Researches of WWER Fuel Rods Behaviour under RIA Accident Conditions

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1. Safety Requirements Showed to WWER-Type Fuel Rods under RIA Conditions

The safety requirements directed on preservation of active zone geometry accepted for cooling and possibility of fuel rods assemblies unloading:

- Melting of fuel is not supposed;
- Fragmentation of fuel rod (the fuel rod destruction on a part) is not supposed.

The safety requirements directed on restriction of radiological consequences for the population and an environment:

- Fuel rod depressurizing is supposed, but is limited.

Acceptance criteria used at a substantiation of safety:

- Fuel temperature is lower than melting temperature: $T_{пл}$=(2840 - 0.56∗B)˚C, B-burnup, MWd/kgU;
- The radial averaged fuel enthalpy is no more experimentally reasonable limiting size for each moment of accident and for each fuel rod;
- The criterion of fuel rod depressurizing is developed.

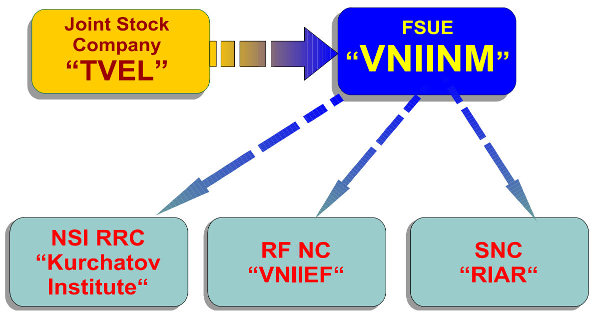


Figure 1. The circuit of works organization

Table 1.

Reactors IGR, GIDRA [1-3]	**Reactor BIGR [3-7]**
1983-1990 – unirradiated fuel rods	**1994-2002 – unirradiated fuel rods**
Test conditions One or two fuel rods are placed in a capsule with the water under initial conditions (20˚C, 0.1-0.5, 16 MPa)	**Test conditions** One fuel rod is placed in a capsule with the water or air under initial conditions (20˚C, 0.1, 14.5 MPa)
Definition of failure thresholds for unirradiated fuel rods (simulators) with E110 (ZR1%Nb) cladding	Reactor BIGR updating and methodical researches. Definition of failure thresholds for unirradiated fuel rods (simulators) with E110 cladding Comparative tests of unirradiated fuel rods with E110 and E635 cladding
Reactor IGR [3,6]	**Reactor BIGR [4,5]**
1990-1992 – refabricated high burnup fuel rods	**1997-2000 – refabricated high burnup fuel rods**
Test conditions **Single fuel rod is placed in a capsule with the water under normal conditions (20˚C, 0.1 MPa)**	
• Burnup 48-51MW d/кg U	• Burnup 48-60 MWd/кg
• Pulse width 600-900 ms	• Pulse width 3 ms
• Initial pressure in a fuel rod 1.7 MPa (He)	• Initial pressure in a fuel rod 0.1; 2.0 MPa (He)
• Maximal peak fuel enthalpy 250 cal/g	• Maximal peak fuel enthalpy 190 cal/g
Posttest examination	
The calculation analysis, interpretation of results, development of a database [16]	
1995-1999	1994-2002

2. Experimental Study of WWER Fuel Behaviour under RIA Conditions

The experimental study of WWER fuel behaviour under RIA conditions is shown in Table 1.

The circuit of works organization is shown on Figure 1.

- Power of fission in the experimental rod fuel as function of time [8,9], Figure 2;
- The axial and azimuthal non-uniformity of fission in the WWER fuel - no more than 5%;
- The fission distribution on fuel radius was de-

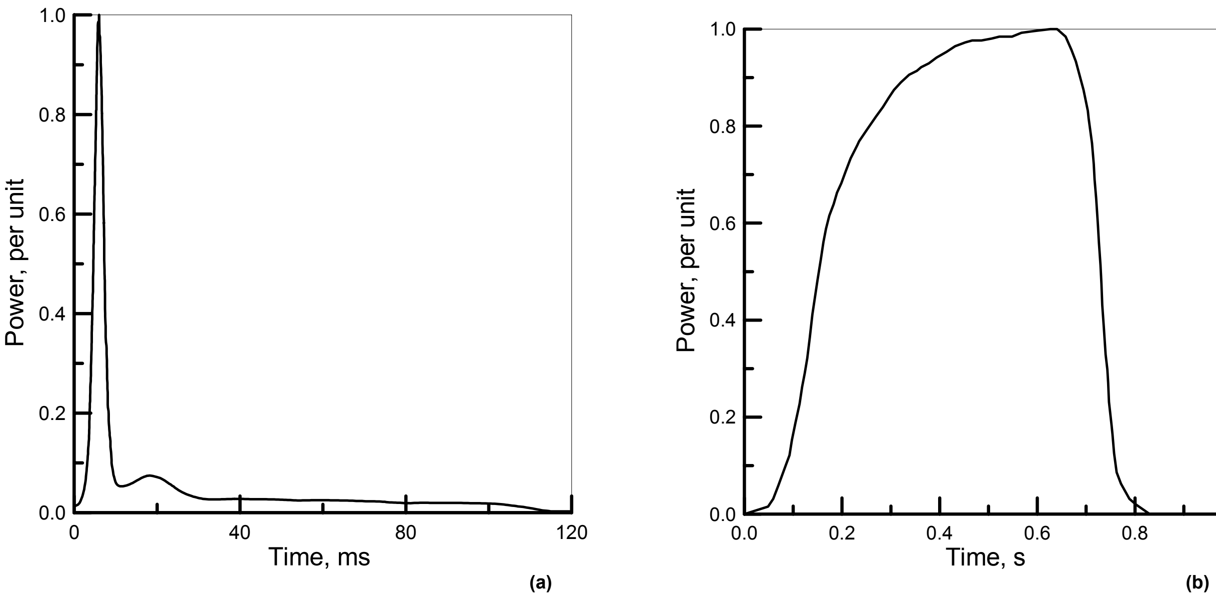


Figure 2. Power of fission in the experimental rod fuel as function of time [8,9]: (a) Short pulse of BIGR; (b) Long pulse of BIGR

