5th Int. Conference Structural Integrity of Welded Structures (ISCS2007), Timisora, Romania, 20-21 Nov 2007
- Testing & risk assessment in the development of advanced materials and joints -
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Advanced Techniques for Investigating of Fatigue Due to the Thermal Transients in Nuclear Equipment

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Abstract

The paper intends to propose a methodology for fatigue investigation related to Nuclear Components subjected to Thermal/ Pressure Transients, by employing the advanced techniques offered by the ANSYS-CFX 11.0 Program, also meeting ASME Class 1.

1. Introduction

The proposal refers to a methodology for investigation the typical stress and fatigue occurred in the Nuclear Components subjected to Thermal/ Pressure Transients, by employing advanced techniques offered by the ANSYS-CFX Program (Hydraulic, Thermal & Structural finite elements Modules and Fatigue Postprocessor) also meeting the ASME Class 1 requirements,.

In short herein below it is a presentation of CANDU 600 NPP's Pressurizer component which must with stand the most drastic Thermal/ Pressure Transient conditions, mostly imposed by the Primary Heat Transport System (PHT).

Tabel 1-1. Operating Conditions (Thermal/Pressure Transients)

Item	Name	Nr. cycles
1.	Heatup & Cooldown	250
2.	Startup & Shutdown	1000
3.	Power Maneuvering	10000
4.	Loss of Feedwater from 100% Power	100
5.	Reactor Trip from 100% Power	500
6.	Loss of Class IV Power from 100% Power	50
7.	Loss of Regulation (Reactor Overpower)	200
8.	Turbine Trip	100
9.	Stepback	500
10.	Pressurizer Startup During Commissioning	50
11.	Emergency Over pressurization	1

2. Methodology

The calculation methodology is based on ASME Code requirements, sect. III, subsect. NB and is tightly bonded with the ANSYS-CFX 11.0 Program code.

In this respect, the followings have been elaborated:

- The transient thermal analyses for each event described in [7,8]. The scope of these analyses was the determination of each event moments and zones in which the maximum temperature gradient distributions are produced.
- The stationary structural analyses at the thermal and pressure loads, at the moments of previous established maximum thermal loads, for the determination of the maximum structural stress state of each event. Sections in the maximum stress zones for the evaluation of primary and secondary stress range S_n (see ASME III, art. NB-3228.5) were selected.
- The fatigue analyses for the previous selected sections and for all maximum structural stress states previously established.

For each item of interest node the corresponding usage factor was determined.

Based on the [7,8], the analyses were conducted on a simplified model, containing the inlet nozzle R3 (which is integrant part of the head geometry) and also one single ¾” R7-X, R8-X type nozzle and 10” R4-X type nozzle.

3. Analysed cases and calculation assumptions.

3.1 Thermal loads.

Taking account:

- the transients imposed by Design Specification, [8];
- the necessity to consider all major temperature fluctuations in the fatigue analysis;
- the need related to the minimum computation volume,

the definition of the events were determined as per the following table3.1-1):

All calculations of transient regimes where made with the insulation resistivity incorporated in the film coefficient on the external face.

Except the thermal event TH.5, for which the film coefficient on the internal surface of the pressurizer was also taken into account(see [7,8]), all the remaining events where analyzed conservatively assuming, that the liquid temperature was integrally and instantaneously transferred to the internal surface of the pressurizer and its nozzles (in other words, for these events, the film coefficient on the internal face was considered $\alpha_I = \infty$, so that $T_{D2O} - T_1 = 0$).

Therefore, as the analysis of the diffuser and of the thermal shield was not introduced, and only the pressurizer wall was modelled, the boundary condition related to the temperature at the internal face of the pressurizer on the inlet nozzle junction with the head (at the diffuser attachment zone) was modelled with the internal surface division in 5 zones, two of them, respectively 1 and 5 being allocated to the internal surface of the head, respectively to the inlet nozzle, while zones 2,3 and 4 were defined as transition zones with the mean temperatures ranging between zones 1 and 5 corresponding temperatures.

