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STRUCTURAL EVALUATION OF IEA-R1 PRIMARY SYSTEM PUMP NOZZLES

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ABSTRACT

The IEA-R1 pumps of the primary coolant system may be required to withstand design and operational conditions.
IEA-R1 nuclear research reactor is an open pool type reactor operated by IPEN since 1957. The reactor can be operated up to 5MW heating power since it was upgraded in a modernization program conducted by IPEN.
The primary coolant system is composed by the piping system, decay tank, two heat pumps and two heat exchangers. In the latest arrangement upgrade of the primary system, conducted in 2014 as part of an aging management program, a partial replacement of the coolant piping and total replacement of piping and pump supports were done. As consequence, reviewed loads in the pump nozzles were obtained demanding a new evaluation of them.
The aim of this report is to present the structural evaluation of the pump nozzles, considering the new loads coming from the new piping layout, according to: API 610 code verification, Supplier loads and structural analysis applying finite element method, by using the ANSYS computer program, regarding ASME VIII Div 1 & 2 recommendations.

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. 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.

In 2014, the latest arrangement upgrade was conducted, as a part of ageing management program. A partial replacement of the coolant piping and total replacement of piping and pump supports were done. As consequence, reviewed loads in the pump nozzles were obtained demanding a new evaluation of them.

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 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 B1-A and/or B1-B, 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.

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

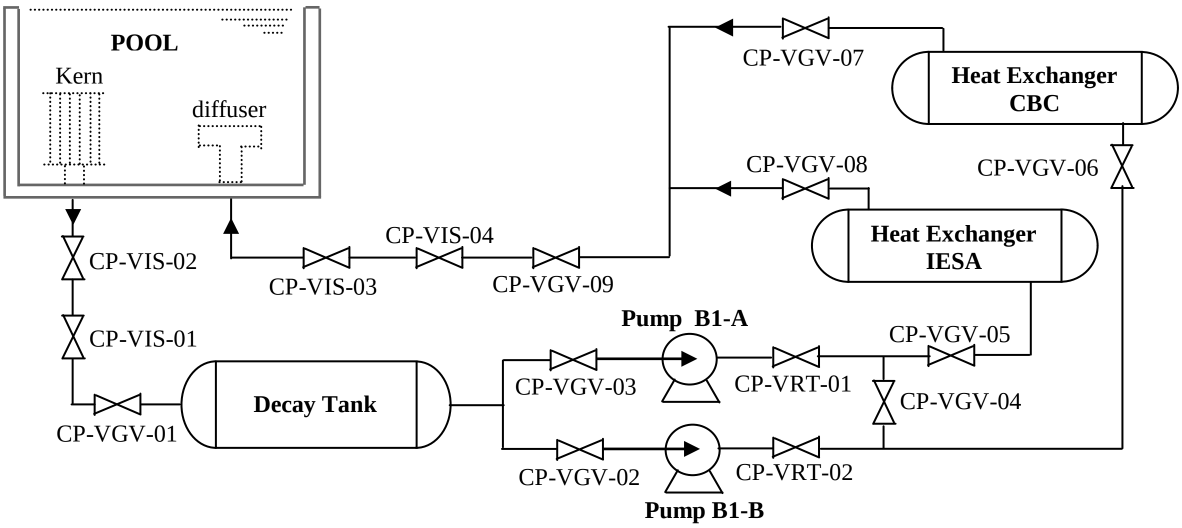


Figure 1: Simplified flowchart of the Primary Circuit of the IEA-R1 reactor

To better analyze the system, in a comprehensive manner, a 3D model of the complete primary circuit was modeled using the program "*SOLIDWORKS*" [4]. This work was initiated with the preparation of a complete isometric drawing of piping, piping supports and all components of the primary circuit based on an as-built.

The resultant 3D model is shown in the Figure 2.

