18 September 1996

Ansaldo Energia

BABAR Cryostat FEM Analysis

- Loads

COLD MASS WEIGTH	7.8	t
Max.AXIAL MISALIGNMENT	25	t
Max.RADIAL MISALIGNMENT	20	t

- Earthquake effect loads

VERTICAL EARTQUAKE	(1.6 g)	7.8 x 1.6 = 12.5	t
HORIZONTAL EARTQUAKE	(0.2 g)	7.8 x 0.2 = 1.6	t

Load cases analized :

1 - Nominal condition (no misalignment , no earthquake) file BAB1

2 - Max. radial & axial misalignment (radial misalignment vertically acting) file BAB2

3 - Max. radial & axial misalignment (radial misalignment vertically acting) plus earthquake effect file BAB3

4 - Max. radial & axial misalignment (radial misalignment horizontally acting) plus earthquake effect file BAB4

For all cases the cryostat loads include :

- cryostat weight
- atmospheric external pressure

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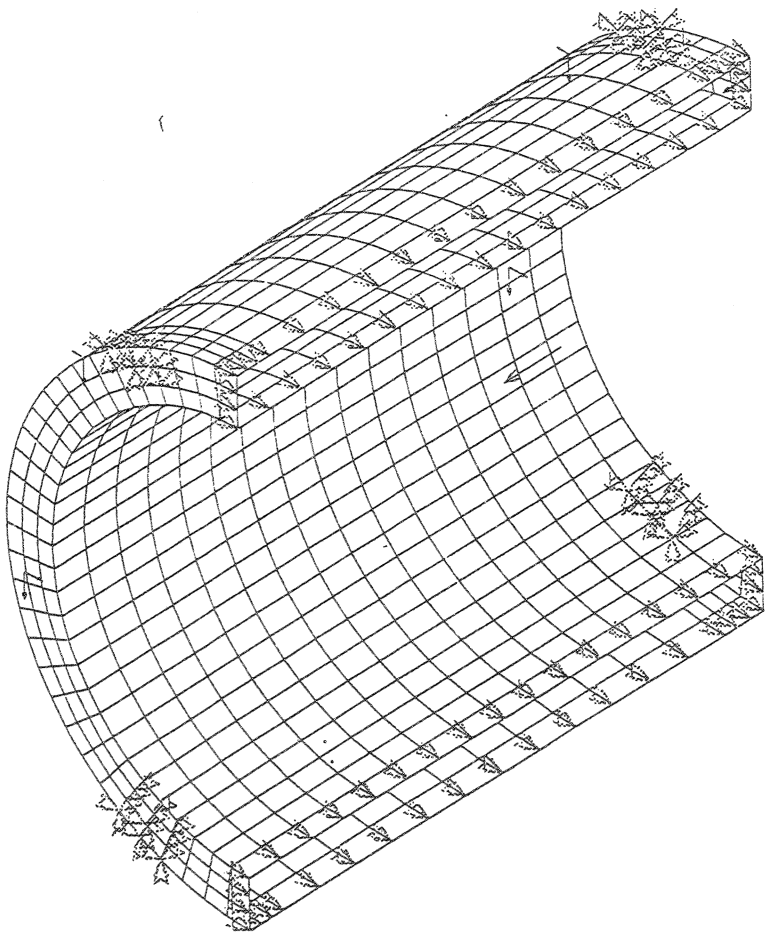
BABAR Cryostat FEM Analysis

Main Results

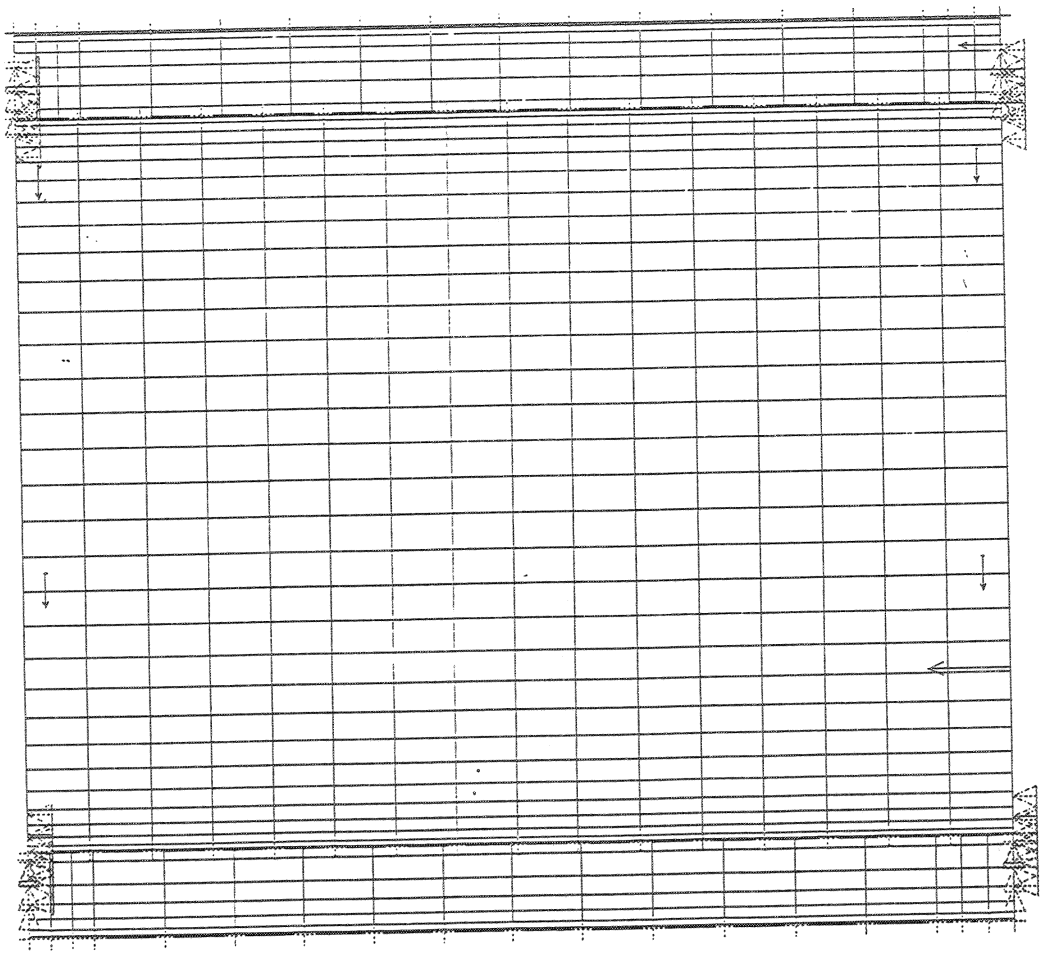
FILE	*BAB1*	*BAB2*	*BAB3*	*BAB4*
Inner Cylinder				
Stress Intensity (MPa)	20	26	27	22
hoop stress (MPa)	18	20	21	21
axial stress (MPa)	10	20	21	13
max.displacement (mm)	0.60	0.71	0.73	0.63
Outer Cylinder				
Stress Intensity (MPa)	13	36	38	37
hoop stress (MPa)	6	10	13	14
axial stress (MPa)	10	28	30	25
max.displacement (mm)	-0.25	-0.26	-0.28	-0.33
Flanges				
Stress Intensity (MPa)	19	69	70	65
axial stress (MPa)	17	60	62	63
max.axial displ. (mm)	0.15	0.33	0.34	0.21



ANSYS 4.4A
AUG 13 1996
17:28:20
PLOT NO. 1
PREP7 ELEMENTS
TYPE NUM
TRIS
FORC

XV =1
YV =1
ZV =1
DIST=2.842
XF =-0.87875
ZF =1.935
PRECISE HIDDEN

BAB2 BABAR CRYOSTAT

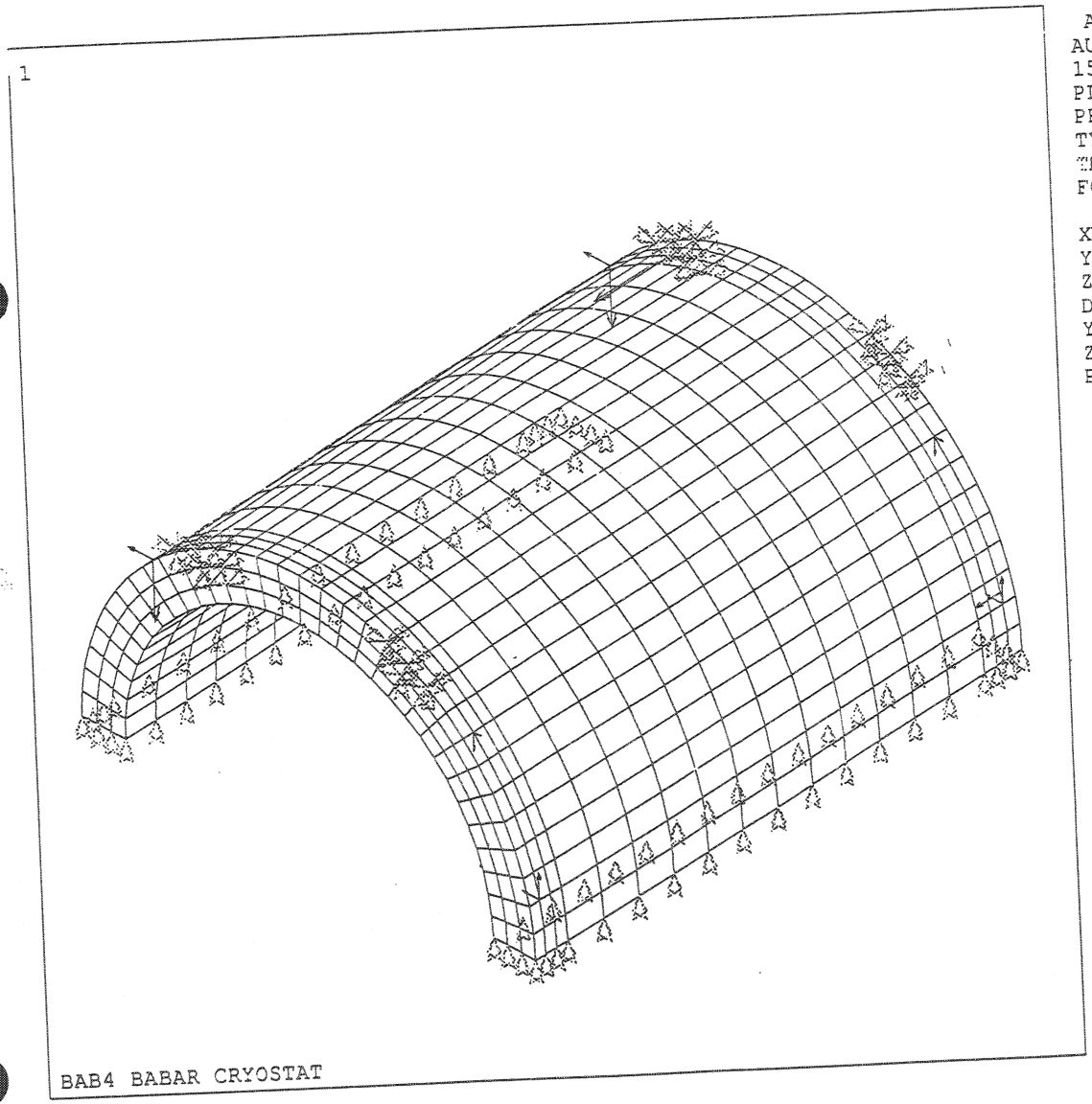


ANSYS 4.4A
AUG 13 1996
17:28:38
PLOT NO. 3
PREP7 ELEMENTS
TYPE NUM
TDIS
FORC

XV =1
DIST=2.129
XF =-0.87875
ZF =1.935
PRECISE HIDDEN

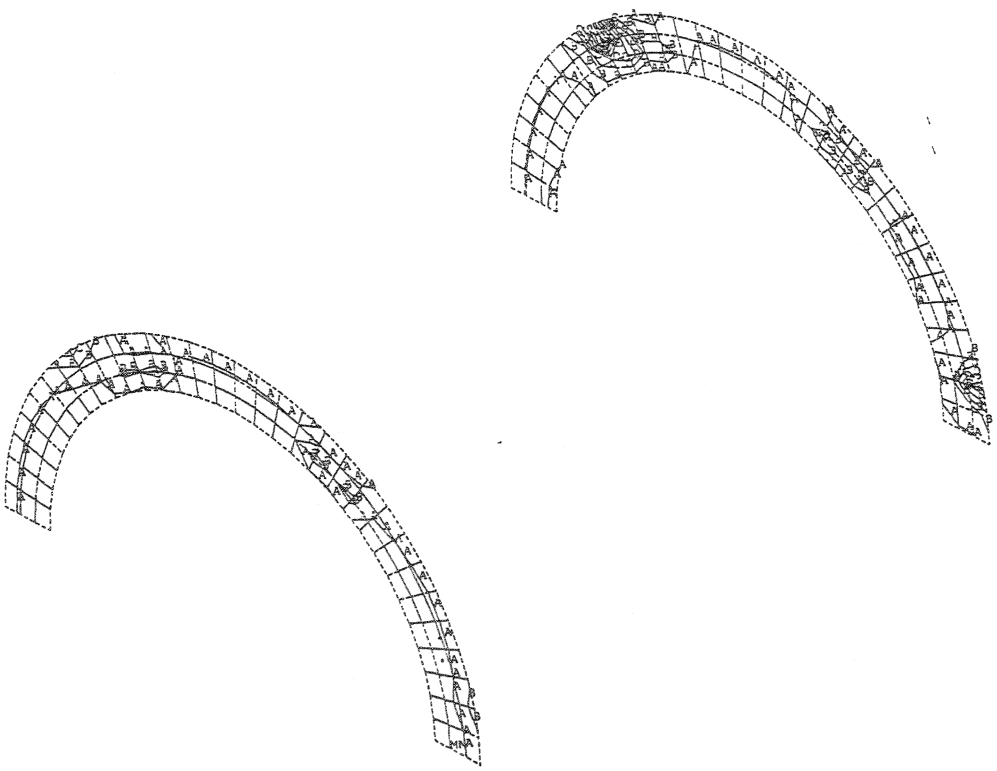
BAB2 BABAR CRYOSTAT

5|13



ANSYS 4.4A
AUG 14 1996
15:29:51
PLOT NO. 1
PREP7 ELEMENTS
TYPE NUM
TDIS
FORC

XV =1
YV =1
ZV =1
DIST=2.872
YF =0.87875
ZF =1.935
PRECISE HIDDEN



ANSYS 4.4A
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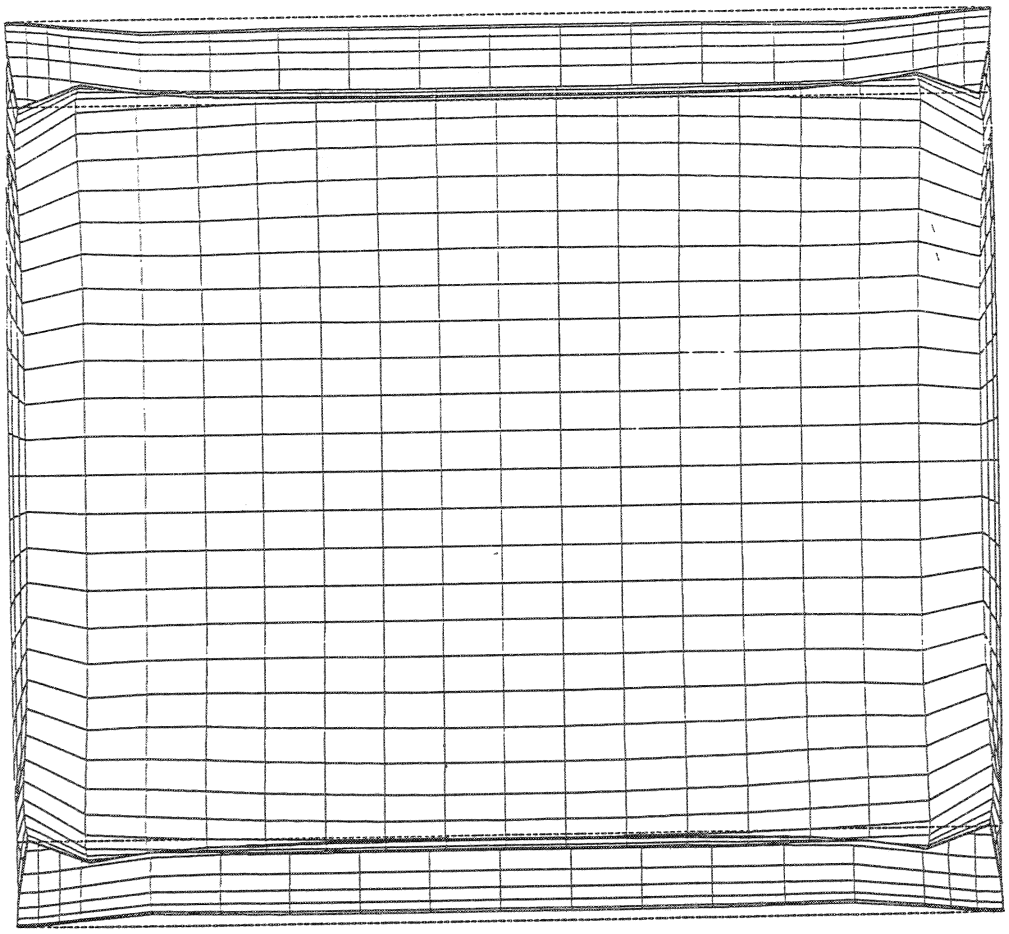
15:37:04
PLOT NO. 20
POST1 STRESS
STEP=1
ITER=2
SIGE (AVG)
TOP
DMX =0.633E-03
SMN =308585
SMX =0.645E+08
SMXB=0.739E+08

XV =1
YV =1
ZV =1
DIST=2.872
YF =0.87875
ZF =1.935
PRECISE HIDDEN
A =0.388E+07
B =0.110E+08
C =0.182E+08
D =0.253E+08
E =0.324E+08
F =0.396E+08
G =0.467E+08
H =0.538E+08
I =0.610E+08

BAB4 BABAR CRYOSTAT END FLANGES

1

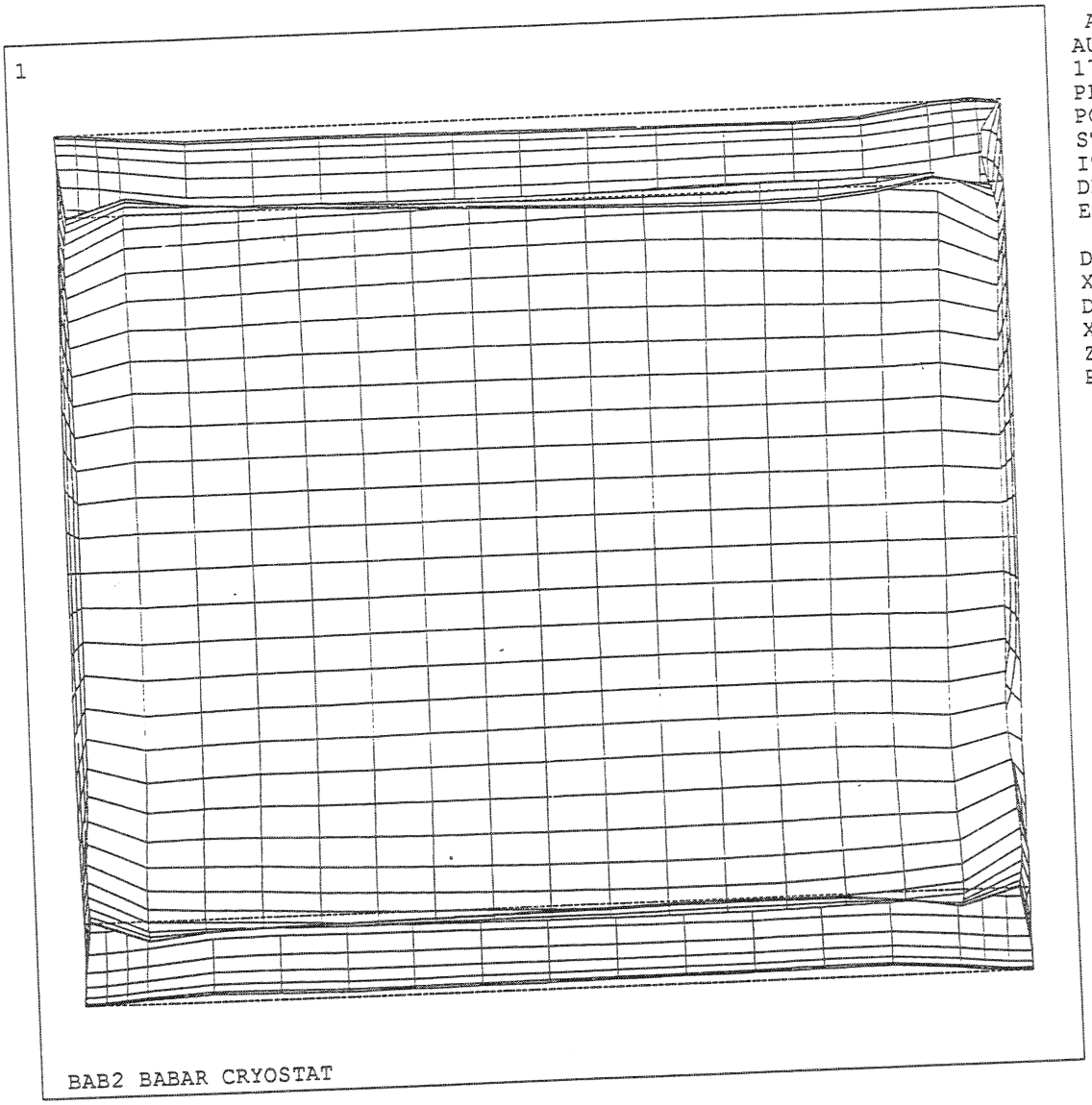


ANSYS 4.4A
AUG 13 1996
16:58:41
PLOT NO. 2
POST1 DISPL.
STEP=1
ITER=2
DMX =0.596E-03
ERPC=0

DSCA=357.421
XV =1
DIST=2.129
XF =-0.87875
ZF =1.935
PRECISE HIDDEN

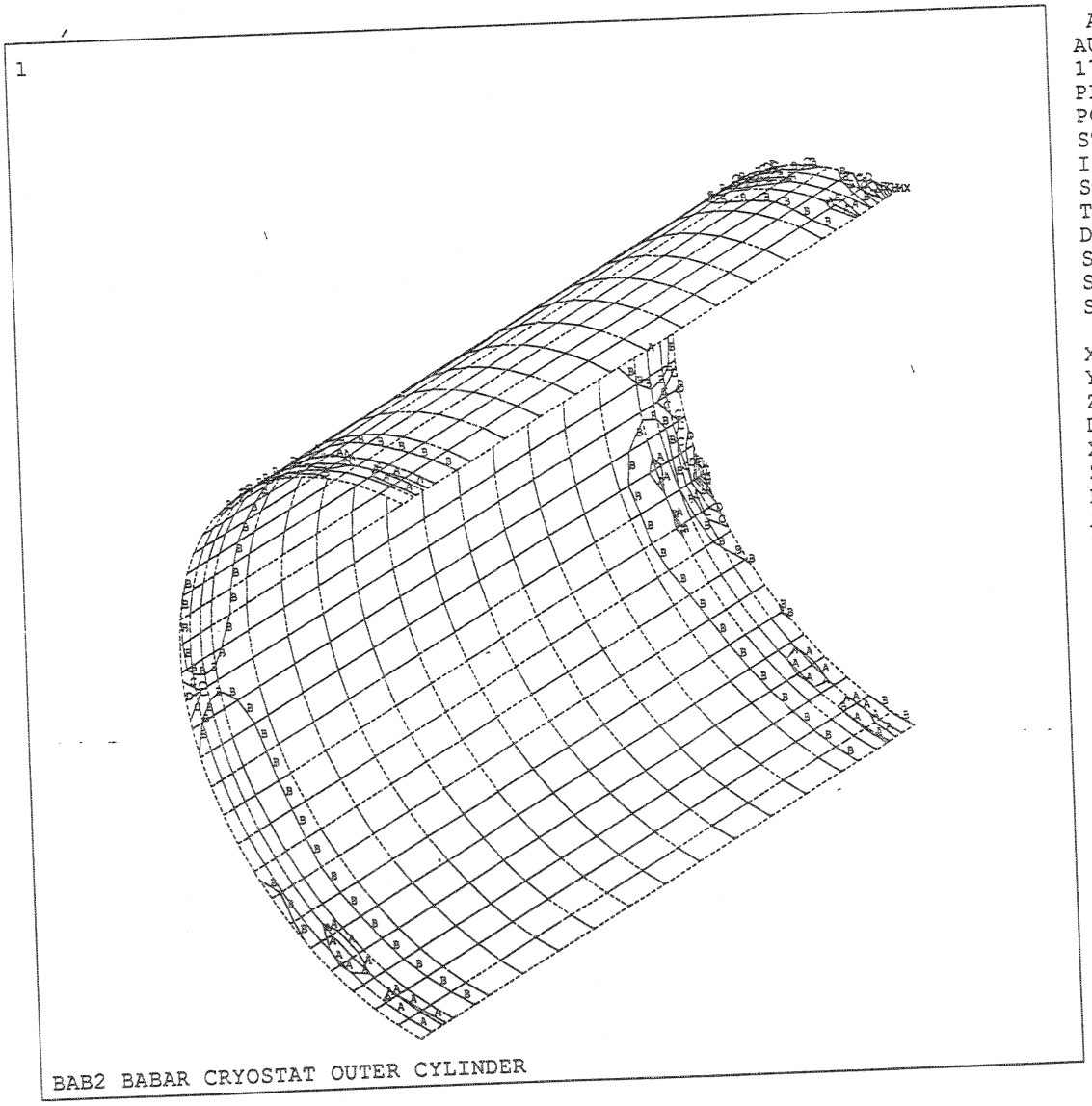
BAB1 BABAR CRYOSTAT

8/13



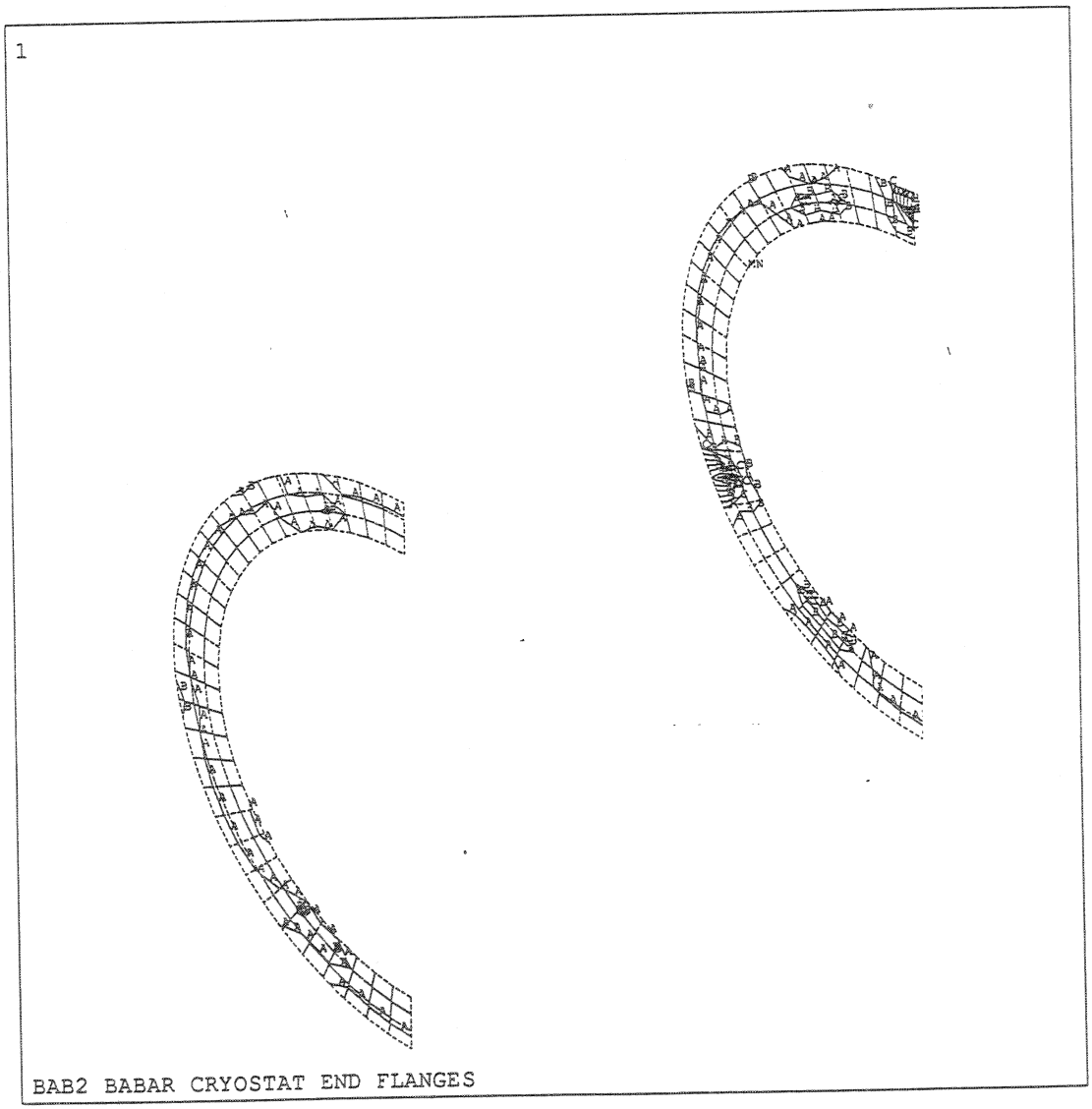
ANSYS 4.4A
AUG 13 1996
17:35:32
PLOT NO. 1
POST1 DISPL.
STEP=1
ITER=2
DMX =0.721E-03
ERPC=0

DSCA=295.06
XV =1
DIST=2.129
XF =-0.87875
ZF =1.935
PRECISE HIDDEN



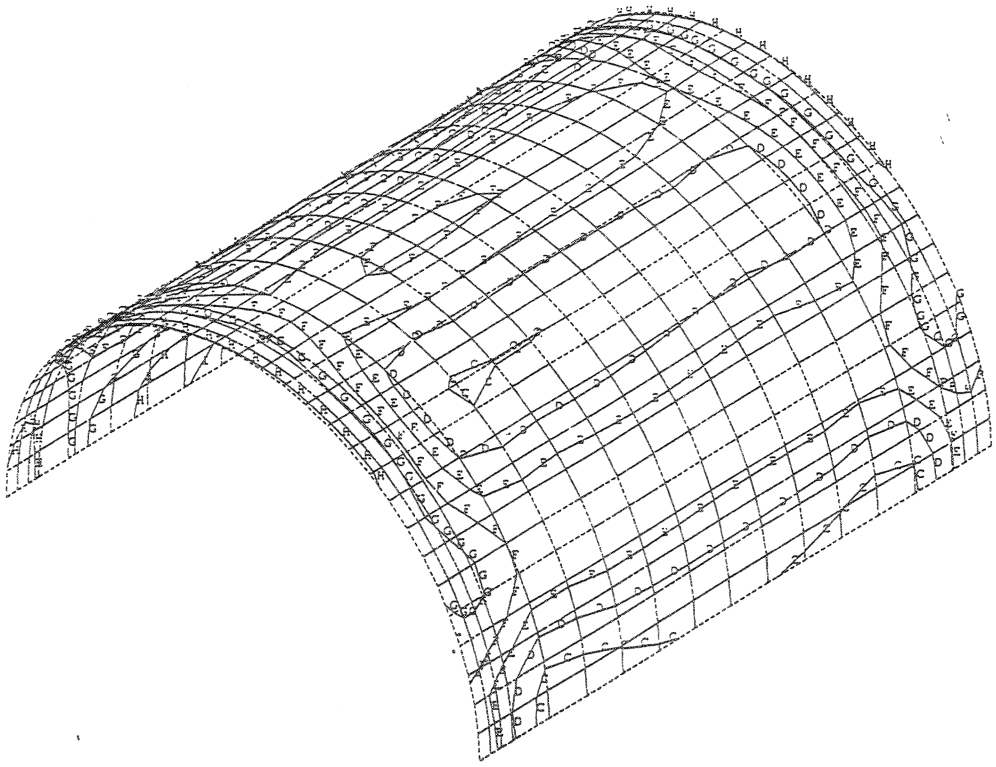
ANSYS 4.4A
AUG 13 1996
17:35:51
PLOT NO. 2
POST1 STRESS
STEP=1
ITER=2
SIGE (AVG)
TOP
DMX =0.721E-03
SMN =0.107E+07
SMX =0.256E+08
SMXB=0.307E+08

XV =1
YV =1
ZV =1
DIST=2.842
XF =-0.87875
ZF =1.935
PRECISE HIDDEN
A =0.243E+07
B =0.516E+07
C =0.788E+07
D =0.106E+08
E =0.133E+08
F =0.161E+08
G =0.188E+08
H =0.215E+08
I =0.242E+08



ANSYS 4.4A
AUG 13 1996
17:37:40
PLOT NO. 18
POST1 STRESS
STEP=1
ITER=2
SIGE (AVG)
TOP
DMX =0.721E-03
SMN =245084
SMX =0.690E+08
SMXB=0.775E+08

XV =1
YV =1
ZV =1
DIST=2.842
XF =-0.87875
ZF =1.935
PRECISE HIDDEN
A =0.406E+07
B =0.117E+08
C =0.193E+08
D =0.270E+08
E =0.346E+08
F =0.422E+08
G =0.499E+08
H =0.575E+08
I =0.652E+08



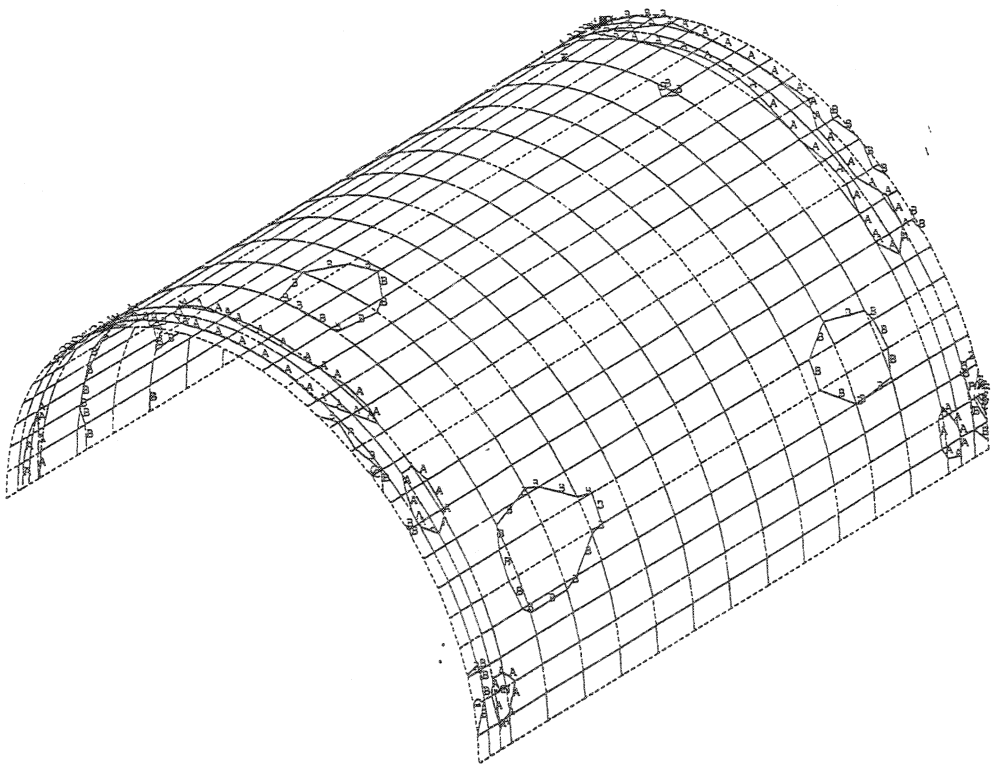
ANSYS 4.4A
AUG 14 1996
15:35:59
PLOT NO. 10
POST1 STRESS
STEP=1
ITER=2
UX
CSYS=11
DMX =0.633E-03
SMN =-0.331E-03
SMX =0.612E-04

XV =1
YV =1
ZV =1
DIST=2.872
YF =0.87875
ZF =1.935
PRECISE HIDDEN
A =-0.309E-03
B =-0.265E-03
C =-0.222E-03
D =-0.178E-03
E =-0.135E-03
F =-0.912E-04
G =-0.476E-04
H =-0.410E-05
I =0.394E-04

BAB4 BABAR CRYOSTAT OUTER CYLINDER

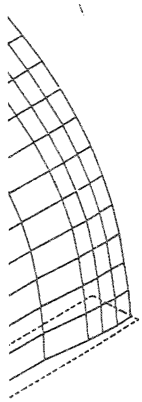
12/1

1



ANSYS 4.4A
AUG 14 1996
15:35:34
PLOT NO. 6
POST1 STRESS
STEP=1
ITER=2
SIGE (AVG)
BOTTOM
DMX =0.633E-03
SMN =0.127E+07
SMX =0.370E+08
SMXB=0.459E+08

