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TESLA Test Facility Cryostat
Gas Helium Return Tube Thermal Gradient Analysis

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Introduction

Concern has been expressed over the course of the TESLA test facility (TTF) cryostat development about thermally induced distortions of the gas helium return tube. Specifically, the issue involves thermal gradients which can occur in this tube from flow stratification during cooldown. These thermal gradients induce mechanical distortions and thermal stresses in the tube and impose structural loads on the support system. The following report summarizes the results of a structural analysis on this tube. The analysis does not attempt to predict the details of cooldown, but rather to assess the behavior of the tube given a set of discrete assumptions.

Tube Geometry

The gas helium return tube is continuous through the entire TTF cryostat. It is supported at three points along its length by support posts attached to the vacuum vessel and serves as the main structural support for all eight cavity helium vessels and the quadrupole. Figure 1 illustrates a cross section through the cryostat assembly at a typical cavity location. For the sake of this analysis the tube is assumed to be symmetric about the center of the cryostat assembly. This is not exactly correct due to the presence of the quadrupole at one end, however, the errors resulting from this assumption are small. Figure 2 illustrates the model of the tube used in this analysis. It is modeled using the left half of INFN drawing number 02.01.00. All of the pertinent tube parameters are summarized in Table 1.

Table 1. Gas helium return tube properties	
Tube property	Value
Material	316L or 316LN stainless*
Length	6050 mm (1/2 model)
OD	298.5 mm
Wall thickness	5.9 mm
Elastic modulus	193 GPa (28.0x10^6 psi)
Poisson's ratio	0.3
Density	0.0079 gm/mm^3 (0.286 lb/in^3)

*: The mechanical and thermal properties of 316L and 316LN stainless are virtually identical. Any differences are insignificant for this analysis.

Table 2 lists the data used for thermal contraction of the tube. This data is for 304L stainless, but is valid for any 300 series stainless.

Table 2. Thermal expansion data for 300 series stainless steel		
T (K)	$(L_{293} - L_T)/L_{293}$	α_{eff} (K^{-1})*
4	3.06E-03	1.06E-05
20	3.06E-03	1.12E-05
40	3.03E-03	1.20E-05
60	2.94E-03	1.26E-05
80	2.81E-03	1.32E-05
100	2.65E-03	1.37E-05
120	2.45E-03	1.42E-05
140	2.22E-03	1.45E-05
160	1.95E-03	1.47E-05
180	1.68E-03	1.49E-05
200	1.40E-03	1.51E-05
220	1.13E-03	1.55E-05
240	8.30E-04	1.57E-05
260	5.20E-04	1.58E-05
273	3.10E-04	1.55E-05
293	0.00E+00	1.55E-05

*: $\alpha_{effective}$ is defined as the total fractional contraction divided by the temperature range over which the fractional contraction is defined.

Structural Loads

There are two sources of structural loading on the tube assembly. The first is simply the weight of the tube itself. For this analysis 1g is assumed to be acting downward on the tube. The density is shown in table 1. The other structural loads are those from the cavity structures. Prior to the recent reduction in size of the cavity helium vessel, each assembly (cavity, vessel, tuner, and coupler) was assumed to weigh 93 kg. For this analysis the weight is assumed to be 80 kg distributed equally to the tube through two hangers. Even significant errors in this estimate have insignificant effects on thermally induced distortions.

Thermal Loads

There is no way to accurately predict thermal gradients in the gas helium return tube during cooldown because the exact nature of the cooldown sequence is unknown at this time. For this analysis, ten different thermal cases are investigated. They are intended to simulate conditions at the start of cooldown and at two points into the cooldown sequence. No analyses below 80K are considered due to the fact that nearly all of the thermal contraction occurs above that temperature. In all cases in which a thermal gradient is defined, it is assumed to be linear from the top of the tube to the bottom with the highest temperature always at the top. Table 3 summarizes the conditions corresponding to each analysis case. Case 1d only accounts for the structural effects and is included in order the separate the structural and thermal effects.

Table 3. Analysis case descriptions

Case number	Tube top temperature (K)	Thermal gradient (K)	Notes
1a	293	10	
1b	293	20	
1c	293	30	
1d	293	0	Structural effects only
2a	200	10	
2b	200	20	
2c	200	30	
3a	80	10	
3b	80	20	
3c	80	30	

Analysis Description

A finite element model is the easiest and most accurate means by which to investigate all the effects of thermal gradients simultaneously. All of the required effects - displacements, reaction forces, and tube stresses are available directly from the analysis. Figure 3 is a mesh plot from the finite element model. The model takes advantage of the x-y plane symmetry described above as well as y-z symmetry. This way only one quarter of the actual structure needs to be modeled. Displacement and rotational restraints are applied at both symmetry planes to simulate the behavior of the 'missing' structure. Supports are modeled as vertical restraints (y-direction) at the center and at 4350 mm from the center, axially. The outer support is allowed to slide axially (z-direction) to accommodate longitudinal shrinkage of the tube during cooldown.

