STRESS ANALYSIS

BaBar Solenoid - Structural considerations

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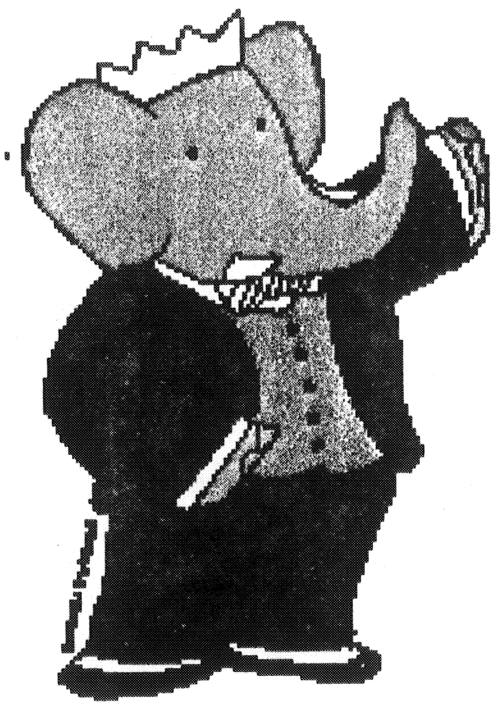
28 March 1995



Items to be covered

- Finite Element work on stresses in glue
- Loads and design stresses
- Support scheme
- Cold mass stresses
- Cryostat

Loads and stresses

- Earthquake loads
- Other loads
- Allowable design stresses

Earthquake loads

- Static approximation

Direction	Acceleration
Radial	1.2g
Axial	1.2g
Vertical	2g (+ weight)

- Masses

Vessel mass	5.2t
cold mass	5.1t
radiation shields etc	2.5t
detector mass	50t

Other loads

- Alignment error of 2cm gives forces up to 20t.
- Asymmetry of the flux return gives axial force of 10t.
- Gravity is acting

Design stresses

Condition	Max allowable design stress
Worst possible loads with no earthquake	50% of Yield stress
Vacuum vessel (Must conform to pressure vessel code)	As per pressure vessel code (65 MPa for 5083 aluminum alloy)
Worst possible loads during earthquake	50% of UTS

Support scheme

- Loads
- Design constraints
- Concept
- Internal supports
- External supports

Loads

Max. radial loads:				
	On cold mass	On cryostat	On detectors	Combined load on supports
g forces	6.1	9.2	60	
magnetic alignment errors	20			
Total	26.1	9.2	60	95.3t
Max. axial loads:				
g forces	6.1	9.2	60	
magnetic loads due to known geometry	10			
magnetic alignment errors	20			
Total	36.1	9.2	60	105.3t
Max. vertical loads:				
weight	5.1	7.7	50	
g forces	10.2	15.4	100	
magnetic alignment errors	20			
Total	35.3	23.1	150	208.4t

Design constraints on cold mass supports

Movement. The support system must allow for contraction of 4mm per metre during cooldown.

Strength. The direct stress in each rod must be less than half the yield stress under normal loading, AND less than half the ultimate stress under earthquake loading.

Conduction. The heat conduction over half the rod's length (assumed) must be acceptable between 80K and 4K. Total for all supports should be less than 10W.

Stability. The buckling load of the rods must be at least twice the highest load they will see.

Size. The size of the rod ends may be a problem, and the overall length must be possible to accommodate in the design.

Concept

- Internal - to support the cold mass from the vacuum vessel

- External - to support the vacuum vessel and the inner detectors

Support scheme concept Fig 6.1

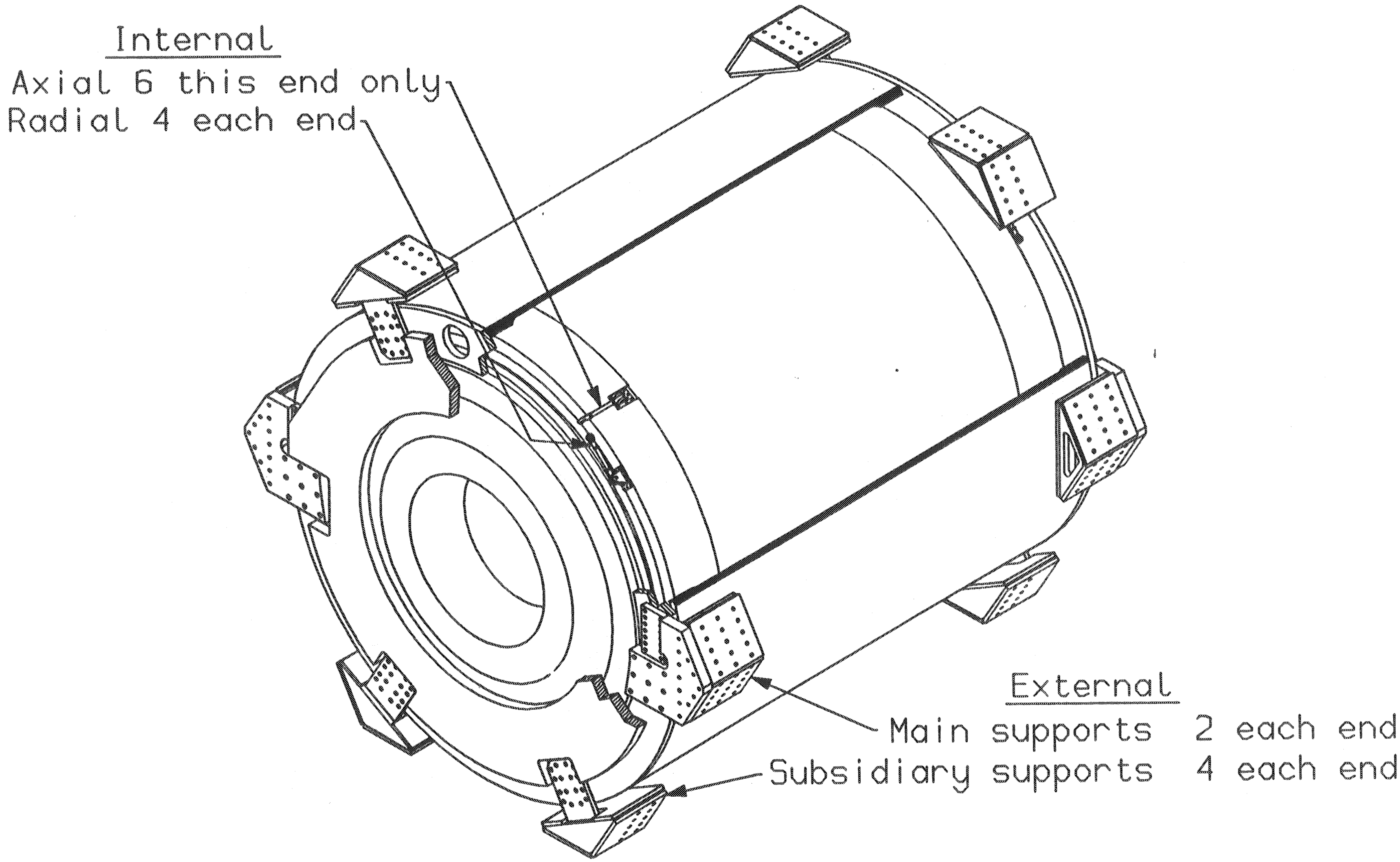


Fig 6.1 SUPPORTS OVERVIEW

Internal supports

- Radial supports, 4 each end at 45° points
- Axial, 6 at one end only

Picture showing internal supports, fig 4.10
ditto , fig 6.2

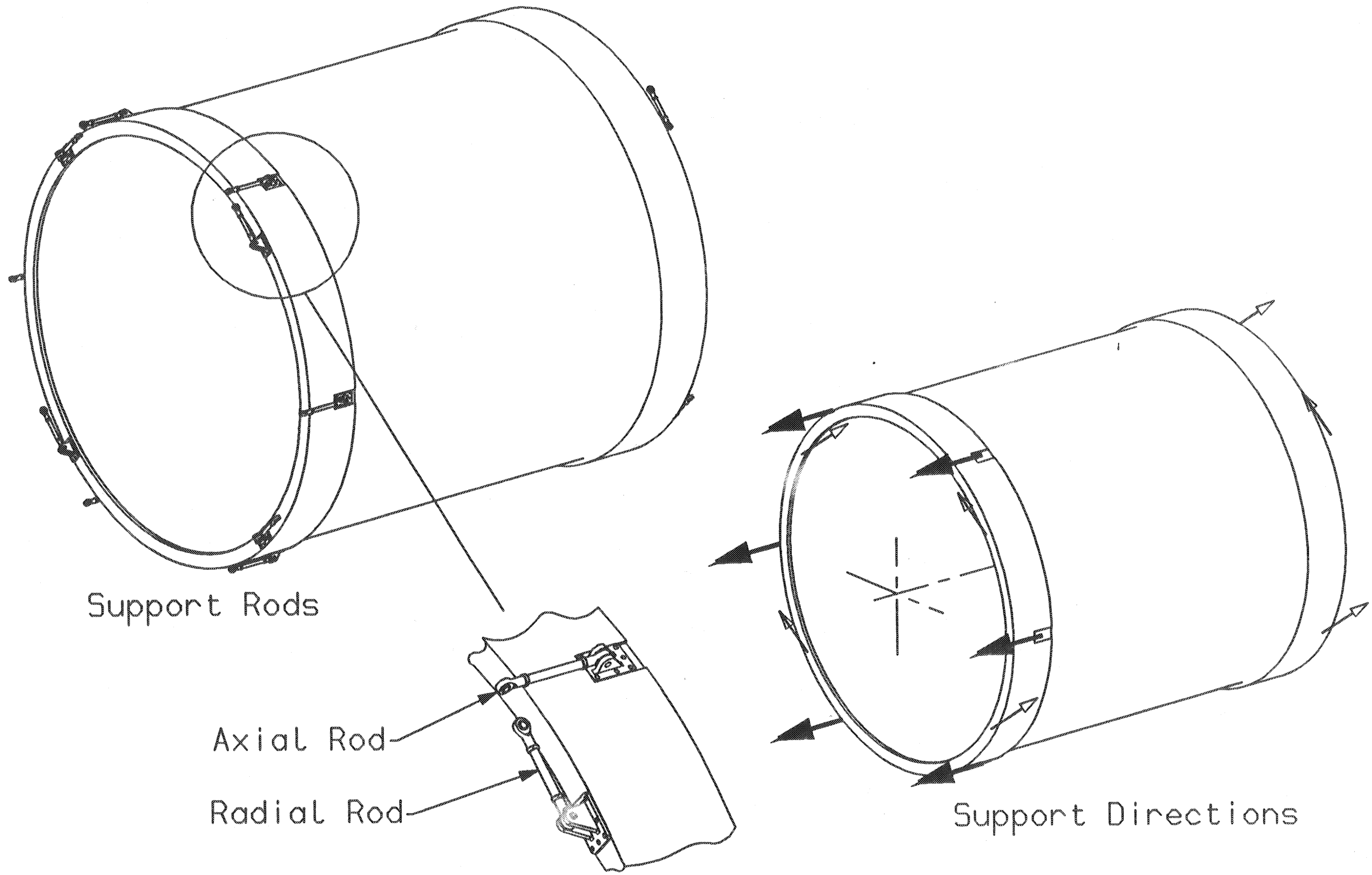


Fig 4.10 Support of the Cold Mass

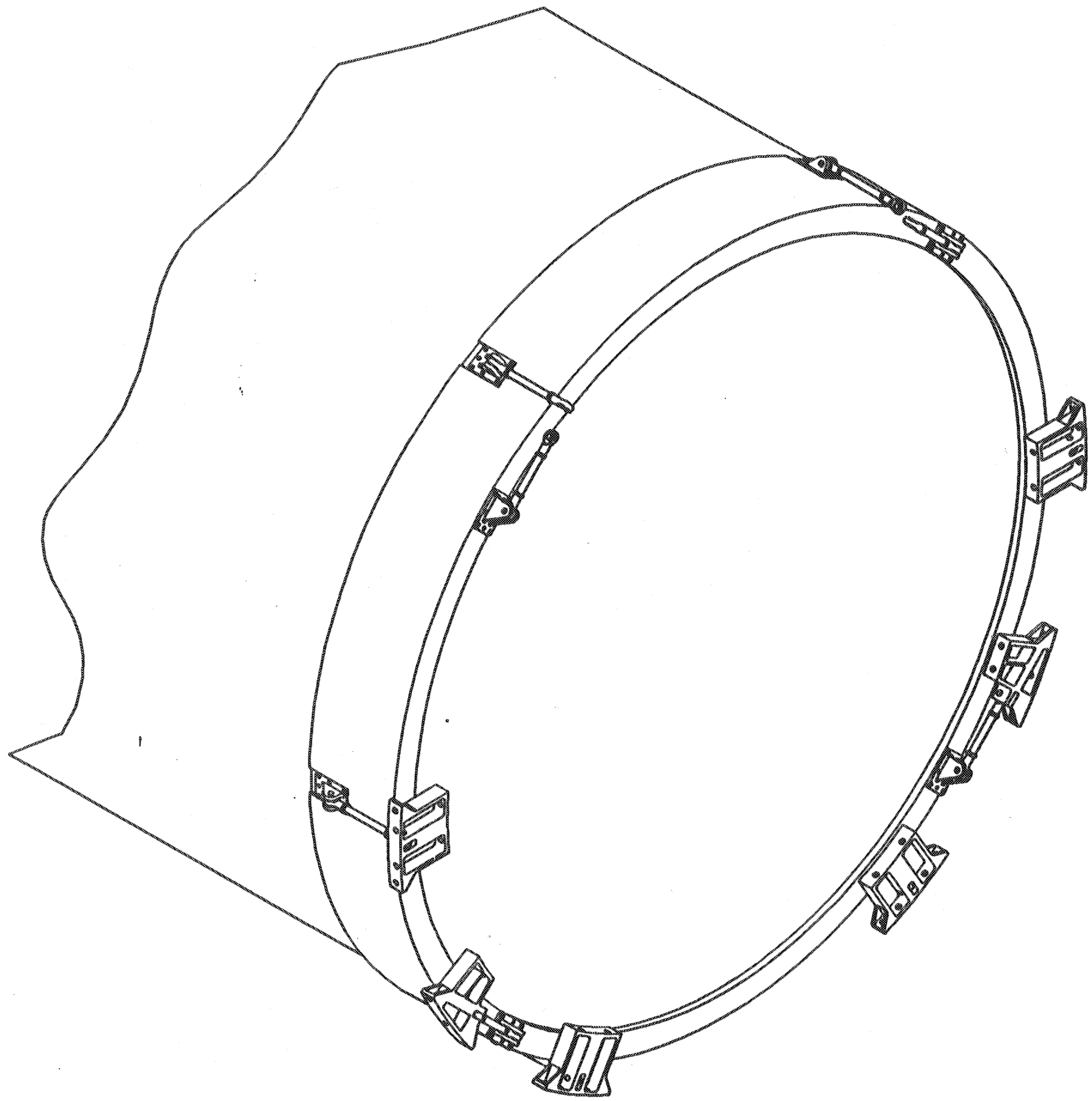


Fig 6.2 Internal Supports (for Cold Mass)

Loads on internal supports

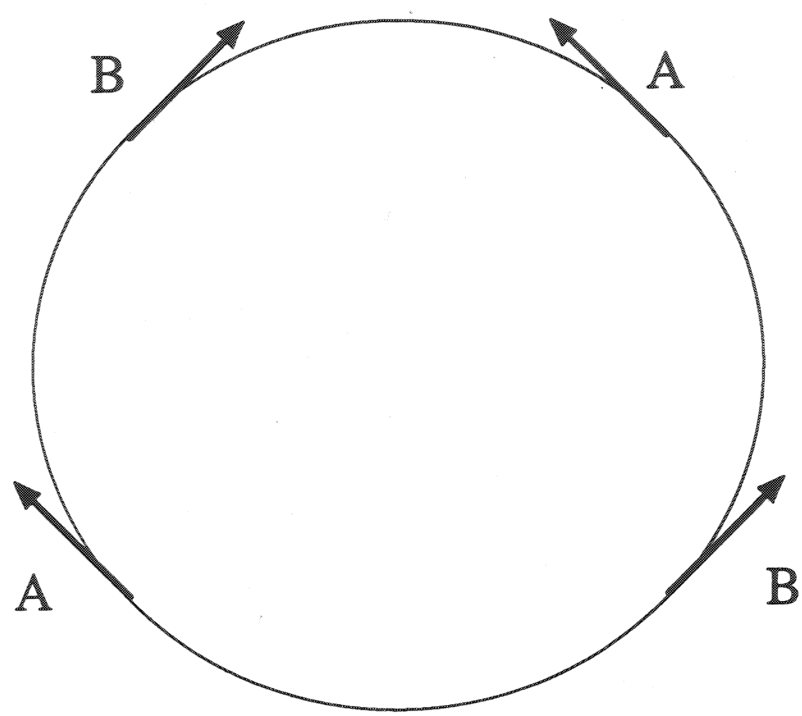
- Can consider axial separately from radial

But, for radial supports:

- Need to consider effects of loads in varying directions in order to check for worst effect on particular supports.