XV =1
YV =1
ZV =1
DIST=2.872
YF =0.87875
ZF =1.935
PRECISE HIDDEN
A =0.326E+07
B =0.723E+07
C =0.112E+08
D =0.152E+08
E =0.191E+08
F =0.231E+08
G =0.271E+08
H =0.310E+08
I =0.350E+08

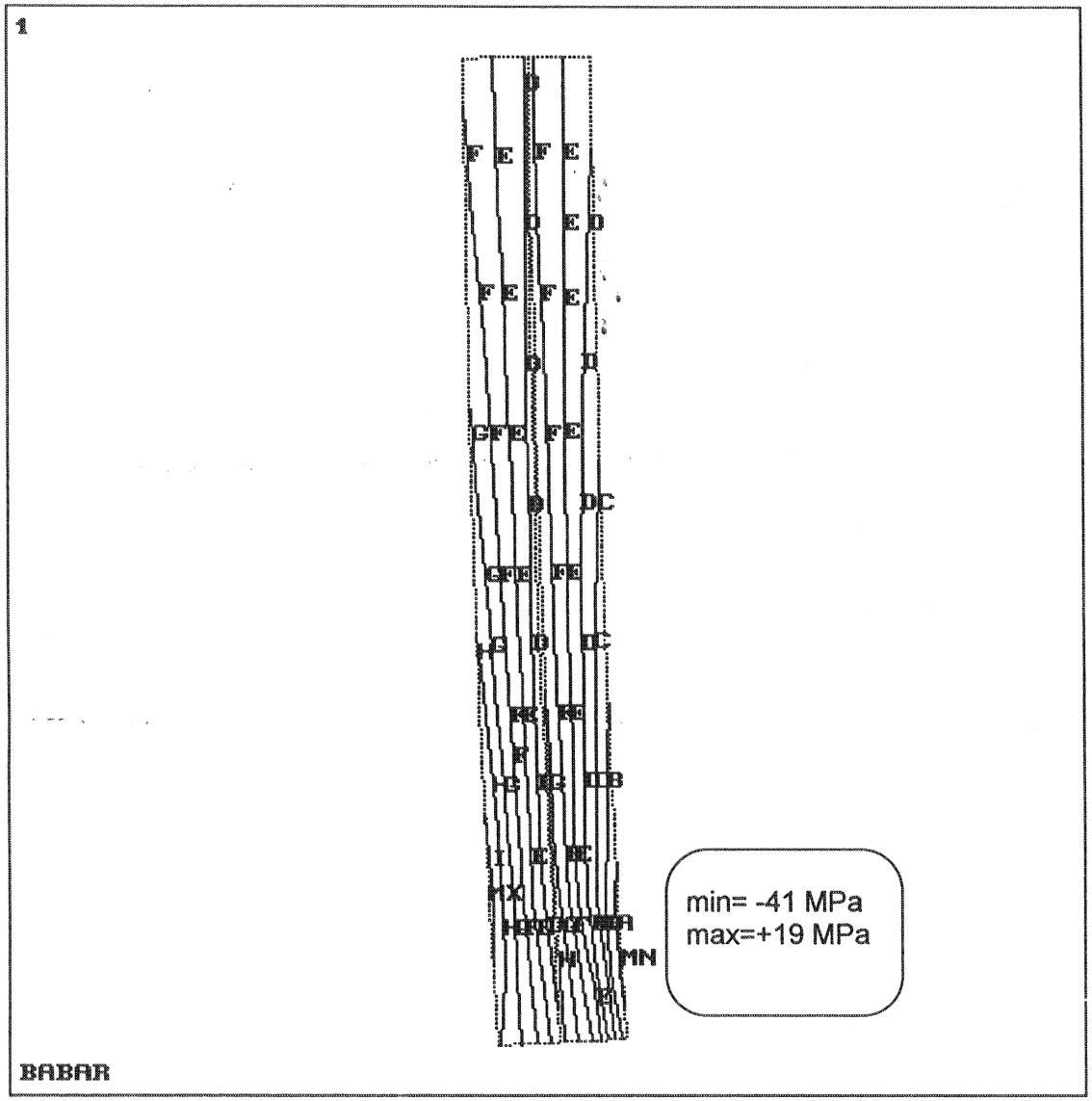


BAB4 BABAR CRYOSTAT OUTER CYLINDER

stress (MPa)	mat.1 (lateral cable)	mat.2 (interlayer insulation)	mat.3 (central cable)	mat.4 insulation on external radius of coil	mat.5 Al - cylinder
Sx (radial)	-5, +7	- 5, + 8	-0.04, +0.6	-7, +1	-13, +5
Sy (axial)	**- 40**, +19	- 8, + 9	- 2, +0.8	- 4, + 4	- 28, **+ 52**
Sz (hoop)	**- 44**, +3	- 12, + 3	- 2, +1	- 4, + 15	+0.3, **+ 77**
Sxy (shear)	-3, +8	- 0.5, + 3	-0.3, +0.04	-0.8, + 19	-5, +7
Sint (intensity)	-------	------	------	------	90

FULL - RANGE STRESS TABLE FOR T_{ref} = 4 Kelvin STRESS ANALYSIS

(WORST QUENCH TEMPERATURE DISTRIBUTION)

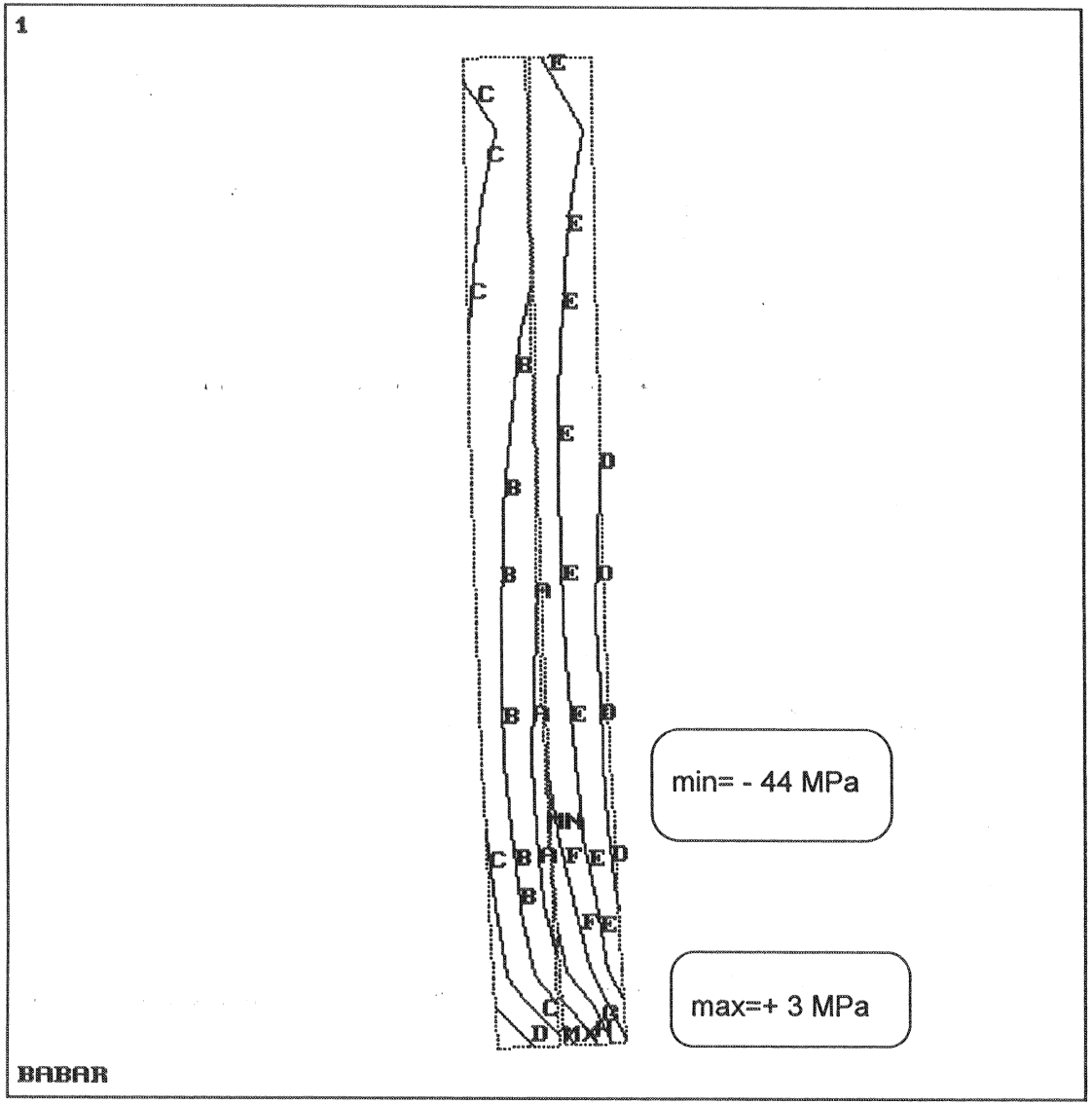


ANSYS 5.1
SEP 11 1996
13:55:47
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SY (AVG)
RSYS=0
DMX =0.001817
SMN =-0.405E+08
SMX =0.189E+08
A =-0.372E+08
B =-0.306E+08
C =-0.240E+08
D =-0.174E+08
E =-0.108E+08
F =-0.421E+07
G =0.239E+07
H =0.900E+07
I =0.156E+08

min= -41 MPa
max=+19 MPa

full range:
min= - 41 MPa
max=+19 MPa

Tref = 4 K - axial stress in the coil (warm end)



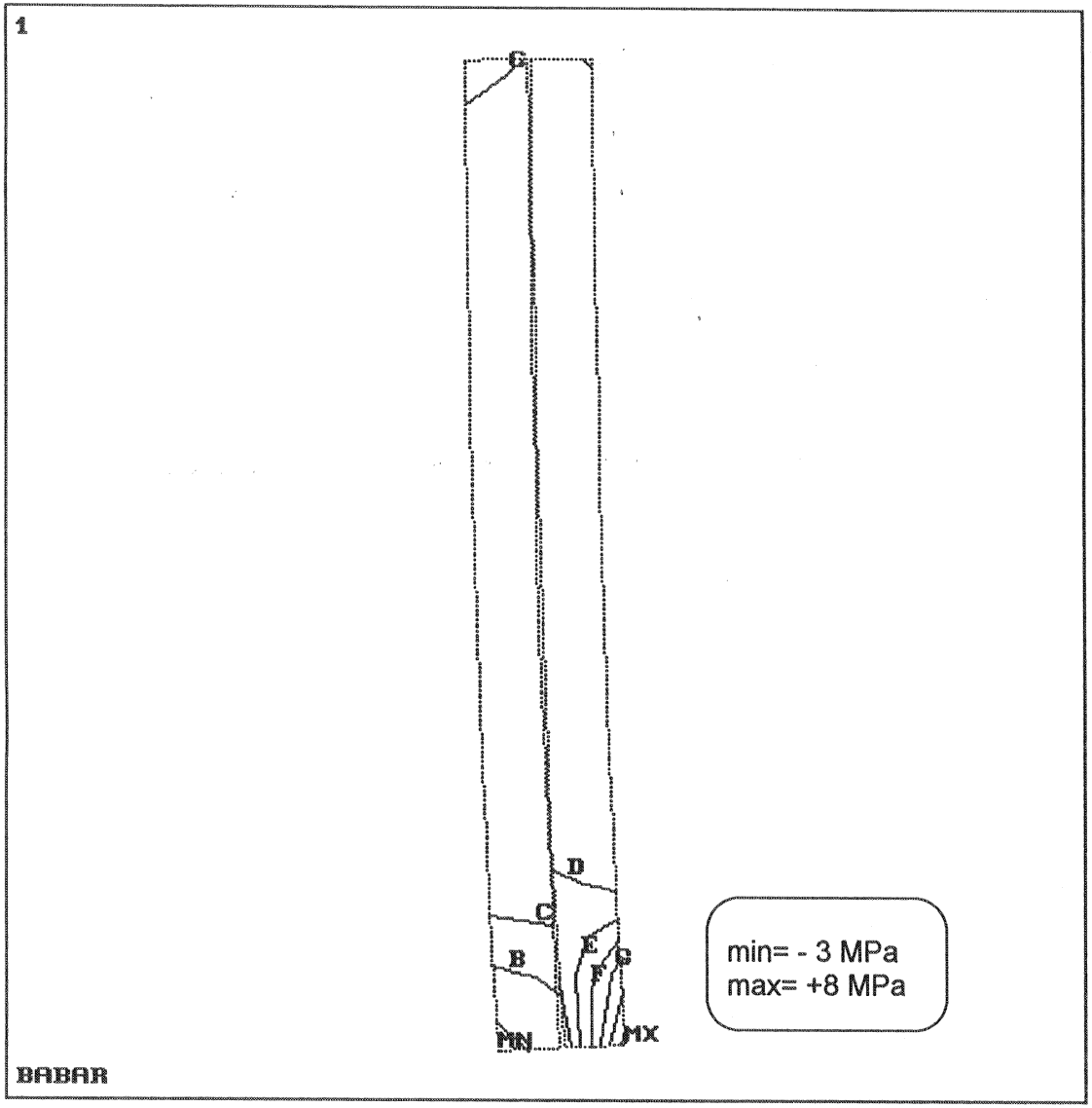
ANSYS 5.1
SEP 11 1996
13:55:50
PLOT NO. 2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SZ (AVG)
RSYS=0
DMX =0.001817
SMN =-0.440E+08
SMX =0.294E+07
A =-0.414E+08
B =-0.362E+08
C =-0.310E+08
D =-0.257E+08
E =-0.205E+08
F =-0.153E+08
G =-0.101E+08
H =-0.488E+07
I =331727

min= - 44 MPa

max=+ 3 MPa

full range:
min= - 44 MPa
max= +3 MPa

Tref = 4 K - hoop stress in the coil (warm end)

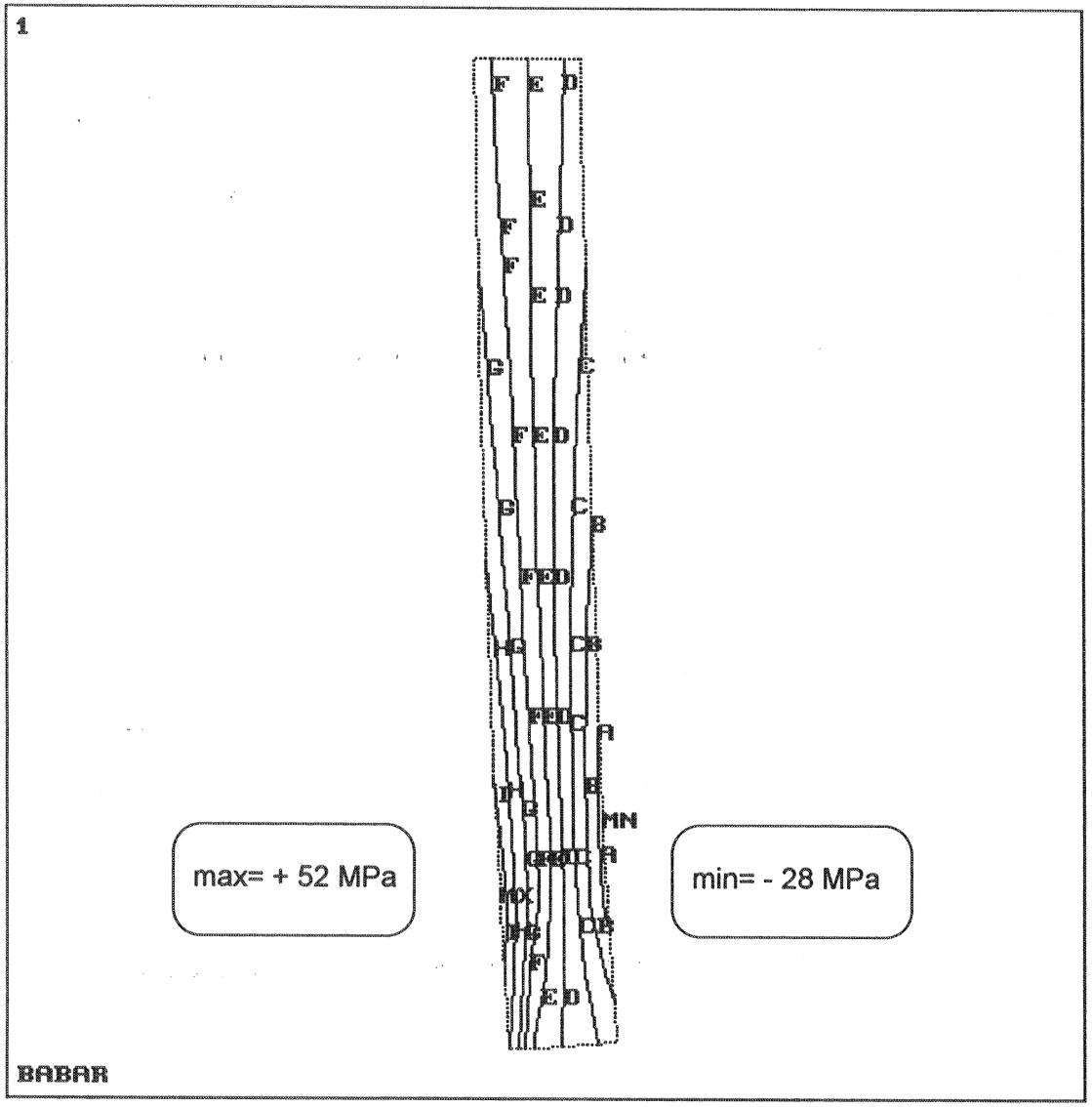


min= - 3 MPa
max= +8 MPa

ANSYS 5.1
SEP 11 1996
13:55:57
PLOT NO. 3
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SXY (AVG)
RSYS=0
DMX =0.001817
SMN =-0.275E+07
SMX =0.764E+07
A =-0.218E+07
B =-0.102E+07
C =132910
D =0.129E+07
E =0.244E+07
F =0.360E+07
G =0.475E+07
H =0.591E+07
I =0.706E+07

full range:
min= - 3 MPa
max= +8 MPa

Tref = 4 K - shear stress in the coil (warm end)



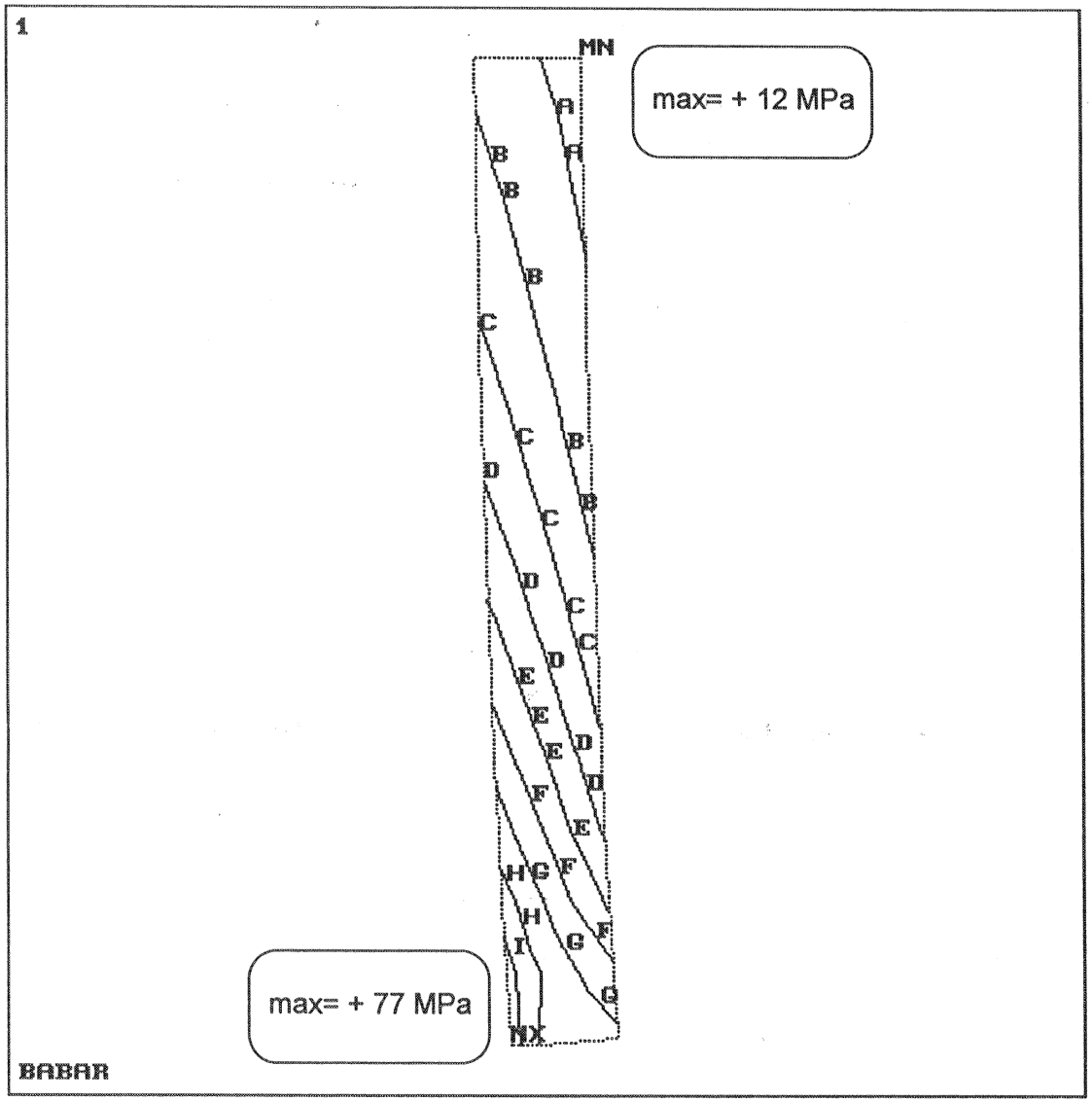
max= + 52 MPa

min= - 28 MPa

```
ANSYS 5.1
SEP 11 1996
13:56:22
PLOT NO.    4
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SY        (AVG)
RSYS=0
DMX =0.001785
SMN =-0.284E+08
SMX =0.523E+08
A   =-0.239E+08
B   =-0.149E+08
C   =-0.597E+07
D   =0.299E+07
E   =0.120E+08
F   =0.209E+08
G   =0.299E+08
H   =0.388E+08
I   =0.478E+08
```

full range:
min= - 28 MPa
max= +52 MPa

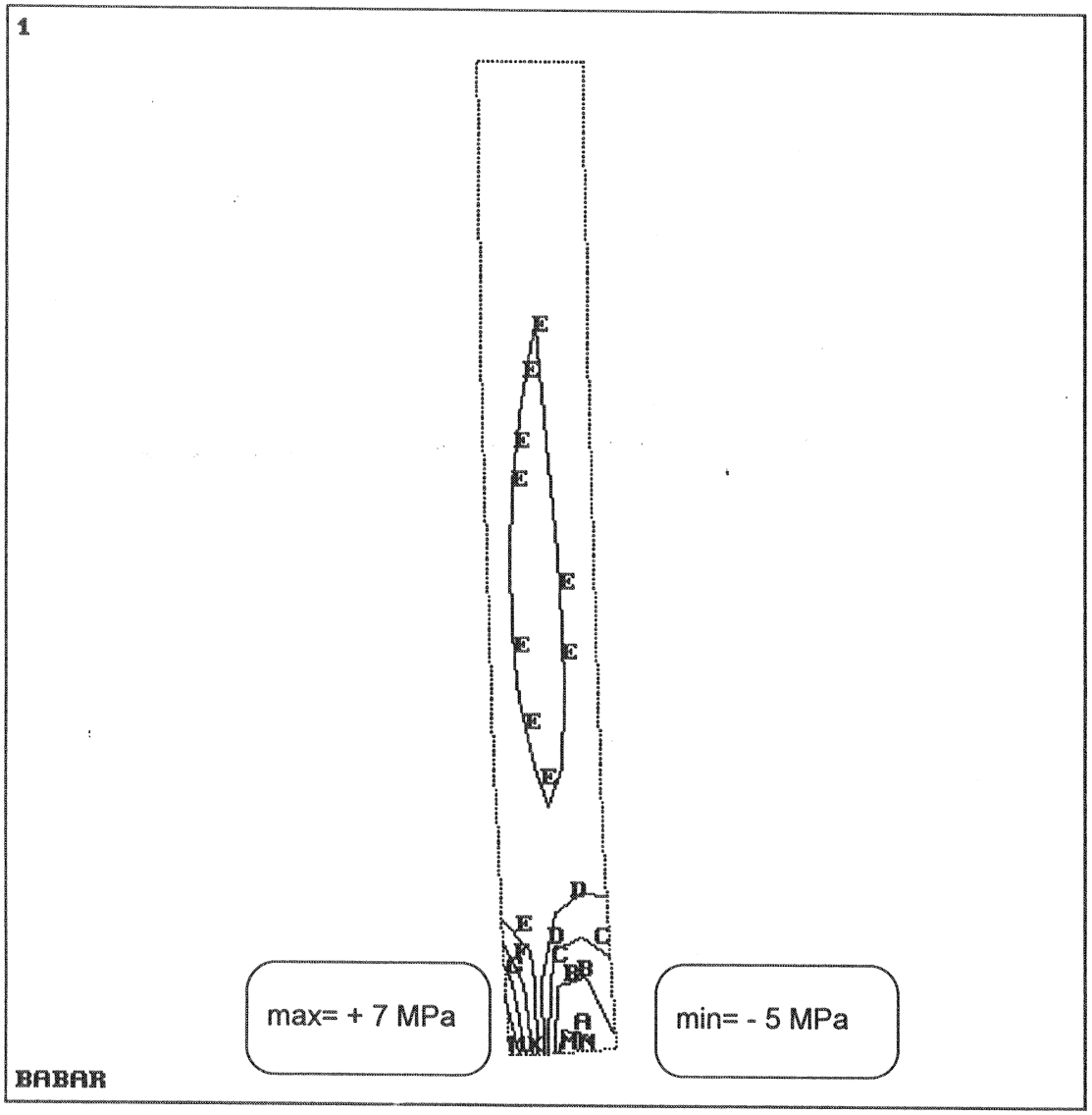
Tref=4 K - axial stress in the Al-cylinder (warm end)



ANSYS 5.1
SEP 11 1996
13:56:27
PLOT NO. 5
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SZ (AVG)
RSYS=0
DMX =0.001785
SMN =0.120E+08
SMX =0.769E+08
A =0.156E+08
B =0.229E+08
C =0.301E+08
D =0.373E+08
E =0.445E+08
F =0.517E+08
G =0.589E+08
H =0.661E+08
I =0.733E+08

full range:
min= + 0.3 MPa
max= + 77 MPa

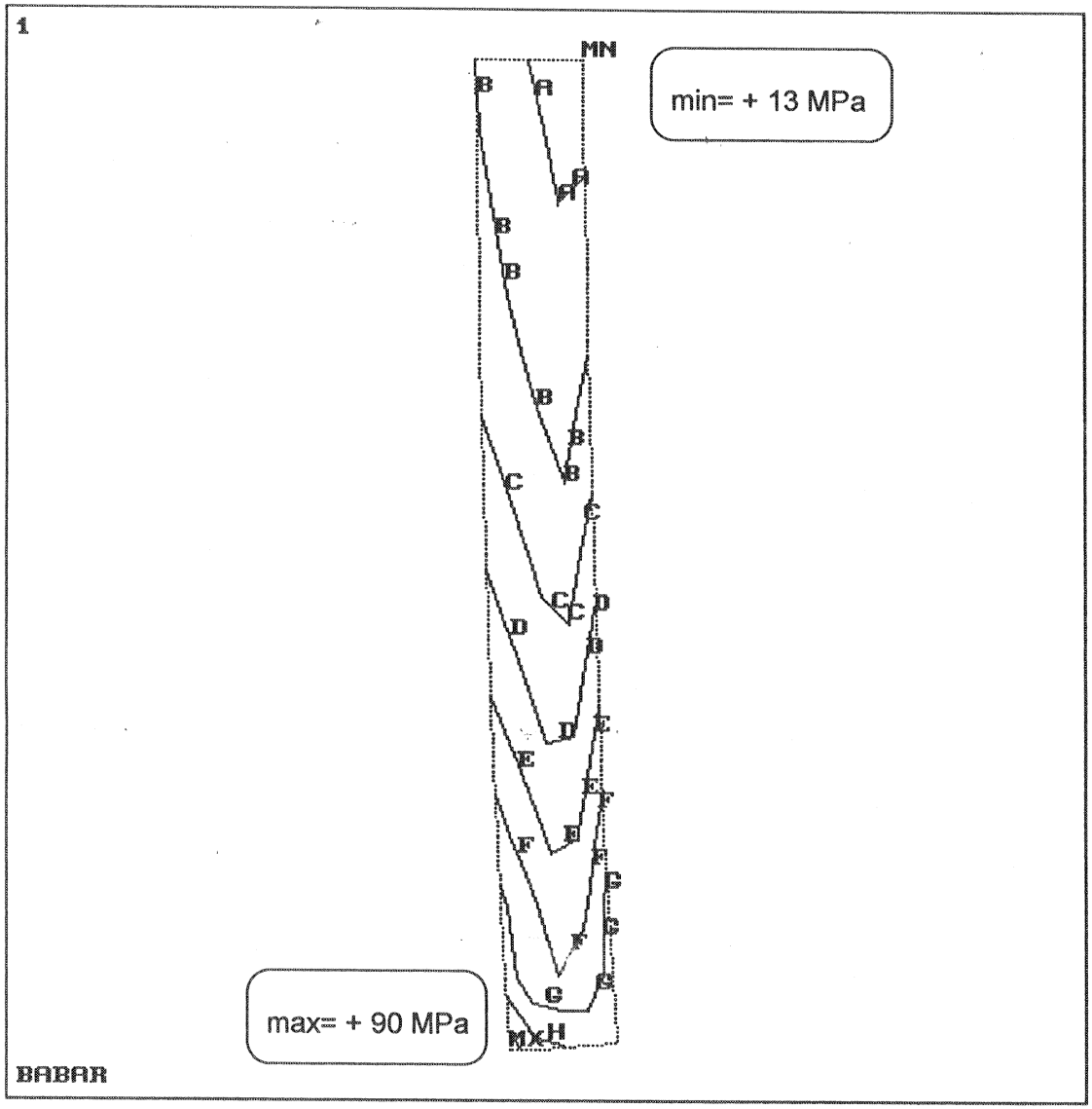
Tref = 4 K - hoop stress in the Al-cylinder (warm end)



ANSYS 5.1
SEP 11 1996
13:56:32
PLOT NO. 6
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SXY (AVG)
RSYS=0
DMX =0.001785
SMN =-0.505E+07
SMX =0.684E+07
A =-0.439E+07
B =-0.307E+07
C =-0.175E+07
D =-427333
E =893435
F =0.221E+07
G =0.353E+07
H =0.486E+07
I =0.618E+07

full range:
min= - 5 MPa
max= + 7 MPa

Tref = 4 K - shear stress in the Al-cylinder (warm end)



ANSYS 5.1
SEP 11 1996
13:56:36
PLOT NO. 7
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SINT (AVG)
DMX =0.001785
SMN =0.134E+08
SMX =0.896E+08
A =0.177E+08
B =0.261E+08
C =0.346E+08
D =0.431E+08
E =0.515E+08
F =0.600E+08
G =0.685E+08
H =0.769E+08
I =0.854E+08

full range:
min= + 0.3 MPa
max= + 90 MPa

Tref = 4 K - stress intensity in the Al-cylinder (warm end)

Progetto
Project

"BABAR" MAGNET

APPROVATO

DA P. VAMENTE

Data 23/10/96

SIMPRO
Componenti S.r.l.

Commessa job no.	TITOLO/title
MGN012	BABAR MAGNET - quench, stress and aluminum strips

Fornitore supplier		IDENTIFICATIVO/document no.	PAG./page	DI/of
N. documento document no.		RDC.034.96.MGN12	1	54

Rev. rev.	Data date	Descrizione description	Redazione prepared by	Verifica checked by	Approv.ne approv. by	Autorizz.ne authoriz. by
0	23.10.96	FIRST ISSUE	MENICATTI		VALLERINI	

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2.4) - quench from end point of internal side, with protection

2.5) - comments on quench analysis results

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5 - REFERENCE DOCUMENTS

1) - ABSTRACT

• Babar winding is a 2-layers solenoid, thermally connected to an aluminum-alloy containment cylinder on the external radius.

• Quench analysis was performed for BABAR magnet in the following 4 cases:

quench starting from internal radius,
central point , with protection resistance
end point, with protection resistance
central point , without protection resistance
end point, without protection resistance

• Temperature distribution in the coil at the end of quench was considered.

• We say "the end of quench" to mean a time when:

1) - almost all magnetic energy has been transformed into thermal energy (see ***Figures 2.1.2, 2.2.2, 2.3.2, 2.4.2***);

2) - maximum temperature in the coil has reached a saturation value (see ***Figures 2.1.1, 2.2.1, 2.3.1, 2.4.1***);

3) - the highest temperature gradient is present (before temperature in the coil goes towards uniformity, that is before maximum temperature saturation value spreads throughout the coil).

• The worst temperature distribution is considered, that is the case with the highest thermal gradient between different points in the coil.

This case was the one with quench starting from one end of internal side od the coil, without protection resistance.

• Temperature distribution in the coil and the aluminum cylinder was imposed to the elements of an Ansys model which was used in previous stress calculations (see ***Ref.1***), to see the resulting stress.

• In order to riduce the stress, it was thought to add aluminum strips on the coil internal radius, placed parallel to the axial direction to spread the quench more quickly in longitudinal direction by thermal conduction, so to make the temperature distribution more uniform and reduce the thermal gradient.

While the external cylinder acts also like a turn where an induced current flows, the internal strips just offer a passive protection by thermal contact.

• The choice of the aluminum type for the strips greatly affects the result: an aluminum alloy like the one of the external cylinder gives a low effect, while an almost-pure aluminum type (high RRR) results in a very positive, decisive effect.

Note: **RRR = residual resistivity ratio = ρ(293 K) / ρ(4K)**

2) QUENCH ANALYSIS (coil + Al-alloy containment cylinder)

Quench analysis for Babar magnet was performed using "Protect" code (see *Ref.2*).

• Geometrical parameters for Babar coil and containment cylinder are summarized in the following table:

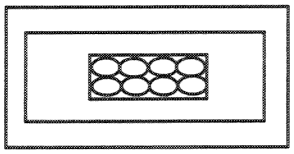
	dimensions [mm]
1st layer internal radius	1500
1st layer external radius	1520.4
interlayer insulation thickness	0.6
2nd layer internal radius	1521
2nd layer external radius	1541.4
insulation thickness between 2nd layer and containment cylinder	1
containment cylinder internal radius	1542.4
containment cylinder thickness	35
containment cylinder external radius	1577.4
total length of coil	3480

Table 1.1)

(note: according to the most recent project, internal radius of first layer is not 1500 mm but 1507.8 mm)

• Containment cylinder is made with aluminum alloy 5083(O).

• The cable is rectangular-shaped, made by a central Rutherford cable (copper+superconductor) surroundend by high-purity aluminum (RRR=1000) and 0.2 mm thick insulation.



• In the real magnet there are 2 different cable sizes, one is 20.4 x 5.33 mm^2 (insulated) which is used for the side parts of the coil (for both layers) and the other one is 20.4 x 8.89 mm^2 (insulated) which is used for the central part of the coil (for both layers).

The Rutherford and insulation are the same, so the only difference is the amount of aluminum in the cable.

The Rutherford size is 1.4 x 5.75 mm^2.

• In "Protect" analysis the higher current density (=the smaller) cable was used for the whole coil.

Keeping the same coil length, this means a higher number of ampere-turns:
- real # of ampereturns = (188+166+188) = 542 per layer;
- # of ampereturns for this analysis = 3480 mm / 5.33 mm = 653 per layer.

• As a consequence, in this analysis we consider a higher magnetic field and magnetic energy (in this sense, the analysis is conservative).

• We can show that the calculation is conservative also if we consider the iron contribution to magnetic energy.
In fact:

- real coil, without iron: L=2.19 H, E=25 MJ

- energy (or inductance) ratio with iron / without iron, from Opera calculations for the previous 1-layer project: 1.27

- So, estimation for real coil with iron is: L=2.78 H, E=32 MJ

- Comparison with calculation coil, without iron: L=3.18 H, E=37 MJ

So magnetic energy in the <u>calculation</u> case, <u>without</u> iron, is higher than magnetic energy in the <u>real</u> case, <u>with</u> iron.

This means the calculation is really conservative from the point of view of magnetic energy which is transformed into thermal energy during the quench.

