2013 International Nuclear Atlantic Conference - INAC 2013
Recife, PE, Brazil, November 24-29, 2013
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: **978-85-99141-05-2**

IEA-R1 PRIMARY AND SECONDARY COOLANT PIPING SYSTEMS COUPLED STRESS ANALYSIS

Gerson Fainer[1], Altair A. Faloppa[1], Carlos A. Oliveira[1] and Miguel Mattar Neto[1]

[1] Instituto de Pesquisas Energéticas e Nucleares - IPEN / CNEN - SP
Av. Professor Lineu Prestes, 2242
05508-000, São Paulo, SP, Brazil
gfainer@ipen.br; afaloppa@ipen.br; calberto@ipen.br; mmattar@ipen.br

ABSTRACT

The aim of this work is to perform the stress analysis of a coupled primary and secondary piping system of the IEA-R1 based on tridimensional model, taking into account the as built conditions. The nuclear research reactor IEA-R1 is a pool type reactor projected by Babcox-Willcox, which is operated by IPEN since 1957. The operation to 5 MW power limit was only possible after the conduction of life management and modernization programs in the last two decades. In these programs the components of the coolant systems, which are responsible for the water circulation into the reactor core to remove the heat generated inside it, were almost totally refurbished. The changes in the primary and secondary systems, mainly the replacement of pump and heat-exchanger, implied in piping layout modifications, and, therefore, the stress condition of the piping systems had to be reanalyzed. In this paper the structural stress assessment of the coupled primary and secondary piping systems is 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 Sao 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. The main modifications up to 2012 are listed bellow: [2], [3]

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 ^{16}N 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 by 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.

The modifications indicated by these processes: “duplication of primary coolant system to redundancy”, “installation of decay tank” and “replacement of a heat exchanger” in the Primary Circuit, and “installation of a new cooling tower”, “withdrawal of check valves” and “Replacement of secondary pumps” in the Secondary Circuit caused changes in piping layout.

This paper is the outcome of the structural analysis of the IEA-R1 coupled Primary and Secondary Circuits piping after these modifications. In order to develop this work it was carried out the following schedule:

- assessment of piping documents;
- verification of the as-built condition of the primary and secondary piping systems;
- construction of a 3D solid model of the primary and secondary piping systems;
- preparation of the isometric drawings for stress calculation;
- development of the primary and secondary piping structural model, processing and post-processing of results, and analysis of the obtained results.

The piping analysis was performed by using the program *CAESAR II* [4], a very well know piping system analysis software, which has become the standard for piping stress analysis.

The stress analysis was performed as follow: the Primary Circuit Piping was classified as nuclear safety class 2, according to the *ASME* code, section III, subsection NC [5] and the Secondary Circuit Piping was classified as non nuclear, according to the *ASME* code B31.1 [6].

2. PRIMARY AND SECONDARY CIRCUIT DESCRIPTION

The figure 1 shows a simplified flowchart of the Primary and Secondary Systems 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 piping nozzle. Then, passes through a decay tank of ^{16}N and it is pumped by pumps B1A and/or B1B, to the respective heat exchanger TC1-A and/or TC1-B, where it's cooled, returning, then, to the pool through a diffuser plugged in the piping nozzle. The system has redundant pumps, heat exchangers and valves.

The secondary circuit provides the water to cool the heat exchanger TC1-A and/or TC1-B. It is also an open circuit, since the refrigeration is provided by cooling towers TR1-A and/or TR1-B. The returning water is pumped by B102-A and/or B102-B to the respective heat exchanger TC1-A and/or TC1-B.