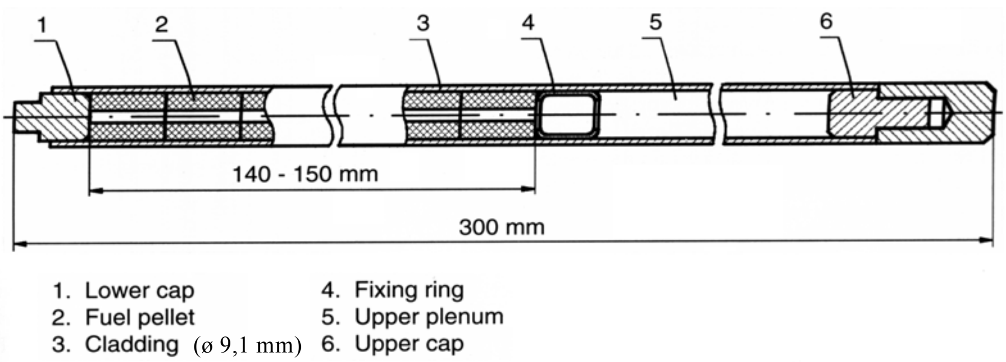


Figure 3. Scheme of WWER type simulator

Table 2.

Variant №	Experimental conditions	Notes
1	Experiments in an capsule with water at atmospheric pressure, width of a power pulse 3-5 ms	Definition of failure thresholds, comparative tests with E110 and E635 cladding
2	Experiments in an capsule with air at atmospheric pressure, width of a power pulse 3-5 ms	Reception experimental data for RAPTA-5[10] code verification by use of simple heat transfer model from cladding to air
3	Experiments in an capsule with water at atmospheric pressure, width of a power pulse 500-700 ms	Reception experimental data for comparison of simulators behaviour under conditions of different power pulse width (variants 1 and 3)
4	Experiments in an capsule with water at high pressure 14.5 MPa, width of a power pulse 3-5 ms	Reception experimental data for comparison of simulators behaviour under conditions of different pressure drop across the cladding (variants 1 and 4), comparative tests with E110 and E635 cladding

termined for everyone experimental fuel rod on the basis of neutron-physical accounts in view of the NPP irradiation history and radiochemical measurement results.

2.1. Unirradiated Fuel Rod Tests at the BIGR Reactor

The basic characteristics of the tests:

- More than forty WWER type simulators;
- Methodical tests + four variants of experimental conditions;
- Cladding material - alloys E110, E635;
- Initial gas pressure (He) in simulators 0.1; 0.5-0.6; 2.1-2.3 MPa;
- Peak fuel enthalpy - 60-310 cal/gUO_2.

The scheme of WWER type simulator is shown on Figure 3.

Variants of experimental conditions at realization of unirradiated fuel rods tests at the BIGR reactor are shown in Table 2.

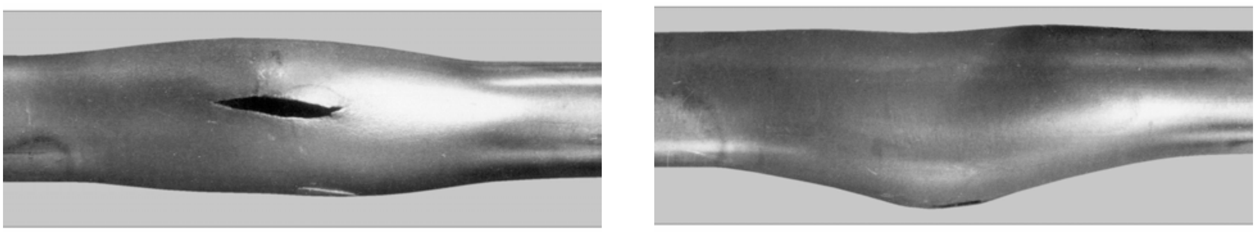
2.2. Test Results of WWER Type Simulators at the BIGR Reactor

Test results of WWER type simulators at the BIGR reactor are shown in Table 3.

On Figure 4 appearance of simulator №16 after BIGR tests can be seen. Experimental condition variant - 1, initial pressure drop simulator/capsule – 2.3 MPa /0.1MPa, cladding material – E110, peak fuel enthalpy ~190 cal/g. The type of cladding failure is plastic deformation with rupture in a place of local non-axis-symmetrical gas ballooning.

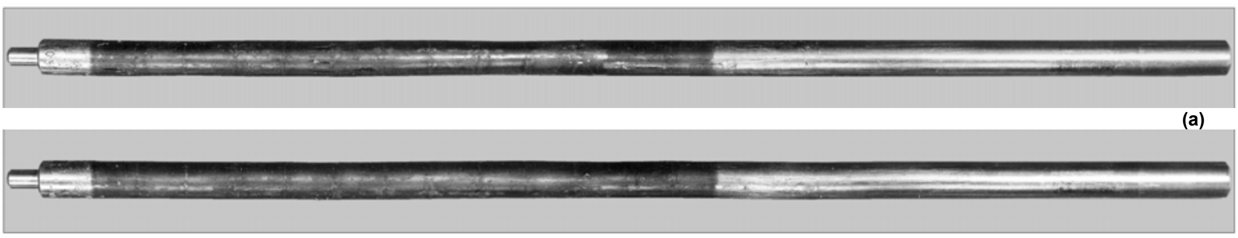
Table 3.

