Experimental Studies of Fuel Assemblies Cooling in Loss-of-coolant Accidents

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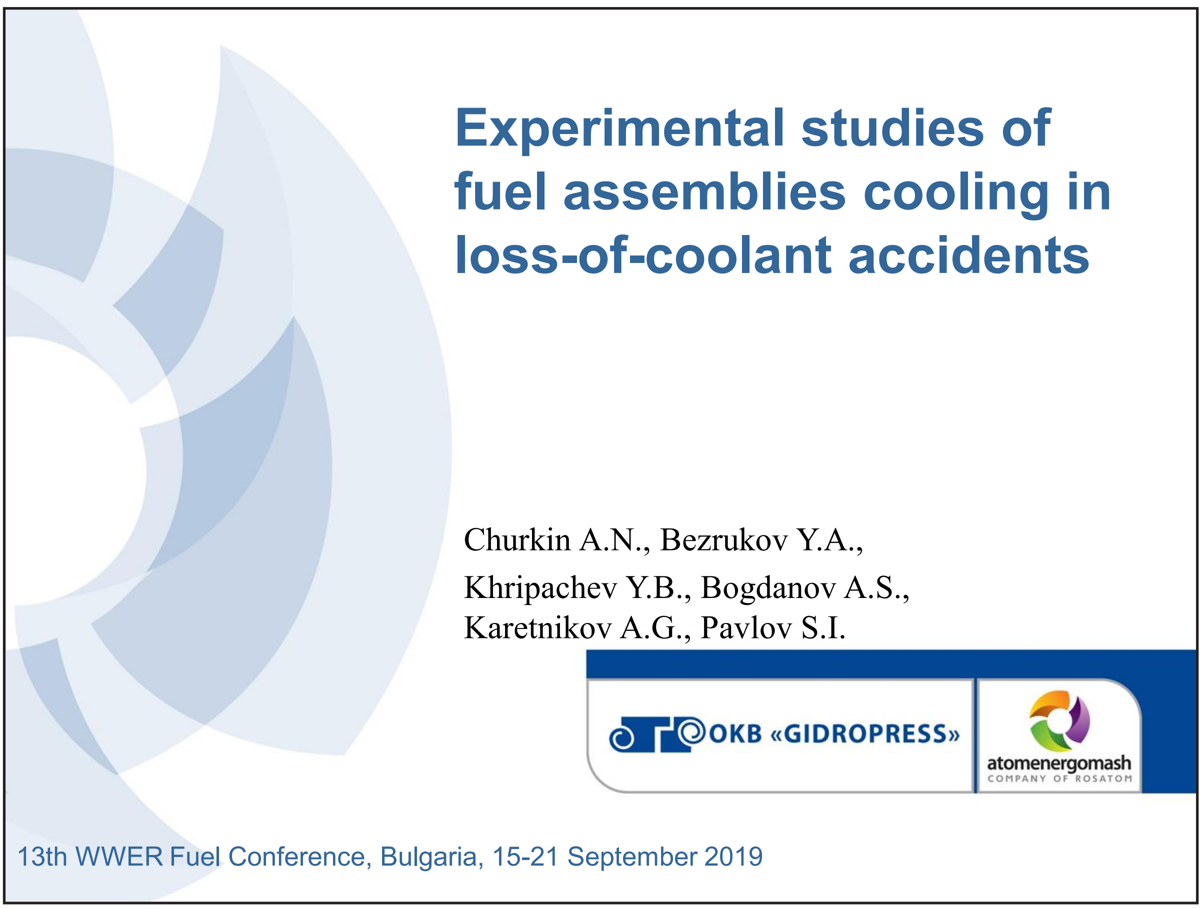

Introduction

Loss of primary coolant accidents (especially **LB LOCA**) for pressurized water reactors belong to the most severe cases in the spectrum of accidents in nuclear energy.

Different thermal-hydraulic processes take place in the reactor in the course of such accidents, namely, a sharp drop of pressure and coolant boiling up, loss of large primary coolant, which leads to partial reactor emptying. At this moment the fuel rods get heated up to high temperature due to a sharp decrease in heat removal.

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Introduction

After the emergency core cooling system (ECCS) actuation coolant mass is replenished and the partially dried out core is reflooded.

