EXTENDED STUDY OF COOLABILITY OF VVER BUNDLE WITH BALLOONED REGION

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ABSTRACT

During a LOCA incident the high pressure in the fuel rods can lead to clad ballooning and the debris of fuel pellets can fill the enlarged volume. The evaluation of the role of these two effects on the coolability of VVER type fuel bundles was the main objective of the experimental series that have been done up to now. The experimental results confirmed that a VVER bundle with even 86% blockage rate remains coolable after a LOCA event. The ballooned section creates some obstacles for the cooling water during reflood of the bundle, but this effect depends strongly on the initial temperature that the bundle proposed to and on the rate of coolant water applied at the bottom of the bundle. The accumulation of fuel pellet debris in the ballooned volume results in a local power peak, which leads to a further slowing down of the cooling phase. The effect of the intact bundles in the neighbourhood was also considered with a bypass line connected parallel to the test section. It proved a useful way to sense more watchfully the thermal hydraulic behaviour of the bundle during reflooding phase.

KEYWORDS
LOCA, ballooning, reflooding, coolability, VVER fuel

1. INTRODUCTION

In a PWR design basis loss-of-coolant accident (LOCA) it is a basic requirement to guarantee the coolability of the fuel rods during the reflood phase of the event. The LOCA conditions can lead to significant deformations of the cladding and it can reduce the flow cross section for the coolant [1, 2]. The high inside pressure of the rods, which is reasonable at a high temperature, and the low vessel pressure due to the accidental events can lead to the ballooning phenomena of fuel bundles. This process reduces the capability of accessing the emergency coolant in that region of the reactor core.

The coolability of ballooned fuel bundles was investigated in several experimental programmes. The FEBA and SEFLEX test series were carried out in Germany, THETIS tests in the UK and FLECHT-SEASET tests in the US [2-4]. These out-of-pile tests were performed with electrical heating. The experiments pointed out that thermal conditions in the vicinity of blocked section are rather complex. The reduction of the cross sectional area obviously creates an obstacle against water injection, but there are some other effects (e.g. relatively increased coolant flowrate in the reduced area of the water subchannel), which can enhance the cooling phenomenon.

In the above mentioned test series the coolability of Western PWR type assemblies characterized by square lattice was investigated. In VVER reactors the fuel rods are arranged in triangular lattice and the ballooning creates a different picture from that of Western PWR bundles. The reflooding process is influenced by the geometrical arrangements and the possibly present water bypass effect, so the conclusions drawn from square lattice tests cannot be directly applied to the triangular geometry. Furthermore, the VVER-440 type bundle is covered by shroud, which prevents the cross flow between fuel assemblies. For this reason the local heat-up in the bundle can result in more severe consequences compared to other PWRs.

A recent review on the main findings of past experimental programmes on the coolability of blocked regions in a rod bundle after ballooning under LOCA conditions pointed out that the effect of fuel relocation upon the blockage coolability was not explored in any existing tests and therefore remains to be investigated in specific tests [3].

Considering those facts and in order to extend our knowledge of VVER type bundles a new experimental series has been launched at the AEKI in 2008, with the objectives of examining the coolability of VVER type bundles after LOCA involving the effect of local power peak in the ballooned region [5]. The first series of 23 tests consisted of a 1 m length, 19 rod electrically heated bundle with VVER-440 type fuel geometry and with the following conditions:

- 14 or 19 rods of the bundle have ballooning simulators
- The power peak is or is not simulated in the ballooning section
- The initial bundle temperature could be 600°C or 700°C
- The flowrate of the coolant water can be selected between 2 cm/s and 15 cm/s

The first series of these experiments have been executed on the CODEX-COOL facility, which collects the necessary equipment to ensure the representative LOCA environment for the VVER bundle. Different cross sections of the bundle at the elevation of balloonings can be seen on the Figure 1.

