NEW CORE CONFIGURATIONS FOR THE IPEN/CNEN-SP IEA-R1 RESEARCH REACTOR USING HIGHER DENSITY FUELS

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ABSTRACT

This study was performed considering prospective candidates for the IEA-R1 research reactor core. Some neutronic calculations were developed in order to pick up a new core configuration and push forward the thermal-hydraulic and safety analysis. The current IEA-R1 core configuration is a 5x5 (5MW) using U_3O_8-Al and U_3Si_2-Al as fuels, containing, respectively, 2.3 gU/cm^3 and 3.0 gU/cm^3. The new core configuration will be smaller for several reasons (e.g., better fuel utilization and neutron fluxes). In order to achieve such a smaller arrangement, the U-fuel density has to be increased. In the current study, configurations with 4.8gU/cm^3 U_3Si_2-Al fuels were tested using the software MCNP and a set of new core configurations for the IPEN/CNEN-SP research reactor has been created and discussed.

1. INTRODUCTION

This study was proposed in order to change the current IEA-R1 research reactor core configuration (5x5), through neutronic and thermal-hydraulic (TH) calculations, establishing a set of new prospective candidates. The neutronic analysis of nine different core configurations was performed, starting from 3x3 up to higher ones, calculating the multiplication factor (K_{eff}) for the clean core and the power density profile using the code *MCNP5* [1]. The composition of the fuel and control elements is LEU U_3Si_2-Al (4.8gU/cm^3, 42,5% of U_3Si_2 in the volume). The power density was calculated for each fuel plate in order to find out the hottest one. Thus, a steady-state thermal-hydraulic analysis took place to calculate the temperature profile at the hottest fuel plate per configuration. The *nodal method* combined with the *Engineering Equation Solver* (EES) program [2] was used and the TH margins were checked. In summary, the main target of this study is to reach new smaller core configurations for the IEA-R1 research reactor, once this study has already been performed for other research reactors, providing better neutron fluxes and fuel utilization.

2. THE IEA-R1 RESEARCH REACTOR

The IEA-R1 research reactor core is composed of LEU (19.9% in U^{235}) U_3O_8-Al and U_3Si_2-Al fuels containing, respectively, 2.3 gU/cm^3 (33% of U_3O_8 in volume) and 3.0 gU/cm^3 (26% of U_3Si_2 in volume). It's a pool-type reactor and has light water as coolant [3]. In 2007, the IEA-R1 heat exchanger was replaced, alloying, reliably, a power increase from 3MW up to 5 MW. The current IEA-R1 core arrangement has 20 fuel elements (FE), each one with 18 fuel plates; 4 control elements (CE), containing 12 fuel plates and 2 control rods; 1 beryllium irradiator (BI) and graphite (GR) and beryllium (BR) reflectors surrounding the core. The IEA-R1 current core configuration is depicted in Fig 1. The control rods are composed of Ag-In-Cd alloy.

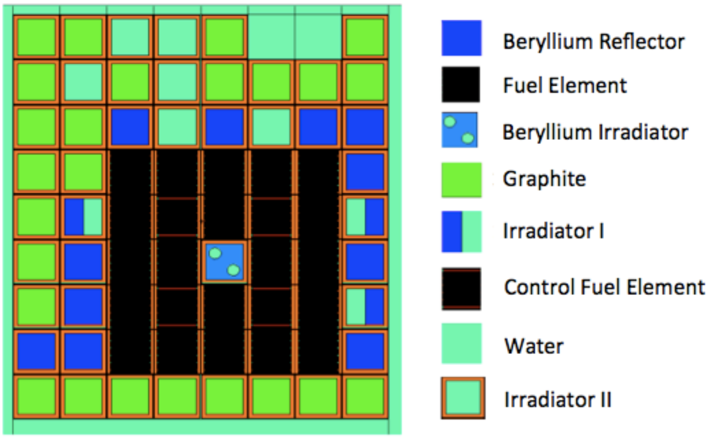

Fig 1. The current IEA-R1 core configuration (5x5) top view (MCNP)

This configuration was changed into others, changing the U-fuel density to 4.8gU/cm^3 (using only U_3Si_2-Al), allowing arrangements with less fuel elements (FE).

