NODALIZATION EFFECTS ON RELAP5 RESULTS RELATED TO MTR RESEARCH REACTOR TRANSIENT SCENARIOS

by

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The present work deals with the analysis of RELAP5 results obtained from the evaluation study of the total loss of flow transient with the deficiency of the heat removal system in a research reactor using two different nodalizations. It focuses on the effect of nodalization on the thermal-hydraulic evaluation of the research reactor. The analysis of RELAP5 results has shown that nodalization has a big effect on the predicted scenario of the postulated transient. Therefore, great care should be taken during the nodalization of the reactor, especially when the available experimental or measured data are insufficient for making a complete qualification of the nodalization. Our analysis also shows that the research reactor pool simulation has a great effect on the evaluation of natural circulation flow and on other thermal-hydraulic parameters during the loss of flow transient. For example, the onset time of core boiling changes from less than 2000 s to 15000 s, starting from the beginning of the transient. This occurs if the pool is simulated by two vertical volumes instead of one vertical volume.

Key words: research reactor, loss of flow, natural circulation, nodalization effect, thermal-hidraulic parameters, RELAP5

INTRODUCTION

Nowadays, the best estimate (BE) system codes (like RELAP5) are extensively used in the area of design and safety evaluation of thermal hydraulics of nuclear power/research reactors. A preliminary request for such use is the comprehensive code-user-nodalization qualification [1].

Since the '60s, system codes have undergone big changes and substantial improvements by the code's developing group and relevant research centres around the world. This has imposed, among other things, a continuous assessment process leading to new released versions of the codes [1, 2, 3].

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To decrease the influence of the code user on code results, the user should follow closely the instructions printed in the code manual. A good knowledge of reactor systems, the phenomena addressed, capability and limitations of the models, meaning and significance of the input and output variables is also required [4, 5].

Generally, there are two different levels for a complete qualification of a nodalization, steady state level and transient level [6]. In the steady state level, the nodalization is qualified against data available from nominal operating conditions and by comparing the input data with the relevant geometrical parameters of the facility. In the transient level, the nodalization is tested in time-dependent conditions reproducing the available experimental or measured data.

This paper will focus on the effects of nodalization on code results and, consequently, on the safety evaluation of the reactor. It illustrates the importance of executing a complete qualification of the nodalization before its utilization in the evaluation process. To do this, a comparison between code results for two different nodalizations during the analysis of loss of flow transients (LOFT) in benchmark research reactor (RR) are presented here. These two nodalizations were previously used in the evaluation process of different transients in benchmark RR [7-11]. A typical MTR 10 MW benchmark RR was considered as the reference reactor for this study. The LOFT with scram due to the loss of offsite power is corresponding to the reference transient. RELAP5/mod3.3 is used to predict the consequences of this transient. Two input decks, one for each nodalization, are prepared based on the instructions and precautions mentioned in [12] and the data mentioned in [13, 14].

REFERENCE REACTOR DESCRIPTION

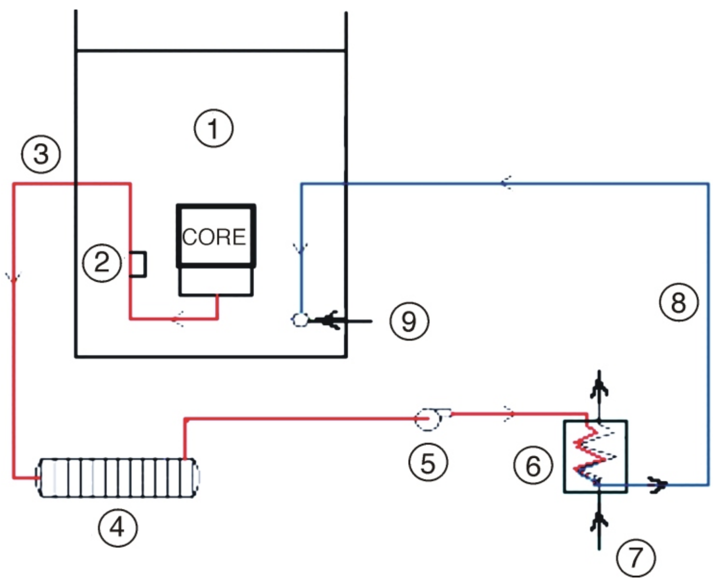
The reference reactor is a benchmark 10 MW pool-type RR. The core is cooled by downward forced flow of light water during the normal operation stage. During shutdown stage, the core is cooled by upward natural convection through the opening of the natural convection valve (NCV) on the core outlet line. As shown in fig. 1, the components of the core cooling system are typical for those in most RR. Its main components are the pool of water in which the reactor core is placed at its bottom, hold-up tank, pump, heat exchanger and connecting pipes. The main reactor data are outlined in tab. 1 [13, 14].

