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

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***Abstract***. *RELAP5/MOD 3 code is widely used for thermal hydraulic studies of commercial nuclear power plants. However, several current investigations have shown that RELAP5 code can be also applied for thermal hydraulic analysis of nuclear research systems with good predictions. This work presents initial calculations of steady state operation of Osiris reactor using the RELAP5 model. The multipurpose reactor Osiris has thermal power of 70 megawatts and it is a water moderated and cooled open pool type research reactor. The Osiris reactor characteristics are being used as a base for the development of a model for the Multipurpose Brazilian Reactor (RMB). Therefore the validation and qualification of a RELAP5 model for the Osiris reactor will be also useful to perform future simulations of steady state and transient events at the Brazilian RMB reactor. This initial study presents the Osiris nodalization and the first results of steady state calculations.*

***Keywords***: RELAP5, Osiris, RMB

## 1. INTRODUCTION

*Comissão Nacional de Energia Nuclear – CNEN* is leading the project of Multipurpose Brazilian Reactor (RMB), with the participation of three of its research institutes: *Instituto de Pesquisa Energéticas e Nucleares – IPEN/CNEN/SP; Centro de Desenvolvimento da Tecnologia Nuclear – CDTN/CNEN/BH; Instituto de Engenharia Nuclear – IEN/CNEN/RJ;* and the partners: *Centro Tecnológico da Marinha em São Paulo – CTMSP; Centro Tecnológico do Exército - CTEX; Instituto de Estudos Avançados do Centro Tecnológico Aeroespacial CTA – IEAv.*

The RMB will be projected, constructed and operated to attend the present Brazilian necessity of a multipurpose neutron source, which will be able to supply the demand of radioisotopes, carry out material tests, and develop scientific, commercial, and medical applications with the use of such a neutron source.

Among the different types of 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 and Júlio Horowitz from France, and the OPAL reactor projected by Argentina and built in Australia will be used as initial references for the RMB project.

Originally, the RELAP5/MOD 3.3 thermal hydraulic code was developed to simulate commercial power reactors. However, recent works have demonstrated that the code can be also used with good results for thermal hydraulic analysis of research reactors, like Osiris and RMB. This can be verified in the present literature (Reis *et al.*, 2010, Costa *et al.*,2010, Reis, 2009, Adorni *et al.*, 2007, Antariksawan *et al.*, 2005, Khedar *et al.*, 2005, Končar and Mavko, 2003).

Within RMB project context, this code has been initially used for the simulation of steady state conditions and some transients of Osiris reactor, while the RMB characteristics are not available. The results have indicated critic points of the simulation of this reactor type and the acquired experience will be important to develop a reasonable model for the new multipurpose pool reactor.

## 2. OSIRIS REACTOR

Osiris is an experimental reactor with thermal power of 70 megawatts located at the French Atomic Energy Commission (CEA) Centre at Saclay. It is a light-water reactor, open-core pool type whose principal aim are to carry out tests, to irradiate the fuel elements and structural materials of nuclear power reactors under a high neutron flux and to produce radioisotopes.

The Osiris reactor was modified three times since its construction in 1964 with significant changes in some of its characteristics, mainly in the fuel. The first reactor version operated between 1964 and 1968, with a nominal power of 50 MW; the second one between 1968 and 1979 with a power increased to 70 MW and during the third period, between

1979 and 1993, the fuel was changed from 22 to 17 plates with a different geometry conserving the same power. Since 1993 the fuel was changed to an alloy $U_3Si_2Al$, known as silicide.

This study developed with RELAP5 was based on the third version of the Osiris reactor. There is more information and data available for this version than for the others, so it was chosen because it can provide better and more real data for developing the model and evaluate its results.

Osiris pool is 11 m deep, 7.5 m long and 6.5 m wide. It has three main circuits, one for cooling the core, another one to cool the pool and the third is dedicated to the water purification. The water in the pool has several functions; it acts as cooling, as well as moderator, neutron reflector and biological shielding for the core radiation.

Tab. 1 shows the main operational characteristics of Osiris 3 reactor.

Table 1 – General characteristic of Osiris 3 reactor.

| **Description** | **Value** |
|---|---|
| Nominal Power | 70 MW |
| Moderator | $H_2O$ |
| Reflector | $H_2O$, Beryllium |
| Thermal Neutron Flux in the Core | $3.0 \times 10^{18}$ neutrons.m$^{-2}$.s$^{-1}$ |
| Fast Neutron Flux in the Core (E>0.1 MeV) | $4.5 \times 10^{18}$ neutrons.m$^{-2}$.s$^{-1}$ |
| Core flow rate (inlet/outlet) | 1092.2 / 1133.7 kg/s |
| Flow rate from pool to core by chimney | 41.5 kg/s |
| Core circuit heat exchanger temperature difference (inlet/outlet) | 31.5ºC(1)/17.5º C(1) |
| Pool circuit heat exchanger temperature difference (inlet/outlet) | 8ºC(1)/6ºC(1) |
| Pool flow rate (inlet/outlet) | 179.6 / 138.1 kg/s |
| Water Purification Circuit Flow Rate (inlet and outlet) | ~8.3 kg/s |

(1) Increment above of cool water temperature of cooling tower outlet, calculated using the heat transfer coefficient of 1800 Kcal/(h*m2*ºC) (Commissariat a l'Energie Atomique, 1970).

