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THERMAL HYDRAULIC ANALYSIS OF THE MULTIPURPOSE RESEARCH REACTOR RMB USING A RELAP5 MODEL

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Abstract

The Multipurpose Brazilian Reactor (RMB) will be an open pool multipurpose research reactor using low enriched uranium fuel (LEU). This paper presents the RMB nodalization and the first thermal hydraulic results of steady state calculations using the RELAP5-MOD3.3 code. Several current investigations have shown that RELAP5 code can be also applied for thermal hydraulic analysis of nuclear research systems with good predictions in spite of such code was initially projected to studies of commercial nuclear power plants.

Introduction

The Multipurpose Brazilian Reactor (RMB) has been projected and will be constructed and operated to attend the present Brazilian need for a multipurpose neutron source, which will be able to supply the demand for radioisotopes, carry out material tests and develop scientific, commercial and medical applications with the use of neutron beams. Therefore, RMB will have three main functions: radioisotope production (mainly molybdenum); fuel and material irradiation testing to support the Brazilian nuclear energy program; and it will provide neutron beams for scientific and applied research.

Among the different types of research nuclear reactors, the open pool reactors are the most common and the most used, because of their great versatility, easy operation and safety. The reactors Osiris (in France) and mainly the Australian Replacement Research Reactor (OPAL) projected by Argentina and built in Australia are being used as initial references for the RMB project.

In the present work, a nodalization for the RMB reactor in the RELAP5/MOD3.3 code and the most important components of the pool loop and core loop circuits are presented. Steady state and transient simulations have been performed. RELAP5 has been developed for best estimate transient simulation of light water power reactor systems during postulated accidents. Recent works have demonstrated that the code can be also used with good results for thermal hydraulic analysis of research reactors as it can be verified in the present literature [1 - 9].

1. RMB Reactor

The Multipurpose Brazilian Reactor (RMB) will be an open pool multipurpose research reactor using low enriched uranium fuel, with a neutron flux higher than 2.0 x 10^{14} n/cm^2/s. The reactor core will be compact with MTR (material testing reactor) fuel assembly constituted of planar plates and will be cooled and moderated by light water. Beryllium and heavy water will be used as reflectors. The reactor will work with maximum power of 30 MW.

Table 1 presents the main characteristics of the RMB. It will have geometric characteristics close to the OPAL reactor. The RMB pool is cylindrical with 12.8 m of high and 5.6 m of diameter, as shown in the Figure 1 [10]. The reactor cooling has four circuits: hot layer, primary (core), secondary (pool) and heavy water (D_20).

Table 1 General characteristics of RMB.

Reactor	
Nominal Power	30 MW
Moderator and coolant	Light water
Reflector	H_2O, D_2O, Beryllium
Thermal and fast neutron flux in the core (higher than)	2.0 x 10^{14} neutrons.cm^{-2}.s^{-1}
Core	
Flow direction in core	Upwards
Control rods drive location	Below core
Grid array	6 x 5
Dimensions	0.51 x 0.55 x 0.815 m
Number of fuel and control elements	27 / 6
Absorbing material	Ag-ln-Cd
Fuel assembly type	MTR (LEU)
Nuclear fuel	U_3 Si_2-Al enriched at 20%
Fuel density	4,8 gU/cm^3
Cooling	
Core and pool inlet coolant temperatures	311 / 306 K
Mass flow rate from pool to core by chimney	83.3 kg/s
Core mass flow rate (inlet/outlet)	750.0 / 833.3 kg/s

The core cooling is accomplished by forced circulation of demineralized water, in the upwards direction in the core. In normal operation, the coolant is pumped through the core going to heat exchanger before to back to the core inlet. This upwards outflow induce the transport of active water by core to pool surface, inducing an increase of radioactive exposure rate in the reactor building. In some reactors, the hot layer is utilized to stratify the pool water and avoid the incidence of radioactive water in the pool surface.

The water injection (3.8 kg/s and 318 K) from the hot layer occurs at 1.5 m from the top and the suction at 0.1 m. The heavy water is contained in a tank that surrounds the core, being one of its faces composed by reflector of beryllium. The water injection (150 kg/s and 306 K) from the pool circuit is provided in a point of the lateral side while the suction occurs through the bottom of the pool. The primary circuit (750 kg/s and 311 K) provides the heat exchanger from the core elements and its injection occurs through two piping system at 7 m from the bottom. The suction occurs through the chimney avoiding ascending of the water from the core. The general schema of the reactor is shown in the Figure 1 [10] and details of the core are illustrated in the Figure 2 [10].

