FATIGUE ANALYSIS OF ITER 6-100K CRYOLINES

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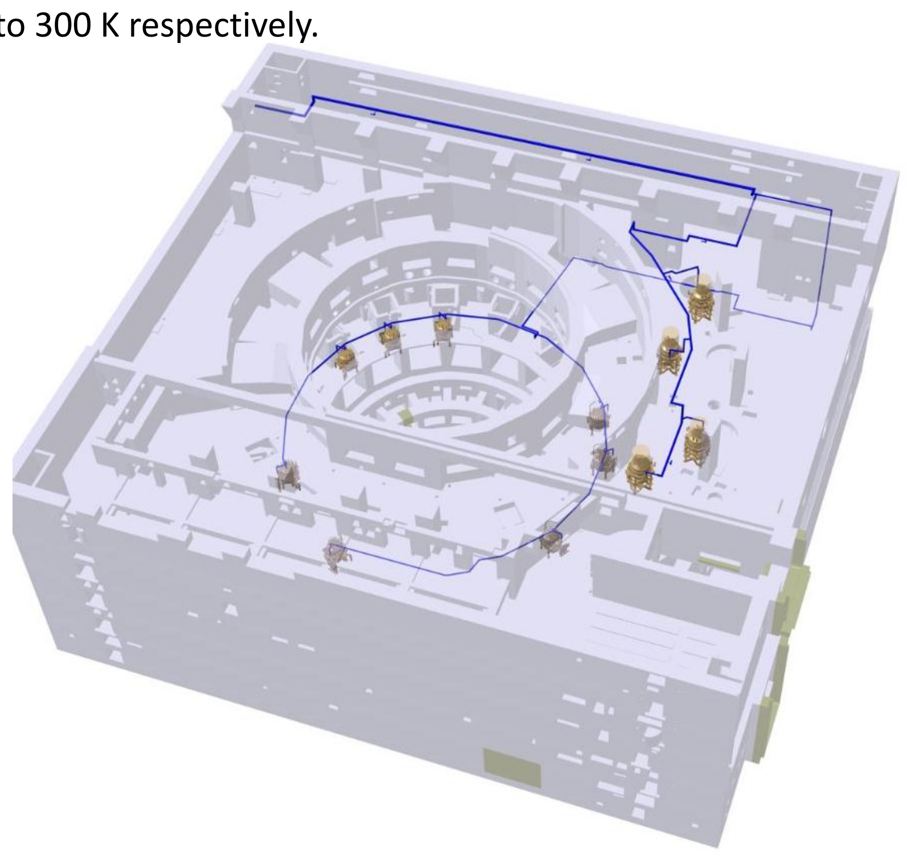
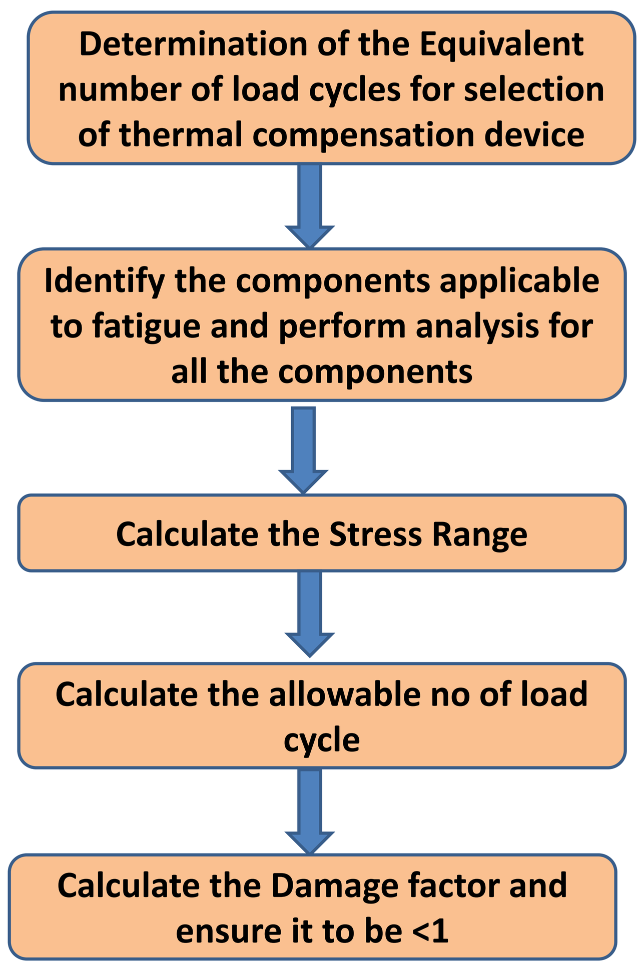
INTRODUCTION

