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Experimental Results of Reflood Bundle Test QUENCH-15 with ZIRLO™ Cladding Tubes

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The QUENCH-15 experiment investigated the effect of ZIRLO™ cladding material on bundle oxidation and core reflood, in comparison with test QUENCH-06 (ISP-45, standard Zircaloy-4), QUENCH-12 (VVER, E110), and QUENCH-14 (M5®). The PWR-type bundle QUENCH-15 consisted of 24 heated rods (internal tungsten heaters between 0 and 1024 mm, cladding oxidised region between -470 and 1500 mm), six corner rods made of Zircaloy-4, two corner rods made of E110, and a Zr-702 shroud. The test was conducted in principle with the same protocol as QUENCH-06, -12 and -14, so that the effects of the change of cladding material could be more easily observed. This involved pre-conditioning in superheated steam followed by a power ramp leading to bundle temperatures of about 1900 °C. The experiment was concluded by reflood with water at room temperature and reduction of electrical power.

The experiment was successfully conducted at the Forschungszentrum Karlsruhe on 27 May 2009 based on pre-test calculations performed by the Paul Scherrer Institute (PSI) using SCDAP/RELAP5. The experiment started with an application of electrical bundle power of ca. 4.0 kW, which was ramped step-wise over nearly 3000 s to pre-oxidation phase with power of 11.4 kW. The pre-oxidation phase lasted about 3000 s to achieve the desired oxide layer thickness at bundle peak temperature of ca. 1200 °C (based on corner rod thermocouple TIT G/13 at elevation of 950 mm), in a flow of 3.45 g/s argon and 3.45 g/s steam. To check the oxidation level a first corner rod (rod B) was withdrawn on the end of pre-oxidation. Maximal oxide layer thickness of 150 µm was reached at elevation of 950 mm.

The power was then ramped at a rate of 5.9 W/s to cause a temperature increase until the desired maximum bundle temperature of 1880 °C (based on TIT G/13), which was reached after about 1100 s. Approximately 30 s earlier corner rod F was withdrawn from the bundle. Eddy current measurement showed maximal oxide layer thickness of 550 µm at bundle elevation of 950 mm. Then reflood with 48 g/s water at room temperature was initiated, following fast water injection to fill the lower plenum. The electrical power was reduced to 4.2 kW during the reflood phase, approximating effective decay heat level. Following reflood initiation no temperature excursion was observed. Failure of rod simulators was detected 30 s after flooding initiation (mass spectrometer measurement of Kr). No shroud failure was detected. The E110 corner rods extracted after the test evident intensive breakaway effect.

The post-test endoscopy of the bundle showed neither noticeable breakaway cladding oxidation nor melt release into space between rods. Average oxide layer thickness at hottest elevation of 950 mm is 620 µm (QUENCH-06: 630 µm). Measured hydrogen production during the QUENCH-15 test was 40 g in the pre-oxidation and transient phases and 8 g in the quench phase being similar to those in QUENCH-06, i.e. 32 g and 4 g, respectively. Reasons of higher hydrogen production for QUENCH-15 were increased bundle surface (factor 1.09) and usage of not prototypical corner rods.

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Presented by J. Stuckert

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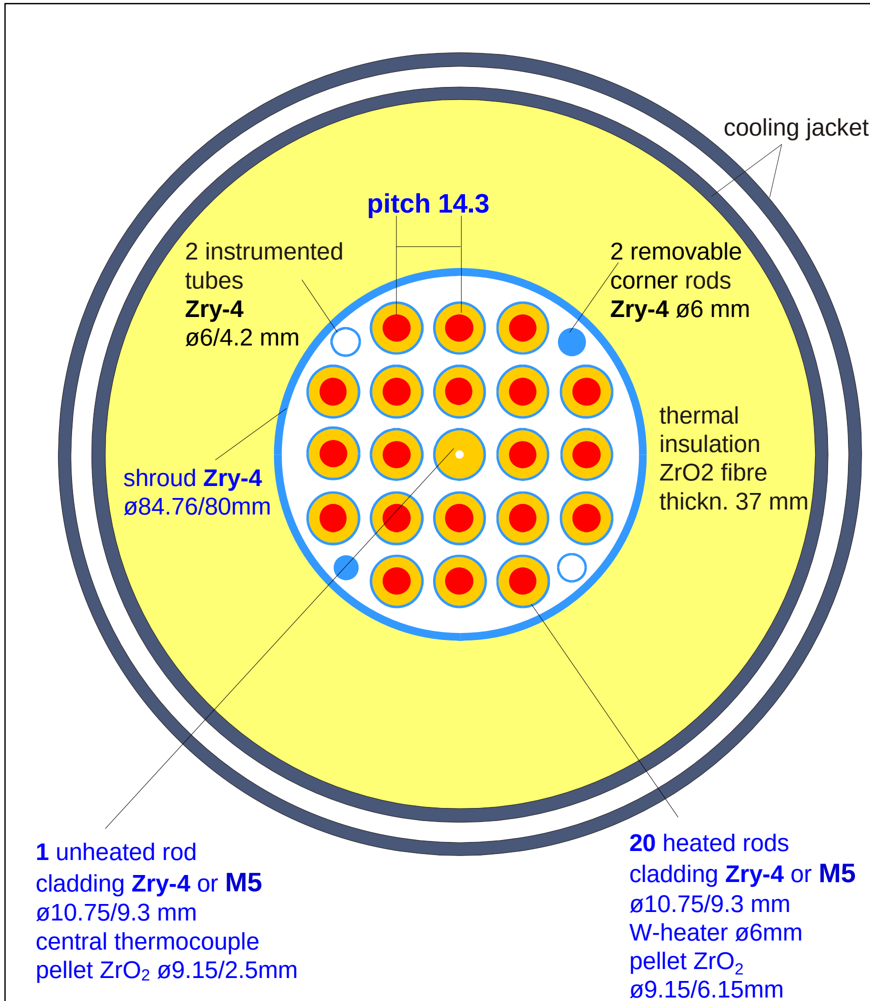
Objectives of the QUENCH-15 test

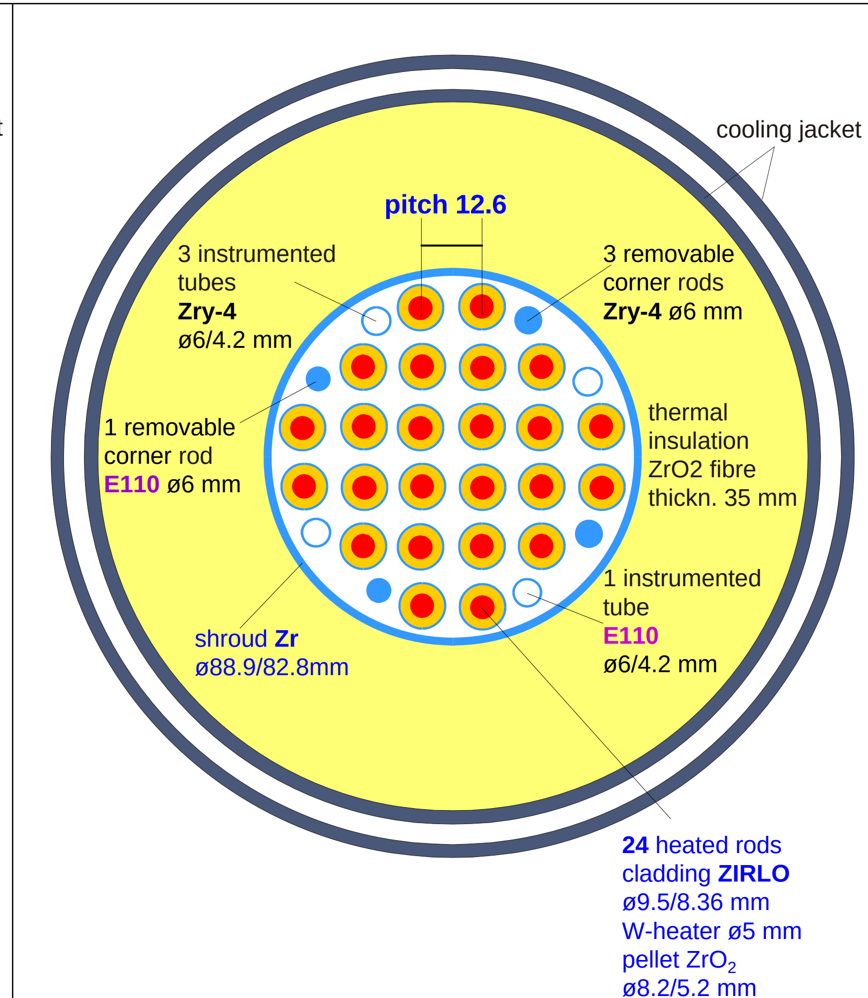
- investigation the effect of tin-niobium-bearing ZIRLO™ cladding material on bundle oxidation and core reflood, in comparison with test QUENCH-06 (ISP-45) that used standard Zircaloy-4
- comparison of advanced cladding materials under conditions of severe accident

Different bundle compositions



Bundle with 21 rod simulators

(Q-06 with Zry-4; Q-14 with M5®)