Variants of experimental conditions	Initial internal pressure in the simulator / Initial internal pressure in the capsule, [MPa]	Test results
1	2.0-2.3/0.1	The type of cladding threshold failure is formation of local non-axis-symmetrical gas ballooning with rupture in the maximal deformation field; The failure threshold - peak enthalpy of fuel 180 cal/g. Fragmentation was not observed up to peak enthalpy of fuel 275 cal/g, distinctive features of E635 cladding behavior (in comparison with E110 cladding) is not revealed
	0.1-0.6/0.1	Cladding failure is not observed at peak enthalpy 240-270 cal/g (cladding crumpling is observed at peak enthalpy 270 cal/g and initial pressure 0.1/0.1)
2	2.1/0.1	The type of cladding threshold failure is the same as one in variant 1. The failure threshold is reduced to it corresponds peak enthalpy of fuel 80 cal/g
3	2.1/0.1	Behavior of simulators is the same as one in variant 1
4	0.1; 0.5-0.6/14.5	Cladding failure is not observed at peak enthalpy 230-310 cal/g (cladding crumpling is observed at peak enthalpy more than 280 cal/g). Distinctive features of E635 cladding behavior (in comparison with E110 cladding) is not revealed



(a) (b)

Figure 4. Appearance of simulator №16 after BIGR tests: (a) - 0˚; (b) - 90˚



(b)

Figure 5. Appearance of simulator №03 after BIGR tests: (a) - 0˚; (b) - 90˚

Appearance of simulator №03 after BIGR tests is shown on Figure 5. Experimental condition variant - 4, initial pressure drop simulator/capsule – 0.5 MPa/14.5MPa, cladding material – E110, peak fuel enthalpy ~230 cal/g, the simulator is tight.

2.3. High Burnup Fuel Rod Tests at the BIGR Reactor

The basic characteristics of tests:

- Eight refabricated fuel rods with burnup 48 MWd/kgU;
- Four refabricated fuel rods with burnup 60 MWd/kgU;
- Cladding material - alloys E110;
- Pulse width 3 ms;
- Initial gas pressure (He) in fuel rods 0.1; 2.0 MPa;
- Peak fuel enthalpy - 115-190 cal/gUO_2.

Scheme of the WWER type high burnup fuel rod refabricated from a commercial fuel element is shown on Figure 6.

2.4. Test Results of WWER Refabricated Fuel Rods at the BIGR Reactor

The test results of WWER refabricated fuel rods at the BIGR reactor are shown ion Figure 7.

- Fuel rods fragmentation was not observed;
- Four fuel rods had cladding failure;
- For all fuel rods the type of cladding failure sites is similar – formation of local non-axis-symmetrical ballooning with rupture in the maximal deformation field;
- Fuel rods with burnup 48 MWd/kgU had on one rupture site;
- Fuel rods with burnup 60 MWd/kgU had two (RT8) and four (RT9) rupture sites.

About increase of burnup to 60 MWd/kgU the essential influence on cladding deformation and depressurizing is rendered by the following factors [11]:

- Significant reduction or absence of a gap between fuel and cladding;
- Presence of a peripheral fuel layer (rim-layer) with the high contents Pu, increased porosity, fine grain;
- Increase of fission gas release.

In all cases of cladding failure the hoop strain made not less than 5%, thus the relative narrowing of cross section reached ~100%, that is in turn explained by a satisfactory condition of fuel rod claddings after NPP irradiation:

- Hydrogen concentration 60-80 ppm;
- Oxide thickness on an outside surface up to 10 microns, on internal up to 20 microns;
- The mechanical properties poorly depend on burning out, high residual ductility.

Deforming of refabricated fuel rod cladding with burnup 60 MWd/kgU in rupture cross section is shown on Figure 8.

Thermomechanical parameters of refabricated fuel rod at the BIGR-experiment – an example of RAPTA-5 calculation, is shown on Figure 9.

2.5. Test Results of WWER Refabricated Fuel Rods at the IGR Reactor

Test results of WWER refabricated fuel rods at the IGR reactor [1,2] are shown on Figure 10.

- The type for all cladding failure sites is similar – formation of local non-axis-symmetrical ballooning with rupture in the maximal deformation field;
- H2T, H3T and H7T had till two cladding failure sites, the cladding residual hoop strain in rupture cross sections made 12-25%;
- H5T had one cladding failure site, the cladding residual hoop strain in rupture cross sections made 6.5%.

Figure 11 shows the cladding of refabricated fuel rod (H5T) in rupture cross section. Pulse width 600-900 ms, initial gas pressure (He) in fuel rods 1.7 MPa.

