DA DOCUMENT DELIVERABLE

IDM UID
TF7JJV
VERSION CREATED ON / VERSION / STATUS
16 Dec 2016 / 2.2 / Approved
EXTERNAL REFERENCE / VERSION

DA Analysis or Calculation

Structural Analysis of Torus Cryo Pump Housing(TCPH)

This document is the structural analysis of TCPH to assess the changes proposed by INDA based on manufacturing feasibility and change in TCPH Ribs done by IO

Approval Process			
	Name	*Action*	*Affiliation*
Author	**Jogi G.**	**16 Dec 2016:signed**	
Co-Authors			
Reviewers	**Gupta G. K.** **Joshi V.** **Prajapati R.** **Tailhardat O.** **Vitupier G.**	**23 Dec 2016:recommended** **16 Dec 2016:recommended** **27 Dec 2016:recommended** **26 Jan 2017:reviewed** **22 Dec 2016:reviewed**	**IPR - Institute for Plasma Research (IN)** **ITER India (IN)** **ITER India (IN)** **IO/DG/COO/TED/VSD** **IO/DG/COO/TED/VSD**
Approver	**Bhardwaj A.**	**26 Jan 2017:approved**	**IO/DG/COO/TED/VSD**
Document Security: Internal Use *RO: Bhardwaj Anil*			
Read Access	**LG: RO 2.4.P1A.IN.01, AD: IO_Director-General, AD: EMAB, AD: Auditors, project administrator, RO, LG: TCPH task force team, LG: Cryostat IO team, AD: ITER, AD: External Collaborators, AD: ITER Management Assessor**		

Change Log			
Structural Analysis of Torus Cryo Pump Housing(TCPH) (TF7JJV)			
Version	***Latest Status***	***Issue Date***	***Description of Change***
v1.0	Revision Required	24 Jun 2016	
v2.0	Signed	30 Nov 2016	Analysis re-performed for Category I & II for Plastic Collapse, Local Failure & Ratcheting and results updated Analysis re-performed for Category III & IV for Plastic Collapse & Local Failure and results updated. 3.4 Details of Change in Geometry added Details of addition Rib on shell 3 & justification for fillet weld is added 3.5.1 Mesh Sensitivity results added 4.2 VV Convection area updated as per IO comment 6.3.2.5 Justification for the fillet weld added 6.3.6 Justification added for fatigue usage fraction acceptance
v2.1	Signed	16 Dec 2016	3.5.1 Mesh Sensitivity results incorporated based on IO comments 6.3.2.5 Detailed fillet calculation incorporated 6.3.5 Ratcheting results for other LC added based on IO comments
v2.2	Approved	16 Dec 2016	Clarified Emissivity value referenced in revision history

Structural Assessment of Torus Cryo Pump Housing (TCPH)

Abstract

The purpose of this document is to perform structural assessment of TCPH with proposed changes in Ribs & Vertical Plates after FDR with regards to ASME Section VIII Div. 2. Thermal & Structural analysis was performed based on load specification to obtain thermal plot, displacements and stresses to evaluate: Plastic Collapse, Local Failure, Ratcheting, Buckling and Fatigue. Assessment shows a margin of 2.62% in Plastic Collapse, 19% in local failure, 30% in ratcheting (elastic plastic criteria) and fatigue is checked with usage fraction of 0.8.

	External Number:	*Date:*
	Name	*Affiliation*
Author	**Gaurav Jogi**	**Cryostat & VVPSS Group, ITER-India**
Co-Author	**Olivier Tailhardat**	**ITER Organisation**
Reviewers	**Vaibhav Joshi**	**Cryostat & VVPSS Group, ITER-India**
	Girish Gupta	**Cryostat & VVPSS Group, ITER-India**
	Xie Han	**ITER Organisation**
	Guillaume Vitupier	**ITER Organisation**
	Vertongen Patrick	**ITER Organisation**
Approver	**Anil Kumar Bhardwaj**	**ITER Organisation**

Table of Contents

Revisions

Version number	Date	Chapter	Description of the revision
1.0	23-06-2016		First version
2.0	30-11-2016		Analysis re-performed for Category I & II for Plastic Collapse, Local Failure & Ratcheting and results updated
			Analysis re-performed for Category III & IV for Plastic Collapse & Local Failure and results updated.
		3.4	Details of Change in Geometry added
			Details of addition Rib on shell 3 & justification for fillet weld is added
		3.5.1	Mesh Sensitivity results added
		4.2	VV Convection area updated as per IO comment
		6.3.2.5	Justification for the fillet weld added
		6.3.6	Justification added for fatigue usage fraction acceptance
2.1	14-12-2016	3.5.1	Mesh Sensitivity results incorporated based on IO comments
		6.3.2.5	Detailed fillet calculation incorporated
		6.3.5	Ratcheting results for other LC added based on IO comments
2.2	16-12-2016	4.2	Emissivity values clarified

1. Introduction

1.1. Introduction

The Torus Cryo-Pump Housing (TCPH) is a penetration located on the Cryostat cylinder which main functions are to accommodate and support the Torus Cryo-Pump (TCP), connect it to the Vacuum Vessel and provide tritium confinement and primary vacuum boundary. There are a total of six TCPH located at the lower port level of the Cryostat lower cylinder in Port Cell numbers 4/6/10/12/16/18, figure 1.

The objective of this report is to assess the structural assessment of TCPH in accordance with ASME [1]. Analyses are performed following the load specification [3].

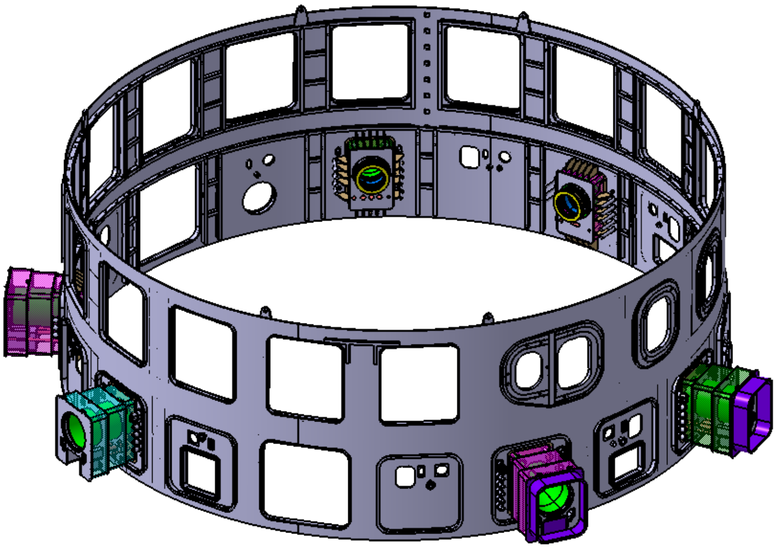


Figure 1 TCPH with Lower Cylinder port nos. 4/6/10/12/16/18

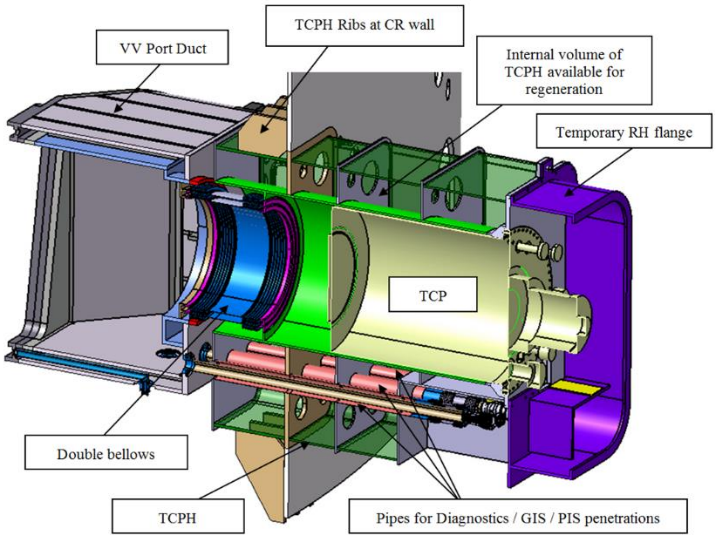


Figure 2 TCPH Model

1.2. Scope of this Analysis

The scope of this structural analysis is to verify the structural integrity of TCPH with proposed changes considering the failure modes described in paragraph 2.4 according to ASME Section VIII Div. 2.

1.3. System Classifications

TCPH is a SIC-1 component. As a SIC-1 component, the seismic class of TCPH is SC1 (S and F). This means that structural stability and required functional seismic safety performance has to be maintained in the event of an earthquake.

Given its volume and maximum allowable pressure, TCPH is not subjected to pressure equipment regulatory rules (French Decree 99-1046 regarding conventional pressure equipment or French Order dated 12th December 2005 related to nuclear pressure equipment).

As being a SIC-1 component, TPCH is a Quality Class 1 component.

In summary, the system classifications of the TCPH are as follows:

- Safety Classification (for confinement function): SIC-1
- Vacuum Classification: VQC 1A
- Remote Handling classification: RH Class 3
- Tritium classification: TC 1A
- Quality Classification: QC1
- Seismic Classification SC1(S and F)

1.4. System Description

1.4.1. General

A description of the TCPH is given in [3].

1.4.2. Design Status

The analysis models are based on the Catia models of the TCPH prepared after the FDR, which can be found in Enovia inside PBS 24 CRYOSTAT #2ZGE27 CM: This model was used during manufacturing feasibility study & changes were made to the model which will be updated in the IDM.

Table 1 TCPH Model location in ENOVIA

Part of the VVPSS	3D Model
TCPH Assembly	CRYOSTAT_TCPH#AFR7YC—C Draft

1.5. Abbreviations

Table 2 Abbreviations used

TCPH	Torus Cryo-Pump Housing

TCP	Torus Cryo-Pump
PC	Port Cell
SIC	Safety Important Component
VDE	Vertical Displacement Event
Cr	Cryostat
TGCS	Tokamak Global Coordinate System
VV	Vacuum vessel
ICE	Ingress of Coolant Event
RCS	Relative Coordinate System
COG	Centre of Gravity
SL	Seismic Level
SL-1	Seismic Level 1 – Defined by ITER for investment protection
SL-2	Seismic Level 2 – Equivalent to Safe Shutdown Earthquake
SMHV	Sěismes Maximaux Historiquement Vraisemblables = Maximum Historically Probable Earthquake
DW	Dead Weight
MPC	Multi Point Constraints
NA	Not Applicable

2. Structural Design Criteria

The structural design criteria for category loading conditions given in this chapter are an extraction from ASME VIII, Div. 2, Design by Analysis, 2013[1] & ITER_D_3G3SYJ[6].

2.1 General Requirements

The criteria listed in this section are used to provide protection against the failure modes listed below:

a) Protection against Plastic Collapse
b) Protection against Local Failure
c) Protection against Collapse From Buckling
d) Protection against failure from Cyclic Loading

2.2 Equivalent Stress

The maximum distortion energy yield criterion is used to establish the equivalent stress. In this case, the equivalent stress is equal to the von Mises equivalent stress given by the equation below:

$$S_e = \sigma_e = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{0.5}$$

2.3 Overview of the Analysis Performed

2.3.1. *Protection against Plastic Collapse – Elastic Analysis*

To verify the structure against plastic collapse, a linear elastic stress analysis was performed, according to ASME VIII Div. 2.

2.3.2. Protection against Local Failure

To verify the structure against local failure, a linear elastic stress analysis was performed, according to ASME VIII Div. 2.

2.3.3. Protection against Collapse from Buckling – Elastic Analysis

To verify the structure against buckling, a linear elastic analysis was performed. The analysis was performed according to ASME VIII, Div. 2.

2.3.4. Protection against failure from Cyclic Loading

2.3.4.1. Fatigue

To verify the structure against fatigue, a linear static analysis results were used for fatigue calculations for the high stress value nodes.

2.3.4.2. Ratcheting

To verify the structure against ratcheting, a linear static analysis results were used for ratcheting calculations for secondary loads.

2.4 Design Criteria

2.4.1. Protection against Plastic Collapse

2.4.1.1. Elastic Analysis

To evaluate protection against plastic collapse, compare the computed linearized equivalent stresses to the allowable values below:

Table 3 Allowable stresses for Elastic Analysis

	P_m	P_l	P_m+P_b	P_m+P_b+Q
Category I & II events	$\leq S^{I,II}$	$\leq 1.5S^{I,II}$	$\leq 1.5S^{I,II}$	$\leq 3S^{I,II}$
20^0C	138	207	207	414
100^0C	113	169	169	339
115^0C	108	162	162	324
Category III events	$\leq 1.2S^{III}$	$\leq 1.8S^{III}$	$\leq 1.8S^{III}$	**None**
20^0C	166	249	249	-
100^0C	136	204	204	-
115^0C	129	194	194	-
Category IV events	$\leq 2S^{IV}$	$\leq 3S^{IV}$	$\leq 3S^{IV}$	**None**
20^0C	276	414	414	-
100^0C	226	339	339	-
115^0C	216	324	324	-

2.4.2. Protection against Local Failure

To evaluate protection against local failure, the sum of first, second & third principal stress of linear elastic stress analysis are compared with the allowable values as below;

Table 4 Local Failure Criteria

	$4S_m$ (MPa)		
	20^0 C	100^0 C	115^0 C
Service Level A	552	452	432
Service Level C	664	544	516
Service Level D	664	544	516

2.4.3. Protection against Collapse from Buckling

To evaluate protection against buckling, linear elastic analysis is performed to calculate linear buckling factor.

The minimum design factor is :
$\Phi_B = 2/k\ \beta_{cr}$

K=1 for Service level A, k=1.2 for service level C and k=2 for service level D.

Minimum β_{cr} from [1] is 0.124.

Table 5 Minimum Design factor

	$(\Phi_{B})_{min}$
Service Level A	16.1
Service Level C	13.42
Service Level D	8.05

2.4.4. Protection against failure from Cyclic Loading

2.4.4.1. Fatigue

The permissible number of cycle N_k for one event is given by fatigue curve [1] based on the effective alternating equivalent stress amplitude $S_{alt,k}$

$S_{alt,k} = (Kf * K_{e,k} * \Delta S_{p,k})/2$

$K_{e,k} = 1$ for $\Delta S_{n,k} \leq S_{PS}$

$K_{e,k} = 1.0 + \{(1-n)/(n(m-1)\}*\{(\Delta S_{n,k}/S_{PS}) -1\}$ for $S_{PS} < \Delta S_{n,k} \leq mS_{PS}$

$K_{e,k} = 1/n$

Where -Kf is the fatigue strength reduction factor

-m=1.7 and n=0.3, see table 5.13 from reference[1]

- $\Delta S_{n,k}$ is the primary plus secondary equivalent stress range

- $\Delta S_{p,k}$ is the range of primary plus secondary plus peak equivalent stress

- $S_{PS} = 3S$

The fatigue usage fraction is given by the ratio of the number of cycle given by load specification (n_k) and the permissible number of cycles (N_k),

$D_{f,k} = n_k / N_k$

The assessment criterion is that the sum of all cyclic fatigue manage should be less than 1.

2.4.4.2. Ratcheting

It is proposed to follow rules provided in section 5.5.6.3 [1] completed by requirement of section 5.5.6.2 of [1].

i. The range of primary plus secondary membrane plus bending equivalent stress, excluding thermal stress is less than 3S;
ii. The value of alternating stress is multiplied by factor $K_{e,k}$
iii. The material has a ratio of the specified minimum yield strength to specified minimum tensile strength of less than or equal to 0.8.

In order to determine the allowable limit, it is assumed a parabolic distribution of the secondary stress range. In a first step, the ratio of primary membrane stress to the specified yield strength is calculated. The allowable limit on the secondary equivalent stress range from thermal loading is calculated. The ratcheting is checked if criteria is verified.

