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IEA-R1 RENEWED PRIMARY COOLANT PIPING SYSTEM STRESS ANALYSIS

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ABSTRACT

A partial replacement of the IEA-R1 piping system was conducted in 2014. The aim of this work is to perform the stress analysis of the renewed primary piping system of the IEA-R1, taking into account the as built conditions and the pipe modifications.
The nuclear research reactor IEA-R1 is a pool type reactor designed by Babcox-Willcox, which is operated by IPEN since 1957.
The primary coolant system is responsible for removing the residual heat of the Reactor core.
As a part of the life management, a regular inspection detected some degradation in the primary piping system. In consequence, part of the piping system was replaced.
The partial renewing of the primary piping system did not imply in major piping layout modifications. However, the stress condition of the piping systems had to be reanalyzed.
The structural stress analysis of the primary piping systems is now presented and the final results are discussed.

1. INTRODUCTION

IEA-R1 reactor is a pool type, light water moderated and graphite reflected research reactor. Its first operation was in 1957 in the ancient Institute of Atomic Energy, currently named IPEN (Nuclear and Energy Research Institute) in São Paulo. The original design was developed by the American company *Babcock* & *Wilcox*, and the reactor started with 2 MW power [1].

Since its start-up in 1957, the IEA-R1 has been modified for several reasons such as replacement of aged structures and components, upgrading of systems, and adequacy to safety codes and standards that have changed during the years. In the early nineties, IPEN set off a process of modernization in order to upgrade the reactor power from 2 MW to 5 MW [2]. At the same time, IPEN has introduced the process of evaluation and management of the reactor ageing [3], to ensure the safe operation after the power upgrade.

The main modifications up to 2014 are listed bellow:

1971: - Changes in reactor building ventilation system.
1974: - Duplication of the primary coolant system to redundancy;
- Introduction of flywheels on the primary centrifugal pumps;
- Installation of a N^{16} decay tank to reduce operational dose.
1976: - Replacement of original instrumentation and control operation console;
- Replacement of the original control drive mechanism;
- Changes in the pneumatic system.
1978: - Replacement of the original ceramic liner of the pool walls for a steel liner;
- Installation of an auxiliary bypass system for emergency water supply.
1987: - Separation of the reactor building area into radiological hot and cold rooms;
- Introduction of access chambers;
- Introduction of vertical duct for irradiated material transfer;
- Installation of a new cooling tower;
- Main maintenance of the emergency generators.
1991: - Construction of a radiation shielding for the resins columns in the pool water purification and treatment system.
1995: - Power upgrade from 2 MW to 5 MW.
2001: - Main maintenance of the cooling towers.
2002: - Main maintenance of primary pumps;
- Installation of beryllium reflectors.
2005: - Replacement of a heat exchanger (TC1A).
2007 - Installation of a new pneumatic system
2012: - Withdrawal of check valves of the secondary system;
- Replacement of secondary pumps.
2014: - Partial Replacement of primary piping system.

The process: **Partial replacement of primary piping system**, in the year of 2014, can be summarized in the following steps:

- Step 1 - furnishing documents and drawings to the public notice;
- Step 2 – enterprise that was contracted to perform the works presents the documents and drawings related to the design of piping and piping supports;
- Step 3 – fabrication of piping and piping supports;
- Step 4 – erection of piping and piping supports in IPEN;
- Step 5 – piping pressure test;
- Step 6 – As built verification of piping and piping supports and the emission of piping isometric and support drawing with the as built status [4].

This paper is the outcome of the structural analysis of the IEA-R1 Primary Circuit Piping considering “As Built” conditions, as treated in the technical report [5].

The analysis was performed by using the program *CAESAR II* [6]. The following steps were carried out: verification of the as-built conditions in the system construction of the 3D model of the 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.

2. PRIMARY CIRCUIT DESCRIPTION

The Figure 1 shows a simplified flowchart of the Primary System of the IEA-R1 reactor.

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 plates of the reactor core and the header located at the bottom of the pool, coming out of the pool through the pool outlet nozzle. Then, passes through a decay tank of N^{16} and is pumped by pumps B1A and/or B1B, to the respective heat exchanger TC1-A and/or TC1-B, where it is cooled. Then the water returns to the pool through a diffuser connected to the pool inlet nozzle. The system has redundant pumps, heat exchangers and valves.