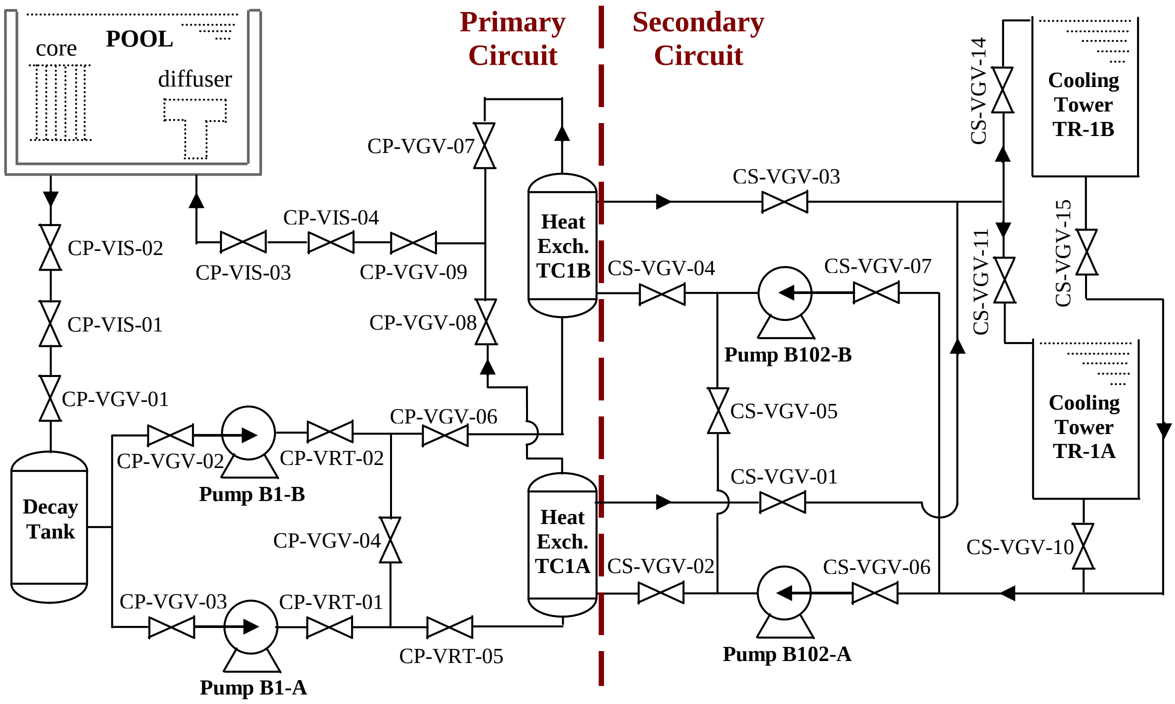

Figure 1. Simplified flow chart of the IEA-R1 Primary & Secondary Circuit

To better analyze the system, in a comprehensive manner, a three-dimensional solid model of the complete primary and secondary circuit was built using the program "*SOLIDWORKS*" [7]. This work was initiated with the preparation of a complete isometric drawing of all components of the primary and secondary circuits based on the as-built condition. Then, with the objective to show the whole system, to recheck the dimensions to guarantee that the as-built is correct, and to allow the preparation of the isometric for stress calculation, a 3D solid model was done. The resultant 3D solid model is shown in the figure 2.