$X=P_m/S_y$

$S_{Qmb} = S_y\{1/(0.1224+0.9944X^2)\}$ for $0 < X < 0.615$

$S_{Qmb} = 5.2\ S_y\ (1-X)$ for $0.615 < X < 1.0$

$\Delta Q_{mb} \leq S_{Qmb}$

3. Description of the FE Analysis

3.1. Software Package

The FE analysis was performed using ANSYS Workbench 16.0

3.2. Units

Table 6 Units used in the analysis are given below

Quantity	Name	Unit	
Length	Millimetre		mm
Mass	Kilogram		kg
Acceleration	Millimetre per sq. second		mm/sec^2
Density	Kilogram per cub. millimetre		kg/mm^3
Pressure	Mega Pascal	MPa	N/mm^2

3.3. Coordinate System

The TCPH is modelled in the TGCS in the Ansys global Cartesian co-ordinate system.

A relative coordinate system is associated to port cell#6 (TCS PC) with

- x: radial direction in the Port Cell Centre Plane;
- y: toroidal direction;
- z: vertical direction identical to the TGCS

Its origin is located at the torus centre, the same as TGCS.

The TCPH relative coordinate (RCS TCPH) has the same definition as the RCS PC. Its origin is located at the centre of the Cryostat Wall flange. The position of this local co-ordinate system with respect to TGCS IS (14269, 0,-4292). It corresponds to the ANSYS local Cartesian coordinate system.

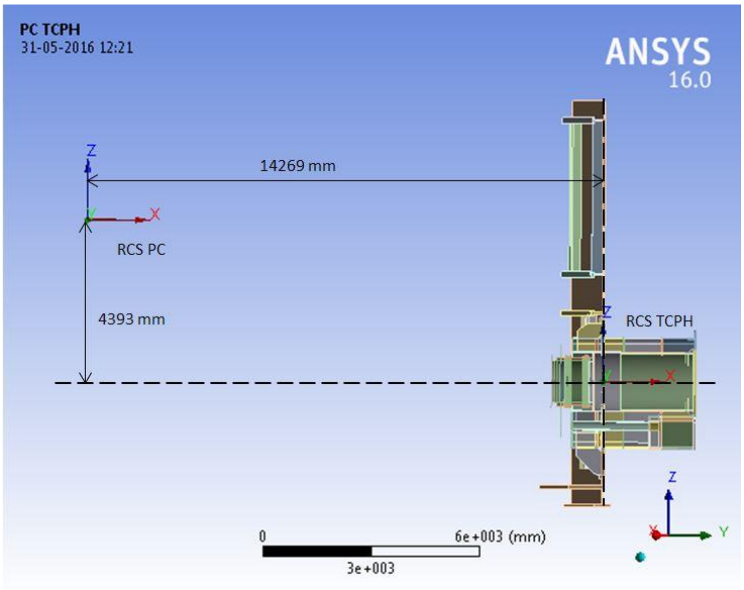


Figure 3 Relative Co-ordinate System

3.4. TCPH Geometry

The TCPH Structure is made of shell, ribs, vertical plates, cylinder & flange. TCPH Geometry used in the assessment is of port #6. The TCPH geometry is uniform for all 6 ports.

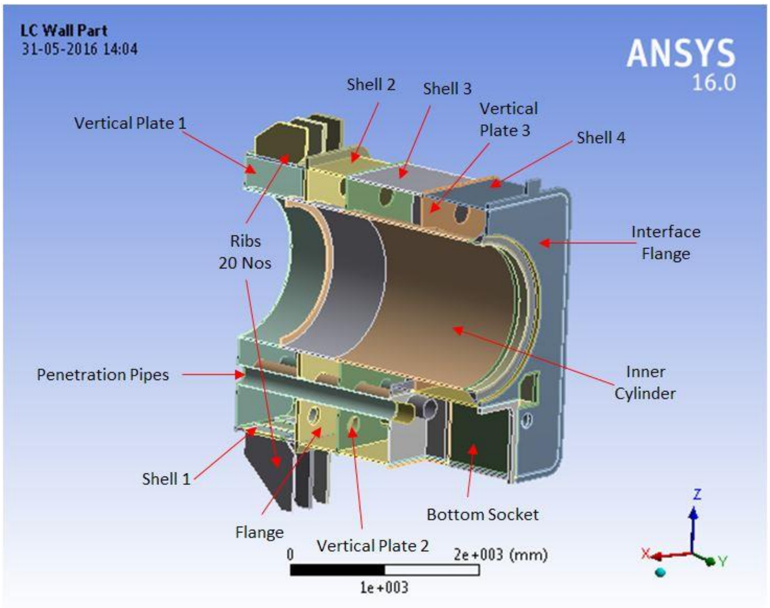


Figure 4 TCPH Structure

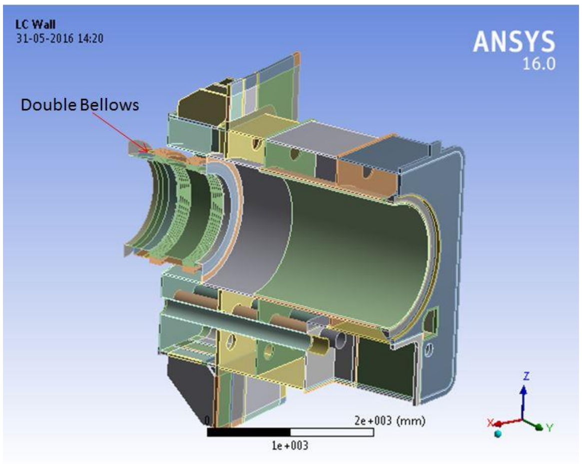


Figure 5 TCPH with double bellows

After FDR, IO has changed the TCPH Ribs. In addition to the ribs, IN-DA has recommended some changes in TCPH based on the manufacturing feasibility study. The connection between the vertical plates & the cylinder is suggested to be removed.

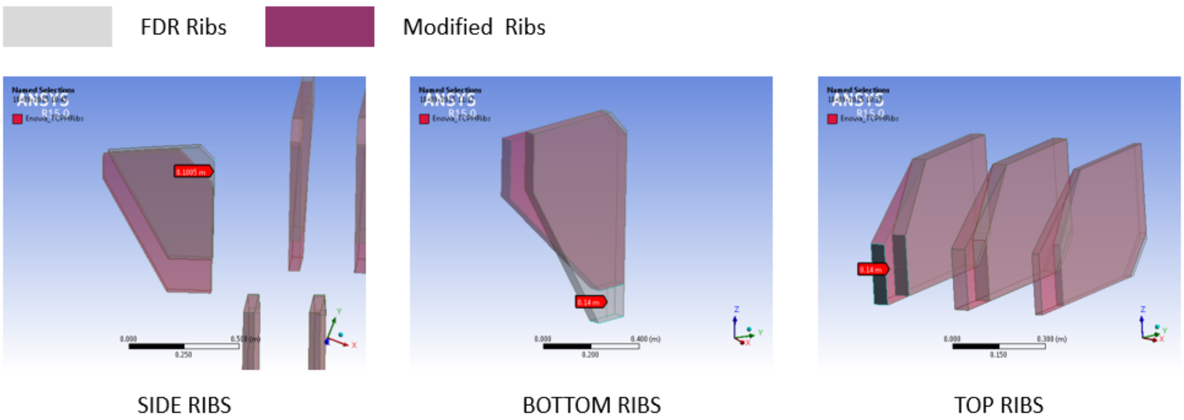


Figure 6 TCPH Rib Modification

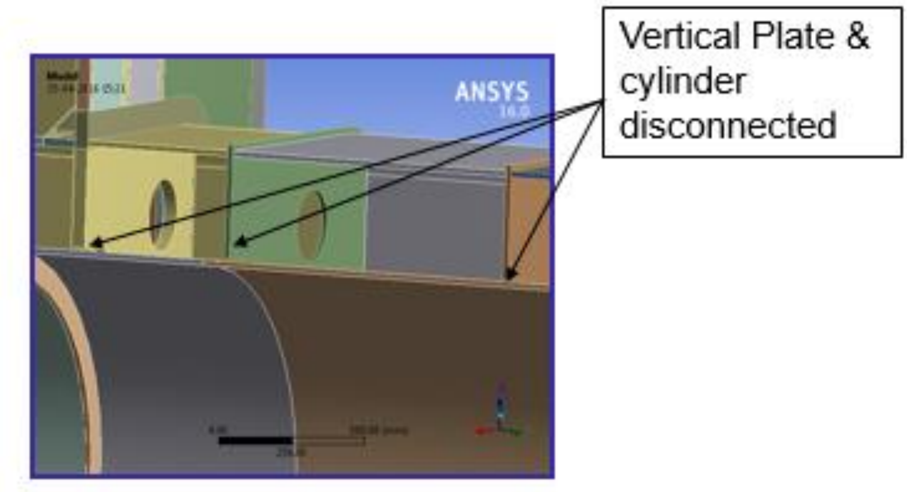


Figure 7 Connection between Vertical Plate & Cylinder disconnected

TCPH Shell 3 was failing in bending for Category III event LOCA PC III. So a rib structure of cross section 50mmx70mmx700mm is fillet welded horizontally on the shell 3 location. This rib will be welded on both the sides of Shell 3. Since the shell is outside the vaccum boundary, fillet weld can done at rib location. For analysis, the nodes on the edges of the rib are merged with the corresponding nodes on the shell.

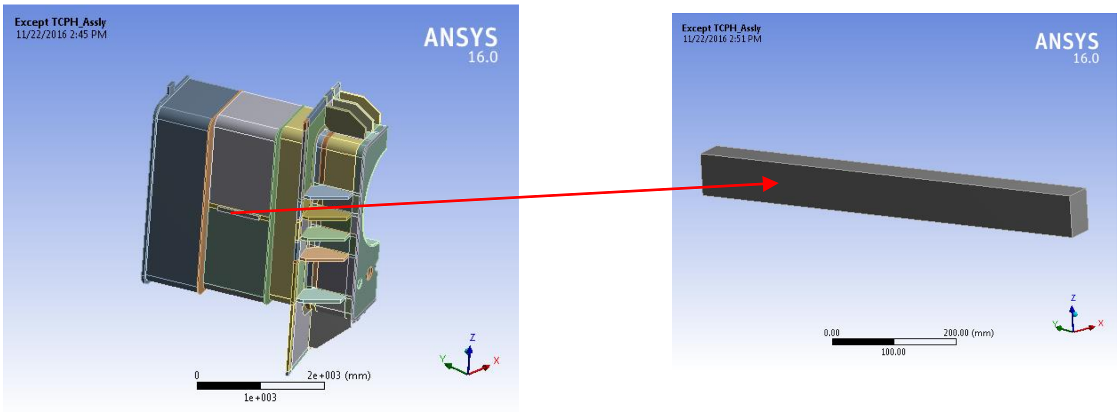


Figure 8 Shell Rib_50x70x700 mm on both side of Shell 3

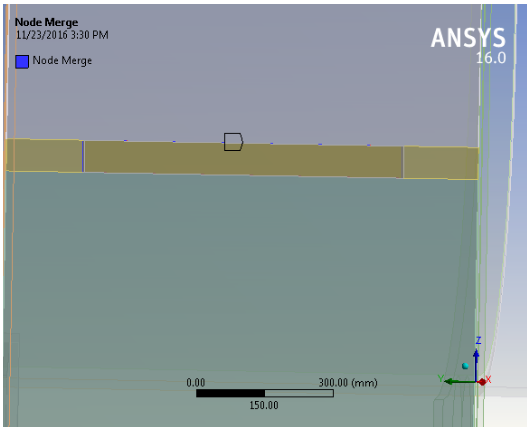


Figure 9 Nodes on edges merged with corresponding on the shell

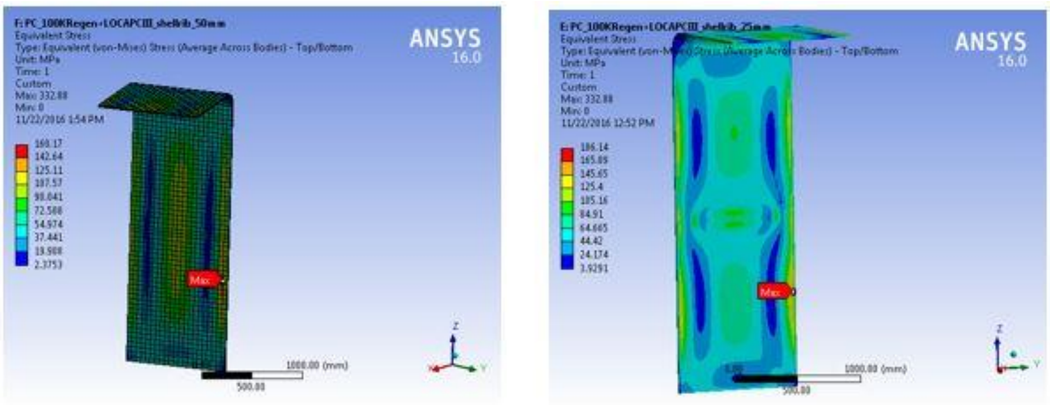
3.5. <u>FE Mesh and Element Types</u>

3.5.1. <u>Mesh Sensitivity</u>

A mesh sensitivity analysis is performed for TCPH to confirm the mesh for the integrity assessment. Inputs were taken from the previous analysis report to define mesh density at various locations. Density for Ribs was taken in accordance with [2]. Mesh sensitivity was performed & below are results for shell location.

Table 7 Mesh Sensitivity results for Shell Location

Iteration No (Element Size)	Membrane + Bending Stress P_m+P_b MPa
1st Iteration (E=100)	99.36
2nd Iteration (E=50)	161.17
3rd Iteration (E=25)	187.33



Linearized Pm+Pb = 161.17 MPa   Linearized Pm+Pb = 187.33 MPa

Figure 10 Mesh Sensitivity results

3.5.2. *Solid Inserted Cryostat*

A 20^0 FE model of TCPH (half model) is build using solid elements including Cryostat LC Wall & part of Skirt & Horizontal plate.

For structural analysis, Solid185 is used to model the solid bodies and shell181 is used to model shell elements.

For thermal analysis, Solid70 is used to model the solid bodies and shell131 is used to model shell elements.

Contact elements are defined by TARGE170 & CONTA174 elements.

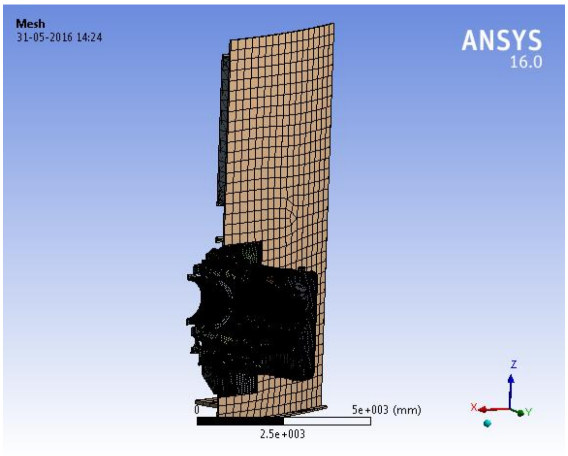


Figure 11 TCPH Mesh

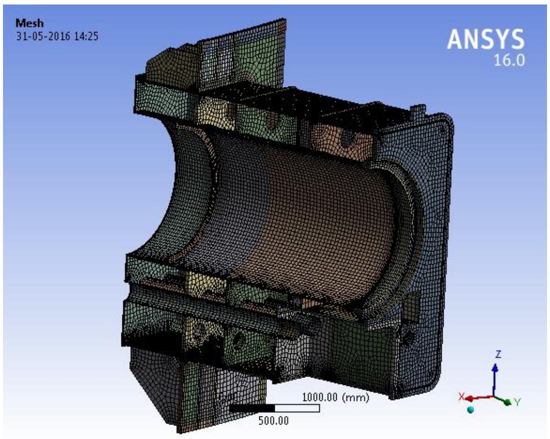


Figure 12 TCPH Model Mesh

3.5.3. __Bifurcation analysis model__

Cryostat is omitted in bifurcation model in order to account for failure modes of TCPH only. The full TCPH model is built.

