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Progress Report on the Project # 1648.2

Examination of VVER fuel behaviour under severe accident conditions, Quench state (VVER-QUENCH)

STAGE C. Quench Model

Presented by

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11th Meeting CEG-CM
Dresden, Germany
Forschungszentrum Dresden-Rossendorf (FZD)
Institute of Safety Research
March 7-9, 2007

SVECHA/QUENCH code modification

- Initially SVECHA/QUENCH (S/Q) code was developed for PWR fuel rod materials. To simulate the behaviour of the VVER fuel rod under sever accident conditions it should be modified to take into account the material properties of the VVER fuel rods.
- The necessary adaptations of the S/Q code were performed and the following modules were modified:
  - ✓ the heat exchange module,
  - ✓ the cladding oxidation module,
  - ✓ the mechanical behaviour module,
  - ✓ the driver module (to take into account all modifications).

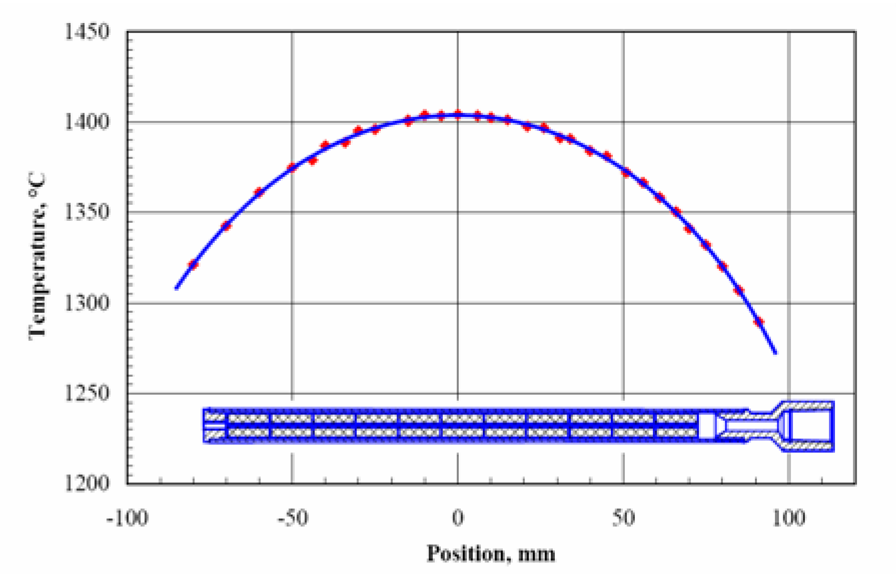
Heat exchange module development (1/7)

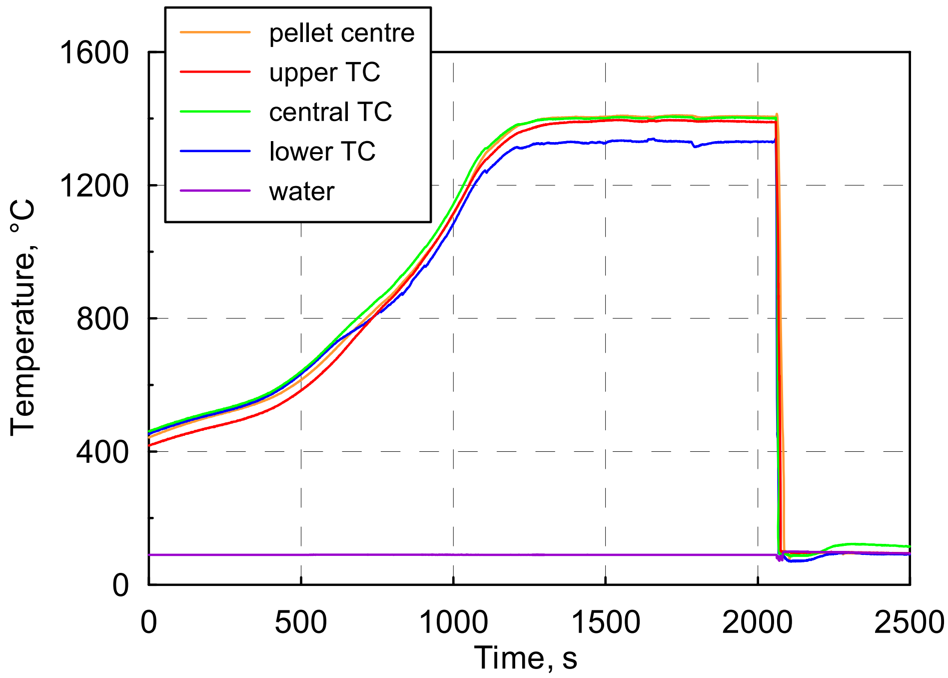
Analysis of the RIAR tests

- In contrast to the FZK quenching tests, the heating of samples was carried out by resistive furnace, rather than by induction coil.
- In the FZK tests the heat was released inside metal layer of the sample cladding, in the RIAR tests the hot internal surface of the operating channel was the heating source.
- Temperature evolution of the sample is determined by its heat exchange with the operating channel internal surface, i.e. in calculations temperature of the operating channel internal surface represents the boundary condition for the heat exchange problem.
- Temperature of the operating channel was adjusted to reproduce correctly the experimentally measured temperatures of the sample outer surface and of the fuel pellet centre (iteration procedure).

Heat exchange module development (2/7)

Analysis of the measured temperature distribution and evolution (1)





Measured temperature distribution along the heating unit.

Measured sample temperature evolution at different elevations. RIAR test # 12.

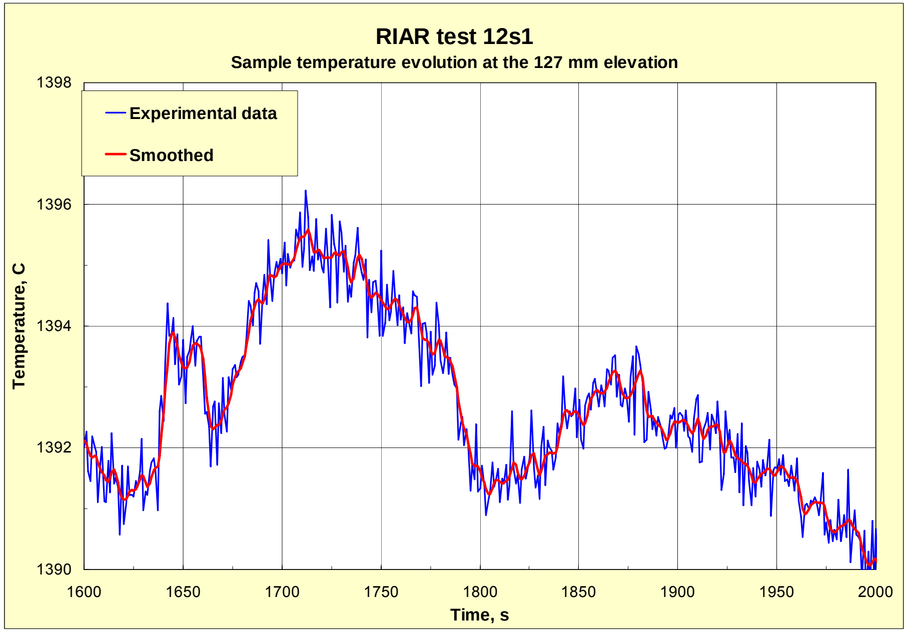
Heat exchange module development (3/7)

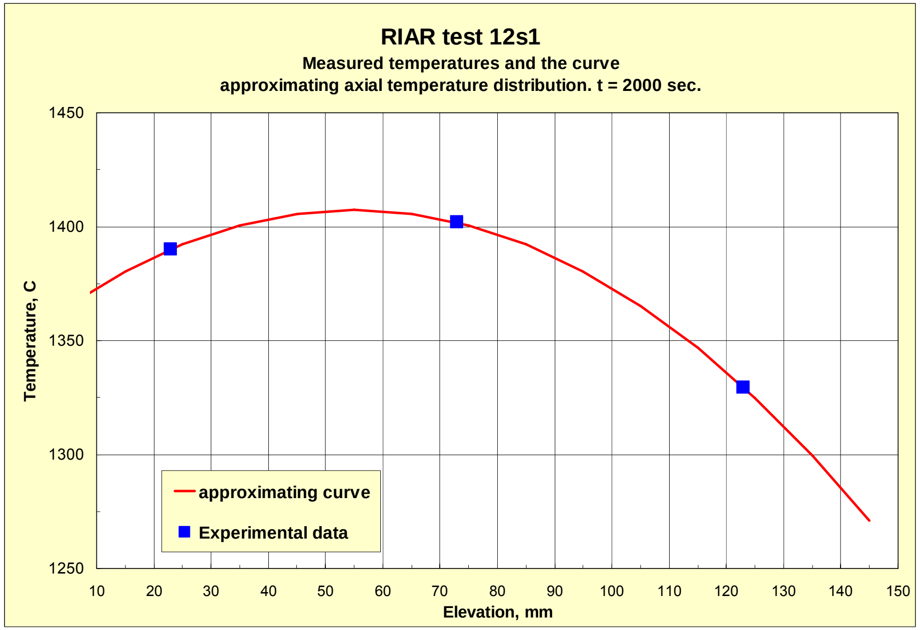
Analysis of the measured temperature distribution and evolution (2)

- Stable temperatures of the sample's TCs in the pre-oxidation stage of the tests and small difference between the fuel pellet centre and the sample outer surface give evidence that the radial temperature gradient in the test facility was rather small.
- Thus, the temperature difference between the sample outer surface and the internal surface of the operating channel was also rather low.
- The measured temperatures of the sample outer surface can be used as the basis for the operating channel temperature determination.
- Before using, the experimentally measured temperatures should be smoothed.
- The operating channel temperature can be approximated by a parabolic dependence: $T(z) = A \cdot z^2 + B \cdot z + C$
- In the quench stage the operating channel temperature is fixed equal to steam temperature

Heat exchange module development (4/7)

Processing of the experimental data





Smoothing of the experimental temperature curves. Upper TC data.

