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Institute for Applied Materials

Experimental program QUENCH at KIT on core degradation during reflooding under LOCA conditions and in the early phase of a severe accident

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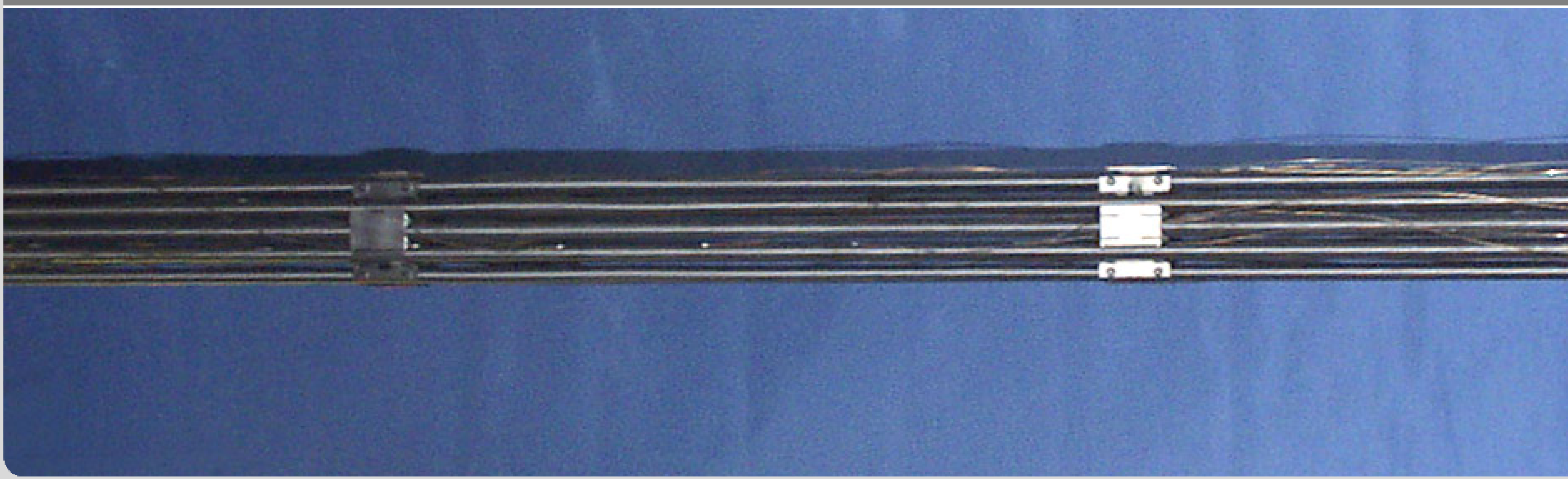
IAEA TM on DBA and SA

Institute for Applied Materials, IAM-WPT, IAM-AWP; Program NUKLEAR



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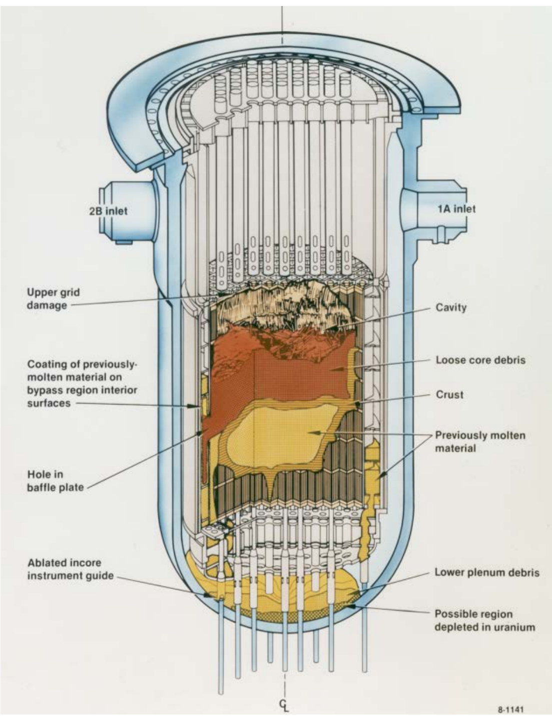
Investigations to core degradation:

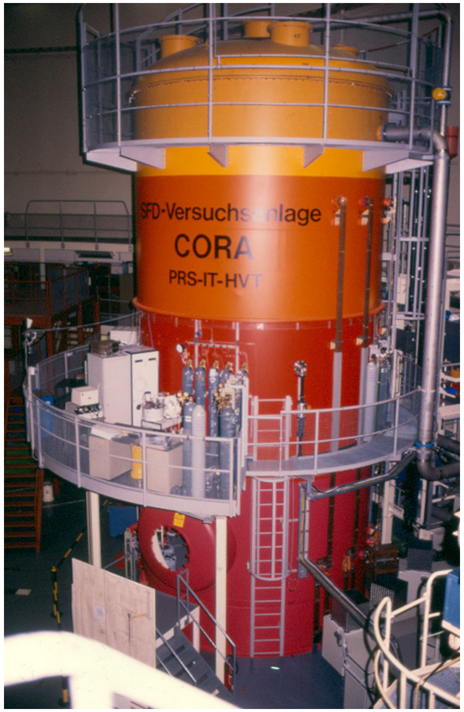
TMI-2-Accident ➡ CORA ➡ QUENCH

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

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

1997 ⟶ now, 17 Tests:
Hydrogen source term, Material behaviour





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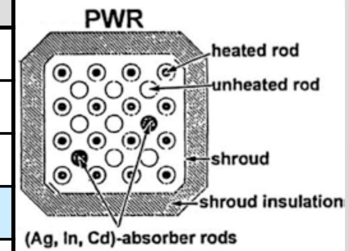
CORA test matrix: 19 bundle tests

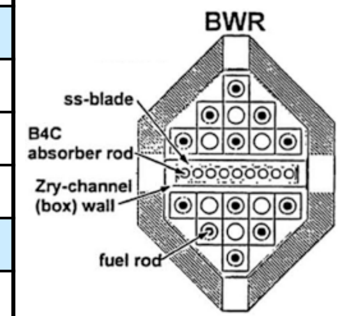
Test No.	Date of Test	Max Cladding Temperature	Absorber Material	Other Test Conditions
2	Aug. 6,1987	≈ 2000°C		U0$_2$ refer. Inconel spacer
3	Dec. 3,1987	≈ 2400°C		U0$_2$ refer. high temperature
5	Feb. 26,1988	≈ 2000°C	AgInCd	PWR-absorber
12	**June 9,1988**	**≈ 2000°C**	**AgInCd**	**quenching**
16	Nov. 14,1988	≈ 2000°C	B$_4$C	BWR-absorber
15	March 2, 1989	≈ 2000°C	AgInCd	rods with internal pressure
17	**June 29,1989**	**≈ 2000°C**	**B$_4$C**	**quenching**
9	Nov. 9,1989	≈ 2000°C	AgInCd	10 bar system pressure
7	Feb. 22, 1990	< 2000°C	AgInCd	57-rod bundle, slow cooling
18	June 21, 1990	< 2000°C	B$_4$C	59-rod bundle, slow cooling
13	**Nov. 15, 1990**	**≈ 2200°C**	**AgInCd**	**quench initiation at higher temperature; OECD/ISP**
29	Apr. 11, 1991	≈ 2000°C	AgInCd	pre-oxidized
31	July 25, 1991	≈ 2000°C	B$_4$C	slow initial heat-up (≈ 0.3 K/s)
30	Oct. 30, 1991	≈ 2000°C	AgInCd	slow initial heat-up (≈ 0.2 K/s)
28	Feb. 25, 1992	≈ 2000°C	B$_4$C	pre-oxidized
10	July 16, 1992	≈ 2000°C	AgInCd	cold lower end; 2 g/s steam flow rate
33	Oct. 1, 1992	≈ 2000°C	B$_4$C	dry core conditions, no extra steam input
W1	Feb. 18, 1993	≈ 2000°C		WWER-test
W2	Apr. 21, 1993	≈ 2000°C	B$_4$C	WWER-test with absorber

Initial heat-up rate ≈ 1.0 K/s. Steam flow rate, PWR: 6 g/s, BWR: 2 g/s.

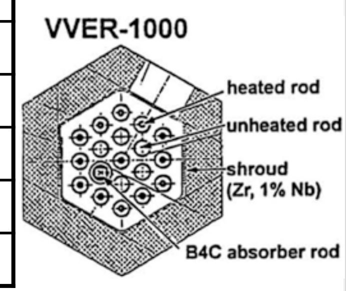
Quench rate (from the bottom) ≈ 1 cm/s.



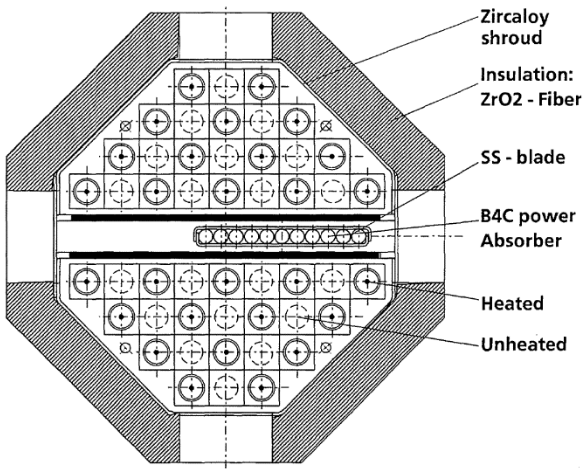
11 Tests



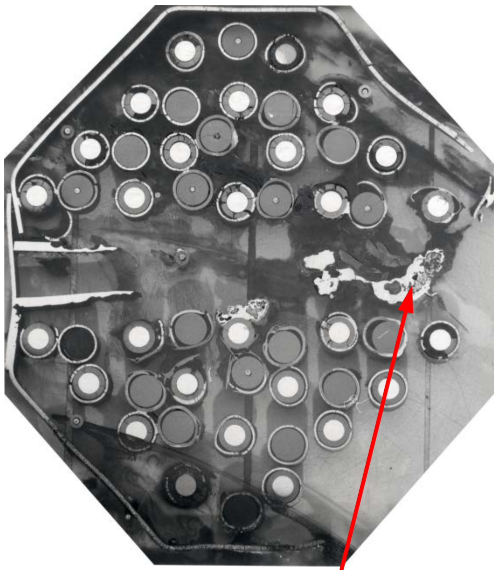
6 Tests



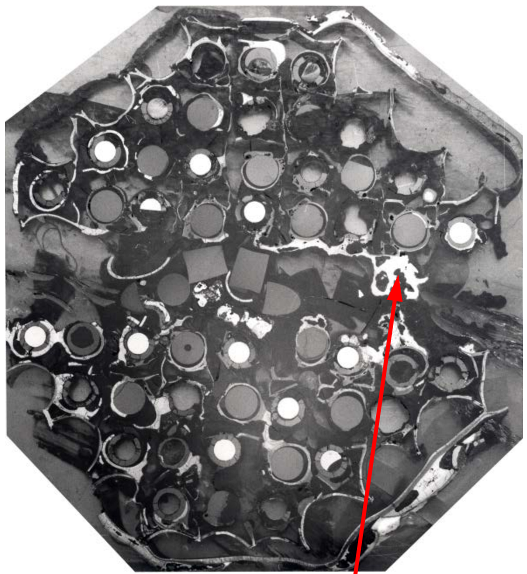
2 Tests



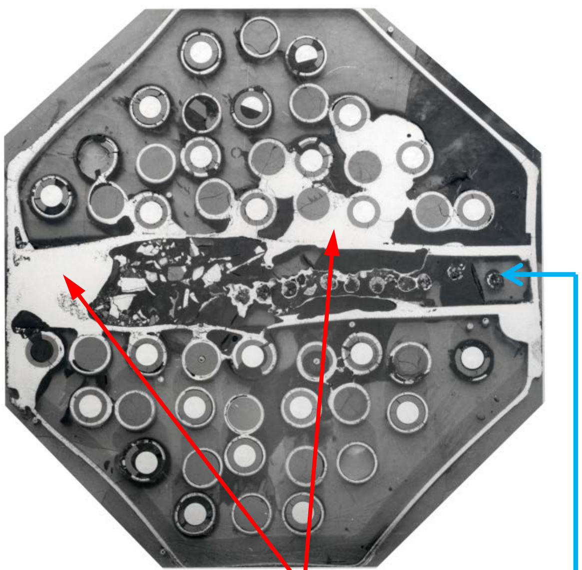
CORA-18: large BWR bundle



874 mm: remnants of B_4C-SS eutectic melt formed at T>1200°C



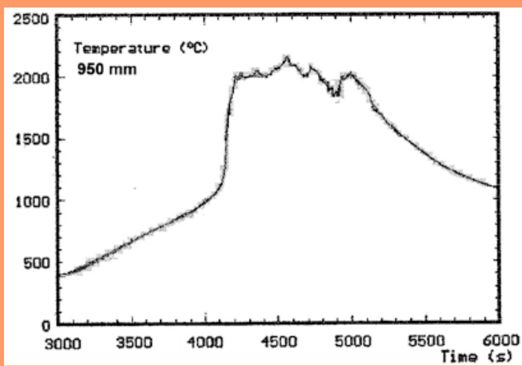
560 mm: 1) remnants of B_4C-SS eutectic melt; 2) strong degraded fuel rods (U-Zr-SS-O melt)

