Nuclear accident research at KIT: overview of bundle tests

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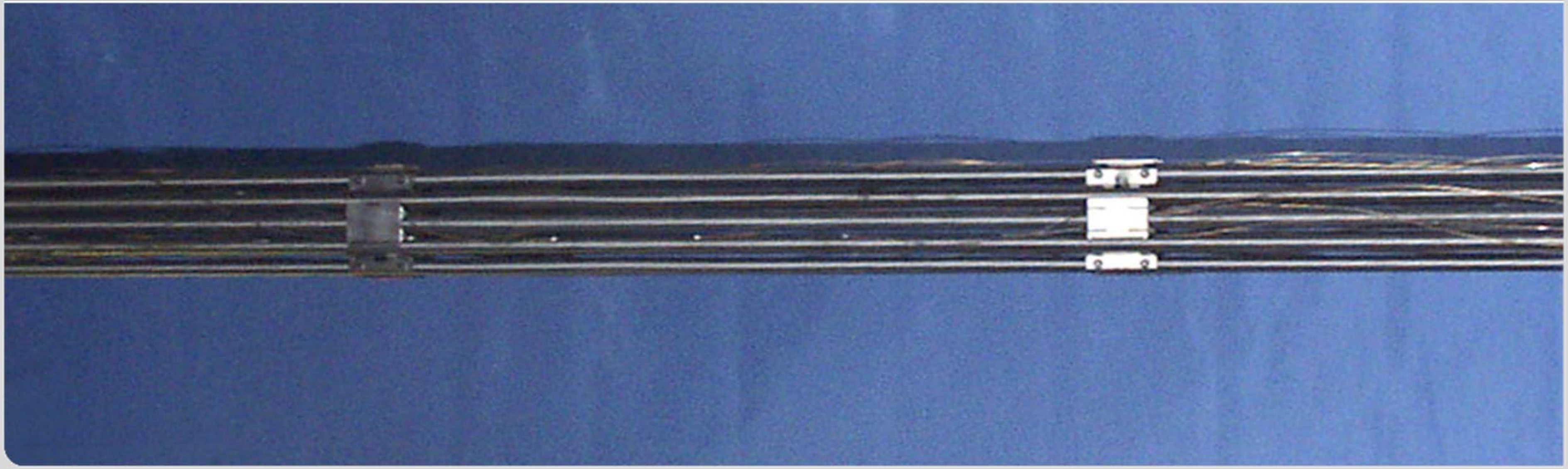
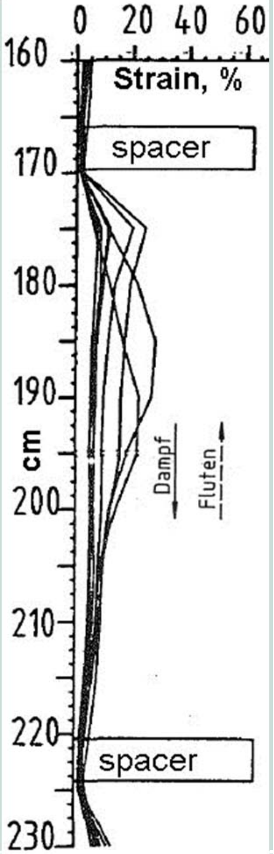
Institute for Applied Materials, IAM-WPT; Program NUKLEAR



Overview of REBEKA/LOCA program (1978-1987) at KfK (now KIT):
electrical heated facility with 3.5 m rods; thermo-hydraulic tests

REBEKA 1



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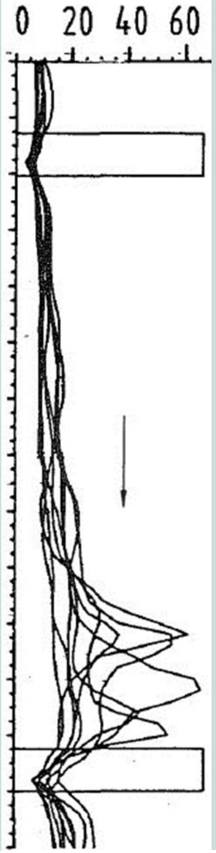

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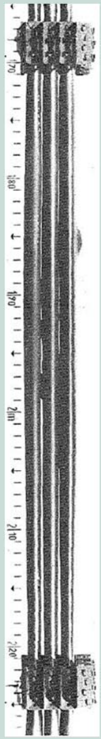
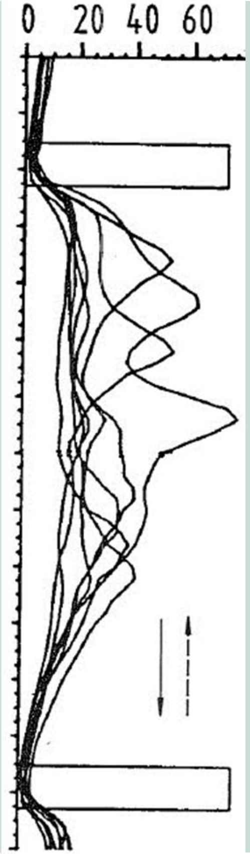
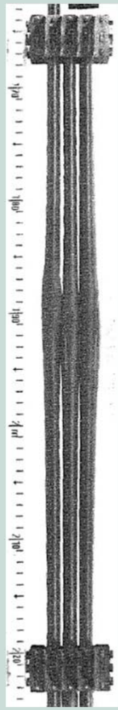