Representation of the axial temperature distribution on the basis of the test data.

Heat exchange module development (5/7)

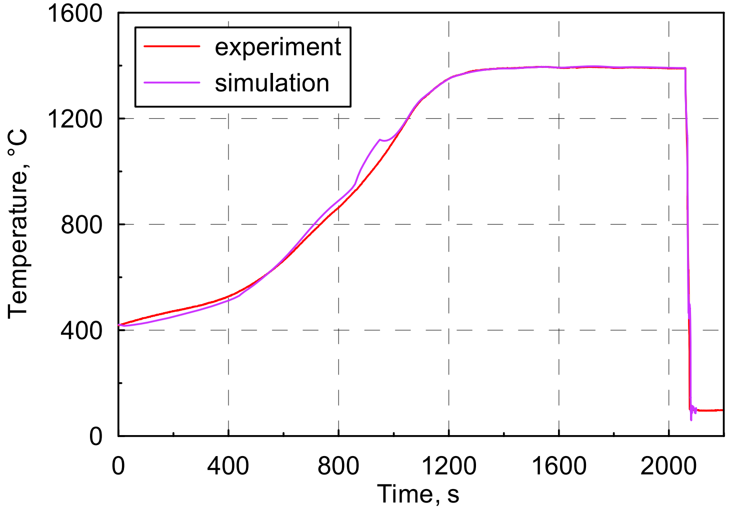
Simulation of the temperature evolution in the RIAR test #12

Test procedure:

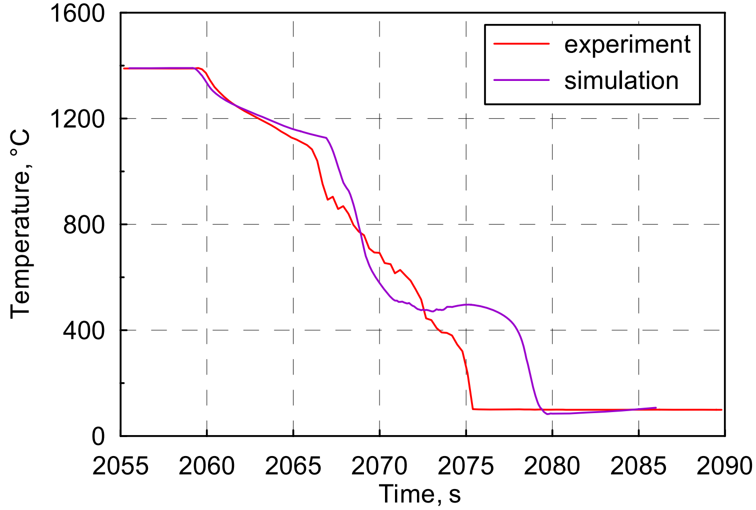
- specimen was heated up to 600 °C in the inert medium (argon);
- steam was supplied with a flow rate of about 0.04 g/s with the following temperature rise up to 1400°C and the heating rate of about 1.5 °C/s;
- specimen was subjected to isothermal exposure at 1400°C in the steam-argon medium during 800 s to reach the target oxide film thickness;
- steam supply from the steam generator was switched off;
- the heater was switched off and specimen was quickly relocated into the flooding tank;
- then specimen was immersed into water heated up to 90°C at a rate of 15 mm/s.

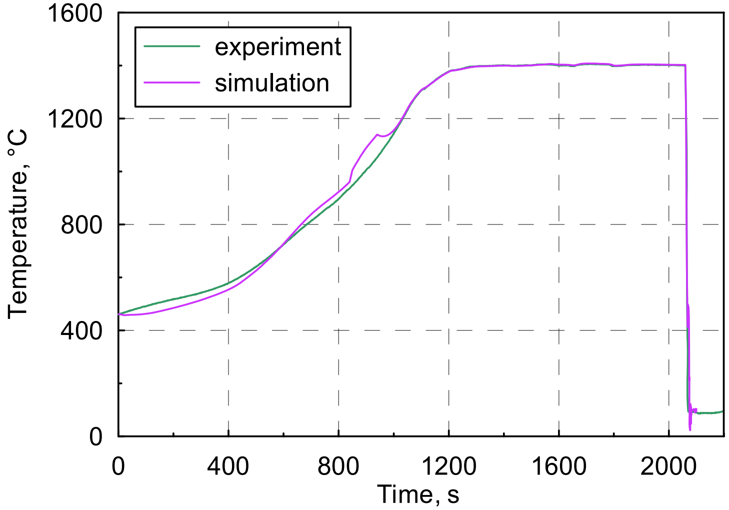
Heat exchange module development (6/7)

Simulation of the temperature evolution in the RIAR test #12

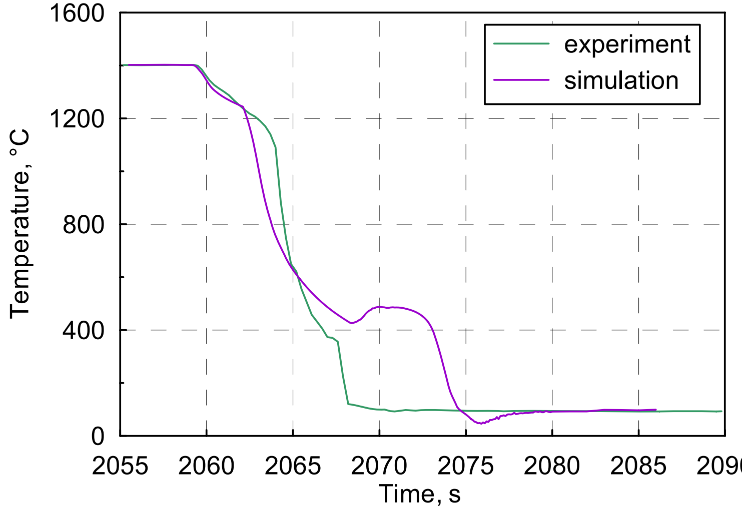


upper TC location





central TC location



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Heat exchange module development (7/7)

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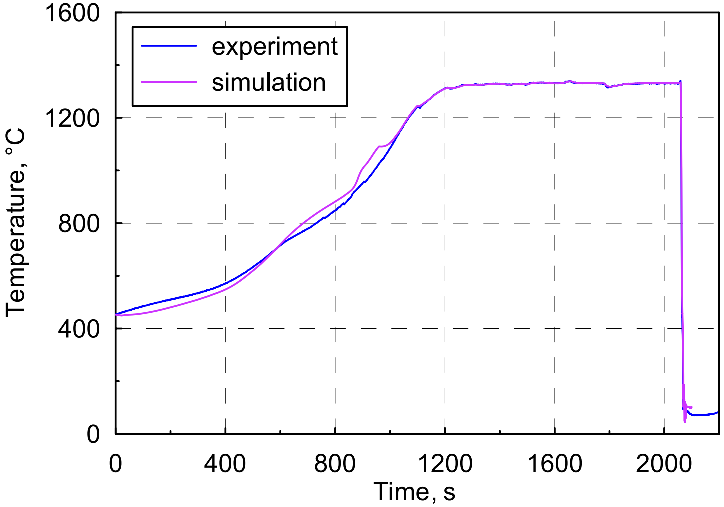
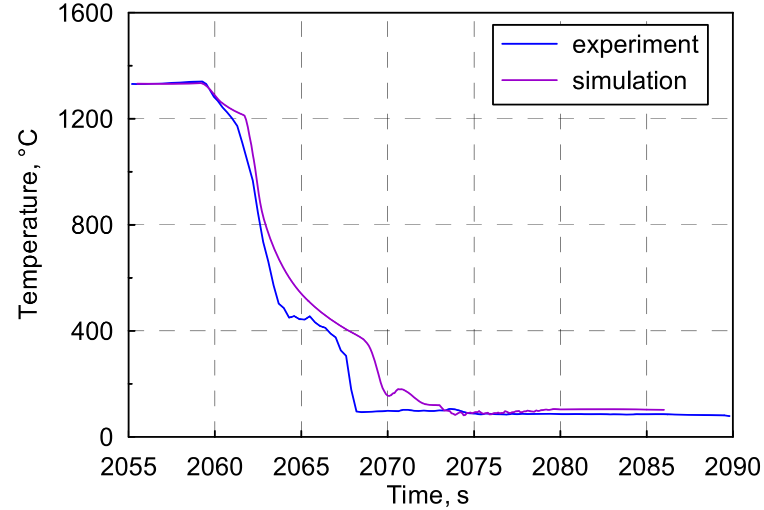
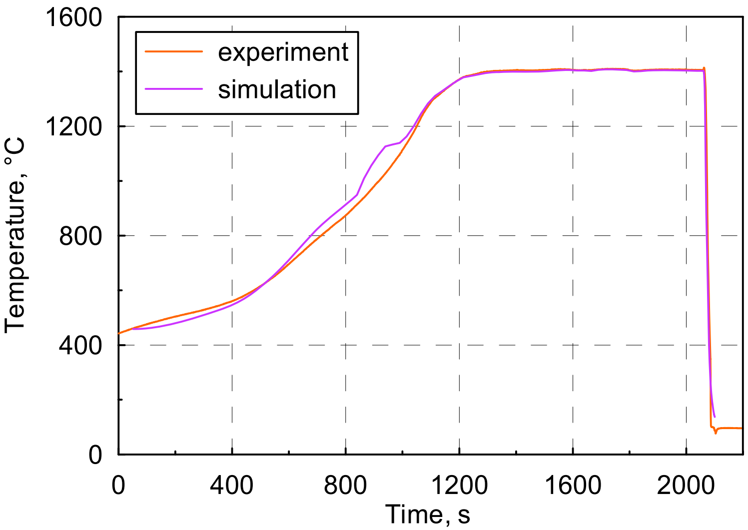
Simulation of the temperature evolution in the RIAR test #12