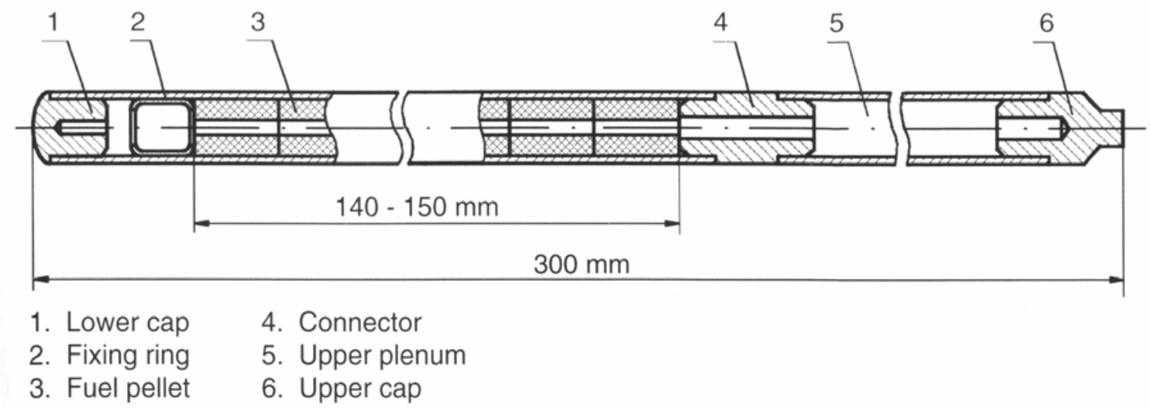


Figure 6. Scheme of the WWER type high burnup fuel rod refabricated from a commercial fuel element