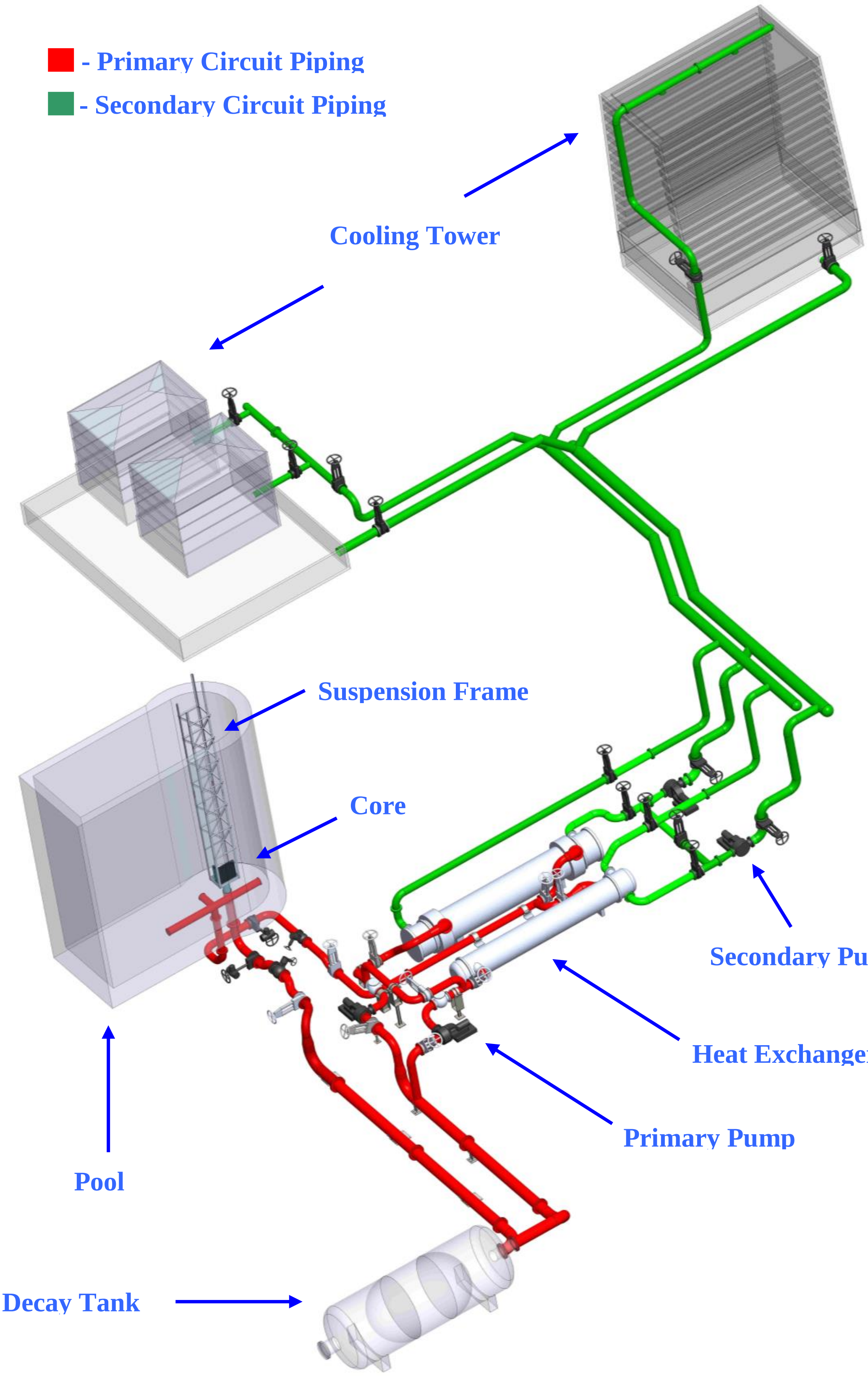

Figure 2. 3D Model of the IEA-R1 Primary & Secondary Circuit

3. PIPING MODEL DESCRIPTION

For piping analysis purpose, the primary and secondary circuits of the reactor IEA-R1, as described in item 2, were 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 figures 3 and 4.

The following theoretical premises were adopted:

- The Primary Circuit Piping was considered as Nuclear Safety Class 2, according to the *ASME* code, section III, subsection NC [5], and the Secondary Circuit Piping as non nuclear, according to ASME B31.1 [6];
- 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 components were modeled as equivalent beams;
- 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 exchangers nozzles, the decay tank nozzles, the cooling towel 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.

The Calculation Model will be valid whether the following premises were true:

- The piping, valves, tees, flanges and reductions must be without defects, it means: there is no denting, no pitting, no misalignments, no out of roundness and nor any corroded points on external or internal surface of the piping or fittings;
- The attachments, welded or threaded, that connects piping to piping, piping to equipment and piping to fittings (valves, tees, flanges, reductions) must be without defects, it means: there is no denting, no pitting, no misalignments, no out of roundness and nor any corroded points on external or internal surface of the fittings;