3. NEW CORE CONFIGURATIONS

3.1 Neutronic Analysis

New configurations were tested starting from 3x3 as shown in from Fig 2 to Fig 4. The simulations were performed with *MCNP5*, using the Mont Carlo approach to solve the real *transport equation* [4]. The code NJOY [5] was also applied to upgrade the cross section library (ENDF/B-VII) also considering the temperature effects. Further information is found in Table 1. Check the Fig. 1 in order to identify, properly, each element in the next pictures.

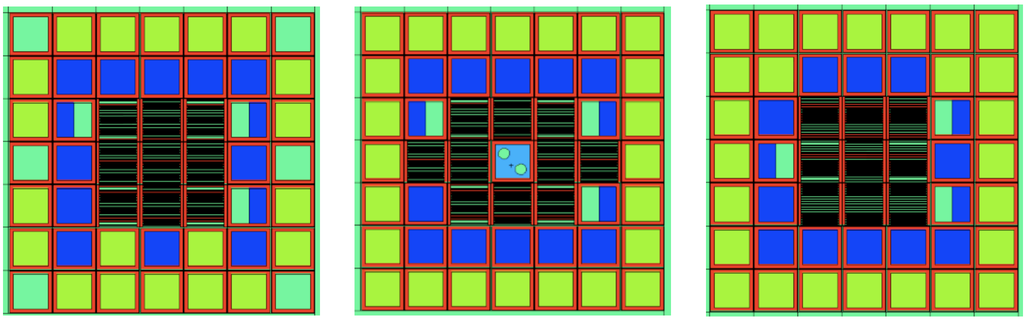

Fig 2. Configuration 5: 5FE+4CE - Configuration 6: 6FE+4C - Configuration 7: 7FE+2CE

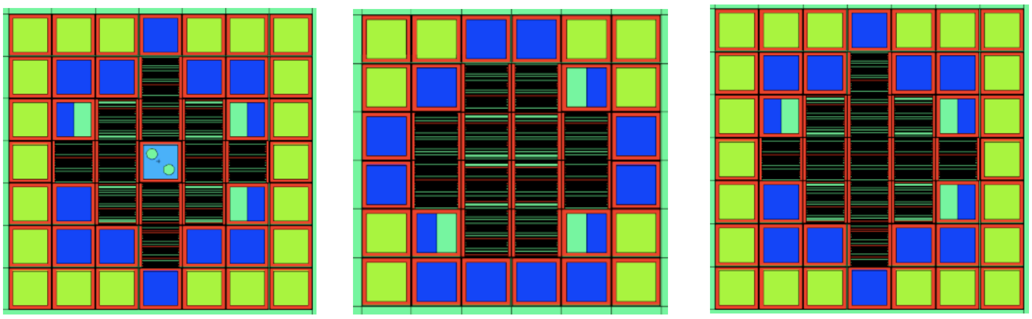

Fig 3. Configuration 8: 8FE+4CE - Configuration 8*: 8FE+4CE - Configuration 9: 9FE+4CE

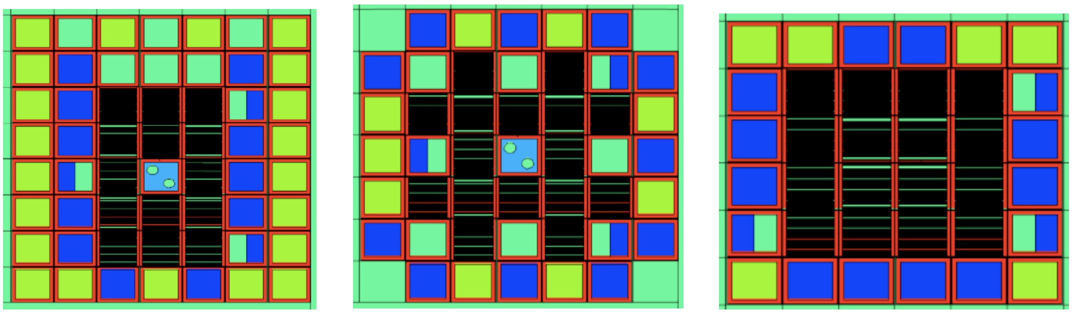

Fig 8. Configuration 10: 10FE+4CE - Configuration 12: 12FE+4CE - Configuration 12*: 12FE+4CE.

