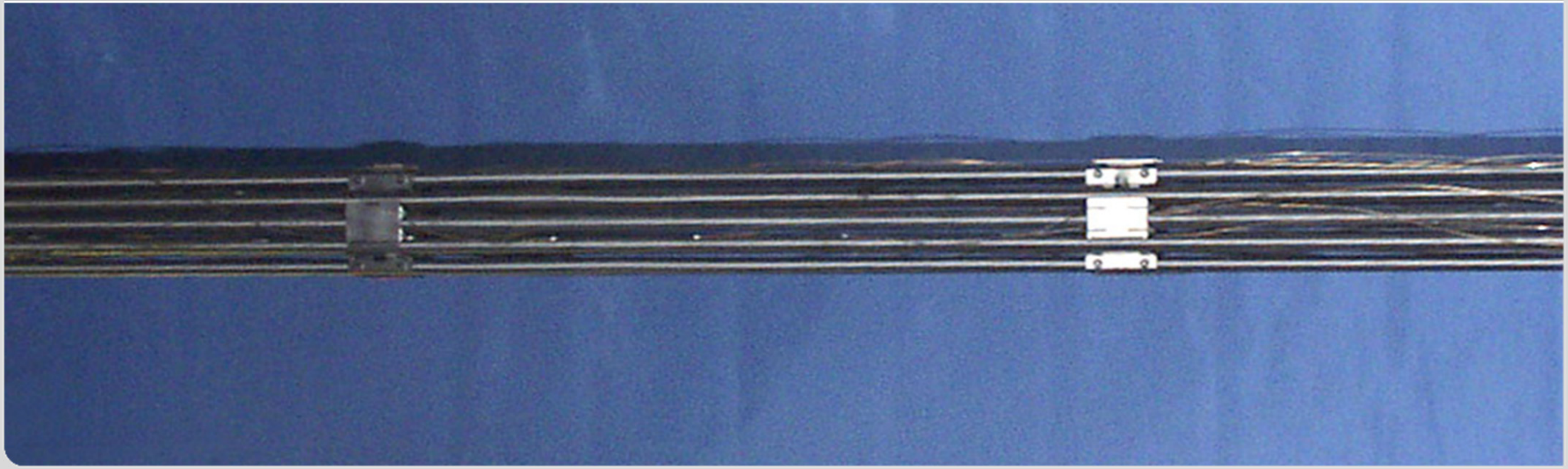
Overview of LOCA tests performed at KIT during last 30 years

J. Stuckert

QWS19, Karlsruhe 2013

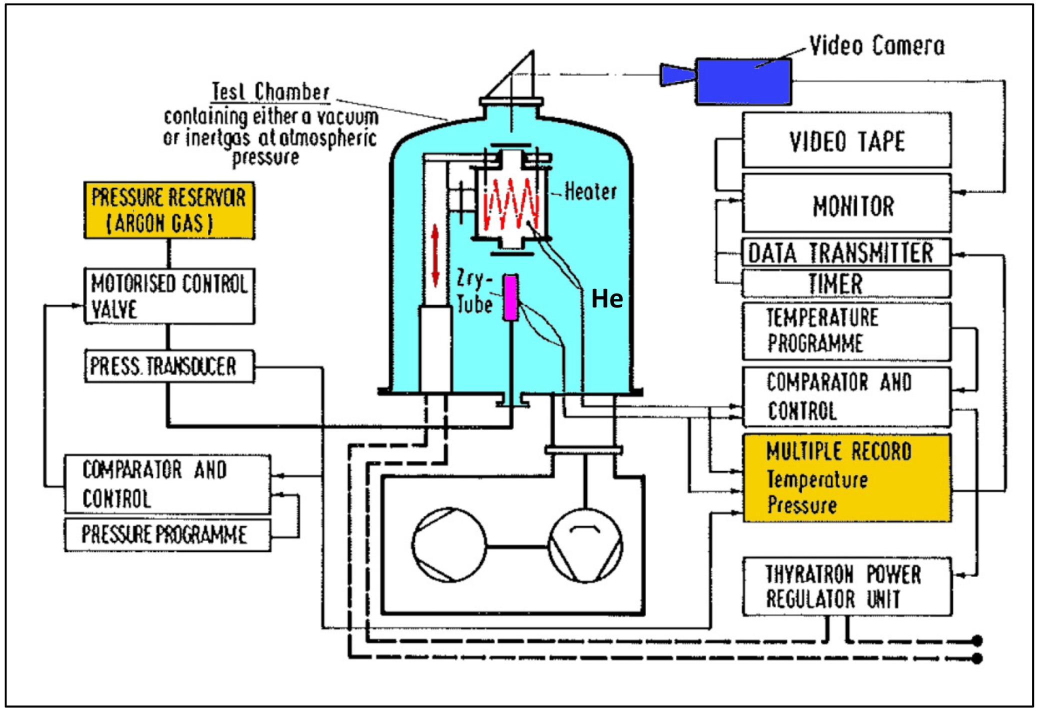
Institute for Applied Materials; Program NUKLEAR



Out-of-pile KfK single tube isothermal tests TUBA between 600°C and 1200°C: investigation of creep rupture time

P. Hofmann, S. Raff. KfK 3168, Juli 1981

60 tests



scheme of **TUBA** rig (TUbe Burst Apparatus)

samples: as received Zry-4 tubes (without pellets) with length of 60 mm;

pressure-less heating to work T in He;

filling of sample with Ar during 1 s to overpressures 2…200 bar;

one TC at sample bottom;

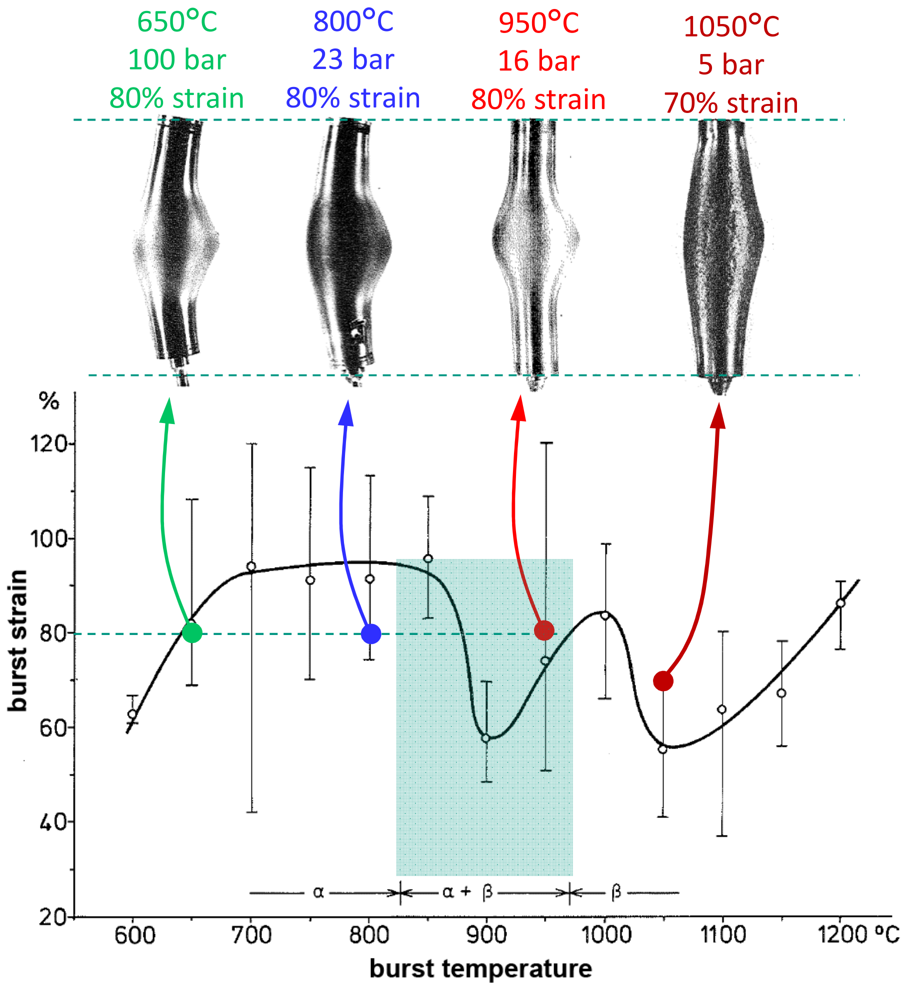
axial T difference between sample middle and sample end-plugs (pre-test): 25 K;

azimuthal ΔT: < 3 K;

strain measurement on cross projection with video camera.

