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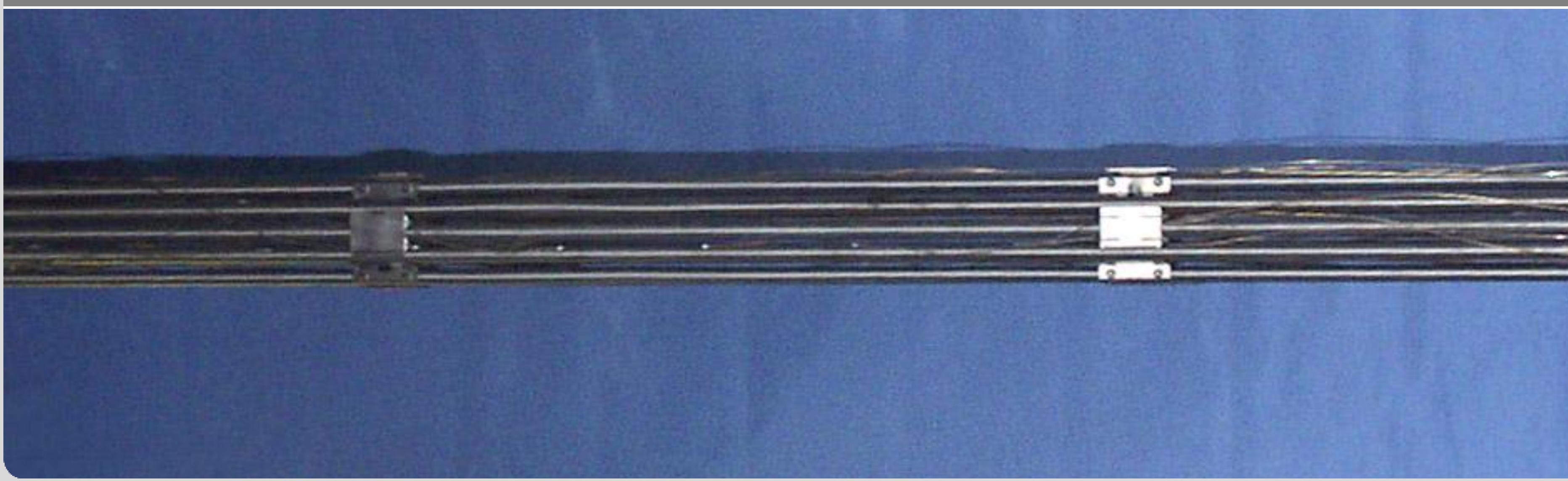
Towards ASTEC modeling of the QUENCH-LOCA-1

H. Muscher

QWS-22, Karlsruhe 2016

Institute for Applied Materials; Program NUKLEAR



Introduction/ outline

- The **QUENCH** high temp **test series** investigate the H_2 production as well as the transient behavior of core materials

- The aim is to present the experimental & ASTEC simulation results of the Q-L1 **test**.

- Start with installing and validating the new ASTEC v. 2.1.0.3 against TMI-2 SA complete reactor case, (w/o reflood, base case) using the results of the former OECD BE

- Motivation was: get experience with the new ASTEC **V2.1**.0.3

- In the **Q-L1** experiment, the effect of on bundle oxidation & core reflooding was investigated. The bundle configuration of Q-L1 with 21 heated rods & 4 corner rods was similar to the design of former tests, however:

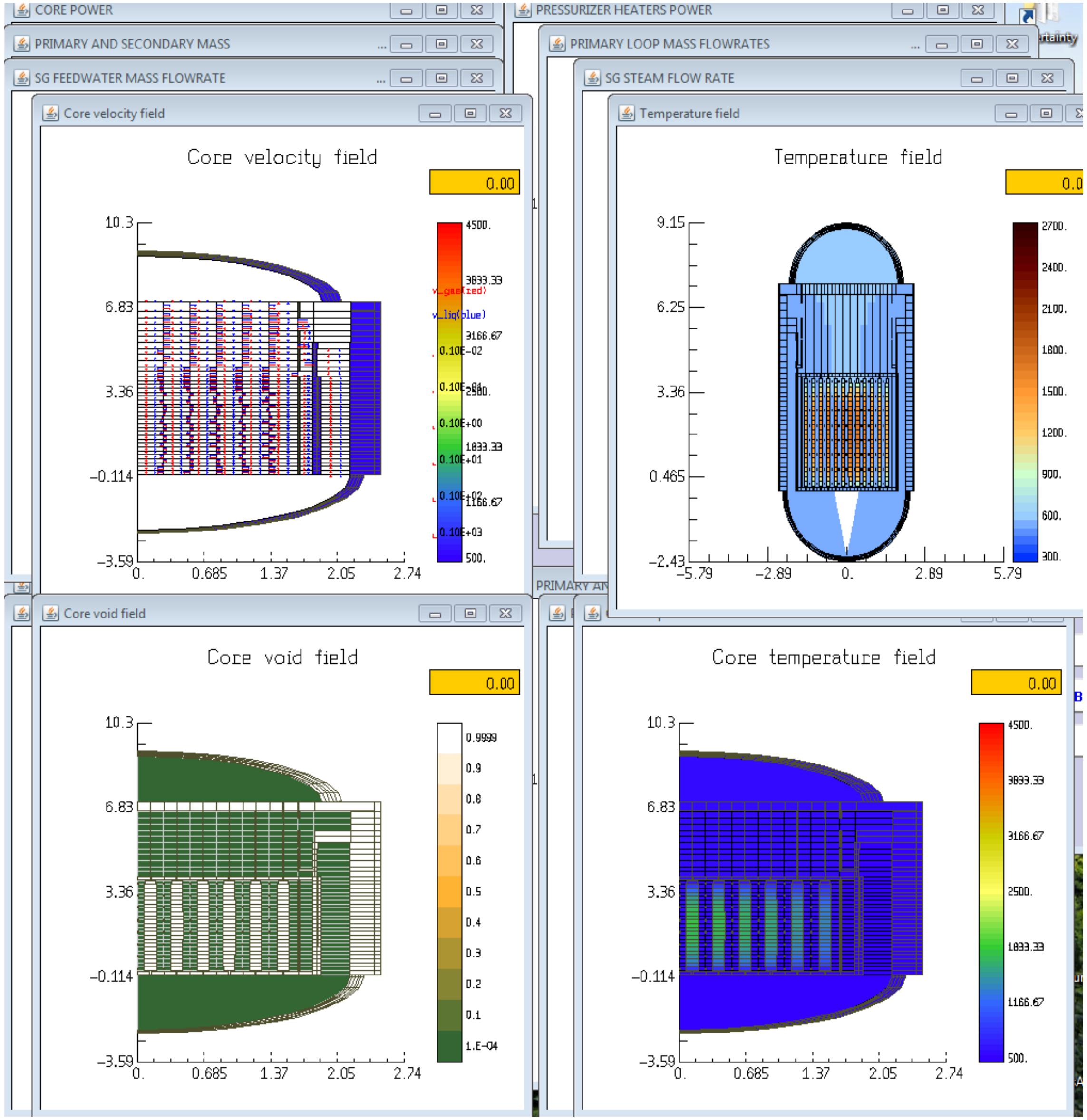
the **Q-L1 test** was conducted with **another** protocol as the former QUENCH tests 1-17 (**a short-time** –experiment) - thermo-**mechanical ASTEC investigation** is crucial here

- QUENCH-LOCA topics: among others the secondary hydriding :

as the burst occurs, steam reaches the inside of the cladding →oxidizes the inner side. H_2 produced during the oxidation will be absorbed at the boundary to the inner oxide region.

- Local mechanical LOCA properties – **how to model them**?