Table 3.1-1 – Thermal events

No	Name	Nr. Cycles	Temperature evolution	Remarks
1.	TH.1	500	38°C(ext.)-100 min.-310°C(ext.)-100min	Cover the “heatup & cooldown” A1
2.	TH.2	1000	R3 Nozzle Temp. 310°C(ext.)-2sec.-149°C(5sec.)-3sec.-260°C(inst.)-70sec.-310°C(ext.)	Cover partial the “Startup and shutdown” A2/1
			Bulk liq. Temp. 310°C(ext.)-7sec.-268°C(ext.)	
3.	TH.3	2000	Temp. 310°C(ext.)-2min.-149°C(5sec.)-3sec.-260°C(inst.)-70sec.-310°C(ext.)	Together with TH2 cover entirely “Startup and shutdown” A2/2
4.	TH.4	10000	Temp. 310°C(ext.)-4min.-290.5°C(inst.)-21min.-310°C(ext.)	Cover partial the “Power Maneuvering” A3/1
5.	TH.5	10000	R3 Nozzle Temp. 310°C(ext.)-5sec.-149°C(35sec.)-5sec.-290.6°C(inst.)-200sec.-310°C(ext.)	Together with TH4 cover entirely the “Power Maneuvering” A3/2
			Bulk liq. Temp 310°C(ext.)-40sec.-296°C(inst.)-14min.-310°C(ext.)	
6.	TH.6	850	R3 Nozzle Temp. 310°C(ext.)-10sec.-268°C(inst.)-40min.-310°C(inst.)-2sec.-260°C(5sec.)-73sec.-310°C(ext.)	Cover the “Total Loss of Feedwater from 100% Power”, ”Reactor Trip from 100% Power”, “Loss of Class IV from 100% Power” & “Loss of Regulation” B1, B2, B3 & B4
			Bulk liq. Temp. 310°C(ext.)-10sec.-268°C(inst.)-40min.-310°C(inst.)-7sec.-296°C(inst.)-15min.-310°C(ext.)	
7.	TH.7	600	R3 Nozzle Temp. 310°C(ext.)-15sec.-288°C(inst.)-24min.-310°C(inst.)-2sec.-288°C(5sec.)-13sec.-310°C(ext.)	Cover the “ Turbine Trip” & “Reactor Step Back” B5 & B6
			Bulk liq. Temp. 310°C(ext.)-15sec.-288°C(inst.)-24min.-310°C(inst.)-7sec.-307°C(inst.)-2min.-310°C(ext.)	
8.	TH.8	50	R3 Nozzle Temp. 310°C(ext.)-2sec.-38°C(inst.)-5min.-310°C(ext.)	Cover the “Startup During Commisioning” B7
			Bulk liq. Temp. 310°C(ext	
9.	TH.9	1	Temp. 310°C(ext.)-30min.-335°C (ext.)	Cover the “Emergency Overpresurization” C2

From the boundary condition, view point (i.e. the imposed temperature at the internal surface), this approach consider both the effect of the diffuser elimination from model and the thermal stratification in the stagnant liquid zone in the rear of the diffuser in its proximity.

3.2 Pressure loads.

Correspondingly to the pressure transients imposed by the design specification values of the pressure were taken into account as described in [8].

4. Acceptance criteria.

The acceptance criteria given by ASME NB-3222, NB-3223 and NB-3224 for thermal and pressure loads due to imposed transients were applied.

- For design conditions:

  $P_m \leq S_m$

  $P_L \leq 1.5S_m$

  $P_m(\text{or}P_L) + P_b \leq 1.5S_m$

- For A/B level conditions:

  $P_e \leq 3S_m$

  $P_L + P_b + P_e + Q \leq 3S_m$

  $P_L + P_b + P_e + Q + F \leq S_a$

- For level C conditions:

  $P_m \leq 1.2S_m$ or $P_m \leq S_y$

  $P_L \leq 1.8S_m$ or $P_L \leq 1.5S_y$

  $P_L + P_b \leq 1.8S_m$ or $P_L + P_b \leq 1.5S_y$

Where:

- P_m – primary general membrane stresses P_L – primary local membrane stresses
- P_b – primary bending stresses
- P_e – secondary expansion stresses
- Q – membrane plus bending secondary stresses
- F – peak stresses
- S_m – allowable stress intensity
- S_a – alternating stresses
- S_y – yield stress

For most stressed nodes the maximum fatigue usage factor should meet the max. requirement US factor < 1.

5. Elaborated analyses

5.1 *Geometric model*

The simplified geometric model of the pressurizer lower head is shown below:

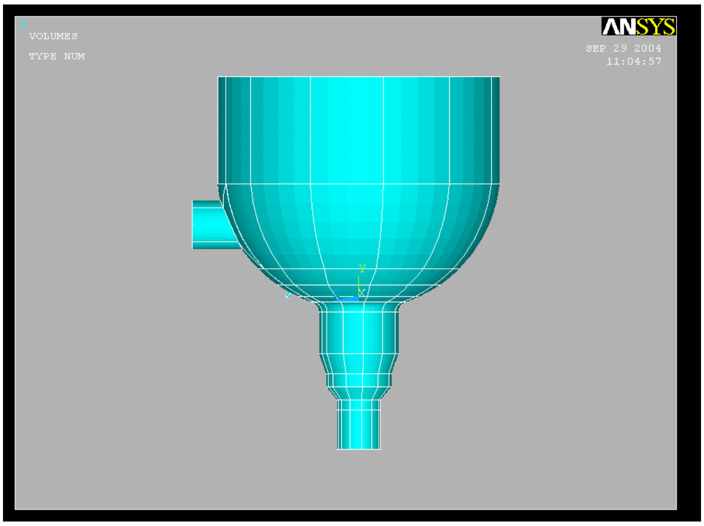

Figure 5.1-1. The simplified geometric model

5.2 *The model mesh*

Considering the coupled thermal – structural analysis two types of compatible elements from view point of coupling, were used, namely for the thermal analysis – element 90 type 3D prismatic solid with 20 nodes and for structural analysis – element 95 type 3D elastic prismatic solid with 20 nodes. So, one single mesh (generating the same number of elements and nodes for both analyses), necessary for information transfer between these two analyses is provided.