Fig. 1 (Santos *et al.*, 2010) presents the arrangement of the core and part of the pool and core cooling circuits within the pool. The chimney, which in normal operation has a downwards flow, limits the mixture between water leaving the core and the water in the reactor pool and thus it blocks the activated water flow into pool.

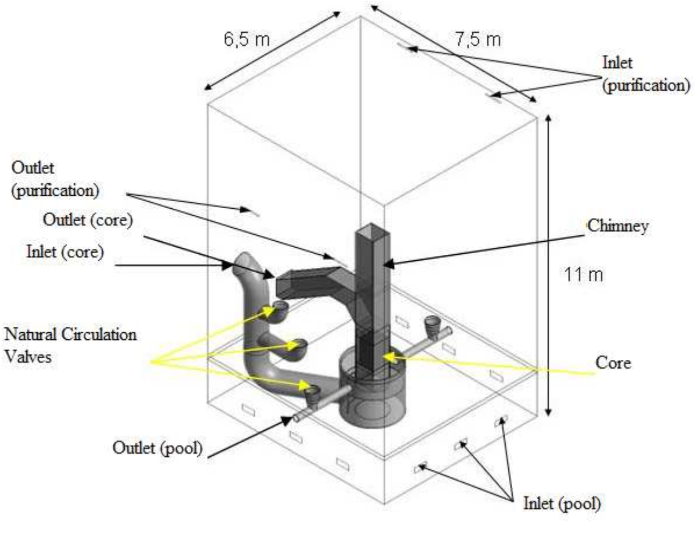
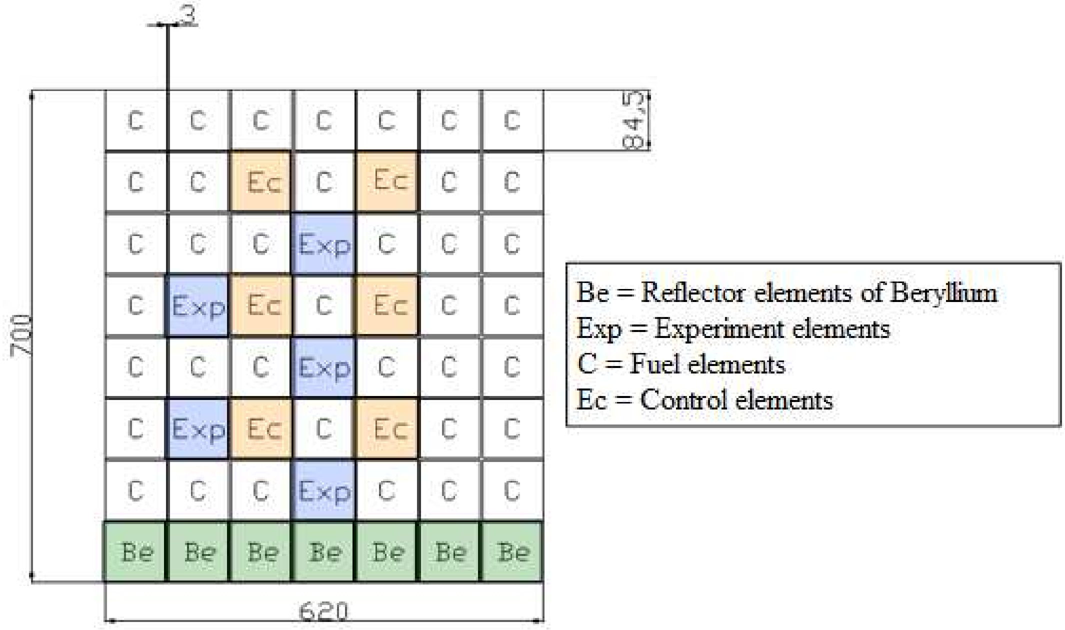


Figure 1. Osiris reactor general model.

The core vessel has a parallelogram shape, 0.620 m wide, 0.700 m long and 1.2 m deep, is made of 40 mm thick zircaloy plates (Santos *et al.*, 2010). All the parts placed in the core (fuel element, control units, reflectors, experimental water tanks) are linked at their lower part by a rod crossing the bottom of the reactor pool.

Osiris core is composed of 38 standard fuel elements; 6 control elements, 7 reflectors made of beryllium (located on the southern face of the core in Fig. 2) and 5 experiment elements that allow irradiations within the core. As shown in the Fig. 2. The fuel elements consist of 17 fuel plates, and the control elements consist of 14 plates. The fuel plates of Osiris have an active length of 0.600 m (Santos *et al.*, 2010).



|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| C | C | C | C | C | C | C |
| C | C | Ec | C | Ec | C | C |
| C | C | C | Exp | C | C | C |
| C | Exp | Ec | C | Ec | C | C |
| C | C | C | Exp | C | C | C |
| C | Exp | Ec | C | Ec | C | C |
| C | C | C | Exp | C | C | C |
| Be | Be | Be | Be | Be | Be | Be |

Be = Reflector elements of Beryllium
Exp = Experiment elements
C = Fuel elements
Ec = Control elements

Figure 2. Reactor core arrangement.

