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ROSATOM STATE CORPORATION ENTERPRISE

Experimental Study of the VVER-1000 Fuel Rods Behavior under the Design-basis RIA and LOCA in the MIR reactor

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Since 2001 RIAR has been conducting irradiation tests in the MIR reactor under the design basis loss-of-coolant accident (LOCA) and reactivity-initiated accident conditions (RIA), which are targeted at obtaining experimental data on the VVER-1000 fuel performance under these conditions. Each experiment confined itself to examination of fuel, fuel-cladding interaction and analysis of gaseous fission products release from irradiated fuel.

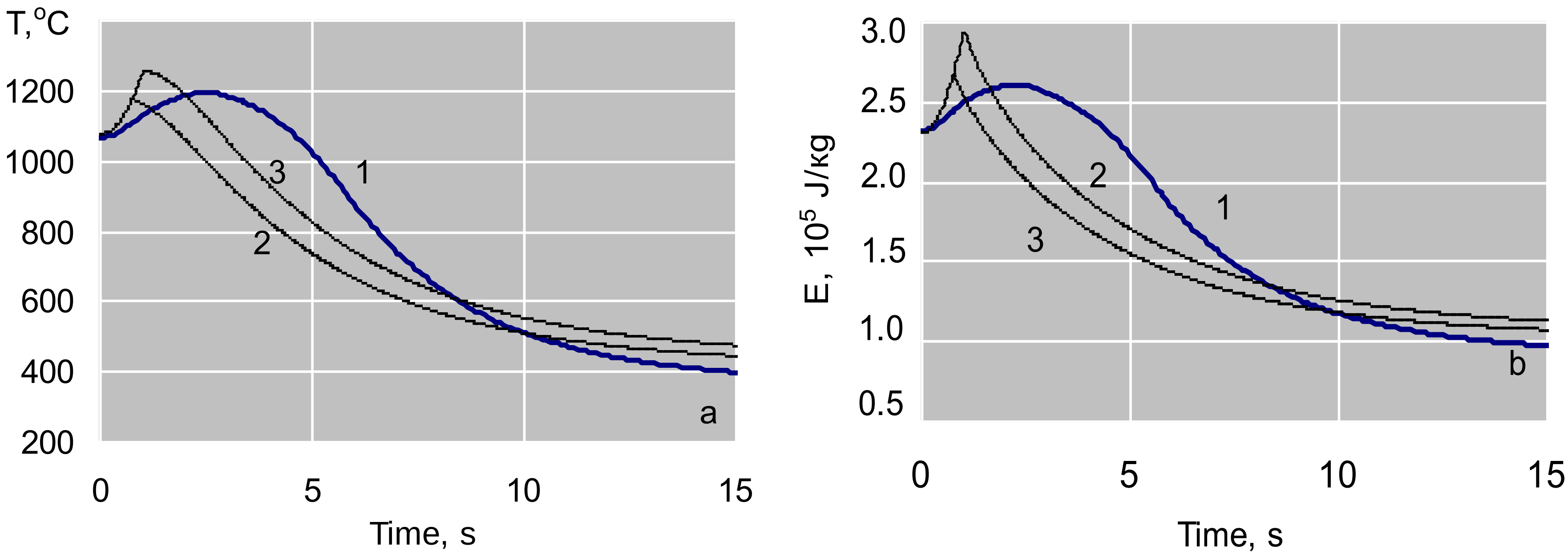
Several experiments were carried out under both the RIA and LOCA conditions with the use of the VVER-1000 fuel rods operated at nuclear power plants and attained a burnup of 40 to 70 MW·d/kgU.

RIA tests:
testing methodology and experimental data

Main parameters of RIA tests attained in power pulse reactors

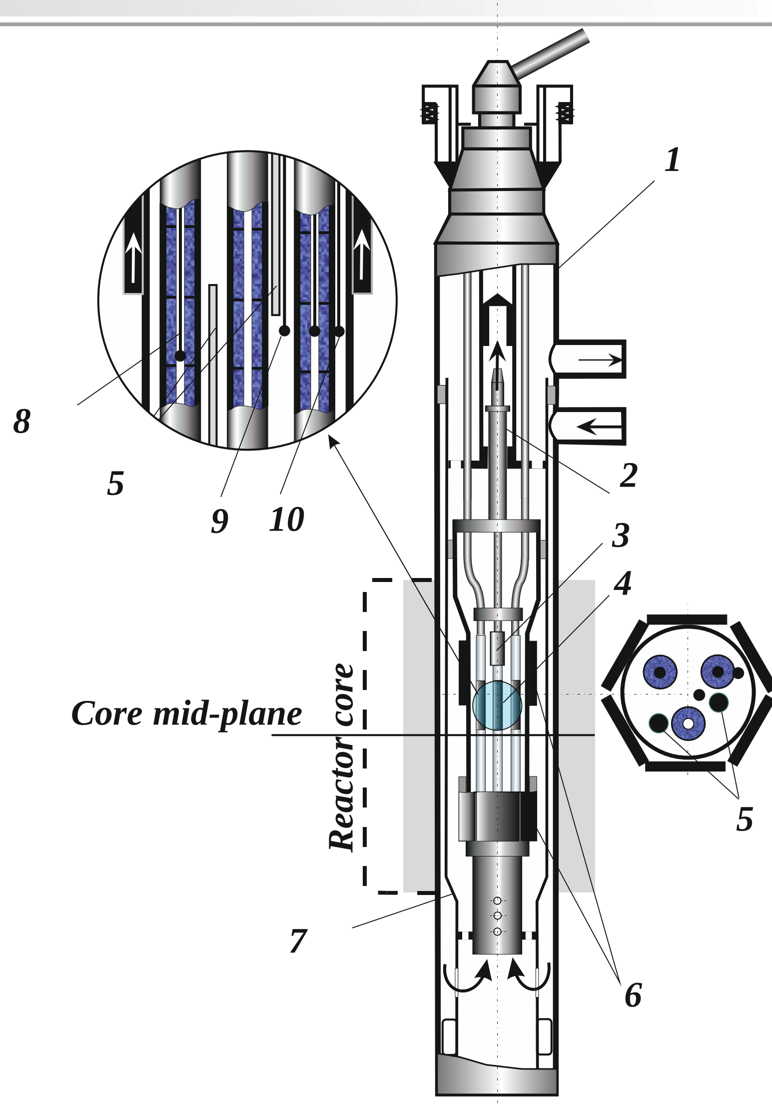
	Number of fuel rods under testing	Fuel burnup, MW day/kg U	Power pulse half-width, ms	Peak radial average enthalpy, 10^5J/kg
IGR	8	50	750 – 900	2.5 – 11.1
BIGR	8	50	2 - 4	4.8- 7.8
	4	60	2 - 4	5.2- 6.9

RIA tests:
testing methodology and experimental data



Changes in the temperature in the center of fuel stack for irradiated fuel rodlet (a) and radial average enthalpy (b) of irradiated fuel as a function of time at different parameters of pulse: 1- calculated profiles for the VVER-1000 fuel; 2-3 – calculated profiles for pulse irradiation tests in the MIR reactor at a linear heat generation rate of 250 W/cm (initial value), pulse amplitude of 3.25, τ=0c(2); τ=0.5s(3).

