Nuclear Engineering and Design 363 (2020) 110610

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Total and partial loss of coolant experiments in an instrumented fuel assembly of IEA-R1 research reactor

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ARTICLE INFO

Keywords:
Loss of coolant accident
Natural circulation
Research reactors

ABSTRACT

The safety of nuclear facilities has been a growing global concern, mainly after the Fukushima nuclear accident. Studies on nuclear research reactor accidents such as the Loss of Coolant Accident (LOCA), many times considered a design basis accident, are important for ensure the integrity of the plant. A LOCA may lead to the partial or complete uncovering of the fuel assemblies and it is necessary to assure the decay heat removal as a safety condition. This work aimed to perform, in a safe way, partial and complete uncovering experiments for an Instrumented Fuel Assembly (IFA), in order to measure and compare the actual fuel temperatures behavior for LOCA in similar conditions to research reactors. A test section for experimental simulation of Loss of Coolant Accident named STAR was designed and built. The IFA was irradiated in the IEA-R1 core and positioned in the STAR, which was totally immersed in the reactor pool. Thermocouples were installed in the IFA to measure the clad and fluid temperatures in several axial and radial positions. Experiments were carried out for five levels of uncovering of IFA, being one complete uncovering and four partial uncovering, in two different conditions of decay heat. It was observed that the cases of complete uncovering of the IFA were the most critical ones, that is, those cases presented higher clad temperatures when compared with partial uncovering cases, for the specific conditions of heat decay intensity and dissipation analyzed. The maximum temperatures reached in all experiments were quite below the fuel blister temperature, which is around 500 °C. The STAR has proven to be a safe and reliable experimental apparatus for conducting loss of coolant experiments.

1. Introduction

The International Atomic Energy Agency (IAEA, 2014) has strongly working with the licensing agencies of the countries that have nuclear facilities in order to ensure the reactors safety and safety of the population around nuclear power and research reactors. This concern grows face any accident that occurs in nuclear reactors around the world, and got worse after Fukushima's accident (TEPCO, 2012). The last one caused serious consequences to the population around the nuclear power plants and the cities nearby, causing insecurity and fear concerning to nuclear facilities in operation. The Loss of Coolant Accident (LOCA) is many times considered a design basis accident in these reactors.

In pool type research reactors, such as IEA-R1 (Maiorino et al., 1998), located at Nuclear and Energy Research Institute (IPEN), the reactor core is immersed in a demineralized water pool, which assures the safe removal of the decay heat after the reactor shutdown. The heat removal occurs in a passive way through the natural circulation of water, without depending on external energy sources, during the necessary time to maintain the physical integrity of the fuel assemblies and to assure the radioactive material confinement. If a LOCA in a research reactor occurs, it is also essential to ensure the fulfillment of the basic safety function of adequate removal of decay heat, to provide the integrity of the fuel. LOCA can lead to a total or partial loss of water of the reactor pool, or tank to research reactors, with total or partial uncovering of the fuel assemblies.

A LOCA in a research reactor with total or partial uncovering of the core may lead to a core meltdown, depending on the reactor power, operation time and core emptying time and if there is no action of some decay heat removal system. In this case, the main forms of heat removal are the thermal radiation and the natural convection of the air through the fuel assemblies (Hamidouche and Si-Ahmed, 2011). For partial core uncovering, there is an obstruction of the air natural circulation in the internals channels of the fuel assemblies. Depending on the uncovering level and decay heat, this may represents a condition more severe than the total core uncovering (Bousbia-Salah et al, 2006; Wett, 1960). For

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https://doi.org/10.1016/j.nucengdes.2020.110610
Received 28 June 2018; Received in revised form 31 January 2020; Accepted 11 March 2020
Available online 09 April 2020

Nomenclature

Symbol

A	Area (mm^2)
BH-3	Beam hole 3
DAS	Data Acquisition System;
D_{hGap}	Hydraulic diameter of the gap (mm)
IAEA	International Atomic Energy Agency
IEA-R1	IPEN Research Reactor (5 MW)
IFA	Instrumented Fuel Assembly
IPEN	Nuclear and Energy Research Institute
LOCA	Loss of Coolant Accident
LOCE	Loss of Coolant Experiment
$LOCE_i$-1	Group 1 specific loss of coolant experiment
$LOCE_i$-2	Group 2 specific loss of coolant experiment
P	Reactor power operation (W)
PA-1 and PA-2	IFA partial uncovering of the 1st level experiments for groups 1 and 2
PB-1 and PB-2	IFA partial uncovering of the 2nd level experiments for groups 1 and 2
PC-1 and PC-2	IFA partial uncovering of the 3rd level experiments for groups 1 and 2;
PD-1 and PD-/2	IFA partial uncovering of the 4th level experiments for groups 1 and 2
p	Wetted perimeter (mm)
Q	Reactor decay heat (W)
RMB	Multipurpose Brazilian Reactor
SFA	Standard fuel assembly
STAR	Loss of coolant test section
TC_i	Specific IFA clad thermocouples
t_d	decay time (s)
TF_i	Specific IFA fluid thermocouples
t_{ir}	irradiation (or operation) time (s)
TOT-1/2	IFA total uncovering experiments for groups 1 and 2

Subscript

$_1$	group 1 experiments
$_2$	group 2 experiments
$_a$	actual
$_s$	scheduled

higher levels of partial uncovering there are most favorable heat removal conditions by the water covering.

In fact, there are few LOCA experiments for research reactors and an even smaller number of comparisons between uncovering levels for these accidents, available in literature (WETT, 1960; Cox and Webster, 1964; Webster, 1967; Wenzel and Arnold, 1970; Warinner et al., 1984; Dreier and Winkler, 1985; Sedvik and Yavuz, 1998; Aharon and Hochbaum, 2006; Ito and Saito, 2016).

The objective of this work is to perform, in a safe way, experimental tests of total and partial uncovering of an instrumented fuel assembly, simulating and comparing a LOCA at similar conditions of a research reactor. The LOCA experiments were realized in five different uncovering levels and in two heat decay conditions. The fuel plate temperature and its behavior with uncovering are the main parameters to be observed in the tests. The fuel plate temperature must be below the safety limits. The experimental DATA results of the obtained fuel temperatures were compared at each uncovering levels and decay heat condition, to observe the behavior of the heat removal mechanisms in each experimental case and which level of uncovering was the most critical.

For this, a loss of coolant test section, called STAR, was designed, constructed, assembled and commissioned (Maprelian et al., 2013, 2015; Maprelian, 2018). The STAR section uses the Instrumented Fuel Assembly (IFA) of the IPEN (Durazzo et al., 2019; Umbehaun, 2016; Hainoun, et al., 2014). The IFA, used in the experiments, is identical to the standard fuel assembly (SFA) of the IEA-R1, with fifteen k type thermocouples, to measure the fluid and clad temperatures, with actual axial and radial heat flux distributions and decay heat of a core fuel assembly. The IFA was the main component of the STAR LOCA experiments. Thus, the integrity of IFA was essential to the safety of all experiments. Blister temperature is commonly used as an of the safety limits for fuel assemblies.

The whole experimental procedure occurred in the pool of the IEA-R1 Reactor, without the need of an additional lead or concrete shielding, bringing more safety to the operators, researchers and to the IFA itself. The IFA uncovering level control was done by using a compressed air system and a differential pressure transducer, obtaining good results. This system allowed an excellent control of the uncovering and rewetting of the IFA. Information of the temperatures of the IFA in transient conditions of uncovering and refilling and steady state conditions in constant level were obtained. Maprelian (2018) provides more information about these experiments.