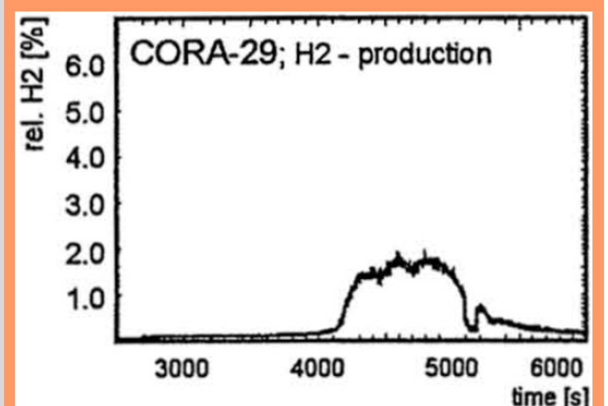


269 mm: 1) melt relocated from upper elevations; 2) degraded absorber

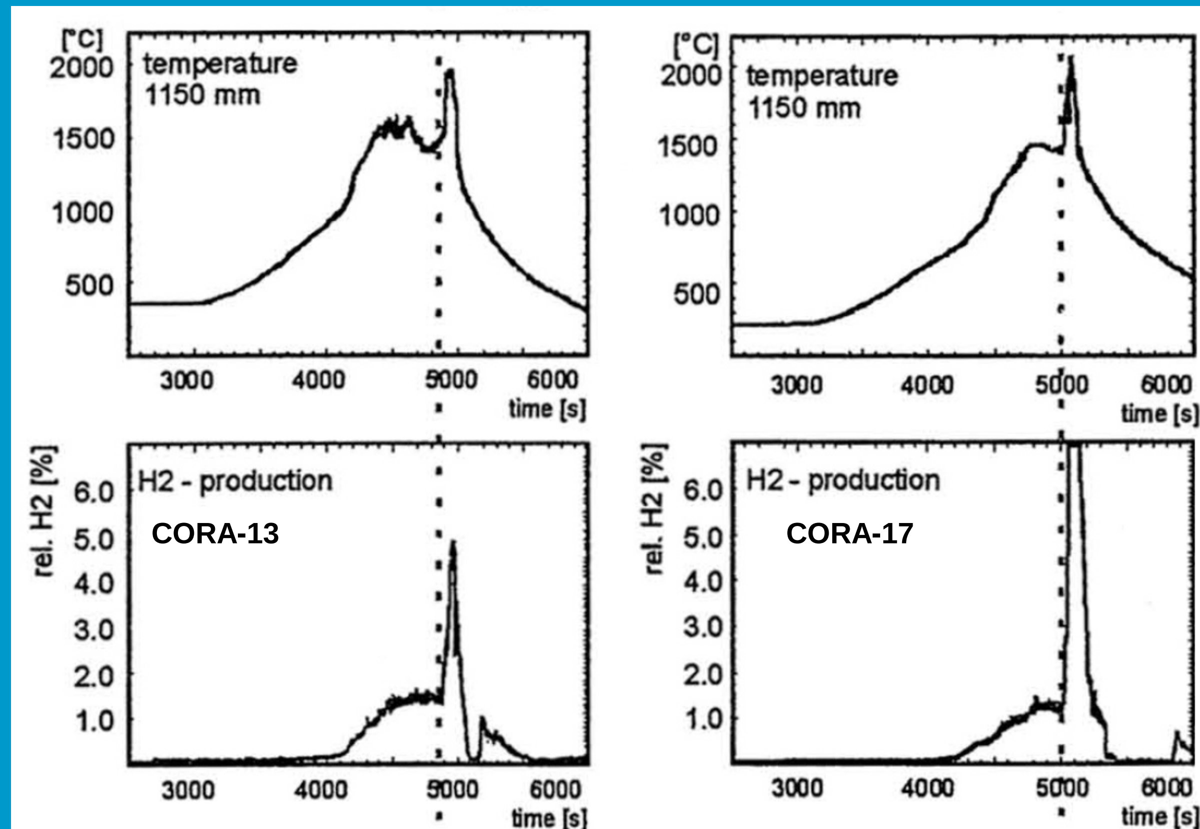
Hydrogen production during CORA tests without/with reflood (quenching)