The general characteristics of Osiris 3 reactor core and its fuel plate are shown in Tab. 2.

Table 2. General characteristics of 3 Osiris reactor core.

| Description | Value |
|---|---|
| Element length | 950 mm |
| Fuel plates length | 672 mm |
| Active length | 600 mm |
| Power density | ~ 1.1 MW/m$^2$ |
| Number of fuel elements (Number of plates/FE) | 38 (17) |
| Number of control elements (Number of fuel plates*) | 6 (14) |
| Number of reflector elements | 7 |
| Number of experiment elements | 5 |
| Number of positions | 56 |
| Rate of free flow area / total area | 0.333 |
| Total area of heat transfer | 63.86 m$^2$ |
| Core head loss | 1.2 x10$^5$ Pa |

*The control elements do have fuel plates.

The fuel plates in all 3 different Osiris reactor cores have 600 mm of active length within the 670 mm of total length. The fuel plates are formed by layers. A central plate with fuel tablets is enveloped by two equal Zircaloy plates, as shown in the Fig. 3. This fuel type is known as Caramel. The general characteristics of fuel plate are shown in Tab. 3.

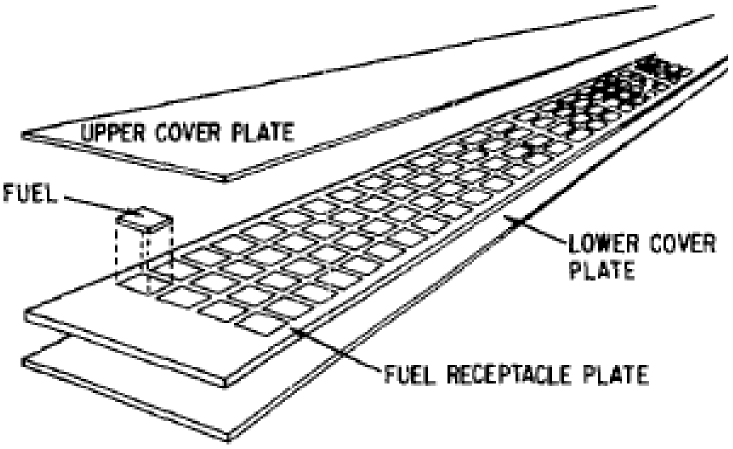


Figure 3. Caramel fuel plate of Osiris.

Table 3. General characteristics of Osiris fuel plate.

| **Description** | | **Value (mm)** |
|---|---|---|
| Thickness (mm) | Caramel ( $UO_2$) | 1.45 |
| | Zircalloy Cladding | 0.4 |
| | *Total* | 2.25 |
| Active width | | 72.9 |
| Active length | | 600 |

## 3. THERMAL HYDRAULIC MODEL

Fig. 4 shows the RELAP5 nodalization developed to simulate Osiris. Aiming to simulate OSIRIS using the RELAP5/MOD3.3 code, the reactor pool was modeled using two pipes components composed by twenty-one volumes each one. These pipes are connected by cross junctions to allow the modeling of water circulation between the two parts of the pool. Volume 140 is a branch component that represents the upper pool surface, which is in contact with the atmosphere. Volume 190 is a time dependent volume that simulates the atmosphere on the top of pool surface.

In OSIRIS there are one water purification circuit and two cooling loops, the pool loop and the core loop.

The pool cooling loop is composed by a heat exchanger (210 and 700, 710 and 720), a pipe (200) and two single volumes (206, 220). Due to lack of information some data of this pool cooling loop were estimated using available data. This part of reactor is responsible for cooling just the small fraction of the heat generated by the core that is transferred to pool, about 1.23% of total power.

The whole core structure is placed inside a square section piping that is part of core cooling loop and this structure is surrounded by the pool. In normal operation, the water is pumped through pipes into 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 out of the pool are represented by the volumes from 400 up to 470 while those within the pool are simulated by volumes from 300 up to 340. Component 410 represents the 4 pumps of the reactor cooling system and components 480 and 810 represent the heat exchangers responsible for withdrawing the nuclear generated power. Component 300 is the core inlet lower plenum, which conducts the water to the core, component 310, where it is heated. The heated water goes through the riser, vol. 320, to vol. 330 where it is mixed with a small downward flow coming from the pool through the chimney, vol. 340. There is a connection between the reactor and the pool cooling loops that is modeled by branch 440, where the amount of water taken from the pool through the chimney is returned to the pool circuit, injected in vol. 206. Two valves (463 and 467) are responsible for providing the cooling through natural circulation (NC) when needed.

The point kinetics model was used in the presented simulations.

