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Stress and Seismic Calculation of HTR-10 Primary Loop Pressure Relief System

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Abstract

Steam Generator (SG) heat transfer tubes of 10MW High Temperature Gas Cooled Reactor (HTR-10) are protective screens between the primary loop of helium and the secondary loop of water and steam. Water and steam will enter into the primary loop from the secondary loop if SG heat transfer tubes rupture, which is one of reasons leading to increase of the primary loop pressure. Function of the primary loop pressure relief system (PLPRS) is to reduce pressure of the primary loop so that the pressure not to exceed the designed maximum pressure value and to guarantee the integrity of pressure boundaries by discharging part of helium. PLPRS is connected to the lower head of SG pressure vessel. The piping part between the PLPRS nozzle of SG and the safety relief valves constitutes one of the primary loop pressure boundaries. If the pipe of PLPRS ruptures, helium of the primary loop will lose. This might cause unplanned reactor shut down. So it is important to guarantee the integrity of PLPRS. This paper presents stress and seismic calculation and analysis of PLPRS. Results show that stress distributions satisfy the requirements of ASME codes for Classes 1 components.

Key words: high temperature gas cooled reactor, primary loop pressure relief system, pipe and stress

1. Introduction

10MW High Temperature Gas Cooled Reactor (HTR-10) was constructed in INET of Tsinghua University and reached the first full power operation in January 26, 2003. Steam Generator (SG) heat transfer tubes of HTR-10 are protective screens between the primary loop of helium and the secondary loop of water and steam. Water and steam will enter into the primary loop from the secondary loop if SG heat transfer tubes rupture, which is one of reasons to lead to increase of the primary loop pressure.

Function of the primary loop pressure relief system (PLPRS) is to reduce pressure of the primary loop so that the pressure does not exceed the designed maximum pressure value of the primary loop and to guarantee the integrity of the primary loop pressure boundaries by discharging part of helium in the primary loop[1].

PLPRS is connected to the lower head of SG pressure vessel. The piping part between the PLPRS nozzle of SG and the safety relief valves constitutes one of the primary loop pressure boundaries. If the pipe of PLPRS ruptures, helium of the primary loop will lose. This might cause unplanned reactor shut down. So it is important to guarantee the integrity of PLPRS. This paper presents stress and seismic calculation and analysis of PLPRS by use of PIPESTRESS. Results show that stress distributions satisfy requirements of ASME codes for Classes 1 components.

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2. PLPRS and its working environment

Figure 1 is the layout of PLPRS[2]. Origin of the system is located in the cold end of the steam generator. From the lower penetrative part as shown in figure 1, the system becomes into three branch circuits. The first branch circuit is one part of the helium purification system. The second branch circuit and the third branch circuit are called as No.1 branch circuit and No.2 branch circuit. Pressure responses of No.1 branch circuit and No.2 branch circuit are different. Two safety relief valves are installed in parallel in No.1 branch circuit and No.2 branch circuit, respectively, to guarantee that the system could still work in case that one of the valves could not be opened. After the safety valve in No.1 branch circuit is opened, the safety valve in No.2 branch circuit is not opened if the pressure of the system does not increase further. The purpose for this is to prevent the primary loop from suffering from great interference. The response pressure of the safety valve in No.1 branch circuit is 3.5MPa, while the response pressure of the safety valve in No.2 branch circuit is 3.72MPa. All the two branch circuits have the discharge capacity of 85l/s. There are two electric power shutoff valves installed before safety valves, which will be shut down if the safety valve does not reseat. Two hand power shutoff valves are located between the safety valves for testing safety valves.

After the safety valves, there is a rupture disc device. In each of two branch circuits, safety valve, rupture disc device and the pipe between them form en enclosed container. When the safety valve leaks, pressure of the container will rise. Two side tubes are connected to the pipe between the safety valve and the rupture disc device; through one of them the pressure of the container is monitored and through the other helium in the container is discharged. During the normal operation of the reactor, when the safety valve leaks, a manometer will have indications. If leakage amount of the safety valve is still acceptable, but the pressure in the container exceed a certain value, the electric power shutoff valve installed in one of the two side tubes will be opened to discharge the helium in the container. The design pressure of the PLPRS piping system is 3.5MPa, the design temperature 300 ^{o}C.