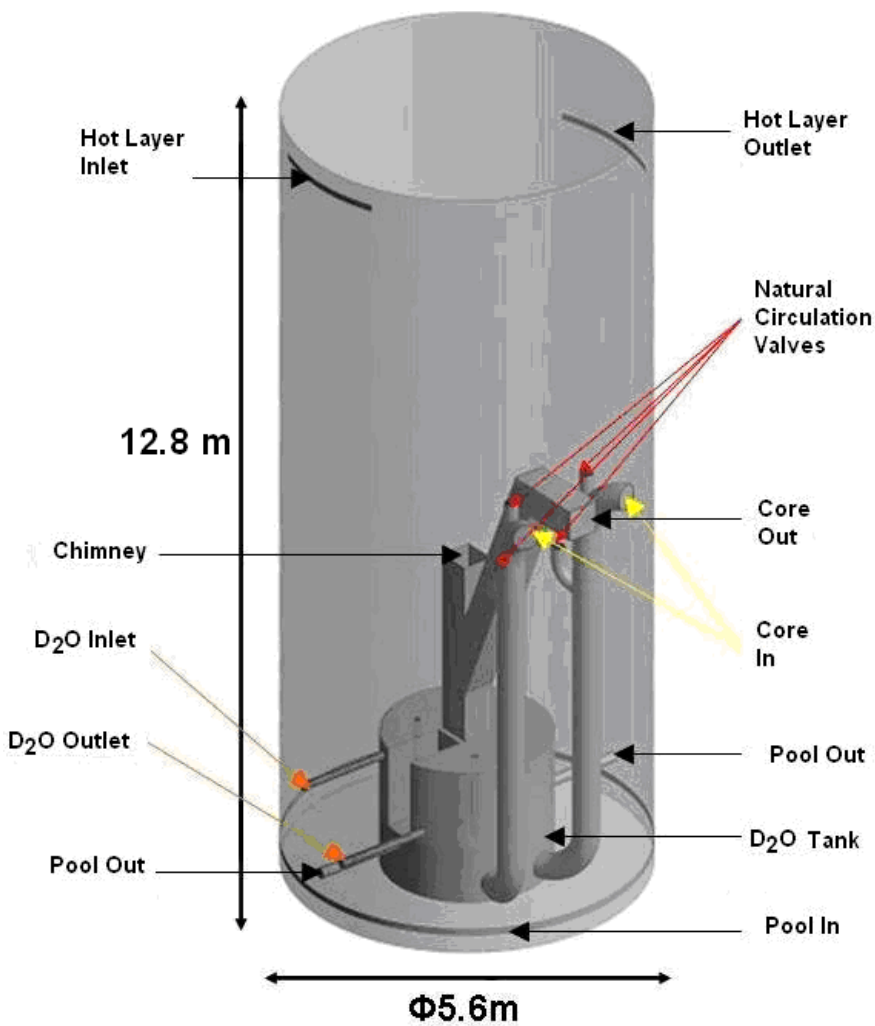

Figure 1 RMB - General schema of the reactor [10].

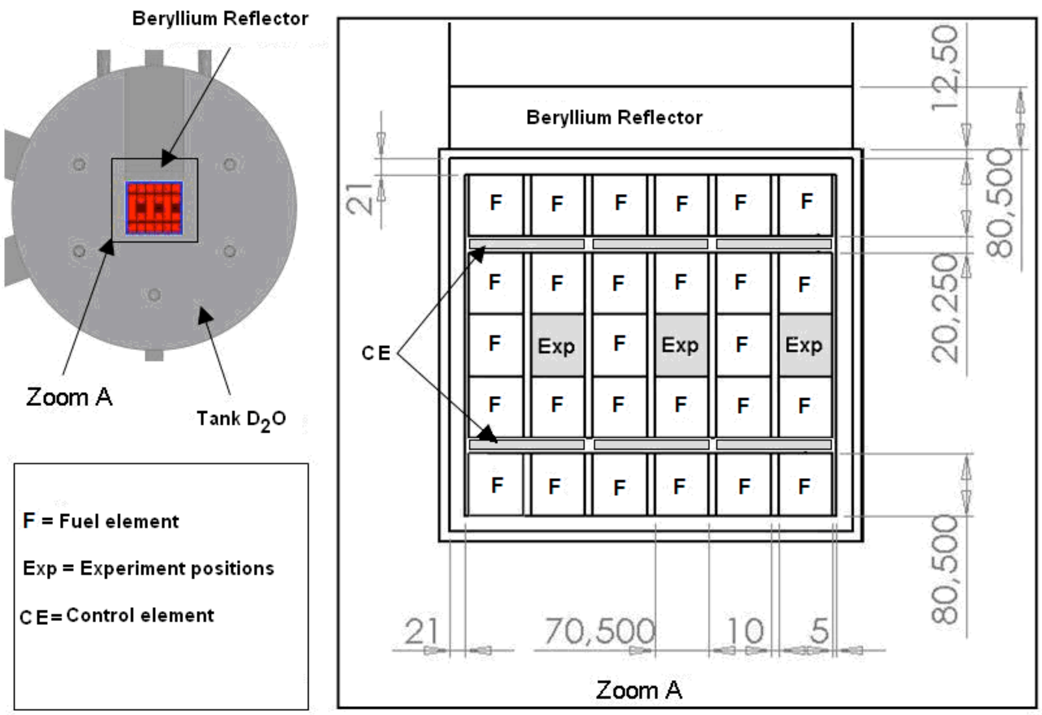

Figure 2 RMB - Core details [10].