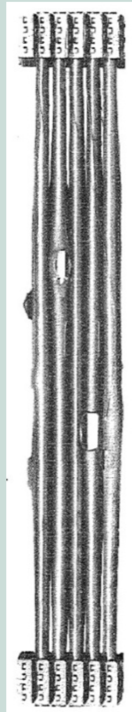
REBEKA 4



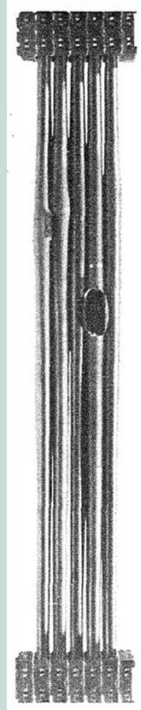
REBEKA M



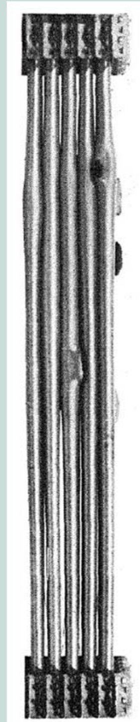
REBEKA 5



REBEKA 6

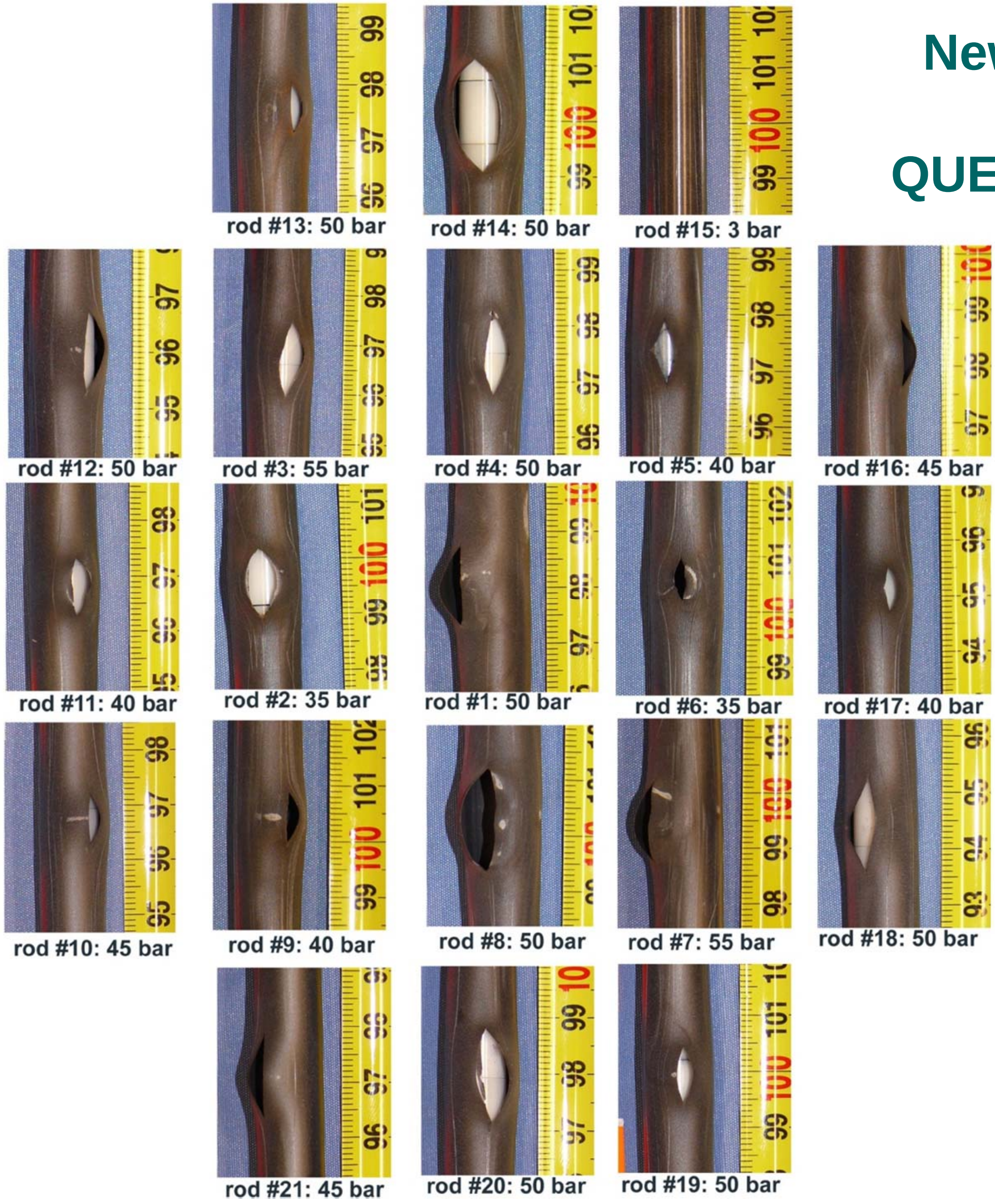


REBEKA 7

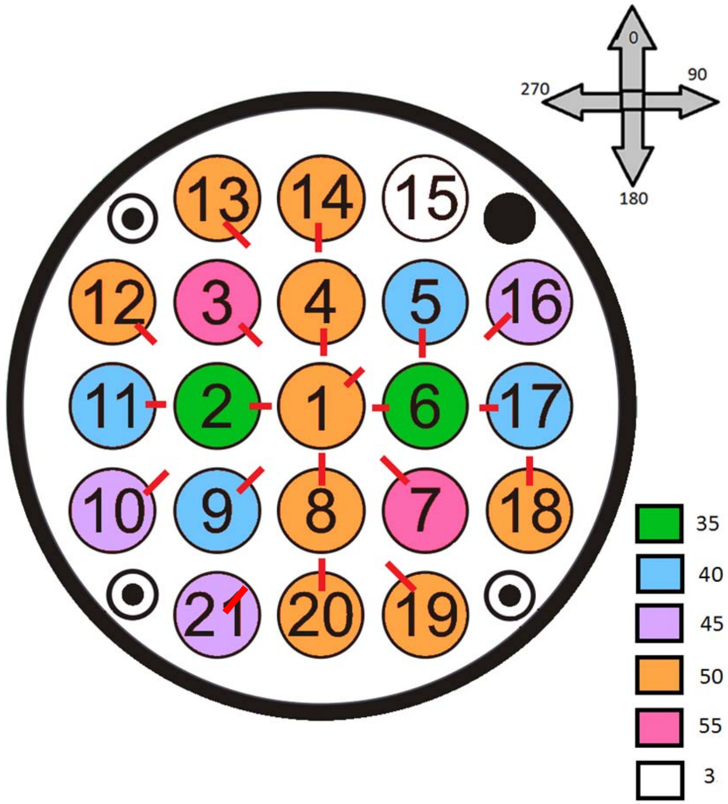


	REBEKA 1	REBEKA 2	REBEKA 3	REBEKA 4	REBEKA M	REBEKA 5	REBEKA 6	REBEKA 7
pressure, bar	60	55	51	53	70	68	62	57
burst T, °C	810	870	830	830	754	800	790	790
strain, %	28	54	44	46	63	49	42	55
blockage, %	25	60	52	55	84	52	60	66
burst region, mm		95	203	242	28	242	140	200