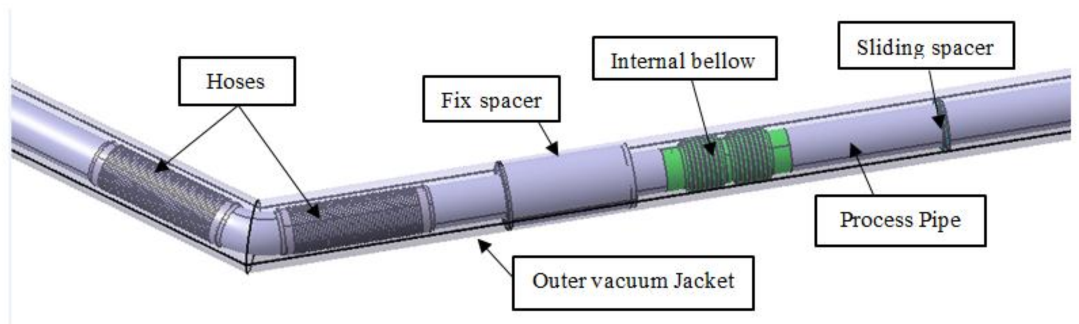
The evacuation of the torus and cryostat of the experimental fusion reactor ITER relies on cryo-pumps located at B1 level of the ITER tokamak building. During operational phases, these pumps need to be regenerated through cold and warm helium recovered via vacuum jacketed cryogenic transfer line called as 6-100 K regeneration line. The function of 6-100 K regeneration line is to collect the cold helium from cryopumps of neutral beam, torus as well as cryostat in Tokamak Building and send it to helium cold box. Pressure and temperature for 6-100 K regeneration line varies from 0.1 MPa to1.0 MPa and 6 K to 300 K respectively.



Cyclic changes in pressure, temperature and external loading can cause damage by fatigue cracking. As per load specifications for ITER cryolines [1] the total number of load cycles applicable to 6-100 K regeneration line is greater than 1000. Hence, detailed fatigue analysis is performed for 6-100 K regeneration line in steps as shown in Figure-1. As shown in Figure-2, 6-100 K regeneration line consists of different components i.e. (a) Process pipe (b) Fix spacers (c) Sliding spacers (d) Thermal compensation devices (Hoses and Bellows) enclosed within the vacuum jacket to transfer the helium at variable cryogenic temperature. Process pipe sizes for 6-100 K regeneration line ranging from DN 50 to DN 150 with corresponding outer vacuum jacket ranging from DN 100 to DN 250. The fatigue calculations have been performed to check the piping system and internal supports in fatigue failure for 6 – 100 K regeneration line. For fatigue calculations, the stress-life method has been used.



Pressure Fluctuation Criteria : Detailed fatigue analysis has been performed as the pressure fluctuations superimposed on the service pressure exceeds 10% of the allowable operating pressure [2].



Input Condition: Pressure and temperature range as shown in Table have been used to extract the forces and moments on internal components from flexibility analysis of process pipe.

No. of cycles in machine lifetime (20 years)	Range	Total no of cycles to be considered
Pressure cycle		
Full cycle	0.1-1.0-0.1 MPa	150
Small range pressure cycle	0.1-0.2-0.1 MPa	Branch line : 75000 Main line and manifolds : 490000
Temperature cycle		
Full cycle	6-300-6 K	1000
Small range temperature cycle	6-100-6 K	Branch line : 75000 Main line and manifolds : 490000

REFERENCE

[1] ITER load specifications (ITER_D_3XUCRS)

[2]BS EN 13480-3:2002 Metallic industrial piping - Part 3: Design and calculation

[3] BS EN 13445-3:2002 Unfired pressure vessels - Part 3: Design

APPROACH FOR FATIGUE CALCULATION

As the 6-100 K regeneration line is constructed with different components, all components have to be checked for fatigue failure. All components are made of austenitic stainless steel except sliding spacers of process pipe.

Process Pipe: The stress analysis is carried out at different pressure and temperature as shown in Table-1. The approach for calculating the allowable number of load cycles is shown below.

Thermal Compensation Devices: Thermal compensation devices are used in the process pipe to take care of thermal contraction and expansion. Axial bellows are used to take care of axial contraction and hoses are used to take care of lateral displacement. These components are designed for 4000 cycles as per the manufacturer's data sheet which are higher than total required fatigue cycles as shown in Table .

Fix Spacer: To validate the fix spacer for fatigue cycle, the reaction forces and moments have been extracted by performing the flexibility analysis using CAESAR® software considering the pressure and temperature for different fatigue cycles given in Table 1. The same has been used to extract the stress for different cycle using ANSYS 15.0® software. The details of calculations performed for fix spacer as shown below.

Sliding Spacer: Internal sliding spacers are made of G-10 CR material. The S-N data for this material is not available. Hence these components are designed considering higher factor of safety to avoid fatigue.

METHODOLOGY FOR FATIGUE CALCULATIONS

This section covers the methodology of fatigue calculation for process pipe, thermal compensation devices and fix spacers of 6-100 K regeneration line.

Analysis of the Process Pipe [PP] For Applicable Fatigue Load Cycles: Flexibility analysis has been carried out for different pressure and temperature as per Table 1 to extract maximum and minimum stress. After getting maximum and minimum stress for the particular fatigue cycle, the stress range and allowable no. of cycles have been calculated as shown in Table .