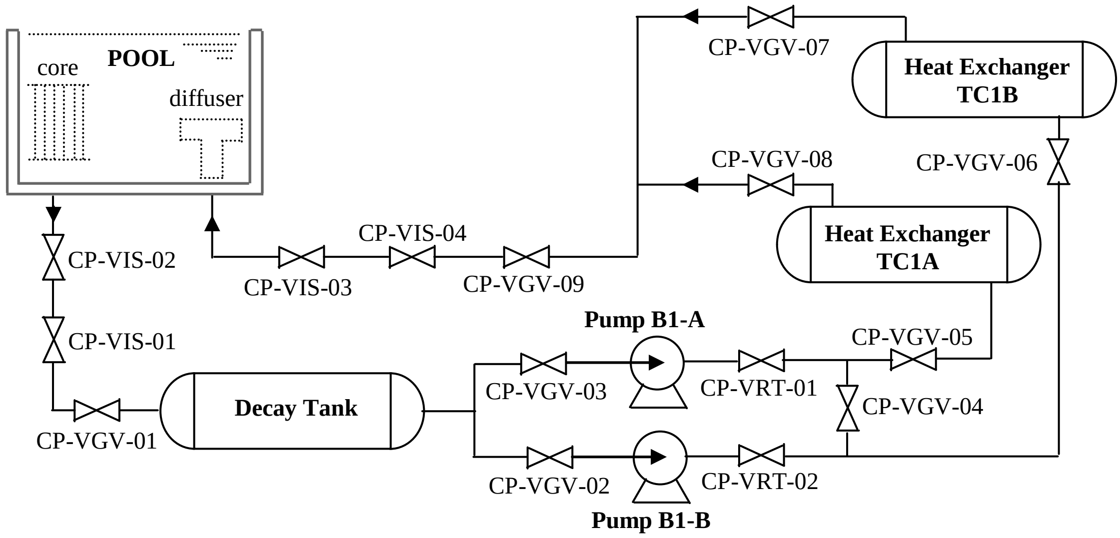

Figure 1: Simplified flow chart of the IEA-R1 Primary System

To better analyze the system a 3D – Tree Dimensional model of the complete primary circuit was modeled using the computer program *SOLIDWORKS* [7]. 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 of showing the whole system, rechecking all of the dimensions to guarantee that the as-built is properly represented and of preparing the isometric for stress calculation the 3D model was done. This model is shown in the Figure 2.