Bundle with 24 rod simulators

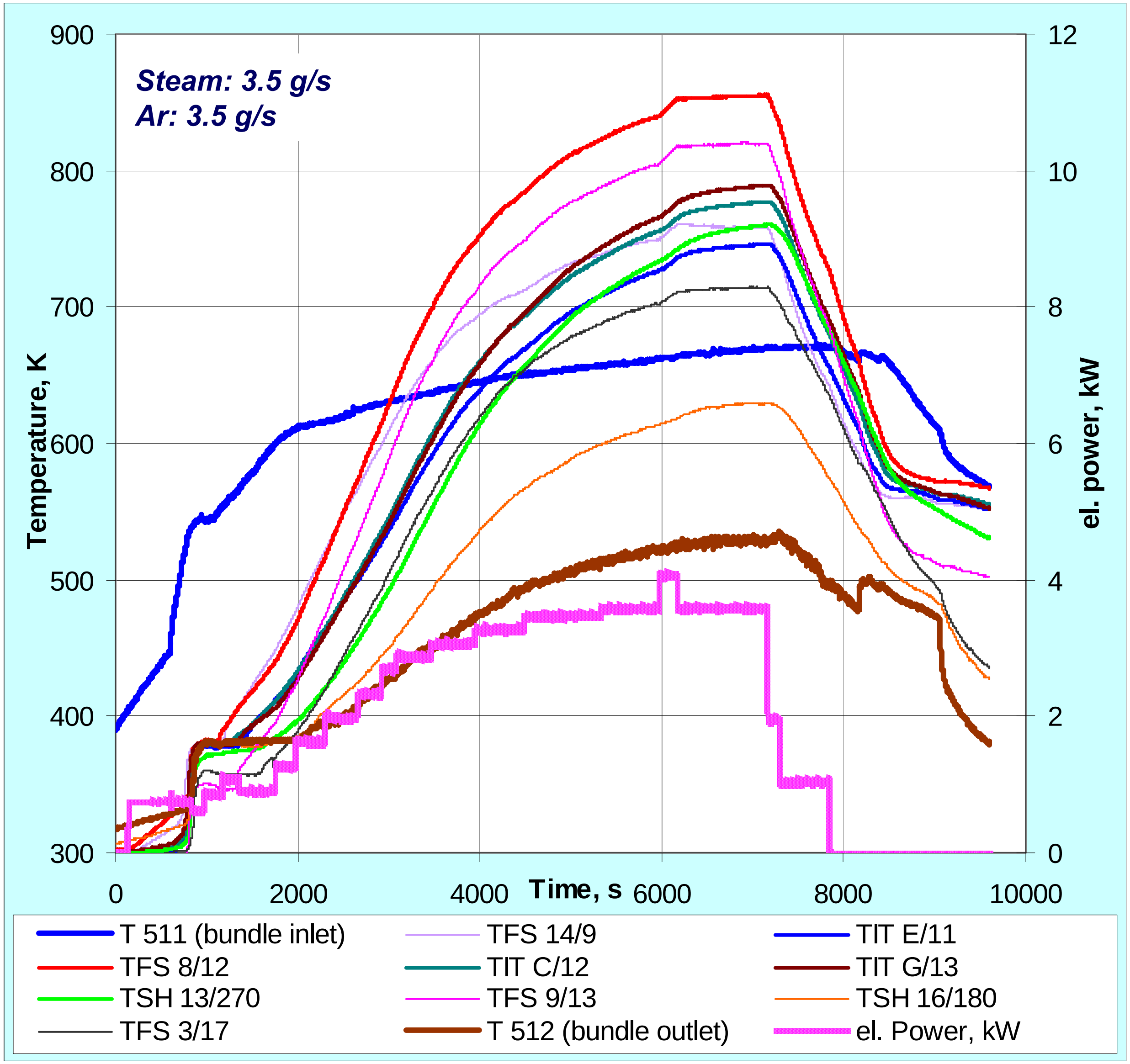
(Q-15 with ZIRLO™ claddings)

Comparison of geometrical parameters of the QUENCH-15 bundle with the QUENCH-06 bundle:

1) **coolant channel area relationship Q15/Q06 = 1.16 ⇒ *the fluid flow rate should be 16% higher for the Q15 bundle than for the Q06 bundle to provide the same flow velocity***

2) **metallic surface relationship Q15/Q06 = 1.09 ⇒ *increased chemical energy production for the Q15 bundle due to exothermic steam-metal reaction***

Pretest to adjusting of calculation parameters



elev. 1150 mm

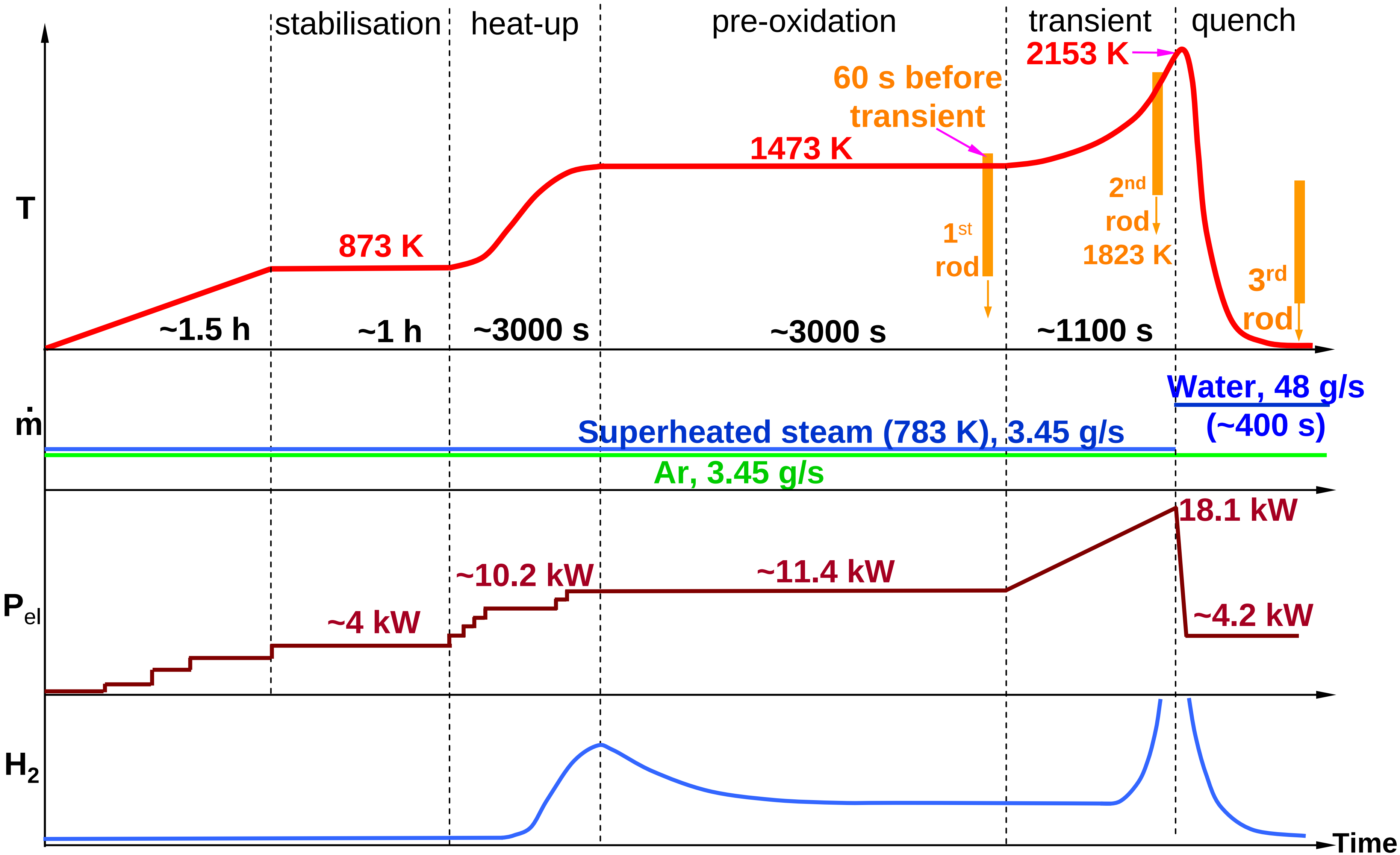
post-pretest videoscope inspection: intact rods, spacer grids and thermocouples