• Other parameters useful for the analysis are summarized in the following table:

operative current	4811 A
copper / superconductor ratio	1.1
filament diameter	40 μm
twist pitch	20 mm
RRR copper in the cable	100
RRR aluminum in the cable	1000
RRR containment cylinder aluminum	1.87
protection resistance	0.068 Ω

Table 1.2)

QUENCH starting from INTERNAL RADIUS, CENTRAL POINT;
WITH PROTECTION (Rdump=0.068 Ohm);
aluminum cylinder on esternal radius

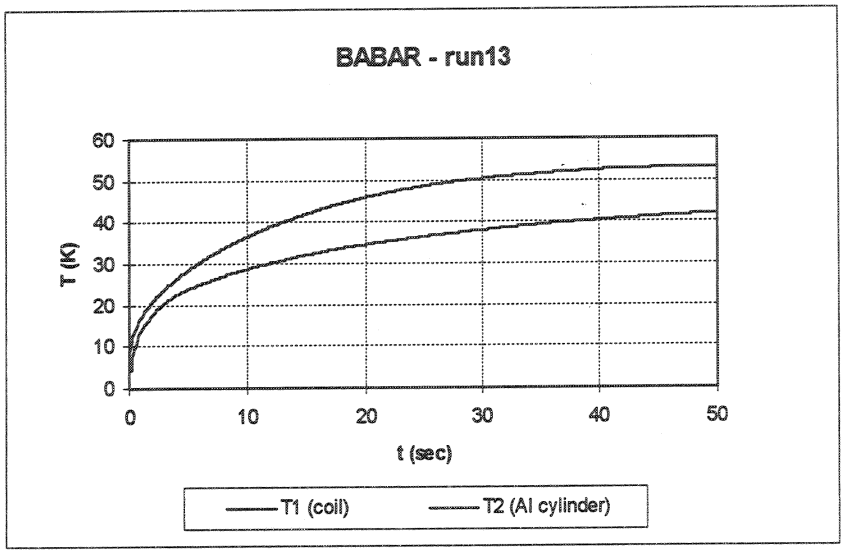


Fig. 2.1.1) - plot of maximum temperature (versus time) in coil and cylinder:
final Tmax of coil = **53 Kelvin**
final Tmax of Al cylinder = 42 Kelvin

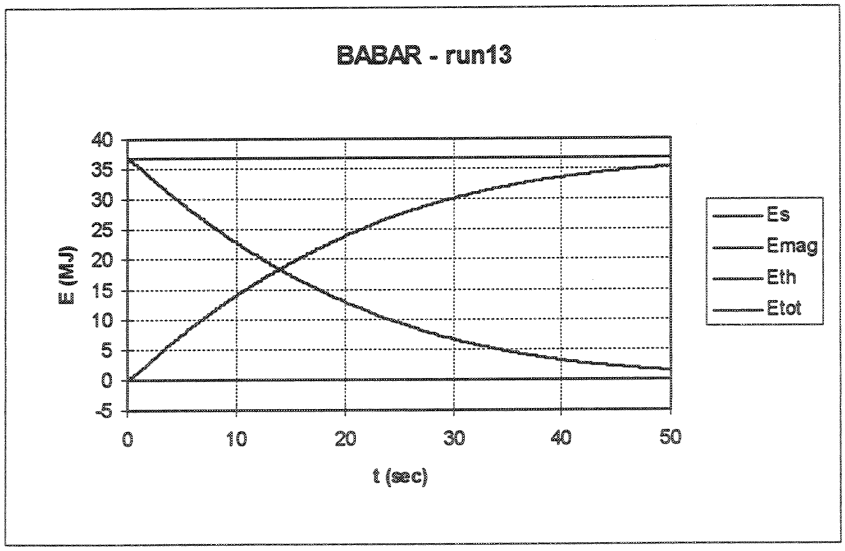


Fig. 2.1.2) - Energy plot:
E_{mag}= Magnetic energy, E_{th}=thermal energy, E_{tot}=total energy=E_{mag}+E_{th}

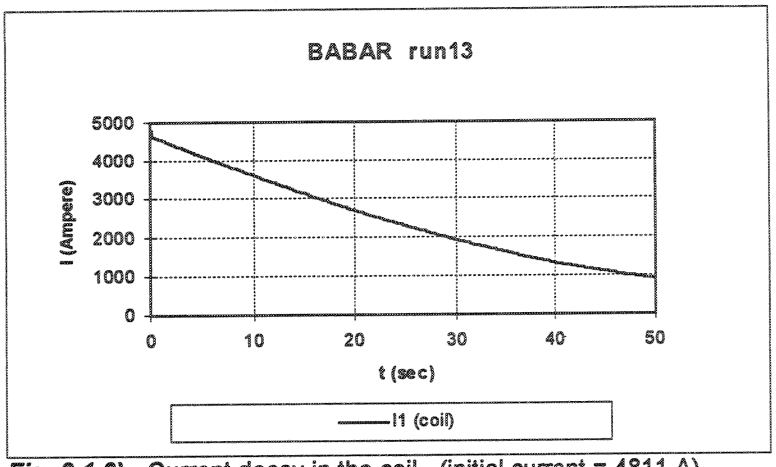


Fig. 2.1.3) - Current decay in the coil (initial current = 4811 A)

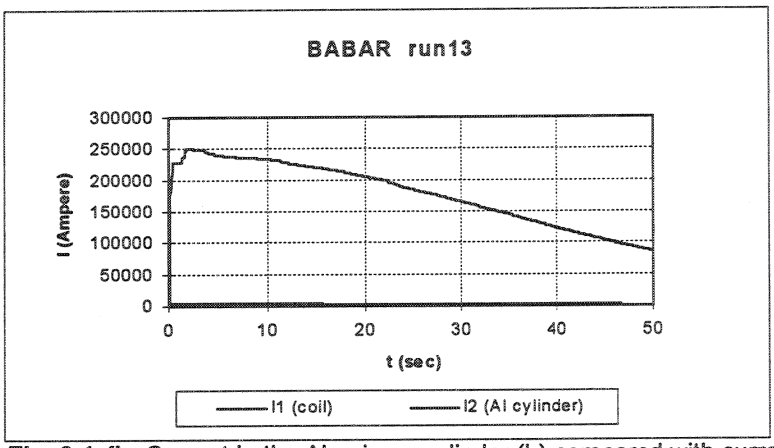


Fig. 2.1.4) - Current in the Aluminum cylinder (I_2) compared with current in the coil (I_1): I2,max = 251000 A, at t ≅ 2 sec.

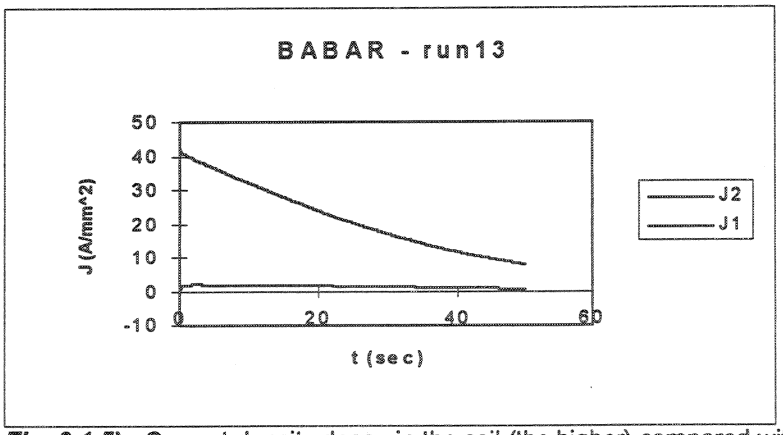


Fig. 2.1.5) - Current density decay in the coil (the higher) compared with current density in the Aluminum cylinder (the lower)

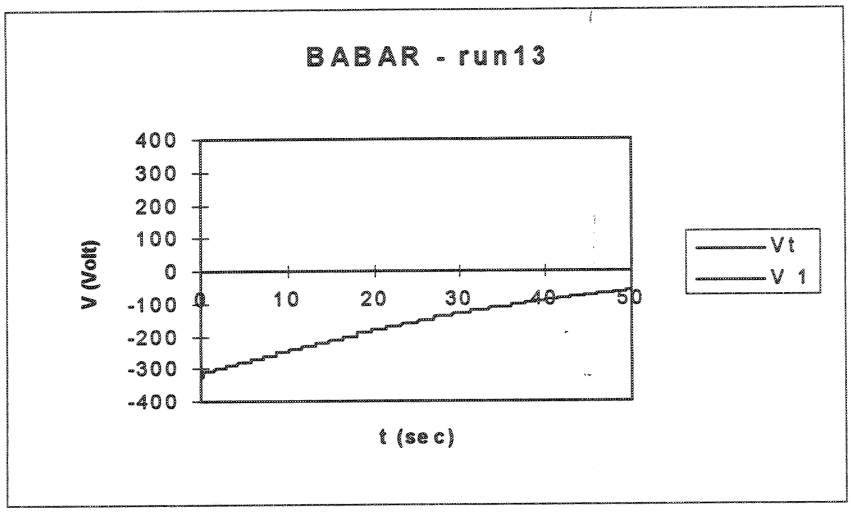


Fig. 2.1.6) - Voltage plot

Vo= - (4811 A) * (0.068 Ohm) = - 327 Volt

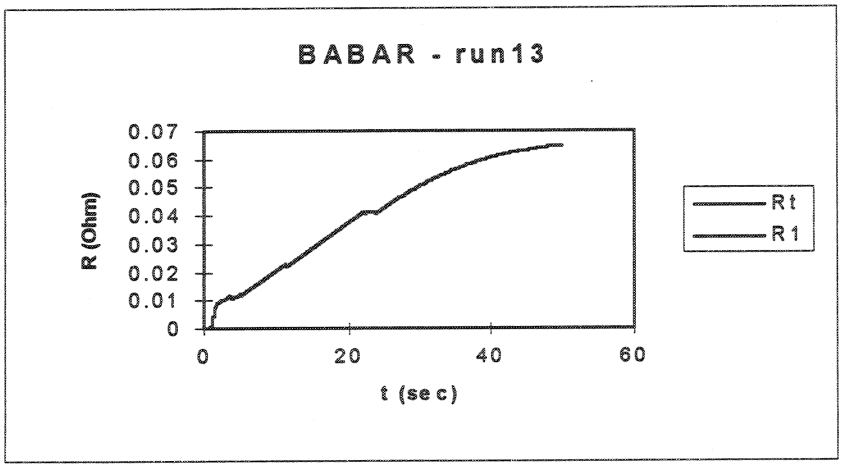


Fig. 2.1.7) - Growing resistance in the coil

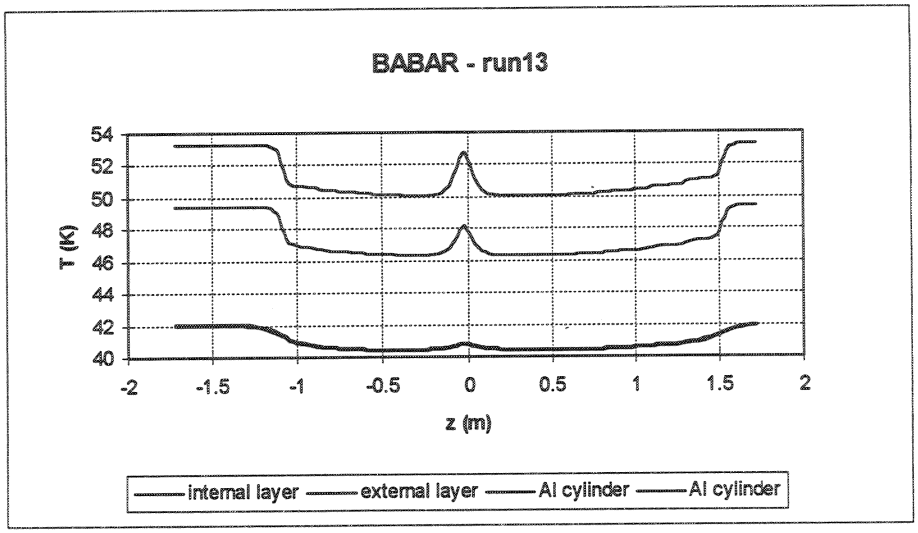


Fig. 2.1.8) - Axial temperature distribution at the "final" time (t=50 sec from the quench start)

QUENCH starting from INTERNAL RADIUS, CENTRAL POINT;
WITHOUT PROTECTION (Rdump=0.0001 Ohm for the calculation);
aluminum cylinder on esternal radius

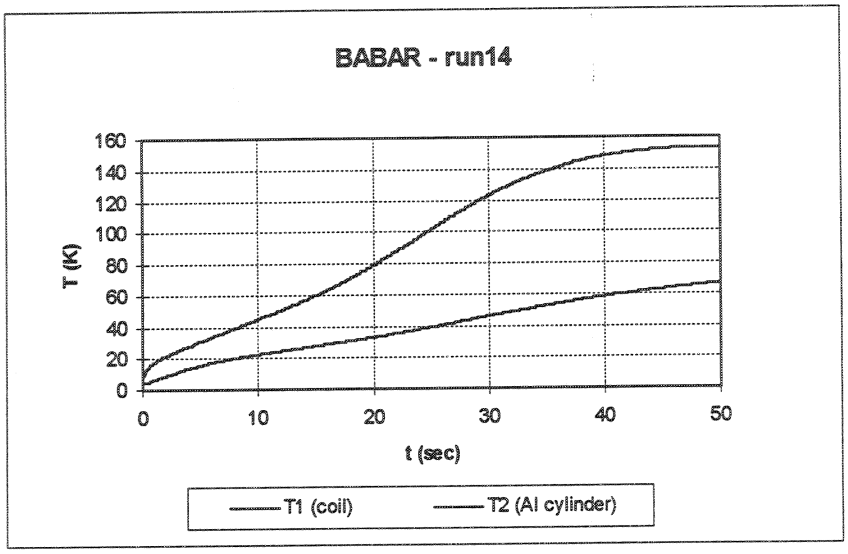


Fig. 2.2.1) - plot of maximum temperature (versus time) in coil and cylinder:

final Tmax of coil = **154 Kelvin**
final Tmax of Al cylinder = 67 Kelvin

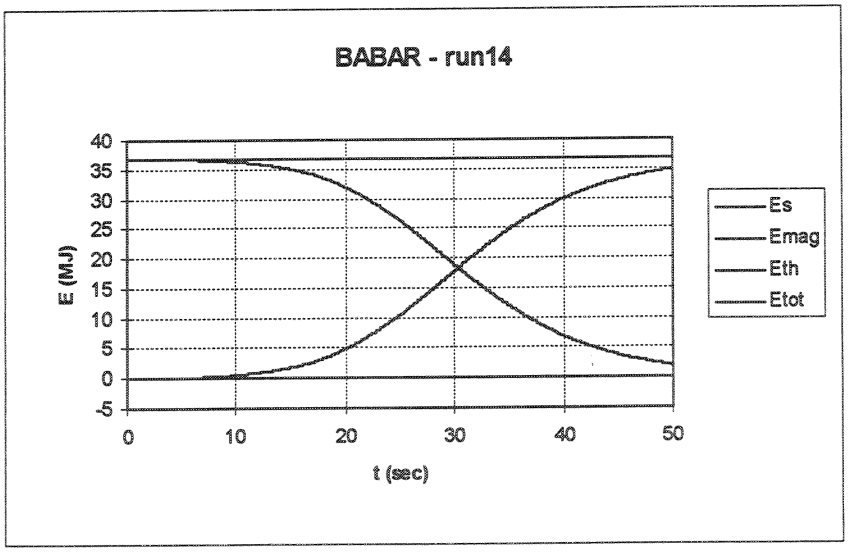


Fig. 2.2.2) - Energy plot:
E_{mag}= Magnetic energy, E_{th}=thermal energy, E_{tot}=total energy=E_{mag}+E_{th}

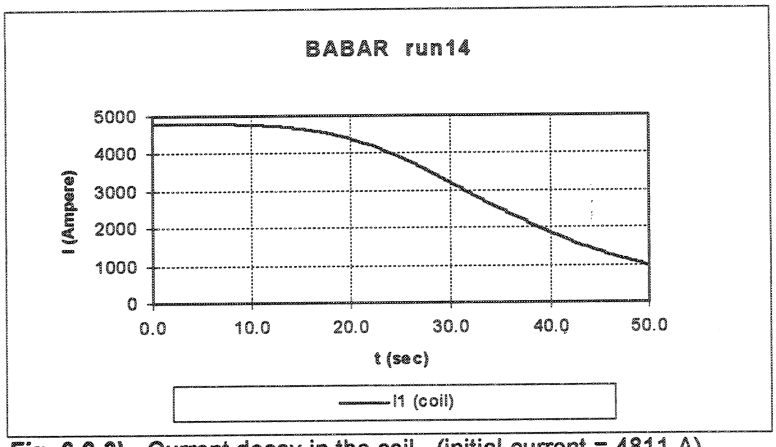


Fig. 2.2.3) - Current decay in the coil (initial current = 4811 A)

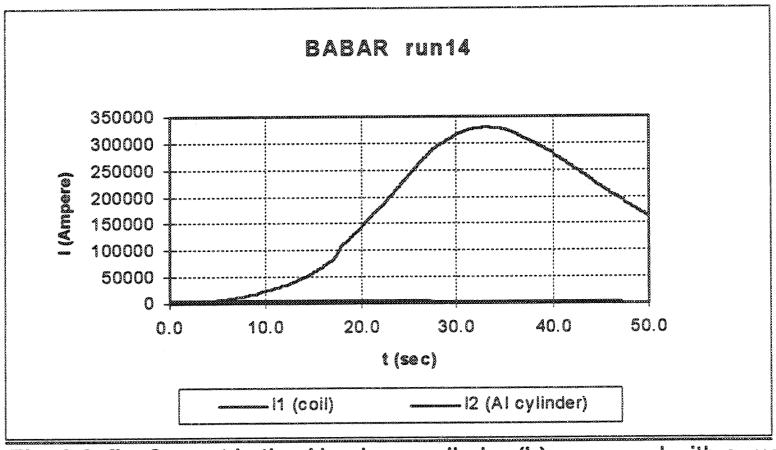


Fig. 2.2.4) - Current in the Aluminum cylinder (I_2) compared with current in the coil (I_1): I2,max = 330000 A, at t ≅ 33 sec.

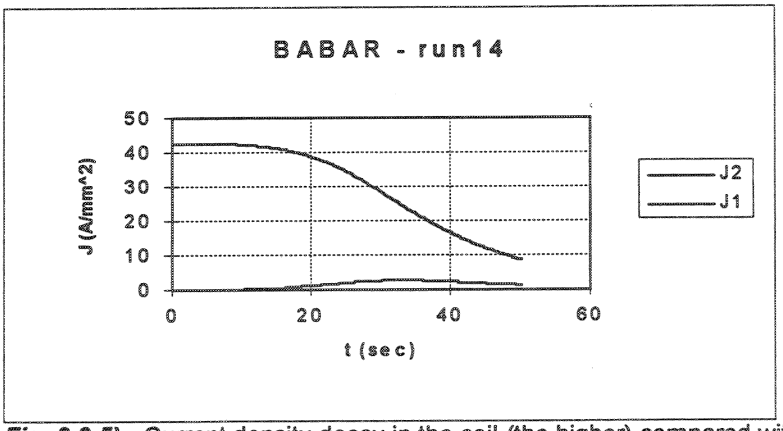


Fig. 2.2.5) - Current density decay in the coil (the higher) compared with current density in the Aluminum cylinder (the lower)

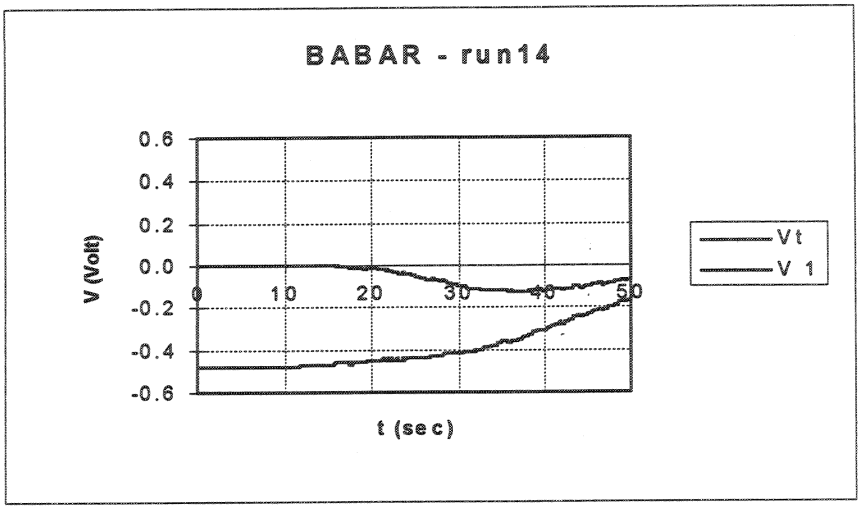


Fig. 2.2.6) - Voltage plot

Vo= - (4811 A) * (0.0001 Ohm) = - 0.48 Volt

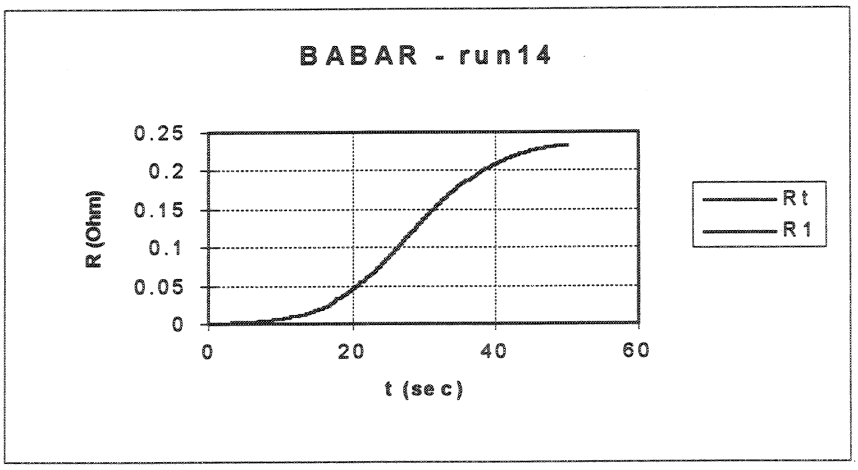


Fig. 2.2.7) - Growing resistance in the coil

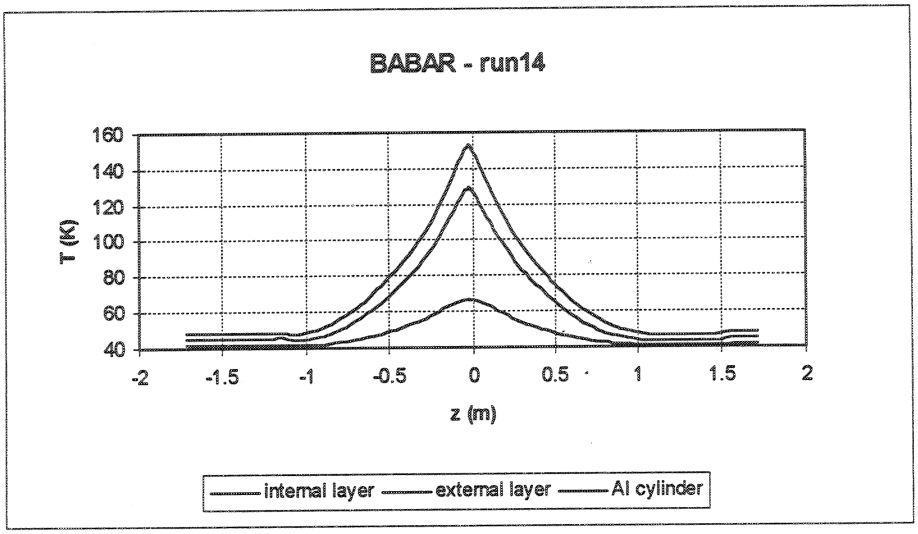
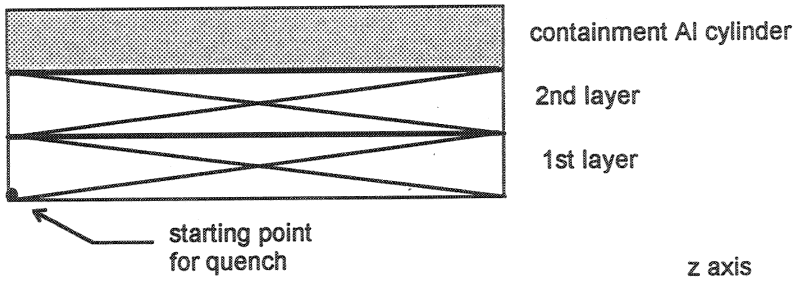


Fig. 2.2.8) - Axial temperature distribution at the "final" time (t=50 sec from the quench start)

2.3) - QUENCH FROM END POINT OF INTERNAL SIDE, WITHOUT PROTECTION



- Protection resistance: Rdump=0.0001 Ohm (for the computation)
- Containment aluminum cylinder (RRR=1.87)

2.4) - QUENCH FROM END POINT OF INTERNAL SIDE, WITH PROTECTION

- Protection resistance: Rdump=0.068 Ohm
- Containment aluminum cylinder (RRR=1.87)

Results are shown in the following Figures:

QUENCH starting from INTERNAL RADIUS, END POINT;
WITHOUT PROTECTION (Rdump=0.0001 Ohm for the calculation);
aluminum cylinder on esternal radius

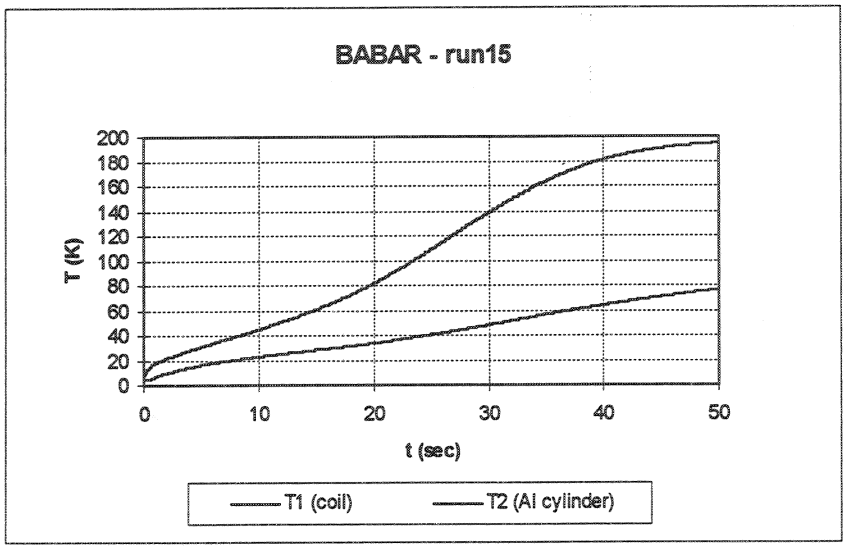


Fig. 2.3.1) - plot of maximum temperature (versus time) in coil and cylinder:

final Tmax of coil **= 195 Kelvin**
final Tmax of Al cylinder = 77 Kelvin

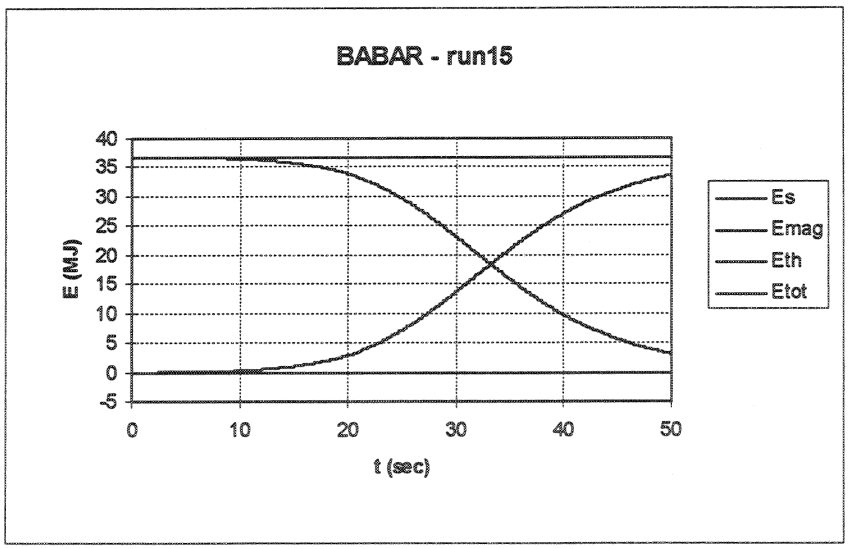


Fig. 2.3.2) - Energy plot:
E_{mag}= Magnetic energy, E_{th}=thermal energy, E_{tot}=total energy=E_{mag}+E_{th}

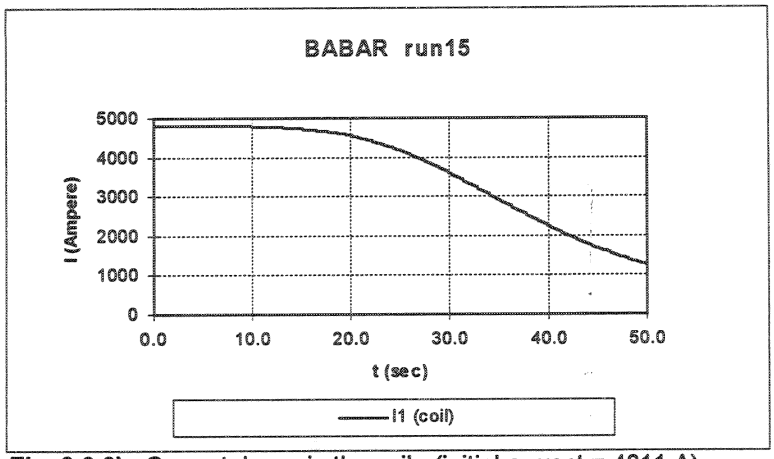


Fig. 2.3.3) - Current decay in the coil (initial current = 4811 A)

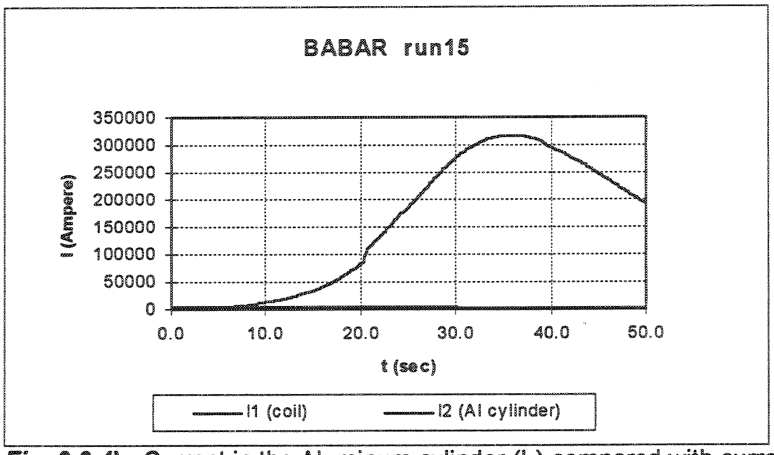


Fig. 2.3.4) - Current in the Aluminum cylinder (I_2) compared with current in the coil (I_1): I2.max = 318000 A, at t ≅ 36 sec.

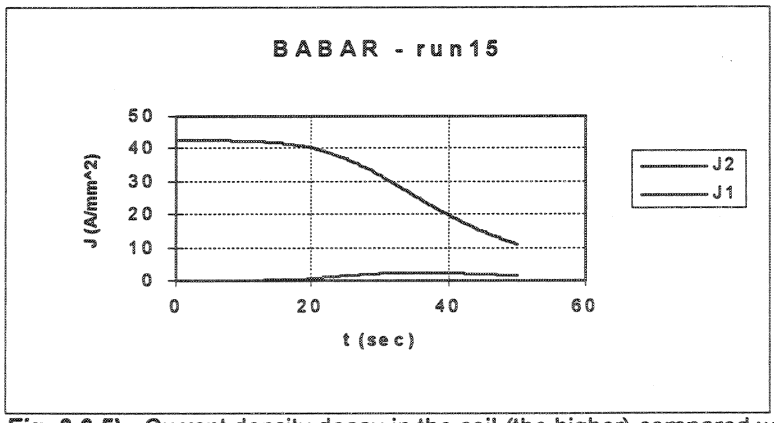


Fig. 2.3.5) - Current density decay in the coil (the higher) compared with current density in the Aluminum cylinder (the lower)

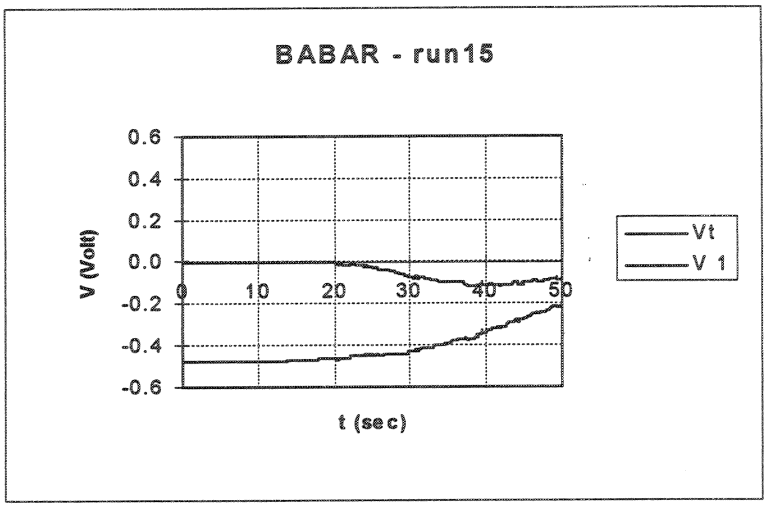


Fig. 2.3.6) - Voltage plot

Vo= - (4811 A) * (0.0001 Ohm) = - 0.48 Volt

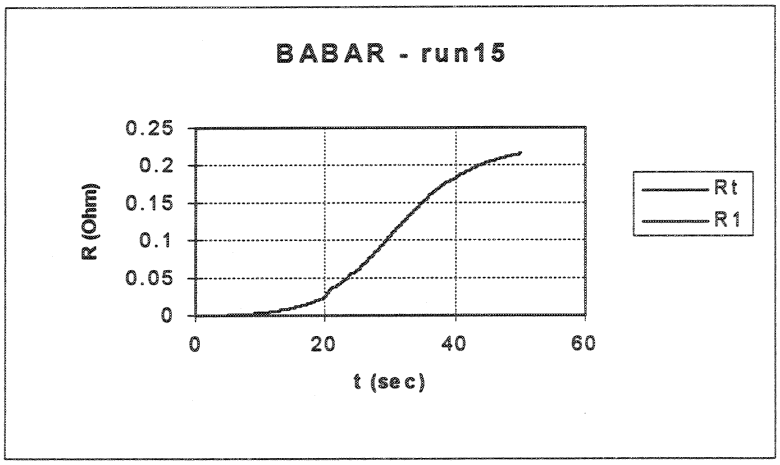


Fig. 2.3.7) - Growing resistance in the coil

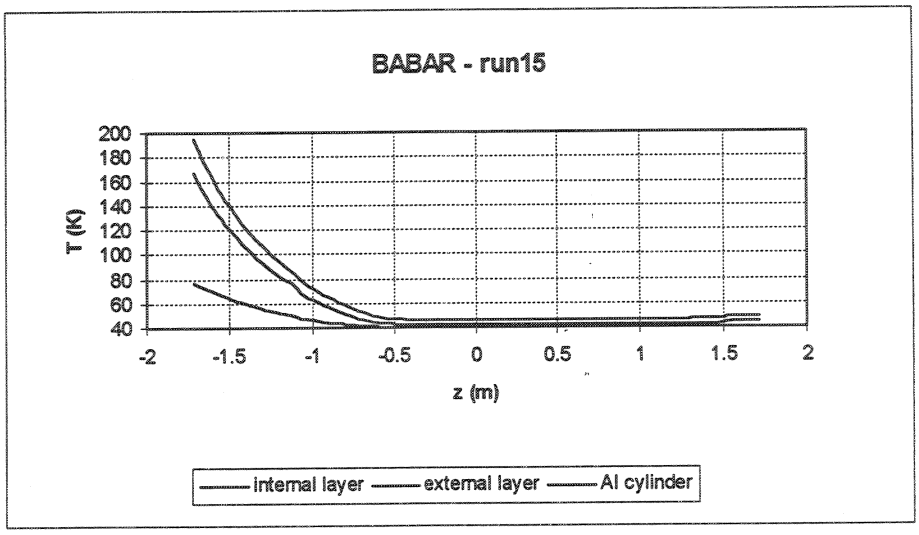


Fig. 2.3.8) - Axial temperature distribution at the "final" time (t=50 sec from the quench start)

QUENCH starting from INTERNAL RADIUS, END POINT;
WITH PROTECTION (Rdump=0.068 Ohm);
aluminum cylinder on esternal radius

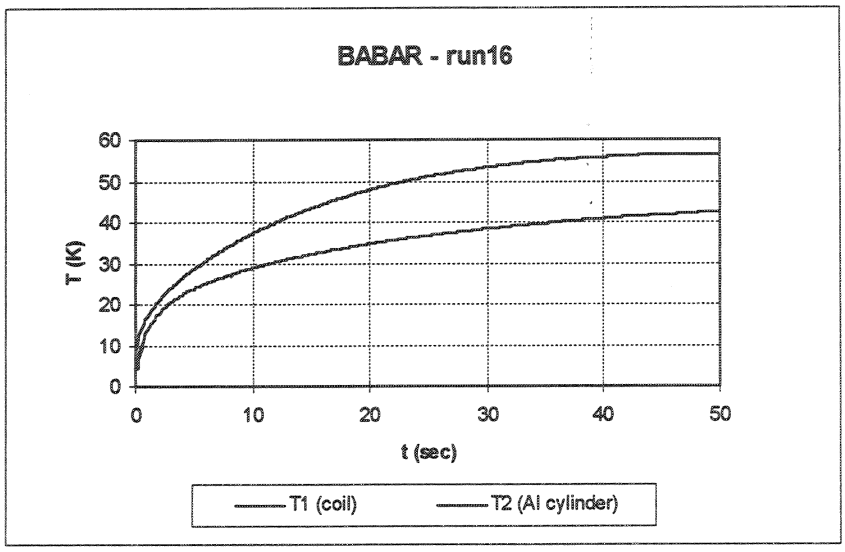


Fig. 2.4.1) - plot of maximum temperature (versus time) in coil and cylinder:

final Tmax of coil = **57 Kelvin**
final Tmax of Al cylinder = 43 Kelvin

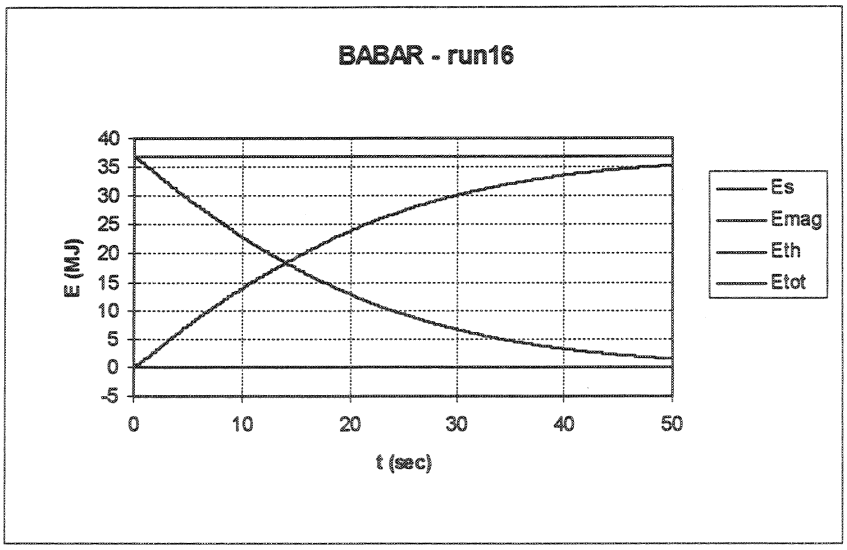


Fig. 2.4.2) - Energy plot:
E_{mag}= Magnetic energy, E_{th}=thermal energy, E_{tot}=total energy=E_{mag}+E_{th}

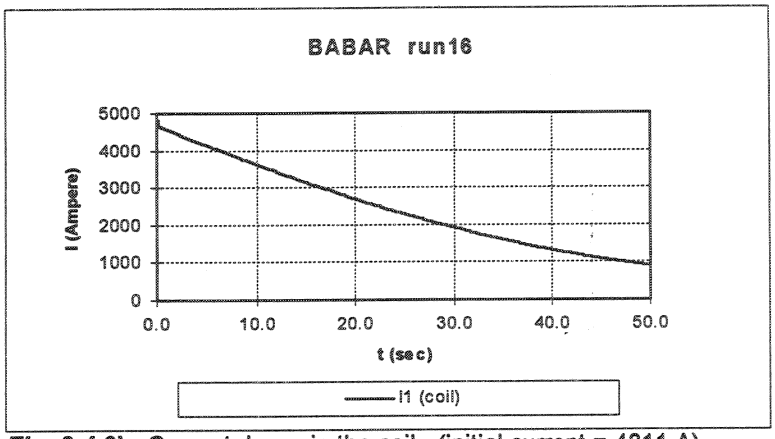


Fig. 2.4.3) - Current decay in the coil (initial current = 4811 A)

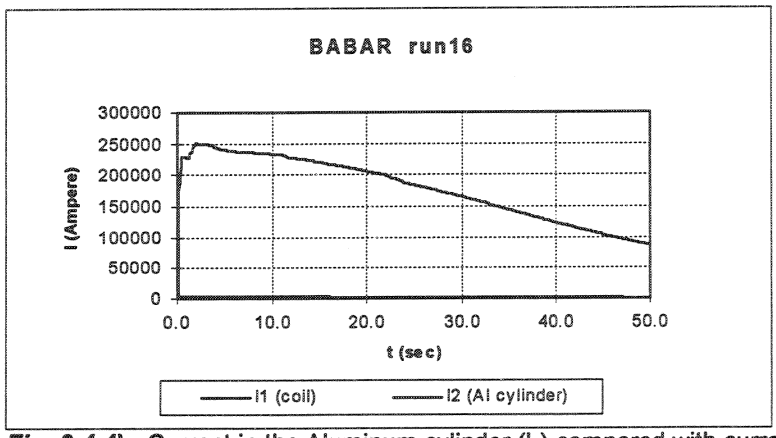


Fig. 2.4.4) - Current in the Aluminum cylinder (I_2) compared with current in the coil (I_1): I2.max = 229000 A, at t ≅ 1 sec.