Analysis Results

As expected, the effect of the thermal gradients is to force the outboard end of the tube downward. This is due to the fact that the top of the tube is always at the highest temperature because of the nature of flow stratification. Reaction forces in the supports and thermal stresses in the tube result from the fact that the supports attempt to restrain the tube from deflecting. Worst case deflections occur at the beginning of cooldown (tube top at 293K) because this is where the highest differential contraction occurs. As cooldown progresses, the difference in contraction between the top and bottom of the tube decreases, resulting in lower thermal distortions. Table 4 summarizes the critical results from all ten analysis cases. Figures 4 through 7 illustrate the deflected shape of the tube for all cases. Figure 8 illustrates the vertical reaction forces in the center and outer supports and figure 9 illustrates the maximum stress intensity in the tube. Figure 10 is a stress intensity contour plot for case 1c. Stress intensity is defined as the maximum difference in principal stresses and is a good measure of how near or far a structure is from its yield strength.

Table 4. Summary of analysis results

Case	Top temp (K)	dT (K)	Max displ (mm)	Center support reaction (N)	Outer support reaction (N)	Max SI (MPa)
1d	293	0	-0.10	4526	3851	14.4
1a	293	10	-1.84	370	5929	24.1
1b	293	20	-3.58	-3787	8007	44.8
1c	293	30	-5.39	-8095	10161	66.8
2a	200	10	-1.66	752	5738	22.2
2b	200	20	-3.24	-2970	7599	40.7
2c	200	30	-4.77	-6637	9432	58.9
3a	80	10	-0.83	2770	4729	14.7
3b	80	20	-1.50	1175	5526	20.0
3c	80	30	-2.10	-260	6244	26.9

Summary and Conclusions

It is difficult to determine a limit on the allowed thermal gradient given the above results. The worst case in any of the above analyses is that in which the top of the tube is at room temperature and a 30K gradient exists from top to bottom. In that case, the reactions on the supports are well below the strength of the posts. Supports are routinely tested in tension and compression to 40000 N without failure, four times the worst case shown above. In the case of tube stresses, the yield strength of 316 stainless steel at room temperature is approximately 230 MPa, over three times the worst case reported above. The most worrisome aspect of thermal deflections may very well be displacements along the length of the tube, particularly at the end. Any deflection of the tube will cause misalignment of the cavities. In theory, all components will return to their original positions when thermal equilibrium is established in the return tube, however, it is always a good idea to keep movement of critical components small. In addition, each tube has bellows at the end and any large deflection could cause permanent distortions of this bellows, particularly at the beginning of cooldown when deflections are large and the adjacent tube in the next cryostat in the string has not yet begun to deflect.

One final implication from this analysis pertains to stress relieving of this tube prior to assembly. As reported above, in a stress-free tube, the bending stresses resulting from thermal bow are small compared to the yield strength. However, residual stresses from fabrication of the tube and welding of various cryostat components to the tube imply that some parts of the tube may in fact be on the verge of yield. Any additional stresses will result in permanent deformation of the tube. For this reason, a good job of stress relieving is crucial to the long term stability of this tube.

It is prudent to define some limit on the allowed thermal gradient during cooldown. For all the reasons stated above, the initial limit should be defined to be no greater than 10K. This limits the maximum deflection of the tube to less than 2 mm, which seems reasonable, and limits the bending stress to 10% of the yield strength, which should provide an adequate margin of safety in the event that stress relieving is not completely successful at removing all the fabrication stresses.