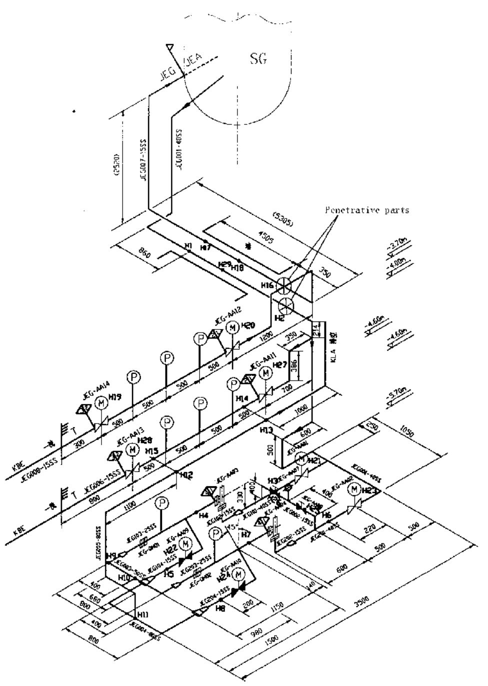

Figure 1 Layout of PLPRS

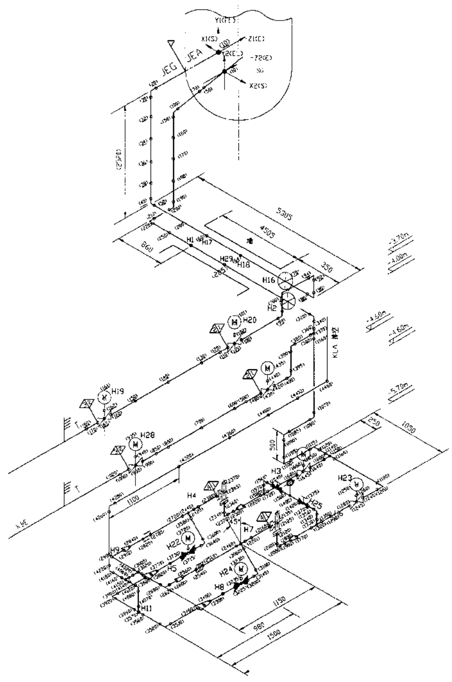

Figure 2 FEM model

3. Mechanical properties and other parameters of pipes, valves and rupture disc devices

The pipe materials of the PLPRS piping system are all stainless steel 321[1-4]. Mechanical properties and other parameters are shown in table 1, table 2 and table 3.

Table 1 Mechanical properties of stainless steel 321[4]

Temperature (^{0}C)	40	300
Allowable stress S_h (MPa)	S_c=138	114
Yield stress S_{yh} (MPa)	S_{yc}=207	127
Young's modulus E_h (MPa)	E_c=195	175
Coefficient of linear thermal expansion LTE (10^{-3}m/m)	0	4.67

Table 2 Geometry parameters of pipes

Material	321			
External diameter O.D. (mm)	22	34	48	89
Wall thickness (mm)	2.8	3.5	4	5.5
Weight of pipe (kg/m)	1.35	2.67	5.61	11.5
Thickness of the insulation layer (kg/m)	40	40	40	40
Weight of insulation layer (kg/m)	2.94	4.56	8.12	14.96

Table 3 Geometry parameters of valves and rupture disc devices

Valve and rupture disc	Length (m)	Height of gravity center (m)	Weight of valves (kg)	Weight of electric driven device
JEG-AA01, JEG-AA02	0.241	0.414	86.8	43
JEG-AA05, JEG-AA06	0.160		6	
JEG-AA07, JEG-AA08	0.165	0.1235	17.9	89
JEG-AA09, JEG-AA10, JEG-AA11, JEG-AA13	0.165	0.315	46	28
Rupture disc	0.100		6	

4. Stress calculations

4.1 FEM model[3]

According to the distribution of the fixed supports shown in figure 1, the PLPRS piping system was considered as comprising three parts. The first part was between the PLPRS nozzle of SG and the first fixed support H_2. The second part was between the fixed support H_2 and the fixed supports H_4 and H_7. The third part was between the fixed support H_4 and H_7 and the supports H_{13}.

The helium purification system consists of the helium input piping system and the helium output piping system. According to distribution of the fixed supports shown in figure 1, the helium output piping system was considered as comprising two parts, one was between the helium purification nozzle of SG and the fixed support H_{19}, the other was between the fixed support H_{19} and the interface T. The helium input piping system was also considered as comprising two parts. One was between the PLPRS nozzle of SG and the fixed support H_2, while the other was between fixed support H_2 and the interface T.