ASTEC V2.0 -→ V2.1 validation on a TMI-2-like scenario/1



ASTEC V2.0 -→ V2.1 validation on a TMI-2-like scenario/2

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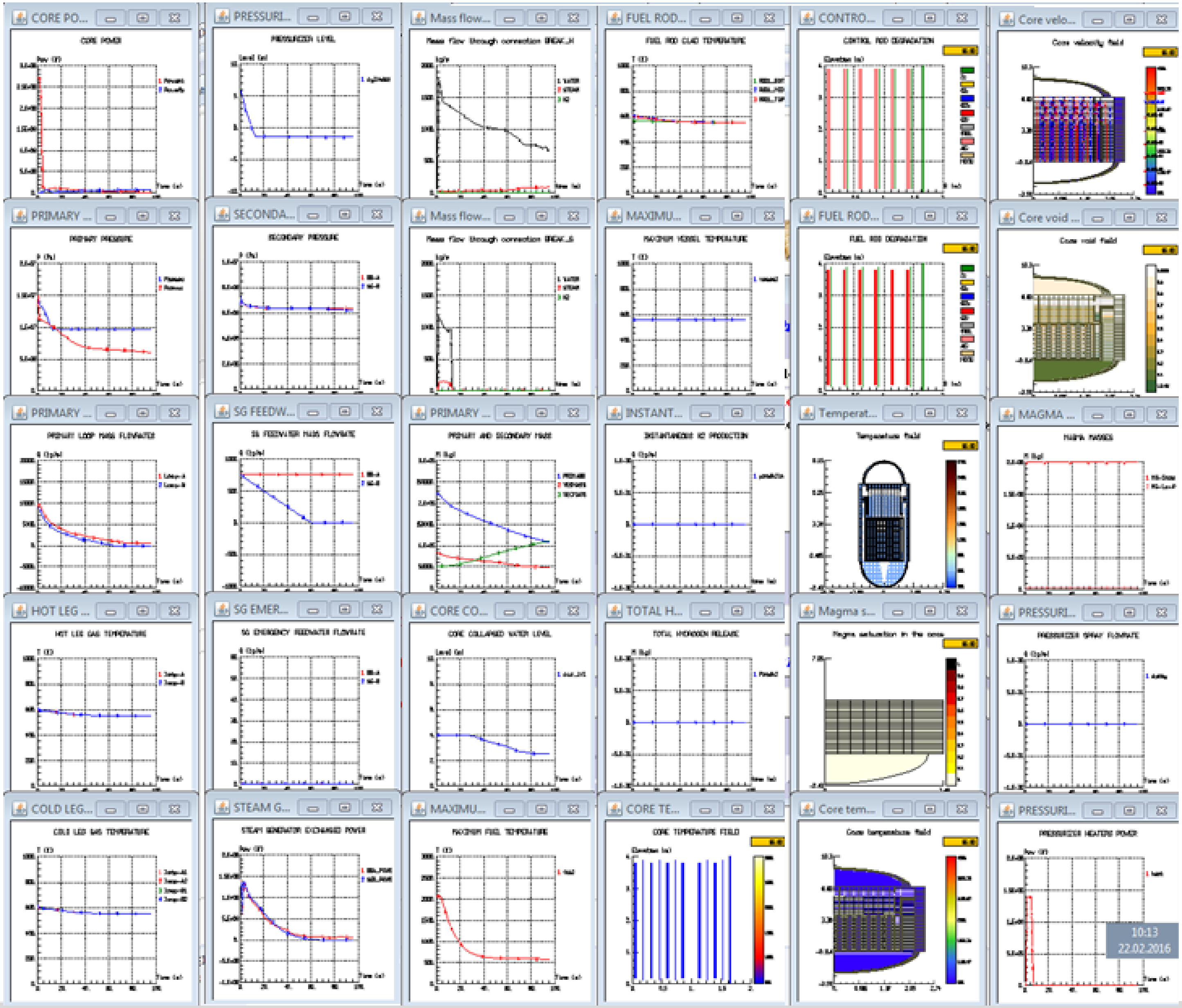
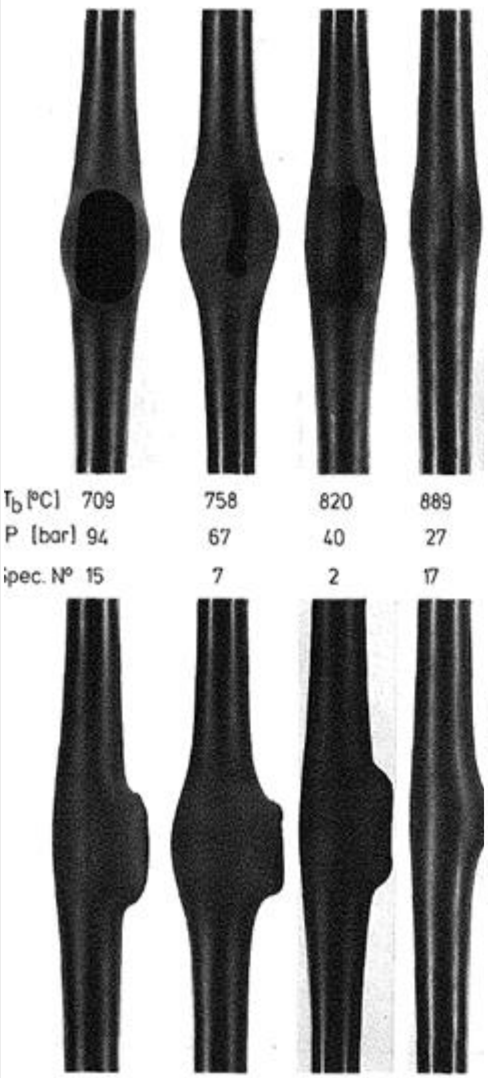
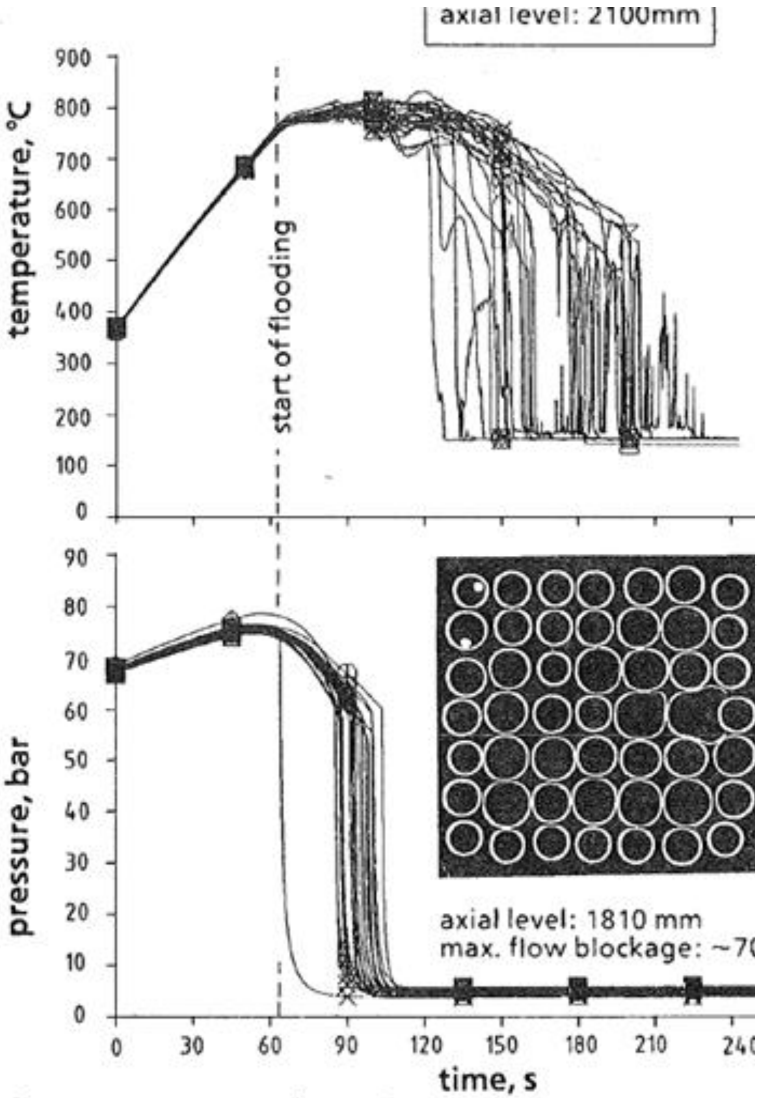