without quench



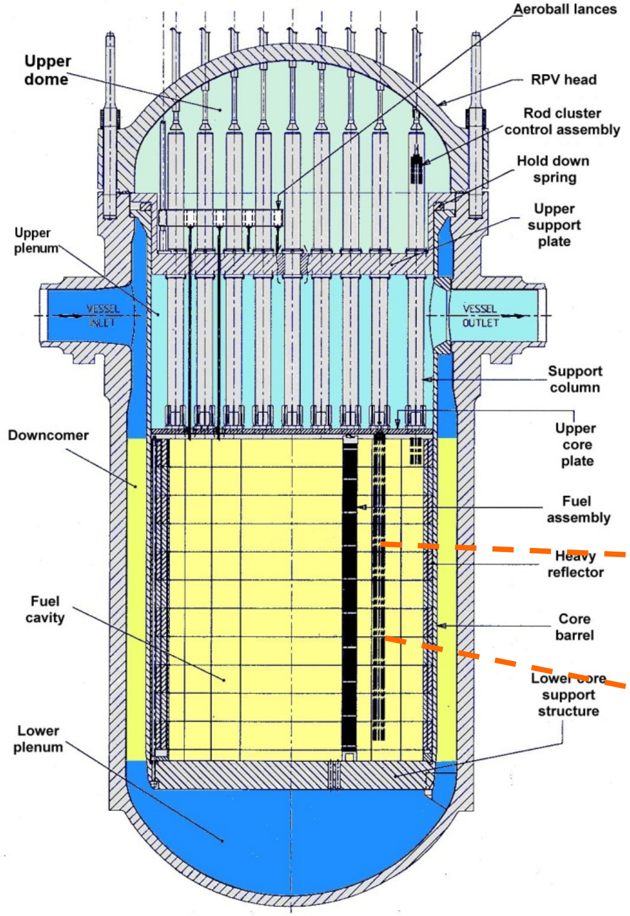


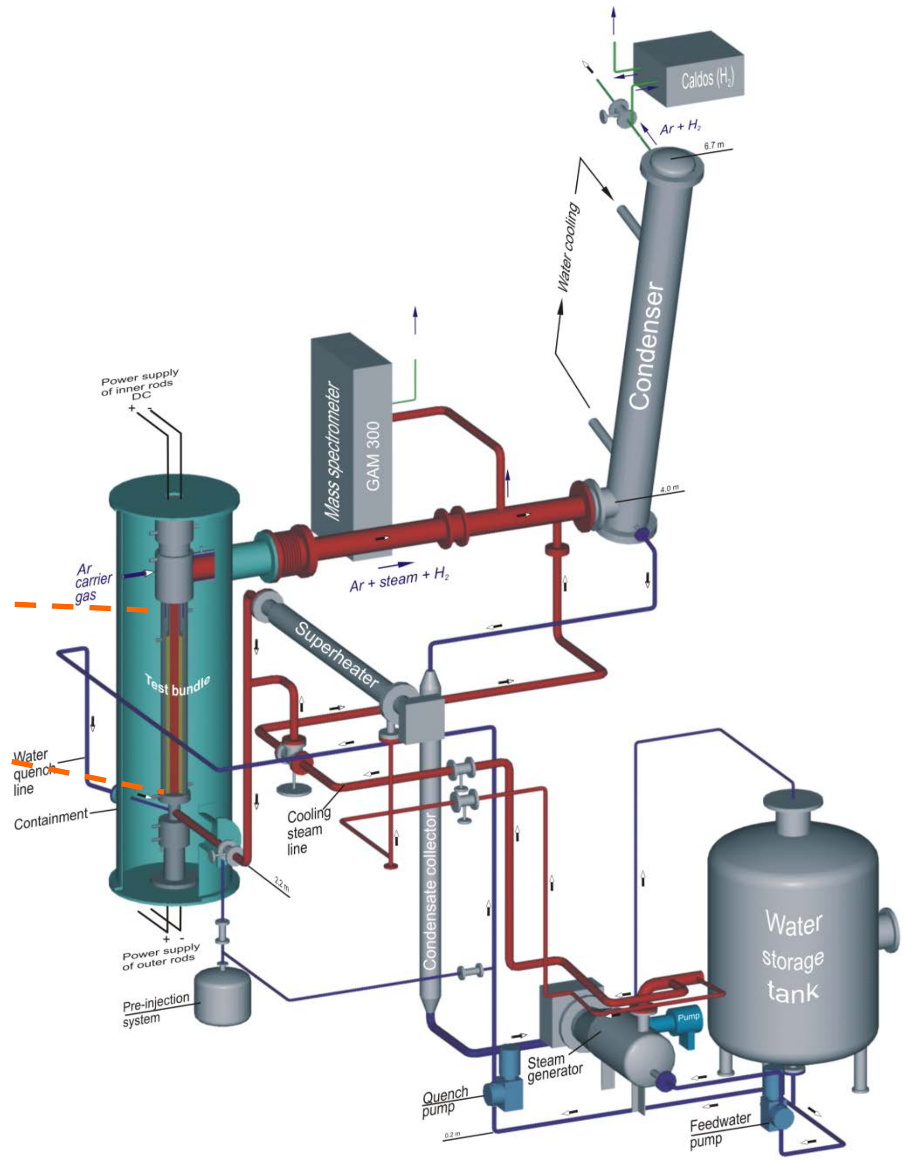
with quench: T escalation; H_2 peak



QUENCH-facility

PWR-Reactor

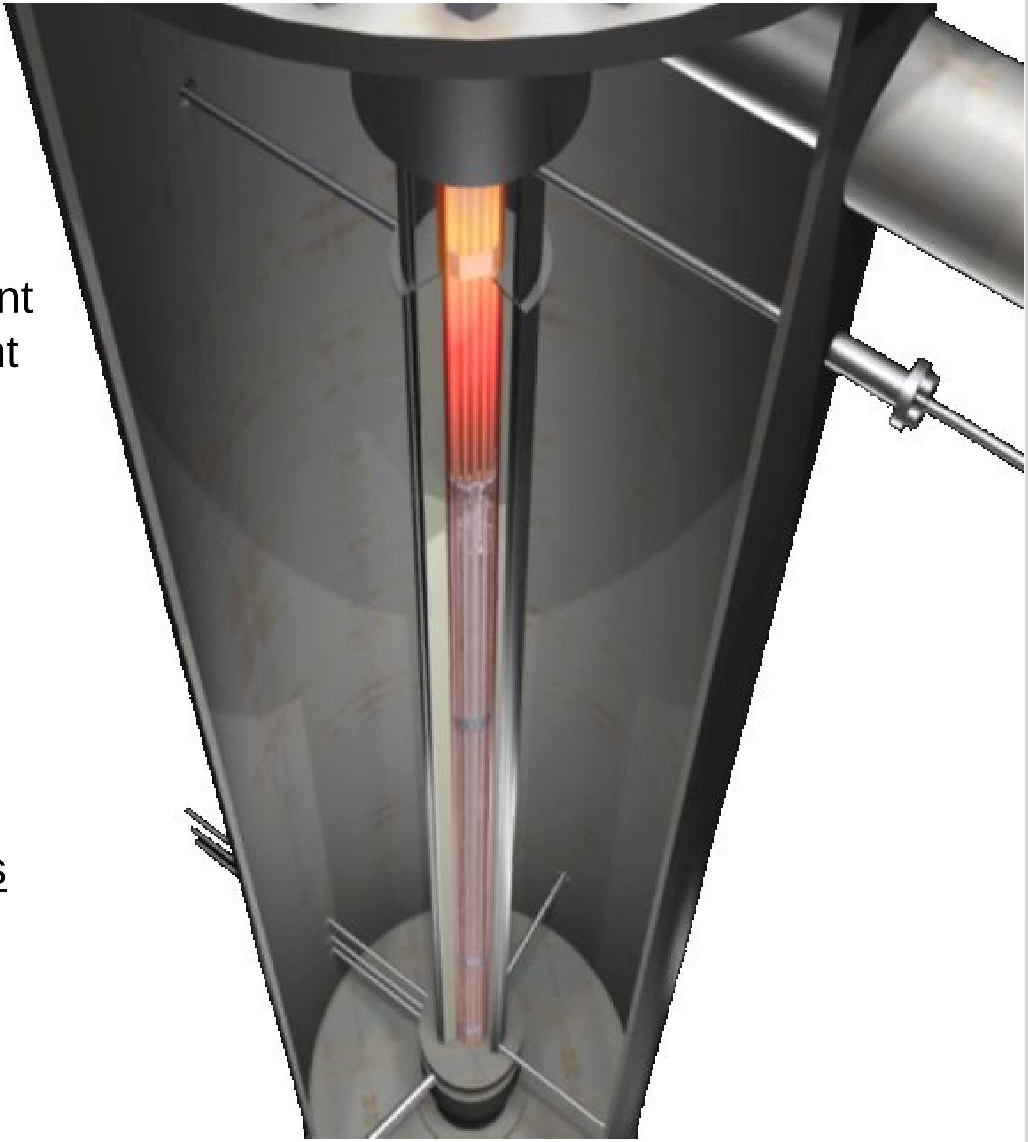




Experiments on reflood

Motivation

- Reflood is a prime accident management measure to terminate a nuclear accident
- Reflood may cause temperature excursion connected with increased hydrogen and FP release
- Simulation of core behaviour at high temperatures and during quenching is still a matter of improvement
- QUENCH experiments (bundle+SET) provide data for development of models and validation of SFD code systems

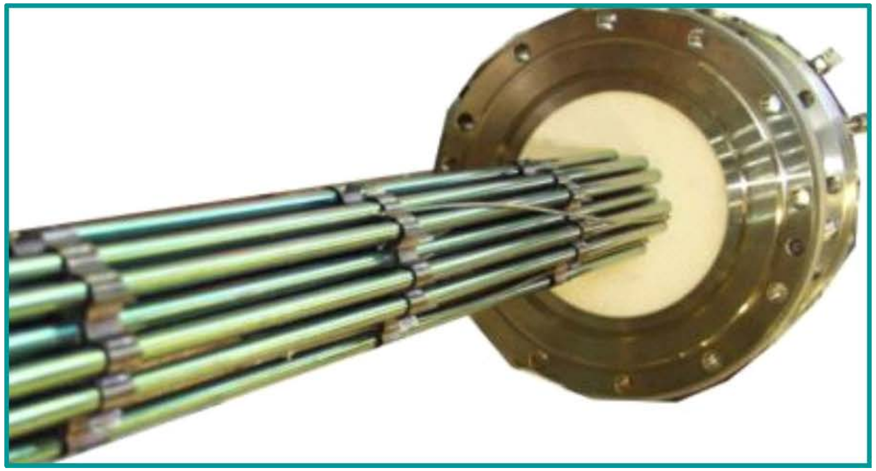


QUENCH Programme

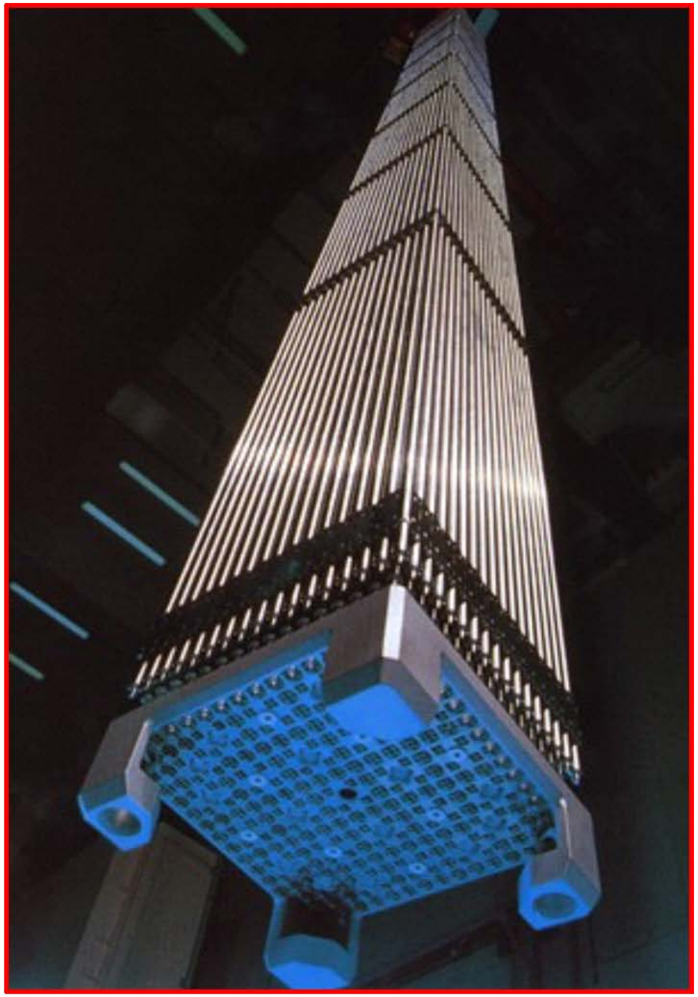
Separate-effects tests

Modelling → CODES → Application

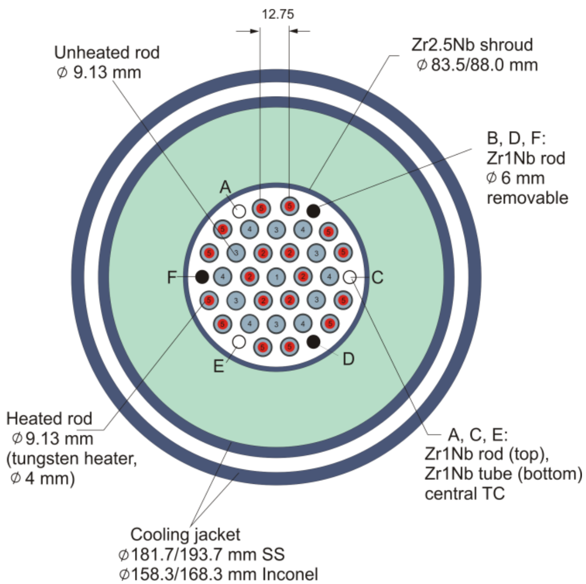
Validation



Bundle experiments



Composition of bundles



QUENCH-12 VVER

claddings: **E110** - alloy

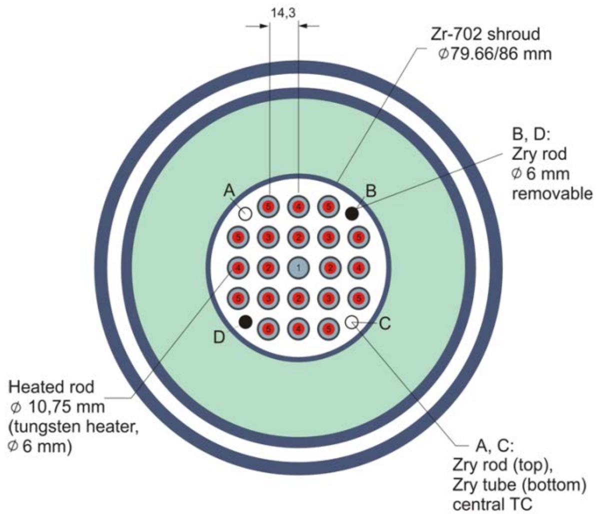
Fuel rod simulators:

18 heated

13 not heated

6 corner rods

metallic surface ratio: Q12/Q14=1.22



QUENCH-14 (**typical geometry**)

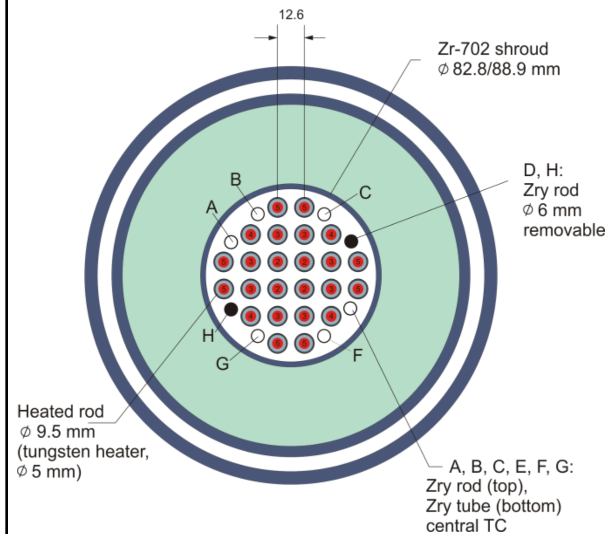
claddings : **M5**® - alloy

Fuel rod simulators :

20 heated

1 not heated

4 corner rods



QUENCH-15

claddings: **ZIRLO™** - alloy

Fuel rod simulators :