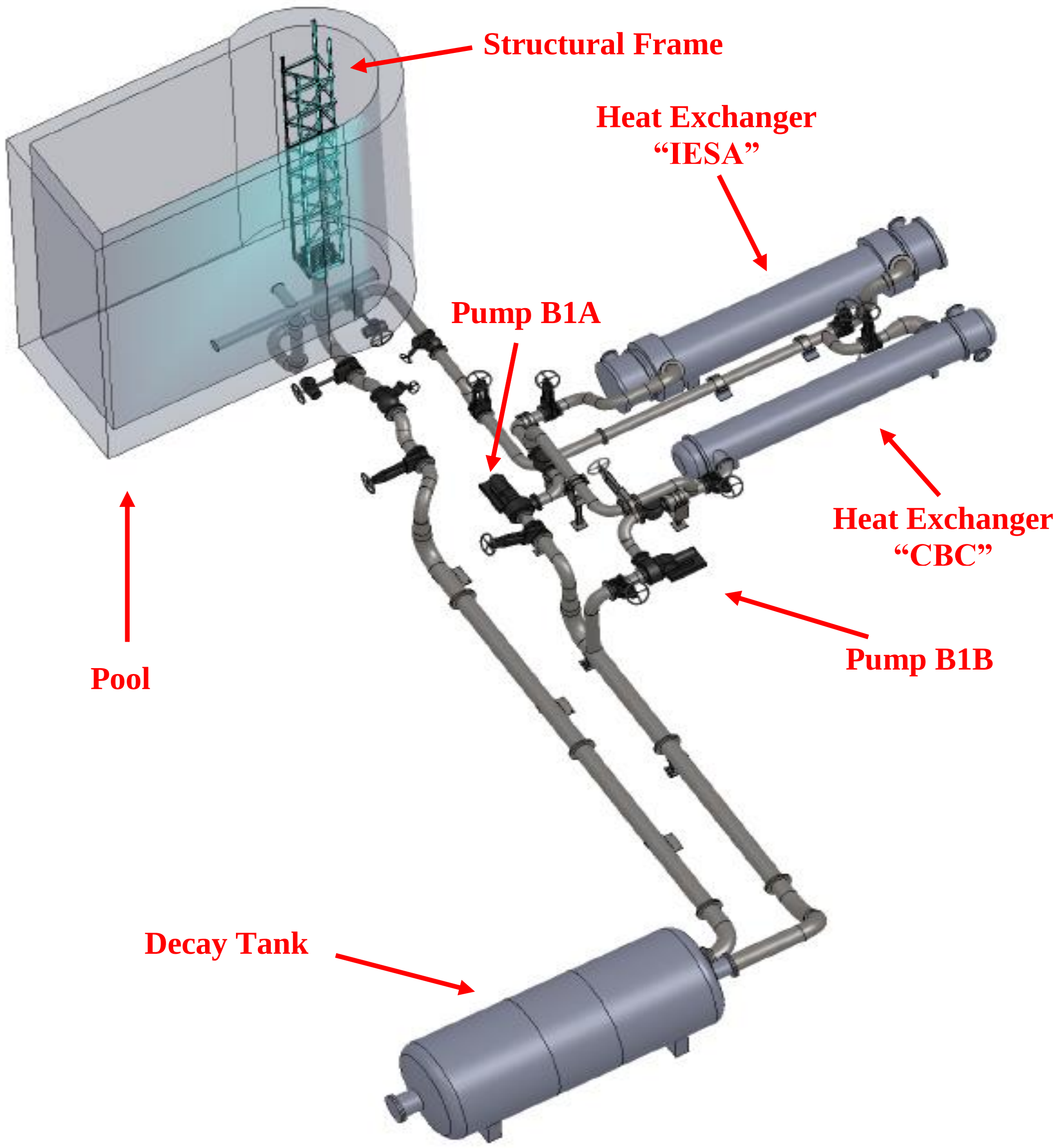


Figure 2: 3D model of the Primary Circuit of the IEA-R1 reactor

3. PUMP DESCRIPTION

The IEA-R1 Primary Circuit has two centrifugal pumps [5] that operate in an alternate way. The main function of the pumps is to feed demineralized water, extracting the water from the outlet pool nozzle and leading it to the ^{16}N decay tank and heat exchangers, and finally injecting it in the pool through the inlet pool nozzle.

Simplified geometry of the IEA-R1 Primary Circuit pumps B1-A e B1-B is shown in Figure 3, and the general dimensions in Table 1.