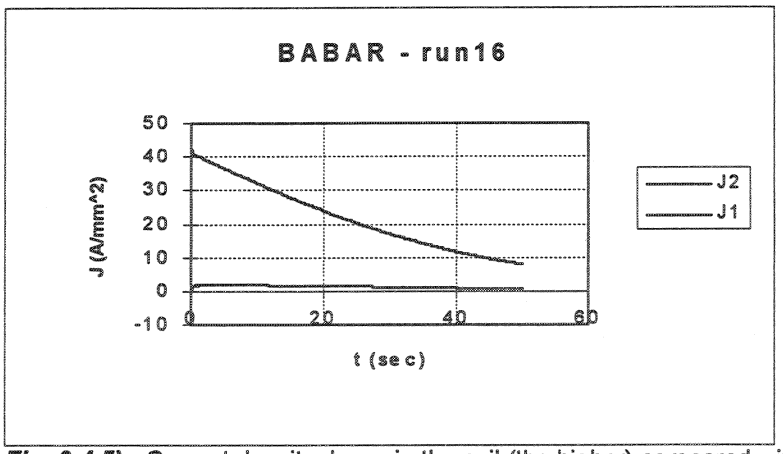


Fig. 2.4.5) - Current density decay in the coil (the higher) compared with current density in the Aluminum cylinder (the lower)

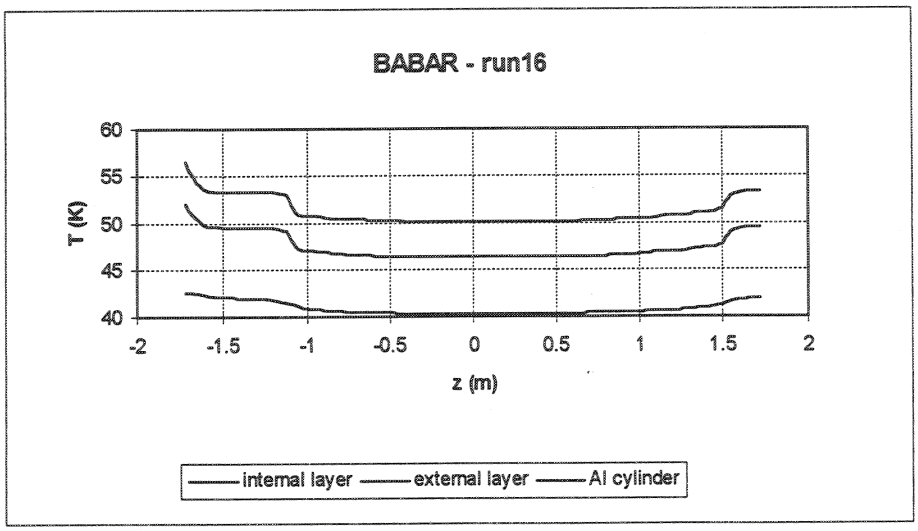


Fig. 2.4.8) - Axial temperature distribution at the "final" time (t=50 sec from the quench start)

2.5) - COMMENTS ON QUENCH ANALYSIS RESULTS

Let's compare final maximum temperature in the 4 cases:

central point, with protection	53 [Kelvin]
central point, without protection	154 [Kelvin]
end point, without protection	**195** [Kelvin]
end point, with protection	57 [Kelvin]

The worst case is: quench started from end point, without protection resistance (Tmax,fin = 195 Kelvin).

Temperature distribution at time t=50 sec from the quench start, is shown in ***Figure 2.3.8***).

Note the high temperature gradient

- between 2 points of internal layer (the warmest point where quench started and a point 1 meter far in z axis: $\Delta T \cong 140$ K)

  and

- between internal layer and containment cylinder ($\Delta T \cong 120$ K for the warmest point of coil and cylinder).

These high gradients lead to high stress components.

3) STRESS ANALYSIS for the worst temperature distribution induced by quench

• Temperature results for the worst situation of quench (quench starting from one end of coil, without protection resistance: see ***Figure 3.0a***) were transfered to Ansys axi-symmetric model (see ***Figure 3.0b***) for stress calculations.

• Babar Ansys model is the same "coarse model" used for previous calculations (see ***Reference 1***), but flanges at the end of the aluminum cylinder were not included (to avoid fictitious stress peaks which we already discussed about, and which hide the other, significant, results).

• In this model, both cables are represented: cable type I (20.4 x 5.33 mm^2) at the ends of the coil and type II (20.4 x 8.89 mm^2) in the central part of the coil.
In the quench analysis the two cables were not distinguished.

• Results show that the higher components of stress are the axial stress (Sy) and the hoop stress (Sz). Radial and shear components of stress (Sx, Sxy) are very lower.

• Minimum and maximum algebric values for stress results are reported in the following tables. (A negative value means compression, positive means tension.)

• Thermal expansion always is calculated in connection with a "reference temperature" T_{ref} where all thermal tensions are zero.
In the previous analysis (***Ref.1***) we assumed Tref=450 Kelvin (impregnation temperature).
Now we have done a consistent calculation assuming the same Tref, but we have also repeated the analysis with Tref=4 Kelvin.
The real situation can be halfway the two opposite assumptions.

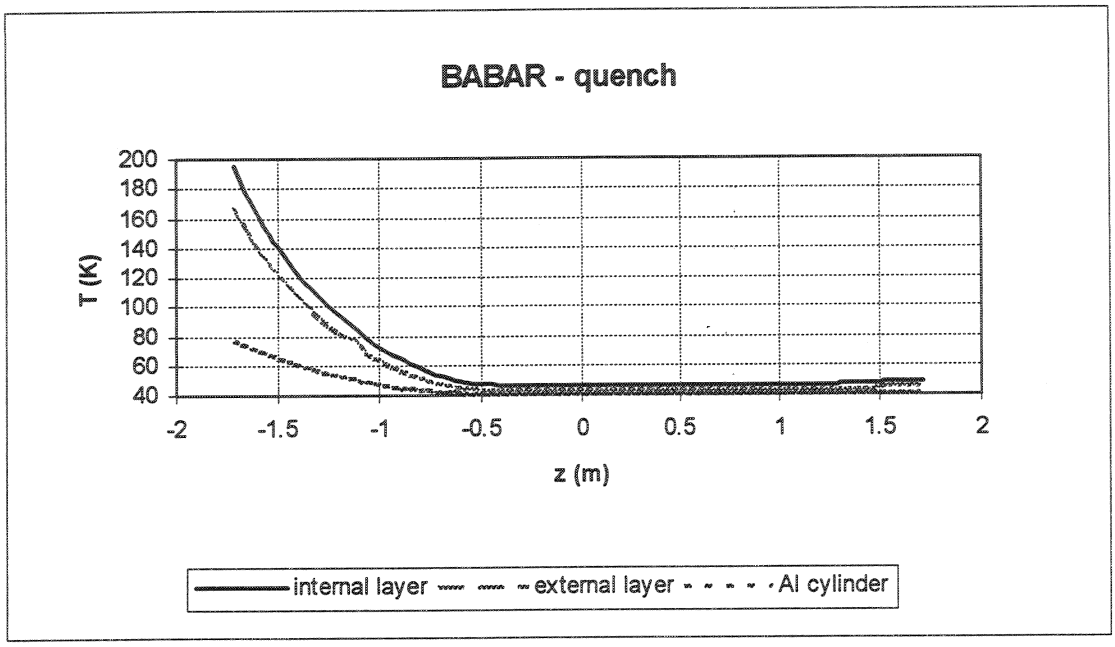
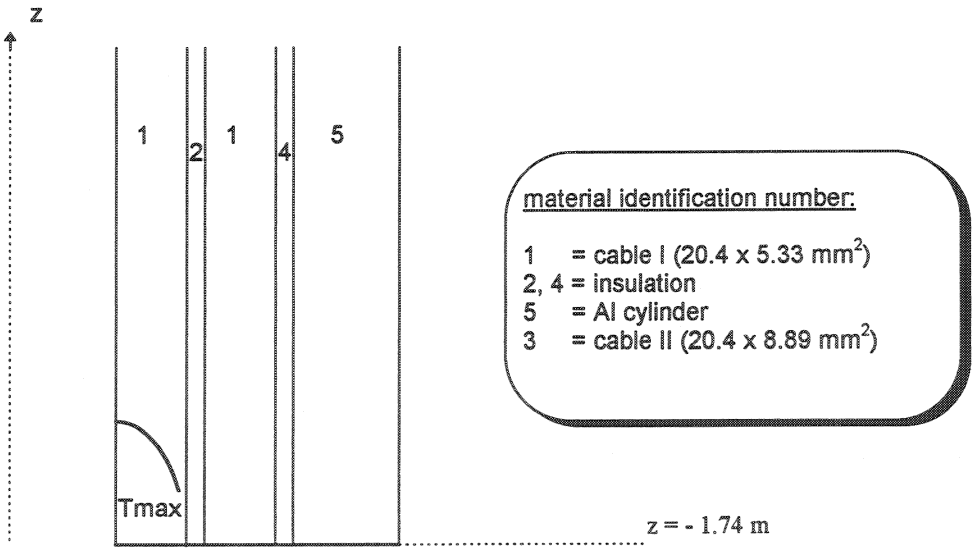
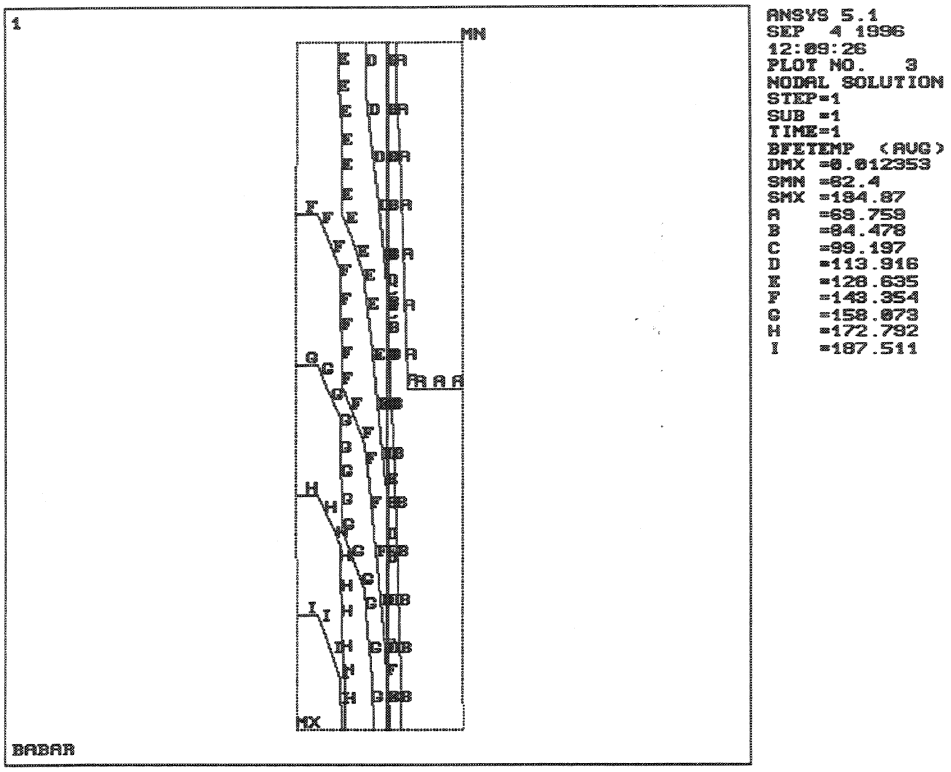


FIG. 3.0a) - TEMPERATURE DISTRIBUTION AT THE END OF QUENCH ANALYSIS (t= 50 SEC); QUENCH STARTED FROM INTERNAL RADIUS, END OF COIL, WITHOUT PROTECTION RESISTANCE; Z = COIL AXIS, MIDPLANE AT Z=0.





3.0b) - TEMPERATURE DISTRIBUTION OF FIG.**3.0a)** WAS TRANSFERED TO ANSYS AXI-SYMMETRIC MODEL ; HERE IS THE DETAIL OF THE MODEL AT THE WARM END .

3.1) - Reference temperature = 450 K

Material properties are the same which were reported in (***Ref.1***), except for thermal expansion coefficients which have been recalculated (the uncorrected coefficients give similar stress values, a little lower for aluminum).

properties at T = 4K, 77 K, 295 K;
x=radial component, y=axial component, z=hoop component

	mat.1 (cable I)	mat.2, mat.4 (insulation)	mat.3 (cable II)	aluminum-alloy cylinder
E [GPa] (elasticity modulus)	Ex=72.9,71.8,64.3 Ey=68.9,67.4,59.8 Ez=74.4,73.5,66.2	Ex=29.1,27.0,22.4 Ey=35.9,33.7,28.0 Ez=35.9,33.7,28.0	Ex=74.1,73.0,65.5 Ey=72.1,70.8,63.3 Ez=75.7,74.8,67.4	Ex=Ey=Ez= 77.7, 77.2, 70.1
ν (Poisson's ratio)	0.34, 0.34, 0.35	0.21, 0.19, 0.15	0.34, 0.34, 0.35	0.327,0.328, 0.338
α [K^{-1}] (thermal expansion, mean coefficient)	17.8e-6, 20.8e-6, 24.2e-6	α_x = 29.9e-6, 34.0e-6, 38.0e-6 $\alpha_y = \alpha_z$ = 9.02e-6, 10.0e-6, 10.0e-6	17.8e-6, 20.8e-6, 24.2e-6	17.9e-6, 20.9e-6, 24.2e-6

$$\alpha_{mean}(T, Tref) := \frac{1}{(Tref - T)} \cdot \frac{L(Tref) - L(T)}{L(Tref)}$$

$$\Updownarrow$$

$$L(T) = L(Tref) \cdot \left(1 - \alpha_{mean} \cdot (Tref - T)\right)$$

Taking into account a reference temperature Tref = 450 K, stress by thermal expansion is dominated by a contribution due to the {T = 4 K} operative situation, to which the temperature distribution due to the quench is added.

For this reason we think the {Tref=4 K} analysis (next chapter) is more significant, showing the stress distribution to be superimposed when the quench happens, no matter what the base stress-state is.

However, the stress values in this computational case (Tref=450 K) are reported in the following ***Table 3.1*** and ***Figures 3.1.1 to 3.1.7***.

stress (MPa)	mat.1 (lateral cable)	mat.2 (interlayer insulation)	mat.3 (central cable)	mat.4 insulation on external radius of coil	mat.5 Al - cylinder
Sx (radial)	-9, +16	- 10, + 18	-0.1, +0.5	-3, +6	-17, +8
Sy (axial)	**- 60**, +34	- 173, -117	+ 0.4, + 3	- 174, - 140	- 39, + **83**
Sz (hoop)	**- 57**, +14	- 173, - 129	+ 1, +4	- 174, - 126	+ 6, + **129**
Sxy (shear)	-6, +10	- 4, + 4	-0.3, +0.05	- 6, + 34	-7, +14
Sint (intensity)	-------	------	------	------	145

Table 3.1 - FULL - RANGE STRESS TABLE FOR T_{ref}= 450 Kelvin ANALYSIS (WORST QUENCH TEMPERATURE DISTRIBUTION)

(full-range = all the model, not only the warm end)

Comments on Table 3.1:

- Stress intensity is defined only for isotropic materials

- Sx, Sxy greatest values are often very localised peaks, while almost all the model has quasi-zero stress component (see ***Figures 3.1.3 and 3.1.6*** for example).

- Focalizing on axial and hoop stress, we point out a strong compression on insulation (fiberglass between first layer and second layer of coil, and between coil and containment cylinder).
As to cables and cylinder, we see that central cable (material 3) has no stress (as it should be because nothing happens in the central part of the coil: maximum temperature is at one end, see ***Figure 3.0a***).
Higher stress is on side cable (material 1) and cylinder (material 5), both at the warm end (see ***Figures 3.1.1, 3.1.2, 3.1.4, 3.1.5***).

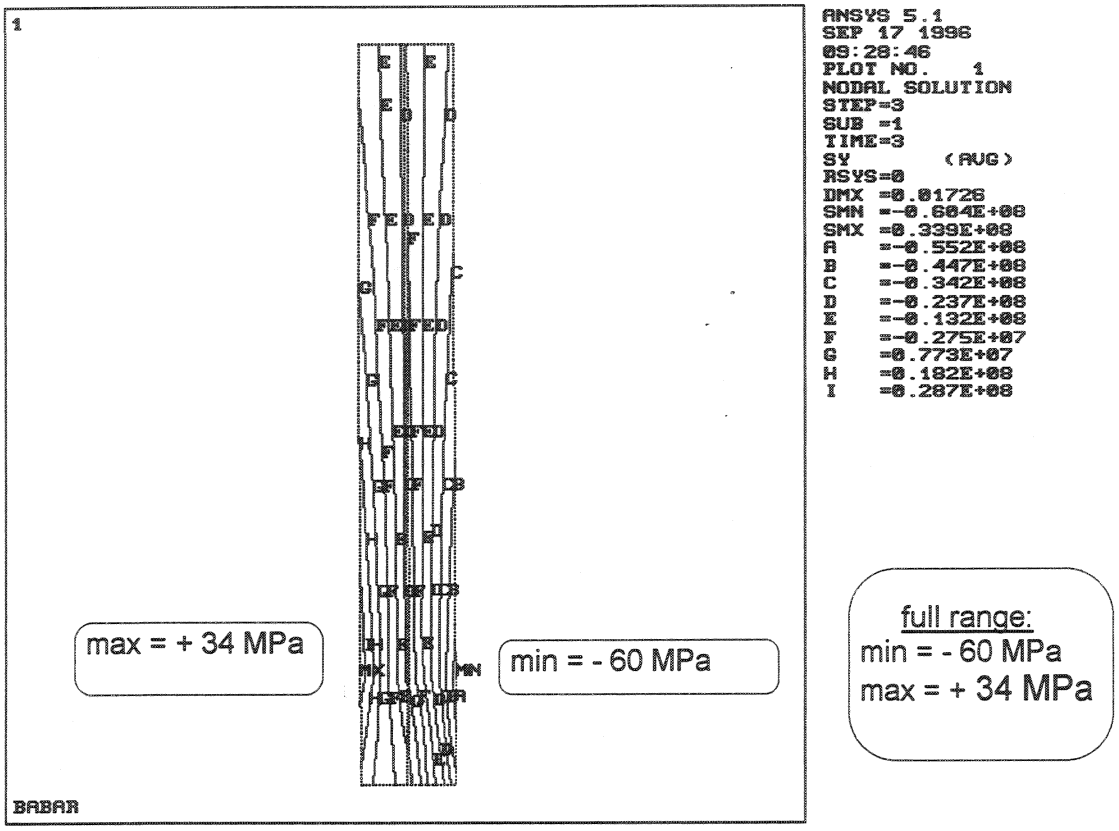


Fig. 3.1.1) - axial stress in the coil (warm end) for T_{ref}=450 K

Notes:
Coil in compression on external side, tension on internal side.
Compare with ***Fig.3.1.4***).

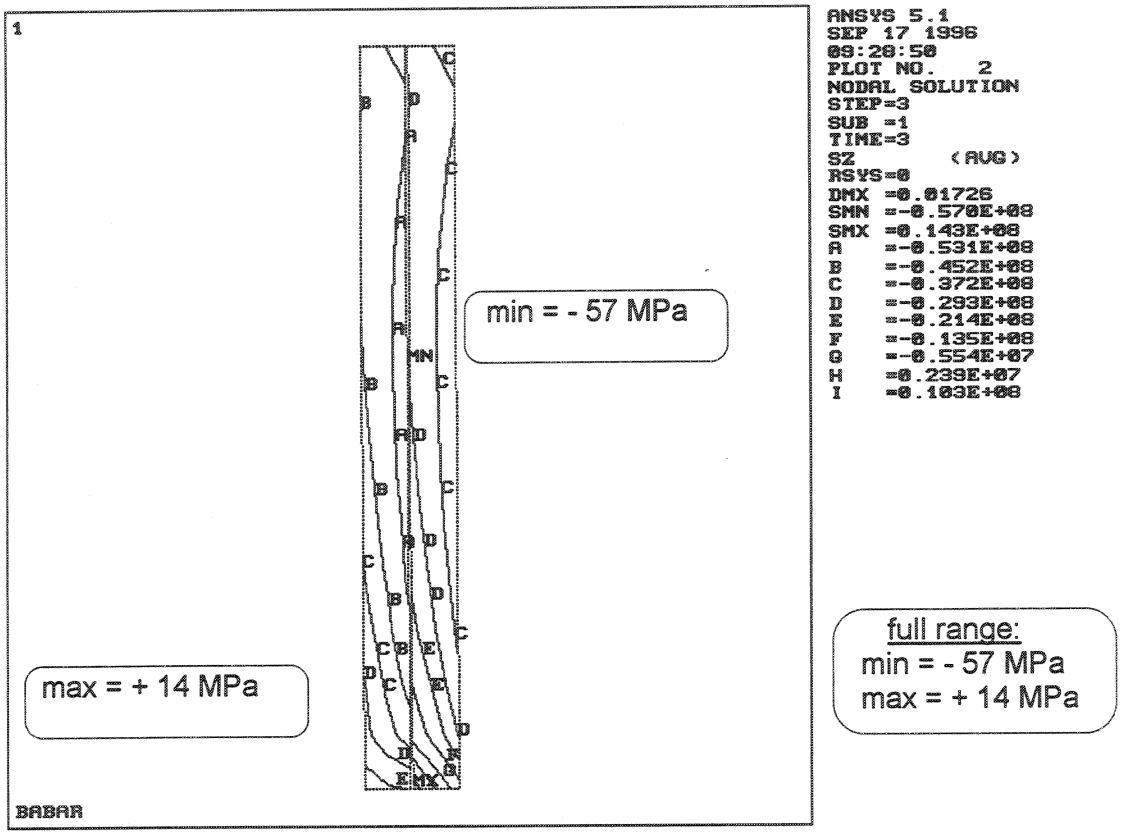


Fig. 3.1.2) - hoop stress in the coil (warm end) for T_{ref}=450 K

Notes:
Coil is almost all in compression, especially on external side (near containment cylinder)

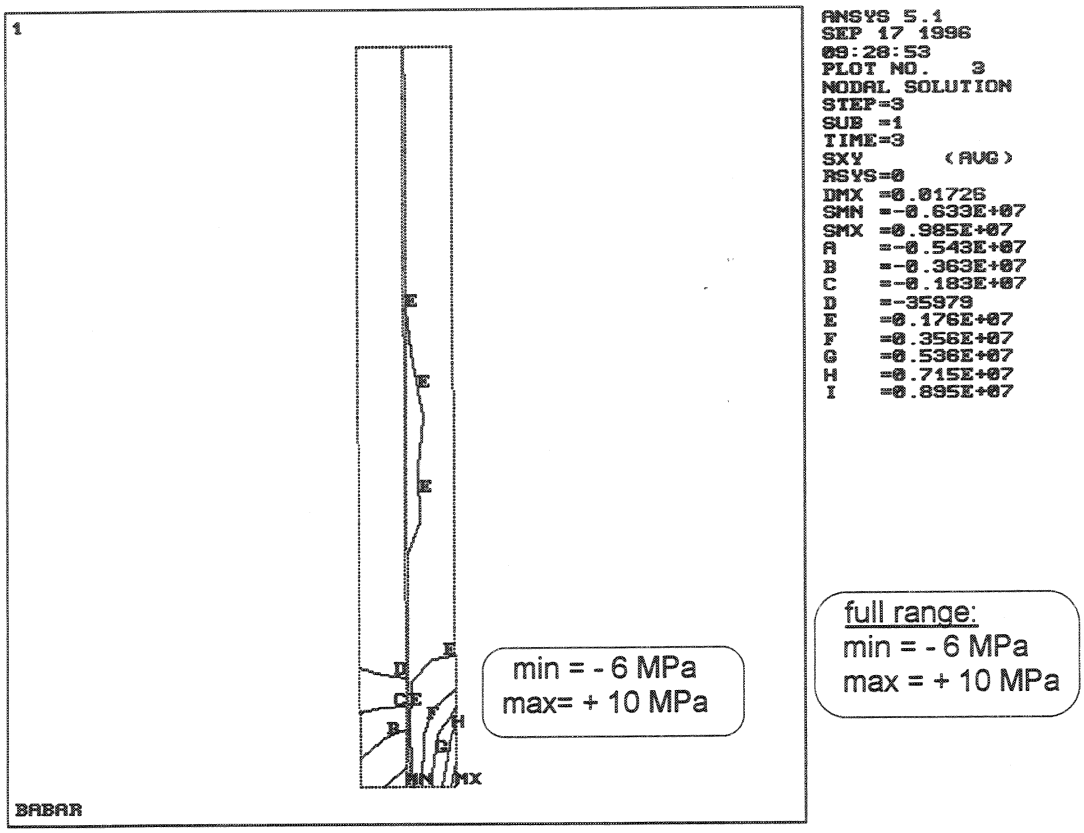


Fig. 3.1.3) - shear stress in the coil (warm end) for T_{ref} = 450 K -

Notes:
Min. and Max. are just localised peaks.
Throughout the rest of the model shear stress is about zero (lines D-E).

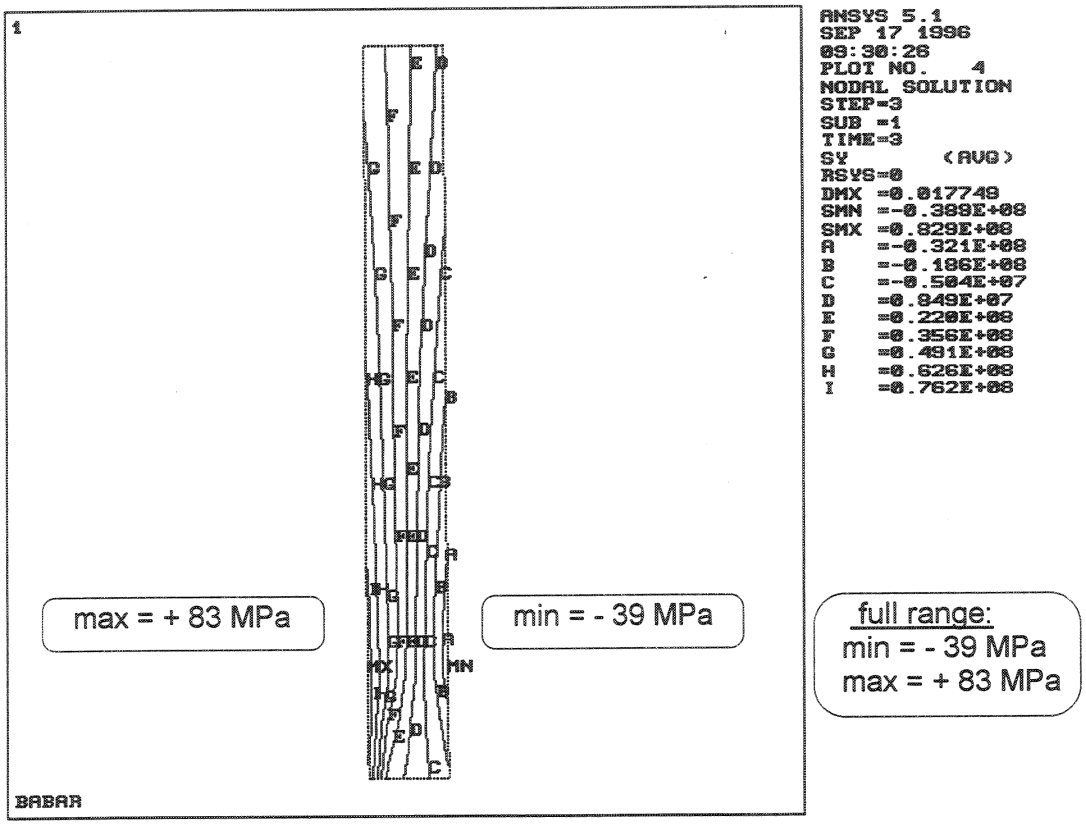


Fig. 3.1.4) - axial stress in the Aluminum cylinder (warm end) for T_{ref}=450 K

Notes:
Containment cylinder is in tension at the internal side (near the coil, which in turn is in compression: see ***Figure 3.1.1***).

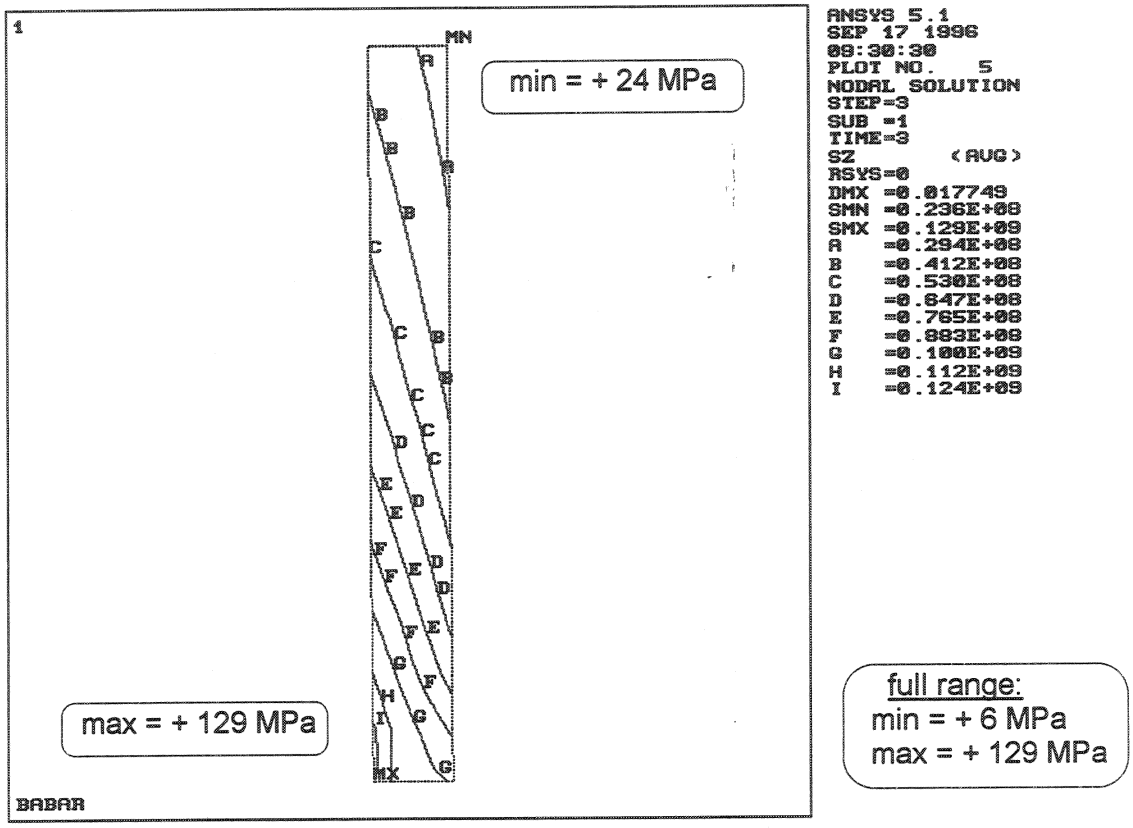


Fig. 3.1.5)- hoop stress in the aluminum cylinder (warm end) for T_{ref}=450 K

Notes:
Containment cylinder is in tension, with a maximum at the warmest point.
Compare with ***Fig. 3.1.2*** (coil in compression).