2. RMB – thermal hydraulic model

For the thermal hydraulic RELAP5 modeling, many design and dimensions information of the OPAL reactor has been used in the conception of the RMB nodalization. Figure 3 shows the RELAP5 nodalization developed to simulate RMB. The pool was modeled using two pipes composed by twenty volumes each one. The heat generated by reactor in the one side of the pool (100) allow water circulation inside the pool through of the cross junctions between the volumes of the pipes. Volume 140 is a branch component that represents the upper pool surface, which is in contact to the atmosphere. Component 190 is a time dependent volume that simulates the atmosphere on the top of pool surface.

The main heat exchanger (430 and 810) belong the core cooling loop and it removes practically all the heat of the reactor. The pool cooling loop is simulated using a heat exchanger (210 and 710), a pipe (200) and two single volumes (206, 220). Due to the insufficient design information, some data of the pool cooling loop were estimated using available data.

The whole core structure is placed inside a squared section piping that is part of core cooling loop and such structure is surrounded by the pool. In normal operation, the water is pumped through pipes into a heat exchanger where it is cooled, and then returns to the core where it is heated.

In the RELAP5 nodalization the core cooling circuit components in outside of the pool are represented by the volumes from 400 up to 440 while those within the pool are simulated by volumes from 300 up to 340. Component 300 is the core inlet lower plenum which conducts the water to the core (pipe 316).

The heated water goes through the components 320 and 330 where it is mixed with a small downward flow coming from the pool through the chimney (pipe 340). There is a connection between the reactor and the pool cooling loop that is modeled by the branch 440, where the mass of water taken from the pool through the chimney is returned to the pool circuit, injected in the component 206. Four valves (363, 364, 367 and 368) provide the cooling through natural circulation (NC) when needed. Valves 363 and 367 are of type trip valves and 364 and 368 are of type check valves. Both valves behave as on/off switch. The trip valves (363 and 367) work according to the condition determined by user in the input desk; if the trip is false, the valve is closed and if the trip is true, the valve is open. These valves will open if the pool coolant level decreases until a determined value. The check valves (364 and 368) work obeying static pressure/flow-controlled check valve (by hysteresis effect) between the two components where the valves are connected.

The point kinetics model was used to estimate the fuel power in the presented simulations.