ZrO_2 layer thickness after pretest: 2 µm

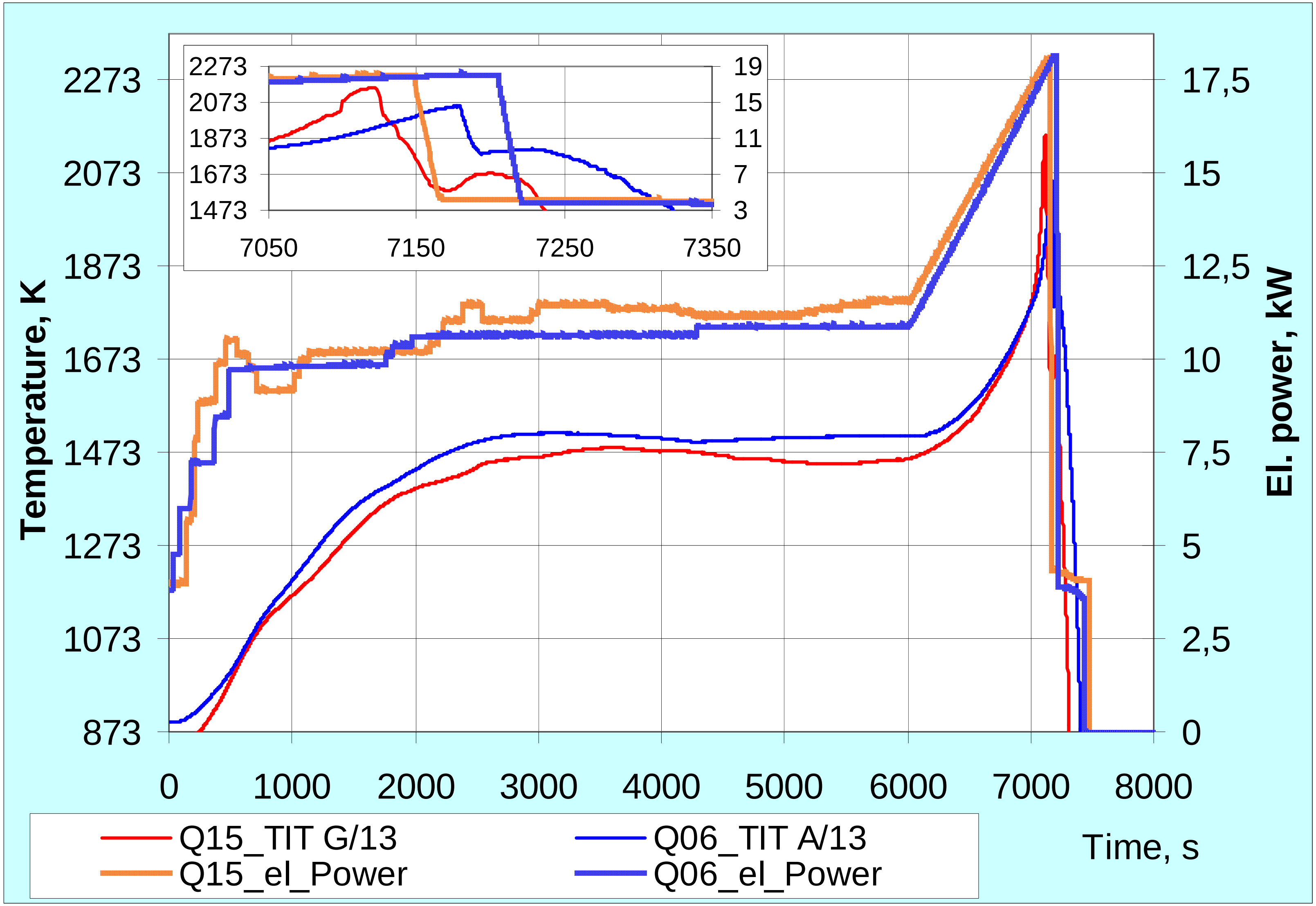
Pretest modelling support:

SCDAP/SIM simulations: J. Birchley, *PSI, Switzerland*.

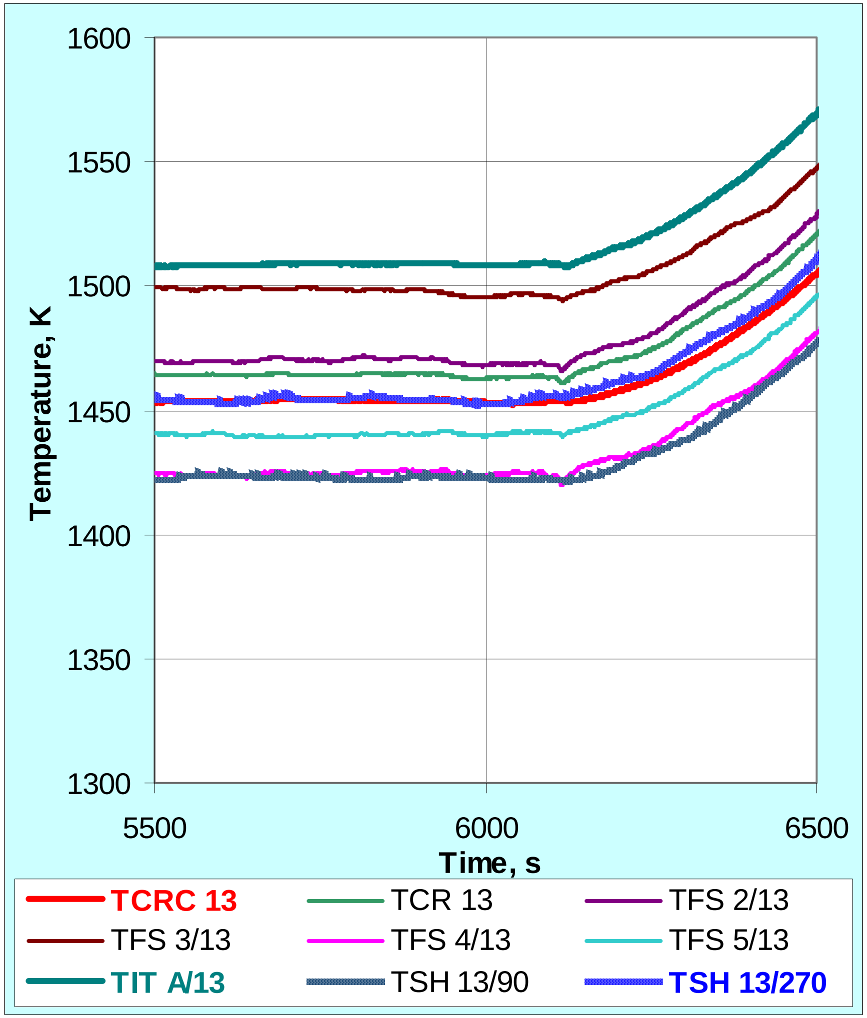
Time scheme of the QUENCH-15 test
performed on May 27, 2009



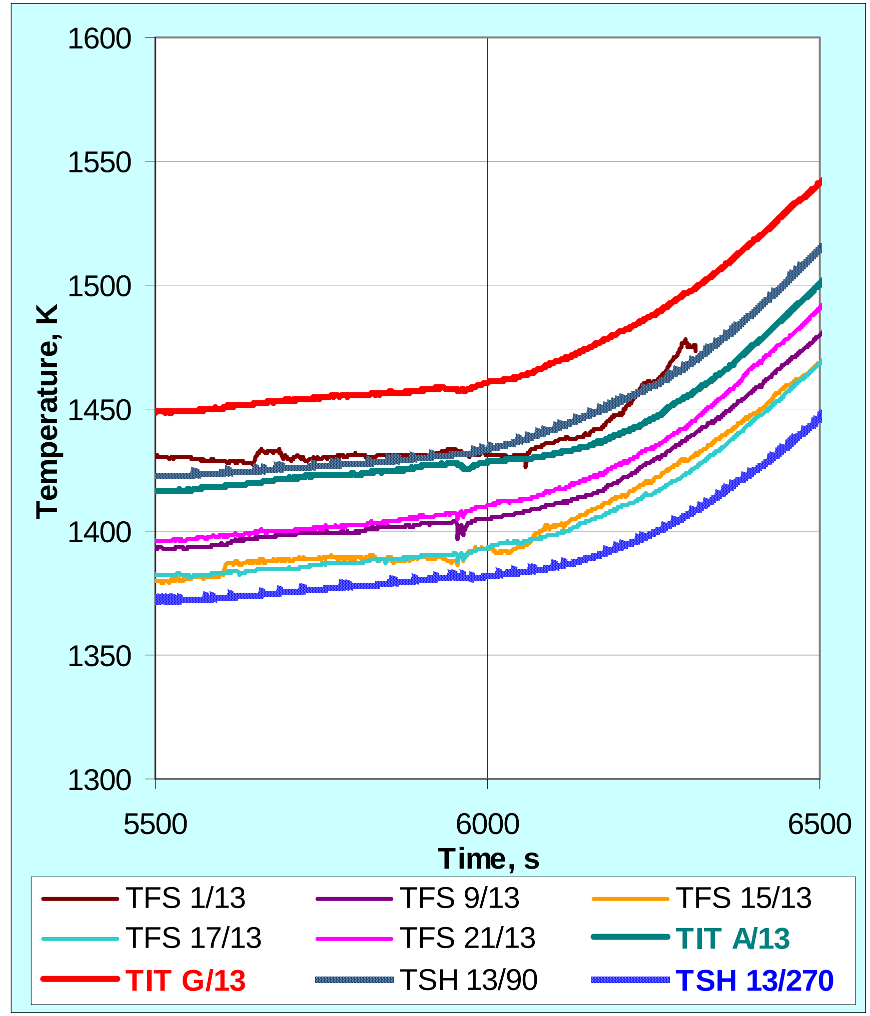
QUENCH-15 test performance: good reproduction of QUENCH-06 (Zry-4) temperature history
/on the basis of TC with uppermost axial temperature reading/



Comparison of temperature radial scattering at hottest elevation of 950 mm for bundles QUENCH-06 (Zry-4) and QUENCH-15 (ZIRLO) <u>on beginning of transient</u> (~6000 s)