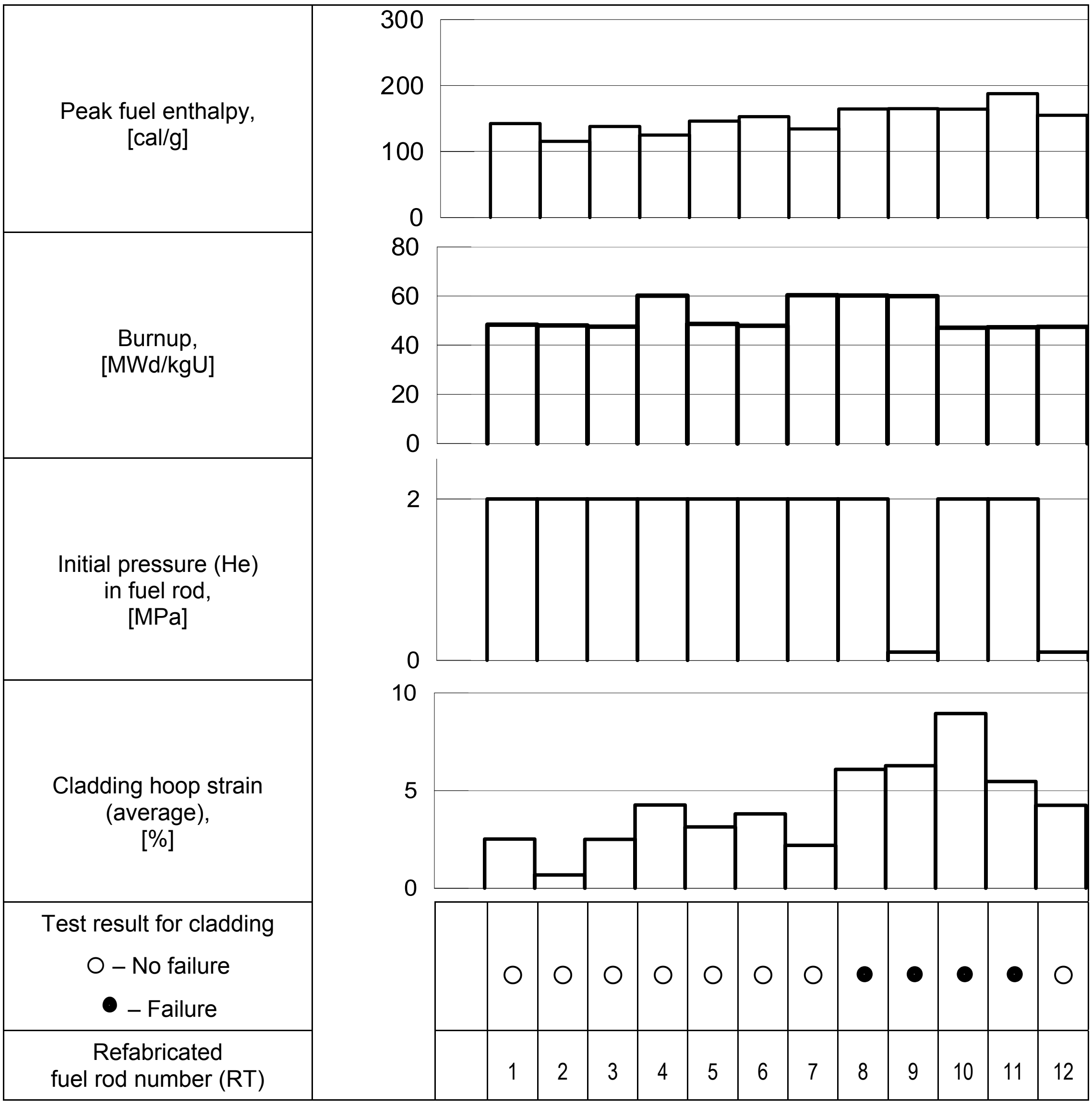


Figure 7. Test results of WWER refabricated fuel rods at the BIGR reactor

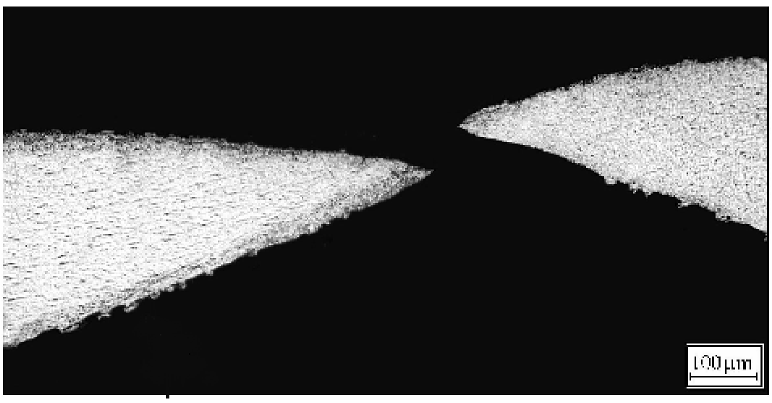
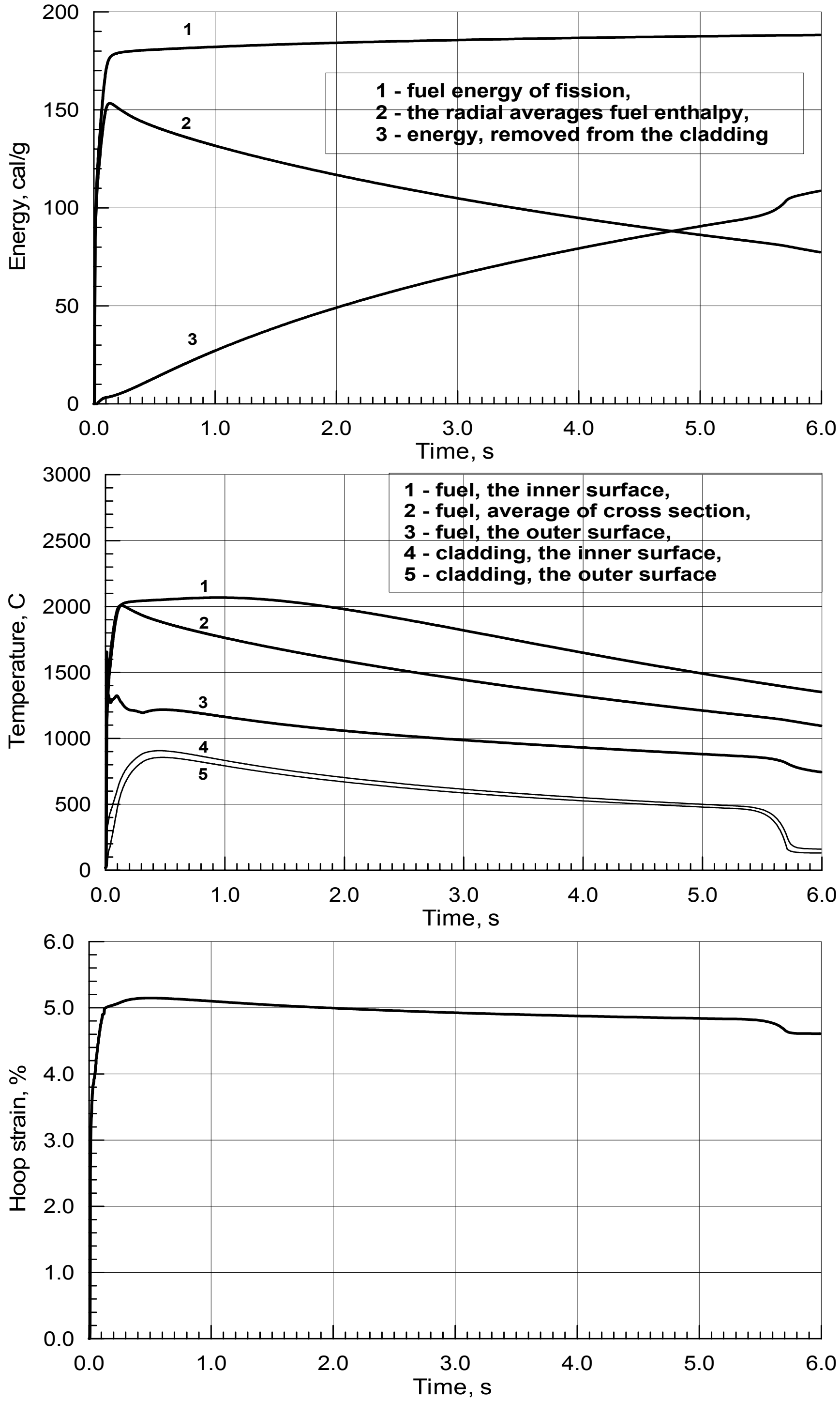


Figure 8. Deforming of refabricated fuel rod cladding with burnup 60 MWd/kgU in rupture cross section



Refabricated fuel rod №12

Fuel burnup	47.4 MWd/kgU,
He initial pressure	0.2 MPa,
Total pulse energy	198 cal/g
Peak fuel enthalpy	154.3 cal/g
Fuel temperature	2434 K
Cladding temperature	1185 K

	Calculation	Experiment
Cladding deformation, [%]	4.53	5.55
FGR estimation, [%]	29.1	22.7

Figure 9. Example of RAPTA-5 calculation: thermomechanical parameters of refabricated fuel rod at the BIGR-experiment

