Piping Flexibility Analysis of the Primary Cooling System of TRIGA 2000 Bandung Reactor due to Earthquake

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A B S T R A C T

Earthquakes in a nuclear installation can overload a piping system which is not flexible enough. These loads can be forces, moments and stresses working on the pipes or equipments. If the load is too large and exceed the allowable limits, the piping and equipment can be damaged and lead to overall system operation failure. The load received by piping systems can be reduced by making adequate piping flexibility, so all the loads can be transmitted homogenously throughout the pipe without load concentration at certain point. In this research the analysis of piping stress has been conducted to determine the size of loads that occured in the piping of primary cooling system of TRIGA 2000 Reactor, Bandung if an earthquake happened in the reactor site. The analysis was performed using Caesar II software-based finite element method. The ASME code B31.1 arranging the design of piping systems for power generating system (Power Piping Code) was used as reference analysis method. Modeling of piping systems was based on the cooling piping that has already been installed and the existing data reported in Safety Analysis Reports (SARs) of TRIGA 2000 reactor, Bandung. The quake considered in this analysis is the earthquake that occurred due to the Lembang fault, since it has the Peak Ground Acceleration (PGA) in the Bandung TRIGA 2000 reactor site. The analysis results showed that in the static condition for sustain and expansion loads, the stress fraction in all piping lines does not exceed the allowable limit. However, during operation moment, in dynamic condition, the primary cooling system is less flexible at sustain load, ekspansi load, and combination load and the stress fraction have reached 95,5%. Therefore a pipeline modification (rerouting) is needed to make pipe stress does not exceed the allowable stress. The pipeline modification was carried out by applied a gap of 3 mm in the X direction of the support at node 25 and eliminate the support at the node 30, also a gap of 3 mm was applied in X and Z directions of the support at the node 155. The axial force (F_Y) that occurred in the pump outlet nozzle (dia. 4 in.) of PriPump line have also exceeded the allowable limit that lead to the pump nozzle failure during an earthquake of Lembang fault. The modifications is necessary to be applied on the cooling system for PriPump line so the nozzle would not receive the force that exceed the allowable limits. The modification can be done by removing the support at node 105 and node 135 so the primary cooling system piping of Bandung TRIGA 2000 reactor would be safe to operate during an earthquake originated from Lembang fault.

INTRODUCTION

Indonesia often experience many disasters, including tsunamis, earthquakes, landslides, volcanic eruption, and flood. In Bandung, small vibration due to the earthquake are some times felt, therefore serious attention is needed, especially for vital installations building such as a nuclear reactor and the other supporting systems, so the operation failure can be avoided. The unpredictable failure of a nuclear installation, especially due to the earthquakes can result in fatality, since various radioactive materials can possibly be released into the environment. The earthquake impact to the important installations, such as nuclear reactor, therefore is necessary to be studied for the safety purpose. In this research, the earthquake impact to the primary cooling system of Bandung TRIGA 2000 reactor owned by BATAN (Badan Tenaga Nuklir Nasional) was studied. The Bandung TRIGA 2000 reactor has been built since 1965 and used for

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research, training, and radioisotopes production, so it is relevance to be apprehensive on the operation failure following the high magnitute of earthquake in Bandung. The primary cooling system of TRIGA 2000 reactor is an important system that consists of pumps, heat exchangers and piping in which coolant fluid remove the energy in the form of heat from the reactor to be released to the environment. In the case of earthquake happened the equipments will be overloaded, due to the load in the form of force, moment and stress, which is originated from the primary coolant system piping to the equipment nozzles. If the overloading exceeds the allowable load, the failure of equipment nozzles can be happened and lead to the radioactive materials release into the environment.