2. Loss of coolant experiments

The loss of coolant experiments were performed using the IFA and

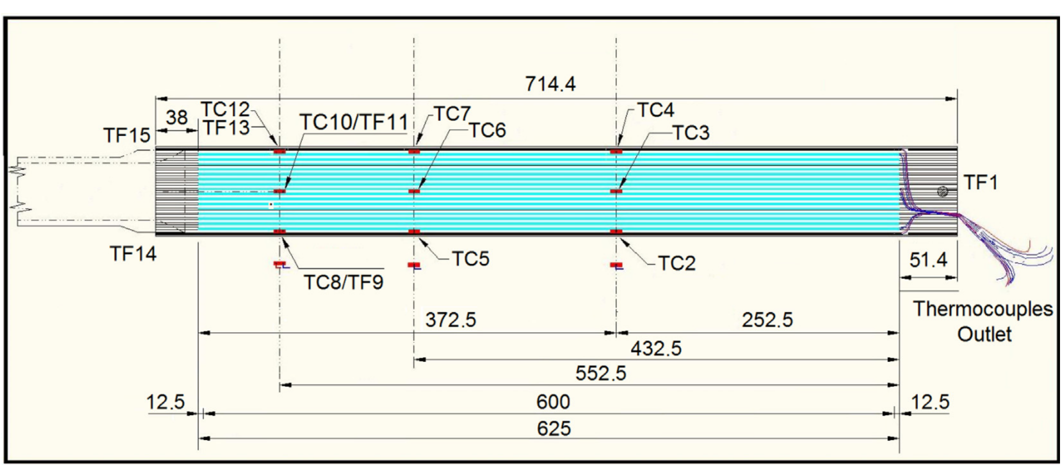

Fig. 1. IFA schematic representation.

the STAR test section, in the IEA-R1 Reactor facility. The IEA-R1 Reactor is described in the following.

2.1. IEA-R1 reactor

The research reactor IEA-R1 located in IPEN, in the campus of the University of São Paulo (USP), at São Paulo, SP (IPEN, 2005). The reactor designed by Babcok & Wilcox Company (IPEN, 2005) is a 5 MW pool type, nowadays operating at 4.5 MW. As mentioned earlier, after a safety shutdown of the reactor, the core decay heat is removed by natural circulation by the water of the reactor pool (IPEN, 2005).

The LOCAs of the IEA-R1 reactor were analyzed in detail by Maprelian (1998). Currently, the LOCA with the most critical total core uncovering, would be the pool drain pipeline rupture, at an estimated time of 1 h, 16 min and 40 s The most critical LOCA with partial loss, would be the beam hole BH-3 rupture with the partial submersion of 32.5% of the fuel assemblies, in an estimated time of 23 min and 40 s.

The standard fuel assembly (SFA) comprises an inlet aluminum nozzle, two aluminum side support plates, eighteen uranium fuel plates covered with aluminum and an aluminum handling pin for their transportation (IPEN, 2005). The limit temperature for the safety of the SFA is the blister threshold temperature of the plates, which is around 500 °C (Maprelian et al., 2015; Santos et al., 1998).

2.2. IFA description

The IFA was developed by IPEN researchers to operate in the IEA-R1 reactor core. Details of this project and experimental results are presented by Umbehaun (2016), Durazzo et al. (2019) and Hainoun, et al. (2014). It was designed to keep the design of a SFA of U_3S_{i2} with a density of 3 g U/cm^3, and was equipped with fifteen thermocouples, to the measure of the fluid temperatures (TF) and clad temperatures (TC). Three IFA channels were monitored with thermocouples, the central channel and the two more external channels, with four thermocouples in each one. In the IFA also were installed thermocouples to measure the inlet fluid temperature (TF1) and outlet fluid temperatures (TF14 and TF15). Currently, TF1 and TF15 are out of work by faults. The schematic drawing of the IFA with the thermocouples and respective positions is shown in Fig. 1.

The thermocouples installed in the IFA were k type stainless steel sheathed with 0.50 mm diameter and 10 m length. They were mechanically fixed on the fuel plates by means of aluminum support pads. The clad temperature thermocouples (TC) measured the average surface temperature of two adjacent fuel plates, because the support pad was in contact with both (Umbehaun, 2016; Durazzo et al., 2019). The SFA blister temperature, around 500 °C, was used as safety limit temperature of the IFA (Maprelian et al., 2015; Santos et al., 1998). Fig. 2 shows a detail of the gaps near the nozzle, and an illustration of them. These gaps allowed air passage through the plates, when the partial uncovering occurred below them. The hydraulic diameter of the gap was estimated in 2.3 mm.

The IFA was irradiated in the IEA-R1 reactor for the experiments execution. All experiments were accomplished with the STAR section, as described below.

2.3. Loss of coolant test section (STAR)

STAR was formed of a base, where the IFA was placed, a cylindrical stainless steel hull, a compressed air system and the instrumentation. Regarding its safety, all experiments with the test section were performed inside the IEA-R1 reactor pool and no abnormality, incident or accident, were recorded. The effective control of the emptying and refilling with own pool water, allowed the performance of the proposed experiments at various IFA uncovering levels. Each one of these parts that constitute the STAR will be described in the following.

2.3.1. Star base

The base was composed of two aluminum pallets, two aluminum supports (for the aluminum nozzle), aluminum and stainless steel plates, stainless steel threaded bars, nuts and washers, four lifting eyes, the lead and steel counterweight wrapped in an aluminum box, two aluminum rebars and the aluminum nozzle.

Two M20 stainless steel threaded bars were fixed on the base to make the coupling and closing with the cylindrical hull through the special M20 closing nuts. The lead and steel counterweight and aluminum rebars were used to compensate the buoyancy force in the section when it is emptied. The aluminum nozzle was for the positioning of the IFA. On the faces of the nozzle supports were placed thermal insulation (Celeron®). The estimated mass of the base was 527 kg. During the simulated experiments, the IFA was removed from the core and positioned in the aluminum nozzle.

2.3.2. STAR cylindrical hull

The STAR hull was cylindrical, of stainless steel and bell type. The hull mass was approximately 70 kg. The hull internal volume was approximately 0.45 m^3. The hull coupling with the base M20 spindles was done by the closing rips of its lower part, and its closing by the special M20 closing nuts. In the lower part, the hull also had the cable rips for the passage of the IFA thermocouples cables. Fig. 3 shows the hull over the base and details of the rips and the closing nuts. The internal diameter and height of hull were of 600 mm and 1598 mm, respectively. The thickness of the hull wall and cover was of 2 mm.

In order to allow the internal hull air or water heat dissipation to the pool water, there was no thermal insulation between the hull and the pool. The hull had a plate on its top cover, which allowed its transport and placement on the base (see Fig. 4). In addition, it had connections for inlet and outlet of air (see Fig. 4).