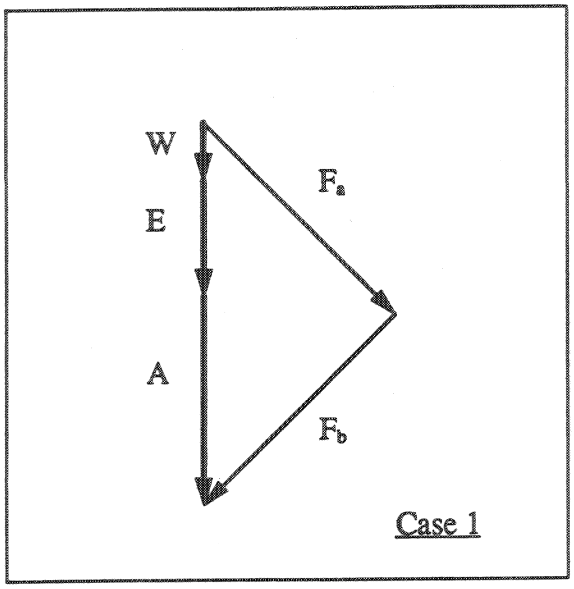
- Vector sum required

Picture showing forces "a" and "b"
Vector sum picture
Cross-section of a rod



Force directions A and B

Figure 6.5. Forces in cold mass "radial" support rods



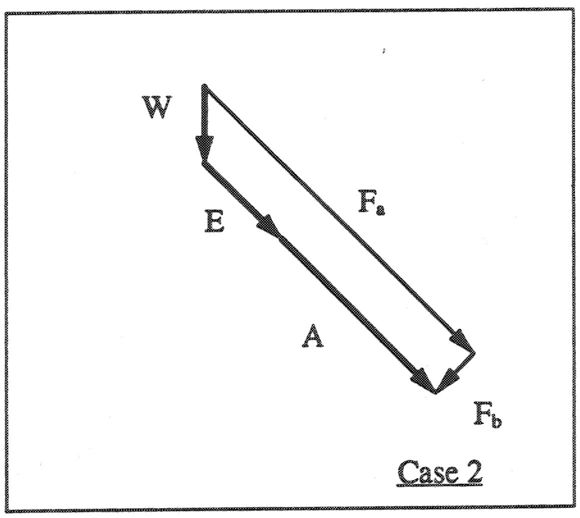
W = weight, 1g gives 5.1t
E = earthquake load, 2g gives 10.2t
A = Magnetic alignment error force, 20t
F_a = load in rods, set a (four rods)
F_b = load in rods, set b (four rods)

Case 1 - largest total load

$F_a = F_b = .707 \times (5.1+10.2+20)$
$= 25t$

Case 2 - largest load in a set of rods

$F_a = 10.2 + 20 + .707 \times 5.1$
$= 33.8t$

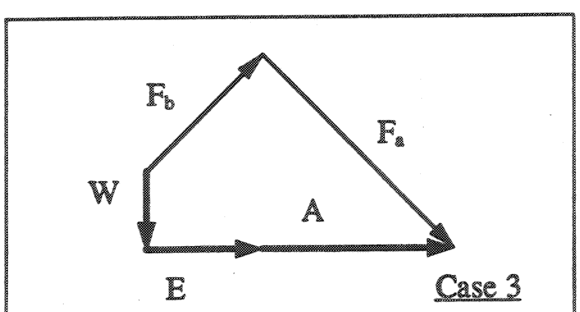


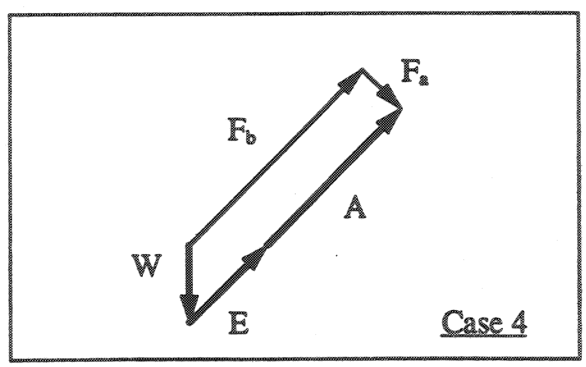
Case 3 - moving forces act sideways

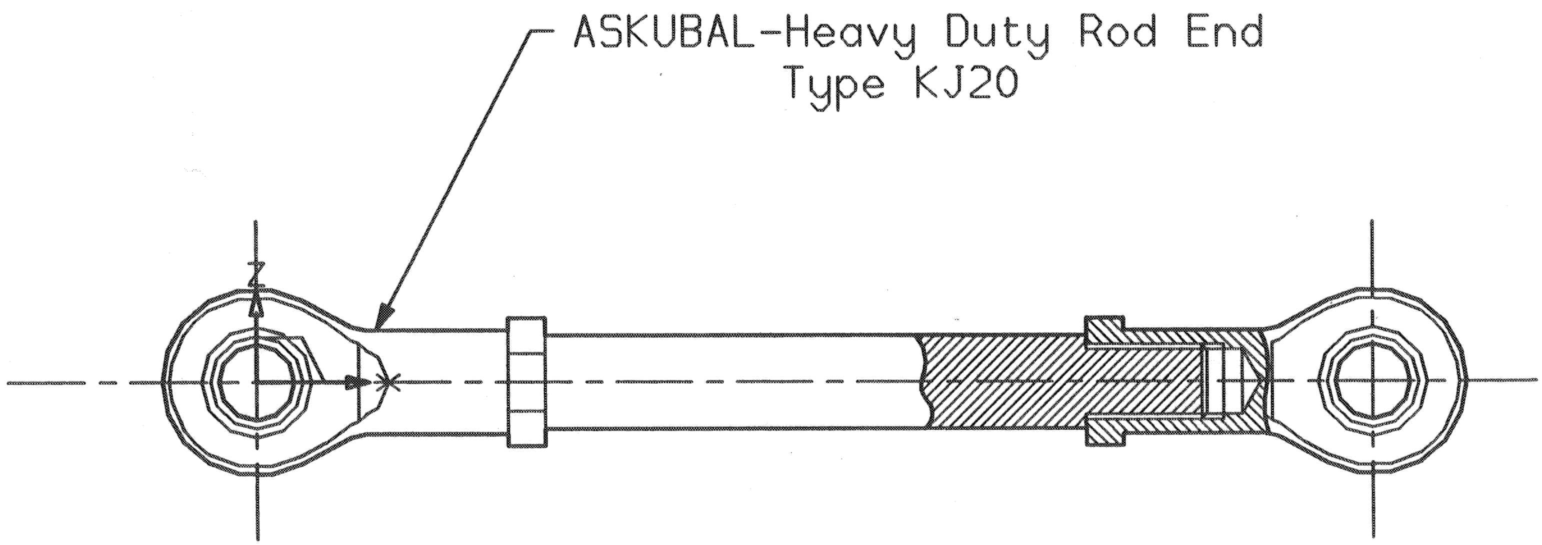
$F_a = .707 \times (5.1+10.2+20) = 25t$
$F_b = .707 \times (5.1 - 10.2 - 20) = -17.7t$
(compressive)

Case 4 - largest compression force
(typical of several possible cases)

$F_b = .707 \times 5.1 - (10.2 + 20) = -26.6t$
(compressive)







Radial Rod

Internal support details

Loads

		Units	Axial	Radial
Nominal load		tonne	30	23.6
Rods to resist nominal load			6	4
Quake load	Tension	tonne	26.1	33.8
	Compression	tonne	-36.1	-26.6
Rods to resist quake load			6	4

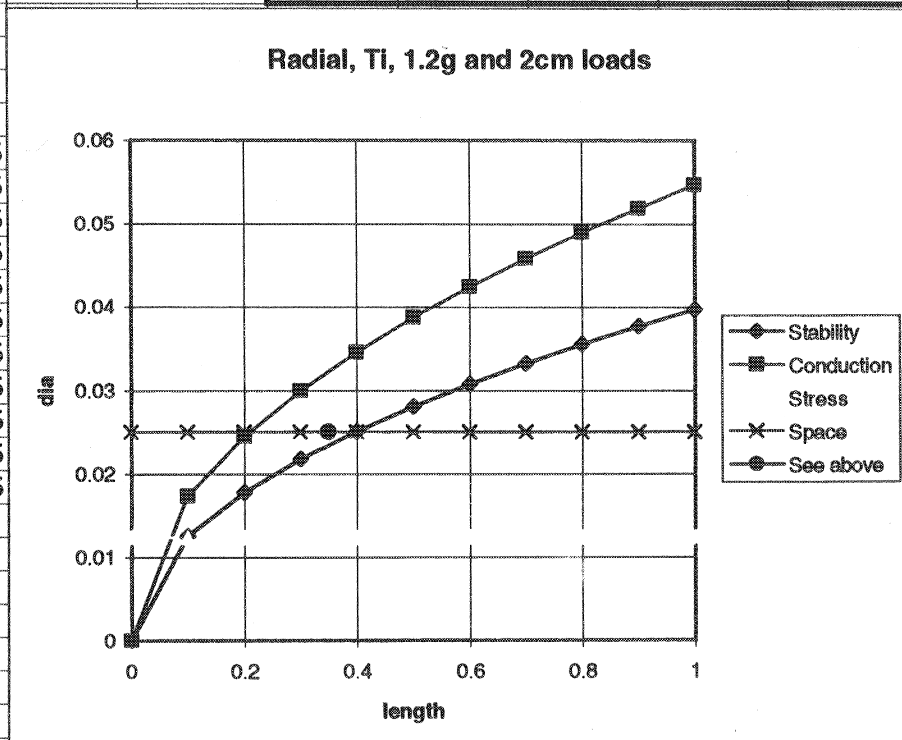
Material

Material	Titanium alloy 6%Al, 4%V	
Ultimate stress	MPa	1000
Yield stress	MPa	900
Conductivity integral 80K to 4K	W/m	213

Rod sizes			
Rod diameter - nominal. This is the diameter of the rod over all of its length except the ends, where it is turned down to M20.	mm	25	25
Rod length	mm	350	300
Rod diameter in thread root	mm	16.9 (M20)	16.9 (M20)
Stress, buckling			
Stress under Earthquake load in thread root			
Tension Compression	MPa	194 268	377 296
Factor of safety on ultimate stress under earthquake load		3.7 (compressive)	2.6 (tensile)
Factor of safety on buckling (using nominal diameter)		2.6	3.2
Thermal conductivity			
Rods in conductivity calculation		6	8
Total heat load over half the length of the rods	Watts	3.6	5.6

Load =	20	tonne		200000	N	Direct stress on 400mm^2				Ti	SS
n (nom) =	6	supports for nominal load				Nominal	83.33333	MPa		100	180
Quake loa	36.1	tonne		361000	N	Quake	150.4167	MPa		900	180
n (quake)	6	supports for quake load				Nominal (sy/2) d min		0.009712	m	1000	480
Quake P =	6.016667	tonne/support for stability		60166.67	N	Quake (Sult/2)d min		0.012378	m	213	300
n (cond)	6	rods for conductivity									
Material	Ti					Stress criterion =		Quake			
E =	100	GPa		1E+11	Pa	d min =		0.012378			
sy =	900	MPa		9E+08	Pa	For l =	0.35	m			
sult =	1000	MPa		1E+09	Pa	d =	0.025	m			
K int =	213	W/m				stress =	123	MPa	Fof S	8.158568	
Q max =	6	W				Q =	0.60	W per rod over half length			
Q per rod	1	W				Stability =	2.57		Q tot	3.584782	
Stability factor of safety =			2								

l	Stability	Conductio	Stress	Space
0.1	d min	d max	d min	dmax
0	0	0	0.012378	0.025
0.1	0.012554	0.017288	0.012378	0.025
0.2	0.017754	0.024449	0.012378	0.025
0.3	0.021744	0.029944	0.012378	0.025
0.4	0.025108	0.034576	0.012378	0.025
0.5	0.028071	0.038658	0.012378	0.025
0.6	0.030751	0.042347	0.012378	0.025
0.7	0.033215	0.04574	0.012378	0.025
0.8	0.035508	0.048898	0.012378	0.025
0.9	0.037662	0.051865	0.012378	0.025
1	0.039699	0.05467	0.012378	0.025
0.35				