It's important to mention that all parameters in the Table 1 were calculated for clean and "ideal" cores, meaning that there was no impurities in the fuel, only the main components: U_3Si_2-Al and Al (cladding). Depending on the core, impurity levels may change considerably the multiplication factor (K_{eff}) and the neutron flux profile.

	All control rods withdrawn				All control rods Within				
		S. Dev.				S. Dev.			
Core	**K_{eff}**	**MCNP**	**pcm**	**ρ_{ex}**	**Keff**	**MCNP**	**pcm**	**ρ_{SM}**	**Δρ**
5	1.00312	0.00030	29.81	311.03	0.79186	0.00031	49.44	-26284.95	-25973.92
6	1.01671	0.00033	31.92	1643.54	0.79282	0.00031	49.32	-26132.04	-24488.50
7	1.03063	0.00032	30.13	2971.97	0.88447	0.00029	37.07	-13062.06	-10090.09
8	1.06388	0.00031	27.39	6004.44	0.84794	0.00031	43.12	-17932.87	-11928.44
8*	1.08691	0.00031	26.24	7996.06	0.84976	0.00029	40.16	-17680.29	-9684.22
9	1.09327	0.00034	28.45	8531.29	0.89129	0.00030	37.76	-12196.93	-3665.64
10	1.09849	0.00029	24.03	8965.94	0.88789	0.00031	39.32	-12626.56	-3660.62
12	1.11973	0.00034	27.12	10692.76	0.91097	0.00032	38.56	-9773.10	919.66
12*	1.15367	0.00030	22.54	13320.10	0.95053	0.00031	34.31	-5204.46	8115.64

Table 1: Clean Core Multiplication Factor (k_{eff}), Excess of Reactivity (ρ_{ex}), Shutdown Margin (ρ_{SM}) and Total Control Element Worth ($\Delta\rho=\rho_{ex}+\rho_{SM}$).

Fig 11 shows the multiplication factor variation with the core configuration and Fig 12, the core-average power density per arrangement.

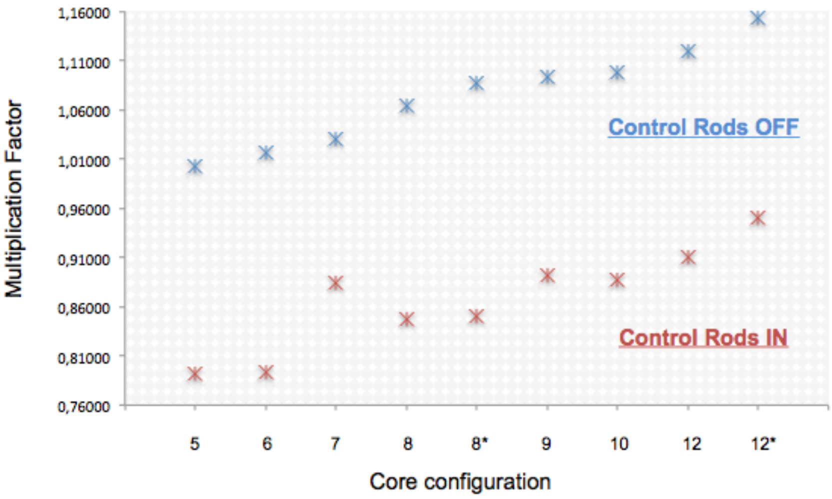

Fig 11. Multiplication Factor Variation vs. Core Configuration

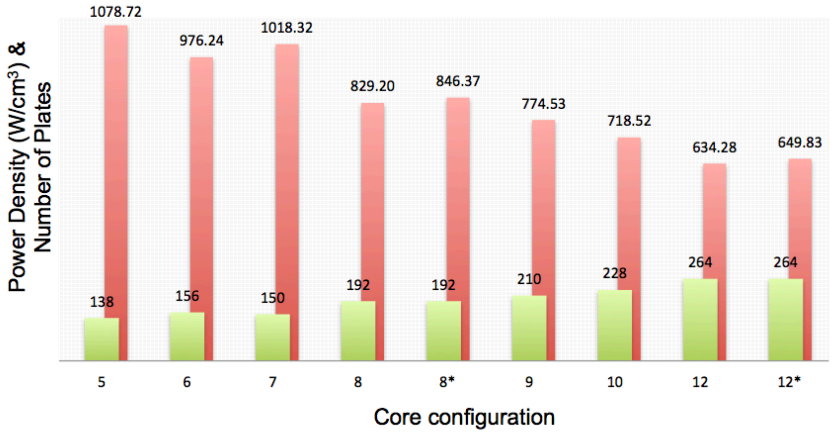

Fig 12. Core-Average Power Density per Configuration

For each new configuration, the hottest plate, the one in which the higher average power density appears, was found and the axial power density profile (in 21 nodes) was calculated in order to determine the temperature distribution and the TH margins. The hottest fuel plate average power density for each configuration is depicted in Table 2. Fig 13 shows the axial peaking factor (local power density/core-average power density) profile for each hottest fuel plate per arrangement.