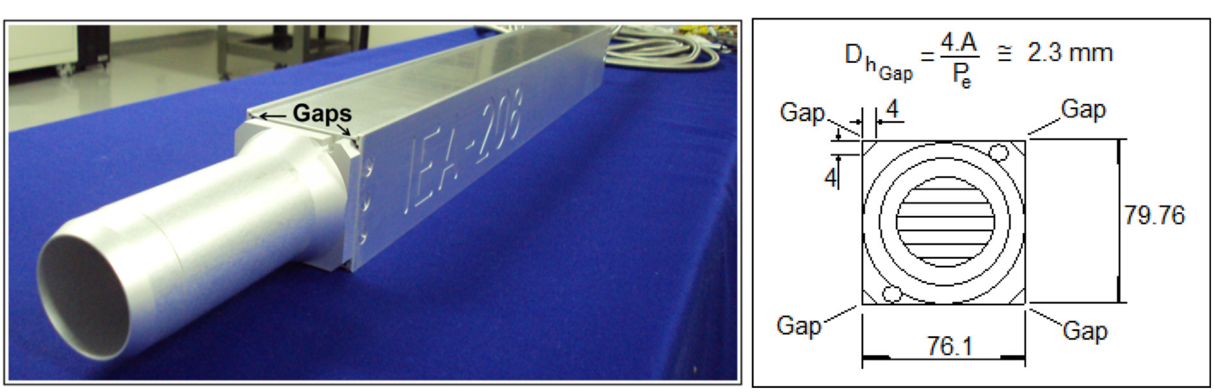

Fig. 2. IFA gaps detail and ilustration.

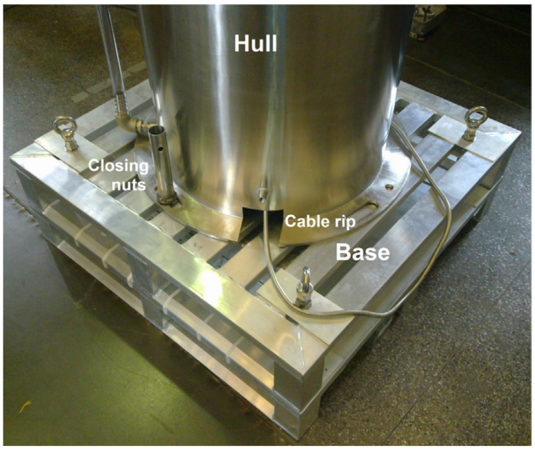

Fig. 3. Hull over the base of STAR.

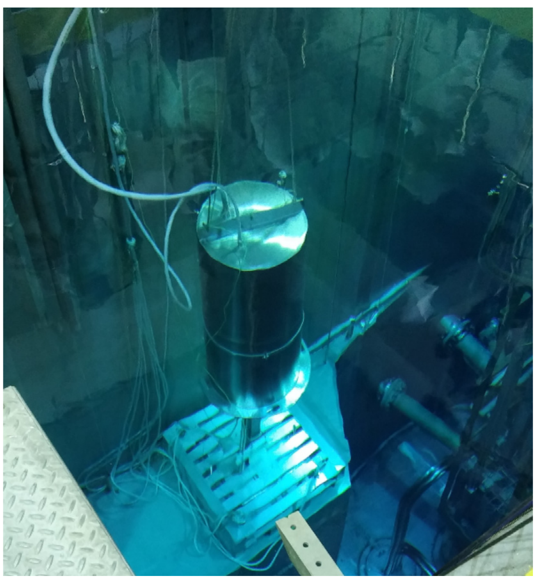

Fig. 4. STAR commissioning test – Hull placement.

2.3.3. Compressed air system and instrumentation

The compressed air system was responsible for the emptying, refilling of water and the closing for STAR experiment. It received air from the reactor compressed air system. The air from the hull was sent directly to the reactor ventilation and air conditioning system duct, which had radiation detectors. The system consisted of valves, hoses, connections and expansion vessels to reduce the air velocity. For the safe end of the experiment, it was required the closing of the compressed air inlet valve and the opening of outlet air valve. In order to isolate the system, there were two redundant valves, in addition to the reactor compressed air system valve itself. For the compressed air removal of the section, the system had three redundant valves in parallel.

The water level measurements in the section were done by a Validyne differential pressure gauge. The temperature and level signals were sent to the IEA-R1 Data Acquisition System (DAS) that was adapted to receive in a screen and to record these values in a specific file.

The uncertainties expected for the IFA TC3 thermocouple were of $|-0.8|$ °C and for its DAS channel, of $|0.7|$ °C, with a total error of 1.5 °C. The accuracy of the Validyne (Validyne, 2017) level gauge was of ± 0.5% (of range).

2.3.4. Assembling and commissioning

The STAR was placed inside the IEA-R1 pool, over a concrete platform coated stainless steel. The STAR commissioning test is shown in Fig. 4.

2.4. STAR loss of coolant experiments (LOCE)

In this section, the ten experiments with the STAR are described. It should be emphasized that there were some differences between STAR experiments when compared with LOCA in research reactors, as: (a) absence of an insulation on the IFA external lateral sides to limit the convection and radiation heat exchange, that had resulted in lower IFA clad temperatures and less realistic and conservative condition than in a reactor core, (b) safety limitation to test higher decay heat conditions and (c) the small internal volume of air inside STAR hull that had resulted in higher inlet air temperatures and more conservative than in a research reactor pool.

The STAR LOCE were analyzed and approved by IEA-R1 Reactor Internal Security Committee and by IPEN Safety Analysis Committee. The experiments were approved for IFA maximum temperatures of 130 °C, far from blister temperature of 500 °C for fuel assemblies. The

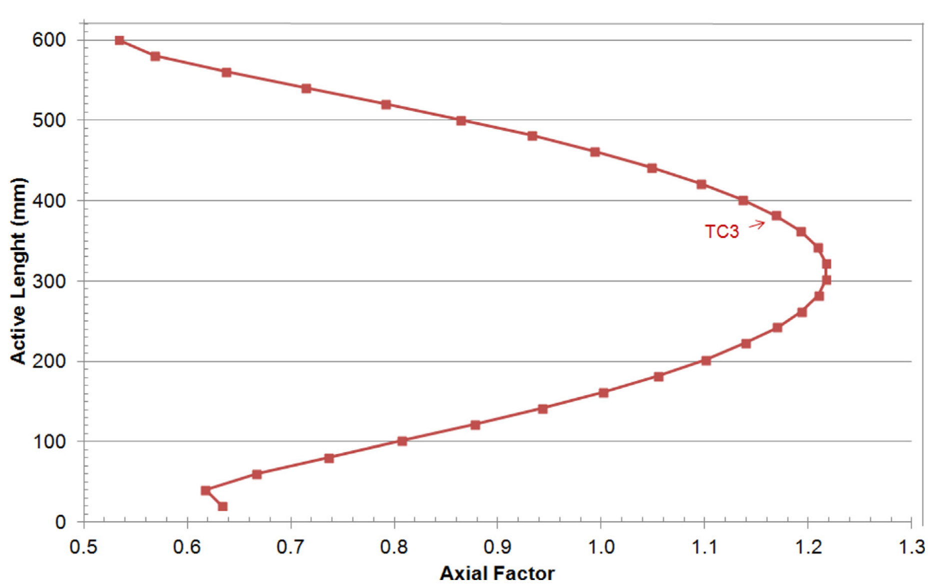

Fig. 5. Axial thermal power profile – IFA average central plates.

IFA was reintroduced in the core, in the configuration change, occurred during May 2nd–6th, 2016, especially for these experiments.

The axial and radial power distribution of IFA, obtained with the CITATION code (Flowler et al., 1971), are provided in (Maprelian, 2018). Fig. 5 shows the axial thermal power profile of average central plates, where is located the TC3 thermocouple.

The decay heat was estimated using the equation attributed to Way and Wigner (Pond and Matos, 1996) as,

$$Q = 6.22.\ 10^{-2}.\ P(t_d^{-0.2} - (t_{ir} + t_d)^{-0.2}) \quad (1)$$

where P is the reactor power operation, t_{ir} the irradiation (or operation) time and t_d the decay time, with time in seconds. The Eq. (1) was used to generate an Excel spreadsheet, which considered the IEA-R1 reactor operation history with beginning and end operation times, for many weeks of operation. In this spreadsheet, the reactor operation conditions, since the IFA reintroduction in the core until the experiments end, were considered. Through the spreadsheet calculations, it was possible to estimate the needed decay times for the start of each experiment.