New QUENCH-LOCA program. QUENCH-L0 test (2010)

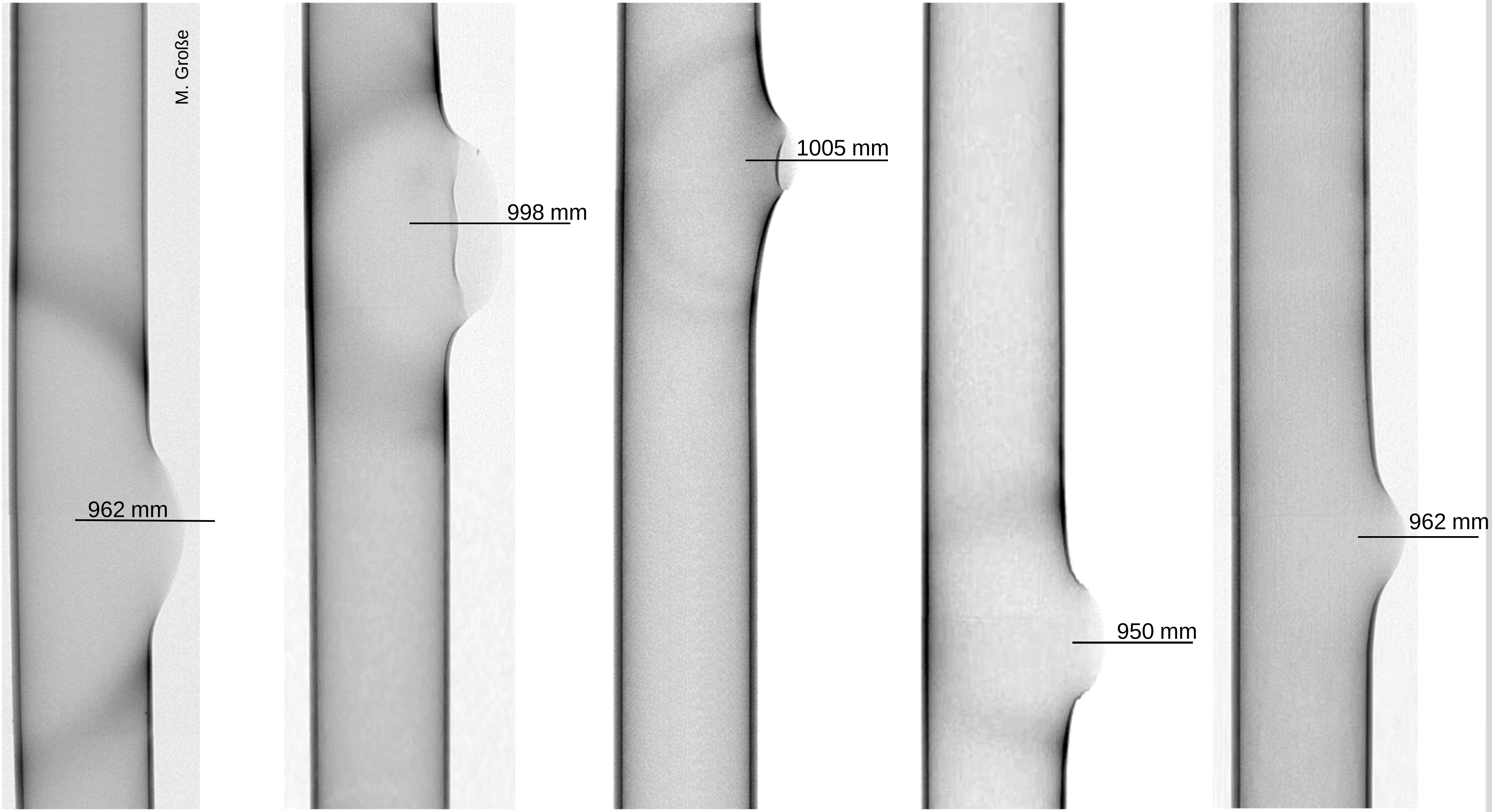


axial positions



circumferential positions with burst directions

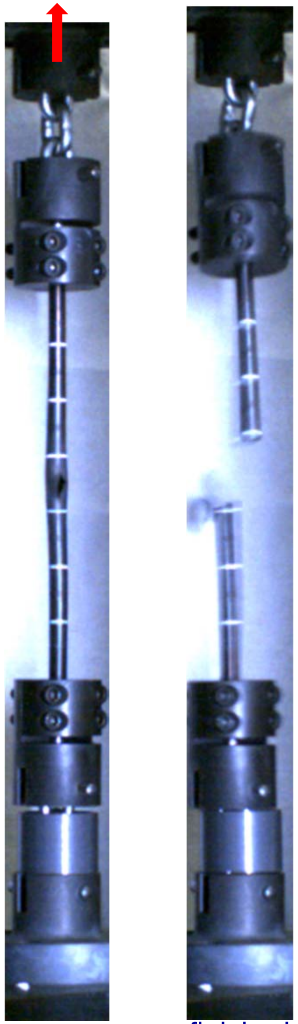
Hydrogen bands around burst location: dependence on burst temperature T_b and duration τ_Q between burst and reflood



rod #3	rod #8	rod #6	rod #17	rod #10
τ_Q=104 s	**τ_Q=101 s**	**τ_Q=93 s**	**τ_Q= 71 s**	**τ_Q=49 s**
T_b=820°C	**T_b=820°C**	**T_b=830°C**	**T_b=860°C**	**T_b=800°C**