Core	Average Power Density [W/cm^3]
5	1447.88
6	1438.41
7	1458.56
8	1281.14
8*	1508.53
9	1113.84
10	1179.19
12	1056.64
12*	1259.23

Table 2: Average Power Density in the Hottest Fuel plate per configuration.

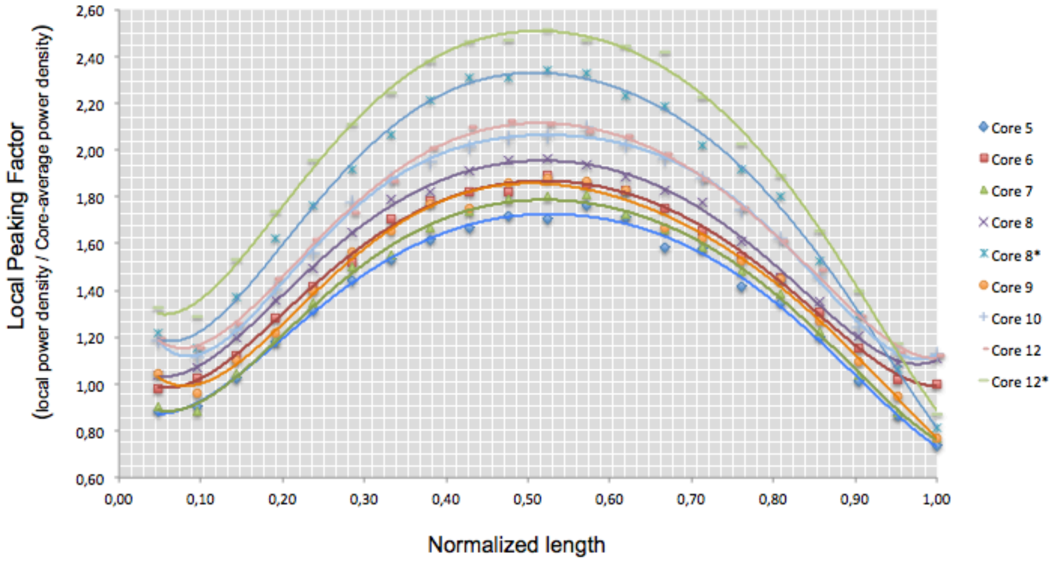

Fig 13. Local Peaking Factor vs. Hottest Fuel Plate Axial Normalized length

3.2 Thermal-Hydraulic Analysis

In this section, it’s presented the temperature profile in the hottest fuel plate for each new configuration, as well as the verification of the Thermal-Hydraulic (TH) margins, both considering a stead-state behaviour. The study was performed using the *Engineering Equation Solver* program along with the *nodal method*. The distribution of nodes was created as follows: 1 node in the fuel (central position); 1 node at the interface between the fuel and the cladding|; 1 node at the interface between the cladding and the coolant; 1 node in the coolant region (bulk). In principle, the number of axial nodes is variable, but in this study it was fixed in 21 nodes. In the next analysis, it will be considered only the node distribution in the hottest fuel plate, in order to check the maximum temperature as a function of the coolant flow and to verify the TH margins, once all other plates will have lower temperatures and then, automatically, will satisfy these criteria. Remember that all control rods are withdrawn in this study. The main difference when the control rods are partly within is that the neutron flux will be flattened into the bottom also decreasing the multiplication factor. However, once the searching for the worst-case scenario is been the main target, all control rods should be withdrawn. Table 3 shows the minimum and maximum values for the MDNBR (minimum ratio of the critical to actual heat flux found in the core) and FIR (ratio of the heat flux that induces flux instability and the local heat flux) per core configuration per specified coolant flow (the ones in which the temperature at the cladding/coolant interface is always under 90 degrees Celsius, avoiding the Al Corrosion) in the fuel (FE) or control (CE) element under analysis. The configurations 12 and 12* were not taken into account for the temperature profile calculation, once both present no good results in the neutronic analysis (Check Table 1).