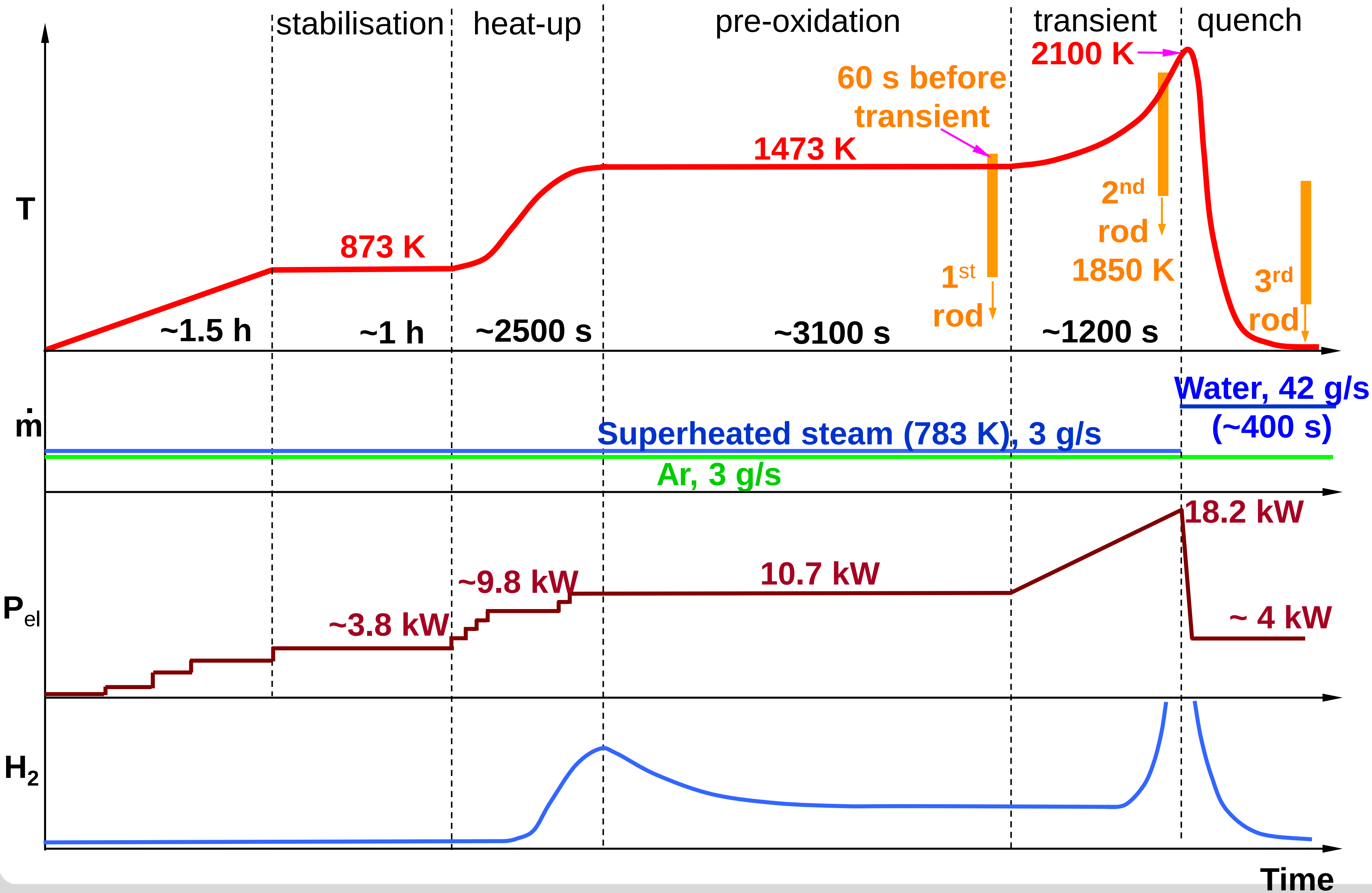
24 heated

0 not heated

8 corner rods

metallic surface ratio: Q15/Q14=1.09

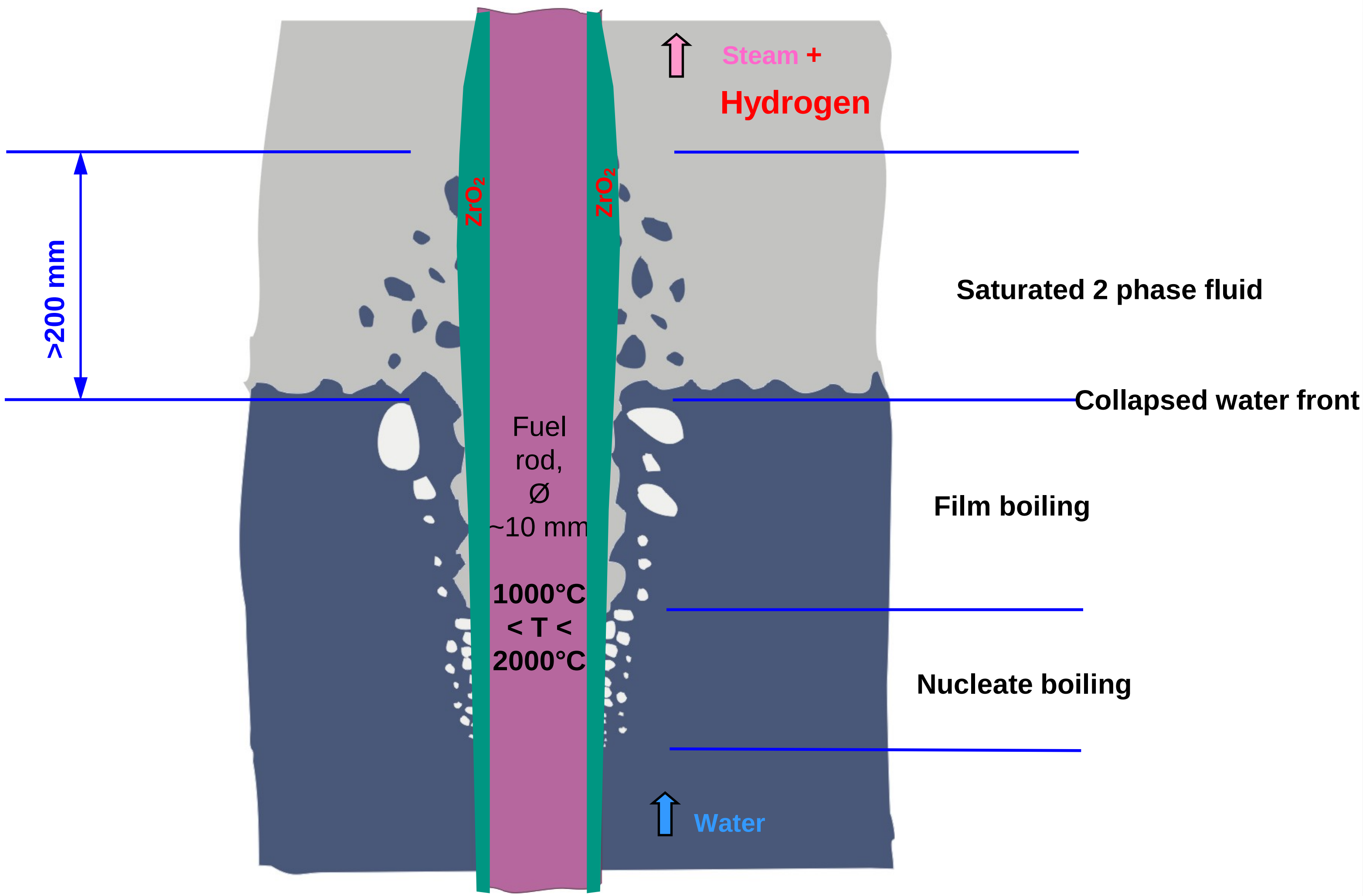
Performance of QUENCH-14 (M5®) – similar to Q-06 (Zry-4), Q-12 (E110) and Q-15 (ZIRLO™)



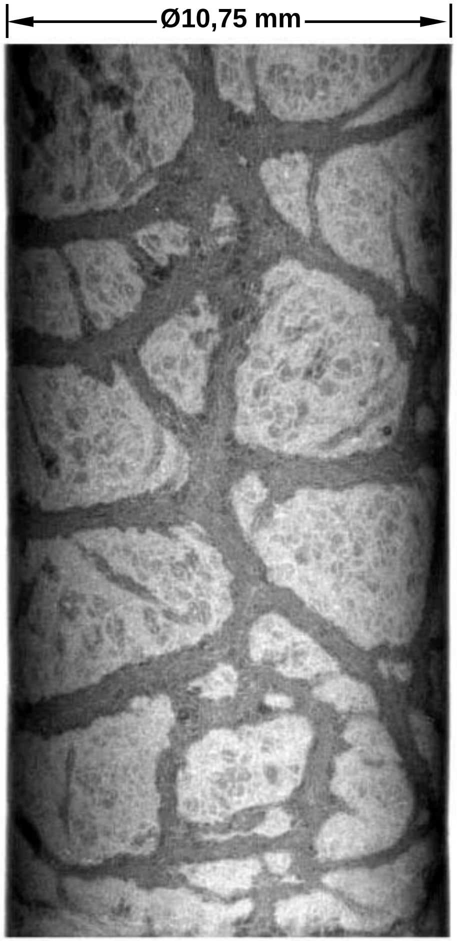
QUENCH test matrix: different test series

Test	Quench medium / Injection rate	Temp. at onset of flooding	Max. ZrO_2 before transient	Max. ZrO_2 before flooding	Max. ZrO_2 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**	B_4C**, eutectic melt**
QUENCH-09 July 3, 2002	Steam 49 g/s	≈ 2100 K			completely oxidized	**60 / 400**	B_4C, **eutectic melt**
QUENCH-08 July 24, 2003	Steam 15 g/s	≈ 2090 K	274 µm		completely oxidized	**46 / 38**	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**	air ingress
QUENCH-11 Dec 08, 2005	Water 18 g/s	≈ 2040 K		170 µm	completely oxidized	**9 / 132**	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**	VVER, **melt**
QUENCH-13 Nov. 7, 2007	Water 52 g/s	≈ 1820 K		400 µm	750 µm	**42 / 1**	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**	air ingress, **melt;** *benchmark*
QUENCH-17 Jan. 31, 2013	Water 10 g/s	≈ 1800 K		completely oxidized	completely oxidized	**110 / 1**	*DEBRIS formation*

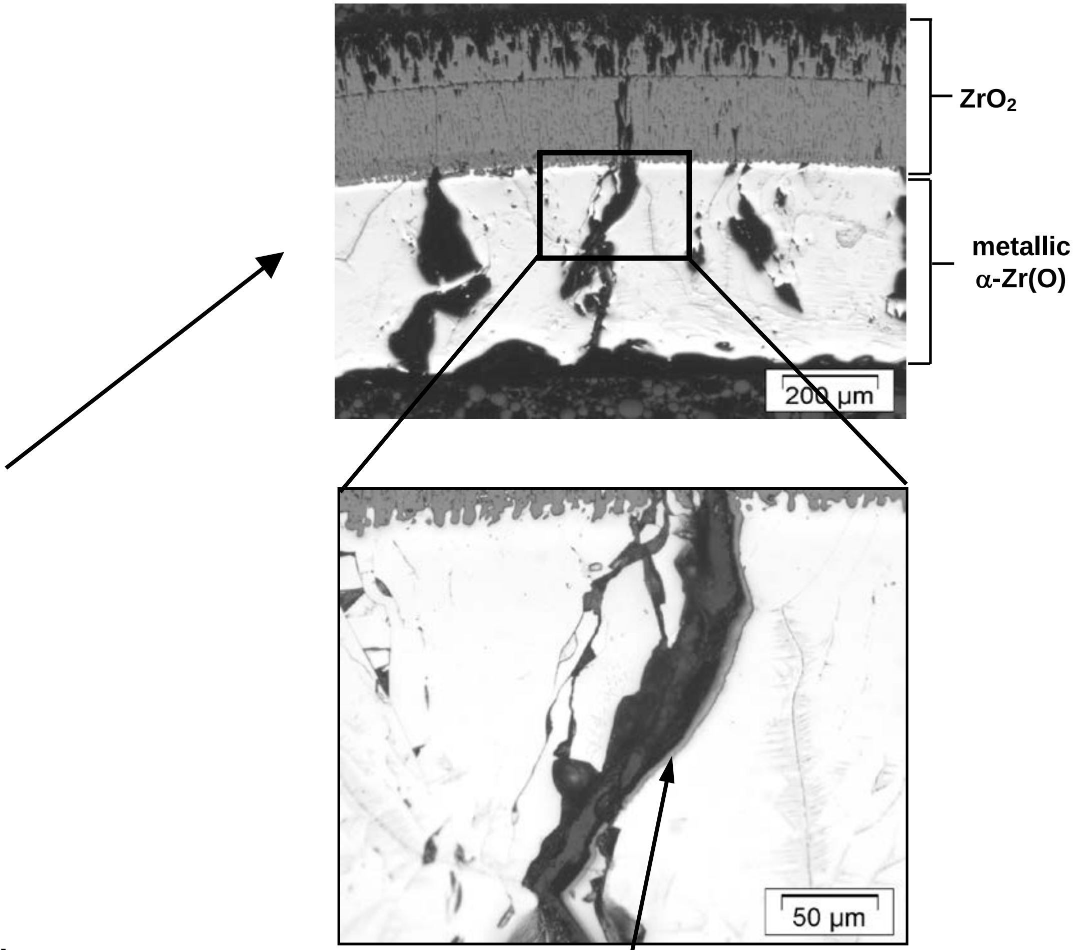
Quenching with emergency cooling water



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



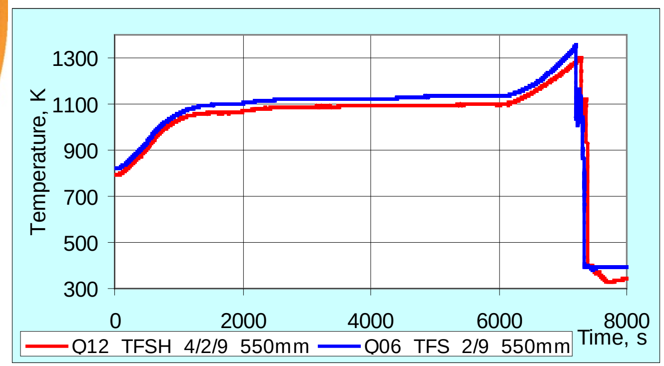
Crack development in the cladding, cooled down with steam.
Crack density ~ 4 cm/cm²

