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STRUCTURAL ANALYSIS OF THE AS-BUILTED IEA-R1 PRIMARY COOLANT PIPING SYSTEM USING A COMPLETE THREE-DIMENSIONAL MODEL

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ABSTRACT

IEA-R1 is an open pool type research reactor, moderated by light water and upgraded from 2 MW to 5 MW of operating power level. Heat generated in the reactor core is removed by a coolant system divided in two circuits, primary and secondary, composed by pumps, piping, heat exchangers, cooling tower, and some other auxiliary components. The 5 MW operating power level is now possible due to a modernization program started in 1996. As a part of the modernization program, ageing assessment studies recommend the replacement of one of the two heat exchangers in the circuit. To manage this replacement, modifications in the layout of the primary and secondary piping and supporting systems were performed, based on preliminary stress analysis study. Then, the aim of this work is to present the final stress analysis of the primary circuit. To reach this and taking the modifications of the primary into account, a 3D model of the whole circuit, in the as-built condition, was made. Stress results and discussions are shown.

1. INTRODUCTION

IEA-R1 reactor is a pool type, light water moderated and graphite reflected research reactor. It was inaugurated in 1957 in the ancient Institute of Atomic Energy, currently named IPEN (Nuclear and Energy Research Institute), in Sao Paulo. The original design was developed by the American company *Babcock* & *Wilcox*, and the reactor began its operation with a power of 2 MW, in a regime of 8 hours daily, 5 days a week. Besides the basic and applied research, along the time it went on producing some radioisotopes for medicine, industry and research. As a result of the growing demand in Brazil for radioisotopes, mainly for the nuclear medicine, the limitation of the IEA-R1 reactor became clear in attending it, as well as, of consequence, the necessity of increasing power and operating in continuous regime. In the early nineties, IPEN set off a process of modernization in order to upgrade the reactor power from 2MW to 5MW and modify its operational regime for 120 continuous hours per week [1], [2]. At the same time, IPEN has introduced the process of evaluation and management of the reactor ageing to ensure the safe operation after the power upgrade. One of the modifications indicated by this process and performed was the replacement of one of the heat exchangers of the IEA-R1 Primary Circuit with consequent changes in piping routing [3].

This paper is the outcome of the structural analysis of the IEA-R1 Primary Circuit piping after these modifications. The work was initiated by executing a general as-built of the primary system. For this work the analysis developed incorporates the changes to the piping route that were implemented in the replacement of Heat Exchanger TC-1A (the original one was designed and built by *Babcock* & *Wilcox*) by the heat exchanger fabricated by *IESA*.

The analysis was performed using the program *CAESAR II* [4]. The following steps were carried out: verification of the as-built condition in the system, construction of the 3D model of the whole system, preparation of the isometric drawing for stress calculation, development of the calculation model, processing and post-processing of results, and analysis of the obtained results.

Figure 1, presented below, shows a flowchart of the IEA-R1Primary Circuit.