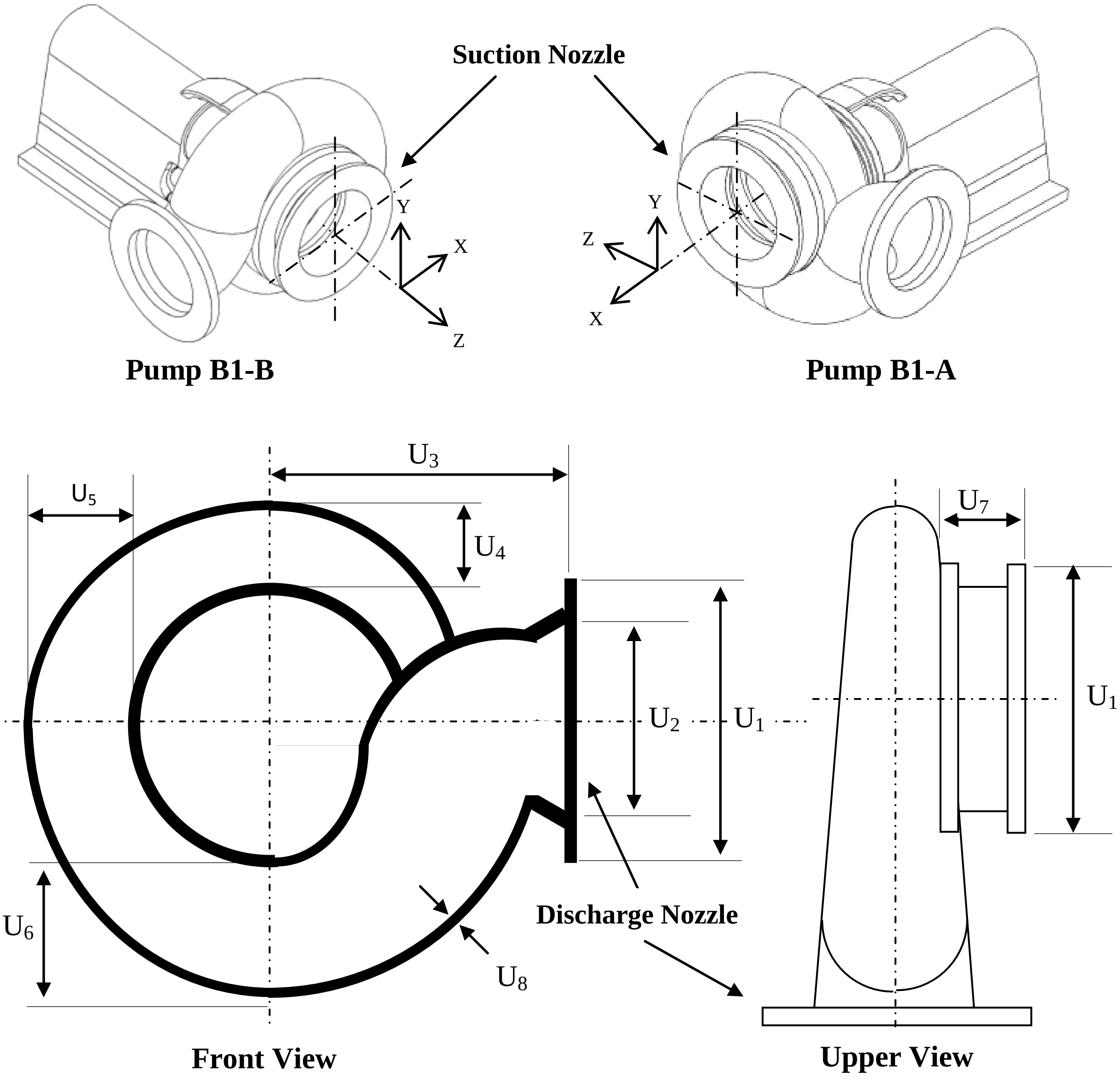


Figure 3: Schematic Drawing of the Pump Nozzles

Table 1: General Dimensions of Pumps B1-A and B1-B (mm)

U_1	=	395.0	U_4	=	85.8	U_7	=	100.0
U_2	=	250.0	U_5	=	122.3	U_8	=	14.0
U_3	=	425.0	U_6	=	153.4			

3.1. General data

Physical and mechanical properties of the pump casing material and the process data for design and operation modes of the IEA-R1 primary circuit are shown in Table 2 [6].

Table 2: General data

Material Properties				
Identification	Thermal Expansion (mm/mm°C)	Modulus of Elasticity (N/mm^2)	Stress (N/mm^2)	
			Allowable	Yield
A351 CF8	$15.6x10^{-6}$	195000	138.0	205.0
Process Data				
Pressure (N/mm^2)	Design - 0.69 Operation - 0.29	Temperature (°C)	Design - 65.6 Operation - 43.9	

3.2. Applied loads

The final loads applied to pump suction and discharge nozzles, obtained from piping stress analysis report of the Primary Circuit of IEA-R1 nuclear research reactor, are shown in Table 3 for the **"as built"** condition [7]. The reference axis of nozzle pumps can be seen in Figure 3. Pump B1-A loads showed to be always greater than pump B1-B ones.

The following load cases were considered:

1(OPE) ⇨ weight (pipe+water+valve+flange) + thermal (pump B1A + TC(1ESA) – "on")
2(OPE) ⇨ weight (pipe+water+valve+flange) + thermal (pump B1B + TC(CBC) – "on")
3(SUS) ⇨ weight (pipe+water+valve+flange)

Table 3: Final loads on B1-A pump nozzles

Nozzle	Load Case	Force (N)			Moment (Nm)		
		X	Y	Z	X	Y	Z
Suction	1(OPE)	-4723	5237	101	89	-307	10900
	2(OPE)	-4528	4956	194	106	-516	10558
	3(SUS)	-292	1657	5	4	-16	-7
Discharge	1(OPE)	-200	576	539	303	391	-205
	2(OPE)	-343	266	297	223	296	-81
	3(SUS)	-6	566	64	305	41	-196

4. PUMP NOZZLES EVALUATION

The new loads applied to suction and discharge pump nozzles, that arose due to partial replacement of the Primary Circuit piping of IEA-R1 nuclear research reactor in 2014, were evaluated according to:

√ API 610 Code – comparison of the loads applied to the nozzles with the allowable loads of the code [8];

√ Supplier Allowable Loads – comparison of the loads applied to the nozzles with the supplier allowable loads [5];

√ Stress Analysis – development of a structural analysis of the pump nozzles according to ASME VIII Div. 1 & 2 [9] [10].