	Maximum		Minimum			
	MDNBR		MDNBR			
	Labuntsov	Mirshak	Labuntsov	Mirshak	FIR	Coolant Flow (m^3/h)
Core 5	15	15	5	5	9	60 (FE)
Core 6	16	16	5	5	9	55 (FE)
Core 7	12	13	4	4	5	35 (CE)
Core 8	17	18	6	6	9	45 (FE)
Core 8*	13	15	4	5	6	30 (CE)
Core 9	17	18	6	6	8	40 (FE)
Core 10	13	14	6	6	8	35 (FE)
Core 12	13	15	6	7	7	30 (FE)
Core 12*	11	14	5	6	5	20 (CE)

Table 3: Maximum and Minimum values for the MDNBR, using both Labuntsov and Mirshak [7] approach, and FIR.

The temperature vs. coolant flow, and the axial temperature profile for the cores 5, 6, 7, 8, 8*, 9 and 10 are depicted below from the Fig. 14 to 20. The temperatures for each core configuration were calculated using the coolant flow value presented in Table 3. Table 4 shows the fuel element geometry information along with the operating pressure and initial coolant temperature.

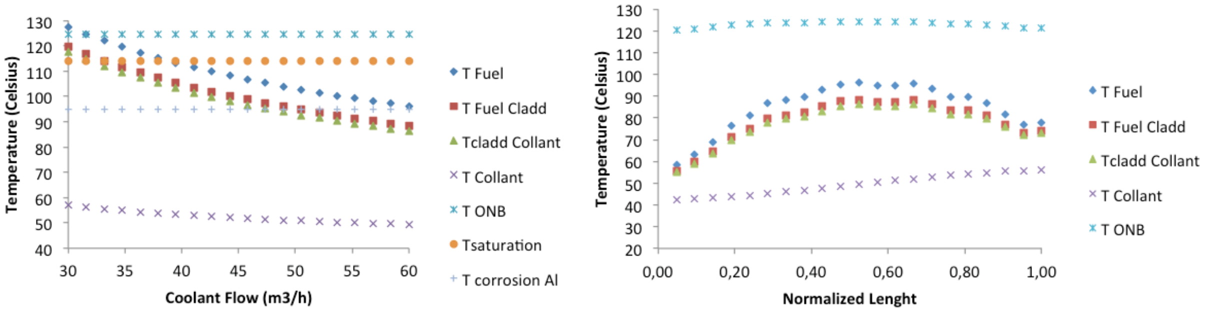

Fig 14. Core 5 - Temperature Distributions

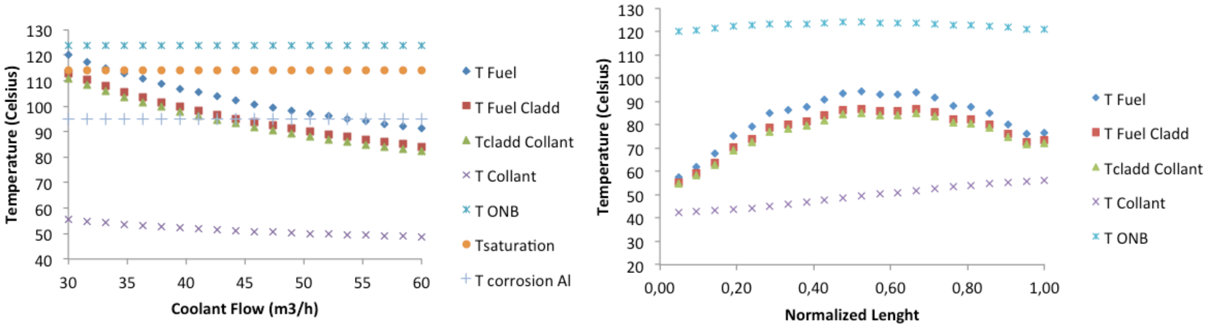

Fig 15. Core 6 - Temperature Distributions

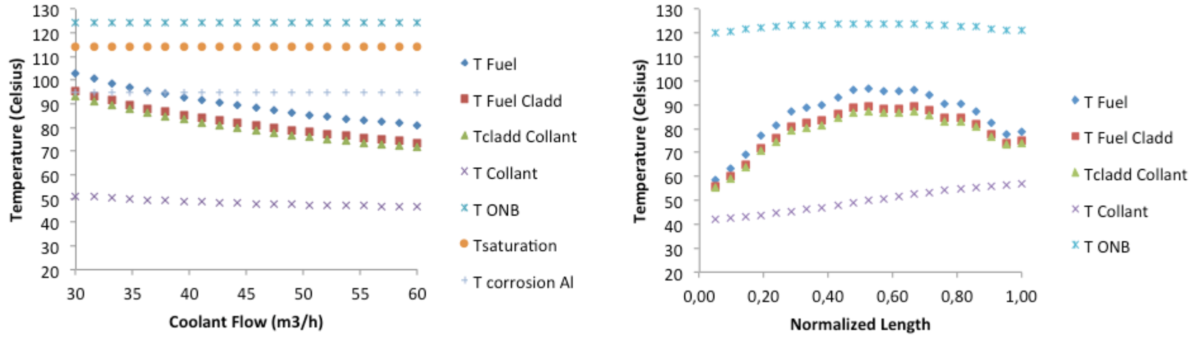

Fig 16. Core 7 - Temperature Distributions