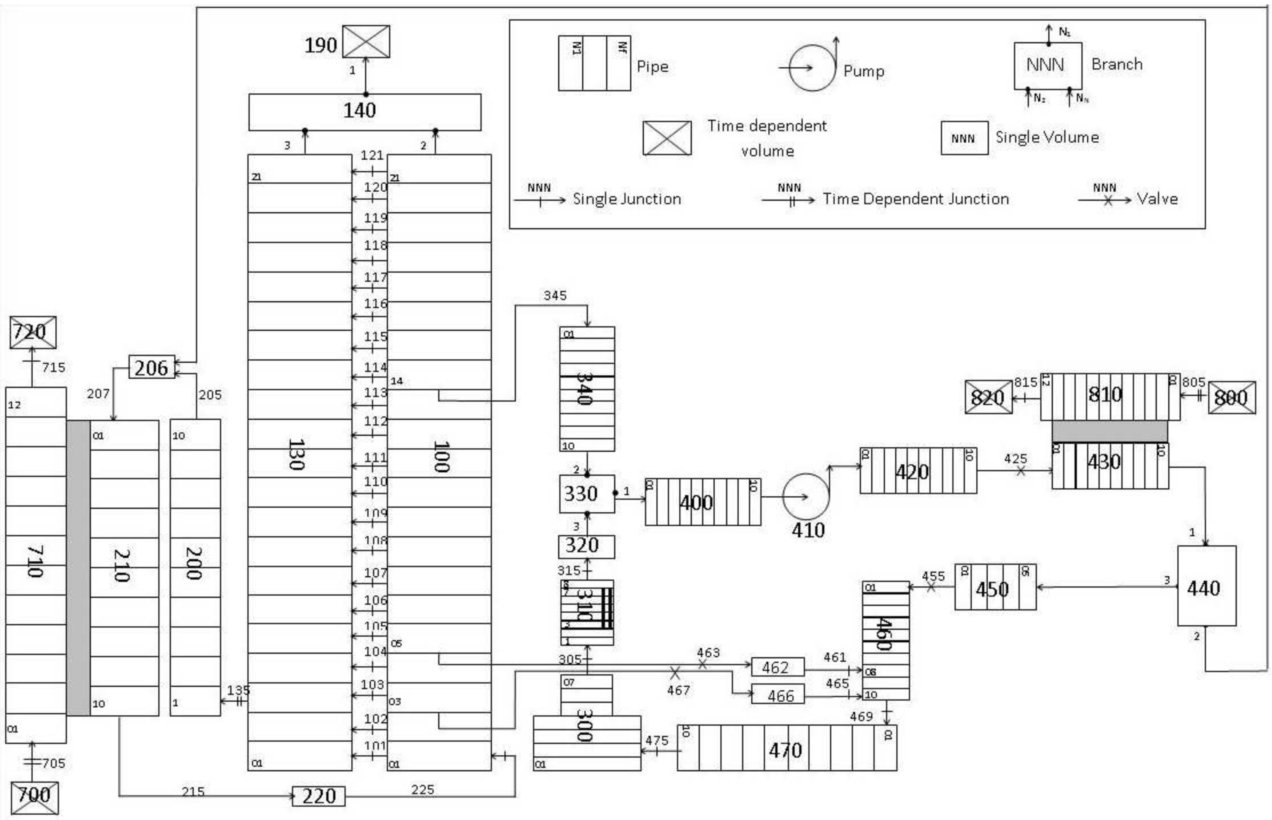


Figure 4.Osiris nodalization for RELAP5.

## 4. STEADY STATE CALCULATION

To validate a RELAP5 nodalization it must be demonstrated that the model reproduces the measured steady-state conditions of the simulated system within acceptable margins. An important aspect related with a nodalization is that in order to be considered qualified it must: have a geometric fidelity with the system, reproduce the measured steady-state condition of the system, and demonstrate satisfactory time evolution conditions (D'Auria et al., 1999). However, sometimes a nodalization qualified to simulate determined condition may not be suitable to simulate other type of situation being necessary modifications and re-qualification of the model.

Steady-state calculations with RELAP5 were performed initially at 70 MW. Tab. 4 presents calculated and experimental data and the percentage differences. The reference secondary heat exchanger inlet temperatures used in this nodalization were 300.15 K and 293.15 K, in time dependent volumes 700 and 820, respectively. The heat exchangers data, particularly their heat transfer areas, were estimated indirectly; this can explain the temperature differences between experimental and calculated values. However, it is far more important to compare the differences between inlet and outlet temperatures of the circuits. The calculated temperature difference between inlet and outlet in the core circuit heat exchanger was 13.5 K against 14 K of experimental data, demonstrating good agreement.

Table 4. Experimental and calculated results for 70 MW power condition.

| **Parameters** | **Experimental** | **RELAP5** | **Error (%)*** |
|---|---|---|---|
| Core circuit heat exchanger temperatures (primary inlet/primary outlet) | 324.6 K / 310.6 K | 330.5 K / 317.0 K | 1.8 / 2.0 |
| Pool circuit heat exchanger temperatures (primary inlet/primary outlet) | 308.1 K / 306.1 K | 311.2 K / 307.9 K | 1.0 / 0.6 |
| Core mass flow rate (inlet/outlet) | 1092 kg/s / 1134 kg/s | 1154 kg/s / 1200 kg/s | 5.6 / 5.8 |
| Mass flow rate from pool to core by chimney | 41.5 kg/s | 44.8 kg/s | 7.9 |
| Pool mass flow rate (inlet/outlet) | 179.6 / 138.1 kg/s | 182.4 / 138.1 kg/s | 1.5 / 0.0 |
| Pressure drop in the core | 0.12 MPa | 0.13 MPa | 8.3 |

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

## 5. TRANSIENT CALCULATIONS

### 5.1. Power Change

A series of simulations were performed simulating, initially, decreasing and then increasing of total reactor power. The changes were of 10 MW in intervals of 50,000 seconds. The power started in 70 MW nominal power and was decreased until 10 MW. Afterwards, the power was increased in 10 MW steps from 10 MW up to 70 MW, the steady state nominal power. Fig. 5 shows this power evolution, where it can be seen that the simulated power control was performed correctly. The total simulation time was 600,000 seconds.