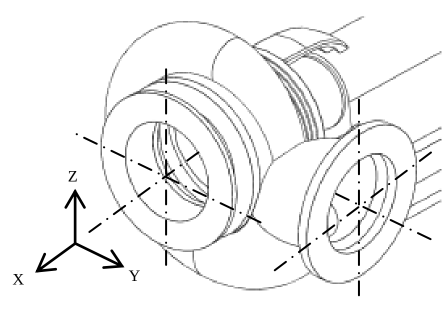
4.1. API 610 Code

API 610 code specifies requirements for the design, building and operation of centrifugal pumps for petroleum, petrochemical and natural gas industries.

The item 5.5 of API 610 code shows the "Table 4 – Nozzle Loadings", which lists the allowable loads for the pumps nozzles, following the layout of the suction and discharge nozzles of the pump. The loads allowed for the IEA-R1 Primary Circuit pumps are shown in Table 4.

Table 4: API 610 Allowable Loads on Pump Nozzles

Description		Suction (End Nozzle)	Discharge (Side Nozzle)
Forces (N)	FX	6670	5340
	FY	5340	6670
	FZ	4450	4450
Moments (Nm)	MX	5020	2440
	MY	2440	5020
	MZ	3800	3800



In the case that loads applied to the nozzles do not fulfill the limits indicated in "Table 4 – Nozzle Loadings" of API 610 code, the application of Annex F is recommended. The procedure of Annex F defines that the applied loads have to satisfy the proposed conditions in item F.1.2, according to:

a) The individual component forces and moments acting on each pump nozzle flange shall not exceed the range specified in Table 4 by a factor greater than 2;

b) The resultant of the applied forces and the resultant of the applied moments acting on each pump nozzle flange shall satisfy the appropriate interaction equations 1 and 2:

$$[FRS_A/(1.5 \text{ x } FRS_{T4})] + [MRS_A/(1.5 \text{ x } MRS_{T4})] \leq 2 \quad (1)$$

$$[FRD_A/(1.5 \text{ x } FRD_{T4})] + [MRD_A/(1.5 \text{ x } MRD_{T4})] \leq 2 \quad (2)$$

c) The applied component forces and moments acting on each pump nozzle flange shall be translated to the centre of the pump. The magnitude of the resultant applied force (FRC_A), the resultant applied moment (MRC_A), and the applied moment shall be limited by equations 3, 4 and 5.

$$FRC_A < 1.5 \times (FRS_{T4} + FRD_{T4}) \quad (3)$$

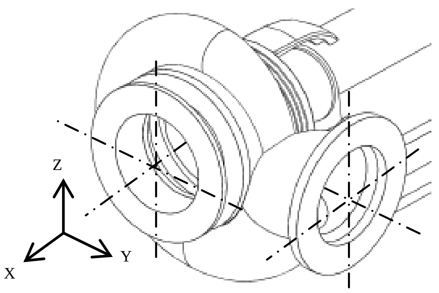
$$\left| MYC_A \right| < 2.0 \times (MYS_{T4} + MYD_{T4}) \quad (4)$$

$$MRC_A < 1.5 \times (MRS_{T4} + MRD_{T4}) \quad (5)$$

4.2. Supplier Allowable loads

Allowable loads to the pump nozzles of Primary Circuit of Nuclear Research Reactor IEA-R1 are shown in Table 5.

Table 5: Supplier Allowable Loads for the Pump Nozzles

Description		Suction (End Nozzle)	Discharge (Side Nozzle)	
Forces (N)	FX	9200	7350	
	FY	7350	9200	
	FZ	6150	6150	
Moments (Nm)	MX	6900	3350	
	MY	3350	6900	
	MZ	5250	5250	

4.3. Stress Analysis – ASME VIII Div. 1 & 2

ASME VIII, Division 1, doesn't incorporate the requirements of "Design by Analysis" of ASME VIII, Division 2, which is usually employed in the stress analysis of equipment nozzles.

Nevertheless, the paragraph **"U-2(g)"** of ASME VIII, Division 1, allows that the designer develops procedures for equipment design, where the code doesn't have specific rules, "setting" the design criteria of ASME VIII, Division 1. These design criteria are satisfied applying Part 4 or Part 5 of ASME VIII, Division 2, with the allowable stress from ASME VIII, Division 1.

Therefore, in order to evaluate the protection against plastic collapse, the results of a linear elastic stress analysis of a component, subject to loads due to design pressure and mechanical loads, may be classified and compared to associated limits, with the allowable stress $\mathbf{S_H}$ = 138.0 N/mm^2 from ASME VIII, Division 1.

The equivalent stresses are calculated using the Von Mises criterion. Table 6 shows categories of equivalent stresses and limits defined according to ASME VIII, Division 2.

Table 6: Stress Categories & Limits

$\mathbf{P_m}$	→	General Primary Membrane Stress
$\mathbf{P_L}$	→	Local Primary Membrane Stress
Q	→	Secondary Stress
Limits	→	$\mathbf{P_m \leq S_H}$; $\mathbf{P_L \leq 1.5xS_H}$; $\mathbf{P_L + Q \leq 3.0xS_H}$

The sections of a nozzle recommended by WRC-429 [11] to analyze equivalent stresses are shown in Figure 4 and listed in Table 7. These equivalent stresses will be linearized and classified, as $\mathbf{P_m}$, $\mathbf{P_L}$ and/or **Q**, and compared to the limits shown in Table 7.