RIA tests: testing methodology and experimental data



Fuel Test Rig :

1 – test channel vessel;

2 – hydraulic power drive;

3 – pressure gage;

4 – fuel rods;

5 – in-reactor direct-charge detector;

6 – movable absorber screens;

7 – flow spreader;

8 – thermocouple attached in the center of fuel stack,

9 – thermocouple in the coolant;

10 – cladding attached thermocouple

RIA tests: testing methodology and experimental data

Main Specifications of Fuel Rodlets for the RIA Simulation Experiment

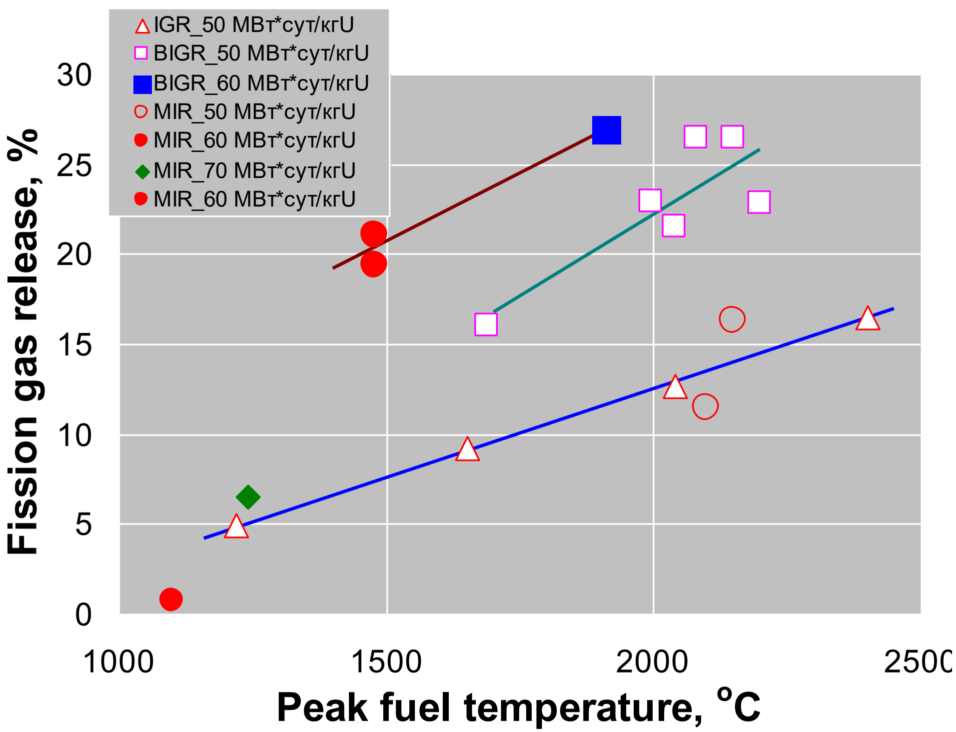
Parameters		Test #1	Test #2	Test #3	Test #4	Test #5
Bundle of fuel rodlets	Un-irradiated fuel rods	1	1	1	1	1
	Re-fabricated rodlets	2	2	2	2	2
	Burn-up of re-fabricated rodlets, MW·d/kgU	~60	~50	~60	~70	~60
Instrumented fuel bundle	Thermocouples exposed to coolant: - at the inlet of fuel bundle; - throughout the fuelled length of rod ; - at the outlet of fuel bundle	 1 1 1	 1 1 1	 1 1 1	 1 1 1	 1 1 1
	Thermocouple in the center of fuel stack (un-irradiated fuel)	1	1	1	1	1
	Thermocouple attached on the cladding of un-irradiated fuel rod	2	2	1	-	2
	Thermocouple in the center of fuel stack of the rodlet	2	2	1	1	2
	Direct-charge detector	1	1	2	2	1
	Gas pressure transducer inside the rodlet plenum	-	-	1	1	-

RIA tests:
testing methodology and experimental data

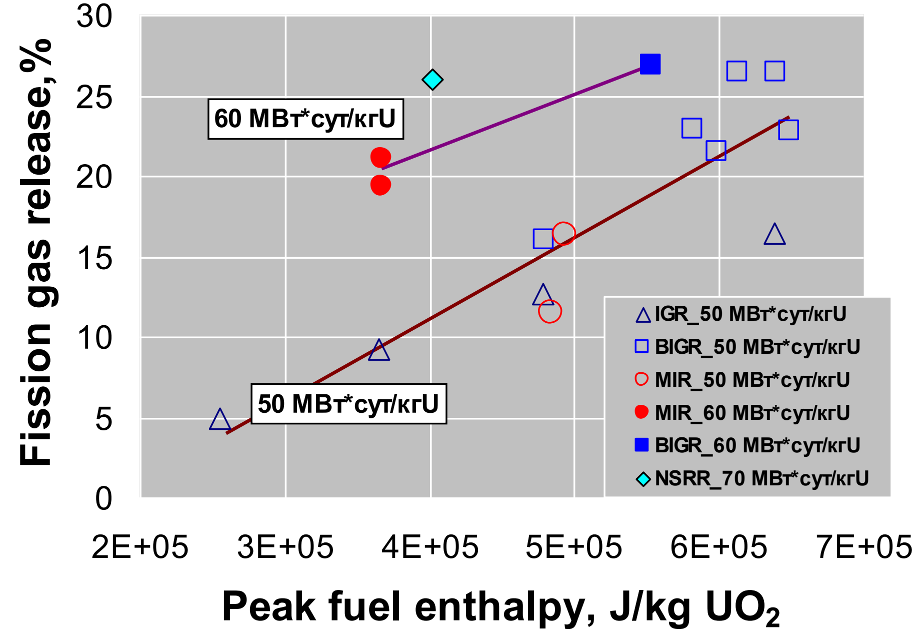
Main Parameters of the RIA Simulation Experiment