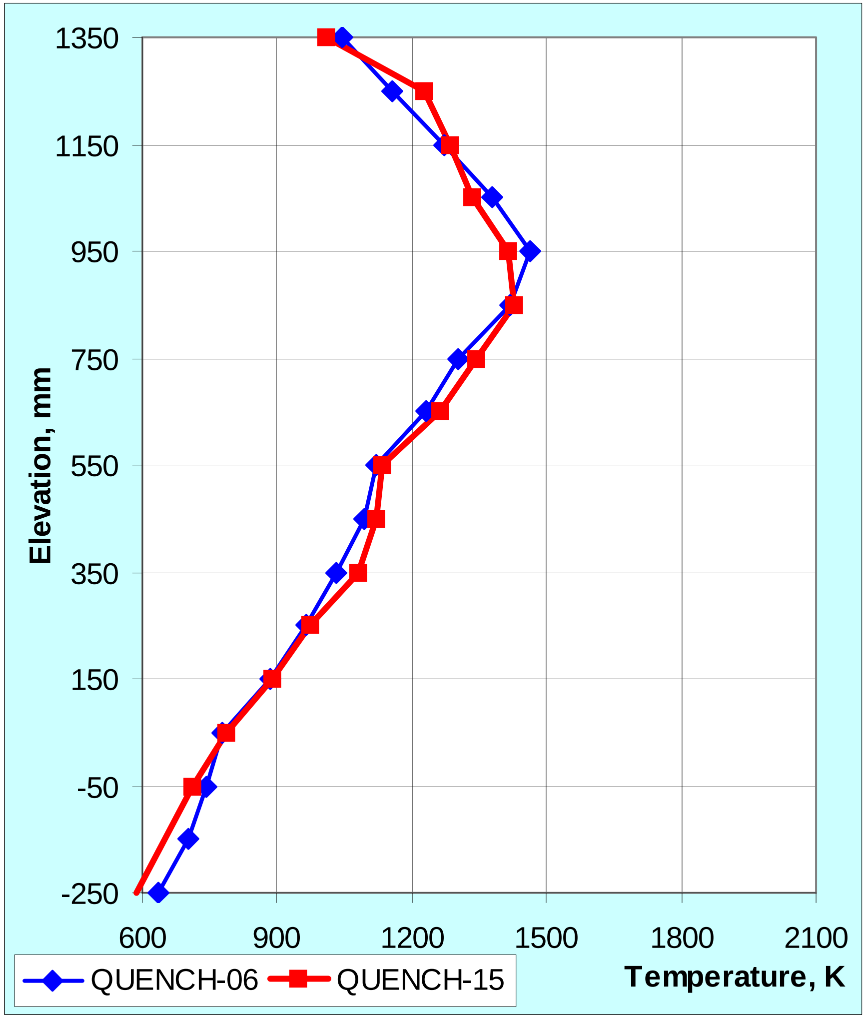


QUENCH-06:
T_{av} = 1459 K
$\Delta T = \pm 22$ K

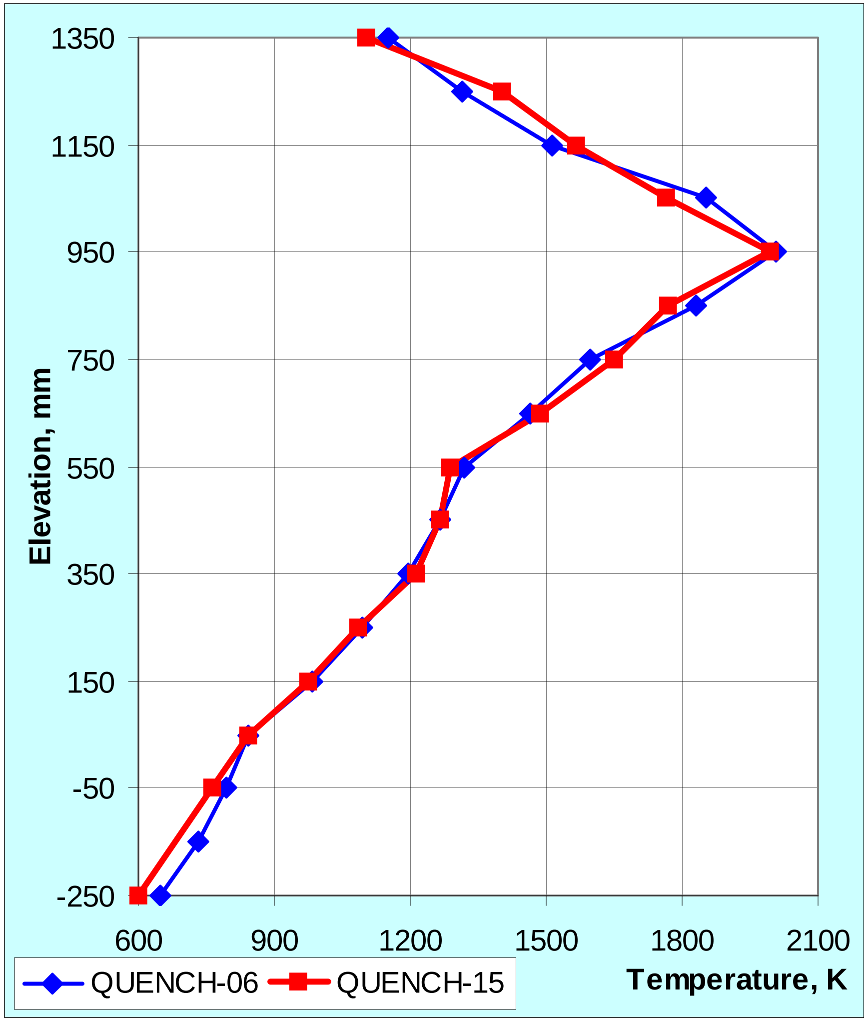


QUENCH-15:
T_{av} = 1415 K
$\Delta T = \pm 21$ K

Comparison of axial bundle temperature profiles for QUENCH-06 (Zry-4), -15 (ZIRLO)

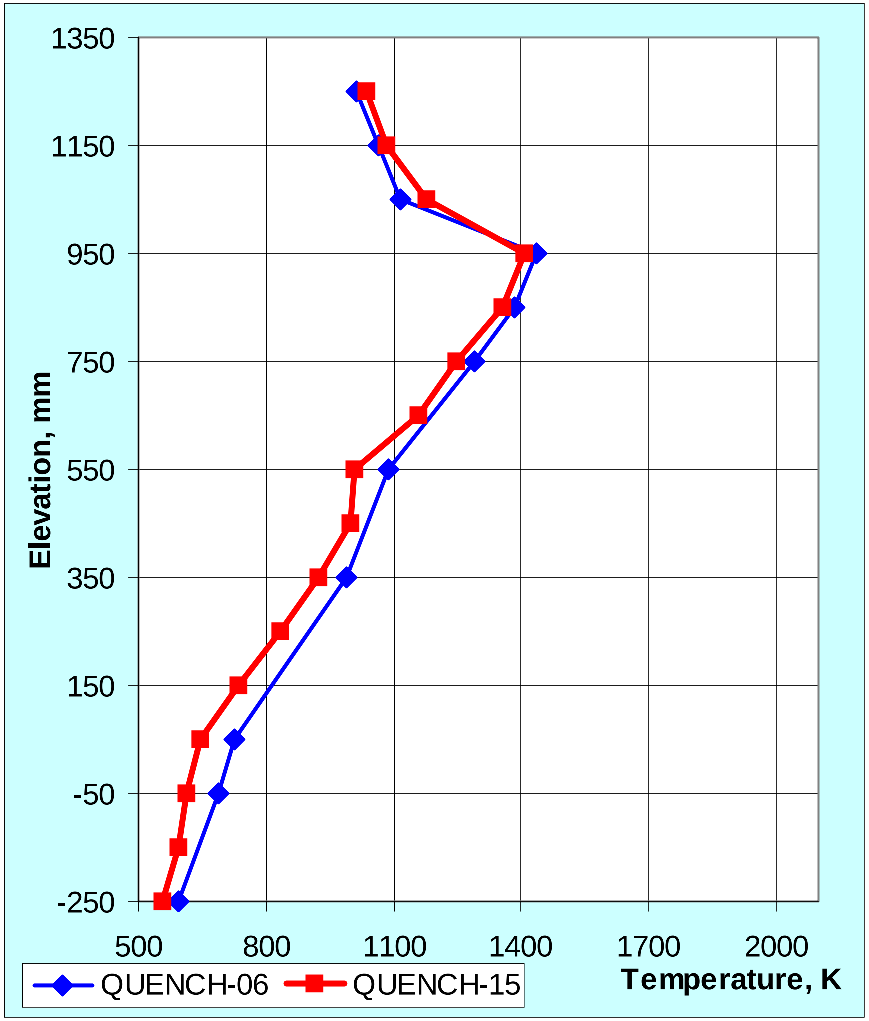


before transient

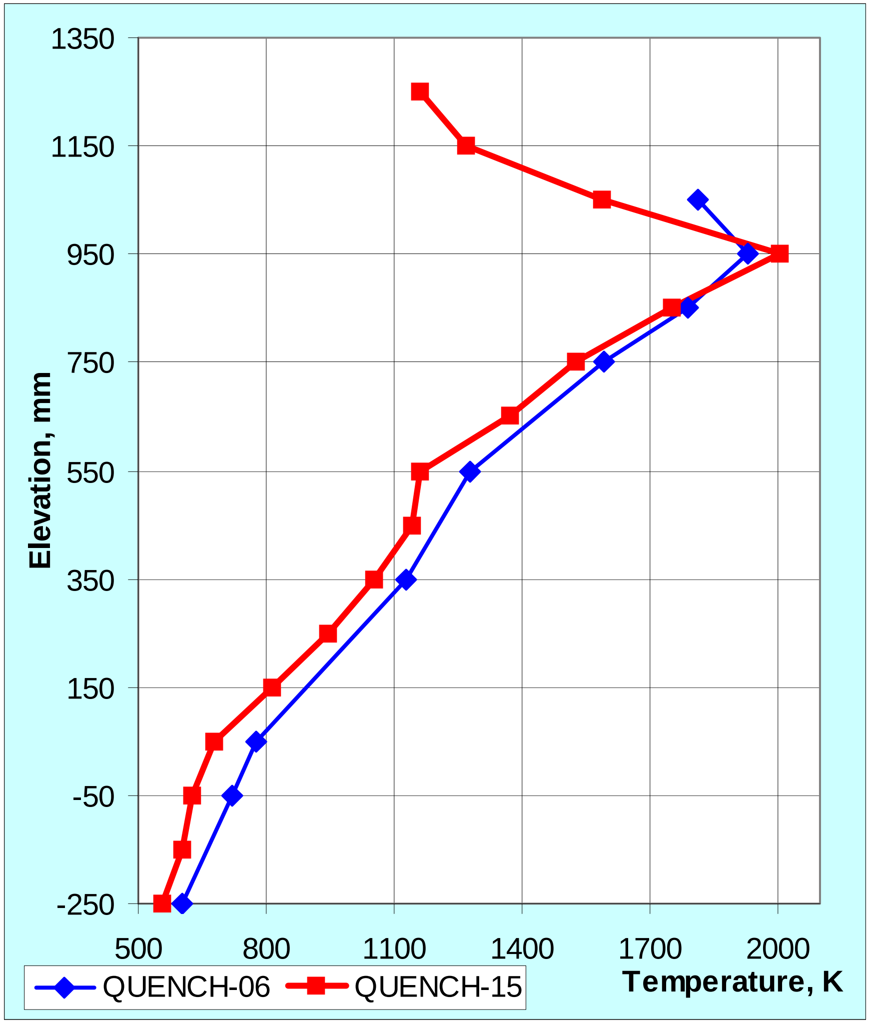


before reflood

Comparison of axial shroud temperature profiles for QUENCH-06 (Zry-4), -15 (ZIRLO)