External supports

- Main supports

  Take Vertical and sideways loads

  Inner detectors supported separately from vac vessel

- Subsidiary supports

  Take axial loads

  Work through vessel

Picture - "My"figure
Fig 6.6
Fig 6.7

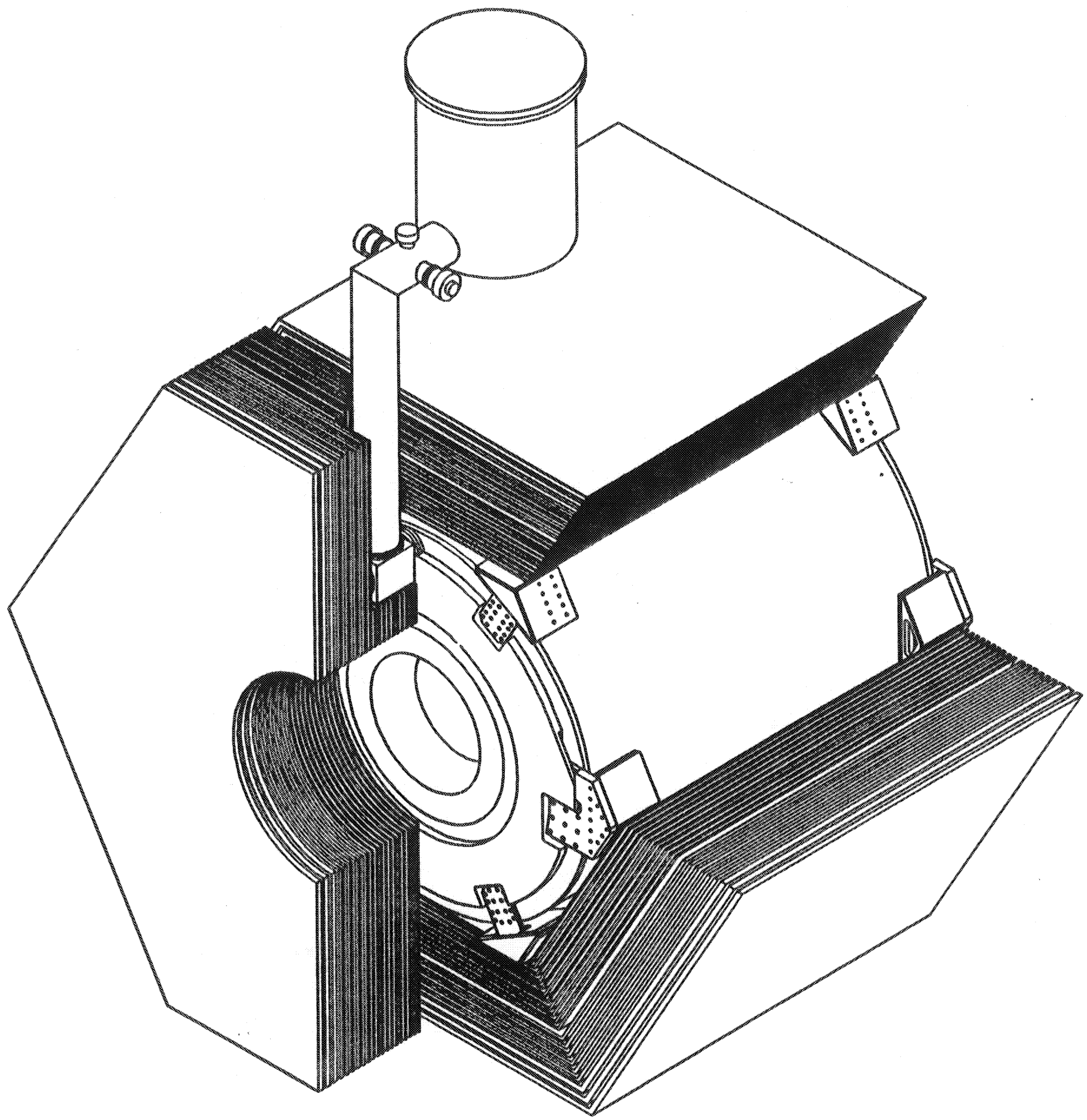


Fig 6.3 External Supports- Outline

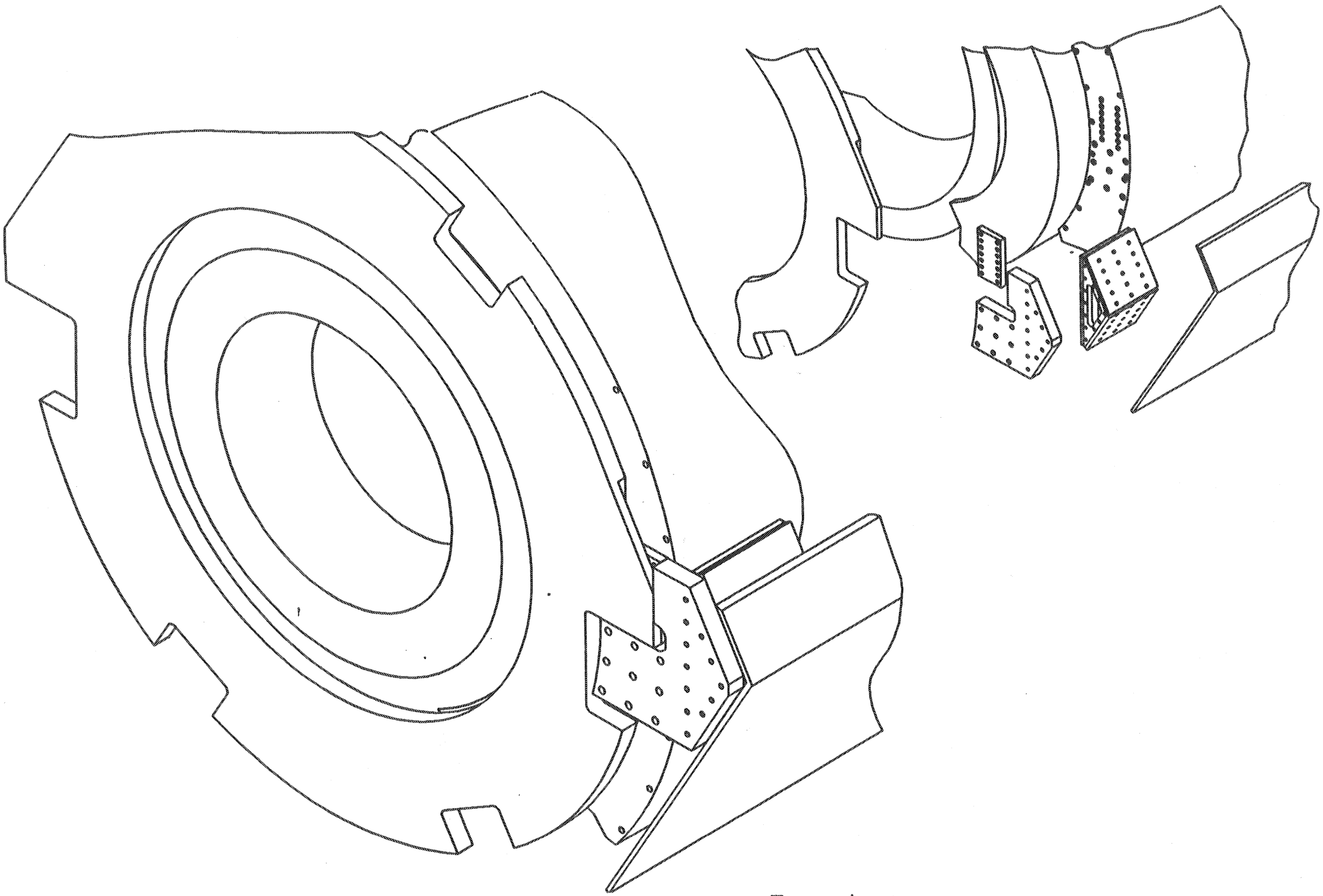


Fig 6.6 Main Support Brackets

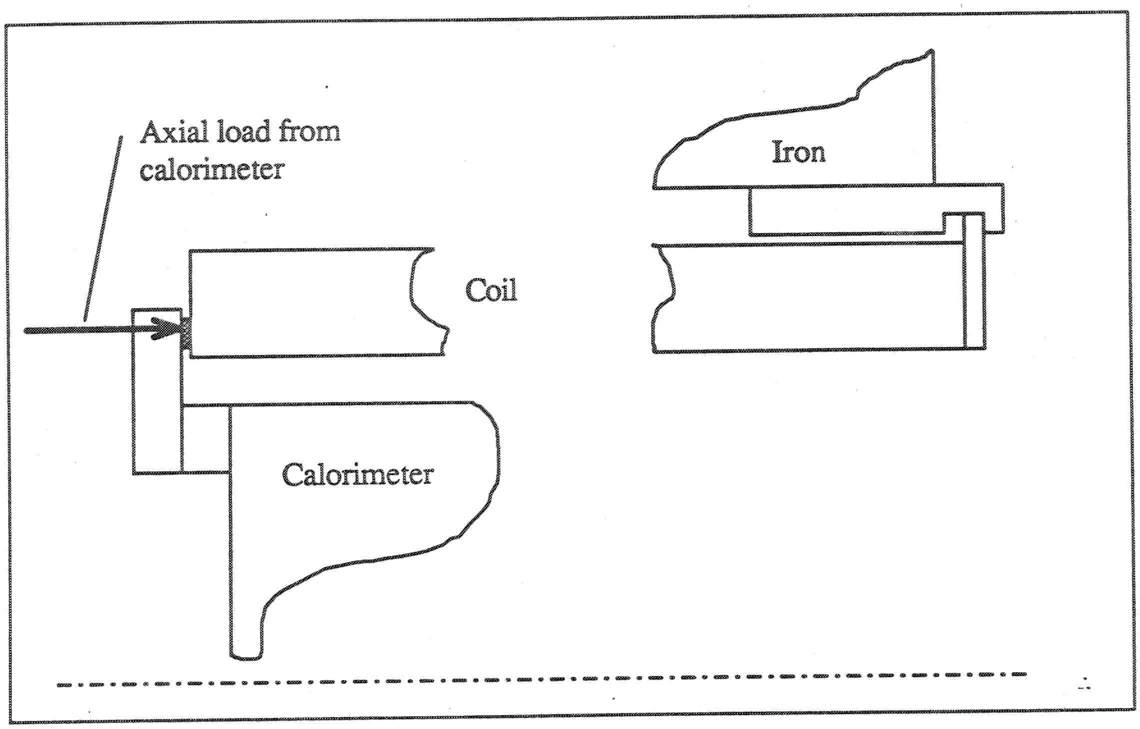
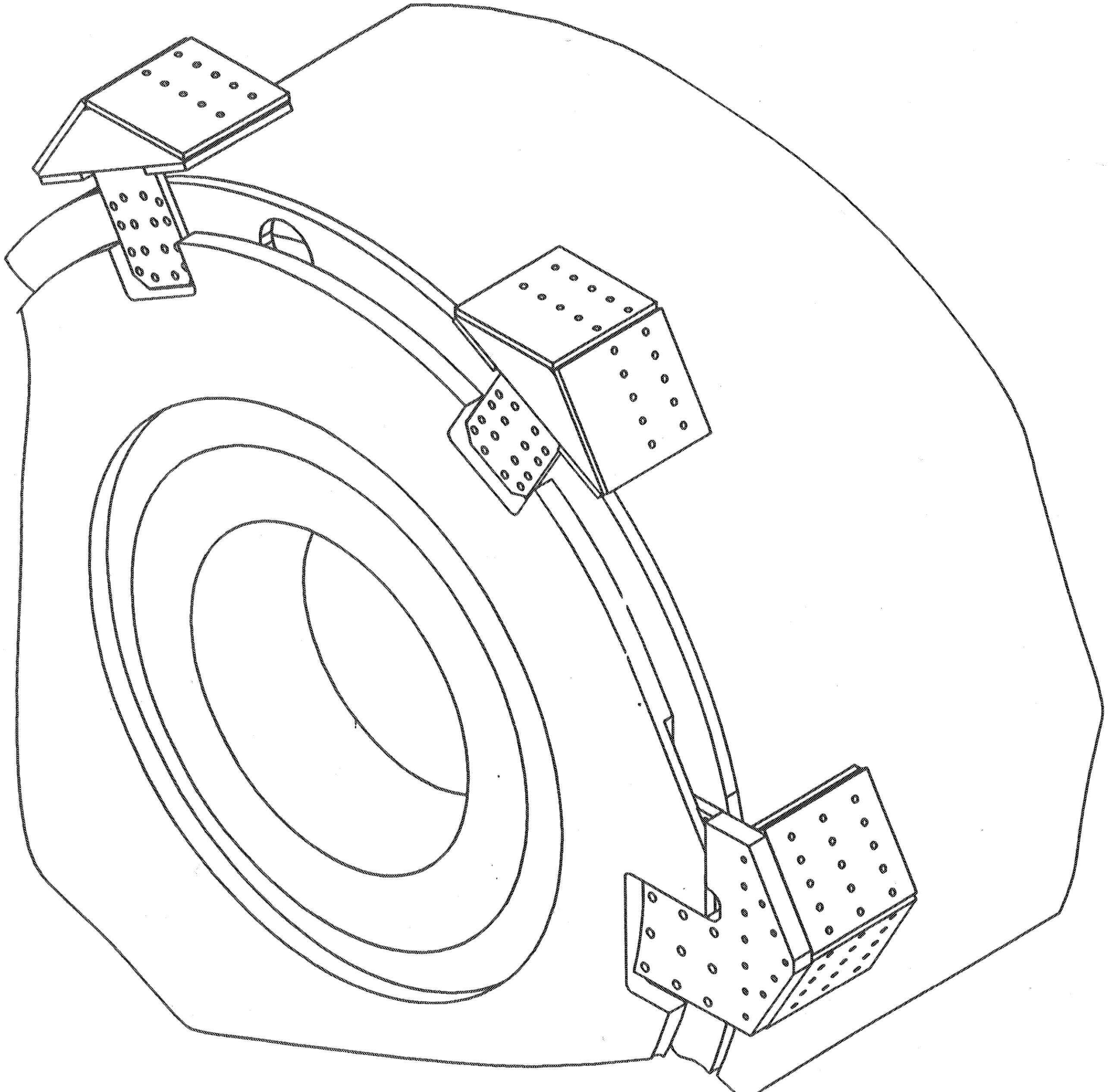
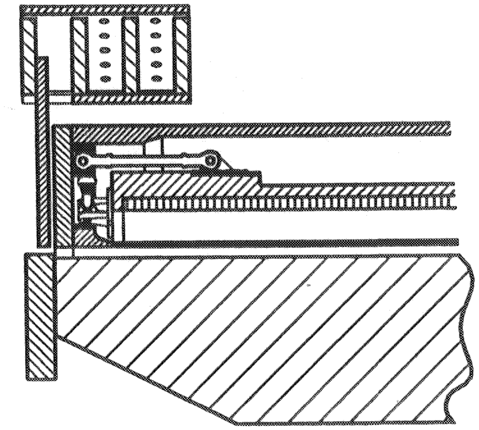


Figure 5.3 Outline scheme for axial support of inner detectors





Typ Cross Section

Fig 6.7 Suubsidiary Support Brackets

P. Fabbricatore

Cold mass - stresses with gravity etc.

- Continuation of the work on stresses due to internal magnetic forces alone.
- Considers internal magnetic forces (radial, axial) as well as other forces:
  - Gravity
  - Earthquake
  - Magnetic net forces - offset geometry (10t), alignment (20t)

The FE model

FE plot

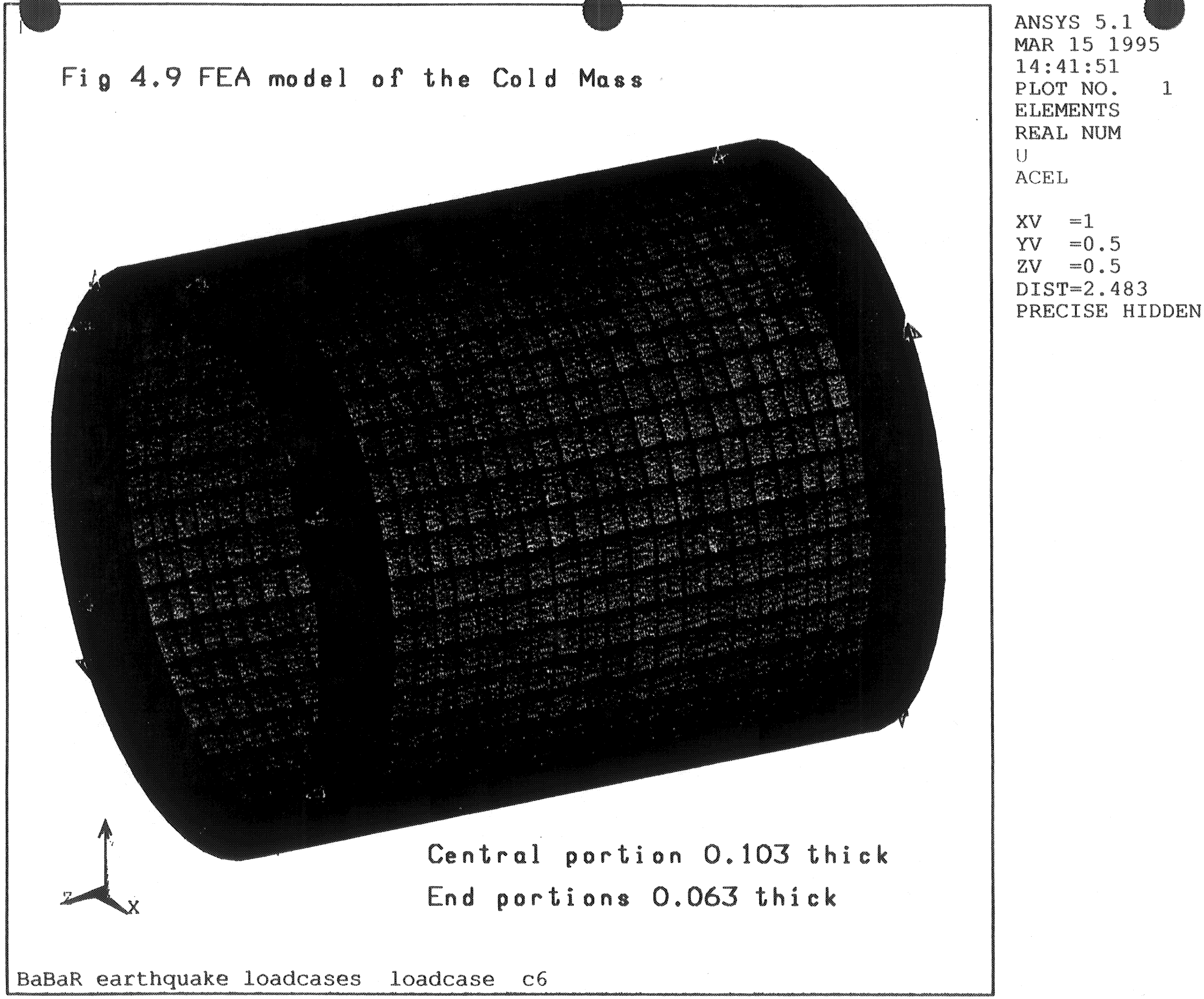


Fig 4.9 FEA model of the Cold Mass

Constraints

Supports		
Type	Location and number	degrees of freedom
Axial	6, evenly distributed around one end of the coil, with two on the horizontal centre plane	"Z"
Radial	4 each end, at +/1 45 degrees from the horizontal centre plane	tangential movement = 0

Loadcases considered

All load cases included magnetic pressure, gravity		
Case	Description	Additional loads
1	Worst case axial loads with earthquake	30t plus 1.2g, axial
2	Worst case sideways loads with earthquake	20t plus 1.2g, sideways
3	Worst case vertical loads with earthquake	20t plus 2g, vertical
4		vertical 20t
5	Worst case of earthquake and magnetic force direction - puts most load onto only two supports each end	2g vertical plus 20t at 45°
In addition to the axial offset magnetic load, there are large forces acting on the conductors which are reacted within the cold mass structure. In order to assess the effects of these, we tried one load case with those forces included:		
6	Nominal load, but with axial magnetic forces included.	vertical 20t, axial 10t

Results

Typical result - case c5 stress, deflection

Case	Description	Additional loads	Max. deflection (mm)	Max. stress (MPa)
1	Worst case axial loads with earthquake	30t plus 1.2g, axial	0.86	38.7
2	Worst case sideways loads with earthquake	20t plus 1.2g, sideways	1.04	39.6
3	Worst case vertical loads with earthquake	20t plus 2g, vertical	1.13	39.9
4		vertical 20t	1.02	39.5
5	Worst case of earthquake and magnetic force direction - puts most load onto only two supports each end	2g vertical plus 20t at 45°	1.13	39.9
6	Nominal load, but with axial magnetic forces included.	vertical 20t, axial 10t	1.19	47.5

Results of case c6

Results

Typical result - case 5 stress, deflection

Case	Description	Additional loads	Max. deflection (mm)	Max. stress (MPa)
1	Worst case axial loads with earthquake	30t plus 1.2g, axial	0.86	38.7
2	Worst case sideways loads with earthquake	20t plus 1.2g, sideways	1.04	39.6
3	Worst case vertical loads with earthquake	20t plus 2g, vertical	1.13	39.9
4		vertical 20t	1.02	39.5
5	Worst case of earthquake and magnetic force direction - puts most load onto only two supports each end	2g vertical plus 20t at 45°	1.13	39.9
6	Nominal load, but with axial magnetic forces included.	vertical 20t, axial 10t	1.19	47.5

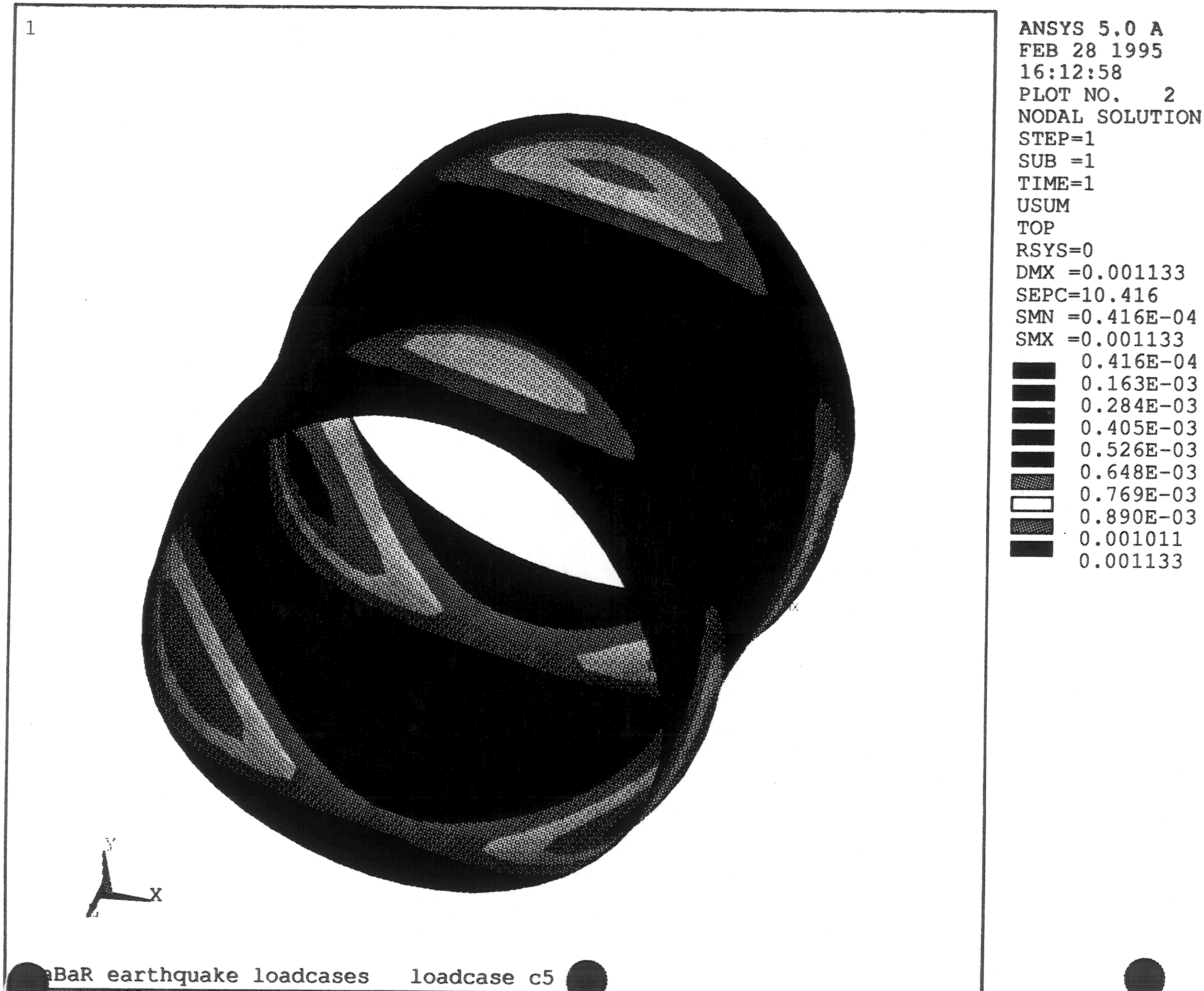
Results of case 6

Results

Typical result - case 5 stress, deflection

Case	Description	Additional loads	Max. deflection (mm)	Max. stress (MPa)
1	Worst case axial loads with earthquake	30t plus 1.2g, axial	0.86	38.7
2	Worst case sideways loads with earthquake	20t plus 1.2g, sideways	1.04	39.6
3	Worst case vertical loads with earthquake	20t plus 2g, vertical	1.13	39.9
4		vertical 20t	1.02	39.5
5	Worst case of earthquake and magnetic force direction - puts most load onto only two supports each end	2g vertical plus 20t at 45°	1.13	39.9
6	Nominal load, but with axial magnetic forces included.	vertical 20t, axial 10t	1.19	47.5

