25 years QUENCH program

Main results of the QUENCH bundle tests

J. Stuckert, M. Große, M. Steinbrück

Abstract

In the framework of the QUENCH program at KIT, over the past 22 years, 21 bundle tests were performed under severe accident conditions with different cladding materials. Additionally, 7 QUENCH-LOCA bundle tests with fresh and pre-hydrogenated different cladding materials (Zry-4, M5®, opt. ZIRLO™) were performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR.

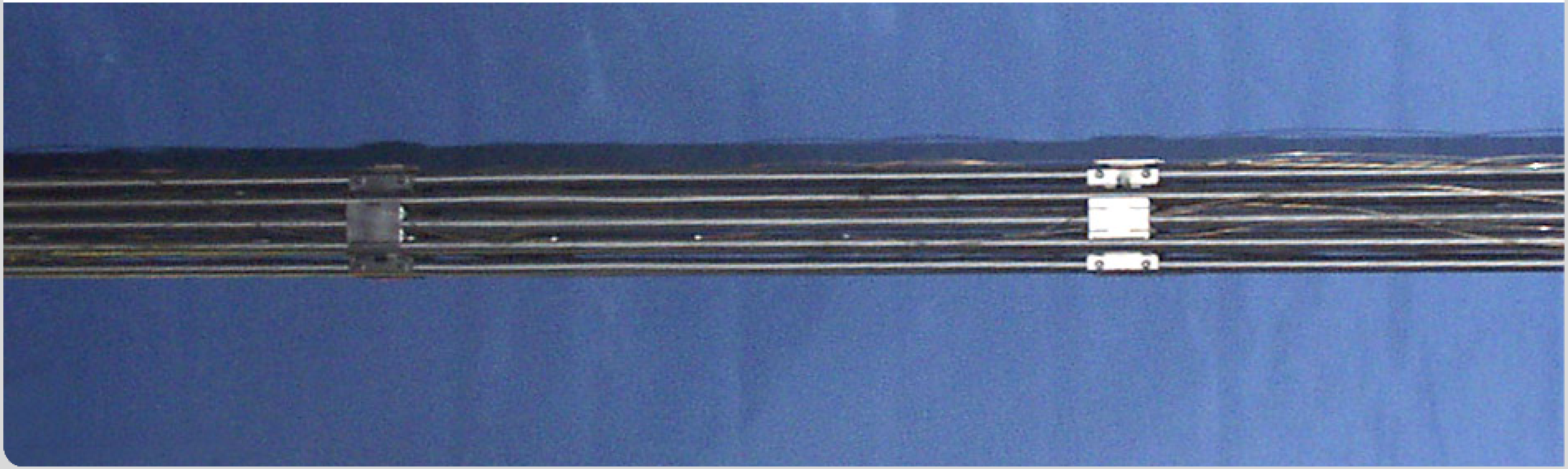
Main purposes of severe accident tests were hydrogen source term, as well as investigation of phenomena on melt relocation, debris, and aerosol formation. Concerning the hydrogen source term, six parameters, enhancing hydrogen production during reflood, have been identified: 1) low reflood flow rates < 1 g/s/rod; 2) breakaway effect with weakness and spallation of protective oxide layer; 3) steam starvation; 4) nitride formation by air ingress with formation of very porous oxide layer during following reflood; 5) high temperatures with melt relocation outside claddings and intensive melt oxidation; 6) eutectic interactions between B_4C, stainless steel and Zircaloy-4 leading to low melting point.

Post-test tensile experiments performed in the framework of the QUENCH-LOCA program evidenced fracture at hydrogen bands (formed during secondary hydriding) for claddings with local hydrogen concentrations >1500 wppm.

25 years QUENCH program
Main results of the QUENCH bundle tests

J. Stuckert, M. Große, M. Steinbrück

Institute for Applied Materials; Program NUSAFE



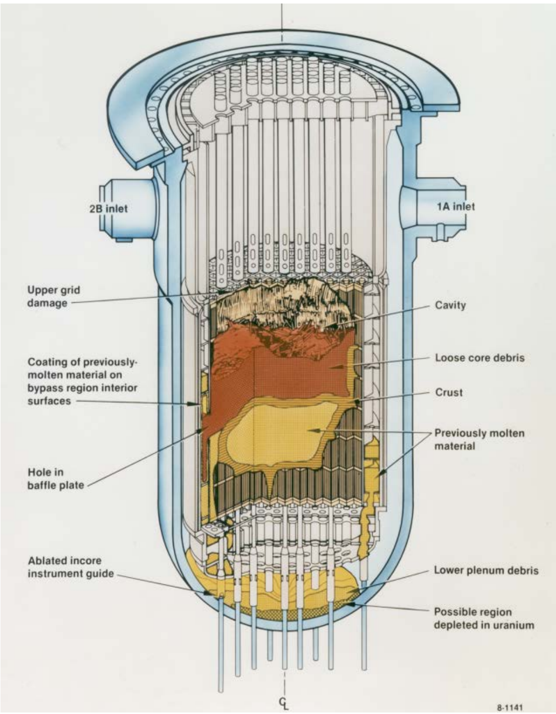
Investigations to core degradation:

TMI-2-Accident → CORA → QUENCH

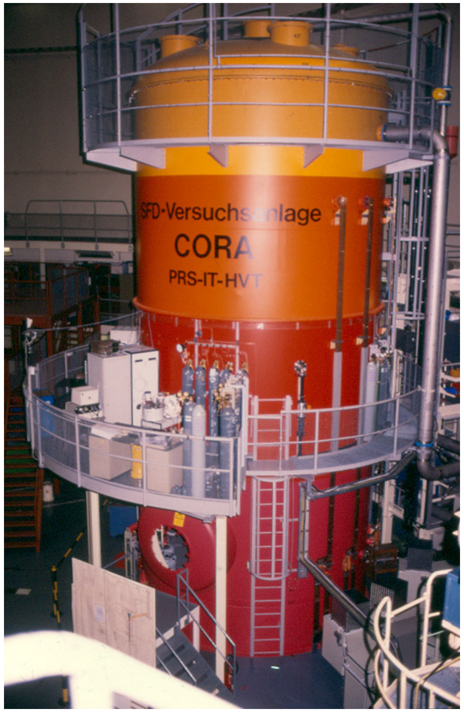
28 March 1979:
50% reactor core fragmented or melted, H_2 generation

1986 - 1993, 19 Tests:
Investigation of melt formation and -relocation

1997 → now, 21 Tests (+7 LOCA):
Material behavior,
Hydrogen source term



Backgrounder on the Three Mile Island Accident, NRC



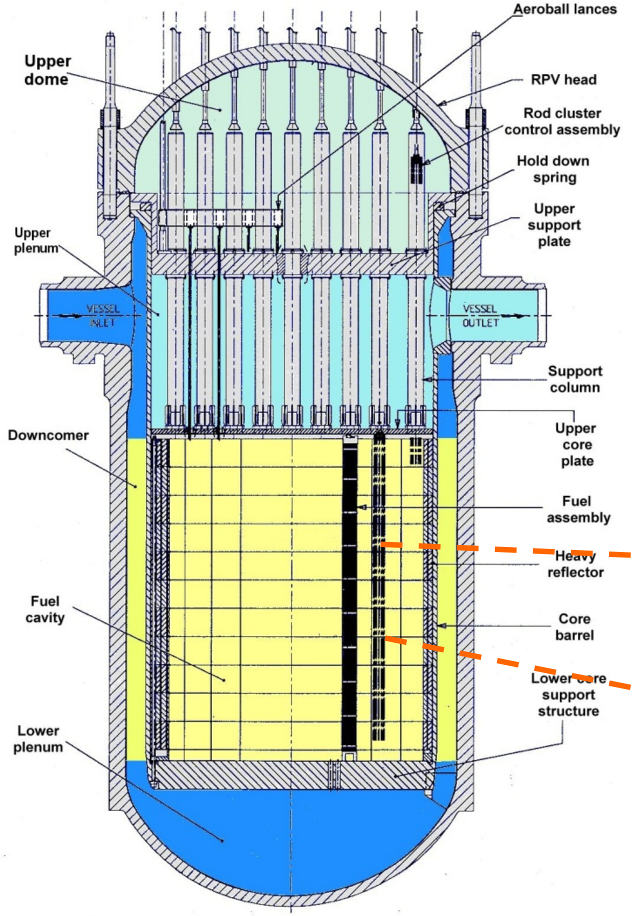
G. Schanz et al., . **Information on the evolution of severe L WR fuel element damage obtained in the CORA program**, JNM 188 (1992) 131-145

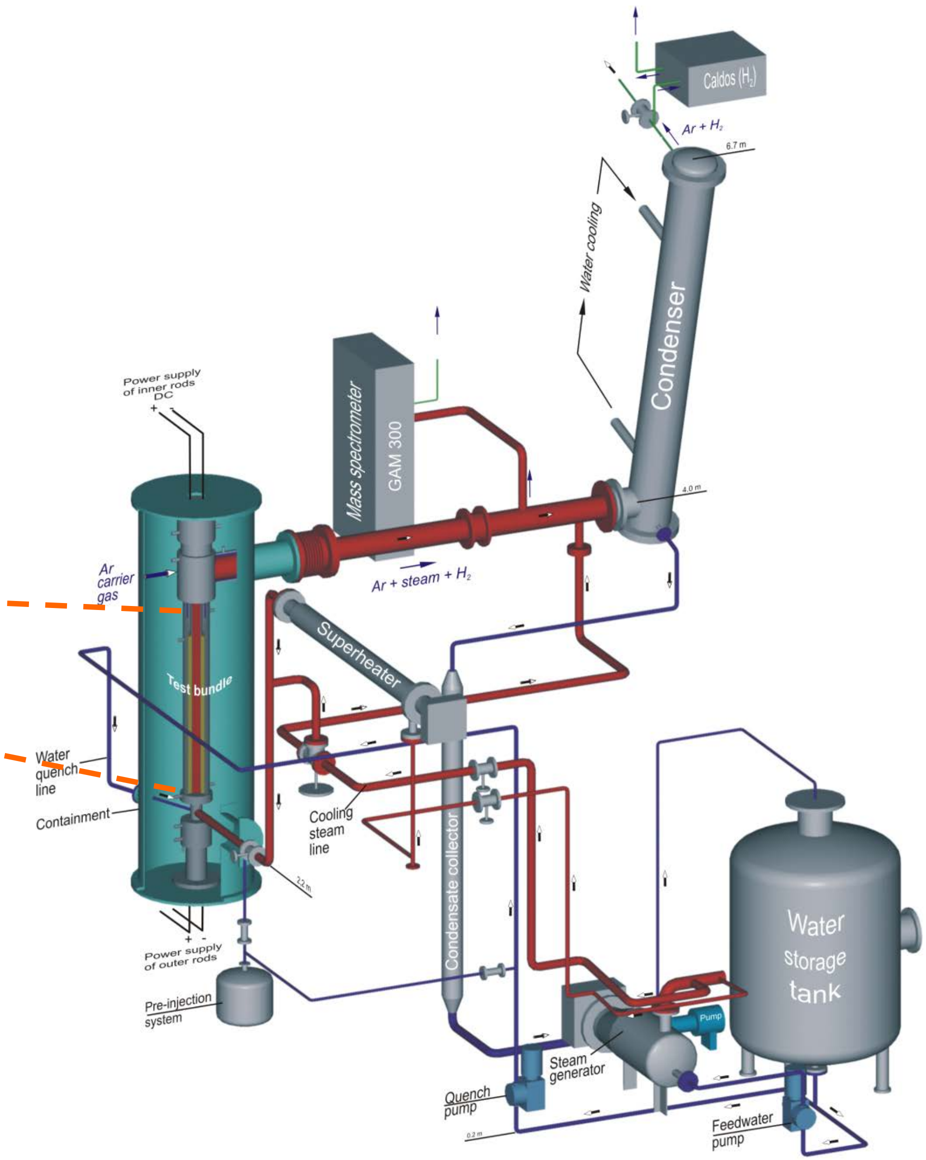
M. Steinbrück et al., Synopsis and outcome of the QUENCH experimental program, NED 240 (2010) 1714–1727

T. Haste et al., A comparison of core degradation phenomena in the CORA, QUENCH, Phébus SFD and Phébus FP experiments, NED 283(2015) 8–20