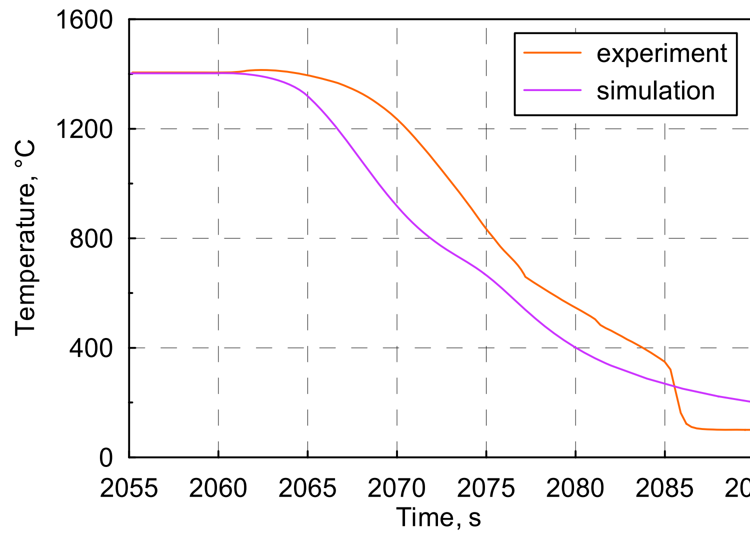




lower TC location



pellet central TC location



Oxidation module development (1/6)

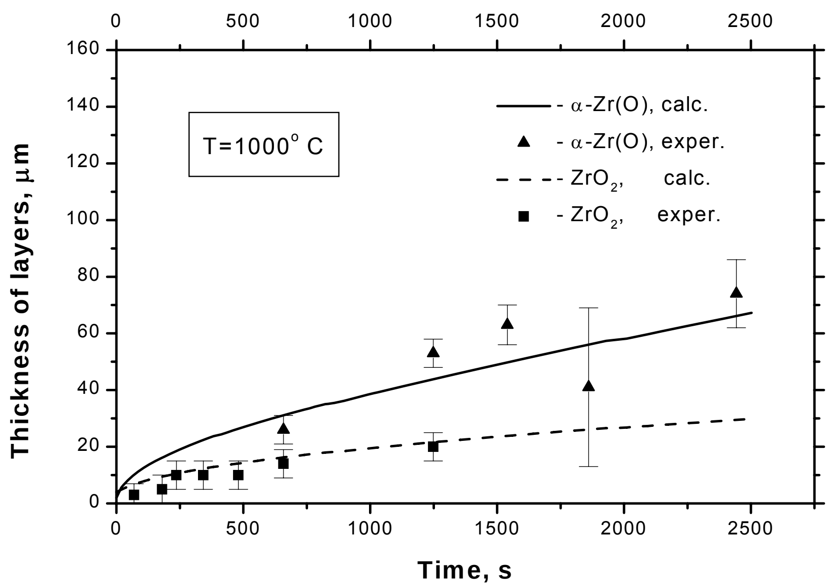
Comparison of Zircaloy-4 and Zr-1%Nb oxidation kinetics [1]

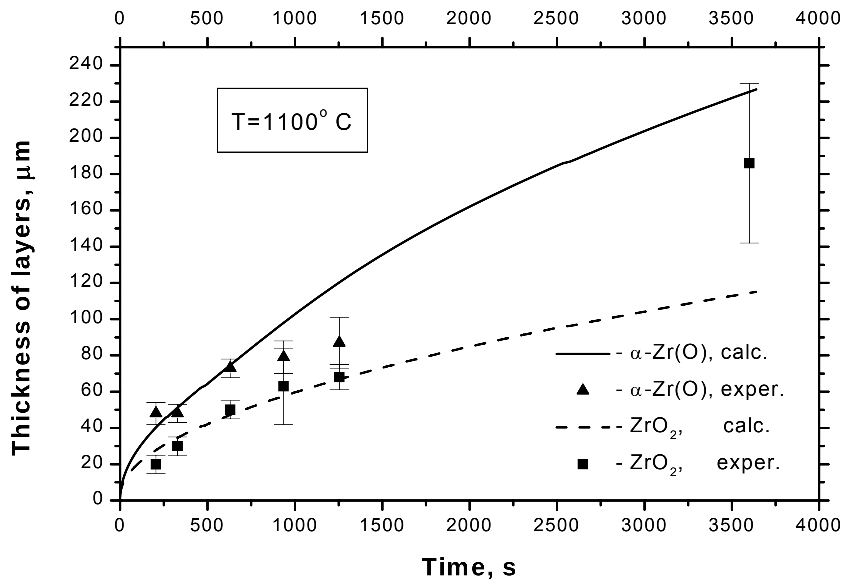
- In general, the high temperature oxidation kinetics of non-irradiated VVER fuel rod cladding is very similar to that of non-irradiated Zircaloy-4 cladding.
- The main difference is the “breakaway” oxidation effect occurred in the VVER cladding in the range of 900 ÷ 1000 °C.
- The breakaway oxidation influences the mechanical deformation behaviour due to further embrittlement of the cladding. The most important factor is the hydrogen embrittlement.
- The hydrogen embrittlement occurs at very low temperature (less than 100 – 150 °C) and it does not affect oxidized fuel cladding fracture at high temperature (>1000 °C).
- New technologies of Nb-bearing alloys manufacturing can decrease or prevent this phenomenon.

[1] L. Yegorova, K. Lioutov, N. Jouravkova, A. Konobeev, V. Smirnov, V. Chesanov, A. Goryachev Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions. NUREG/IA-0211, IRSN 2005-194, NSI RRC KI 3188. March 2005.

Oxidation module development (2/6)