Results of case 6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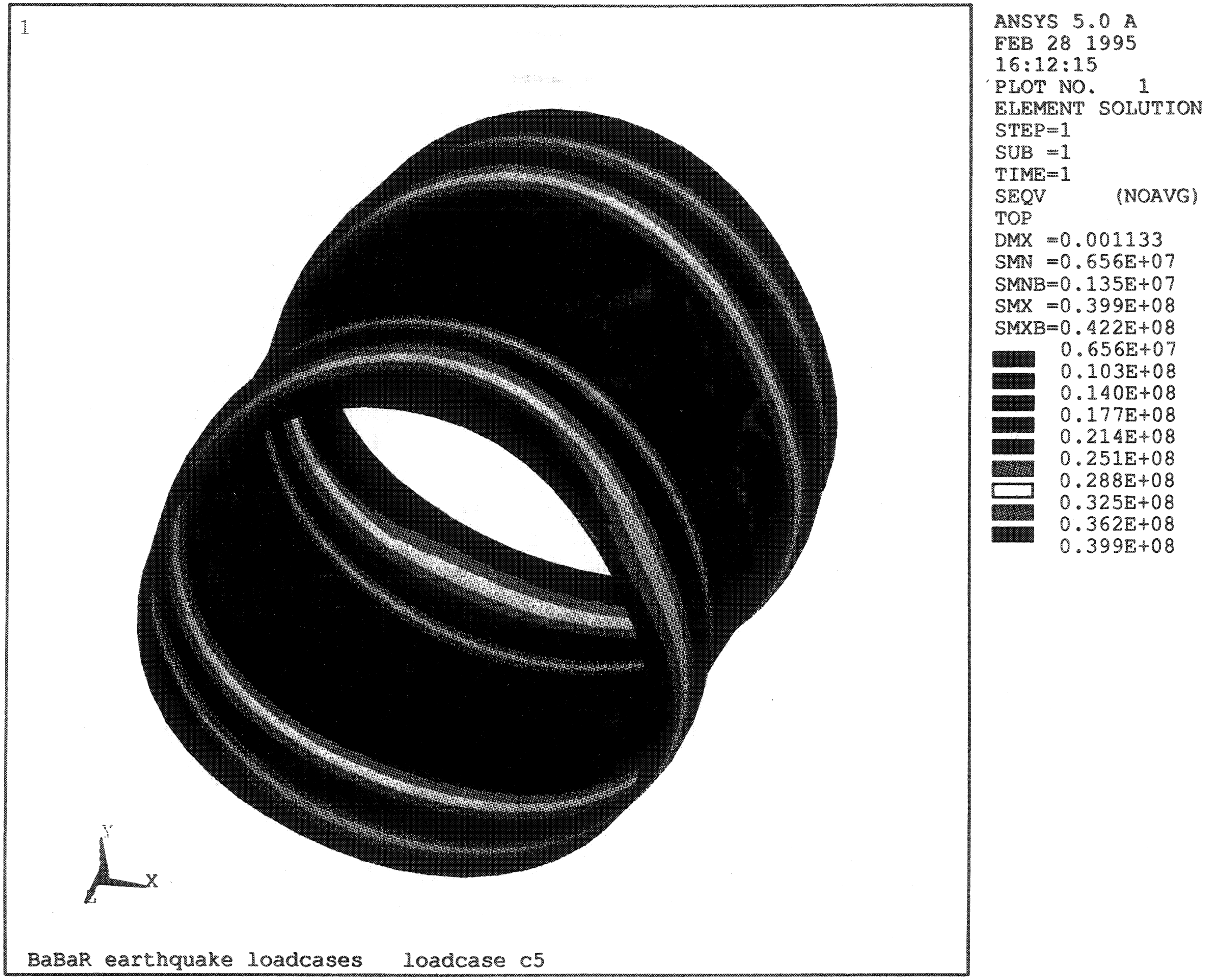
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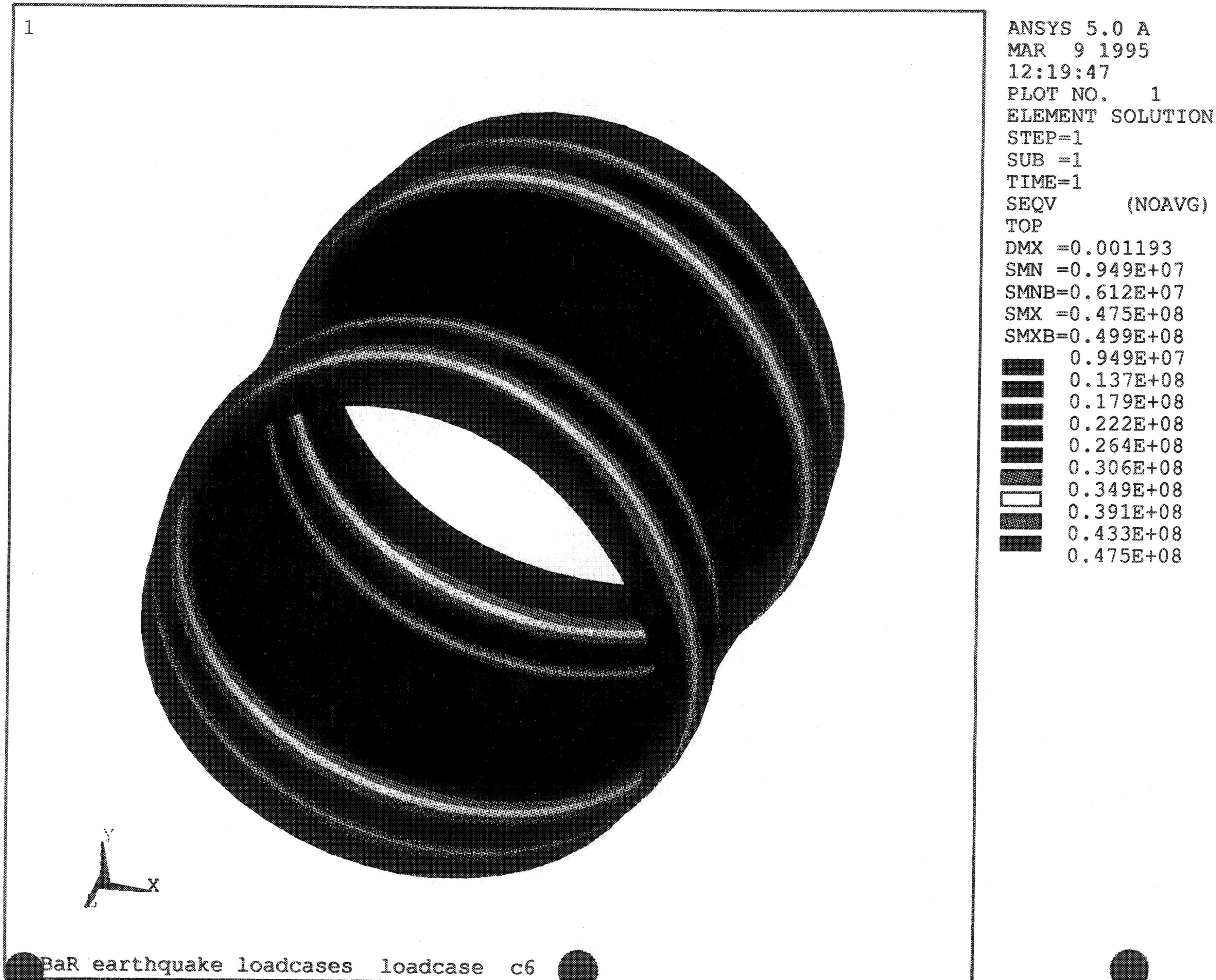
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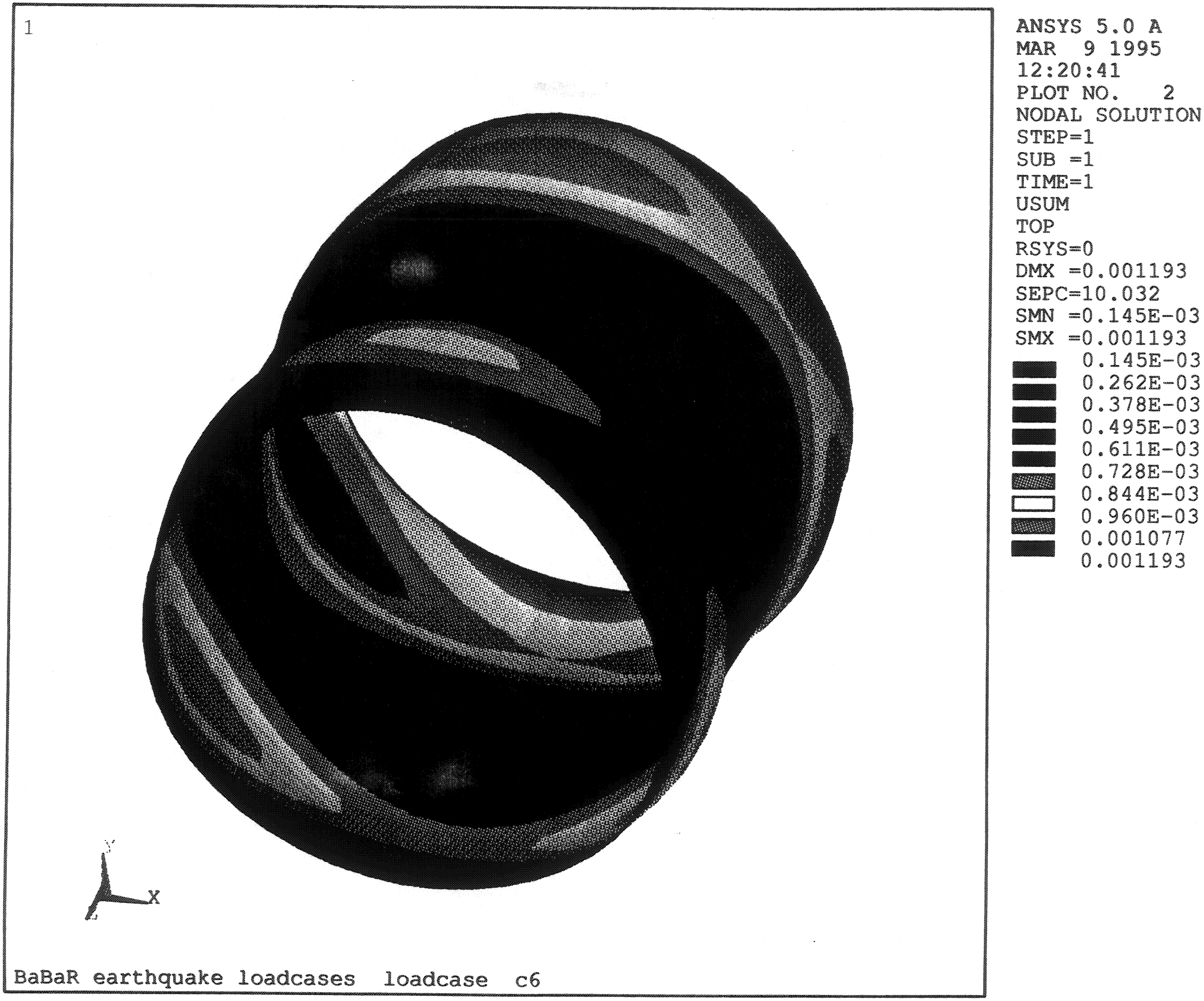
BaR earthquake loadcases loadcase c6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X
BaBaR earthquake loadcases loadcase c6

Cryostat vessel

- Construction
- FE mesh
- Loads
- Results

Construction

- Cryostat = Rad shields + vacuum vessel

Fig 5.1 - cryostat

- Radiation shields: simple construction

Fig 5.5 - rad shield

- Vac vessel:
  - Inner vessel, 10mm thick
  - Outer vessel, 30mm thick thickened to 50mm thick for 200mm each end
  - End flanges, 50mm thick
  - Spacer brackets at the ends, act as fixing points for the inner supports.