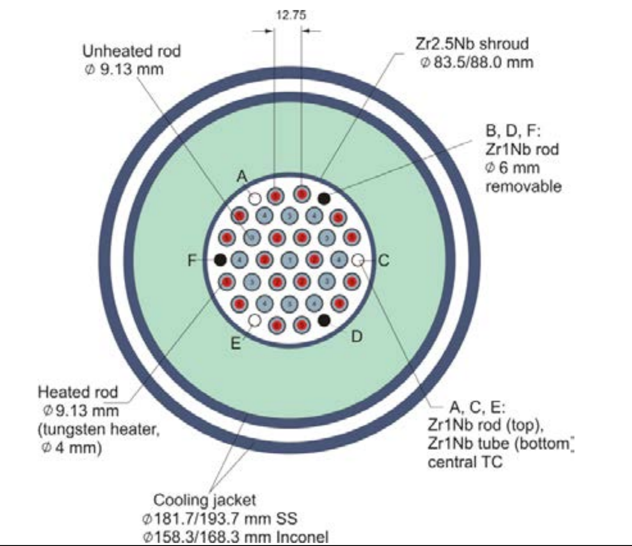
QUENCH-facility

PWR-Reactor





Composition of bundles

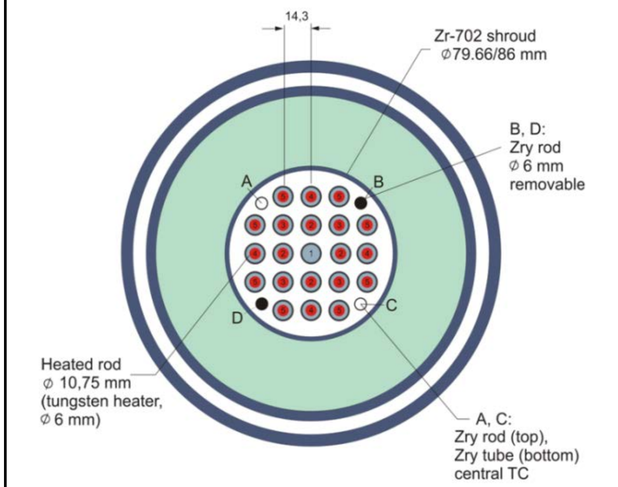


WWER, pitch 12.75 mm

claddings: **E110** - alloy

<u>Fuel rod simulators:</u>

18 heated,13 not heated, 6 corner rods

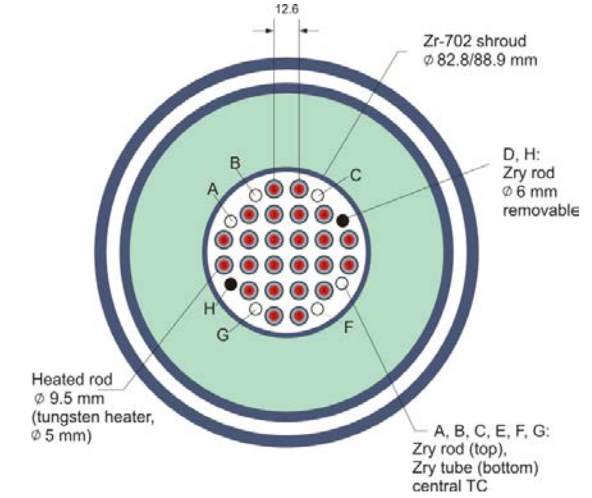


PWR, pitch 14.3 mm

claddings: **Zry-4** or **M5**® alloys

<u>Fuel rod simulators :</u>

20 heated, 1 not heated (or absorber), 4 corner rods

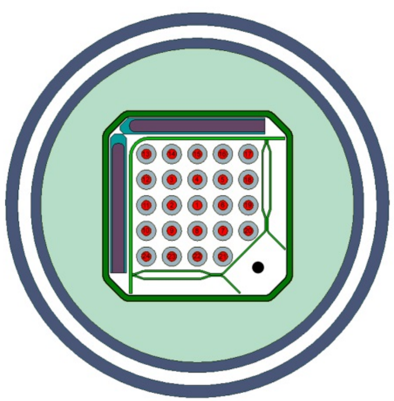


PWR, pitch 12.6 mm

claddings: **ZIRLO**™ or **M5**® alloys

<u>Fuel rod simulators :</u>

24 (22) heated, 0 not heated (or 2 AgInCd absorber), 8 corner rods



BWR, pitch 12.898 mm

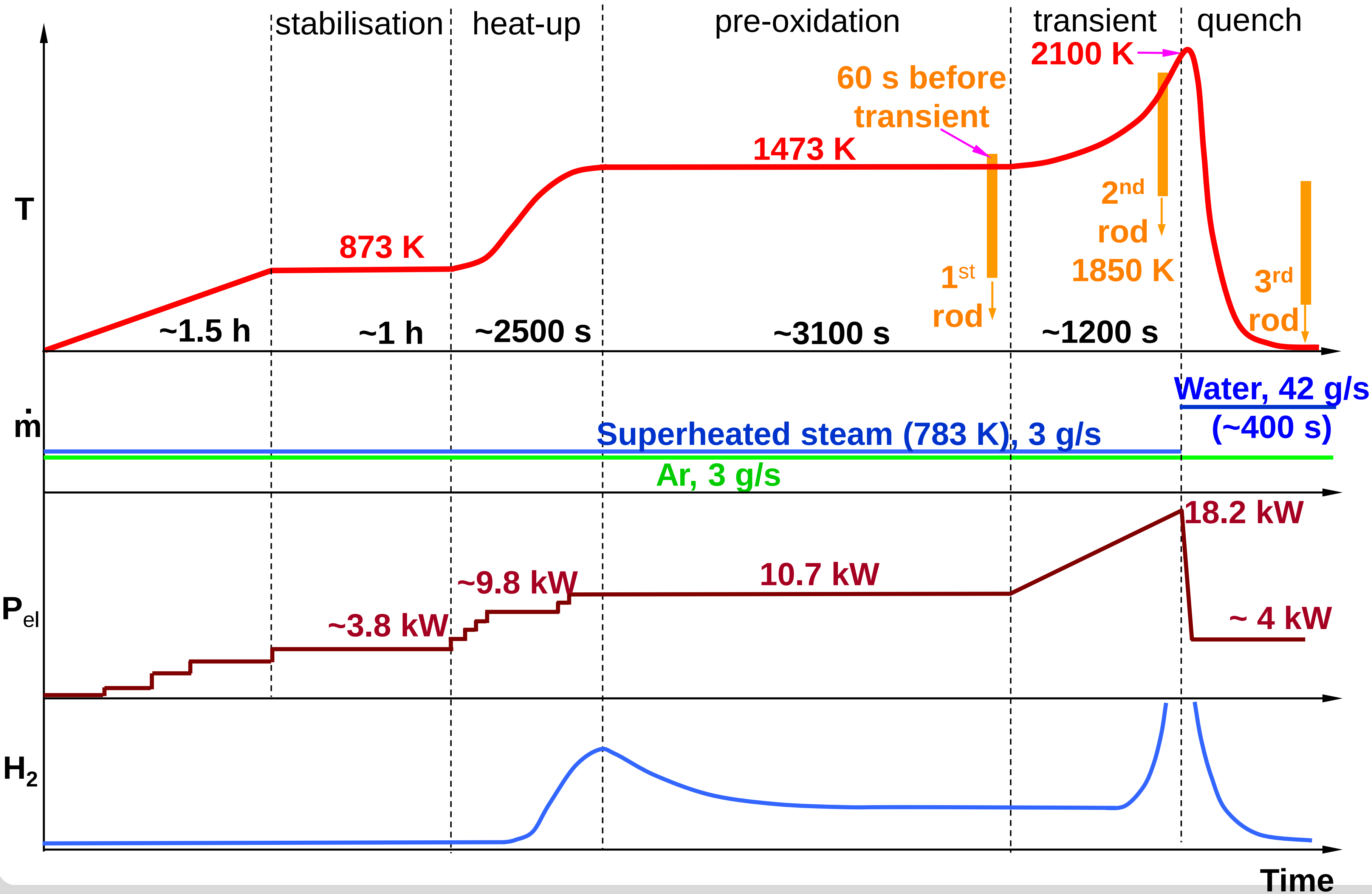
claddings: **Zry-2** alloy

<u>Fuel rod simulators :</u>

24 heated, 1 corner rod

Absorber blades with B_4C pins

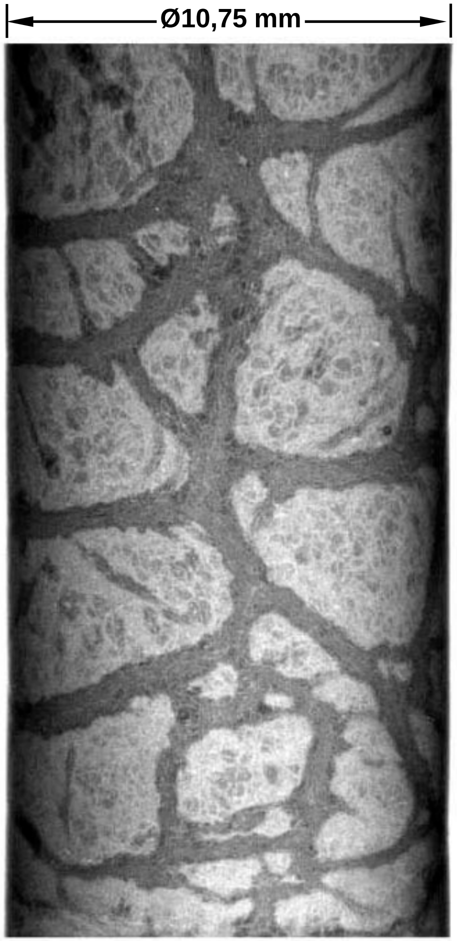
Typical QUENCH scenario: performance of QUENCH-14 (M5®) similar to Q-06 (Zry-4), Q-12 (E110) and Q-15 (ZIRLO™)



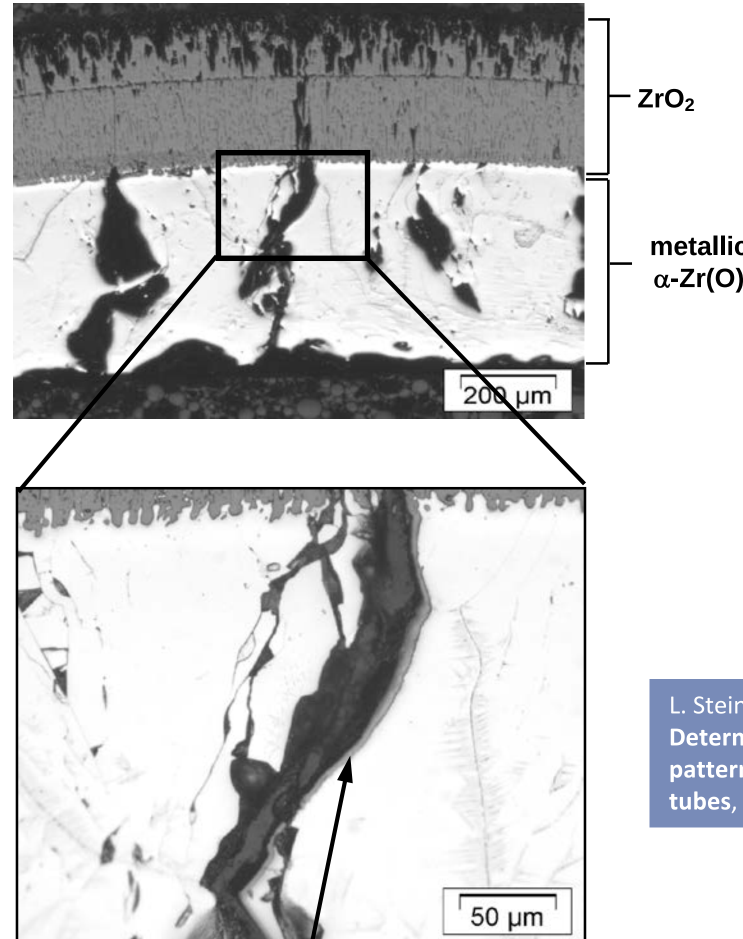
QUENCH test matrix

Test	Quench medium / Injection rate	Temp. at onset of flooding	Max. oxide before transient	Max. oxide before flooding	Max. oxide after test	H_2 production before / during cooldown	Remarks, objectives
QUENCH-00 Oct. 9 - 16, 97	Water 80 g/s	≈ 1800 K			completely oxidized		commissioning test
QUENCH-01 February 26, 98	Water 52 g/s	≈ 1830 K	312 µm		500 µm at 913 mm	**36 / 3**	pre-oxidized cladding
QUENCH-02 July 7, 98	Water 47 g/s	≈ 2400 K			completely oxidized	**20 / 140**	no additional pre-oxidation, **melt**
QUENCH-03 January 20, 99	Water 40 g/s	≈ 2350 K			completely oxidized	**18 / 120**	no additional pre-oxidation, **melt**
QUENCH-04 June 30, 99	Steam 50 g/s	≈ 2160 K	82 µm		280 µm	**10 / 2**	slightly pre-oxidized cladding
QUENCH-05 March 29, 2000	Steam 48 g/s	≈ 2020 K	160 µm		≈ 420 µm	**25 / 2**	pre-oxidized cladding
QUENCH-06 Dec. 13 2000	Water 42 g/s	≈ 2060 K	207 µm	300 µm	≈ 630 µm	**32 / 4**	*OECD-ISP 45*
QUENCH-07 July 25, 2001	Steam 15 g/s	≈ 2100 K	230 µm		completely oxidized	**66 / 120**	EU COLOSS B_4C, **eutectic melt**
QUENCH-09 July 3, 2002	Steam 49 g/s	≈ 2100 K			completely oxidized	**60 / 400**	EU COLOSS B_4C, **eutectic melt**
QUENCH-08 July 24, 2003	Steam 15 g/s	≈ 2090 K	274 µm		completely oxidized	**46 / 38**	EU COLOSS; reference for QUENCH-07, **melt**
QUENCH-10 July 21, 2004	Water 50 g/s	≈ 2200 K	514 µm	613 µm (at 850 mm)	completely oxidized	**48 / 5**	EU LACOMERA; air ingress
QUENCH-11 Dec 08, 2005	Water 18 g/s	≈ 2040 K		170 µm	completely oxidized	**9 / 132**	EU LACOMERA; boil-off, **melt;** *benchmark*
QUENCH-12 Sept 27, 2006	Water 48 g/s	≈ 2100 K	160 µm, breakaway	300 µm, breakaway	completely oxidized	**34 / 24**	ISTC; WWER, **melt**
QUENCH-13 Nov. 7, 2007	Water 52 g/s	≈ 1820 K		400 µm	750 µm	**42 / 1**	EU SARNET; Ag/In/Cd (aerosol)
QUENCH-14 Sept 27, 2006	Water 41 g/s	≈ 2100 K	170 µm	470 µm	900 µm	**34 / 6**	M5® cladding
QUENCH-15 Nov. 7, 2007	Water 41 g/s	≈ 2100 K	145 µm	320 µm	620 µm	**41 / 7**	ZIRLO™ cladding
QUENCH-16 July 27, 2012	Water 50 g/s	≈ 1870 K	135 µm	140 µm	850 µm: outer **porous,** inner dense	**16 / 128**	EU LACOMECO; air ingress, **melt;** *benchmark*
QUENCH-17 Jan. 31, 2013	Water 10 g/s	≈ 1800 K		completely oxidized	completely oxidized	**110 / 1**	*EU SARNET-2; DEBRIS formation*
QUENCH-18 Sept. 27, 2017	Water 53 g/s	≈ 2000 K	90 µm		partially dissolved by **melt**	**56 / 238**	EU ALISA; **AgInCd** absorber (**melt** and aerosols); *air ingress*
QUENCH-19 August 29, 2018	Water 41 g/s	≈ 1740 K				**8.8 / 0.5**	ATF (FeCrAl) clads; cooperation with ORNL
QUENCH-20 October 9, 2019	Water 50 g/s	≈ 2000 K	≈ 100 µm		t.b.d.	**25.4 / 32**	EU SAFEST; BWR bundle with B4C absorber

Oxidation of cracks developed during flooding: low contribution to hydrogen production



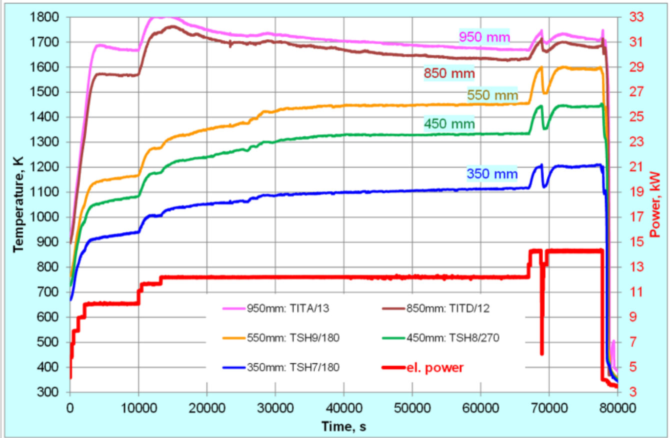
Development of cracks in the cladding with thick oxide layer (>150 µm) and cooled down with steam.
Crack density ~ 4 cm/cm²



Negligible oxidation of crack edges gives only some percent of generated hydrogen

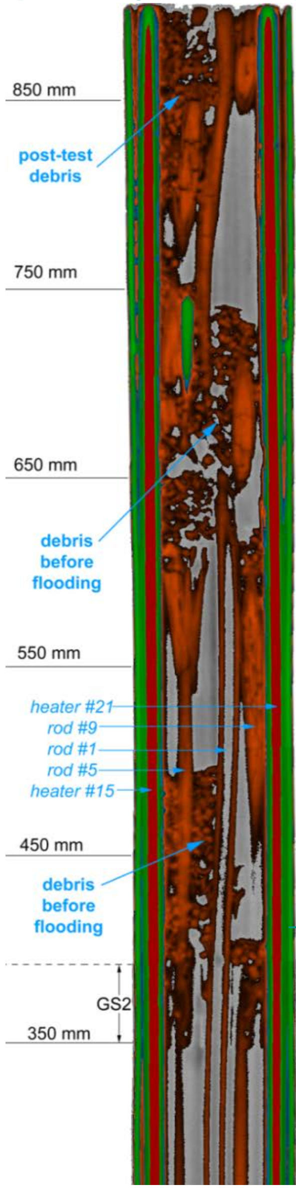
L. Steinbock and J. Stuckert. **Determination of the crack pattern of quenched zircaloy tubes**, FZKA-6013 (1997)

QUENCH-17: Debris formation after degradation of strongly oxidized cladding and release of pre-segmented pellet simulators

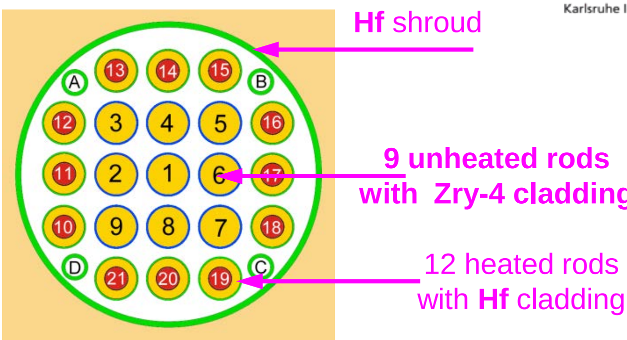


test scenario

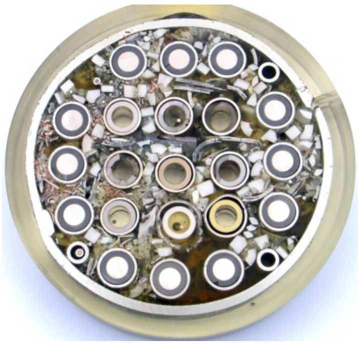
debris: 1) separated parts of fuel pellets simulator; 2) large segments of failed Zry claddings.



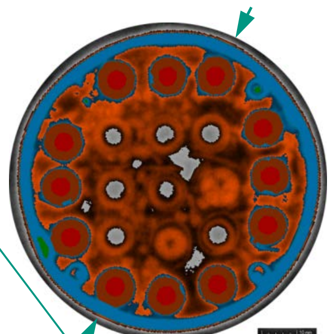
X-ray tomography



bundle composition



cross-section at 400 mm: metallography; debris bed porosity 50%



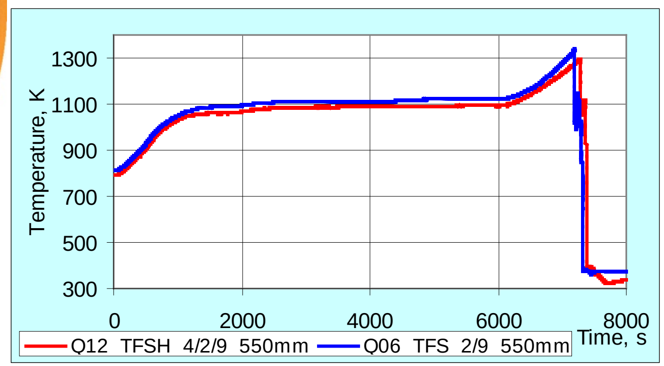
cross-section at 400 mm: tomography; blockage 85%

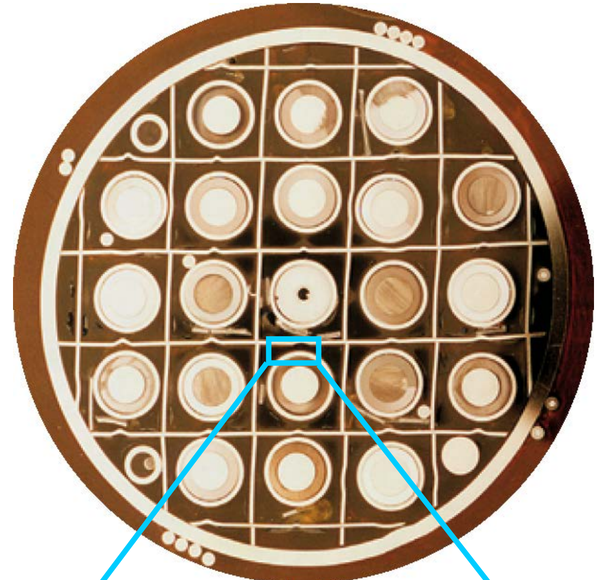
J. Stuckert et al., **Results of the QUENCH-DEBRIS test**, ICAPP 2014, Paper 14150

Weakening of protective oxide layer by <u>breakaway</u> oxidation: QUENCH-12 (WWER, electrolytic E110) vs. QUENCH-06 (Zry-4)

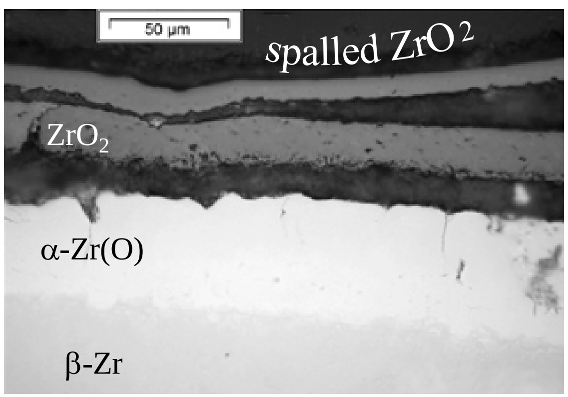
Karlsruhe Institute of Technology

Q12: rubble on spacer grid consists of spalled cladding scales and fragments of partially oxidized cladding

