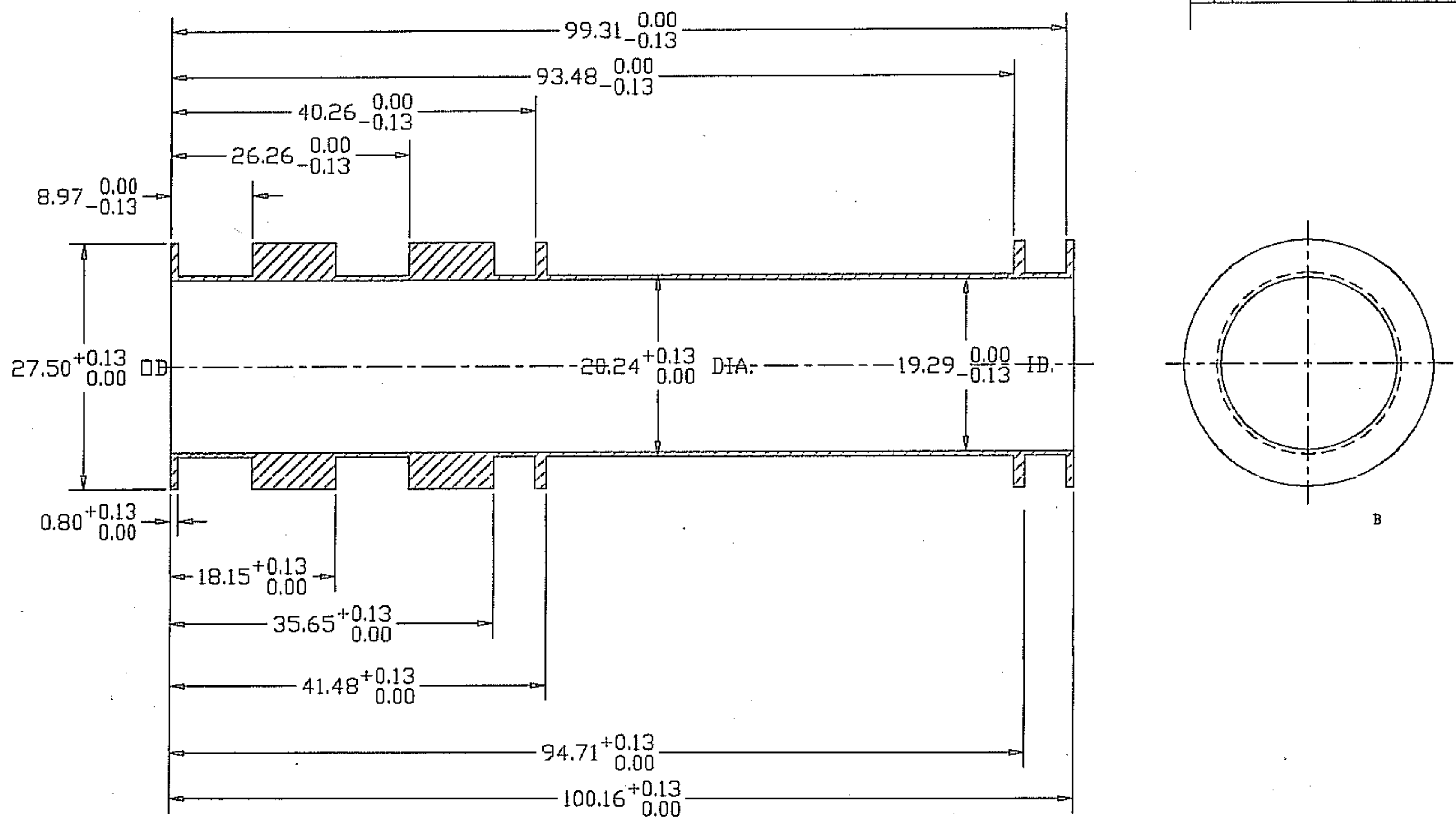
Table II-6-1 MAXIMUM COIL STRESS

	coil	hoop stress (kg/ cm^2)	compress stress (kg/ cm^2)
M_1	match 1	538.8	-182.5
M_2	match 2	643.3	-124.7
E_1	end 1	834.7	-298.2
C	center	818.2	-39.6
E_2	end 2	882.7	208.9

The Von Mise Stress of Reinforce ring is 960.6 kg / cm^2

II-7. Coil Former Fabrication and Quality Control

Coil former is made of forging 6061T6 aluminum. After forging, besides chemical composition analyses and heat treatment certification, it must be inspected for dimensional tolerance and for surface finish, deburring, and for cleaniness. Then, it will be leak check for a sensitivity of better than 1 x 10^{-10} torr-liter/ sec.
The before-machined drawing is shown in Drwg MICE-C001A. The final machined former is shown in Drwg MICE-C001