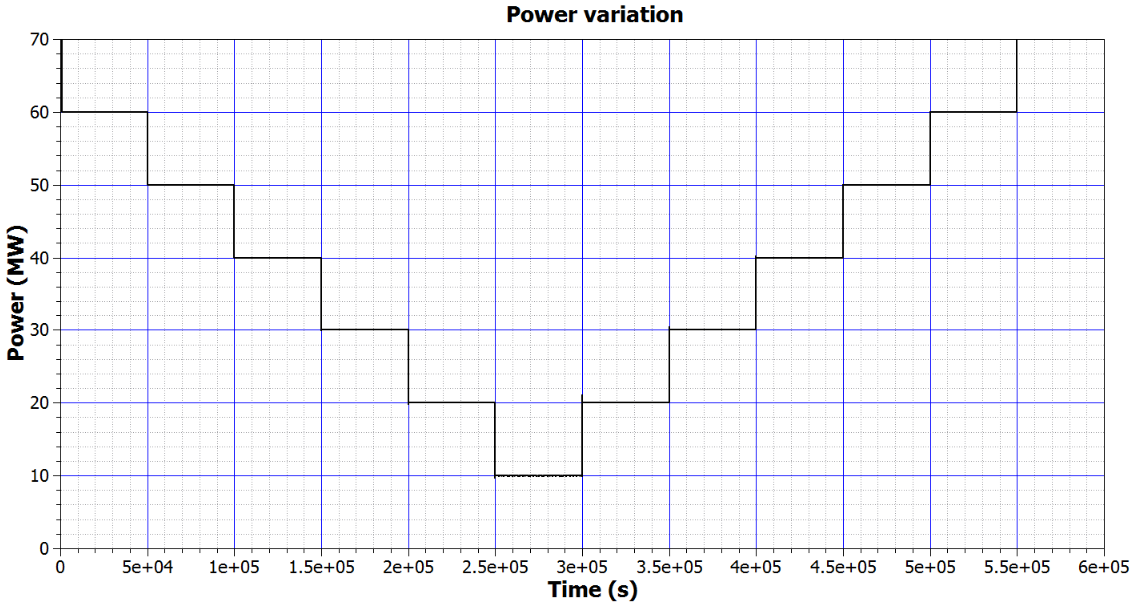


Figure 5. Power evolution

Figure 6 shows the evolution the inlet and outlet liquid temperature of the heat exchanger of the pool cooling circuit during the transient. As_it can seen, the temperature difference between the inlet and outlet of the heat exchanger decreases with decreasing power and increases with increasing power. It can be also observed that 10,000 s after the power transient the temperatures have reached new steady values.

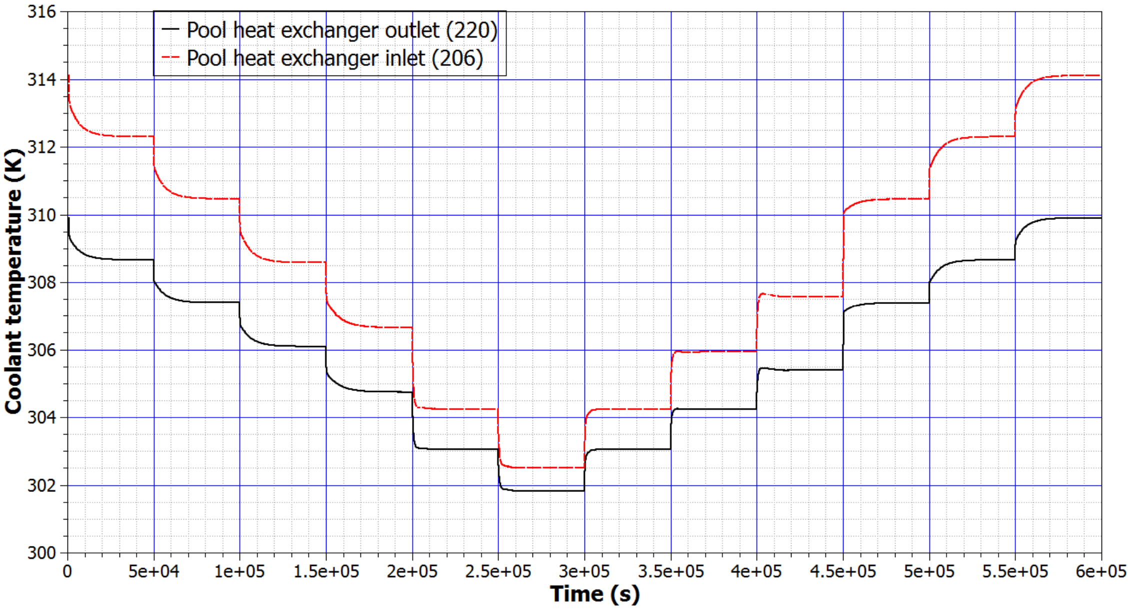


Figure 6. Coolant temperature in the inlet and outlet of the pool cooling loop heat exchanger.