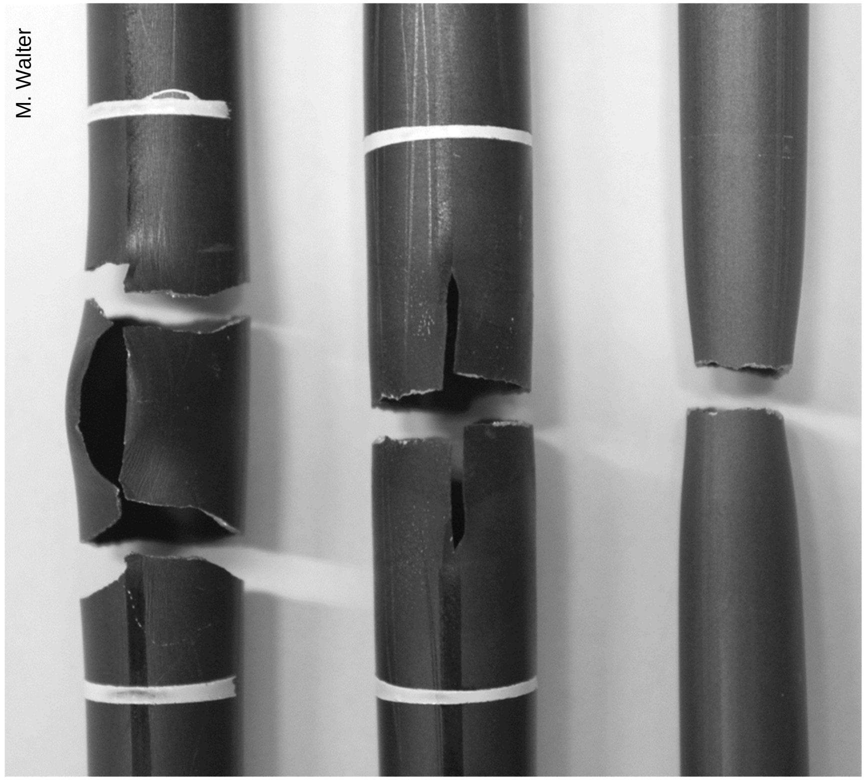
Tensile tests

INSTRON testing machine



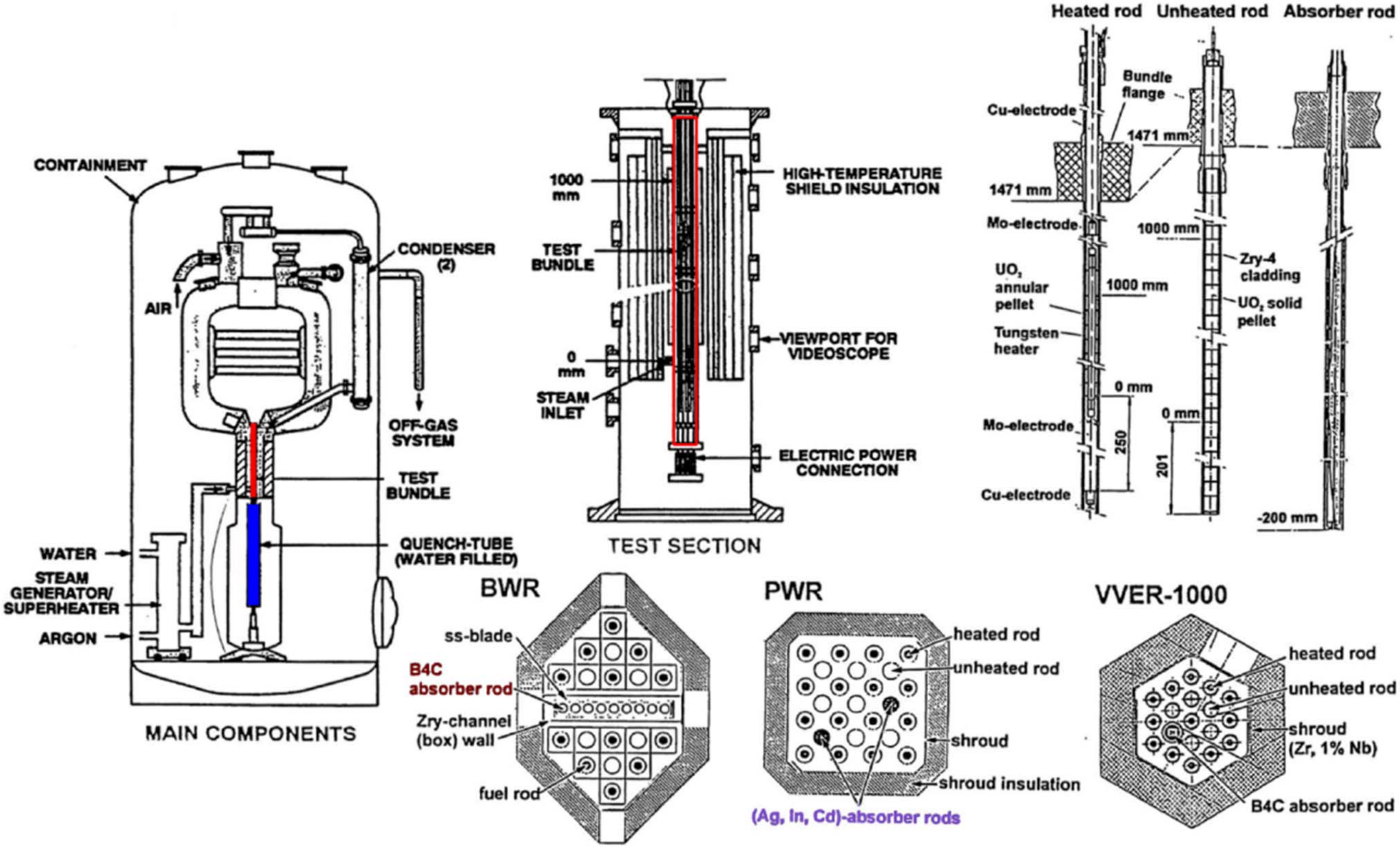
started finished

Three types of cladding failure



Ruptures near to burst opening due to hydrogen embrittlement (7 from 9 internal rods)	Rupture across the burst opening middle due to stress concentration (external rod)	Rupture near end plugs after plastic deformation (external rods)