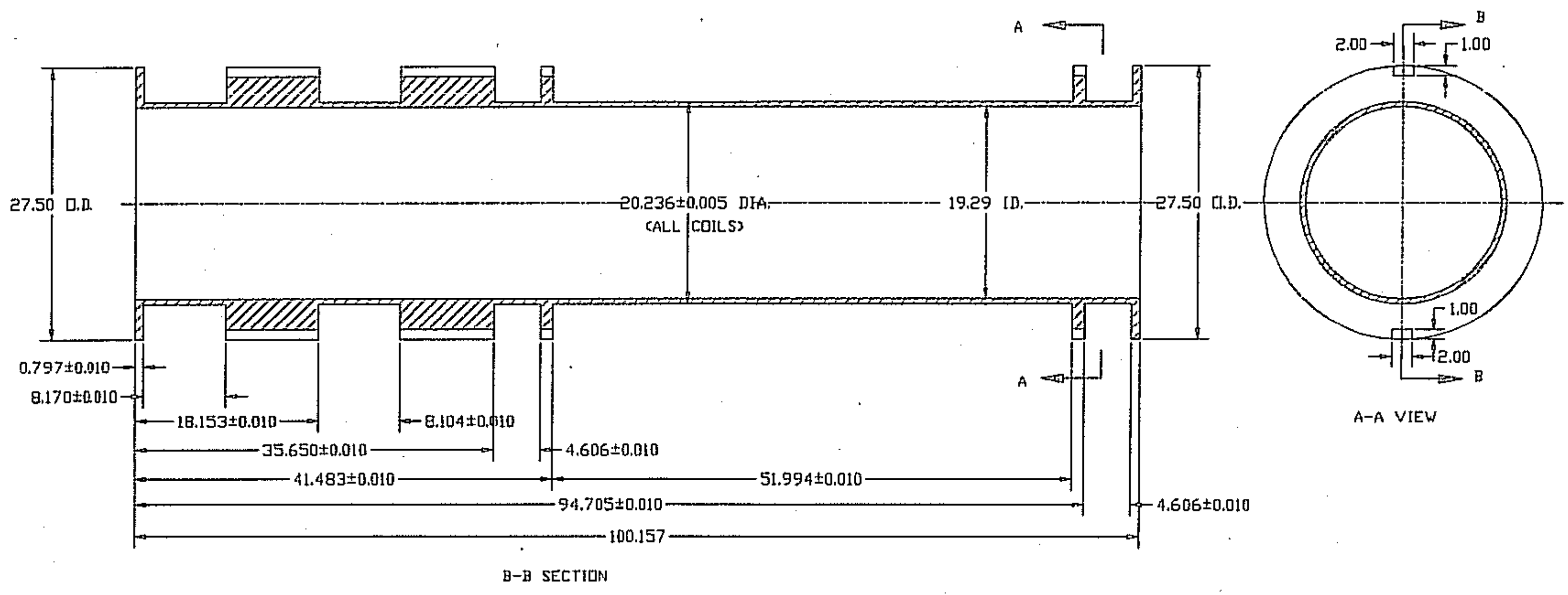


NOTES:
1) DIMENSIONS ARE IN INCHES
2) MATERIAL IS FORGING 6061T6 ALUMINUM
3) WORK: FORGING & ROUGHLY MACHINING WITH TOLERANCE AS SHOWN
4) QTY. 2

WANG NMR, INC.

MICE TRACK MODULE COIL FORM BEFORE MACHINEING

D | MICE-C001A



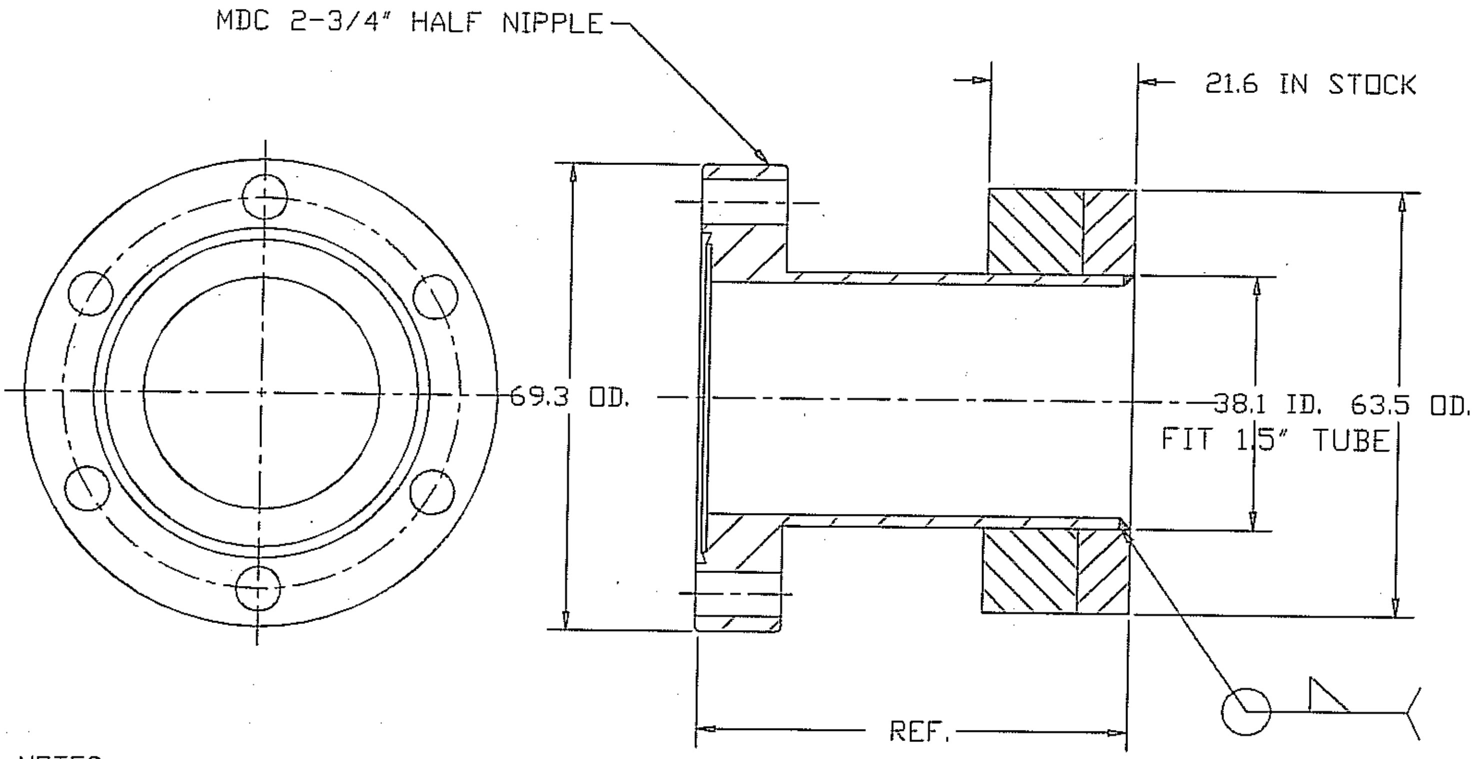
NOTES:
1) DIMENSIONS ARE IN INCHES
2) MATERIAL IS FORGING 6061T6 ALUMINUM
3) QTY. 2

WANG NMR, INC.