The IEA-R1 reactor operated for an approximate time of 2 h and 15 min every Friday, exceptionally to achieve the decay heat demand,

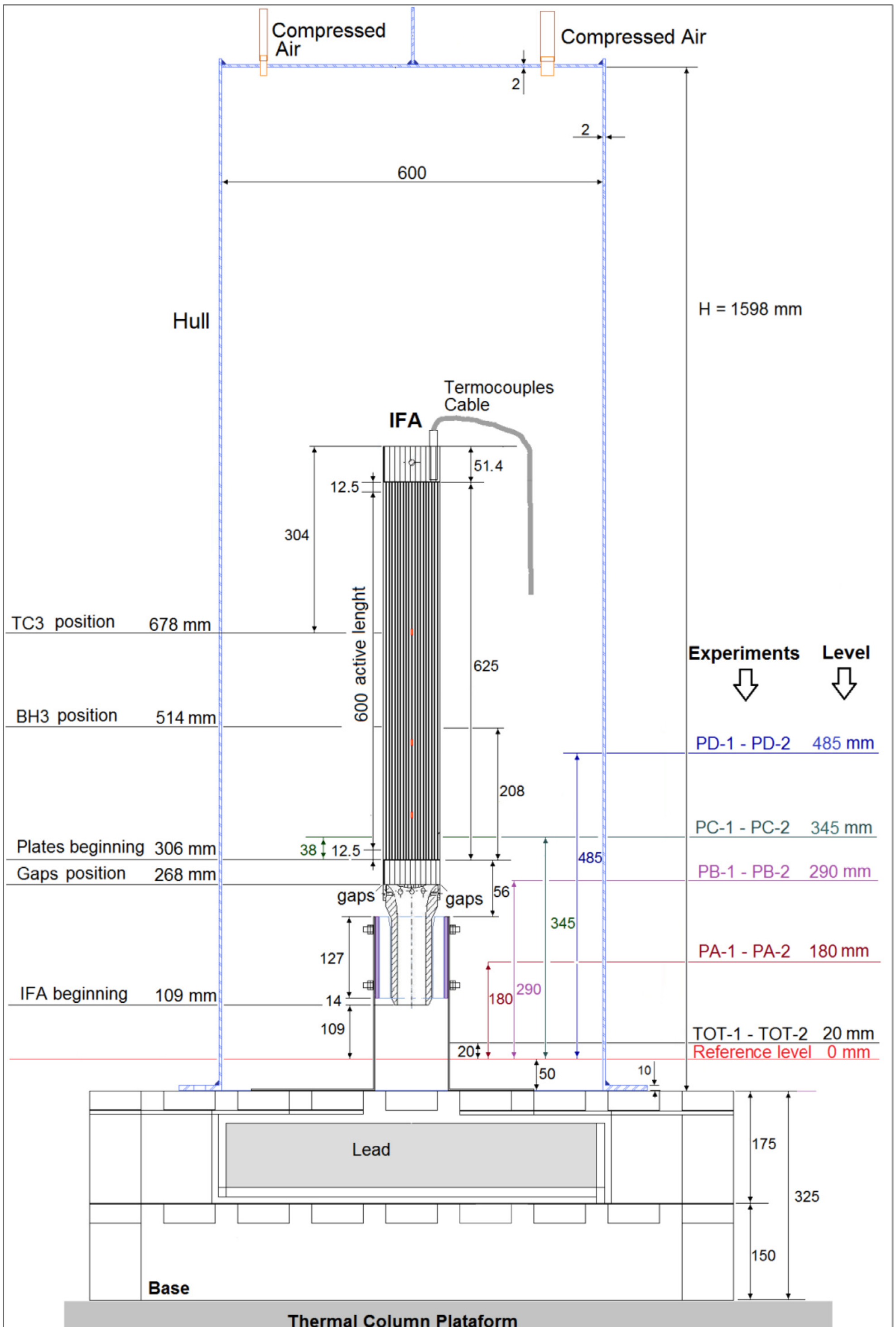

Fig. 6. STAR test section with ten loss of coolant experiments illustration.

needed the experiments. After this time, the IFA was removed from the IEA-R1 core and placed inside the STAR section.

The experiments objective was to analyze and compare five IFA uncovering levels for two different heat decay conditions. The five levels involved the IFA total uncovering plus four partial IFA uncovering. The goal was to realize comparisons in similar heat decay conditions.

Two decay times were estimated for the experiments, t_{d1} and t_{d2}. The first were performed with higher decay power values and the second with lower values. The experiments were divided in two groups with five uncovering levels. In the group 1, there were the five experiments with higher decay power and in the group 2, five with lower decay power. The indices 1 and 2 correspond to the times t_{d1} and t_{d2} of decay time. The scheduled decay times (t_{d1s} and t_{d2s}) estimated by Excel spreadsheet are supplied in Sections 2.4.1–2.4.5 and the actual decay (t_{d1a} and t_{d2a}) are provided in the Section 3.1 for each experiments.

The total transient, consisted of the emptying, the constant level steady state condition, and refilling, for the uncovering levels specified for each experiment. The experiments are described follow. Fig. 6 shows the total and partial uncovering levels for the experiments. It can be identified the IFA zero reference level, IFA bottom, gaps position, plates beginning, the thermocouple TC3 and beam-hole BH-3 position with its comparison with the five water levels experiments.

2.4.1. Total uncovering – TOT-1 and TOT-2

The experiments TOT-1 and TOT-2 corresponded to the IFA total uncovering at water level of approximately 20 mm, too close the STAR section total emptying, that was of 0 mm (zero reference level) (see Fig. 6). The TOT-1 was scheduled for a decay time (t_{d1s}) of 1 h and 17 min, belonging to the group 1, and the TOT-2 for a decay time (t_{d2s}) of 3 h and 17 min, belonging thus to the group 2. TOT-1 was the reference experiment of group 1 and TOT-2 for the group 2.

For these experiments, it was expected the air natural circulation, without any obstruction, as the most important heat transfer mechanism in the IFA channels. Although of the small air internal volume of the STAR hull, a good natural circulation with the pool water as cold source was expected, allowing the air cooling. However, the inlet air temperatures in the IFA, had higher values than those expected in a LOCA in a research reactor and therefore, were more conservative. The air convection and the radiation on the IFA external surfaces were expected too. The heat transfer in all the experiments was also associated with the radial and axial conduction in the IFA.

2.4.2. Partial uncovering – PA-1 and PA-2

In the experiments PA-1 and PA-2, there was the IFA uncovering, until the first level of IFA partial uncovering, 180 mm (see Fig. 6). This level corresponded to the half of STAR aluminum nozzle height. Air natural circulation obstruction in the IFA inlet nozzle was expected, but the natural circulation in the IFA internal channels, through the IFA gaps was expected too. The gap level was approximately 270 mm. Air convection and radiation on the IFA external faces also were expected. And a small IFA conduction and natural convection with the water may occur.

The PA-1 was scheduled for a decay time (t_{d1s}) of 1 h and 19 min and the PA-2 for a time (t_{d2s}) of 3 h, 22 min and 20 s. These decay times were programmed for the PA-1 had decay heat conditions similar to the TOT-1 and the PA-2, to the TOT-2.