Parameters		Measure-ment units	Test #2	Test #3	Test #4
Burn-up of re-fabricated rodlets		MW·d/kgU	48	59	67
Initial average linear heat generation rate throughout the length	Un-irradiated fuel rod	W/cm	270	210	175
	Re-fabricated rodlets		230	205	140
Pulse amplitude at the level of thermocouple attachment	Un-irradiated fuel rod	-	3.32	3.36	3.23
	Re-fabricated rodlets	-	3.32	3.14	3.23
Pulse half-width		c	1.75	1.58	2.9
Time of screen movement (time of pulse rise)		c	2.0	1.2	0.4
Peak temperature in the center of fuel stack at the place of thermocouple attachment	Un-irradiated fuel rod	^oC	1670	1318	1508
	Re-fabricated fuel rodlet #1		1458	1406	1173
	Re-fabricated fuel rodlet #2		1468	-	-
Calculated h_{MAX} of fuel stack	Un-irradiated fuel rod	10^5 J/kg	5.3	4.1	4.0
	Re-fabricated fuel rodlet #1		4.9	3.9	2.8
	Re-fabricated fuel rodlet #2		4.8	-	-
Enthalpy increment of fuel stack in pulse	Un-irradiated fuel rod	10^5 J/kg	2.0	1.6	1.7
	Re-fabricated fuel rodlet #1		2.0	1.5	1.1
	Re-fabricated fuel rodlet #2		2.0	-	-

RIA tests: testing methodology and experimental data



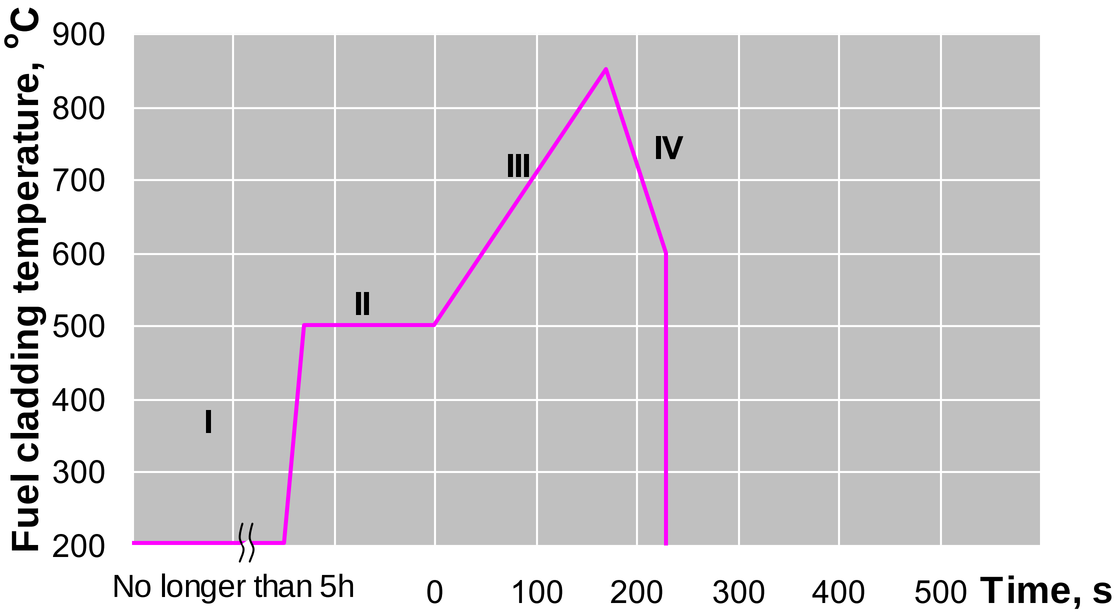
a)



b)

Fission gas release as a function of the peak temperature (a) and peak fuel enthalpy (b).

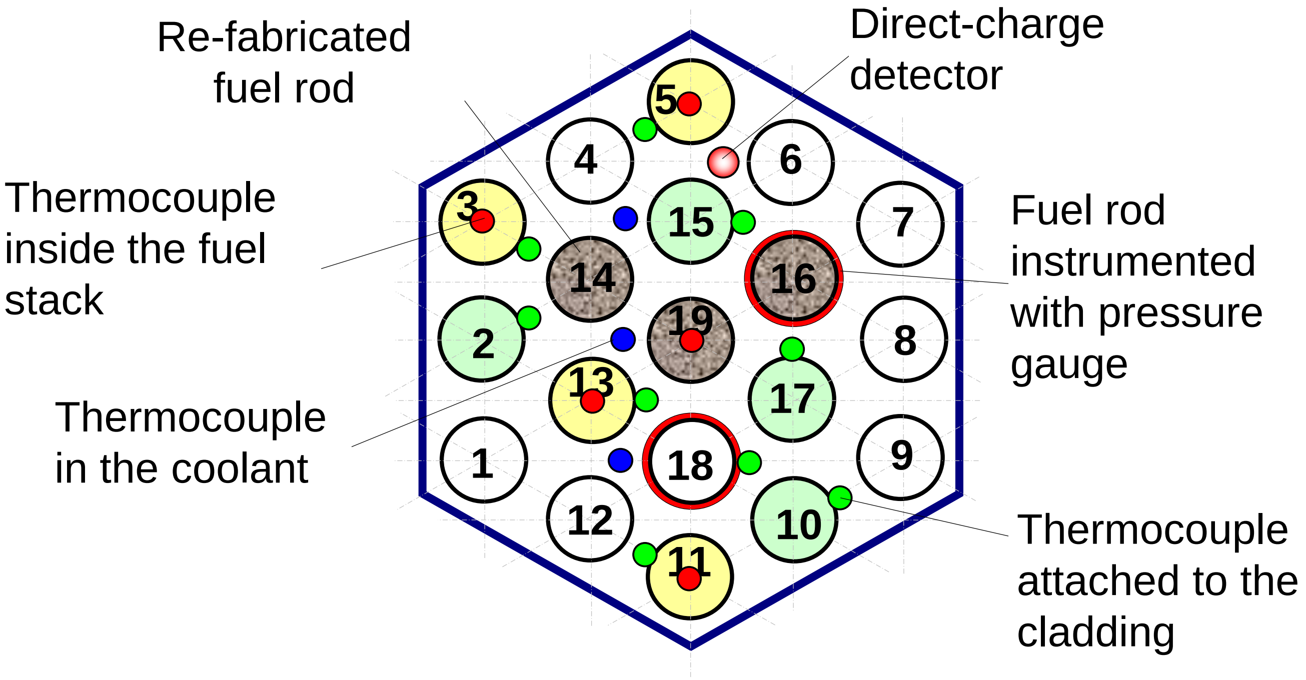
LOCA tests: testing methodology and experimental data