MICE TRACK MODULE COIL FORM

D

MICE-C001



NOTES:
1) DIMENSIONS ARE IN mm
2) MATERIAL IS S.S.-AL BI-METAL & MDC 2-3/4" HALF NIPPLE
3) QTY. 2

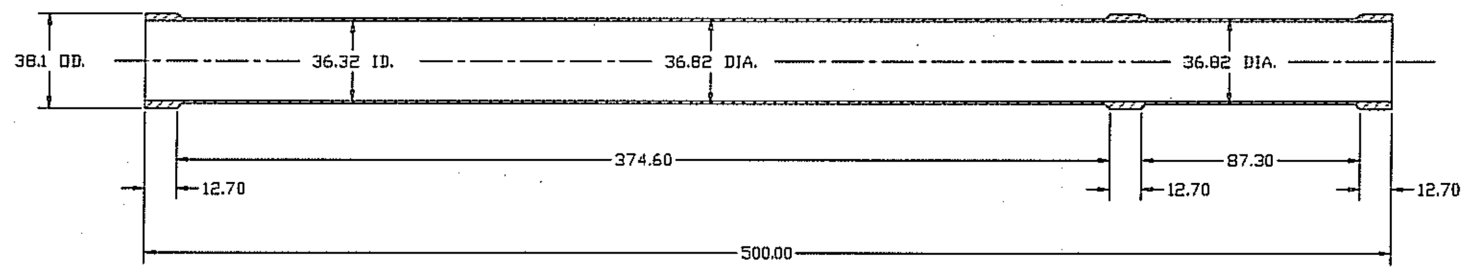
UNLESS OTHERWISE SPECIFIED TOLERANCES:
.XXX ± .005
.XX ± .02

WANG NMR, INC.
550 North canyons Parkway, Livermore, CA 94550

S.S.-AL BI-METAL COUPLING (FOR ELECTRIC FEEDTHROUGH & NECK TUBE)

SIZE: C | DWG NO.: MICE-C008

DO NOT SCALE

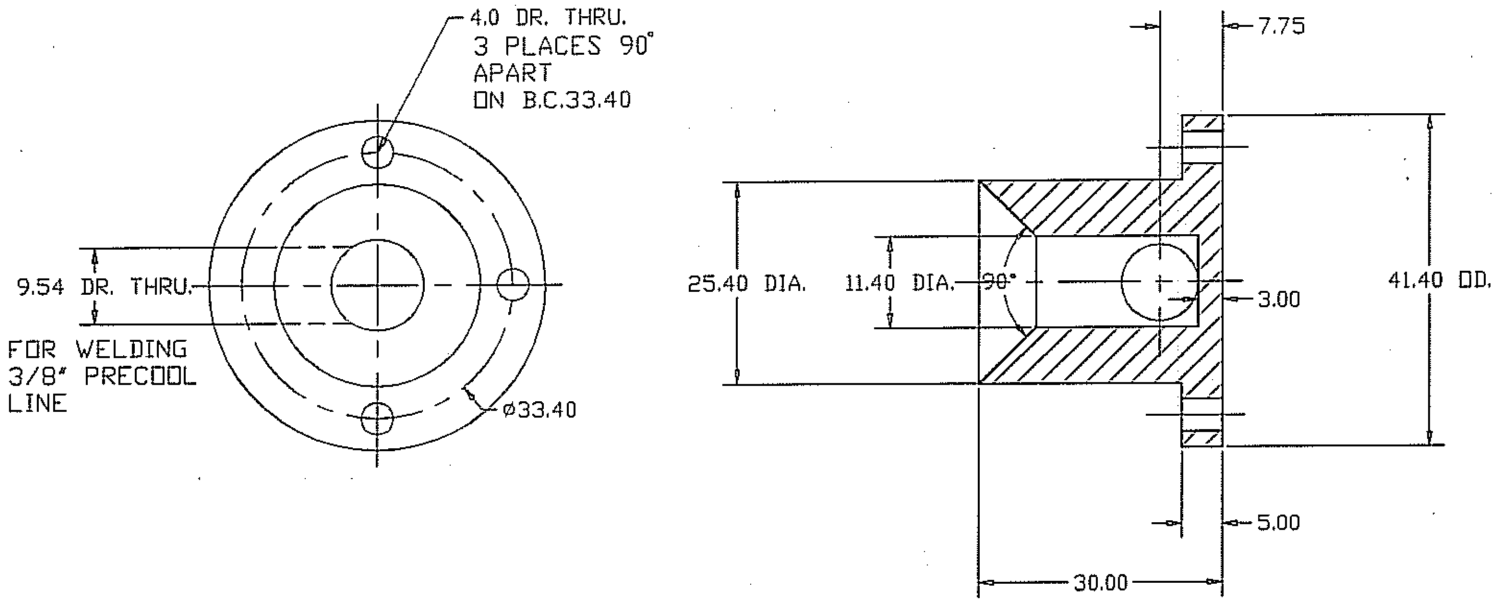


NOTES:
1) DIMENSIONS ARE IN mm
2) MATERIAL IS 1.5" OD. 0.035" WALL 304 S.S.TUBE
3) QTY. 1

WANG NMR, INC.

NECK TUBE

D MICE-C009



NOTES:
1) DIMENSIONS ARE IN mm
2) MATERIAL IS 304 S.S.
3) QTY. 1

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED TOLERANCES:
.XXX ± .005
.XX ± .02