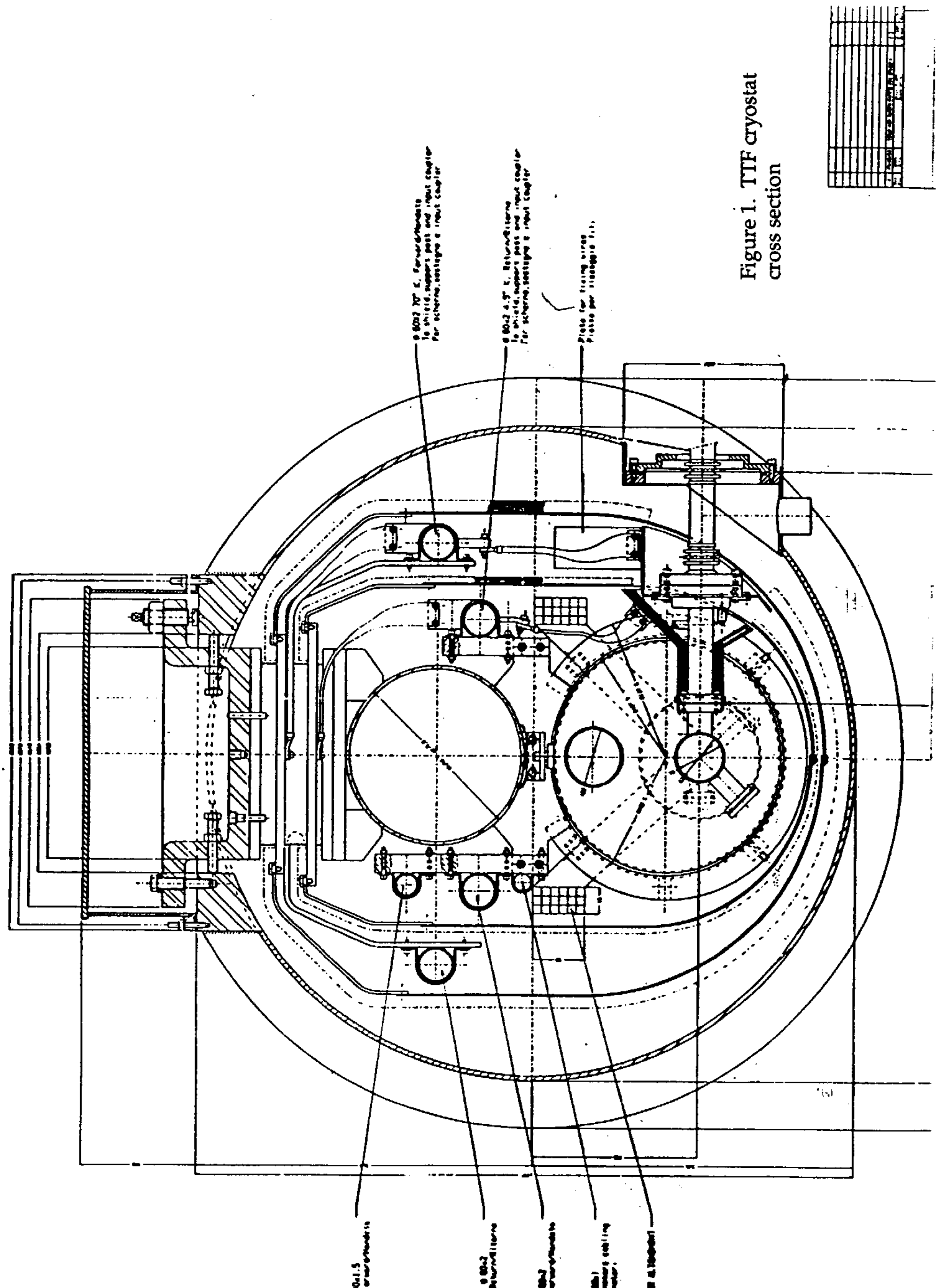

Figure 1. TTF cryostat cross section

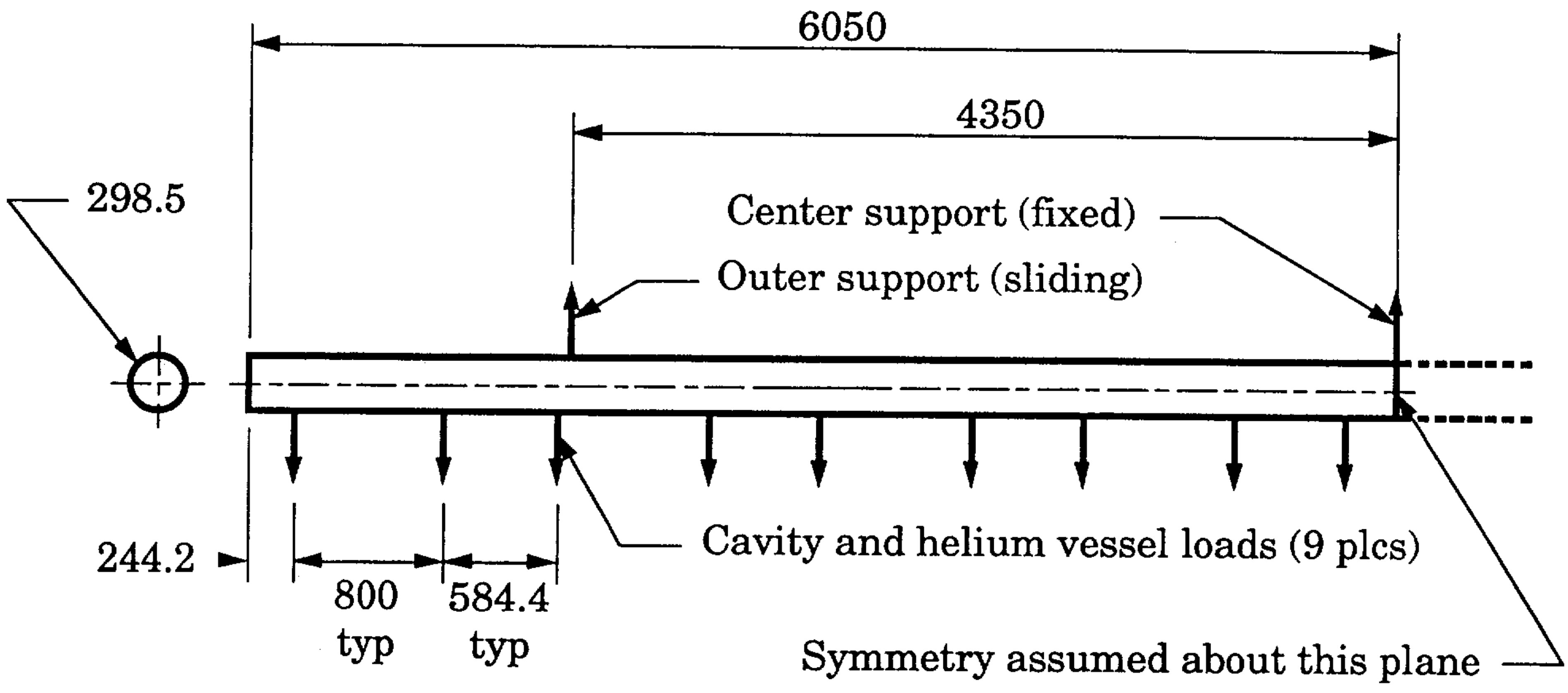

Figure 2. TTF GHe return tube geometry (left half of INFN drawing no. 02.01.00)