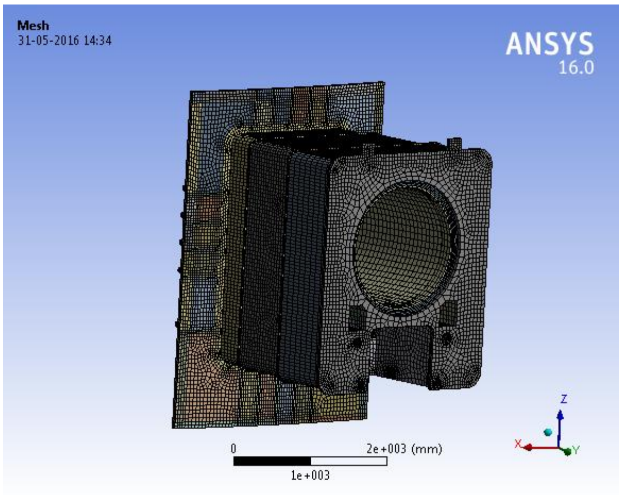


Figure 13 TCPH full model for buckling analysis

3.5.4. Overview over Element types

Table 8 Overview of the list of elements used in the FE model

Element Type	Name	Use in the Mesh of
Solid	SOLID185	All solid components for structural analysis
Solid	SOLID70	All solid components for thermal analysis
Shell	SHELL 181	All shell components for structural analysis
Shell	SHELL 131	All shell components for thermal analysis
Contact Surface	CONTA174	Contact between Wall & Flange, Wall & Wall Circular & vertical ribs
Target Surface	TARGE170	Contact between Wall & Flange, Wall & Wall Circular & vertical ribs

4. Description of Thermal Analysis

4.1. Material Properties

Elastic properties of Dual marked SS 304/304L is extracted from [4] for required temperature. Material properties are taken at the temperature in the model given in section 6.1. For cryogenic temperature, material properties are taken at room temperature.

Table 9 Properties of Dual Marked SS 304/304L

Temperature	Conductivity
^{0}C	**Wm^{-1}K^{-1}**
20	**14.8**
100	**16.2**
115	**16.5**

4.2. Thermal Loads

Thermal analysis have been performed including conduction, convection and radiation phenomenon in order to obtain the temperature distribution across the TCPH. Four thermal scenarios are considered.

- TCP Regeneration : REGEN
- Normal Operation : NO and NO (REGEN)
- Cr ICE events : NO + Cr ICE and NO(REGEN) + Cr ICE
- VV ICE events : NO + VVICE and NO(REGEN) + VV ICE

Convective Heat transfer coefficients were applied to external surfaces of Cryostat and TCPH for all thermal states with an ambient temperature of 25^{0}C. HTCs were applied to the internal surfaces of cryostat to model Cr ICE event with a bulk temperature as given in section 4.3. HTCs were applied on the inner cylinder of TCPH to model a VVICE event with a bulk temperature as given in section 4.3. Radiation between TCP & TCPH was not applied for VV ICE event.

Table 10 HTC and emissivity for thermal analysis

Event	HTC for each convective Zone, W/m^2 K			Emissivity for radiative zone		
	1	2	3	1	2	
					TCPH Shell	Cryo Pump Surface
Normal Operation	5	-	-	0.4	0.4	0.04
Cr ICE	5	-	6	0.4	0.4	0.04
VV ICE	5	6	-	0.4	-	-

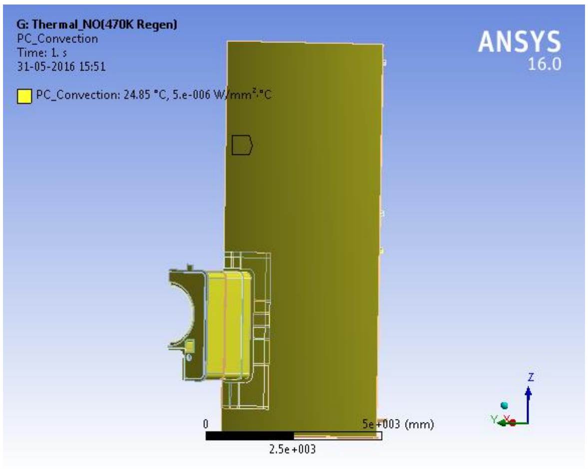


Figure 14 Port Cell Convection outside Cryostat Structure

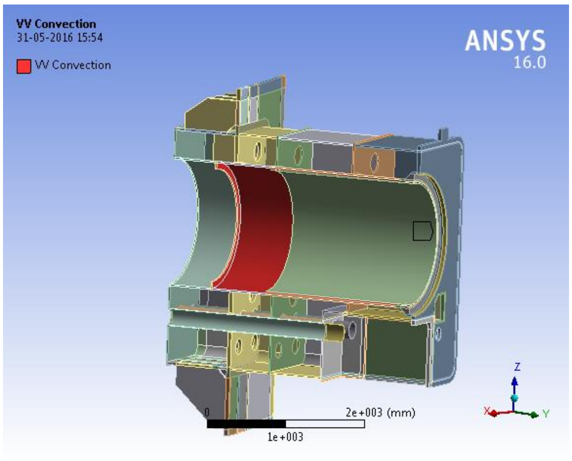


Figure 15 VV Convection in TCPH Structure

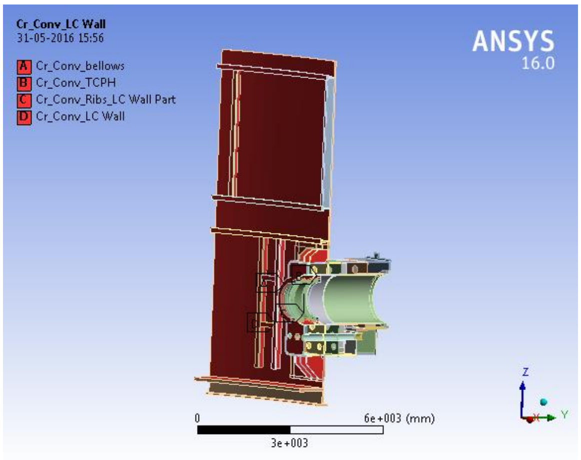


Figure 16 Cr Convection inside Cryostat Structure

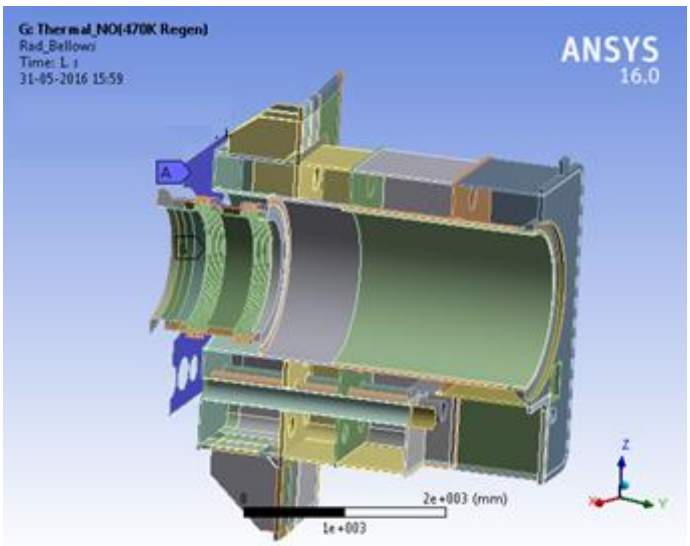


Figure 17 Zone 1: Radiation between VV Wall and TCPH & bellows

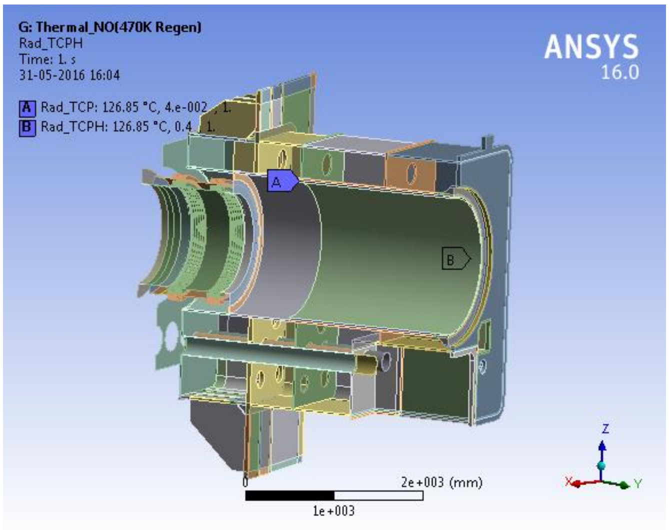


Figure 18 Zone 2: Radiation between TCP & Inner Cylinder

4.2.1. <u>TCP Regeneration</u>

Temperatures on TCP casing during regeneration are given in table 10. See fig 17. There are three types of regeneration.

- 100 K REGEN: The temperature of TCP Casing is 245K for 350 s every 1800 s, 100K REGEN is done during plasma operation.
- 300 K REGEN: The temperature of TCP casing is 300K. As the temperature of the casing is similar to room temperature, this situation is not further analysed.
- 470K REGEN: The temperature of TCP casing is 400K. There are two possibilities for this regeneration. Either it occurs during normal operation, 470K Regen is happening every 2 days for all six TCPs. When considering a single TCP, this means a 470K REGEN event every week and thus a number of cycles of 1000 (50 weeks * 20 years). This case is happening under vaccum conditions in the VV and thus in the space in between TCP & TCPH. Or it occurs after an accidental situation, 470K REGEN is triggered when torus is vented. Internal pressure of 98kPa needs to be considered in the VV and thus in the space between the TCP & TCPH.

The temperature of TCP Flange, at the interface between TCP and TCPH, is around 12 degree lower than the temperature in port cell which is around 285K considering air circulation in port cell.

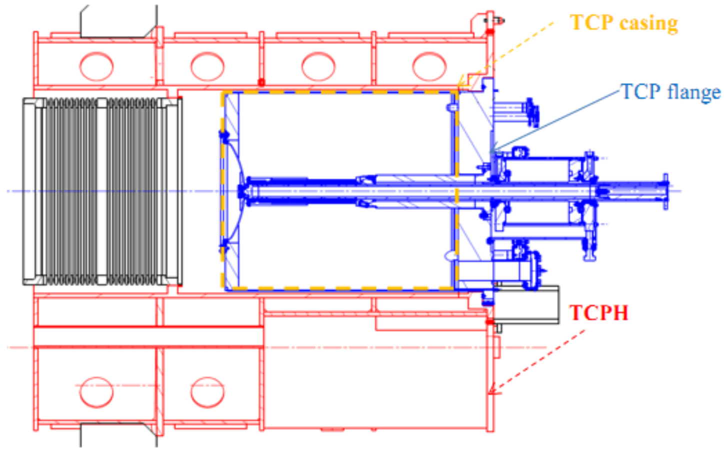


Figure 19 TCP Casing facing TCPH

4.2.2. Normal Operation conditions

During Normal Operation, VV, TCPH, TCP and Cr environments are in a vaccum state and thus only radiative and conductive heat transfers occur. Convective heat transfer occurs only outside the Cryostat in the Port Cell environment which is at ambient temperature (298K).

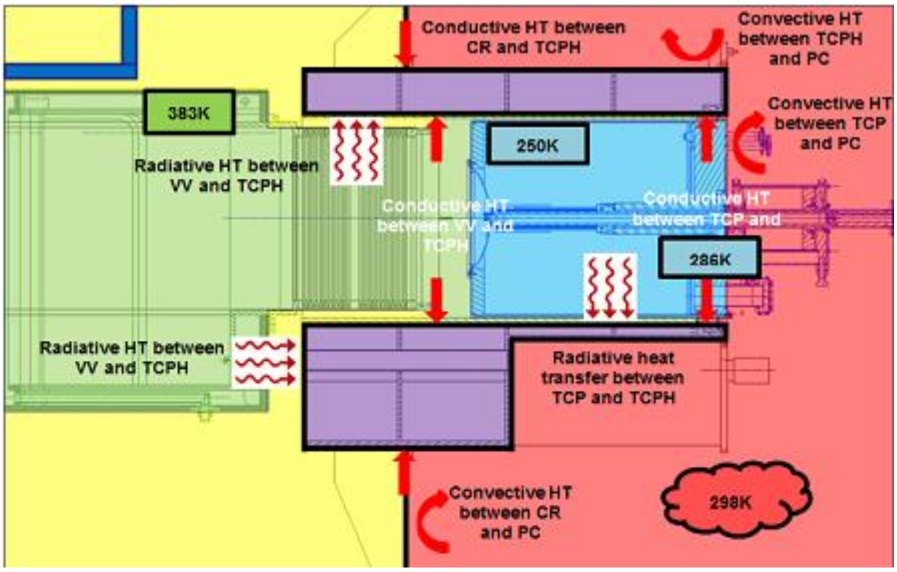


Figure 20 Heat transfer during Normal Operation

4.2.3. Cryostat Cr ICE Event

During Cr ICE events, convective heat transfer takes place between the inner cryostat environment and TCPH. Convection is considered as a dominant phenomenon compared to radiation and therefore radiation heat transfer between VV & TCPH is neglected.

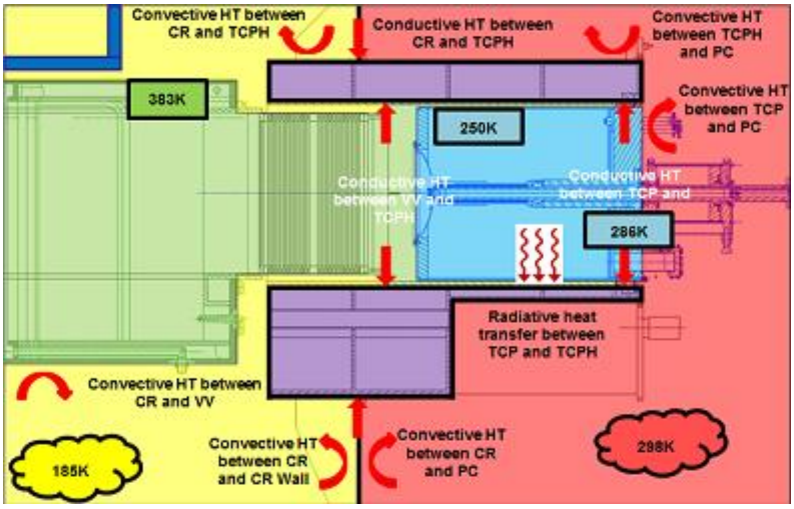


Figure 21 Heat transfer during Cr ICE Event

4.2.4. Vaccum Vessel VV ICE event

During VV ICE events, VV, TCP and TCPH form a unique enclosure filled with a convective gas whose temperature is governed by VV ICE event. Convection can be considered as a dominant phenomenon compared to radiation and therefore radiative heat transfer between TCP & TCPH can be neglected.

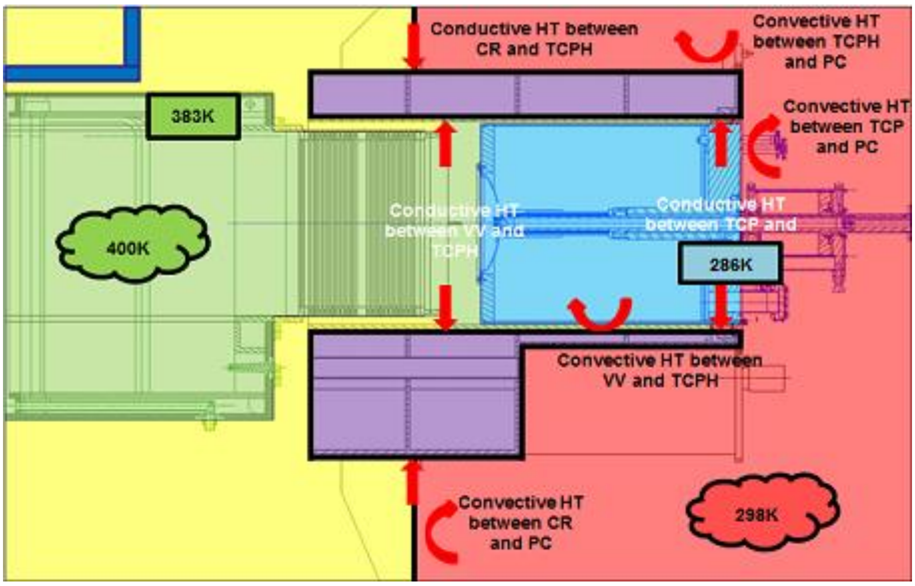


Figure 22 Heat transfer during VV ICE Event

4.3. Boundary Conditions

The boundary conditions applied for thermal analysis are listed in Table 10. For Cr ICE event, temperature of pedestal ring is taken as -10^{0}C [8].