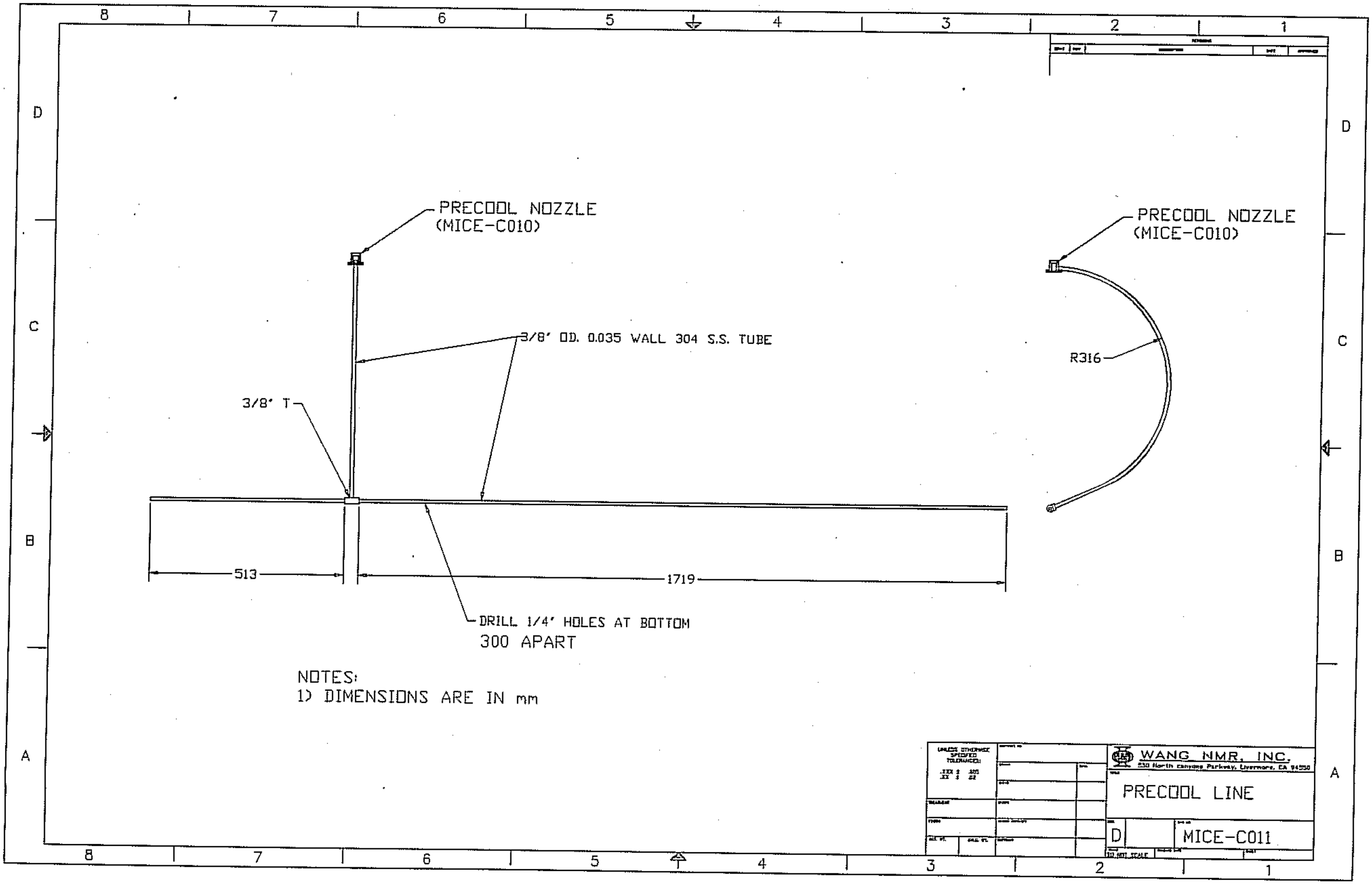
WANG NMR, INC.
550 North canyons Parkway, Livermore, CA 94550

TITLE: PRECOOL NOZZLE

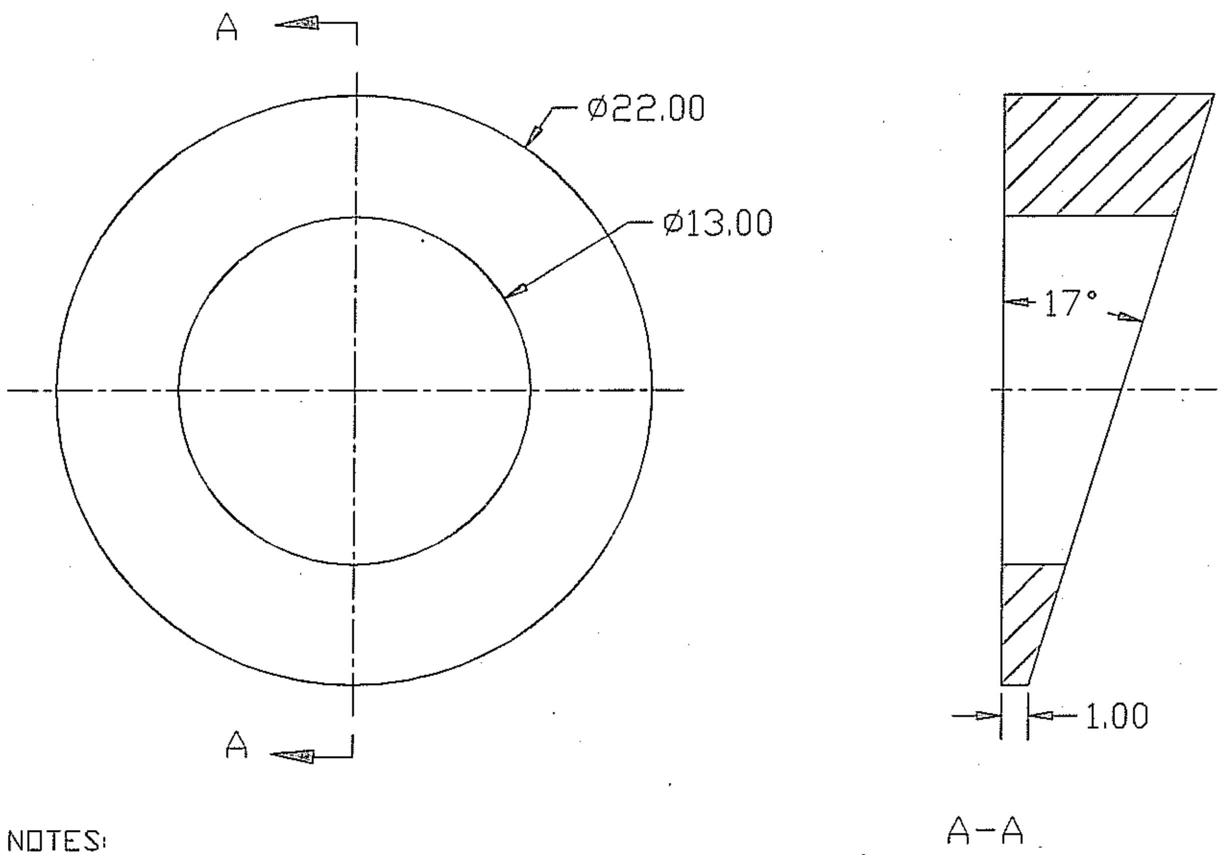
SIZE: C

DWG NO: MICE-C010

SCALE: DO NOT SCALE



PRECOOL NOZZLE
(MICE-C010)
3/8' OD. 0.035 WALL 304 S.S. TUBE
3/8' T
513
1719
DRILL 1/4' HOLES AT BOTTOM
300 APART
PRECOOL NOZZLE
(MICE-C010)
R316
NOTES:
1) DIMENSIONS ARE IN mm
WANG NMR, INC.
PRECOOL LINE
D
MICE-C011