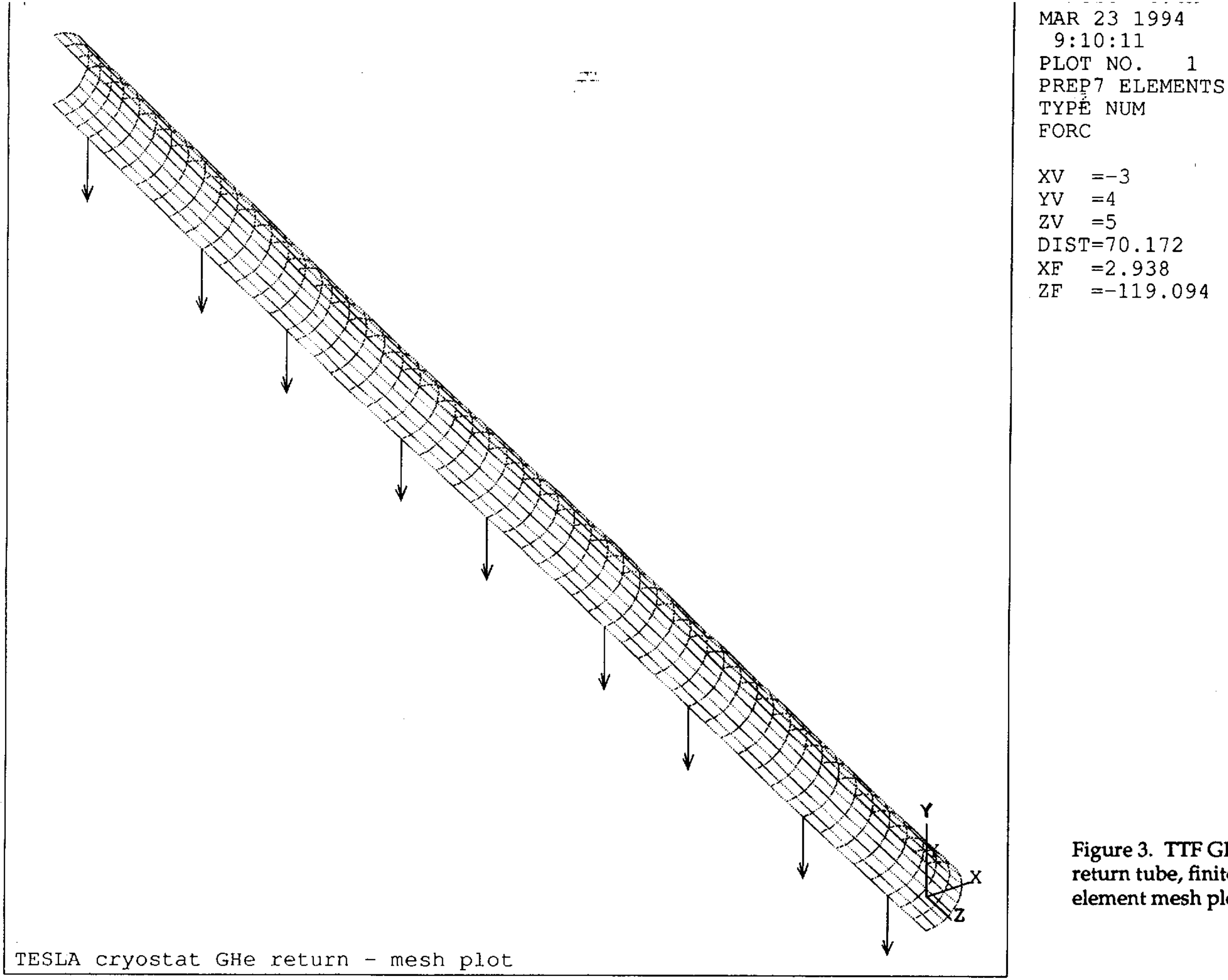

Figure 3. TTF GHe return tube, finite element mesh plot

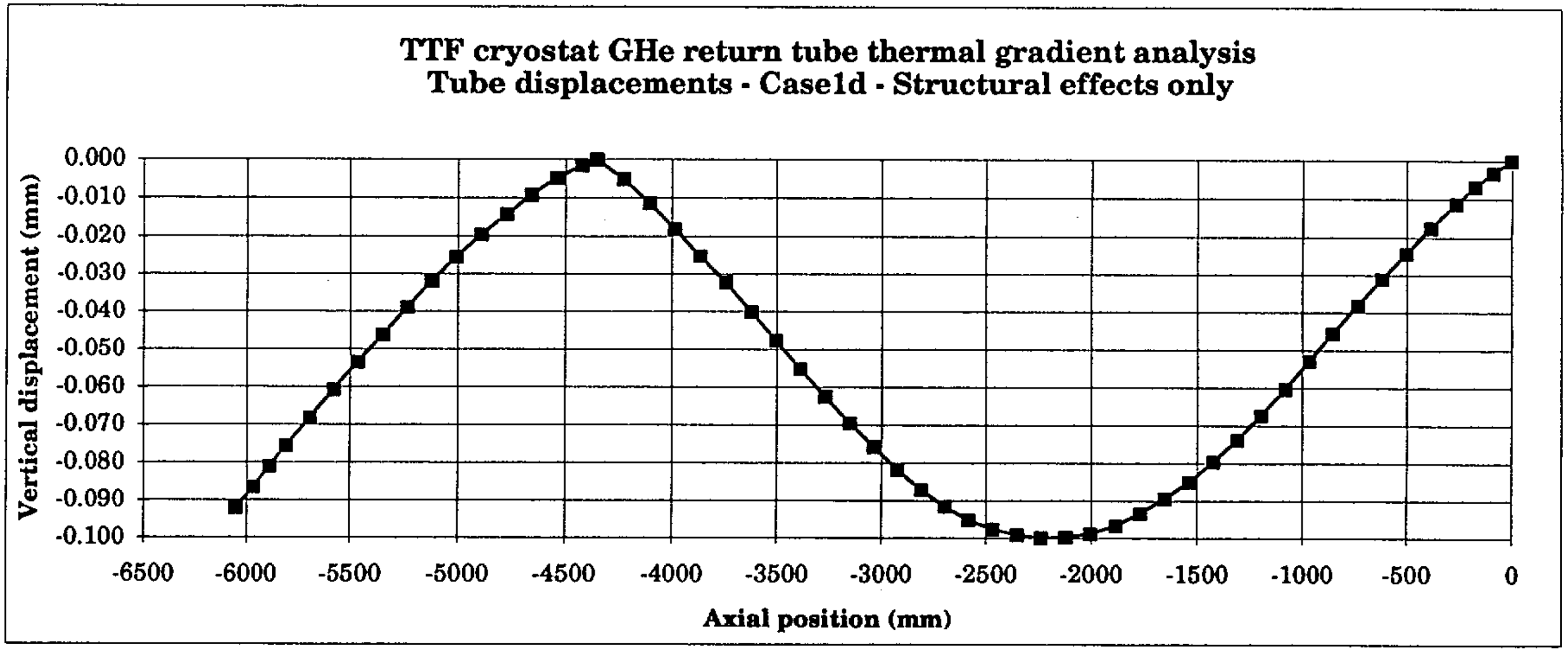
TTF cryostat GHe return tube thermal gradient analysis
Tube displacements - Case1d - Structural effects only
Vertical displacement (mm)
0.000
-0.010
-0.020
-0.030
-0.040
-0.050
-0.060
-0.070
-0.080
-0.090
-0.100
-6500
-6000
-5500
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
Axial position (mm)