Fig 5.2 - the vacuum vessel

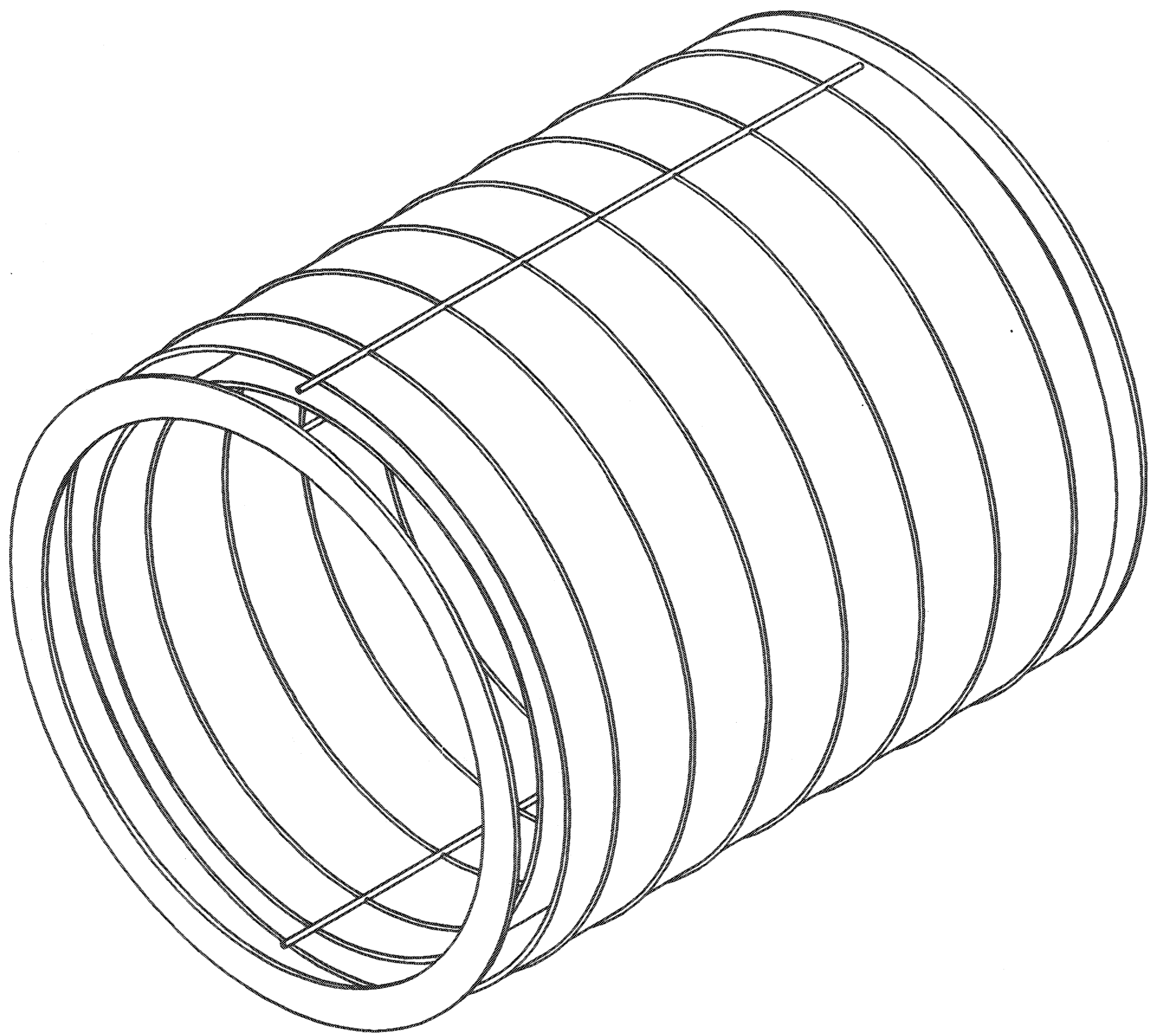


Fig 5.5Radiation Shield Schematic

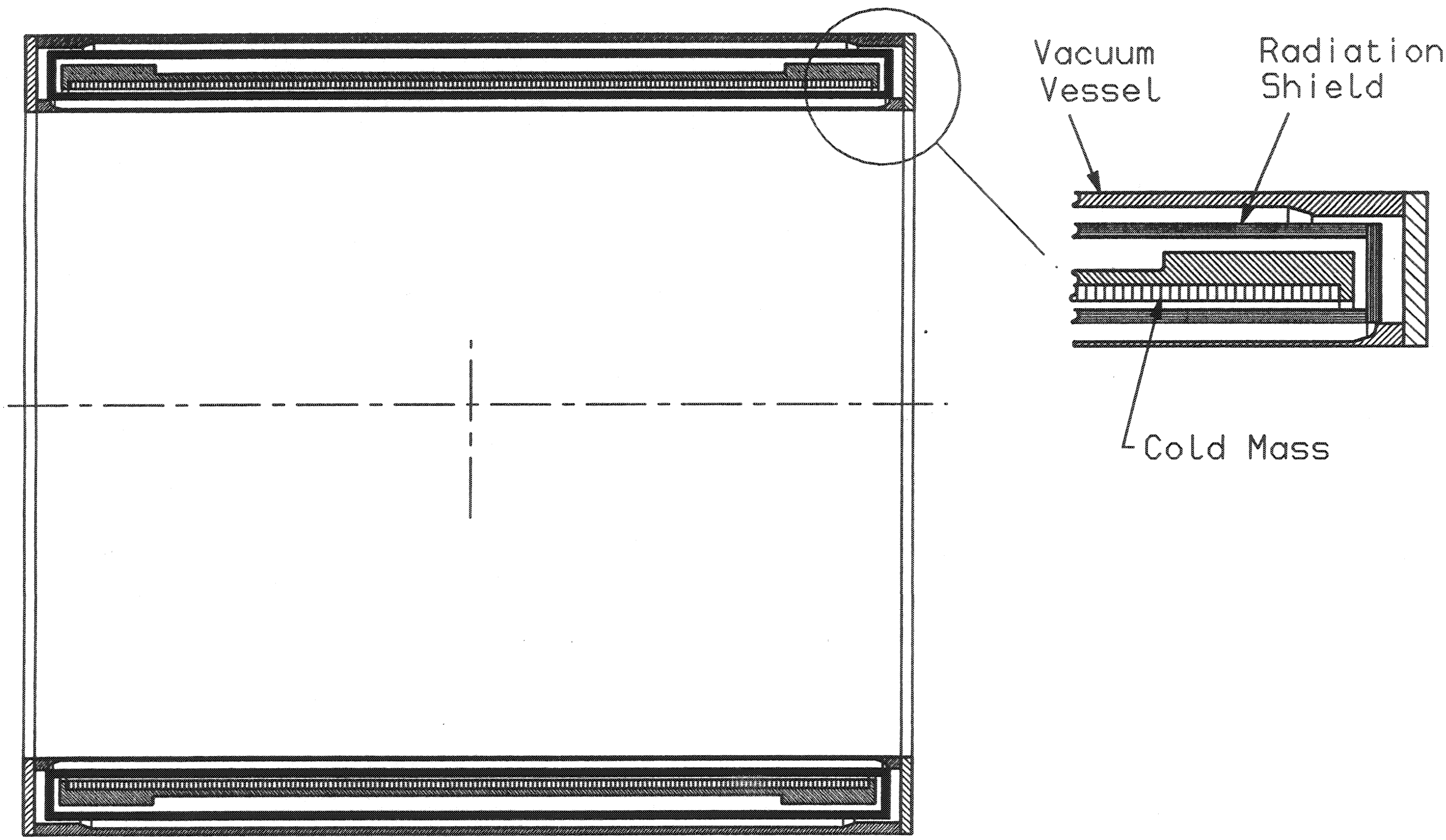


Fig 5.1 The Cryostat

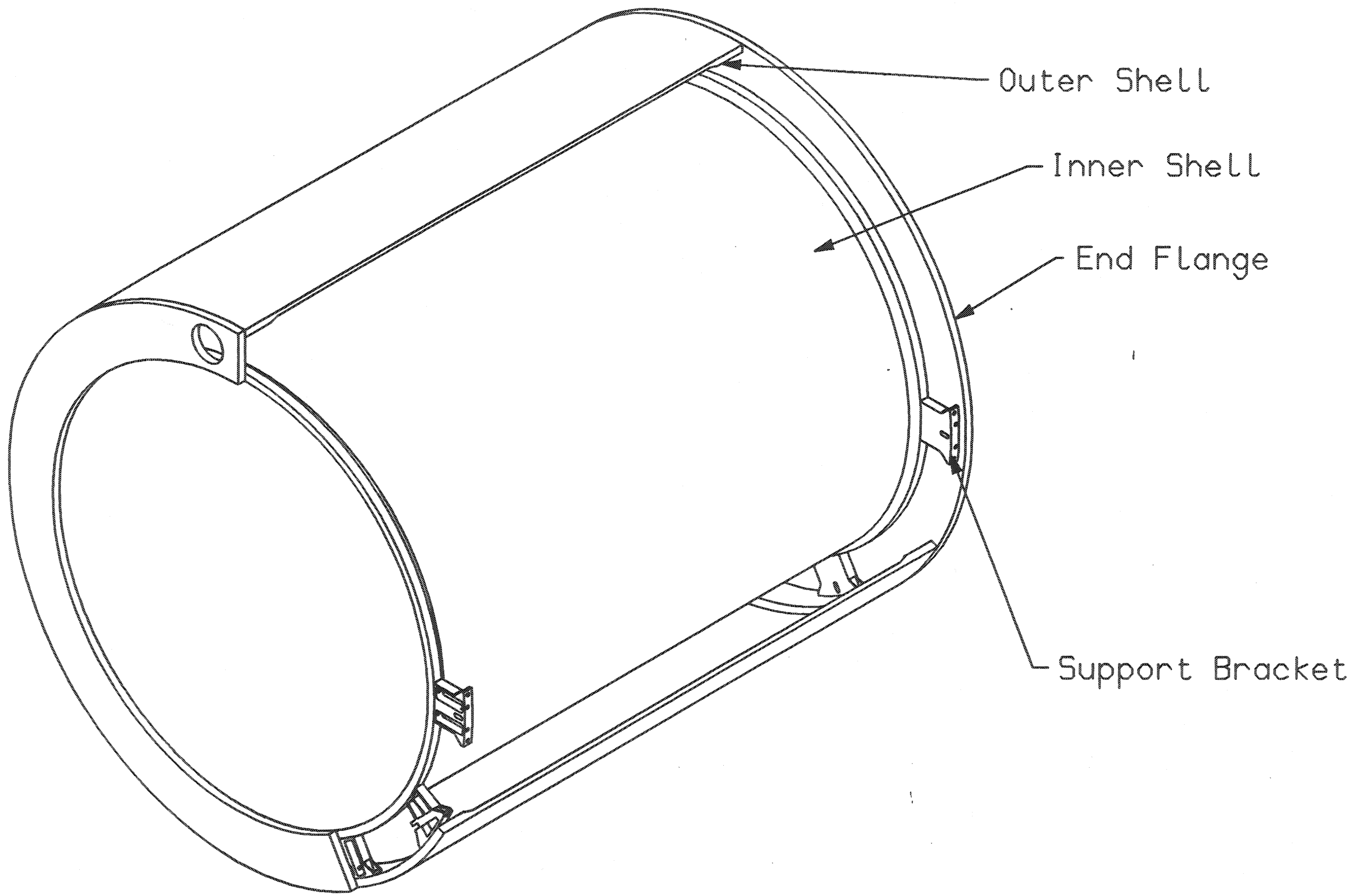


Fig 5.2 The Vacuum Vessel

Finite Element analysis

FE plot

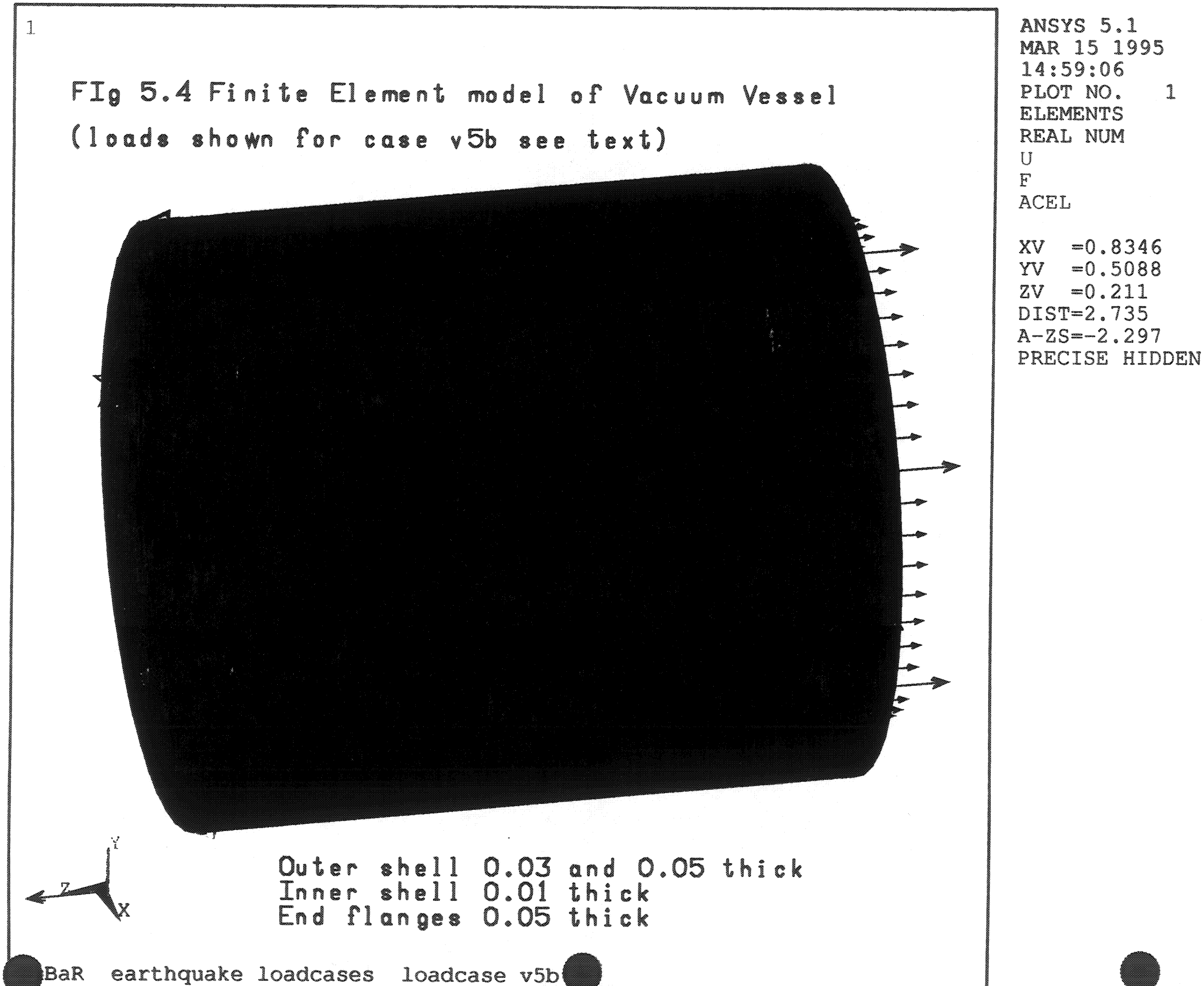


FIg 5.4 Finite Element model of Vacuum Vessel
(loads shown for case v5b see text)

Constraints

Supports - axial	Four at one end, at ±30° to the vertical	"Z" - axial. See note below.
Supports - radial	One each end, at one side, on the horizontal centreline	"X" - sideways. See note below.
Supports - vertical	Two each end, on the horizontal centreline	"Y" - vertical

Loads

All load cases included 1g downwards and vacuum loads.		
Case	Description	Additional loads
1	Nominal	None
2	Earthquake - vertical	2g downwards
3a	Earthquake - sideways	1.2g +X direction
3b	Ditto - opposite direction	1.2g -X direction
4a	Earthquake - Axial Middle support	1.2g axial plus 60t load from detectors at middle radius of end flange
4b	Earthquake - Axial Inner support	1.2g axial plus 60t load from detectors at inner radius of end flange

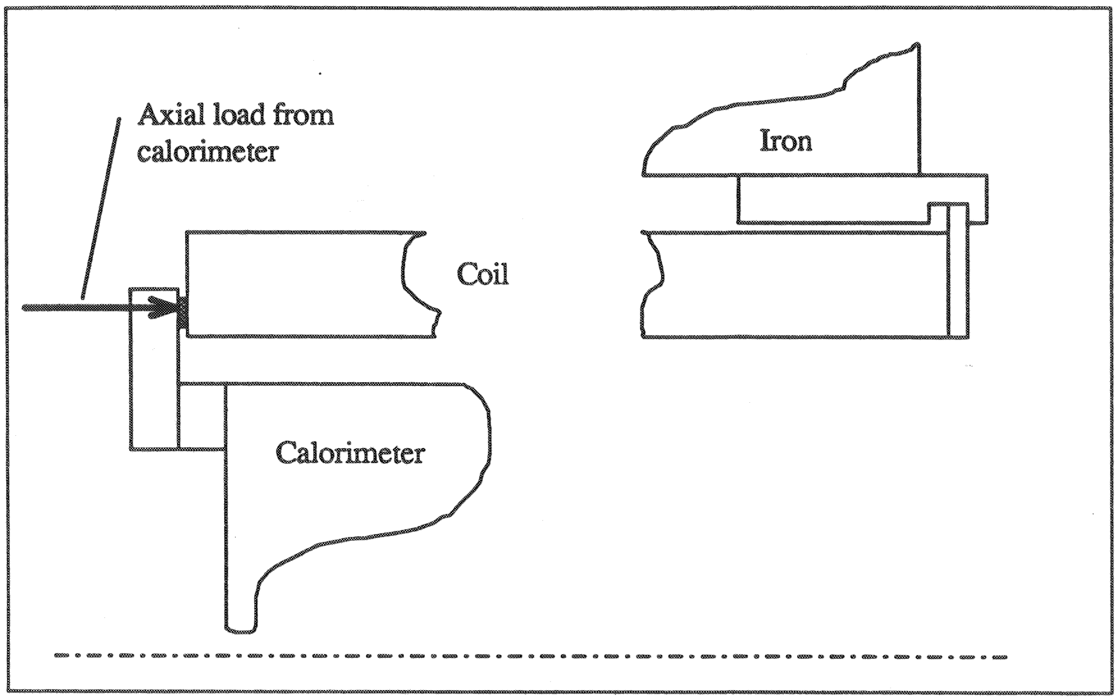


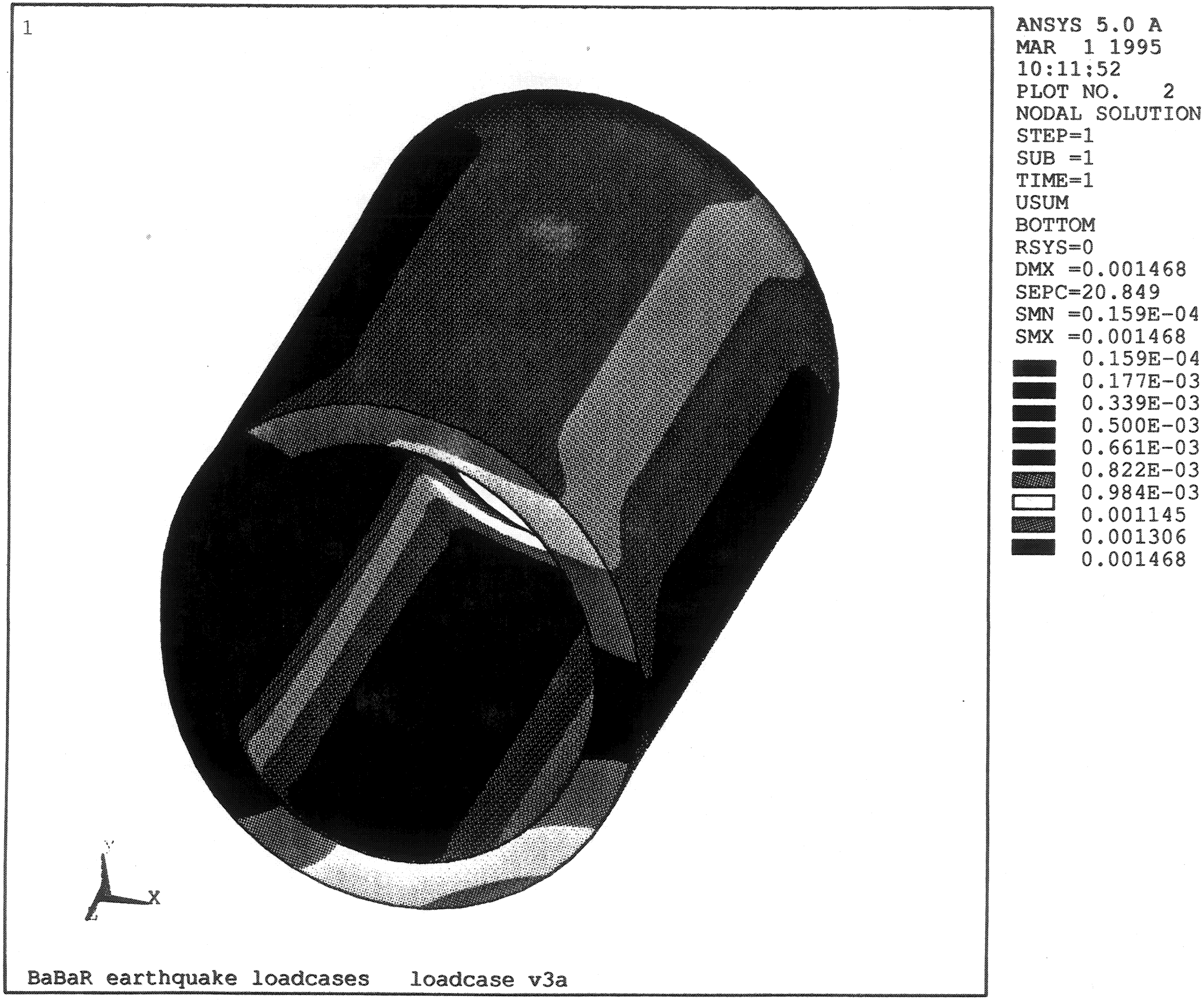
Figure 5.3 Outline scheme for axial support of inner detectors

Results

FE plots case v3a, v3b, v4b

All load cases included 1g downwards and vacuum loads.