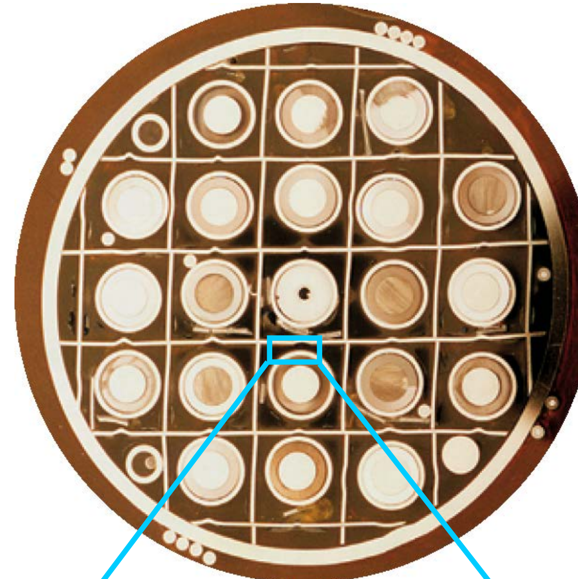


Negligible oxidation of crack edges gives only some percent of generated hydrogen

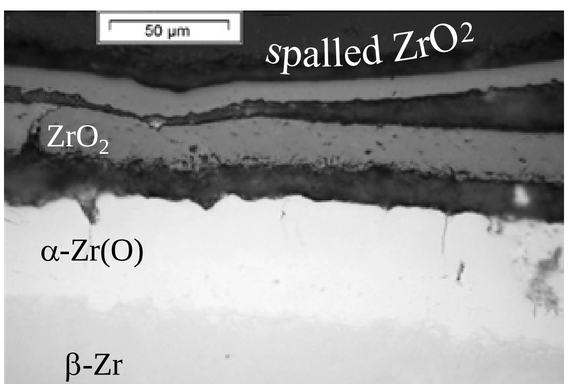
Weakening of protective oxide layer by breakaway oxidation: QUENCH-12 (VVER, old E110) vs. QUENCH-06 (Zry-4)

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

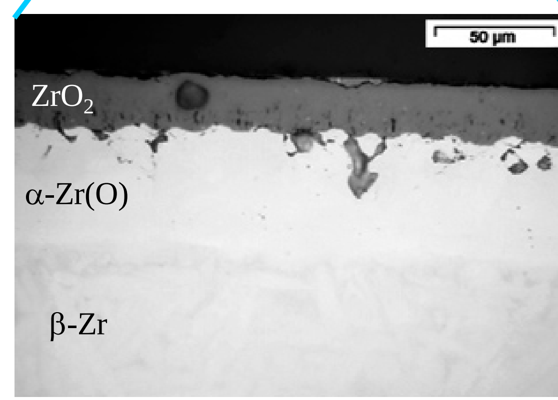




Q06 cross-section

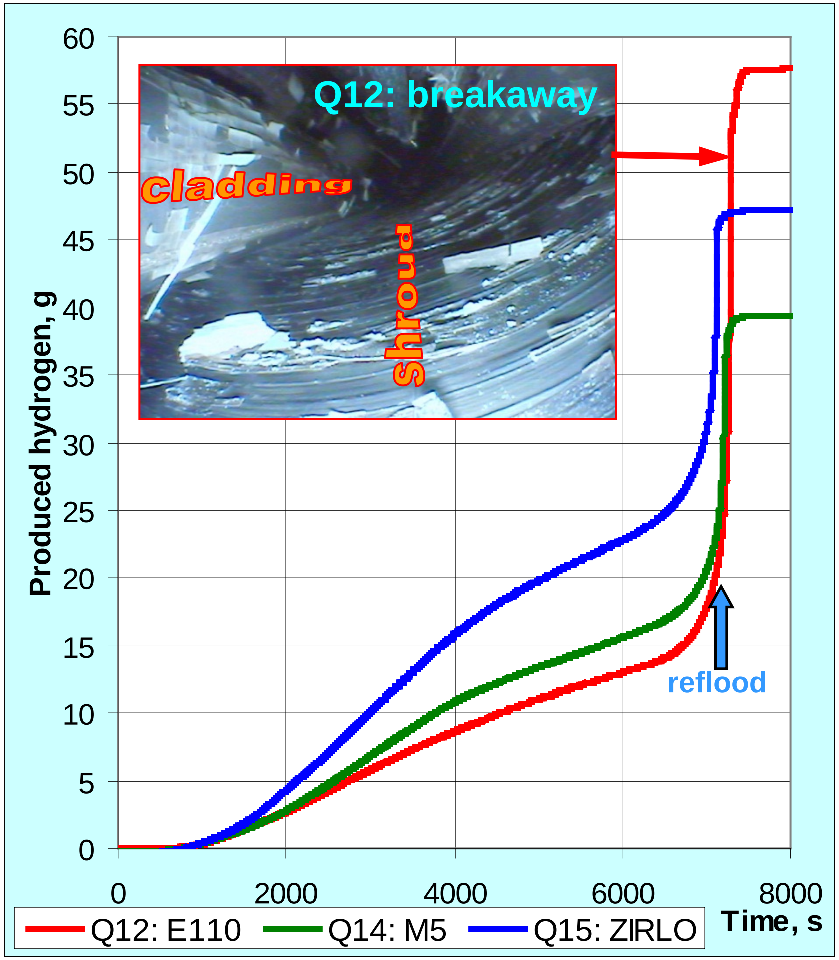


Q12 cladding: spalling of oxide scales due to breakaway effect

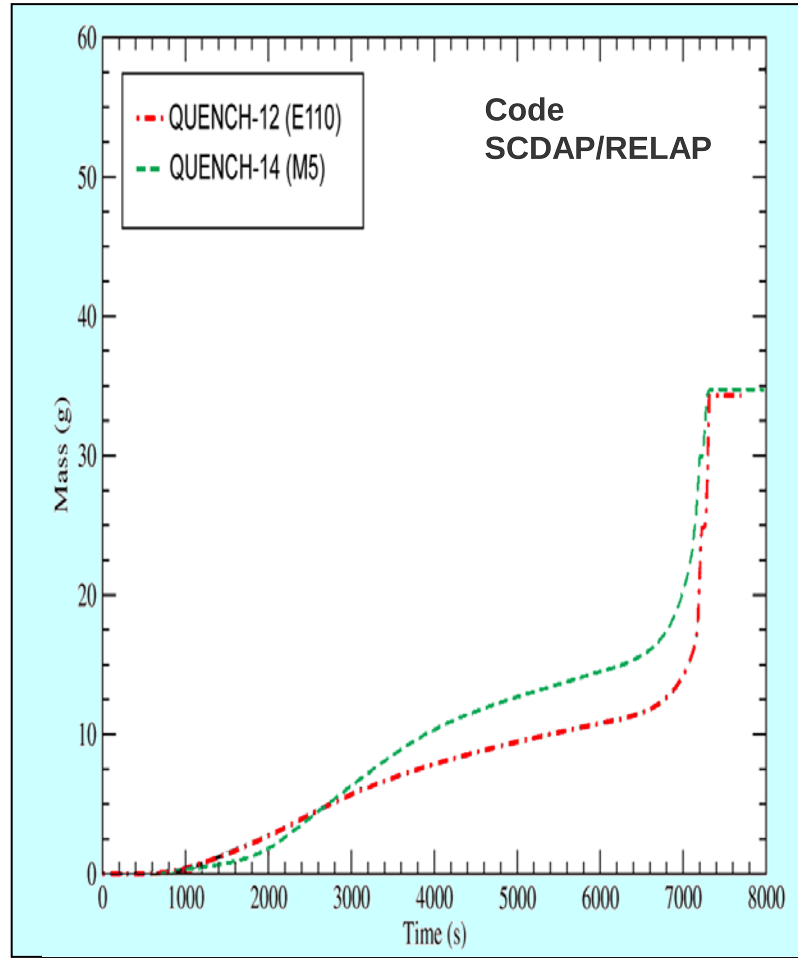


Q06 oxidized cladding

Increased hydrogen production during reflood after breakaway: QUENCH-12 (old 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 starvation conditions

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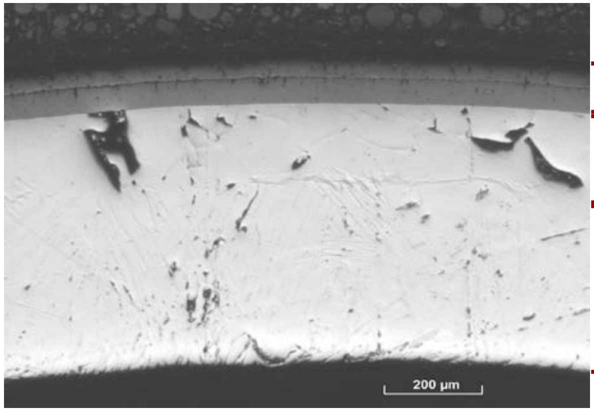