2.4.3. Partial uncovering – PB-1 and PB-2

The experiments PB-1 and PB-2 was the second level IFA partial uncovering, with an approximated value of 290 mm. This level corresponded to a height of 15 mm below the IFA plates beginning. It was observed that the level for these two experiments were very close to the gaps level, therefore, natural circulation in the internal channels similar to the PA-1 and PA-2 experiments may also occurs. In these experiments, air convection and radiation on the IFA external surfaces, conduction in the IFA and natural convection with the water were expected. These two experiments can be seen in Fig. 6, too.

The scheduled decay time (t_{d1s}) for the PB-1 was of 1 h, 22 min and 30 s and the time (t_{d2s}) for the PB-2 of 3 h, 35 min and 10 s, in such a way that the PB-1 had decay heat conditions similar to the TOT-1 and PA-1, and the PB-2, to the TOT-2 and PA-2.

2.4.4. Partial uncovering - PC-1 and PC-2

The experiments PC-1 and PC-2, corresponded to the third IFA partial uncovering, with an approximated value of 345 mm. This level was equivalent to a height of 38 mm above the beginning of the IFA plates or 4% of its active length. In this case, it was expected the total obstruction of the IFA nozzle and gaps, thereby preventing the air natural circulation in the IFA internal channels. This reduction in heat removal by natural circulation caused by obstructions may be compensated by a higher heat removal by radial and axial conduction in the IFA and the natural convection with the water. Also, was expected the heat exchange by air convection and thermal radiation on the IFA external faces. The levels for these two experiments are illustrated in Fig. 6.

The PC-1 had a scheduled decay time (t_{d1s}) of 1 h and 14 min and the PC-2 for a time (t_{d2s}) of 2 h, 58 min and 30 s, with decay heat conditions similar to the experiments of group 1 and 2, respectively.

2.4.5. Partial uncovering – PD-1 and PD-2

For the experiments PD-1 and PD-2 occurred the fourth IFA partial uncovering level, of 485 mm. This level was equivalent to an uncovering level of 28% of the IFA active length, very close to the IEA-R1 core uncovering, if happens the Beam-Hole 3 (BH-3) rupture accident: 32.5% of the IFA active length. The levels for these two experiments are represented in Fig. 6.

For the PD-1 was scheduled a decay time (t_{d1s}) of 1 h, 22 min and 20 s and for the PD-2 a time (t_{d2s}) of 3 h and 31 min, in a manner that

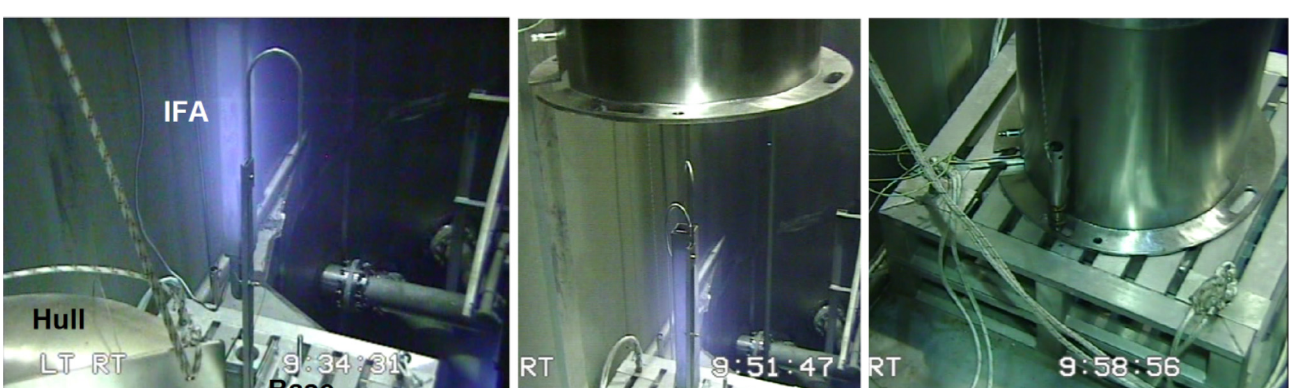

Fig. 7. IFA and hull placement in PD-1 experiment. Setion STAR.

the PD-1 had decay heat conditions similar to the group 1 experiments and the PD-2 to the group 2.

The heat transfer mechanisms in these experiments were similar to the PC-1 and PC-2 experiments, being expected a higher heat removal by the natural convection with the water in the PD-1 and PD-2 due its higher covering level.

2.4.6. Images of the PD-1 experiments

Fig. 7 shows images of the filming recorded during the experiments of September 16th 2016. The filming was made by the operators of the IEA-R1 Reactor. In these images, the IFA that was already removed from reactor core and was positioned in the support on the base, which received the hull.

3. Comparison among uncovering experiments

3.1. Actual decay and transient total times

In this section, the results of the actual decay and transient total times registered for the experiments are presented. The scheduled decay times (t_{d1s} and t_{d2s}) (from the Section 2.4), the actual decay (t_{d1a} and t_{d2a}), the difference between the scheduled and the actual decay time (($t_{d1s} - t_{d1a}$) and ($t_{d2s} - t_{d2a}$)) and the actual transient total times are shown in Table 1.

As the TOT-1 and TOT-2 were the reference experiments, the difference between the scheduled decay times and the actual times, shown in Table 1, were disregarded and these actual decay times and equivalents decay heat were considered as standards for the others experiments. The only one experiment in which was observed advance in the actual times was the PA-2 with excellent time of 35 s. Except PC-1 and PC-2 (27 min and 35 s; 28 min and 15 s), all other experiments presented small delay in the range (40 s to 6 min and 5 s). The effects of these delays on the decay curves will be presented in Section 3.2.

3.2. Decay heat estimates

This section provides the heat decay estimated for the experiments, as defined in Section 2.3.4, and using the actual information of the Section 3.1. The target, as defined above, with reactor power, times of operation and decay control was the comparison of the experiments for five different uncovering levels and two decay power conditions or in the two experiments groups, in similar heat decay conditions.

Fig. 8 shows the decay curves estimates of the five experiments of loss of coolant of group 1 of experiments and Fig. 9 of the group 2. The time 0 of the Figs. 8 and 9 corresponds to the reactor shut down for each experiment. The estimates of the decay heat percentage changes among the four partial loss of coolant experiments and the total uncovering, of the groups 1 and 2 are shown in Table 2.

The analysis of the results of Figs. 8 and 9 and Table 2 showed that, with the exception of the PC-1 and PC-2, all the other experiments presented decay heat estimates very close of the TOT-1 and TOT-2, with changes between −0.64% and 0.80%. Thus, this allowed a good comparison among them. As already mentioned in Section 2.4.4, delays have occurred, for the start of experiments PC-1 and PC-2, above of 27 min. These delays led to an estimated difference of 7.1% to 12.37% in relation to the TOT-1 and TOT-2. When of the utilization of the PC-1 and PC-2 temperatures results, this difference needs to be considered.

3.3. Level and temperature results

In this section, experimental results of level and temperature are compared for two groups of experiments. Figs. 10 and 11 show the level versus time, of group 1 and group 2, respectively. The time 0 of the Figs. 10–13, is the instant immediately after the actual decay time for each experiment, which are provided in Table 1.

Tables 3 and 4, shows the average level in the steady state condition, and also the emptying and refilling velocity and time, for the group 1 and 2. In addition, the IFA nozzle and gaps levels and the TC3 thermocouple level are supplied in Table 3.