In PWR reactors the coolant of ECCS is supplied only in lower reactor plenum. In WWER reactors water is uniformly supplied into the upper and lower reactor plenums. Water supply into the upper plenum is connected with the problem of counter-current flow of the water (which flow down into the core) and steam (which flow up from core).

This report mentions the reflooding studies performed in different countries and the relevant tests performed in OKB “GIDRORESS” are discussed in more detail.

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Experimental studies abroad

Large studies of the structure of the steam-water flow in the rod bundle and core reflooding for BWR and PWR were performed in the USA since the 60s of the last century:

- FLECHT, 7x7 bundle;
- FLECHT-SEASET ,161-rod bundle;
- RBHT, 7x7 bundle.

A large cycle of studies of reflooding was carried out in Germany under the program FEBA (5x5) and REBEKA (7x7).

Experiments ACHILLES with 69-rod bundle were carried out in the UK.

In Japan, experiments were performed at the CCTF test facility (1824 heated rods).

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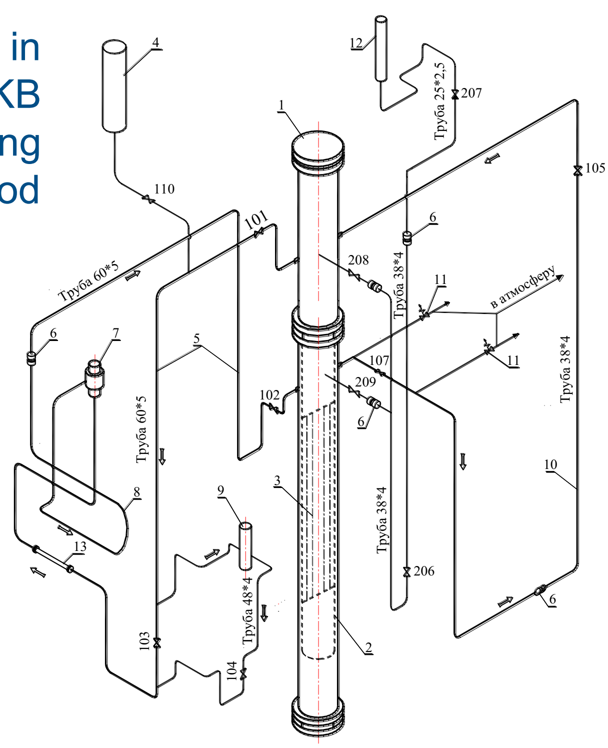
OKB "GIDROPRESS" test facilities

The study of the reflooding in Russia began in 1974 in OKB "GIDROPRESS" with using single simulators and seven-rod bundles ("Safety" test facility).

1 – model of WWER-440 pressure vessel,
2 – model of reactor shaft,
3 – 7-rod bundle,
4 – pressurizer,
5 – working loop,
6 – orifice plate,
7 – circulation pump,
8 – electric heater,
9 – cooler,
10 – emergency loop,
11 – diaphragm valve,
12 – accumulator



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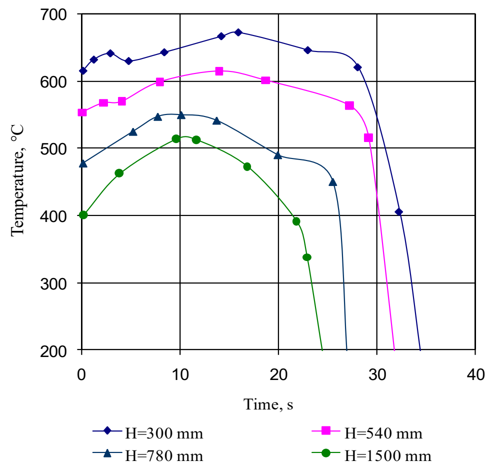
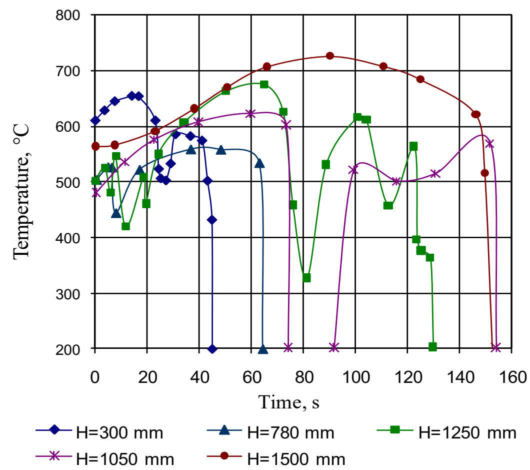
Results of “Safety” test facility