Single tube isothermal TUBA tests: dependence of burst strain and rod bending on temperature

Karlsruhe Institute of Technology



max burst strain vs. temperaure

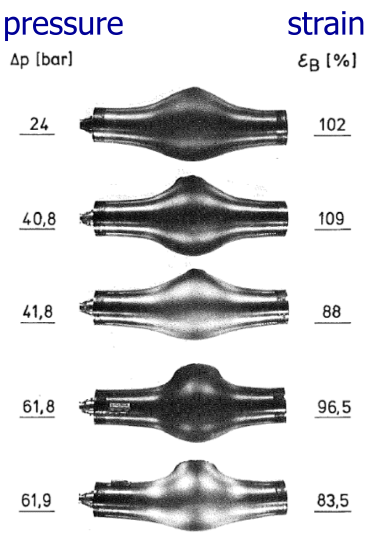
1) two minimums of the burst strain:
at 900°C (α+β region) and 1050°C (β region);

2) significant rod bending at temperatures before phase transition (α region);

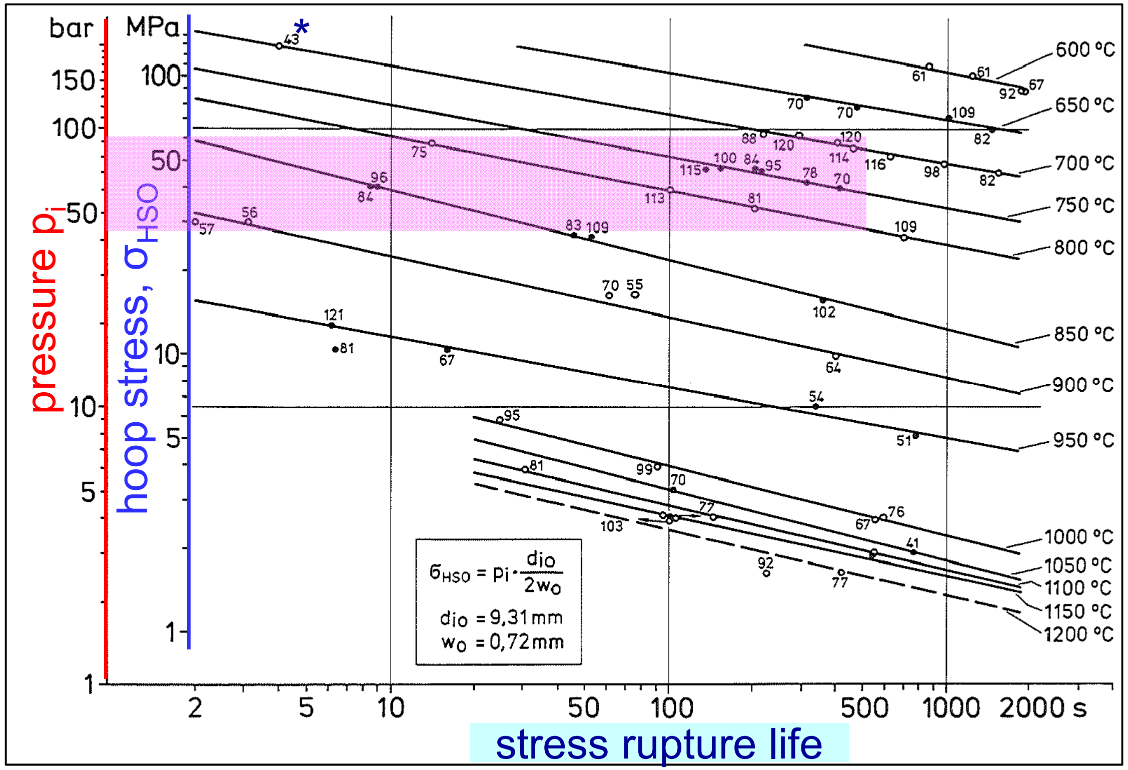
absence of rod bending at temperatures during and after phase transition;

3) axial contraction in α region due to anisotropy.

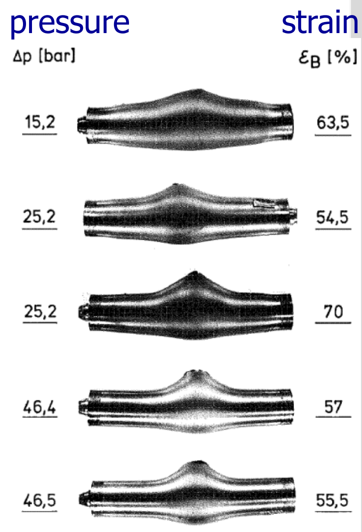
Single tube isothermal TUBA tests: criterion of creep rupture time (dependence of burst time on temperature and pressure)



Zry-4 samples after burst at 850°C



*burst strain expressed as a percentage

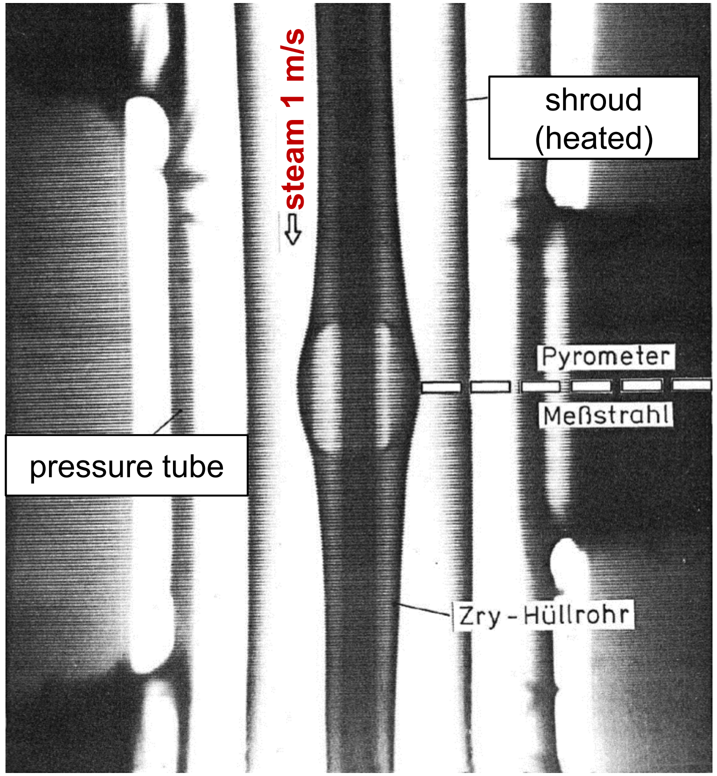


Zry-4 samples after burst at 900°C

KfK single rod transient tests FABIOLA

L. Schmidt, H. Lehning, K. Müller, D. Piel, H. Schleger. KfK 3250, Juni 1982

> 100 tests



X-ray picture of FABIOLA rig

samples: as received Zry-4 tubes with length of 200 mm, filled with Al_2O_3 or UO_2 pellets (*no influence of pellet material was detected*);

filling of sample with He during 1 s to overpressures 40…125 bar at 600°C;

transient heating in steam with rates 2…11 K/s until clad burst;

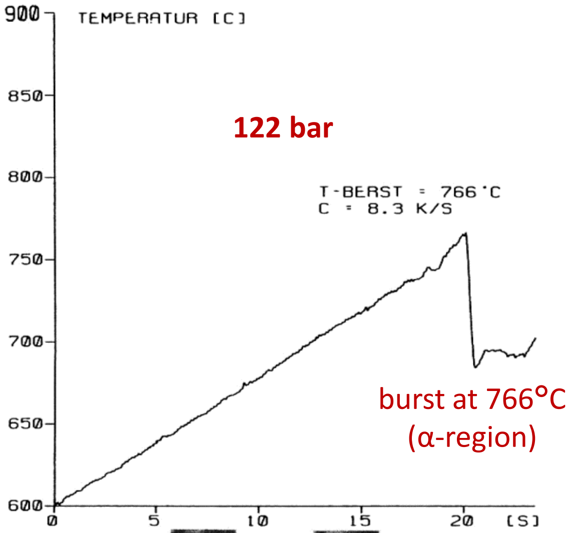
temperature measurements: 3 pyrometers along axial direction (75 mm interval), 3 thermocouples at burst position (only few samples; 120° interval);

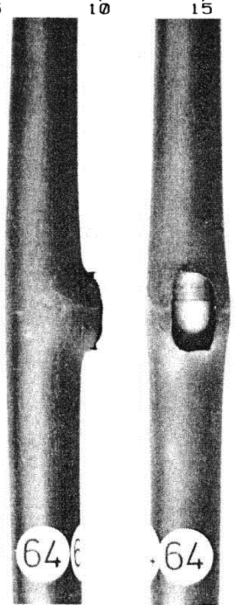
axial T gradient between sample middle and sample end-plugs: 0.2 K/mm;

azimuthal ΔT: 15 K;

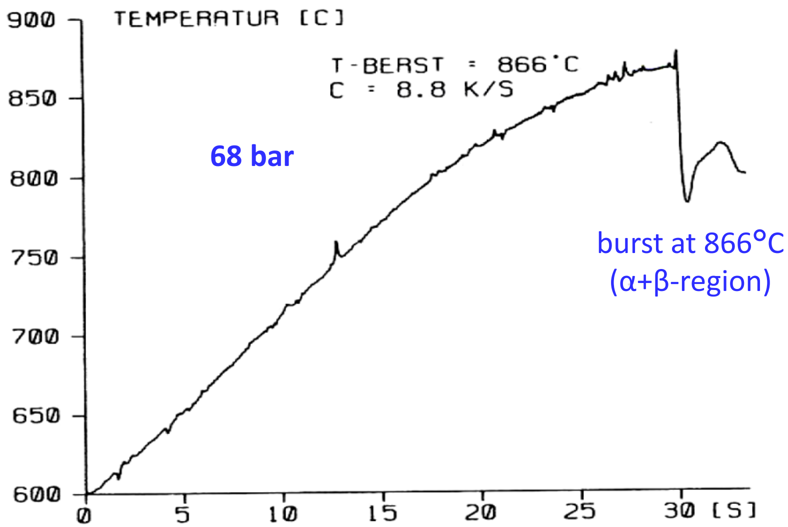
strain measurement on longitudinal projection with X-ray camera.