I - Evaporation (no longer than 5h)
II - Holding at cladding draying temperature (150-250c)
III(180-200c), IV(60-120c) - Ultimate DBA (phase 2)

Temperature scenario of the LOCA simulation experiment

LOCA tests: testing methodology and experimental data



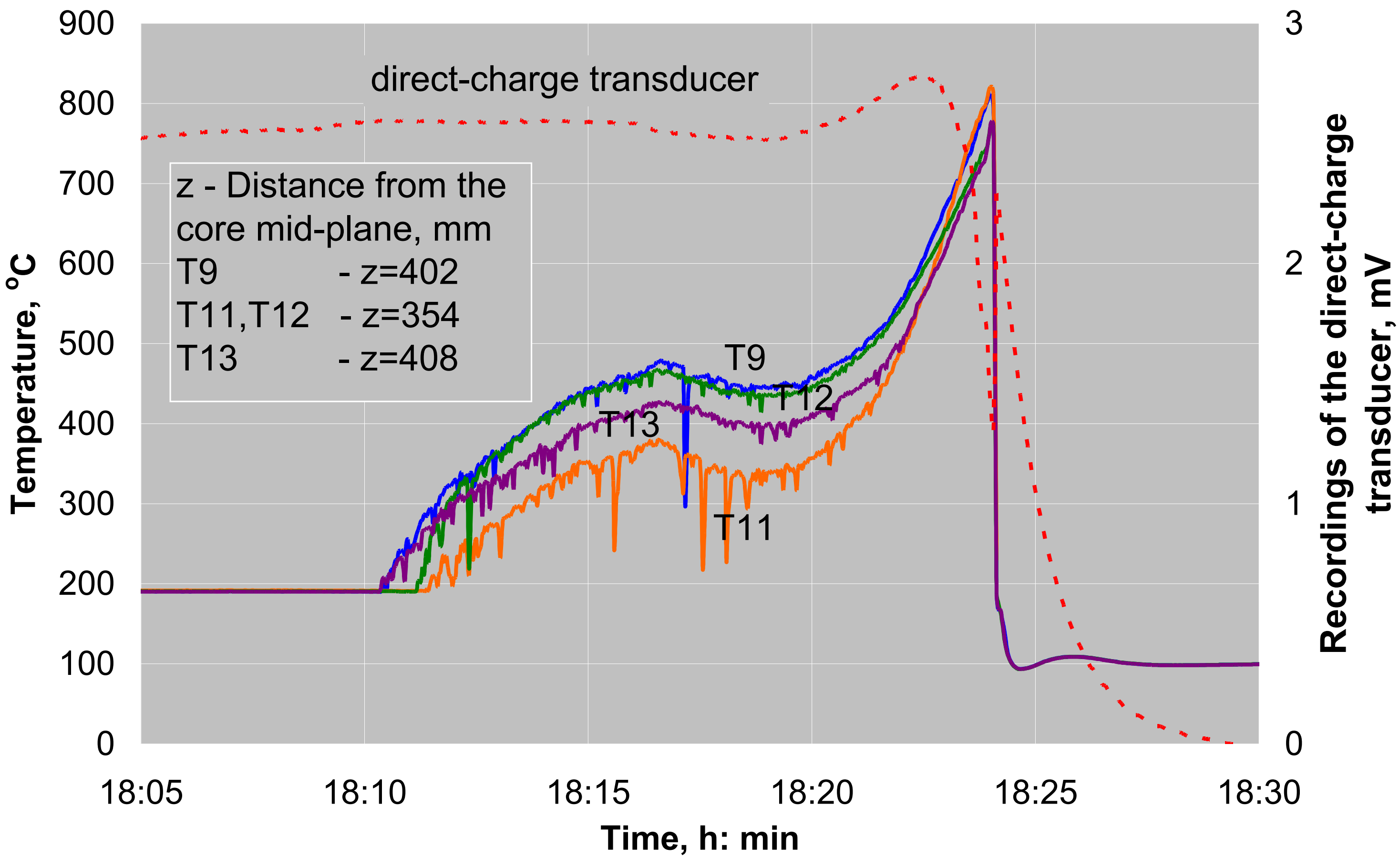
Schematic arrangement of fuel rodlets, thermocouples and sensors in the test assembly