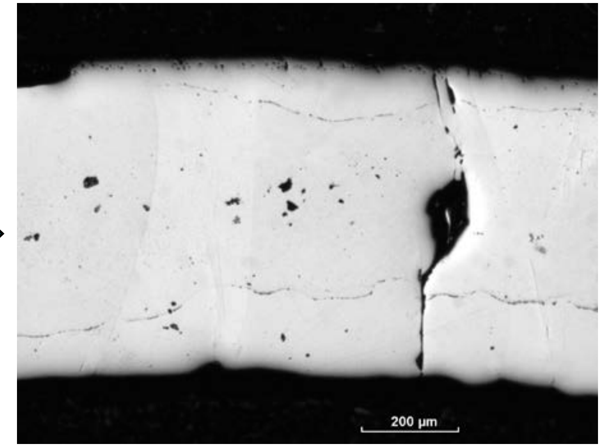
ZrO_2, 134 µm

α-Zr(O), 182 µm

β-Zr, 431 µm

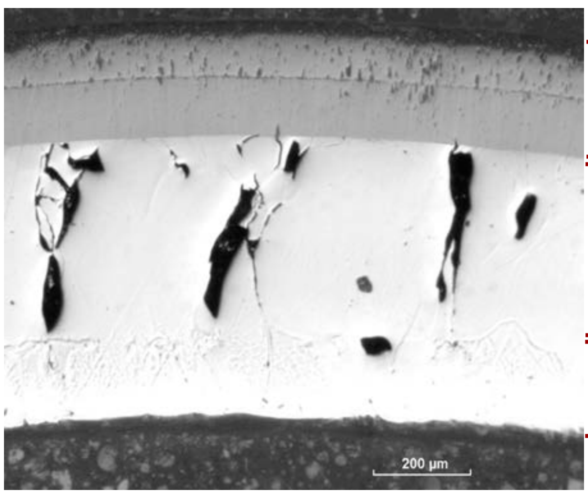
„Thin“ oxide layer

Steam starvation at 1700K



α-Zr(O), 733 µm

Complete decomposition of oxide layer



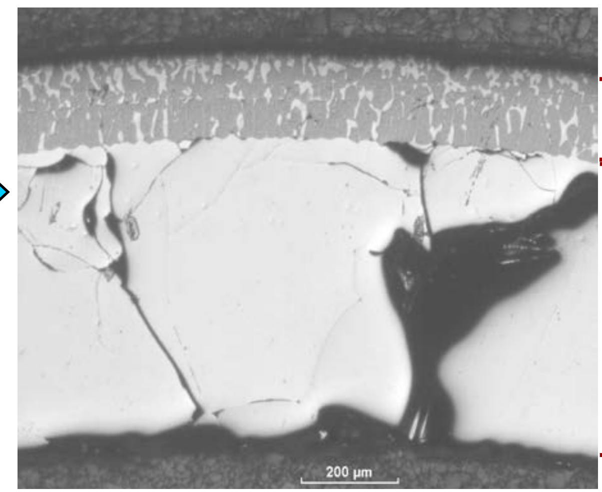
ZrO_2, 228 µm

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

Oxidation of Zircaloy-4 in O_2, N_2, and air /thermogravimetric measurements/

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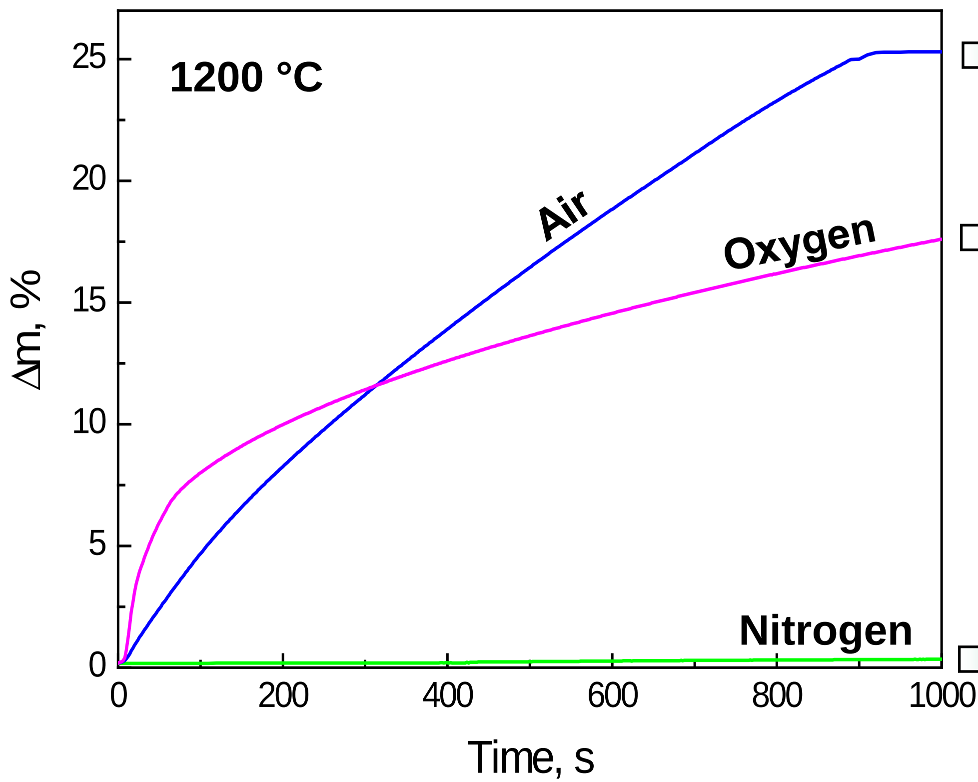

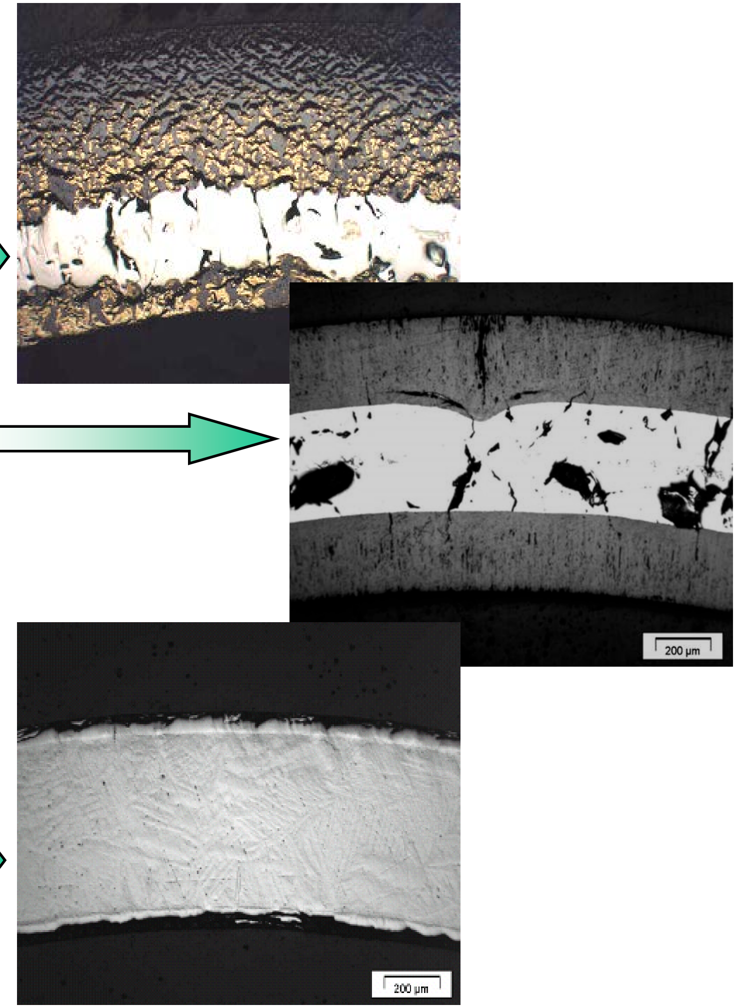

Significant nitride formation in air but not in pure nitrogen

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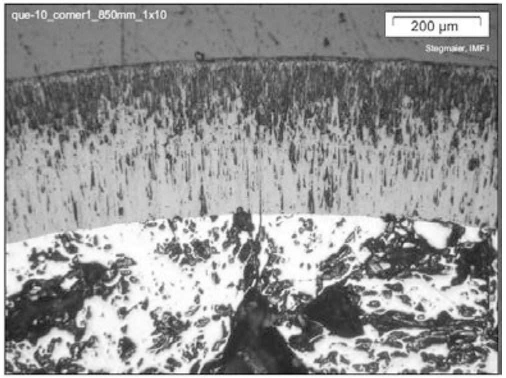
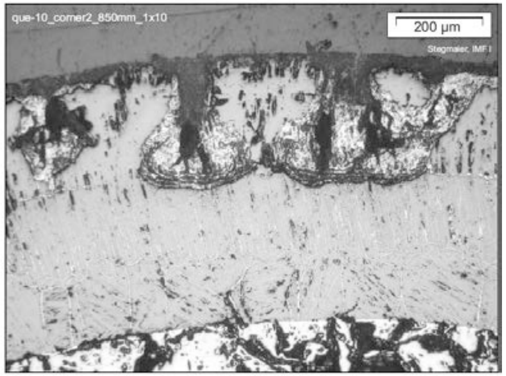
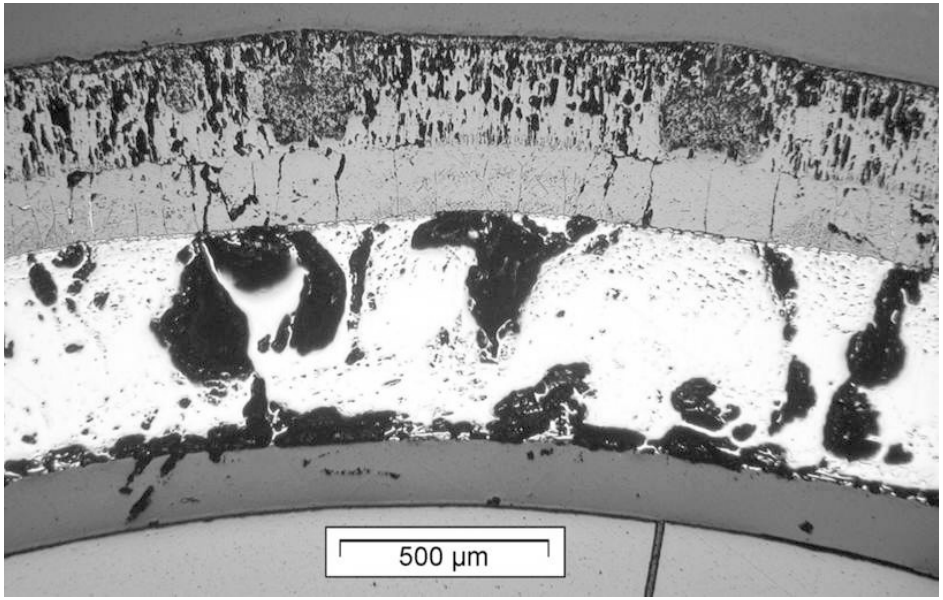
Air ingress after strong cladding pre-oxidation (QUENCH-10): local nitride formation with formation of reoxidised “pockets” during reflood



pre-oxidation: thick ZrO_2



post-air-ingress: nitrided “pockets”



post-reflood: re-oxidised “pockets”

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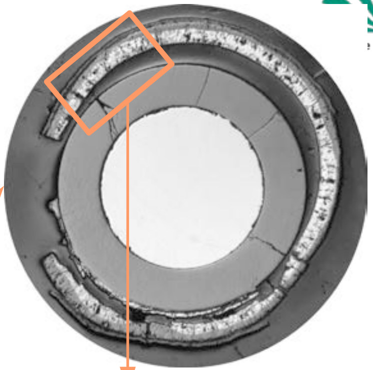
Air ingress after moderate pre-oxidation (QUENCH-16): massive nitride formation with their intensive re-oxidation during quench