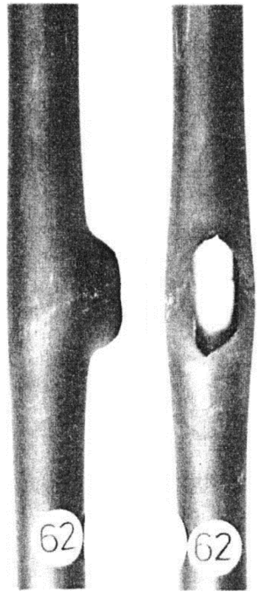
Single rod transient tests FABIOLA: dependence of burst time and burst strain on pressure





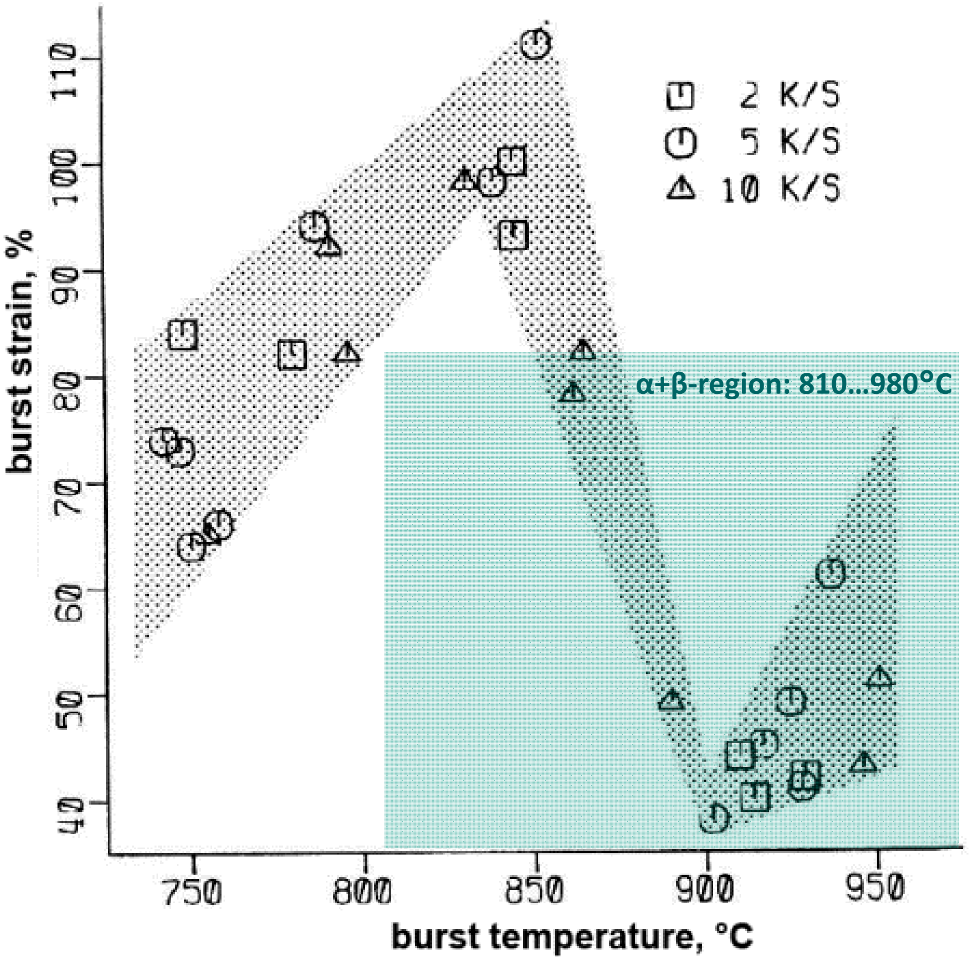
strain 39%





strain 52%

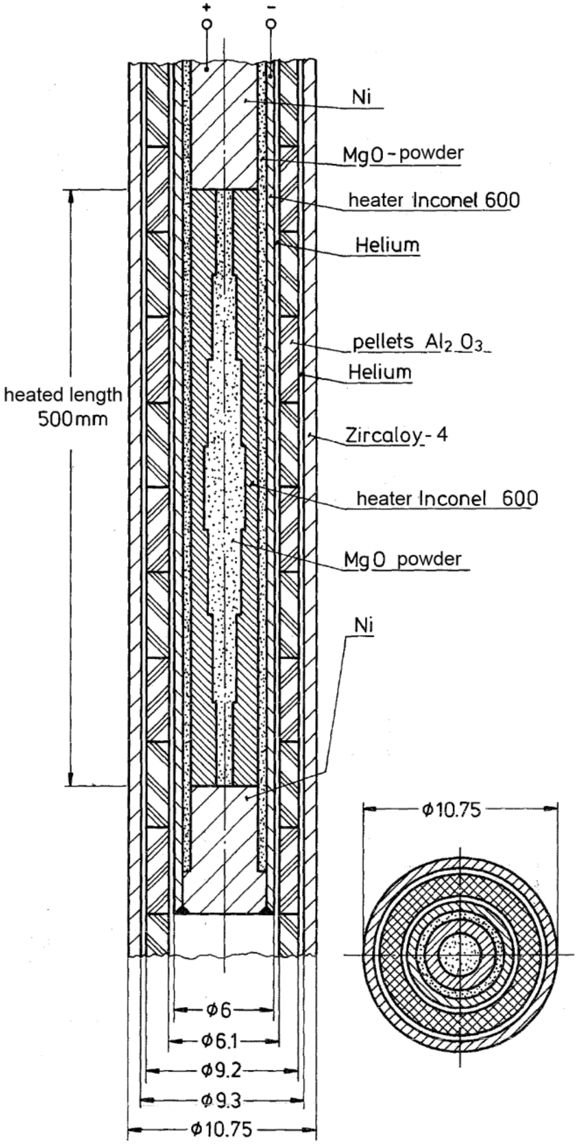
Out-of-pile single rod transient tests FABIOLA: dependence of burst strain on temperature



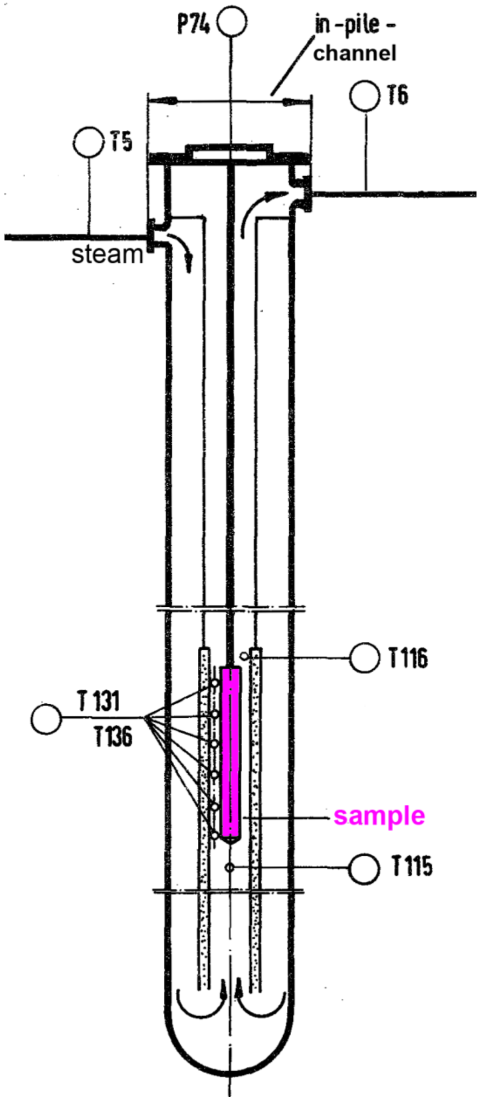
minimum of burst strain lies in α+β-region at 900°C - similar to isotherm tests

FR2 in-pile single rod tests with electrical heating

M. Prüßmann, E. H. Karb, L. Sepold. KfK 3255, September 1982



electrically heated rod BSS



FR2 test channel

8 reference tests with rod simulators inside FR2 reactor channel (reactor out of order)

samples: as received Zry-4 tubes filled with Al_2O_3;

Internal Inconel heater 50 W/cm;

filling of sample with He during to overpressures 20…110 bar at 370°C;

transient heat up with rate 12 K/s until desired T of 820…1000°C;

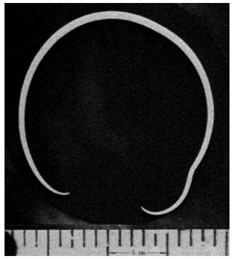
temperature measurements: 6 surface TC along axial direction;

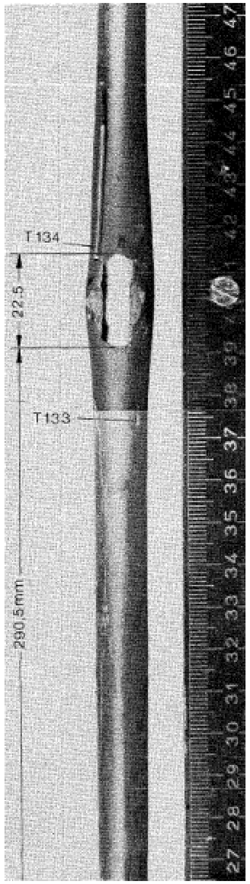
axial ΔT between sample middle and sample end-plugs: > 50 K;

azimuthal ΔT: < 60 K;