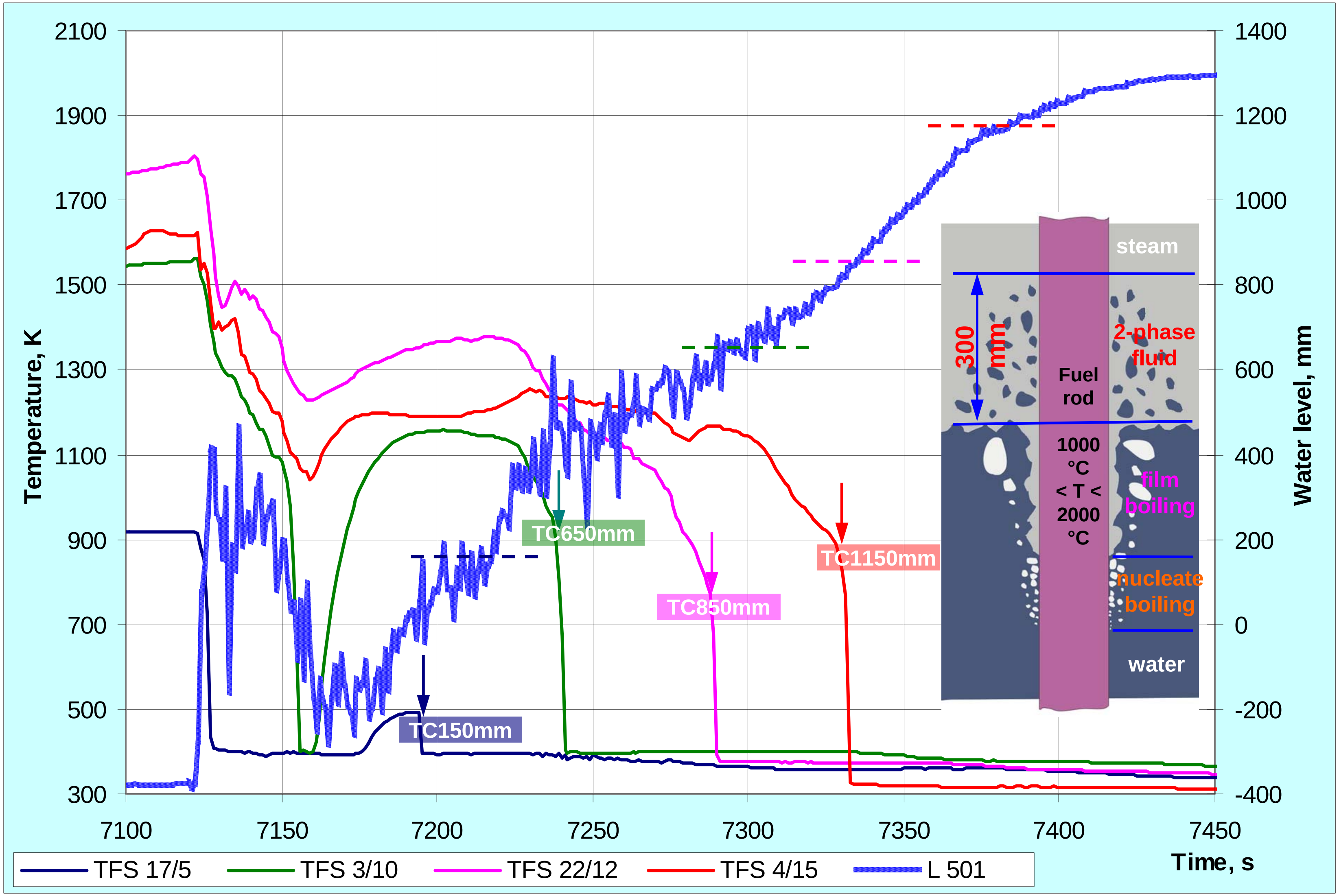


before transient

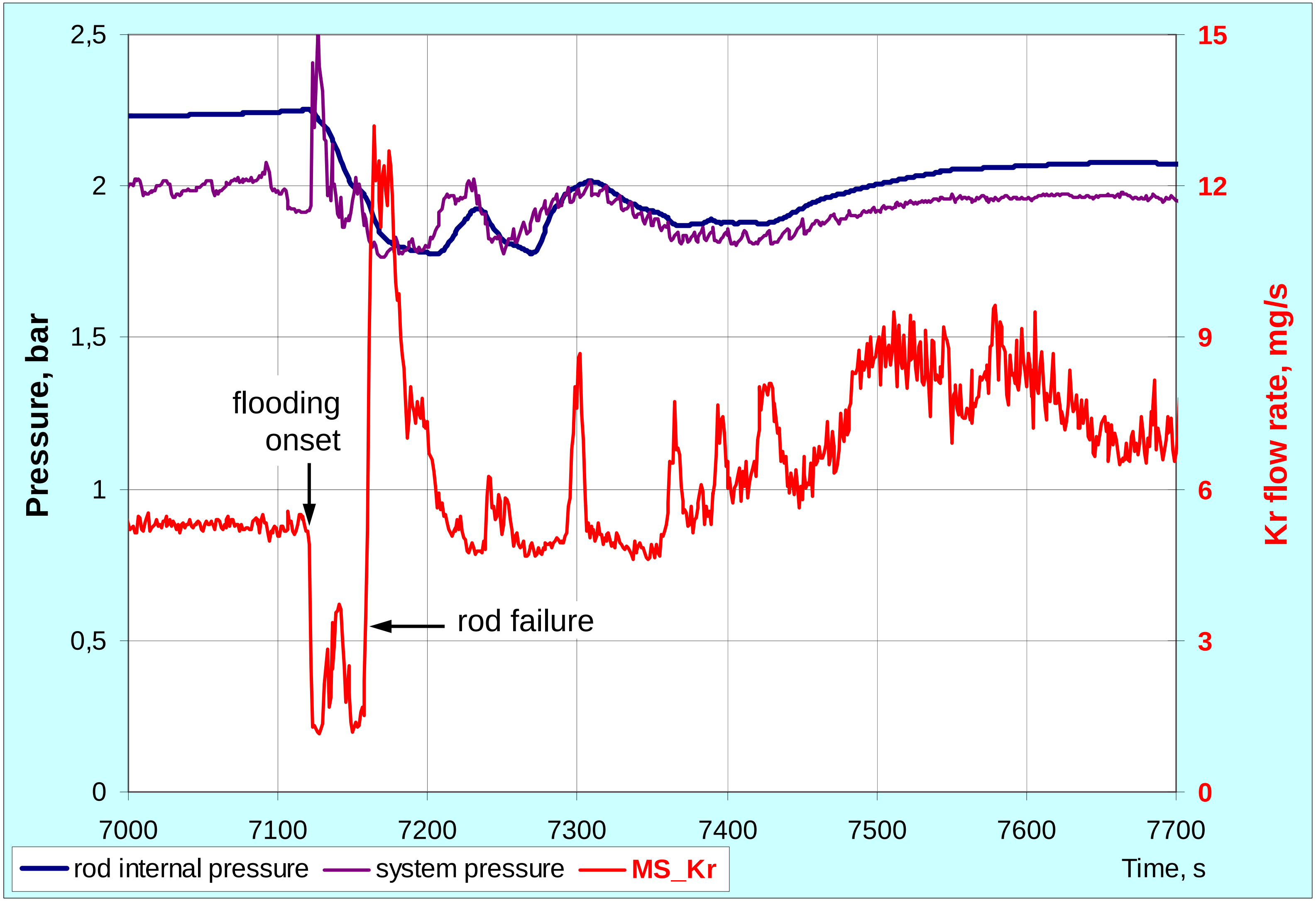


before reflood

QUENCH-15 reflood phase: cooling in 2-phase fluid above collapsed water surface



QUENCH-15: indication of rod simulator failures on the basis of Kr release (mass spectrometer measurement)



QUENCH-15: Videoscope photos at the location of withdrawn corner rod A: 1) cladding failures, 2)no melt observation

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700 mm, relocated part of grid spacer 4

900 mm, circumferential and longitudinal cracks of the fuel rod cladding

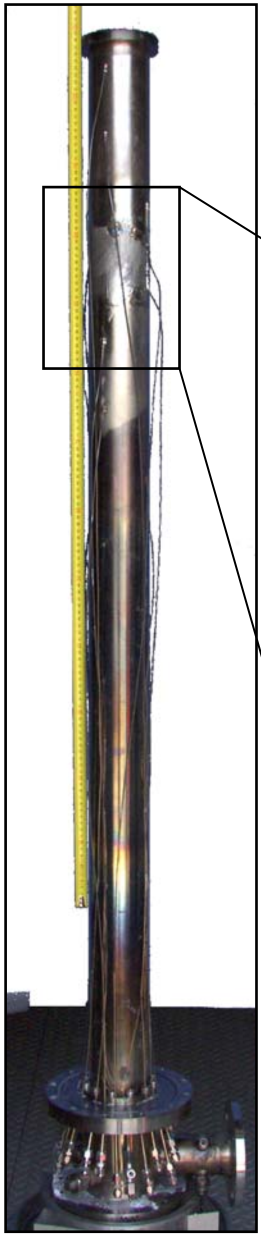
930 mm, spalling of thin oxide scales

950 mm, circumferential cracks and negligible oxide spalling; spot from destroyed thermocouple