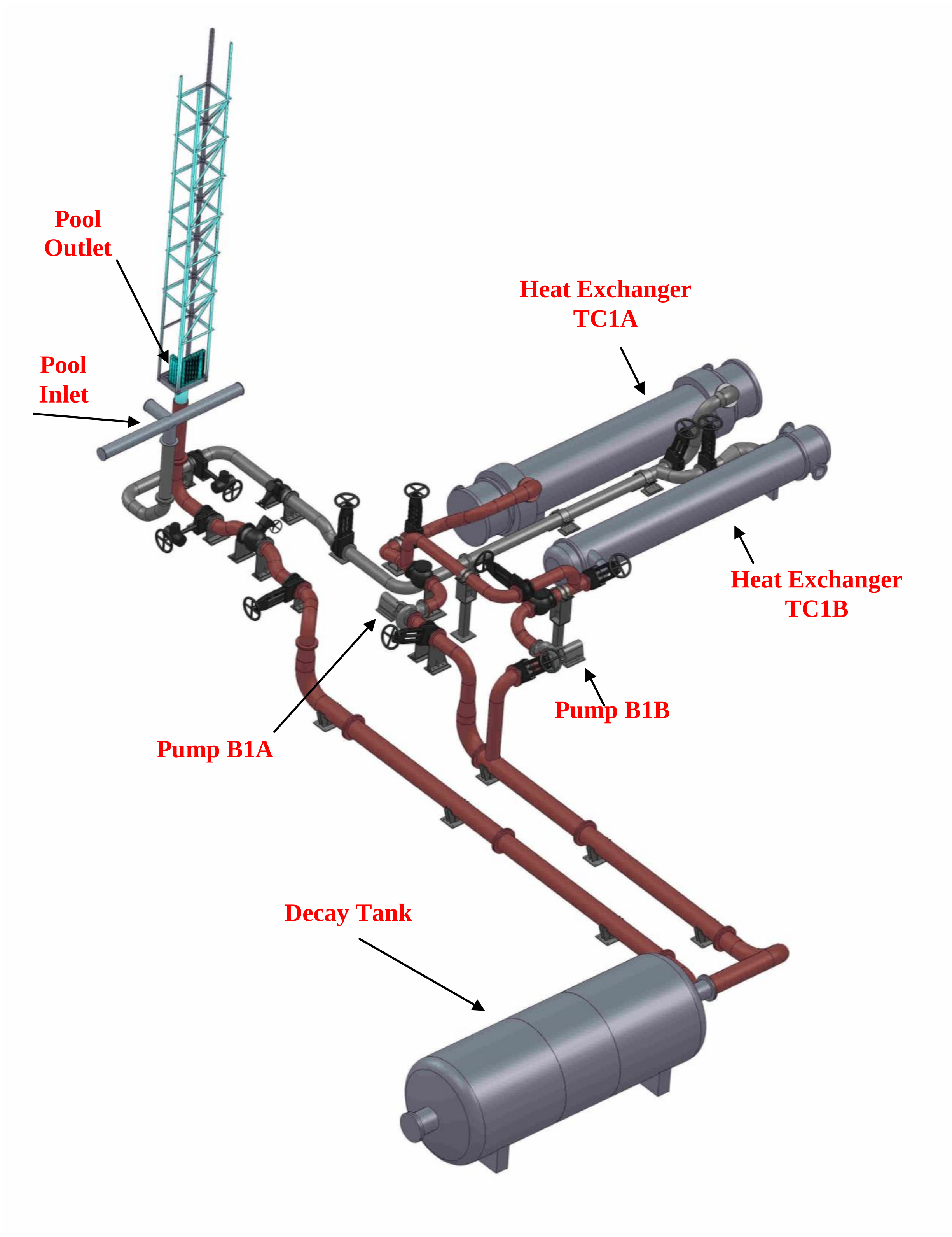

Figure 2: 3D Model of the IEA-R1 Primary Circuit

3. PIPING MODEL DESCRIPTION

The piping system of the IEA-R1 primary circuit (see references from [8] to [12]) was modeled by taking into account the concept that the anchorages are the final boundaries of the calculation model, according to the following three-dimensional models:

Model #1 – from outlet nozzle of Pool till inlet nozzle of Decay Tank;

Model #2 – from outlet nozzle of Decay Tank till suction nozzles of the pumps;

Model #3 – from discharge nozzles of the pumps till inlet nozzle of the Heat Exchangers;

Model #4 – from outlet nozzles of the Heat Exchangers till inlet nozzle of the Pool.

Figure 3 shows the dimensions of the whole piping system and locations of piping supports that were used in the building of the models referenced above.

The following theoretical premises were adopted:

- The Primary Circuit Piping was considered as non nuclear, according to the *ASME* B31.1, [13];
- To build the model, straight pipe and bend elements 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 adopting a restraint stiffness of 1 x 10^5 N/mm to the restrained direction;
- The inlet and outlet pool nozzles, the heat exchanger nozzles, the decay tank nozzles, and the suction and discharge pump nozzles were modeled by adopting a restraint stiffness of the 1 x 10^7 N/mm for the translational DOF's and 1 x 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.

CAESAR II [6] was the program used for the analysis.

3.1. General Data

The material of the Primary Circuit Piping is a SA-312-TP 304L stainless steel. The physical and mechanical properties of the piping material are shown in Table 1 and the geometric properties of the piping in Table 2.