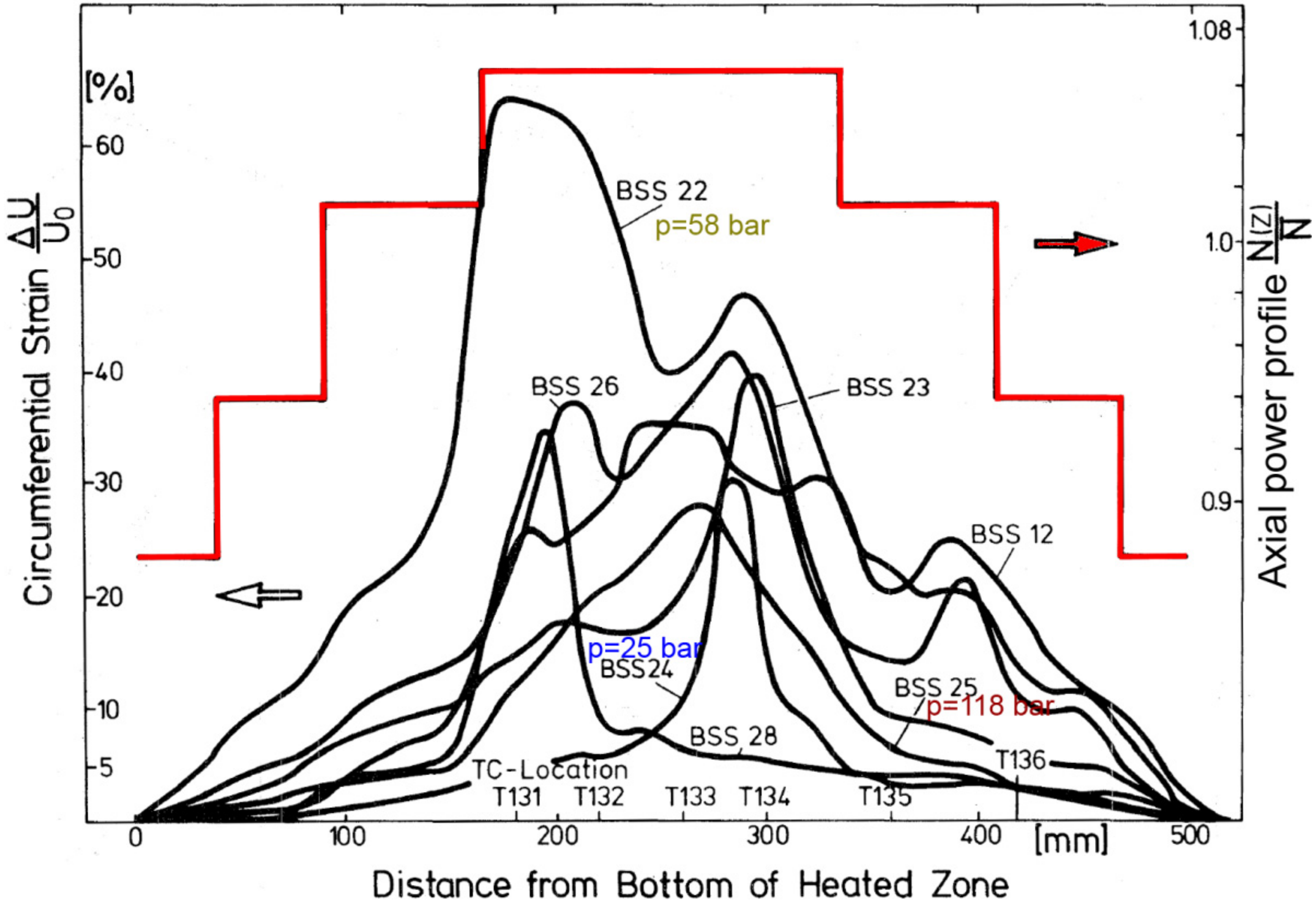
tests performed without reflood.

FR2 in-pile single rod tests with electrical heating: axial changes of circumferential strain



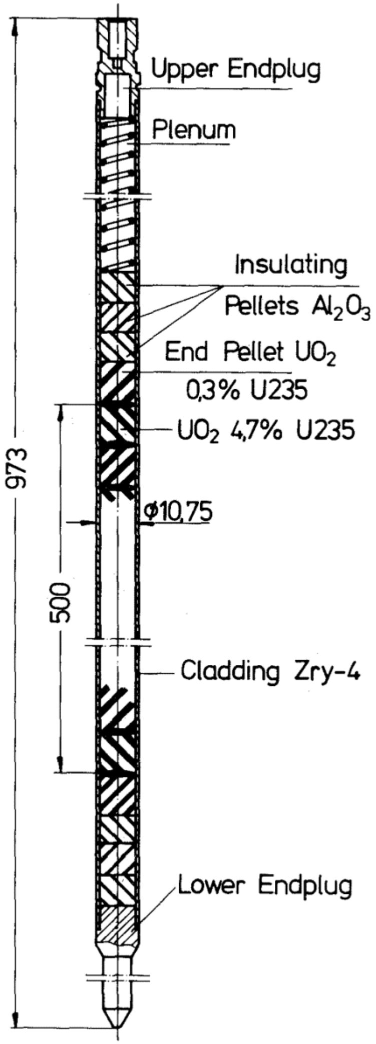


(sample BSS 23: Tburst=810°C Pburst=85 bar)

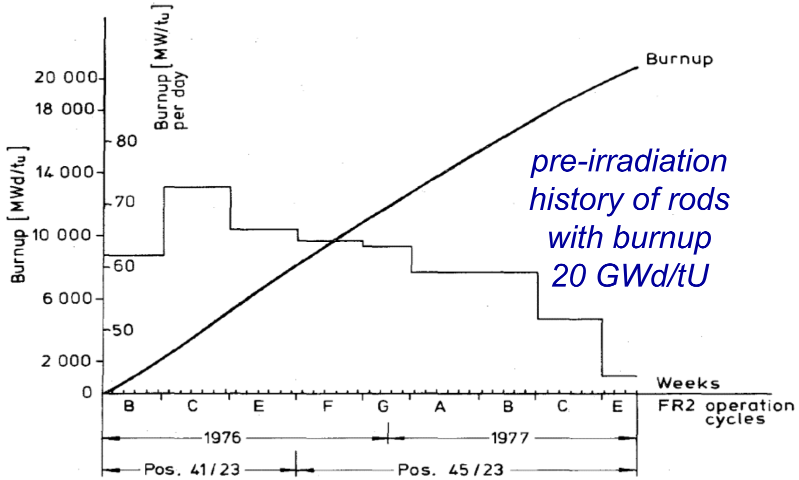


FR2 in-pile single rod tests

E. H. Karb, M. Prüßmann, L. Sepold, P. Hofmann, G. Schanz. KfK 3346, March 1983



test rod design



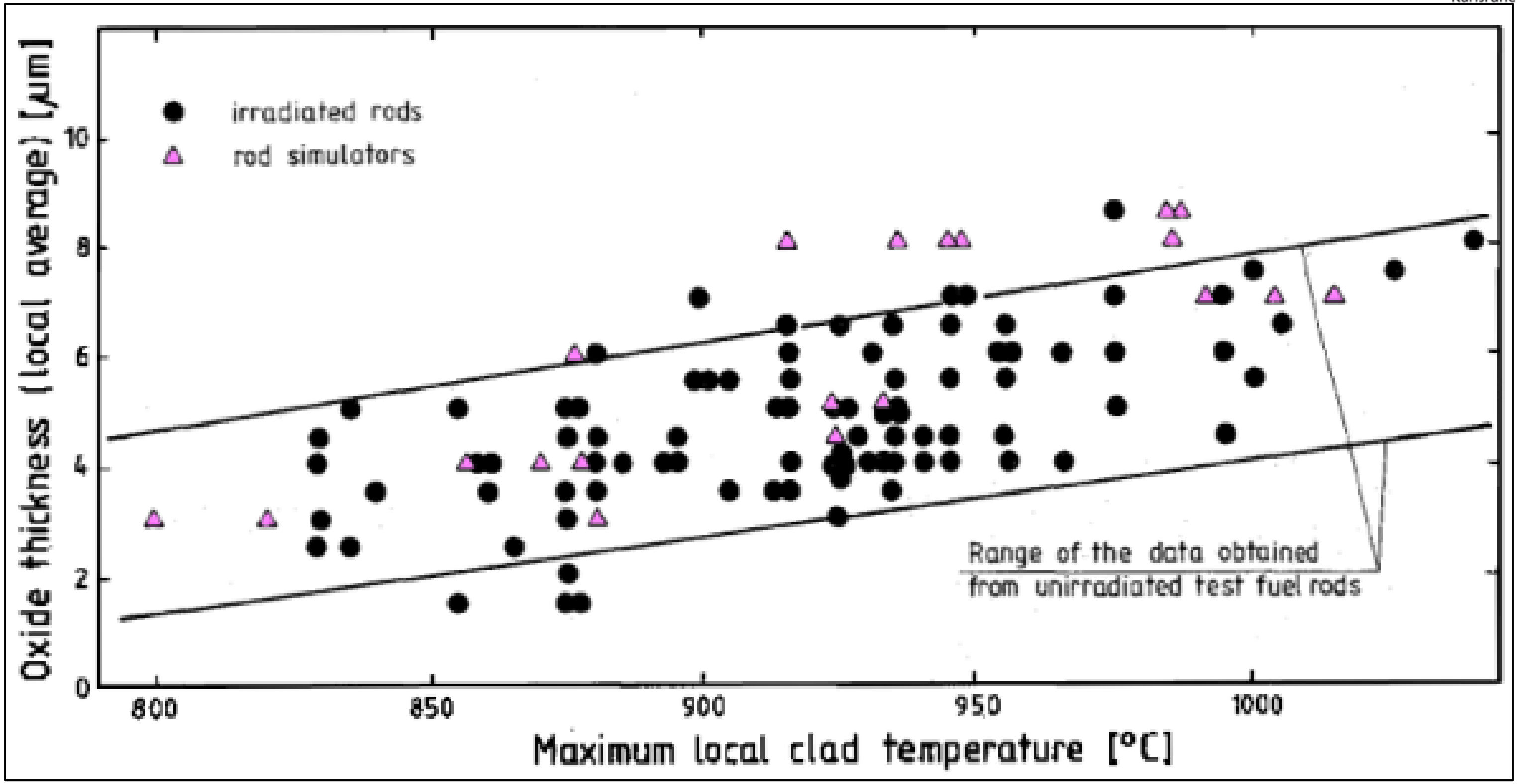
pre-irradiation history of rods with burnup 20 GWd/tU

The same test scenario as for electrically heated rods (BSS), but with <u>nuclear</u> heating.

Tests performed without reflood.