Table 11 Thermal Boundary Conditions

<table>
<tr><th rowspan="2">Load Combinations</th><th rowspan="2">Cat.</th><th rowspan="2">Port Duct Wall Temp [K]</th><th rowspan="2">TCP Casing Temp [K]</th><th rowspan="2">TCP Flange Temp [K]</th><th colspan="3">Environment Temp [K]</th></tr>
<tr><th>VV</th><th>CR</th><th>PC</th></tr>
<tr><td>Maintenance</td><td>I</td><td>298</td><td>298</td><td rowspan="17">285</td><td>298</td><td rowspan="12">298</td><td rowspan="12">298</td></tr>
<tr><td>NO</td><td>I</td><td>383</td><td>250</td><td>383</td></tr>
<tr><td>NO (100K REGEN)</td><td>I</td><td>383</td><td>245</td><td>383</td></tr>
<tr><td>VV BK</td><td>I</td><td>473</td><td>250</td><td>473</td></tr>
<tr><td>VV BK (100K REGEN)</td><td>I</td><td>473</td><td>245</td><td>473</td></tr>
<tr><td>NO + VV ICEII</td><td>II</td><td>383</td><td>250</td><td>400</td></tr>
<tr><td>NO (100K REGEN) + VV ICEII</td><td>II</td><td>383</td><td>250</td><td>400</td></tr>
<tr><td>NO (470K REGEN)</td><td>II</td><td>383</td><td>400</td><td>383</td></tr>
<tr><td>NO + VV ICE III</td><td>III</td><td>473</td><td>250</td><td>300</td></tr>
<tr><td>NO (100K REGEN) + VV ICEIII</td><td>III</td><td>473</td><td>245</td><td>300</td></tr>
<tr><td>NO + VV ICEIV</td><td>IV</td><td>473</td><td>250</td><td>300</td></tr>
<tr><td>NO (100K REGEN) + VV ICEIV</td><td>IV</td><td>473</td><td>245</td><td>300</td></tr>
<tr><td>NO + LOCA PC III</td><td>III</td><td>473</td><td>250</td><td>473</td><td>393</td><td>393</td></tr>
<tr><td>NO (100K REGEN) + LOCA PC III</td><td>III</td><td>473</td><td>245</td><td>473</td><td>393</td><td>393</td></tr>
<tr><td>NO(100K REGEN) + Cr ICE II</td><td>II</td><td>383</td><td>245</td><td>383</td><td>185</td><td rowspan="3">298</td></tr>
<tr><td>NO(100K REGEN) + Cr ICE III</td><td>III</td><td>383</td><td>245</td><td>383</td><td>178</td></tr>
<tr><td>NO(100K REGEN) + Cr ICE IV</td><td>IV</td><td>383</td><td>245</td><td>383</td><td>178</td></tr>
</table>

5. Description of Structural Analysis

5.1. Material Properties

Elastic material properties of Dual Marked SS 304/304L are extracted from [4] as required. Material properties are taken at the temperature in the model given in section 6.1. For cryogenic temperature, material properties are taken at room temperature.

Table 12 Physical properties of SS 304/304L Dual Mark

Temperature	Density	Young's Modulus	Poisson's Ratio	Mean Thermal Expansion
^{0}C	Kg/m^3	GPa		10^{-6} 1/K
20	8030	195	0.31	15.3
100	8030	189	0.31	16.2
115	8030	188	0.31	16.4

Table 13 Tensile properties of SS 304/304L Dual Mark

Temperature	Tensile Ultimate Strength Values, S_u [MPa]	Tensile Strength Values, S_y [MPa]
^{0}C		
-30 to 40	515	205
100	485	170
115	479	163

5.2. Mechanical Loads

5.2.1. Gravity

The gravity is applied setting a vertical downward acceleration of 9810 mm/s^2. The density of double bellows is modified to obtain the mass given in ref [3].

Table 14 Summary of density used in Ansys

Components	**Density [kg/m^3]**
TCPH	8833
Double Bellows	5973

The position of COG for TCP is given with respect to the status of the TCP valve head, see fig 22. The mass of TCP & COG are given in RCS TCPH (see section 3.3) in Table 14.

Table 15 TCP COG Positions and Masses with 10% additional uncertainty

Components	Weight (kg)	COG Location [mm]		
		X	Y	Z
TCP Valve – open	8800	2022	0	0
TCP Valve – close	8800	2092	0	0

5.2.2. Seismic

Seismic acceleration is applied to the TCPH structure considering Newmark's Combinations.

Seismic Load: ± X ± Y ± Z

Since TCPH is symmetrical about Y axis. Total number of combinations are reduced to 12.

Table 16 Seismic acceleration multiplied by 1.5

	Estimated Horizontal Acceleration [m/s^2]	Estimated Vertical Acceleration [m/s^2]
SL-2	10.05	6.75
SMHV	7.29	4.39
SL-1	3.42	2.29

Table 17 Seismic combinations used for analysis

Sr. No	Combination	Sr. No	Combination	Sr. No	Combination
1	100X + 40Y+40Z	5	40X + 100Y + 40Z	9	40X+40Y+100Z
2	-100X + 40Y+40Z	6	-40X + 100Y+ 40Z	10	40X+40Y-100Z
3	100X + 40Y-40Z	7	40X + 100Y - 40Z	11	-40X+40Y+100Z
4	-100X + 40Y-40Z	8	-40X + 100Y - 40Z	12	-40X+40Y-100Z

Based on several iterations using all the 12 combinations, it was found that structure gives maximum responses for 5 combinations.

So for all other iterations following 5 combinations were used for seismic loads. The result of the maximum response was used in the assessment. For most of the analysis, combination 2: -40X + 100Y + 40Z gave the maximum response and was used in the assessment results.

Table 18 Combinations used for seismic loads

Sr. No.	Combination
1	-40X+40Y+100Z
2	-40X + 100Y+ 40Z
3	100X + 40Y+40Z
4	-100X + 40Y-40Z
5	-40X + 100Y - 40Z

5.2.3. Pressure Loads

TCP is connected to TCPH in order to increase the regeneration volume of TCP thus pressure inside TCPH depends on the various pressure states existing in TCP. Vaccum Vessel and TCPH can form either a unique environment if TCP valve head is opened or two separate environments if TCP valve head is close see fig 21. Table 18 lists the pressure values for different environments given in fig 21 for all possible corresponding single load case and Table 19 gives the conservative pressure loads considered in FE analysis.

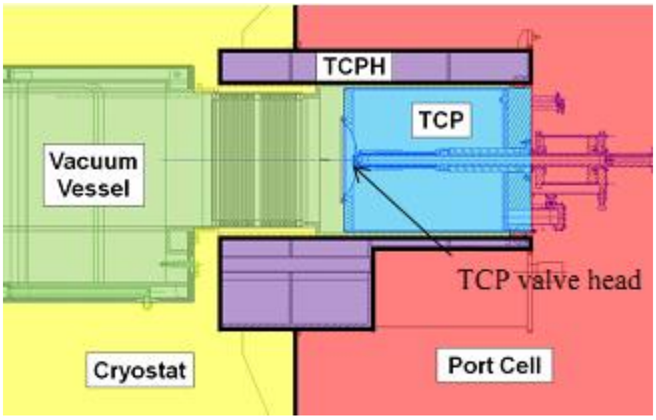


Figure 23 Description of pressure environment

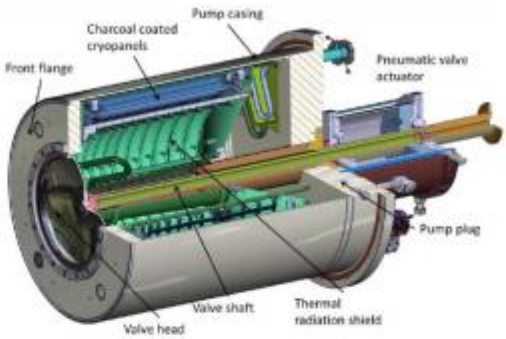


Figure 24 Description of TCP Valve Head

Table 19 Pressure Loads

Load Combination	Cat.	TCP Valve Head Status	Pressure [kPa]			
			VV	TCP / TCPH	PC	CR
Maintenance	I	NA	100	100	100	100
NO	I	open	0	0	100	0
NO (100K REGEN)	I	close	0	0	100	0
VV BK	I	open	0	0	100	0
VV BK (100K REGEN)	I	close	0	0	100	0
NO + VV ICEII	II	open	106	106	100	0
NO (100K REGEN) + VV ICEII	II	close	106	0	100	0
NO (470K REGEN)	II	close	0	0	100	0
NO + VV ICE III	III	open	150	150	100	0
NO (100K REGEN) + VV ICEIII	III	close	150	0	100	0
NO + VV ICEIV	IV	open	200	200	100	0
NO (100K REGEN) + VV ICEIV	IV	close	200	0	100	0
NO + LOCA PC III	III	open	150	150	160	0
NO (100K REGEN) + LOCA PC III	III	close	150	0	160	0

NO + Cr ICE II	II	open	0	0	100	31
NO + Cr ICE III	III	open	0	0	100	156
NO + Cr ICE IV	IV	open	0	0	100	247

Table 20 Conservative Pressure Loads

	Cat.	TCP Valve Status	Pressure [kPa]			
			VV	TCP / TCPH	PC	CR
Maintenance	I	NA	100	100	100	100
NO (100K REGEN)	I	close	0	0	100	0
NO (100K REGEN) + VV ICEII	II	close	106	0	100	0
NO (100K REGEN) + VV ICEIII	III	close	150	0	100	0
NO (100K REGEN) + VV ICEIV	IV	close	200	0	100	0
NO (100K REGEN) + LOCA PC III	III	close	150	0	160	0
NO + Cr ICE II	II	open	0	0	100	31
NO + Cr ICE III	III	open	0	0	100	156
NO + Cr ICE IV	IV	open	0	0	100	247

5.2.4. Displacements from VV

Interface loads are defined through imposed displacements. Displacements from VV at the level of lower port are applied on the double bellows though a pilot node as in fig 23. The co-ordinate of pilot node are given in RCS PC (11023, 0, -4607) see section 3.3. Table 20 summarizes the displacements applied on pilot node for single event.

Table 21 Remote Displacement from Vaccum Vessel

Event	u_{rad}	u_{tor}	u_{vert}	rot_{rad}	rot_{tor}	rot_{vert}
Normal Operation at 100^0C	16.82	0	7.04	0	0	0
Baking at 200^0 C	39.48	0	17.61	0	0	0
VDE II	± 9.17	±5.22	±2.54	0	0	0
SL-1	±2.23	±1.32	±0.68	0	0	0
SMHV	±4.78	±2.8	±1.44	0	0	0
SL-2	±6.53	±3.83	±1.97	0	0	0

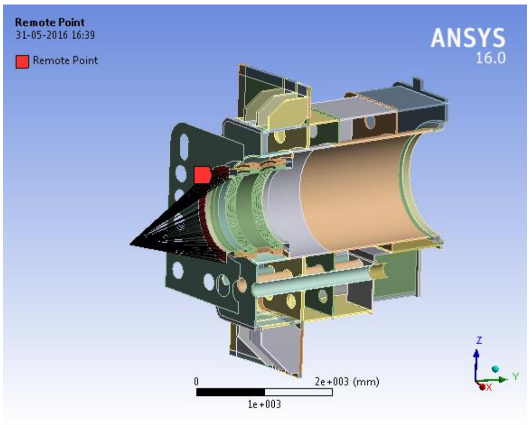


Figure 25 Pilot Node with Co-ordinate (11023, 0,-4607) in RCS TCP

5.3. Thermal Loads

The map of temperature is obtained from thermal analyses described in section 4.2. These temperatures are then imported in the structural FE model in order to obtain stresses from thermal gradient. The temperatures applied for structural analysis are given in section 6.1.

5.4. Boundary Conditions

5.4.1. Symmetric Loads

Symmetric Boundary conditions are applied on the surfaces of symmetric plane. Fixed boundary conditions are applied on surface of all the directions other than symmetric plane.

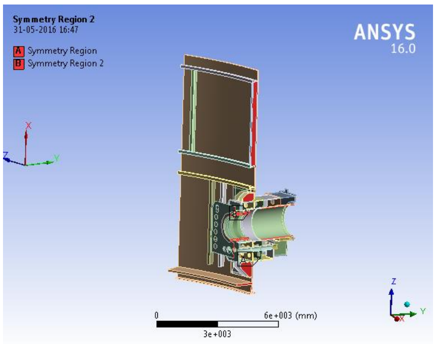


Figure 26 Symmetric Surface

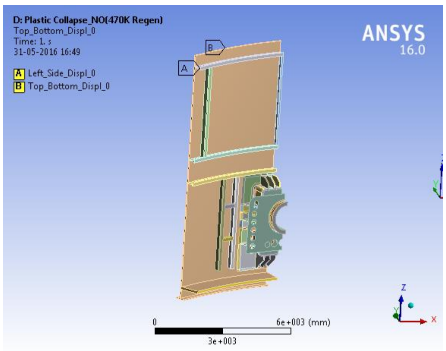


Figure 27 Symmetric boundary condition on outer surface

5.4.2. Asymmetric Loads

Anti-symmetric boundary conditions are applied on the model for horizontal seismic event, see fig 26.

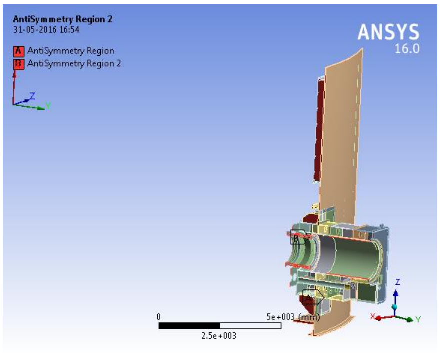


Figure 28 Anti symmetric boundary condition for seismic loads

5.4.3. Thermal Loads

Symmetric boundary conditions are applied on all the edges of model see fig 27.

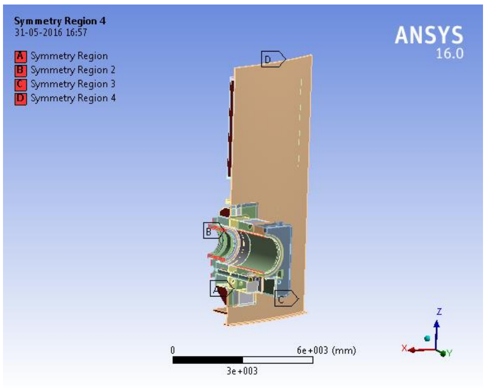


Figure 29 Symmetric boundary condition on all the surfaces for thermal loads

5.4.4. Bifurcation analysis boundary condition

All degrees of freedom are locked in all the directions of external surface of model.