Figure 4

Date: 3/24/94 Time: 16:55 Filename: GHERETRN.XLS Chart 3

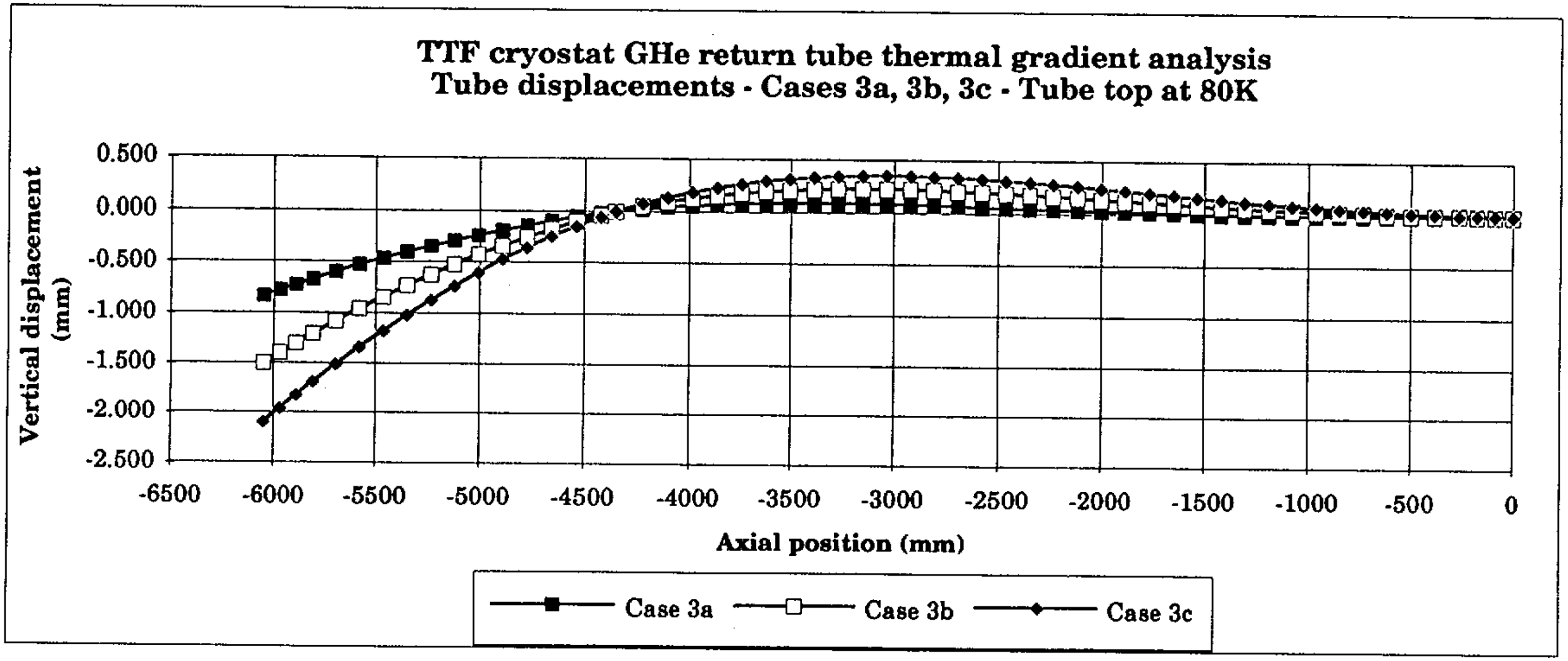

Figure 7

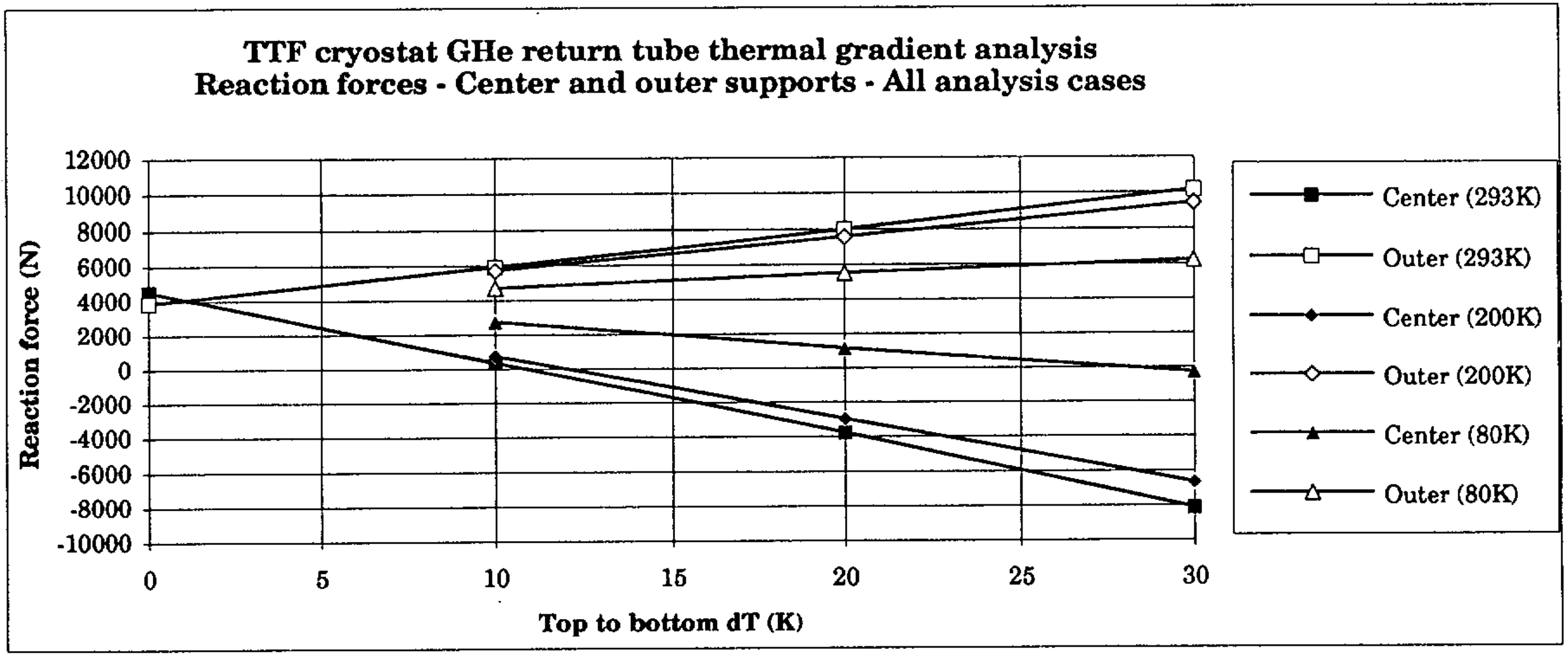
TTF cryostat GHe return tube thermal gradient analysis
Reaction forces - Center and outer supports - All analysis cases
Reaction force (N)
12000
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
5
10
15
20
25
30
Top to bottom dT (K)