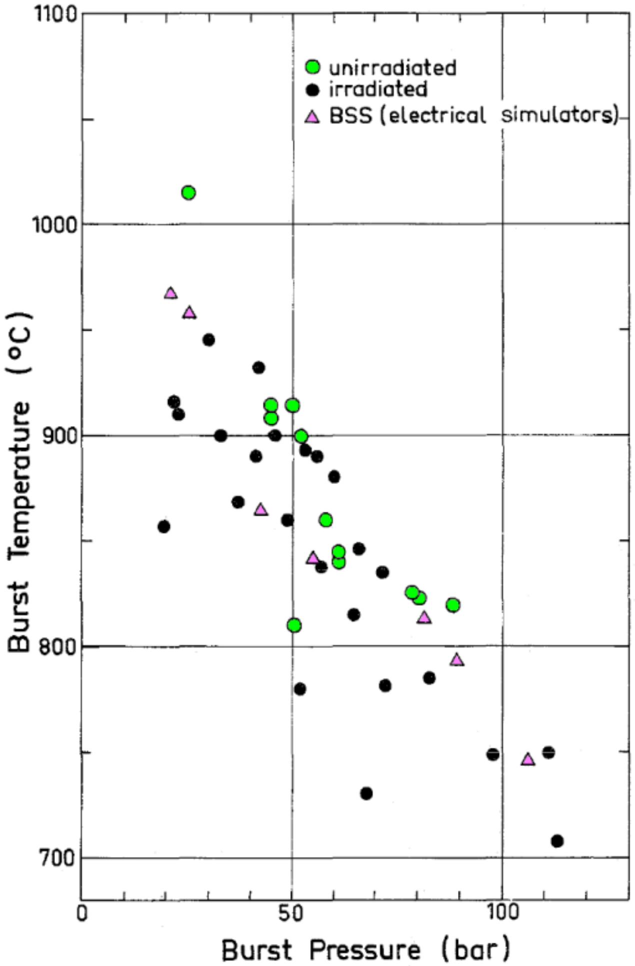
Type of Tests	Test series	Number of irradeated rods	Number of tests	Burnup (MWd/tU)	Range of internal pressure at steady state temperature (bar)
Calibration, Scoping	A	0	5	0	25 -100
Unirradiated rods (Main parameter: Internal pressure)	**B**	**0**	**9**	**0**	**55 - 90**
Irradiated rods (Main parameter: Burnup)	**C**	**6**	**5**	**2500**	**25 - 110**
	E	**6**	**5**	**8000**	**25 - 120**
	F	**6**	**5**	**20000**	**45 - 85**
	G1	**6**	**5**	**35000**	**50 - 90**
	G2/3	**6**	**5**	**35000**	**60 - 125**
Electrically heated fuel rod simulators (Main parameter: Internal pressure)	*BSS*	*0*	*8*	*0*	*20 - 110*

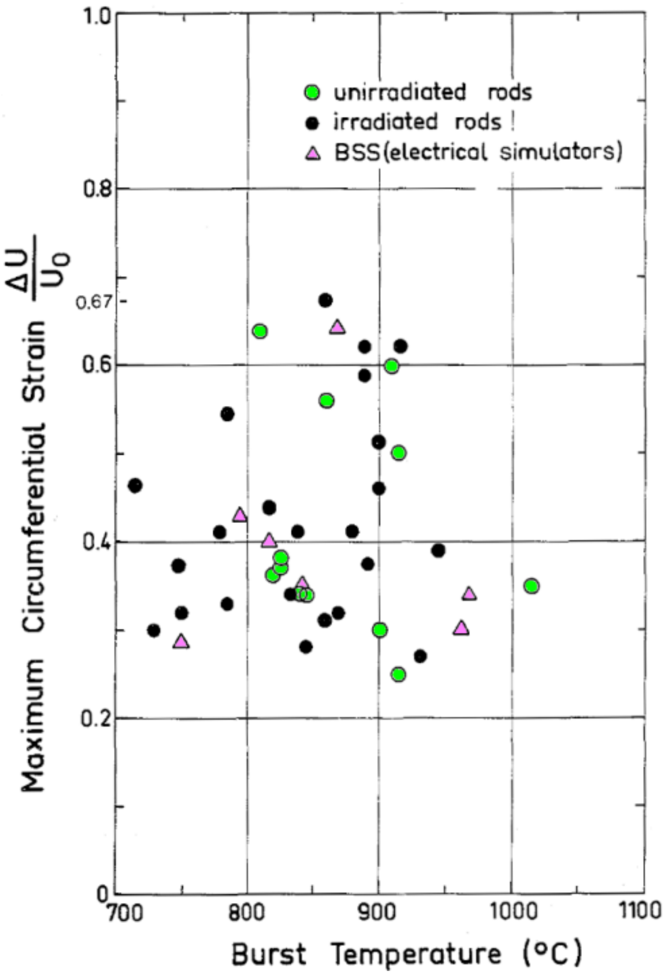
FR2 in-pile single rod tests: cladding oxidation close to the burst opening



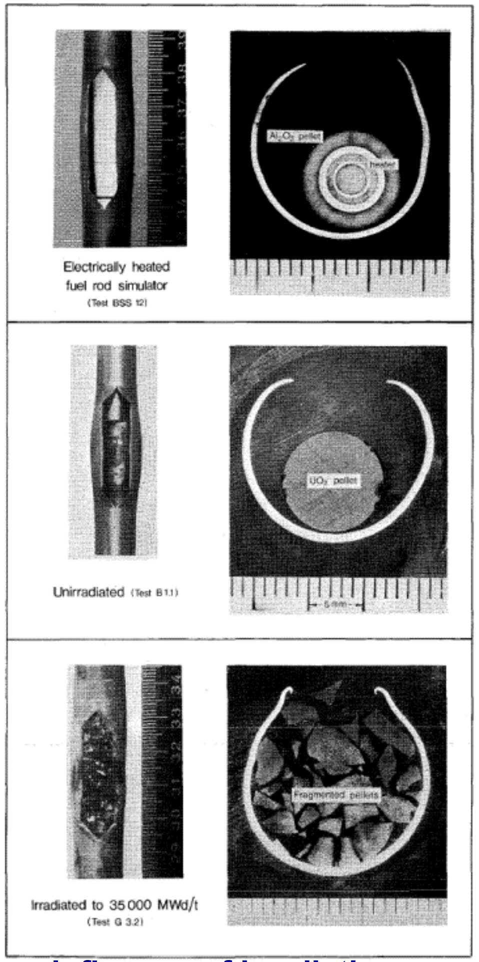
- ➢ **No influence of irradiation on the oxide growth was indicated (up to 35 GWd/tU)**
- ➢ **Close to the burst opening, the thickness of the inner oxide layer was similar to outer oxide**
- ➢ **Essentially no oxide was found on the inner surface more than about 100 mm from the burst location**
- ➢ **The observed oxidation did not influence the circumferential strain**

FR2 in-pile single rod tests: no influence of irradiation (<35 GWd/tU) on burst parameters

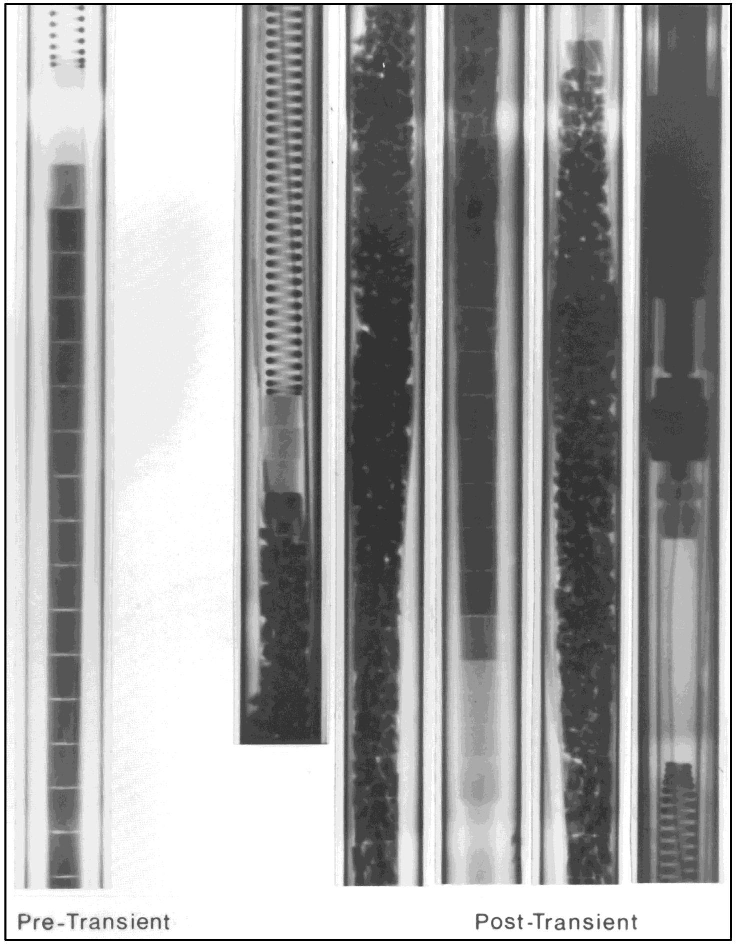




FR2 in-pile single rod tests: shape of claddings and pellets at ballooning positions



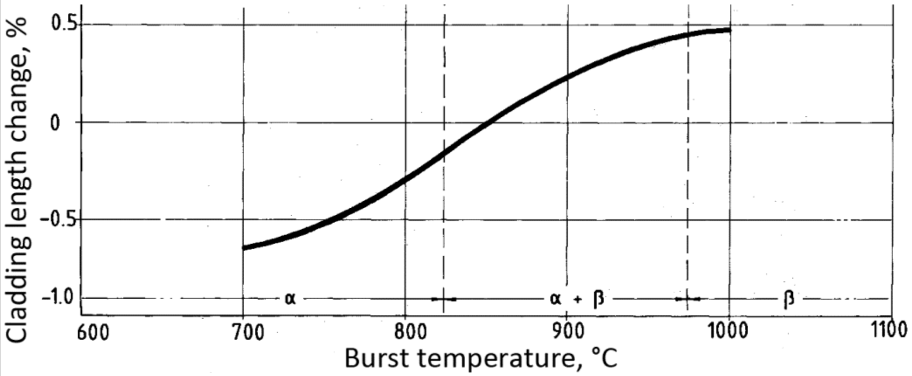
no influence of irradiation on burst shape



neutron radiography: lost of shape of fragmented pellets after ballooning (rod F1, burnup 20 GWd/tU**)**