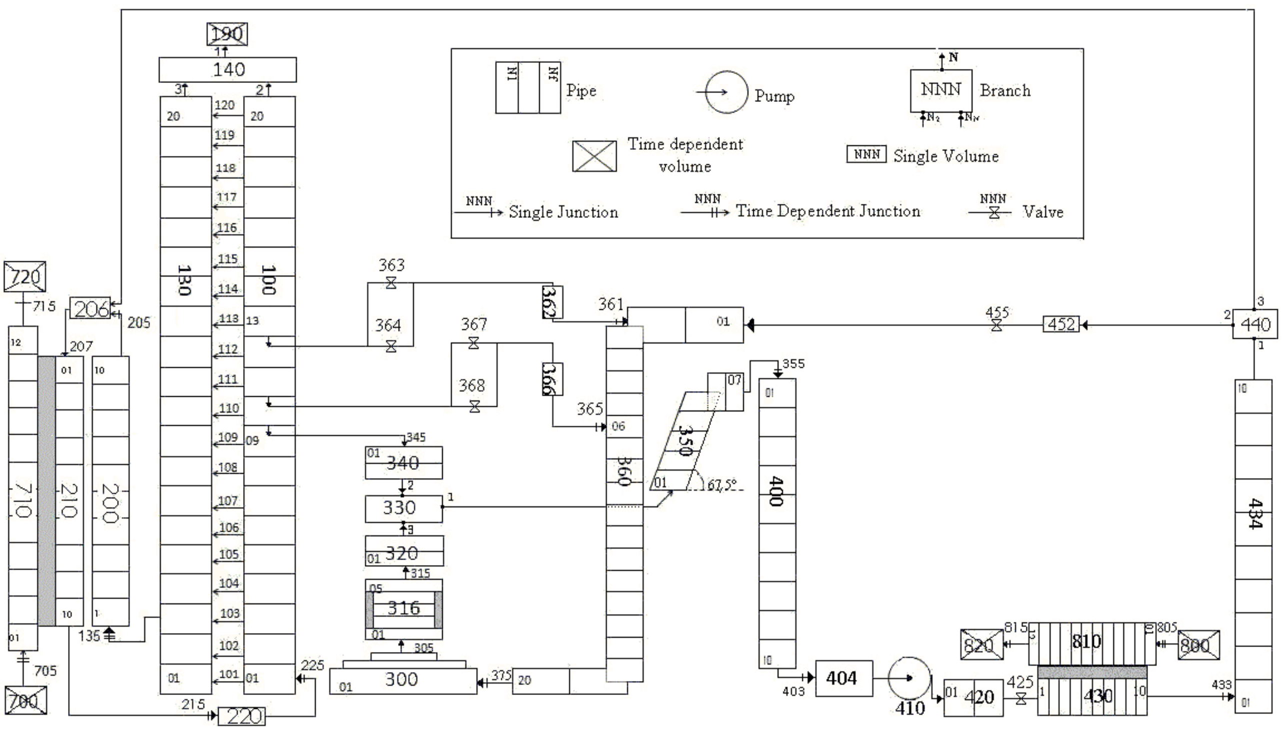

Figure 3 RMB represented by RELAP5 nodalization.

3. Stead state calculation

Some thermal hydraulics parameters in RMB like energy balance, the pool and the core flow circuits, the heat transfer in the heat exchangers and the heat generated in the core and in the pool, pressure drop in the core, core and pool temperatures, and other parameters have not been totally defined in this project because it is being developed and tested. Therefore, their values are constantly changing and being redefined. There are not experimental data to compare with the present RELAP5 calculation.

However, the mass flow rate and temperature in the core has been defined by a research team which used the Computational Fluid Dynamics (CFD) codes [10], and therefore these values have been used in the RELAP5 simulation. Table 2 shows the steady state calculations with RELAP5 performed at 30 MW and the comparison with some reference values [10].

As can be seen in the Table 2, only core and pool inlet temperatures and mass flow rate have available data of reference. The temperatures simulated in the RELAP5 calculation were a little overestimated in relation to the reference data. The mass flow rate in the core and chimney showed good agreement with the reference. The heat exchangers data, particularly their heat transfer areas, were estimated indirectly; this can explain the temperature differences between reference and calculated values. The heat exchanger of core circuit system (primary circuit) remove 92.5% of the generate power in the core and the residual power is removed by pool circuit system (secondary circuit).

Table 2 Reference and calculated data considering 30 MW of power operation.

Parameters	Reference	RELAP5	Error (%)*	Acceptable Error (%)
Core coolant temperatures (inlet/outlet)	311 K / ---	316.24 / 325.77 K	1.7	0.5
Pool coolant temperatures (inlet/outlet)	306 K / ---	309.82 / 309.86 K	1.2	0.5
Mass flow rate from pool to core by chimney	83.33 kg/s	83.05 kg/s	0.3	2.0
Core mass flow rate (inlet/outlet)	750 / 833.33 kg/s	744.15 / 827.18 kg/s	1.0 / 1.0	2.0
Core pressure drop	---	74.7 kPa	---	10.0
Power removed by primary circuit	---	27.75 MW (92.5%)	---	2.0
Power removed by secondary circuit	---	2.25 MW (7.5%)	---	2.0

*Error = 100 × (calculation − experimental)/experimental

Figure 4 shows the coolant temperature in three regions of the pool represented by the pipe 100 being taken at the bottom (volume 01), at middle (volume 10) and at the top (volume 20). The Figure shows also the coolant temperature in the core middle (316-03). The simulation time was 100,000 seconds and both coolant temperatures reach the steady state at about 10,000 seconds. The coolant temperature along the pool is practically constant. The coolant temperature in the core middle is about 12 K higher than that the pool.

Mass flow rate evolution in the component 330 is shown in the Figure 5. The coolant mass flow reaches the core outlet and it is added to coolant mass flow that downwards by chimney. The total coolant moves in direction to core cooling system. The chimney pulls 10 % of the total core cooling system.