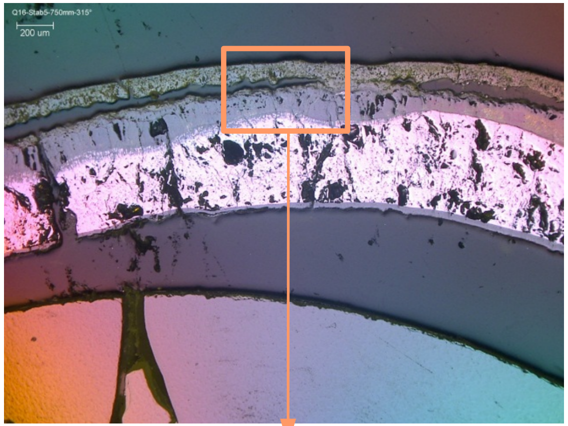
pre-reflood

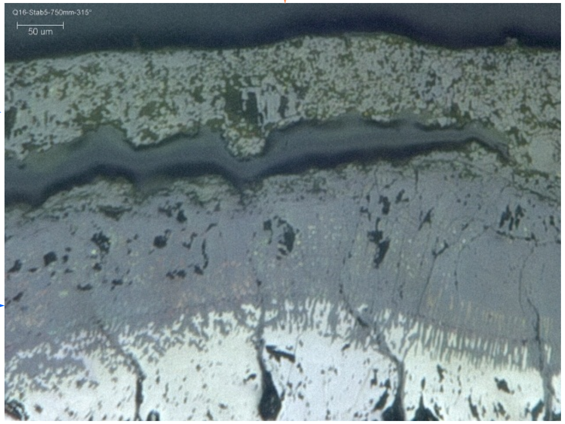
nitride formation inside oxide layer

post-reflood

Endoscope observation at ~850 mm





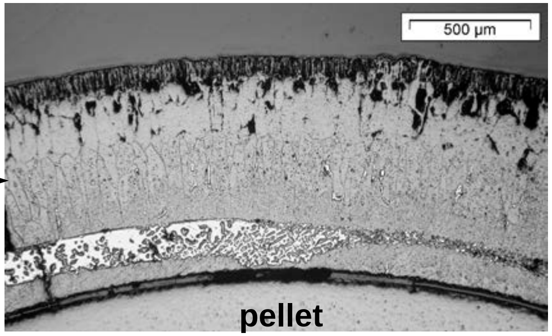


prior nitrided scale ***re-oxidised*** **during quench and spalled**

thick internal ZrO_2 sub-layer *growing during flooding*

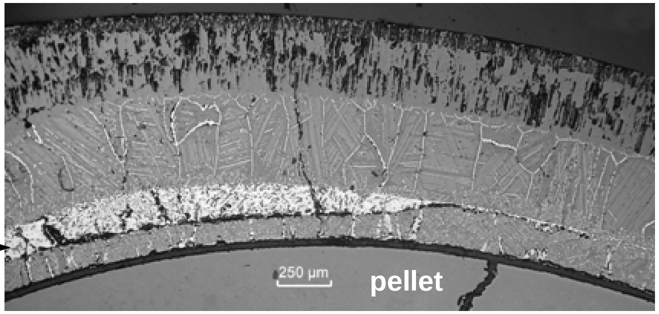
Typical layer structure of strong oxidised cladding at hottest bundle elevation of 1000 mm after reflood

outer ZrO_2 formed during pre-oxidation and reflood



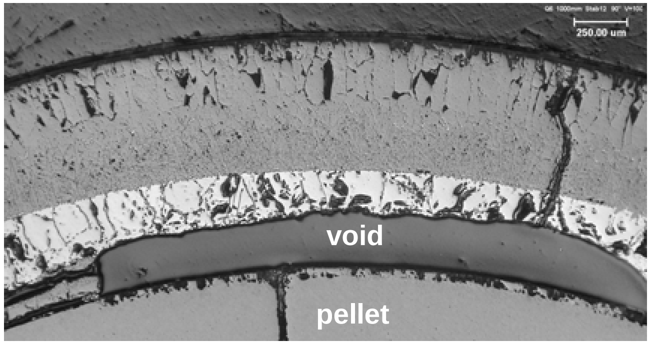
QUENCH-15 (ZIRLO)
rod #17

melt formed at ~2030 K and partially oxidised due to dissolution of ZrO_2



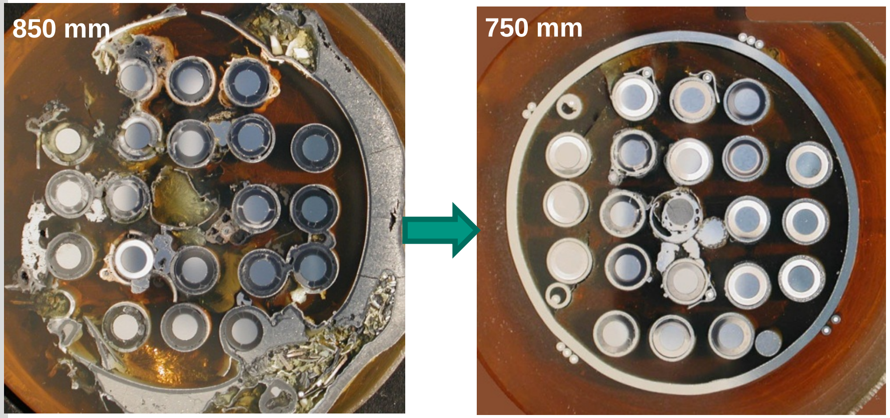
QUENCH-14 (M5)
rod #11

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

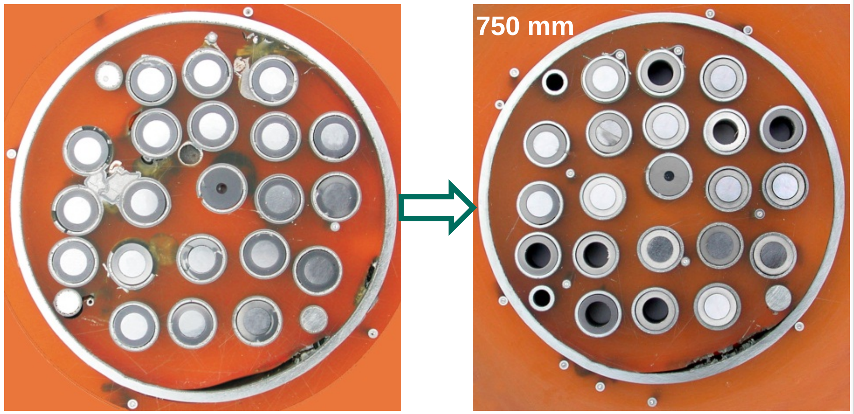
Eutectic melt induced upper 1200°C by absorber rod: *complementary* tests Q-07 (B_4C rod) and Q-08 (without absorber)