### 5.2. Blackout with Natural Circulation

Four trips were actuated at the same time in order to simulate the blackout. As a consequence of these trips actuation the pump (410) was turned off; the heat exchangers were isolated by closing valves 425 and 455 and by 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 blackout simulated in this way lead to the opening of the natural circulation check valves 463 and 467.

This blackout was started at 10,000 seconds, after the simulation of a 70 MW steady state, which allowed Osiris to reach the steady state conditions at the nominal power. Fig. 7 shows the power evolution during 100,000s of simulation. Although the initial power was 70MW, the graphic shows only the evolution below 3 MW. The power decreases exponentially approximating 0.3 MW at the time of the simulation end.

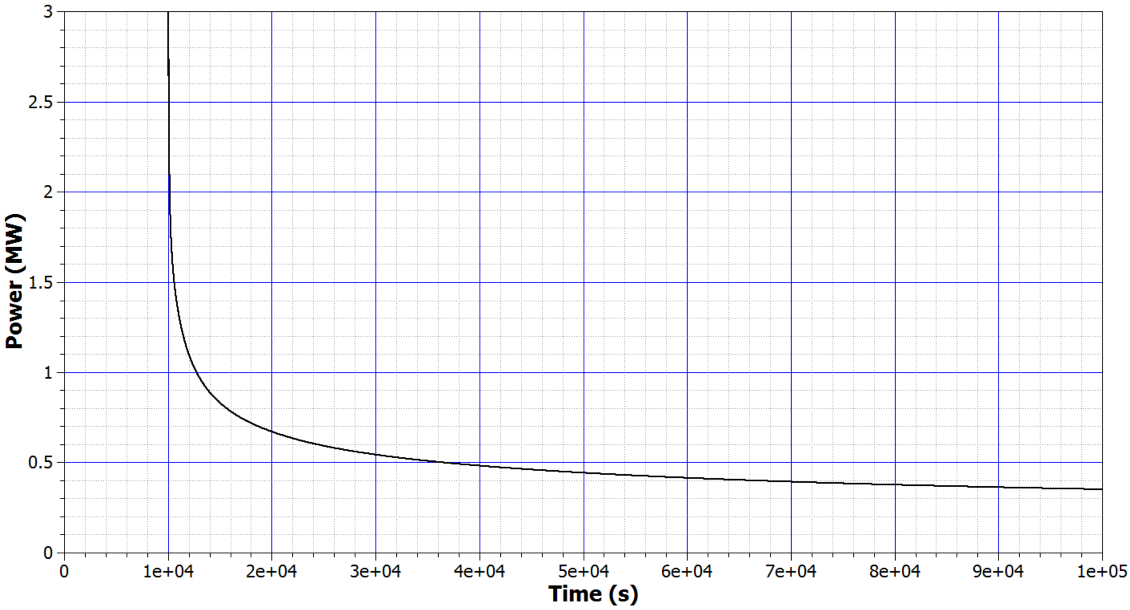


Figure 7. Power evolution during blackout transient.

Fig. 8 shows the coolant temperature in the core inlet and outlet and the central fuel temperature in the lower and higher parts of the core. The fuel temperatures decreases after a very short transient in the beginning of the blackout and it increases very slowly following the also slow increase of the coolant temperature; their final values are lower than those of the nominal steady state.

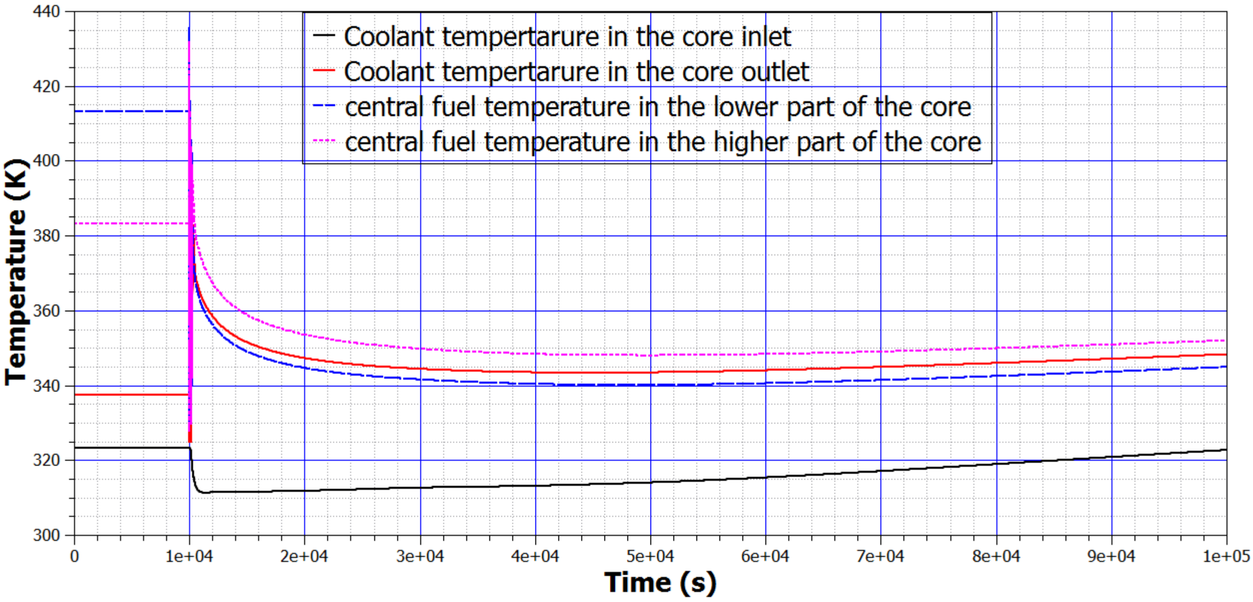


Figure 8. Coolant and fuel temperatures evolution during the transient.