Analysis of RIAR separate-effect tests

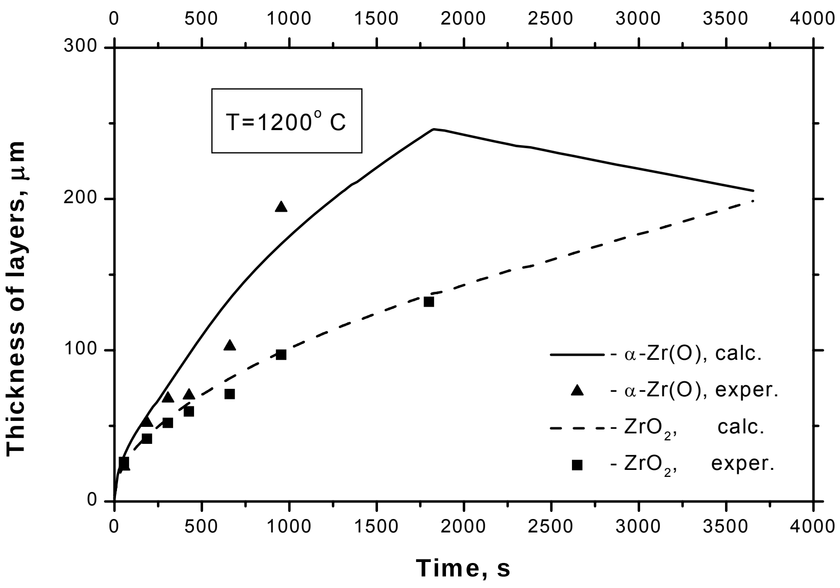


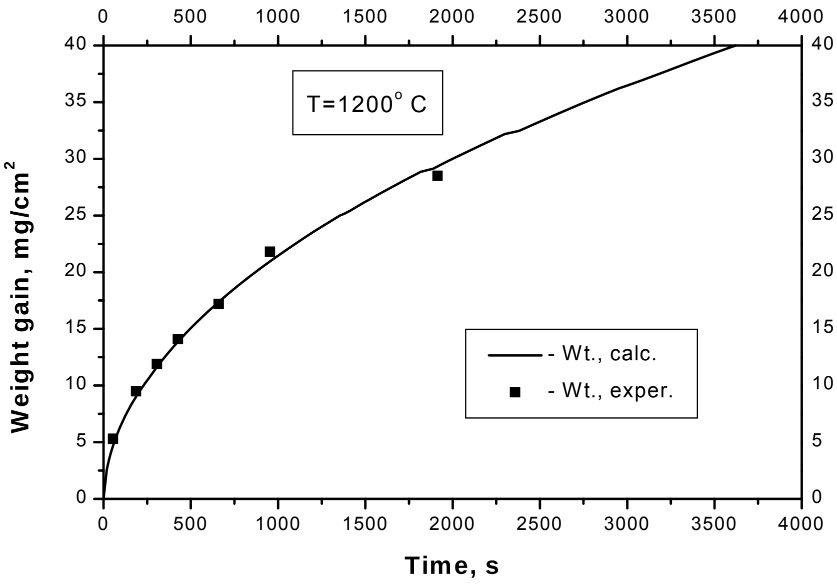


Simulation of the α-Zr and ZrO_2 layers growth kinetics in the RIAR isothermal tests on Zr-1%Nb cladding oxidation in steam at 1000 and 1100ºC

Oxidation module development (3/6)

Analysis of RIAR separate-effect tests

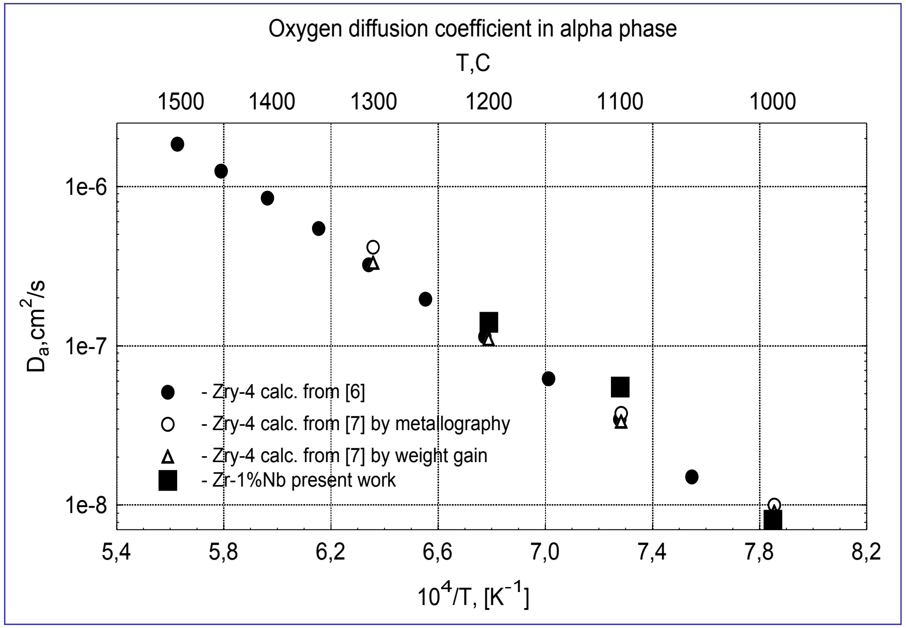


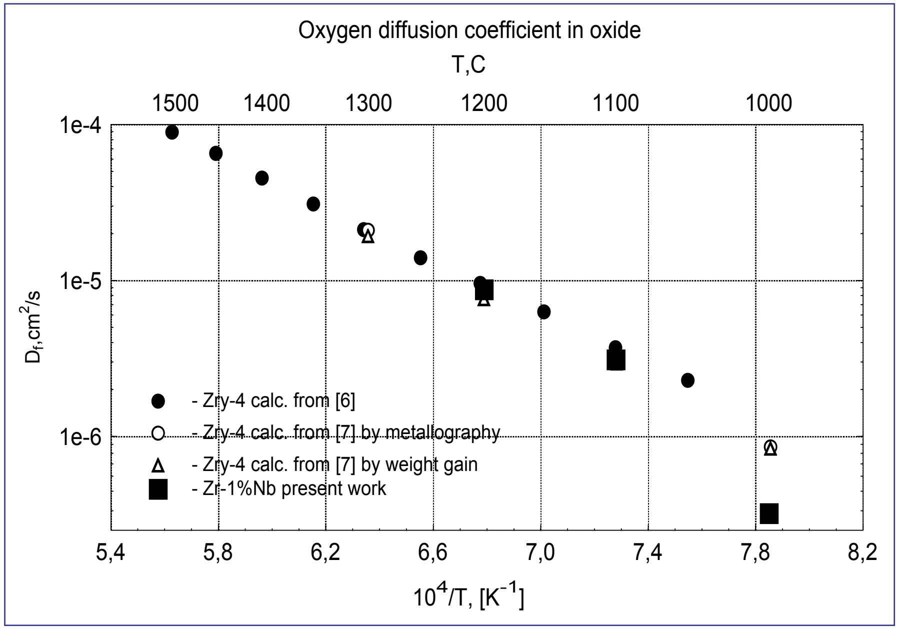


Simulation of the α-Zr and ZrO_2 layers growth and weight gain kinetics in the RIAR isothermal tests on Zr-1%Nb cladding oxidation in steam at 1200ºC

Oxidation module development (4/6)

Analysis of RIAR separate-effect tests



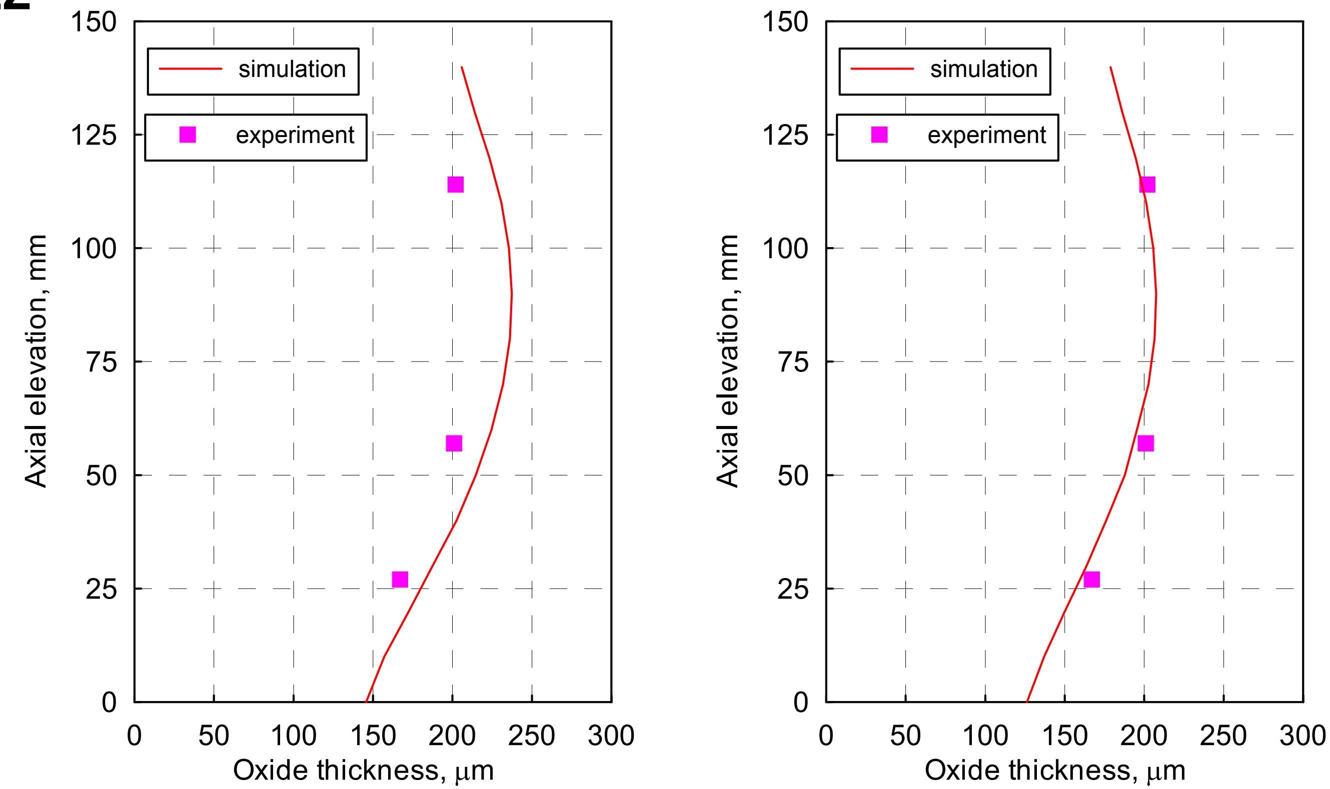


Calculated oxygen diffusion coefficients in α-Zr and ZrO_2 phases of Zr-1%Nb and Zry cladding materials