REACTOR NODALIZATION

Figures 2 and 3 show the two nodalizations (N1, N2) used previously in [7-11] and considered in this study. These two nodalizations, due to the lack of experimental data, were not qualified before their utilisation in the analysis of RR transients. In these nodalizations, the core is represented by a channel (100) and bypass (101) connected to an upper and lower plenum. NCV required to develop the natural convection loop is represented by a valve (245) connecting the core outlet line with the reactor pool during the shutdown phase. As can be seen, the only difference between the two nodalizations is in the simulation of the upper part of the reactor pool. In the N1 nodalization, the upper part is represented by one volume (110), whereas in N2 the nodalization is simulated by two volumes (110) and (120). The correspondence of the main reactor components, as defined by the basic system in fig. 1, as well as their equivalent elements in (N1) and (N2) nodalizations, are shown in tab. 2.

Table 1. Main reactor data [13, 14]

Reactor description	
Reactor type	Pool type
Power	10 MW
No. of fuel elements	23 standard fuel elements 5 control fuel elements
Fuel description	
Type	MTR, straight plates
Fuel meat	UAL_x-AL HEU
Plate thickness, [mm]	1.27
No. of plates per fuel element	23 in standard fuel element 17 in control fuel elements
Meat thickness, [mm]	0.51
Clad thickness, [mm]	0.38
Water channel thickness, [mm]	2.188
Core thermal hydraulics	
Coolant	Light water
Coolant flow rate, [m^3/h]	1000 (downward forced flow)
Core inlet temperature, [°C]	38
Core outlet pressure, [Pa]	1.56 10^5



1 – Reactor pool
2 – Natural convection valve
3 – Core outlet line
4 – Hold-up tank
5 – Primary pump
6 – Heat exchanger primary side
7 – Heat exchanger secondary side
8 – Core return line
9 – Distribution ring

Figure 1. Description of the basic system [13]

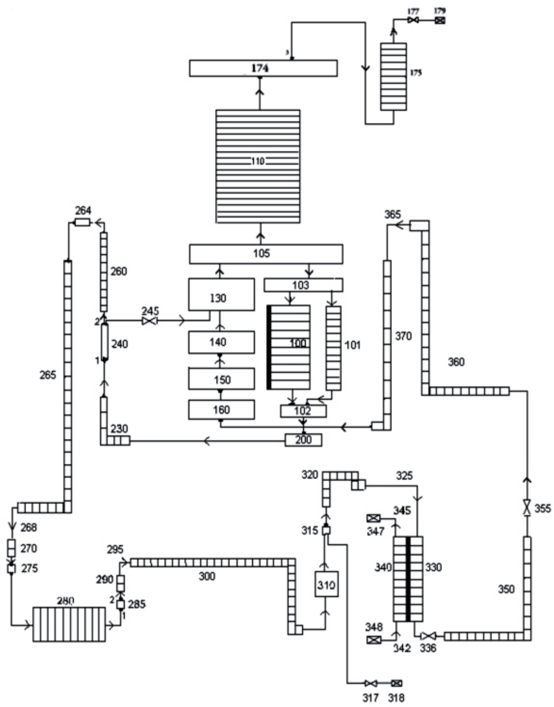


Figure 2. First nodalization (N1)

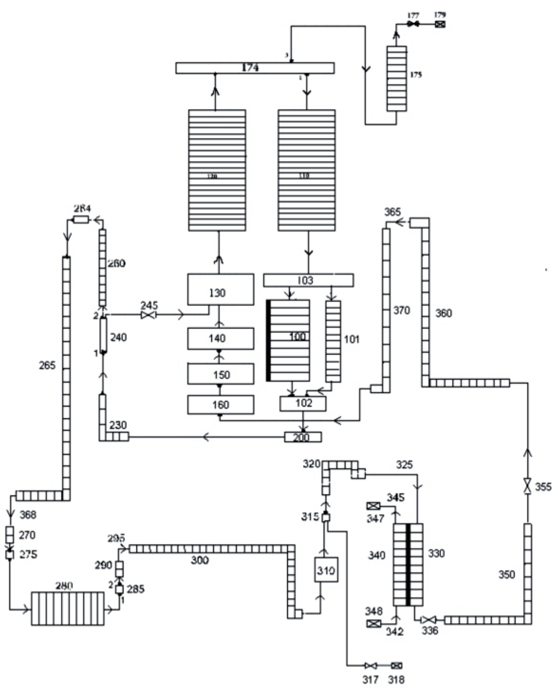


Figure 3. Second nodalization (N2)