- **Fuel pellet fragmentation did not affect the cladding deformation process**
- **No influence of fission products on cladding burst strain was detected**

Single rod tests: change of axial cladding dimensions and rod bending

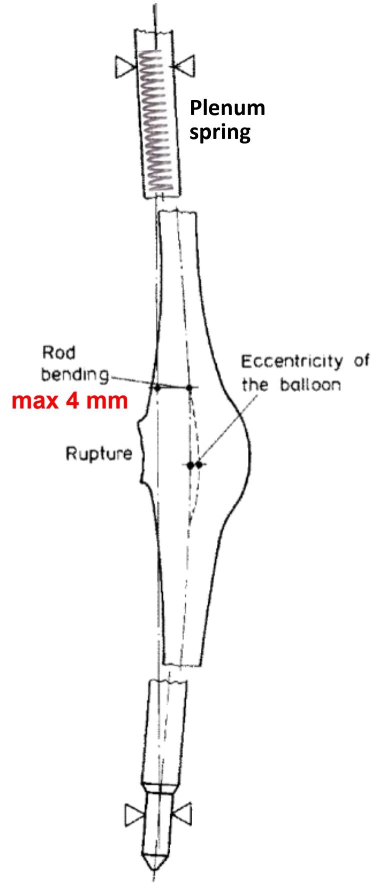


Axial cladding contraction and growth depends on temperature:

results of later REBEKA tests with single Zry-4 tubes surrounded with heaters;

rod length 500 mm;

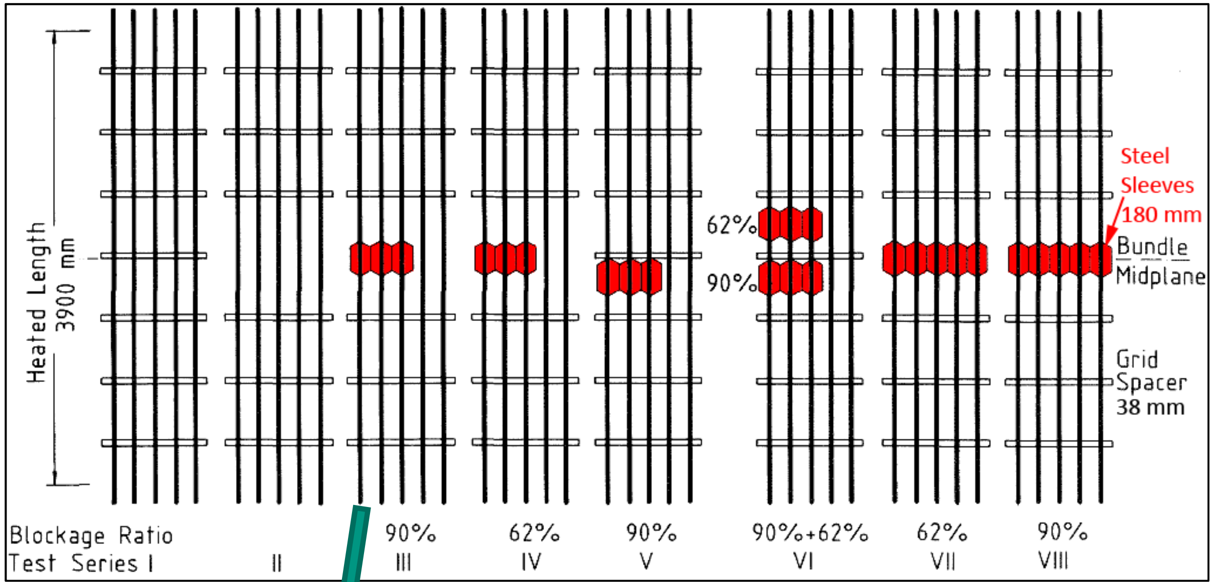
heating rates 1…30 K/s



Results of the FR2 in-pile single rod tests: out-of-pile results [Chung], showing significant bending below 840°C (α-Zr(O)) and negligible values above 840°C, **were not confirmed** by the in-pile tests. However, the orientation of the rod bend was consistent with out-of-pile results, i.e., the rupture was on the inside of the bend.

Out-of-pile bundle tests FEBA on investigation of coolability of bundles blocked by ballooning simulators

P. Ihle, K. Rust. KfK 3657, March 1984

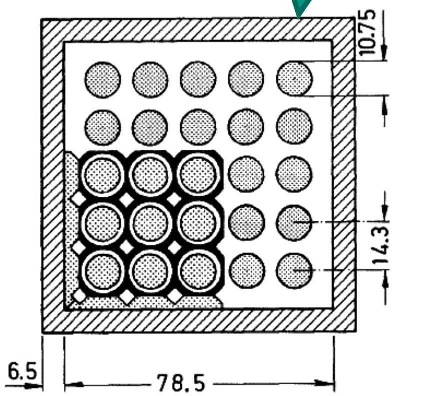


Flooding Experiments with Blocked Arrays:

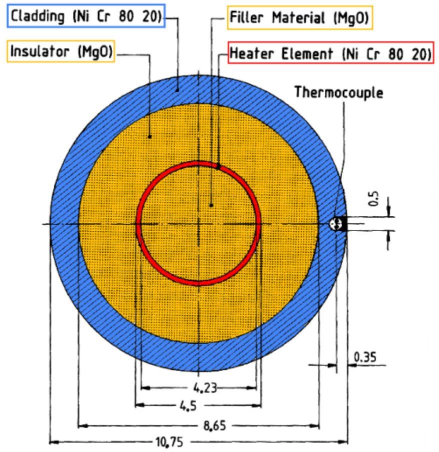
8 electrical heated bundle simulators, length 3.9 m

Outcome:

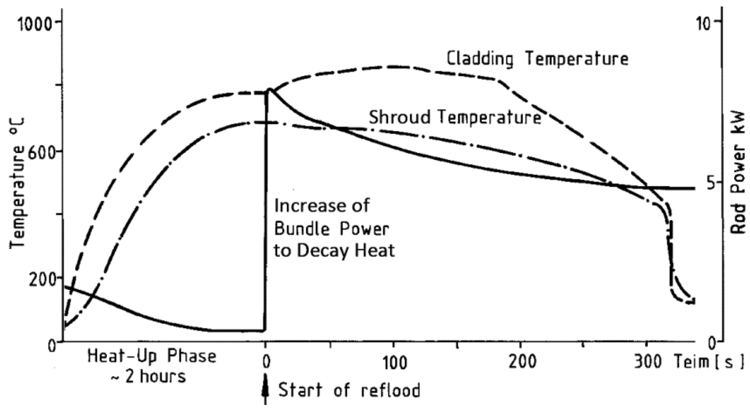
- Blockage of rod clusters up to 90% don't affect their coolability for flow rates 2…6 cm/s;
- Grid spacers increase the cooling effectiveness.