Oxidation module development (5/6)

Simulation of Zr-1%Nb fuel cladding oxidation in RIAR tests

Test #12

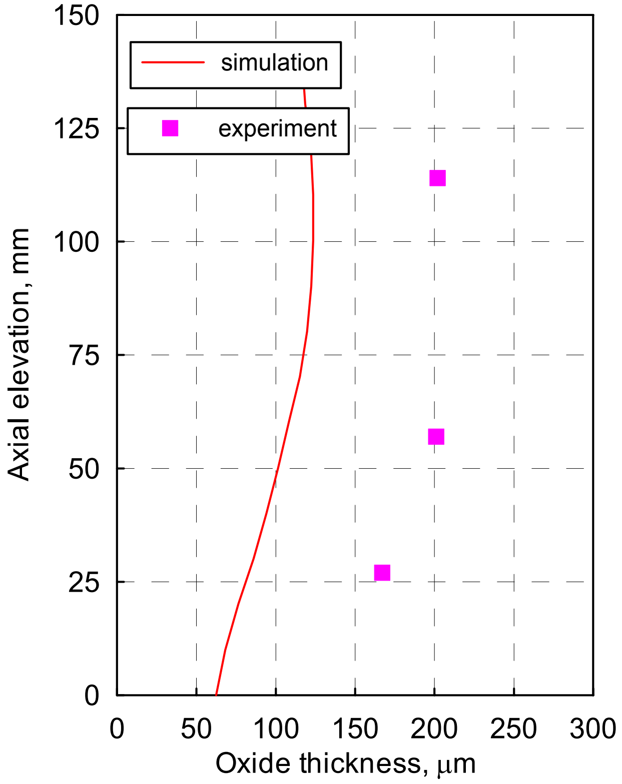


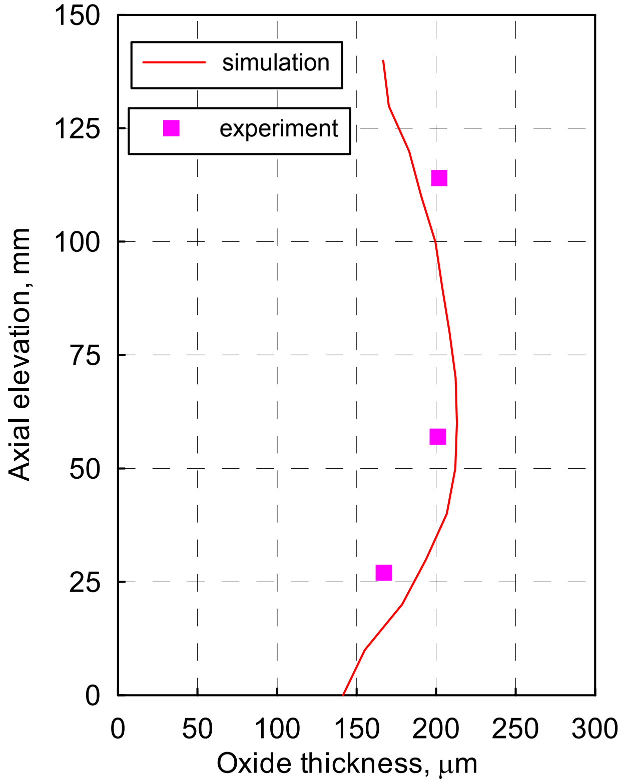
Comparison of measured and simulated axial profiles of ZrO_2 layer thickness in the cases of real history (left) and reduced exposure (210 s) providing the best fit (right).

Oxidation module development (6/6)

Simulation of Zr-1%Nb fuel cladding oxidation in RIAR tests

Test #14





Comparison of experimental and simulated axial profiles of ZrO_2 layer thickness in the cases of real history (left) and without starvation (right).

Mechanical deformation module development (1/5)

Comparison of Zry-4 and Zr-1%Nb deformation behaviour [2]

- The main difference in the deformation behaviour of the non-oxidized Zry-4 and Zr-1%Nb cladding materials occurs at temperature below ~ 1000 °C and depends on the phase content, which is a temperature dependant function. At higher temperatures the difference in the deformation behaviour is negligible.
- At temperatures above the ($\alpha \rightarrow \beta$) phase transition in the non-oxidized Zr-1%Nb alloy (> 900 °C) mechanical properties do not depend on the strain rate.
- Mechanical properties of the non-oxidized Zr-1%Nb alloy are affected by irradiation at low temperature. At high temperatures (> 600 °C) mechanical properties of irradiated and non-irradiated claddings are similar owing to the effect of radiation damage annealing. Similar results were obtained for Zry-4.

[2] L. Yegorova, K. Lioutov at al. Experimental Study of Narrow Pulse Effects on the Behavior of High Burnup Fuel Rods with Zr-1%Nb Cladding and UO2 Fuel (VVER Type) under Reactivity-Initiated Accident Conditions. NUREG/IA-0213, Vol. 1-2, IRSN/DPAM 2005-275, NSI RRC KI 3230. May 2006.

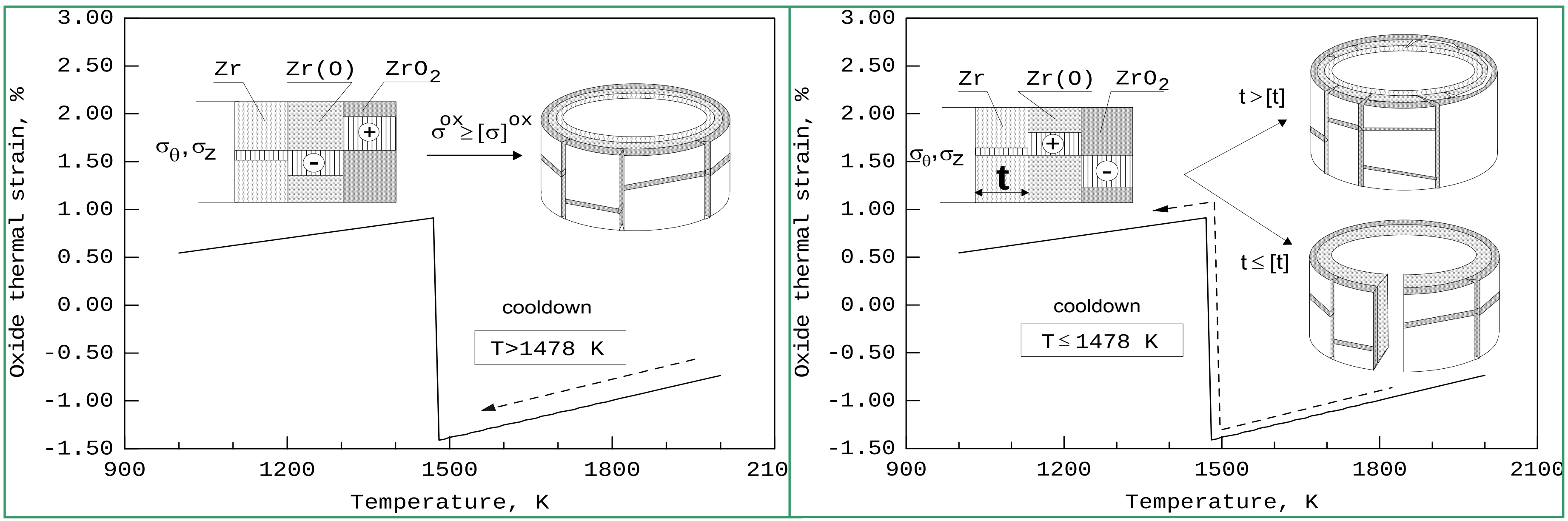
Mechanical deformation module development (2/5)

Zr-1%Nb mechanical properties

- Taking into account similar deformation behaviour of Zry-4 and Zr-1%Nb cladding at high temperatures and lacking data for mechanical properties of the α-Zr(O) and ZrO_2 phases of Zr-1%Nb, the corresponding mechanical properties of Zry-4 are used in calculations.
- At low temperatures (< 1000 °C) and in the case of an inert atmosphere (i.e. when oxidation is small) the mechanical properties of the metal Zr-1%Nb phase are used.
- For these reasons, formation of the net of through wall cracks under quench conditions in the case of the oxidized VVER cladding are foreseen owing to the same mechanism: tetragonal-to-monoclinic phase transition in the ZrO_2 scale which induces a strong increase of thermal strains in the ZrO_2 material.
- Therefore, the main peculiarities derived from the analysis of the results of FZK small scale quench test program are expected be valid for the RIAR tests with non-irradiated VVER fuel rod simulators.