LOCA tests: testing methodology and experimental data

Main Specifications of the LOCA Simulation Tests

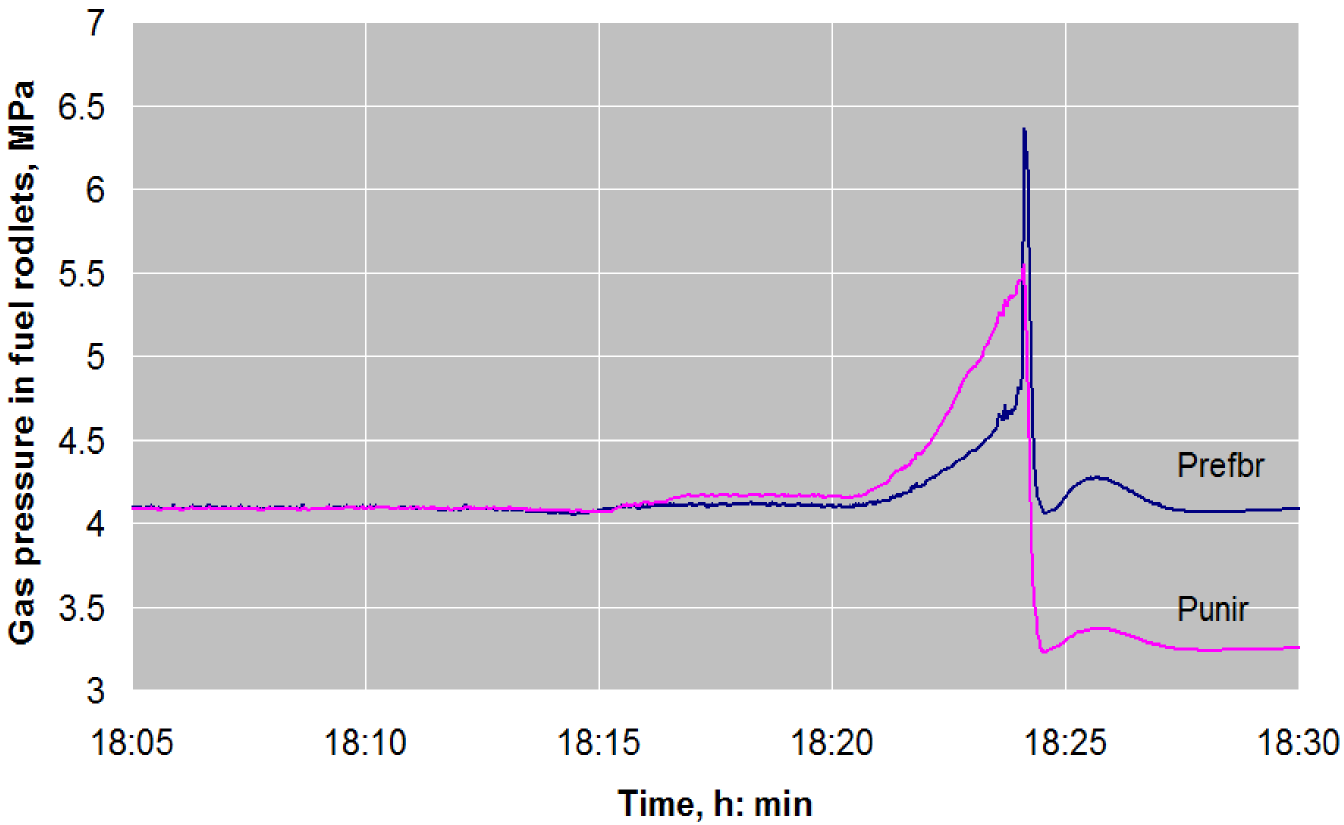
Test	Fuel, number of rodlets in the test assembly		Primary pressure, MPa	Temperature range, °C	Dewatering time, min	State of fuel rodlets	
	Un-irradiated fuel rods	High-burn-up fuel rodlets (burn-up, W·d/kgU)				Intact	Failed
BT-2	16	3(50)	1.7	500-940	40		+
BT-3	16	3(58)	1.2	500-820	10	+	+

BT-3 LOCA test experimental data



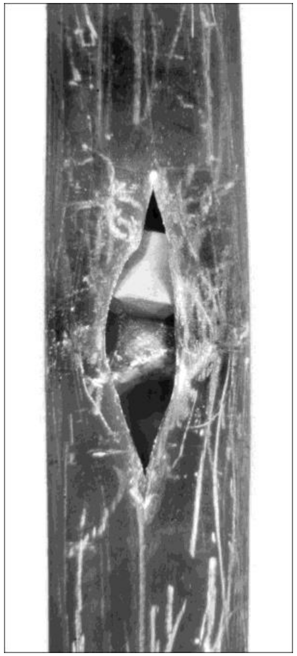
BT-3 experiment data: of the direct-charge detector and temperatures of claddings

BT-3 LOCA test experimental data



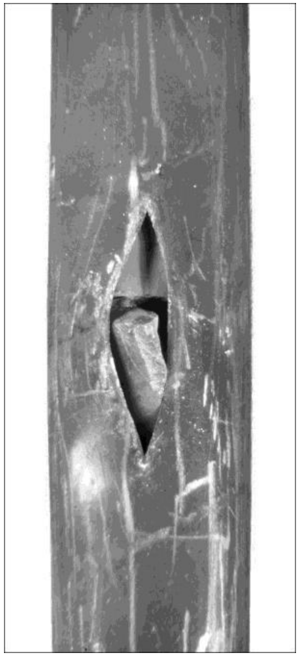
Gas pressure in un-irradiated (Punir) and irradiated (Prefbr) fuel rodlets.