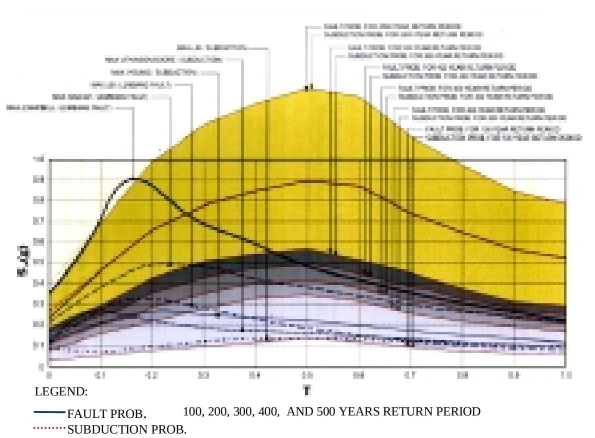

Fig. 1. Eearthquake spectrum of Bandung TRIGA 200 reactor site.

In this study the stress analysis of primary coolant pipe system of TRIGA 2000 Reactor Bandung was carried out to predict the load that occured in the equipment nozzle during an earthquake at the reactor site.

The analysis was performed using Caesar II finite element method-based software. The ASME B31.1 code that arranges the design of piping systems for power generating system (Power Piping Code Stress) was used as analysis reference. Those piping systems model was applied to the piping system already installed at Bandung TRIGA 2000 reactor and Safety Analysis Reports (SARs) data. The analysis was separately carried out for 3 sections of the pipeline, those are from the pump nozzle to the heat exchanger nozzle, from heat exchanger nozzle to the reactor tank, and from the reactor tank to the pump nozzles. The quake considered in this analysis is the earthquake that occurred due to Lembang fault, because in 2000 the Seismic Hazard Analysis of the Bandung TRIGA 2000 Reactor Site have been performed and the results showed that the largest earthquake is contributed by Lembang fault, with the largest Peak Ground Acceleration (PGA), is at the Bandung TRIGA 2000 reactor site, as shown in earthquake spectrum (Fig. 1) [1,2,3,4].

From the analysis results it is expected that the primary cooling system piping of Bandung TRIGA 2000 reactor would be remain in the safe condition during the operation at the earthquakes in Bandung.

THE COOLING SYSTEM OF BANDUNG TRIGA 2000 REACTOR

The cooling system of TRIGA 2000 reactor consists of primary cooling system, which transfers heat from the reactor vessel to a heat exchanger and secondary cooling system, which transfers heat from heat exchanger to the cooling tower to discharge the heat into the air. Both cooling systems use water as the working fluid. Block diagram of the TRIGA 2000 reactor cooling system in Fig. 2 shows that the primary cooling system piping consists of pipes and equipment, those are tanks, pumps and heat exchangers. The pipeline starts from the primary pump outlet nozzle into the nozzle of heat exchanger inlet, from the nozzles of heat exchanger outlet toward the reactor tank, and from the reactor tank to the nozzle the primary pump inlet.

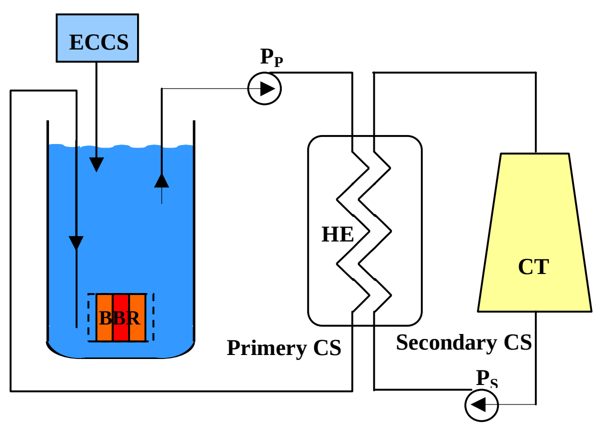

Fig. 2. Block diagram of Bandung TRIGA 2000 reactor cooling system.

During the reactor operation, the piping of primary cooling system will experience a load attribute to working fluid inside the pipe, pipe weight itself, the working temperature, pressure and other load that come from the outside of the pipe such as earthquake, wind and others. Such loads will arise the stress on piping systems and can cause a system failure if the stress occured exceeds the allowable stress, hence a pipe stress analysis is needed.