NOTES:
1) DIMENSIONS ARE IN mm
2) MATERIAL IS 304 S.S.
3) QTY, 32

UNLESS OTHERWISE SPECIFIED TOLERANCES:
.XXX ± .005
.XX ± .02

WANG NMR, INC.
550 North canyons Parkway, Livermore, CA 94550

TITLE: WASHER

SIZE: C

DWG NO: MICE-C012

DO NOT SCALE

Appendix II-6-1

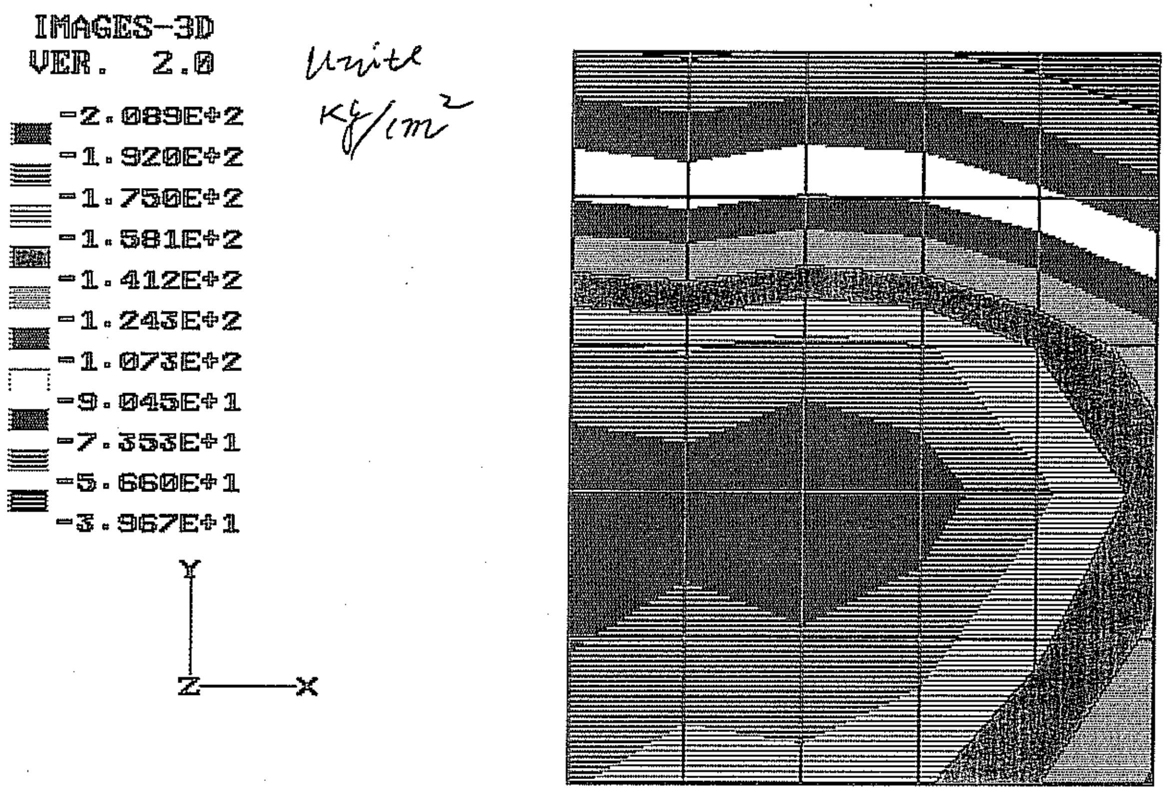
Finite Element Stress Analyses of

Coil and Reinforce Rings

Wang NMR Inc.