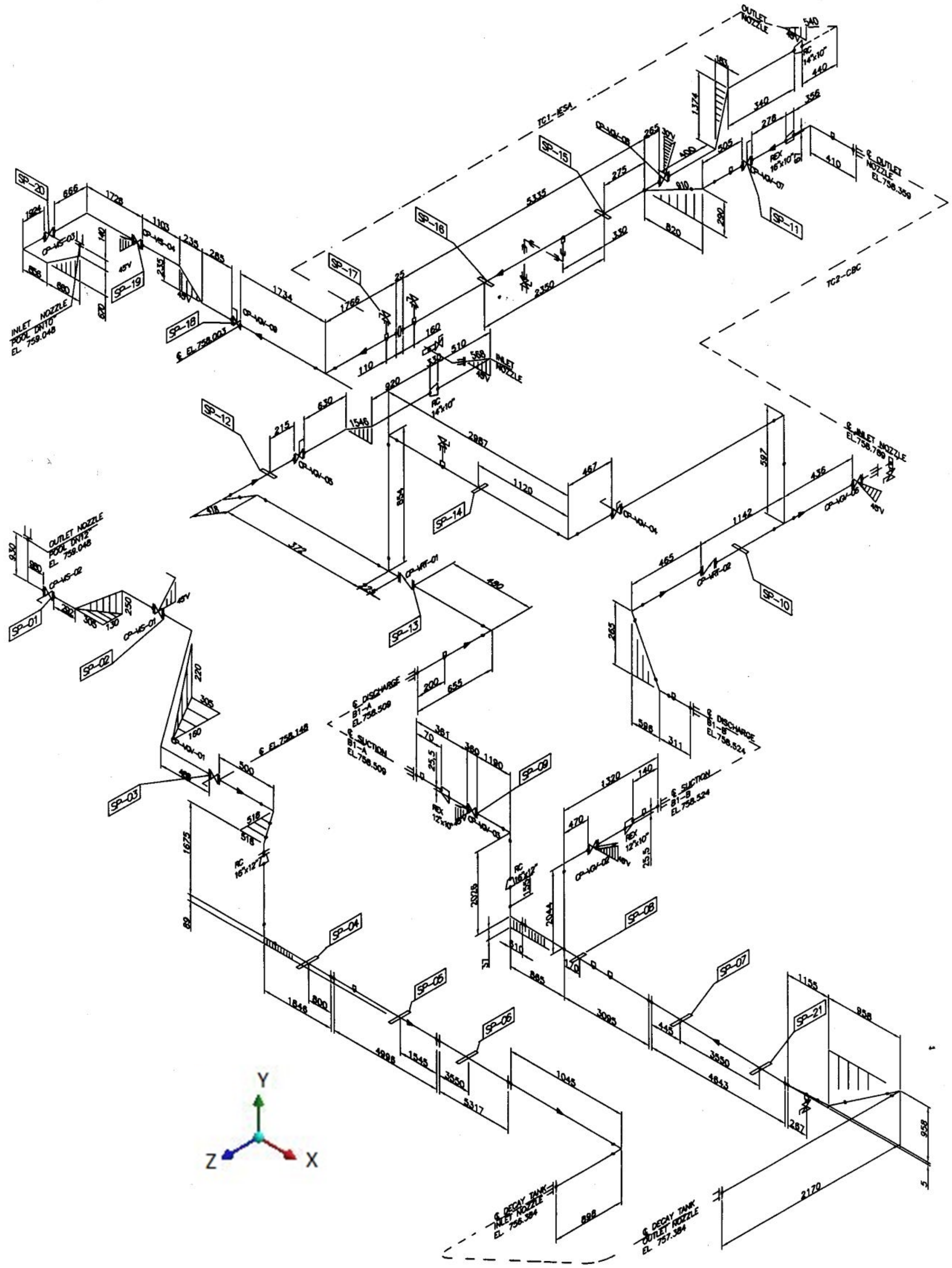

Figure 3: IEA-R1 Primary Circuit Isometric drawing for stress calculation

Table 1: Materials Properties [14]

Material	Thermal Expansion (mm/mm°C)	Modulus of Elasticity (N/mm^2)	Stress (N/mm^2)	
			Allowable	Yield
SA-312 TP304L	$15.6x10^{-6}$	195100	108.3	172.5

Table 2: Piping Cross Sections Properties (mm)

DN	Outlet diameter	Thickness
250	273.05	3.40
300	323.85	3.96
350	355.60	3.96
400	406.40	4.19

The operation modes of the IEA-R1 primary circuit are shown in Table 3. Table 4 lists the process data for pressure and temperature applied in the analysis.

Table 3: Operation Modes

Operation Mode	Pump		Heat Exchanger	
	B1A	B1B	TC1A	TC1B
1	On	Off	On	Off
2	Off	On	Off	On
3	On	On	On	On

Table 4: Process Condition [15]

	Primary Circuit
Pressure (N/mm^2)	0.69
Temperature (°C)	43.9

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 valve weight,
P_D - (Design Pressure) - Maximum pressure applied to the lines (see Table 4),
Th - (Thermal Expansion) - Three Thermal load cases (see Table 3):

- **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. As stated before, the primary circuit piping was classified as non nuclear and analyzed by *ASME* B31.1 [13].

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

A non-self-limiting stress is produced by the mechanical load that causes primary stresses, which are 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 are typical mechanical loads.