CORA Severe Fuel Damage Facility (1987 – 1993)



Overview of CORA matrix: 19 bundle tests performed;

initial heat-up rate ≈1.0 Kj/s; steam flow rate, PWR: 6 g/s, BWR: 2 g/s; quench rate (from the bottom) ≈1 cm/s; UO_2 pellets;

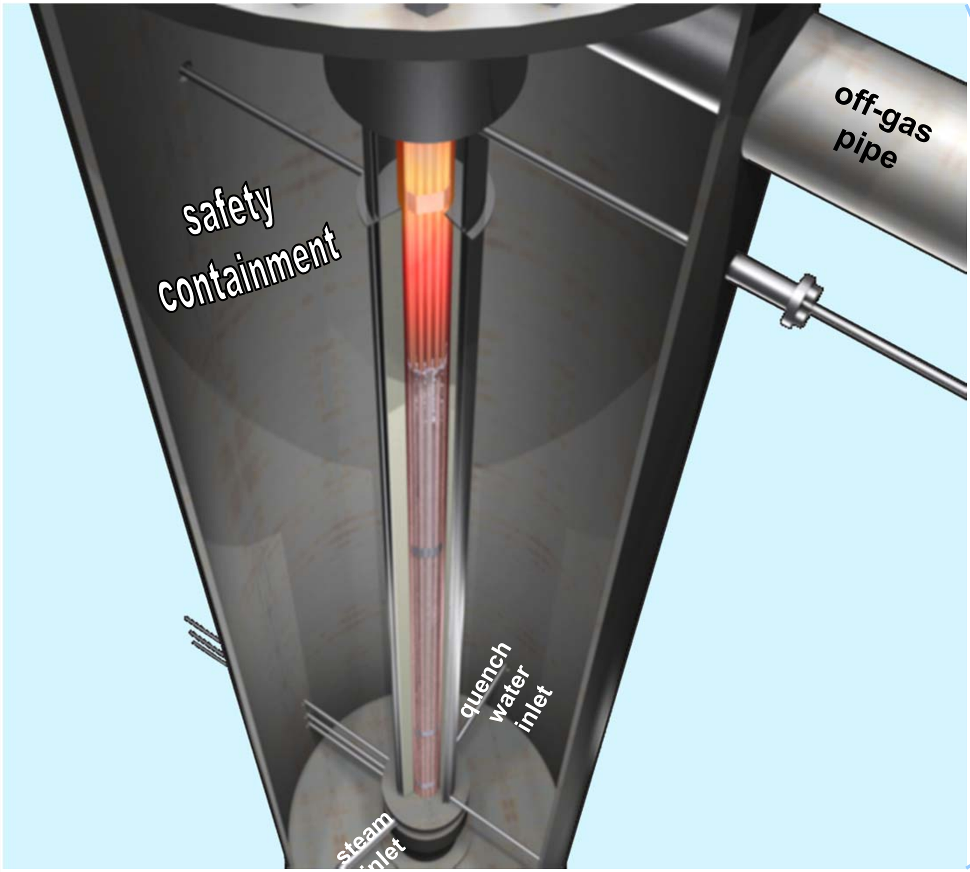
planned tests 24-27 and 32 (three with quench, all with B_4C) were not performed

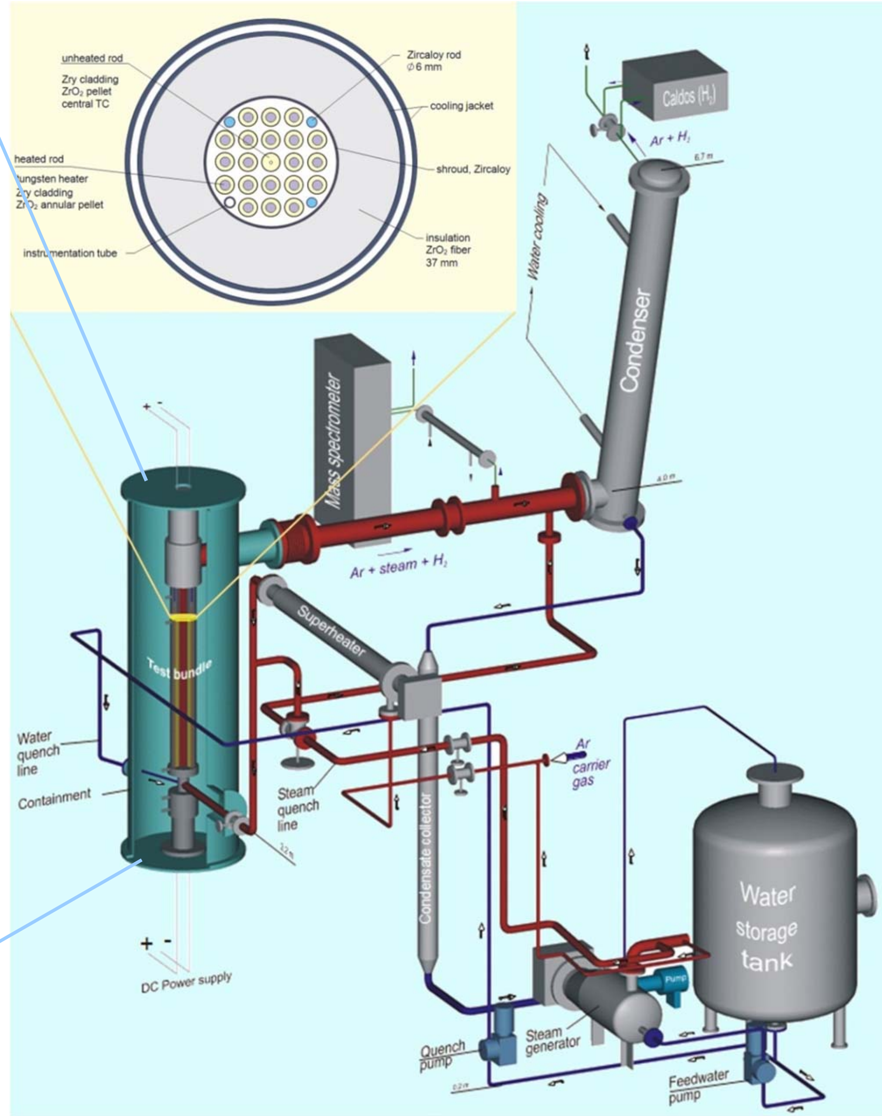
Test No.	Max. Cladding Temperatures	Absorber Material	Other Test Conditions	Date of Test
2	2000°C	-	$U0_2$ refer., Inconel spacer	Aug. 6, 1987
3	2400°C	-	$U0_2$ refer., high temperature	Dec. 3, 1987
5	2000°C	Ag, In, Cd	PWR-absorber	Febr. 26, 1988
12	2000°C	Ag, In, Cd	quenching	June9, 1988
16	2000°C	B_4C	BWR-absorber	Nov. 24, 1988
15	2000°C	Ag, In, Cd	rods with internal pressure	March 2, 1989
17	2000°C	B_4C	quenching	June 29, 1989
9	2000°C	Ag, In, Cd	10 bar system pressure	Nov. 9,1989
7	<2000°C	Ag, In, Cd	57-rod bundle, slow cooling	Febr. 22, 1990
18	<2000°C	B_4C	59-rod bundle, slow cooling	June 21, 1990
13	2000°C	Ag, In, Cd	OECD/ISP; quench initiation at higher temperature	Nov. 15, 1990
29	2000°C	Ag, In, Cd	pre-oxidized	April 11 , 1991
31	2000°C	B_4C	slow initial heat-up (0.3 K/s)	July 25,1991
30	2000°C	Ag, In, Cd	slow initial heat-up (0.2 K/s)	Oct. 30, 1991
28	2000°C	B_4C	pre-oxidized	Febr. 25, 1992
10	2000°C	Ag, In, Cd	cold lower end, 2 g/s steam flow rate	July 16, 1992
33	2000°C	B_4C	dry core conditions, no extra steam input	Oct. 1,1992
W1	2000°C	-	VVER-test	Febr. 18, 1993
W2	2000°C	B_4C	VVER-test with absorber	April 21 , 1993