Description	Equations/ Symbol	Full Range Pressure	Small Range Pressure	Full Range Temperature	Small Range Temperature
Maximum stress (MPa)	σ_{max}	9.33	3.69	99.03	99.03
Minimum stress (MPa)	σ_{min}	2.98	2.98	4.48	87.5
Stress range $\Delta\sigma_f$ (MPa)	$\sigma_{max} - \sigma_{min}$	6.35	0.71	94.55	11.53
Correction factor					
Thickness correction Factor f_{ew}	According to EN 13445-3	1			
Temperature correction Factor f_t		1			
Overall correction factor f_w		1			
Stress range $\Delta\sigma_f/f_w$ (MPa)	$\Delta\sigma_f/f_w$	6.35	0.71	94.55	11.53
Allowable no. of cycles for Full Range Pressure Cycle	$N = \frac{C_1}{\left(\frac{\Delta\sigma}{f_w}\right)^{m_1}}$	≈ 1E8	≈ 1E8	≈ 7.75E4	≈ 1E8

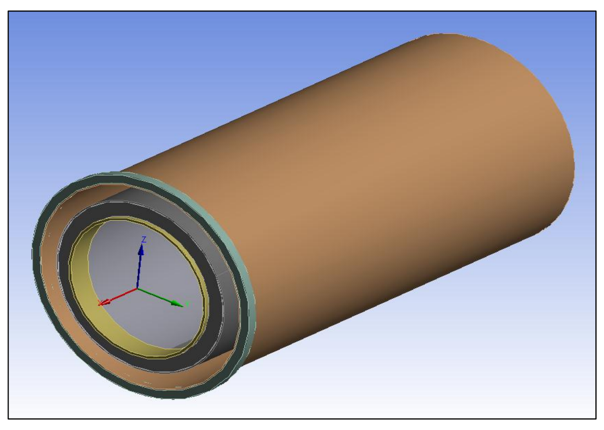
Miner's Rule [3]: After calculating allowable no. of cycles, Damage factor D for given no. of cycles has been calculated according to Miner's rule

Description	Equations/ Symbols	Value
Full range pressure cycles	n1	150
Small range pressure cycles	n2	490000
Full range temperature cycles	n3	1000
Small range temperature cycles	n4	490000
Allowable no. of cycles for Full Range Pressure Cycle	N1	≈ 1E8
Allowable no. of cycles for small Range Pressure Cycle	N2	≈ 1E8
Allowable no. of cycles for Full Range Temperature Cycle	N3	≈ 7.75E4
Allowable no. of cycles for Small Range Temperature Cycle	N4	≈ 1E8
Damage Factor D	$\sum_{1}^{4} \frac{ni}{Ni}$	≈ 0.022

Equivalent Fatigue Cycle for Thermal Compensation Devices: For pressure cycles and temperature cycles , an equivalent number of full load cycles have been determined according to EN 13480-3 :2002

Main Line	Pressure Cycle	374 Cycles
	Thermal Cycle	2637 Cycles
Branch Line	Pressure Cycle	184 Cycles
	Thermal Cycle	1247 Cycles

Analysis of the Fix Spacer for Applicable Fatigue Load Cycles: For the fatigue calculations of fix spacer, the forces and moments have been extracted from flexibility analysis by considering different pressures and temperatures given for different fatigue cycle according to Table 1. Forces and moments for different pressure and temperature are shown in Table.



Load Case	Fx (N)	Fy (N)	Fz (N)	Mx (N.m)	My (N.m)	Mz (N.m)
Pressure 0.1 MPa	2708	5	-146	2	26	-2
Pressure 0.2 MPa	5414	5	-146	2	26	-2
Pressure 1 MPa	27060	5	-146	2	26	-2
Temperature 6 K	-9559	-248	-169	241	14	132
Temperature 100 K	-8444	-218	-166	215	15	116
Temperature 300 K	-202	5	-146	27	26	-3

Using forces and moments for different pressure and temperature, the analysis of fix spacer has been performed in ANSYS 15.0 to extract maximum and minimum stresses for the particular fatigue cycle with effect of structural discontinuity and notch effect. After getting maximum and minimum stress for the particular fatigue cycle, the stress range and allowable no. of cycles have been calculated.

Miner's Rule [3]: After calculating allowable no. of cycles, Damage factor D for given no. of cycles has been calculated according to Miner's rule.

Description	Equations/ Symbols	Value
Full range pressure cycles	n1	150
Small range pressure cycles	n2	490000
Full range temperature cycles	n3	1000
Small range temperature cycles	n4	490000
Allowable no. of cycles for Full Range Pressure Cycle	N1	≈ 8.67E04
Allowable no. of cycles for small Range Pressure Cycle	N2	≈ 1E8
Allowable no. of cycles for Full Range Temperature Cycle	N3	≈ 1.75E6
Allowable no. of cycles for Small Range Temperature Cycle	N4	≈ 1E8
Damage Factor D	$\sum_{1}^{4} \frac{ni}{Ni}$	≈ 0.012

CONCLUSION

From the calculations, it can be observed that the allowable no. of cycles for different load cycles is very high; therefore, the damage factor D is less than 1. It fulfills the design acceptance criteria mentioned in code. There will be no damage due to fatigue in fix spacers, thermal compensation devices and process pipe.