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

Table 5: *ASME* code B31.1 equations

Condition	Failure Mode	Equation	Stress categorization
Design	plastic collapse	11A	Primary
Thermal Expansion	plastic shakedown	13A	Secondary

To prevent gross rupture of the system, the general and local membrane stress criteria must be satisfied. This is accomplished by meeting equation (11A) of 104.8.1 of the *ASME* B31.1. This equation requires that primary stress intensity resulting from design pressure, weight and other sustained loads meets the stress limit for the design condition as showed below:

$$\frac{PD_o}{4t_n} + (0.75 \times i)\frac{M_a}{Z} \le 1.0 \times S_h \quad \text{(Equation 11A)} \qquad (1)$$

Where:

$\boldsymbol{i} \rightarrow$ primary stress indice,

$\mathbf{D_o} \rightarrow$ outside diameter of pipe,

$\boldsymbol{t_n} \rightarrow$ nominal wall thickness,

$\boldsymbol{P} \rightarrow$ internal design pressure,

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

$\boldsymbol{Z} \rightarrow$ section modulus of pipe,

$\boldsymbol{S_h} \rightarrow$ 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 (13A) of 104.8.3 of the *ASME* B31.1. This equation requires that secondary stress intensity resulting from thermal expansion due to warm up of the plant meets the limit of secondary stress.

$$\frac{i \times M_c}{Z} \leq S_A \quad \text{(Equation 13A)} \qquad (2)$$

Where:

$\boldsymbol{i} \rightarrow$ stress intensification factor,

$\boldsymbol{Z} \rightarrow$ section modulus of pipe,

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

$\boldsymbol{S_A} \rightarrow$ allowable stress range for expansion stresses:

$$S_A = f\left(1.25S_c + 0.25S_h\right) \qquad (3)$$

$\boldsymbol{S_h} \rightarrow$ basic material allowable stress at design temperature,

$\boldsymbol{S_c} \rightarrow$ basic material allowable stress at room temperature,

$\boldsymbol{f} \rightarrow$ stress range reduction factor for cyclic loads

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

4. STRESS ANALYSIS RESULTS

The piping calculations proceeded with model #1, model #2, model #3 and model #4 were done with *CAESAR II* [6] computer program by taking into consideration the load cases described in item 3.2. All of them were built in accordance with the routing of the lines presented in isometric drawing from Figure 3. Stress analysis of piping was performed according to *ASME* B31.1, 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 by considering the primary stresses defined by equation (11A) of the code, and secondary stresses defined by equation (13A) of the code. The highest values of stress for each piping calculation model, obtained from the computing simulation, in all load cases for both conditions, are presented in the Table 6.

The resulting stresses shown in Table 6 are identified in Figure 4, according to the following:

Model #n - Equation

With: Model # 1 to #4, combined with equation 11A or/and 13A.

Table 6: Stress Results Summary (N/mm^2)

Model	Design (equation 11A)			Thermal Expansion (equation 13A)		
	Stress		%	Stress		%
	Calc.	S_h		Calc.	S_A	
#1	22.0	108.3	20.3	101.0	162.4	62.2
#2	20.6		19.0	123.3		75.9
#3	40.6		40.6	46.1		28.4
#4	38.7		35.7	9.0		5.5