cross section of FEBA bundle with 5x5 rods

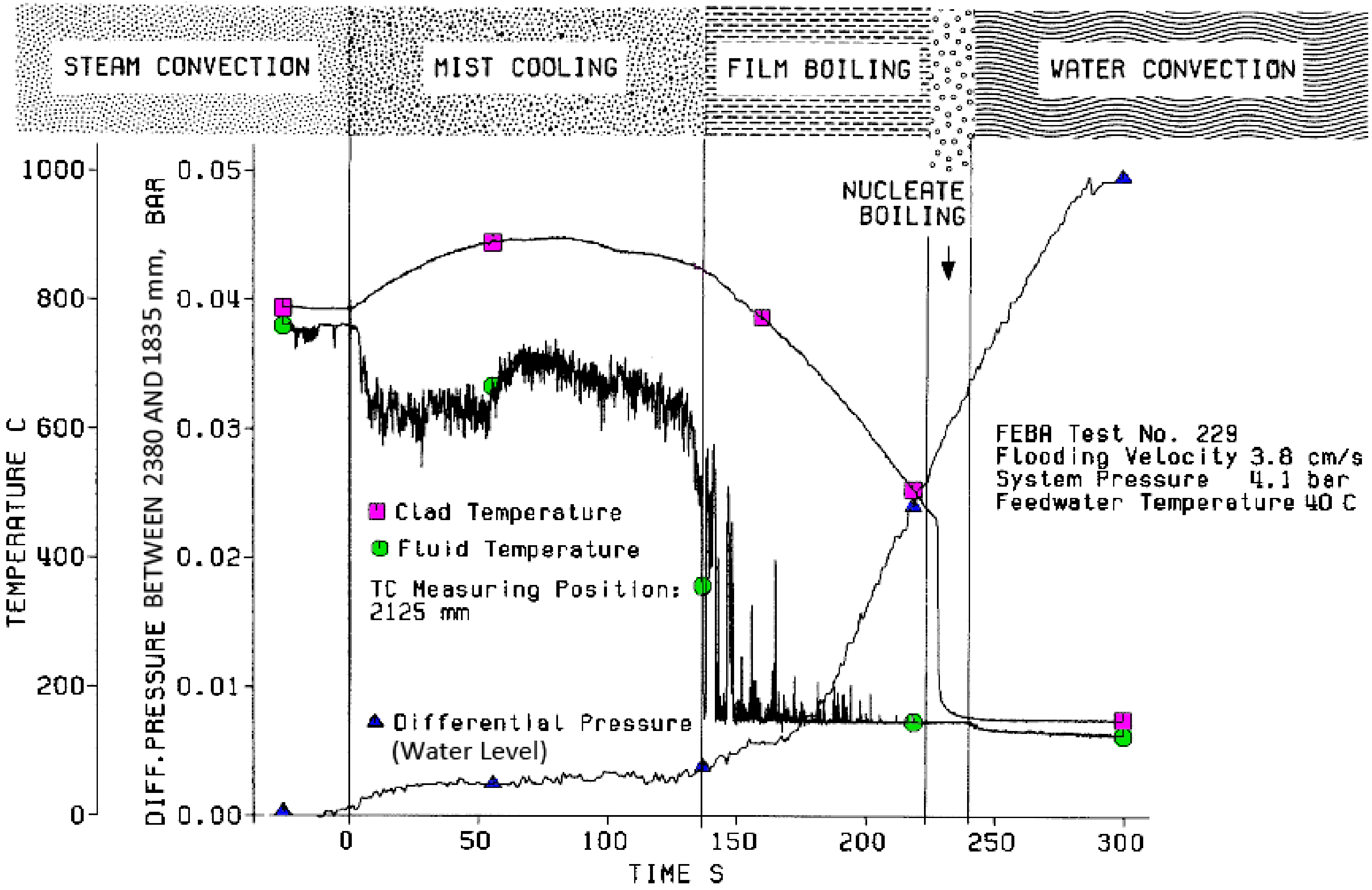


FEBA rod simulator



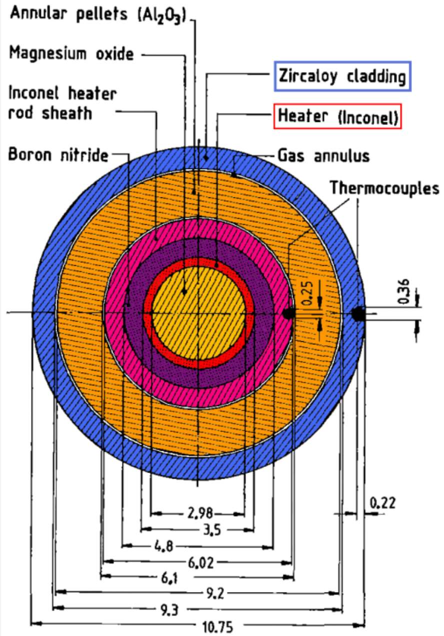
FEBA test scenario

FEBA: clad temperature evolution

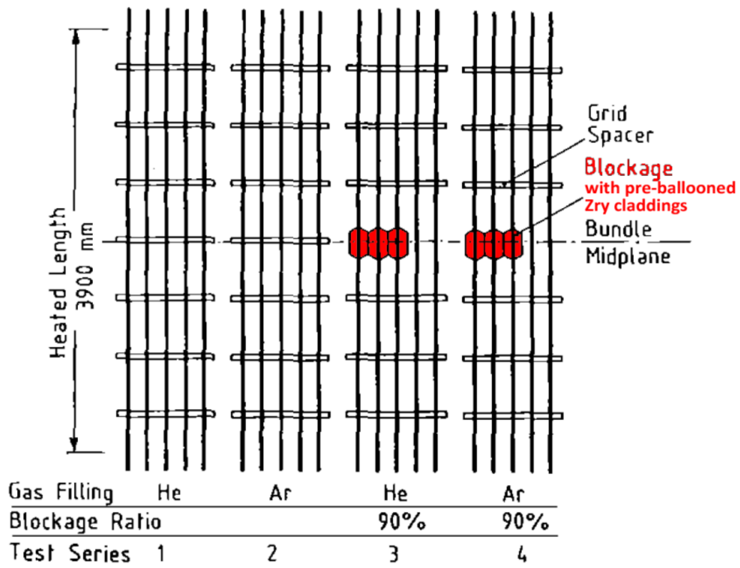


Out-of-pile bundle tests SEFLEX on influence of clad-fuel gaps and coolability of bundles blocked by pre-ballooned clads

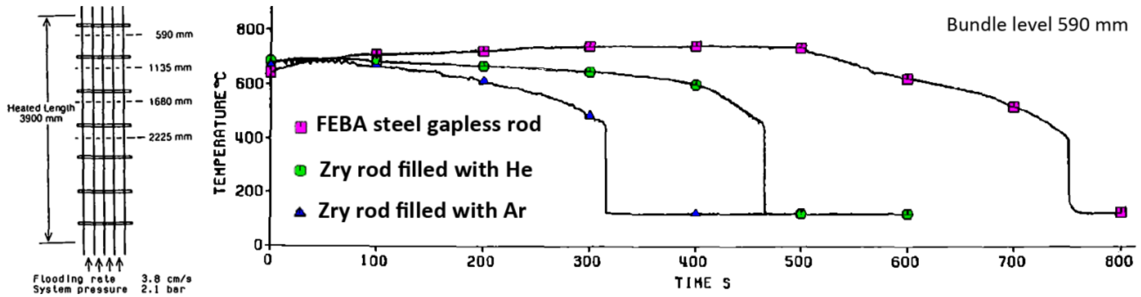
P. Ihle, K. Rust. KfK 4024, March 1986



SEFLEX (REBEKA) rod simulator



SEFLEX bundles



Peak cladding temperatures and quench times of SEFLEX (Zry) and FEBA (SS) bundles

Fuel Rod Simulator Effects in Flooding Experiments:

4 electrical heated bundle simulators with Zry-4 clads, length 3.9 m.

The required outer shape of the ballooned Zircaloy claddings was produced in a furnace by heating up the pressurized cylindrical tubes placed in correspondingly shaped molds.

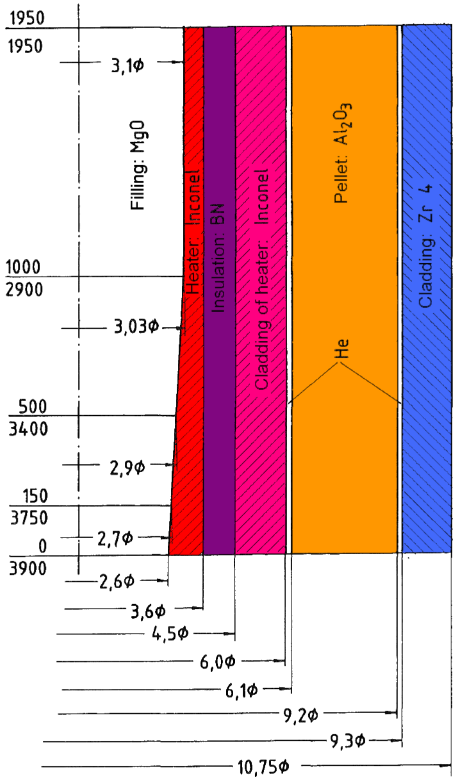
Outcome:

- Ballooned Zircaloy claddings, forming e.g. a coplanar 90% blockage, are quenched substantially earlier than thickwall FEBA stainless steel blockage sleeves, and even earlier than undeformed rod claddings.
- Rods with Zry-4 clads exhibit lower peak cladding temperatures and shorter quench times during reflood than gapless heater rods with FEBA steel claddings.

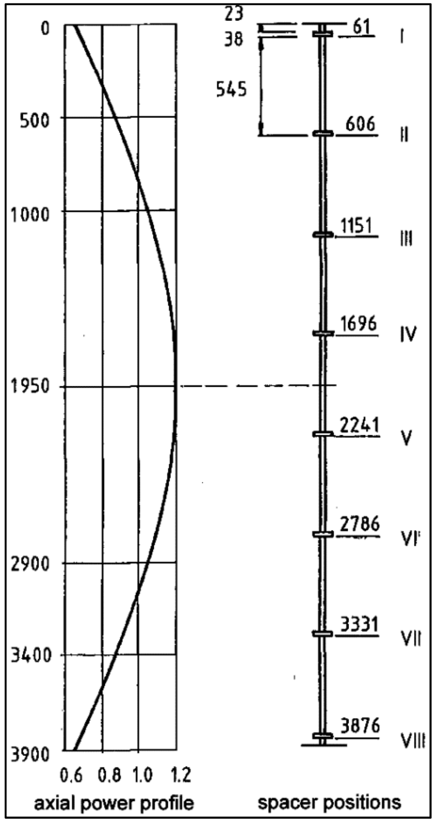
Out-of-pile REBEKA bundle tests (1978-1987) on Zry-4 clad behaviour under LOCA conditions