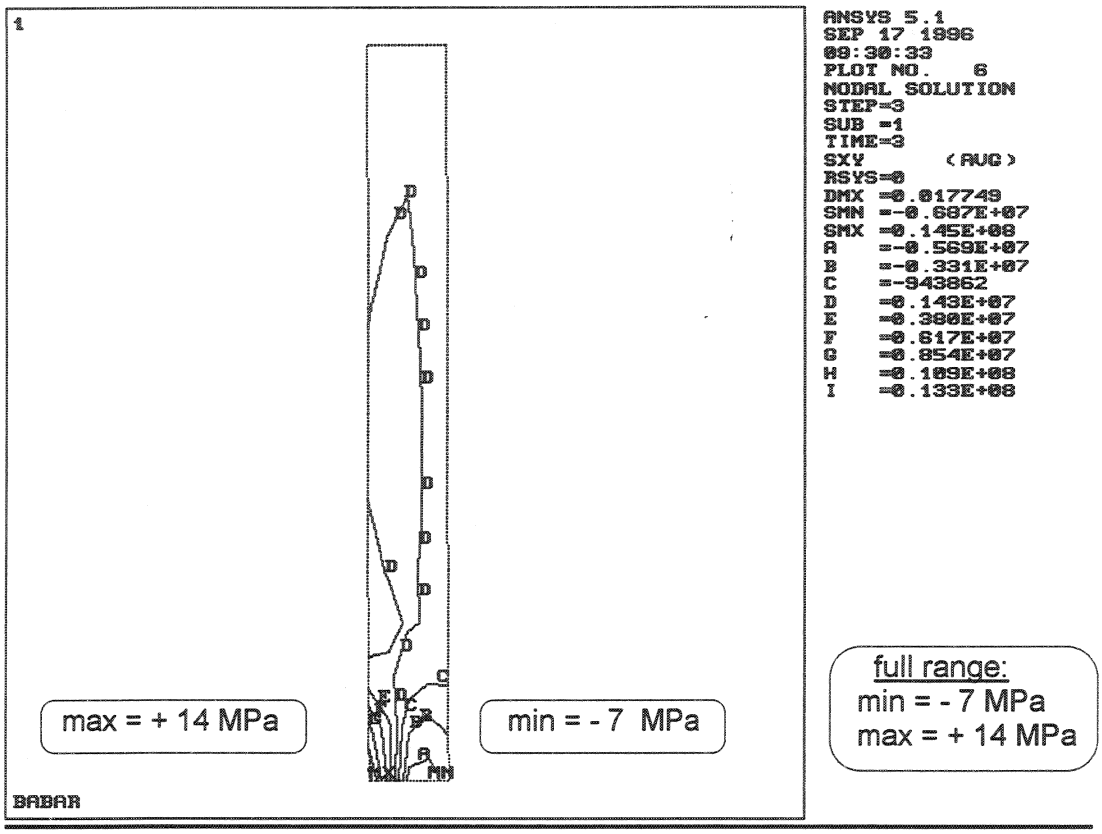


Fig. 3.1.6) - shear stress in the Aluminum cylinder (warm end) for Tref=450 K

Notes:
Min. and Max. are just localised peaks.
Throughout the rest of the model shear stress is about zero (lines C-D).

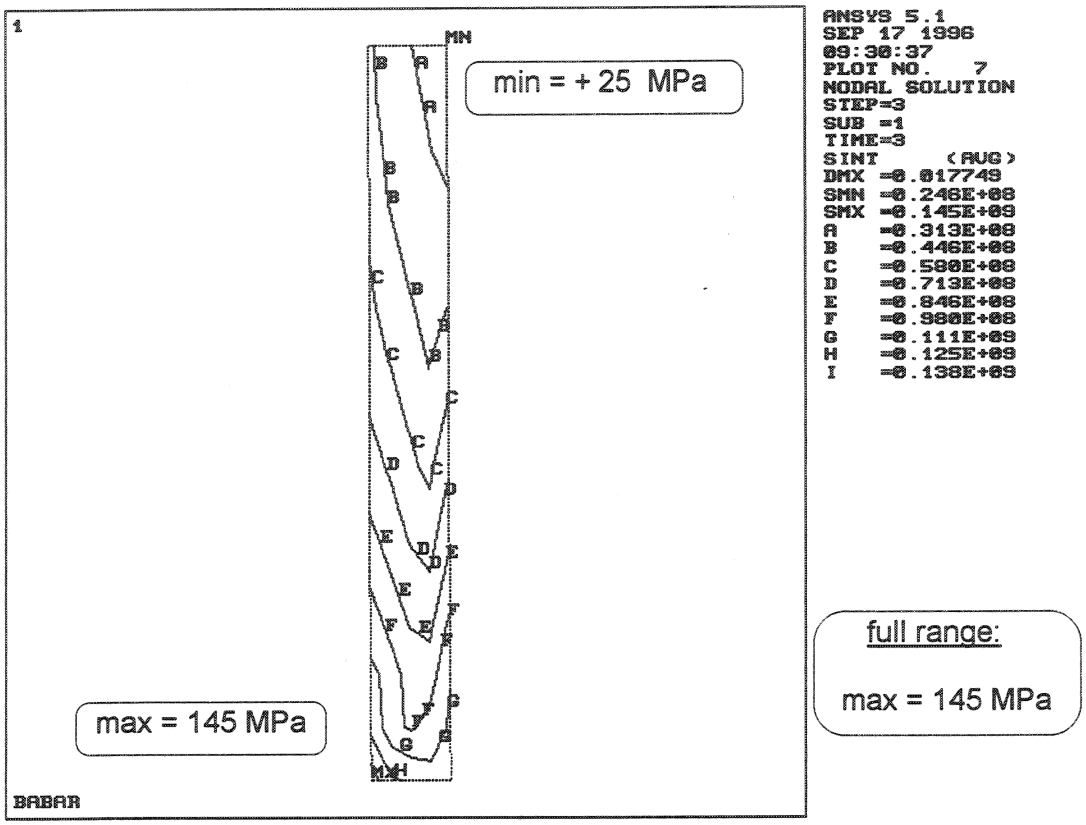


Fig. 3.1.7) - stress intensity in the Aluminum cylinder (warm end) for T_{ref} = 450 K

Notes:
Stress intensity map is similar to hoop stress map (***Fig. 3.1.5***).

3.2) - Reference temperature = 4 K

Material properties are the same of chapter ***3.1***), except for thermal expansion coefficients which have been recalculated for reference temperature Tref = 4 K, basing on ***Ref. 3 and 4***.

properties at T = 4K, 77 K, 295 K;
x=radial component, y=axial component, z=hoop component

	mat.1 (cable I)	mat.2, mat.4 (insulation)	mat.3 (cable II)	aluminum-alloy cylinder
E [GPa] (elasticity modulus)	Ex=72.9,71.8,64.3 Ey=68.9,67.4,59.8 Ez=74.4,73.5,66.2	Ex=29.1,27.0,22.4 Ey=35.9,33.7,28.0 Ez=35.9,33.7,28.0	Ex=74.1,73.0,65.5 Ey=72.1,70.8,63.3 Ez=75.7,74.8,67.4	Ex=Ey=Ez= 77.7, 77.2, 70.1
ν (Poisson's ratio)	0.34, 0.34, 0.35	0.21, 0.19, 0.15	0.34, 0.34, 0.35	0.327,0.328, 0.338
α [K^{-1}] (thermal expansion, mean coefficient)	0, 3.16e-6, 14.4e-6	α_x =0, 12.1e-6, 19.4e-6 $\alpha_y = \alpha_z$=0,4.9e-6,9.2e-6	0, 3.16e-6, 14.4e-6	0, 3.55e-6, 14.5e-6

$$\alpha_{mean}(T, Tref) := \frac{1}{(Tref - T)} \cdot \frac{L(Tref) - L(T)}{L(Tref)}$$

$$\Updownarrow$$

$$L(T) = L(Tref) \cdot \left(1 - \alpha_{mean} \cdot (Tref - T)\right)$$

Note that alpha coefficient is always defined as positive.
If Tref>T, L(Tref)>L(T). This is the case Tref=450 K, for example.
If Tref<T, L(Tref)<L(T). This is the present case, Tref=4 K.

In the following pages, ***Table 3.2)*** shows maxima and minima for the whole model; ***Figures 3.2.1 to 3.2.7*** show stress components in the coil and the containment cylinder.

stress (MPa)	mat.1 (lateral cable)	mat.2 (interlayer insulation)	mat.3 (central cable)	mat.4 insulation on external radius of coil	mat.5 Al - cylinder
Sx (radial)	-5, +7	- 5, + 8	-0.04, +0.6	-7, +1	-13, +5
Sy (axial)	**- 40**, +19	- 8, + 9	- 2, +0.8	- 4, + 4	- 28, **+ 52**
Sz (hoop)	**- 44**, +3	- 12, + 3	- 2, +1	- 4, + 15	+0.3, **+ 77**
Sxy (shear)	-3, +8	- 0.5, + 3	-0.3, +0.04	-0.8, + 19	-5, +7
Sint (intensity)	-------	------	------	------	90

Table 3.2) - FULL - RANGE STRESS TABLE FOR T_{ref} = 4 Kelvin STRESS ANALYSIS (WORST QUENCH TEMPERATURE DISTRIBUTION)

Comments on Table 3.2):

The only relevant components are the axial stress Sy and the hoop stress Sz on lateral cable and constraintment cylinder, at the warm end.

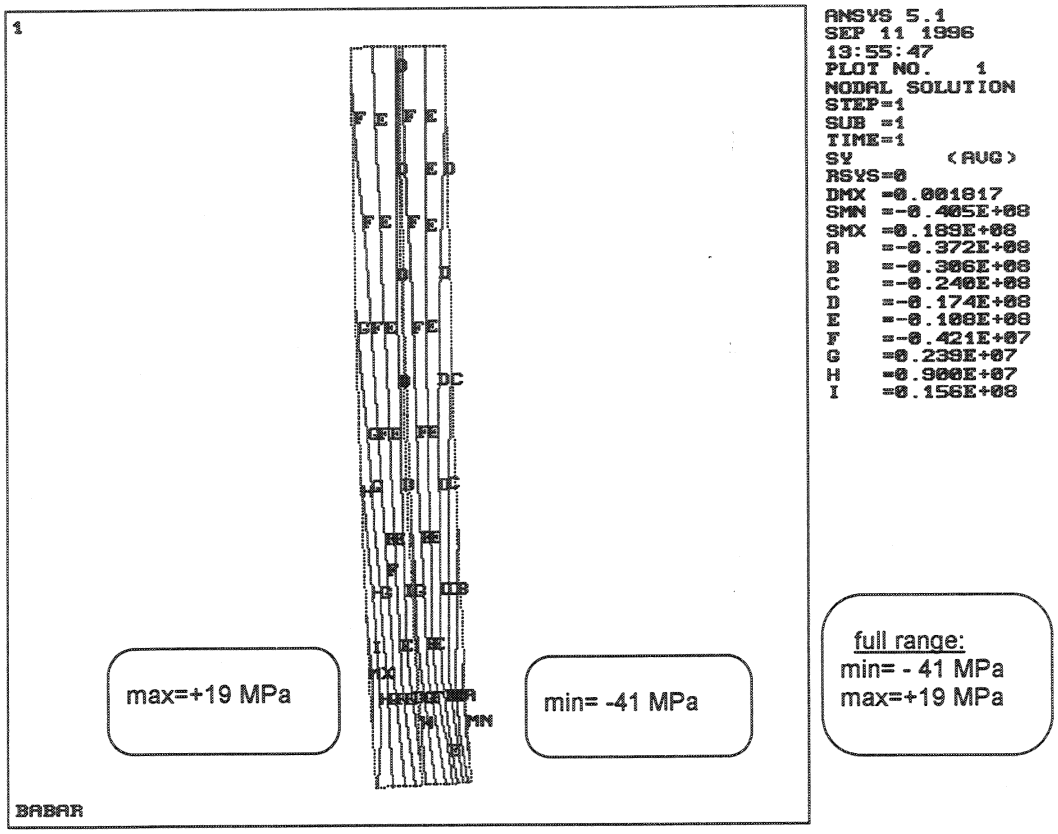


Fig. 3.2.1) - axial stress in the coil (warm end) for T_{ref} = 4 K

Notes:

Coil in compression on external side, tension on internal side (as in ***Figure 3.1.1***).

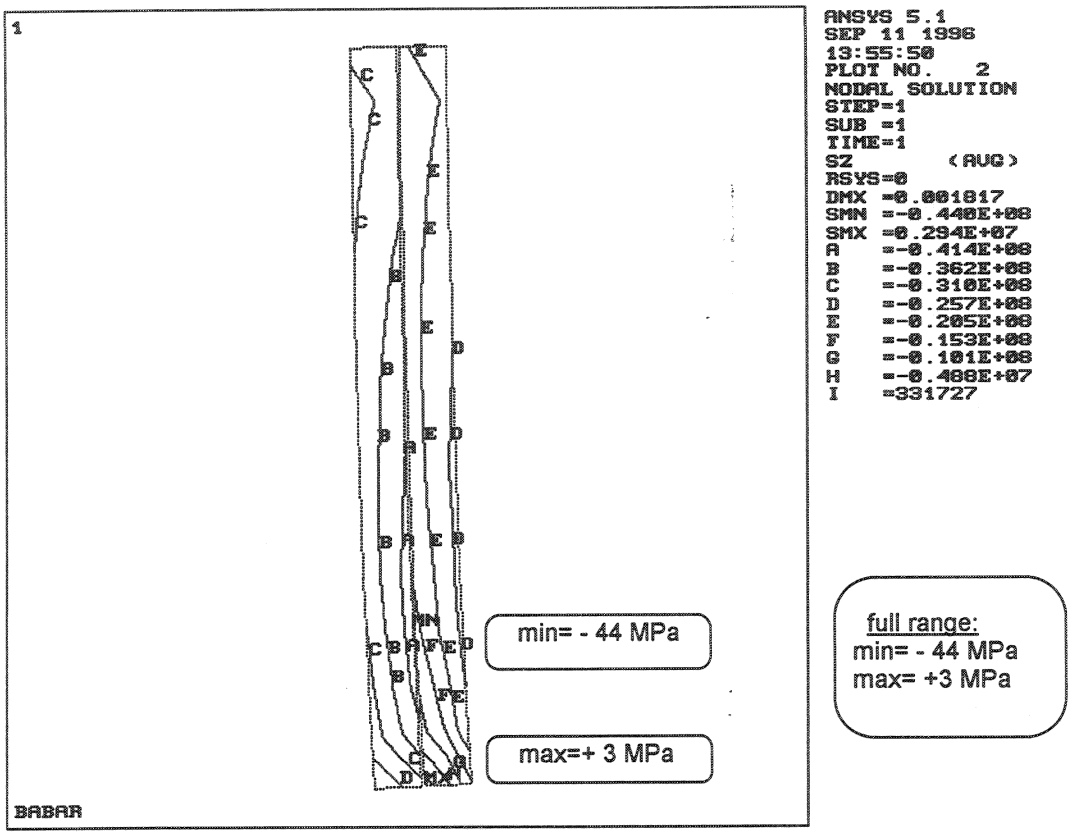


Fig. 3.2.2) - hoop stress in the coil (warm end) for T_{ref} = 4 K

Notes:

Coil is almost all in compression especially on external side, near containment cylinder (as in ***Figure 3.1.2***).

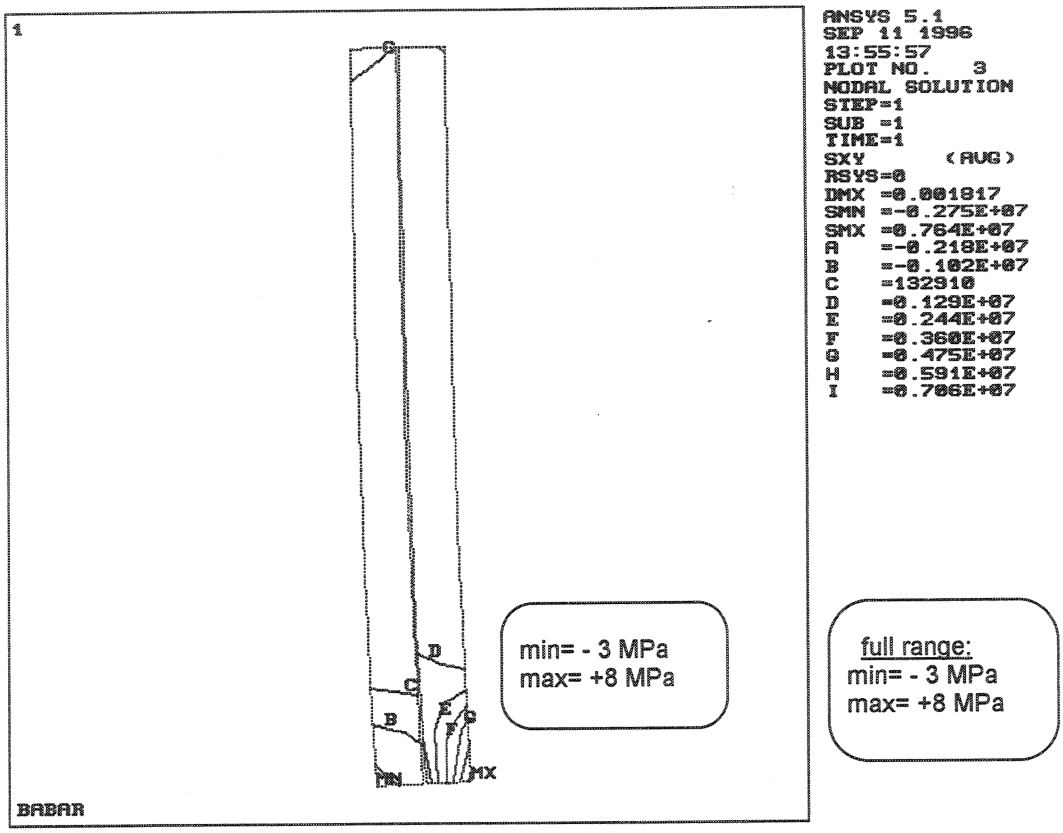


Fig. 3.2.3) - shear stress in the coil (warm end) for T_{ref} = 4 K

Notes:

Min. and max. are just localised peaks (as in ***Figure 3.1.3***).
Throughout the rest of the model shear stress is about zero (lines C-D).

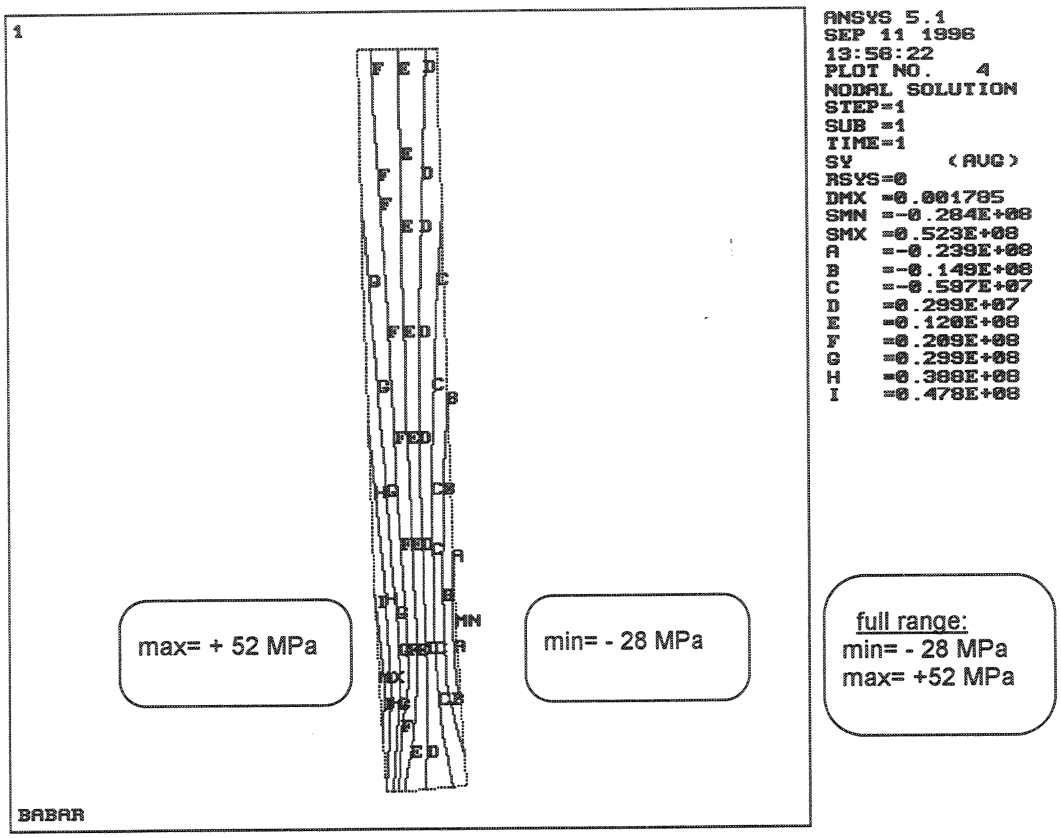


Fig. 3.2.4) - axial stress in the Al-cylinder (warm end) for T_{ref} = 4 K

Notes:

Containment cylinder is in tension at the internal side (near the coil, which in turn is in compression) (as in ***Figure 3.1.4***).

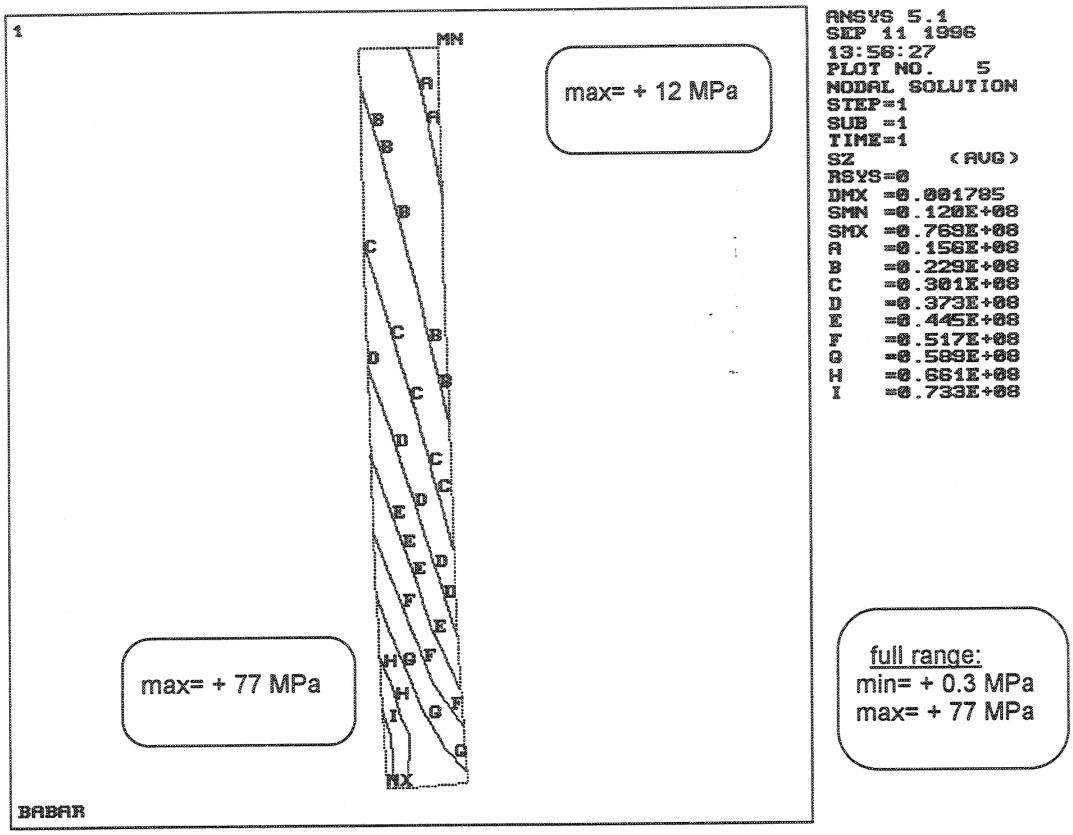


Fig. 3.2.5) - hoop stress in the Al-cylinder (warm end) for T_{ref} = 4 K

Notes:

Containment cylinder is in tension, with a maximum at the warmest point.
(As in ***Figure 3.1.5***).

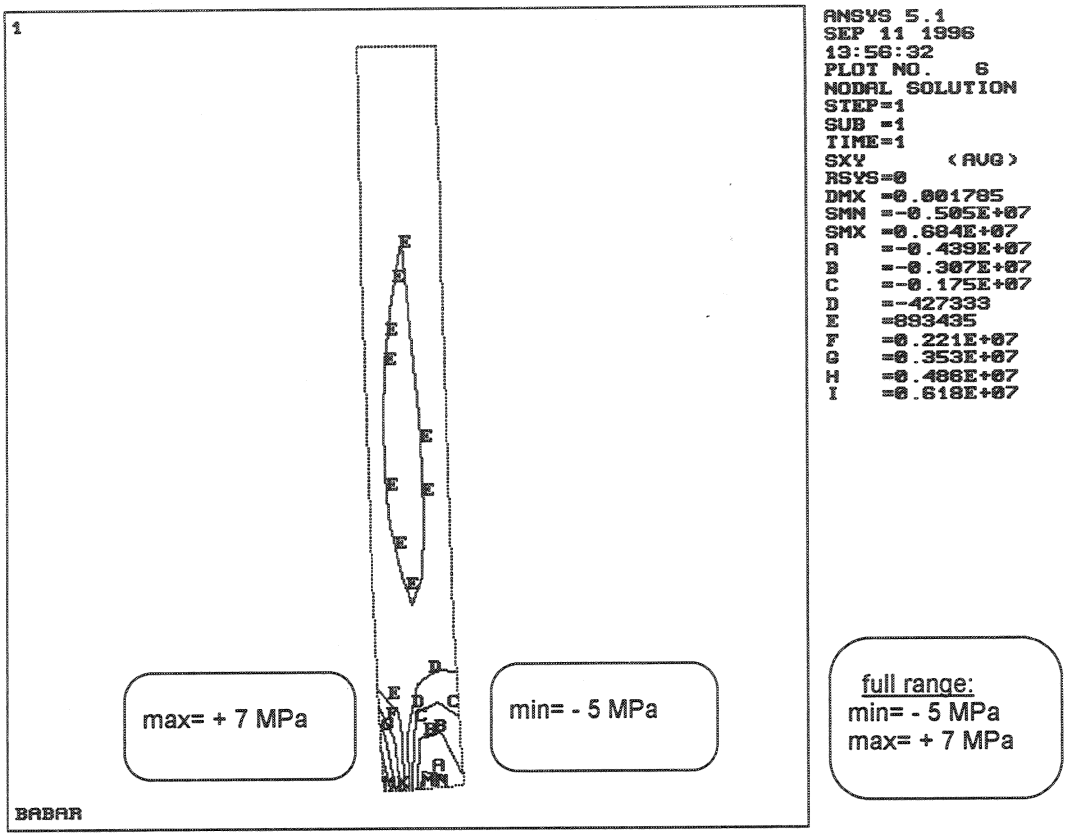


Fig. 3.2.6) - shear stress in the Al-cylinder (warm end) for T_{ref} = 4 K

Notes:

Min. and max. are just localised peaks (as in ***Figure 3.1.6***).
Throughout the rest of the model shear stress is about zero (lines D-E).

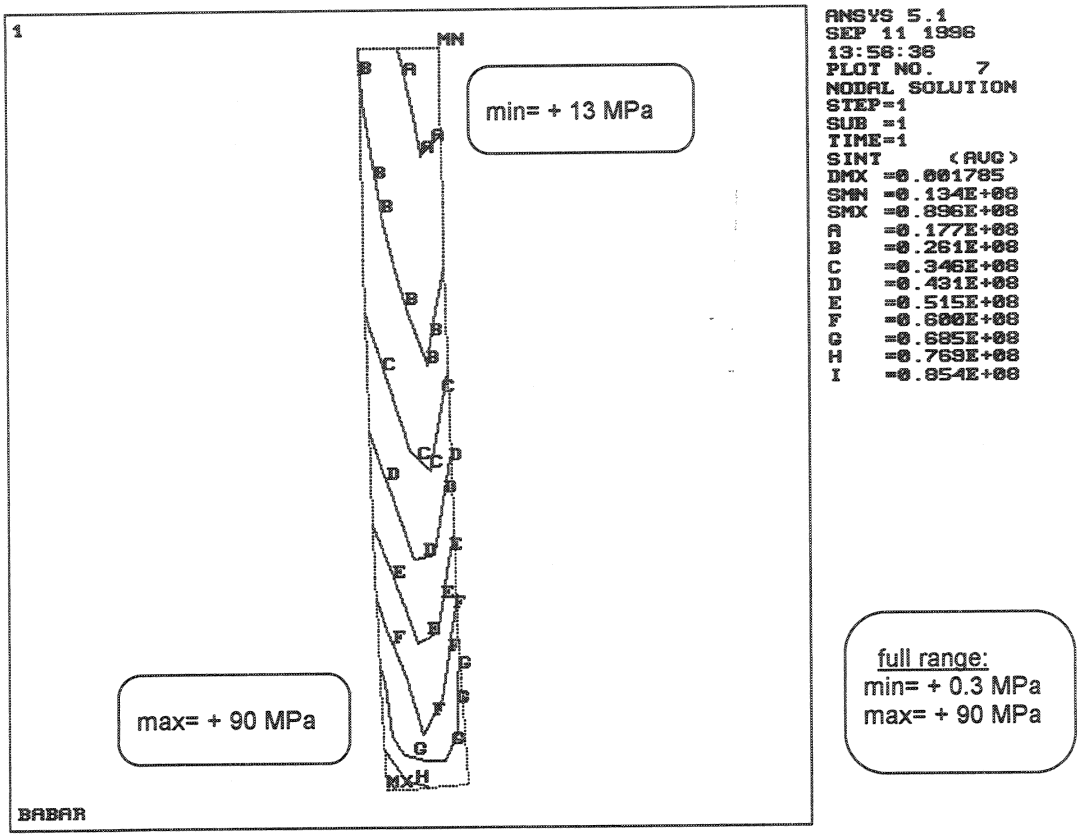


Fig. 3.2.7) - stress intensity in the Al-cylinder (warm end) for T_{ref} = 4 K

Notes:

Stress intensity map is similar to the case with Tref=450 K (***Figure 3.1.7***), with properly scaled values.

Influence of aluminum strips placed on internal radius of BABAR coil: (thickness of strips = 1 mm, thickness of insulation = 1 mm)

• It came out from quench calculations a strong dependence of maximum final temperature $T_{max, fin}$ of the coil from aluminum strips RRR parameter.

• It came out also a strong dependence of resulting $T_{max, fin}$ from integration time *dt* to be used for the computation, especially for high RRR value.

If *dt* is not little enough, it leads to a lower $T_{max, fin}$ and wrongly uniform distribution of temperature in the axial direction.

This was the result of all the runs with code "Protect":

aluminum strips RRR	$T_{max, fin}$ of coil (K)	$\Delta T_{max,fin}$ (K) between coil and cylinder	*dt* (sec)
no strips	195	118	1e-2,
1.87 (alloy 5083)	180	105	1e-2, 5e-3
32 (Al 1100)	152	82	(1e-2), 5e-3 , 1e-3, 5e-4
100	141.5	74	(1e-2), (5e-3), 1e-3, 5e-4
1000	126.5	63	(1e-2),(5e-3),(1e-3), 5e-4

Table 4.1)

Time interval *dt* in the table is in brackets to mean an intermediate run, while it is out-of-brackets to mean a final run, that is a time interval little enough.

For example, in the case RRR=100 integration times 1e-3 sec and 5e-4 sec give the same $T_{max, fin}$ (which is indicated in the second column) so it is probably the right result, while 1e-2 sec and 5e-3 sec give a lower temperature and a wrong result.

The complete set of results for every RRR and every dt is shown in the following ***Figure 4.1***).

It can be seen a common behaviour: a linear dependence of function $T_{max,coil}$ (*dt*) for every RRR curve until a saturation value, which is reached at higher *dt* for lower RRR.

Of course a higher *dt* means a quicker computational time (as run always goes from t=0 to t=50 sec).

The case RRR=1000 is a little strange, its behaviour is not clear (temperature versus time plot in ***Figure 4.1*** is a curve, not a straigh line plus saturation).

However, RRR=100 should be sufficient for the aim.

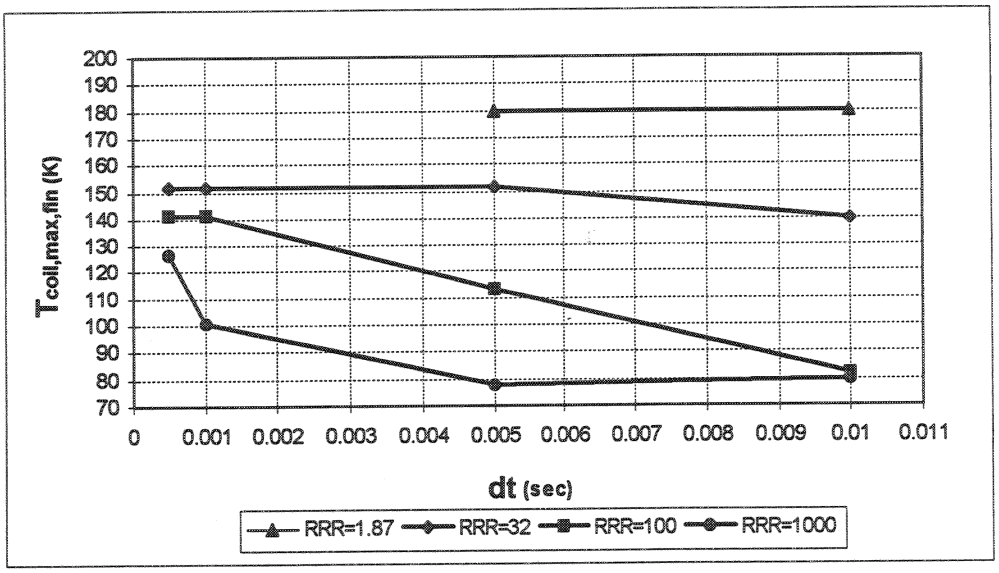
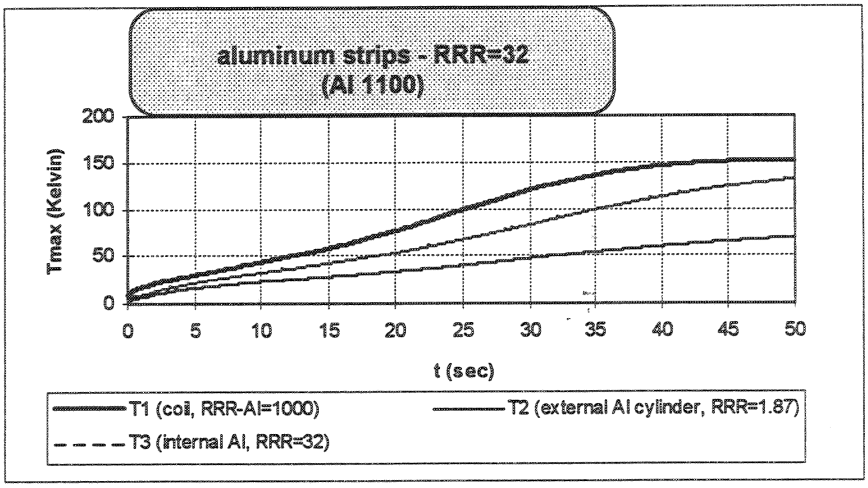
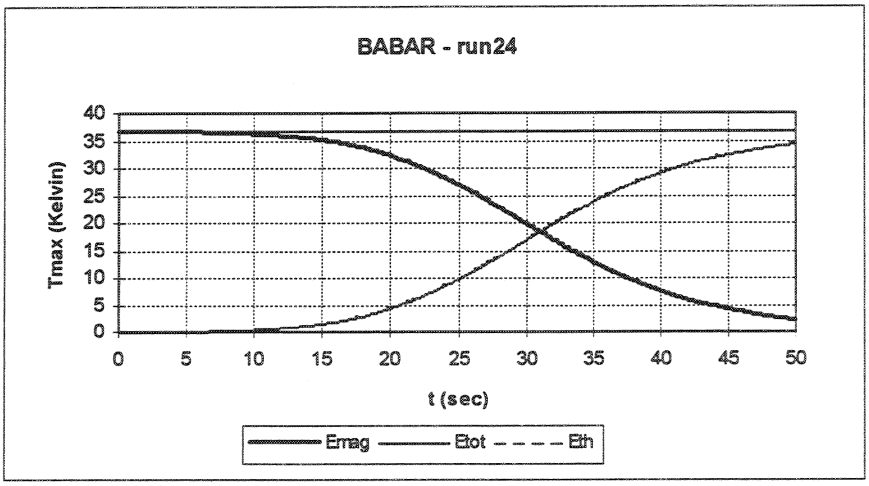


Figure 4.1) - Final maximum temperature in the coil, from "Protect" run, as a function of RRR of aluminum strips and integration time *dt*.

The most important plots resulting from "Protect" calculus for RRR=32 and RRR=100 cases are reported in ***Fig.4.2*** and ***4.3***, for the proper integration time.





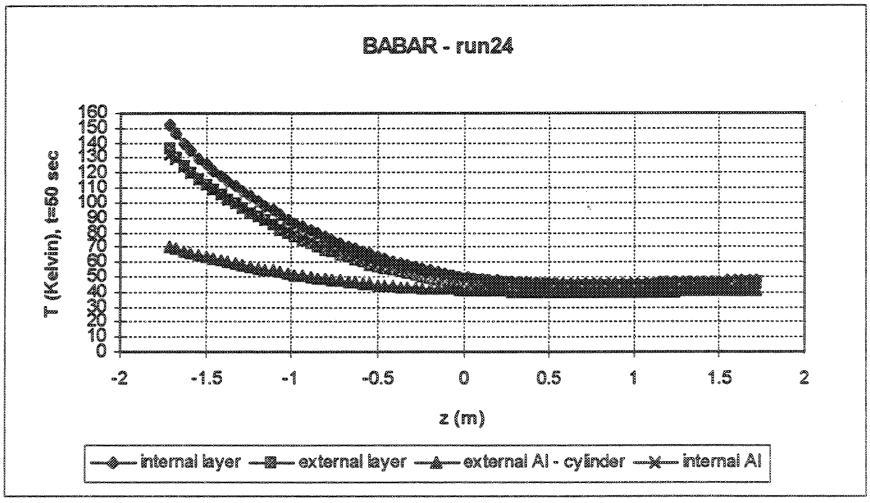


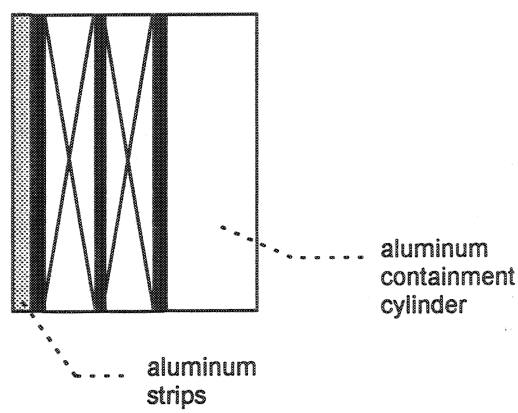
Fig.4.2) - "Protect" results for **RRR=32** case: max. temperature versus time, energy versus time, final temperature versus axial coordinate z.