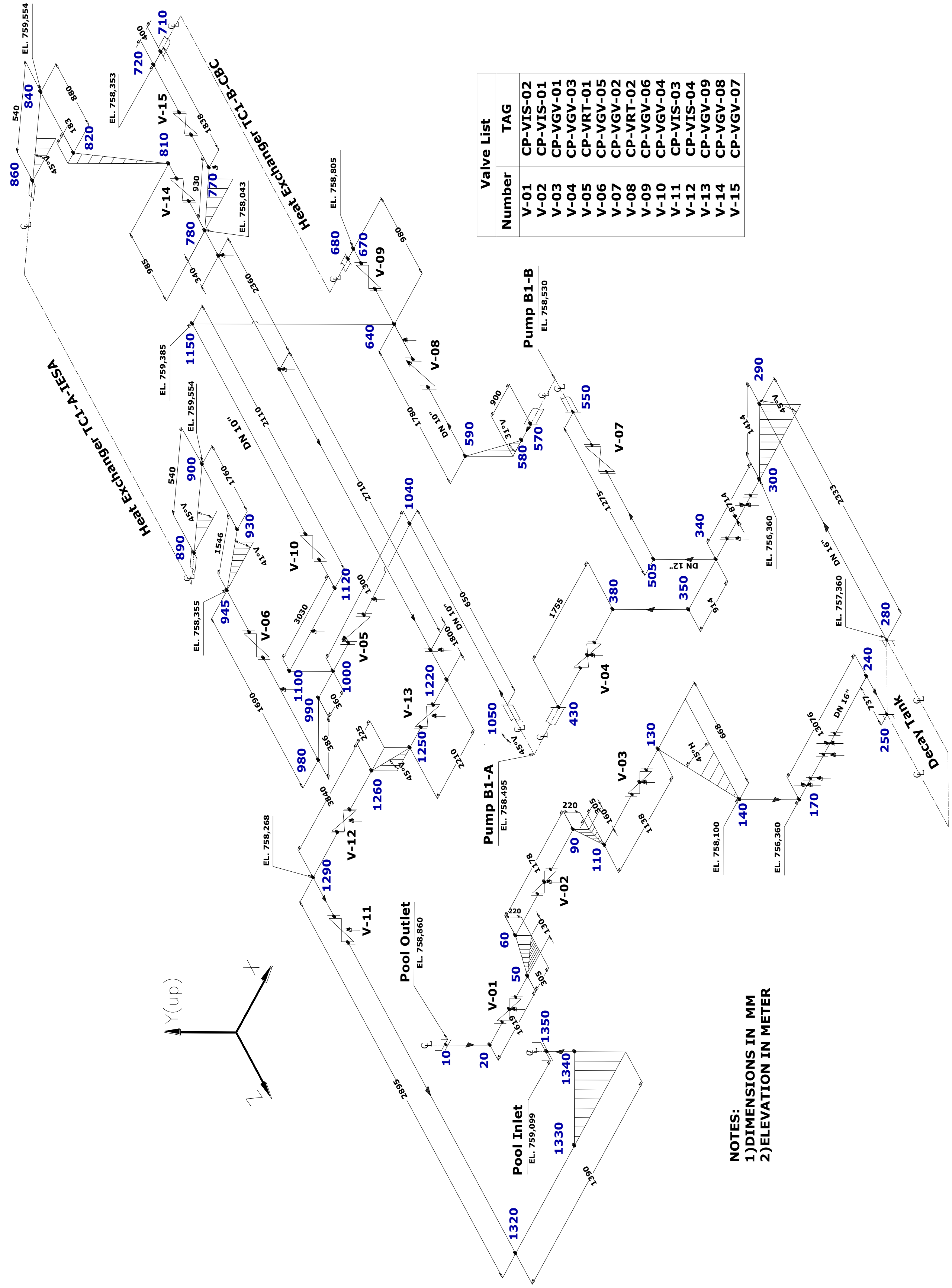

Figure 3. Isometric drawing for stress calculation of the IEA-R1 Primary Circuit

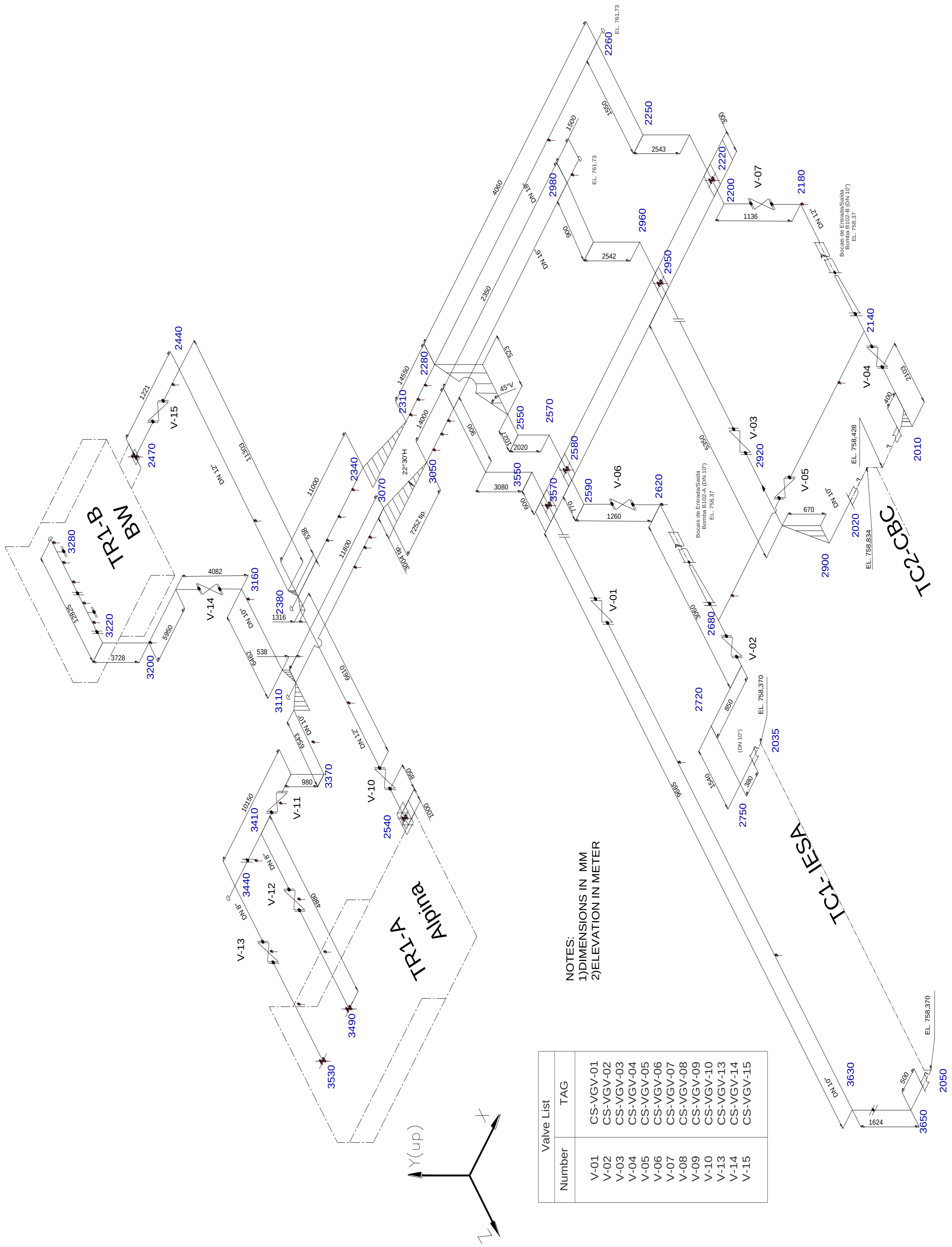

Figure 4. Isometric drawing for stress calculation of the IEA-R1 Secondary Circuit

3.1. General Data

The materials used in the analysis are: a stainless steel for the Primary Circuit Piping and carbon steel for the Secondary Circuit Piping. The physical and mechanical properties of the piping materials are shown in table 1 and the geometric properties of the piping in table 2.

Table 1: Materials Properties ([6], [8])

Material	Thermal Expansion (mm/mm°C)	Modulus of Elasticity (N/mm^2)	Stress (N/mm^2)	
			Allowable	Yield
SA-358 TP304 (stainless steel)	15.6×10^{-6}	195100	137.0	206.0
A 671 C65 (carbon steel)	11.8×10^{-6}	201000	112.5	241.5

Table 2: Piping Cross Sections Properties (mm)

Primary Circuit			Secondary Circuit		
DN	Outlet diameter	Thickness	DN	Outlet diameter	Thickness
250	274.64	3.175	200	219.07	8.18
300	311.15	3.175	250	273.05	9.27
350	355.60	3.960	300	323.85	9.52
400	410.37	3.581	400	406.04	9.52
			450	457.20	9.52

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

Table 3: Operation Modes

	Primary Circuit				Secondary Circuit			
Operation Mode	Pump		Heat Exchanger		Pump		Cooling Towel	
	B1A	B1B	TC1A	TC1B	B102A	B102B	TR1A	TR1B
#1	On	Off	On	Off	On	Off	On	Off
#2	Off	On	Off	On	Off	On	Off	On
#3	On	On	On	On	On	On	On	On

Table 4: Process condition [2]

	Primary Circuit	Secondary Circuit
Pressure (N/mm^2)	0.69	0.518
Temperature (°C)	43.9	37.3

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 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 nuclear safety class 2 and analyzed by section III subsection NC [5], and the secondary circuit piping was classified as non-nuclear and analyzed by B31.1 [6].