BT-3 LOCA test experimental data

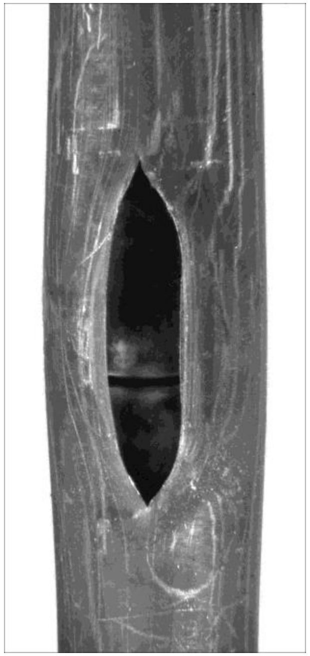


Fuel rodlet #2

Fuel rodlet #3



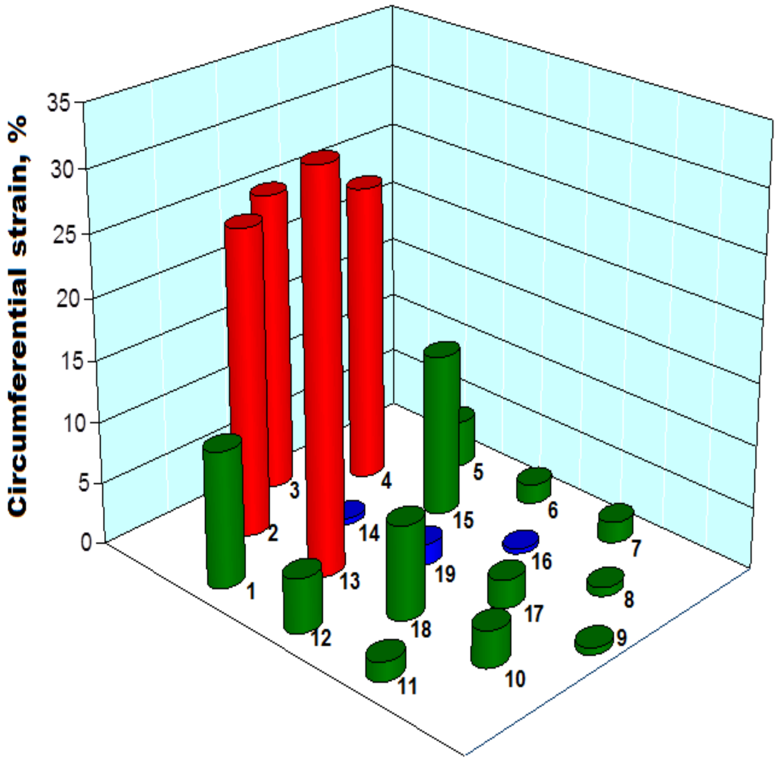
Fuel rodlet #4

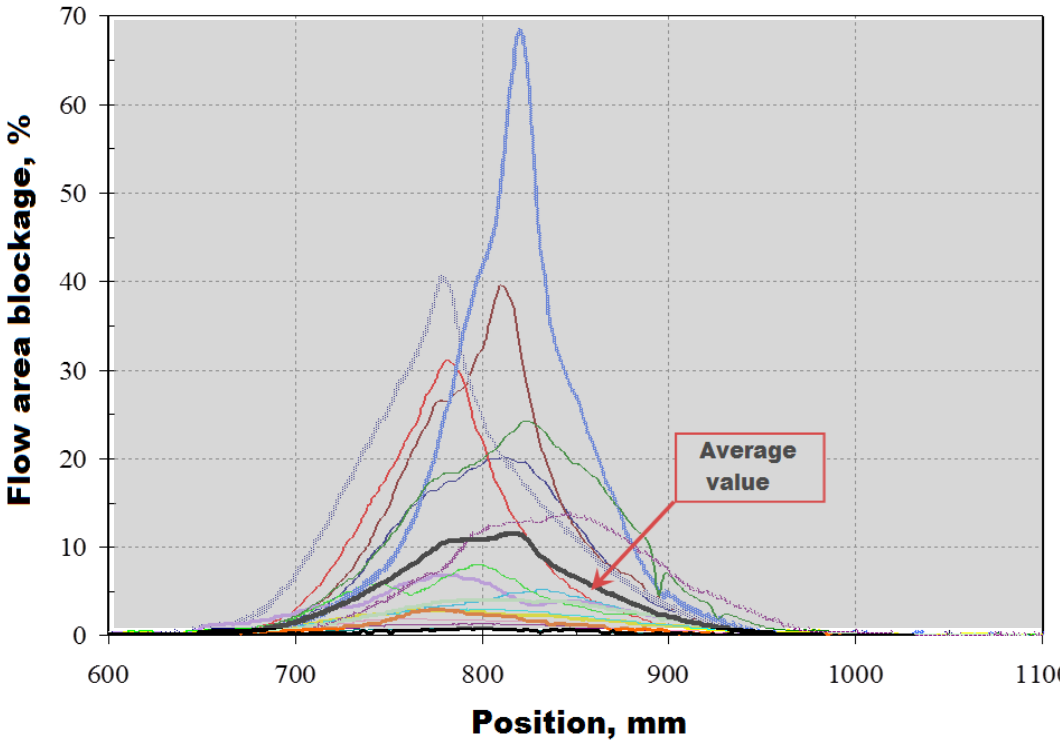


Fuel rodlet #13

Outer appearance of the claddings at the place of fuel failure

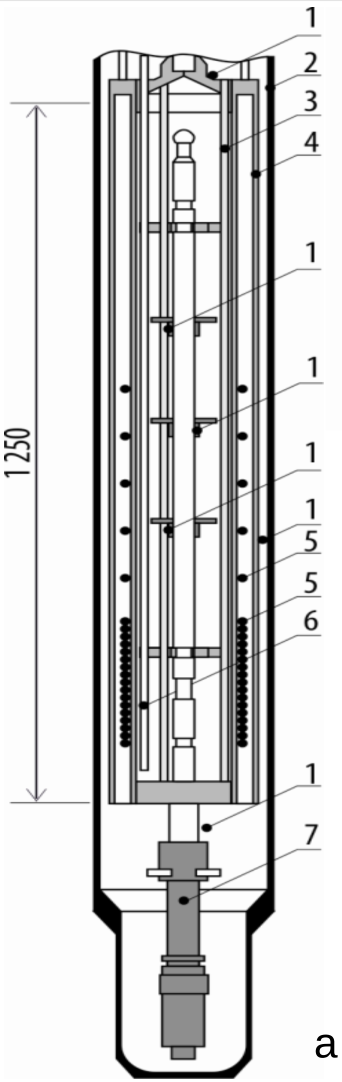
BT-3 LOCA test experimental data



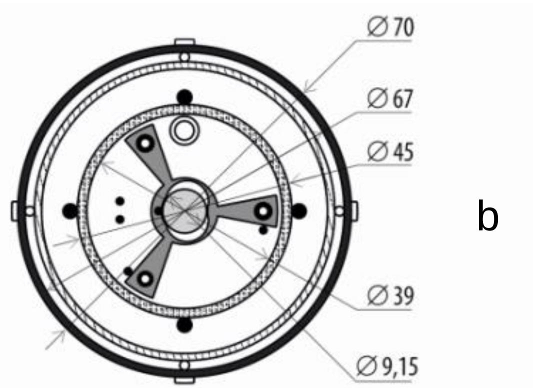


Maximum circumferential strain of claddings in the test fuel assembly (a). Changes in the cross-sectional flow area of the coolant (b)

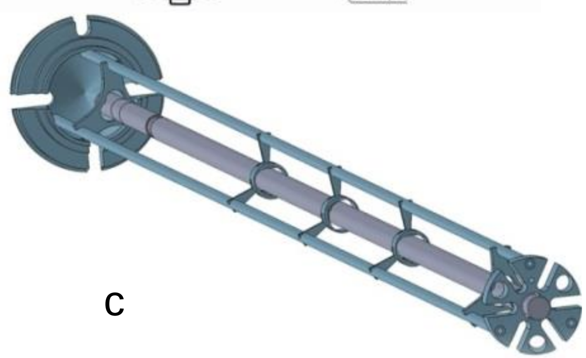
LOCA tests methodology of single fuel rods



a



b



c

Schematic representation of design (a), cross-section (b) and fixing of fuel rodlet (c) in the test rig:

1 - thermocouple;

2 - shroud;

3 - basket;

4 - insulator;

5 - heater;

6 - water supply pipe of the test rig;

7 - pressure gage

Fuel rodlet intended for irradiation testing in the MIR reactor channel: 1 - ferromagnetic core; 2 - pressure gage; 3 - lower gas plenum; 4 - fuel stack; 5 - upper gas plenum