Variation of cladding temperature in 7-rod bundle at the **lower** reflooding



Variation of cladding temperature in 7-rod bundle at the **upper** reflooding

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Results of “Safety” test facility

The plots show that in the 7-rod bundle reflooding and cooling of bundle are quick and without significant temperature pulses. At this, the cooling front goes from the bottom to the top.

At the core flooding from the top, the time of cooling significantly increases. The nature of the cooling front movement is changed. Upper part of rod bundle is cooled the first. Below parts of rod bundle are cooled down later and with considerable pulsations. It means that it is difficult for water to go inside the narrow bundle. The steam that is leaving the bundle impedes the water flow, i.e. the effect of the countercurrent flow of steam and water is quite significant.

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“Reflood” test facility

In 1976 OKB “GIDROPRESS” began the construction of the test facility which schematically modeled the primary circuit of WWER-440 reactor with full-scale FA mock-up (126-rod) as the core simulator with heating length 2.5 m.

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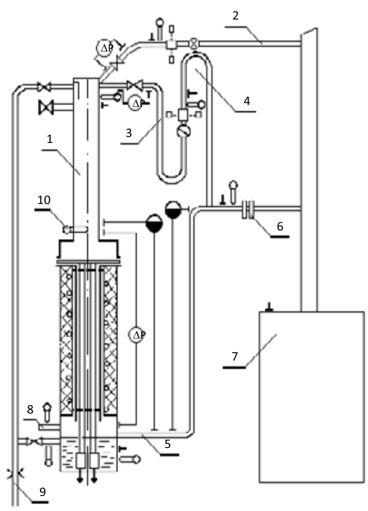
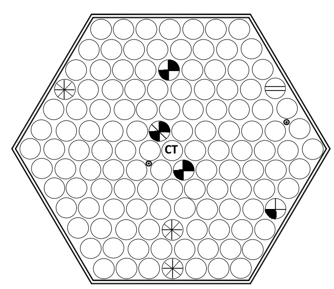
“Reflood” test facility



1 – test section; 2 – tube of emergency leg; 3 - tube of operable leg; 4 – loop seal; 5 – dowmcomer; 6 – exchangeable diaphragm; 7 – discharge tank; 8 – steam pipe; 9 – tube of flooding water; 10 –water-steam probe

Diagram of test facility with full-scale mock-up of the VVER-440 FA



CT - central tube with 5 submerged thermocouples
- simulator with 5 thermocouples
- simulator with 4 thermocouples
- simulator with 6 thermocouples
- simulator with 3 thermocouples
- tube with 4 pressure taps
- the physical level sensor

The diagram of layout of imitators in mockup and their equipment by measuring sensors

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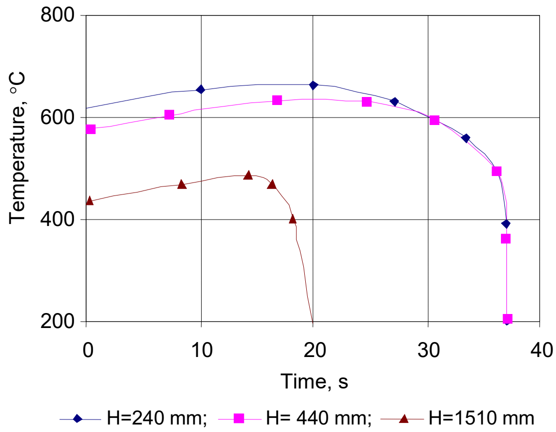
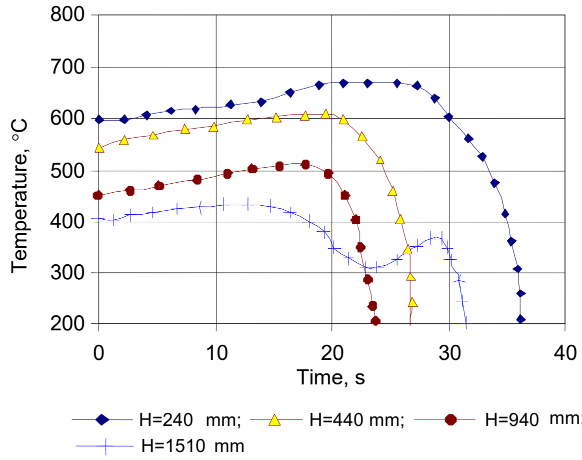
Variation of cladding temperature of 126-rod bundle depending on a kind of a reflood (WWER-440)