Mechanical deformation module development (3/5)

Through-wall crack formation mechanism



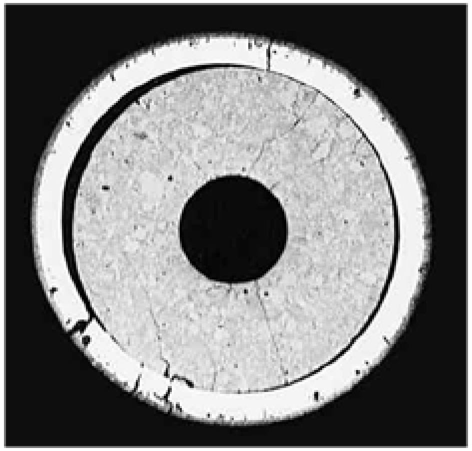
Cladding deformation behaviour on cool-down above and below oxide phase-transition temperature (tetragonal → monoclinic)

Mechanical deformation module development (4/5)

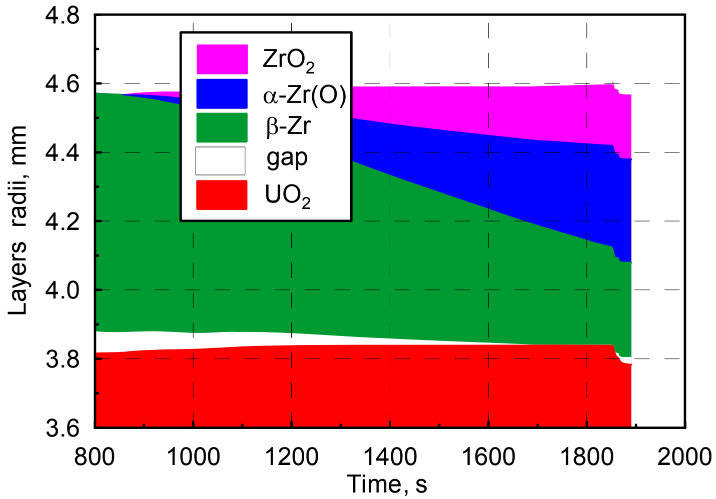
Simulation of Zr-1%Nb fuel rod deformation behaviour in RIAR tests

Test #12 observations:

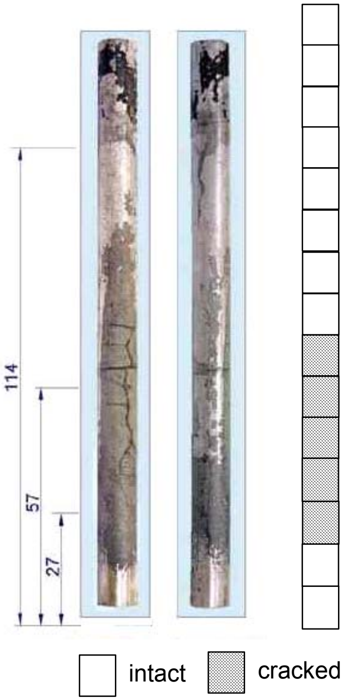
- Gap disappearance and fuel-to-cladding interaction were observed in some areas of the cladding inner surface
- Sample had a net of through wall cracks in the centre, which were visualized by wetting with acetone.



Cross section at elevation 57 mm.



Evolution of the cladding layers at elevation 57 mm.



Comparison of experimental and calculated states of the quenched fuel rod simulator

Mechanical deformation module development (5/5)

Simulation of deformation behaviour of Zr-1%Nb fuel rod in RIAR tests

Test #14

S/Q simulations well reproduce:

- Temperature evolution of the cladding outer surface and the fuel pellet centre;
- Axial profile of the cladding oxide layer thickness;
- Mechanical state of the oxidized Zr-1%Nb cladding after quenching;
- However, predictions of the total hydrogen generation in the tests ## 12 and 14 noticeably differ from the measured values:

Hydrogen generation, mg

Test ID	Experiment	Simulation
12	320	199
14	276	209

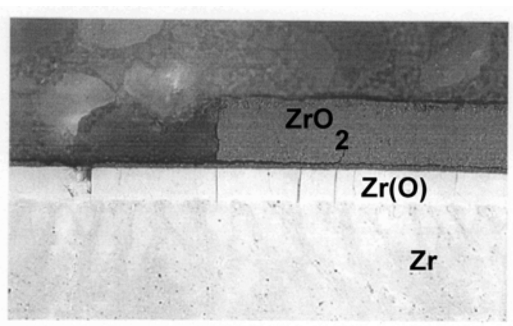
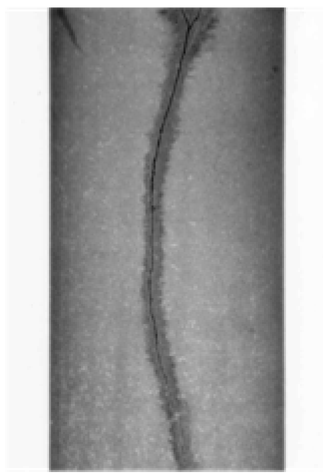
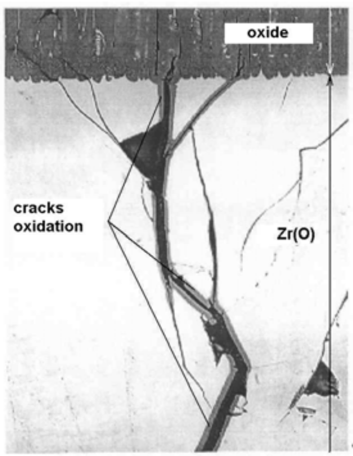
Test matrix of the carried out RIAR quenching tests with fresh fuel rods

Group	Test №	UO_2 pellets	Exposure at 1400 °C	Oxidation atmosphere	Cool down media	Atmosphere reverse *	TC location	Initial temp. ° C
I	12	yes	800	Ar+steam	water	0	pellet, surf.	1400
	14	yes	240	Ar+ steam	water	0	pellet,surf.	1600
	15	yes	240	Ar+ steam	water	0	pellet,surf	1600
II	21	yes	280	$Ar+O_2$	water	1	pellet	1400
	22	yes	370	$Ar+ O_2$	water	1	pellet	1400
	23	yes	410	$Ar+ O_2$	water	1	pellet	1400
	24	yes	450	$Ar+ O_2$	water	1	pellet	1400
III	25	yes	249	Ar+ steam	water	0	pellet, surf.	1700
	26	yes	257	Ar+ steam	water	2	pellet	1700
	27	no	257	Ar+ steam	steam	2	inside	1700
	28	no	240	Ar+ steam	Ar	2	inside	1700
IV	31	yes	0	Ar+ steam	water	2	pellet	1700
	32	yes	600	Ar+ steam	water	2	pellet	1700
	35	yes	240	Ar+ steam	water	2	pellet	1400

Cracks formation in the FZK small scale quench tests (1/2)

Oxide thickness, µm	Initial temperature, °C 1200	1400	1600
0	Cracks in Zr(O).	Cracks in Zr(O). Local spalling (water).	Cracks in Zr(O). Local spalling (water).
100÷150	No through wall cracks. Cracks in Zr(O). Local spalling (water).	No through wall cracks. Cracks in Zr(O). Local spalling (water).	A few through wall cracks. Local spalling (water). No cracks and inner surface oxidation.
150÷350	Net of through wall cracks. Cracks and inner surface oxidation.	Net of through wall cracks. Cracks and inner surface oxidation.	A few through wall cracks. Crack surfaces partially oxidized.

Cracks formation in the FZK small scale quench tests (2/2)

			
0 μm/ 1600°C/ water	260 μm/1400°C/steam	250 μm/1400°C/steam	300 μm/1400°C/water

RIAR tests observations

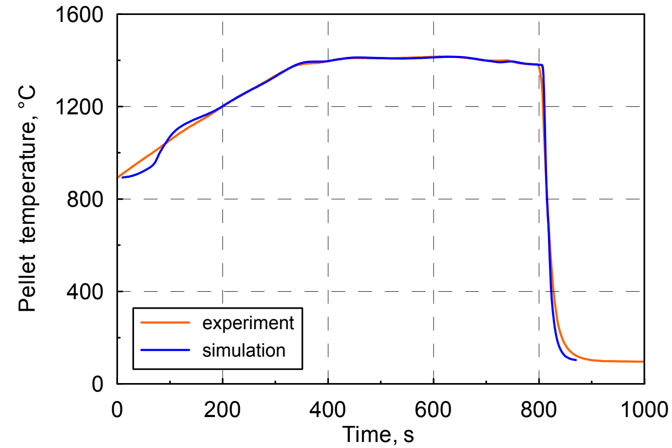
Group	Test №	Initial temp, °C	Oxide thickness ,µm	Metal thickness, µm	Elevation, mm	Cladding state after the test
I	12	1400	201	574	57	Net of through wall cracks in the central part of the rod.
	14	1600	216	571	77	One circumferential through wall crack.
	15	1600	-	-	-	One circumferential through wall crack. Breakdown into 2 parts.
II	21	1400	13	703	127	Intact. No through wall cracks.
	22	1400	-	-	-	
	23	1400	155	605	27	
	24	1400	127	618	127	
III	25	1700	251	530	80	Breakdown into 3 parts due to heater failure.
	26	1700	144	614	77	Intact.
	27	1700	83	656	141	Intact after test. Broken during handling.
	28	1700	124	619	77	Intact.
IV	31	1700	140	636	75	Broken during handling. Net of the cracks is observed for wetted with water sample.
	32	1700	288	508	77	Breakdown into 2 parts. Net of the cracks is observed for wetted with water sample.
	35	1400	99	636	77	Intact. No through wall cracks.