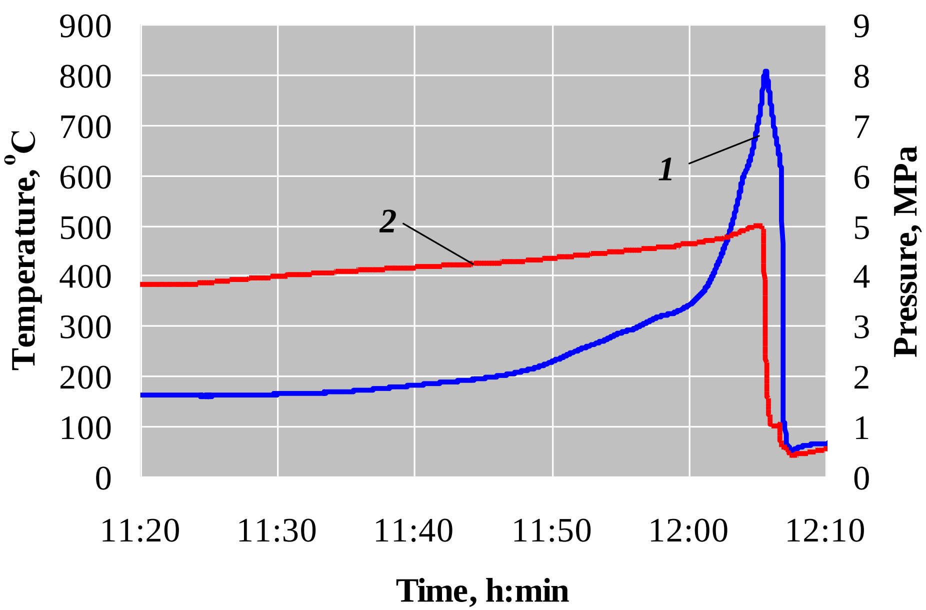
Main Specifications of the LOCA tests of single fuel rods

Main Specifications of the LOCA simulation tests with the use of single fuel rods

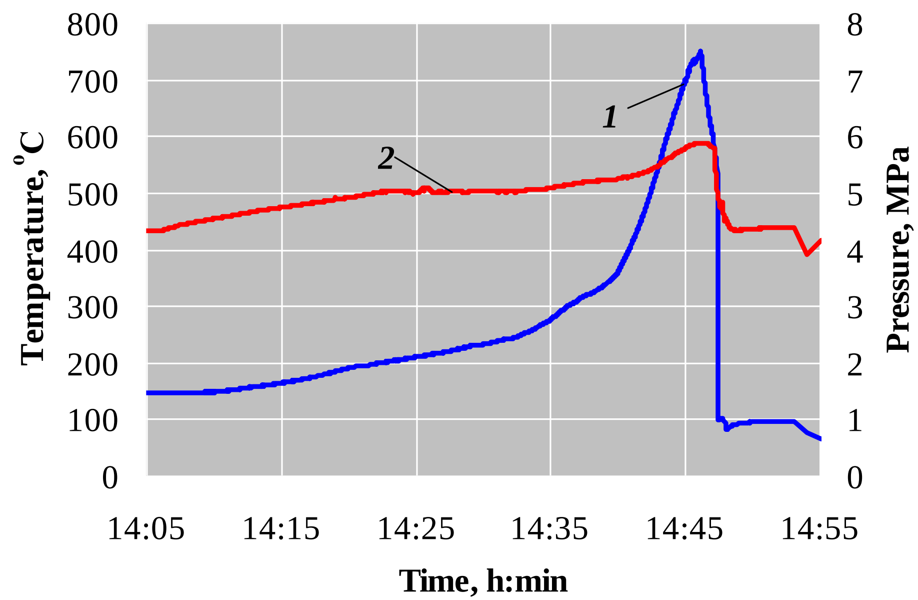
Parameter	Test 1	Test 2
Outer / inner diameter of standard fuel rod selected for refabrication, mm: cladding fuel stack	9.1/7.93 7.8/0	9.1/7.93 7.8/0
Maximum fuel burn-up in the fuel rod under test, MW·day/kgU	45	60
Peak cladding temperature, °C	807	750
State of fuel rodlet after testing	failed	intact
Cladding temperature during cladding failure, °C	770-780	-
Rate of temperature increase during failure, °C/s	3.6	1.2*
Pressure drop on the cladding during fuel failure, MPa	5.0	5.8*

*Note: * pressure drop and rate of temperature increase for the intact fuel rodlet are given at the maximum temperature of 750°C achieved during test #2.*

Experimental data of single fuel rods testing



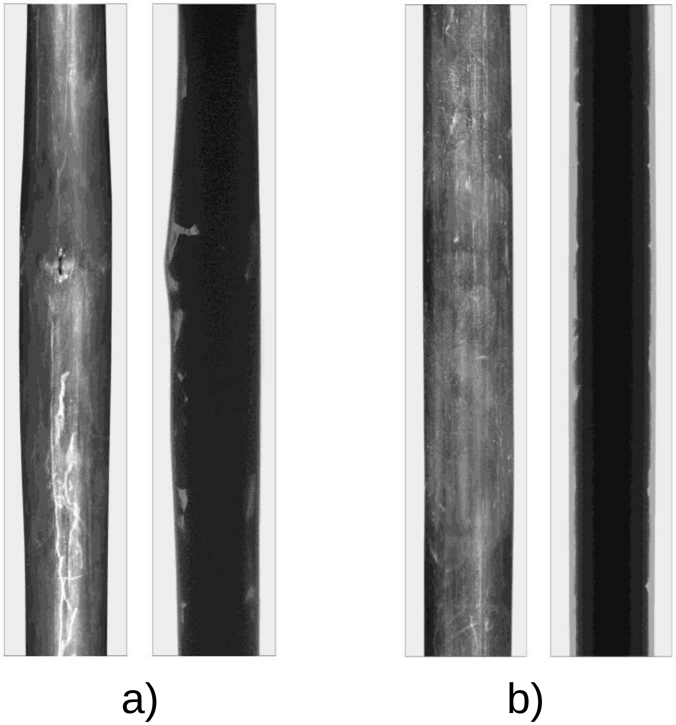
a)



b)