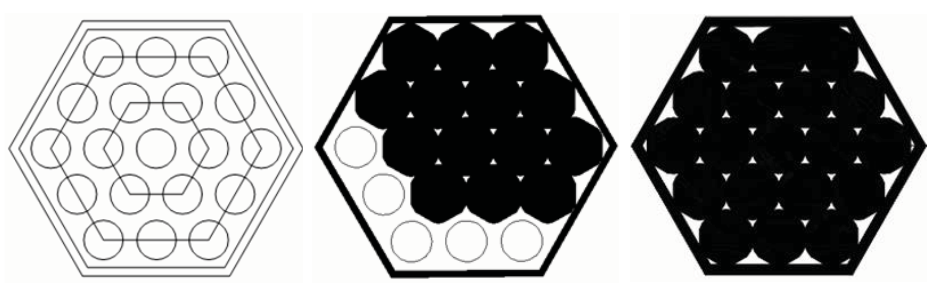

Figure 1. Cross section of the bundle without sleeves (left) and with 14 (centre) and 19 (right) sleeves in the CODEX-COOL experiments

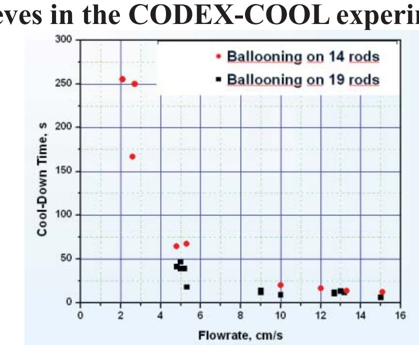

Figure 2. Cooling-down time dependency in the first 23 CODEX-COOL test

The results of these experiments have indicated a very important effect of coolant flow rate. At high velocities the simulation of both ballooning and local power peak had only weak effects, since the high coolant flow rate could quickly cool the bundle down. However, in cases when the flow rate is around 5 cm/s, differences in the bundle conditions can cause significant scattering in the cool-down time. Lowering the flow rate down to 2 cm/s these effects are rapidly gained (Figure 2.). The cool-down time in Figure 2. means the time needed for reflooding the experimental bundle (i.e. the time elapsed from the observed temperature drops at the top and at the bottom of the bundle).

2. New series of CODEX-COOL experiments

In spite of the fact that the results of the first series of CODEX-COOL experiments have confirmed the coolability of the ballooned bundle in the applied range of investigated parameters, it was intended to continue the investigation of study in an extended manner. Furthermore, some code calculations predicted the oscillation of the level of coolant water in the centre of the vessel during emergency cooling which can require to take into account not only the bundle, but its environment (e.g. non-ballooned bundles in the core), too. The thermal hydraulic connection between them gives the possibility to draw a more adequate picture of coolability.

This paper gives a detailed description of the last series of CODEX-COOL experiments where the ballooning and the power peak phenomena are also considered but an unheated bypass line was connected parallel to the test section as an additional item to study them together.

The experimental facility is the same as it was for the first series CODEX-COOL tests (total 23 tests) except for the bypass line which is marked in red (Figure 3.) and it is connected to the bottom of the test section and to the top of the expansion tank. There is also a glass pipe next to the bypass line to make the propagation of the water level visible. The main parts of the facility are shown in Figure 3.

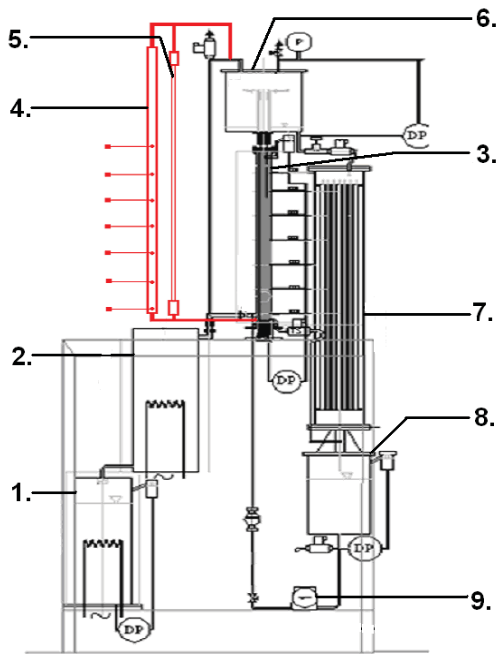

Figure 3. The CODEX-COOL facility and the connected bypass line (1. Steam generator, 2. Super heater, 3. Test section, 4. Bypass line, 5. Level measuring glass tube, 6. Expansion volume, 7. Condenser, 8. Moisture tank (reservoir), 9. Pump)

The instrumentation of the facility included 44 thermocouples and several other devices for the measurement of pressure, flow rate and water levels in different positions. The thermocouples were fixed with small steel flag, which were welded to the cladding tubes. In the ballooned section the thermocouples were soldered directly to the sleeves. The detailed measurement of the temperature field enabled the tracking of quench front during the reflood phase of the facility.