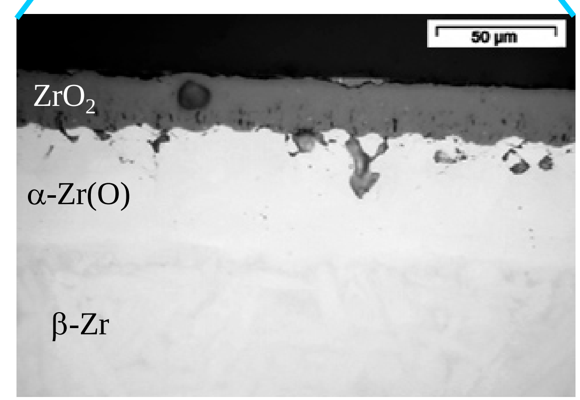




Q06 cross-section



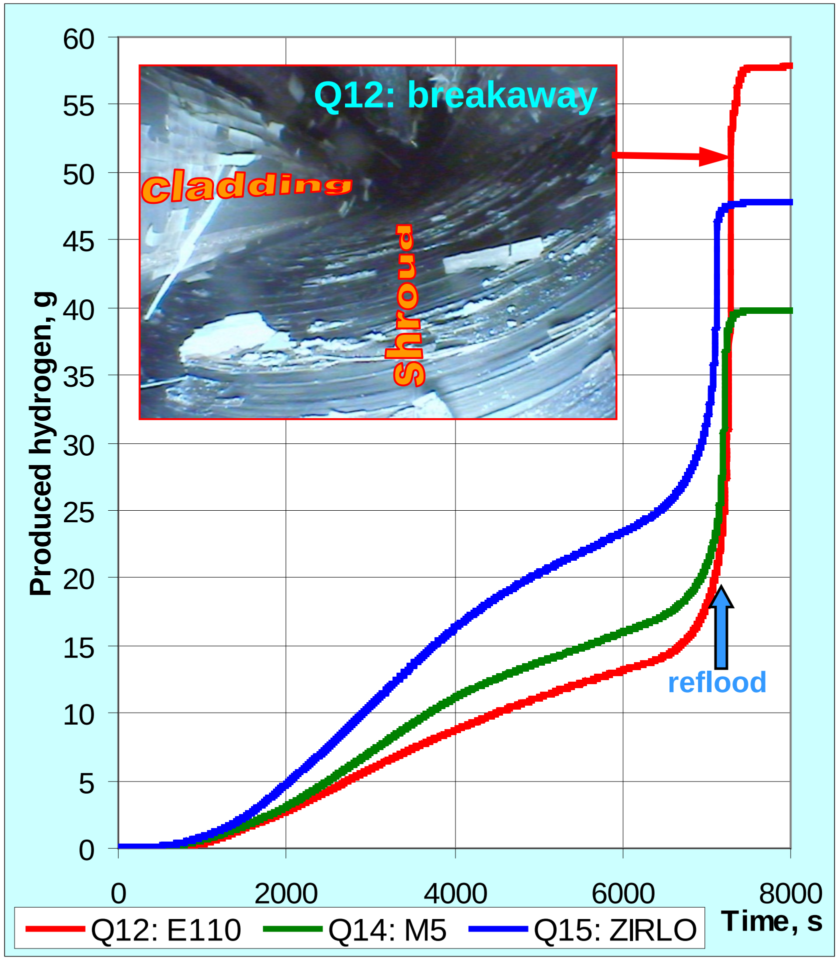
Q12 cladding: spalling of oxide scales due to breakaway effect



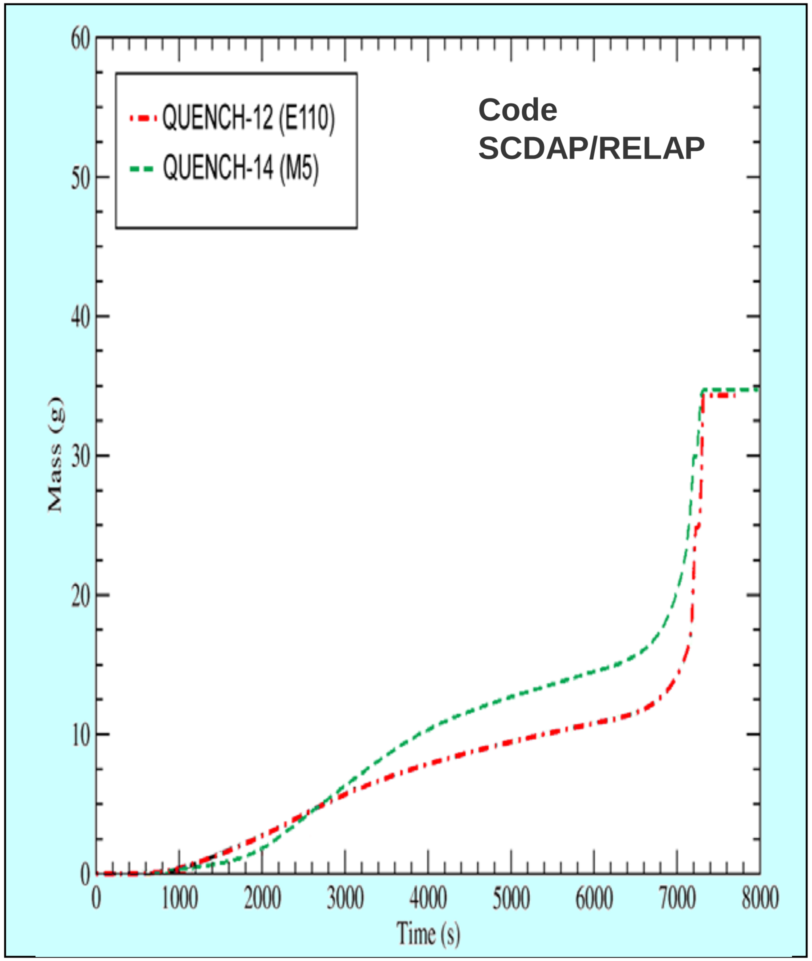
Q06 oxidized cladding

J. Stuckert et al. **Experimental and post-test calculation results of the integral reflood test QUENCH-12 with a VVER-type bundle**, ANE 36 (2009) 183–192

Increased hydrogen production during reflood after breakaway: QUENCH-12 (electrolytic E110) vs. QUENCH-14 (M5®)

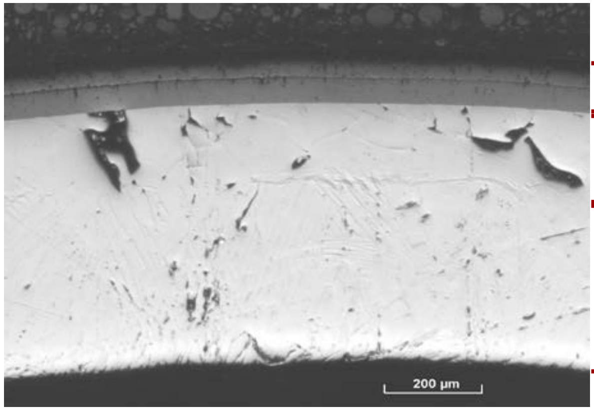


Consequences of breakaway enhanced hydrogen release: 1) new metallic surfaces, 2) melt release outside cladding, 3) release of hydrogen absorbed in metal.



Post-test calculations: need for improvement of model for quench phase

Influence of pre-reflood steam or oxygen starvation conditions (QUENCH-09, -11, -16, -18)



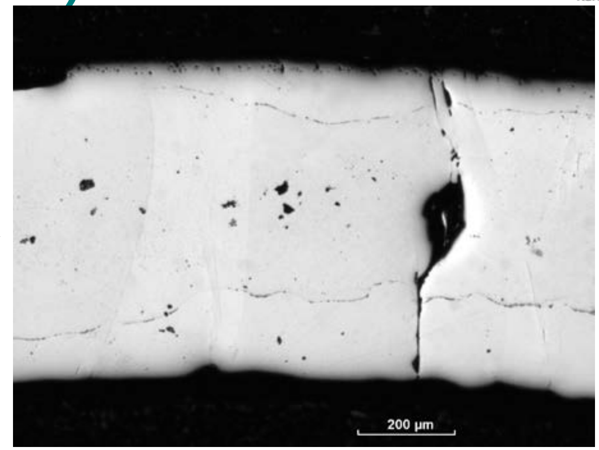
ZrO_2, 134 µm

α-Zr(O), 182 µm

β-Zr, 431 µm

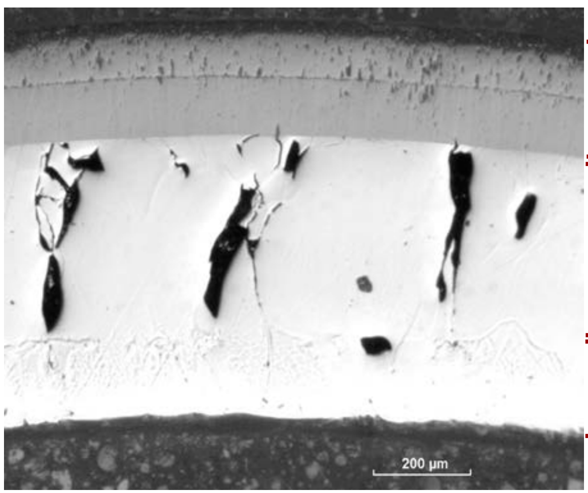
„Thin“ oxide layer

Steam starvation at 1700K



α-Zr(O), 733 µm

Complete decomposition of oxide layer



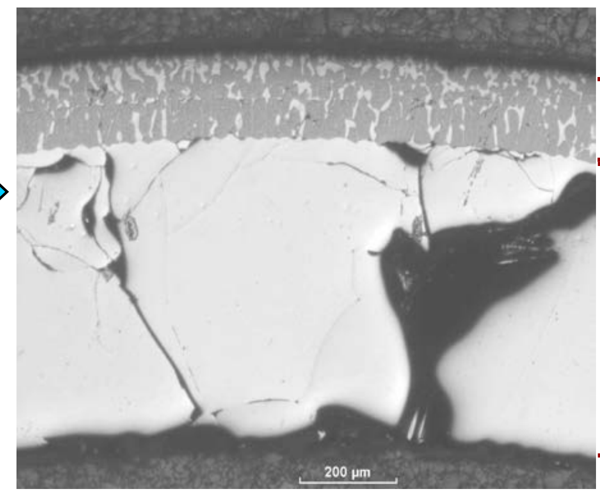
ZrO_2, 228 µm

α-Zr(O), 397µm

β-Zr, 177 µm

„Thick“ oxide layer

Steam starvation at 1700K



ZrO_2: 186µm, Metallic precipi-tations 24%

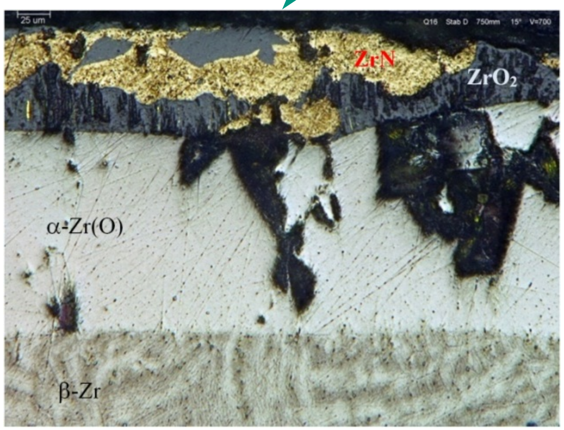
α-Zr(O), 646 µm

Development of metallic precipitations inside oxide layer. Precipitates will expose to intensive oxidation during following flooding

J. Stuckert and M. Veshchunov
Behaviour of Oxide Layer of Zirconium-Based Fuel Rod Cladding under Steam Starvation Conditions,
FZKA-7373 (2008)

Air ingress after moderate pre-oxidation (QUENCH-10, -16): massive nitride formation during *oxygen starvation* and their intensive re-oxidation during quench

Q16 pre-reflood

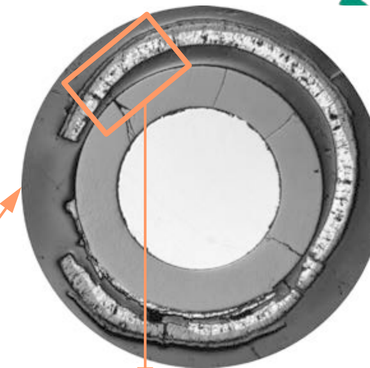


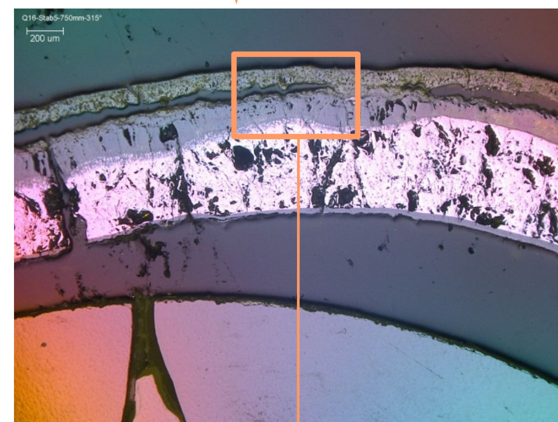
nitride formation inside oxide layer

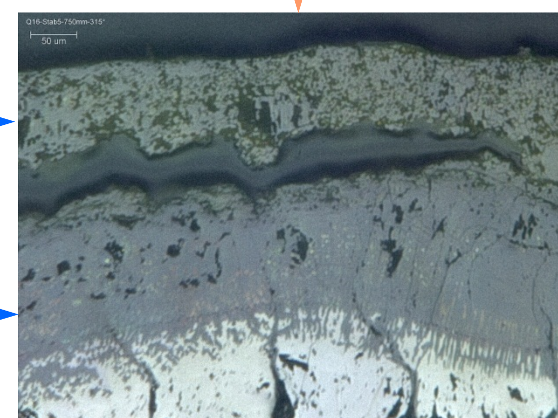
J. Stuckert and M. Steinbrück
Experimental results of the QUENCH-16 bundle test on air ingress, PNE 71 (2014) 134-141

Q16 post-reflood

Endoscope observation at ~850 mm





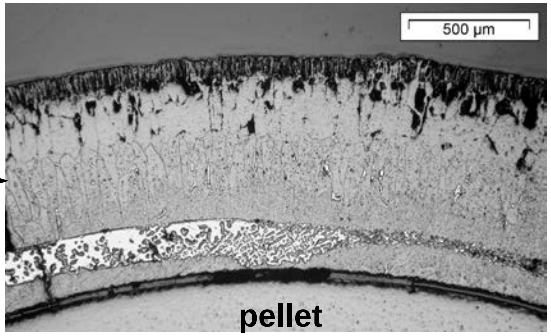


prior nitrided scale *re-oxidised* during quench and spalled →

from internal ZrO_2 layer growing during quench →

Typical layer structure of strong oxidised cladding at hottest bundle elevation of 1000 mm after reflood

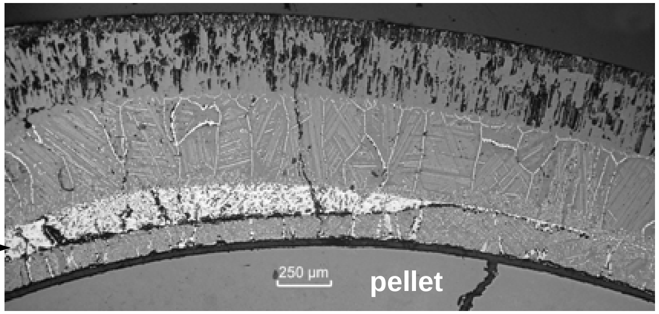
outer ZrO_2
formed during pre-oxidation and reflood



QUENCH-15 (ZIRLO™)
rod #17

J. Stuckert et al., **Experimental and calculation results of the integral reflood test QUENCH-15 with ZIRLO™ cladding tubes in comparison with results of previous QUENCH tests**, NED 241 (2011) 3224–3233

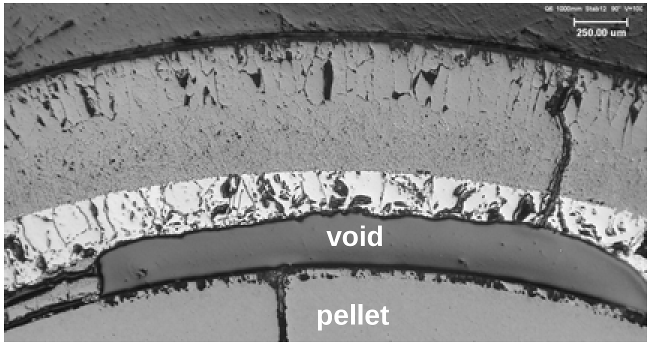
<u>melt</u>
formed at ~2030 K
and partially oxidised
due to dissolution of ZrO_2



QUENCH-14 (M5®)
rod #11

J. Stuckert et al., **Experimental and calculation results of the integral reflood test QUENCH-14 with M5® cladding tubes**, ANE 37 (2010) 1036–1047

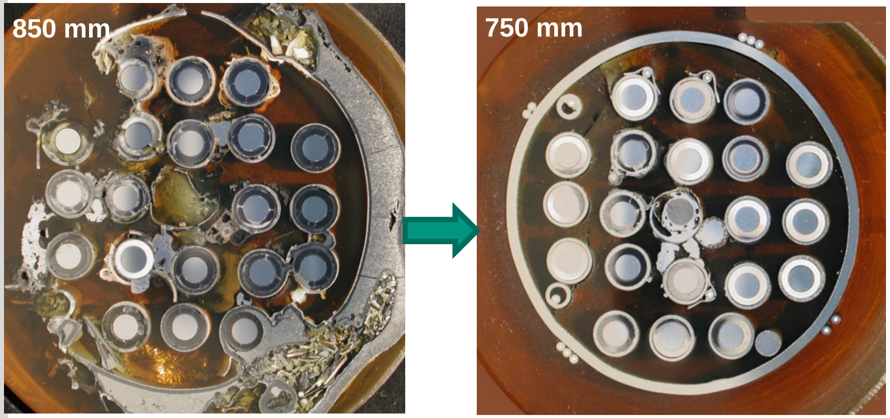
inner ZrO_2
formed during reflood
(due to interaction with steam penetrated under breached cladding; no interaction with pellet)

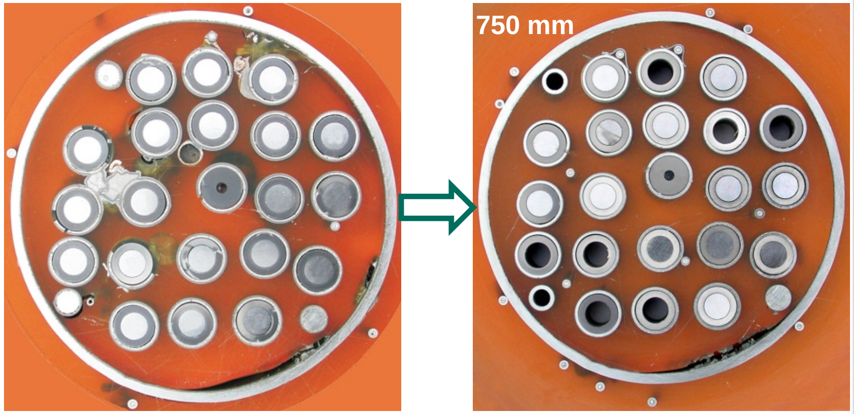


QUENCH-06 (Zry-4)
rod #12

L. Sepold et al., **Experimental and computational results of the QUENCH-06 test (OECD ISP-45)**, FZKA-6664 (2004)

Eutectic melt induced upper 1200°C by absorber rod: *complementary* tests Q-07 (B_4C rod) and Q-08 (without absorber)