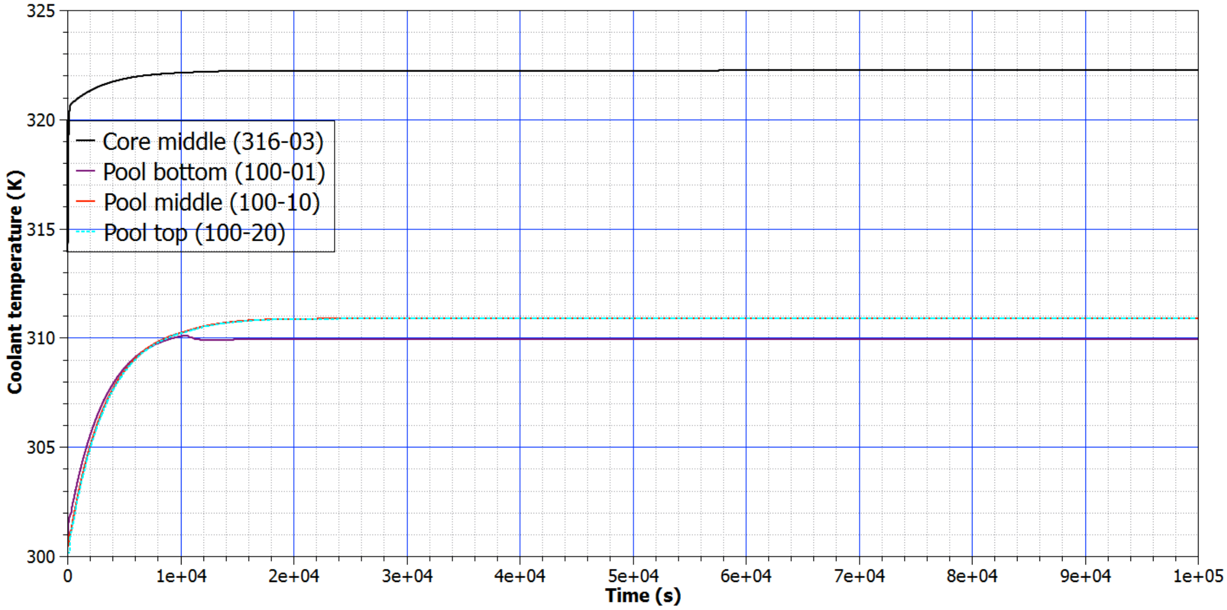

Figure 4 Coolant temperature in the pool and in the core.

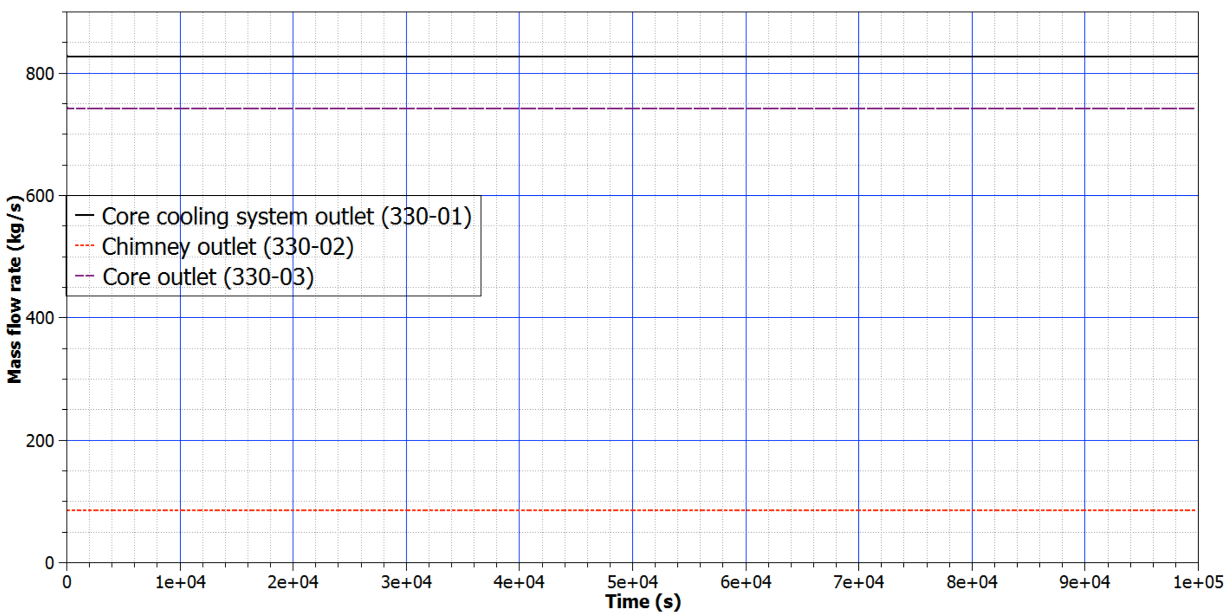

Figure 5 Mass flow rate evolution in the component 330.

4. Transient calculation - Analysis of the loss of electric power

Postulated Initiating Events (PIEs) are transients with the potential to disturb the reactor up to the safety limits of the plant. They are the initiators of fault sequences. A PIE may be initiated by equipment failure and operator errors. Following the guidance of the IAEA, a set of PIEs is assembled for assessment against the design of the Replacement Research Reactor. This list covers all aspects of the design, operation and utilization of research reactors [11].

Loss of electric power supplies is itself not an initiating event, but, in general, regulations require analysis of the behavior of the facility under loss of electric power. When the reactor has a reliable standby power supply system (e.g. appropriately qualified diesel generators), it is only necessary to analyze loss of normal power. When reliability of the system cannot be assured, loss of standby power needs to be evaluated. Low power reactors that can be cooled by natural circulation may not have a standby power supply beyond uninterruptible power systems (batteries) for instrumentation and control. Higher power MTRs may have diesel generators and rely on their functioning for decay heat removal [12].