• 550 North Canyons Parkway • Livermore, CA 94551

END 2 compress Stress



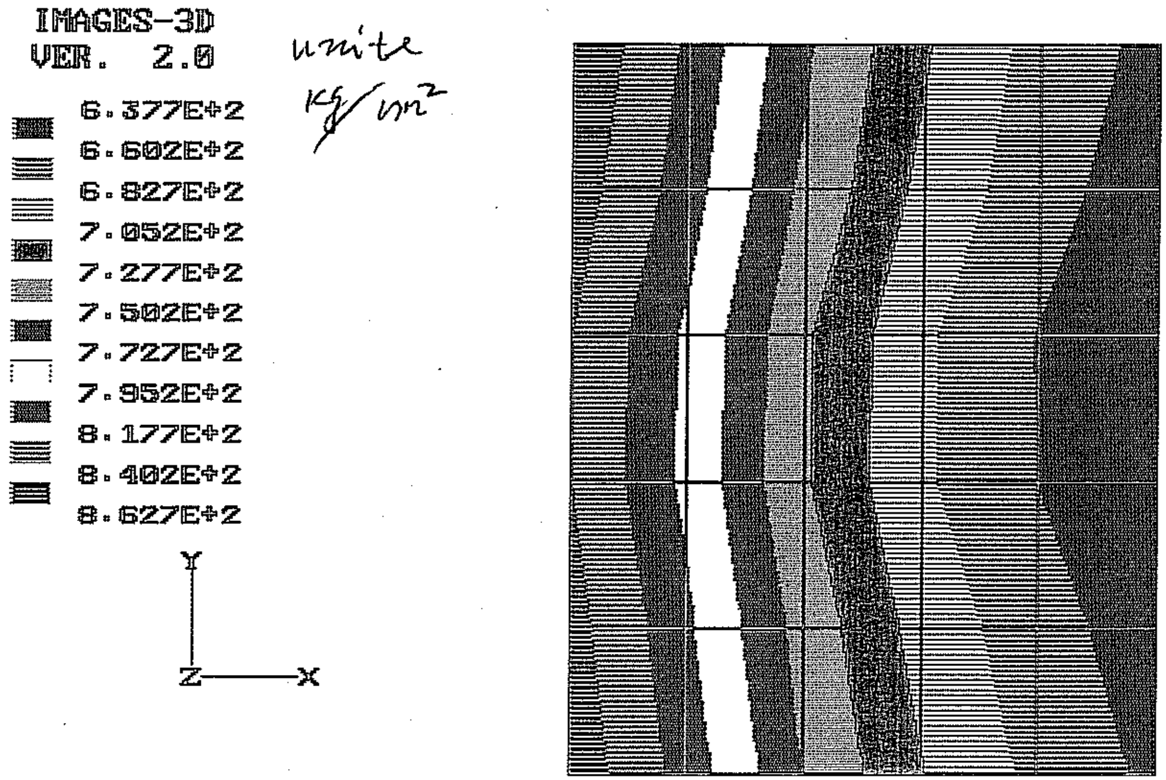
Load Case
1

Stress Contour Plot
Gl St: S22

8/10/ 6
6:42:52

END 2 hoope stress

unite kg/cm²

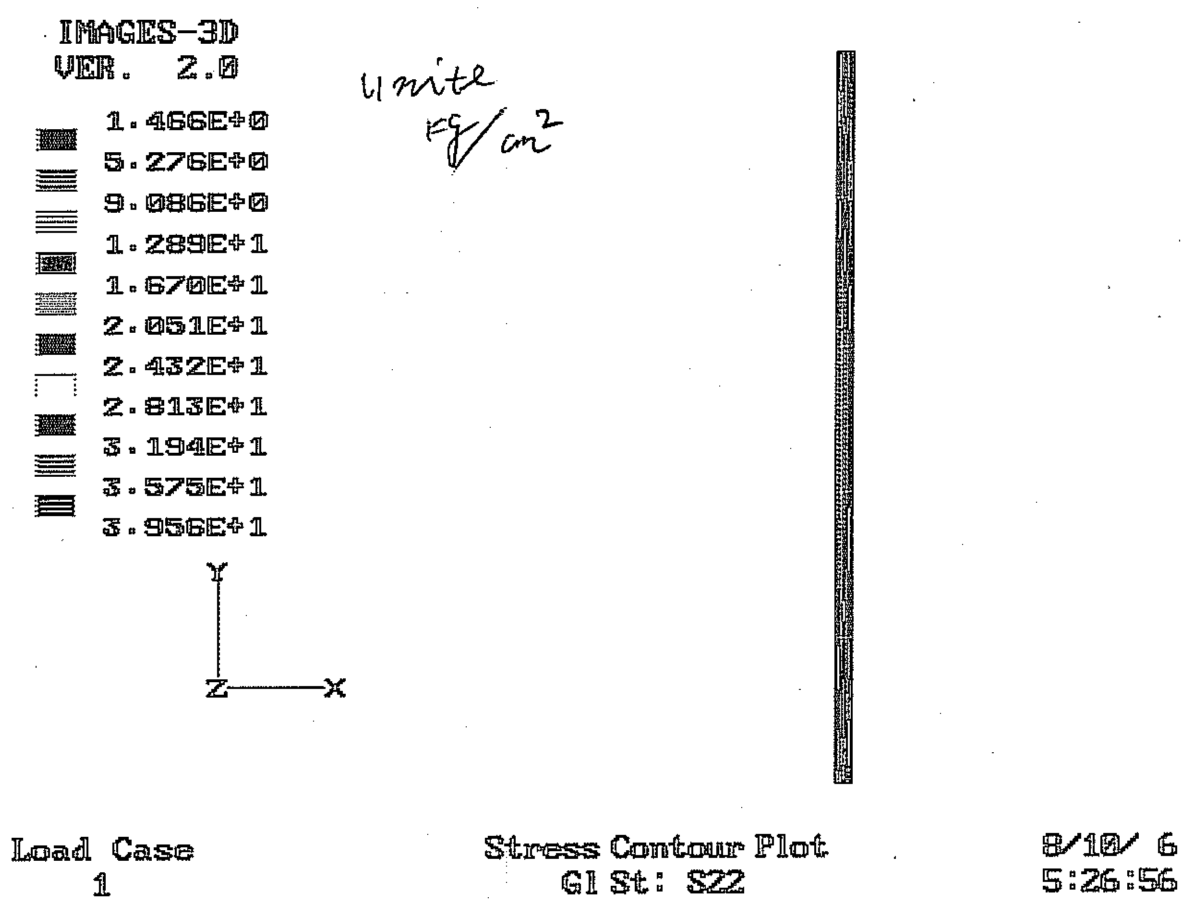


Load Case
1

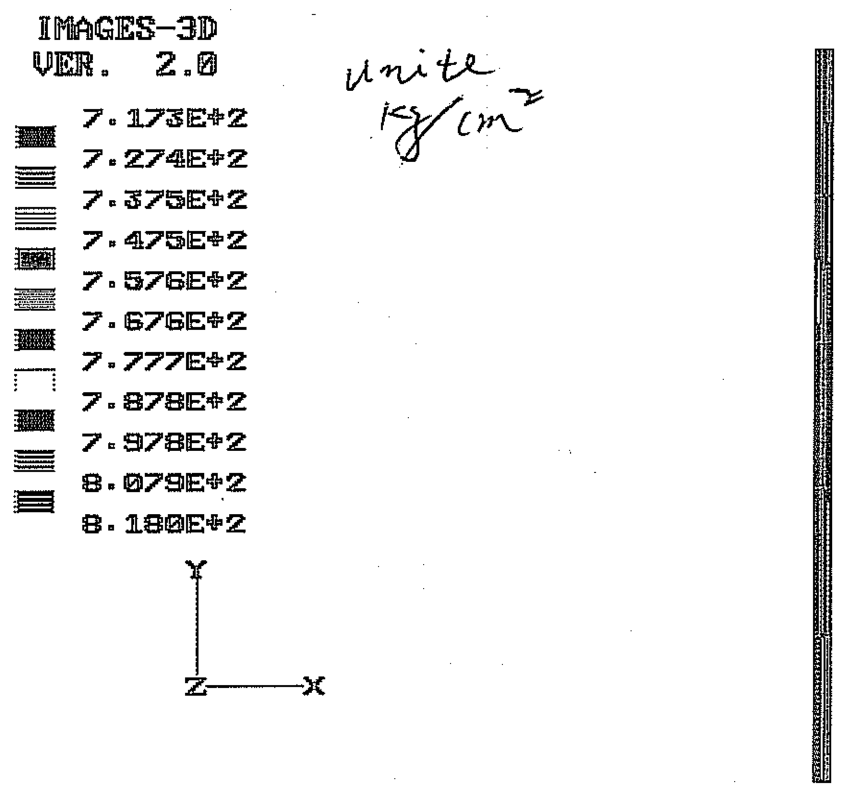
Stress Contour Plot
Gl St: S33

8/10/ 6
6:42:24

CENTER


IMAGES-3D
VER. 2.0
Unite
Kg/cm²
1.466E+0
5.276E+0
9.086E+0
1.289E+1
1.670E+1
2.051E+1
2.432E+1
2.813E+1
3.194E+1
3.575E+1
3.956E+1
Y
Z
X
Load Case
1
Stress Contour Plot
Gl St: S22
8/10/ 6
5:26:56