TRANSIENT DESCRIPTION

The LOFT in RR was extensively studied in various research centres [10–13]. These studies were focused on reactor safety during the first 100 s after the initiation of the transient through the verification of safety parameters like clad temperature, onset of nucleate boiling, flow instability limits. Limited work has been done for extended times beyond 100 s [7-9]. This paper focuses on the coolability of the reactor over a prolonged period, >100 s, after the beginning of the transient. The transient time is extended to 20000 s to permit the code to predict any expected or unexpected phenomenon in core cooling.

Table 2. Main components of the nodalization

Componenet	Equivalent element	
	N1	N2
Core	100	100
Reactor pool	110	110, 120
Natural convection valve	245	245
Hold-up tank	280	280
Pump	310	310
Primary side heat exchanger	330	330
Secondary side heat exchanger	340	340

Description of imposed events

The imposed events involved in this transient are outlined in tab. 3. The code runs at steady state for 100 s to stabilize all the relevant thermal-hydraulic parameters. At 100 s, the cooling pumps of the primary and secondary circuits are stopped due to the loss of offsite power. The reactor protection system receives a scram signal from the core flow measurement device at 85% of core nominal flow. After 0.2 s, the first shutdown system makes an actual scram. At 15% of core flow (~41.7 kg/s), the NCV opens and the natural circulation develops. The sequence of events is summarized in tab. 3. This sequence is typical to that used in [13] during the analysis of LOFT, except that the transient time is extended here to 20000 s.

Table 3. Imposed sequence of events

Time	Imposed event
0-100 s	Steady-state normal operation regime
At 100 s	Pump trip
At core flow 85% of nominal	Scram signal
Time of scram signal +0.2 s	Actual scram
At 15% of core flow	NCV opens
20000 s	End of transient calculations

RESULTS AND DISCUSION

The steady state code results for thermal hydraulic parameters of the two nodalizations are compared with the corresponding reactor design parameters described in [13]. To qualify the nodalizations on the steady state level, errors in calculated values are compared with permissible errors mentioned in [6]. Due to lack of experimental or measured data, the nodalizations are not qualified in the transient stage. The values of the calculated thermal-hydraulic parameters of the two nodalizations are compared in order to clarify the effect of the said difference between the two nodalizations on code results.

Steady state

The analysis of calculated steady state code results of nodalizations N1, N2 shows that both are identical in values, tab. 4. This means that the difference between the two nodalizations has no effect on steady state results. The comparison of calculated values with those of design parameters mentioned in TECDOC 233 [13] shows that they are identical, except for the inlet core temperature, core pressure drop and core outlet pressure, the difference being within the acceptable error mentioned in [6]. Consequently, the two nodalizations are qualified to simulate the reactor thermal hydraulic on the steady state level.

Transient state

A comparison between the code results of the two nodalizations for some thermal-hydraulic parameters is presented in figs. 4 to 8. In them, the steady state period (0-100 s) is represented as a negative period (from –100 to 0), while the transient begins at time zero. This period is very short with respect to the transient time and appears as one point on the left side of time zero. The parameters studied are: the core mass flow, coolant temperature at core outlet, coolant void fraction and the clad temperature. Since there are no available data in literature relating to reactor measurements or experiments, the nodalizations can not be qualified on the transient level. On the other hand, they are evaluated from the safety point of view, in order to determine which of the two is more conservative with respect to reactor safety.