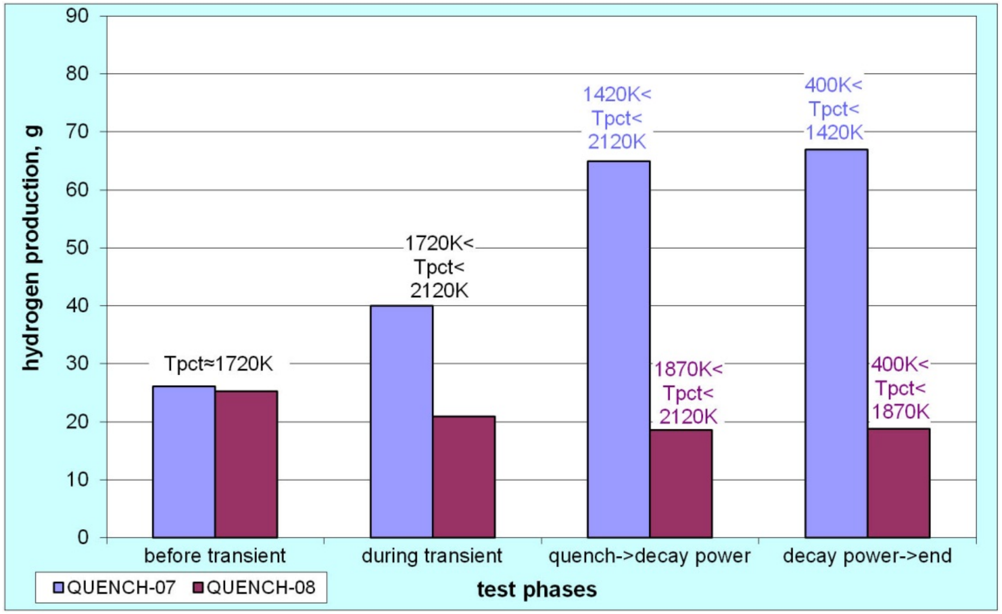
QUENCH-07: formation of significant melt amount and melt relocation

B_4C<->Fe eutectic at ~1150°C

Zry <-> SS eutectic at ~1300°C

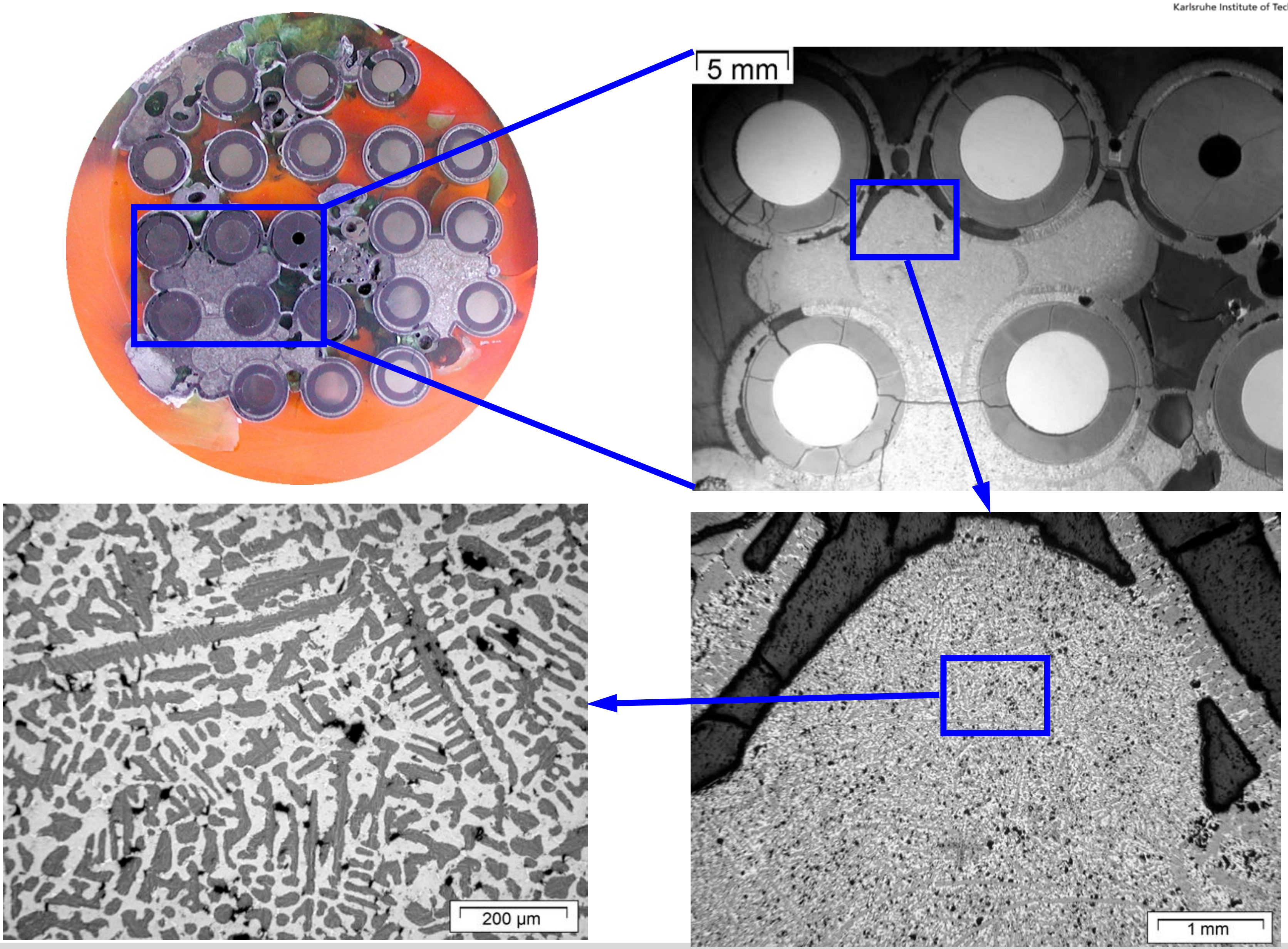
QUENCH-08: moderate melt formation; no noticeable melt relocation

hydrogen productions for different test phases with indication of temperature evolution during the phase:



J. Stuckert et al., **Experimental and Computational Results of the QUENCH-08 Experiment (Reference to QUENCH-07)**, FZKA-6970 (2005)

QUENCH-11, elev. 837 mm: melt relocated outside fuel rods and oxidised in steam

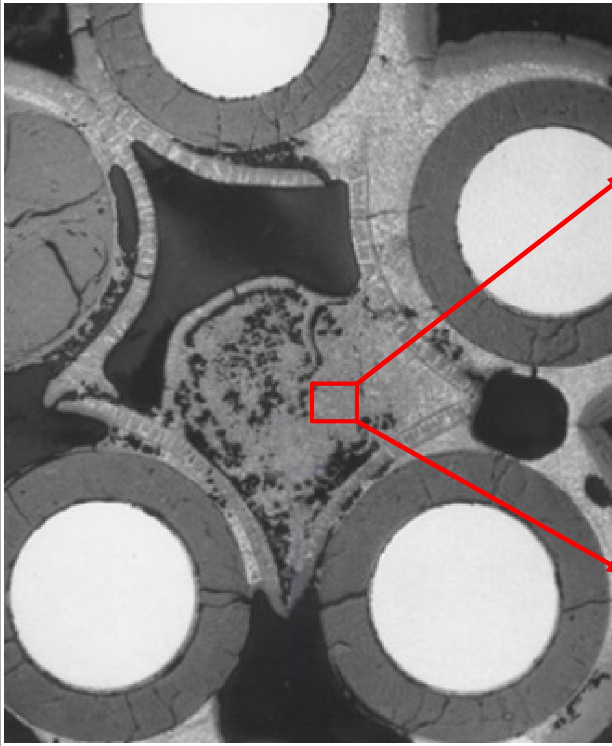


Molten pools frozen at middle and upper elevations of the PWR QUENCH-03 bundle flooded from the bundle bottom at $T_{pct} \approx 2350$ K by water with flow rate $F_q \approx 1$ g/s/rod

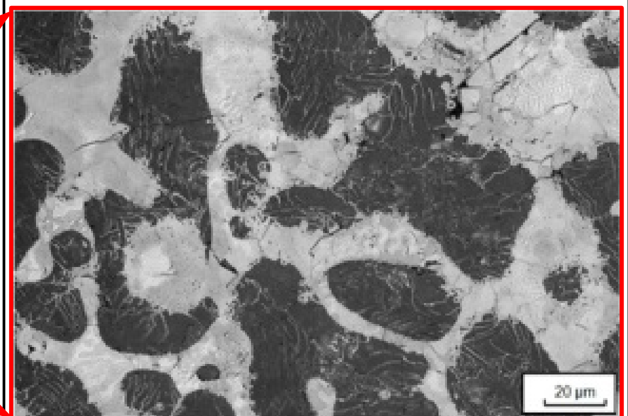
		
650 mm	**950 mm**	**1150 mm**

P. Hofmann et al., **Experimental and calculation results of the experiments QUENCH-02 and QUENCH-03**, FZKA-6295 (2000)

Analysis of the melt composition formed in the PWR QUENCH-02 bundle flooded from bottom at $T_{pct} \approx 2400$ K with flow rate $F_q \approx 1$ g/s/rod

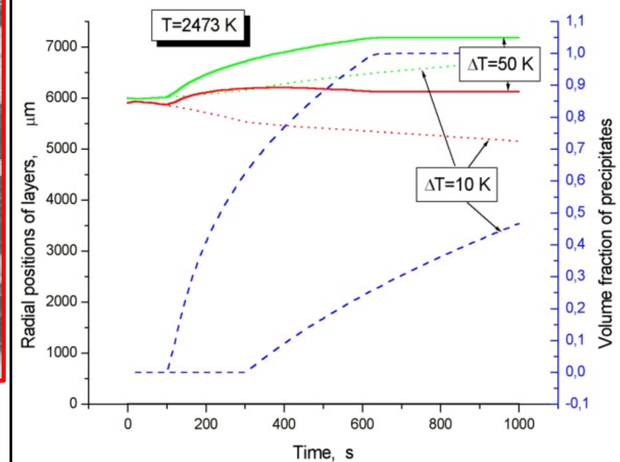


Post-test image of cross section of the QUENCH-02 bundle at elevation of 850 mm showing an oxidized molten pool surrounded by oxide



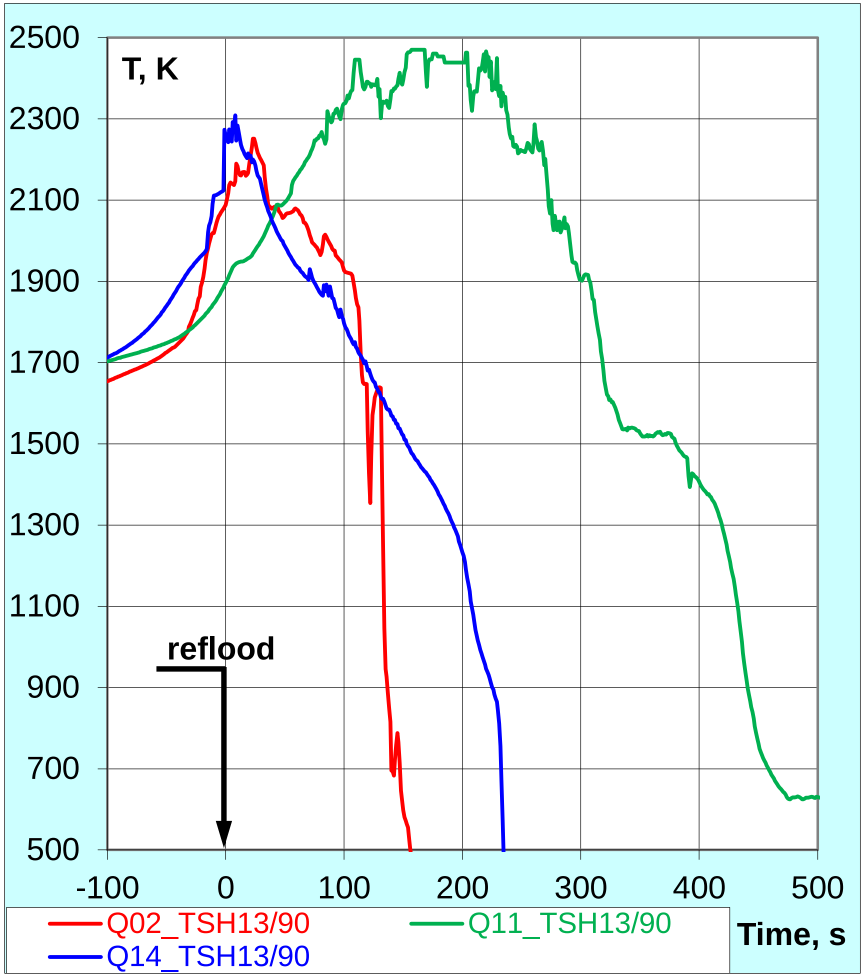
Ceramic precipitates inside QUENCH-02 molten pool, oxygen concentration 53 at% (image analysis): above saturation limit of 46%

M. Veshchunov et al., **Modelling of Zr-O and U-Zr-O melts oxidation and new crucible tests**, FZKA-6792 (2002)

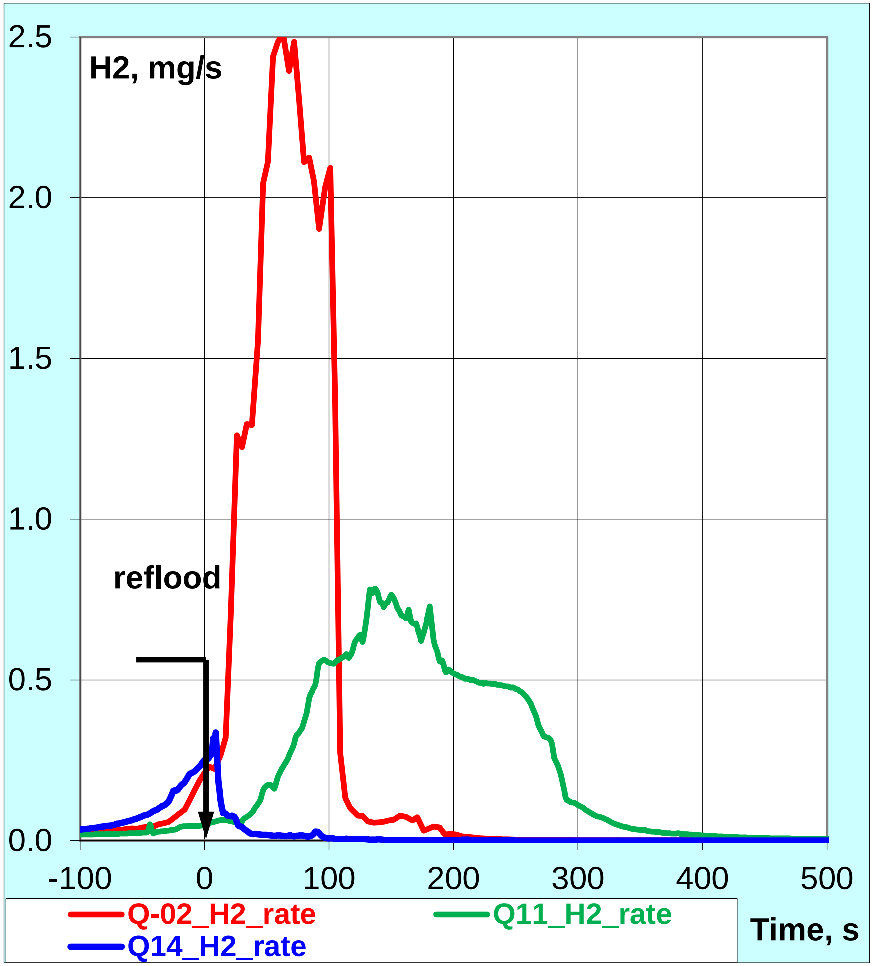


SVECHA simulation of Zr melt oxidation at 2473 K for two temperature drops in the boundary oxide layer ΔT = 10 K and 50 K for cylindrical molten pool with radius of 6 mm; solid and dotted curves: radial positions of internal (red) and external (green) oxide layer boundaries; dashed curves: volume fraction of precipitates

Hydrogen release
with (Q-02, Q-11) and without (Q-14) melt oxidation in steam



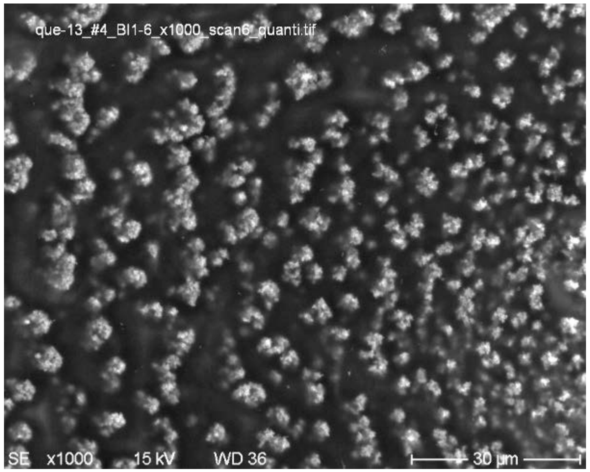
temperature histories

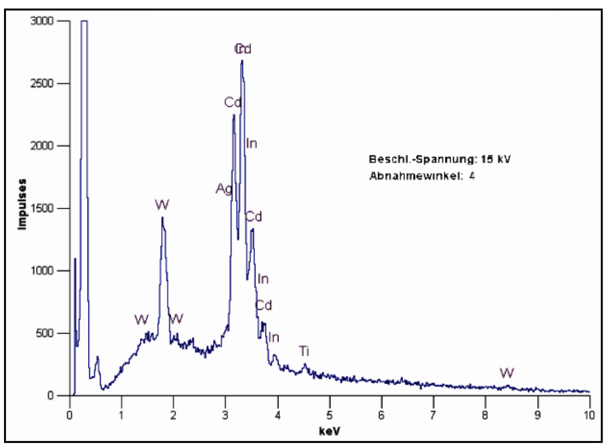


hydrogen releases

QUENCH-13: aerosol release after failure of AgInCd absorber rod

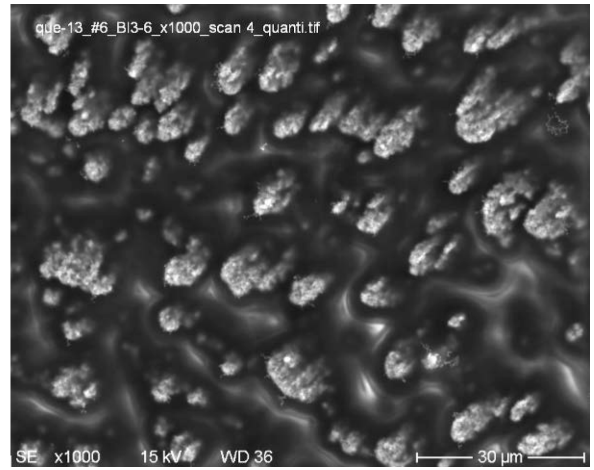
Sample PSI BI1/6 (D_{ae}=0.4-0.7 µm): collected after control rod failure