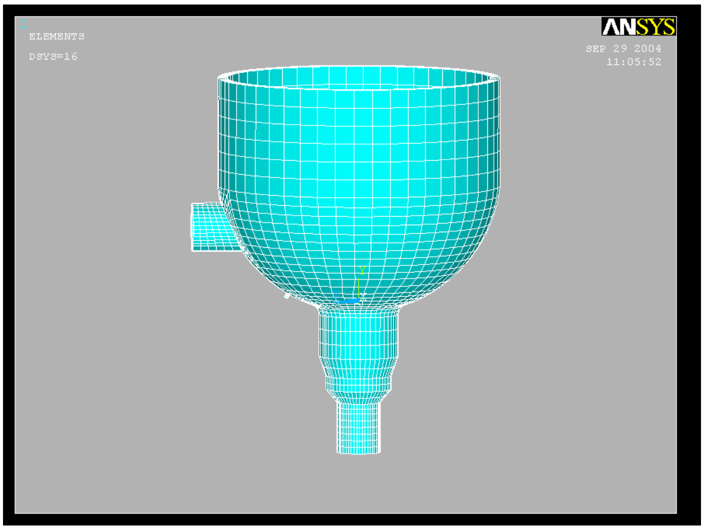

Figure 5.2-1. The model mesh

The mesh is a mapped type, performing a special control of elements dimension in the nozzle zone, in order to get an accurate thermal distribution over the wall thickness and fatigue analysis. So, the thickness of the lower head and the nozzles R4X and R3 was meshed with 10 segments, and the thickness of nozzles R7X and R8X was meshed with 4 segments.

The mesh characteristics:

- Mesh type: mapped with SOLID90 / SOLID95
- Nodes number: 82272
- Elements number: 18036

5.3 Thermal analyses.

For each event a transient thermal analysis was made.

The initial condition was calculated in an stationary step and was defined as “Step 1”.

The temperature evolution at the internal wall, divided in zones as shown in para. 3.1, was defined by time intervals and evolutions as “step2, 3,…”. The given temperatures in the below tables for the “step2, 3, …” are the corresponding end of the interval temperatures.

Function of the time and speed variation of the temperatures for each step, a time step, crucial in view point of the computation volume and time, was established.

In this mode 9 transient analyses were made, [7,8]

As an example see the Table 5.3-1 ”Turbine Trip & Step Back B1&B6 600 cycles”

*5.4 **Structural** analyses – Thermal loads*

As shown in para 3.1 above correspondingly to each thermal analysis, more stationary structural analyses at maximum thermal loads moments have been elaborated. It was observed (see cap. 6) that these moments are the moments at each final interval “step2, 3, …., when the maximum thermal gradients over the wall thickness are obtained.

On the other hand, this is explained, taking into account the thermal inertia of the pressurizer wall, which makes the temperature vary slower than the node in which the evaluation is made, far from the internal surface. So, the maximum thermal gradient distribution is obtained at each final interval “Step 2, 3, …”.

As it was already shown, the elaborated structural analyses for each thermal event, make it possible that the structural stress state determination which are after that used for imposed acceptance criteria verifications (see Chap. 4).

In all structural analyses the model was blocked for translations and rotations over all the three directions at the extended pressurizer shell end.

*5.5 **Structural** analyses – Pressure loads.*

At the same time with the thermal load conditions the model was also loaded with the pressure load, applying the relative pressure at the internal surfaces of the structure .

The values of the applied pressure in the structural analyses correspond to the imposed transients stipulated in the design specification at the thermal loads imposed moments.

For the verification of the design acceptance criteria requirements (see chap. 4.), a structural analysis for a maximum pressure load of 10 MPa(a), was supplementary made.

In the following tables the elaborated structural analyses, specifying the thermal and pressure loads used like inputs are briefly shown: Tab 5.4-1

6. Results

6.1 Thermal analyses

As shown in para. 5.3, 9 transient thermal analyses which correspond to the 9 events defined according to the chapter 3 specifications were made.

The results of these analyses show that:

- the maximum thermal load moments are the moments of each Step 2, 3, … interval end. For all analyses and for all investigated zones it was noticed that the maximum thermal gradient distributions over the pressurizer or its nozzles wall thickness, were obtained as previously mentioned;
- the most thermally loaded zones are at the nozzle, and out of them the most loaded one is R3 inlet nozzle.

The maximum thermal gradient distribution was obtained over the R3 inlet nozzle wall thickness at moment t = 2 sec. for the event TH.8 (see fig. 6.1-1).

Consequently, the results of thermal analyses for all the investigated events are selectively presented in the form of:

- time evolution graphs of temperature in some sections of interest for some events
- temperature distribution maps associated to the temperature distribution graphics for some sections of interest, for some events and moment of time considered significant.