Summary of the CORA program

- The extent of severe fuel damage is mainly determined by the peak temperature. Critical temperature regimes are
  - 1200-1400°C (low-temperature melt formation/ relocation, localized core damage),
  - 1760-2000°C (fuel rod failure, extended core damage),
  - 2600-2850°C (melting of ceramic constituents, total core destruction).
- It might be impossible to stop the temperature increase. The CORA quench tests have demonstrated, that the quench process did not result in an immediate decrease of the bundle temperature. A preliminary temperature increase (due to exothermic Zirconium /steam reaction) connected to a rise in hydrogen production was registered in all tests. This is in agreement with the in-pile tests LOFT LP-FP2 and PBF-ST4 and the TMI accident.
- The BWR test CORA-17 shows a higher temperature and hydrogen increase during to quench phase than the similar PWR tests. This additional temperature and hydrogen increase is caused by the exothermic B_4C/steam reaction.
- To better understanding of quench details with aim to include these phenomena in codes the QUENCH program was initiated.

QUENCH High Temperature Reflood Facility
beginning of operation1997





high temperature large-scale QUENCH facility:

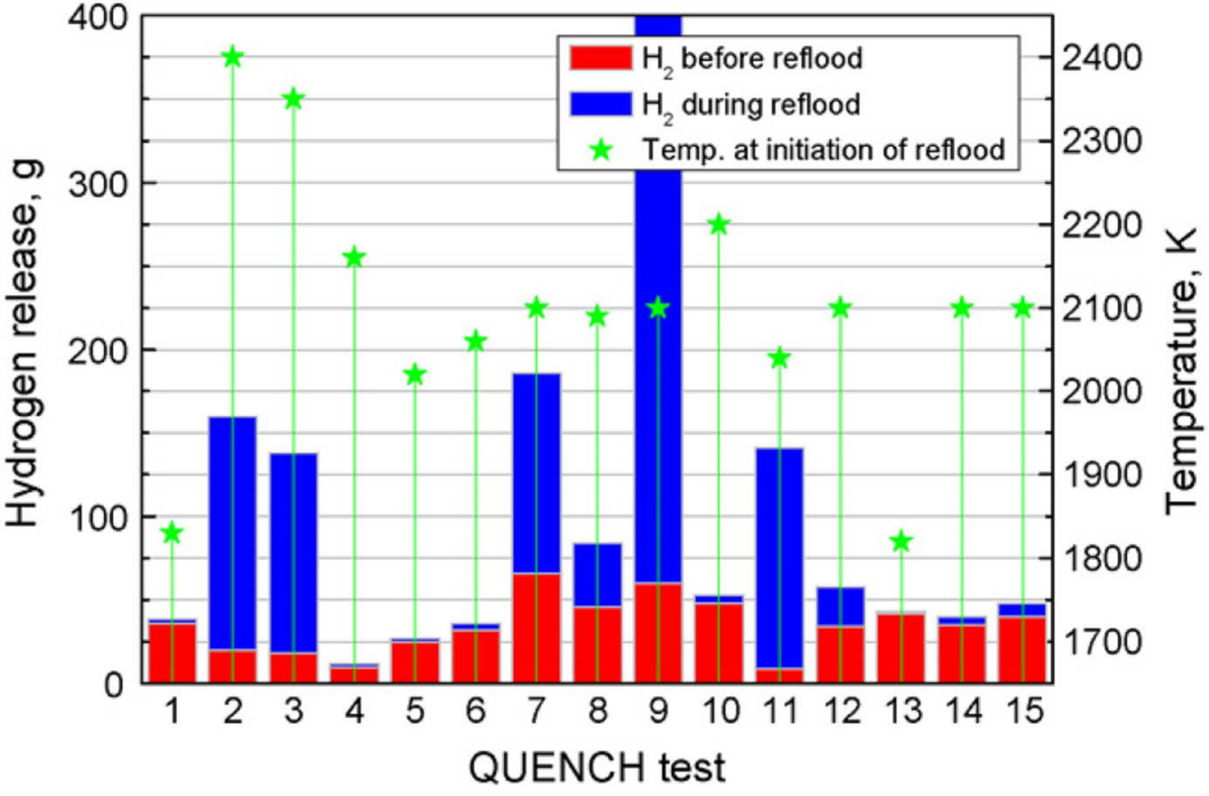
- hydrogen source term
- behavior of cladding materials
- bundle coolability
- validation of computer codes