The discrete piping system was obtained by use of pipe elements, in which one pipe element was connected to the adjacent pipe elements by nodes. Mass of elements was considered to be concentrated in nodes. Valves and the rupture disc devices were simulated by rigid elements. The FEM model is shown in figure 2.

4.2 Loads

Loads applied to the PLPRS piping system were internal pressure, gravitational force, thermal expansion force, propulsive force caused when the safety valve discharge, seismic loads or combination loads above, as shown in table 4.

1) Continuous loads
   Continuous loads were internal pressure, weight and restrain counterforce from supports. Internal pressure in the PLPRS pipe was determined by different load cases. Weight of the PLPRS pipe system included that of pipe itself and thermal insulating layer. Material of the thermal insulating layer was silicate cotton, specific density of which was 207kg/m^3, thickness of which was 40mm. The thermal insulating layer was laid down the pipe between the PLPRS nozzle of SG and safety valves.
2) Propulsive force
   Discharge system of PLPRS was an enclosed type discharge system. The propulsive force caused when the safety valve discharged was calculated according to the method supplied in Appendix O[4]. When the safety valve discharged helium into an enclosed type piping system, during the period of stable discharge, forces exerted on the piping system are of self-balance, so there was no remarkable bending moment imposed on the piping system. The stable force was only exerted on the outlet of PLPRS, not on the safety valve.
3) Seismic loads
   From section 4.1, it is known that the PLPRS piping system was considered as consisting of three parts. Seismic inputs of the first part were from the PLPRS nozzle of SG and the fixed support H_2; while seismic inputs of the second part and the third part were from the relevant fixed supports.

Table 4 Load conditions

Loads		Pipe of the helium purification system	Pipe of PLPRS
Design conditions	Design pressure (MPa)	4.0	4.0
	Design temperature (^{o}C)	300	300
	Mechanical loads	Weight and other continuous loads	
Level A and level B	Pressure (MPa)	3.0	3.0
	Temperature (^{o}C)	250	250
	Mechanical loads	Weight, other continuous loads and accidental loads including propulsive force and seismic load OBE	
Level C	Pressure (MPa)	3.0	3.0
	Temperature (^{o}C)	250	250
	Mechanical loads	Weight, other continuous loads and accidental loads including propulsive force and seismic load SSE	
Level D	Pressure (MPa)	3.0	3.0
	Temperature (^{0}C)	250	250
	Mechanical loads	Weight and limit accidental load cases	
Experimental load case (hydraulic test)	Pressure (MPa)	5.0	5.0
	Temperature (^{o}C)	20	20
	Mechanical loads	Weight, other continuous loads	

Seismic inputs of the first part of the helium output piping system was from the helium purification system outlet nozzle of SG and the fixed support H_{16}; while those of the second part of the helium output piping system was from the fixed support H_{16} to the interface T. Seismic inputs of the first part of the helium input piping system of the helium purification system was from the PLPRS nozzle of SG and the fixed support H_2, and those of the second part was from the fixed support H_2.

The acceleration values of the seismic inputs were determined as follows. Reference 5 supplied acceleration values of different points. But the positions of the seismic input supports of PLPRS and the helium purification system piping system were not just as same as those of the points in reference 5. In such cases, the greater values of the nearest point before the seismic input support and the nearest point after the seismic input support were selected as the seismic input acceleration value of the support. For example, the height mark of the fixed support H_2 was –4.0m, but reference 5 only supplied the acceleration spectrums of the points height mark of which were –6.0m and –0.0m, respectively, and values were OBE (a_{xi}=0.75g, a_{y1}=0.78, a_{z1}=0.66g; and a_{x2}=0.9g, a_{y2}=1.05g, a_{z2}=0.72g). Therefore, the acceleration values were OBE (a_{xi}=0.9g, a_{y1}=1.05, a_{z1}=0.72g).

Diameter of the PLPRS piping system was less than 60mm. So stress calculation was conducted by equivalent static load method according to reference 6. The equivalent static loads of the systems were obtained by multiplying the acceleration values in table 5 by 1.5 times weight of pipes. Values obtained were used as input acceleration values in FEM calculations.