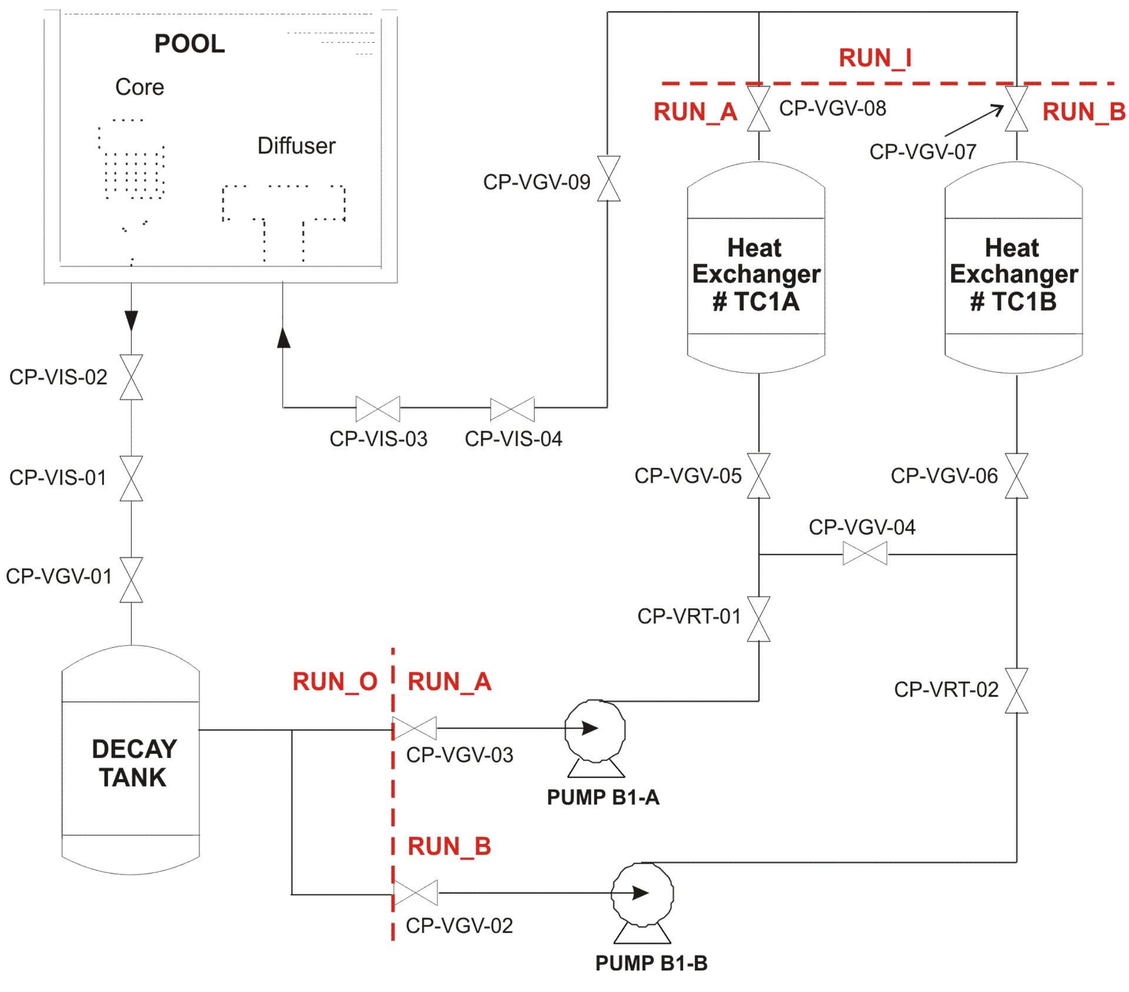

Figure 1. IEA-R1 Primary Circuit System Flow Chart

The lines and equipments were grouped together in order to make easier the identification of operating conditions of the plant, as illustrated in Figure 1 and listed in Table 1.

Table 1: Piping Run Limits

Run	from	through	to
RUN_O	Pool outlet nozzle	Decay Tank	Valves CP-VGV-02/03
RUN_A	Valve CP-VGV-03	Pump B1-A & Heat Exchanger #TC1A	Valve CP-VGV-08
RUN_B	Valve CP-VGV-02	Pump B1-B & Heat Exchanger #TC1B	Valve CP-VGV-07
RUN_I	Valves CP-VGV-07/08	Valves CP-VGV-09 & CP-VIS-03/04	Pool inlet nozzle

2. PRIMARY CIRCUIT DESCRIPTION

The primary circuit provides the water to cool the reactor core. It is an open circuit, since the refrigeration is provided by the own pool water in the reactor. In this system the water passes through the bars of the reactor core and the header located at the bottom of the pool, coming out of the pool through the piping nozzle. Then passes through a decay tank of ^{16}N and it is pumped by one of two pumps (B1A or B1B) to the respective heat exchanger (TC1-A or TC1-B) where it is cooled, returning, then, to the pool through a diffuser plugged in the piping nozzle. The system has redundant pumps, heat exchangers and valves.

To better analyze the system, in a comprehensive manner, a 3D model of the complete primary circuit was modeled using the program "*SOLIDWORKS*" [5]. This work was initiated with the preparation of a complete isometric drawing of all components of the primary circuit based on an as-built. Then, with the objective to show the whole system, to recheck the dimensions to guarantee that the as-built is ok, and to allow the preparation of the isometric for stress calculation, a 3D model was done. The resultant 3D model is shown in the Figure 2.