See the Fig 6.1-1 to Fig. 6.1-3

Tabel 5.3-1

Turbine Trip & StepBack B1&B6 600 cycles

Thermal Analysis 7

	Temperature [grd.C] at internal face					*Interval* *[sec]*	*Time* *[sec]*	Time step [sec]	Number of steps	Evolution Type	Obs.
	zone 1	zone 2	zone 3	zone 4	zone 5						
Step 1	310	310	310	310	310	-	0	stationar	N/A	N/A	cond. Init.
Step 2	287	287	287	287	287	15	15	0.2	75	ramped	N/A
Step 3	310	310	310	310	310	1440	1455	6	240	ramped	N/A
Step 4	309	304	298	293	288	2	1457	0.1	20	ramped	N/A
Step 5	307	302	297	292.5	288	5	1462	0.1	50	ramped	N/A
Step 6	307	308	309	309	310	13	1475	0.2	65	ramped	N/A
Step 7	310	310	310	310	310	120	1595	1	120	ramped	N/A
Step 8	310	310	310	310	310	10	1605	0.5	20	stepped	N/A

Tabel 5.4-1

Turbine Trip & StepBack B1&B6 600 cycles

Thermal Analysis 7		Structural Analysis	
Steps / *Pasi*	***Time*** [sec]	**Pressure** [MPa(a)]	**Analisys Title:**
Step 1	0	9.99	Ref310
Step 2	15	7.27	Th7-1
Step 3	1455	9.99	Th7-2
Step 4	1457	9.99	Th7-3
Step 5	1462	9.99	Th7-4
Step 6	1475	9.99	Th7-5
Step 7	1595	9.99	Th7-6
Step 8	1605	-	-