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.

A self-limiting stress is generated by restraining the deformation of the system and, generally, produces secondary stresses that can lead to ratcheting. Thermal expansion is a typical example of this load.

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

Table 5: *ASME* code Equations

Condition	Failure Mode	Equation		Stress categorization
		NC	B31.1	
Design	plastic collapse	8	11B	Primary
Service	ratcheting	10	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 (8) of NC-3652 of the *ASME* code [5] and equation (11B) of 104.8.1 of the ASME B31.1 [6]. These equations require that primary stress intensity resulting from design pressure; weight and other sustained loads meet the stress limit for the design condition.

To prevent ratcheting, the secondary stress criteria must be satisfied. This is accomplished by meeting equation (10) of NC-3653.2 of the *ASME* code [5] and equation (13A) of 104.8.3 of the ASME B31.1 [6]. These equations require that secondary stress intensity resulting from thermal expansion meet a level A and B service limits.

The equations for design and service conditions for ASME – NC and ASME – B31.1 are summarized in tables 6 and 7.

Table 6: Equations of ASME Code Section III subsection NC [5]

CONDITION: Design	**CONDITION: Thermal Expansion**
(Equation 8) $B_1 \times \frac{PD_o}{2t_n} + B_2 \times \frac{M_a}{Z} \le 1.5 \times S_h$ where: B_1, B_2 → primary stress indices; D_o → outside diameter of pipe; t_n → nominal wall thickness; P → internal design pressure; M_a → resultant moment loading on cross section due to weight and other sustained loads; Z → section modulus of pipe; S_h → basic material allowable stress at design temperature.	**(Equation 10)** $\frac{i \times M_c}{Z} \le S_A$ where: i → stress intensification factor; M_c → range of resultant moments due to thermal expansion; S_A → tensão admissível p/ cargas cíclicas: $S_A = f(1.25S_c + 0.25S_h)$; S_c → basic material allowable stress at room temperature (20° C); f → stress range reduction factor for cyclic loads $f = 1$ ($N \le 7000$ cycles).

Table 7: Equations of ASME Code - B31.1 [6]

CONDITION: Design	**CONDITION: Thermal Expansion**
(Equation 11B) $\frac{PD_o}{4t_n} + (0.75xi)\frac{M_a}{Z} \le 1.0 \times S_h$ where: i → primary stress intensification factor; D_o → outside diameter of pipe; t_n → nominal wall thickness; P → internal design pressure; M_a → resultant moment loading on cross section due to weight and other sustained loads; Z → section modulus of pipe; S_h → basic material allowable stress at design temperature.	**(Equation 13A)** $\frac{i \times M_c}{Z} \le S_A$ where: i → stress intensification factor; M_c → range of resultant moments due to thermal expansion; S_A → allowable stress range for expansion stresses: $S_A = f(1.25S_c + 0.25S_h)$; S_c → basic material allowable stress at room temperature (20° C) f → stress range reduction factor for cyclic loads $f = 1$ ($N \le 7000$ cycles).

4. STRESS ANALYSIS RESULTS

The piping calculation model, built in accordance with the routing of the lines presented in isometric drawings of the figures 3 and 4, 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 of piping according to:

- The Primary Circuit Piping – nuclear safety class 2 (*ASME* III, subsection NC [5]);
- The Secondary Circuit Piping – non- nuclear (ASME B31.1 [6]).

The maximum stress values calculated in the simulation do not exceed the limits set by *ASME* code. These results were obtained considering the:

- **primary stresses**, defined by equation (8) [5] for the Primary Circuit Nuclear Piping and equation (11B) [6] for the Secondary Circuit Non-Nuclear Piping;
- **secondary stresses**, defined by equation (10) [5] for the Primary Circuit Nuclear Piping and equation (13A) [6] for the Secondary Circuit Non-Nuclear Piping.