It is important to affect somehow the flow rate of the pump according to the requirements of the test matrix. In order to perform such an exception a hollow plate was inserted in the way of the pump. Replacing that plate with another one of a different diameter of the hollow could ensure to change the hydraulic feature of the whole loop. On the other hand the reproducibility of that simple plate is very good. The cross section of the bypass line was chosen so that it would be about the same as that of the one throughout the assembly.

In order to control the thermal hydraulic interaction between the bypass line and the test section, there is also a hollow plate in the way of bypass connection with the same benefit as it has in the pump way (Figure 4.).

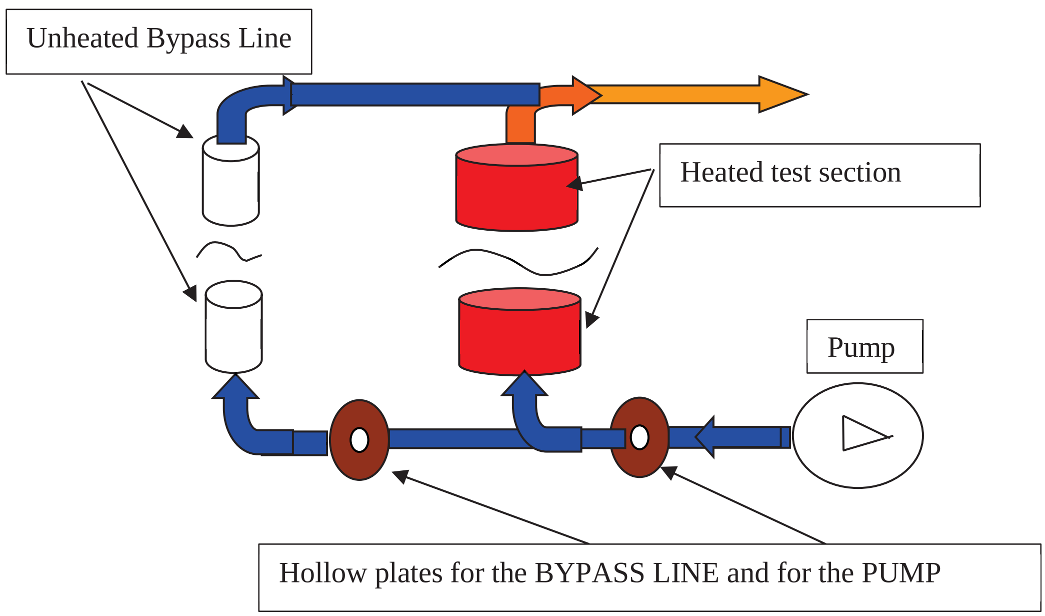

Figure 4. Understanding the connection of the bypass line

3. The test bundle

The bundle – which is the same as the one used in the first series of 23 CODEX-COOL experiments and representative for VVER fuel geometry – included 19 electrically heated fuel rod simulators (Fig. 7.). The heater bars – made of SS and 4 mm in diameter – were positioned by alumina pellets in the centre of the stainless steel cladding. The simulation of ballooning was solved by using hollow sleeves – with 50 mm in length – that were fixed on the external surface of the cladding (Fig. 5.) in such a way that neighbouring sleeves contacted on the 30-mm length. The 50 mm length was selected on the basis of experiments performed with Zr cladding tubes [1]. That arrangement of the sleeves could perform 86% blockage rate in the ballooning area, which could be considered as a conservative upper value for ballooned VVER bundles. The blocked section was positioned in the upper section of the bundle in 200 mm distance from the top.

In the fuel bundle six fuel rods were supplied with six, K-type thermometers in an arrangement seen in Figure 6. Thermometers were placed at positions A, B, C, D, E and F situated above each other along a line. Fuel rods supplied with K-type thermometers were at well-defined positions of the bundle: No. 1, 2, 5, 10, 13 and 17. Shroud with hexagonal arrangement was supplied with thermometers at the same levels (A, B, C, D, E and F) and at level 0 (the lowest position of the fuel bundle). These thermometers made it possible to follow the coolant level during reflooding.