CENTER



Load Case
1

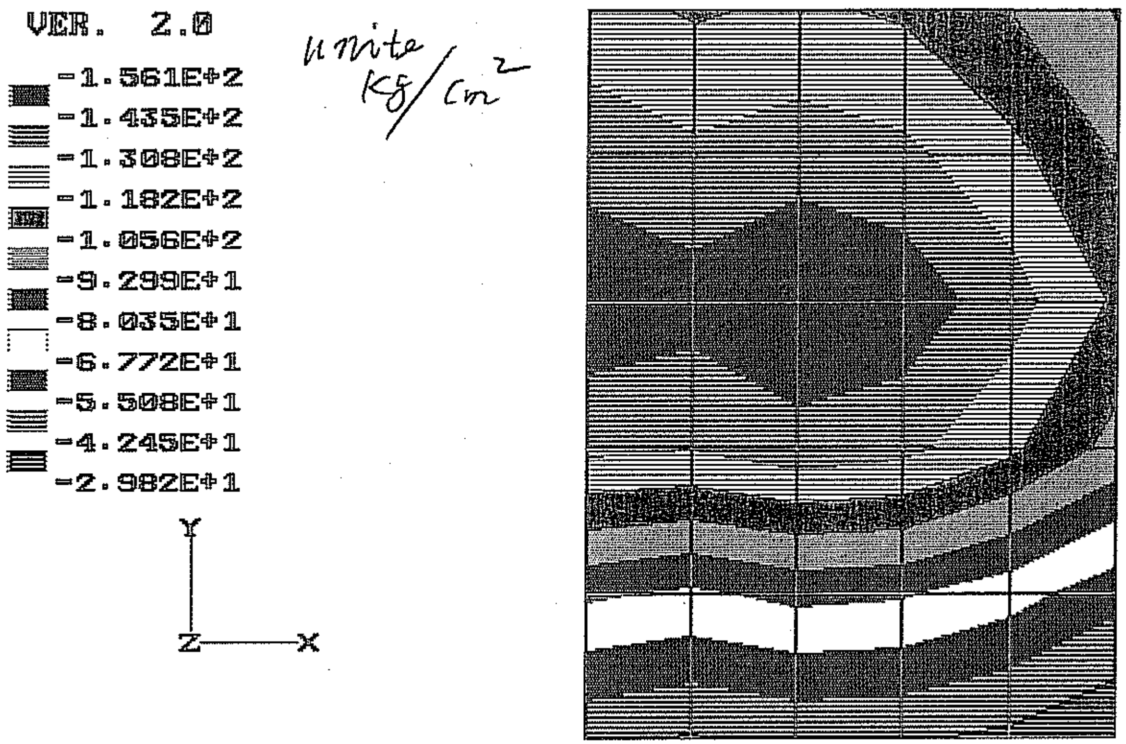
Stress Contour Plot
Gl St: S33

8/10/ 6
5:26:17

END 1

IMAGES-3D
VER. 2.0

unite Kg/cm^2

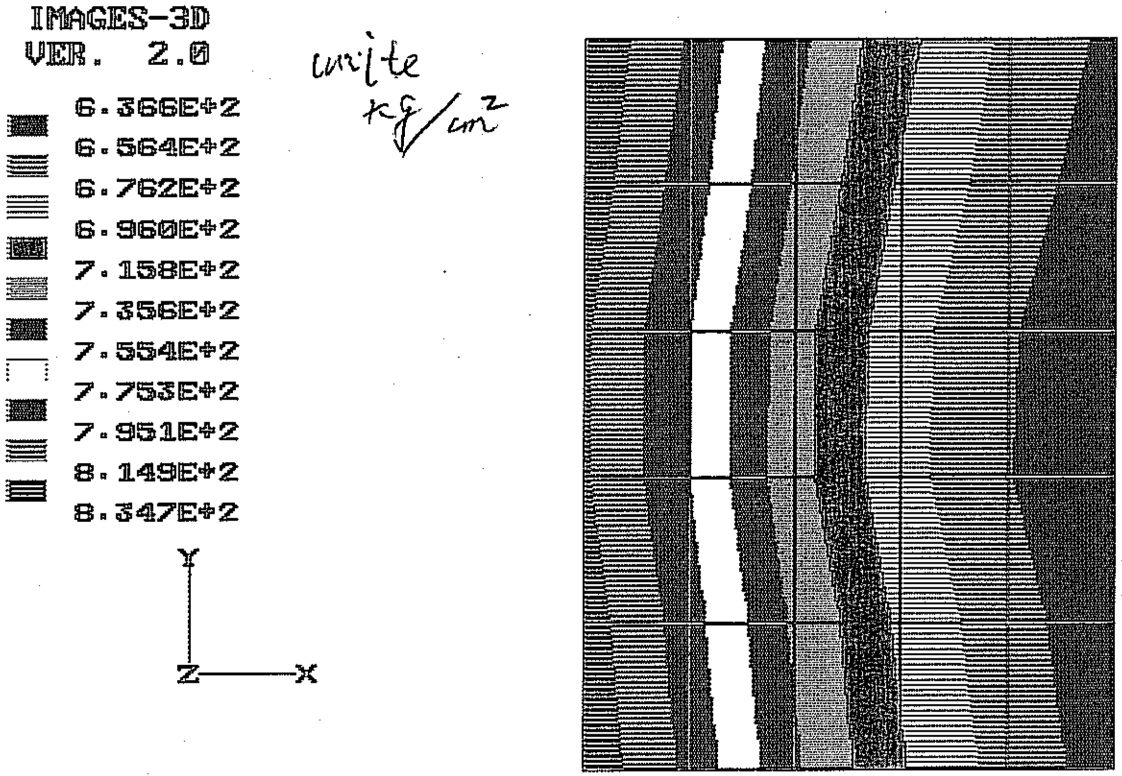


Load Case
1

Stress Contour Plot
Gl St: S22

8/ 9/ 6
12:26:27

END 1



Load Case
1

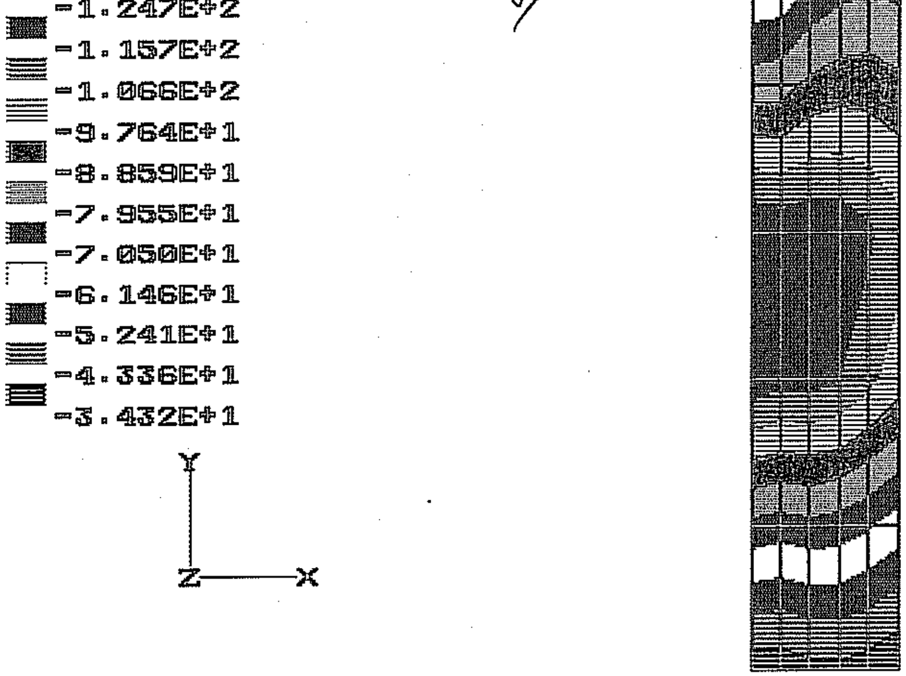
Stress Contour Plot
Gl St: S33

8/ 9/ 6
12:25:59

MATCH 2

IMAGES-3D
VER. 2.0

units kg/cm²



Load Case
1

Stress Contour Plot
Gl St: S22

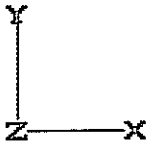
8/ 9/ 6
11:39:21

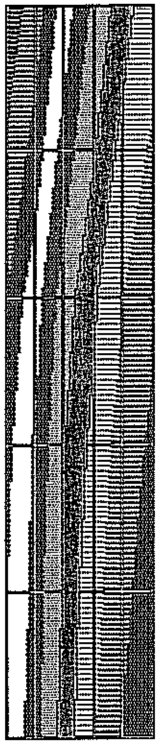
MATCH 2

IMAGES-3D
VER. 2.0

unite kg/cm²

5.330E+2
5.440E+2
5.551E+2
5.661E+2
5.771E+2
5.882E+2
5.992E+2
6.102E+2
6.213E+2
6.323E+2
6.433E+2