Lower reflooding



Upper reflooding

Results of “Reflood” test facility

The results with the lower reflooding show that the **126-rod** bundle cools from the bottom to top.

When the flow rate of the supplied water decreases, the cooling time increases.

In the tests with combined and upper reflooding significant pulsations of cladding temperature, especially in the middle parts of the bundle, are observed.

At the upper reflooding there was no significant increase of the cooling time contrary to the 7-rod bundle.

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"Reflood" test facility modernization

In 2003 a new FA mock-up was installed in the "Reflood" test facility that modeled FA WWER-1000. The number of the fuel rod simulators was the same as that in the previous mock-up (126 rods).

The new mock-up had a cosine power distribution (Kz= 1.345) and heating length 3.5 m.

This mock-up was equipped with instrumentation far better than the previous FA mock-up for WWER-440. The 20 fuel rod simulators were equipped with thermocouples to measure the cladding temperature. Each instrumented simulator had 6 thermocouples, placed at different levels.

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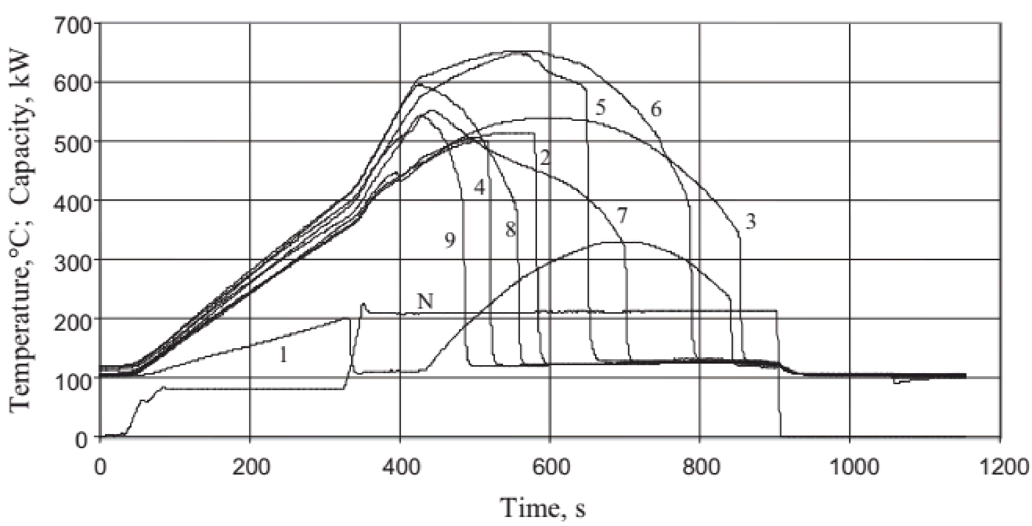
Results with upper reflooding

Variation of cladding temperature of 126-rod bundle (WWER-1000)



1-9 – numbers of thermocouples levels arrangement (from bottom to top); N – capacity.