Figure 5. Balloning simulator (sleeve) on the rod

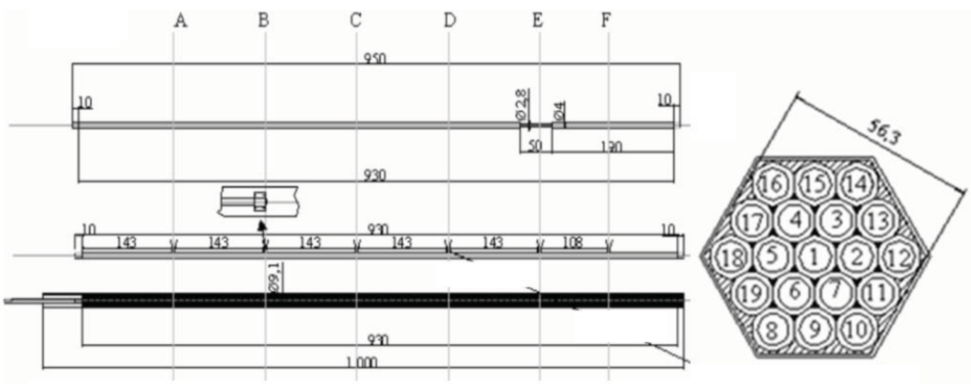

Figure 6. Marked elevations of the thermocouples along the bundle and numbering of the rod simulators

The local power peak in the ballooned area was produced by reduction of the cross section of heating bar in the ballooned region (along 50 mm length of it). This technical solution produced 100% additional heat in that section. The diameter of the bars was 4 mm in the main part of the rods and 2.8 mm in the power peak corresponded to the case when fuel debris could fill perfectly the ballooned volume. At the ballooned section 10 W/cm linear power rate was produced instead of the average 5 W/cm. The double value corresponds to a theoretical maximum, when the ballooned section contains twice as much fuel mass per unit of length than the intact section of the rod.

Thermal insulation was applied around the shroud to limit heat losses and to produce more uniform radial power profile. The total length of the fuel rods was 1000 mm and the length of the heated section 932 mm. The total power applied in the tests was 9 kW, which was derived from the decay heat of VVER fuel during LOCA.

4. Execution of tests

Several technological steps preceded execution of the high temperature tests. Water supply necessary for re-flooding was assured with water collected in the moisture tank below the condenser. Water level of the steam generator was set in such a way that heaters of the steam generator did not remain dry until the end of the test. During experiments the system pressure was ≈ 2.2 bars.

The tests started with a preheating period in order to establish a stable and as much as possible uniform temperature distribution in the bundle. The target temperature in the tests was 600 ºC or 700°C. The bundle power was varied between 650-1500 W in the preheating phase. The steam supply from the steam generator and super heater section produced 600 ºC steam flow. The hot steam entered the test section in the bottom and left at the top. The outlet steam was condensed in the condenser unit and the water was collected in the moisture tank beneath the condenser.

Directly before the reflood phase, the super heater unit was separated from the inlet section of the zone by means of a valve. Bundle power was increased to 9 kW – modelling of the decay heat. Reflooding was started by switching on the pump. The tests were continued until the temperature of level F (at the top) did not decreased to the temperature of the re-flooding water. Then the electrical power was switched off and re-setting of the original water levels was started for the next experiment.

The current experiments did not simulate the whole scenario of a loss-of-coolant accident. The blowdown phase with very fast temperature increase and a temporary peak with maximum temperature was not covered. The CODEX-COOL tests focused on the last phase of LOCA transient when the bundle is cooled down by cold water injected by the emergency core cooling system from the bottom of the reactor core.

5. Experimental results

The temperature history of the CODEX-COOL-24 test (Figure 7) and of the COOL-30 test (Figure 8) can be seen on the next figures. The A, B, C, D, E, and F labelled temperatures are corresponding to the thermocouples on the fuel rod Nr. 2 at the elevations of A, B, C, D, E, and F, respectively, while the highlighted thermocouples, which are placed from the side of the shroud, are corresponding to measure the water subchannel at the indicated elevations of 0, A, B, C, D, E, and F as well.

The estimated uncertainties of the measurements are the following:

- Temperature: ±9 °C for the scale of 1000 °C
- Electric power: ±5% for the scale of 9 kW
- Flow rate: ±3% for the scale of 15 cm/s

Regarding how many rods of the 19 rod bundle had ballooning simulator the new series of CODEX-COOL experiment is divided into two series. Table 1 summarizes the main parameters and the most important results for the two test series.