The 3 highest values of stress, obtained from the computing simulation, in all load cases for both conditions, are presented in the table 8.

Table 8: Stress Results Summary

	Condition	**Equation**	**Node**	**stress (N/mm^2)**		**Ratio**
				Nodal	**Allowable**	
Primary Circuit	Design	8	1000 898 780	70,7 63,4 47,4	205,5	0,34 0,31 0,23
	Thermal Expansion	10	340 129 99	115,0 101,0 83,0	205,5	0,56 0,49 0,41
Secondary Circuit	Design	11B	3010 3410 3480	79,1 50,3 42,1	112,5	0,70 0,45 0,37
	Thermal Expansion	13A	2160 2470 2100	79,4 70,2 53,3	168,7	0,47 0,42 0,32

The resulting stresses shown in table 8 are all bellow the limits of the ASME code.

5. CONCLUSIONS

The modifications in the IEA-R1 Primary Circuit Piping caused by:

- "duplication of primary coolant system to redundancy";
- "installation of decay tank";
- "replacement of the heat exchanger"

The modifications in the IEA-R1 Secondary Circuit Piping caused by:

- "installation of a new cooling tower"
- "withdrawal of check valves"
- "Replacement of secondary pumps"

This paper is the outcome of the structural analysis of the IEA-R1 coupled Primary and Secondary Circuits piping after these modifications and changes in the layout. The structural analysis developed in this paper is valid and can be considered correct, if the piping systems are according to the following:

- The piping, valves, tees, flanges and reductions must be without defects, it means: there is no denting, no pitting, no misalignments, no out of roundness and nor any corroded points on external or internal surface of the piping or fittings;
- The attachments, welded or threaded, that connects piping to piping, piping to equipment and piping to fittings (valves, tees, flanges, reductions) must be without defects, it means: there is no denting, no pitting, no misalignments, no out of roundness and nor any corroded points on external or internal surface of the fittings;

For the analysis purpose, the primary and secondary circuit of the reactor IEA-R1 was modeled as a whole, encompassing piping and equipment coupled together. The Primary Circuit Piping was classified as Nuclear Safety Class 2 (*ASME* III - subsection NC [5]) and the Secondary Circuit Piping was classified as non nuclear (ASME - B31.1 [6]). Piping calculation model was developed and the stress analysis was performed with the program *CAESAR II* [4] considering the load cases presented below:

"DW" - Dead Weight; **"P_D" -** Design Pressure; **"Th1/ Th2/ Th3" -** Thermal Expansion.

The values of the stresses calculated to the primary and secondary circuit piping do not exceed the limits set by *ASME* code.

To sum up, the modifications made in the piping routing of the primary circuit for the replacement of the heat exchanger, duplication of primary coolant system, installation of decay tank and installation of a new cooling tower, replacement of secondary pumps and withdrawal of check valves in the secondary circuit are guaranteed.

ACKNOWLEDGMENTS

We acknowledge the help of colleagues in doing this work, particularly the IEA-R1 staff, which have facilitated the documents assessment and/or guided us into internal areas of the IEA-R1 reactor building.

REFERENCES

1. "The *Babcock & Wilcox* Co., "Open-Pool Research Reactor – Instituto de Energia Atômica", Instruction Book – Vol. 1, 1957.
2. Maiorino, J. R. et al, "The conversion and power upgrade of the IEA-R1", "The International Reduced Enrichment for Test Reactor Conference" 1998, SP Brasil
3. Faloppa, A. A. and Ting, D. K. S, "Safety of research reactors: IEA-R1 Ageing management", AIEA – Projeto Arcal LXVIII "Seguridad de Reactores de Investigacion" 2002, Lima - Peru
4. *CAESAR II*, Structural Analysis Guide & Theory Reference Manual
5. *ASME* Boiler & Pressure Vessel Code, "Section III, Division 1, Subsection NC – Class 2 Components", *ASME*, 2007.
6. *ASME* Boiler & Pressure Vessel Code, "B31.1 – Power Piping", *ASME Code for Pressure Piping B31*, 2007.
7. *SOLIDWORKS* Premium 2010 SP4.0, Dassault Systems.
8. *ASME* Boiler & Pressure Vessel Code, "Section II, Part D – Properties (Materials)", *ASME*, 2007.