Center (293K)
Outer (293K)
Center (200K)
Outer (200K)
Center (80K)
Outer (80K)

Figure 8

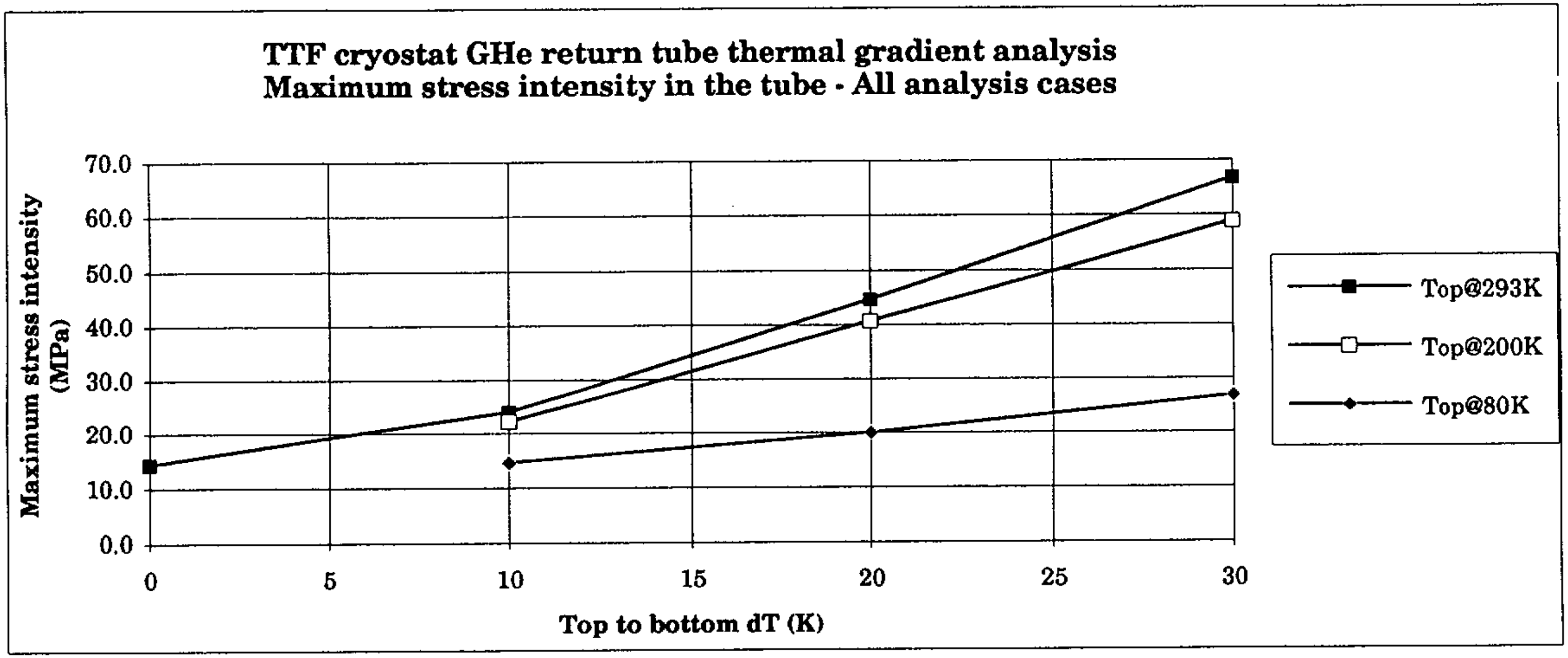
TTF cryostat GHe return tube thermal gradient analysis
Maximum stress intensity in the tube - All analysis cases
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Maximum stress intensity (MPa)
0
5
10
15
20
25
30
Top to bottom dT (K)
Top@293K
Top@200K
Top@80K