Results of tests – from CODEX-COOL-24 to 26 – performed on fuel bundles with the same construction have shown that there was a reverse relationship between the reflooding rate and the cooling-down time: the highest reflooding rate in test CODEX-COOL-24 went together with the lowest cooling- down time. It seems that the increase of degree of choking both in the bypass tube and in the pressure section of the pump resulted in decrease of the re-flooding rate and increase of the cooling down time.

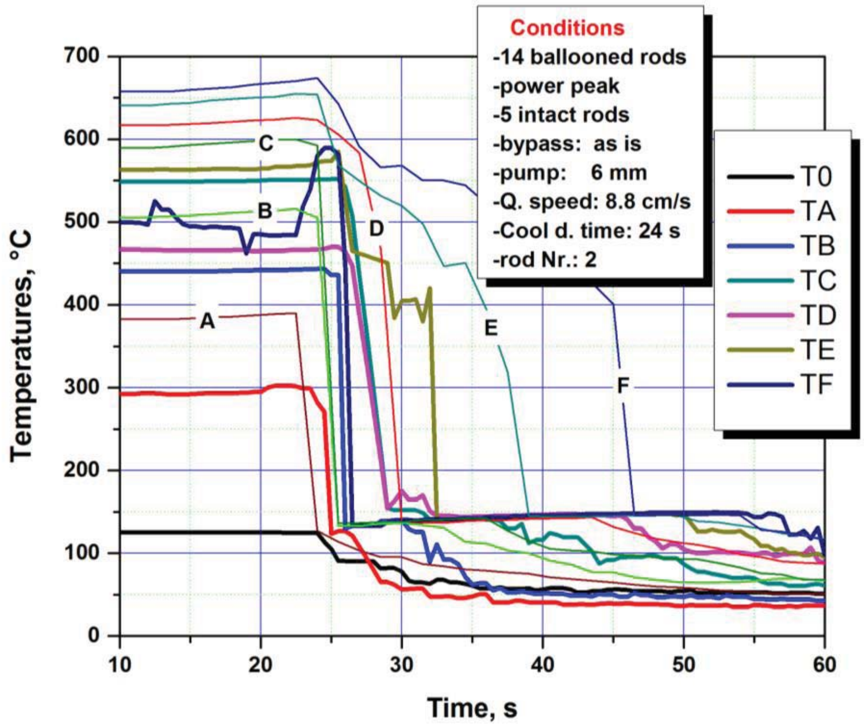

Figure 7. Temperature – time diagram for test CODEX-COOL-24

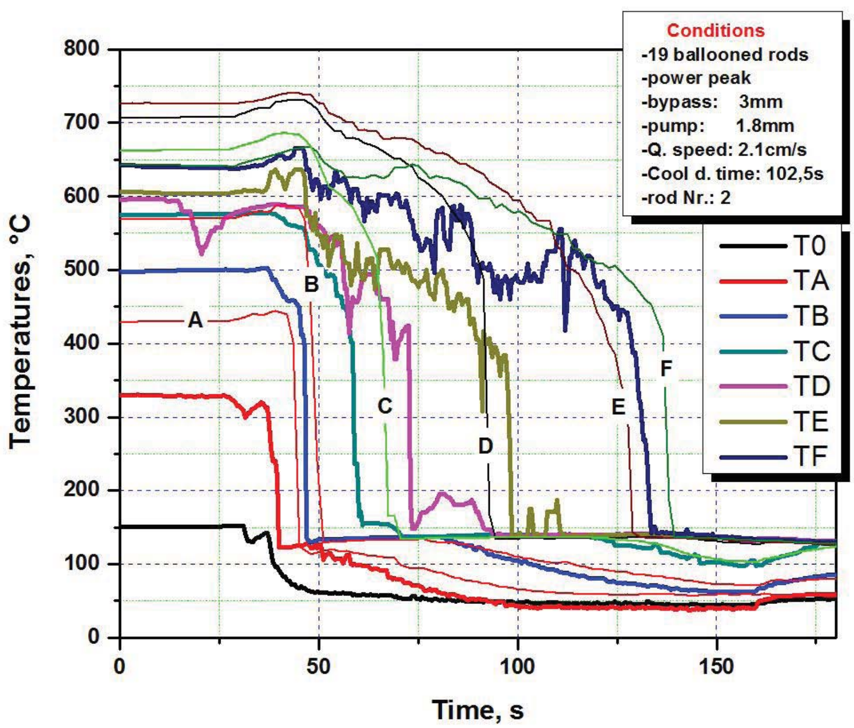

Figure 8. Temperature – time diagram for test CODEX-COOL-30

In tests – from CODEX-COOL-27 to 30 – four experiments were performed on bundles with the same parameters. The effect of the bypass section on the coolability was obvious for tests CODEX-COOL-30 and CODEX-COOL-29, where the only difference was the opening or closing of the bypass section.
In the presence of the bypass tube the cooling-down time of the bundle was 102.5 s, while without bypass tube, the cooling time was 86 s , although the average reflooding rate were 2.1 cm/s for both cases.

The presence of bypass tube without choke and at high flow rate of the coolant water of the bundle (i.e. 8.8cm/s in the CODEX-COOL-24) can double the cool-down time relative to the case where the condition of the bundle was the same but without bypass tube (CODEX-COOL-17). The cool-down time in that experiment of CODEX-COOL-17 – which is not detailed on this paper – was 10.5 s.

The presence of bypass tube with a choke of 2 mm at a bundle flow rate of 3,37 cm/s (CODEX-COOL-25) can significantly increase the cool-down time (58,5 s for the CODEX-COOL-25) relative to the case without bypass tube (44,5 s for the CODEX-COOL-28) despite the fact that the bundle condition is different for the two cases.

The presence of bypass tube with a choke of 3 or 2 mm could not change sensibly the average flow rate of the bundle (2,1 cm/s for CODEX-COOL-30 and 27) relative to the case without bypass tube (2,1 cm/s for CODEX-COOL-29 too), however the cool-down time is affected.

It can be stated that the presence of the bypass section increased the cool-down time of the bundle. In other tests of this series changing of the hole-diameter in the pressure section of the pump has shown that at larger hole diameter the reflooding rate was increased and the cooling-down time was decreased and vice versa.