It was observed, from Tables 3 and 4 and Figs. 6, 10 and 11, that TOT-1 and TOT-2 experiments levels were more than 90 mm below the IFA nozzle, configuring the total uncovering and thus allowing the air natural convection in its internal channels. In PA-1 and PA-2 experiments, the levels were above the IFA nozzle, but below the gaps level. Thus, partially obstructing the air intake through the nozzle, but allowing the air inlet through the gaps. In PB-1 and PB-2 experiments, the levels were very close to the gaps level. The Validyne gauge accuracy error (± 20 mm for this experiment) (Validyne, 2017) and the level fluctuations also showed that may be possible the air passage during these two experiments. The PC-1, PC-2, PD-1 and PD-2 experiments were in levels above the gaps level, obstructing totally the air passage to the IFA internal channels.

Figs. 12 and 13 shows the temperature results obtained for the thermocouple TC3 for the five experiments of group 1 and group 2, respectively. The TC3 was the chosen, because it presented the higher IFA temperatures, in all experiments. Other clad (TC) and fluid (TF) temperatures are provided in Maprelian (2018). In Figs. 12 and 13, the start of the air natural circulation for the experiments TOT-1, TOT-2, PA-1, PA-2, PB-1 and PB-2 and its end for the TOT-1, TOT-2, PA-1 and PA-2 experiments are still highlighted.

The air natural circulation beginning, in Figs. 12 and 13 were identified by an inflection point, with the decrease of the TC3 thermocouple temperature. This reduction occurred when the stagnant air was heated until the difference in density was sufficient to result in its movement, allowing the admission of cold air in the channel. In the end of the natural circulation, it was observed a temperature elevation inflection point. This increase was due to the air intake obstruction, by refilling water. Then, the air stayed stagnant and it was slightly heated until the effective heat removal by the refilling water. Figs. 12 and 13, proved the expectation of a free natural circulation, without IFA nozzle obstruction for the TOT-1 and TOT-2 experiments. Also, they confirmed the expectation of natural circulation through the IFA gaps, for PA-1 and PA-2 experiments. As already, mentioned the proximity of the PB-1 and PB-2 experiments levels, with the IFA gaps, also allowed the natural circulation through the gaps. In all experiments, it was observed that the TC3 thermocouple temperature increase, until the equilibrium between the heat decay generated and the heat removed was reached. This behavior was also observed in other LOCA tests in research reactors (Sedvik and Yavuz, 1998; Webster, 1967) or tests of fuel elements suspended in air (Wett, 1960). It is also important to mention that the TC3 temperatures were influenced conservatively, by the section STAR air temperatures that were higher than the expected in a research reactor LOCA. It was observed, also, that until the beginning of air natural circulation in PA-1 and PA2, and in PB-1 and PB-2

Table 1
Actual decay time, actual transient total time and scheduled decay time for the ten experiments.

Experiments	TOT-1	PA-1	PB-1	PC-1	PD-1
t_{d1s}	01:17	01:19	01:22:30	01:14	01:22:20
t_{d1a}	01:18	01:19:40	01:28:00	01:41:35	01:26:10
($t_{d1s} - t_{d1a}$)	−00:01	−00:00:40	−00:05:30	−00:27:35	−00:03:50
Actual transient total time	01:48	01:45	01:46	01:45	01:42
Experiments	**TOT-2**	**PA-2**	**PB-2**	**PC-2**	**PD-2**
t_{d2s}	03:17	03:22:20	03:35:10	02:58:30	03:31
t_{d2a}	03:18:50	03:21:45	03:41:15	03:26:45	03:33:10
($t_{d2s} - t_{d2a}$)	−00:01:50	00:00:35	−00:06:05	−00:28:15	−00:02:10
Actual transient total time	02:01	01:58	02:14	01:58	02:00

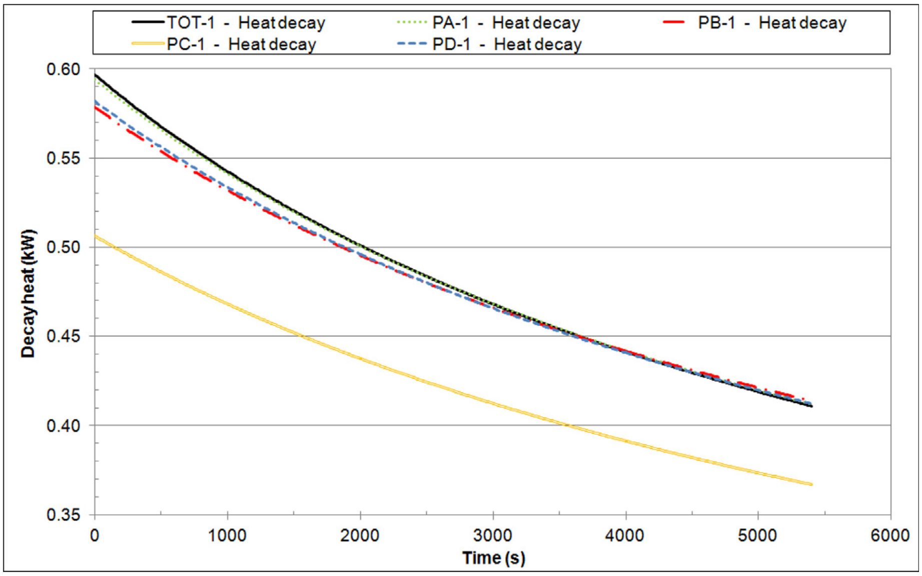

Fig. 8. Decay heat of the the group 1 experiments.

experiments, higher temperatures than the TOT1 and TOT-2 experiments, were recorded in the TC3 thermocouple. Before of the air natural circulation beginning (Fig. 12), time 1156 s, the temperatures in PA-1 (92.1 °C) and in PB-1 (92.3 °C) reached 8 °C above of the TOT-1 (84.1 °C). This behavior showed that the absence of the air natural circulation in the internal plates of the IFA, through the nozzle or through the gaps, may represent a less favorable cooling condition.

Table 5 shows the TC3 thermocouple maximum temperatures for the groups 1 and 2 experiments, its percentage changes and temperature differences (in absolute values) of this thermocouple in relation to the total uncovering experiments. The ***i*** index of the LOCEi term that appears in this table are relative to TC3 thermocouple values for each one of the loss of coolant experiments.

For the two groups of experiments studied, the higher maximum temperature of the TC3 thermocouple occurred in the total loss of coolant case, the TOT-1 and TOT-2. The higher value was around 123.8 °C for the total loss of water experiment (TOT-1). The TC3 maximum value in PA-1, of 122.6 °C, was only 1% (1.3 °C) lower than the TOT-1. In PA-2 the same relation presented a value 2% (2.3 °C) lower than the TOT-2. Although they are very close, it was expected that the PA-1 and PA-2 experiments were the most critical with higher temperatures than the TOT-1 and TOT-2. The justification for these results can be assigned to the IFA nozzle gaps that have allowed the air passage for natural circulation through the IFA Internal plates. In addition, the IFA nozzle insulation reduced but not stopped the heat conduction through the aluminum nozzle and by natural convection and conduction of the small covering water. Also, lower decay powers

Table 2
Decay heat percentage changes of the groups 1 and 2 of experiments.