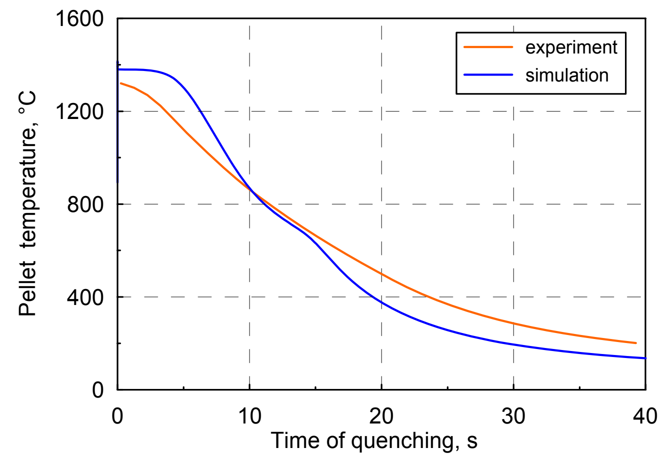
Example of the RIAR quench tests simulation with the S/Q code

Test #24 procedure:

- Oxidation in the argon/oxygen mixture at 1400 °C during 450 s.
- Water quenching from 1400 °C.

		Test	Simulation
ZrO_2 thickness at elevation, µm	127	**122 ÷ 149**	**153**
	77	**81 ÷ 106**	**152**
	27	**-**	**150**
Mass gain, mg		**973**	**1428**
Hydrogen release, mg		**2.5**	**0.96**
Cladding state		**intact**	**intact**





Comparison of calculated and measured temperatures in the pellet centre at elevation 77 mm.

Analysis of the S/Q code simulation results for the RIAR tests with fresh fuel

- The modified S/Q code well predicts the temperature evolution in the quench stage and the maximum extent of the Zr-1%Nb cladding oxidation in the RIAR tests with fresh uranium fuel.
- This allows correct prediction of the final state the oxidized cladding of the fuel rod simulator.
- However, an axial profile of ZrO_2 and, hence, mass gain and hydrogen generation differ from the experimental values.
- The are two possible reasons of this discrepancy:
  - ✓ **Temperature measurements.** In the new tests only the central TCs are used. In the first tests (##12, 14) the surface TC were used which provided the real temperature profile and correct oxidation kinetics before quenching.
  - ✓ **Steam measurement.** a) Steam mass flow rate is not measured during the tests and in some cases starvation instead of oxidation occurs; b) inside the test rig uncontrollable amount of steam is always present due to water evaporation from the flooding tank.

Test matrix of the carried out RIAR quenching tests with irradiated fuel rod simulators

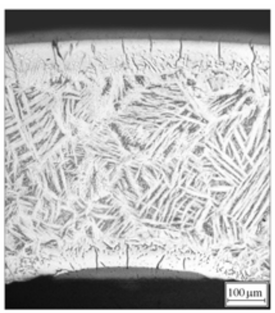
Test №	Burnup	Exposure at 1400 °C	Oxidation atmosphere	Cool down media	Atmosphere reverse *	TC location	Initial temp.
	MWd/kg U	s					°C
36	53.5	240	Ar + steam	water	2	pellet	1405
37	53.5	250	Ar	water	1	pellet	1703
39	65	240	Ar + steam	water	2	pellet	1418
40	65	0	Ar	water	1	pellet	1411

* 0 – gas flow is supplied from below upwards during the test, 1 – gas flow is supplied from the top downward during the test, 2 – gas flow is supplied from below upwards during pre-oxidation and from the top downward during quenching.

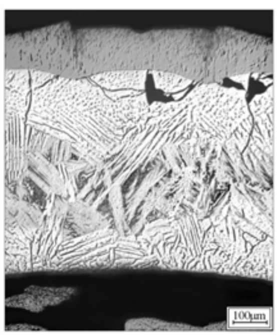
Analysis of the RIAR quench tests with irradiated fuel rod simulators

Layers thickness in test #36

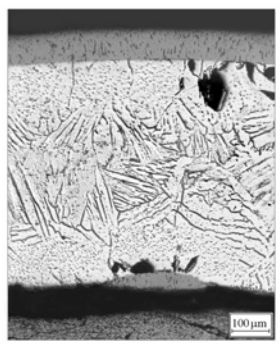
Elevation mm	Inner Zr(O) μm	Outer Zr(O) μm	Outer ZrO_2 μm
127	**183**	**162**	**108**
77	**170**	**186**	**111**
27	**0**	**47**	**51**



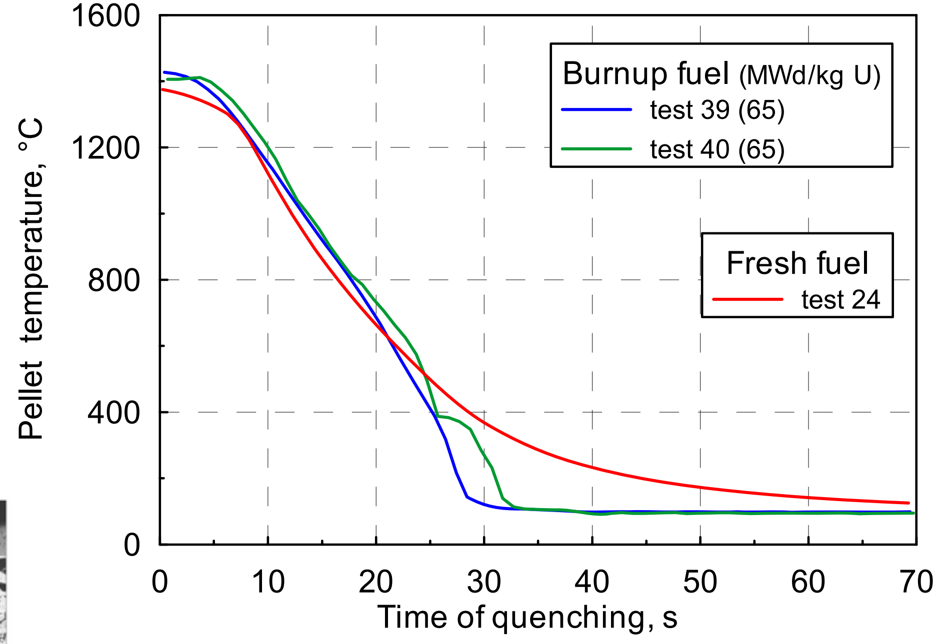
27 mm



77 mm



127 mm



Comparison of the measured temperature evolution in the fuel pellet centre at elevation 77 mm during quenching phase in the tests ## 24, 39, 40.

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Modelling of the RIAR quench tests with irradiated fuel rod simulators

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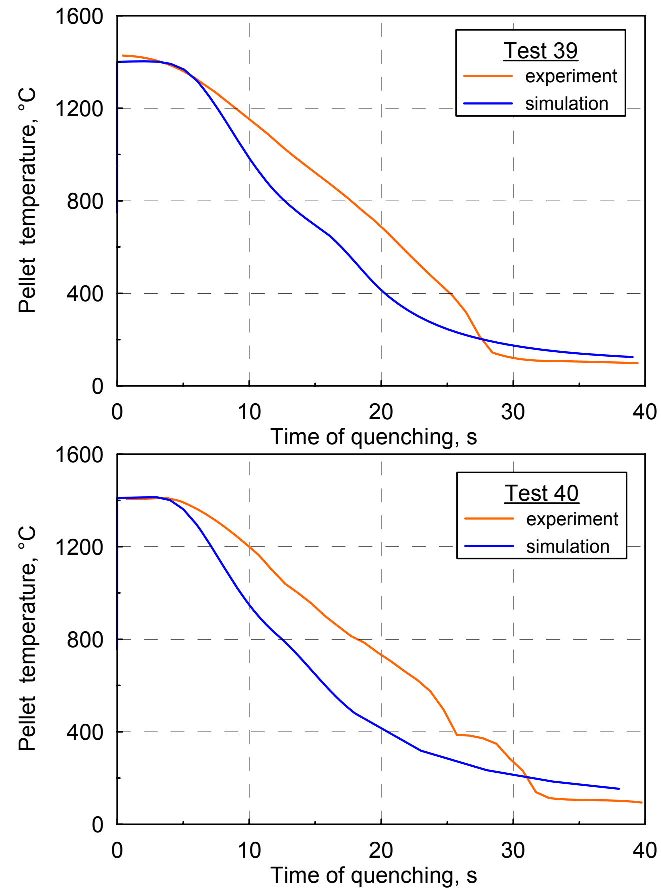
Layers thickness in test #36, μm

Elevation, mm	Measurement		Simulation	
	Outer Zr(O)	Outer ZrO_2	Outer Zr(O)	Outer ZrO_2
127	**162**	**108**	**161**	**111**
77	**186**	**111**	**158**	**113**
27	**47**	**51**	**157**	**112**

Hydrogen release, mg

Test ID	Measurement		Simulation	
	Total	Quench	Total	Quench
36	**165.0**	**6.7**	**129.5**	**0.2**
39	**173.2**	**7.1**	**126.9**	**0.2**
40	**13.6**	**13.6**	**12.6**	**12.6**