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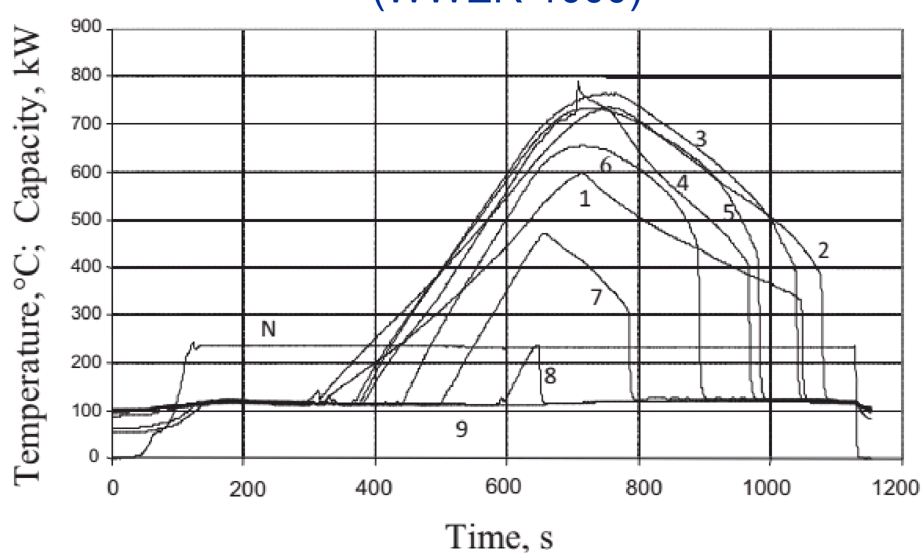
Results with upper reflooding

FA mock-up cooling takes place **simultaneously** from the top and bottom. The central axial part of the rod bundle stays hot for a longer time.

There is no water level in the upper plenum. Thus, the upper reflooding can be considered as efficient enough and the supplying water passes quickly through the periphery of the FA and cools rods from below too.

Results with lower reflooding

Variation of cladding temperature of 126-rod bundle (WWER-1000)



1-9 – numbers of thermocouples levels arrangement (from top to bottom); N – capacity.

Results with lower reflooding

If in experiments with a upper reflooding the bundle was completely drained before the start of heating, then in experiments with a lower reflooding bundle was with water which boiling during a heating. This makes it difficult to compare reflooding types.

It is seen that at first due to water boiling down there was a level decrease in the mock-up and after partial drying out and heat up of the upper part of the fuel rod simulator cooling water supply into the lower plenum of the experimental model began. Due to water supply the level in the model increased and the FA mock-up was cooled down.

The model cooldown time depended on the flowrate of the cooling water and the value of the supplied power.

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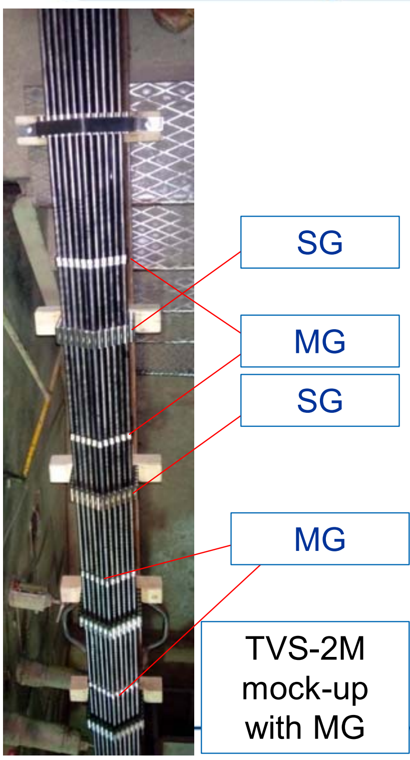
Investigation of the mixing grids affect



In 2015, experiments were performed on the rod bundle described above to study the affect of mixing grids (MG) on core cooling.

First, the basic experiments were performed on the FA mock-up equipped with spacer grids (SG) only.

Then the mixing grids “Vikhr” and “Progonka” were installed in the mock-up, and the experiments were repeated.

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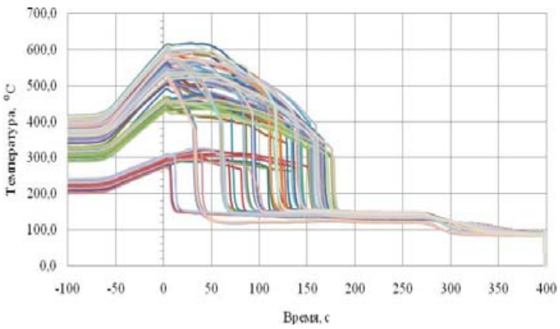
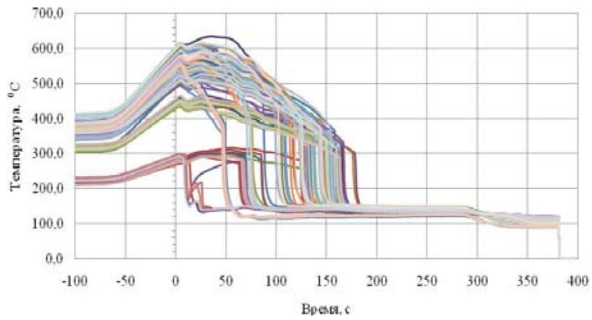
Investigation of the mixing grids affect