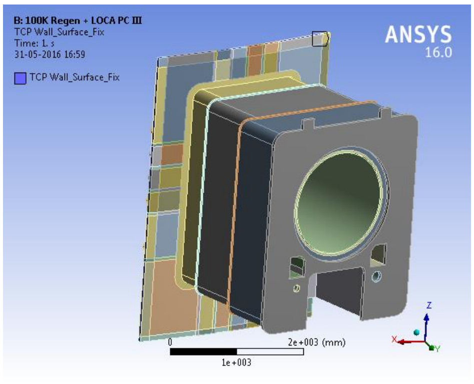
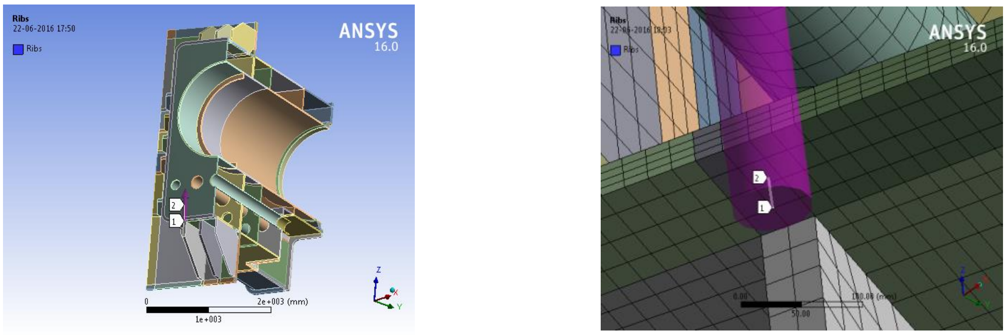


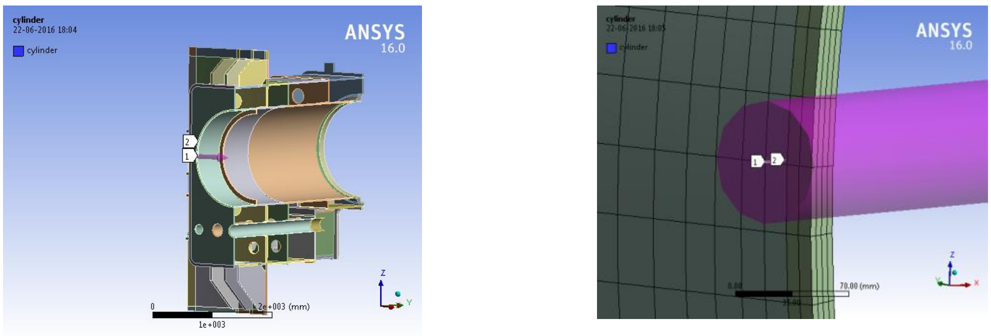
Figure 30 Fixed boundary condition for buckling analysis

5.5. Linearization Path

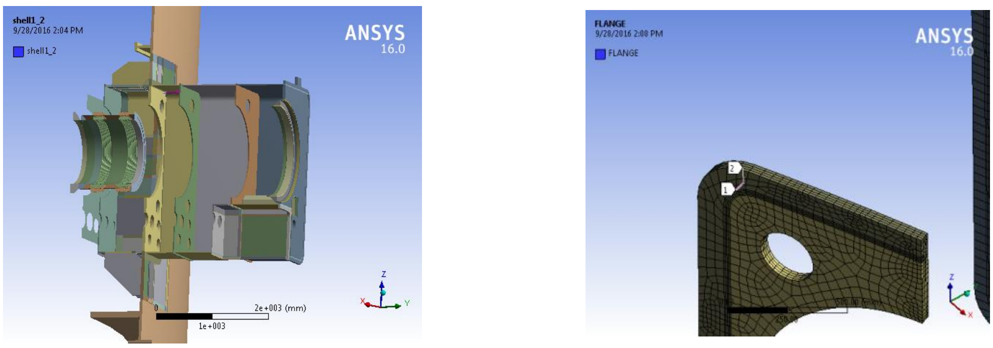
Von Mises stresses are linearized in order to extract the membrane & membrane plus bending stress to compare them with allowable limits given in section 2.4 for checking the structural integrity of TCPH. Linearized stress values given in the report are obtained with Stress Classification Line built across the thickness, see fig 29 & 30. For the area near holes on wall flange, the stresses are linearized across thickness up to the side surface or between the holes at multiple section in order to obtain approximation of membrane stress, see fig 30. The membrane stress is then the average of linearized membrane stress for all the linearization path and the evolution of membrane plus bending stress is plot in order to extrapolate the results on outer surfaces for each path.



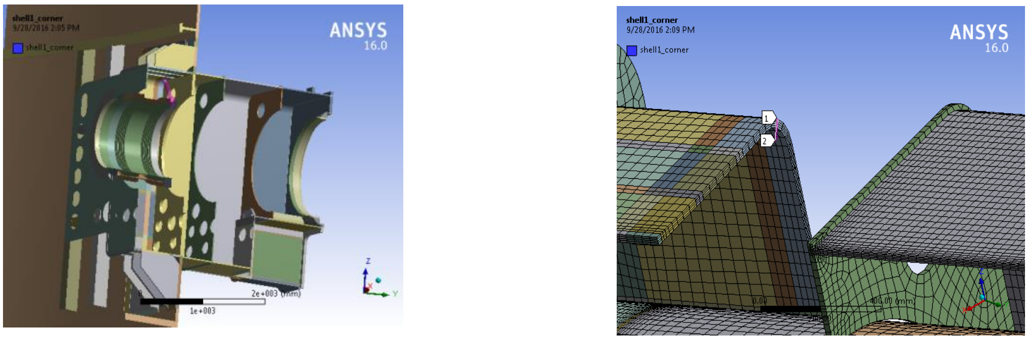
a. Path on Ribs



b. Path on Cylinder

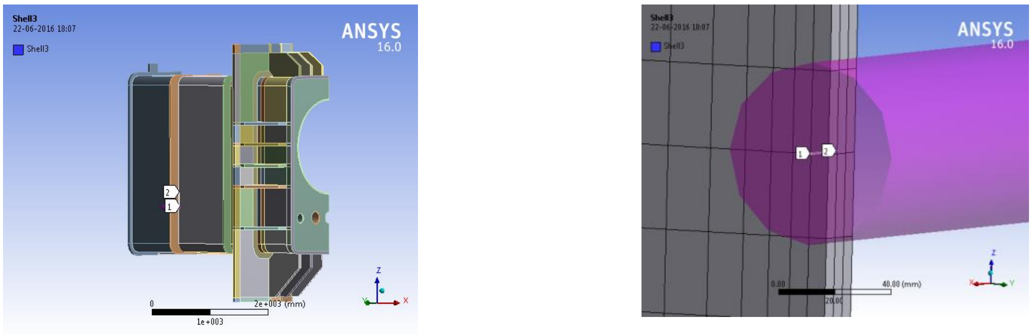


c. Path on Flange



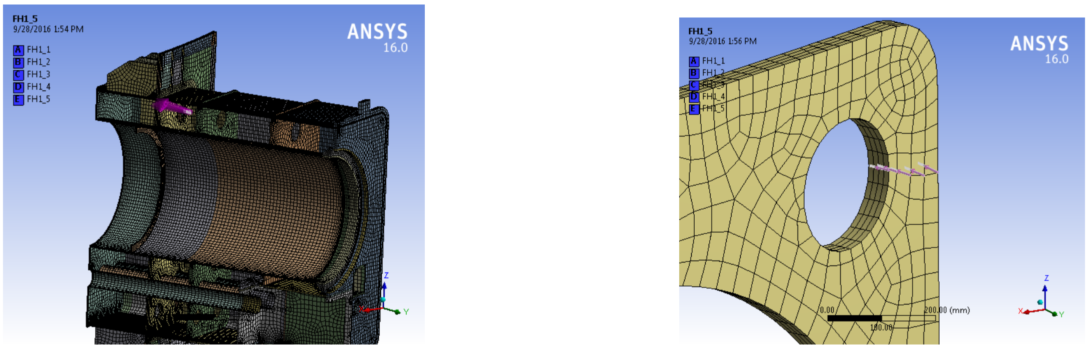
d. Path on shell1corner

e. Path on shell2corner

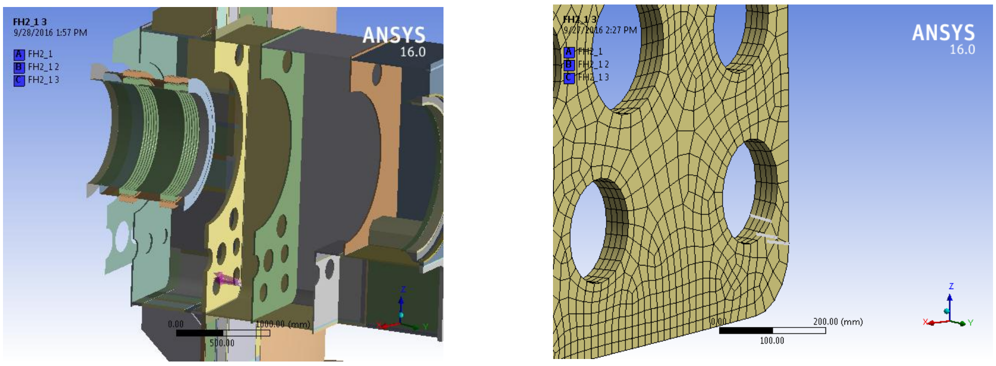


f. Path on shell3

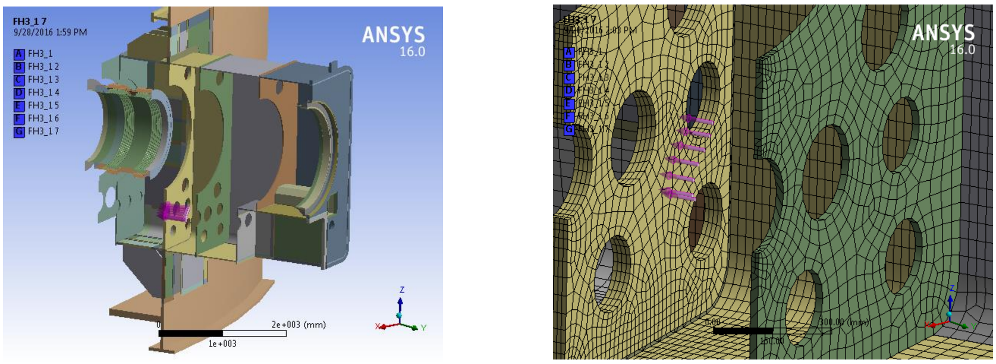
Figure 31 Linearization path across points 1,2



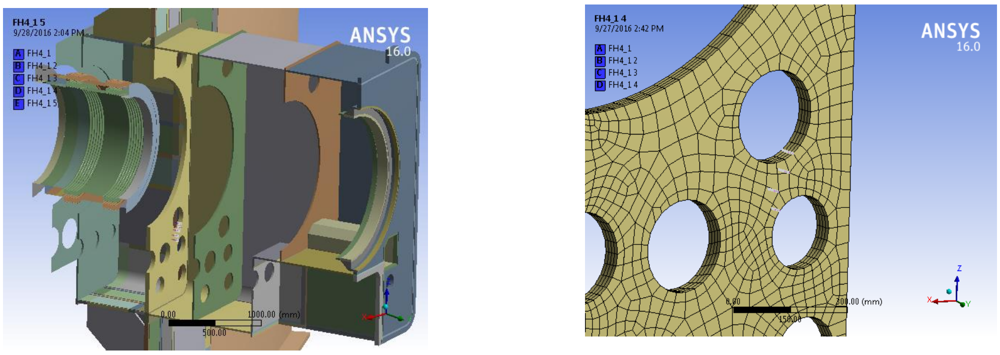
g. Path on FLANGE HOLE(FH1)



h. Path on Flange Hole(FH2)



i. Path on Flange Hole(FH3)



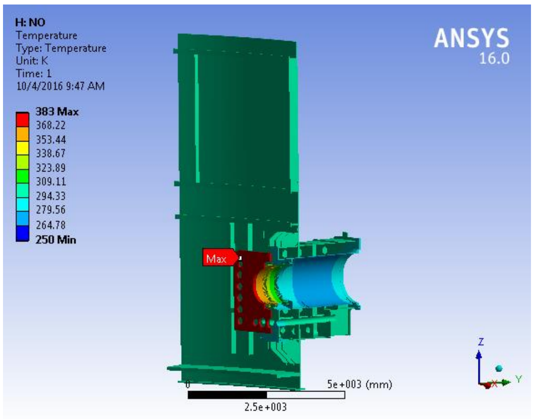
j. Path on Flange Hole(FH4)

Figure 32 Linearization path across several points

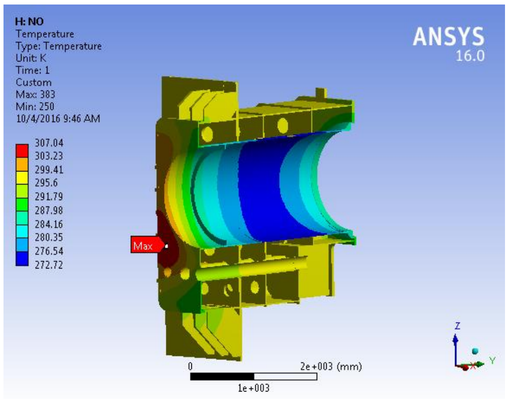
6. Results

6.1. Thermal Analysis

The temperature distribution in the structure is given for each of the thermal state analysed from fig 26 to 31.

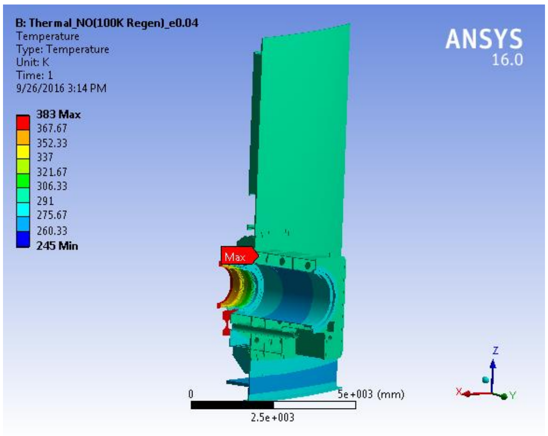


a. Global View

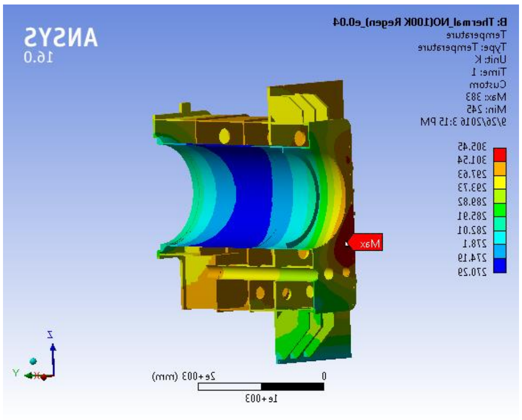


b. TCPH

Figure 33 Temperature Distribution: NO

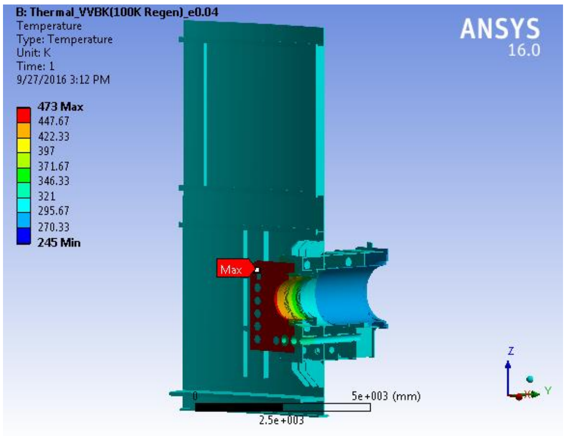


a. Global View

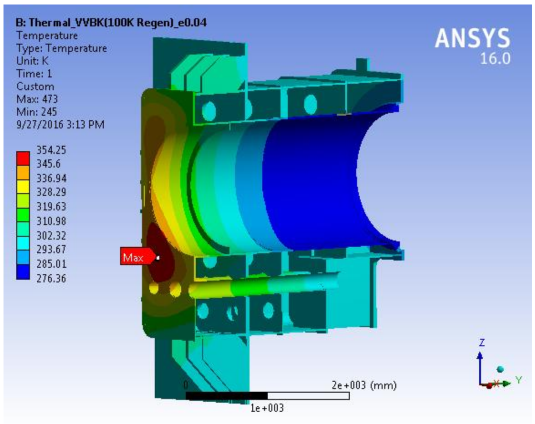


b. TCPH

Figure 34 Temperature Distribution: NO (100K Regen)

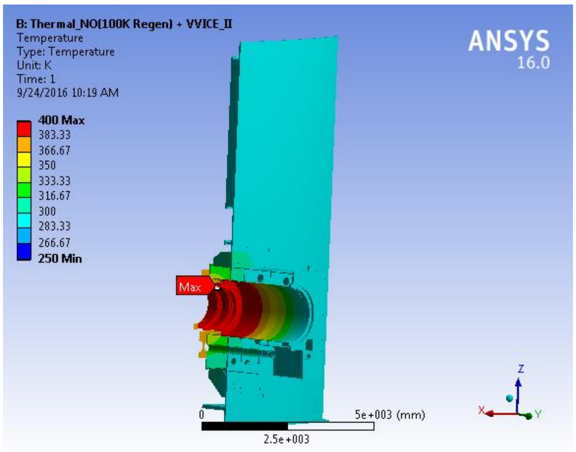


a. Global View

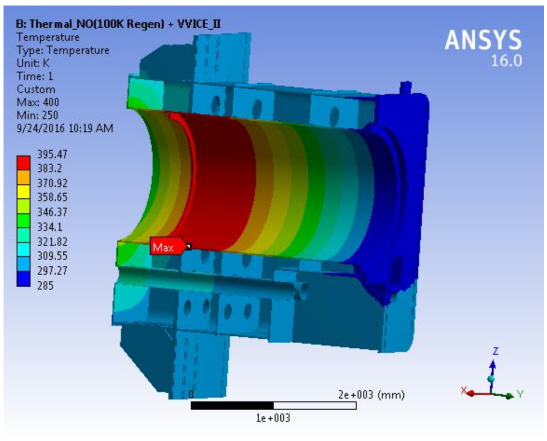


b. TCPH

Figure 35 Temperature Distribution: Baking (100K Regen)