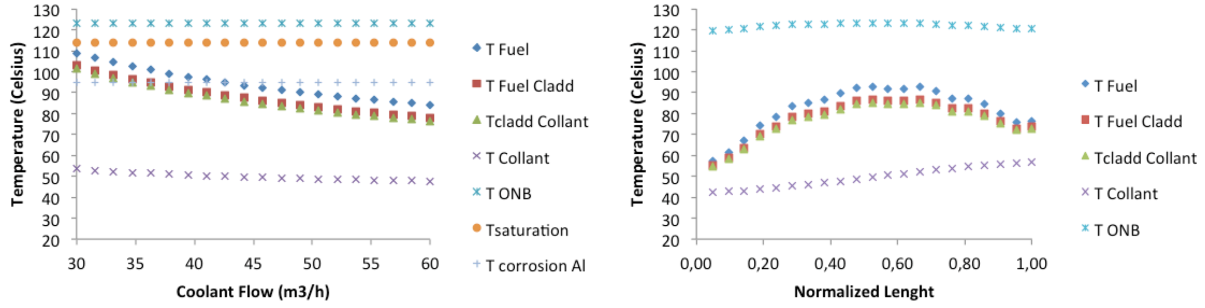

Fig 17. Core 8 - Temperature Distributions

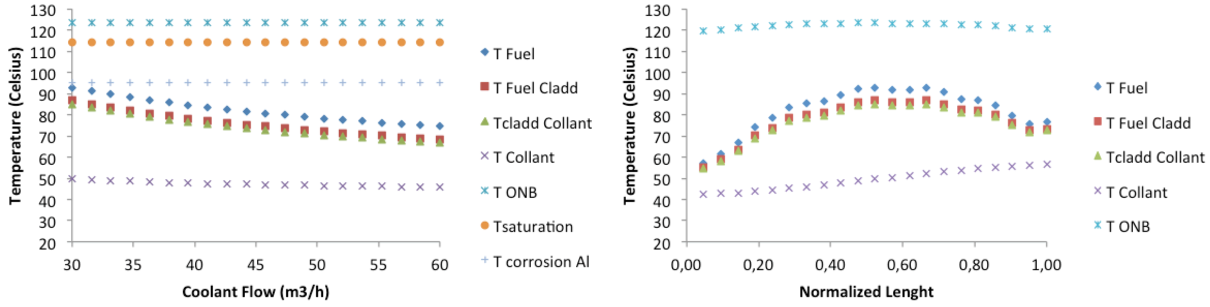

Fig 18. Core 8* - Temperature Distributions

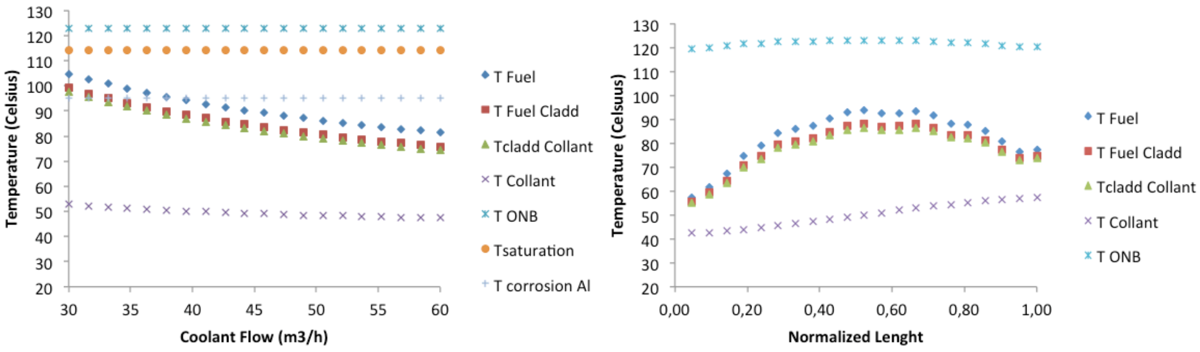

Fig 19. Core 9 - Temperature Distributions

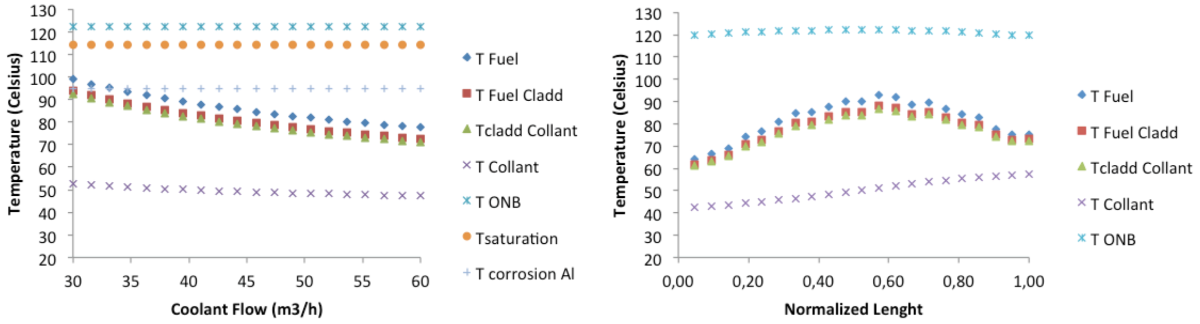

Fig 20. Core 10 - Temperature Distributions

Cooling channel width	67.1 mm
Fuel plate active width	62.0 mm
Channel thickness	2.89 mm
Fuel plate thickness	1.52 mm
Fuel thickness	0.80 mm
Cladding thickness	0.38 mm
Plate total height	625 mm
Plate active height	600 mm
Coolant	light water (42°C)
Operating pressure	1.6 bar

Table 4: IEA-R1 Fuel Element Geometry, Operating Pressure and Initial Coolant Temperature

4. CONCLUSIONS

Among nine different new core configurations for the IEA-R1 research reactor presented in this study, seven of them are good enough to replace the current core of this Brazilian research reactor. The neutronic calculation shows that the core 12 and 12* are week from the control rods safety point of view (Table 1), but they could be useful if the number of control rods increase. The thermal-hydraulic analysis ensures that no TH margins are exceeded and also depicts that, from a steady-state analysis point of view, no high temperatures are reached and calibrating the main pump one can control the critical temperature that induces corrosion in the aluminium (~95 degrees Celsius). The next step of this study will be the safety analysis of each new core, along with the *burnup* calculation and at the very end, choose the best configuration depending on the desired characteristics.

5. References

1- “MCNP – A General Monte Carlo N-Particle Transport Code, Version 5”, Los Alamos National Laboratory, April 24 2003 (Revised 10/3/05);
2- “EES - Engineering Equation Solver for Microsoft Windows Operating Systems”, F-Chart Software, 1992-2014 by S.A. Klein;
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4- John R. Lamarsh-Anthony John Baratta “Introduction to nuclear engineering”, Upper Saddle River, NJ-Prentice Hall-2001-3rd Ed;
5- NJOY 2012 User Manual LA-UR-12-27079;
6- Y. komori, M.Kaminaga et al, “Safety Criterion for Burnout of the Plate-Type Fuel in Pressurized Conditions”, JAERI-M 92-028;