Case	Description	Additional loads	Max. defl	Max. general stress	Max. local stress
1	Nominal	None	0.4	16	23.9
2	Earthquake - vertical	2g downwards	0.5	18	32.2
3a	Earthquake - sideways	1.2g +X direction	1.47	23	40.6
3b	Ditto - opposite direction	1.2g -X direction	1.72	20	58.6
4a	Earthquake - Axial, Middle support	1.2g axial plus 60t load from detectors at middle radius of end flange	1.05	16	46.1
4b	Earthquake - Axial, Inner support	1.2g axial plus 60t load from detectors at inner radius of end flange	1.43	25	42.1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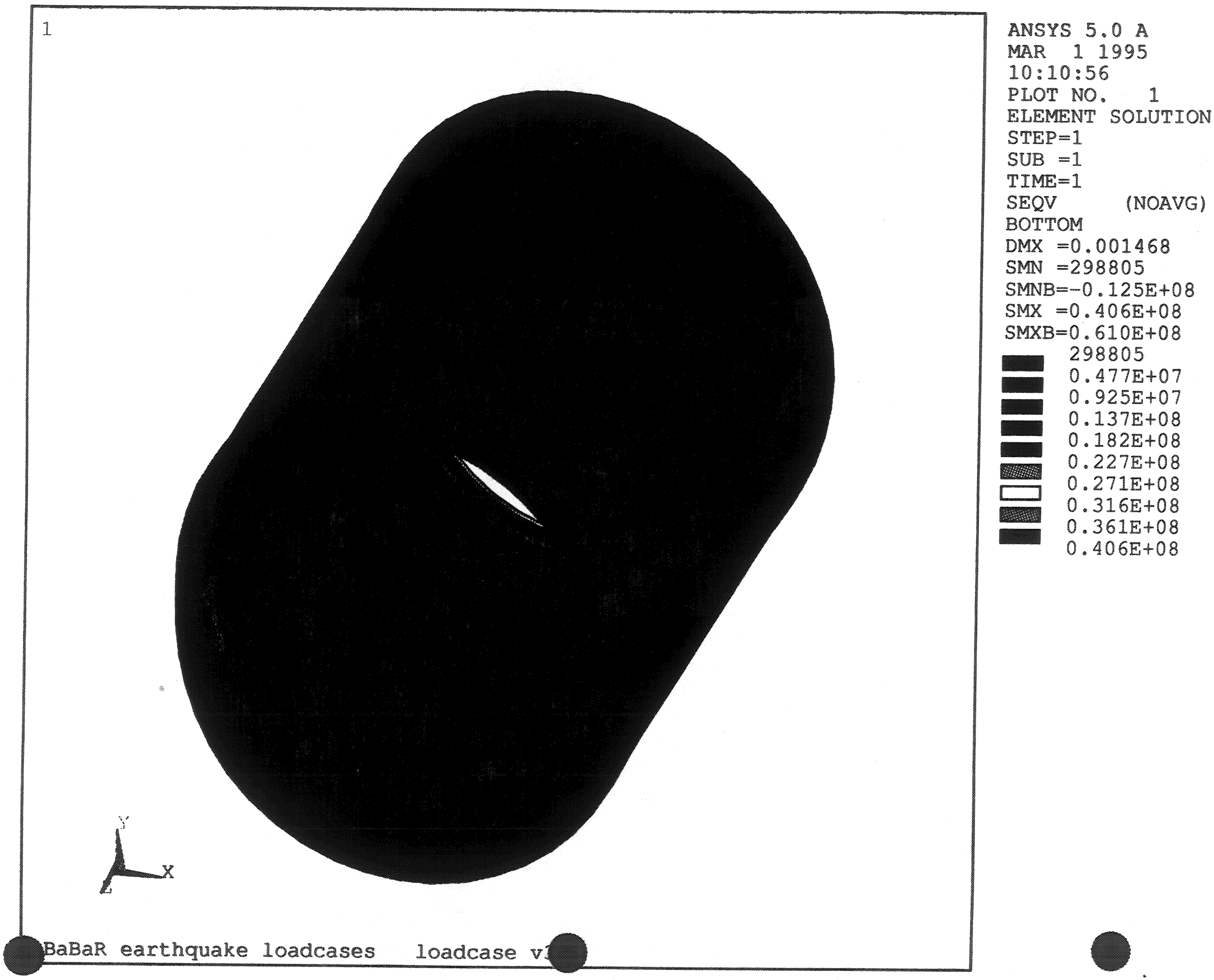
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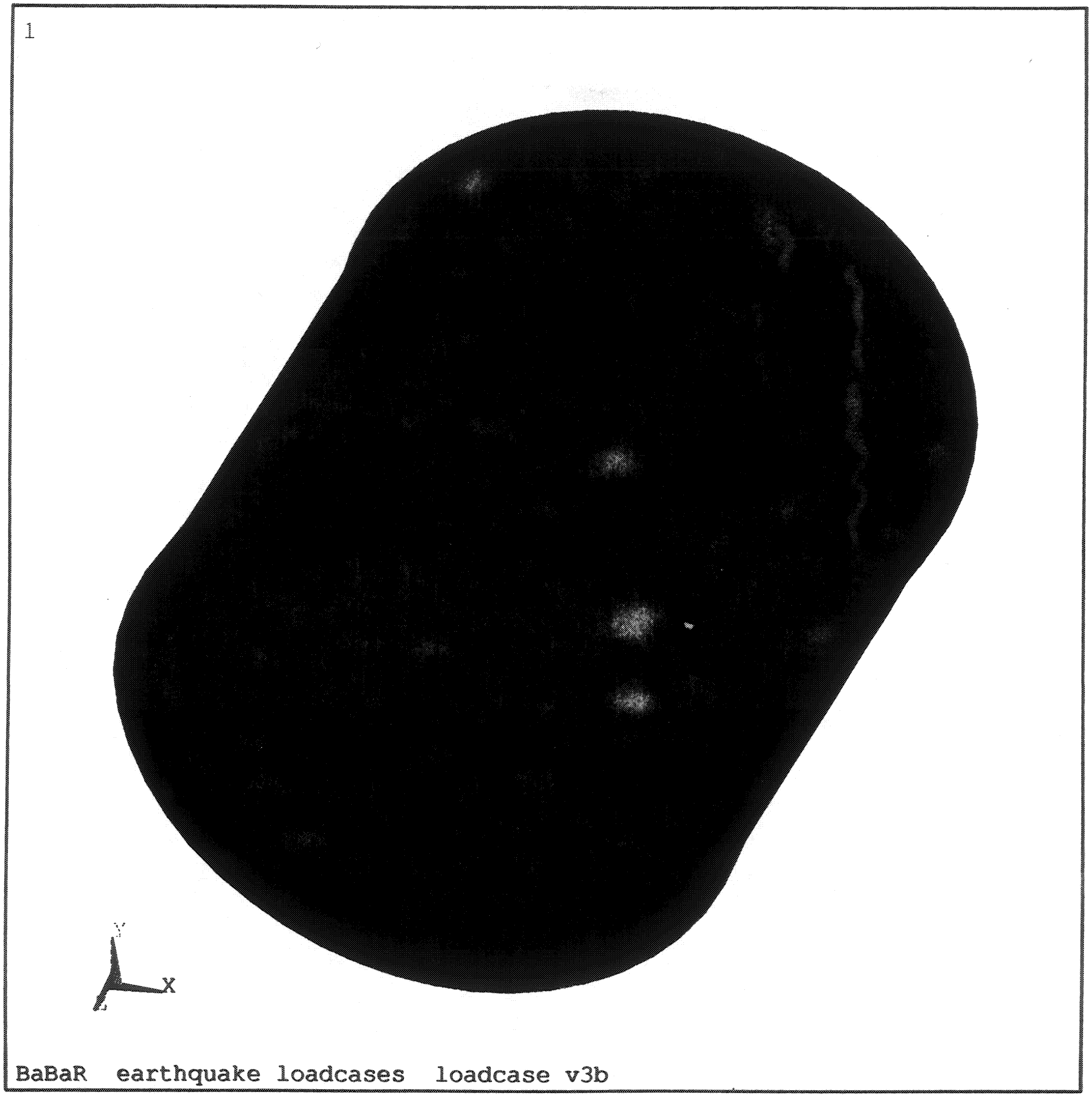
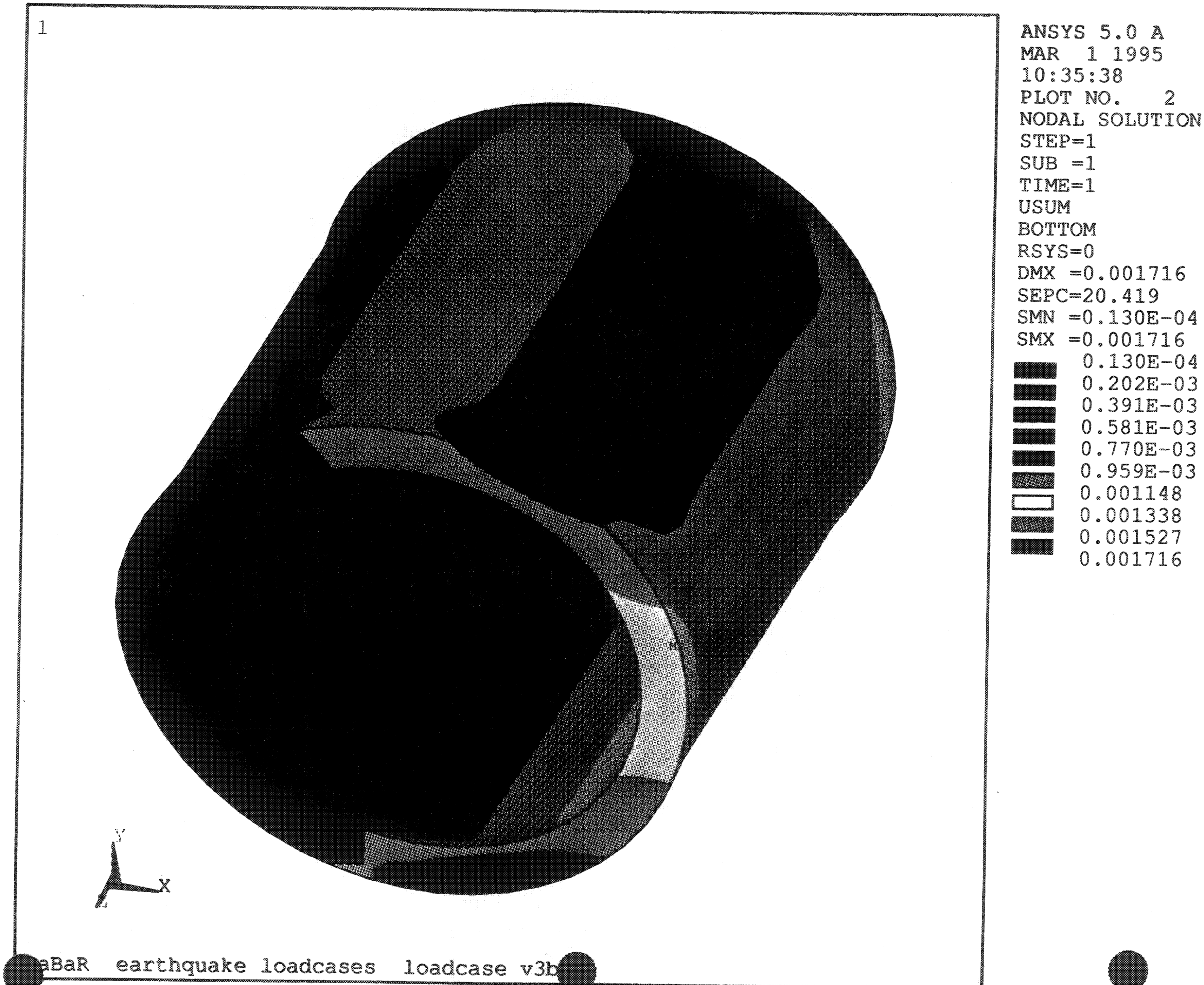
0.477E+07
0.925E+07
0.137E+08
0.182E+08
0.227E+08
0.271E+08
0.316E+08
0.361E+08
0.406E+08
Y
X
BaBaR earthquake loadcases loadcase v