Percentage Changes – Group 1		Percentage Changes – Group 2	
	Total Transient		Total Transient
(PA-1-TOT-1)/TOT-1	−0.06%	(PA-2-TOT-1)/TOT-2	−0.41%
(PB-1-TOT-1)/TOT-1	0.80%	(PB-2-TOT-2)/TOT-2	−0.64%
(PC-1-TOT-1)/TOT-1	12.37%	(PC-2-TOT-2)/TOT-2	7.10%
(PD-1-TOT-1)/TOT-1	0.78%	(PD-2-TOT-2)/TOT-2	−0.15%

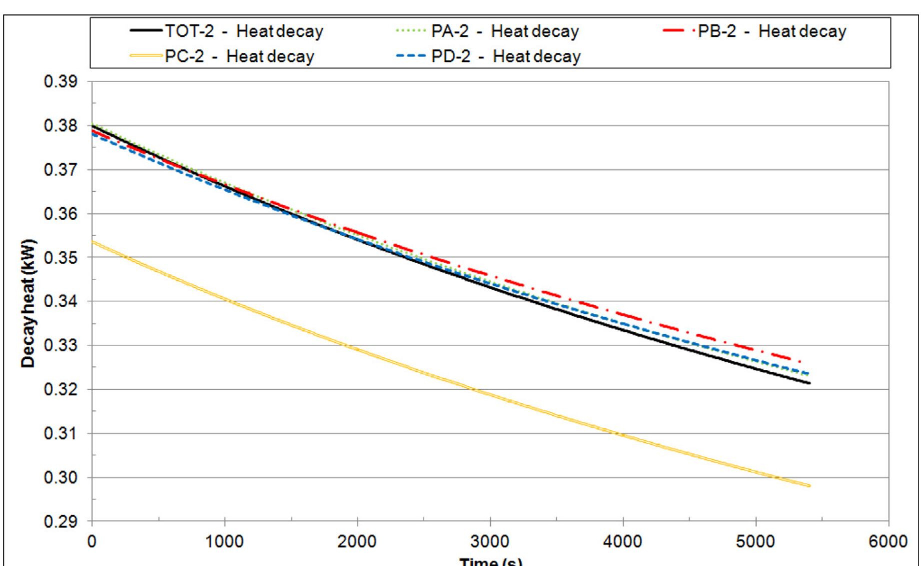

Fig. 9. Decay heat of the the group 2 experiments.

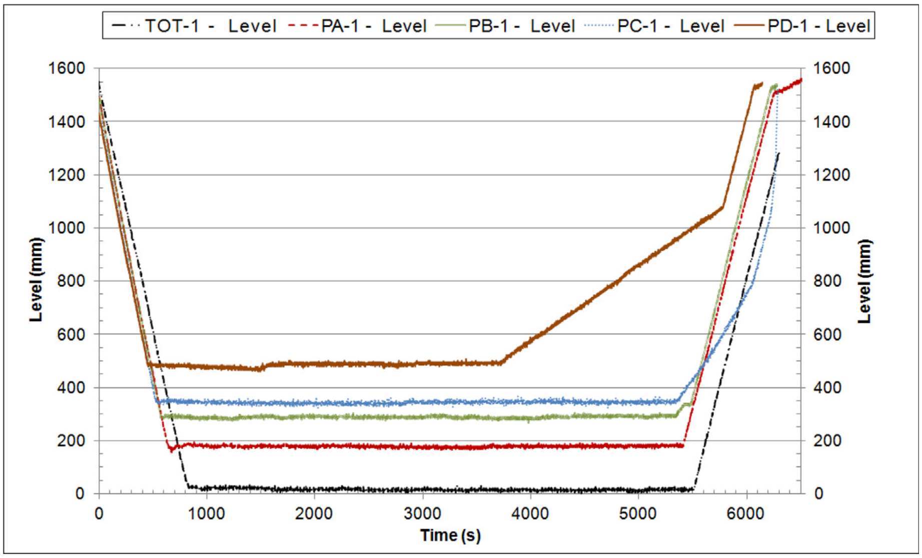

Fig. 10. Group 1 experiments levels.

used in the experiments may be a reason for these temperatures were not the higher ones. Other factor to be considered was the absence of a thermal insulation on the IFA external sides that has contributed to a free and effective natural convection on the IFA external surfaces.

In the PB-1 and PB-2 experiments, the uncovering level was very close to the gaps level, still was observed the internal air natural convection in the IFA. Also, there was the air natural convection on the IFA external faces and a higher heat transfer to the covering water. Therefore, the TC3 thermocouple temperatures were between 4% (4.8 °C) and 6% (6.4 °C) lower, when compared to the TOT-1 and TOT-2 experiments, respectively. This heat transfer was associated to the IFA radial and axial conduction.

Regarding to the PC-1, PC-2, PD-1 and PD-2 experiments, there was a more efficient heat transfer from IFA because of the covering water. This higher transfer was due mainly to the covering water natural convection that also, was strongly associated to the radial and axial conduction in the IFA. The results showed that TC3 thermocouple temperatures were around 20% lower in PC-1 (26.5 °C) and PC-2 (20.8 °C) experiments in relation to the TOT-1 and TOT-2 experiments. T, and in PD-1 and PD-2 were approximately 30% (36.4 °C–30.8 °C) lower, when compared to the total uncovering experiments. The lower value of the TC3 maximum temperatures, among the ones in group 1, was of 87.4 °C for the PD-1 experiment. Among the group 2 experiments, the PD-2 reached the lower value that was of 70.9 °C. The decay heat estimated for the PC-1 and PC-2 were of 6.5% to 12.4% lower than the TOT-1 and TOT-2 experiments.

Except for the PC-1 all the other group 1 experiments presented temperature percentage change in relation to the total uncovering experiment, lower than the group 2 experiments. This may indicate a decay heat influence over the heat transfer mechanisms.

The highest temperature reached in the experiments, 123.8 °C, was very below to the blister temperature of 500 °C, thereof the IFA integrity during the experiments was assured.

4. Conclusions

The objectives of the experimental tests simulating and comparing LOCA in similar conditions of research reactors, using an instrumented fuel assembly, in five different levels of uncovering and in two heat decay conditions, in a safe way were fully achieved.

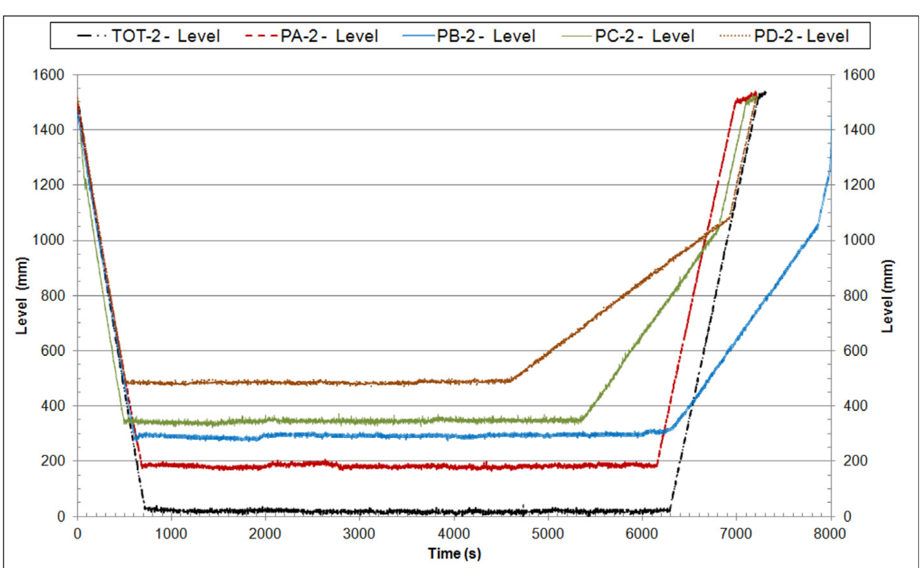

Fig. 11. Group 2 experiments levels.