Variation of cladding temperature for lower reflooding



FA mock-up without MG



FA mock-up with MG

By results of experiments it is established that influence of the MG is insignificant. The presence of MG does not deteriorate heat transfer and does not prevent the penetration of cooling water into the core.

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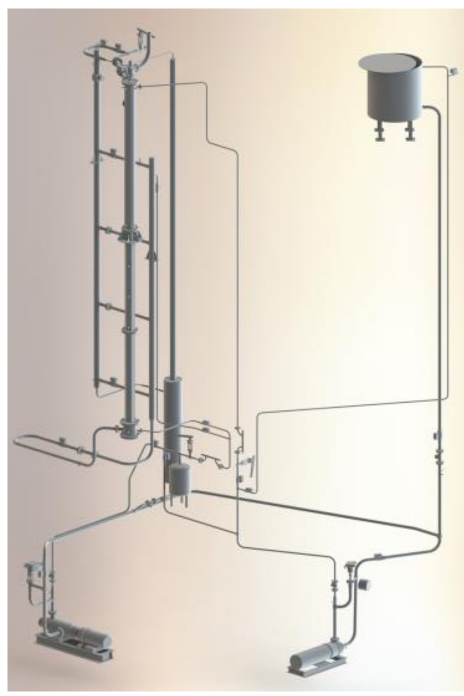
New modernization of “Reflood” test facility

In 2017-2018, there was additional modernization of the "Reflood" test facility, which allowed to improve the experiment automation, repeatability and to increase the number and quality of the measured parameters.

New experiments are performed to obtain additional experimental data for verification of thermo-hydraulics computer codes.



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New modernization of “Reflood” test facility

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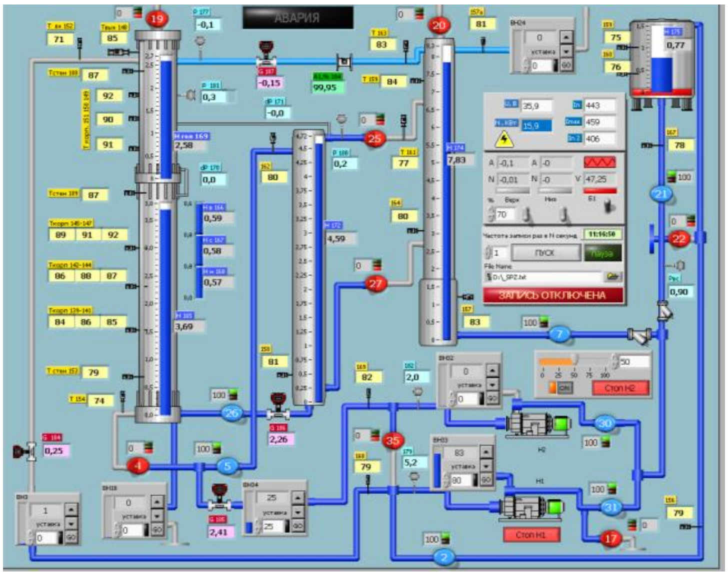

Interactive diagram for monitor and operation

Rod bundle

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Conclusion

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1. A significant part of the OKB “GIDROPRESS” research was devoted to the upper reflooding, since the WWER applies the water supply to the inlet and outlet chambers of the reactor. Experiments have shown that the efficiency of the upper reflooding is strongly influenced by the scale factor, i.e. the number of rods in the FA mock-up.

2. The experiments of OKB "GIDROPRESS" showed that the upper reflooding can be used for effective core cooling. This is consistent with the findings of experiments at the UPTF facility in Germany, where "locking" of the flow on a large-scale model was not observed.

3. The "Reflood" test facility is periodically modernized to solve new tasks and obtain new experimental data for verification of computer codes.

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