BaBaR earthquake loadcases loadcase v3b


1
Y
X
ANSYS 5.0 A
MAR 1 1995
10:35:38
PLOT NO. 2
NODAL SOLUTION
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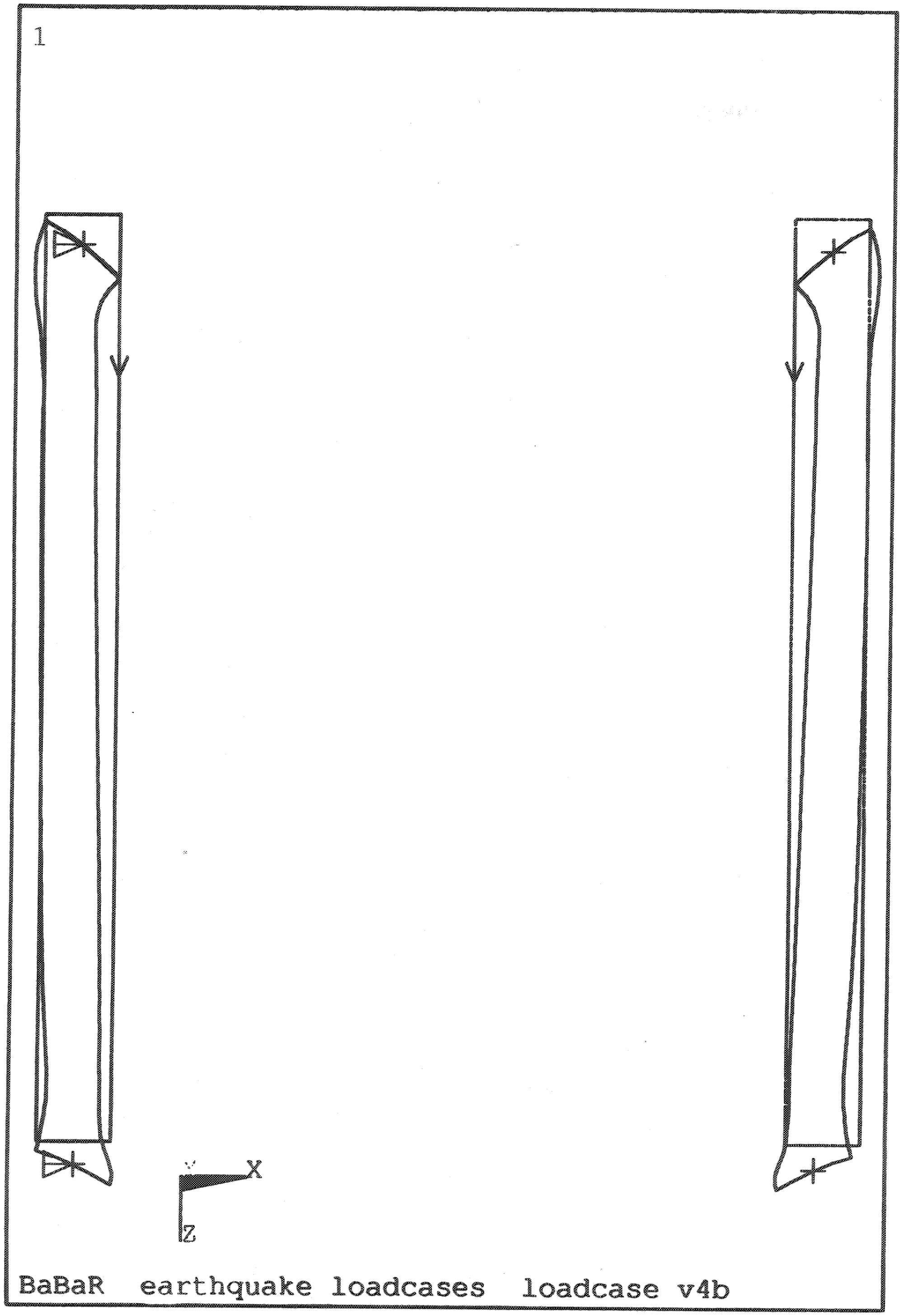
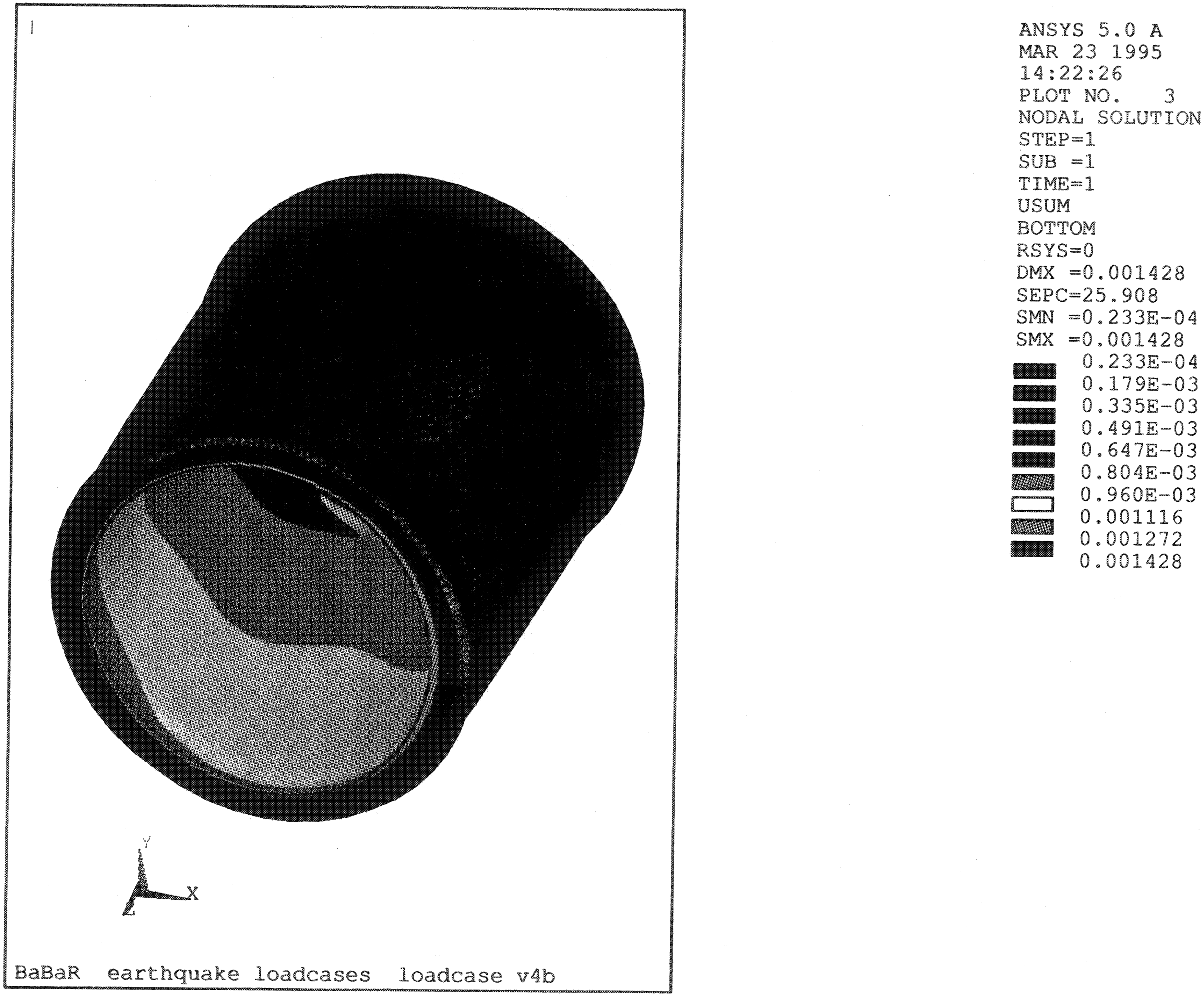
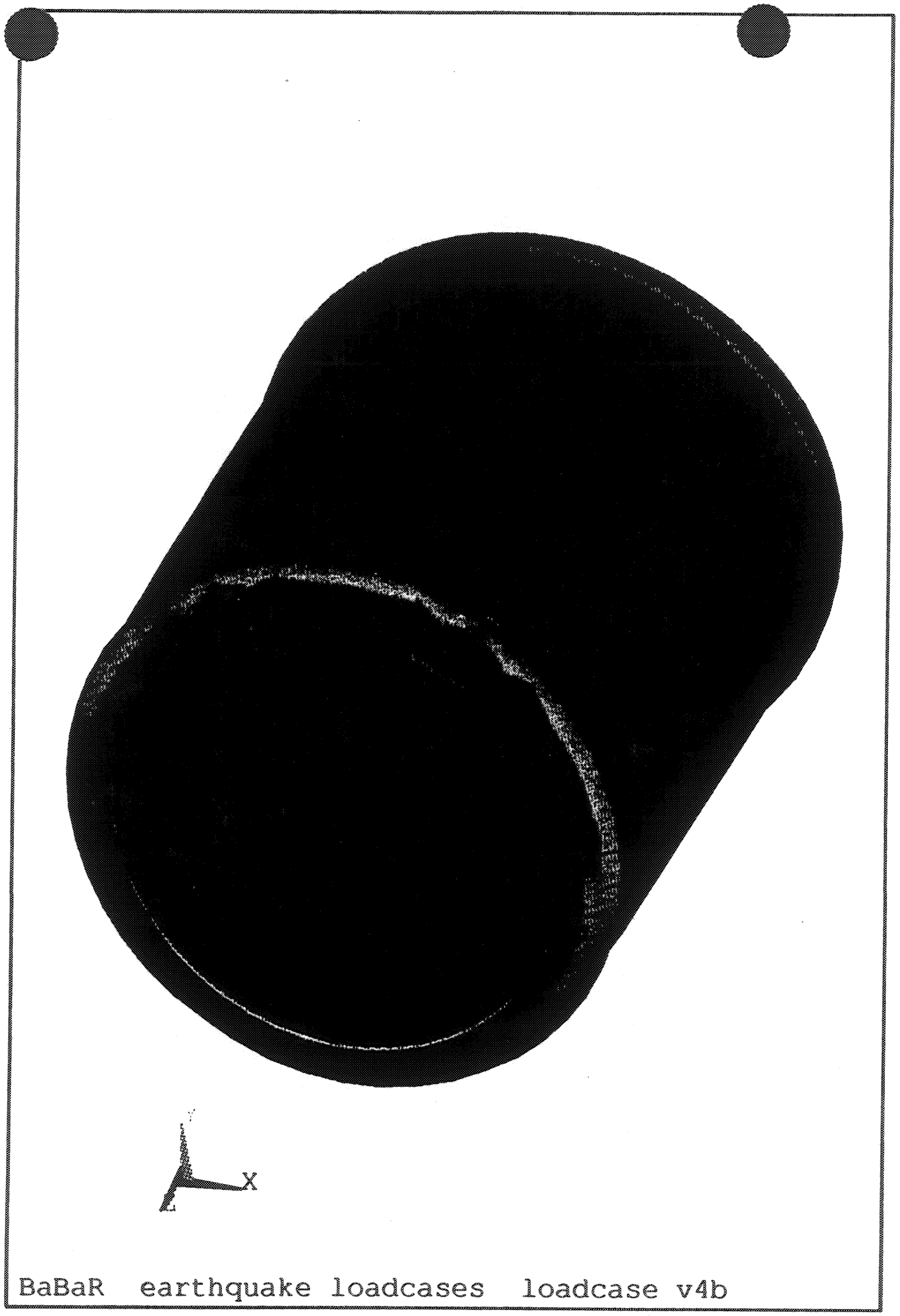
SUB =1
TIME=1
USUM
BOTTOM
RSYS=0
DMX =0.001716
SEPC=20.419
SMN =0.130E-04
SMX =0.001716
0.130E-04
0.202E-03
0.391E-03
0.581E-03
0.770E-03
0.959E-03
0.001148
0.001338
0.001527
0.001716
aBaR earthquake loadcases loadcase v3b



ANSYS 5.0 A
MAR 23 1995
14:15:14
PLOT NO. 1
DISPLACEMENT
STEP=1
SUB =1
TIME=1
RSYS=0
DMX =0.001424
SEPC=25.908
U
F

*DSCA=200
YV =1
*DIST=2.663
*XF =-0.009386
*YF =-0.561E-03
*ZF =-0.086853
PRECISE HIDDEN
EDGE


ANSYS 5.0 A
MAR 23 1995
14:22:26
PLOT NO. 3
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
USUM
BOTTOM
RSYS=0
DMX =0.001428
SEPC=25.908
SMN =0.233E-04
SMX =0.001428
0.233E-04
0.179E-03
0.335E-03
0.491E-03
0.647E-03
0.804E-03
0.960E-03
0.001116
0.001272
0.001428
X
BaBaR earthquake loadcases loadcase v4b



ANSYS 5.
MAR 23 1995
14:21:25
PLOT NO. 2
ELEMENT SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (NOAVG)
BOTTOM
DMX =0.001428
SMN =0.205E+07
SMNB=-0.240E+08
SMX =0.421E+08
SMXB=0.690E+08

0.205E+07
0.649E+07
0.109E+08
0.154E+08
0.198E+08
0.243E+08
0.287E+08
0.332E+08
0.376E+08
0.421E+08

Interface issues

- Geometry
- Loads + Force transfer
- Earthquake loads

Geometry

Must pay heed to

- Nominal size
- Tolerance
- Clearance

The first two are up to the supplier of the solenoid, and together define the maximum envelope.

The third is set by the integration team.

Interface drawing showing envelope

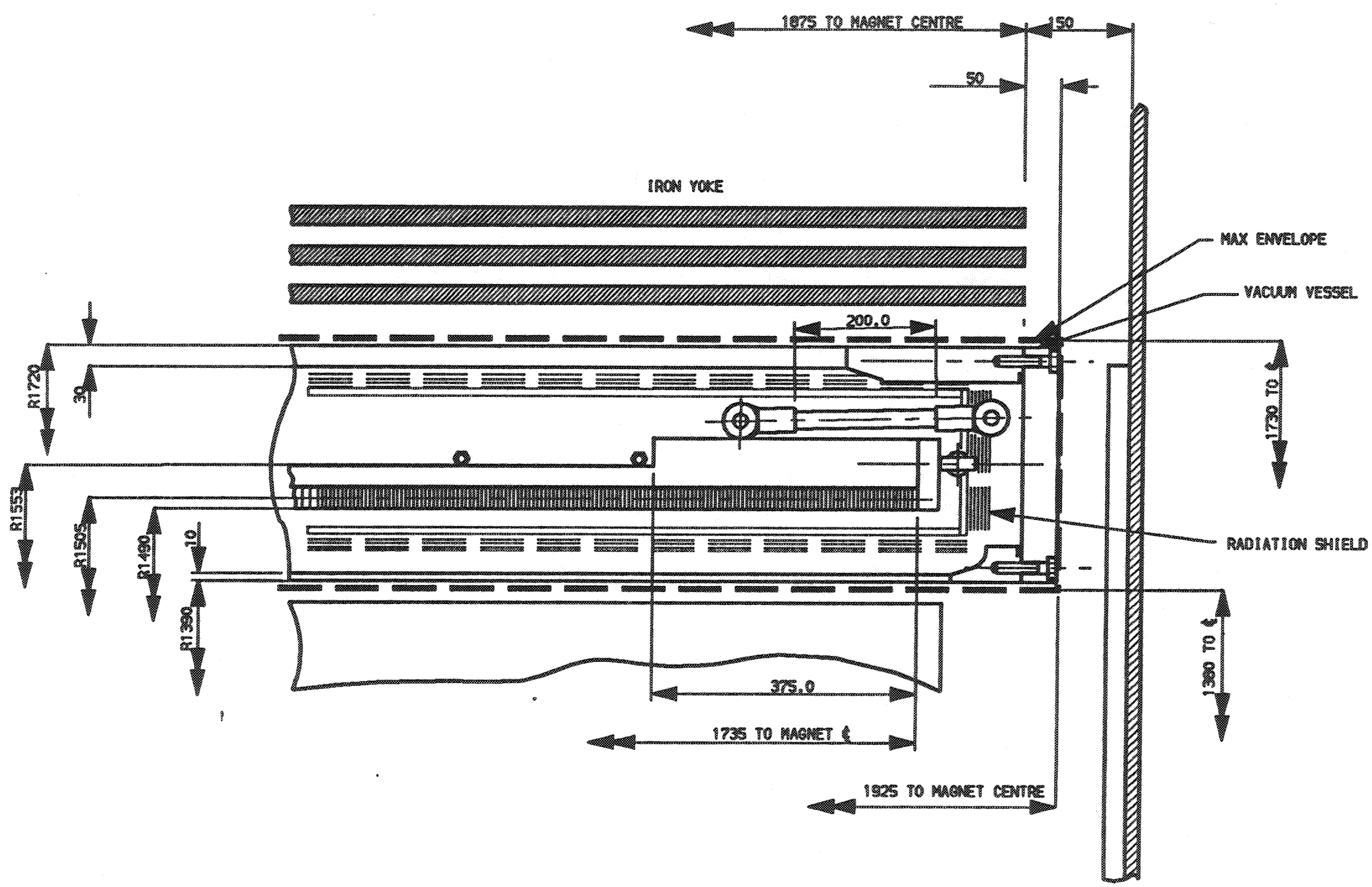


Fig 11.1 Interface Dimensions

Potential clashes

- The 100mm gap with the inner detector flange
- The 100mm gap with the external supports
- The external supports inside the iron yoke with detectors there.

3D view fig 6.3

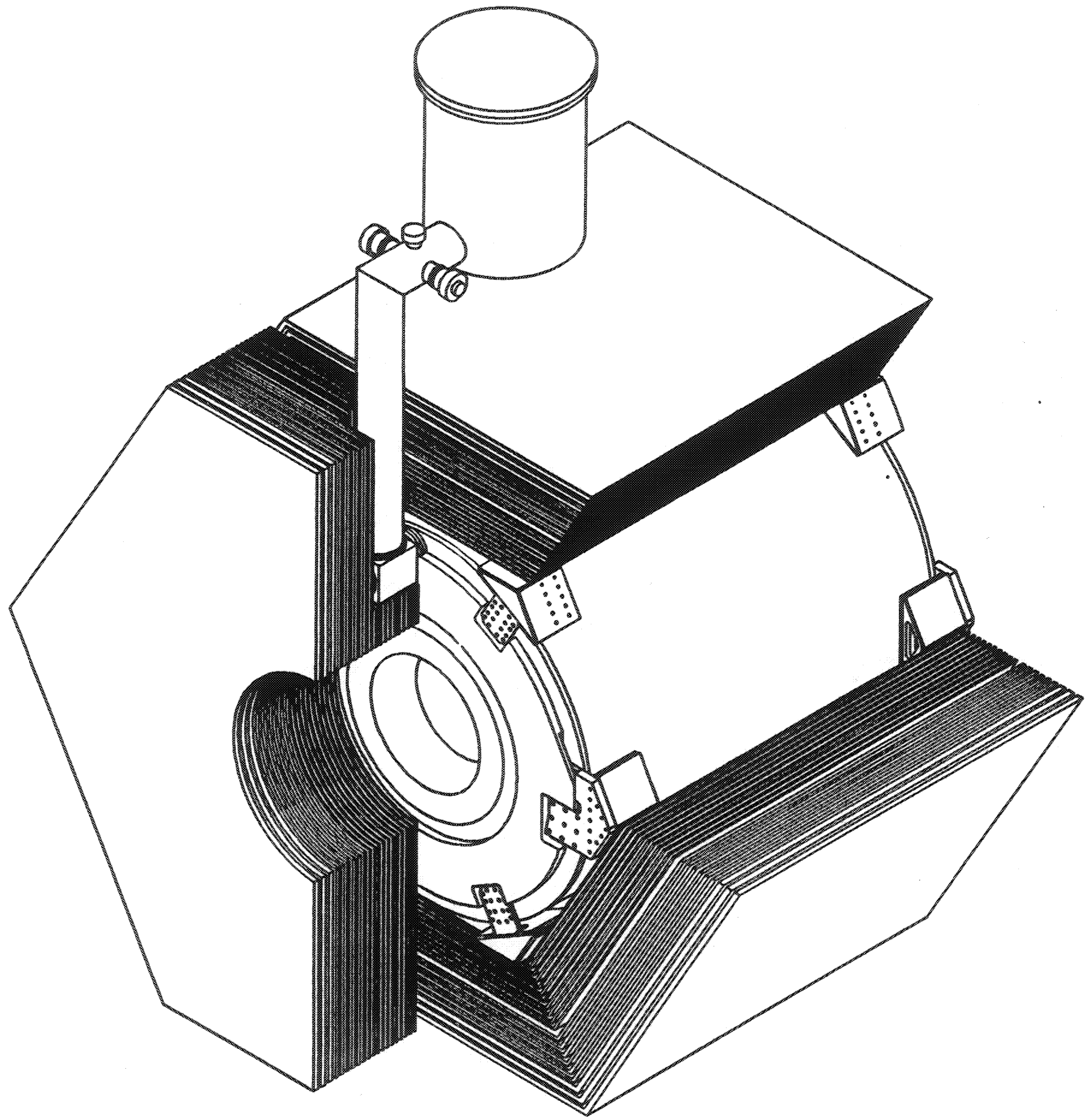


Fig 6.3 External Supports- Outline

Force transfer - inner detector

- Taken by a flange
- Radial and vertical loads at 4 points
- Axial loads distributed around the flange at a radius slightly larger than the inner radius of the vac vessel