EMPIRICAL EQUATIONS OF ASME CODE B 31.1

A code for power piping, ASME B31.1.[5, 6], is used as piping analysis reference. This code includes empirical formulas to be applied to the stress of sustain load, expansion load, combination of sustain and expansion (operations) load, and occasional load.

Sustained stress

The sustained stress, S_{ls}, is the algebraic summation of the longitudinal pressure stress and longitudinal sustained weight stress. S_{ls} is calculated using the following code equation :

$$S_{ls} = \left(\frac{PD_o}{4t_n}\right) + 1000\left(\frac{0.75\, i\, M_a}{Z}\right) \le 1.0\, S_h \quad (1)$$

where,
S_{ls} = longitudinal stress [psi]
P = internal design pressure [psi]
D_0 = outside diameter [in]
t_n = nominal wall thickness [in]
i = stress intensification factor
M_a = the moment due to sustain load [in-lb_f]
Z = pipe section modulus [in^3]
S_h = allowable stress for the hot condition [psi]

The load attribute to the pipe system weight can be classified into two types:

- Live the load, is loads arise from fluid streaming inside the pipe.
- Dead load, covering the weight of component, isolator, and the other permanent load working on the piping system.

As can be seen in the equation (1), the longitudinal stress due to pressure, weight, and other sustained loads should be less than or equal to the S_h.

Thermal expansion stress

The thermal expansion stress occure due to the following reasons:

- Movement restrictions by the pedestal during the pipe expansion.
- The large and very fast temperature changing in the pipe wall that causing stress.
- Expansion coefficient difference of pipes made of two different metals.

Stress that occurs due to thermal expansion can be expressed by the following equation:

$$S_e = 1000\left(\frac{i\, M_C}{Z}\right) \le S_a + f\left(S_h - S_l\right) \quad (2)$$

where,
S_e = thermal expansion stress [psi]
M_c = the moment due to thermal expansion [in-lbs]
S_a = allowable stress range for expansion stresses [psi]
f = stress range reduction factor for cyclic conditions
S_l = longitudinal stress due to temperature [psi]

As can be seen in the equation (2), the thermal expansion stress should be less than or equal to S_a and f (S_h - S_l)

Sustain and thermal expansion stress

The sustained and thermal expansion stress, $S_{ls}+S_e$, is the algebraic summation of the longitudinal stress due to sustained loads and the thermal expansion stress. $S_{ls}+S_e$ is calculated using the following equation:

$$S_{ls} + S_e = \left(\frac{PD_o}{4t_n}\right) + 1000\left(\frac{0.75\, i\, M_a}{Z}\right) + 1000\left(\frac{i\, M_c}{Z}\right) \le \left(S_h + S_a\right) \quad (3)$$

As can be seen in the equation (3), the sustained and thermal expansion stress should be less than or equal to the sum of S_h and S_a

Occasional stress

The occasional stress, S_{lo}, is the load rarely occur, usually represent the dynamic load, such as wind and earthquake. The occasional stress is the algebraic summation of the longitudinal sustained weight stress, the longitudinal pressure stress, and occational stress. S_{lo} is calculated using the following code equation:

$$S_{lo} = \left(\frac{PD_o}{4t_n}\right) + 1000\left(\frac{0.75\, i\, M_a}{Z}\right) + 1000\left(\frac{0.75\, i\, M_b}{Z}\right) \le K\, S_h \quad (4)$$

where,
M_b = the moment due to occasional load [in-lb_f]
K = 1.15 for occasional loads acting less than 10 % of the operation period and 1.20 for occasional loads acting less than 1 % of the operation period.

As can be seen in the equation (4), the longitudinal stresses due to occasional loads should be less than or equal to KS_h.