K. Wier, KfK 44407, May 1988;

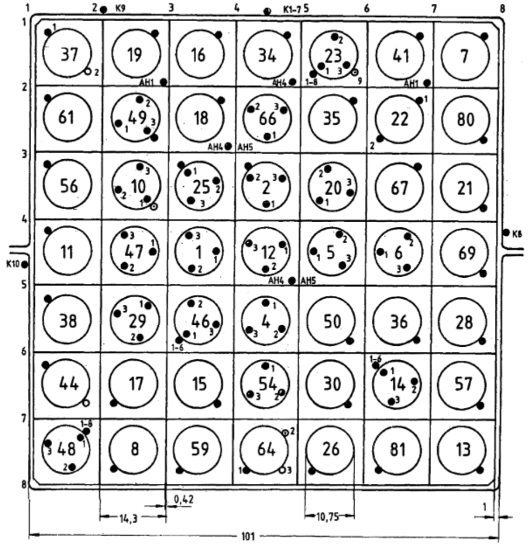
F. J. Erbacher, H. J. Neitzel, K. Wiehr: KfK 4781, August 1990



radial structure of REBEKA rod



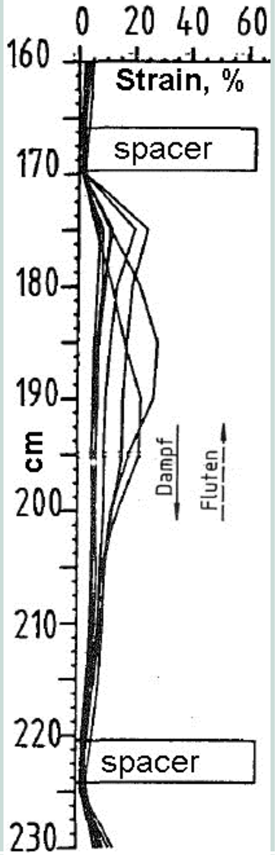
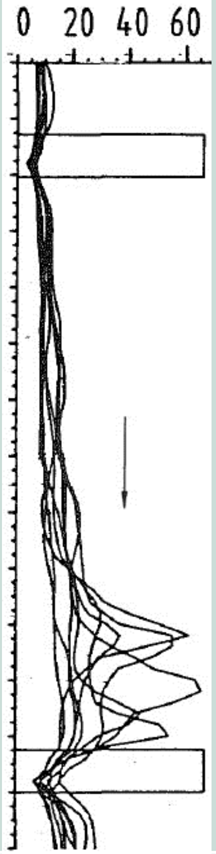
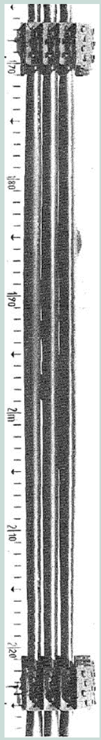
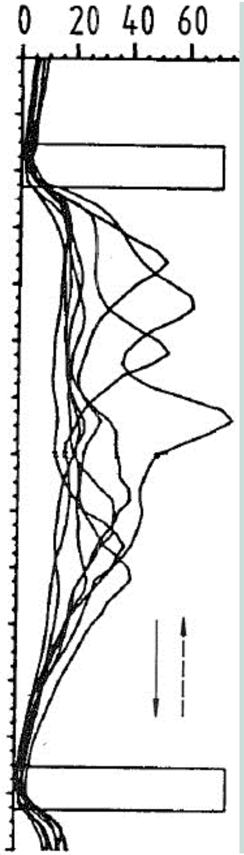
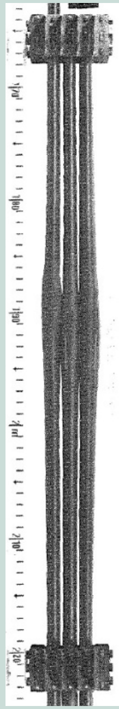
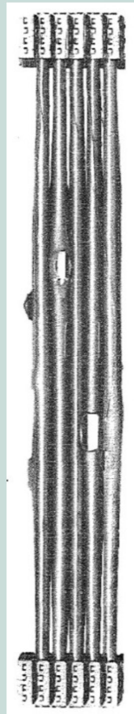
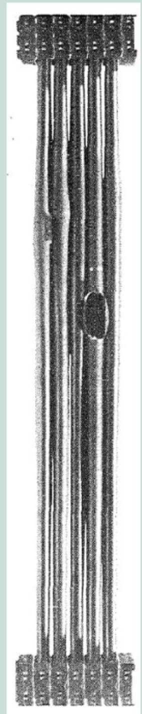
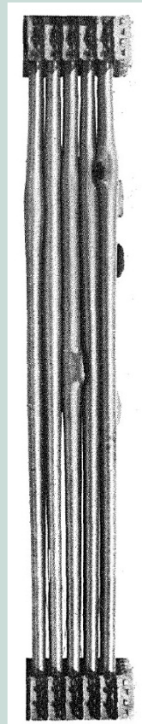
"cosines" axial power profile



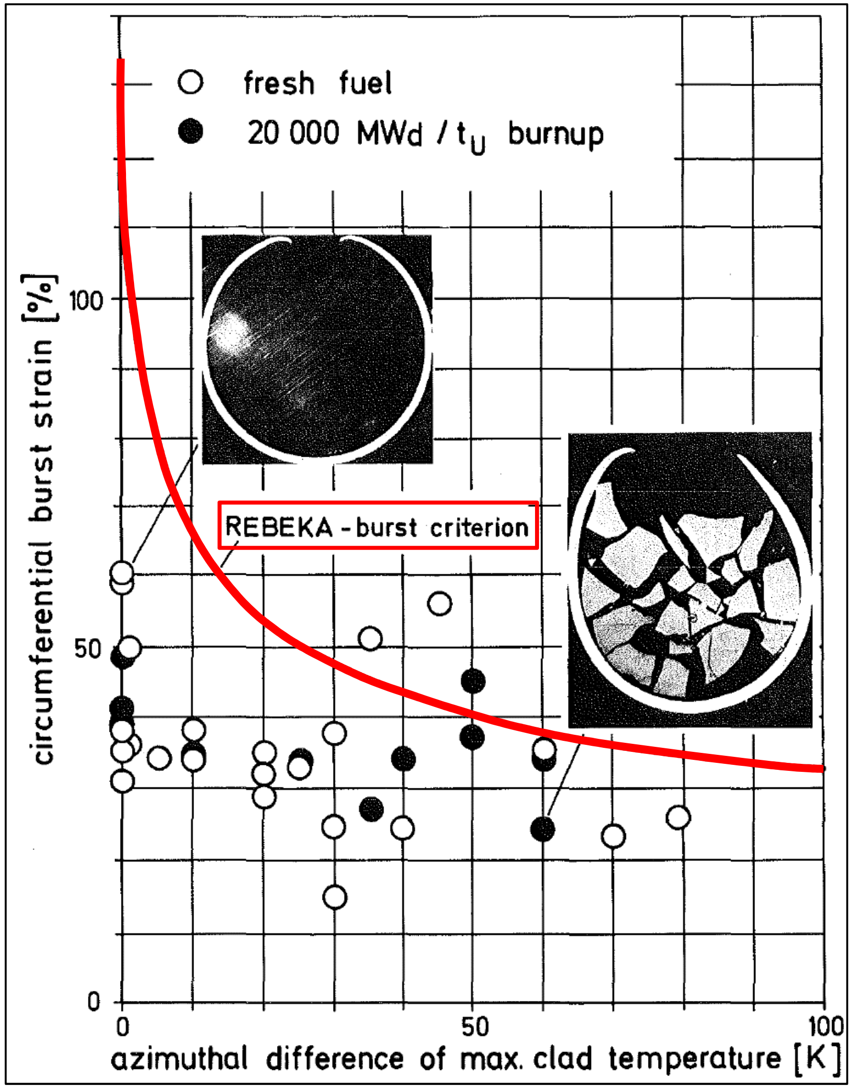
allocation of thermocouples

REBEKA-5 post-test appearance: burst positions

REBEKA test matrix

	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

Outcomes of REBEKA program



comparison of FR2 data with REBEKA burst ctriterium

- The cooling effect of the two-phase flow increases the temperature differences on the cladding tube circumference and limits in this way the mean circumferential burst strains to values of about 50%.
- The circumferential burst strains of Zircaloy cladding tubes are kept relatively small due to temperature differences on the cladding circumference and the anisotropic strain behavior of Zircaloy.

Summary of single rod and bundle tests (not pre-oxidised claddings) performed between 1978 and 1987

- Isothermal single cladding tests TUBA given conservative values on maximal burst parameters (dependence of stress burst life on temperature and pressure)
- Rod bending was observed only at temperatures below phase transition α → α+β in Zircaloy-4 material (810°C)
- Single rod tests FABIOLA with temperature transient confirmed observation of isothermal tests: minimum of burst strain lies in α+β-region at 900°C
- Single rod FR2 in-pile tests up to burn-up of 35 GWd/tU showed that 1) Fuel pellet fragmentation did not affect the cladding deformation process; 2) No influence of fission products on cladding burst strain was detected
- The observed oxidation degree did not influence the circumferential burst strain
- Conclusions of out-of-pile tests REBEKA, SEFLEX and FEBA on bundle thermal-hydraulic behaviour: 1) The cooling effect of the two-phase mixture which is intensified during reflooding increases temperature differences on the cladding tube circumference and thus limits the mean circumferential burst strains to values of about 50%; 2) An unidirected flow through the fuel rod bundle during the reflooding phase causes maximum cooling channel blockage of about 70%; 3) The coolability of deformed fuel elements can be maintained up to flow blockages of about 90%.

Bundle experiments of the new QUENCH-LOCA series

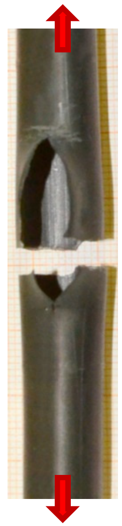
Karlsruhe Institute of Technology

Objective and results

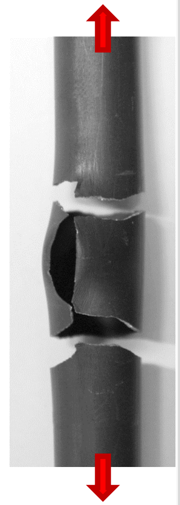
- Investigation of ballooning, burst and secondary hydrogen uptake of the cladding under representative design basis accident conditions
- Detailed post-test investigation of the mechanical properties of the claddings to check the embrittlement criteria and measurement of residual ductility
- Two experiments with Zircaloy-4 bundles were performed up to now as commissioning and reference tests
- Four bundle tests with non- and pre-hydrogenated M5® and ZIRLO™ claddings will be performed up to 2015

Zircaloy-4 rods

hydrogen bands inside cladding detected with n^0-radiography



rupture of cladding during tensile tests due to stress concentration (rods with C_H<1000wppm)



double ruptures due to hydrogen embrittlement (C_H<1000wppm)

Acknowledgment

The on-going QUENCH-LOCA experiments are supported and partly sponsored by the association of the German utilities (VGB).

Thank you for your attention

https://www.iam.kit.edu/wpt/loca/
http://www.iam.kit.edu/wpt/471.php
http://quench.forschung.kit.edu/