1030 mm, parts of destroyed grid spacer 4

1150 mm, W/Re thermocouple TFS 12/15

QUENCH-15 shroud appearance


180°


0°

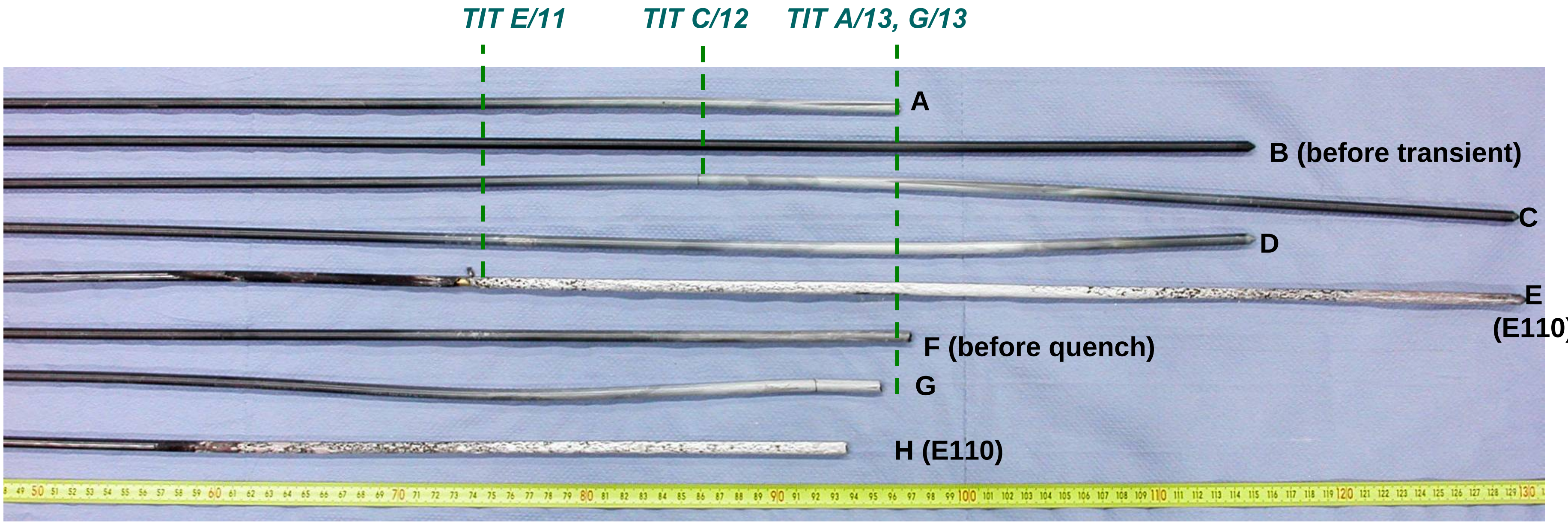

90°


180°


270°

no cracks; negligible melt formation

QUENCH-15: appearance of withdrawn corner rods



B, D, F, H – solid rods;

A, C, E, G – composited of tube (lower part up to TIT-thermocouple position) and solid rod (upper part)

QUENCH-15: two types of corner rods

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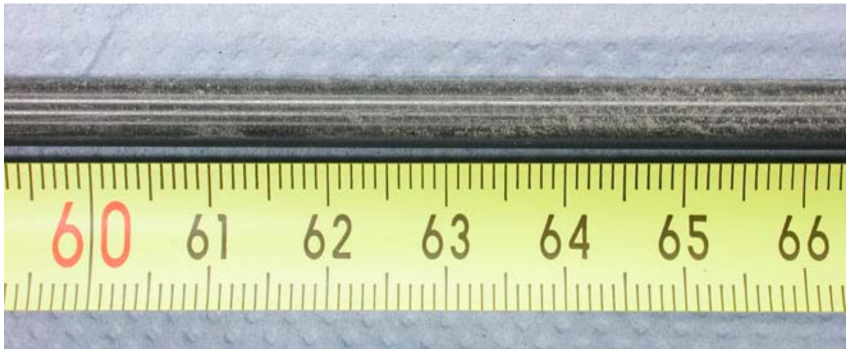
Tube appearance

Solid rod appearance



corner rod A, Zry-4: negligible breakaway,
no oxide spalling

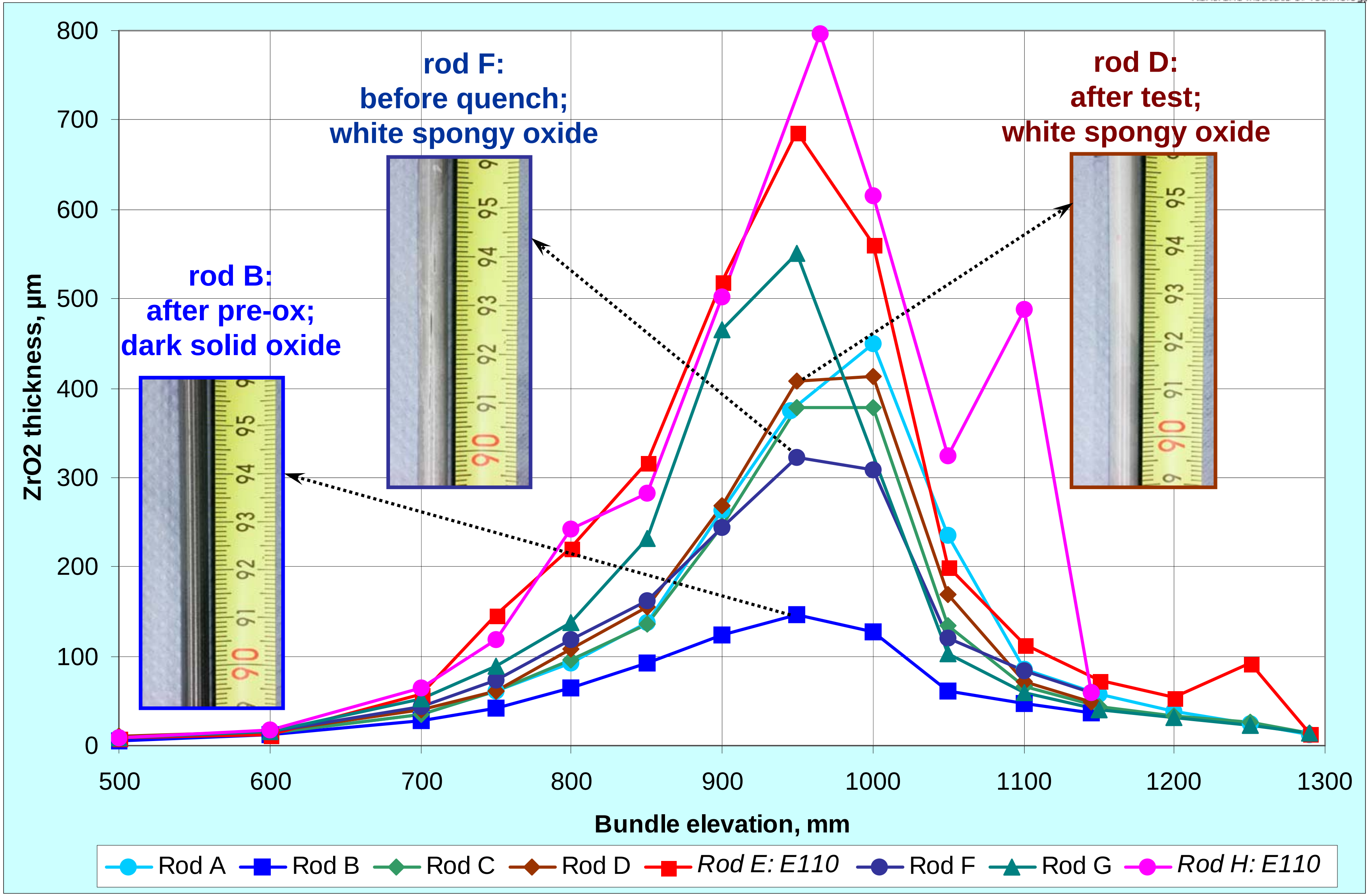
corner rod D, Zry-4: no breakaway,
no oxide spalling