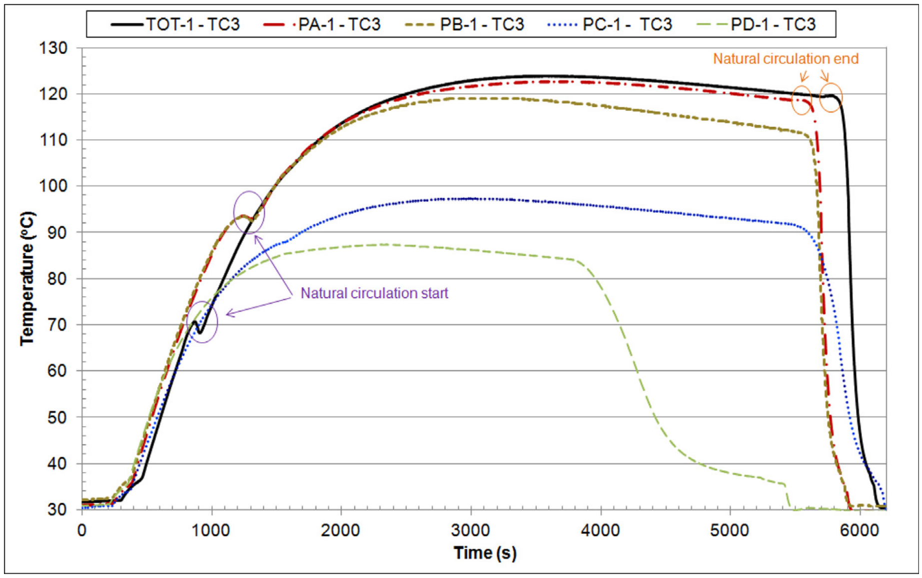

Fig. 12. Group 1 experiments temperature curves.

The experiments were performed in similar conditions of a research reactor LOCA. Comparing the STAR results with a actual research reactors LOCA condition, the STAR presented an influence for higher cladding temperatures due to its small air internal volume and for lower temperatures due to the absence of an insulation on the IFA external lateral sides. STAR LOCA experiments also presented safety limitation to test higher decay heat conditions. Thus, despite the existence of some differences in relation to actual research reactors LOCA, the objective of similar conditions also was reached and the experimental results proved to be very relevant to these safety analyses.

From comparisons among results of experiments, it is possible to conclude that the TOT-1 and TOT-2, for the specific conditions of the STAR experiments, of heat decay intensity and dissipation, the total uncovering conditions were the most critical ones, with higher clad temperatures than the partial uncovering conditions. The PA-1 and PA-2 experiments, with a partial obstruction of the air natural convection in the IFA, presented temperatures of only 1.3 °C to 2.3 °C lower than the TOT-1 and TOT-2. Natural convection in the covering water had been shown an excellent heat transfer condition. It was strongly associated to the radial and axial conduction in the IFA. This behavior was observed even more strongly with the increase in the water covering levels, mainly in the PC-1, PC-2, PD-1 and PD-2 experiments.

Table 3
Levels, velocities and times of group 1 experiments.

Experiments	TOT-1	PA-1	PB-1	PC-1	PD-1
Stationary average level (mm)	17	179	288	343	484
Emptying velocity (mm/s)	1.8	2.1	2.1	2.2	2.1
Emptying time (s)	827	635	569	516	454
Refilling velocity (mm/s)	1.6	1.5	1.4	1.3	0.4
Refilling time (s)	935	918	866	910	2346
IFA nozzle level	110	110	110	110	110
IFA gaps level	270	270	270	270	270
TC3 thermocouple level	680	680	680	680	680

The experimental results of this work can be used in the validation of thermal-hydraulic programs calculation models, as the RELAP5 code.

The STAR section has been proved to be a very safe and efficient tool for the thermal-hydraulic LOCA experiments for research and

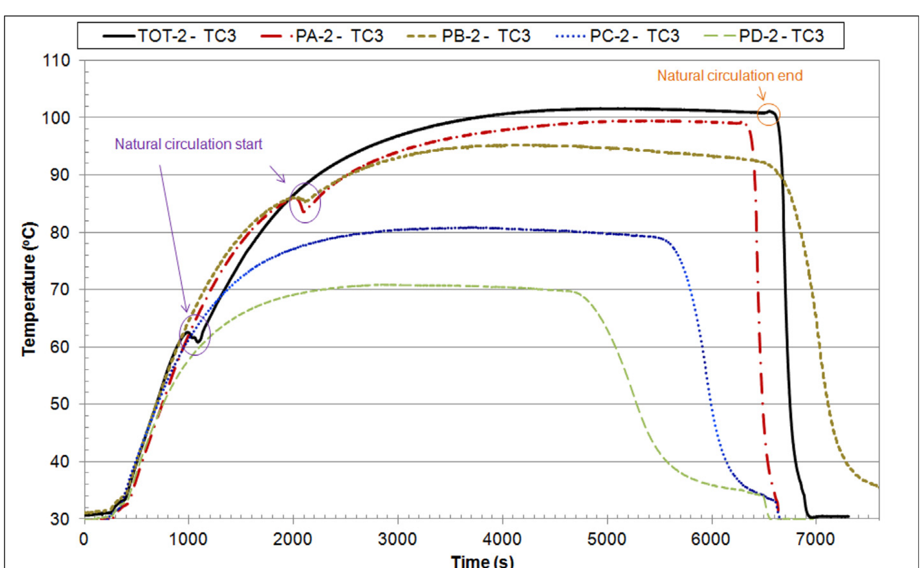

Fig. 13. Group 2 experiments temperature curves.

Table 4
Levels, velocities and times of group 2 experiments.

Experiments	TOT-2	PA-2	PB-2	PC-2	PD-2
Stationary average level (mm)	17	181	293	344	484
Emptying velocity (mm/s)	2.0	1.9	1.9	2.4	2.0
Emptying time (s)	716	682	605	492	514
Refilling velocity (mm/s)	1.6	1.4	0.7	0.6	0.4
Refilling time (s)	936	945	1766	1912	2617

Table 5
TC3 maximum temperatures and percentage changes for the ten experiments.

Experiment	TC3 (°C)	Percentage change (LOCE-i1-TOT-1)/TOT-1 (%)	Temperature difference (LOCE-i1-TOT-1) (°C)
TOT-1	123.8	0	0,0
PA-1	122.6	1	1.3
PB-1	119.1	4	4.8
PC-1	97.4	21	26.5
PD-1	87.4	29	36.4

Experiment	TC3 (°C)	Percentage change (LOCE-i2-TOT-2)/TOT-2 (%)	Temperature difference (LOCE-i2-TOT-2) (°C)
TOT-2	101.7	0	0.0
PA-2	99.4	2	2.3
PB-2	95.3	6	6.4
PC-2	80.9	20	20.8
PD-2	70.9	30	30.8

development, including future works. The STAR safety was attested by the non-occurrence of any accident or incident involving the section or the IFA during the experiments. It has also proved the safety of the STAR experiments, since the levels of radioactive doses near the pool surface during the experiments, monitored by the IPEN radiological protection group, were below the safety limits. The blister temperature of 500 °C was far to be reached in these experiments, thus assuring the IFA integrity.

The gap between the nozzle and the plates of the IFA, present in all standard fuel assemblies made by IPEN, showed useful path for air inlet and aids in the heat removal process in a LOCA occurrence. Thus, this concept which allows the air passage by the gaps must be maintained or even increased in design and manufacturing of new fuel assemblies.

In some new design of research reactors, as the Brazilian Multipurpose Reactor (RMB) (Perrotta and Soares, 2015) the fuel assemblies have two lateral windows between the nozzle and the beginning of the fuel plates that helps in air natural convection in an accident of partial uncovering of the core. Thus the RMB fuel assemblies can have a most favorable condition than the IEA-R1 in a partial uncovering of the core.

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