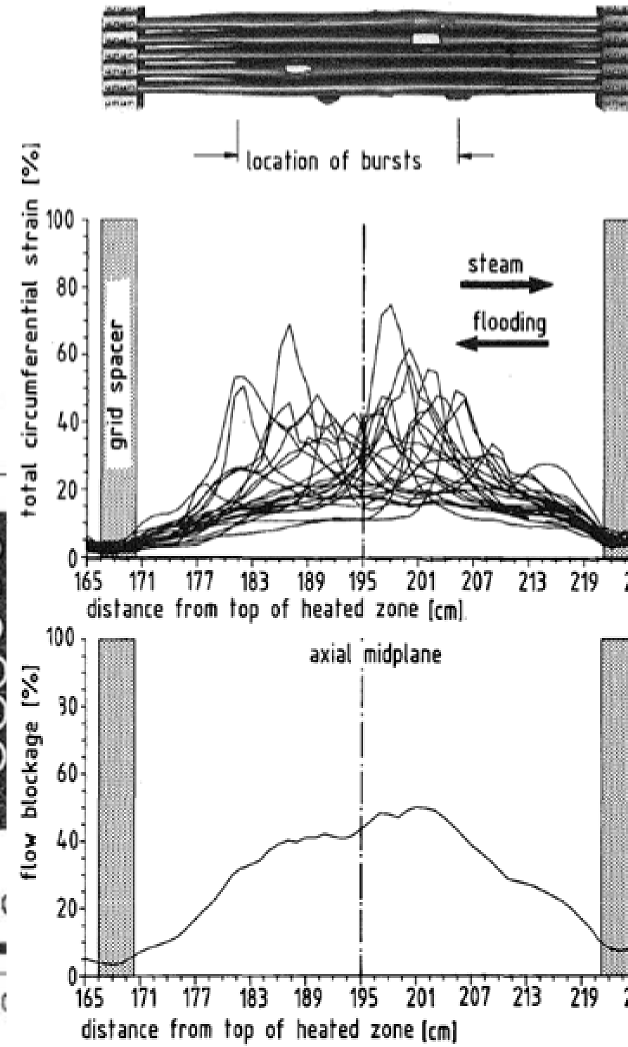
REBEKA-7 results, *KfK (now KIT)*



Typical failure mode at different burst temp

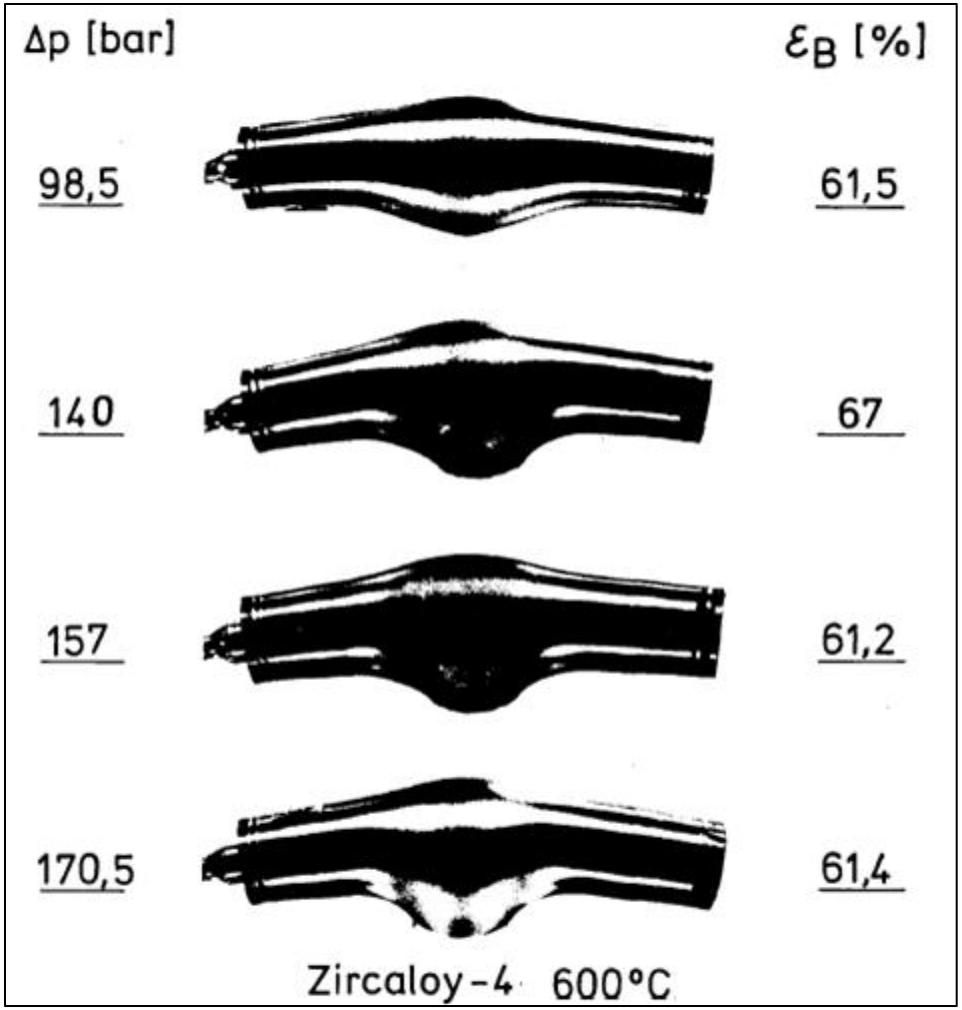


Temp pressure transients of a 70 % blocked rod bundle