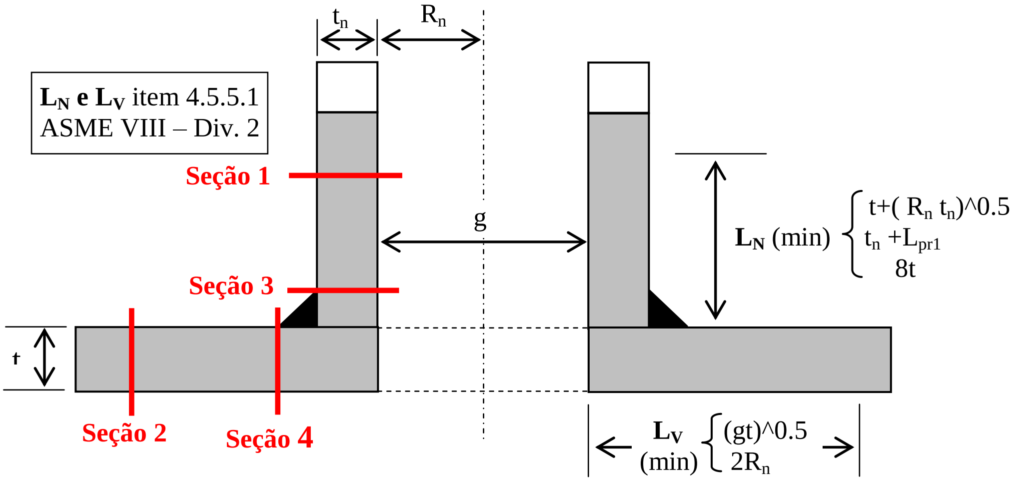


Figure 4: Nozzle schematic drawing

Table 7: Stress analysis of nozzles – Sections and Limits

Section	Position	Stress	
		Design	**Operation**
1 2	nozzle area near reinforcement limit vessel area near reinforcement limit	$P_L \leq 1.5xS_H$	$P_L + Q \leq 3.0xS_H$
3 4	at nozzle area inside reinforcement area at vessel area inside reinforcement area	$P_m \leq S_H$	$P_m \leq S_H$

5. RESULTS

5.1. API 610 Code

Table 8 shows that the loads applied to the discharge pump nozzle are less than the limits of Table 4 of the item 4.1. Otherwise, the component force FZ and the bending moment MY applied to the suction pump nozzle do not fulfill the limits of Table 4 of the item 4.1.

Table 8: API 610 Allowable Loads x Pump Nozzles Loads

Description		API 610 (Table 4)	IEA-R1 Pump	
			Suction	Discharge
Forces (N)	FX	6670	-4723	-200
	FY	5340	-101	-539
	FZ	**4450**	**5237**	576
Moments (Nm)	MX	5020	89	303
	MY	**2440**	**-10900**	205
	MZ	3800	-307	391

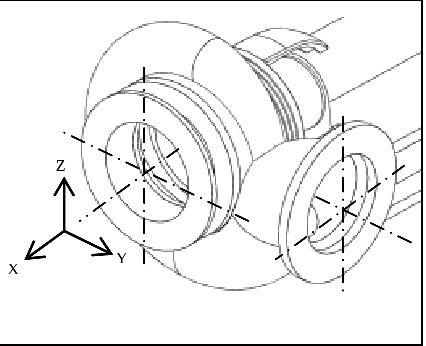


Table 9 shows the results of application of API 610 annex F, item F.1.2, to the nozzles pump. The bending moment MY applied to the suction pump nozzle is beyond the allowable limit of the API 610 code.

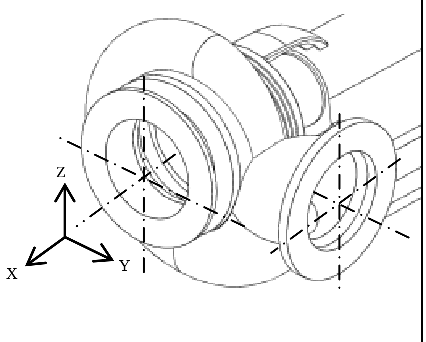
Table 9: API 610 Annex F verification

F.1.2 (a)	Relationship [applied forces (moments) x allowable loads] must be < 2 Suction → **Not OK !** (MY → 2 x 2440 < 10900) Discharge → Ok !
F.1.2 (b)	Final applied forces (moments) have to obey equations 1 e 2 Equation 1 → Ok ! (1.56 < 2) Equation 2 → Ok ! (0.11 < 2)
F.1.2 (c)	Applied forces (moments) translated to the centerline of the pump, have to obey equations 3, 4 e 5 Equation 3 → Ok ! (7637 < 28890) Equation 4 → Ok ! (11963 < 14920) Equation 5 → Ok ! (11990 < 20250)

5.2. Supplier Allowable loads

Table 10 shows the applied loads to the pump nozzles versus supplier allowable loads. It can be seen that the bending moment MY applied to the suction pump nozzle is beyond the supplier allowable limit.