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

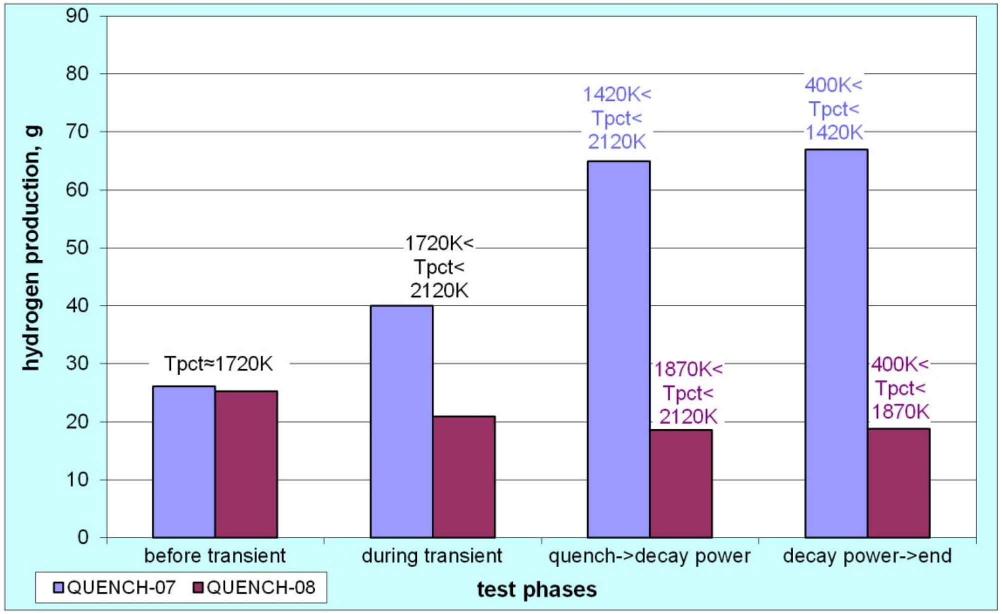
B_4C<->Fe eutectic at ~1150°C

Zry <-> SS eutectic at ~1300°C

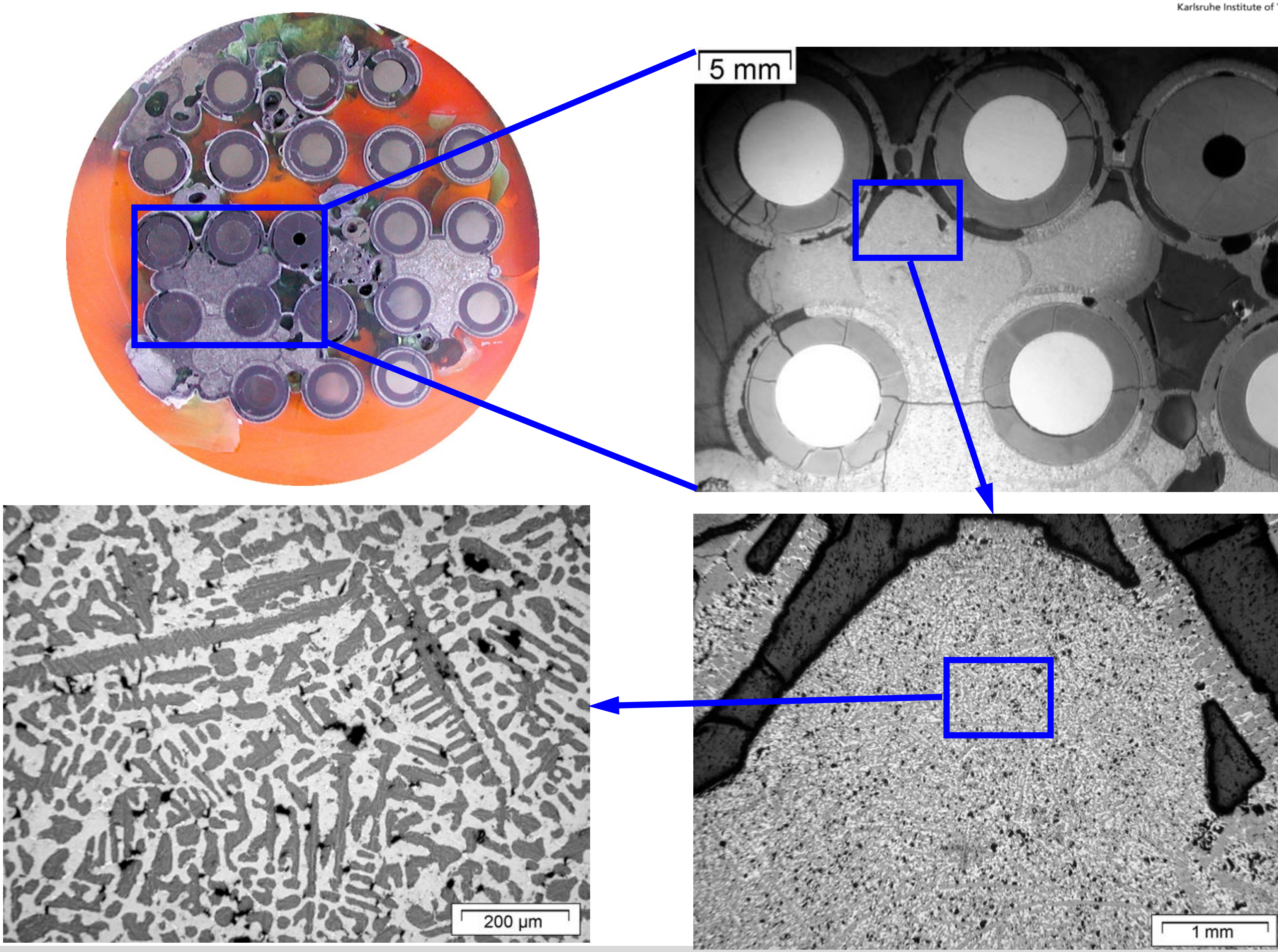


QUENCH-08: moderate melt formation; no noticeable melt relocation

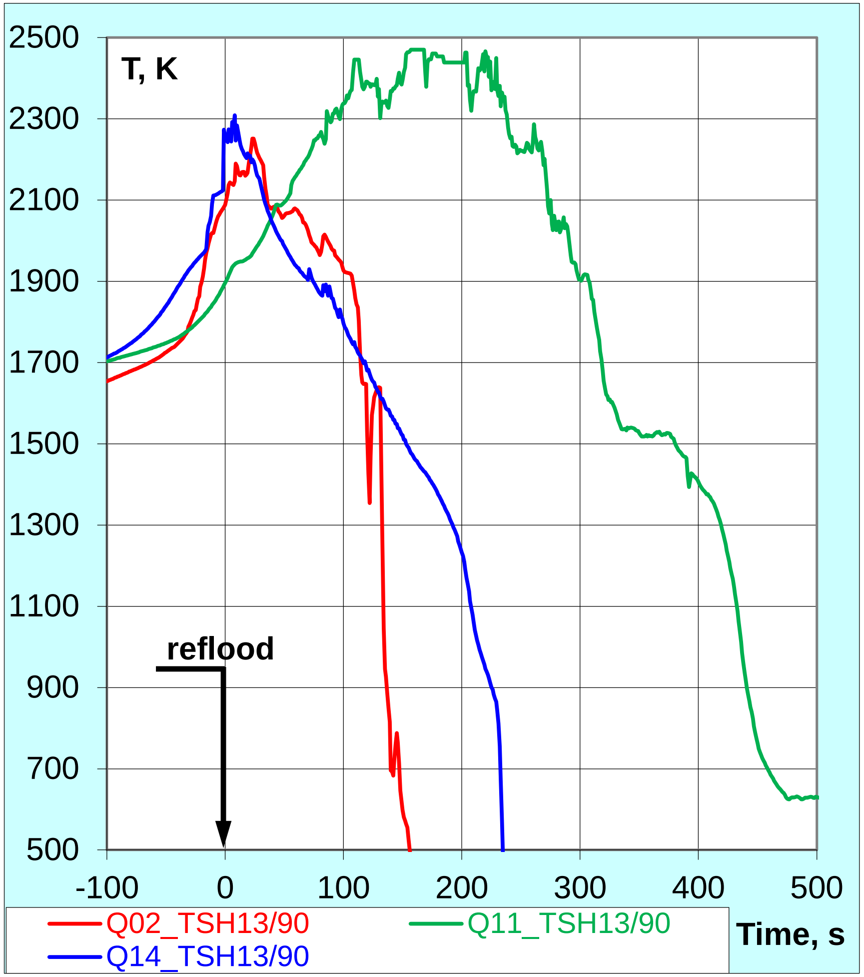
hydrogen productions for different test phases with indication of temperature evolution during the phase:

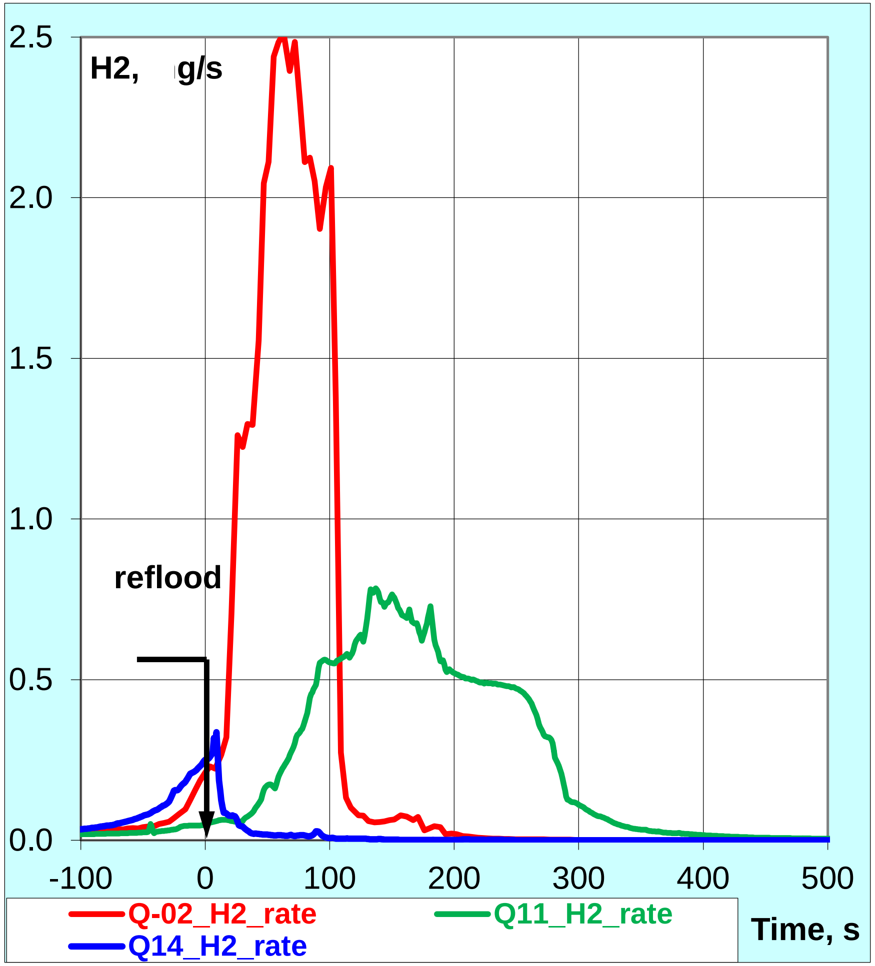


QUENCH-11, elev. 837 mm: melt relocated outside fuel rods and oxidised in steam



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



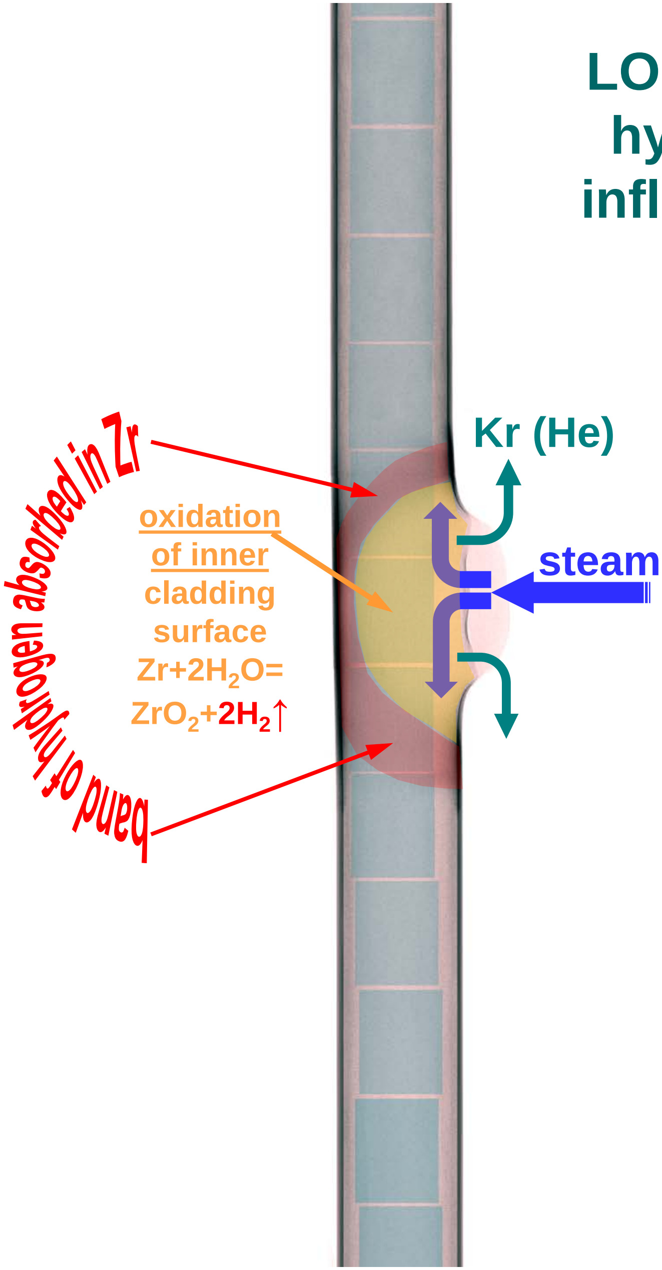


SUMMARY of the QUENCH program

Six parameters, enhancing hydrogen production, have been identified:

- **Low reflood flow rates < 1 g/s/rod (QUENCH-07, -08, -11)**
- **Breakaway effect with weakness and spallation of protective oxide layer (QUENCH-12)**
- **Steam starvation (QUENCH-09)**
- **Nitride formation by air ingress with formation of very porous oxide layer during following reflood (QUENCH-10, -16)**
- **High temperatures with melt relocation outside claddings and intensive melt oxidation (QUENCH-02, -03, -11)**
- **Eutectic interactions between B_4C, stainless steel and Zircaloy-4 leading to low melting point (QUENCH-07, -09)**

LOCA program at KIT on secondary hydrogenation of cladding and its influence on cladding embrittlement

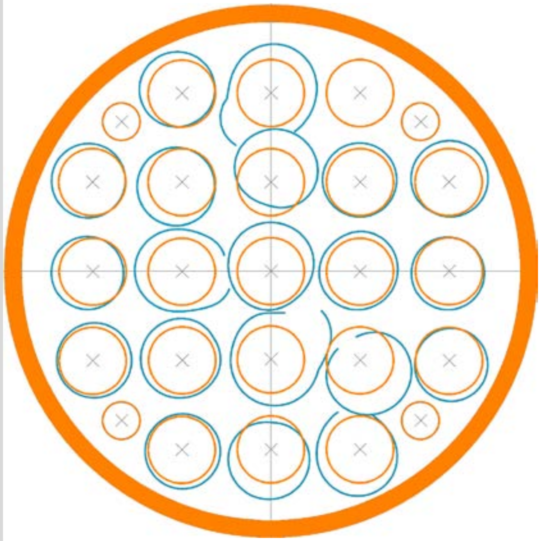


Sequence of phenomena:

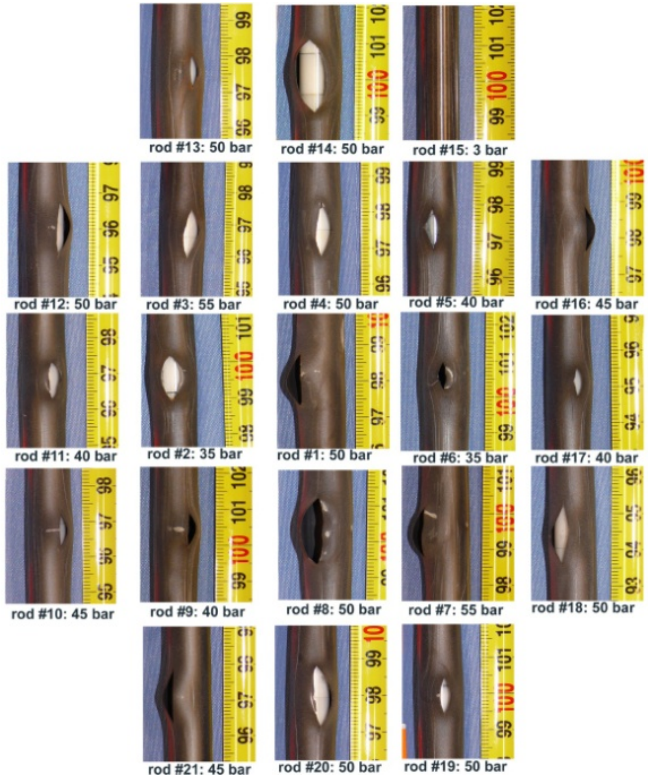
- cladding ballooning and burst at T>700°C, relief of inner rod pressure
- steam penetration through the burst opening, steam propagation in decreasing gap between cladding and pellet
- oxidation of inner cladding surface with hydrogen release
- absorption of hydrogen by cladding at the boundary of inner oxidised area
- local embrittlement of cladding near to burst opening

QUENCH-LOCA program at KIT (2010-2015): Influence of hydrogen uptake after LOCA-burst on mechanical properties of claddings

Karlsruhe Institute of Technology



ballooning and burst of claddings in comparison to pre-test fuel rod positions in the QUENCH-LOCA bundle



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

hydrogen bands inside cladding detected with n^0-radiography: max 2500 wppm hydrogen content

secondary hydriding

double rupture of cladding along hydrogen bands during tensile tests (UTS $R_m \approx 300$ MPa)

Outlook: Four bundle tests with non- and pre-hydrogenated M5® and ZIRLO™ claddings will be performed up to 2015

Thank you for your attention

http://www.iam.kit.edu/wpt/english/471.php/

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