4) - INTRODUCTION OF ALUMINUM STRIPS

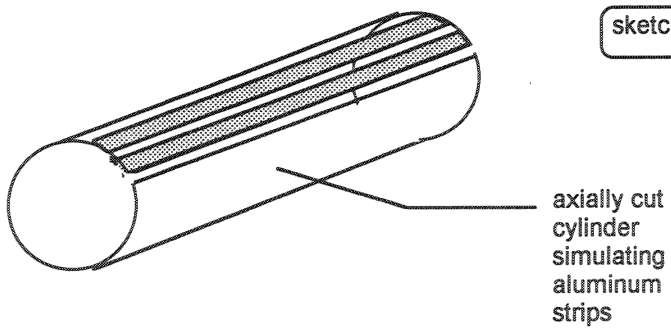
In order to reduce the thermal gradient and consequently the stress in the coil material, it was thought to insert aluminum strips on the coil internal side to spread local heat axially by thermal conduction.

Quench analysis was repeated with "Protect" code, inserting aluminum thickness 1 mm + insulation thickness 1 mm (see sketch *4.1*).

Formally in the input file another aluminum cylinder appeared (as program allows only axisymmetric models) but it was prevented from assuming inductive current by putting all its mutual inductance terms equal to zero in the inductances file (so it was like a cut cylinder, see sketch *4.2*) .



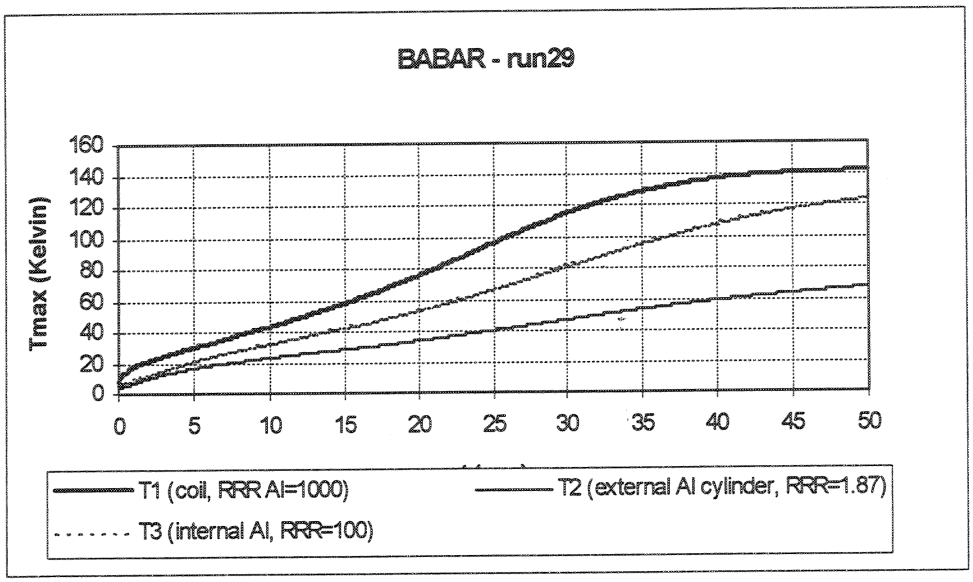
sketch *4.1)*



sketch *4.2)*

Real dimensions of strips are: **31 strips, 303 mm wide, 2.6 mm mean gap**, 1 mm thickness.

aluminum strips - RRR=100



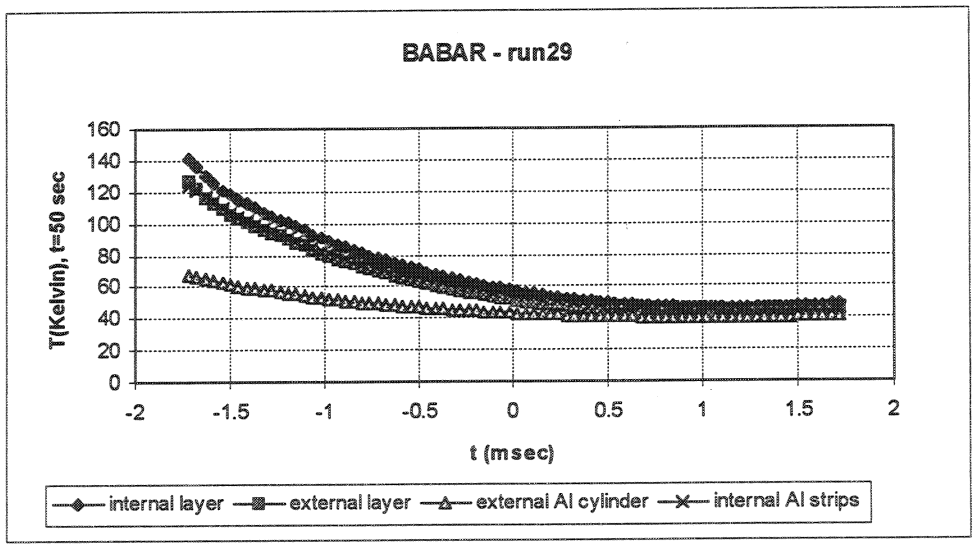


Fig.4.3) - "Protect" results for **RRR=100** case: max. temperature versus time, final temperature versus axial coordinate z.

In the following ***tables 4.2*** and ***4.3***, stress values for the cases RRR=32 and RRR=100 are reported.

Reference temperature for thermal expansion calculus: **Tref=4 K**
(compare with ***Table 3.2***).

RRR=32 (=Al 1100, 99% pure)

mat.1 (cable)	mat.5 (Al cylinder on external radius)
Sy = -27, +13 MPa Sz = -29, +6 MPa	Sy = -19, +35 MPa Sz = +0.3, +56 MPa Sint,max = 65 MPa

Table 4.2)

RRR=100

mat.1 (cable)	mat.5 (Al cylinder on external radius)
Sy = -23, +11 MPa Sz = -25, +6 MPa	Sy = -16, +30 MPa Sz = +0.3, +47 MPa Sint,max = 54 MPa

Table 4.3)

If we recall that maximum stress intensity for aluminum constraintment cylinder for the case with no strips was 90 MPa, and maximum compression values for the cable material were Sy= -40 MPa and Sz= -44 MPa, we see now that the adding of strips with RRR between 32 and 100 has a decisive bettering effect: stress values are almost halved.

It was considered convenient to use **aluminum type 1050 or 1060**, that is pure **99.5% or 99.6%,** but it was not possible to find out from literature the exact RRR value of these kinds of material.

However it should lie in the range 32÷100, as it can be derived from the following ***Figure 4.4***).

It can be seen that an almost linear plot comes out, when a log-log plot is done.

For impurity value 0.5% or 0.4%, an RRR value of about 50 can be extrapolated.

Note that all values are taken from ***Ref.5*** (ALCOA values from Mondolfo's book) except the last one (RRR=32) which is taken from ***Ref.3*** ("Material at low temperatures").

Note also that ALCOA values are refered to 273 K instead of 293 K (in the definition of RRR), while Al-1100 value (99%pure, 1%impure, RRR=32) is referred to 293 K as usual, so this could lead to some mistake in comparing values.

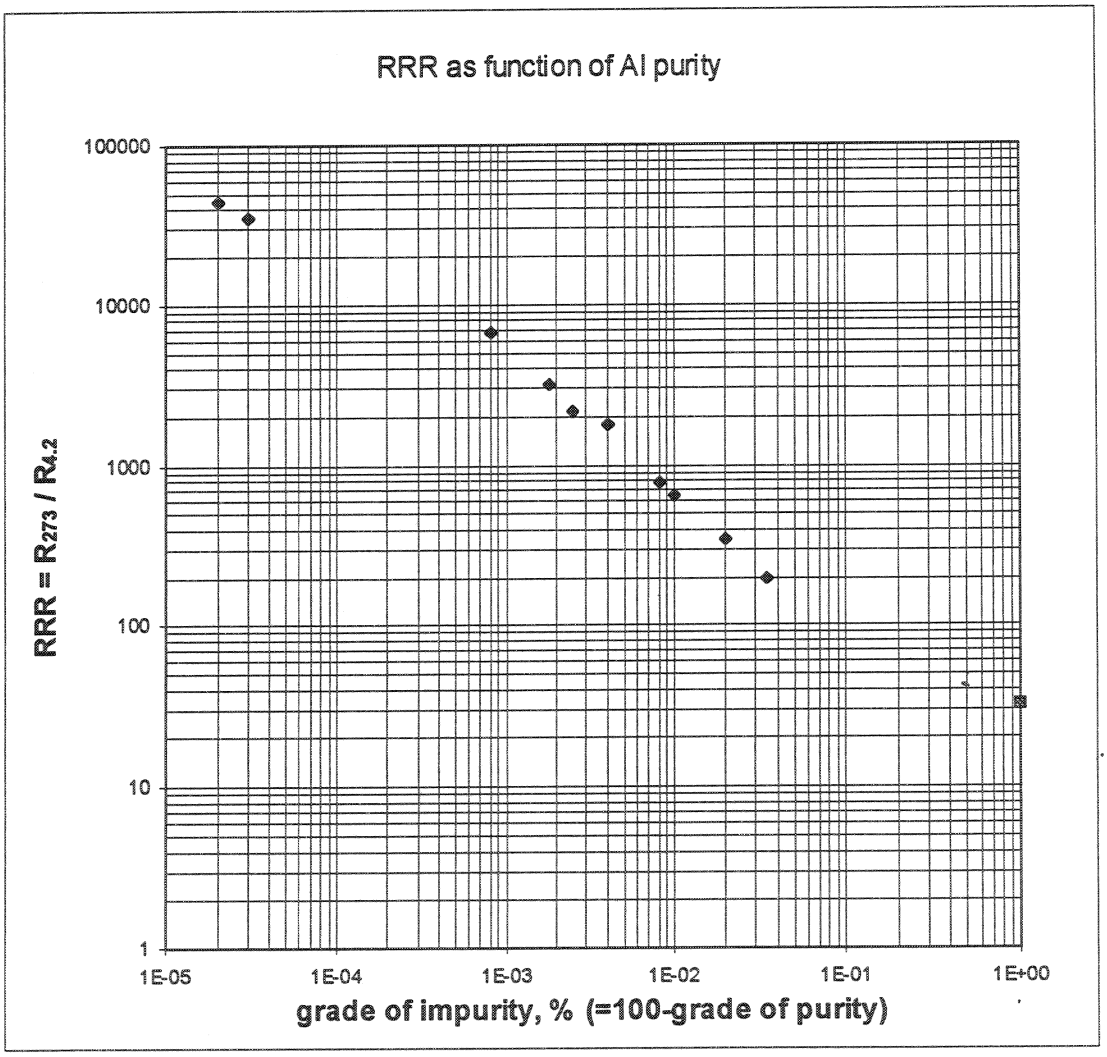


Fig.4.4) -RRR of aluminum as a function of grade of purity, from ***Ref.5*** (ALCOA data) and Ref.3 ("Materials at low temperatures")

5) - REFERENCE DOCUMENTS

1) "Simpro Componenti" technical report RDC.019.96 , date of issue 23/5/1996, "MAGNETE BABAR - analisi tensionale degli effetti termici e di energizzazione" ("BABAR MAGNET - stress analysis of thermal and current effects") , Rev.0

2) "Quench simulation, magnetic and thermal diffusion in coupled solenoidal magnet system", Yehia M.Eyssa and W.Denis Markiewicz, National High Magnetic Field Laboratory-FSU, Tallahassee, FL 32306 USA

3) "Materials at low temperatures", edited by Richard P. Reed and Alan F. Clark, American Society for Metals (for aluminum properties)

4) BBC tables for fiberglass properties

5) ALCOA ITALIA S.p.A. data from "Aluminum alloys: structure and properties", L.F.Mondolfo, Butterworths London-Boston

Progetto
Project

MAGNETE BABAR PER SLAC

SIMPRO
Componenti S.r.l.

Commessa job no.	TITOLO/title
MGN012	CALCOLI DI CAMPO PER MAGNETE BABAR

Fornitore supplier		IDENTIFICATIVO/document no.	PAG./page	DI/of
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Questa relazione riporta la continuazione dei calcoli eseguiti per il magnete BABAR alla ricerca di una configurazione ideale dal punto di vista delle richieste sul campo magnetico e della scelta di un cavo ragionevole dal punto di vista costruttivo.

Le richieste sul campo magnetico sono le seguenti:
- campo al centro del magnete = 1.5 Tesla;
- omogeneità di campo compresa fra ± 2% (poi portata a ± 3%) in una data zona;
- minimizzazione della forza assiale risultante sull'avvolgimento, dovuta all'asimmetria fra gli schermi magnetici "forward" e "backward" collegati alle flange.

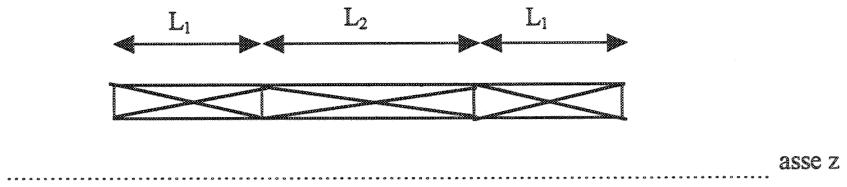
I calcoli precedenti sono riportati nella relazione ***[Rif.1]*** e riassunti per comodità nel paragrafo che segue.

1) - RIASSUNTO DELLA RELAZIONE PRECEDENTE

Utilizzando una certa configurazione per il giogo di ferro del magnete (Fig.1 di Rif.1), si era partiti da un avvolgimento a 1 strato corrispondente all'offerta originaria Ansaldo (configurazione di magnete denominata Babar_F3 in Rif.1) , caratterizzata da una densità di corrente lineare D1=1900 A/mm per le parti laterali a più alta densità.

Questo cavo laterale (rettangolare) risultava però di spessore troppo piccolo (3.6 mm isolato, mai costruito prima, così da impensierire abbastanza per la difficoltà di fabbricazione) ; si cercava quindi di ottenere la stessa omogeneità di campo con un cavo più largo.

Un primo set di calcoli era caratterizzato da una densità D1=1600 A/mm (spessore cavo laterale isolato = 4.4 mm); i casi analizzati erano denominati F4, F5, F6 e differivano per il parametro β (rapporto fra le lunghezze laterali e la lunghezza centrale dell'avvolgimento: $\beta = 2 \cdot L_1 / L_{tot}$); le quantità tenute costanti erano la lunghezza totale dell'avvolgimento (L_{tot} =3470 mm) e il numero di amperespire ($NI = 5 \cdot 10^6$).



Il calcolo ad amperespire costanti serviva a non allontanarsi troppo dal campo richiesto.
Si aveva di volta in volta una deformazione della curva del campo lungo l'asse del magnete, mantenendo costante l'area (che è determinata dal numero di amperespire: $\int Bdz = \mu o \cdot NI$).

Il valore puntuale del campo in questo modo può variare, e infatti il campo al centro del magnete risultava di volta in volta leggermente diverso; però una volta trovata la soluzione ideale dal punto di vista dell'uniformità (calcolata rispetto a Bo e quindi indipendente da Bo, almeno per piccole variazioni), sarebbe stato sufficiente scalare proporzionamente la corrente per ottenere esattamente 1.500 Tesla al centro.

Si era mostrato che non era possibile ottenere l'uniformità richiesta con D1=1600 A/mm; vi erano 2 code negative che non si riuscivano a riportare nei margini voluti del ±2%. Infatti, è vero che queste code negative miglioravano alzando il parametro β (cosa che d'altronde faceva leggermente peggiorare i 2 picchi positivi di inomogeneità), però si arrivava quasi a far scomparire la parte centrale della bobina (quella a più bassa densità) senza avvicinarsi ancora al limite richiesto (con il caso F6, avente β=0.8, l'omogeneità su Bz andava da -10.38% a +2.55%).

Si era passati quindi ad analizzare un cavo intermedio: 4.0 mm isolato, D1=1750 A/mm.

In [Rif.1] si studiavano 2 casi, denominati F7 ed F8, aventi rispettivamente β=0.5 e β=0.6.

La configurazione di offerta F3 risultava una sorta di via di mezzo fra le 2; quindi si concludeva che un valore di β intorno a 0.55 avrebbe potuto riprodurre abbastanza fedelmente l'omogeneità data da F3, con il vantaggio di usare un cavo più facile da costruire. Si avevano solamente delle code negative un po' al di sotto del -2%.

Dato che però erano in attesa di definizione da parte del cliente sia la forma del ferro che la zona di omogeneità di effettivo interesse, si attendevano queste informazioni per scegliere una configurazione piuttosto che un'altra.

La zona di analisi per le mappe di omogeneità era, fino a questo punto, la seguente:

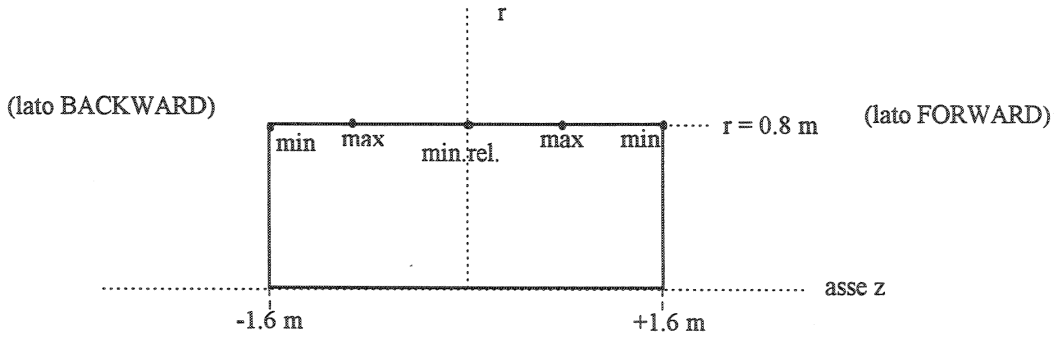
- raggio da zero a 0.8 m;
- coordinata assiale z da -1.6 m a +1.6 m (rispetto al centro del magnete).

Per comodità i casi venivano confrontati non sulle mappe ma su linee:

linea 1) - sull'asse, da z = -1.6 m a z = +1.6 m

linea 2) - parallela all'asse, a raggio 0.8 m , estremi z come sopra.

Infatti, sulla linea 2) in particolare si trovavano sempre i 2 picchi positivi e le 2 code negative di omogeneità.



2) PROSEGUIMENTO DEI CALCOLI CON D_1=1750 A/mm:

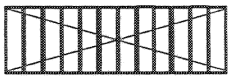
Ai calcoli precedenti è stato aggiunto il caso con β=0.55.
Proseguendo la denominazione già usata, indichiamo questo calcolo come Babar_F9.

Le grandezze di interesse sono le seguenti:

I = 7000 A
D1=1750 mm (spessore cavo laterale isolato = 4.0 mm)

$\beta = 2 \cdot L_1/L_{tot} = 0.55$
$K = J_2/J_1 = 0.558$

larghezza cavo isolato = 32.4 mm (= spessore della bobina)



..... asse z

$(NI)_{tot}=5.0 \cdot 10^6$ Ampere-spire
L_{tot} = 3470 mm

L_1 = 954.25 mm
L_2 = 1561.5 mm

J_1 = 54.012 A/mm^2
J_2 = 32.785 A/mm^2

Risultati:

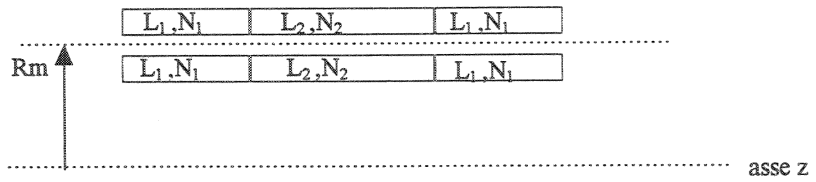
- Campo al centro — Bo = 1.5225 T
- Omogeneità — (|Bz| - Bo) / Bo = -6.12 ÷ +3.38 %
  (B_{mod} - Bo) / Bo = -6.01 ÷ +3.39 %

In ***Figura 1*** si riporta l'andamento del campo (normalizzato) lungo la linea 2), confrontato con i casi studiati precedentemente F3, F7, F8.
Si osserva che, come immaginato, la curva F9 simula abbastanza bene la curva F3.

Comunque, la configurazione F3 (bobina dell'offerta) non rispetta su questa linea l'omogeneità richiesta del ±2%; da questo punto di vista, la curva F7 è migliore. Infatti i massimi sono quasi entro i limiti, e i minimi potrebbero rientrare se si restringesse la zona lateralmente (indicativamente, *z* fra ±1.4 m anziché ±1.6 m).

3) CONFIGURAZIONE A 2 STRATI (BABAR F10):

. Nel frattempo si prova la seguente configurazione a 2 strati (non shiftati):



$L_1 = 0.42382$ m
$L_2 = 2.6028$ m
$N_1 = 99$ spire per lato, per strato
$N_2 = 304$ spire per strato
$I = 5000$ A
R_m = raggio medio = 1.53 m

Il gap fra i 2 strati ha poca importanza, così come pure lo spessore di ogni strato; il presente calcolo è stato fatto con:

- spessore di ogni strato = 1 cm
- gap = 6 mm

Lo spessore di 1 cm simula solo la zona del superconduttore, dove effettivamente scorre la corrente; isolamento e alluminio sono lasciati fuori.

L'importante è dare la densità di corrente **J** corrispondente.

Con questo spessore risulta:

$J_1 = 116.795$ A/mm^2
$J_2 = 58.3986$ A/mm^2

Per avere un confronto con gli studi precedenti a 1 strato, osserviamo che:

- con 2 strati, è possibile avere una densità lineare D_1 molto più alta (e quindi, come abbiamo verificato, un'omogeneità migliore) utilizzando un cavo laterale non troppo piccolo (in questo caso si ha un cavo di 423.82 mm / 99 spire = 4.28 mm isolato).

Infatti si ha $D_1 = 2$ [strati] $\cdot$ 5000 [A] / 4.28 [mm] = 2 $\cdot$ 1168 = 2336 [A/mm].

Risultati :

- Campo al centro — Bo = 1.5176 [T]
- Omogeneità — (|Bz| - Bo) / Bo = - 2.61 ÷ + 1.87 %
  (B_{mod} - Bo) / Bo = - 2.58 ÷ + 1.87 %

E' un'omogeneità molto buona, anche perchè la zona compresa fra -2.58 % e -2.00 % è estremamente localizzata: inferiore all'1 per mille del volume interessato.

I risultati ottenuti da INFN - Genova con il modello assialsimmetrico di Ansys sono i seguenti:

- omogeneità (Bmod-Bo)/Bo = -3.5 ÷ +1.5 %.

4) ALTRA CONFIGURAZIONE A 2 STRATI (BABAR_F11):

I parametri sono i seguenti:

L1 = 0.45867 m
L2 = 2.534352 m
N1 = 107 spire per lato, per strato
N2 = 296 spire per strato
I = 4910 A
Rm = 1.53 m
spessore strato per il calcolo = 1 cm
$J_1 = 114.7 \cdot 10^6$ A/m^2
$J_2 = 57.35 \cdot 10^6$ A/m^2

Risultati:

- campo al centro Bo = 1.5025 T
- omogeneità (Bmod-Bo)/Bo = -2.50 ÷ + 2.24 %

Dal punto di vista dell'omogeneità, rispetto al caso precedente questo risulta un pò migliore con il modello assialsimmetrico di Ansys e un po' peggiore con il nostro modello -3D di Opera.

5) CALCOLO DELLE FORZE ASSIALI SULLA BOBINA:

Sulla bobina agisce una forza risultante in direzione assiale, dovuta alla diversa geometria flangia+schermo dai lati backward / forward.

I risultati sono del seguente ordine di grandezza, calcolati con Opera-3D tramite il comando BODY usando il massimo di punti di Gauss per il calcolo (n1 = n2 = n3 = 8):

caso	strati	Fz sull'avvolgimento:
F3	1	-8.4 tonn.
F10	2	-9.5 tonn.

I calcoli di INFN- Genova davano risultati confrontabili; il buco del camino nella flangia backward aveva poi l'effetto di invertire questa forza (cioè il contributo di questo buco è all'incirca di 17 tonnellate verso il lato forward).

Questo buco non è stato considerato nei nostri calcoli fino ad ora perchè la sua presenza rompe la simmetria esagonale del magnete e non permette di usare una mesh di 30° molto fitta (come fatto finora per avere la precisione necessaria nella mappa di omogeneità). Infatti, il massimo numero di nodi utilizzabile complessivamente in un modello con il nostro Opera-3D è 50000.

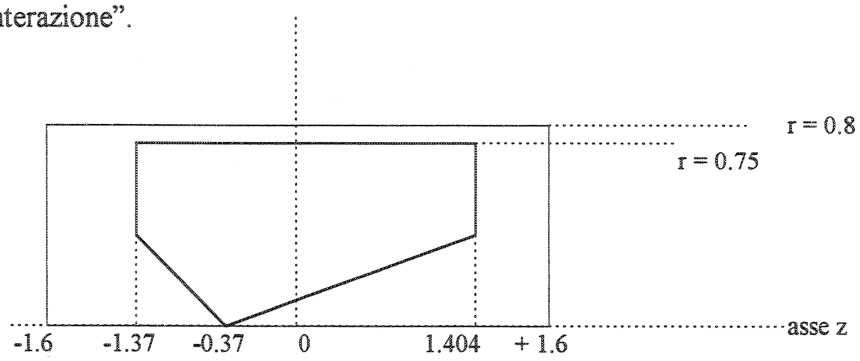
6) NUOVA REGIONE DI INTERESSE PER L'OMOGENEITA' E NUOVA CONFIGURAZIONE PER IL GIOGO DI FERRO:

Durante la riunione con SLAC del 17/10/1995 ci viene comunicata la seguente nuova zona di interesse per il calcolo dell'omogeneità, più ristretta del rettangolo usato finora (vedere schizzo di confronto di seguito).

In sezione, è un poligono con 5 lati aventi i seguenti vertici:

r (m)	z (m)
0	-0.37
0.546	-1.37
0.75	-1.37
0.75	1.404
0.549	1.404

Il punto (x,y,z) = (0,0,-0.37), spostato di 0.37 m rispetto al centro del magnete, è il "punto di interazione".



Nella nuova zona di interesse, l'omogeneità richiesta è del ± 3%.

Grazie a questo doppio indebolimento della richiesta, adesso il caso F7 (con la configurazione di ferro usata finora) si trova completamente entro i margini: l'omogeneità di Bz (avendo deciso di guardare Bz e non Bmod) rispetto al campo al centro Bo è

(|Bz| - Bo) / Bo = - 2.67 ÷ + 1.82 % (dunque compreso fra ± 3%)

Però durante questa riunione ci viene anche comunicata una nuova configurazione per il giogo di ferro; sono cambiati soprattutto gli schermi (la loro forma ricorda quella precedente con un taglio delle cosidette "fingers" che si protendevano verso l'asse del magnete).

Si rimanda ai disegni tecnici ***Rif.2***.

Nel seguito la definirò come la configurazione di ferro "ottobre '95".

Costruisco quindi un nuovo modello con Opera-3D che rispecchi questa nuova configurazione (vedere ***Figure 2***).

Il modello si estende per 30 gradi e rispecchia la forma spezzata di Barrels, Doors e Spacers (con spaziatura uguale su tutti i lati, cioè uniformando agli altri anche il lato dell'esagono in corrispondenza del foro del camino).

7) - INFLUENZA DELLA QUANTITA' DI FERRO DAL LATO BACKWARD SULLE FORZE ASSIALI

7.1) - CASO OTT95-1

Il primo lancio considera tutta la zona fra flangia e schermo backward (= da raggio 0.746 a raggio 1.020 m) come materiale NON magnetico, cioè aria oppure stainless steel.

La bobina usata è quella del caso F7; se ne ricordano brevemente i parametri principali:

L1 = 868 mm N1 = 217 spire (cavo da 4.0 mm isolato) $\beta = 0.500$ K = 0.647 $D_1 = 1750$ A/mm

Risultati:

- campo al centro — Bo = 1.5162 T
- omogeneità — (| Bz | - Bo) / Bo = -6.81 ÷ + 2.23 %
- forza assiale sulla bobina — Fz = + **56 tonn.**

La zona al di fuori del -3% di omogeneità si trova dal lato backward.

7.2) - CASO OTT95-2

Il secondo lancio considera di materiale magnetico (ferro) tutta la zona fra flangia e schermo backward, compresa cioè fra raggio 0.746 e raggio 1.020 m.

La bobina è la stessa.

Risultati:

- campo al centro — Bo = 1.5349 T
- omogeneità — (| Bz | - Bo) / Bo = -3.72 ÷ + 2.38 %
- forza assiale sulla bobina — Fz = **- 54 tonn.**

La zona al di fuori del -3% di omogeneità si trova questa volta dal lato forward.

Come si nota, la forza assiale si inverte fra il primo e il secondo caso.

Intuitivamente, una quantità di ferro magnetico intermedia, inserita fra flangia e schermo backward, dovrebbe annullare la forza assiale sulla bobina.

7.3) - CASO OTT95-3

Il terzo lancio considera come parte di ferro magnetico fra flangia e schermo backward solo il volume compreso fra 0.810 m e 1.020 m (come ricavato dai disegni *Rif.2*).

Il nuovo volume di ferro del support è il 79.4% rispetto a quello del lancio precedente.

La bobina è la stessa.

Risultati:

- campo al centro — Bo = 1.5316 T
- omogeneità — (| Bz | - Bo) / Bo = -3.55 ÷ + 2.05 %
- forza assiale sulla bobina — Fz = **- 36 tonn**.

La zona al di fuori del -3% di omogeneità si trova anche questa volta dal lato forward.

Togliendo ancora ferro dal lato backward, è prevedibile un ulteriore miglioramento della forza.

7.4) - CASO OTT95-4

Il quarto lancio toglie anche il gap di aria compreso fra raggio 0.945 e 0.955 m, che si era pensato di trascurare ma che, come mostrano i risultati sotto, ha in realtà un'influenza non trascurabile sulla forza assiale che agisce sulla bobina.

Risultati:

- campo al centro — Bo = 1.5308 T
- omogeneità — (| Bz | - Bo) / Bo = -3.52 ÷ + 1.98 %
- forza assiale sulla bobina — Fz = **- 31 tonn**.

Con questo gap di aria di appena 10 mm si osserva quindi:

a) un leggero miglioramento negli estremi di omogeneità (la zona al di fuori del -3% di omogeneità si trova anche questa volta dal lato forward);

b) una diminuzione della forza assiale sulla bobina da 36 a 31 tonnellate.

8) MODIFICA DELLA BOBINA PER MIGLIORARE L'OMOGENEITÀ

Contemporaneamente al caso Ott95_4, girano anche i seguenti 2 calcoli di cui riportiamo i risultati.

Sono fatti ancora con la mesh del caso Ott95_3, provando a cambiare la bobina (a partire da quella usata finora, che era la stessa del caso F7) per ottenere un rapporto β più alto (si ricorda che per il caso F7 era β=0.5) e migliorare l'omogeneità delle code negative (a discapito dei 2 picchi positivi, che però hanno un buon margine):

8.1) CASO OTT95-5 (+13 spire per parte)

L_1 = 920 mm
N_1 = 230 spire

β = 0.531
K = 0.6262

Risultati:

- campo al centro — Bo = 1.5247 T
- omogeneità — (| Bz | - Bo) / Bo = **-3.42 ÷ + 2.50 %**
- forza assiale sulla bobina — Fz = ...

8.2) CASO OTT95-6 (+22 spire per parte)

L_1 = 956 mm
N_1 = 239 spire

β = 0.551
K = 0.6150

Risultati:

- campo al centro — Bo = 1.5276 T
- omogeneità — (| Bz | - Bo) / Bo = **-3.13 ÷ + 2.81 %**
- forza assiale sulla bobina — Fz = ...

9) CASO OTT95-7:
PRIMA SOLUZIONE PER IL MAGNETE BABAR A 1 STRATO
(BOBINA CENTRATA, FORZA 30 TONN.)

Il seguente calcolo costituisce una prima soluzione per il magnete BABAR con avvolgimento di 1 strato:

- la mesh è quella del caso OTT95_4 , comprendente il gap da 10 mm (è la situazione reale per il ferro, ed è anche più favorevole dal punto di vista sia dell'omogeneità nella zona richiesta che della forza assiale sulla bobina).

- le dimensioni degli avvolgimenti sono quelle del caso OTT95_6 (è la bobina che ha ottenuto la migliore omogeneità, quasi entro il ± 3%)

- la corrente è stata scalata per avere un campo al centro di 1.50 Tesla (abbandonando il vincolo di $5 \cdot 10^6$ Amperespire).

Il fattore di scala usato è il rapporto : $(1.500 / 1.52764 = Bo_{ideale} / Bo_{reale})$.

Dunque : **I = 6873 Ampere** (anziché 7000 Ampere) per spira.

Questo significa che la densità di corrente lineare per la parte laterale diventa:

$\mathbf{D_1 = 1718.33}$ **A/mm** (anziché 1750 A/mm).

Risultati:

- campo al centro — Bo = 1.4999 T
- omogeneità — (| Bz | - Bo) / Bo = **-3.05 ÷ + 2.76 %**
- forza assiale sulla bobina — Fz = **- 30 tonn**

Questa configurazione si può considerare accettabile dal punto di vista dell'omogeneità; dal punto di vista delle forze, può essere desiderabile ridurre quelle 30 tonnellate che richiedono dei tiranti esagerati.

Questo può essere fatto spostando la bobina assialmente verso il lato forward (per bilanciare l'attrazione verso il backward).

Questo avrà sicuramente effetto sull'omogeneità nella zona di interesse (zona che rimane la stessa di prima), migliorandola nello spigolo lato forward e peggiorandola nello spigolo dal lato backward.

L'estremo -3.05 % scritto sopra si trova dal lato z > 0 (forward); il minimo nella spigolo dal lato z < 0 vale -2.76%. La situazione è dunque favorevole.

In ***Figura 3*** viene riportata la mappa di omogeneità per questo caso.

(Nota: questa configurazione è stata verificata da INFN - Genova con un modello assialsimmetrico di Ansys, con i risultati in ***Allegato 1***.)

10) BOBINA SPOSTATA ASSIALMENTE DI 1 CM: RIDUZIONE FORZE, RI-OTTIMIZZAZIONE OMOGENEITA'

10.1) Caso OTT95-8

Questo caso è uguale al precedente, salvo lo spostamento della bobina in direzione assiale di 1 cm verso il lato forward.

Risultati:

- campo al centro — Bo = 1.4999 T
- omogeneità — (| Bz | - Bo) / Bo = **- 3.28 ÷ + 2.57 %**
- forza assiale sulla bobina — Fz = **- 17 tonn**

La forza è scesa notevolmente (da 30 a 17 tonnellate, quindi conosciamo già la pendenza della retta da usare per la progettazione dei tiranti: 13 tonnellate / centimetro).

Per quanto riguarda l'omogeneità, migliora e rientra la coda negativa dal lato forward (da -3.05 % sale a -2.51 %) ma peggiora ed esce dai limiti la coda negativa dal lato backward (da -2.76 % scende a -3.28 %).

Conclusione: lo spostamento di 1 cm sembra ragionevole (almeno 1 cm per far scendere la forza assiale, non più di 1 cm per non allontanarsi troppo dall'omogeneità nella zona di interesse).

La bobina è da ri-ottimizzare dal punto di vista dell'omogeneità aumentando ancora il parametro β.

10.2) Caso OTT95-9

Tenendo la bobina spostata di 1 cm in direzione assiale, modifico in questo modo i parametri della parte laterale(= + altre 6 spire per parte)

L_1 = 980 mm
N_1 = 245 spire (cavo da 4.0 mm isolato)

β = 0.565
K = 0.6097

D_1 = 1718.33 A/mm

Risultati:

- campo al centro — Bo = 1.5050 T
- omogeneità — (| Bz | - Bo) / Bo = **- 3.24 ÷ + 2.70 %**
- forza assiale sulla bobina — Fz = **- 17 tonn**

La situazione non è cambiata molto. Evidentemente siamo in una zona di comportamento stabile.

10.3) Caso OTT95-11

(Nota: il caso Ott95_10 è solo una verifica, che non aggiunge nuove informazioni.)

Tenendo sempre la bobina spostata di 1 cm in direzione assiale, modifico in questo modo i parametri della parte laterale (= + altre 20 spire per parte):

L_1 = 1060 mm
N_1 = 265 spire (cavo da 4.0 mm isolato)

β = 0.611
K = 0.5634

D_1 = 1718.33 A/mm

Risultati:

- campo al centro — Bo = 1.4961 T
- omogeneità — (| Bz | - Bo) / Bo = **- 2.37 ÷ + 3.62 %**
- forza assiale sulla bobina — Fz = **- 17 tonn**

Questa volta siamo andati troppo oltre, abbiamo aggiunto troppe spire laterali facendo rientrare i minimi ma mandando fuori i massimi.