To simulate such accident using the RELAP5 code, four trips were actuated in the same time. As a consequence of such trips, actuation of the pump (410) was turned off; the heat exchangers were isolated closing valves 425 and 455 and also stopping the secondary flow rates through time dependent junctions 705 and 805 and finally the reactor was scrammed by inserting 10 dollars of negative reactivity in 0.5 second. The loss of electric power was simulated in this way leading to the opening of the natural circulation check valves 364 and 368.

The transient event was started at 10,000 seconds, after the simulation of a 30 MW steady state. Both graphics in the Figure 6 show the power evolution during 410,000 s of simulation. The smaller graphic in the same figure shows the decay power in details, and it's possible to see that the power decreases exponentially until to reach 110 KW of power. This power is due to the heat generated by fission product.

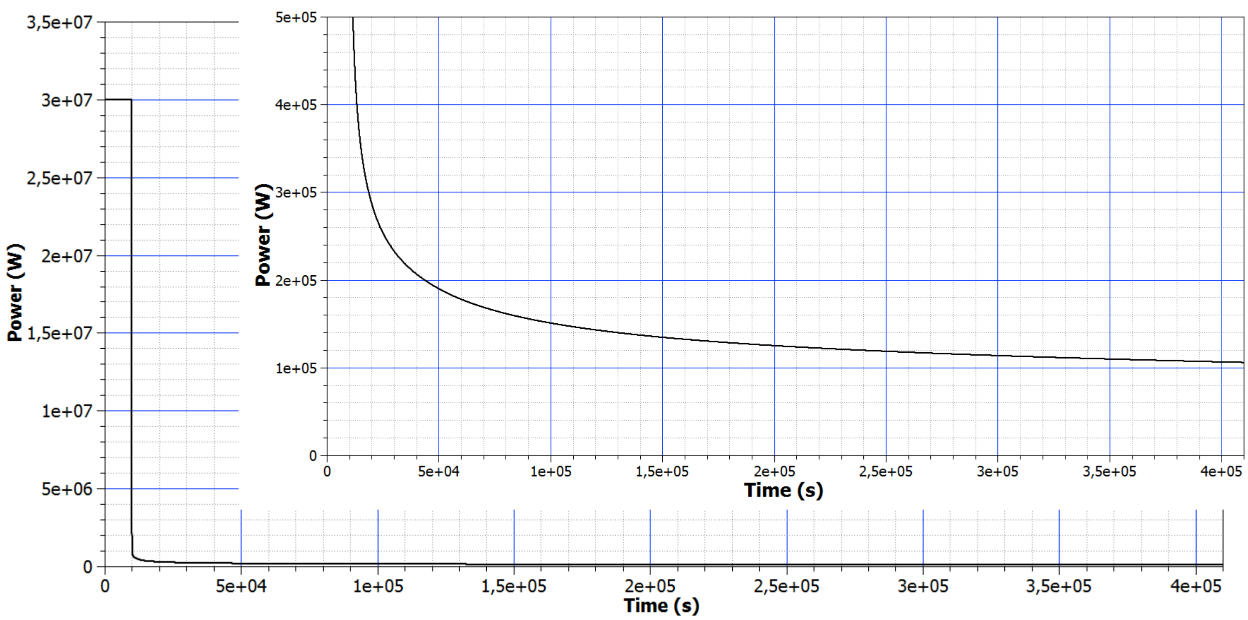

Figure 6- Power evolution during the transient.

Figure 7 shows the evolution of coolant temperatures at the bottom, middle and top of the pool (pipe 100 in the nodalization). As it can be seen, after the scram, the pool temperature began to increase and, 111 hours after the accident, the coolant temperature in the pool middle and top reached almost the saturation point.

Differences between the coolant temperature in the middle and the top of the pool were not observed. The temperature between the beginning and the end of the simulation (a time interval of 400,000 s) presented a difference of about 50 K. The temperature difference between the bottom and the top increased after the event showing that the middle and the top receive and accumulate more power than the bottom of the pool in natural circulation.