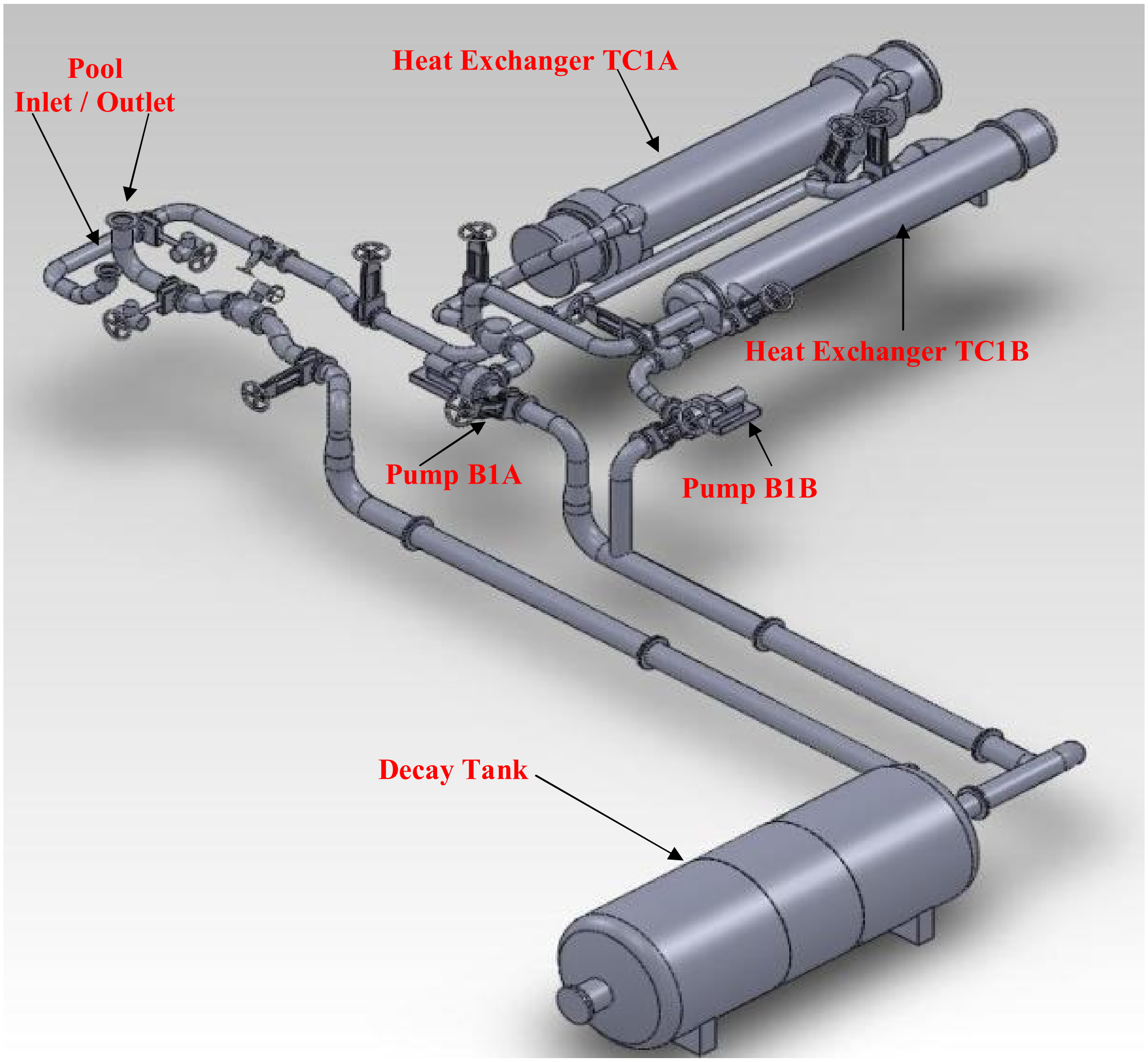

Figure 2. 3D Model of the IEA-R1 Primary Circuit

3. MODEL DESCRIPTION AND HYPOTHESIS OF CALCULATION

For the analysis purpose, the primary circuit of the reactor IEA-R1, as described in item 2, was modeled as a whole, encompassing piping and equipment coupled together. The program *CAESAR II* [4] was used for the analysis. Calculation model was developed and nodes and elements are shown in the isometric for stress calculation presented in figure 3.