Questo però significa che probabilmente esiste una configurazione intermedia di bobina avente sia i minimi che i massimi entro i limiti richiesti di omogeneità del ± 3%.

10.4) Caso OTT95-12

Tenendo sempre la bobina spostata di 1 cm in direzione assiale, modifico in questo modo i parametri della parte laterale (= - 10 spire per parte rispetto al caso precedente, cioè caso intermedio fra gli ultimi 2 analizzati):

L_1 = 1020 mm
N_1 = 255 spire (cavo da 4.0 mm isolato)

β = 0.588
K = 0.5878

D_1 = 1718.33 A/mm

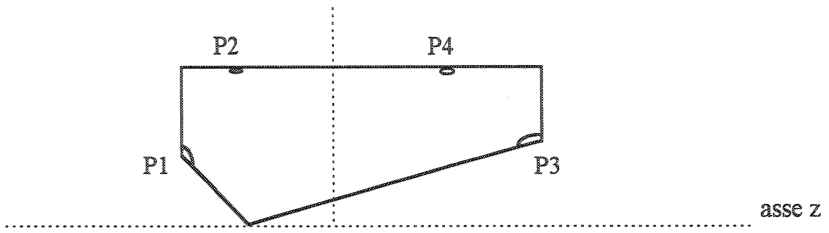
Risultati:

- campo al centro — Bo = 1.5004 T
- omogeneità — (| Bz | - Bo) / Bo = **- 2.76 ÷ + 3.19 %**
- forza assiale sulla bobina — Fz = **- 17 tonn**

10.5) CONFRONTO ULTIMI 4 CASI

In ***Figura 4*** rappresento il valore di omogeneità dei 4 estremi, i 2 minimi laterali e i 2 massimi, in funzione della lunghezza L_1 (o del parametro β, che è proporzionale).

Chiamo questi punti P1, P2, P3, P4 ; nella zona di interesse sono posizionati come nello schizzo seguente:



La ***Figura 4*** include anche il caso del paragrafo successivo (L_1=1000 mm).

Si vede che la finestra di valori di L_1 tali che tutti e 4 gli estremi si trovano all'interno del $\pm$ 3% è molto ristretta, tanto più che la variabile in ascissa L_1 non è continua ma discreta, secondo un passo di 4 mm che è la larghezza di una spira (rappresentata sull'asse x dalle tacche minori); si vede che l'unica scelta possibile è L_1=1000 mm oppure 1004 mm (cioè una sola spira di differenza per parte).

(La possibilità di scelta sul numero di spire, ovviamente, si può allargare se si accetta che qualche estremo superi il $\pm$ 3% in una piccola regione del volume di interesse.)

10.6) - CASO OTT95-13: SECONDA SOLUZIONE PER IL MAGNETE BABAR A 1 STRATO (BOBINA SPOSTATA, 17 TONNELLATE)

L_1 = 1000 mm
N_1 = 250 spire (cavo da 4.0 mm isolato)

β = 0.577
K = 0.599

D_1 = 1718.33 A/mm

Risultati:

- campo al centro — Bo = 1.5030 T
- omogeneità — (| Bz | - Bo) / Bo = **- 3.06 ÷ + 2.91 %**
- forza assiale sulla bobina — Fz = **- 17 tonn**

In ***Figura 5*** si può vedere la mappa di omogeneità per questo caso, che consideriamo come soluzione n° 2 per il magnete Babar a 1 strato (con la configurazione di ferro dei disegni in ***Rif.2*** e la regione di omogeneità scelta).

DOCUMENTI DI RIFERIMENTO:

Rif.1 - Relazione Simpro Componenti RDC.013.95.MGN12 :
"Studio soluzione a 1 strato per magnete Babar", Rev.0 del 4/10/1995

Rif.2 - Disegni tecnici "Babar Detector Magnet Assembly Reference Flux Return",
SA 350-600-IO-PO, Stanford Linear Accelerator Center, 18 fogli

---

LISTA FIGURE :

FIG.1 - Confronto casi F3, F7, F8, F9: grafico omogeneità del campo
su una linea a raggio 0.8 m parallela all'asse.

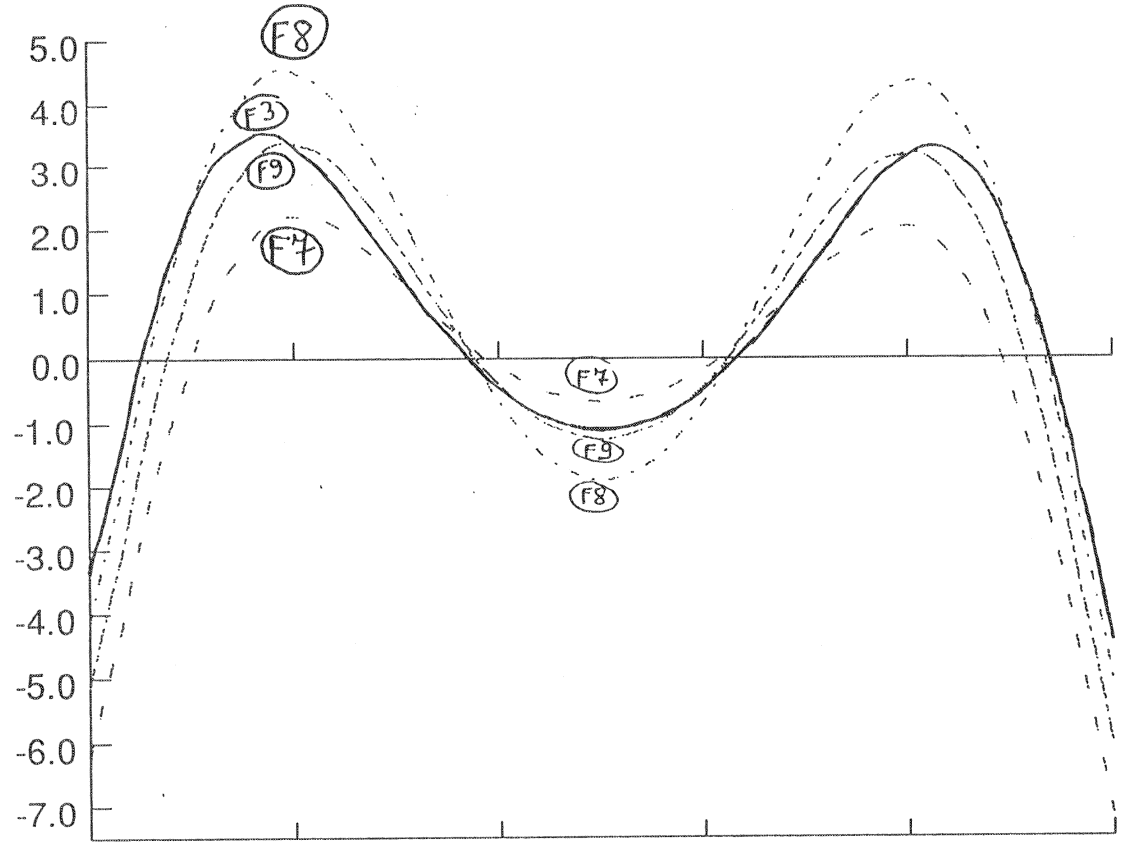
FIG.2 - Nuovo modello Babar:
2a) - piano-base
2b) - layer intermedio: spazio libero Spacers, Doors e Barrels
2c) - vista in 3D

FIG.3 - Mappa di omogeneità per caso ott95_7 (prima soluzione)

FIG.4 - Ottimizzazione estremi di omogeneità (bobina spostata 1 cm)

FIG.5 - Mappa di omogeneità per caso ott95_13 (seconda soluzione)

ALLEGATO 1 - verifica soluzione n° 1 con modello assialsimmetrico Ansys
(INFN_Genova)



Local X coord	0.8	0.8	0.8	0.8	0.8	0.8
Local Y coord	0.0	0.0	0.0	0.0	0.0	0.0
Local Z coord	-1.6	-0.96	-0.32	0.32	0.96	1.6

——— Component: (-BZ-1.5283)/1.5283*100, Integral = 2.774832 :(f3)

- - - Component: (-BZ-1.5342)/1.5342*100, Integral = -0.0500198 :(f7)

- - - - Component: (-BZ-1.5123)/1.5123*100, Integral = 3.626725 :(f8)

— — — Component: (-BZ-1.5225)/1.5225*100, Integral = 1.819052 :(f9)

UNITS

Length	: METR
Flux density	: TESL
Magnetic field	: AM
Scalar potential	: AMP
Vector potential	: WBM
Conductivity	: SM
Current density	: AM2
Power	: WATT
Force	: NEWT
Energy	: JOUL
Electric field	: VCM

FIG. 1

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OPERA-3d

Post-processor 2.3

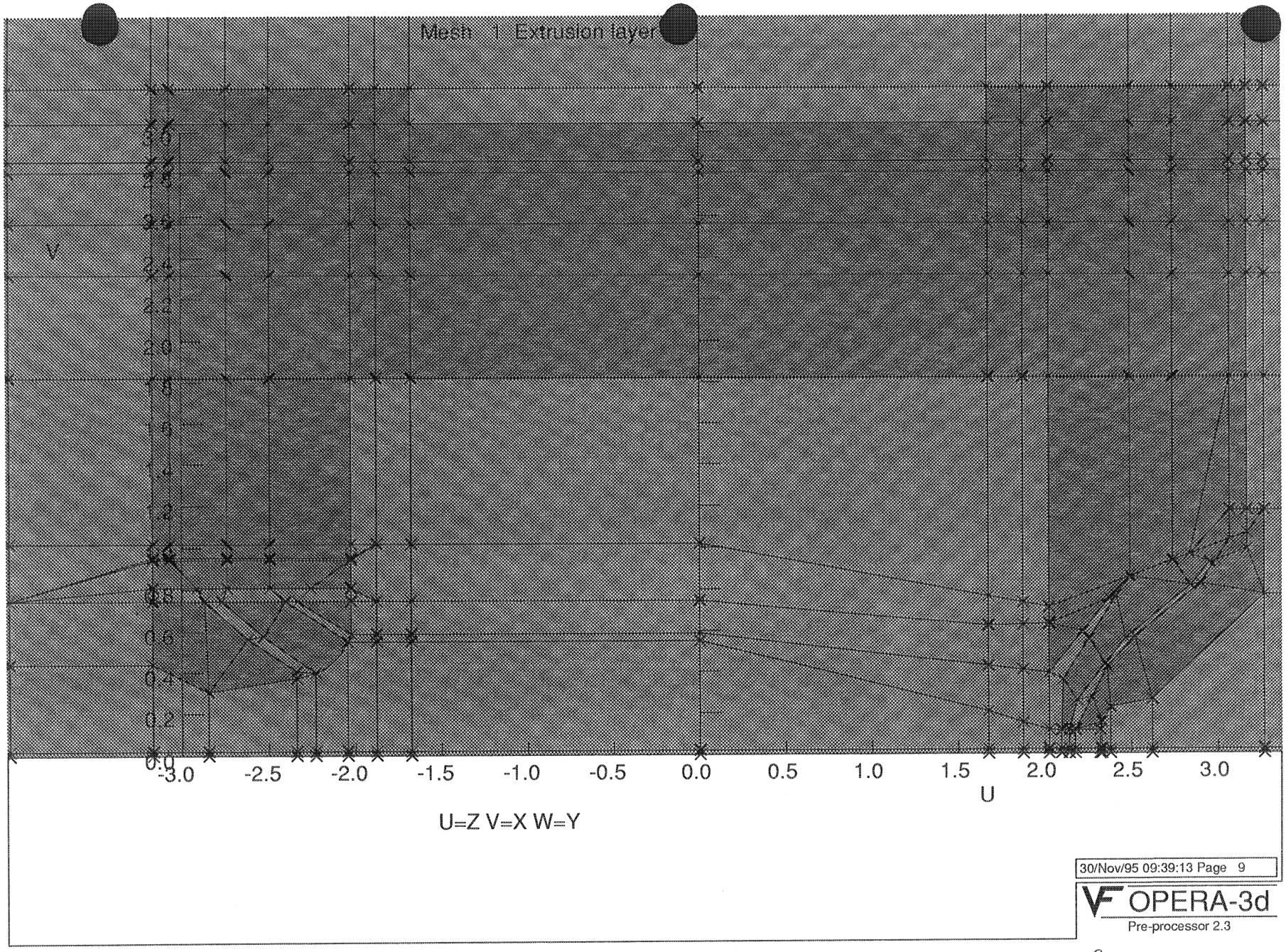

Mesh 1 Extrusion layer
V
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
U
U=Z V=X W=Y
30/Nov/95 09:39:13 Page 9
OPERA-3d
Pre-processor 2.3

FIG. 2A

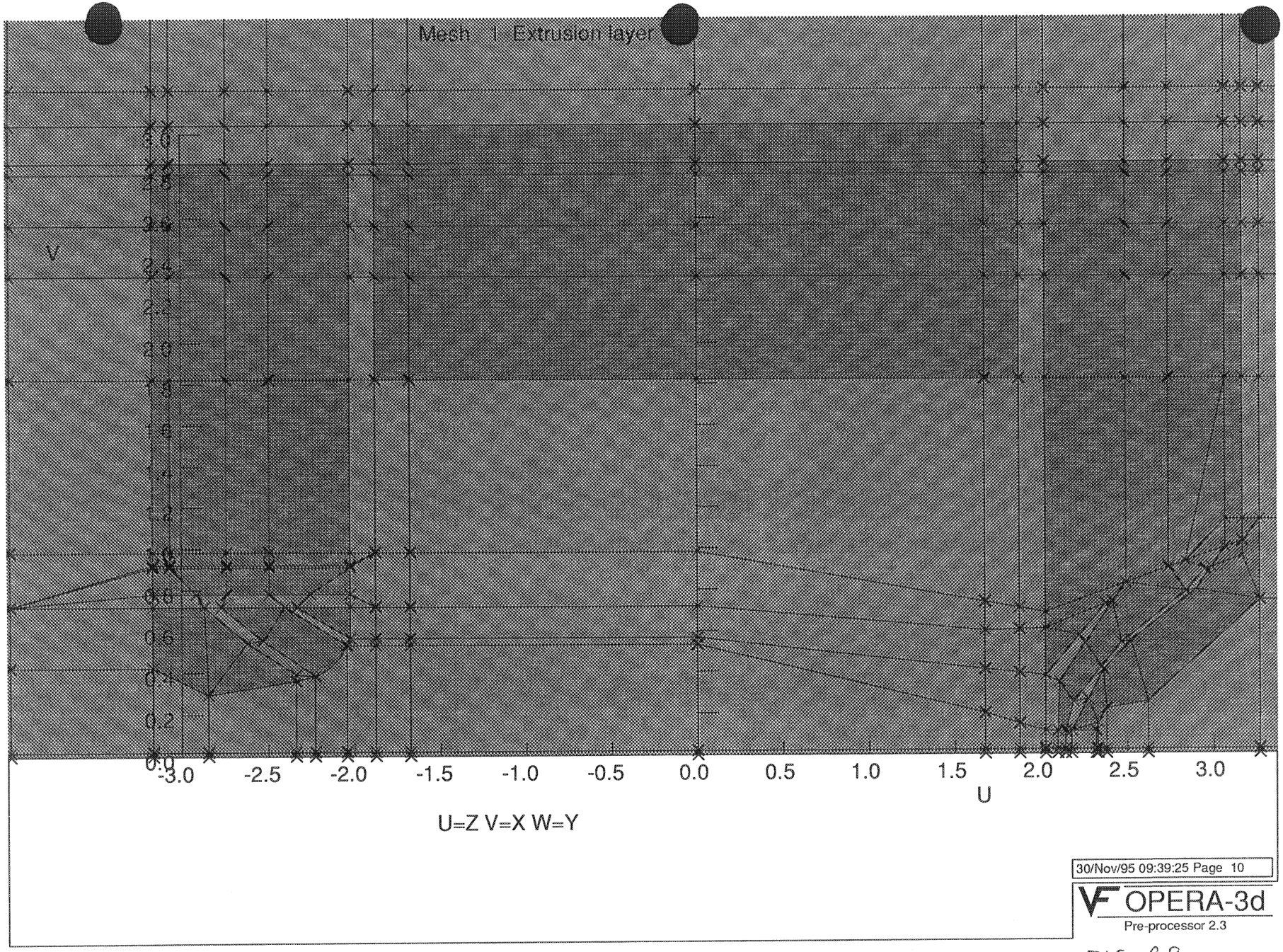

Mesh 1 Extrusion layer
V
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
U
U=Z V=X W=Y
30/Nov/95 09:39:25 Page 10
OPERA-3d
Pre-processor 2.3

FIG. 2B

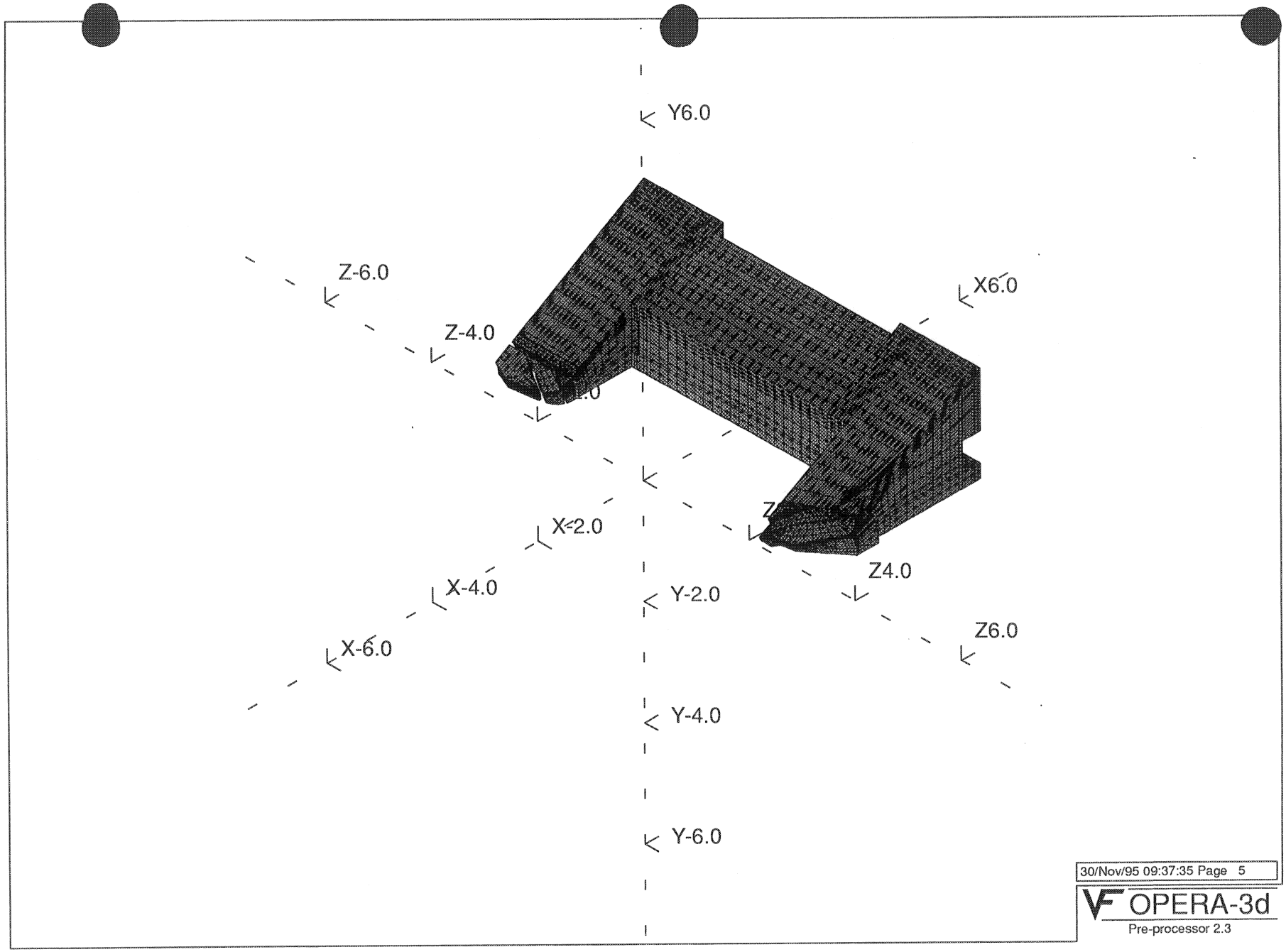

Y6.0
Z-6.0
Z-4.0
X6.0
X-2.0
Z4.0
X-4.0
Y-2.0
Z6.0
X-6.0
Y-4.0
Y-6.0
30/Nov/95 09:37:35 Page 5
OPERA-3d
Pre-processor 2.3

FIG. 2C

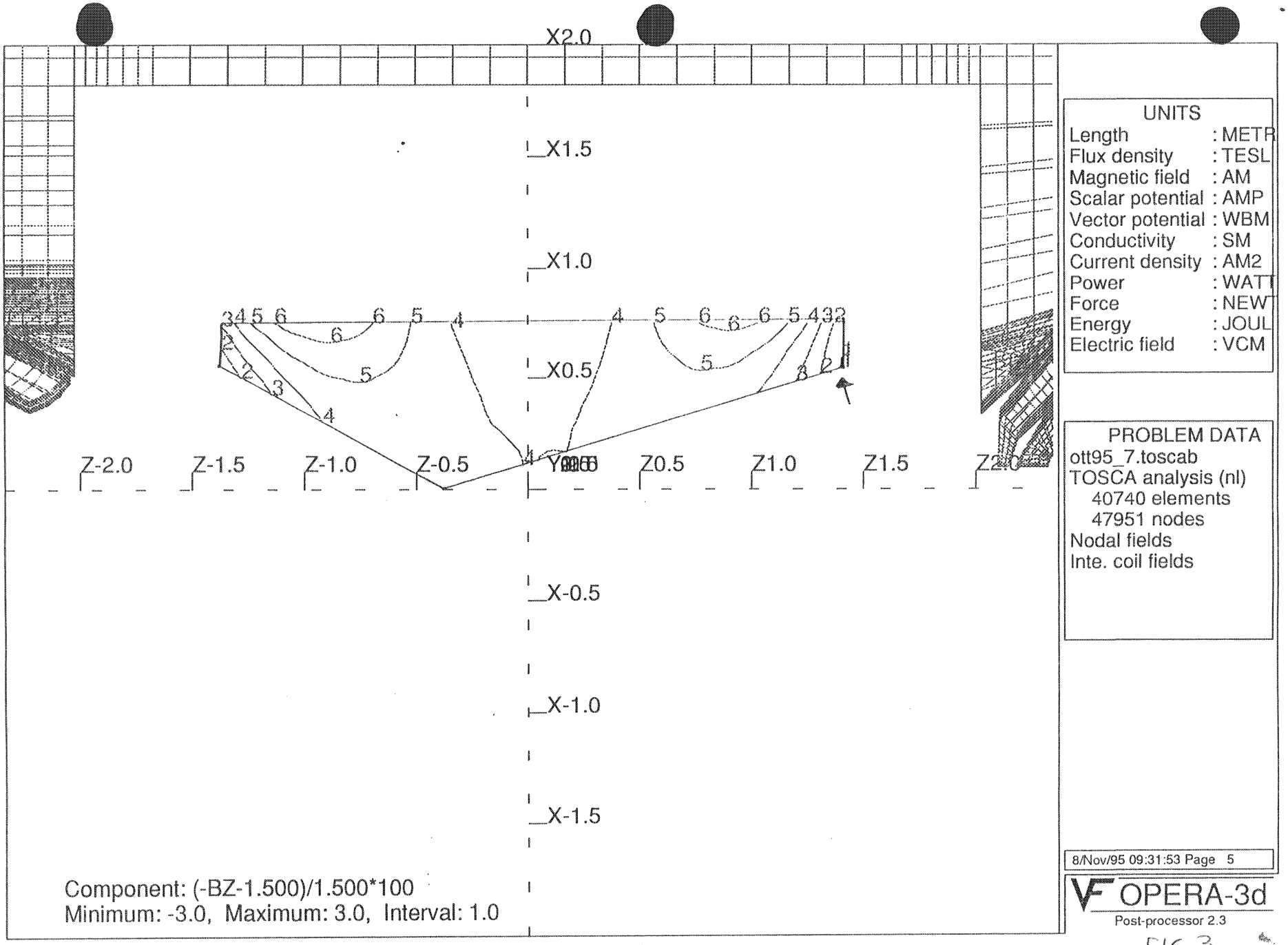

X2.0
X1.5
X1.0
X0.5
X-0.5
X-1.0
X-1.5
Z-2.0
Z-1.5
Z-1.0
Z-0.5
Z0.5
Z1.0
Z1.5
UNITS
Length : METR
Flux density : TESL
Magnetic field : AM
Scalar potential : AMP
Vector potential : WBM
Conductivity : SM
Current density : AM2
Power : WATT
Force : NEWT
Energy : JOUL
Electric field : VCM
PROBLEM DATA
ott95_7.toscab
TOSCA analysis (nl)
40740 elements
47951 nodes
Nodal fields
Inte. coil fields
Component: (-BZ-1.500)/1.500*100
Minimum: -3.0, Maximum: 3.0, Interval: 1.0
8/Nov/95 09:31:53 Page 5
OPERA-3d
Post-processor 2.3

FIG. 3

L1 (mm)	P1	P2	P3	P4	BETA
956	-3.28	2.57	-2.51	2.47	0.551
980	-3.24	2.7	-2.47	2.6	0.565
1000	-3.06	2.91	-2.29	2.815	0.576
1020	-2.76	3.19	-1.99	3.09	0.588
1060	-2.37	3.62	-1.59	3.51	0.611

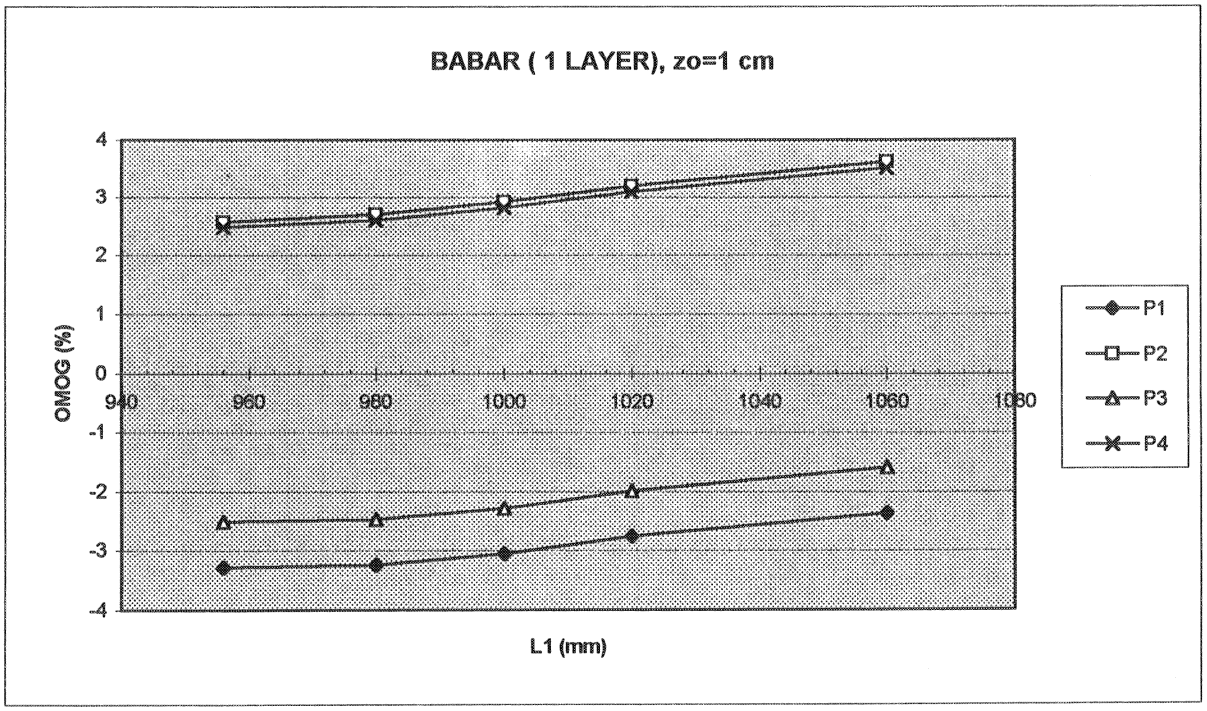
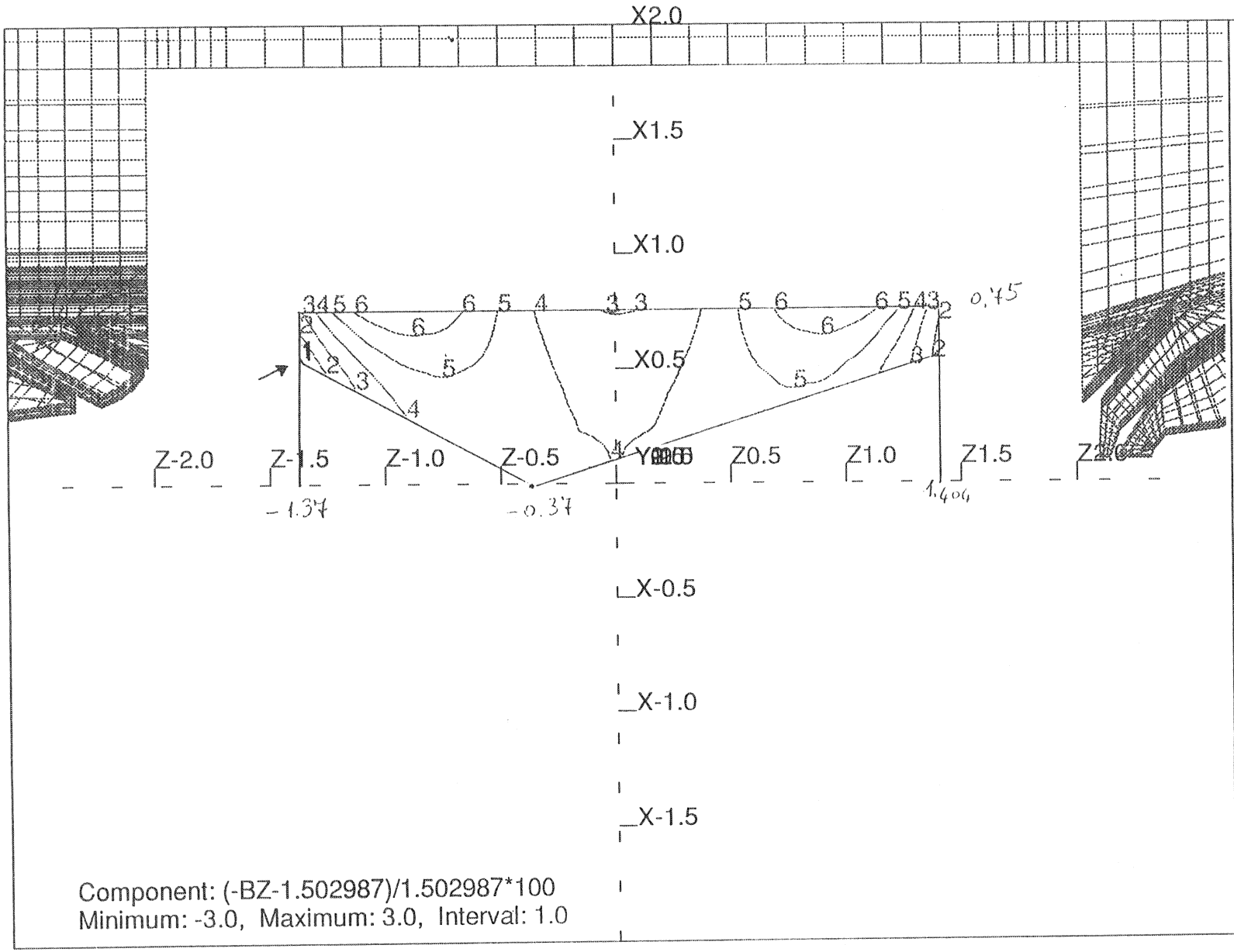


FIGURA 4 - OTTIMIZZAZIONE ESTREMI DI OMOGENEITA'



UNITS

Length	: METR
Flux density	: TESL
Magnetic field	: AM
Scalar potential	: AMP
Vector potential	: WBM
Conductivity	: SM
Current density	: AM2
Power	: WATT
Force	: NEWT
Energy	: JOUL
Electric field	: VCM

PROBLEM DATA
ott95_13.toscab
TOSCA analysis (nl)
40740 elements
47951 nodes
Nodal fields
Inte. coil fields

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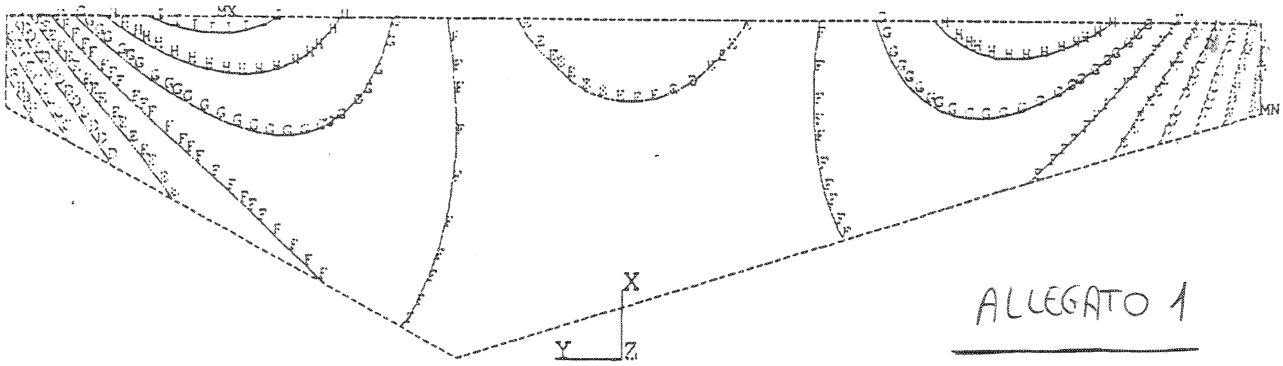
OPERA-3d
Post-processor 2.3

FIG. 5



ALLEGATO 1

$B_0 = 1.5066\ T$

$B_{MN} = 1.452\ T \rightarrow -3.6\%$

$B_{MX} = 1.548\ T \rightarrow +2.7\%$

$A = 1.458\ T \rightarrow -3.2\%$

$B = 1.468\ T \rightarrow -2.6\%$

$C = 1.479\ T \rightarrow -1.8\%$

$D = 1.49\ T \rightarrow -1.1\%$

$E = 1.5\ T \rightarrow -0.4\%$

$F = 1.511\ T \rightarrow +0.3\%$

$G = 1.522\ T \rightarrow +1.0\%$

$H = 1.532\ T \rightarrow +1.7\%$

$I = 1.543\ T \rightarrow +2.4\%$

FORZE SULLA BOBINA:

$F_x = 0.354 \cdot 10^8\ N$

$F_y = 0.293 \cdot 10^6\ N = 30$ tonn.

Progetto
Project

MAGNETE BABAR PER SLAC

SIMPRO
Componenti S.r.l.

Commessa job no.	TITOLO/title
MGN012	CALCOLI DI CAMPO PER MAGNETE BABAR

Fornitore supplier		IDENTIFICATIVO/document no.	PAG./page	DI/of
N. documento document no.		RDC.013.95.MGN12	1	37

Rev. rev.	Data date	Descrizione description	Redazione prepared by	Verifica checked by	Approv.ne approv. by	Autorizz.ne authoriz. by
0	04.10.95	FIRST ISSUE	A. Menicatti MENICATTI			

Informazioni strettamente riservate di proprietà SIMPRO Componenti S.r.l. - Da non utilizzare per scopi diversi da quelli per cui sono state fornite
confidential information property of SIMPRO Componenti S.r.l. - not to be used for any purpose other than that for which is supplied

Ansaldo Energia

2nd BABAR Meeting

Genoa, April 23,1996

Cryostat Design

Dimensions

Inner Diameter	2840 mm
Outer Diameter	3540 mm
Length	3850 mm

Preliminary Design according to ASME VIII "Rules for Construction of Pressure Vessel". Div.1 Par.UG-28 "Thickness of shells and tubes under External Pressure" and. for the end flanges Par. UG-34 "Unstayed flat heads and covers".