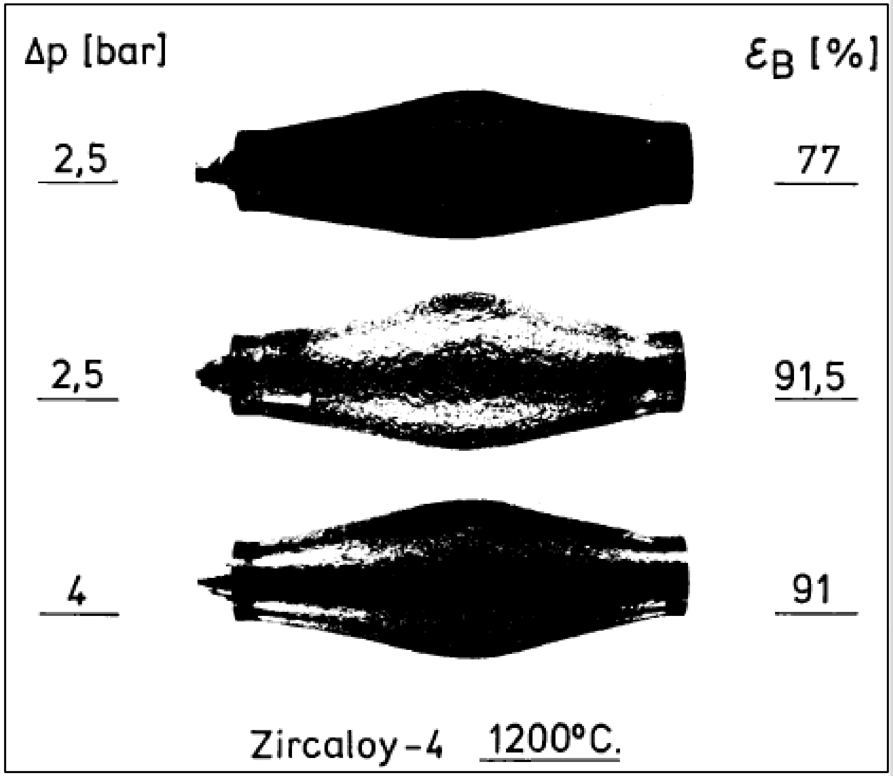


Cladding deformation and flow blockage
under reversed flow (REBEKA 5)

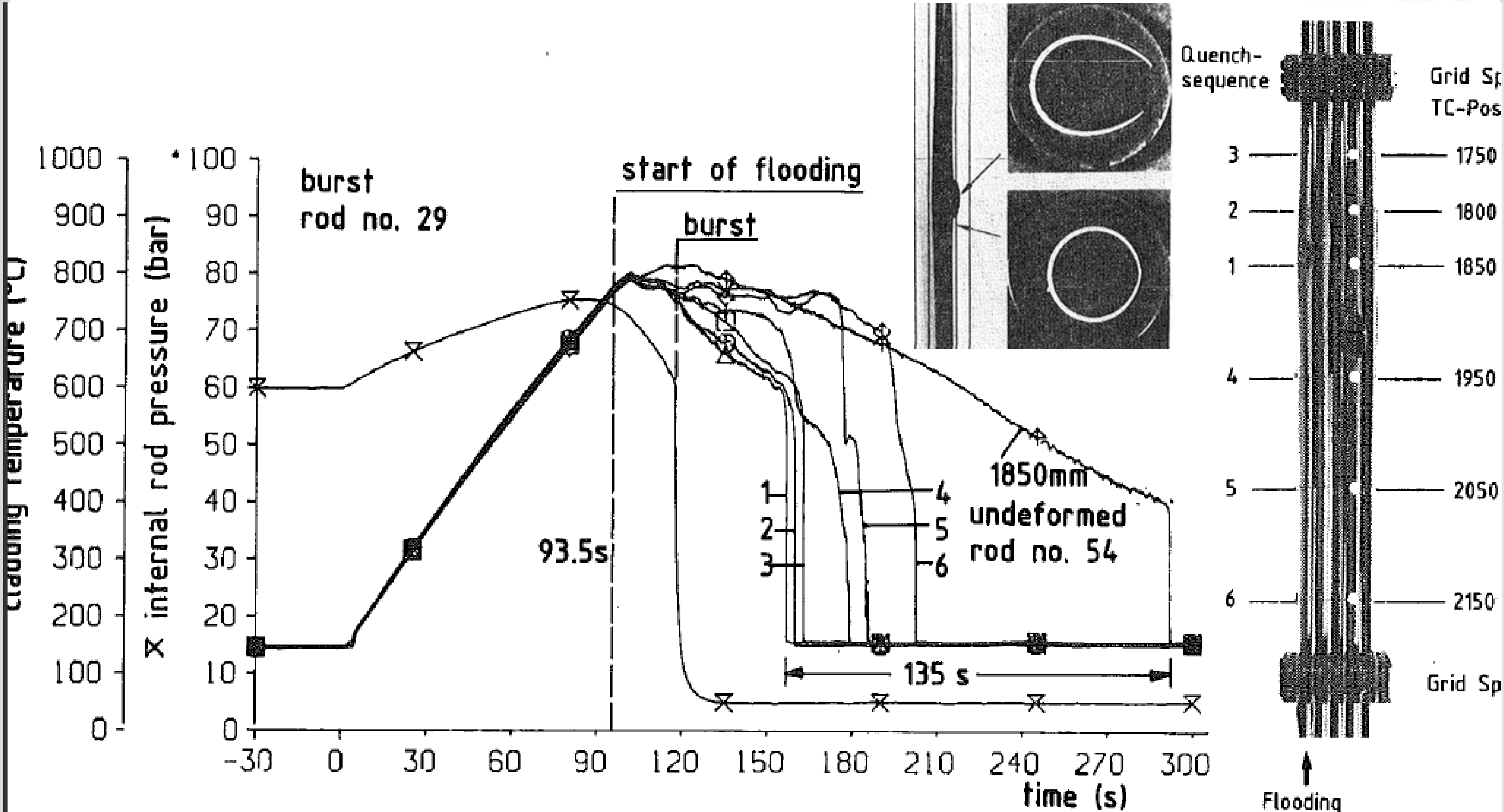
Single rod LOCA tests, KfK (now KIT)