corner rod E, E110: breakaway,
intensive spalling of oxide scales

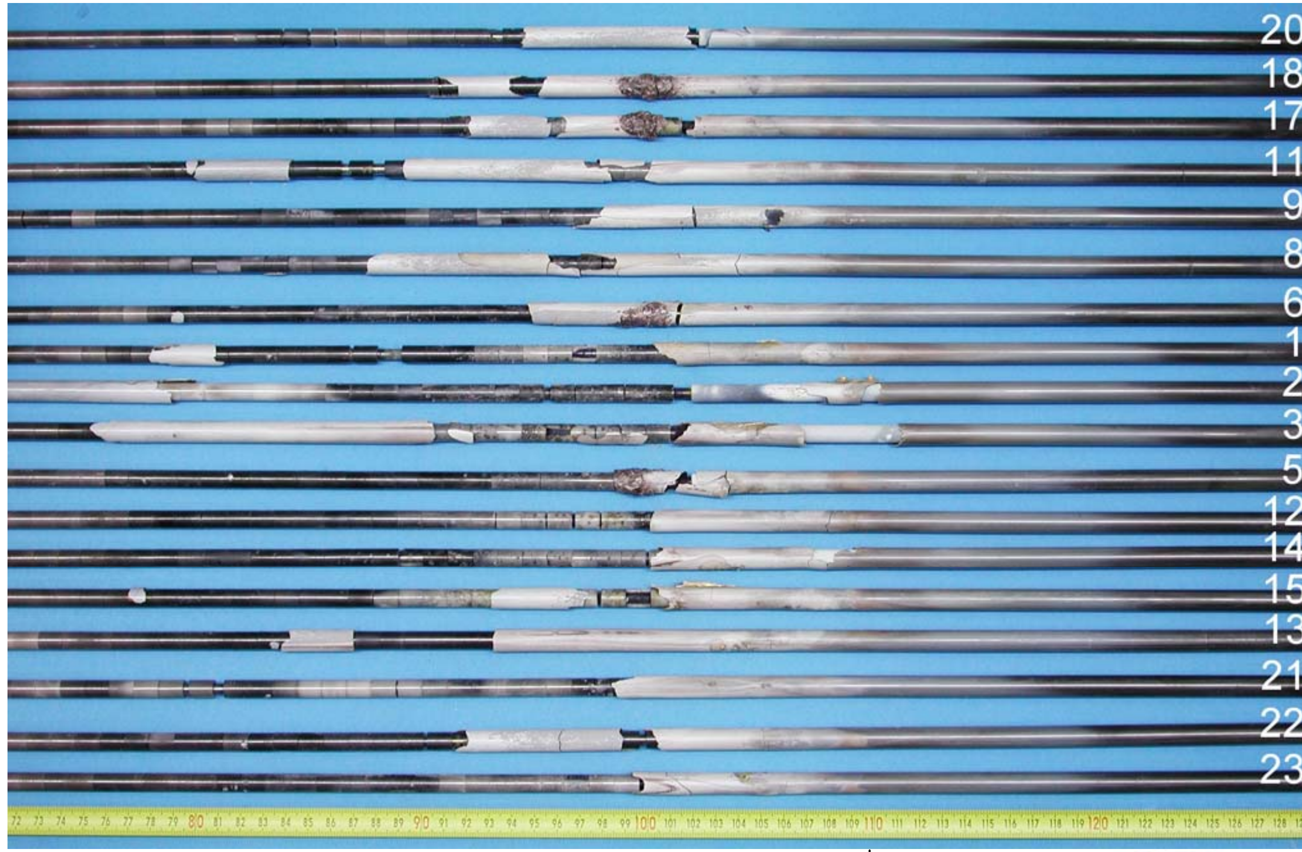
corner rod E, E110: breakaway,
intensive spalling of spongy oxide scales

QUENCH-15: axial distribution of ZrO_2 for corner rods.

Eddy current measurement



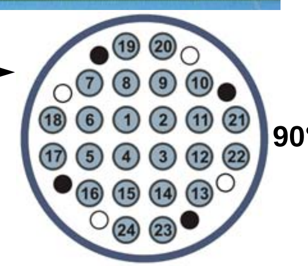
QUENCH-15: fuel rod simulators (18 rods) upward withdrawn from bundle after the test



solid dark oxide layer; stoichiometric ZrO2 pellets

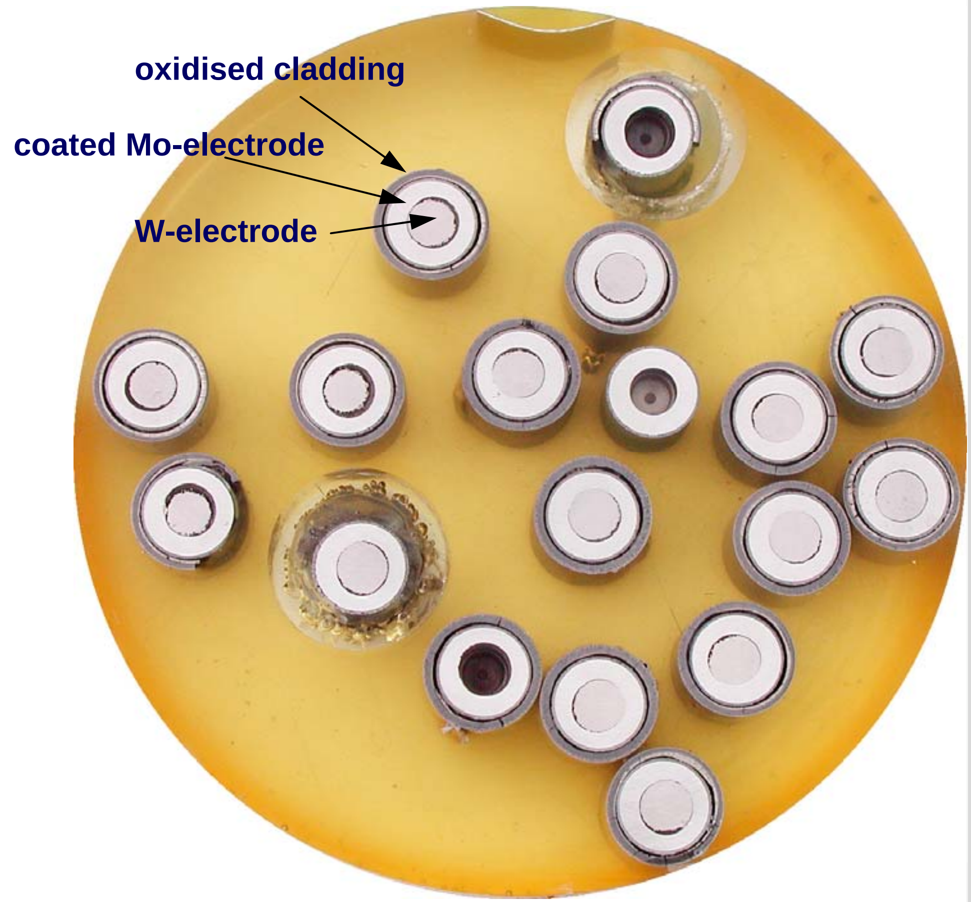
650 – 1100 mm: hot zone: white spongy oxide layer; reduced substoichiometric ZrO_2 pellets

solid dark oxide layer;



QUENCH-15: cross sections of bundle reassembled from fuel rod simulators

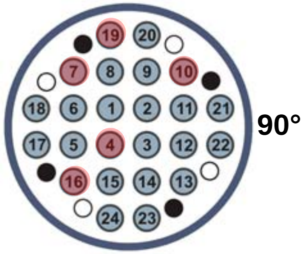
elevation 950 mm
top view



elevation 1034 mm
(junction W-heater to Mo-electrode)
top view

no melt indication

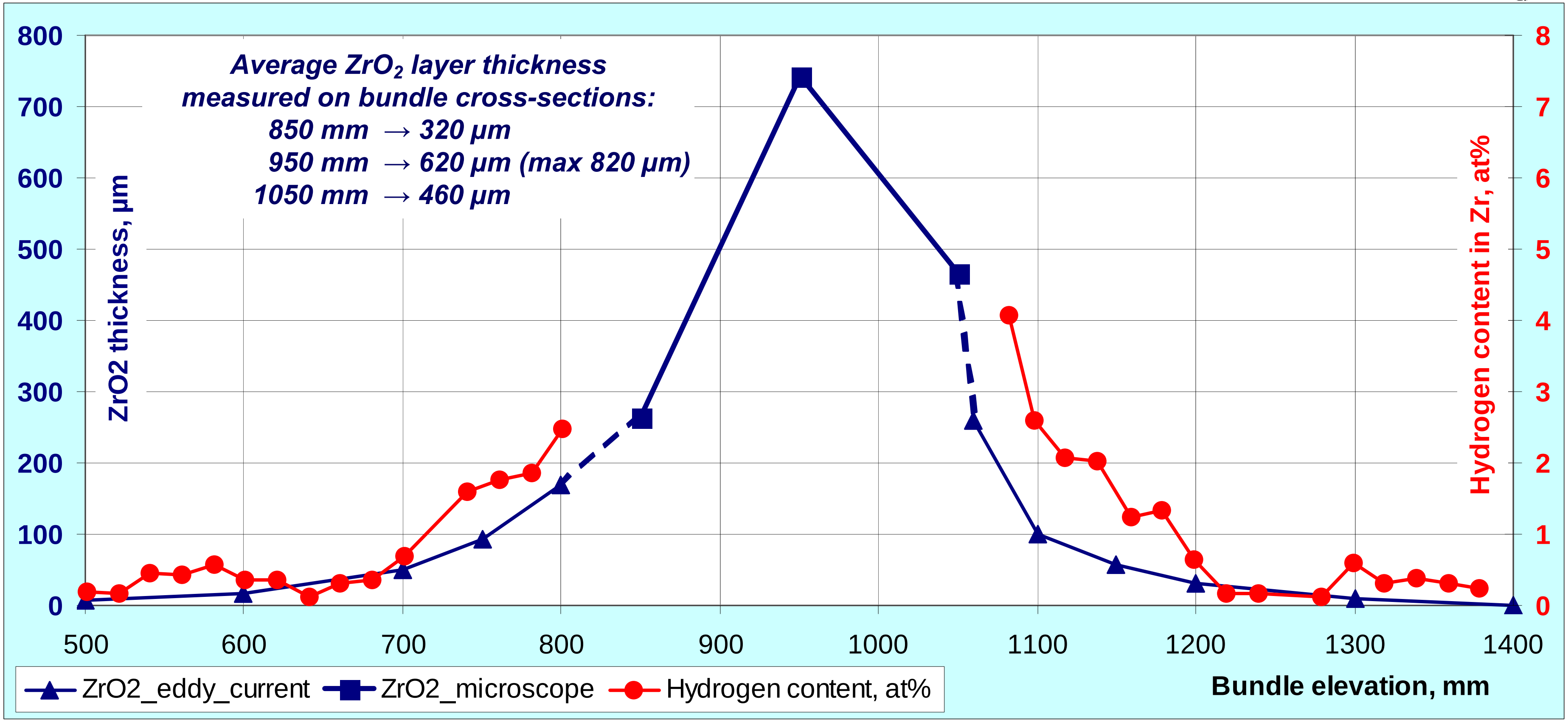
QUENCH-15: bundle rest after dismounting