As a conclusion it can be stated that the bundle remained coolable at the given experimental circumstances, independently of the presence of outer or inner bypass section.

Table I. Experimental parameters and main results for CODEX-COOL test series with bypass line

Test	Bundle parameters	Bundle temperature before reflooding (°C)	Choke on bypass section hole diameter (mm)	Choke on pressure section of the pump hole diameter (mm)	Average reflooding rate (cm/s)	Cool-down period (s)
CODEX-COOL-24	Bundle with 19 fuel rods (VVER geometry), ballooning simulators on 14 rods and local power peak at the ballooning section	600	Totally opened	6	8.8	24
CODEX-COOL-25		700	2	3	3.37	58.5
CODEX-COOL-26		700	2	1.8	2.3	120
CODEX-COOL-27	Bundle with 19 fuel rods (VVER geometry), ballooning simulators on 19 rods and local power peak at the ballooning section)	700	2	1.8	2.1	82.5
CODEX-COOL-28		600	0 (closed)	3	6.3	44.5
CODEX-COOL-29		700	0 (closed)	1.8	2.1	86
CODEX-COOL-30		700	3	1.8	2.1	102.5

6. CONCLUSIONS

In test series CODEX-COOL with bypass line there were differences in the bundle arrangement which resulted in various flowing cross-sections. The highest degree of blockage was 86% for cross section of subchannels around fuel rods, which was typical for test series from CODEX-COOL-27 to 30. In this test series there were ballooning simulators on each of the 19 fuel rods, while in test series from CODEX-COOL-24 to 26 there were only on 14 fuel rods. Therefore an inner bypass section could be formed at this series.

It can be concluded from the performed tests, that at high reflooding rate (8.8 cm/s) and with a bypass tube but without any choke the cooling-down time is affected during the whole time of the cooling phase so, that acts to strongly increase it. At lower reflooding rate (≈ 3 cm/s), the presence of the bypass section increased the cooling-down time of the bundle. At the reflooding rates of 2.1 cm/s the cool-down time is slightly affected enabling the different bundle conditions to exist.

The tests performed in this work have shown that even the highly narrowed bundle has remained coolable in the experimental condition simulating LOCA event.

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