Fig. 9 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 blackout start, the pool temperature began to increase. The pool temperature difference at the middle and the top is very small, and the temperature difference between the beginning and the end of the simulation, a period of 90,000 s, is also small being about 23 K. The temperature difference between the bottom and the top increased after the blackout showing that the middle and the top receive and accumulated more power than the bottom pool in natural circulation. started and natural circulation was established the higher parts of the pool receive and accumulate more power than the lower parts.

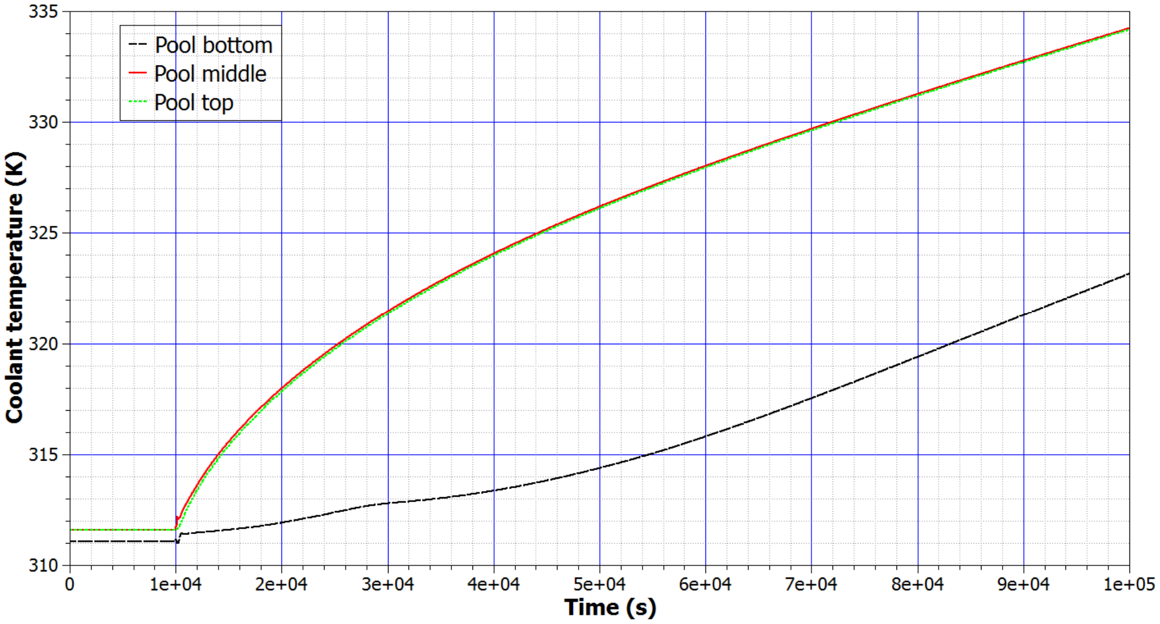


Figure 9. Coolant temperature in the tree levels in the pool.

Fig. 10 shows the mass flow rate in the chimney outlet, in the core outlet and in the natural circulation valves 463 and 467. As it can be seen valve 467 opened after the event and consequently the water from the pool entered this circuit that feeds the core. Therefore the mass flow rate in the core has practically this same value. The other valve, 463, seems to continue closed, because there can not be seen any mass flow through it. However, Fig. 11 shows that both valves stay opened during most of the transient period. Before blackout the mass flow through the chimney was downward, but during the natural circulation phase it is upwards caring the heat from core to pool. The natural circulation mass flow rate is very small, about 4kg/s, but it is enough to cool fuel elements and transfer this heat to the pool.