The following premises were adopted:

⇨ The system was considered as Class 2, according to the *ASME* code, section III, subsection NC [6],

- ⇨ To built the model, straight pipe and bend element were used, with three DOF (degrees of freedom) for translation and three DOF for rotation,
- ⇨ The valves were modeled as rigid elements,
- ⇨ The piping supports were modeled by imposing a default restraint stiffness of 1×10^5 N/mm to the restrained direction,
- ⇨ The inlet and outlet pool nozzles, the heat exchangers nozzles, the decay tank nozzles, and the suction and discharge pump nozzles were modeled by imposing a restraint stiffness of the 1×10^7 N/mm for the translational DOF's and 1×10^{12} Nmm/rad for rotational DOF's,
- ⇨ Components stress-intensification factor's (SIF), were modeled as follows: "tees" were modeled as "welding tee" and "reductions" were modeled according to their geometry.

3.1. General Data

The geometric and physical properties of piping [7] and the valves and flanges weights used in the analysis are shown in the table 2 and table 3, respectively.

Table 2: Piping Properties

DN	Outlet dia. (mm)	Thickness (mm)	Linear weight (N/mm)	Material	Coef. of Thermal Exp (mm/mm°C)	Modulus of Elasticity (N/mm^2)
10	274.64	3.175	0.22	ASTM 304	16.4×10^{-6}	195100
12	311.15	3.175	0.24			
14	355.60	3.960	0.34			
16	410.37	3.581	0.35			