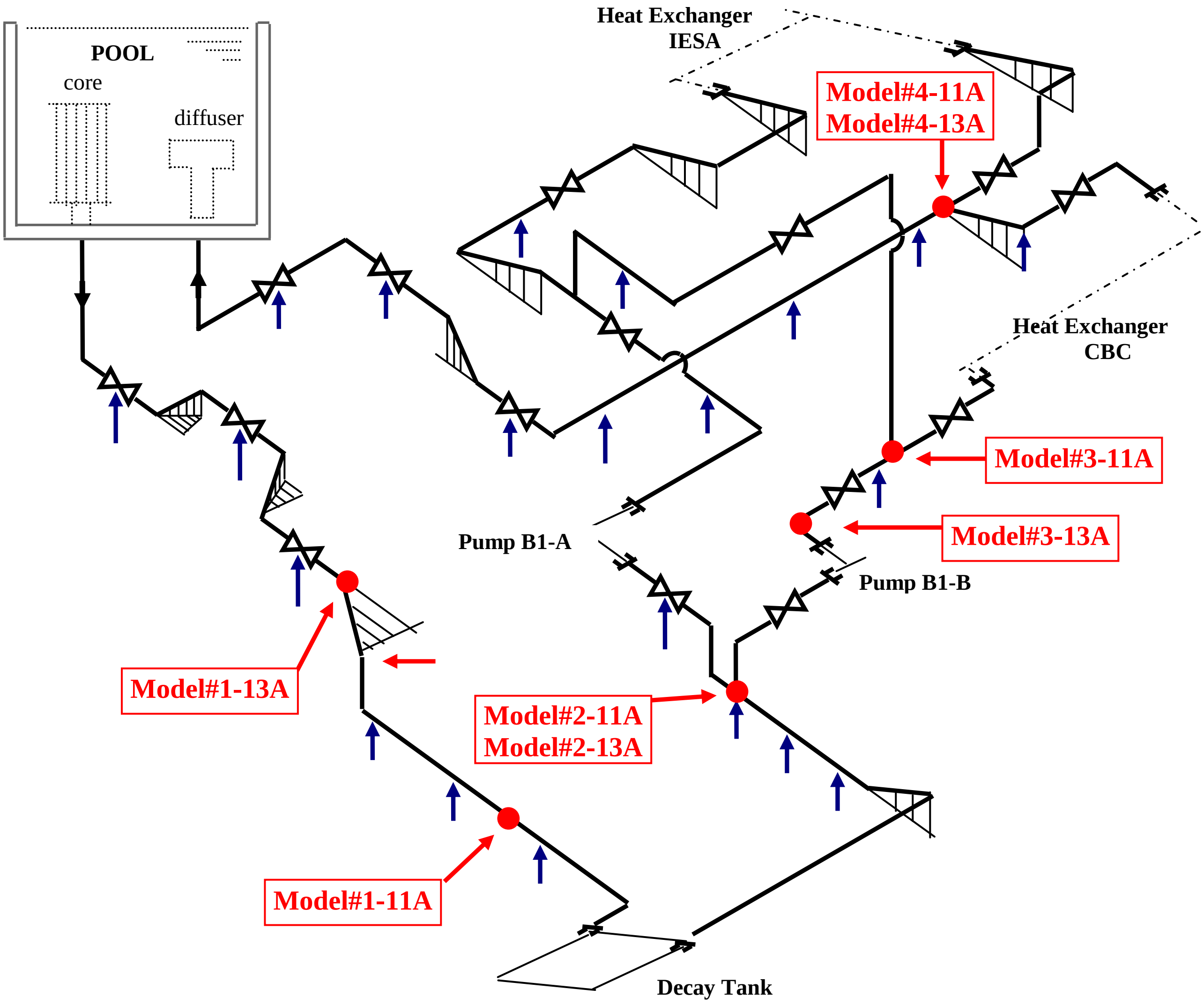

Figure 4: Location of Stresses Shown in Table 6 for IEA-R1 Primary Circuit

5. CONCLUSIONS

The IEA-R1 Primary Circuit Piping that was renewed in the year of 2014 because of corrosion problems in piping and piping supports follows the schedule of the works created by the process: **“Partial replacement of primary piping system”**:

- furnishing documents and drawings to the public notice;
- enterprise that was contracted to perform the works presents the documents and drawings related to the design of piping and piping supports;
- fabrication of piping and piping supports;
- erection of piping and piping supports in IPEN;
- piping pressure test;
- As built verification of piping and piping supports and the emission of piping isometric and support drawing with the as built status [4].

This paper is the outcome of the structural analysis of the IEA-R1 piping after these modifications. For the analysis purpose, the primary circuit of the reactor IEA-R1 was divided into the following models:

Model #1 – from outlet nozzle of Pool till inlet nozzle of Decay Tank;

Model #2 – from outlet nozzle of Decay Tank till suction nozzles of the pumps;

Model #3 – from discharge nozzles of the pumps till inlet nozzle of the Heat Exchangers;

Model #4 – from outlet nozzles of the Heat Exchangers till inlet nozzle of the Pool.

The maximum stress values calculated in the simulation with program CAESAR II do not exceed the limits set by *ASME* B31.1:

- primary stresses - defined by equation (11A);
- secondary stresses - defined by equation (13A).

Therefore, the piping of IEA-R1 Primary Circuit, after the renewing of piping system, attends to the limits prescribed by ASME B31.1, which allows the safe operation of the IEA-R1 nuclear research reactor.

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