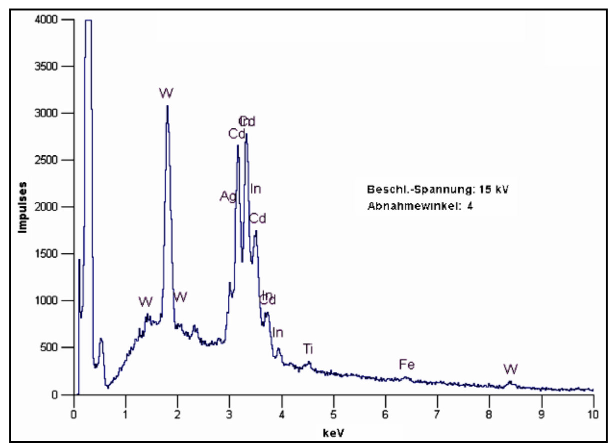




	Cd	In	Ag	W
wt%	42	41	2.5	14.5

Sample PSI BI3/6 (D_{ae}=0.4-0.7 µm): collected before reflood

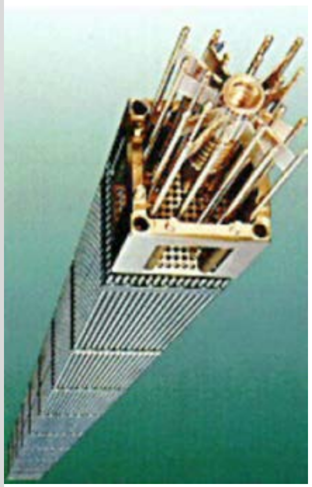




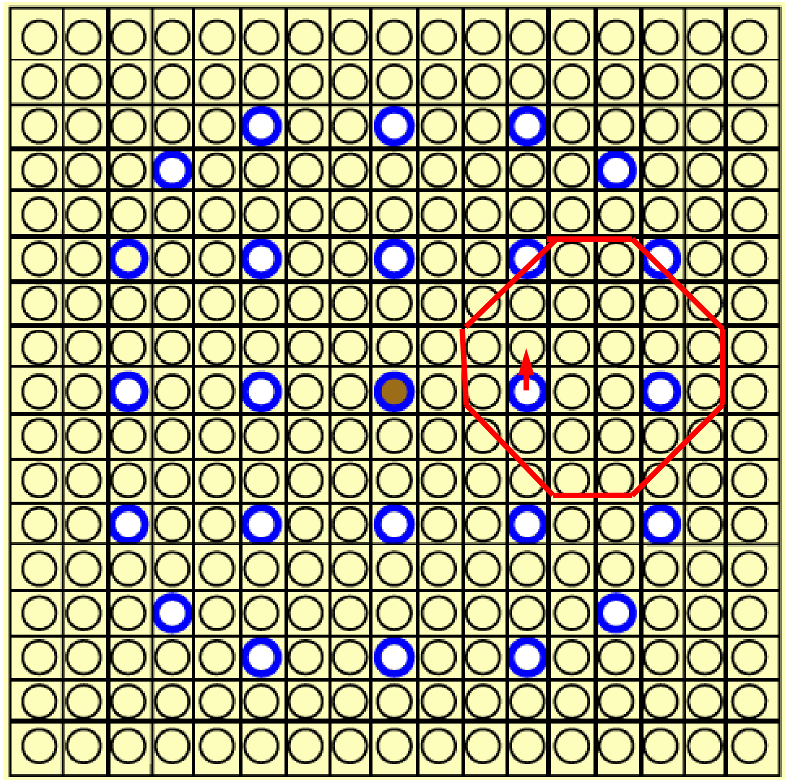
	Cd	In	Ag	W	Fe
wt%	33	31	8	27	1

T. Lind et al., **Aerosol behavior during SIC control rod failure in QUENCH-13 test**, JNM 397 (2010) 92–100

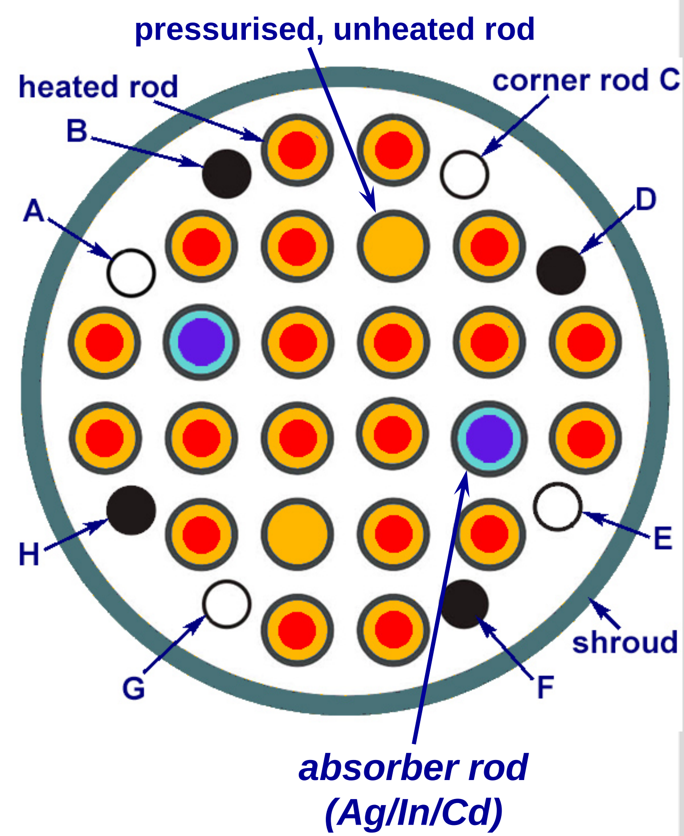
QUENCH-18 test on air ingress and aerosol release



fuel assembly **17x17**



proposed QUENCH test bundle

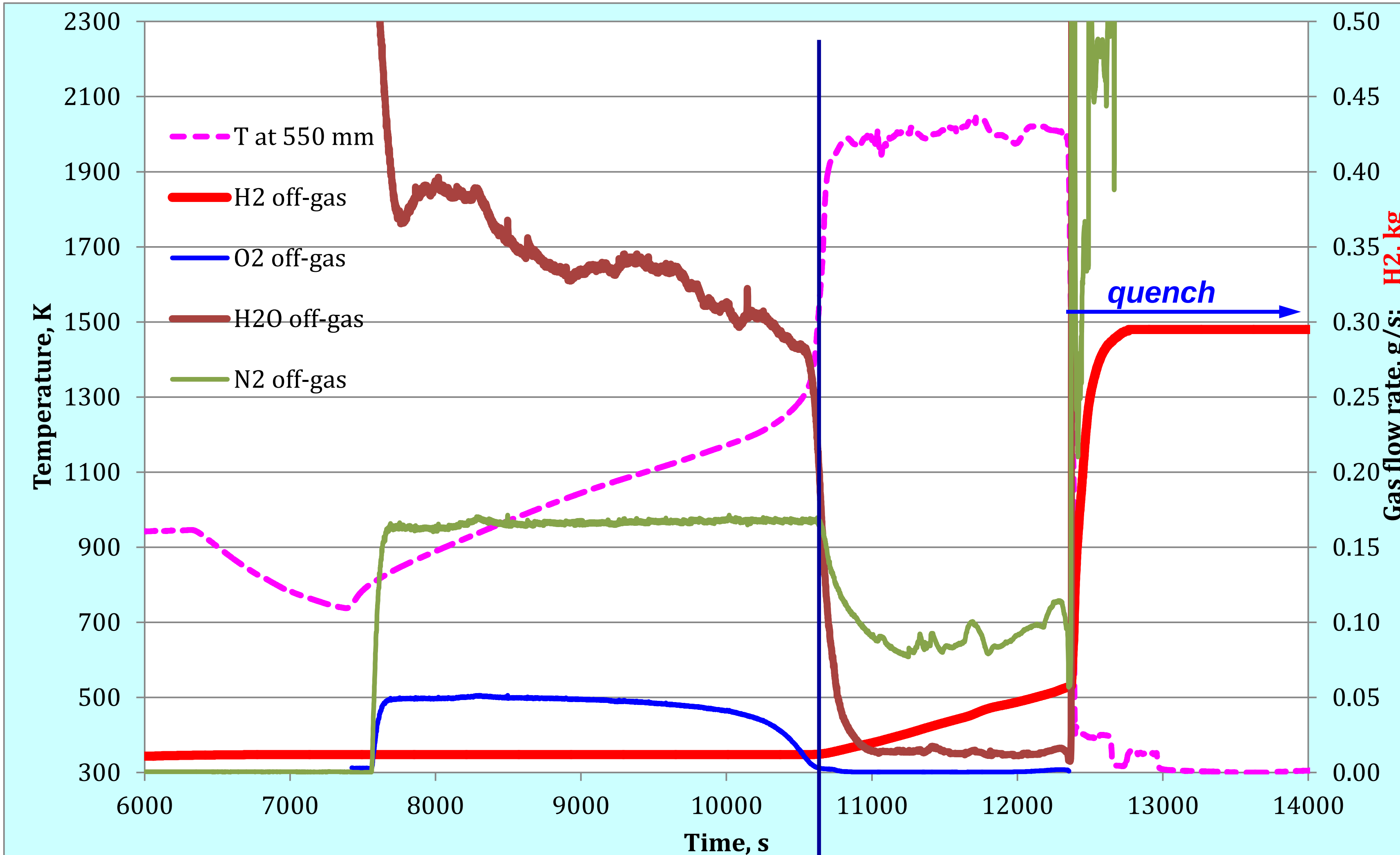


- fuel rod (264)
- guide tube for AgInCd control rod (24)
- instrument thimble

10:1 (fuel rods : guide tubes)

J. Stuckert et al., **First results of the QUENCH-ALISA bundle test**. NUTHOS-2019 (2019)

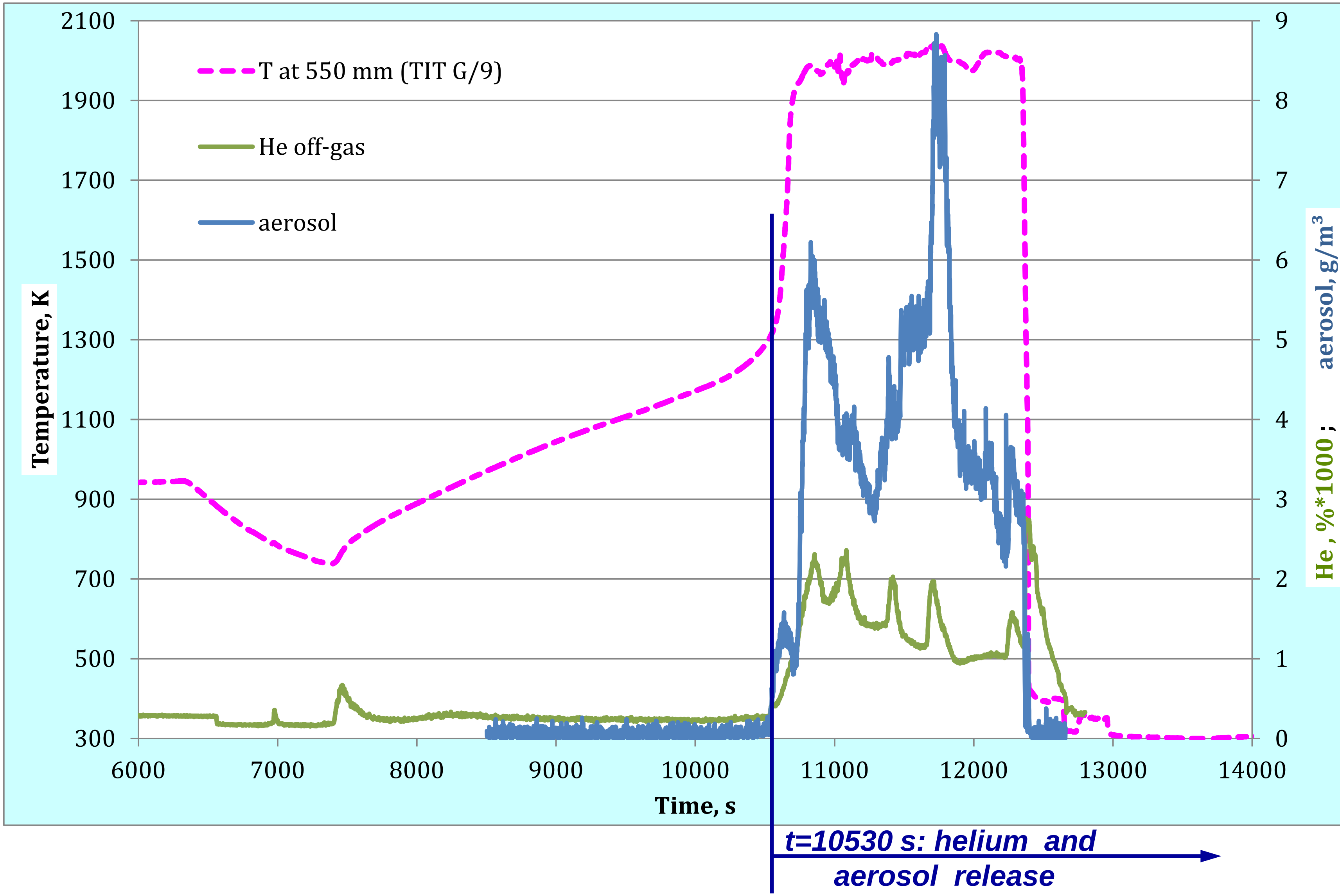
Outlet gas behaviour during air ingress in QUENCH-18: starvation phenomena



consumed oxygen: 100 g; consumed nitrogen: 120 g;
consumed steam: 450 g; released hydrogen: 45 g

t≈10600 s: oxygen starvation, H_2 increase
steam and nitrogen consumption

Failure of absorber rods and aerosol release in QUENCH-18

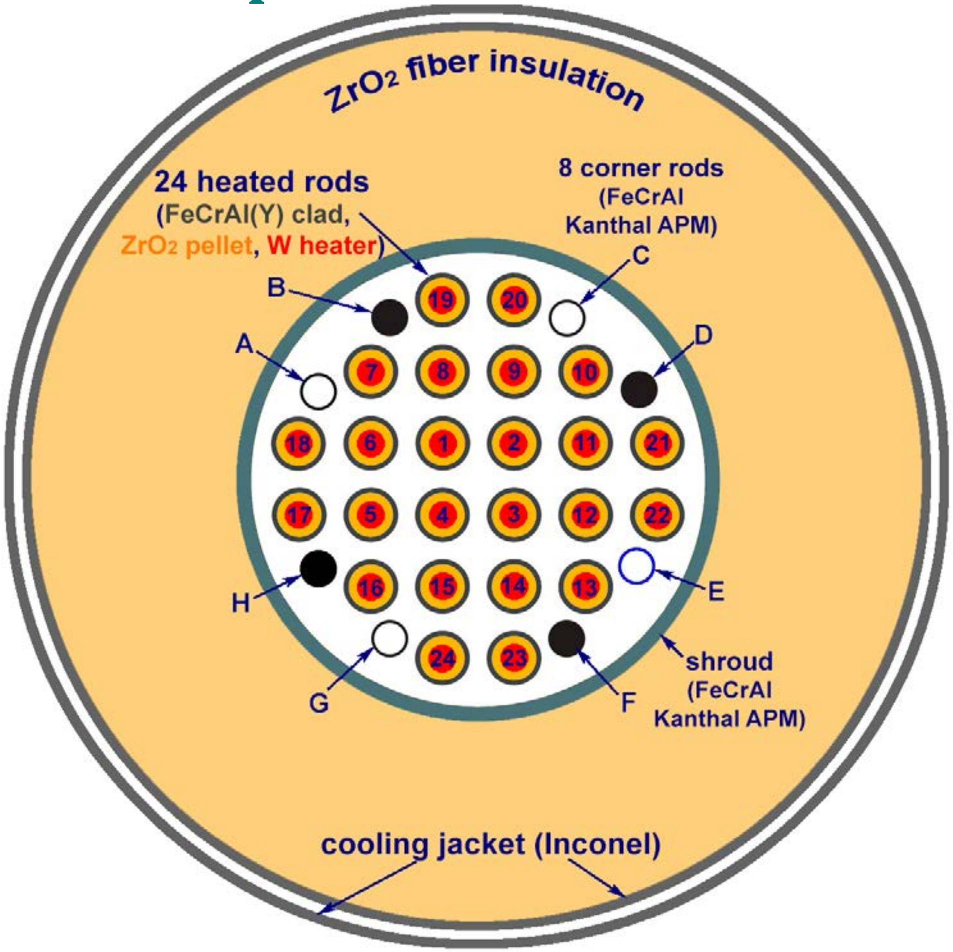


Aerosols in QUENCH-18: release of Cd, Ag, In

Element	Released, g	fraction of total mass in control rods, %
Cadmium	**9.0**	**14.3**
Silver	6.6	0.6
Indium	1.2	0.7
Total	*16.8*	*1.3*

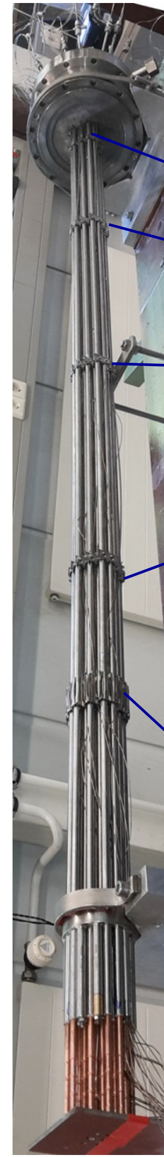
J. Kalilainen et al., **The measurement of Ag/In/Cd release under air-ingress conditions in the QUENCH-18 bundle test**. JNM 517 (2019), pp. 315-327

Composition of the test bundle QUENCH-19 (FeCrAl)

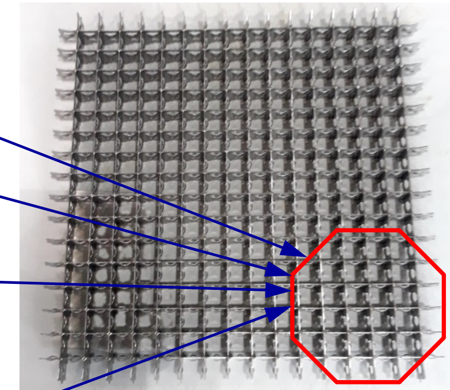


cross section
(arrangement the same as for QUENCH-15)