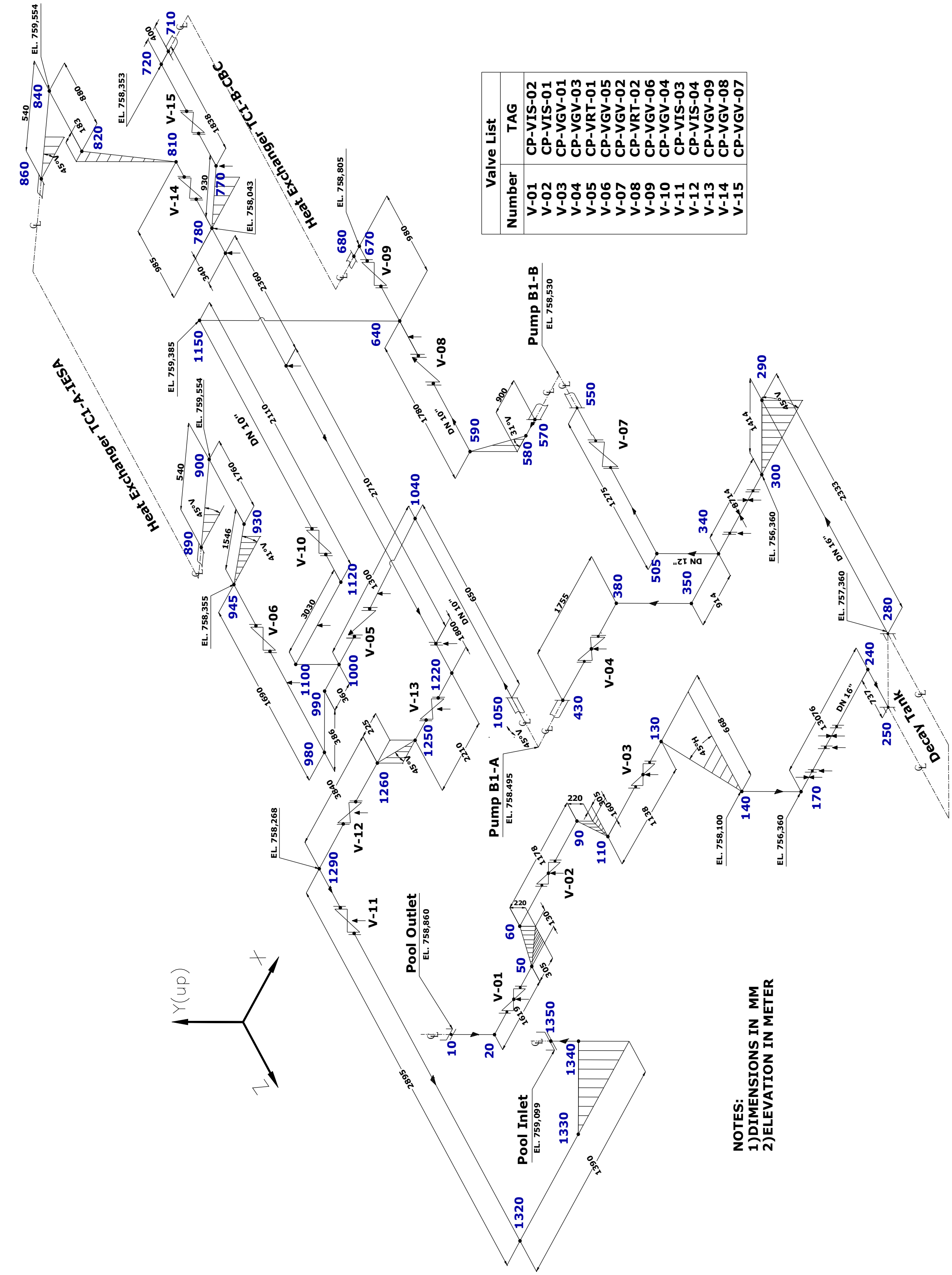

Figure 3. Drawing of isometric for stress calculation of the IEA-R1 Primary Circuit

Table 3: Valve and Flange Weights

Valves					
Tag	**Node**	**Weight (N)**	**Tag**	**Node**	**Weight (N)**
CP-VGV-01	115	3040	CP-VGV-09	1235	2000
CP-VGV-02	515	3040	CP-VIS-01	75	10560
CP-VGV-03	395	3040	CP-VIS-02	35	6360
CP-VGV-04	1135	2000	CP-VIS-03	1305	4200
CP-VGV-05	955	2000	CP-VIS-04	1275	7200
CP-VGV-06	655	2000	CP-VRT-01	1015	7080
CP-VGV-07	755	2000	CP-VRT-02	610	7080
CP-VGV-08	795	2000			

Flanges			
Node	**Weight (N)**	**Node**	**Weight (N)**
180, 200, 230, 310	1270	1210	390

The IEA-R1 primary circuit can operate according to the following:

Operation Mode #1 - Pump B1A e Heat Exchanger #TC1A running.
Pump B1B e Heat Exchanger #TC1B off.

Operation Mode #2 - Pump B1B e Heat Exchanger #TC1B running.
Pump B1A e Heat Exchanger #TC1A off.

Operation Mode #3 - Pump B1A/B e Heat Exchanger #TC1A/B running.

Table 4 lists pressure and temperature values, for each operation mode of the IEA-R1 reactor used in this analysis [1]:

Table 4: Process condition

		RUN_O	**RUN_A**	**RUN_B**	**RUN_I**
Operation Mode #1	Pressure (N/mm^2)	0,69	0,69	0	0,69
	Temperature (ºC)	43,9	43,9	25	37,8
Operation Mode #2	Pressure (N/mm^2)	0,69	0	0,69	0,69
	Temperature (ºC)	43,9	25	43,9	37,8
Operation Mode #3	Pressure (N/mm^2)	0,69	0,69	0,69	0,69
	Temperature (ºC)	43,9	43,9	43,9	37,8

3.2. Load cases

In order to perform the piping stress analysis, the following load cases were defined:

DW -	(Dead Weight)	-	Pipe, fluid, flanges and valves weight,
P_D -	(Design Pressure)	-	Maximum pressure applied to the lines (see table 1),
Th -	(Operating Temperature)	-	Three Thermal load cases (see table 4):
	Th1	⇨	Operation Mode #1;
	Th2	⇨	Operation Mode #2;
	Th3	⇨	Operation Mode #3.

3.3. Stress analysis

Piping stress analysis was performed according to *ASME* code, section III subsection NC [6].

The *ASME* code provides the criteria for the stress evaluation of components and piping based on two categories of loading. Such categories are non-self-limiting and self-limiting loads.