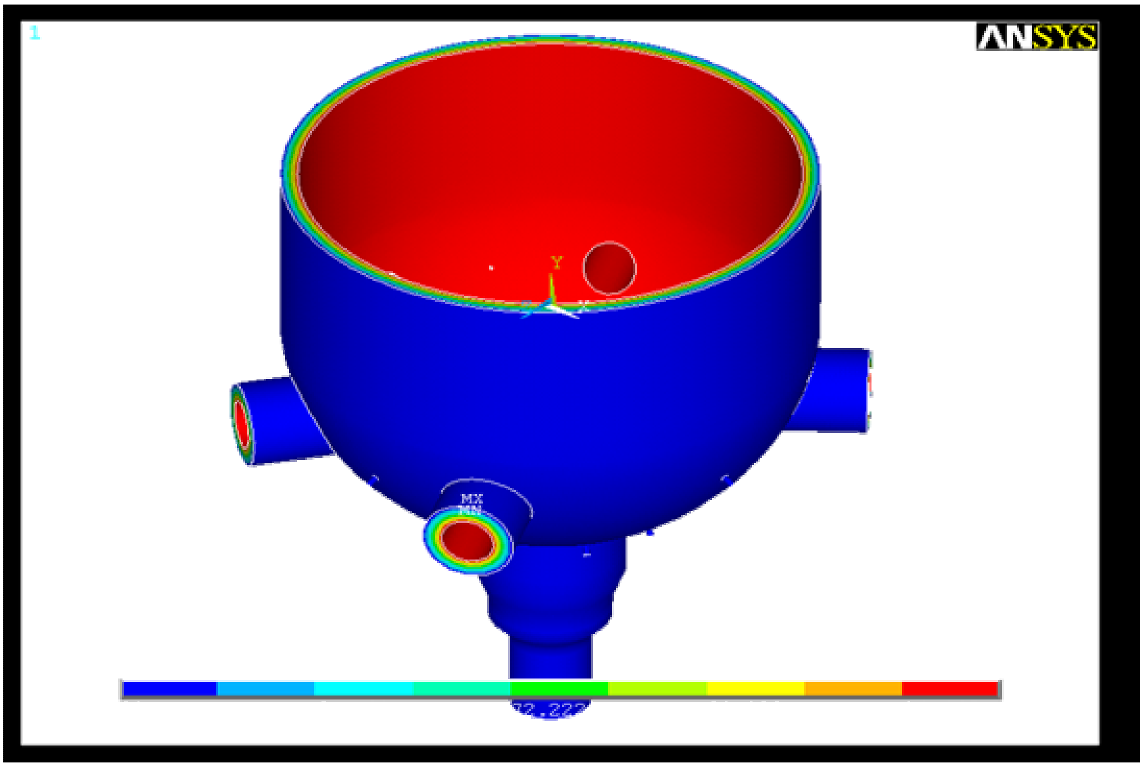

Figure 6.1-1

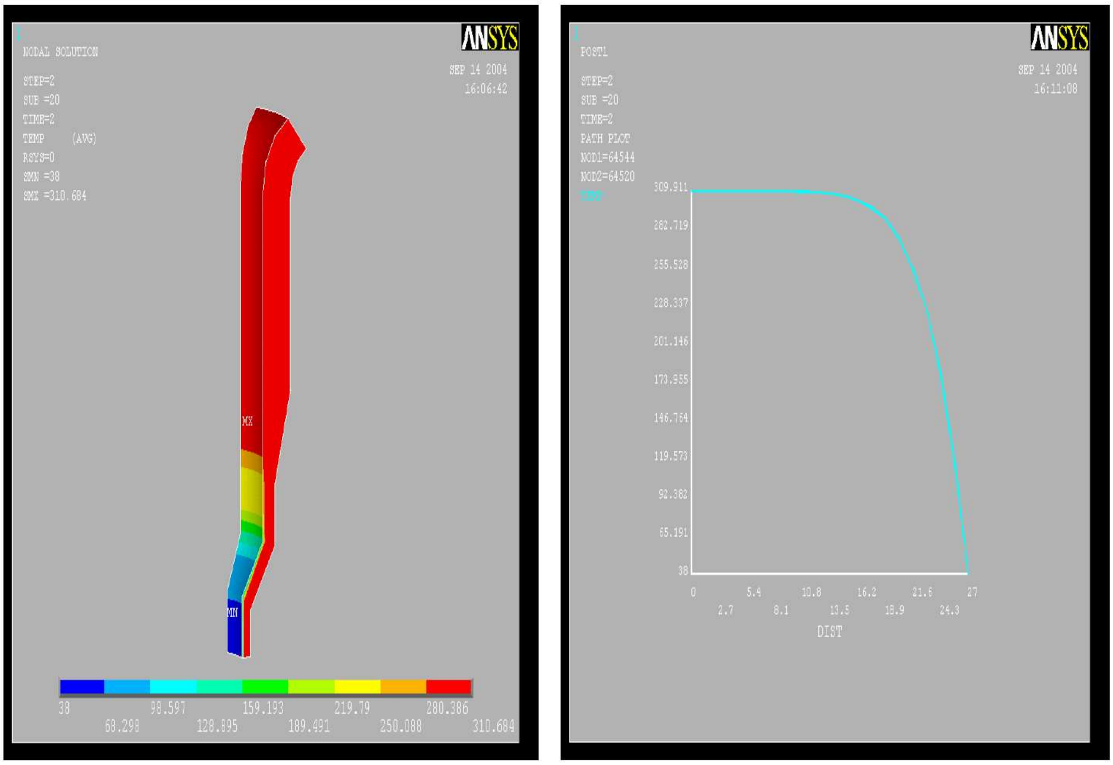

Figure 6.1-2. Thermal distribution over a R3 section at 2 sec.

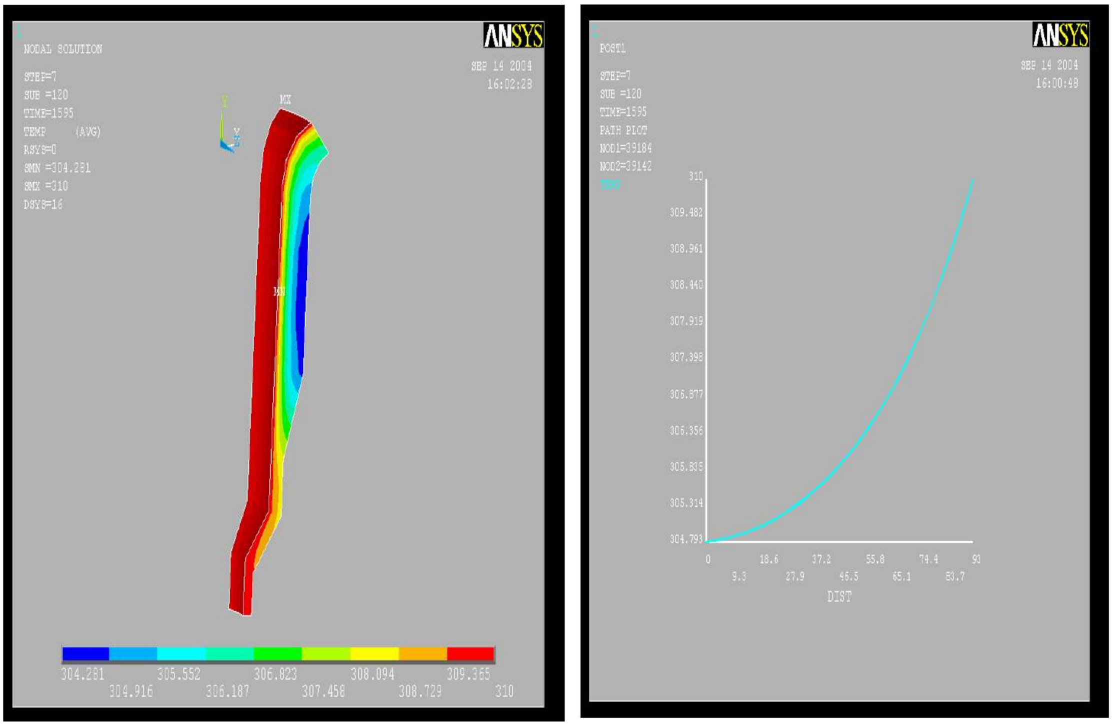

Figure 6.1-3. Thermal distribution over a R3 section at 1595 sec.

6.2 Structural analyses

As shown in para. 5.5 32 structural analyses were developed & showed that:

- the most stressed zones are located at the nozzle and especially in the junction section with the vessel head
- away from nozzle influence zones, the shell had minimum stress.

Taking into account these observations, the results of stress analyses in the nozzle and adjacent zones, for which linearization paths were defined, are presented.

For all analyzed cases the stress maps for nozzles are presented.

Graphs and reports for the most stressed section identified, for the R3 nozzle, finally checking whether the maximum stress values meet the imposed requirements of the acceptance criteria are also presented.