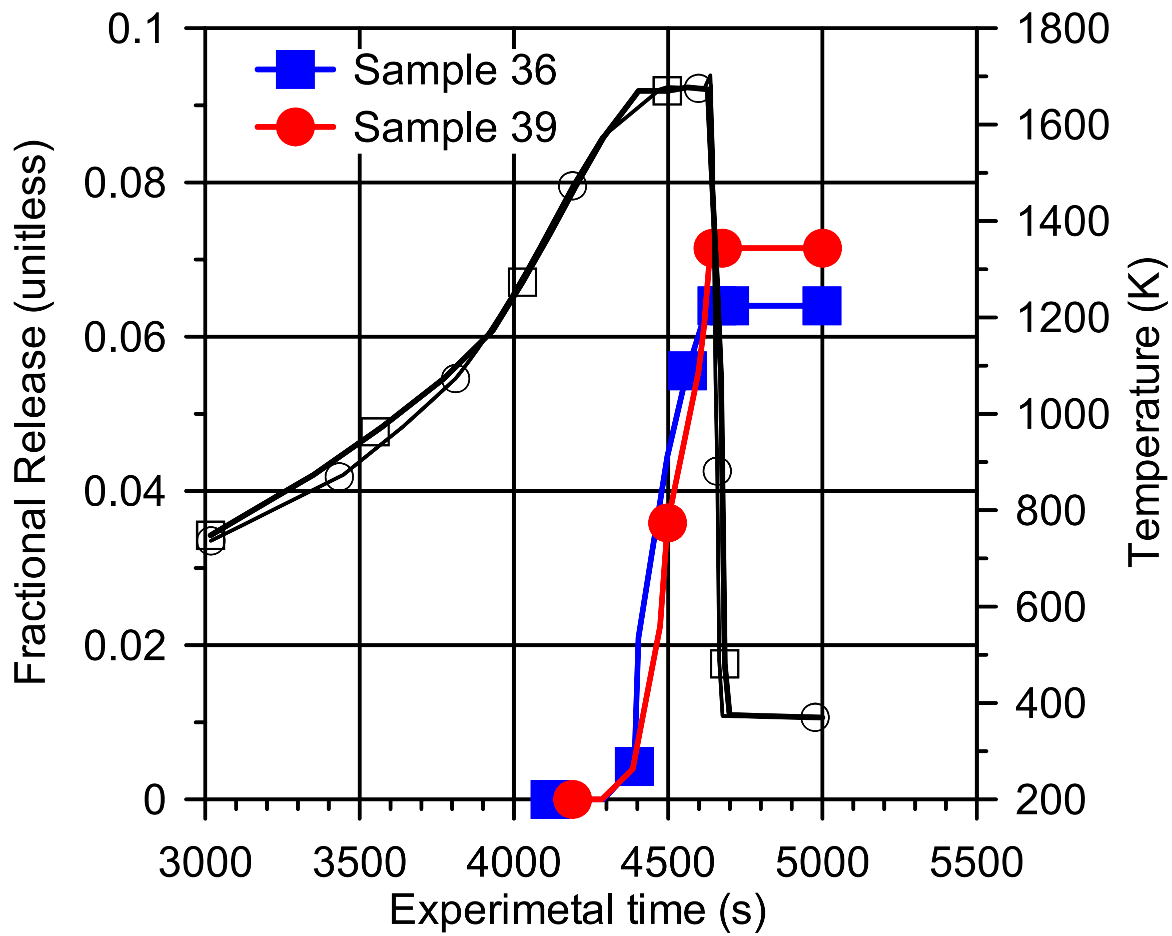
Comparison of the calculated and measured temperatures in the pellet centre at elevation 77 mm during quenching.

Conclusions

- SVECHA/QUENCH (S/Q) code was adapted to simulate behaviour of the VVER fuel rod simulators in the RIAR quenching tests.
- The modified S/Q code well predicts the temperature evolution during quenching, the maximum extent of Zr-1%Nb cladding oxidation and the final mechanical state of the oxidized Zr-1%Nb cladding in the tests with fresh uranium fuel rods.
- An axial profile of ZrO_2 and, hence, mass gain and hydrogen generation differ from the experimental values, for the following two possible reasons:
  - ✓ Temperature measurements;
  - ✓ Steam measurements.
- The S/Q code was extended for simulation of the RIAR quenching tests with irradiated fuel rods.
- Analysis and simulations of the tests show that the gap collapse and chemical interaction between the burned fuel pellets and the cladding due to swelling leads to additional embrittlement of the cladding. This effect along with a possible starvation in the tests prevent irradiated VVER fuel rods from formation of the net of through wall cracks, however, do not prevent failure of the quenched specimens under handling.

MFPR code simulations of FP release in the RIAR quench tests (1/3)

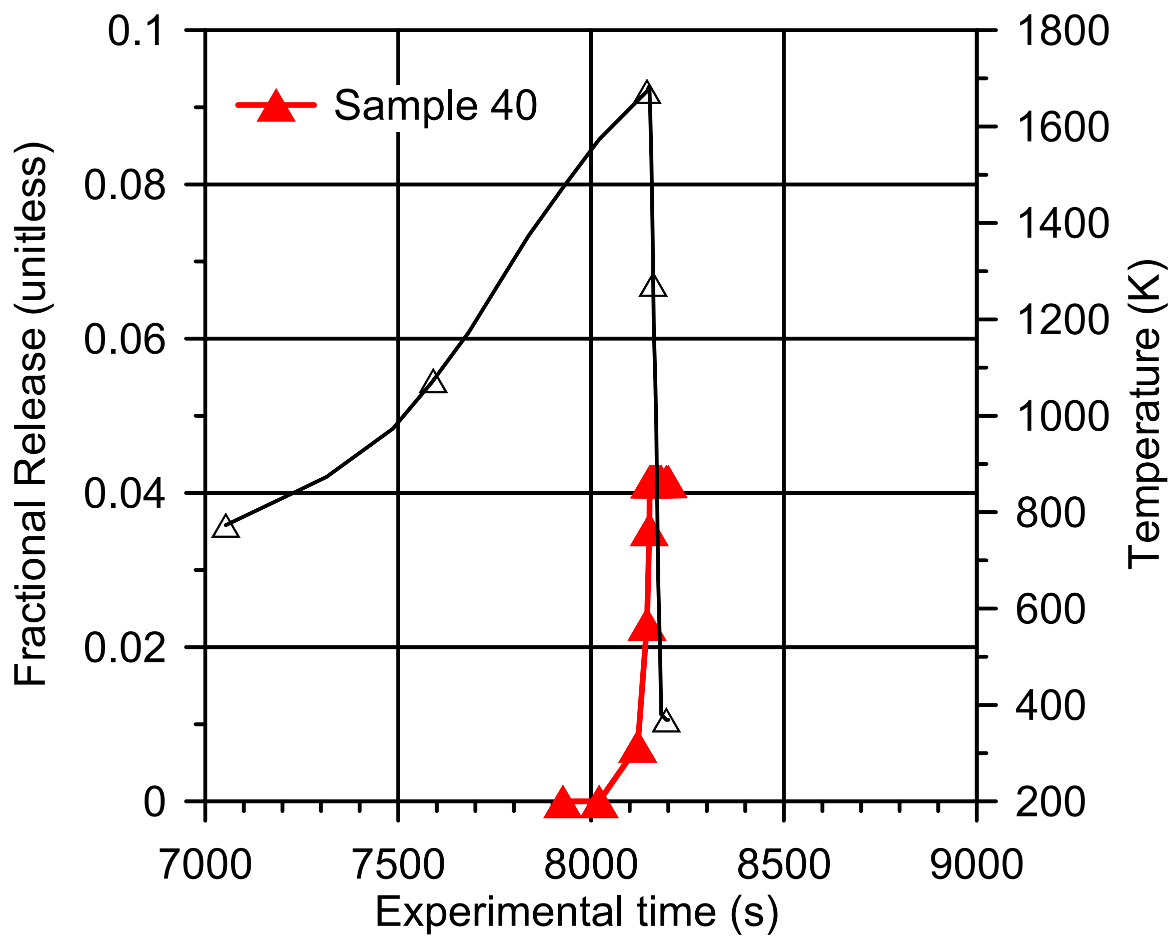
- Fuel burn-ups: **53.5 GW×d/t U** (sample 36); **65 GW×d/t U** (sample 39).
- Maximal oxidation temperature **~1673K.**
- Oxidation time at maximal temperature: **240 s**.



Measured pellet temperature and calculated ***Cs*** fractional release versus experimental time.

MFPR code simulations of FP release in the RIAR quench tests (2/3)

- Fuel burn-up **65 GW×d/t U** (sample 40).
- Maximal oxidation temperature **~1673K.**
- Oxidation time at maximal temperature **~7 s.**



Measured pellet temperature and calculated ***Cs*** fractional release versus experimental time.

MFPR code simulations of FP release in the RIAR quench tests (3/3)

Cs^{137} fractional release (%)

Sample #36		Sample #39		Sample #40	
Exp.	Calc.	Exp.	Calc.	Exp.	Calc.
4.6	6.4	8.8	7.1	2.6	4.1