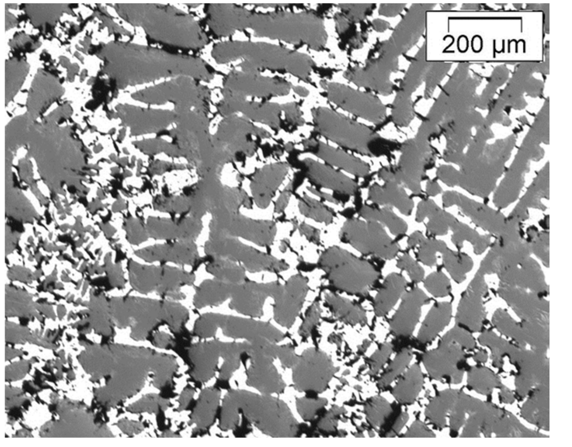
QUENCH matrix: 17 bundle tests performed;

pre-oxidation in steam (≈ 3 g/s) and Ar (≈ 3 g/s); ZrO_2 pellets

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; final conditions
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**	COBE: 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	670 µm	**32 / 4**	OECD-ISP 45
QUENCH-07 July 25, 2001	Steam 15 g/s	≈ 2100 K	230 µm		completely oxidized	**66 / 120**	COLOSS: **B_4C**; melt
QUENCH-09 July 3, 2002	Steam 49 g/s	≈ 2100 K			completely oxidized	**60 / 400**	COLOSS: **B_4C**, steam starvation, very high T; melt
QUENCH-08 July 24, 2003	Steam 15 g/s	≈ 2090 K	274 µm		completely oxidized	**46 / 38**	reference to QUENCH-07 (without **B_4C**); melt
QUENCH-10 July 21, 2004	Water 50 g/s	≈ 2200 K	514 µm	613 µm (at 850 mm)	completely oxidized	**48 / 5**	LACOMERA: air ingress; nitrides
QUENCH-11 Dec 08, 2005	Water 18 g/s	≈ 2040 K		170 µm	completely oxidized	**9 / 132**	LACOMERA: boil-off; melt
QUENCH-12 Sept 27, 2006	Water 48 g/s	≈ 2100 K	160 µm, breakaway	300 µm, breakaway	completely oxidized	**34 / 24**	ISTC: VVER; breakaway
QUENCH-13 Nov. 7, 2007	Water 52 g/s	≈ 1820 K		400 µm	750 µm	**42 / 1**	SARNET: Ag/In/Cd (aerosol)
QUENCH-14 July 2, 2008	Water 41 g/s	≈ 2100 K	170 µm	470 µm	840 µm	**34 / 6**	M5® cladding
QUENCH-15 May 27, 2009	Water 48 g/s	≈ 2100 K	145 µm	320 µm	630 µm	**41 / 7**	ZIRLO™ cladding
QUENCH-16 July 27, 2011	Water 50 g/s	≈ 2400 K	150 µm	tbd	tbd	**14 / 128**	LACOMECO: air ingress; nitrides, breakaway, melt

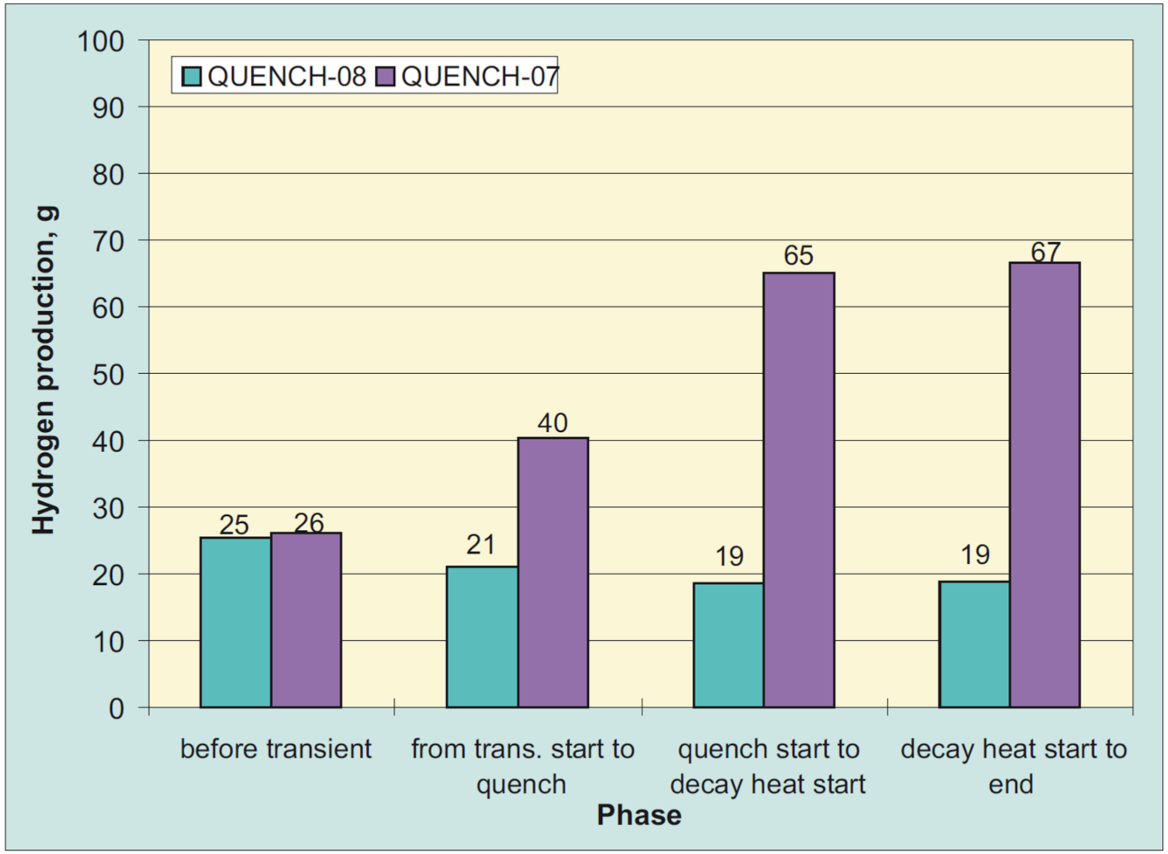
Melt oxidation as main source of hydrogen production