significant influence of temperature on burst



REBEKA-6 results



Temperature transients and quenching behavior of a burst rod (REBEKA 6)

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QUENCH_L1 test

heating phase | cooldown phase | flooding phase

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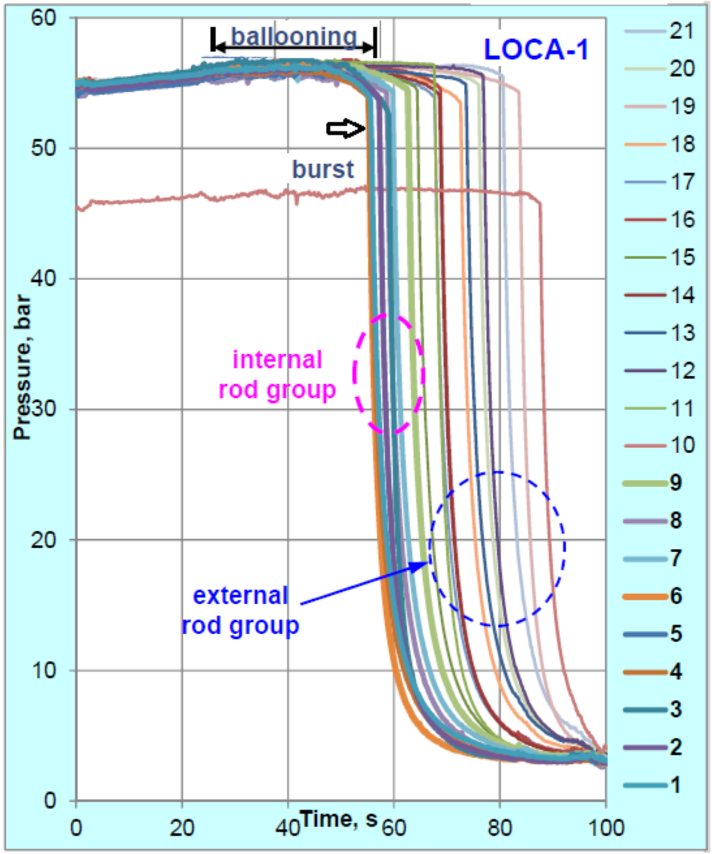
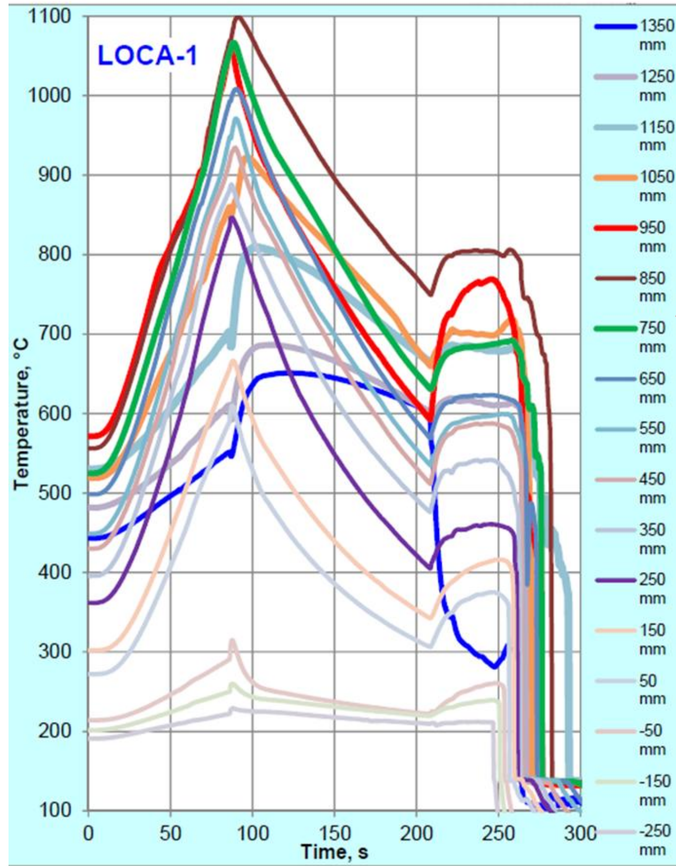
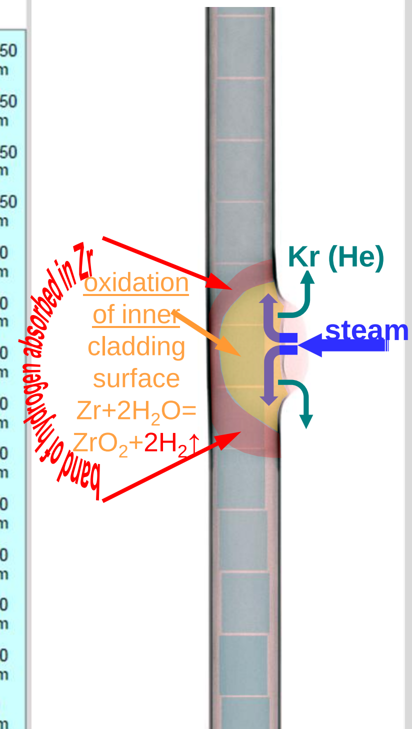
Rod Δp evolution during heating phase: Q-L1 burst time indication (results on Kr release)