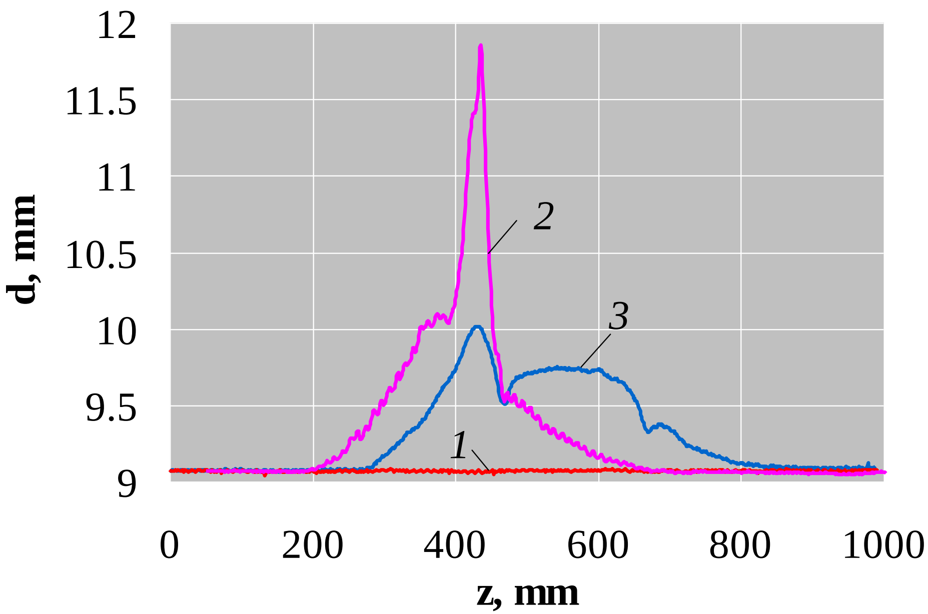
Cladding temperature variation with time (1) at 10 to 20 mm above the middle spacer grid and time history of gas pressure (2) in the lower gas plenum during tests 1 (a) and 2 (b)

Experimental data of single fuel rods testing



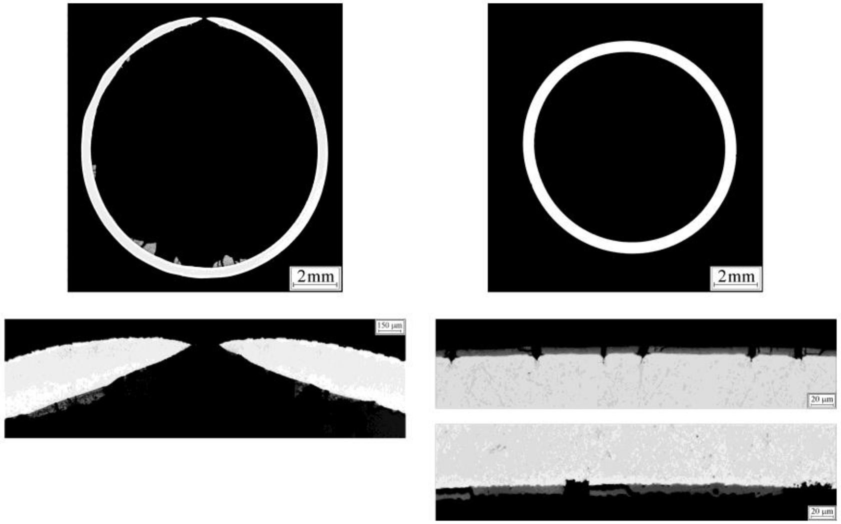
Surface appearance of the cladding and X-ray images taken at place of cladding failure during test #1* (a) and the maximum deformation during test #2(b)

*Note: * - X-ray image is rotated 90º relative to the photograph of surface appearance*



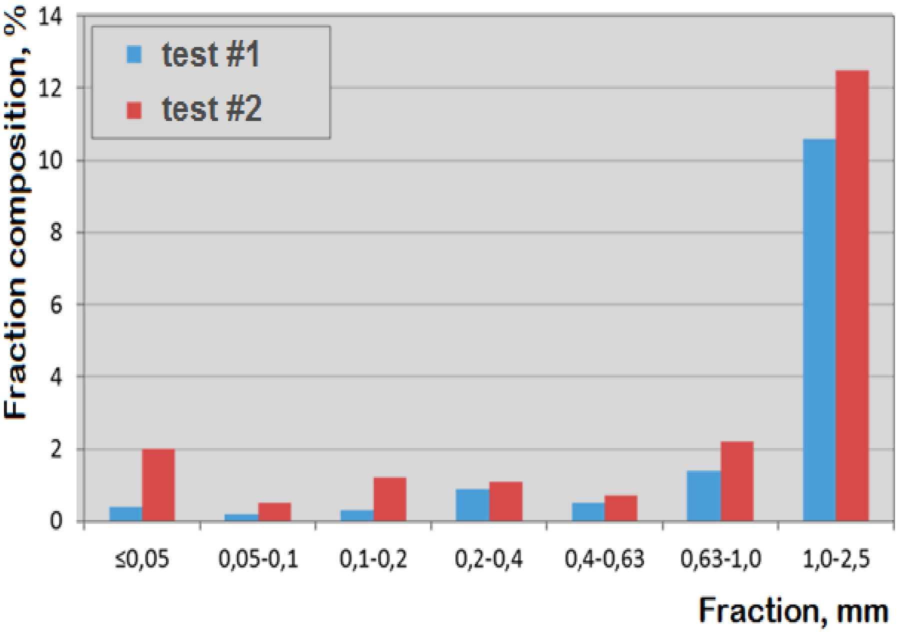
Profile diagrams of the cladding and fuel rodlets before (1) and after test #1 (2) and #2(3)

Experimental data of single fuel rods testing



a) b)

Fuel cladding structure after test #1 (a) at the rupture cross-section and after test #2 (b) at the cross-section of its maximum deformation



Grain particle size of extracted fuel

Conclusion

On the MIR reactor have been developed techniques and devices for testing of VVER-1000 high burn-up fuel with simulation RIA and LOCA design basis accidents. At tests measurements of the coolant, cladding and fuel temperatures, as well as elongation of fuel eleents and fission gas relese are providing.

RIA simulation experiment in the MIR test channel relevant to temperatures and enthalpy of DBA parameters for the VVER-1000 fuel and satisfactory variation of the main parameters can be achieved by selecting the appropriate pulse parameters of experiments.

LOCA experiments could be provided for single fuel rods as well as for fuel assembly with several fuel rods.

Results of investigations are used for qualification of new designs of fuel and verification of of physical models and codes.

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Thank you for your attention!

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