Table 10: Supplier Allowable Loads x Pump Nozzles Loads

Description		Supplier	IEA-R1 Pump		
			Suction	Discharge	
Forces (N)	FX	9200	-4723	-200	
	FY	7350	-101	-539	
	FZ	6150	5237	576	
Moments (Nm)	MX	6900	89	303	
	MY	3550	**-10900**	205	
	MZ	5250	-307	391	

5.3. Stress Analysis Results

The stress analysis of the pump nozzles of Primary Circuit of Nuclear Research Reactor IEA-R1 was developed taking into account the procedure of item 4.3.

Numerical simulation was realized within the following steps:

- development of a solid three-dimensional drawing of the pump with SolidWorks program (see Figure 5);

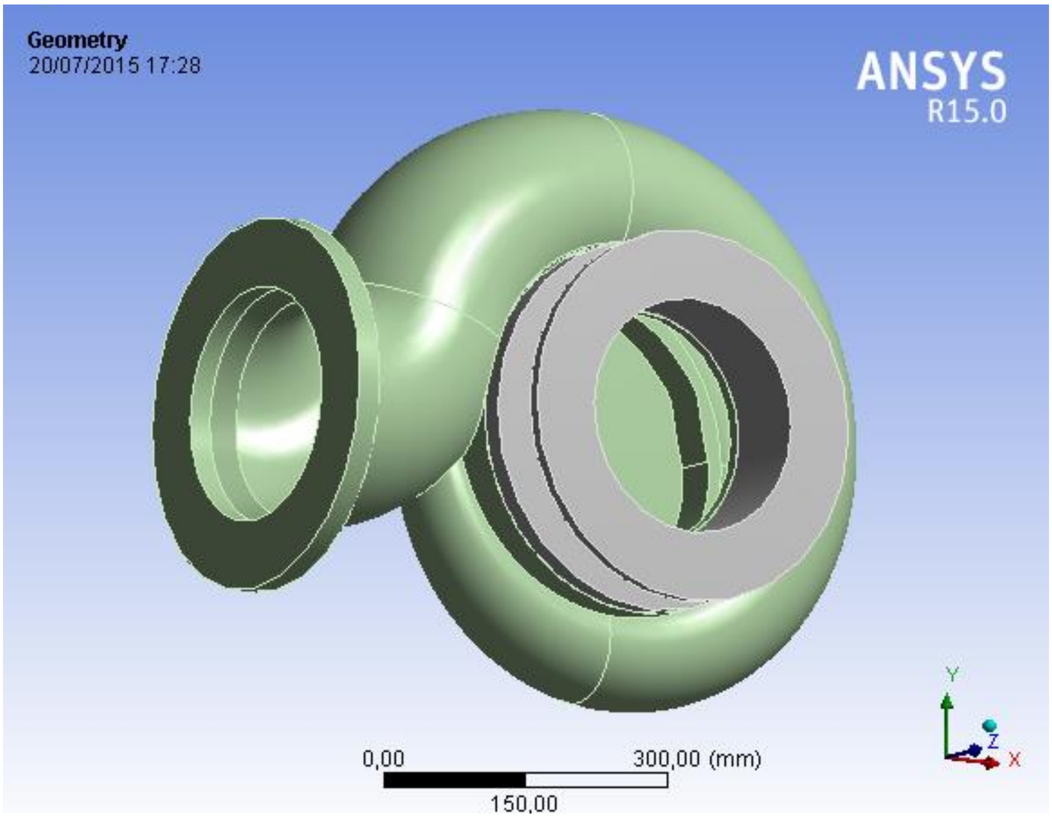


Figure 5: 3D Model of the IEA-R1 pump

- development of the structural model for the pump, inputting the 3D drawing of the pump in the ANSYS [12] computer program and applying the solid finite element with 20 nodes and 3 degrees of freedom (displacement Ux, Uy e Uz) per node;

- build and test various finite element meshes, in order to select an appropriate one to the nozzle pump analysis (see Figure 6);