Core flow

The mass flow rate through the core, as predicted by the code, using both N1 and N2 nodalizations, is shown in fig. 4. The downward core cooling flow during normal core operation appears as a negative value on the vertical axis (–277.8 kg/s). The transient is started at zero time by pump trips and at a core flow of 85% of the nominal flow, the reactor scrams. At a core flow of 15% of nominal value, the NCV opens and the core natural circulation starts. This time the sequence of events is not clear on the time axis due to the long time for the transient. With the development of natural circulation, the core flow is reversed and becomes upward and the core is cooled by a single phase natural convection. The core flow increases gradually, according to the difference in coolant temperature/density between the core channels and the pool. This stage of core cooling extends until core boiling starts at nearly 2000 s and 15000 s in N1 and N2 nodalizations, respectively. The maximum core flow during this stage is nearly 8 kg/s in N1 nodalization and 15 kg/s in N2 nodalization.

After the beginning of boiling, the core flow in N1 nodalization increases to 31 kg/s and remains con-

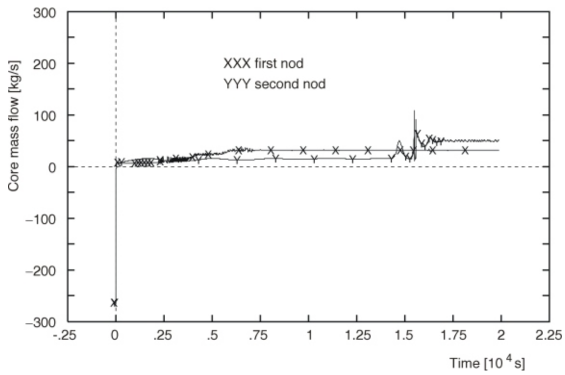


Figure 4. Core mass flow rate

Table 4. Nodalization qualification on steady-state level

	Quantity	Ref. [13]	Calculated (N1) & (N2)	Acceptable error, Ref. [6]
1	Primary circuit power balance, [MW]	10.0	10.0	2%
2	Secondary circuit power balance, [MW]	10.0	10.0	2%
3	Inlet core temperature, [°C]	38	38.15	0.5%
4	Rod surface temperature, average shannel, [°C]		62.0	
5	Pump velocity, [rad/s]	150	150	1%
6	Pressure drops between core inlet and outlet, [Pa]	17000	18000	10%
7	Mass inventory in primary circuit, [kg]		77320	2%
8	Flow rates (primary/secondary circuit), [kg/s]	277.8	277.8/307.0	2%
9	Channel coolant velocity, [m/s]	2.97	2.97	2%
10	Core outlet pressure, [Pa]	$1.56\ 10^5$	$1.55\ 10^5$	0.1%

stant until the end of the transient. In N2 nodalization, the beginning of boiling is accompanied with large fluctuations in flow after which the flow increases to 52 kg/s and then remains constant until the end of the transient.

This large difference in core flow rate between the two nodalizations is due to the difference in pool simulation. In N1, the upper part of the pool (volume 110) is connected to the core and the NCV through the same branch (105), fig. 2. Due to this modulation, the flow outlet from the core goes directly to the NCV through the branch (105) and returns to the core bottom through branch (200). Consequently, a small loop of natural circulation is established without any effect on the value of natural circulation flow in the upper pool head. In N2, the upper pool is represented as two separate columns. One of them (volume 110) is connected to the core and the other (volume 120) is connected to the NCV, fig. 3. This modulation maximizes the driving force for natural circulation flow. The natural circulation loop is extended to include the entire reactor pool head; consequently, the coolant flow is maximized.

Core coolant temperature

Figure 5 shows the coolant temperature in the upper region of the core (sub-volume 11) for the two nodalizations. At this volume, the coolant temperature of both nodalizations increases sharply from 311 K, the nominal core inlet temperature, to 375 K, due to the reverse of core flow from downward to upward and then decreases with the development of natural circulation. In N1, the temperature decreases sharply to 346 K and then increases again due to the generation of heat from the decay of fission products in the fuel, until reaching the saturation temperature at time nearly 2000 s, remaining constant after that. In N2, the coolant temperature first decreases sharply and then slowly, until reaching 326 K at 1660 s. The temperature increases again until it reaches the saturation temperature at 15000 s. It remains at saturation for a short time (~200 s) and then decreases below the saturation point, due to the increase in core flow. The temperature reaches 380 K and remains constant.

This difference in coolant temperature is due to the difference in the mass content of the natural circulation loop. In N1, the natural circulation loop is confined by volumes (100-101-103-105-130--240-230-200-102), fig. 2. The coolant mass in this loop is small compared to the total mass in the reactor pool and, consequently, the rate of its temperature change is fast. In N2, the natural circulation loop is extended to include the entire mass in the upper part of the pool and the heat generated is distributed over this big quantity of the coolant so that the rate of temperature change is slow.