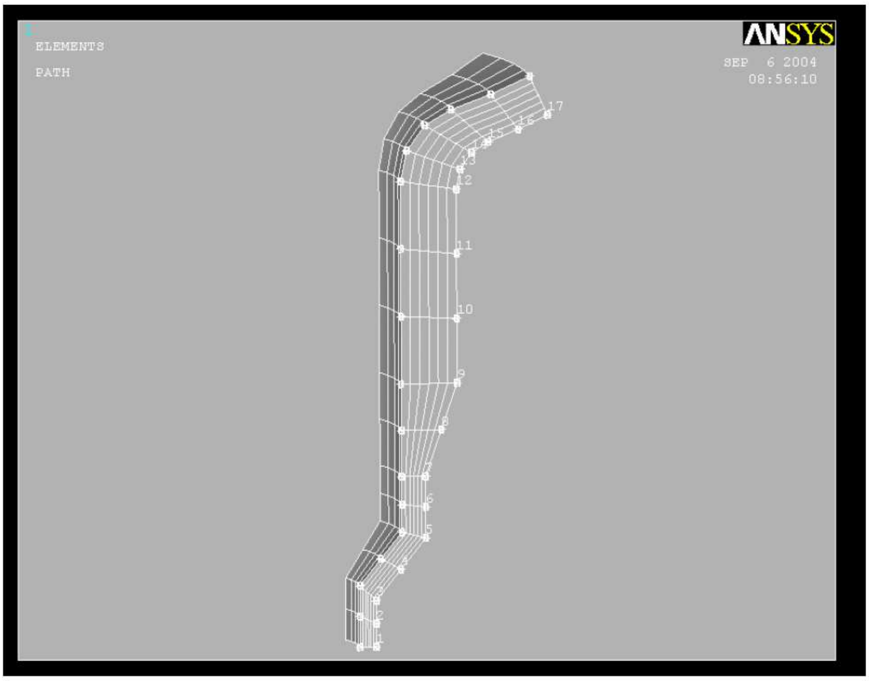

Figure 6.2-1. Path definition for R3 nozzle

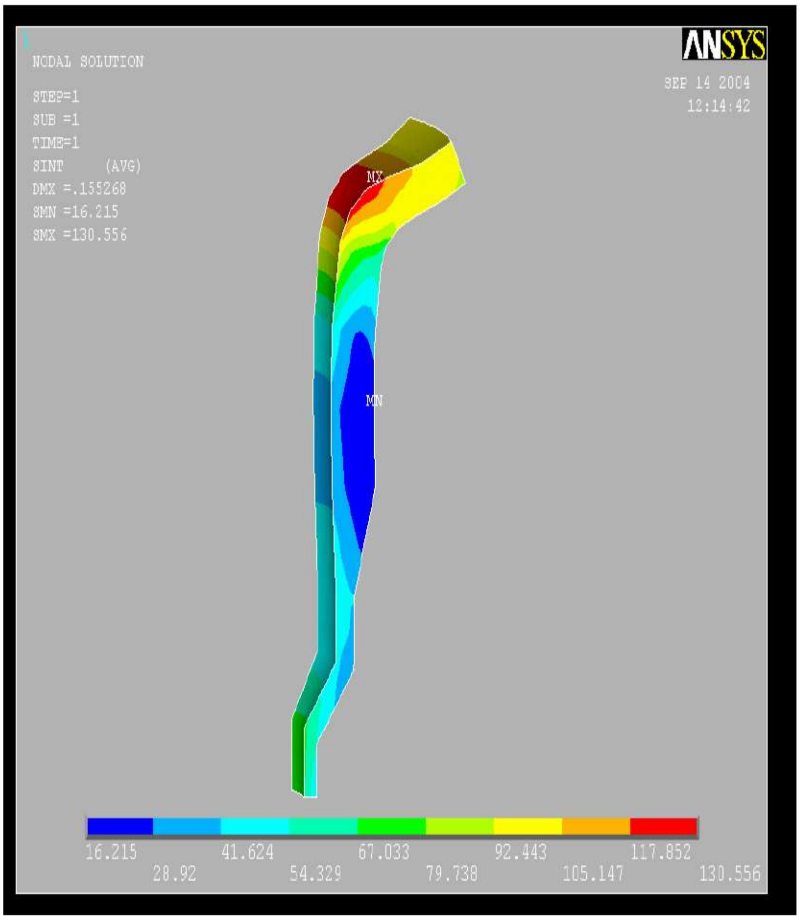

Figure 6.2-2. Stresses map for R3 nozzle at the pressure loads

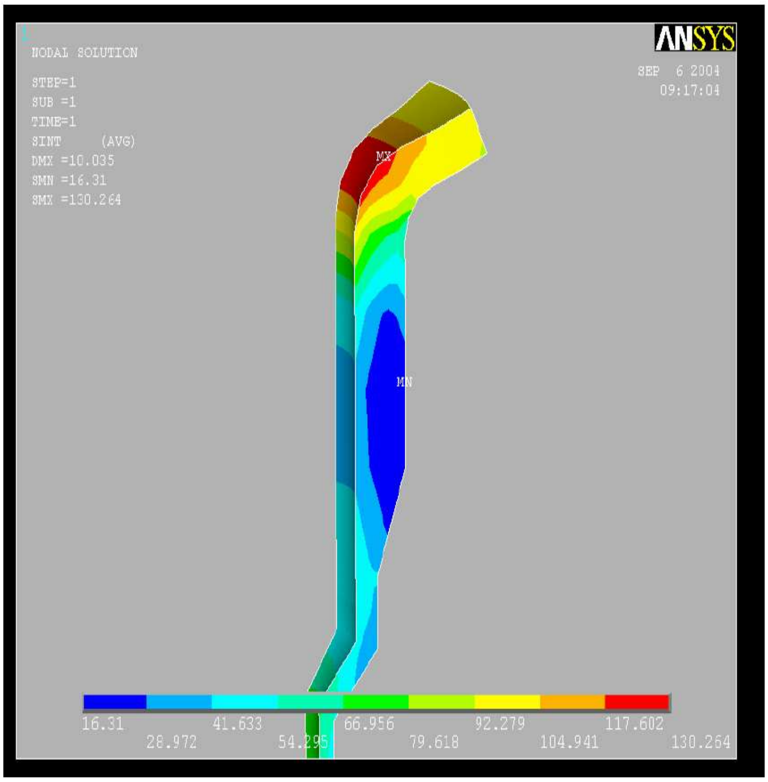

Figure 6.2-3. Stresses map for R3 nozzle at the reference 310°C thermal loads and pressure

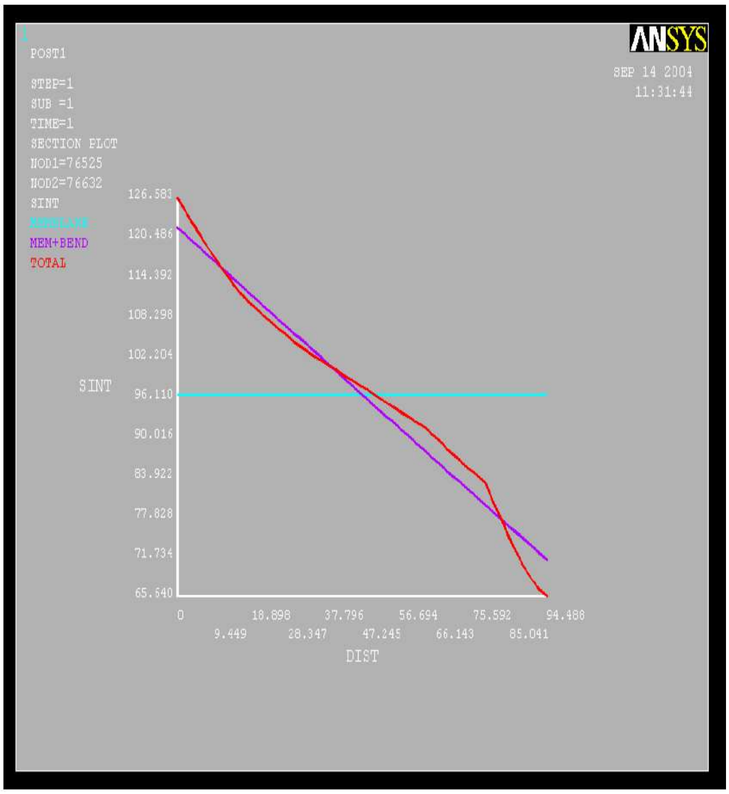

Figure 6.2-4. Stresses linearized at the pressure loads (primary stresses)