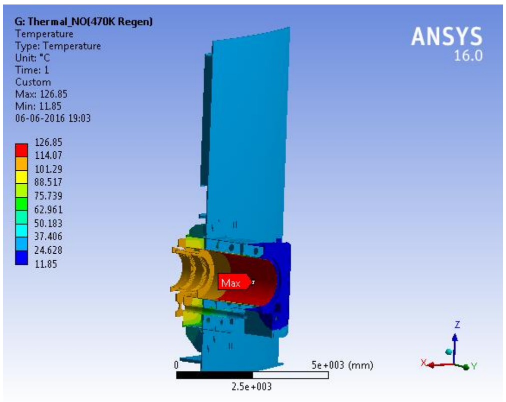


a. Global View

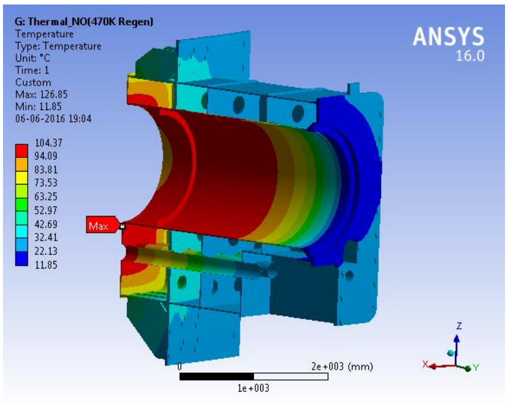


b. TCPH

Figure 36 Temperature Distribution; NO (100 K Regen) + VV ICE II

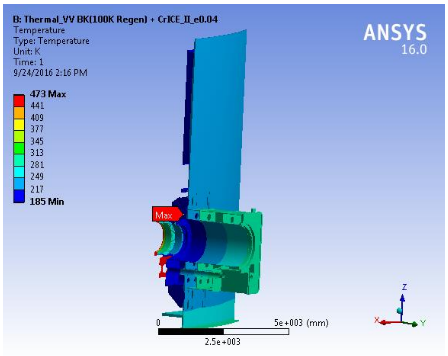


a. Global View

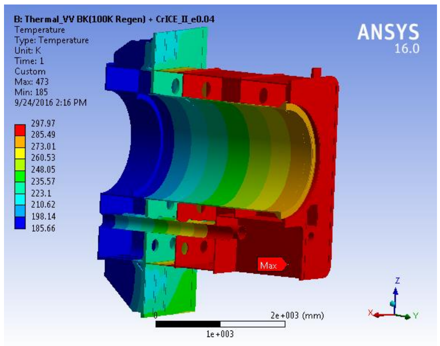


b. TCPH

Figure 37 Temperature Distribution; NO (470K Regen)



a. Global View



b. TCPH

Figure 38 Baking (100K Regen) + Cr ICE II

6.2. Impact of Boundary conditions

As fixed boundary conditions are used on the outer edges of LC Wall, the ratio obtained from the previous reports are used to account for fixed boundary condition.

Table 22 Stress ratio for all the load combinations

Sr. No.	Load Combinations	Stress Ratio			
		Pm	Pm+Pb	Pm+Pb+Q	Q
CATEGORY I & II					
1	Lifting/Assembly/RH + SL-1				
2	NO(100K Regen) + VDE II	1.54	1	1.1	1.1

3	NO(100K Regen) + VV ICE II + VDE II	**1.58**	**1**	**1.14**	**1.14**
4	NO(100K Regen) + VV ICE II	**1.58**	**1**	**1.14**	**1.14**
5	VV Baking(100K Regen) + VV ICE II	**1.58**	**1**	**1.14**	**1.14**
6	NO(100K Regen) + Cr ICE II	**1**	**1**	**1**	**1**
7	VV Baking(100K Regen) + Cr ICE II	**1**	**1**	**1**	**1**
8	NO(100K Regen) + SL-1	**1**	**1**	**1**	**1**
9	VV Baking(100K Regen) + SL-1	**1**	**1**	**1**	**1**
10	NO(300K Regen)	**1.54**	**1**	**1.1**	**1.1**
11	NO(470K Regen)	**1.54**	**1**	**1.1**	**1.1**

CATEGORY III					
1	NO (100K REGEN) + VV ICE III	**1.54**	**1**	-	-
2	NO (100K REGEN) + Cr ICE III	**1**	**1**	-	-
3	NO (100K REGEN) + SMHV	**1**	**1**	-	-
4	NO (100K REGEN) + Cr ICE III + SMHV	**1**	**1.01**	-	-
5	NO (100K REGEN) + LOCA_PC III			-	-

CATEGORY IV					
1	NO (100K REGEN) + VV ICE IV	**1.54**	**1**	-	-
2	NO (100K REGEN) + Cr ICE IV	**1**	**1**	-	-
3	NO (100K REGEN) + Cr ICE III + SL-2	**1.54**	**1.18**	-	-

6.3. Structural Analysis Results

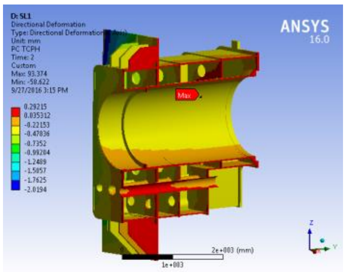
The allowable limits are taken at temperatures with regards to thermal analysis results.

6.3.1. Displacements due to mechanical loads

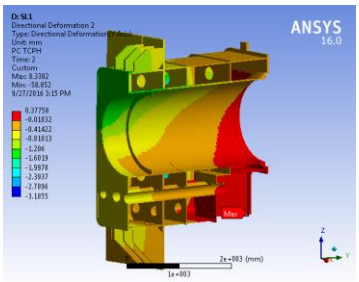
In this chapter, displacements are given in relative co-ordinate system (PC TCPH).

6.3.1.1. VV BAKING (100K REGEN) + SL-1

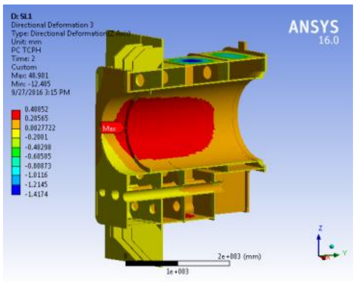
The maximum & minimum values of displacements with elastic analysis are shown below:



a. Radial Displacement



b. Toroidal Displacement

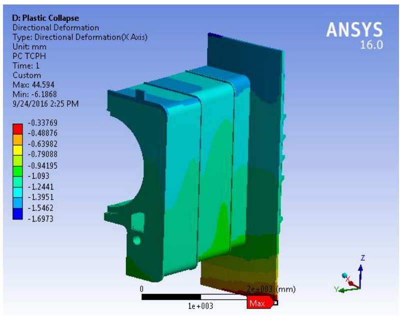


c. Vertical Displacement

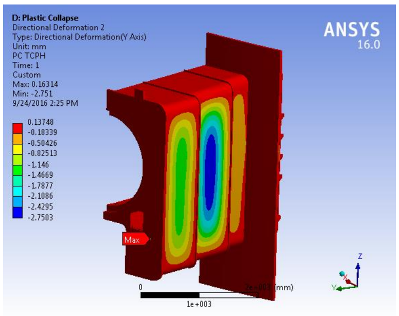
Figure 39 Displacements on TCPH

6.3.1.2. <u>VV BAKING (100K REGEN) + Cr ICE II</u>

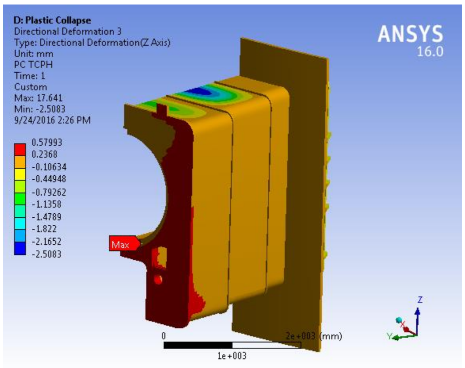
The maximum & minimum values of displacements with elastic analysis are shown below:



a. Radial Displacement



b. Toroidal Displacement

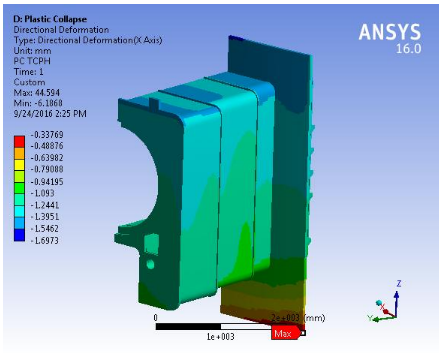


c. Vertical Displacement

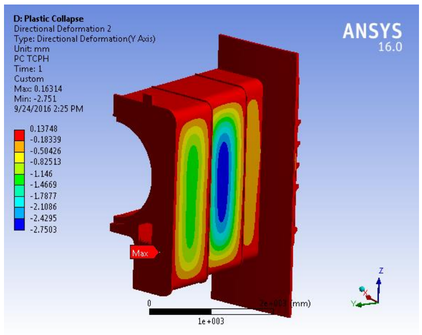
Figure 40 Displacements on the TCPH

6.3.1.3. <u>VV BAKING (100K REGEN) + Cr ICE II</u>

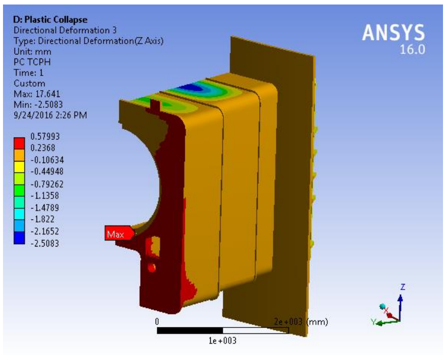
The maximum & minimum values of displacements with elastic analysis are shown below



a. Radial Displacement



b. Toroidal Displacement

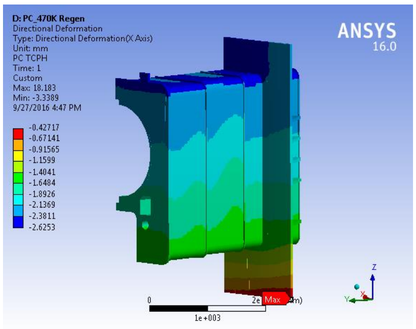


c. Vertical Displacement

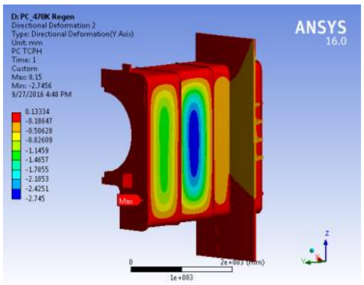
Figure 41 Displacements on the TCPH

6.3.1.4. <u>NO (470K REGEN)</u>

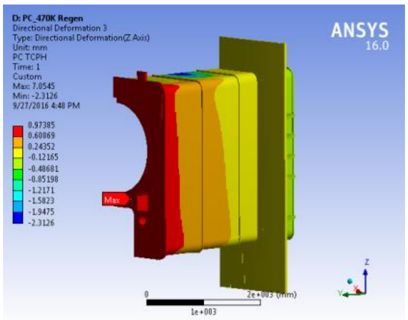
The maximum & minimum values of displacements with elastic analysis are shown below



a. Radial Displacement



b. Toroidal Displacement

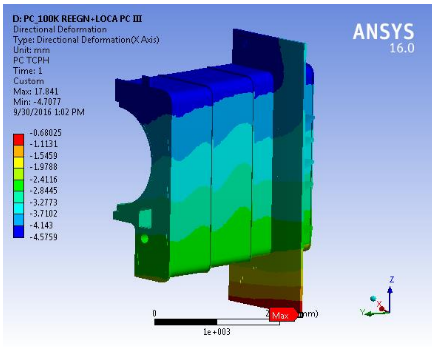


c. Vertical Displacement

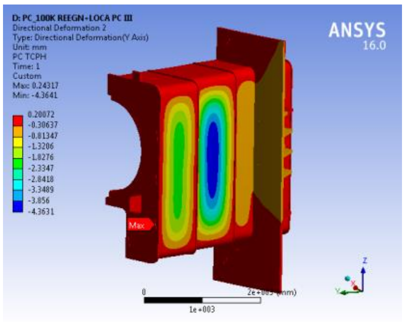
Figure 42 Displacement on the TCPH

6.3.1.5. <u>NO (100K REGEN) + LOCA PC III</u>

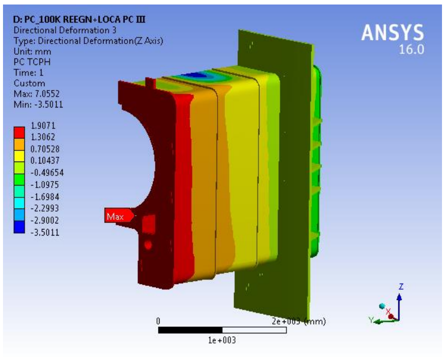
The maximum & minimum values of displacements with elastic analysis are shown below



a. Radial Displacement



b. Toroidal Displacement

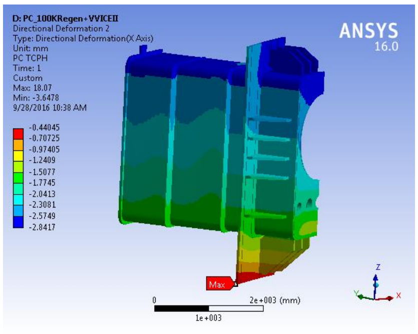


c. Vertical Displacement

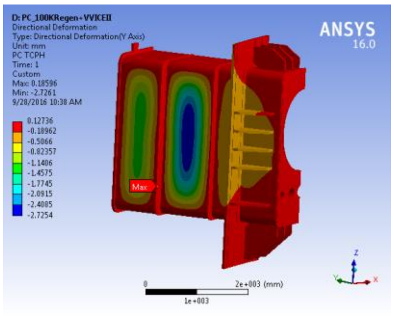
Figure 43 Displacements on the TCPH

6.3.1.6. <u>NO (100K REGEN) + VV ICE III</u>

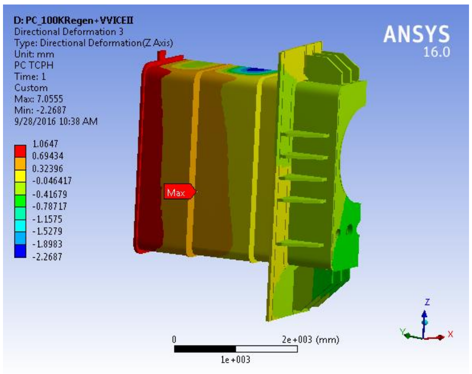
The maximum & minimum values of displacements with elastic analysis are shown below