Load Case
1

Stress Contour Plot
Gl St: S33

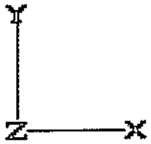
8/ 9/ 6
11:38:53

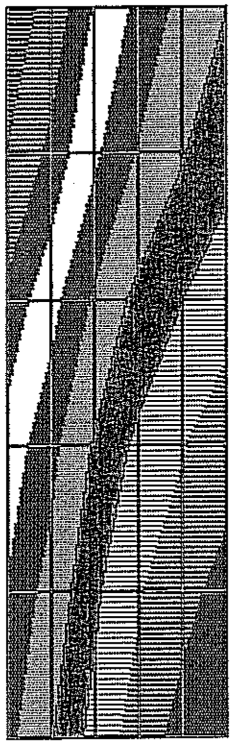
MATCH 1

IMAGES-3D
VER. 2.0

unite kg/cm²

	3.843E+2
	3.997E+2
	4.152E+2
	4.306E+2
	4.461E+2
	4.615E+2
	4.770E+2
	4.924E+2
	5.079E+2
	5.233E+2
	5.388E+2





Load Case
1

Stress Contour Plot
Gl St: S33

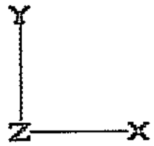
8/ 9/ 6
10:36:20

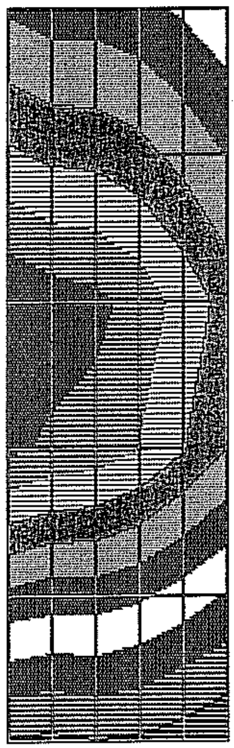
MA1CH1

IMAGES-3D
VER. 2.0

u nite Kg/cm²

-1.825E+2
-1.685E+2
-1.546E+2
-1.406E+2
-1.266E+2
-1.127E+2
-9.878E+1
-8.483E+1
-7.087E+1
-5.692E+1
-4.296E+1





Load Case
1

Stress Contour Plot
Gl St: S22

8/ 9/ 6
10:37:25

4.2K Reinforcement Stress.

unit kg/cm².