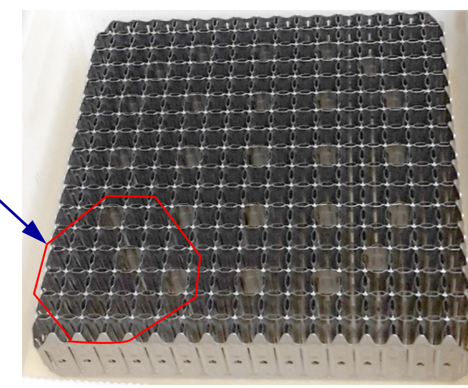
J. Stuckert et al., **First results of the bundle test QUENCH-19 with FeCrAl claddings**. QWS-24 (2018), Karlsruhe



test bundle (length 2m)

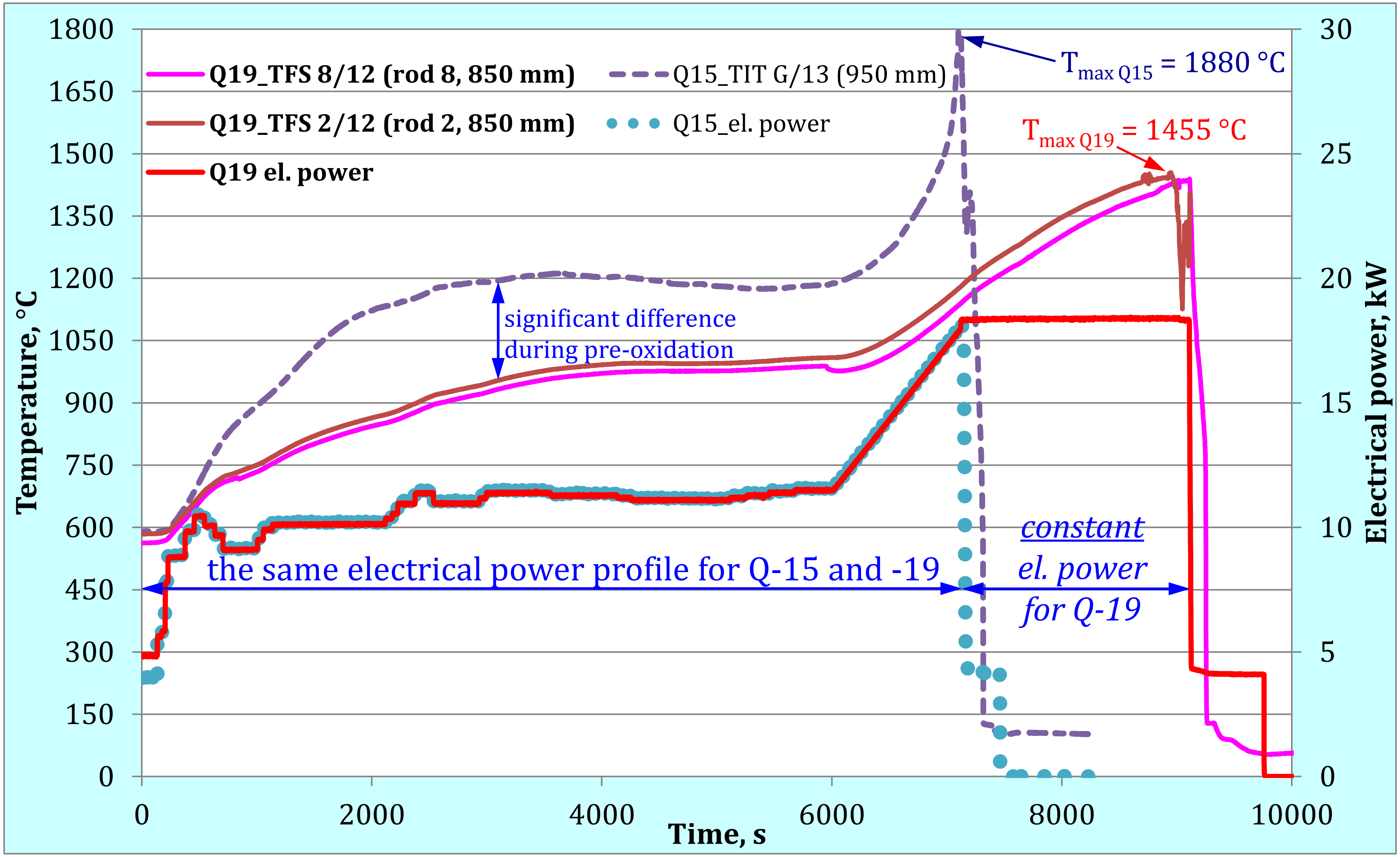


ORNL Kanthal AF **spacer grids**:
height 22 mm,
sheet thickness 0.5 mm



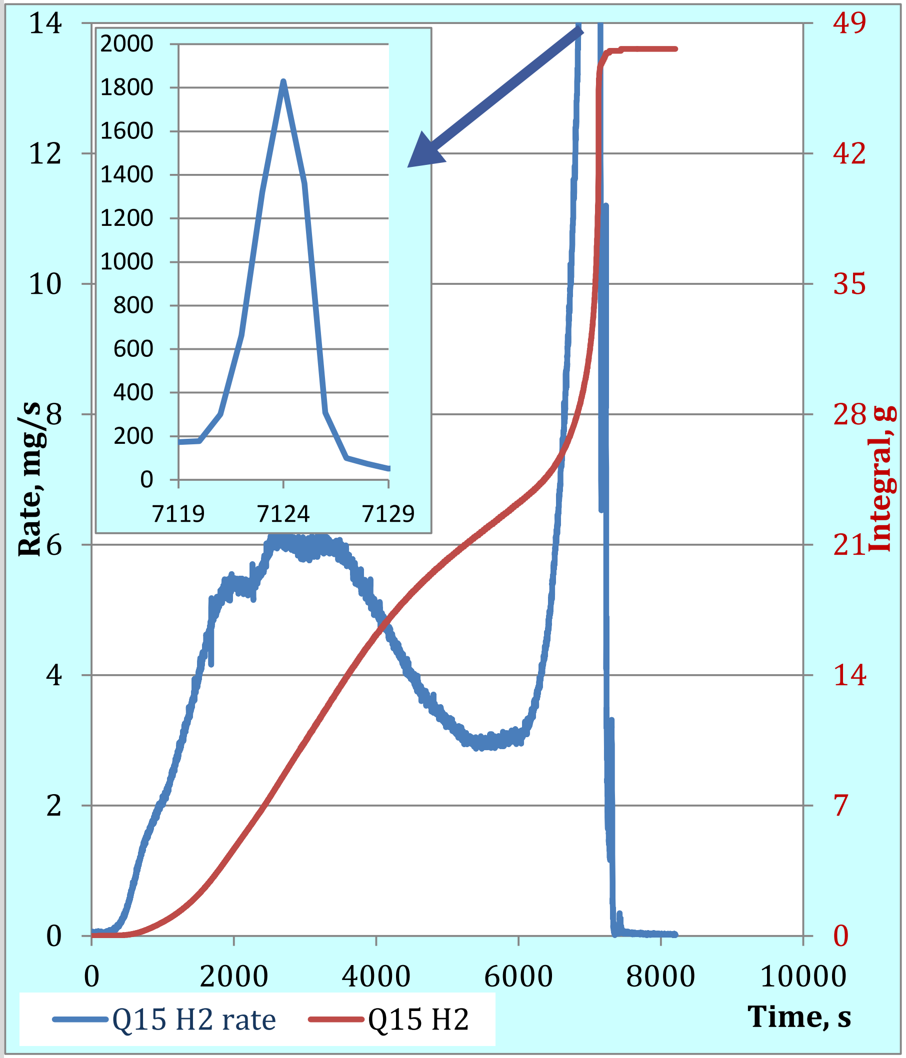
AREVA Inconel **spacer grid**:
height 45 mm,
sheet thickness 0.5 mm

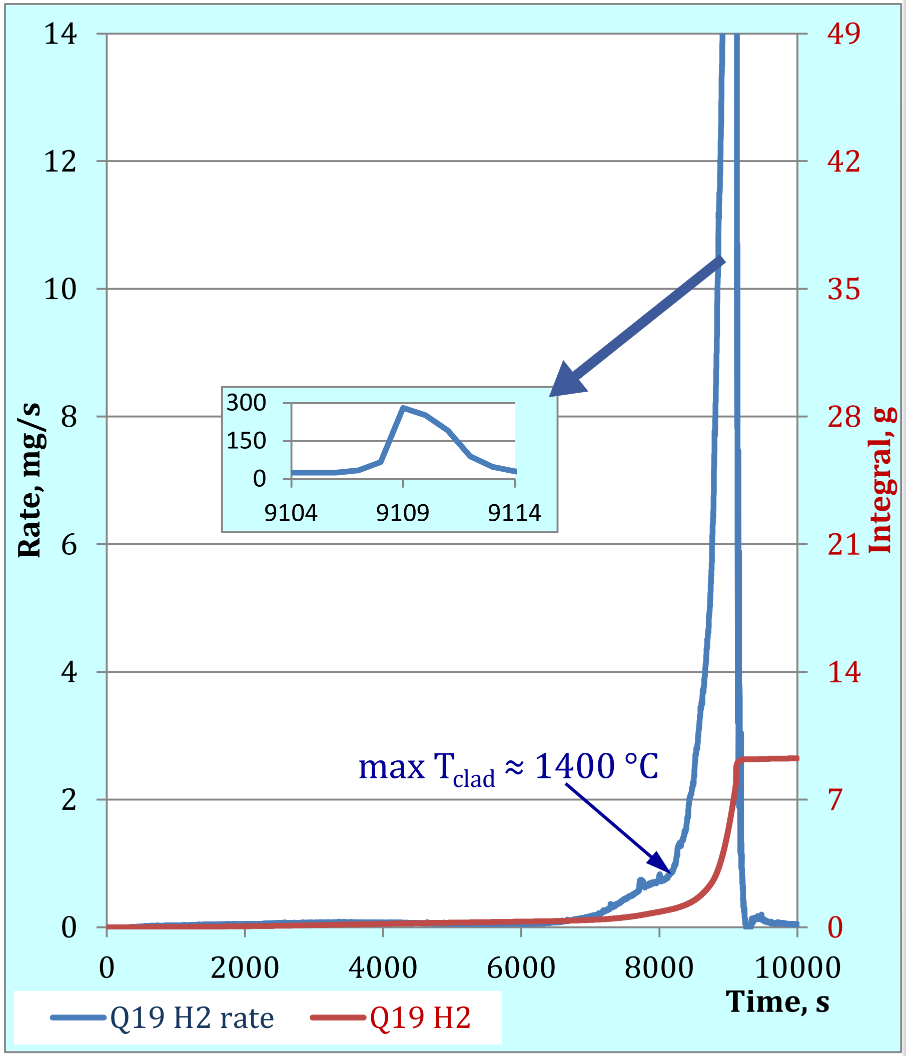
Test performance: comparison of QUENCH-15 (ZIRLO) and -19 (FeCrAl)



Energy release during Q15 pre-oxidation (i.e. until 6000 s): electrical $E_e = 63.7$ MJ, chemical $E_{ch} = 3.5$ MJ $\Rightarrow E_{ch} \ll E_e$

Hydrogen release in QUENCH-15 (ZIRLO) and -19 (FeCrAl)



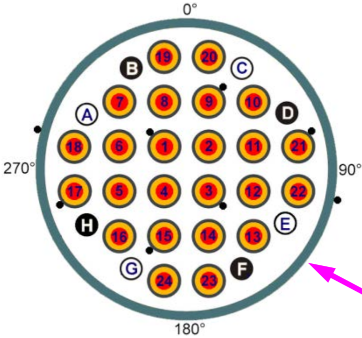


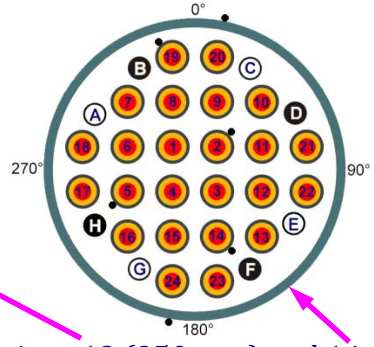
QUENCH-15: max rate 1830 mg/s; totally 47.6 g H_2

QUENCH-19: max rate 280 mg/s; totally 9.2 g H_2

QUENCH-19 bundle at elevations between 900 and 1100 mm: cladding damages by molten thermocouple steel (AISI 304) sheaths

Karlsruhe Institute of Technology

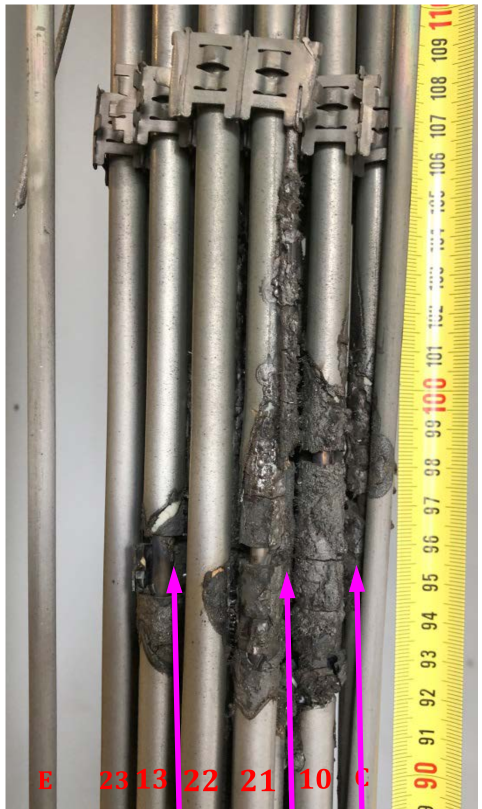




Positions of TC (•) at elevations 13 (950 mm) and 14 (1050 mm)

- the melting range of 304 steel is 1400…1450°C
- the melting range of FeCrAl alloys is 1500…1520°C