A non-self-limiting load is an applied load that produces a primary stress, which is responsible for the equilibrium of the system. When they exceed the material's yield strength it could result in failure or gross distortion. Pressure and weight is typical non-self-limiting loads.

A self-limiting load is generated by restraining the deformation of the system and generally produces secondary stresses that can bring forth to local yielding and minor distortions. Thermal expansion is a typical example of this load.

Table 5 shows *ASME* code limits according to plant condition, failure mode and category of the loads.

Table 5: *ASME* code Equations

Condition	Failure Mode	Equation	Stress categorization
Design	structure failure	8	Primary
Service	plastic shakedown	10	Secondary

To prevent gross rupture of the system, the general and local membrane stress criteria must be satisfied. This is accomplished by meeting equation (1) (equivalent to equation (8) of NC-3652 of the *ASME* code [6]). This equation requires that primary stress intensity resulting from design pressure; weight and other sustained loads meet a stress limit for the design condition as showed below:

$$B_1 \times \frac{PD_o}{2t_n} + B_2 \times \frac{M_a}{Z} \leq 1.5 \times S_h \qquad (1)$$

Where:

$B_1, B_2 \rightarrow$ primary stress indices,

$D_o \rightarrow$ outside diameter of pipe,

$t_n \rightarrow$ nominal wall thickness,

$P \rightarrow$ internal design pressure,

$M_a \rightarrow$ resultant moment loading on cross section due to weight and other sustained loads,

$Z \rightarrow$ section modulus of pipe,

$S_h \rightarrow$ basic material allowable stress at design temperature.

To prevent local yielding and distortion, the secondary stress criteria must be satisfied. This is accomplished by meeting equation (2) (equivalent to equation (10) of NC-3653.2 of the *ASME* code [6]). This equation requires that secondary stress intensity resulting from thermal expansion meet a level A and B service limits.

$$\frac{\mathbf{i} \times \mathbf{M_c}}{\mathbf{Z}} \leq \mathbf{S_A} \qquad (2)$$

Where:

$i \rightarrow$ stress intensification factor,

$Z \rightarrow$ section modulus of pipe,

$M_c \rightarrow$ range of resultant moments due to thermal expansion,

$S_A \rightarrow$ allowable stress range for expansion stresses:

$$S_A = f(1.25S_c + 0.25S_h)$$

$S_h \rightarrow$ basic material allowable stress at design temperature.

$S_c \rightarrow$ basic material allowable stress at room temperature

$f \rightarrow$ stress range reduction factor for cyclic loads

$f = 1$ ($N \leq 7000$ cycles) according to reference [6].

4. STRESS ANALYSIS RESULTS

The calculation model, built in accordance with the routing of the lines presented in figure 3, was simulated with the computer program *CAESAR II* [4], taking into consideration the load cases described in item 3.2 and performing the stress analysis according to *ASME* code, section III, Subsection NC, as described in item 3.3.

The maximum stress values calculated in the simulation do not exceed the limits set by *ASME* code. This result was obtained considering the primary stresses, defined by equation (8) of the code, and secondary stresses defined by equation (10) of the code. The 3 highest values of stress, obtained from the computing simulation, in all load cases for both conditions, are presented in the table 6.

Table 6: Stress Results Summary

Condition	Load case Combination	Equation	Node	stress (N/mm^2)		Ratio
				Nodal	Allowable	
Design	P_D, DW	8	1000 850 720	72,0 65,6 65,2	163,0	0,44 0,40 0,40
Service	Th1/Th2/Th3	10	340 579 89	127,3 87,6 66,9	196,0	0,65 0,45 0,34

5. CONCLUSIONS

Considering the load cases presented below, the stress analysis of the IEAR-1 primary system provided satisfactory results, so the maximum values obtained from the simulation are within the limits proposed by the *ASME* code, section III, subsection NC, for Class 2 nuclear pipe.

DW - (Dead Weight) -
P_D - (Design Pressure) -
Th1 - (Operating Temperature - Operation Mode #1)
Th2 - (Operating Temperature - Operation Mode #2)
Th3 - (Operating Temperature - Operation Mode #3)

To sum up, the modifications made in the piping route for the replacement of the old *Babcock & Wilcox* heat exchanger by the new constructed and mounted by *IESA* are guaranteed.

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