EXPERIMENTAL METHODS

Pipe stress analysis

Pipe stress analysis of the TRIGA 2000 reactor cooling system was performed using CAESAR II software. The required steps in the analysis include data collection for model input, modeling, static and dynamic analysis. The piping data of TRIGA 2000 reactor cooling system input to the Caesar II software [7] consists of:

- Data of routing and pipe components position
- Pipe material of cooling system, that is aluminum alloys B241 6061 T6
- Nominal diameter of pipe, that is 6 in
- Pipe thickness, referring to ANSI standard
- Centrifugal type of pump, that is Peerles A 80 type with the flow rate of 950 gpm
- Heat exchanger, Baltimore Air Coil brand with the plate type of EC7.
- Pipe components i.e. valve, flange, reducer, etc.
- Working temperature of 70^{o}C
- Working pressure of 4.0816 kg/sq.cm
- Water fluid with the mass density of 999.2 kg/cu.m.
- Data of pump and heat exchanger nozzles deflection
- Seismic data, refer to the report of Seismic Hazard Analysis of the Bandung Nuclear Site [1].

According to the report, the most powerful earthquake is originated from Lembang fault, the spectrum can be seen in Fig. 1. The values of the Max Campbell / Lembang fault curve (the blue curve) was taken and listed in Table 1. The graph of earthquake prediction is formed from scaling the earthquake elsewhere (which has complete data) to the environmental conditions of BATAN Bandung. The possibility of an earthquake occurred in BATAN Bandung site is in the cycles of 2500, 500, and 400 years, with the maximum earthquake load at 0.9 G.

After all necessary data are available, a model of primary cooling system is created in Caesar II by entering data into the list already prepared in the program input. The result of the entire primary coolant system piping modeling is displayed in 3 dimensions form. The pipe model is separated into 3 lines based on the nozzle equipment, namely the line of the primary pump outlet nozzle toward the heat exchanger (HE) inlet nozzle (PriPump) (Fig. 3a), the line from the outlet nozzle of heat exchanger (HE) to the reactor tank (PriIn) (Fig. 3b), and the line from reactor tank toward the primary pump inlet nozzles (PriOut) (Fig. 3c).

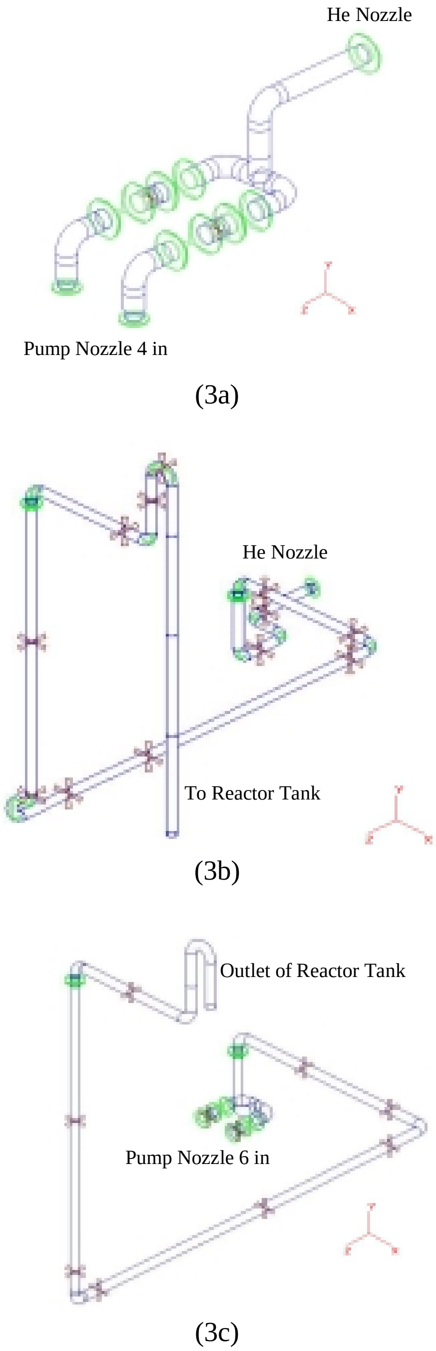

Fig. 3. Piping model of TRIGA 2000 reactor Bandung cooling system (3a. PriPump line, 3b. PriIn line and 3c. PriOut line).