View of inner detctor flange - fig 11.2
Schematic - fig 5.3
Fig 6.6
Fig 6.7

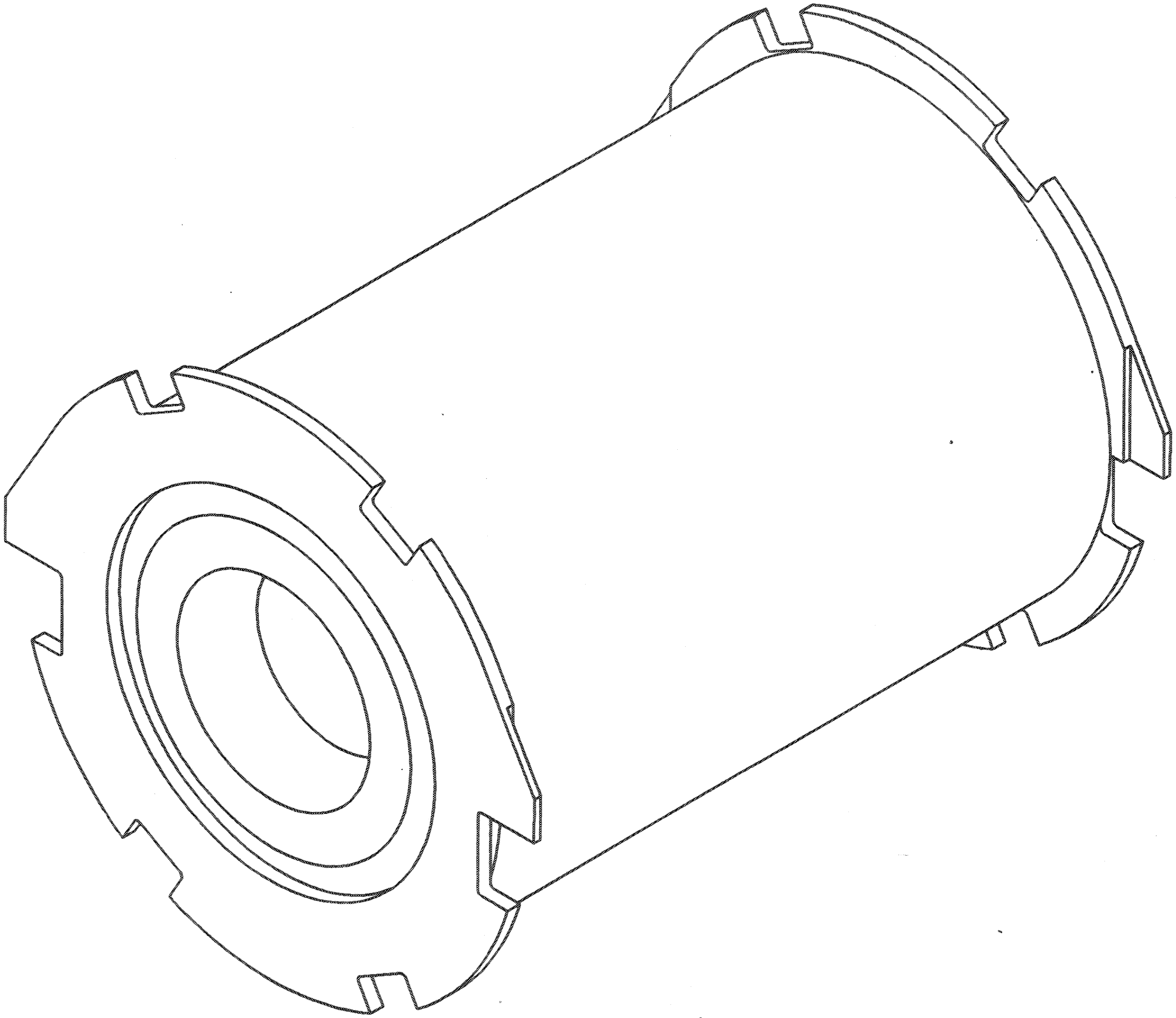


Fig 11.2 Assumed Flange on Inner Detector

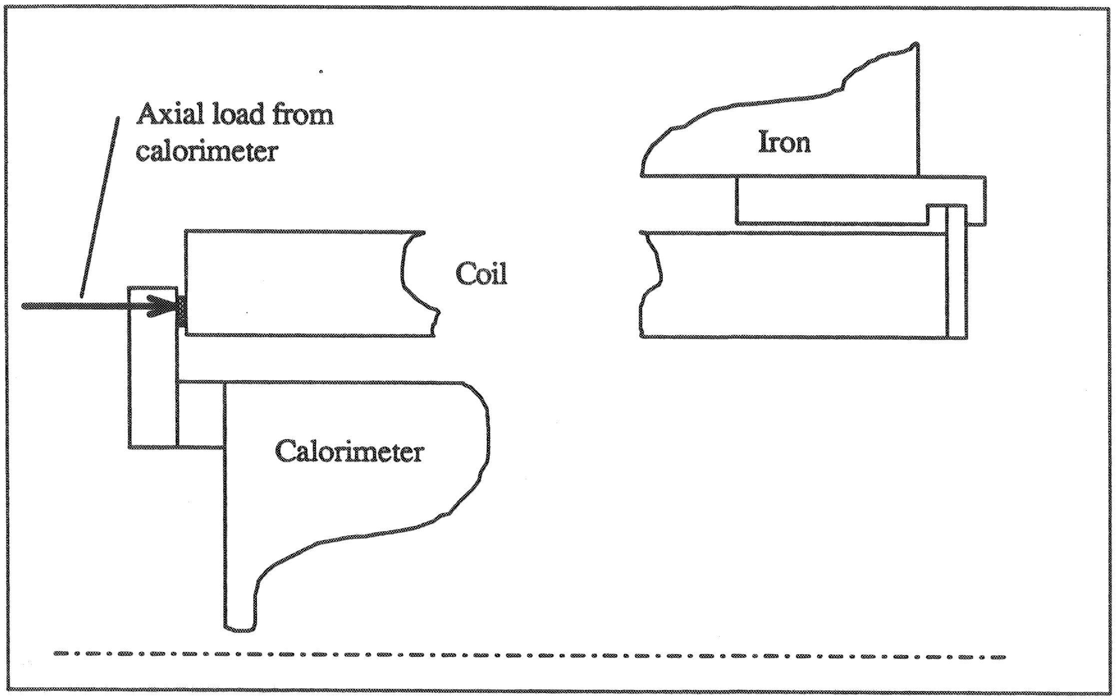


Figure 5.3 Outline scheme for axial support of inner detectors

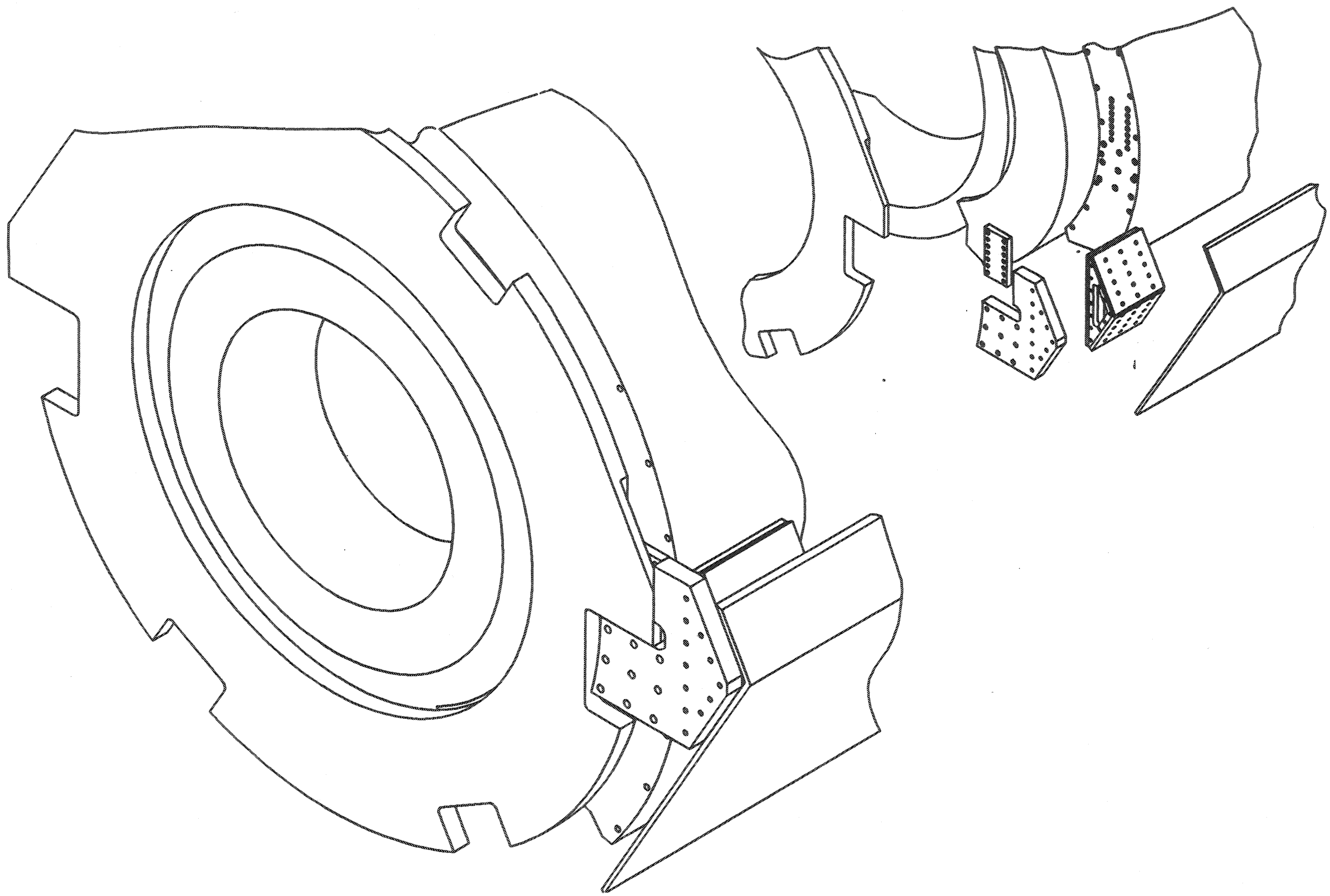
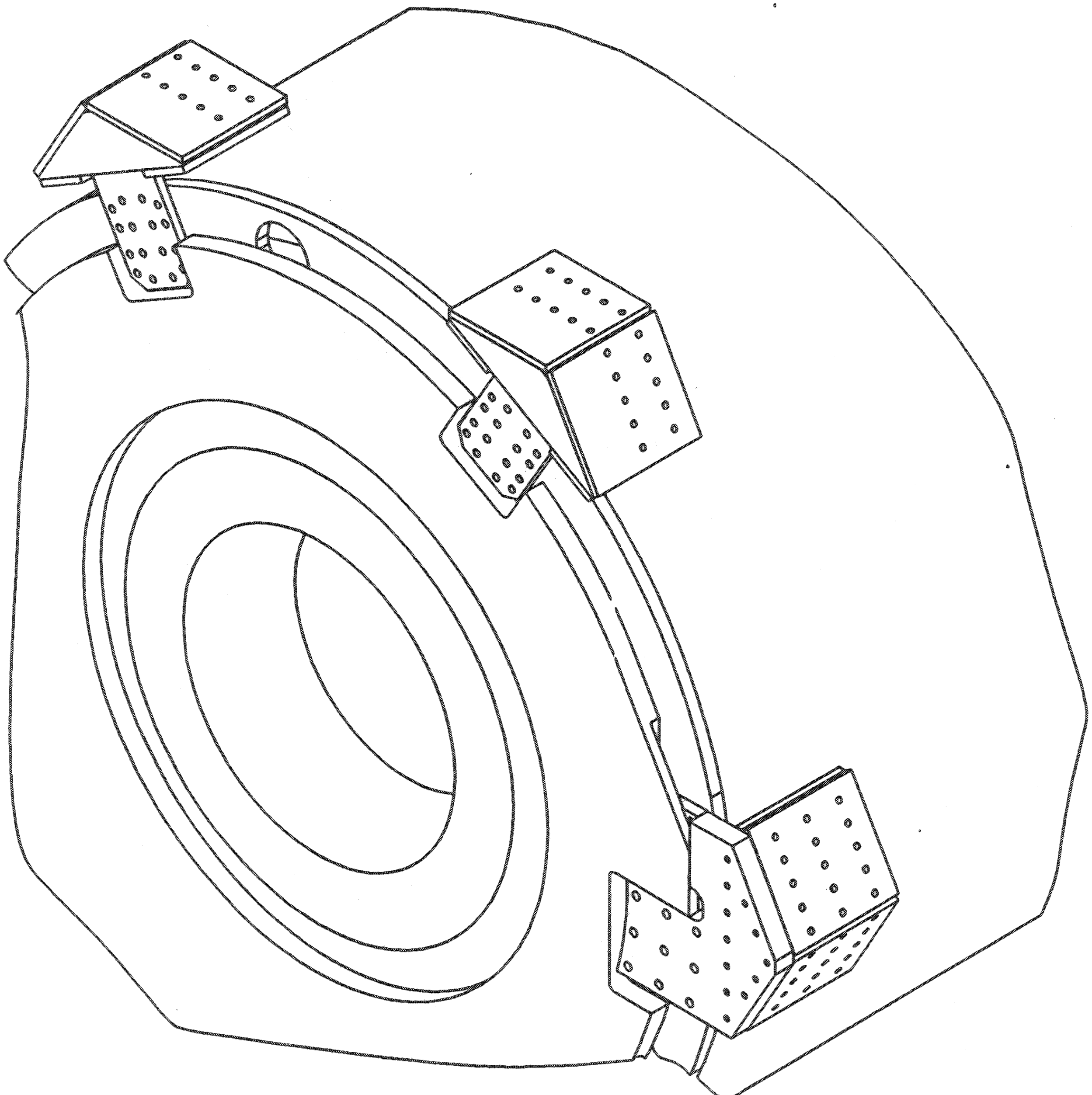
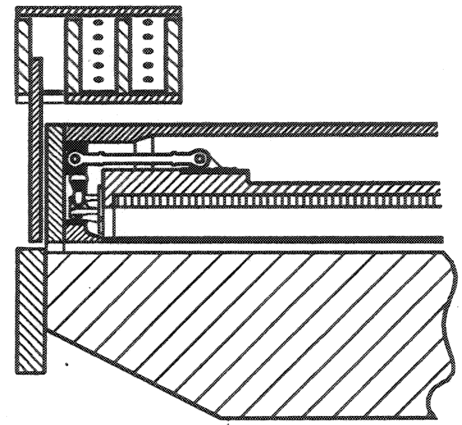


Fig 6.6 Main Support Brackets





Typ Cross Section

Fig 6.7 Suubsidiary Support Brackets

Force transfer - to iron

- Loads:
  - Radial - 95t between 2 points
  - Axial - 105t between 4 points
  - Vertical - 208t between 4 points
  - Do not forget bending moments, especially for the vertical loads.

Fig 6.3

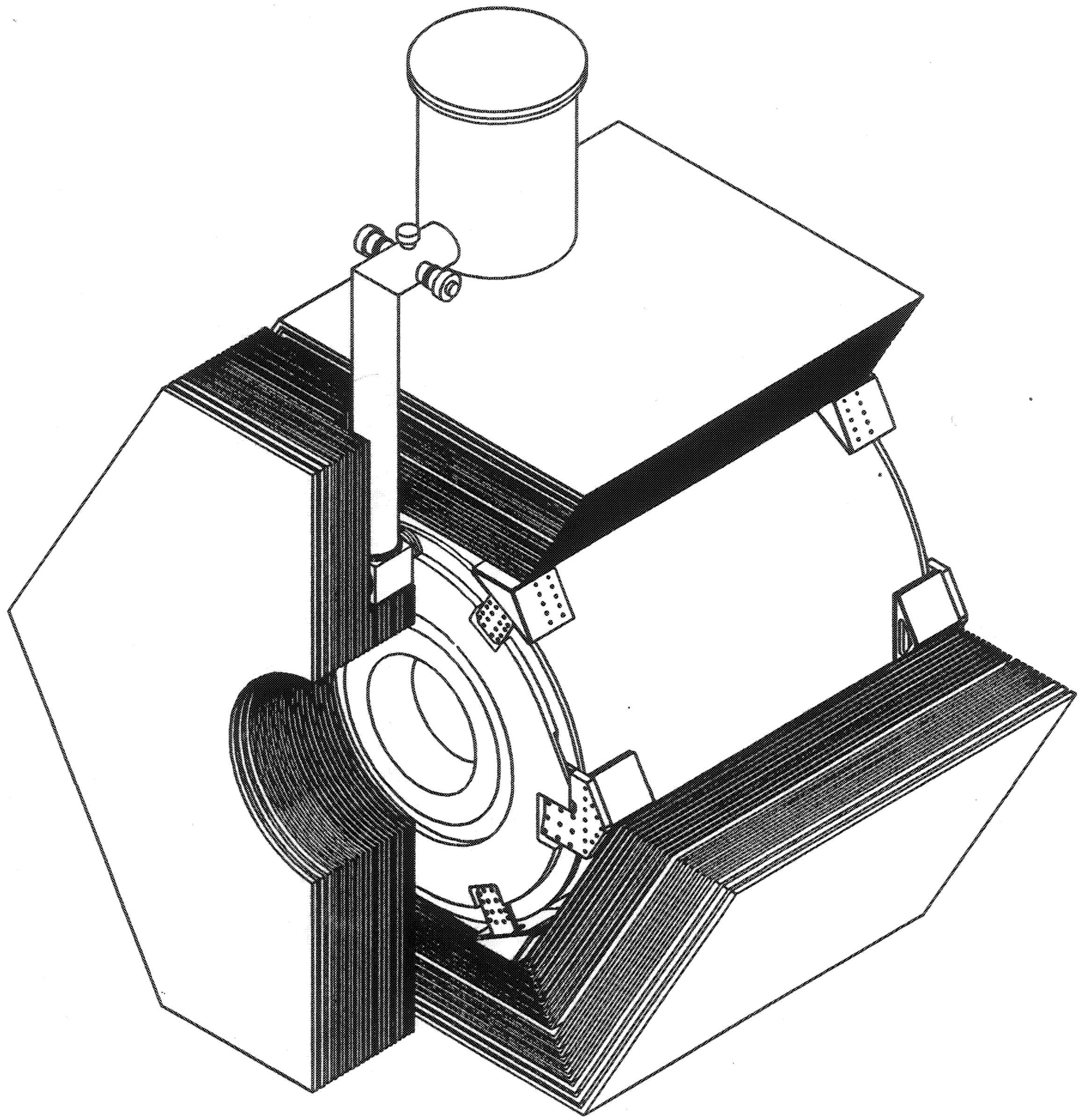


Fig 6.3 External Supports- Outline

Earthquake forces

To integrate with the rest of the design, decisions must be made on:

- What apporach is to be used: full dynamic or equivalent static analysis?
- What are the magnitudes of the accelerations to be used?
- What are the allowable stresses?
- What is the general philosphy on damage levels?

Other interface issues

- Assembly: care needs to be taken that the real design can be assembled within constraints (chimney height, eg) imposed by Babar.
- Electrical/control interfaces need to be defined.
- Cryogenics interfaces need to be defined.