a. Radial Displacement



b. Toroidal Displacement

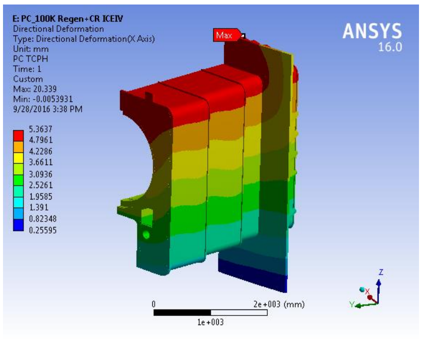


c. Vertical Displacement

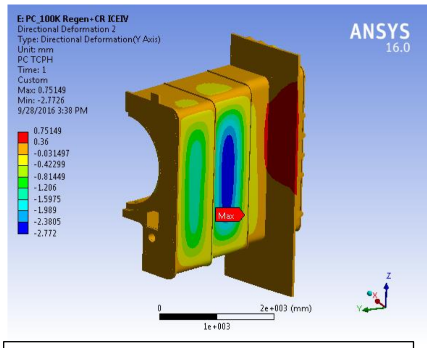
Figure 44 Displacements on the TCPH

6.3.1.7. <u>NO (100K REGEN) + Cr ICE IV</u>

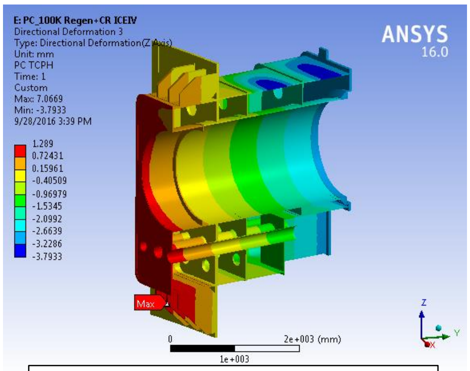
The maximum & minimum values of displacements with elastic analysis are shown below



a. Radial Displacement



b. Toroidal Displacement

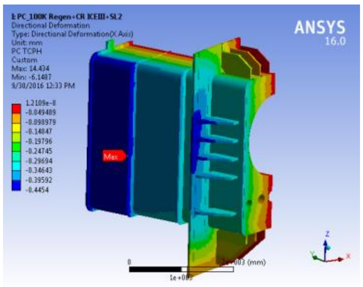


c. Vertical Displacement

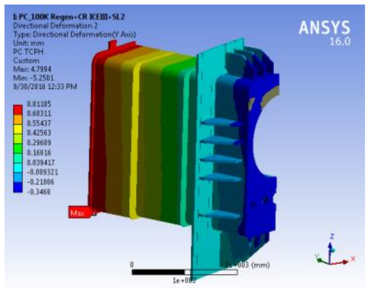
Figure 45 Displacements on the TCPH

6.3.1.8. NO (100K REGEN) + Cr ICE III + SL-2

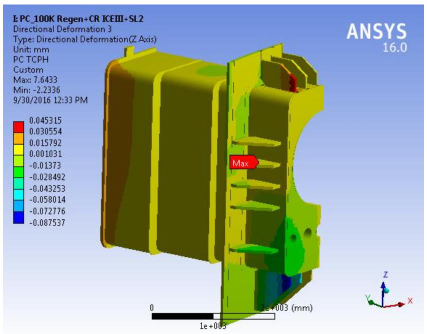
The maximum & minimum values of displacements with elastic analysis are shown below



a. Radial Displacement



b. Toroidal Displacement



c. Vertical Displacement

Figure 46 Displacements on the TCPH

6.3.2. Protection against Plastic Collapse & Local Failure

6.3.2.1. VV BAKING (100K REGEN) + SL-1

Table 22 summarizes Von Mises stress results for VV Baking (100K REGEN) + SL-1. Figure shows stress distribution of Von Mises across TCPH.

Table 23 Stress Results: VV BAKING (100K Regen) + SL-1

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Side Ribs Up	33.86	145.42

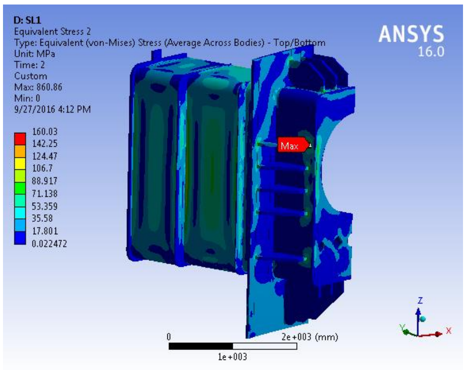


Figure 47 Von Mises Stress Plot

6.3.2.2. <u>VV BAKING(100K REGEN) + Cr ICE II</u>

Table 23 summarizes Von Mises stress results. Figure shows the Von Mises stress distribution across TCPH.

Table 24 Stress Results: VV BAKING (100K Regen) + Cr ICE II

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Shell3top	7.87	110.56
Ribs	18.61	90.25

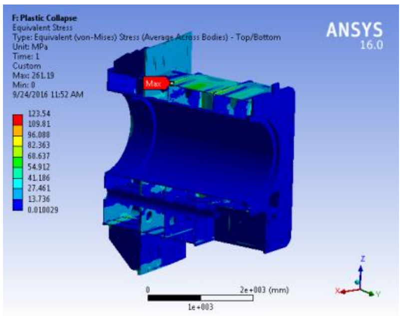


Figure 48 Von Mises Stress Plot

Maximum value of sum of the principal stresses is 225.19 MPa.

6.3.2.3. <u>VV BAKING (100K REGEN) + VVICE II</u>

Table 24 summarizes Von Mises stress results. Figure shows the Von Mises stress distribution across TCPH

Table 25 Stress Result: VVBAKING (100K Regen) + VV ICE II

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Ribs	28.27	133.11

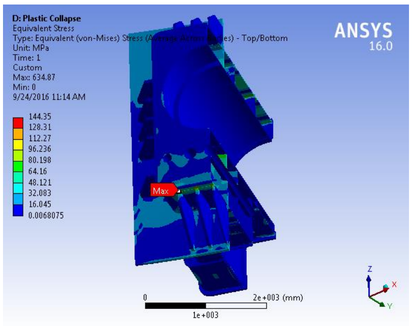


Figure 49 Von Mises Stress Plot

Maximum value of sum of the principal stresses is 332.58 MPa.

6.3.2.4. NO (470K REGEN)

Table 25 summarizes Von Mises stress results. Figure shows the Von Mises stress distribution across TCPH

Table 26 Stress Result: NO (470K Regen)

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Ribs	26.56	125.27

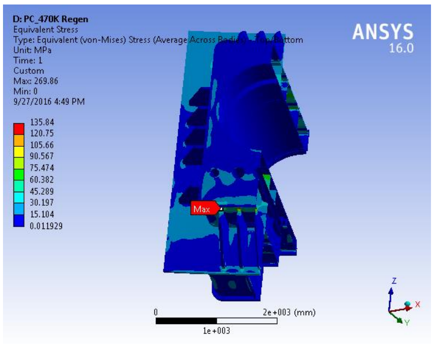


Figure 50 Von Mises Stress Plot

Maximum Value of sum of Principal Stresses is 313.46 MPa.

6.3.2.5. NO (100K REGEN) + LOCA PC III

Table 26 summarizes Von Mises stress results. Figure shows the Von Mises stress distribution across TCPH

Table 27 Stress Result: NO (100K Regen) + LOCA PC III

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Shell3	15.49	180.65
Ribs	40.44	189.29

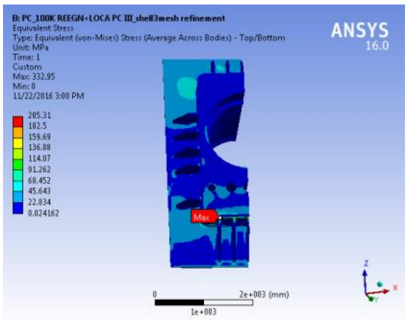


Figure 51 Von Mises Stress Plot

Based on the Mesh Sensitivity results for Shell 3 Location, the value of Linearized Membrane + Bending Stress came at 198.72 MPa which is higher than the allowable value of 194 MPa.

So a Rib was introduced on the outer side of shell 3 and the assessment was performed for the same.

Table 27 summarizes Von Mises stress results for the updated geometry. Figure shows the Von Mises stress distribution across TCPH

Table 28 Updated Stress Result: NO (100K Regen) + LOCA PC III

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Shell3	17.45	187.33
Ribs	40.3	189.31

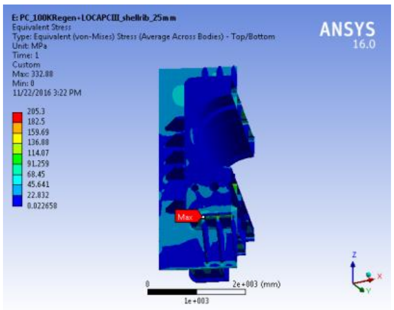


Figure 52 Von Mises Plot for Updated Geometry with Shell rib

The Mesh sensitivity results are giving the same values as obtained. The obtained values are within the allowable limit of 194 MPa

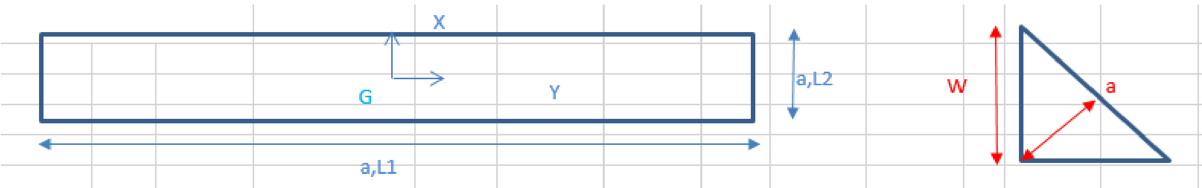
Maximum value of sum of the principal stresses is 474.74 MPa.

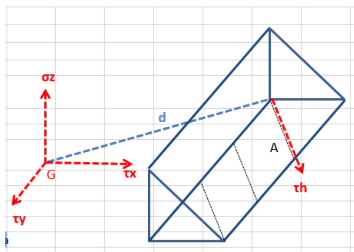
Fillet Weld Calculation

Combined Reaction force & Moment Reaction on all the fillet edges are extracted from the FEA Results.

Table 29 Reaction Forces & Moment Reaction with respect to PC TCPH Co-ordinate System

Direction	Reaction Force	Moment Reaction
	[N]	[N.mm]
X Direction	10340	-5267.6
Y Direction	3763.3	9.3066
Z Direction	-211.97	-43.358
Total	11005	5267.8





Leg Length of Fillet L = 13 mm

Throat Thickness a = 0.707 x L = 9.191 mm

Profile of Fillet Weld = Rectangle

Length of the Fillet Rectangle H = 700 mm

Breath of the Fillet Rectangle B = 70 mm

Total Area of Weld resisting the force = 2 x Lx (H+B) = 20020 mm^2

Moment of Inertia :along X : Ix = 966142298 mm4

along Y : Iy =23294483 mm4

polar : Ig = 989436782 mm4

Maximum distance from Weld to COG on each axis

dx = 35 mm   dy = 350mm d_{norm} = 352mm

Stress in Tangential Direction σ(z) = $\left(\frac{Fz}{A}\right) + \left(\frac{Mx*dy}{Ix}\right) + \left(\frac{My*dx}{Iy}\right)$ MPa

Shear Stress in X direction τ(x) = $\left(\frac{Fx}{A}\right) + \left(\frac{Mz * dy}{Ig}\right)\ MPa$

Shear Stress in Y direction τ(y) = $\left(\frac{Fy}{A}\right) + \left(\frac{Mz * dx}{Ig}\right)\ MPa$

Shear Stress in normal direction to XY τ(h) = $\left(\frac{Fh}{A}\right) + \left(\frac{Mz * d}{Ig}\right)\ MPa$

Von Mises Stress $\sigma_{VM} = \sqrt{\sigma(z)^2 + 3 * (\tau(x)^2 + \tau(y)^2)}$

Stress Calculation Results

Stress	Value	Unit
σ(z) =	0.18	MPa
τ(x) =	0.01	MPa
τ(y) =	0.52	MPa
τ(h) =	0.52	MPa
σ_{VM} =	0.91	MPa

The stress values observed are negligible and acceptable with respect to the allowable values.

6.3.2.6. NO (100K REGEN) + VV ICE III

Table 27 summarizes Von Mises stress results. Figure shows the Von Mises stress distribution across TCPH

Table 30 Stress Result: NO (100K Regen) + VV ICE III

Location	**Linearized Membrane P_m [MPa]**	**Linearized Membrane + Bending $P_m + P_b$ [MPa]**
Ribs	28.76	135.44

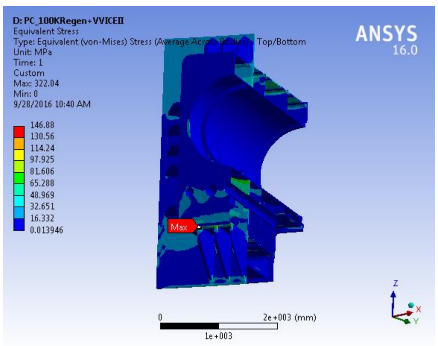


Figure 53 Von Mises Stress Plot

Maximum value of sum of principal stresses is 338.39 MPa.

6.3.2.7. NO (100K REGEN) + Cr ICE IV

Table 28 summarizes Von Mises stress results. Figure shows the Von Mises stress distribution across TCPH

Table 31 Stress Result: NO (100K Regen) + Cr ICE IV

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Ribs	36.79	153.76

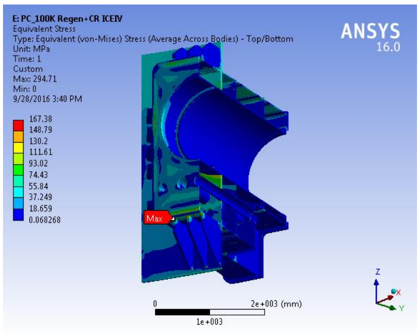


Figure 54 Von Mises Stress Plot

Maximum value of sum of the principal stresses is 393 MPa.

6.3.2.8. NO (100K REGEN) + Cr ICE III + SL-2

Table 29 summarizes Von Mises stress results. Figure shows the Von Mises stress distribution across TCPH

Table 32 Stress Result: NO (100K Regen) + Cr ICE III + SL-2

Location	Linearized Membrane P_m [MPa]	Linearized Membrane + Bending $P_m + P_b$ [MPa]
Ribs	5.8	26.5

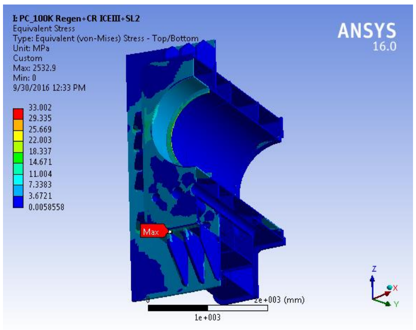


Figure 55 Von Mises Stress Plot

Maximum value of sum of the principal stresses is 70.9 MPa.

6.3.3. Structural Margin against Plastic Collapse & Local Failure

Table 30 & 31 gives the minimum structural margin for plastic collapse & local failure taking into account the stress ratio defined in 6.2 due to application of fixed boundary conditions.