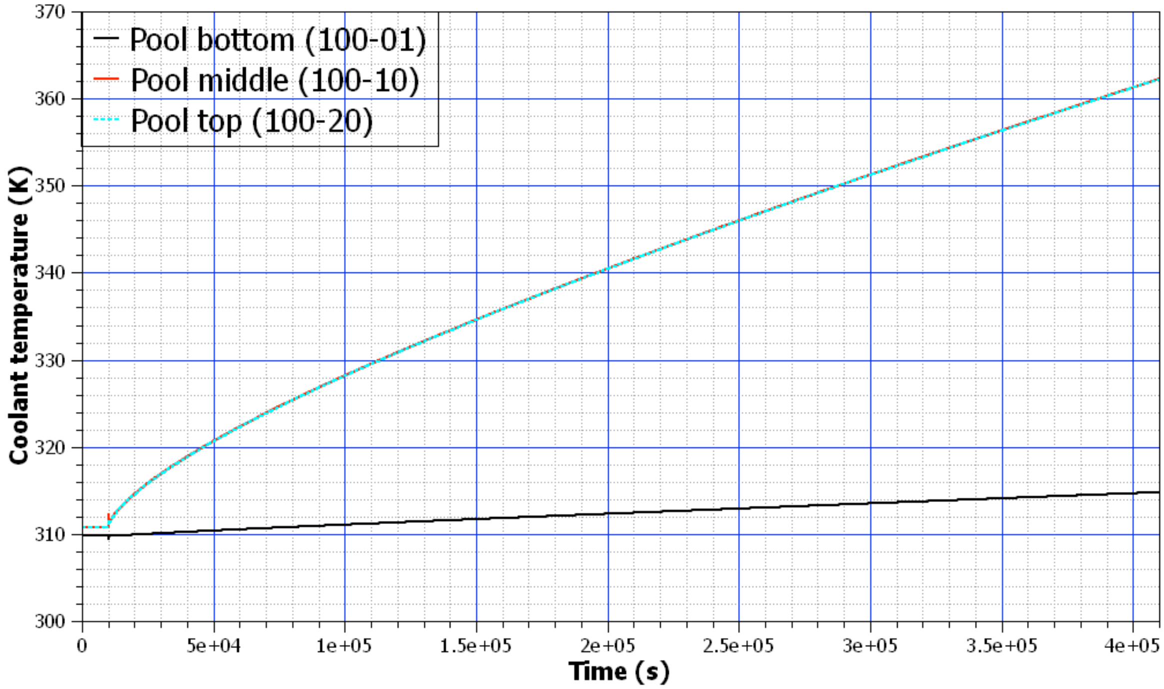

Figure 7- Coolant temperature in the pool during the transient.

Figure 8 shows the coolant and the fuel temperatures at mid-height of the core. The fuel temperature decreases in a very short time immediately after the beginning of the event; after such fast transient, the temperature begins to increase slowly in the time. The core coolant temperature increases slowly following the increase of the fuel temperature.

Figure 9 shows evolution of the mass flow rate in the component 330, chimney outlet, core outlet and core cooling system outlet. The detail shows the mass flow rate evolution enlarged; it is possible to see perfectly that mass flow rate in the core cooling system (330-01) is canceled due to isolation of this circuit. Before the loss of electric power to occur, the mass flow through the chimney was downward. However, during the natural circulation phase, it is upwards carrying the heat from core to pool. The mass flow rate through the core decreases up to the opening of the check valves (364 and 368) reestablishing the natural circulation. The natural circulation mass flow rate is very small, about 10 kg/s, but it is enough to promote cooling of the fuel elements and to transfer the heat to the pool.