Table 5 Seismic input acceleration values (ratio of damping is 0.2%)

Positions	Acceleration (g) Types	X	Y	Z
PLPRS nozzle of SG	OBE	2.60	2.50	2.60
	SSE	2.60	2.45	2.50
The helium purification system outlet nozzle of SG	OBE	2.55	2.60	2.45
	SSE	2.60	2.50	2.50
First fixed support H_2	OBE	0.90	1.05	0.72
	SSE	1.20	1.20	1.20
First fixed support H_4 and H_7	OBE	0.90	1.20	0.65
	SSE	1.20	1.20	1.10
Fixed support H_{14}	OBE	0.90	1.20	0.65
	SSE	1.20	1.20	1.10
Fixed support H_{16}	OBE	0.90	1.05	0.72
	SSE	1.20	1.20	1.10

4.3 Displacement boundary conditions

Suppose that position of the reactor pressure vessel axis does not change. Then expansion of the reactor pressure vessel and the hot gas duct makes the position of the SG pressure vessel axis change. Linear expansion coefficient of the two pressure vessels and the hot gas duct was $13.6\times10^{-6}/^{o}C$ at the temperature of $325^{o}C$. Therefore, the displacement of the SG pressure vessel axis was 30.36mm. According to the position of the PLPRS nozzle in SG, displacement components of the nozzle $\bullet_x$= 3.074mm, $\bullet_y$= -5.784mm, $\bullet_z$= -25.97mm, where the directions of x, y, z were from west to east, vertically upward and south to north, respectively.

4.3 Stress calculations

Calculation of the helium output piping system of the helium purification system was carried out in two parts as stated in section 4.1. The first part was from the helium purification system outlet nozzle of SG to the fixed support H_{16}. The second part was from the fixed support H_{16} to the interface T. The first part of the helium input piping system of the helium purification system shared same pipe with PLPRS, so the helium input piping system and the PLPRS piping system were calculated together. Calculation of the PLPRS piping system was conducted in three parts. The first part was from the PLPRS nozzle of SG to the fixed support H_2. The second part was from the fixed support H_2 to the fixed supports H_4 and H_7. The third part was from the fixed supports H_4 and H_7 to the interface.

The input files of PIPESTRESS could be gotten by use of geometric conditions (length, outer diameter and wall thickness of pipe, etc.), material properties (Young's modulus, allowable stress, linear thermal expansion coefficient, etc.), load cases and displacement boundary conditions. Starting the code, three force components and moment components in nodes could be obtained. Resultant moments were obtained by combining the moments under different load cases. The node stress could be gotten by resultant moments being divided by section module and multiplied by relevant principal stress index (NB-3680) or stress amplification coefficients (NB-3673.2)[7]. If the node stresses satisfied the requirements of equations (8), (9), (10) and (11) in NB-3650[7], that is, maximum stress ratios between the maximum stress and the relevant limit stress were less than 1, it could be said that design of the piping system was acceptable.

5. Calculation results and analysis

Table 6 gives stress ratios. In the table, values in the brackets are node numbers of the FEM model, where the maximum stress ratios equal the maximum stress divided by the stress limit. From table 6, it can be seen that all the stress ratios in these nodes are less than 1, the ratios satisfy the requirements for class 1 components in ASME section III according to reference 7, and so the PLPRS piping system is safe.

Table 6 Stress ratios

Load cases	Stress limits	Maximum stress ratios				
		Helium output piping system of the helium purification system		PLPRS piping system		
		Part 1	Part 2	Part 1	Part 2	Part 3
Design condition	$1.5S_h$[7]	0.302 (7)	0.258 (110)	0.192 (300)	0.239 (1540)	0.247 (3020)
Level A and level B	$1.8S_h$[7]	0.931 (7)	0.560 (110)	0.591 (300)	0.482 (420)	0.409 (3020)
Level C	$2.25S_h$[7]	0.783 (7)	0.508 (110)	0.565 (300)	0.505 (420)	0.472 (3020)
Level D	$3.0S_h$[7]	•	•	•	•	•
Thermal expansion load case	$3.0S_Y$[7]	0.642 (40)	0.496 (160)	0.622 (200)	0.981 (900)	0.927 (3730)
Experimental load case	$1.35S_Y$[7]	0.115 (7)	0.137 (110)	0.145 (300)	0.171 (370)	0.185 (3020)

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