decrease of the inner Δp to the system Δp : $\tau_0 \approx 38$ s

max cladding temps at elevations for Q-L1



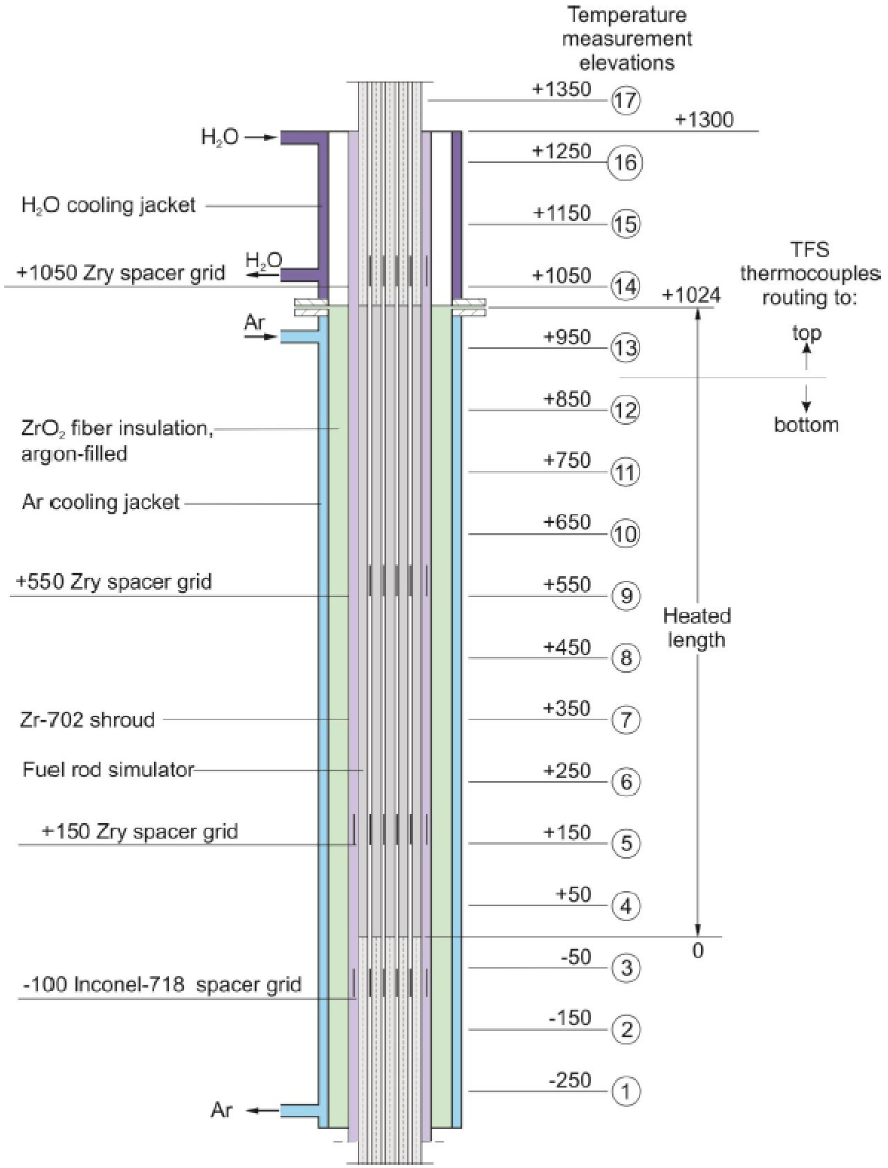


burst time and according temperature to be ASTEC modelled

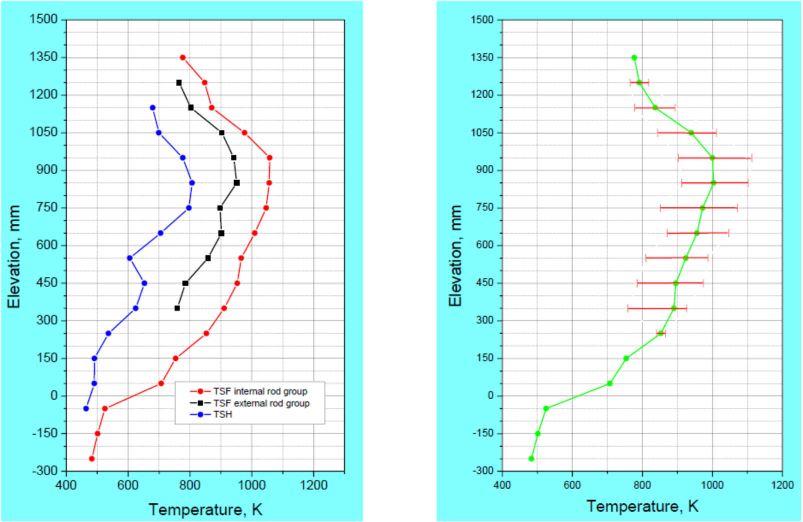
Q-L1 pressure transients

Burst events occured

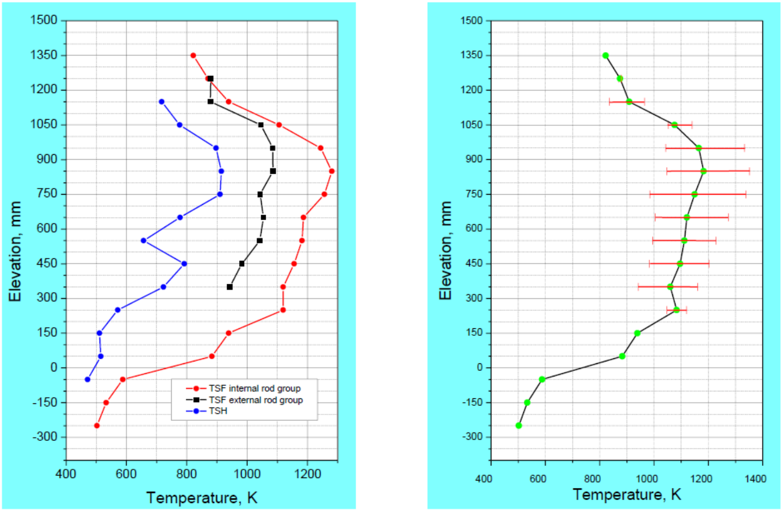
Q-L1 test: axial temp profiles



Axial temperature measurement locations in the QUENCH-L1 test section.



QUENCH-L1; Axial temp profile TFS internal and external rod group together with TSH, left, and axial temp profile of all TFS, right, at 55,2 s (first cladding burst).



Q -L1; Axial temp profile TFS internal and external rod group together with TSH, left, and axial temp profile of all TFS, right, at 87,6 (last cladding burst).

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Bundle test Q-L1- results : sequence of events, design (*quicklook)*

Design characteristics of the QUENCH-L1 test bundle

Bundle type		PWR
Bundle size		21 heated rods
Effective number of rods	(considering surface of heated rods, shroud and corner rods)	30.6 rods (21 + 7.4 from shroud + 2.2 from corner rods)
Pitch		14.3 mm
Coolant channel area		29.65 cm^2
Hydraulic diameter		11.5 mm
Rod outside diameter		10.75 mm
Cladding material		Zircaloy-4
Cladding thickness		0.725 mm
Rod length	(elevations)	2480 mm (-690 to 1790 mm)
Internal rod pressure (gas)		5.5 MPa abs.; rod#10: 4.6 MPa due to leakage before heating; (Kr)