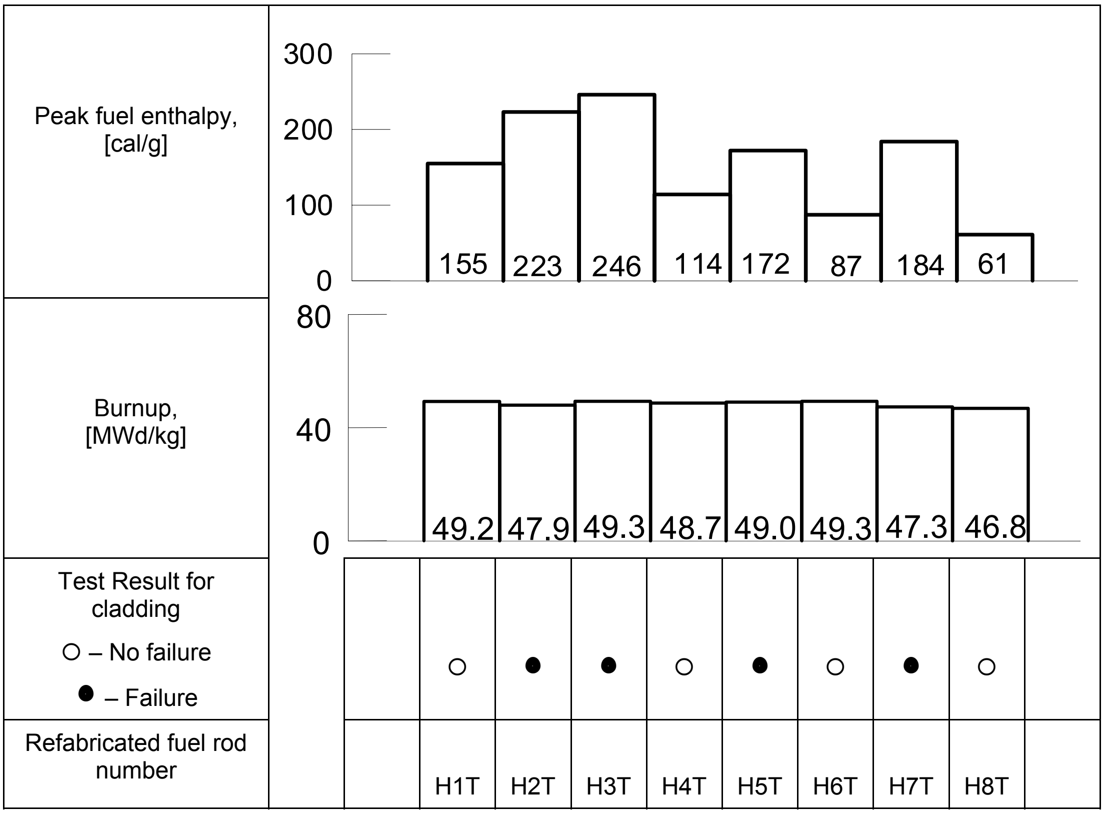


Figure 10.

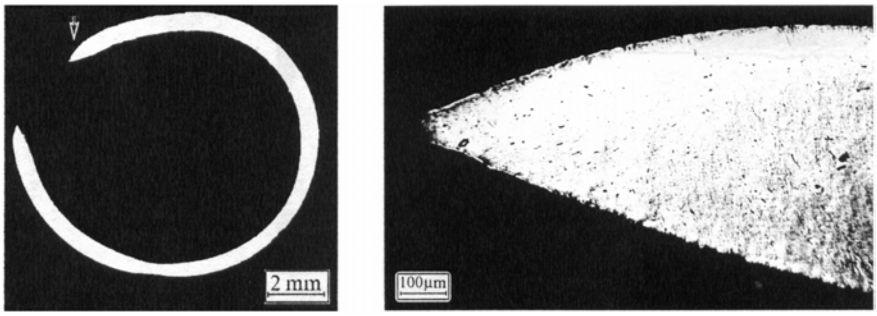


Figure 11.Cladding of refabricated fuel rod (H5T) in rupture cross section

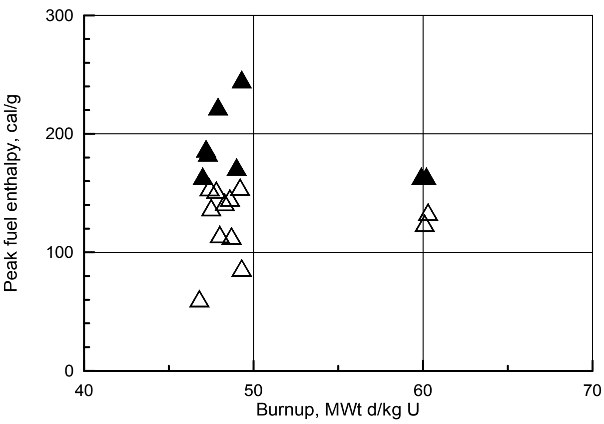


Figure 12.Test results of WWER refabricated fuel rods at the IGR and BIGR reactors: ∆ - no failure, ▲- failure

2.6. Test Results of WWER Refabricated Fuel Rods at the IGR and BIGR Reactors

Test results of WWER refabricated fuel rods at the IGR and BIGR reactors are shown on Figure 12.

2.7. Prospects of Design-Experimental Researches for WWER-Type Fuel Rods Behavior under RIA Conditions

The prospects of design-experimental researches for WWER-type fuel rods behavior under RIA conditions can be seen in Table 4.

Table 4.