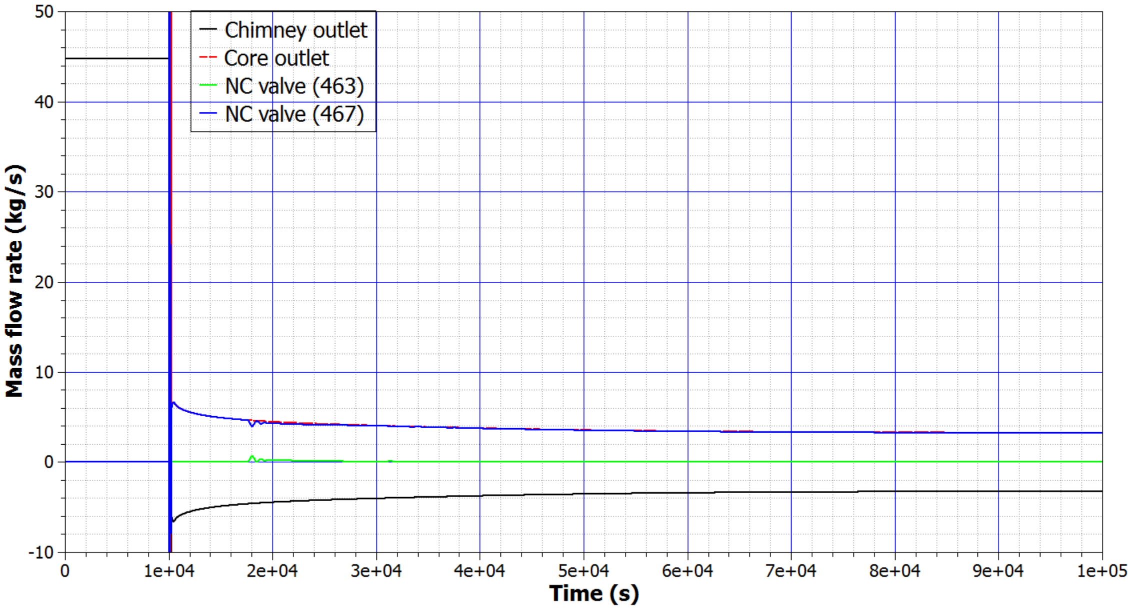


Figure 10. Mass flow rate in the natural circulation circuit.

Fig. 11 shows valves 463 and 467 flow area opened to natural circulation. This Figure shows if these valves are opened or closed; in the y axis of graphic zero value means that the valves are closed and one means that valves are fully opened. NC valve 467 shows a delay to open and at certain periods this valve opened and closed shortly.

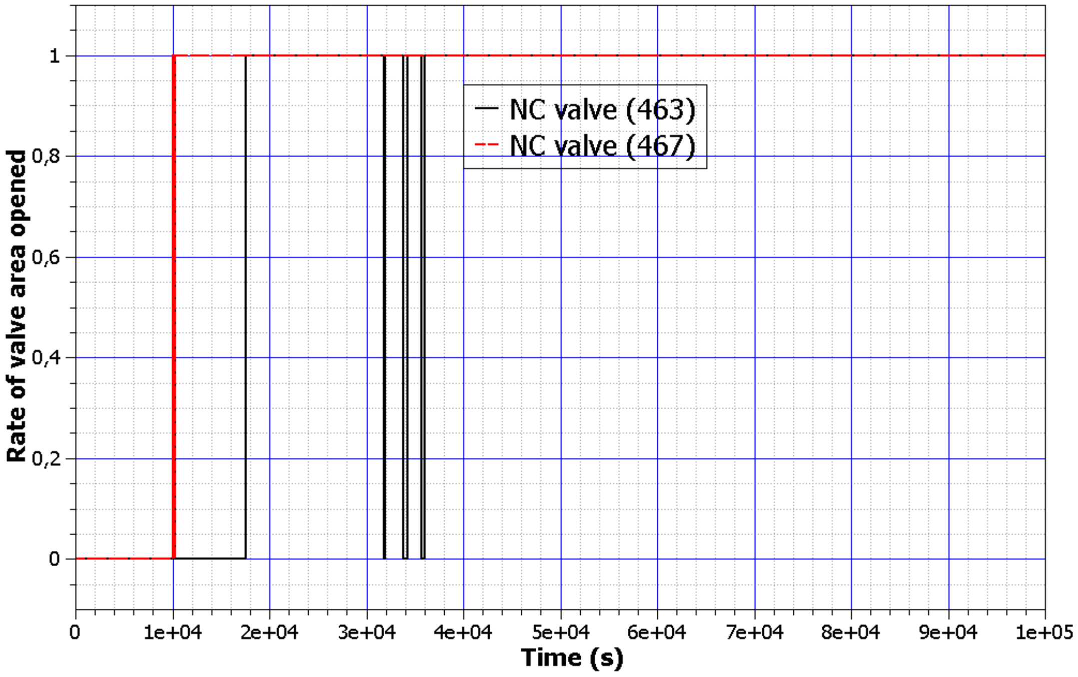


Figure 11. Rate of valve area opened to valves (463 and 467).

## 6. CONCLUSIONS

In this work, a preliminary nodalization of Osiris research reactor was developed for RELAP5/MOD3.3 code and it was presented as a contribution to the assessment of such a scheme for research reactor safety analysis.

This model has been improved and it is still necessary more investigation of its use with RELAP5. However, the main goal of this study was not to qualify this Osiris nodalization but to acquire experience in simulations of this type of pool reactor using a model for an existing reactor with available data for evaluations to as soon as possible start to simulate the RMB reactor.

The results of this work showed a relative good agreement in steady state in comparison with the experimental data. Many thermal hydraulic parameters in nuclear reactors 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 temperature, and so on, showed good agreement with the available data.

The implemented power control model worked as expected, as it was demonstrated by the power change cases. The other transient simulated, the blackout, showed that the natural circulation mode is established and that it is enough to keep the core cooled during an extreme event like that.

This work was important to show the main difficulties to get to the point of having results as those presented by simulating this type of reactor with RELAP5.

## 7. ACKNOWLEDGEMENTS

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