Material : Aluminum Alloy 5083-0

Mechanical Properties (at room temperature)

Young Modulus	72	Gpa
Poisson's ratio	0.33	
Yield Strength	120	MPa
Max. allowable stress	69	MPa

Minimum thickesses obtained to withstand to the ASME rules :

Outer Cylinder thickness	20	mm	1.3 bar
Inner Cylinder thickness	8	mm	0.21 bar
End Flanges thickness	10	mm	

Ansaldo *Energia*

2nd BABAR Meeting

Genoa, April 23,1996

Cryostat Design

F.e.m. Model

Ansys Rev. 4.4a Element n.63 " Elastic Quadrilateral Shell "

Case 1. Static Analisys

a) External atmospheric pressure
b) Solenoid, Support Cylinder plus Accessories weigth
c) Cryostat Weigth
d) Magnetic misalignment Force acting on the eigth radial tie rods
e) Magnetic misalignment Force acting on the three axial tie rods

Point loads on cry

7.8 t
2.5 t
20 t
25 t

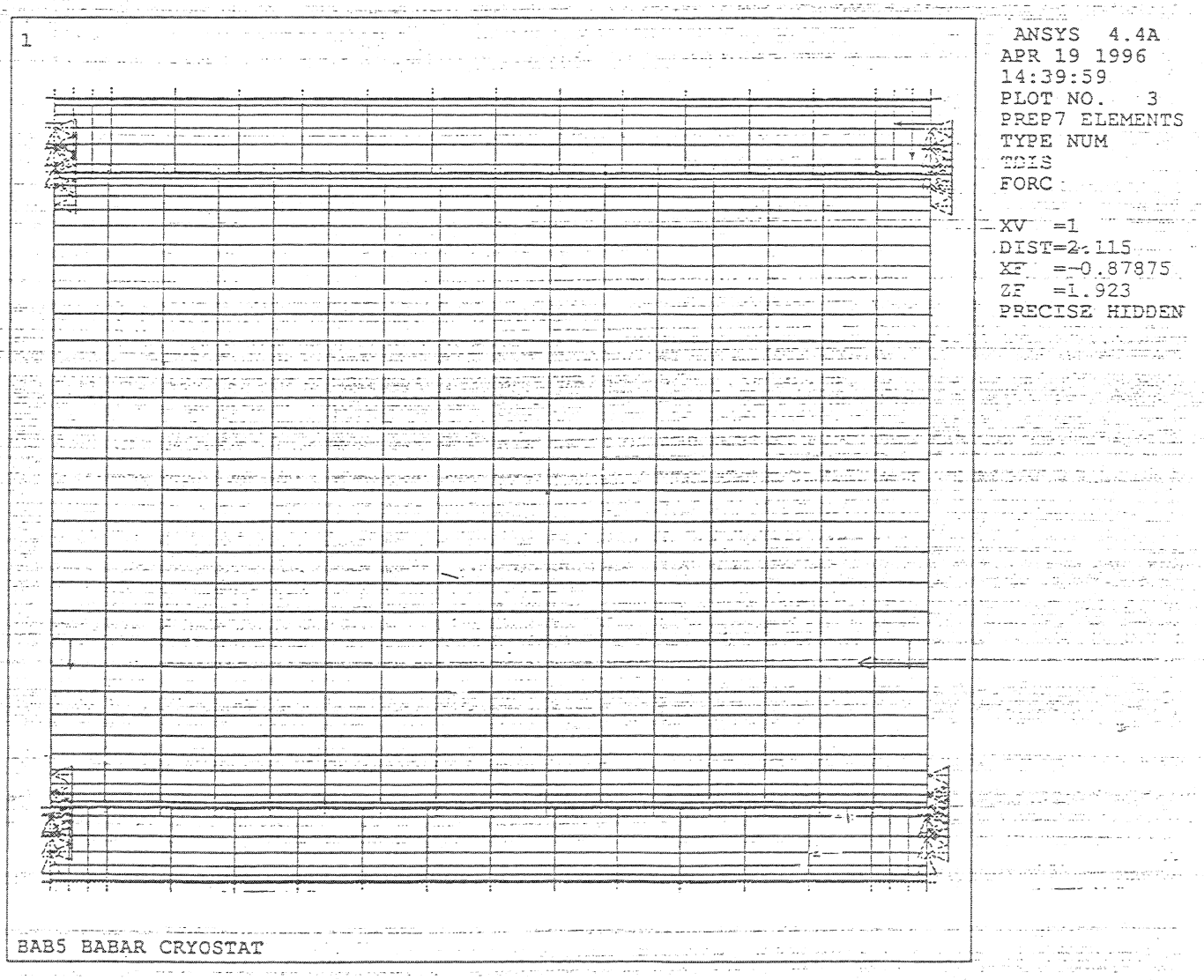
tie rod Point load

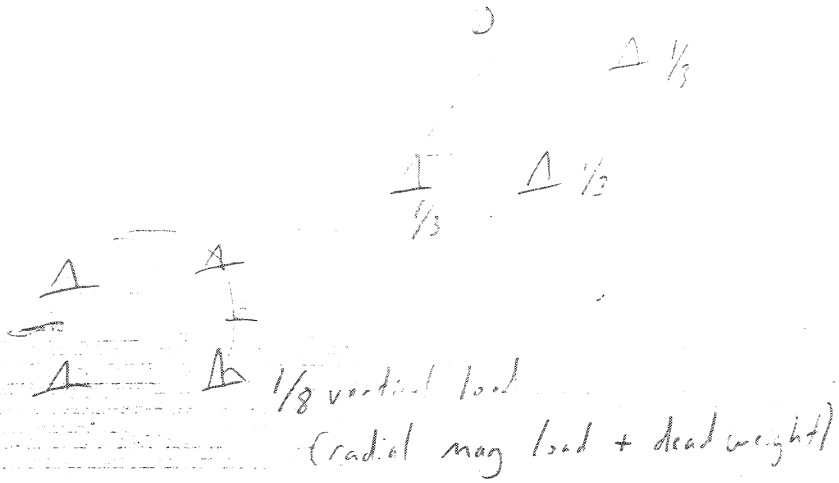
Case 2. Static plus Seismic Loads (statically acting) Analisys

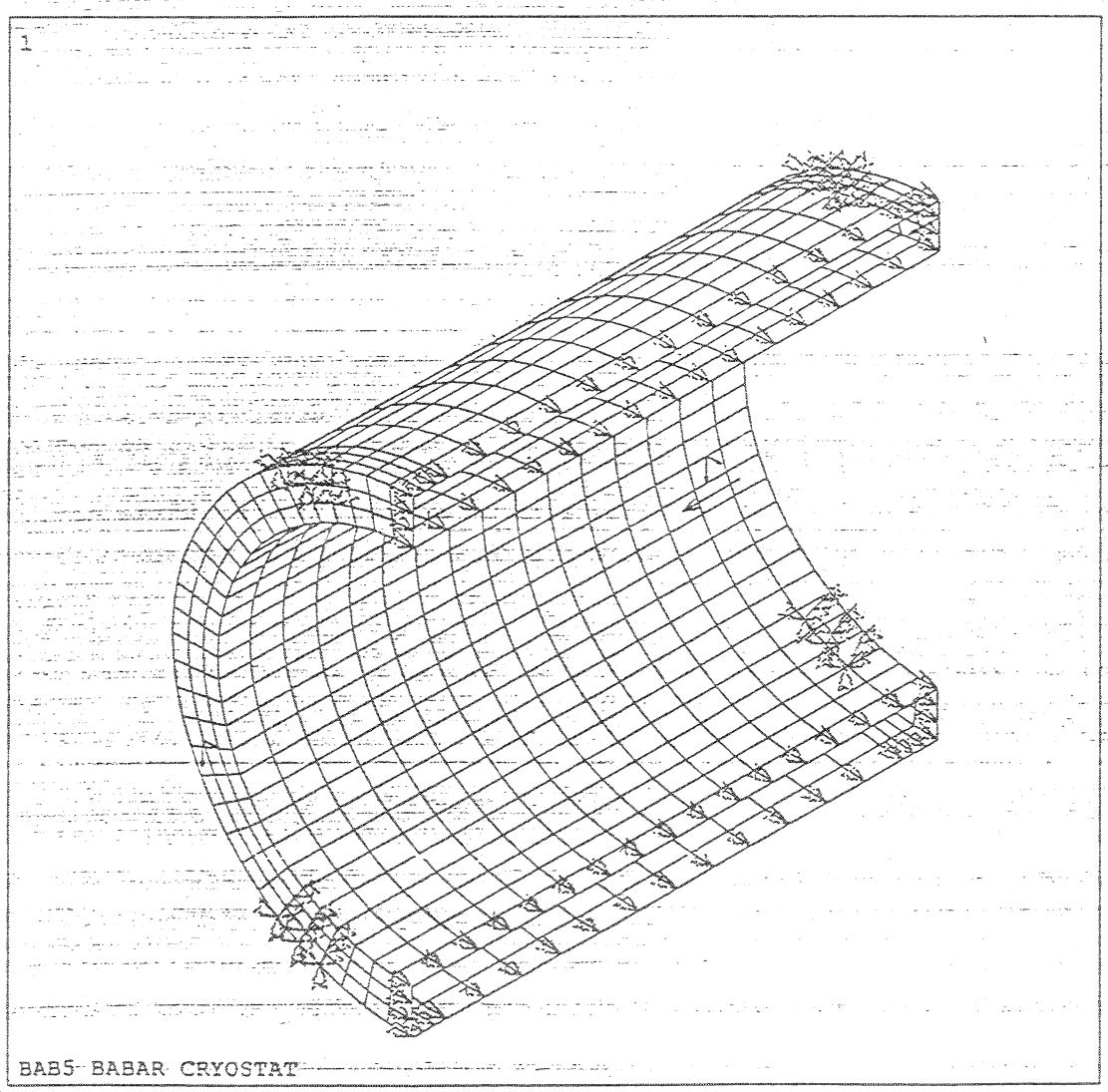
a) External atmospheric pressure	
b) Solenoid, Support Cylinder plus Accessories weigth	7.8 t
c) Cryostat Weigth	2.5 t
d) Magnetic misalignment Force acting on the eigth radial tie rods	20 t
e) Magnetic misalignment Force acting on the three axial tie rods	25 t
f) Seismic Loads (0.2 g axial , 1.6 g vertical)	

Input Thicknesses

Inner Cylinder	10 mm
Outer Cylinder	25 mm
Stiffening Rings	50 mm
End Flanges	40 mm


1
ANSYS 4.4A
APR 19 1996
14:39:59
PLOT NO. 3
PREP7 ELEMENTS
TYPE NUM
TDIS
FORC
XV =1
DIST=2.115
XF =-0.87875
ZF =1.923
PRECISE HIDDEN
BAB5 BABAR CRYOSTAT


1/3
1/3
1/3
1/8 vertical load
(radial mag load + dead weight)


1
ANSYS 4.4A
APR 19 1996
14:39:40
PLOT NO. 1
PREP7 ELEMENTS
TYPE NUM
TDIS
FORC
XV =1
YV =1
ZV =1
DIST=2.837
XF =-0.87875
ZF =1.923
PRECISE HIDDEN
BABS BABAR CRYOSTAT

Static Analisys

File BAB5	Stress Intensity [MPa]		
Outer Cylinder	TOP	MIDDLE	BOTTOM
MAX	26	8	37
MIN	1	0.4	1
Inner Cylinder			
MAX	18	21	25
MIN	3	0.6	0.4
End Flanges			
MAX (*)	68	6	64
MIN	0.3	0.2	0.2

File BAB5	Radial Stress [MPa]	Hoop Stress [MPa]	Axial Stress [MPa]
Outer Cylinder			
MAX	—	-13	31
MIN	—	8	-7
Inner Cylinder			
MAX	—	20	19
MIN	—	-8	-11
End Flanges			
MAX (*)	-73	-60	—
MIN (*)	66	21	10

Maximum displacement : 0.71 mm

(*) these values are concentrated on the application point of the axial tie rod

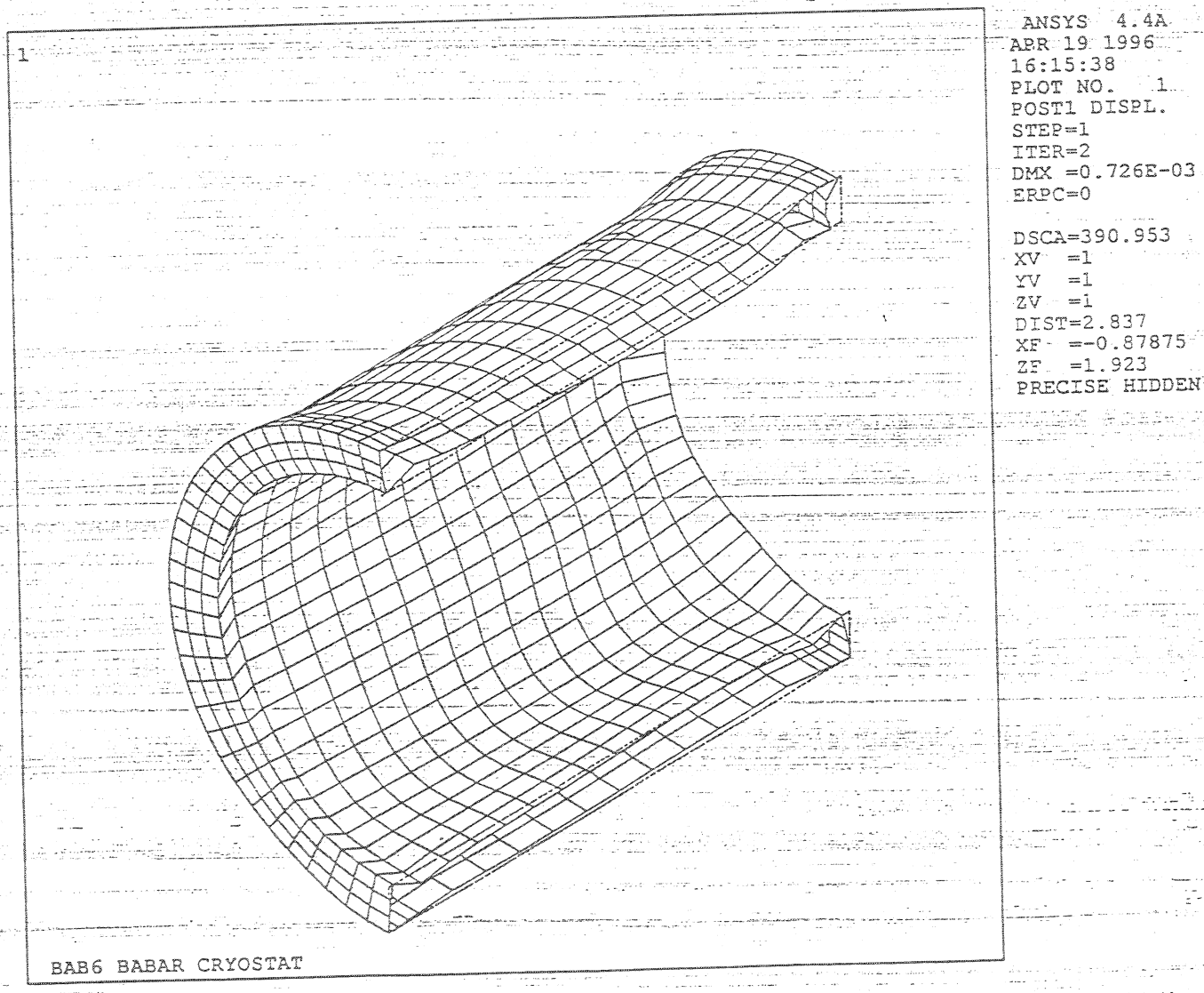
Static plus Seismic Loads Analisys

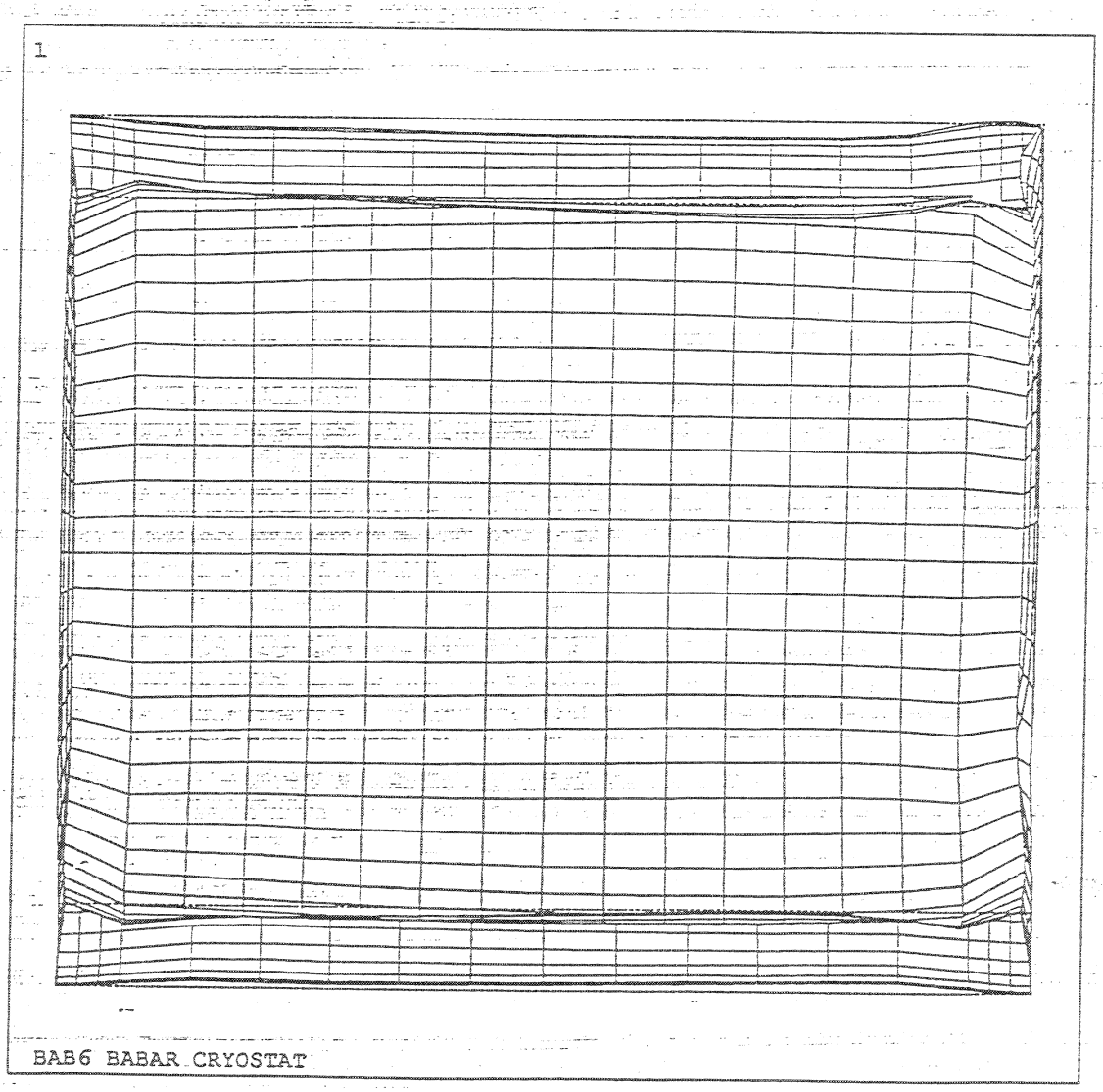
File BAB6	Stress Intensity [MPa]		
Outer Cylinder	TOP	MIDDLE	BOTTOM
MAX	36	8	38
MIN	1	0.3	2
Inner Cylinder			
MAX	18	21	26
MIN	3	2	2
End Flanges			
MAX (*)	69	6	65
MIN	4	0.5	4

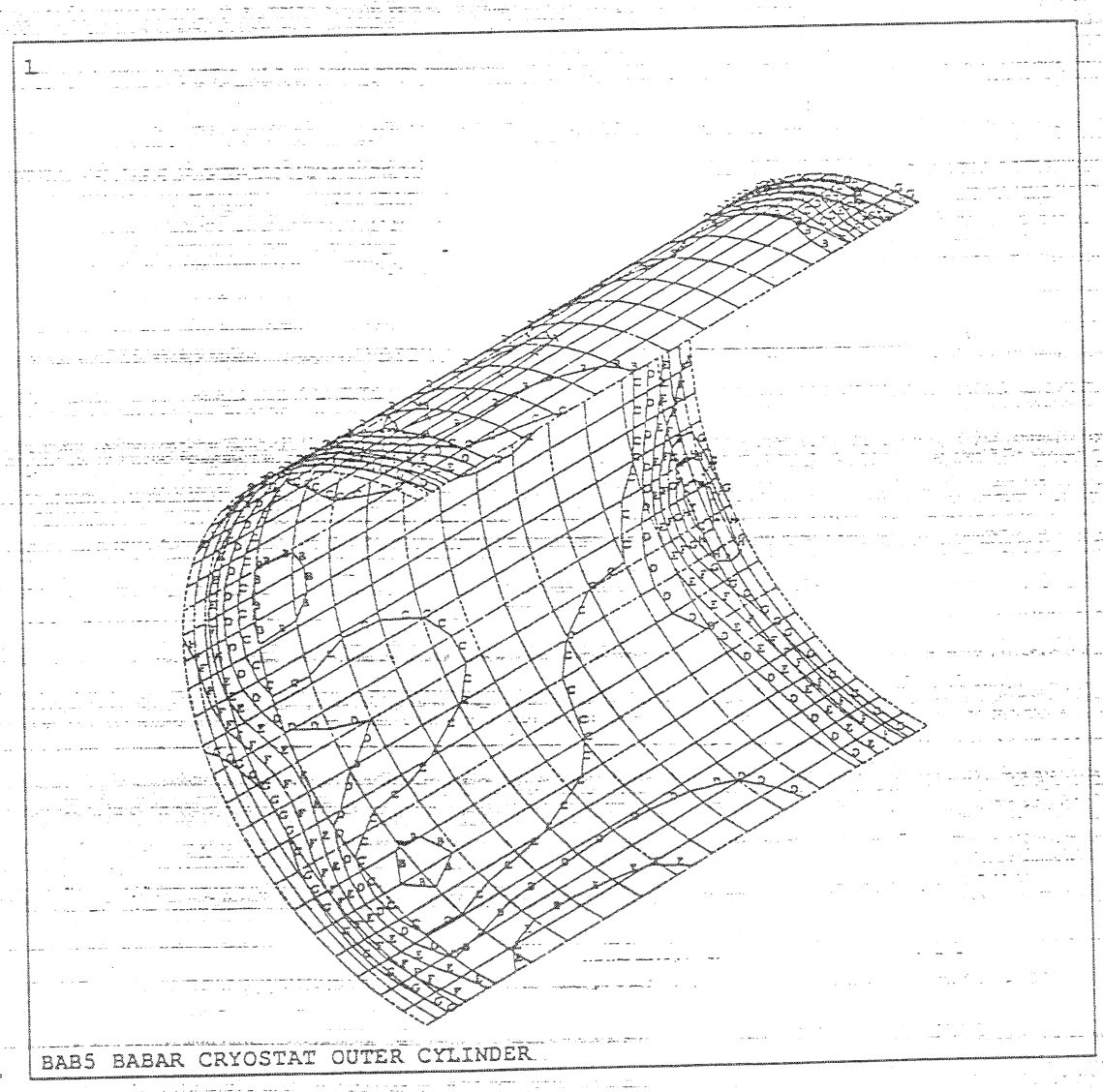
File BAB6	Radial Stress [MPa]	Hoop Stress [MPa]	Axial Stress [MPa]
Outer Cylinder			
MAX	—	-16	38
MIN	—	9	-7
Inner Cylinder			
MAX	—	19	20
MIN	—	-8	-11
End Flanges			
MAX (*)	-70	-60	-7
MIN (*)	62	17	11

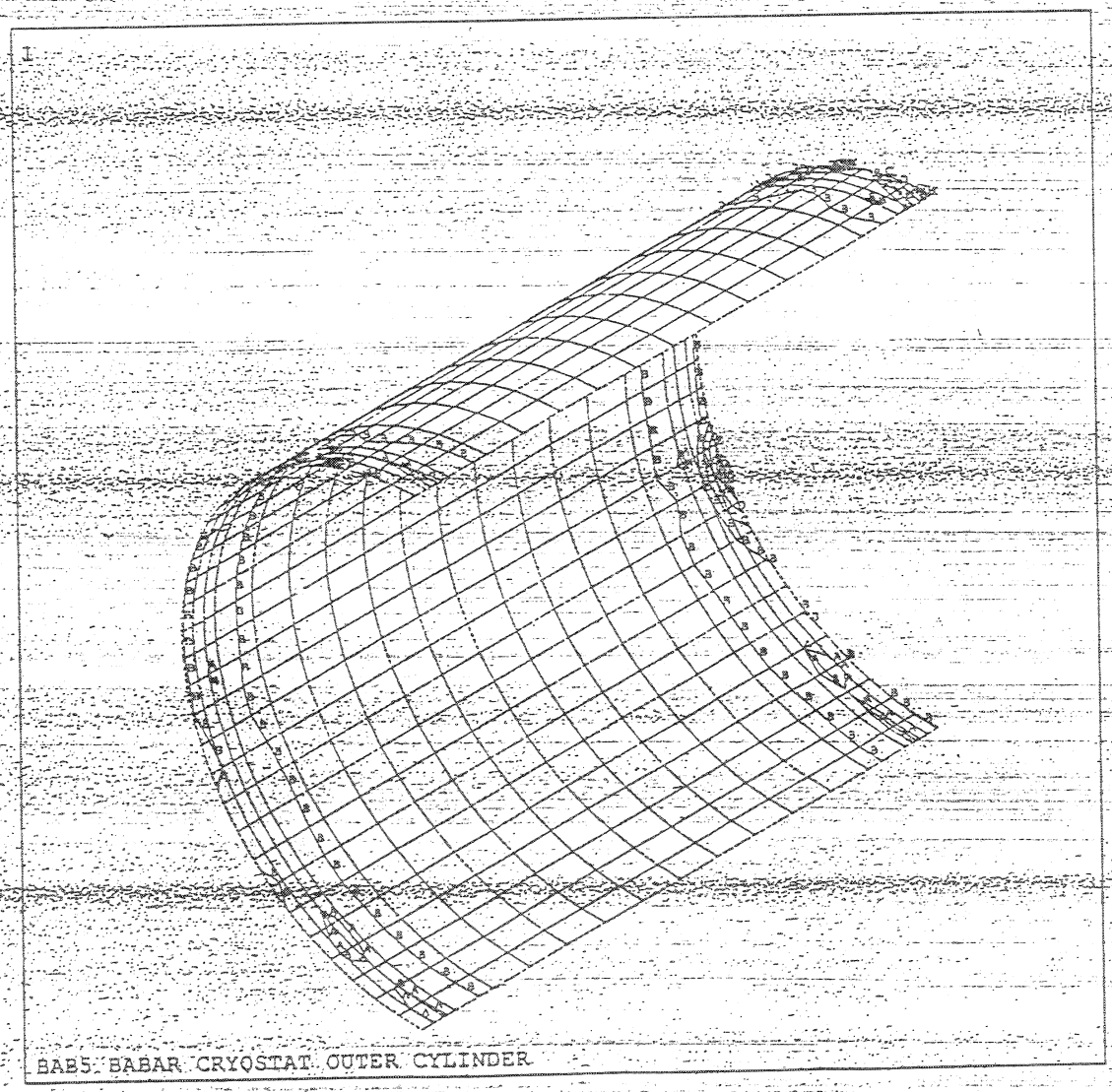
Maximum displacement : 0.73 mm

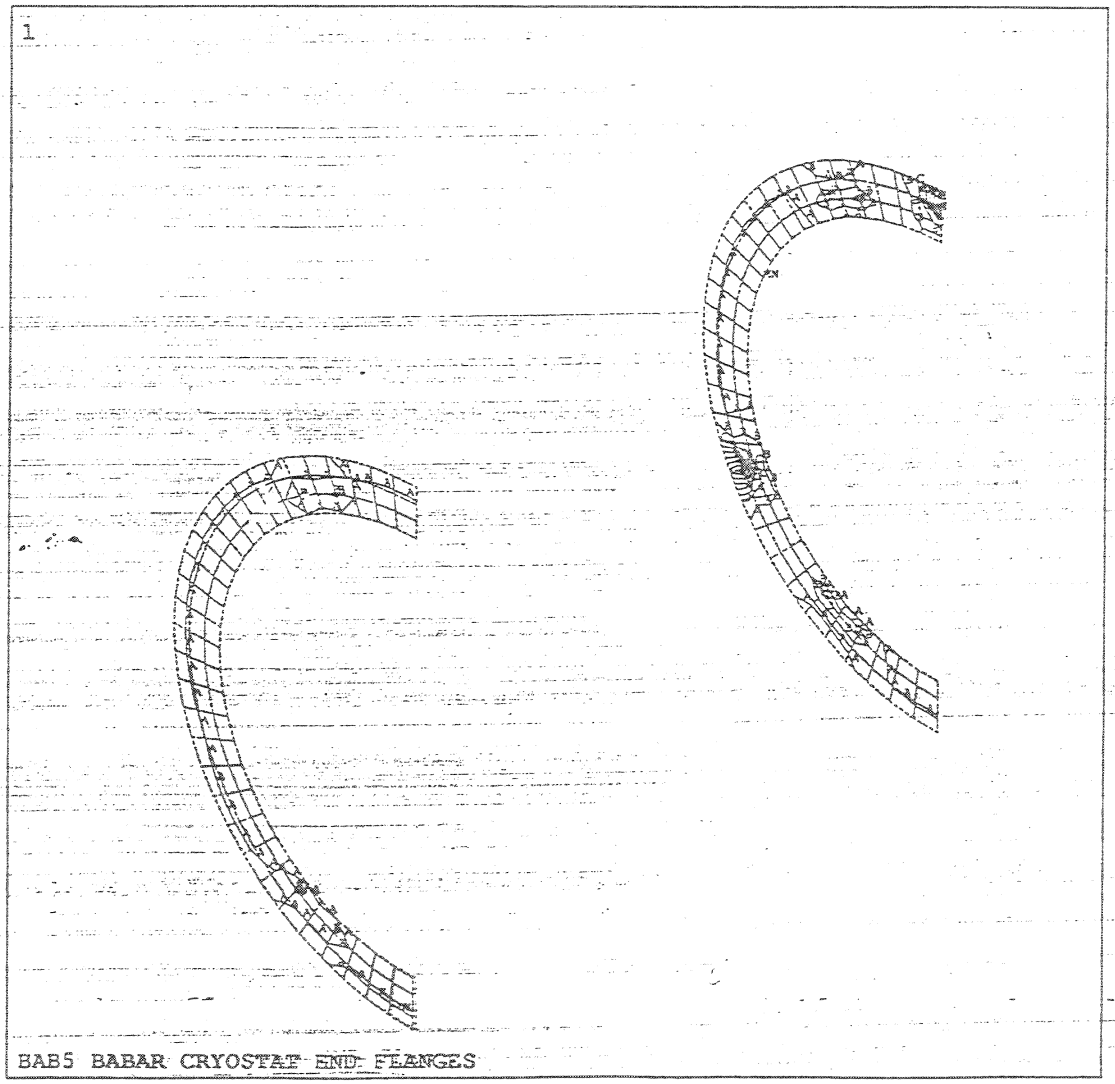
(*) these values are concentrated on the application point of the axial tie rod


1
ANSYS 4.4A
APR 19 1996
16:15:38
PLOT NO. 1
POST1 DISPL.
STEP=1
ITER=2
DMX =0.726E-03
ERPC=0
DSCA=390.953
XV =1
YV =1
ZV =1
DIST=2.837
XF =-0.87875
ZF =1.923
PRECISE HIDDEN
BAB6 BABAR CRYOSTAT


1
ANSYS 4.4A
APR 19 1996
16:15:55
PLOT NO. 2
POST1 DISPL.
STEP=1
ITER=2
DMX =0.726E-03
ERPC=0
DSCA=291.53
XV =1
DIST=2.115
XF =-0.87875
ZF =1.923
PRECISE HIDDEN
BAB6 BABAR CRYOSTAT

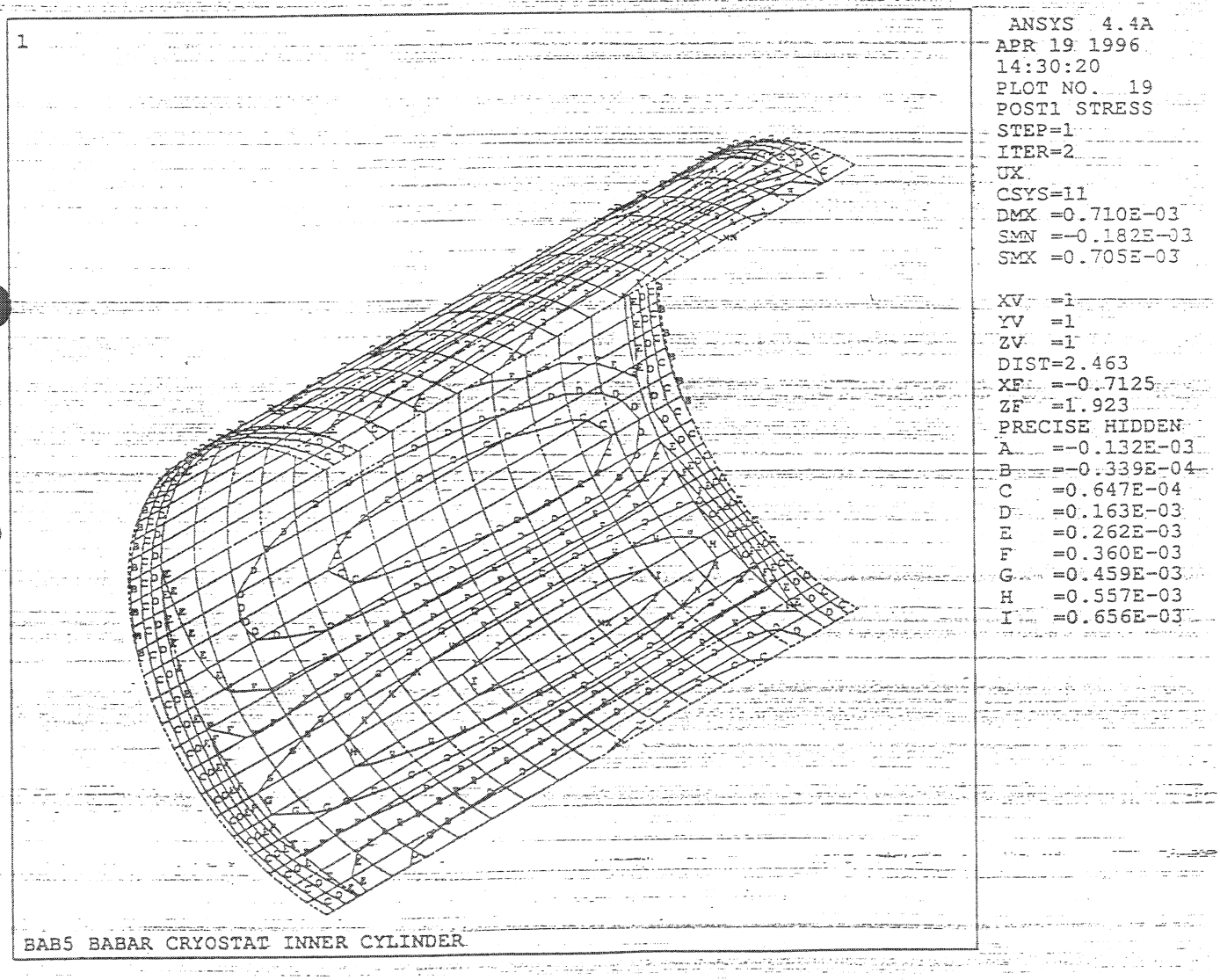

1
ANSYS 4.4A
APR 19 1996
14:29:00
PLOT NO. 10
POST1 STRESS
STEP=1
ITER=2
UX
CSYS=11
DMX =0.710E-03
SMN =-0.235E-03
SMX =0.538E-04
XV =1
YV =1
ZV =1
DIST=2.837
XF =-0.87875
ZF =1.923
PRECISE HIDDEN
A =-0.219E-03
B =-0.187E-03
C =-0.155E-03
D =-0.123E-03
E =-0.905E-04
F =-0.584E-04
G =-0.263E-04
H =0.573E-05
I =0.378E-04
BAB5 BABAR CRYOSTAT OUTER CYLINDER


1
ANSYS 4.4A
APR 19 1996
14:27:58
PLOT NO. 3
POST1 STRESS
STEP=1
ITER=2
SIGE (AVG)
TOP
DMX =0.710E-03
SMN =891085
SMX =0.268E+08
SMXB=0.315E+08
XV =1
YV =1
ZV =1
DIST=2.837
XF =-0.87875
ZF =1.923
PRECISE HIDDEN
A =0.233E+07
B =0.521E+07
C =0.810E+07
D =0.110E+08
E =0.139E+08
F =0.167E+08
G =0.196E+08
H =0.225E+08
I =0.254E+08
BAB5: BABAR CRYOSTAT OUTER CYLINDER



ANSYS 4.4A
APR 19 1996
14:30:32
PLOT NO. 21
POST1 STRESS
STEP=1
ITER=2
SIGE (AVG)
TOP
DMX =0.710E-03
SMN =340053
SMX =0.684E+08
SMXB=0.773E+08

XV =1
YV =1
ZV =1
DIST=2.837
XF =-0.87875
ZF =1.923
PRECISE HIDDEN
A =0.412E+07
B =0.117E+08
C =0.193E+08
D =0.268E+08
E =0.344E+08
F =0.420E+08
G =0.495E+08
H =0.571E+08
I =0.647E+08


1
ANSYS 4.4A
APR 19 1996
14:30:20
PLOT NO. 19
POST1 STRESS
STEP=1
ITER=2
UX
CSYS=11
DMX =0.710E-03
SMN =-0.182E-03
SMX =0.705E-03
XV =1
YV =1
ZV =1
DIST=2.463
XF =-0.7125
ZF =1.923
PRECISE HIDDEN
A =-0.132E-03
B =-0.339E-04
C =0.647E-04
D =0.163E-03
E =0.262E-03
F =0.360E-03
G =0.459E-03
H =0.557E-03
I =0.656E-03
BAB5 BABAR CRYOSTAT INNER CYLINDER