0°: TFS 9/13 and 19/14

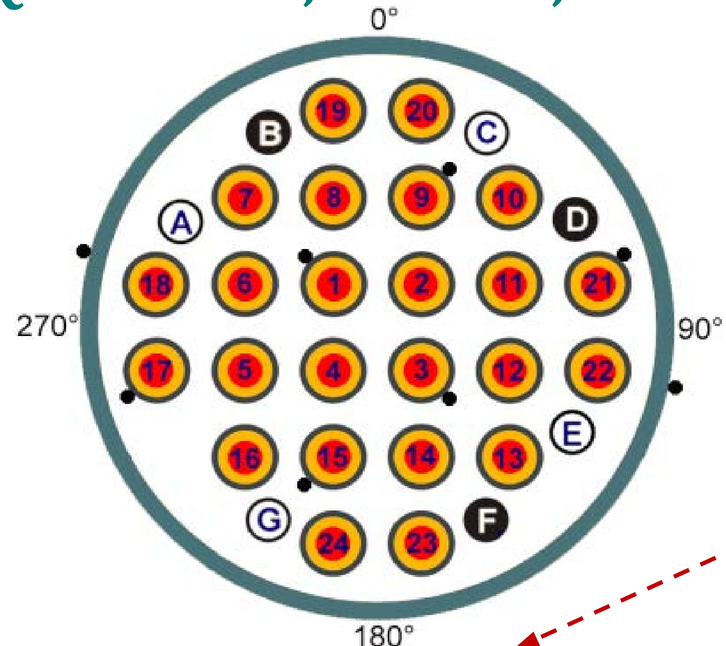


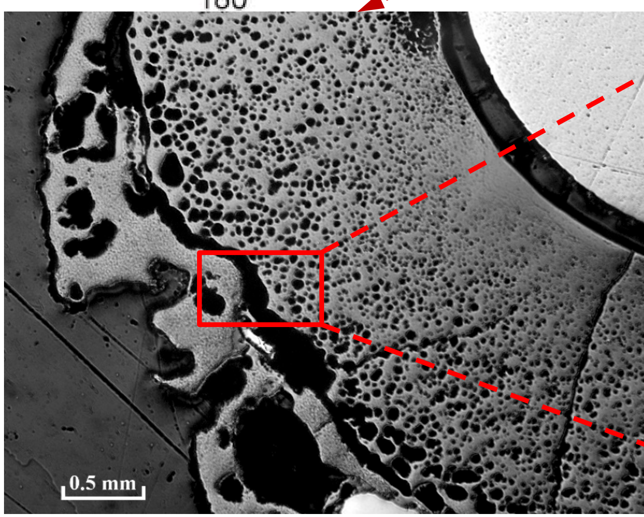
90°: TFS 3/13, 21/13, 9/13

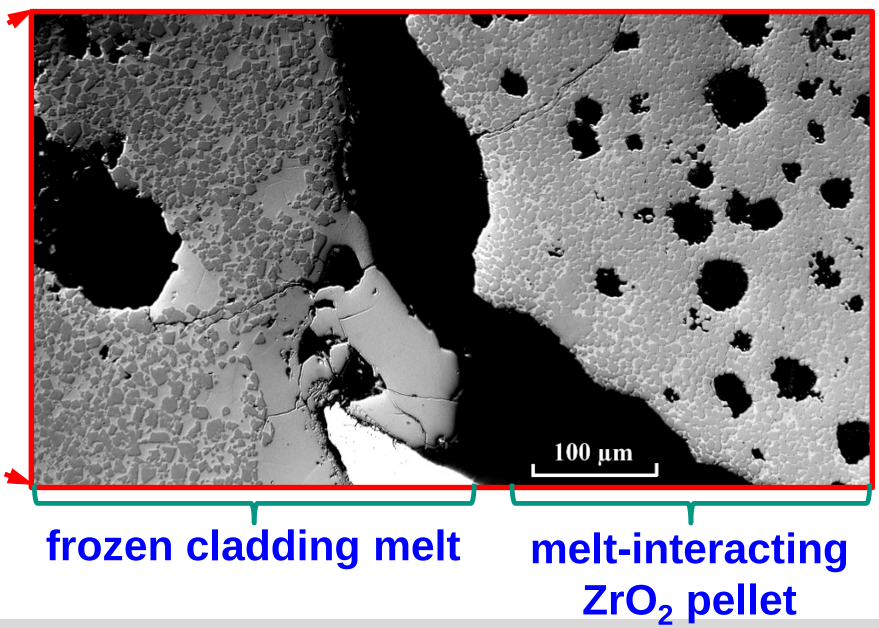
180°: TFS 15/13 and 14/14

270°: TFS 1/13, 15/13

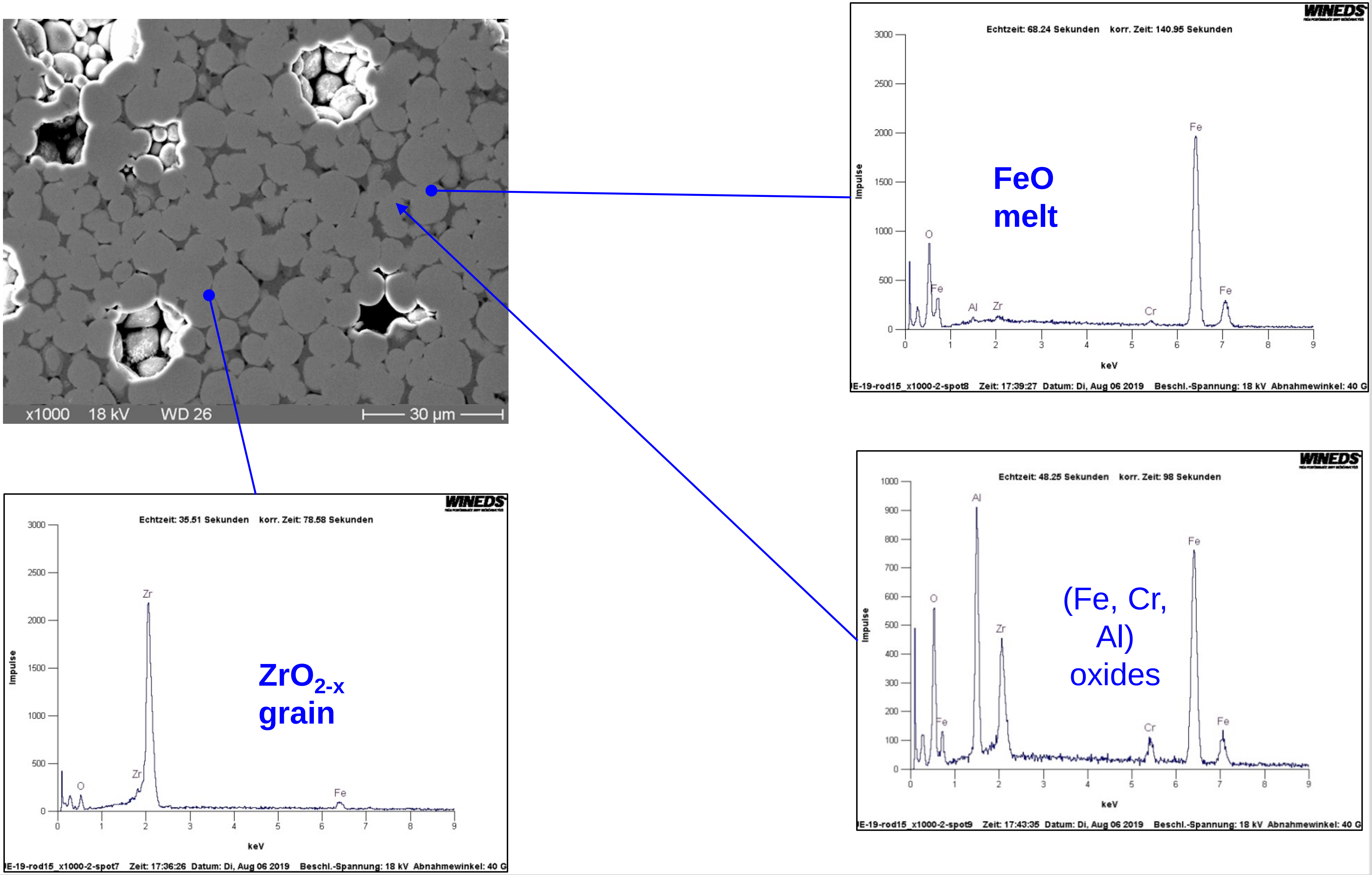
QUENCH-19, 950 mm, rod 2: molten claddings of central rods



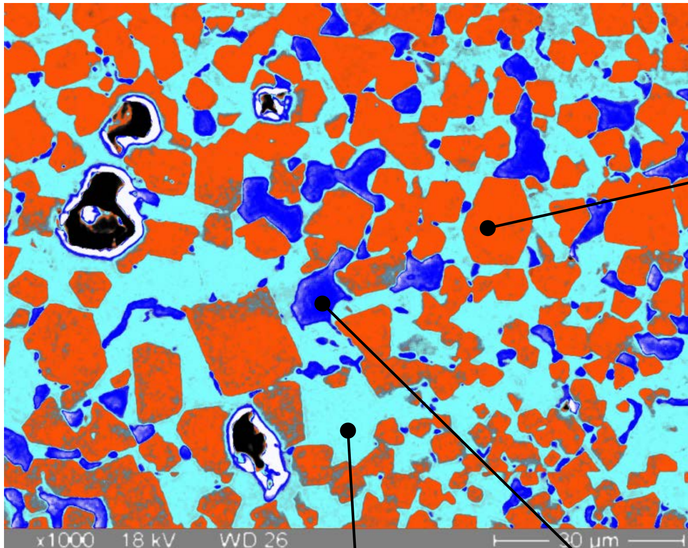


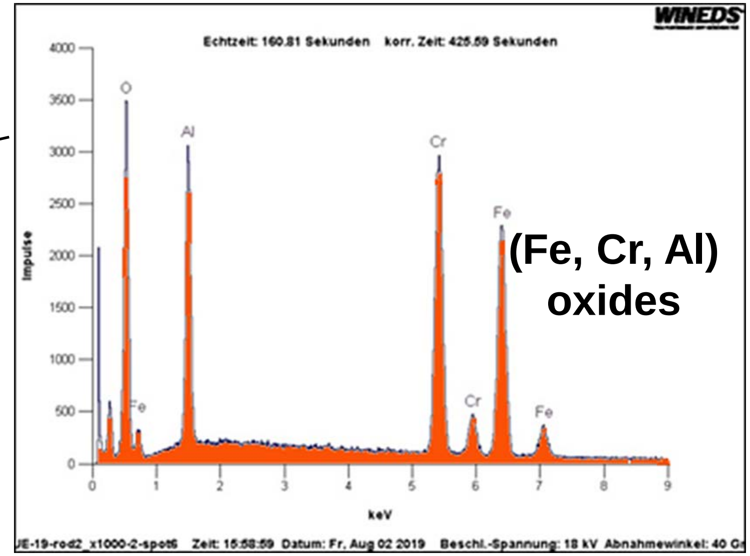


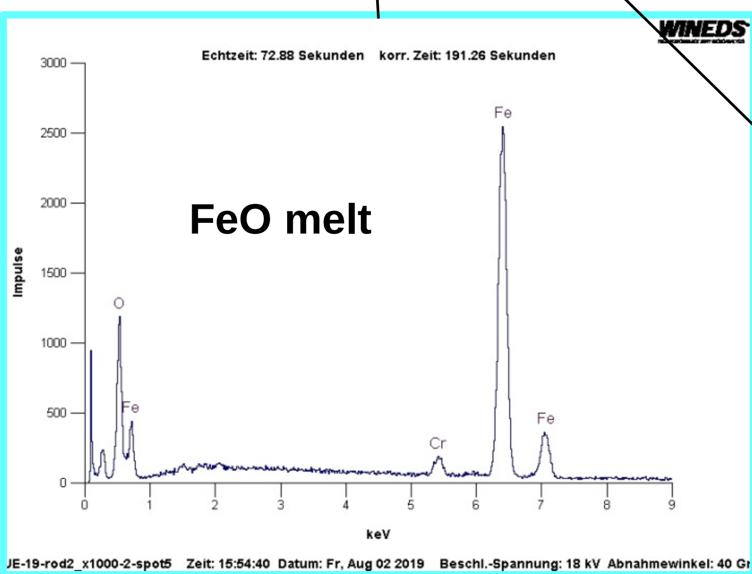
QUENCH-19, 950 mm: penetration of FeO melt into pellet

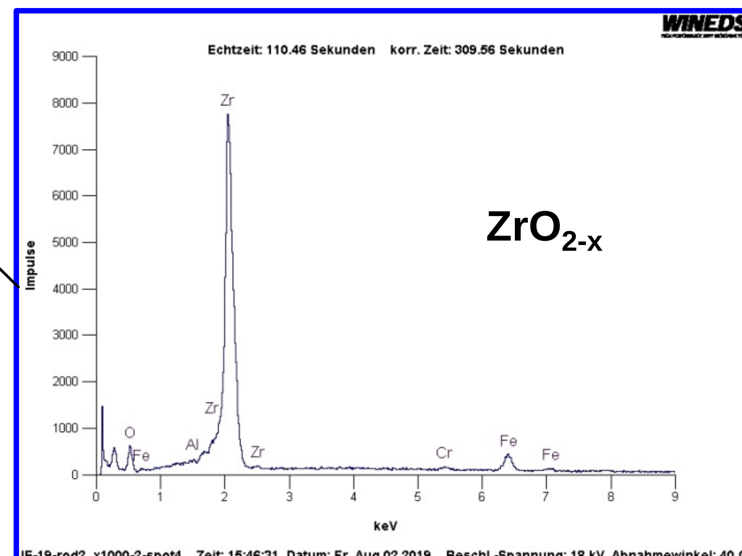


QUENCH-19, 950 mm: oxide precipitates inside molten FeO formed already at 1370 °C

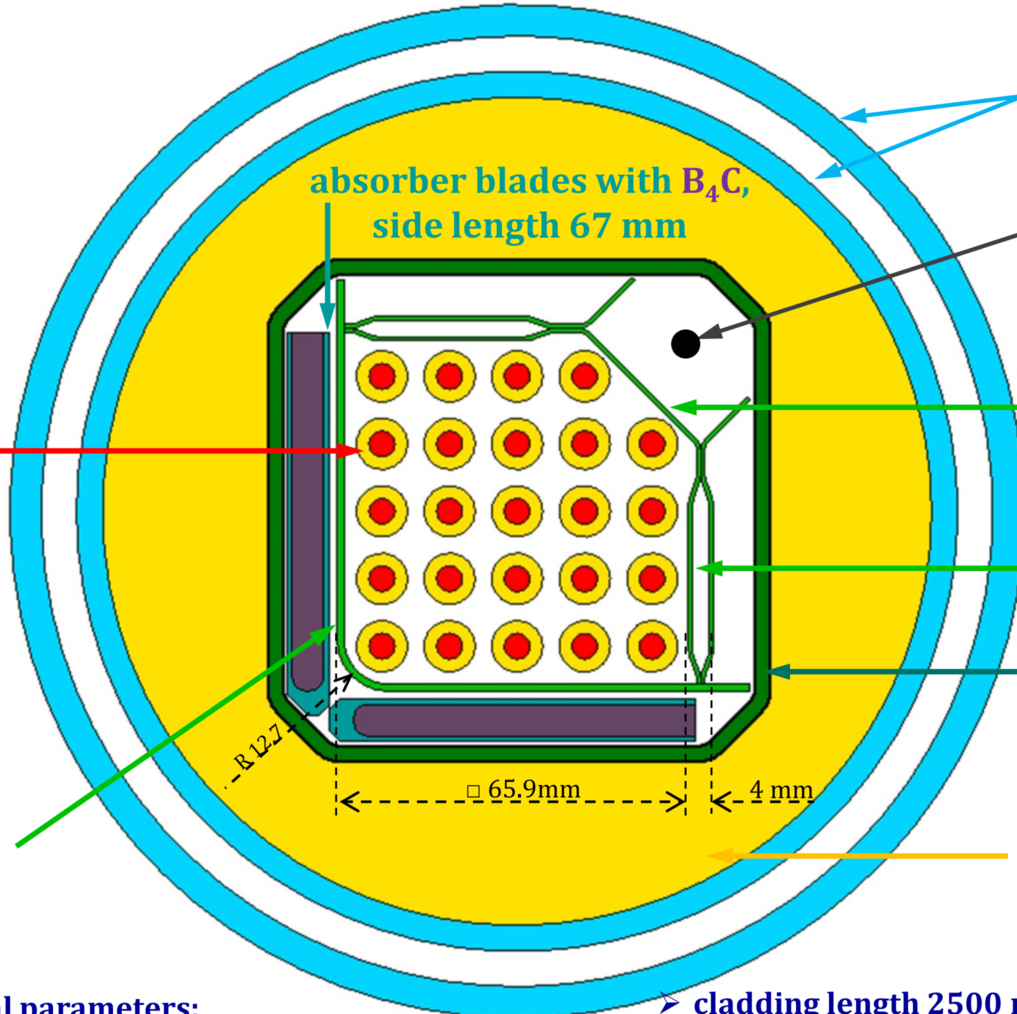








QUENCH-20: test bundle composition
¼ SVEA-96 OPTIMA2 assembly (BWR)

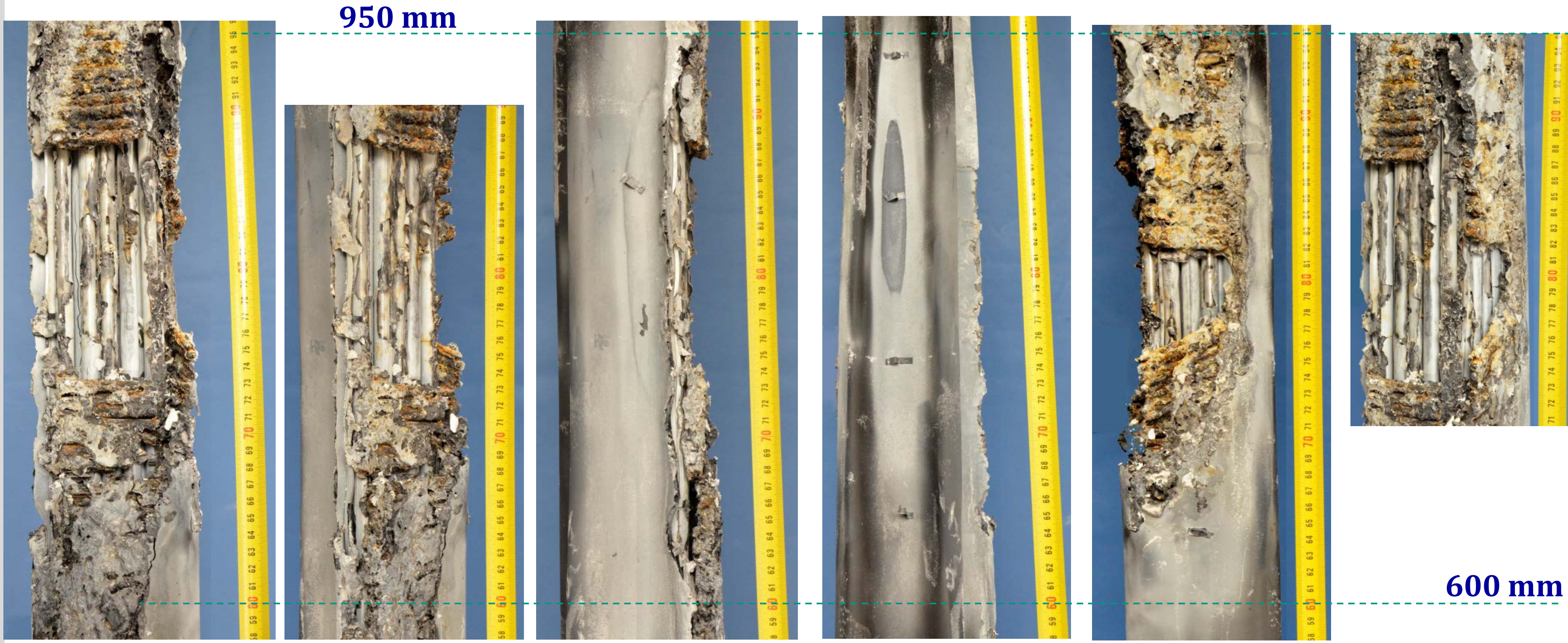


Geometrical parameters:

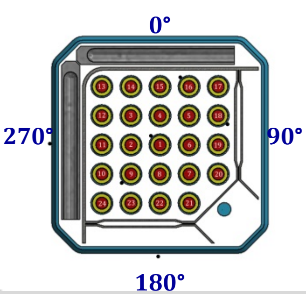
- **bundle pitch 12.898 mm;**
- **outer diameter of claddings 9.84 mm;**
- **thickness of claddings 0.605 mm;**
- **absorber blades: thickness 8.05 mm**

- **cladding length 2500 mm**
- **absorber and cannel box lengths 1600 mm**
- **water gap between channel box and absorber blade 2.5 mm (**nominal inter-assembly gap in BWR-PROTEUS core is 13.8 mm -> water gap 2.875 mm**)**