The modeling results were then analyzed statically and dynamically. The static analysis requires deflection data of pump nozzles and heat exchangers that calculated based on the materials, dimensions and working temperature. The load is selected for the operating load (weight + displacement + temperature + pressure), the sustained (weight + pressure) and expansion (displacement + operation - displacement sustain), and also the occational (weight + pressure + quake). Dynamic analysis is conducted by entering the data spectrum of the earthquake in the TRIGA 2000 reactor site due to the Lembang fault as an input earthquake load (see Fig. 1). The spectrum data input is then listed in Table 1 [1,2,3,4].

The types of loads for analysis are refered to the program recommended in Caesar, those are: seismic load (occasional) and static load plus seismic load (occasional)

Table 1. Earthquake spectrum for input data.

No.	(sec)	(mm/sec^2)
1	0.0001	3433.5000
2	0.1000	6867.0000
3	0.1600	8829.0000
4	0.2000	8632.7998
5	0.3000	6867.0000
6	0.4000	5886.0000
7	0.5000	4905.0000
8	1.0000	2152.2000

RESULT AND DISCUSSION

The result of static analysis shows that the maximum stress due to sustained loads and expansion are below the allowable stress for the lines of PriIn, PriOut and PriPump, as can be se seen in Table 2. The maximum stress of the three lines are less than 33.62% both for sustain as well as the expansion load. These results indicate that all three lines would be safe during experiencing stress in the static condition. The operating condition is included in the load of expansion, since the load is a combination of sustain and operating loads.

Table 2. The Static maximum stress for PriIn line, PriOut line and PriPump line.

Line	PriIn		PriOut		PriPump	
Type of Load	**Sus**	**Exp**	**Sus**	**Exp**	**Sus**	**Exp**
Code Max. Stress node	124	125	247	190	50	130
Code Max. Stress (kPa)	11900	53260	13740	44400	3100	49340
Bending Stress (kPa)	9820	52990	11670	44390	1370	49340
Torsional Stress (kPa)	920	11420	1700	3790	0	5230
Axial Stress (kPa)	2610	3750	2380	3830	2070	6670
Allowable (kPa)	65500	158400	65500	161470	65500	161040
Code stress %	18.2	33.6	20.9	27.5	4.7	30.6

The dynamic analysis results are shown in Table 3, as same as the static results the maximum stress occurs in the three lines of PriIn, PriOut and PriPump, are less than the allowable stress, only a fraction of the stress for PriIn line reached 95.5% at node 130 during affected by the combination load. This indicates that the pipeline is still less flexible, eventhough the three pipelines are still safe if exposed to the dynamic loads. Generally, the primary cooling system piping of TRIGA 2000 (PriPump and PriOut) will be safe if an earthquake happens during reactor operation, however a pipeline modification or / and the changes of location and support type are needed to make the pipelines are more flexible.

Table 3. The dynamic maximum stress for PriIn line, PriOut line and PriPump line.

Line	PriIn		PriOut		PriPump	
Load type	Quake	Combination	Quake	Combination	Quake	Combination
Code Max.Stress node	220	130	214	183	120	130
Code Max.Stress (kPa)	31600	71900	26200	53300	12400	63600
Bending Stress (kPa)	40100	65500	28800	49100	16500	63000
Torsional Stress (kPa)	7300	14100	3000	4800	2400	7700
Axial Stress (kPa)	1900	5500	600	5100	900	6900
Allowable (kPa)		75000		75000		75000
Code stress %		95.5		70.8		84.4