The safety requirements	Tasks of experimental researches	Experimental facilities	Conservatism degree of experimental conditions	Prospects researches
Preservation of active zone geometry accepted for cooling and possibility of a unloading fuel rods assemblies	**Definition of fuel enthalpy appropriate to a fragmentation threshold and/or definition of allowable fuel enthalpy at which fragmentation is excluded**	**BIGR**	Conservative conditions ↓ Conditions approached to real, less conservative	Burnup - 60-70 MWd/kgU and more Peak enthalpy up to 200 cal/g Pressure in a capsule 12-14 MPa
Restriction of radiological consequences for the population and an environment	**Definition of cladding failure (depressurizing) conditions**	**MIR**		Burnup - 50-70 MWd/kgU and more Peak enthalpy up to 90-120 cal/g Initial conditions, linear heat power of fuel rod, parameters of coolant in the loop – according to similar parameters of WWER-1000 reactivity design accident

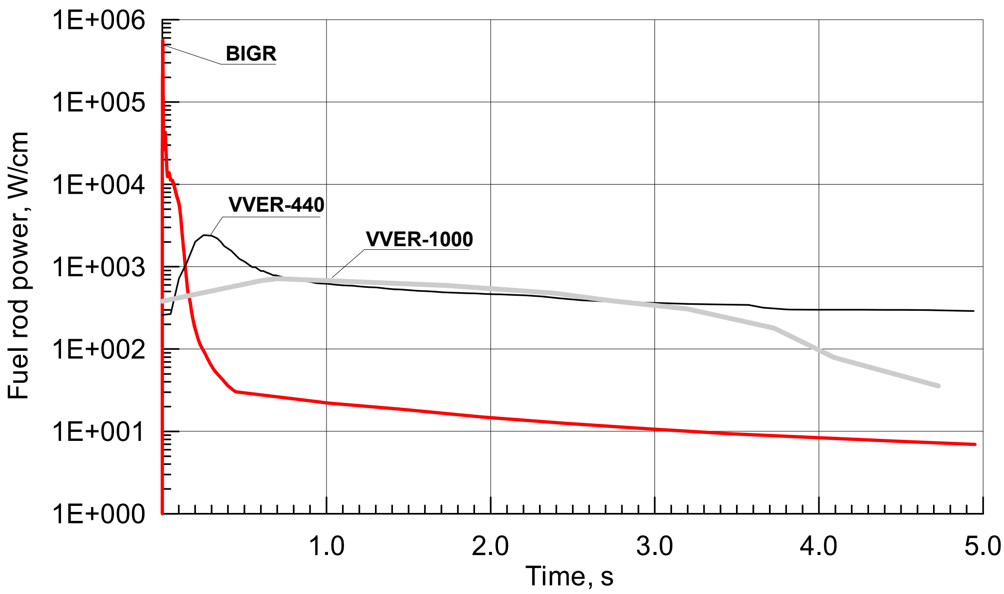


Figure 13.Fuel rod power in the BIGR-test and in WWER design RIA

2.8. Typical Parameters of WWER Fuel Rods in Reactivity Design Accident

Figure 13 shows the fuel rod power in the BIGR-test and in WWER design RIA.

2.9. Conservative Estimations of the Basic Fuel Rod Parameters under Design RIA Conditions

Conservative estimations of the basic fuel rod parameters under design RIA conditions can be seen in Table 6.

Table 6.

Parameter	Design RIA in WWER-1000	Design RIA in WWER-440
Maximum temperature of fuel, [˚C]	2000	2200
Peak fuel enthalpy, [cal/g]	100	120
Maximum temperature of cladding outer surface, [˚C]	600	800

2.10. Example of RAPTA-5 Calculation: Fuel Temperature as Function of Radius

Figure 14 shows the BIGR-tests and Figure 15 - the design RIA in WWER-1000.

3. Experimental Study of Fuel Rod Behaviour at the Research Reactor MIR under Conditions, Simulating Design RIA in WWER-1000 (Prospect)

The purpose of researches:

- Study of WWER-type fuel rod behavior with burnup 50-70 MWd/kgU and more under conditions simulating design RIA in support of reactor safety at licensing (estimation of untight fuel rod amount in active zone);
- Revelation of the determining factors and mechanisms for cladding deforming and development of untight criterion;
- Reception of experimental data for verification and modernization of settlement codes (RAPTA-5), predicting behaviour and possible fuel rod depressurizing in design RIA.

Experimental opportunities of the research reactor MIR:

- The initial experimental conditions correspond to WWER-1000 operation conditions (linear fuel rod power, temperature and pressure of coolant);
- Change of fuel rod linear heat on power in time corresponds to the settlement script of design RIA in WWER-1000;
- The conditions of cooling correspond to coolant parameters of design RIA in WWER-1000;
- Measurements during experiment: cladding and fuel temperatures, inner fuel rod pressure, temperature and pressure of coolant.