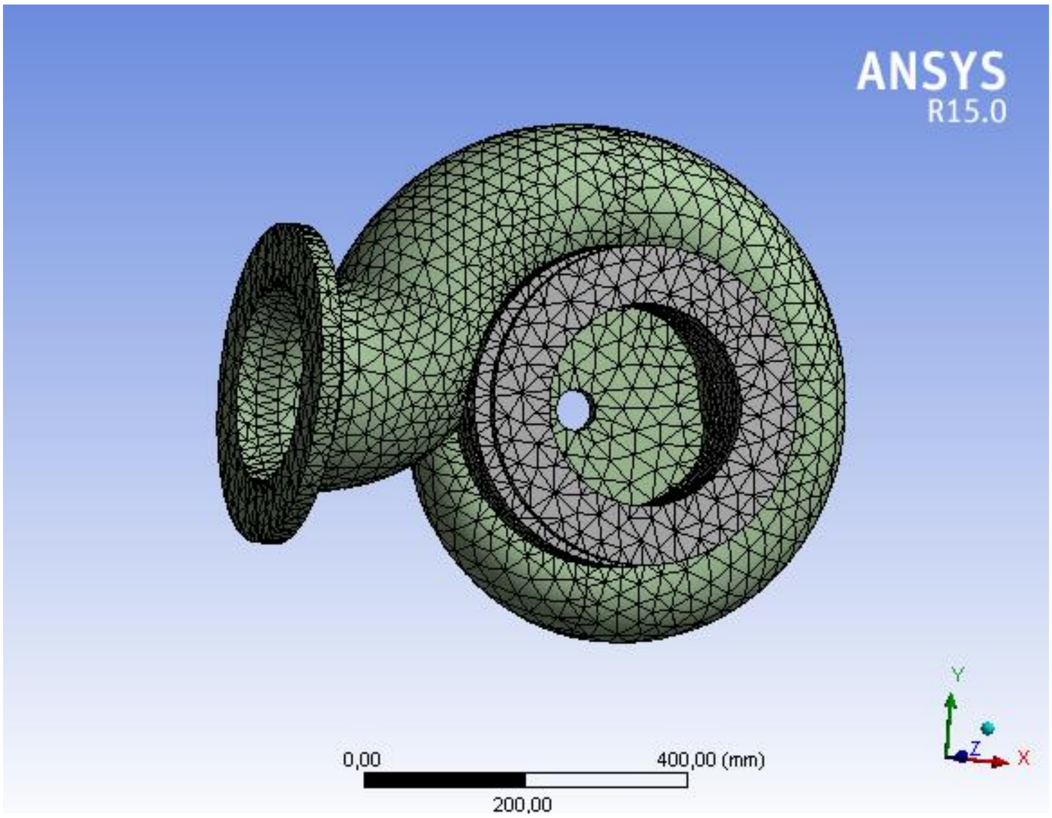


Figure 6: IEA-R1 Pump – Finite Element Mesh

- apply the boundary conditions to the model of the pump, in order to simulate the existing connection between the pump body and the reactor building**;**

- apply the loads, forces and moments from Table 3 of item 3.2 and the internal pressure from Table 2 of item 3.1 to the structural model of the pump.

The results of the numerical simulation are shown in Table 11. The stresses in this table are average values between the maximum stresses and the correspondent stresses of the opposite side of the component thickness.

The results of the Table 11 and Figures 7 and 8 show that the equivalent stress computed to suction and discharge pump nozzles of Primary Circuit of Nuclear Research Reactor IEA-R1, for the design and operational conditions, comply with the prescribed limits of ASME code VIII, Div. 2.

Table 11: Stress verification (N/mm^2)

Nozzle	Section	Design		Operation	
		Computed	Allowable	Computed	Allowable
Suction	1	22.5	207.0	202.0	414.0
	2	76.0	207.0	35.0	414.0
	3	22.5	138.0	130.0	138.0
	4	22.5	138.0	35.0	138.0
Discharge	1	22.5	207.0	16.0	414.0
	2	22.5	207.0	16.0	414.0
	3	22.5	138.0	16.0	138.0
	4	22.5	138.0	16.0	138.0