QUENCH-20 bundle surrounded by shroud: post-test view

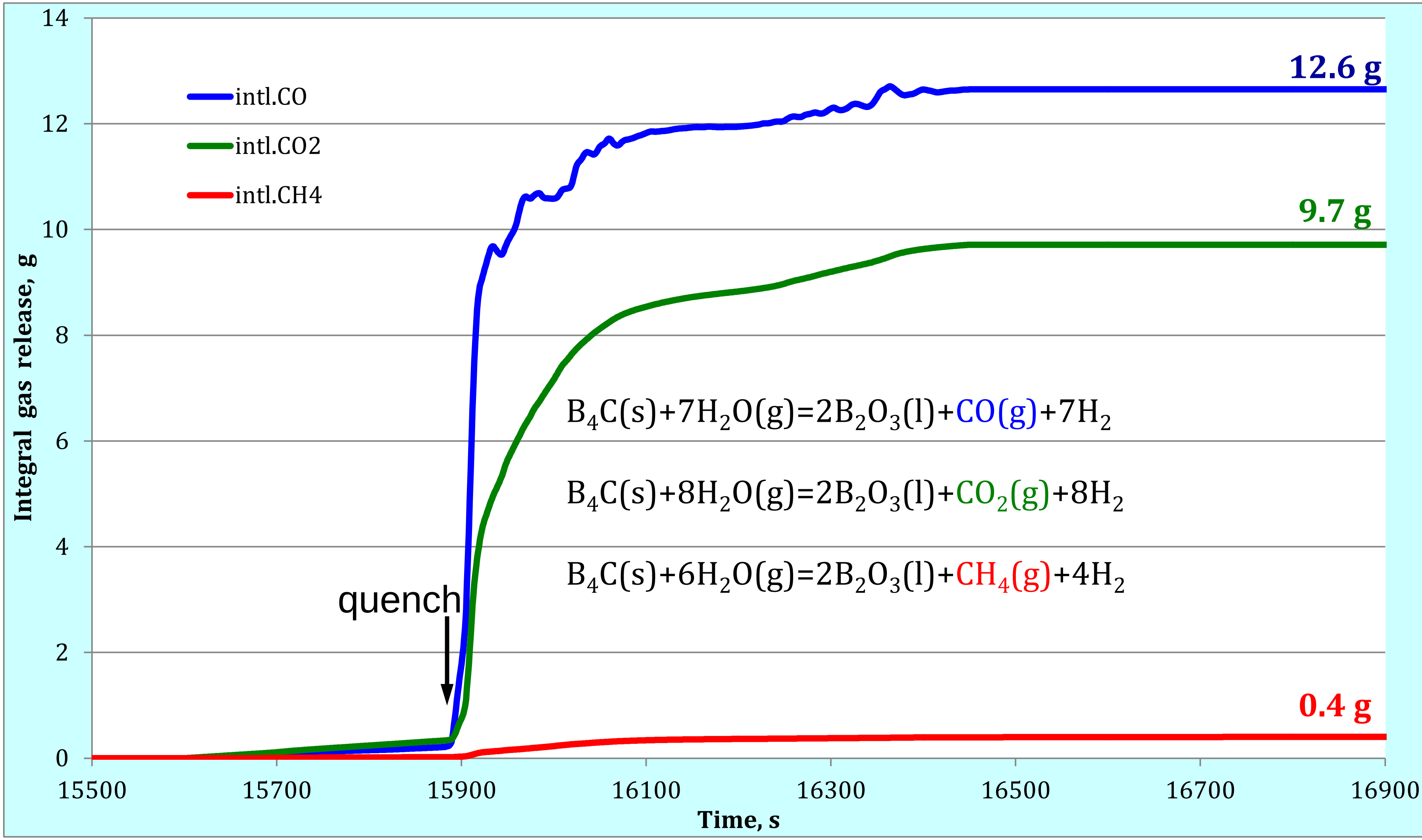


0° 45° 90° 180° 270° 315°



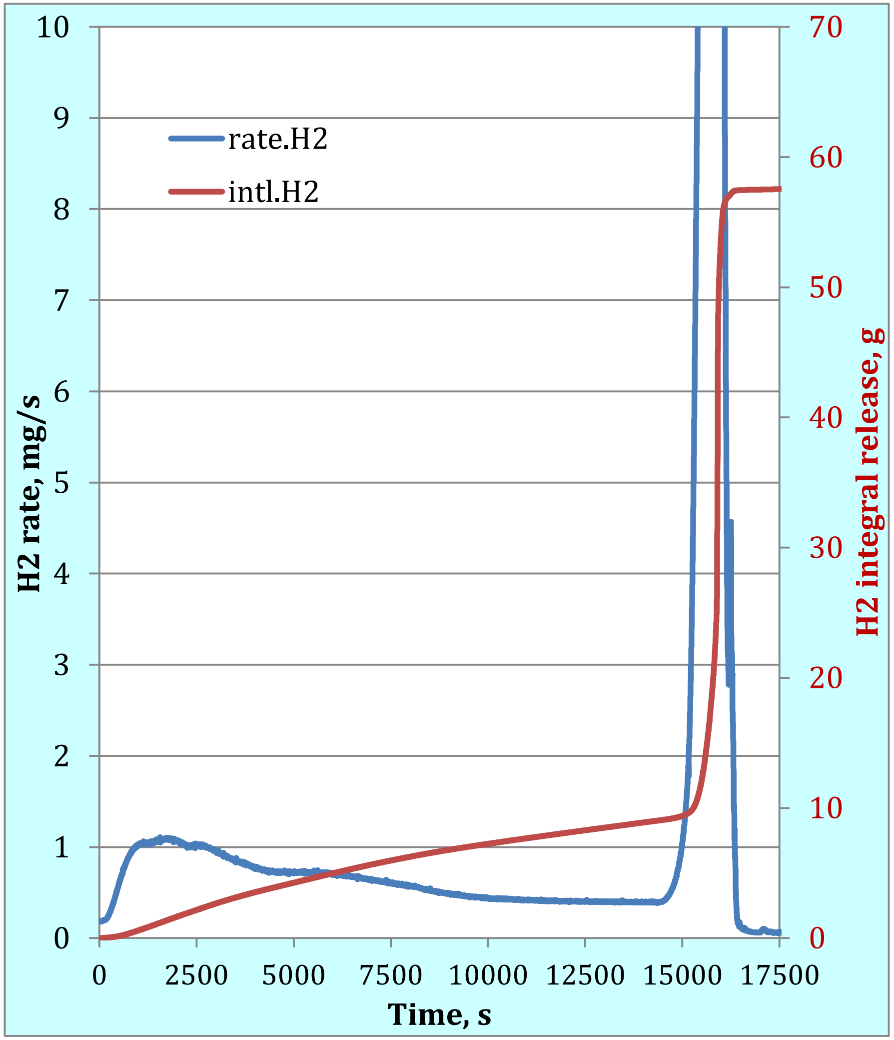
Strong degradation of absorber blades, channel box and shroud between elevations 650 and 950 mm at angle positions 0° and 270°

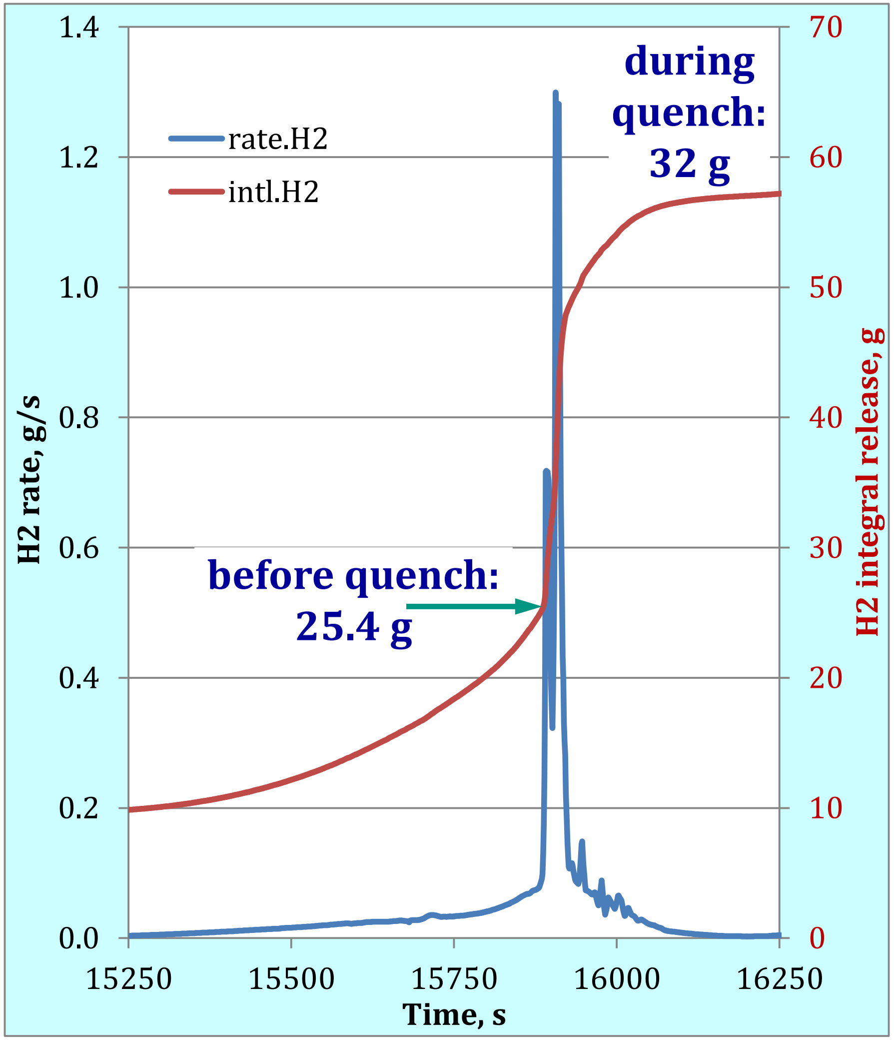
QUENCH-20: reaction of B_4C with steam, integral gas release



According to CO_x and CH_4 release: corresponding mass of B_2O_3 is 96.8 g; H_2 is 10.0 g

QUENCH-20: hydrogen release





H_2 release during the whole test: 57.4 g;
before quench – interaction of steam with Zry,
during quench – steam interaction with Zry and absorber

H_2 release during quench:
22 g (from Zry and molten steel) +
+ 10 g (from B_4C)

Database: contents

- Core damage state and evolution
- Temperatures, Heat-up rates Steam starvation prior to reflood(?)
- Reflood medium and mass flow rate
- Hydrogen data
- Fraction of Zry consumed for H_2 production
- PARAMETER: top, top + bottom flooding

W. Hering et al., **Integration of New Experiments into the Reflood Map**, ICAPP 2015 Paper 15465

Core damage evolution in reflood experiments	Reactor type	Pressure at reflood	Intact / loc. ballooning	Absorber damaged	Fuel rod damaged	Metallic melt relocated	Local debris	Local debris / pool	Global debris / pool	Material relocation ->LH	PCT prior to reflood / during test	Heat-up rate	Steam starvation prior to reflood	Reflood medium	Reflood mass flow rate (RMFR)	Hydrogen before quench	Corrected H2 mass during quench	H2 due to facility effects	Total measured Hydrogen mass	Corrected fraction of total H_2 mass released during quench	Original fraction of total H_2 mass released during quench	Fraction of available Zry mass consumed for H2 production
Data source			0	1	2	3	4	5	6	7	K	K/s			g / s*rod	g	g	g	g	%	%	%
CODEX 3/1	V	L									1420 / 1430	0,3		W	0,9	?	?	?	?	?		?
CODEX 3/2	V	L									1773 / 1923	0,6		W	0,9	1	0	?	1	<5		<5
PARAMETER 2	V	L	B								1700 /~1700	?	No	W	5	---	---	?	---	---		---
PARAMETER SF1 (top)	V	L						Tiny			2123 /~2300	2	No	W	1,4	20	54	17	91	73	78	60
PARAMETER SF2 (t+b)	V	L									1770 / 1850	0,2	No	W	5	23,5	1,5	0	25	6	6	
PARAMETER SF3 (top)	V	L									1870 / 1900	0,3	No	W	1,4	31	4,5	0	35,5	13	13	
PARAMETER SF4 (air)	V	L									1900 / 2300	"	Air	W	3,2	21	66	20	107	76	80	
QUENCH IBS05	P	L									1700 / 1750	?	---	W	2,6	20	33	5	58	62	66	34
QUENCH-01	"	L									1830 / 1900	0,7	No	W	1,8	36	1	2	39	3	8	24
QUENCH-02	"	L									2470 / 2500	"	No	W	1,7	20	109	31	160	84	88	83

Database: (cont.)

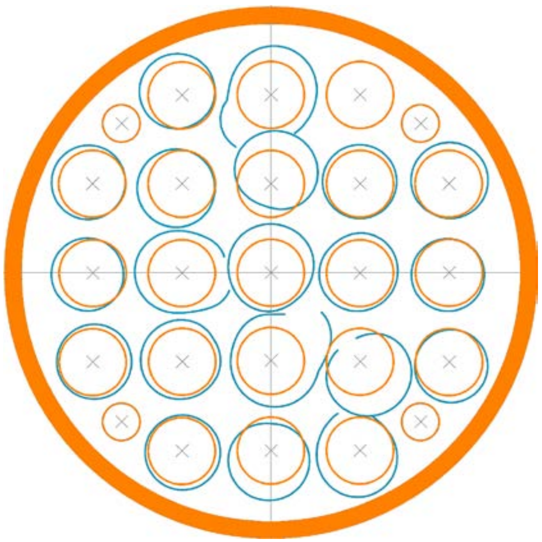
- ZIRLO™ and M5® claddings
- QUENCH-12: WWER
- QUENCH-17: DEBRIS

Core damage evolution in reflood experiments	Reactor type	Pressure at reflood	Intact / loc. ballooning	Absorber damaged	Fuel rod damaged	Metallic melt relocated	Local debris	Local debris / pool	Global debris / pool	Material relocation ->LH	PCT prior to reflood / during test	Heat-up rate	Steam starvation prior to reflood	Reflood medium	Reflood mass flow rate (RMFR)	Hydrogen before quench	Corrected H2 mass during quench	H2 due to facility effects	Total measured Hydrogen mass	Corrected fraction of total H_2 mass released during quench	Original fraction of total H_2 mass released during quench	Fraction of available Zry mass consumed for H2 production
Data source			0	1	2	3	4	5	6	7	K	K/s			g / s*rod	g	g	g	g	%	%	%
QUENCH-10 (Q-L1)	"	L									2180 / 2300	"	Air	W	1,8	46	5	2	53	10	13	33
QUENCH-11 (Q-L2)	"	L						Tiny			2300 />2500	0.6	Yes	W	0,6	9	83	48	140	90	94	59
QUENCH-12 (E110)	V	L									2060 / 2160	0,65	No	W	1,5	34	22	2	58	38	41	36
QUENCH-13	P	L		SIC							2086 / 2086	0,5	No	W	1,7	42	1	0	43	2	2	<40
QUENCH-14 (M5)	"	L									2053 / 2308	0,65	No	W	1,5	34	6	0	40	15	15	26
QUENCH-15 (ZIRLO)	"	L									2100 / 2130	0,65	No	W	1,5	40	8	0	48	17	17	31
QUENCH-16	"	L									1870 / 2400	"	Air	W	1,8	16	81	43	140	58	89	62
QUENCH-17 (DEBRIS)	"	L						Debris			1800 / 1800	"	No	W	0,3	110	1	0	111	1	1	71
QUENCH-L00	"	L									1330 / 1350	2,5	No	W	3,3	0,7	0,3	0	1	30	30	1
QUENCH-L01	"	L									1340 / 1370	6,5	No	W	3,3	0,7	0,0	0	0,71	1	1	0
QUENCH-L02	"	L									1300 / 1330	7,5	No	W	3,3	0,7	0,0	0	0,71	1	1	0

QUENCH-LOCA test matrix

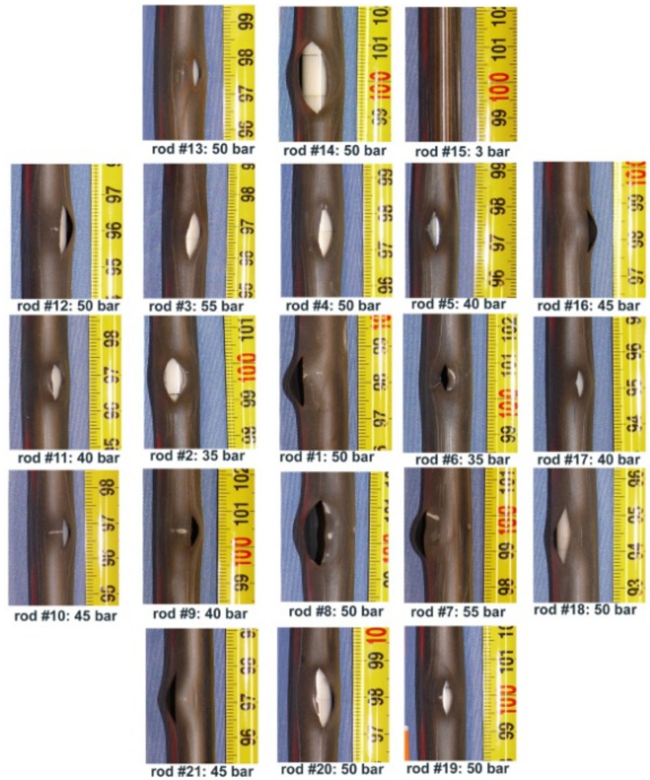
Test	Type of cladding tubes	Max heat-up rate, K/s	Max T on the end of heat-up, K	Duration of inner cladding oxidation at T > 1123 K, s	Secondary cladding hydriding	Post-test fracture due to secondary hydriding
QUENCH-L0 July 22, 2010 Commissioning test	Zry-4	2.5	1350	110	**yes**	**yes**
QUENCH-L1 Feb. 02, 2012 Reference test	Zry-4	7	1373	105	**yes**	**no**
QUENCH-L2 July 30, 2013	M5®	8	1373	88	**yes**	**no**
QUENCH-L3HT March 21, 2014	Opt. ZIRLO™	8	1623	252	**yes**	**yes**
QUENCH-L4 July 30, 2014	Pre-hydriding M5® (100 wppm H)	8	1385	100	**yes**	**yes**
QUENCH-L3 March 17, 2015	Opt. ZIRLO™	8	1346	84	**yes**	**no**
QUENCH-L5 Feb. 17, 2016	Pre-hydr. opt. ZIRLO (300 wppm H)	8	1257	45	**no**	**-**

QUENCH-LOCA program at KIT (2010-2016): Influence of hydrogen uptake after LOCA-burst on mechanical properties of claddings



ballooning and burst of claddings in comparison to pre-test fuel rod positions in the QUENCH-LOCA bundle: 25% blockage of cooling channel

J. Stuckert et al., **QUENCH-LOCA program at KIT on secondary hydriding**, NED 255 (2013), 185-201.



axial burst positions after bundle QUENCH-LOCA test with Zry-4 claddings

J. Stuckert et al., **Lessons learned from the QUENCH-LOCA experiments**, QWS-23 (2017).

secondary hydriding

hydrogen bands inside cladding detected with n^0-radiography: >2000 wppm hydrogen content

double rupture of cladding along hydrogen bands during tensile tests for C_H>1500 wppm

M. Grosse et al., **Secondary hydriding during LOCA – Results from the QUENCH-L0 test**, JNM 420 (2012), 575-582.

SUMMARY

• 21 bundle tests were performed under severe accident conditions with different cladding materials.

• Six parameters, enhancing hydrogen production during reflood, have been identified:

1) Low reflood flow rates < 1 g/s/rod (QUENCH-07, -08, -11);

2) Breakaway effect with weakness and spallation of protective oxide layer (QUENCH-12);

3) Steam starvation (QUENCH-09, -11, -16);

4) Nitride formation by air ingress with formation of very porous oxide layer during following reflood (QUENCH-10, -16);

5) High temperatures with melt relocation outside claddings and intensive melt oxidation (QUENCH-02, -03, -09, -11, -16, -18);

6) Eutectic interactions between B_4C, stainless steel and Zircaloy-4 leading to low melting point (QUENCH-07, -09, -20).

• Additionally to hydrogen source term, other phenomena on melt relocation, debris, and aerosol formation were investigated.

• 7 QUENCH-LOCA bundle tests with fresh and pre-hydrogenated different cladding materials (Zry-4, M5®, opt. ZIRLO™) were performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR. Post-test tensile experiments evidenced fracture at hydrogen bands (formed during secondary hydriding) for claddings with local hydrogen concentrations >1500 wppm.

Thank you for the fruitful cooperation and attention

http://quench.forschung.kit.edu/

http://www.iam.kit.edu/awp/666.php