Void fraction

Figure 6 shows the void fractions at the upper part of the core (sub-volume 11 of volume 100) for the two nodalizations. In N1, after the boiling has been started in the core, the void fraction increases gradually until reaching a relative value, depending on the location of the sub-volume in the core, and then remaining constant until the end of the transient. In N2, the core void fraction remains zero during the transient, apart from a very short period at nearly 15500 s at which the void fraction reaches 0.3.

This large difference in void fractions is due to the difference in the natural circulation loop. In N1, the two phase coolant outlet from the core is separated at branch (105) of fig. 2 where the vapour leaves the loop and, under the effect of buoyancy, moves upward to the upper part of the pool and is then condensed or released into the atmosphere, depending on the pool temperature. In N2, the vapour produced doesn't leave the loop, decreasing instead the coolant density in the right side of the pool (part 110) which enhances the natural circulation flow and, consequently, the cooling of the core. Due to this, the boiling of the core stops, but the coolant temperature at the core outlet still remains

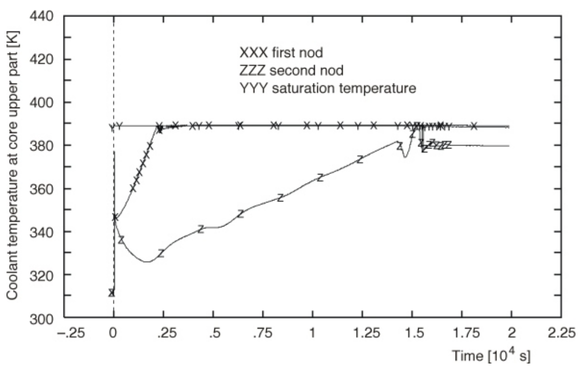


Figure 5. Coolant temperature at core upper part

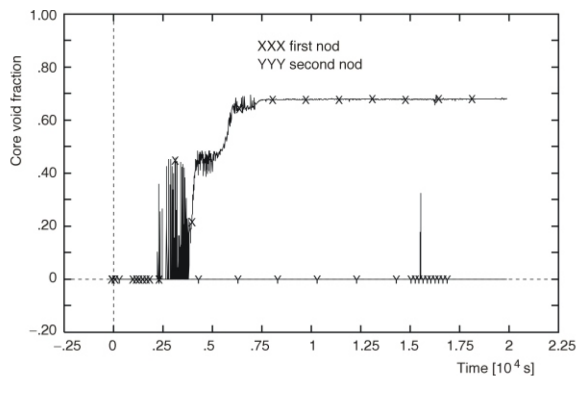


Figure 6. Void fraction at core upper volume

close to its local saturation temperature. The coolant moves upward and the local saturation temperature decreases, until reaching the coolant temperature after which the boiling in the pool starts. This pool boiling promotes the natural circulation flow in the core and prevents it from boiling again. Figure 7 shows the void fraction at sub-volume 20 of the N2 pool, volume 110.

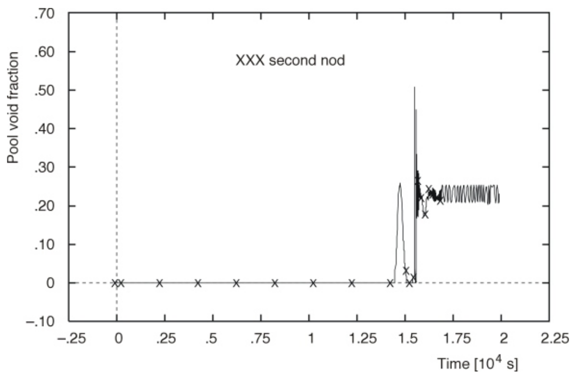


Figure 7. Pool void fraction

Clad temperature

Figure 8 shows the clad temperature at core centreline for the two nodalizations. The clad temperature follows the same behaviour of the core coolant temperature as in fig. 5. In both nodalizations, the clad temperature increases sharply due to the inversion of the core flow from downward to upward, reaches nearly 390 K, and then decreases with the development of natural circulation. In N1, the clad temperature decreases to 352 K and then increases rapidly, due to the increase in coolant temperature. At nearly 2000 s, the clad temperature reaches the onset temperature and remains constant up to the end of the transient. In N2, the clad temperature decreases sharply and then slowly, until reaching 336 K at 1660 s. After that, the temperature increases gradually, due to the increase in the temperature of the coolant. At