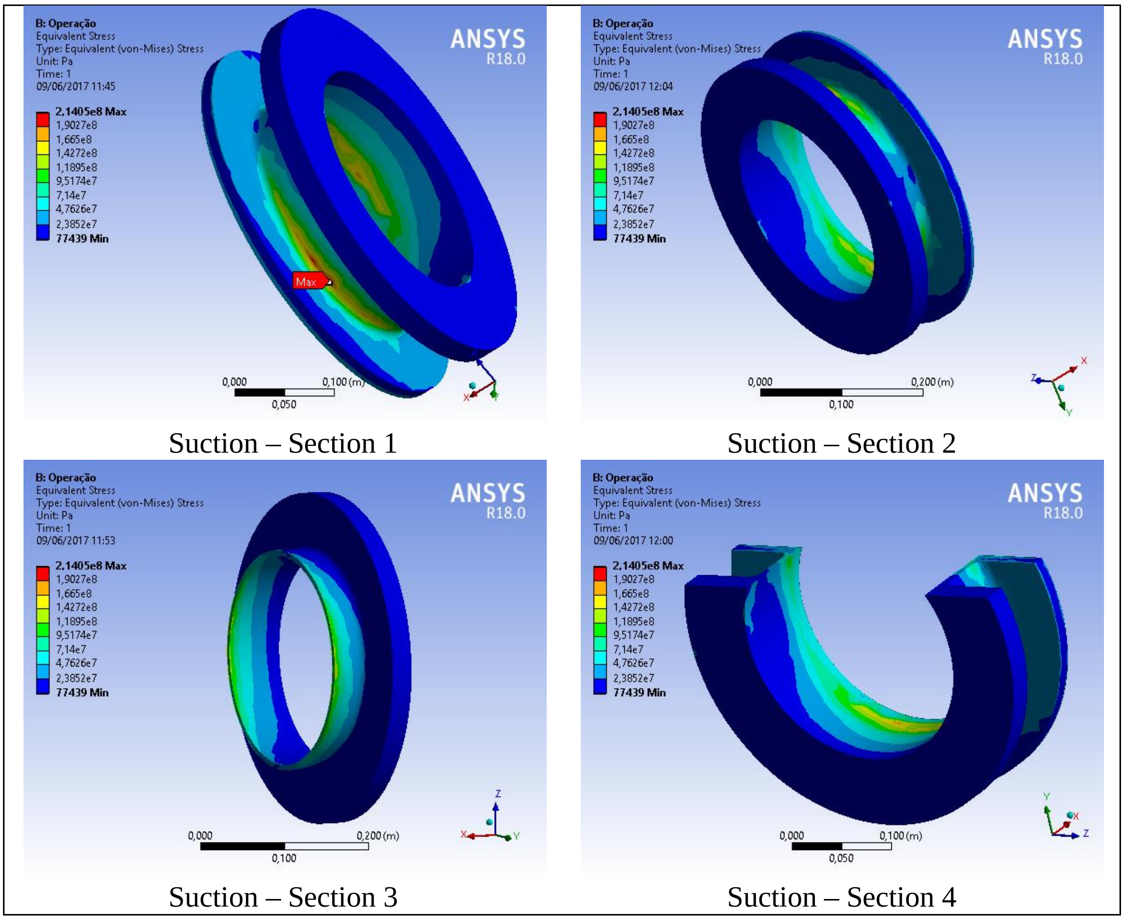
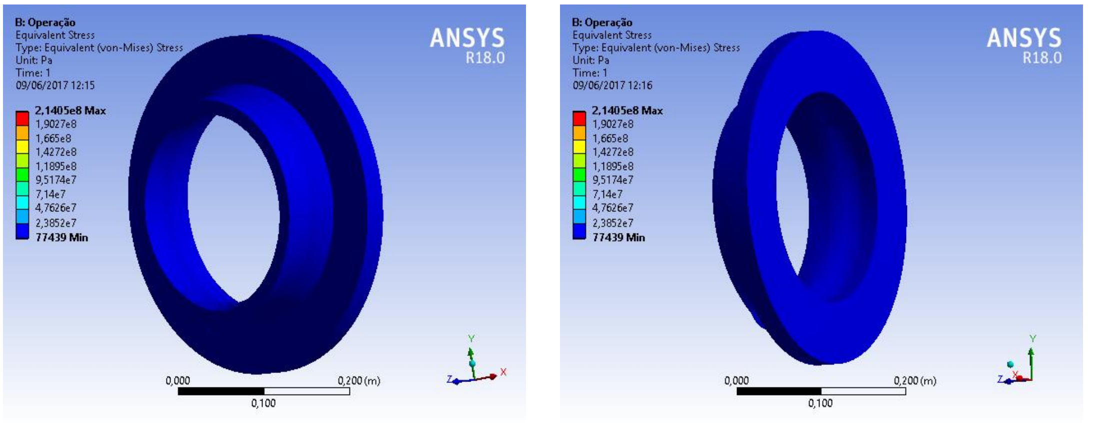


Figure 7: IEA-R1 Suction Pump Nozzles – Stresses in Sections



Discharge – Section 1 & 2　　Discharge – Section 3 & 4

Figure 8: IEA-R1 Discharge Pump Nozzles – Stresses in Sections

6. CONCLUSIONS

The evaluation of the Pump Nozzles of Nuclear Research Reactor IEA-R1 of Primary Circuit was developed according to the following steps:

√ API 610 Code – it was verified the pump nozzles applied loads versus prescribed loads in Table 4 of the API 610 code and also the procedure of the Annex F. The Pump Nozzle Suction shear force and bending moment are beyond the limits of the Table 4 of API 610 code. The procedure of Annex F does not fulfill the bending moment applied to the Pump Nozzle Suction;

√ Supplier Allowable Loads – it was verified that the bending moment applied to the Pump Nozzle Suction is greater than the limits proposed by the pump supplier.

In order to guarantee the safe operation of the pump it is needed:

√ Structural Analysis – development of a stress analysis of pump nozzles by building a numerical model and applying finite element method with ANSYS computer program and verification of the prescribed limits of ASME VIII Division 1 & 2;

√ Operational Control – to provide a monitoring system for the pumps operation, which has a special feature of capturing any pump vibrations.

A structural analysis was developed and the results showed that the equivalent stress computed to suction and discharge pump nozzles of Primary Circuit of Nuclear Research Reactor IEA-R1, taking into account the design and operational conditions, to comply with the prescribed limits of ASME code VIII, Div. 2.

The pumps of Primary Circuit of Nuclear Research Reactor IEA-R1 have a monitoring system on line with the plant operation, in order to prevent operational incidents and high level of pump vibration.

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