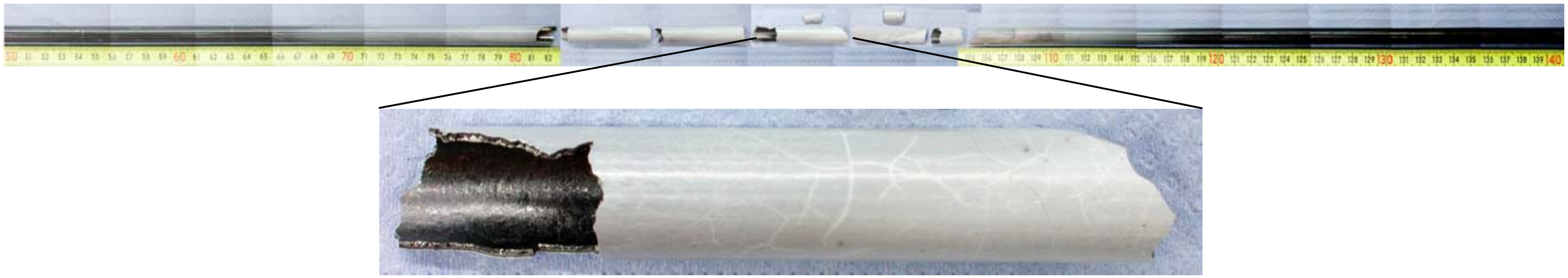


elevation 750 mm
top view

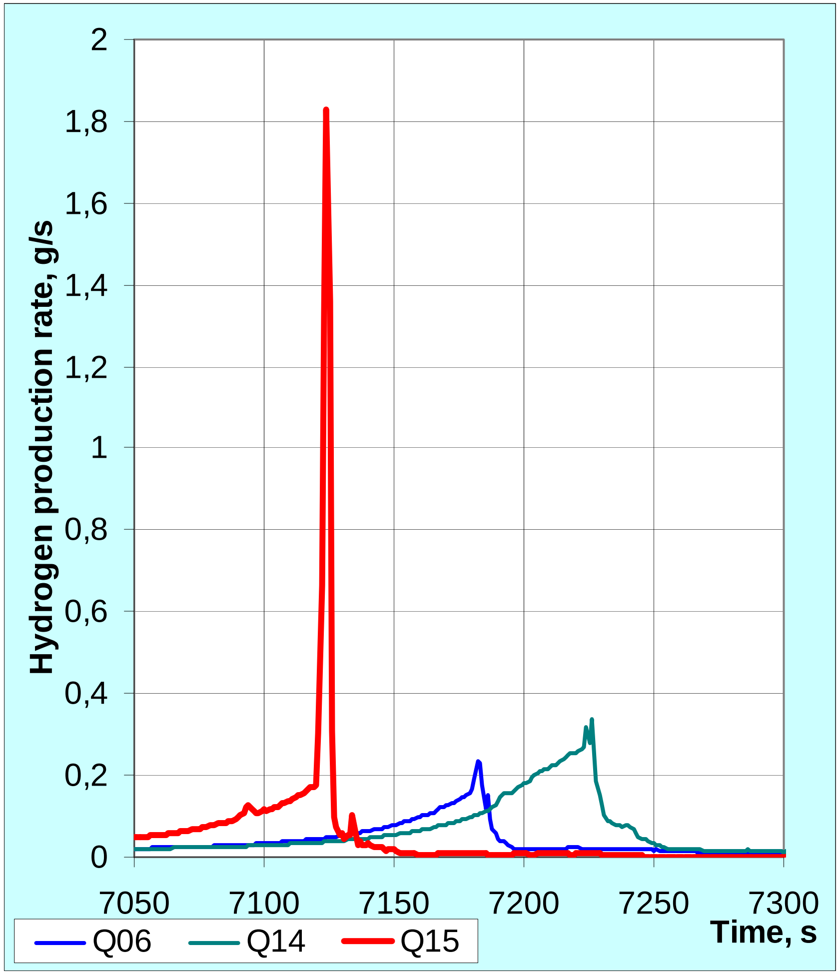
elevation 950 mm
top view

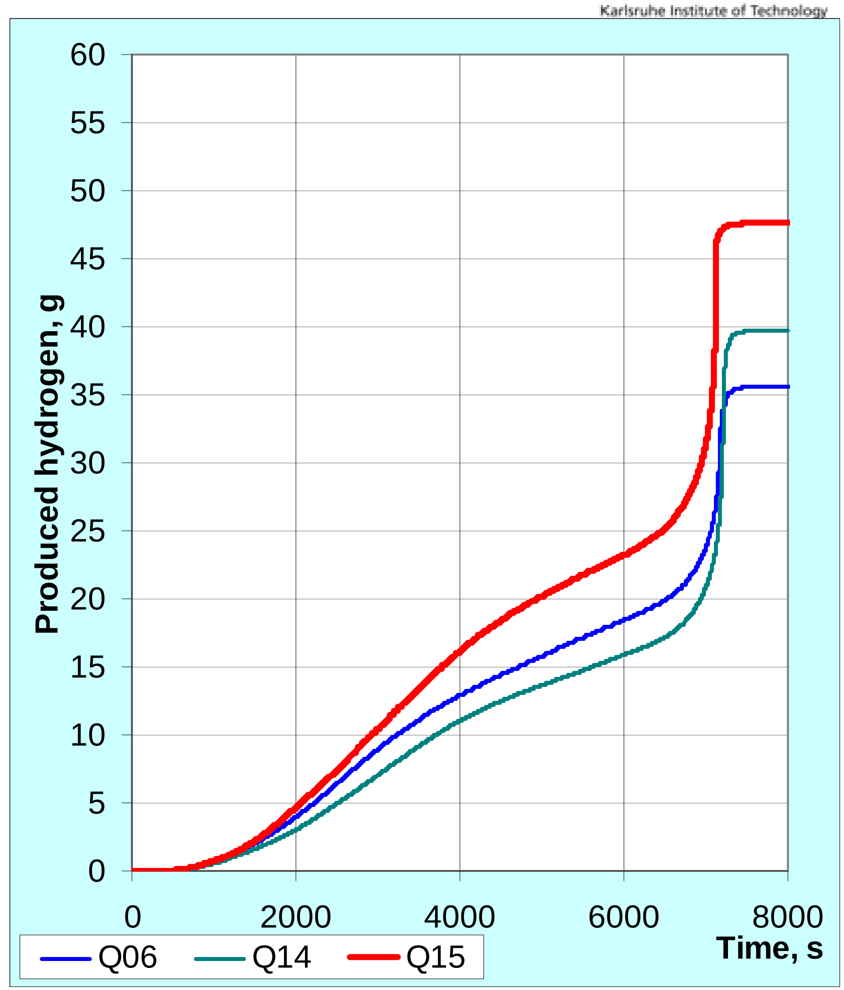
QUENCH-15: oxidation and hydrogenation of cladding
(heated rod 24)





Hydrogen production according to mass-spectrometer measurements





	Q-06 (Zry-4)	Q-14 (M5)	Q-15 (ZIRLO)	increased H_2 production due to:
H_2 production before reflood (g):	**32**	**35**	**40**	*increased Q15 metallic surface*
H_2 production during reflood (g):	**4**	**5**	**8**	*usage not prototypical corner rods*

SUMMARY

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- The QUENCH-15 experiment investigated the effect of tin-niobium-bearing ZIRLO cladding material on bundle oxidation and core reflood, in comparison with test QUENCH-06 (ISP-45) that used standard Zircaloy-4.

- The test was conducted with very similar electrical power changing as by QUENCH-06. After pre-oxidation phase, which lasted 6000 s, the electric power was ramped from 11.4 kW to 18.2 kW at a rate of 5.9 W/s. Desired maximum bundle temperature of 1800 °C was reached after about 1100 s. Following fast water injection the reflood with 48 g/s water was initiated, and the electrical power was reduced to decay heat levels of 4.2 kW.

- Two Zircaloy-4 corner rods were withdrawn during the test from the bundle. The maximal oxide layer thicknesses were measured at elevation ~950 mm with following values: 150 µm on the end of the pre-oxidation phase, 320 µm before reflood and about 550 µm after the test. The E110 corner rods extracted after the test evident intensive breakaway effect.

SUMMARY (Cont.)

- Failure of rod simulators was detected 30 s after flooding initiation (mass spectrometer measurement of Kr). No shroud failure was detected.

- The post-test endoscopy of the bundle showed neither noticeable breakaway cladding oxidation nor melt release into space between rods.

- Average oxide layer thickness at hottest elevation of 950 mm is 620 µm (QUENCH-06: 630 µm).

- Measured hydrogen production during the QUENCH-15 test was 40 g in the pre-oxidation and transient phases and 8 g in the quench phase being similar to those in QUENCH-06, i.e. 32 g and 4 g, respectively. Reasons of higher hydrogen production for QUENCH-15 were increased bundle surface and usage of not prototypical corner rods.

Following activity:

- Metallographic investigation of bundle cross sections

Thank you for your attention!