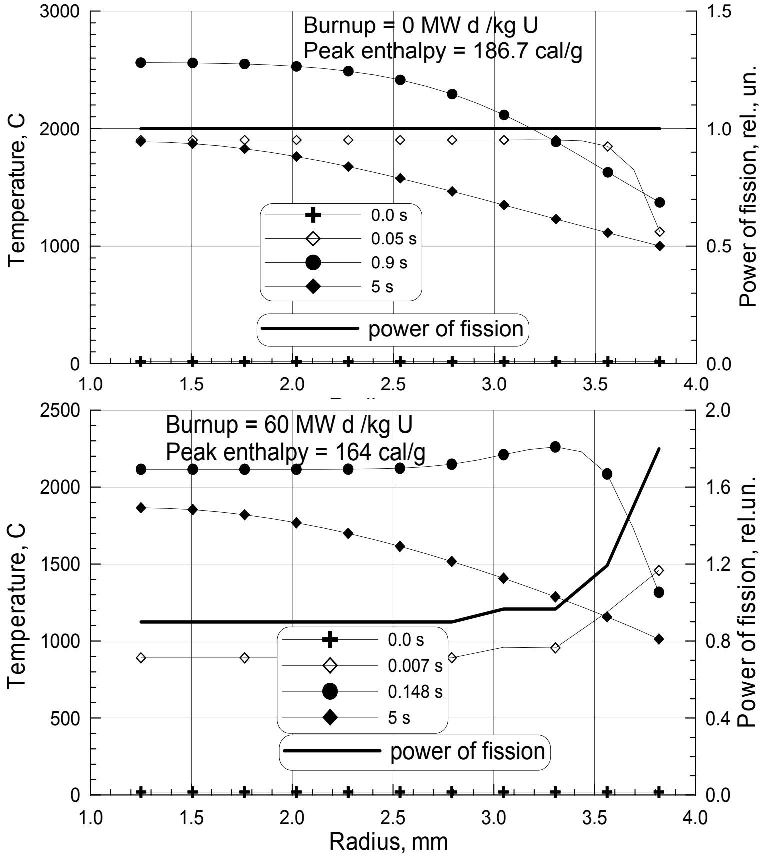


Figure 14.The BIGR-tests

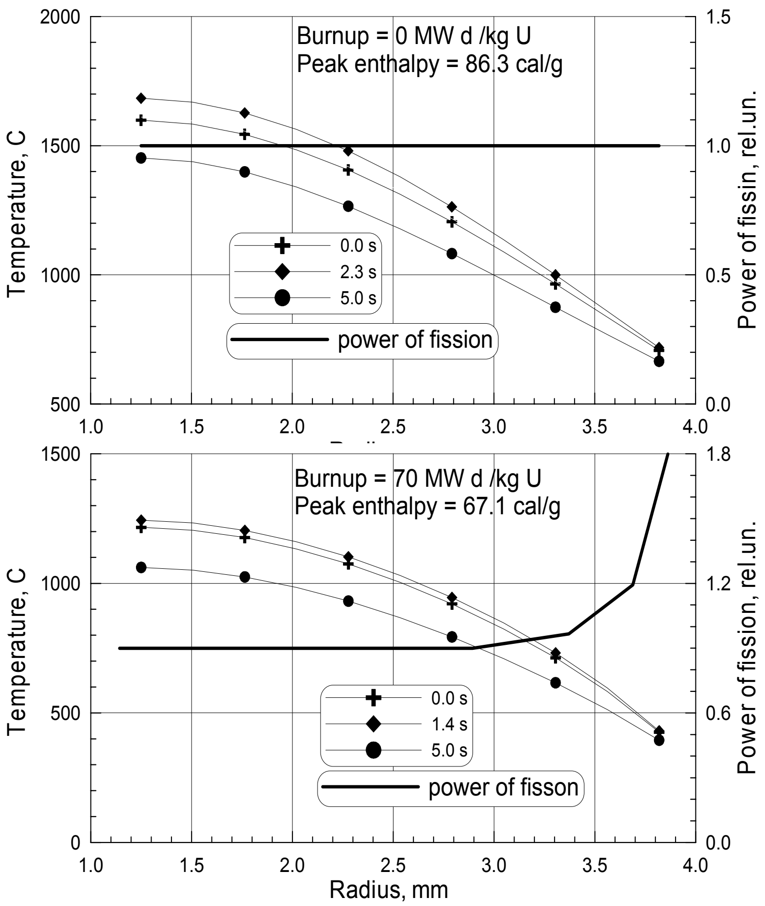


Figure 15.The design RIA in WWER-1000

4. Conclusions

1. Unirradiated fuel rod tests in the BIGR:

- The behaviour of WWER type simulators with E110 and E635 cladding was researched at the BIGR reactor under power pulse conditions simulating reactivity initiated accident. The results of the tests in four variants of experimental conditions are submitted;
- Peak enthalpy of fuel - 60-310 cal/gUO_2;
- Peak fuel enthalpy appropriate to a cladding failure threshold under conditions of cooling by water - 180 cal/g, the type of cladding failure - plastic deformation with rupture in a place of local non-axis-symmetrical gas ballooning, cladding hoop strain in the rupture cross section - more than 20%;
- Fragmentation of simulators was not observed.

2. Refabricated fuel rod tests in the BIGR:

- The behaviour of 12 WWER type refabricated fuel rods was researched in the BIGR reactor under power pulse conditions simulating reactivity initiated accident: burnup 48 and 60 MWd/kgU, pulse width 3 ms, peak fuel enthalpy 115-190 cal/g;
- Four refabricated fuel rods had cladding rupture; peak fuel enthalpy appropriate to a cladding failure threshold - 160 cal/g, type of failure - plastic deformation with rupture in a place of local gas ballooning; cladding hoop strain in the rupture cross section - not less than 5%;
- Fragmentation of refabricated fuel rods was not observed.

3. Acceptance criteria proving absence of fragmentation:

- For fuel rods with burnup no more than 50 MWd/kgU radial averaged fuel enthalpy is not more than 230 cal/g;
- For fuel rods with burnup no more than 60 MWd/kgU radial averaged fuel enthalpy is not more than 165 cal/g.

4. The settlement modeling of refabricated fuel rods thermomechanical behavior in the BIGR-tests using RAPTA-5-code is satisfactory.
5. The program of future tests in the research reactor MIR with high burnup fuel rod (up to 70 MWd/kgU) under conditions simulating design RIA in WWER-1000 is submitted.

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