Table 4 lists the result of analysis and shows the magnitude of force and moment received by the pump inlet nozzle (diameter 6 in.) and pump outlet nozzle (diameter 4 in). Pump inlet nozzles are in the PriOut line, while pump outlet nozzles are in PriPump line. Therefore, the amount of forces and moments that loading the nozzles, will depend on the flexibility of both lines. If the lines are flexible enough, the nozzles will not experience the load that exceeds the maximum allowable load. Static and dynamic analysis results in Table 4 indicate that there are no forces and moments occur at the pump nozzle at the X and Z direction (zero). It means that there is no shear force on the pump outlet nozzle , but only the force at Y direction (axial) that influence the pump outlet nozzle (diameter 4 in). The effect of Y direction force at at the outlet nozzle for both static and dynamic conditions exceed the allowable limit (> 1781.5 N) and can cause the failure of the pump outlet nozzle. The load of input nozzles (diameter 6 in.) has not exceeded the allowable limits (< 2048.3 N), hence the input nozzle is safe.

Table 4. The static and dynamic load on the pump nozzle of instaled pipeline.

	Installed pipeline							
Loads	Static				Dynamic			
Nozzle diameter	4 in		6 in		4 in		6 in	
Force (N), Moment (N.m)	Nozzle	Allow	Nozzle	Allow.	Nozzle	Allow.	Nozzle	Allow.
F_X	0	1425.3	0	2491.7	0	1425.3	0	2491.7
F_Y	3348	1781.5	0	3117.6	4027	1781.5	0	3117.6
F_Z	0	1157.6	466	2048.3	0	1157.6	1446	2048.3
M_X	0	1329,0	0	2305.3	0	1329,0	0	2305.3
M_Y	0	1003.5	0	1763,0	0	1003,5	0	1763,0
M_Z	0	678.1	0	1179.7	0	679,1	0	1179.7

Table 5 shows that the heat exchanger nozzle located in the PriIn line for both static and dynamic conditions are lower than the permissible limit (< 3780 N), whereas the force occured at the heat exchanger nozzle of the PriPump line has exceeded the allowable limit for the Z direction (> 3780 N). This indicates that the installed primary cooling system piping line of TRIGA 2000 reactor, pump nozzles and heat exchanger nozzle are safe from static and dynamic loads only for PriOut line. The installed PriPump and PriIn lines are less flexible, as a result there is an excess load supplied to the nozzles of pumps and heat exchangers. Therefore line modification of PriPump and PriIn is needed by changing the pipe lines and / or the location and type of support, so that expenses load will be distributed to the pump pipe nozzle and the heat exchangers homogenously and do not exceed the permissible nozzle load, therefore the PriIn line must be modified, After several line iterations and modifications of PriPump and PriIn, the load received by all pump inlet nozzles do not exceed the allowable limits for both static and dynamic conditions. The condition obtained by making a gap of 3 mm in the X direction of the support at the node 25, and eliminate the support at node 30, and also apply a 3 mm gap in X and Z direction at the node 155 (see Table 6).

Table 5. The static and dynamic load on the heat exchanger nozzle of instaled pipeline.

	Installed pipeline					
Loads	Static			Dynamic		
Force (N), Moment (N.m)	PriPump	PriIn	Allow.	PriPump	PriIn	Allow.
F_X	39	89	4630	160	208	4630
F_Y	1088	-436	4630	1353	669	4630
F_Z	-6265	2569	3780	6265	2580	3780
M_X	0	0	2880	0	0	2880
M_Y	0	0	2880	0	0	2880
M_Z	0	0	4075	0	0	4075

Table 6. The static and dynamic load on the pump nozzle of modified pipeline.

	Modified pipeline							
Loads	Static				Dynamic			
Nozzle diameter	4 in		6 in		4 in		6 in	
Force (N), Moment (N.m)	Nozzle	Allow	Nozzle	Allow	Nozzle	Allow	Nozzle	Allow
F_X	0	1425.3	-540	2491.7	0	1425.3	763	2491.7
F_Y	-440	1781.5	293	3117.6	942	1781.5	521	3117.6
F_Z	0	1157.6	-1681	2048.3	0	1157.6	1705	2048.3
M_X	0	1329,0	0	2305.3	0	1329,0	3	2305.3
M_Y	0	1003.5	0	1763,0	0	1003,5	1	1763,0
M_Z	0	678.1	0	1179.7	0	679,1	0	1179.7

As the modification result, the stress arised during the pipe is receiving static and dynamic load have the maximum stress fraction below the allowable limit, that is 81.8% for PriIn lines. This value is lower than that before the modification was applied (95.5%). For PriPump line, the modification lead to strees fraction far below the permissible limit (<33.6%) for both static and dynamic conditions (see Table 7). Similarly, after the modification the forces and moments in the heat exchanger nozzle located in the PriPump line (up nozzles) and the PriIn line (bottom nozzle), do not exceed allowable limits (see Table 8).