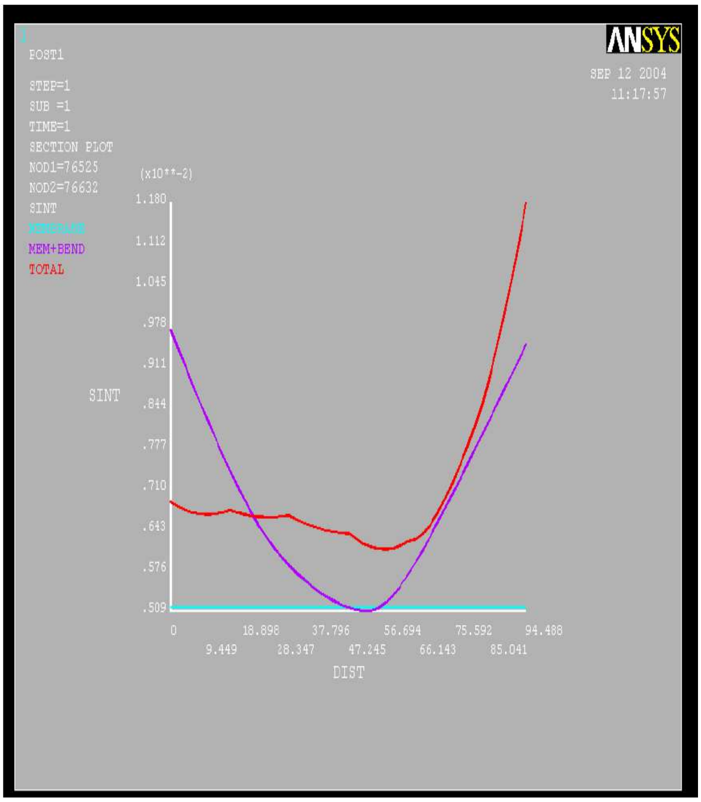

Figure 6.2-5. Stresses linearized at the reference 38°C and pressure

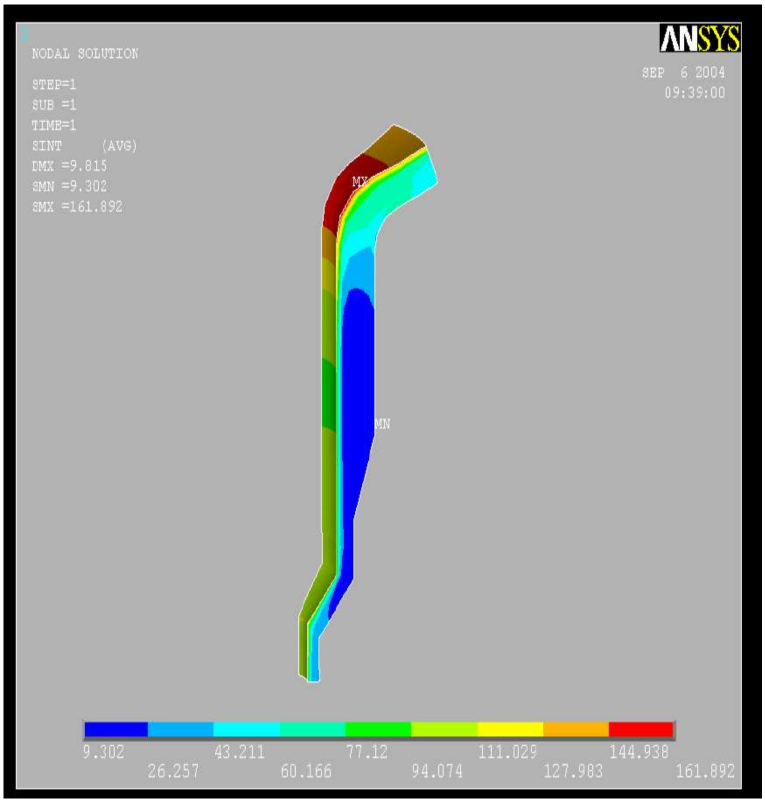

Figure 6.2-6. Stresses map for R3 nozzle at the thermal distribution th7-1 and associated pressure

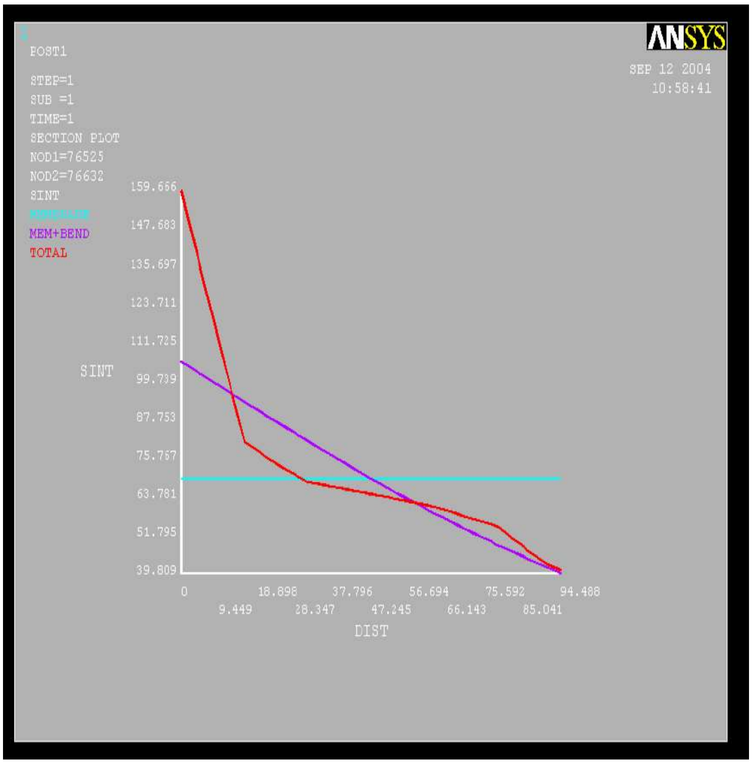

Figure 6.2-7. Stresses linearized due to the thermal distribution th7-1 and associated pressure

6.3 Fatigue analysis

The fatigue analysis was conducted taking into account the stress distributions determined by those 32 structural analyses considered as load cases in the defined events as shown in chap. 3.

The nodes investigated by the fatigue analysis were those located in all defined sections in the structural analyses (see Fig. 6.2-1 for the R3, nozzle).

Tabel 6. 3-1. Cumulative Fatigue usage factor

Pairs				**S_{alt} [MPa]**	**P_l+P_b S_{int} Range [MPa]**	**Ke**	**Ke x Salt [MPa]**	**Cycles**		**Partial US**
Event	**Load**	**Event**	**Load**					**Used**	**Allowed**	
8	2	8	3	448.44	353.75	1	448.44	50	1727	0.02896
1	1	2	2	284.22	229.15	1	284.22	500	12480	0.04007
2	2	2	5	282.83	219.56	1	282.83	500	12690	0.0394
5	2	6	6	186.96	173.82	1	186.96	850	76200	0.01115
5	**2**	**5**	**4**	**185.16**	**83.031**	**1**	**185.16**	**9150**	**80930**	**0.11306**
7	4	7	6	43.381	26.329	1	43.381	600	1000000	0.0006
3	2	9	2	24.726	50.132	1	24.726	1	1000000	0
3	2	4	3	16.414	29.067	1	16.414	1999	1000000	0.002
4	2	4	3	7.0984	14.404	1	7.0984	8001	1000000	0.008
CUMULATIVE FATIGUE USAGE FACTOR = 0.24324										

7. References

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