Table 33 Structural Margin against Plastic Collapse

Sr. No.	Load Combinations	Linearized Stress Values		Stress Ratio		Max Linearized Values		Allowable Stress Values		Available Margin %	
		Pm	Pm+Pb	Pm	Pm+ Pb	Pm	Pm+Pb	Pm	Pm+ Pb	Pm	Pm+Pb
		MPa				MPa	MPa				
	CATEGORY I & II										
1	NO(100K Regen) + VDE II	26.47	124.87	1.54	1	40.7638	124.87	122.7	184	66.78	32.14
2	NO(100K Regen) + VV ICE II + VDE II	28.03	132.06	1.58	1	44.2874	132.06	138	207	67.91	36.20
3	NO(100K Regen) + VV ICE II	28.11	132.46	1.58	1	44.4138	132.46	138	207	67.82	36.01
4	VV Baking(100K Regen) + VV ICE II	28.27	133.11	1.58	1	44.6666	133.11	138	207	67.63	35.70
5	NO(100K Regen) + Cr ICE II	7.8	110.56	1	1	7.8	110.56	138	207	94.35	46.59
6		18.6	90.25	1	1	18.6	90.25	138	207	86.52	56.40
7	VV Baking(100K Regen) + Cr ICE II	7.8	110.41	1	1	7.8	110.41	138	207	94.35	46.66
8		18.7	90.9	1	1	18.7	90.9	138	207	86.45	56.09
9	NO(100K Regen) + SL-1	33.9	145.54	1	1	33.9	145.54	138	207	75.43	29.69
10	VV Baking(100K Regen) + SL-1	33.86	145.42	1	1	33.86	145.42	130	195	73.95	25.43
11	NO(300K Regen)	26.57	125.27	1.54	1	40.9178	125.27	122.7	184	66.65	31.92

12	NO(470K Regen)	26.57	125.27	1.54	1	40.9178	125.27	113	170	63.79	26.31
	CATEGORY III										
1	NO (100K REGEN) + VV ICE III	28.76	135.44	1.54	1	44.2904	135.44	165.6	248.4	73.25	45.48
2	NO (100K REGEN) + Cr ICE III	8.5	110.12	1	1	8.5	110.12	129.6	194.4	93.44	43.35
		19.98	88.57	1	1	19.98	88.57	165.6	248.4	87.93	64.34
3	NO (100K REGEN) + SMHV	1	1.9	1	1	1	1.9	146.4	219.6	99.32	99.13
		7.04	33.23	1	1	7.04	33.23	146.4	219.6	95.19	84.87
4	NO (100K REGEN) + Cr ICE III + SMHV	7.87	32.78	1	1.01	7.87	33.107 8	165.6	248.4	95.25	86.67
		6.4	28.78	1	1.01	6.4	29.067 8	165.6	248.4	96.14	88.30
5	NO (100K REGEN) + LOCA_PC III	17.45	187.3	1	1	17.45	187.3	129	194.4	86.54	3.65
		40.3	189.3	1	1	40.3	189.3	129	194.4	68.9	2.62
	CATEGORY IV										
1	NO (100K REGEN) + VV ICE IV	29.5	138.83	1.54	1	45.43	138.83	276	414	83.54	66.47
2	NO (100K REGEN) + Cr ICE IV	36.78	153.76	1	1	36.78	153.76	276	414	86.67	62.86
3	NO (100K REGEN) + Cr ICE III + SL-2	5.8	26.5	1.54	1.18	8.932	31.27	276	414	96.76	92.45

Table 34 Structural margin against Local Failure

Sr. No.	Load Combinations	Principal Stresses (MPa)			Sum of S1+S2+S3	Allowable Stresses	Criteria Met?	Margin %
		Maximum	**Middle**	**Minimum**				
		S1	**S2**	**S3**		**4Sm**		
	CATEGORY I & II							
1	Lifting/Assembly/RH + SL-1							
2	NO(100K Regen) + VDE II	169.74	92.94	49.86	312.54	490.8	YES	36
3	NO(100K Regen) + VV ICE II + VDE II	179.16	98.29	52.65	330.1	552	YES	40
4	NO(100K Regen) + VV ICE II	179.76	139.36	52.79	371.91	552	YES	40
5	VV Baking(100K Regen) + VV ICE II	178.02	98.97	53.03	330.02	552	YES	40
6	NO(100K Regen) + Cr ICE II	121.89	66.98	35.95	224.82	552	YES	59
7	VV Baking(100K Regen) + Cr ICE II	122.98	67.4	36.18	226.56	552	YES	59

8	NO(100K Regen) + SL-1	59.131	104.56	192.05	355.741	552	YES	36
9	VV Baking(100K Regen) + SL-1	59.131	104.56	192.05	355.741	520	YES	32
10	NO(300K Regen)	170.25	93.2	50	313.45	490.8	YES	36
11	NO(470K Regen)	170.25	93.2	50	313.45	452	YES	31
CATEGORY III								
1	NO (100K REGEN) + VV ICE III	182.52	100.77	53.95	337.24	664	YES	49
2	NO (100K REGEN) + Cr ICE III	35.7	62.7	104.69	203.09	518	YES	61
3	NO (100K REGEN) + SMHV	35.3	26.17	34.8	96.27	589	YES	84
4	NO (100K REGEN) + Cr ICE III + SMHV	40.83	22.3	16.8	79.93	589	YES	86
5	NO (100K REGEN) + LOCA_PC III	258	141	75.7	474.7	589	YES	19
CATEGORY IV								
1	NO (100K REGEN) + VV ICE IV	185.64	103.29	55.26	344.19	664	YES	48
2	NO (100K REGEN) + Cr ICE IV	62.33	115.72	215	393.05	664	YES	41
3	NO (100K REGEN) + Cr ICE III + SL-2	35	21.7	14.2	70.9	664	YES	89

6.3.4. Protection against collapse from buckling

Buckling is assessed with bifurcation analysis. TCPH outer shell is checked for buckling and inner cylinder is assessed as vertical plates are disconnected from it. Bifurcation of TCPH shell is performed for LOCA PC III (160 kPa on the shell). The first buckling mode gives a design factor obtained is 79. The minimum design factor for category III event is 13.42 and obtained factor is higher than the minimum factor.

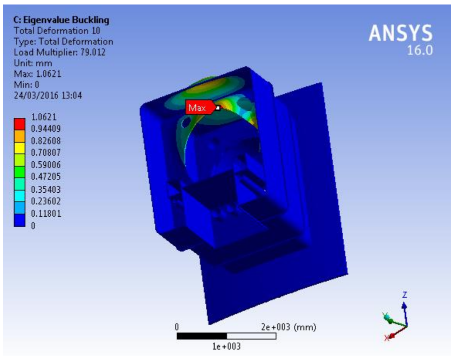


Figure 56 First buckling mode design factor=79

6.3.5. Thermal Stress Ratcheting Assessment

Ratcheting is assessed for thermal stress for worst thermal load cases. Thermal stress is shown for Cr ICE & 470 K Regen.

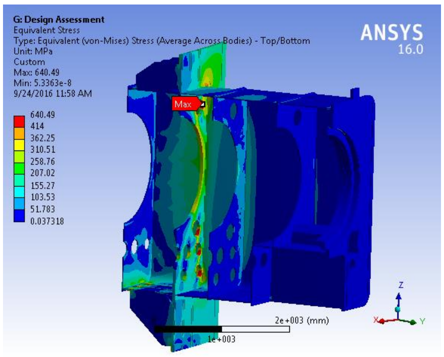


Figure 57 Thermal Stress: NO (100K Regen) + Cr ICEII

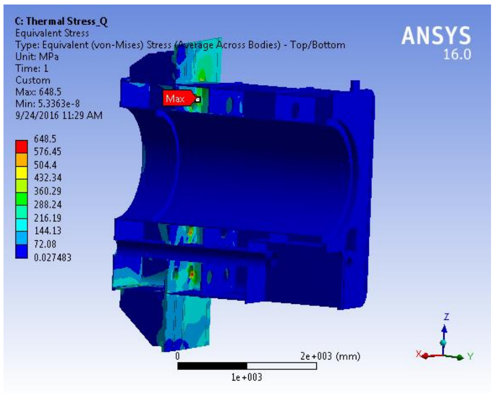


Figure 58 Thermal Stress: NO (100K Regen) + Cr ICEII

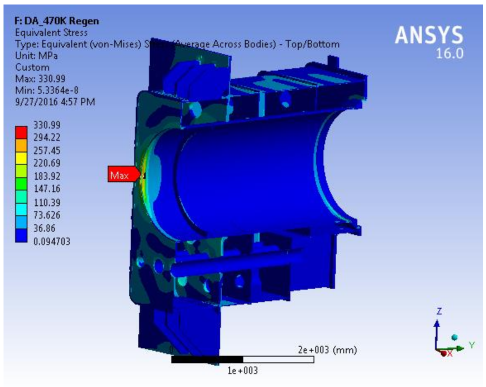


Figure 59 Thermal Stress: NO (470K Regen)

Table 35 Thermal Stress Ratcheting Assessment

	Load Combinations	**Location**							

Sr. No.			Allowable Stress 4Sm	Linearized Pm + Pb + Q	Stress Ratio	Max Linearized Pm+Pb+Q	Margin %	Elastic Criteria Met?	Margin Based on Elastic-Plastic Criteria Margin %
			MPa	MPa		MPa			
1	NO(100K Regen) + VDE II	Ribs	414	124.87	1.1	137.357	67	YES	
2	NO(100K Regen) + VV ICE II + VDE II	Cylinder	368	302.4	1.14	344.736	6	YES	79.52
		Ribs	414	86.28	1.14	98.3592	76	YES	
3	NO(100K Regen) + VV ICE II	Cylinder	368	301.31	1.14	343.4934	7	YES	79.52
		Ribs	414	86.67	1.14	98.8038	76	YES	
4	VV Baking(100K Regen) + VV ICE II	Cylinder	368	298.19	1.14	339.9366	8	YES	79.5
		Ribs	414	87.29	1.14	99.5106	76	YES	
5	NO(100K Regen) + Cr ICE II	Ribs	414	557.34	1	557.34	-35	NO	36.5
		Flange Hole(FH1)	414	375.96	1	375.96	9	YES	77.22
		Flange Hole(FH2)	414	400.74	1	400.74	3	YES	71.17
		FLANGE HOLE(FH3)	414	373.67	1	373.67	10	YES	69.62
		FLANGE HOLE(FH4)	414	443.76	1	443.76	-7	NO	61.3
		FLANGE	414	408.97	1	408.97	1	YES	74.7
		SHELL1 CORNER	414	540.09	1	540.09	-30	NO	30
		SHELL2 CORNER	414	371.49	1	371.49	10	YES	77.53
6	VV Baking(100K Regen) + Cr ICE II	Ribs	414	557.99	1	557.99	-35	NO	36
		FLANGE HOLE(FH1)	414	384.53	1	384.53	7	YES	76.12
		Flange Hole(FH2)	414	400.97	1	400.97	3	YES	71.24
		Flange Hole(FH3)	414	388.97	1	388.97	6	YES	68.71
		Flange Hole(FH4)	414	443.48	1	443.48	-7	NO	61

		FLANGE	414	408.43	1	408.43	1	YES	74.82
		SHELL1 CORNER	414	539.16	1	539.16	-30	NO	30
		SHELL2 CORNER	414	370.91	1	370.91	10	YES	77.63
7	NO(100K Regen) + SL-1	Side Rib Up	414	145.54	1	145.54	65	YES	
		Ribs	414	12.33	1	12.33	97	YES	
8	VV Baking(100K Regen) + SL-1	Side Rib Up	368	131.88	1	131.88	64	YES	
		Ribs	414	29.6	1	29.6	93	YES	
9	NO(300K Regen)	Ribs	414	78.7	1.1	86.57	79	YES	
		Shell 3	414	136.54	1.1	150.194	64	YES	
10	NO(470K Regen)	Ribs	340	43.47	1.1	47.817	86	YES	
		Cylinder	340	309.73	1.1	340.703	0	NO	75.68

6.3.6. Protection against Fatigue

The worst range of primary plus secondary + peak equivalent (Von Mises) stress is calculated for each case on ribs.

The worst loading history is obtained from the linearized stress in order to calculate the stress range in MPa based on the difference in two states. Ratio between peak stress and linearized stress is taken as 4. Fatigue usage fraction is calculated in table 34. The fatigue usage fraction 0.808 is below 1.

This fatigue usage fraction can be accepted based on the following conservative approach followed in the calculation in the fatigue usage fraction.

- The peak stress amplification factor used in the usage fraction calculation is 4 which is very conservative.
- The peak stress are calculated for geometry without making sub-model with fillet which would reduce the peak stresses.
- The load cycle assessed for fatigue is fictitious and the number of cycles for VV ICE, Cr ICE & SL-1 defined in the load specifications are higher than the probable cycles for the same.

Table 36 Worst Loading History for fatigue assessment of Ribs

Worst History_Ribs		ΔSn,k	state	Cycles							
				1	2	3	4	5	6	7	8
DW + Q100KREGEN +QCRICE+PCRICE	NO(100KREGEN)+ Cr ICE	344	8								
DW + QNO+Q100KREGEN+SL1	NO(100KREGEN)+ SL1	132	7								15
DW + QBK100KREGEN+ QVVICE+PVVICE	BK(100KREGEN)+ VVICE	98	6						15	50	

DW + QBK	BAKING	93	5					
DW + QNO+Q470KREGEN+QVVICE+ PVVICE	NO(470KREGEN)	93	4		500			
DW + QNO+Q100KREGEN	NO(100KREGEN)	93	3				1000	500
DW +QBK100KREGEN	BAKING (100KREGEN)	92	2			50000		
DW + QNO	NO	92	1	300				
DW	DW	35	0					

i/j			0	1	2	3	4	5	6	7	8
Value			139	369	370	371	371	371	394	526	1375
		number of cycles	800	51300	515	50065	1000	1000	15	50	15
0	139	800		163	163	163	163	163	170	133	682
1	369	51300			0	1	1	1	12	143	545
2	370	515				0	1	1	12	143	545
3	371	50065					0	0	12	143	545
4	371	1000						0	11	143	544
5	371	1000							11	143	544
6	394	15								148	533
7	526	50									669
8	1375	15									

Figure 60 Stress Range Matrix

Table 37 Fatigue Assessment; Ribs

Fictitious cycle	FU fictitious cycle								
	Sn,k	Sp,k	$K_{e,k}$	Salt,k	Y	X	Nk	nk	FU
1	682	2728	3.16	4307	625	1	20	15	0.754
2	148	592	1.00	296	43	4	20853	15	0.001
3	170	680	1.00	340	49	4	13089	15	0.001
4	163	652	1.00	326	47	4	15080	770	0.051
5	1	4	1.00	2	0	7	29445198	230	0.000
6	1	4	1.00	2	0	7	29445198	1000	0.000
7	1	4	1.00	2	0	7	29445198	49070	0.002
8	0	0	1.00	0	0	8	32929774	515	0.000
								sum	**0.808**

7. Conclusion

Structural integrity of TCPH is checked against criteria provided in ASME VIII D2 2010 including the verification of the following criteria:

- Plastic collapse;
- Ratcheting;
- Buckling;
- Fatigue.

With regards to ASME VIII D2 2010 the dual marked SS304/304L is classified in P-No. 8 Gr1. and Table7.1 gives the examination group 1b. For this group the weld joint efficiency is1.0.

So, the weld joint efficiency has not been introduced in allowable limits used in this report.

For plastic collapse, the minimum margin on membrane stress is 63% for NO (470K Regen) event and 2.6% on membrane plus bending stress for NO (100K Regen) + LOCA PC III. Results show a very low margin for Category III event nevertheless additional margin could be obtain according to the rules provided in paragraph 5.2.4 of ASME VIII D2 2010 Elastic-Plastic Stress Analysis method.

Fillet weld calculation shows negligible amount of stress, so fillet weld is sufficient to weld the shell rib to shell3.

The local failure is checked with a minimum margin of 19% for NO (100K Regen) + LOCA PC III.

Ratcheting is checked including the use of rules provided in paragraph 5.5.7 Ratcheting Assessment – Elastic Plastic Stress Analysis when the criteria given paragraph 5.5.6 Ratcheting Assessment – Elastic Stress Analysis is exceeded. The minimum margin for the verification of ratcheting is 30% for NO (100KREGEN) + CRICEII using the rules of Elastic Plastic Stress Analysis Method.

Maximum fatigue usage fraction for the ribs is 0.808. This very high ratio has been determined with regards to the rules provided in paragraph 5.5.2.3 Fatigue Analysis Screening criteria, Method A with the additional rules given in paragraph 5.5.3 Fatigue Assessment – Elastic Stress Analysis and Equivalent Stresses. The peak stress has been calculated including a stress amplification factor of 4. The value of this peak stress could be reduced thanks to a local sub model of ribs including appropriate fillet in order to reduce the fatigue usage fraction.

As the structural design criteria in accordance with [1] is met, it is recommended to accept the changes proposed based on manufacturing feasibility.

8. References

[1] ASME Section VIII Division 2 2013.

[2] Guideline for Structural Analyses; ITER_D_35BVV3 v1.1

[3] TCPH System Load Specification; ITER_D_P8UMCD v1.6

[4] Summary of material data for Structural Analyses of the ITER Cryostat; ITER_D_3F863L v1.6

[5] IS 24.CR-31-001 Interface between Torus Cryopump (PBS31) and Torus Cryopump Housing; ITER_D_3VVXWS v2.6

[6] Allowable values and limits in service level C and D for ITER mechanical components, ITER_D_3G3SYJ_v3.1

[7] ANSYS, Inc. Release 16.0 Documentation for ANSYS

[8] TCPH_Structural_Analysis_Q4P42N_v2_0