Table 7. The static and dynamic maximum stress of modified PriPump and PriIn line.

Pipeline	ANALYSIS	STATIC		DYNAMIC	
	Load type	Sus	Exp	Quake	Combination
PriPump	*Code Max.Stress* node	170	240	120	240
	Code Max.Stress (kPa)	6590.0	6750.0	12100.0	25300.0
	Bending Stress (kPa)	6020.0	6750.0	16100.0	25500.0
	Torsional Stress (kPa)	90.0	840.0	2400.0	3400.0
	Axial Stress (kPa)	2100.0	150.0	900.0	5000.0
	Allowable (kPa)	65500.0	160640.0		75000.0
	Code stress %	10.05	4.2		33.6
PriIn	*Code Max.Stress* node	193.0	125.0	220.0	214.0
	Code Max.Stress (kPa)	13410.0	39810.0	31600.0	61600.0
	Bending Stress (kPa)	11340.0	39760.0	40100.0	62200.0
	Torsional Stress (kPa)	1190.0	7800.0	7300.0	8700.0
	Axial Stress (kPa)	2610.0	3410.0	1300.0	5400.0
	Allowable (kPa)	65500.0	160200.0		75000.0
	Code stress %	20.48	24.85		81.8

Table 8. The static and dynamic loads of heat exchanger nozzle of the modified pipeline.

	Modified pipeline					
Loads	Static			Dynamic		
Force (N), Momen (N.m)	PriPump	PriIn	Allow.	PriPump	PriIn	Allow.
F_X	2.0	-532.0	4630.0	136.0	752.0	4630.0
F_Y	-631.0	292.0	4630.0	939.0	518.0	4630.0
F_Z	-135.0	1615.0	3780.0	3095.0	1631.0	3780.0
M_X	0.0	0.0	2880.0	0.0	0.0	2880.0
M_Y	0.0	0.0	2880.0	0.0	0.0	2880.0
M_Z	0.0	0.0	4075.0	0.0	0.0	4075.0

CONCLUSION

From the discussion it can be concluded as follows:

The installed piping of primary cooling system of TRIGA 2000 Bandung is still less flexible during the operation, so the pipeline should be modified (rerouting), to keep the stress not to approach the allowable limit both for static and dynamic conditions.

In the static condition the stress fraction on PriIn line is 18.16% at the node 124 for sustain load, and 33.62% at the node 130 for expansion load. The stress fraction on Priout line is 20.98% at the node 247 for sustain load, and 27.50% at the node 190 for load expansion. In PriPump line the stress fraction is 4.74% at the node 50 for sustain load, and 30.64% at the node 130 for the expansion load. The stress fractions on all three pipe lines of primary cooling system of TRIGA 2000 reactor are less than the permissible limit, so it can be said that the reactor will safe if a tremor due to the earthquake happened in the reactor site.

In the dynamic condition, pump outlet nozzle (4 ins) of the installed primary cooling system piping of TRIGA 2000 Reactor experiences overload, hence the PriPump line must be modified to be more flexible by removing the support at the node 105 and 135 so the load on the nozzle does not exceed the permissible limit.

During an earthquake, the installed PriIn line will experience stress fraction of 95.5% at the node 130 (approaching 100%), therefore the PriIn line must be modified, by making a gap of 3 mm in the X direction of the support at the node 25, and eliminate the support at node 30, and also apply a 3 mm gap in X and Z direction at the node 155.

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