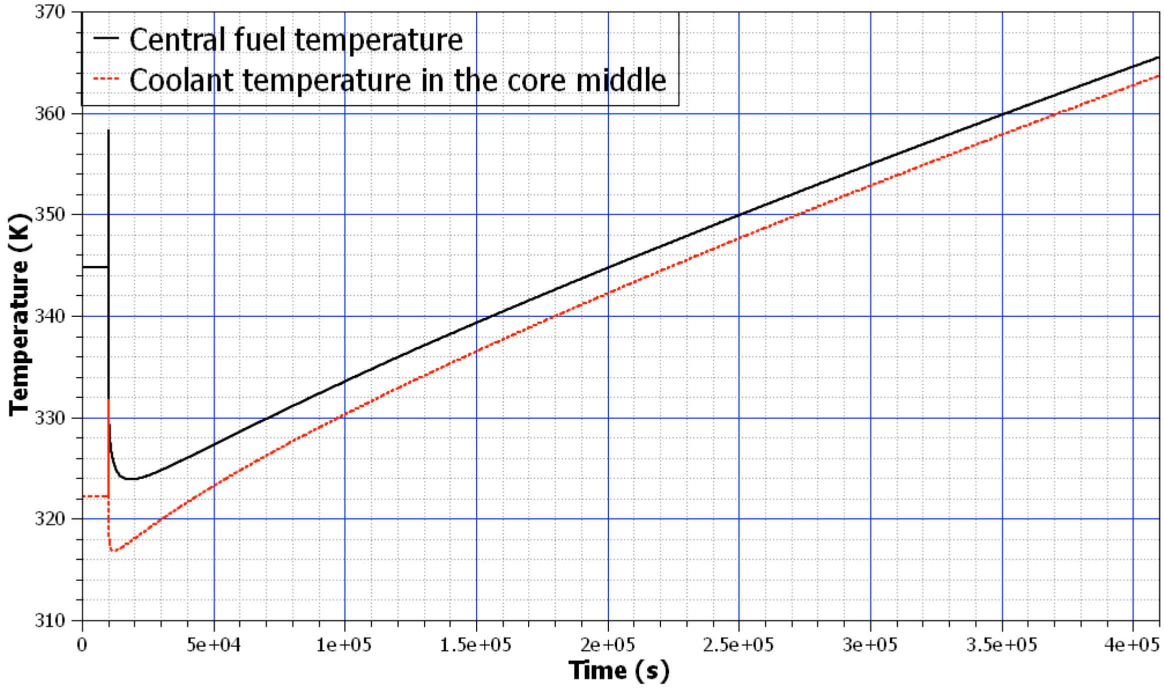

Figure 8 Coolant and fuel temperatures evolution during the transient.

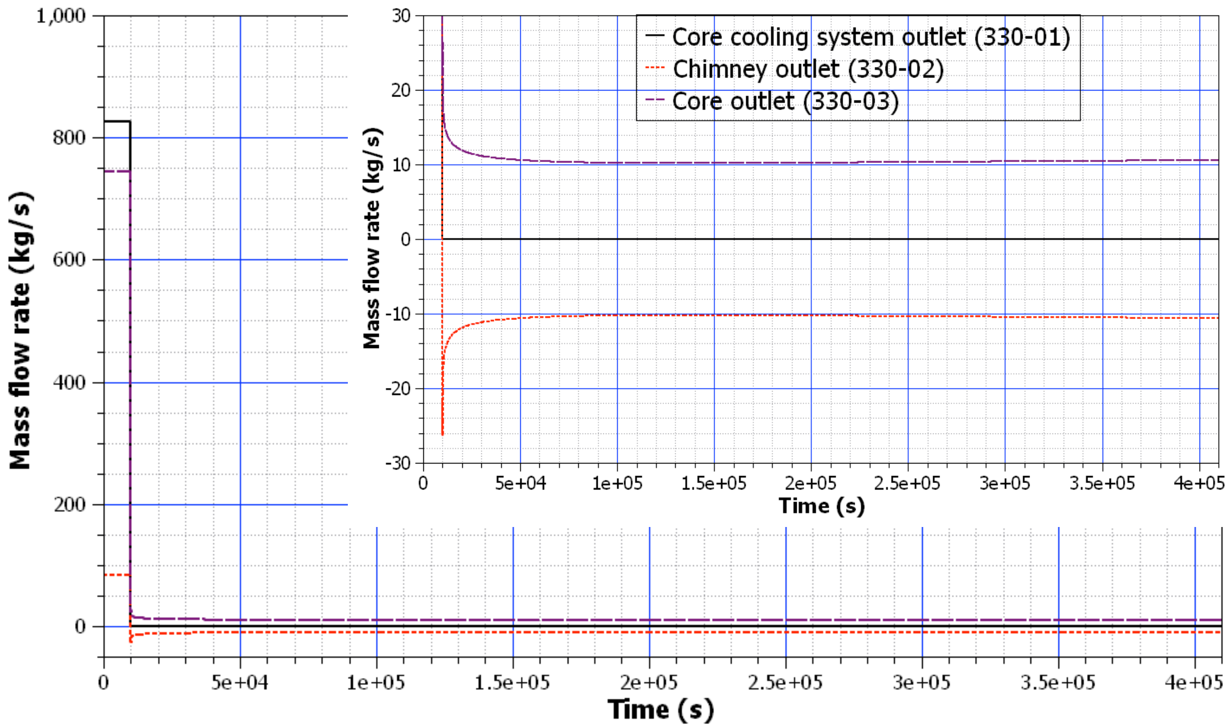

Figure 9 Mass flow rate evolution in the component 330.

5. Conclusions

The Multipurpose Brazilian Reactor (RMB) will have many functions with the main utilization for production of radioisotopes to medical applications. Several characteristics of the OPAL reactor have been used in the initial project of the RMB. At this moment, RMB reactor is on neutronic and thermal hydraulic theoretical development.

The thermal hydraulic model of the RMB is presented in this work using RELAP5 code. After several tests, the steady state operation condition was reached at 30 MW with all thermal hydraulic parameters in stable behavior. Thereafter, a loss of electric power transient was simulated.

To simulate such transient, the recirculation pump was turned off, the reactor was shutdown and the primary circuit was isolated. This event induced a large reduction of mass flow rate in the core and consequently the core and pool coolant temperature increased slowly. However, up to 400.000 seconds of calculation, the coolant did not reach the saturation point. The check valves opened correctly showing that the natural circulation mode was established and it is enough to keep the core cooled during an extreme event like that. In general, the nodalization showed to simulate relatively well the reactor behavior.

6. Acknowledgments

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7. References

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