Figure 9

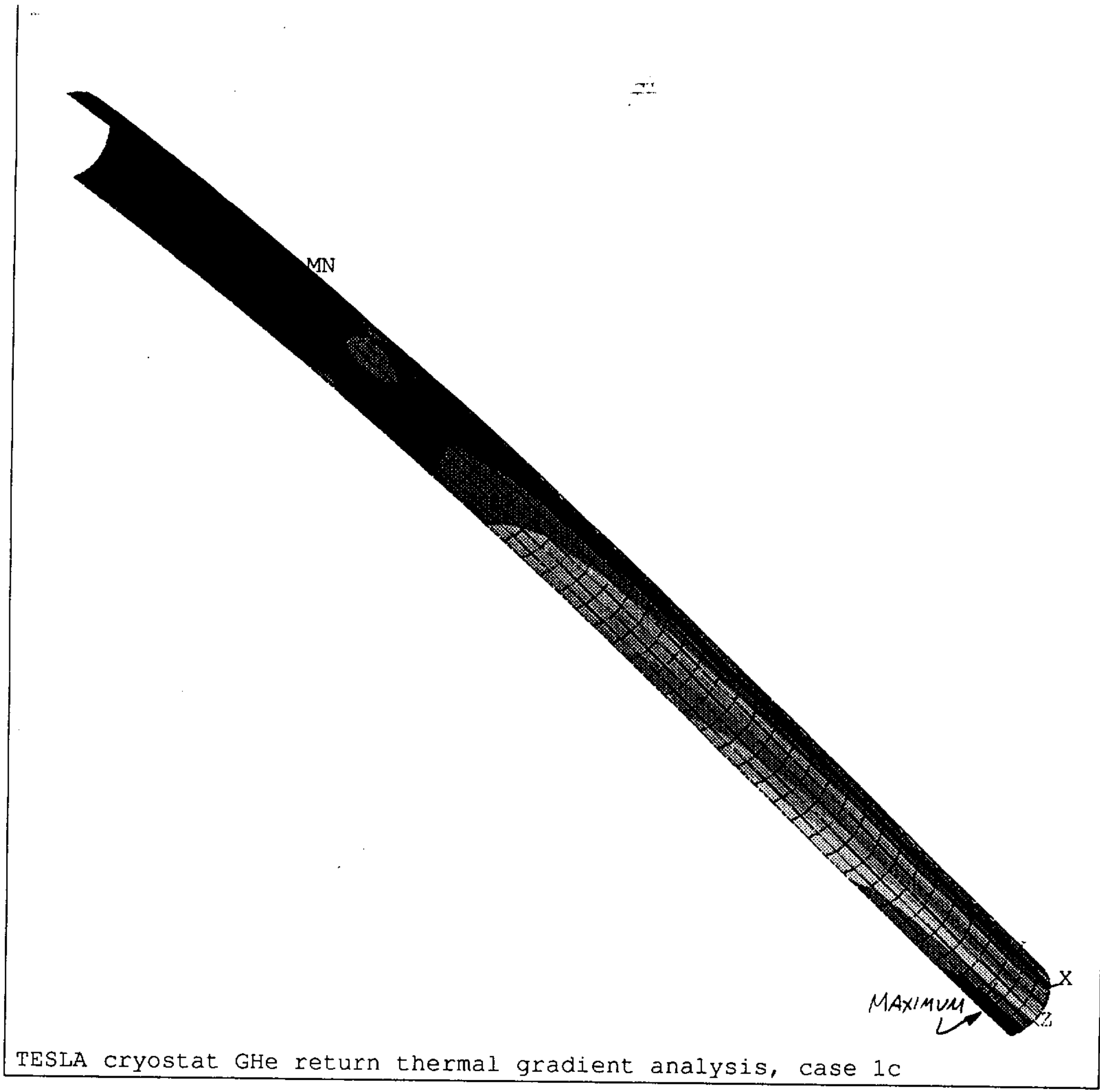

Figure 10. TTF GHe return tube, finite element stress intensity contour plot