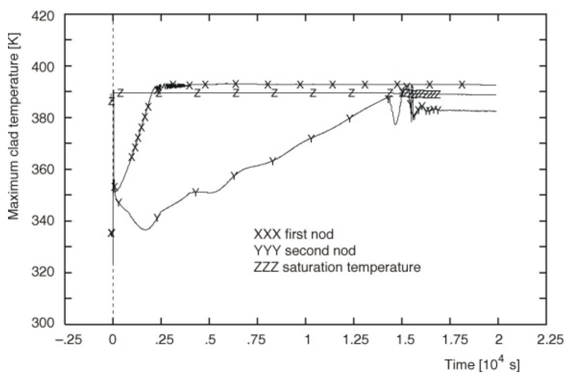


Figure 8. Clad temperature at core centerline

15000 s, the clad temperature becomes higher than the corresponding saturation temperature, but still less than the onset temperature. At 15500 s, in a few seconds, the clad temperature reaches the onset temperature and then decreases under the saturation temperature, due to the increase in the natural circulation flow, remaining below it to the end of the transient.

The results of the clad temperature and core void fractions demonstrate that the core cooling in N1 should be promoted during the LOFT by an emergency cooling and that, after the loss of offsite power, the operator has 2000 s to interact with the event. However, in N2, the cooling of the core components is sufficient and there is no need for any action on the part of the operator.

CONCLUSION

Before using the BE system codes in the evaluation of safety in research reactors, it is of utmost importance to perform a complete qualification for the nodalization of the reactor. This comprehensive qualification requires qualified measurements and/or experimental data for similar transient conditions. RELAP5 results for two different nodalizations simulate the 10 MW RR; qualified at the steady state, they show a significant difference only in the predicted transient scenarios. The first one showed that core boiling is initiated after only 2000 s upon the start of the transient, while the clad temperature reached and remained constant at the onset temperature during the transient time. However, in the second case, there was no boiling in the core and the clad remained below the saturation temperature, except for a very short period (a few seconds) of local boiling.

The two nodalizations represent two extreme conditions for core natural circulation; the first one minimizes the natural circulation flow and the second one maximizes it. Consequently, they don't simulate the actual core conditions during the transient. Nevertheless, some modifications of reactor nodalization require a more realistic prediction for said transient scenarios.

From the point of view of safety, the results of the first nodalization are more conservative than those pertaining to the second nodalization, meaning that its results should be taken into account while evaluating the issue of reactor cooling.

ABBREVIATIONS

BE	–	best estimate
LOFT	–	loss of flow transient
MTR	–	material test reactor
NCV	–	natural convection valve
N1	–	first nodalization
N2	–	second nodalization
RR	–	research reactor

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УТИЦАЈИ НОДАЛИЗАЦИЈЕ НА РЕЗУЛТАТЕ ПРОГРАМА RELAP5 ПРИ ПРОРАЧУНУ ПРЕЛАЗНИХ СТАЊА MTR ИСТРАЖИВАЧКОГ РЕАКТОРА

Рад се односи на анализу резултата програма RELAP5 добијених коришћењем две различите нодализације, а при проучавању прелазног стања у истраживачком реактору услед тоталног губитка струјања са отказивањем система за хлађење. Усмерен је ка последицама нодализације на термохидрауличку процену истраживачког реактора. Анализа резултата програма RELAP5 показала је да нодализација има велики утицај на предвиђени сценарио претпостављеног прелазног стања. Отуда, нодализацију реактора треба извршити веома пажљиво, посебно када су расположиви експериментални или мерени подаци недовољни за њену потпуну оцену. Анализа такође показује да симулација базена истраживачког реактора има великог утицаја на прорачун природног тока струјања и на прорачун других термохидрауличких параметара прелазног стања услед губитка тока. На пример, процена тренутка започињања кључања језгра мења се од времена нижег од 2000 s на 15000 s, мерено од настанка прелазног стања. Ово се догађа уколико је базен моделован у виду два вертикална волумена уместо једног.

Кључне речи: истраживачки реактор, губитак тока, природна циркулација, нодализација, термохидраулички параметри, RELAP5