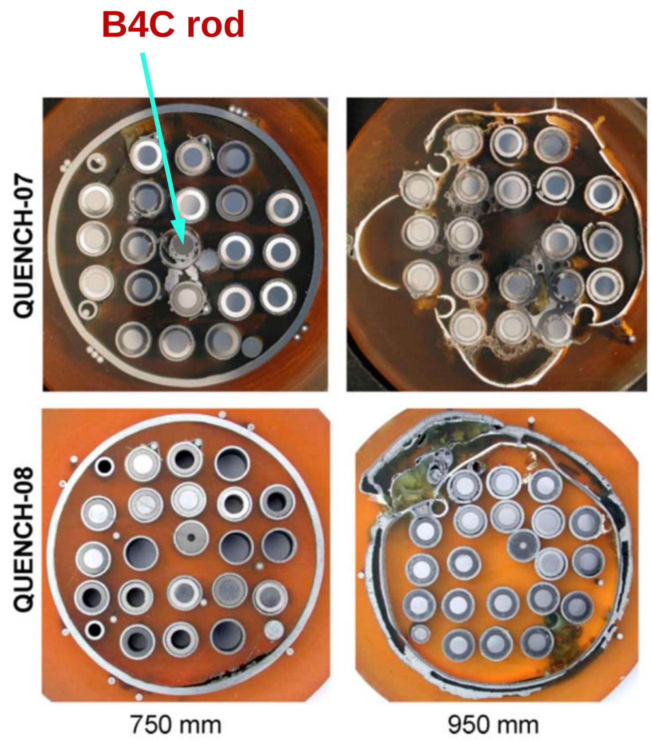




ceramic precipitation growth during melt oxidation

B_4C absorber rod as trigger of early melt formation



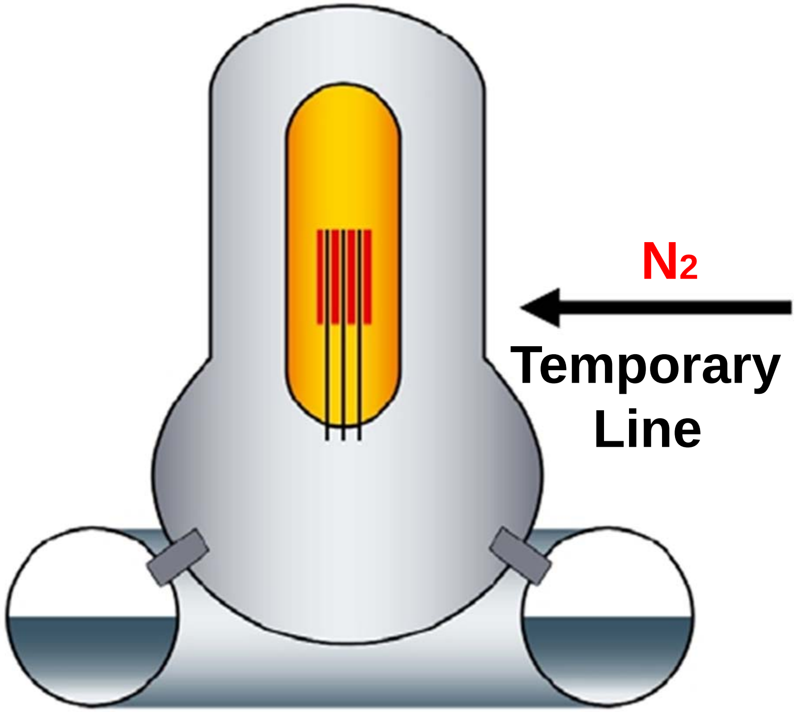


Two tests performed under identical conditions:

- QUENCH-07 with B_4C absorber rod
- QUENCH-08 without absorber rod

Fukushima Recovery Action: Prevention of Hydrogen Explosion

N_2 gas has been injected into unit 1 PCV to reduce the risk of a hydrogen explosion since April 7.



N_2 Generator

Max $14 m^3/h$, 0.6MPa

Air ingress influence on cladding

Oxidation of Zry-4 in mixed nitrogen-steam atmospheres (M. Steinbrück)

1 h, 1000 °C
10% N_2

1 h, 1000 °C
50% N_2

1 h, 1000 °C
95% N_2

1 h, 1200 °C
10% N_2

1 h, 1200 °C
50% N_2

1 h, 1200 °C
95% N_2

Main results of the QUENCH program

- A nuclear reactor core seems to be coolable and the hydrogen production during reflood is not noticeable when the core is still intact and no or only local melt formation has already taken place. This is a realistic boundary condition up to 1900 °C provided if
  - the reflood water flow rate is >1 g/s per rod,
  - no strong eutectic melt formation (e.g. by absorber materials) occurred,
  - breakaway oxidation took no place,
  - extended steam starvation phases before reflooding was avoided.
- Air ingress may have diverse effects on bundle degradation and coolability. On the one hand, energy release by air oxidation is higher, and the cooling effect is lower in comparison with steam. Furthermore, oxidation in a nitrogen-containing atmosphere accelerates the kinetics and may lead to the formation of strongly degraded oxide scales. On the other hand, no hydrogen is produced by oxidation of metals in air, thus reducing the risk of hydrogen detonations.

Outlook

- Bundle tests under LOCA conditions planed to be performed with different cladding materials
- Bundle tests on debris formation and debris coolability are planed in framework of European SARNET-2 program

Thank you for your attention

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

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