Heater material	 surface roughness	Tantalum (Ta) Ra=1.6 µm
Heater length		1024 mm
Heater diameter		6 mm
Annular pellet	material dimensions surface roughness	ZrO_2;Y_2O_3-stabilized ∅ 9.15/6.15 mm; L=11 mm Ra=0.3 µm
Pellet stack		0 mm to ~1020 mm
Corner rod (4)	material instrumented (A, C, D) not instrumented (B)	Zircaloy-4 tube ∅ 6x0.9 (bottom: -1140 mm) rod ∅ 6 mm (top: +1300 mm) rod ∅ 6 mm (-1350 to +1155 mm)
Grid spacer	material length sheet thickness elevation of lower edge	Zircaloy-4, Inconel 718 Zircaloy: 42 mm, Inconel: 38 mm 0.5 mm Inc: -100 mm; Zry: 150, 550, 1050, 1410 mm
Shroud	material wall thickness outside diameter length (extension)	Zirconium 702 (flange: Zry-4) 3.17 mm 86.0 mm 1600 mm (-300 mm to 1300 mm)
Shroud insulation	material insulation thickness elevation	ZrO_2 fiber ~ 36 mm -300 to ~1000 mm
Molybdenum-copper electrodes	length of upper electrodes length of lower electrodes outer diameter: prior to coating after coating with ZrO_2 coat. surface roughness borehole of Cu-electrodes	766 mm (576 Mo, 190 mm Cu) 690 mm (300 Mo, 390 mm Cu) 8.6 mm 9.0 mm Ra=6-12 µm diameter 2 mm, length 96 mm
Cooling jacket	Material: inner/outer tube inner tube outer tube	Inconel 600 (2.4816) / SS (1.4571) ∅ 158.3 / 168.3 mm ∅ 181.7 / 193.7 mm

QUENCH-L1; Sequence of events

Time [s]	Event
-3248 (11:00:00; 02.02.2012)	Start data recording, Tmax = TFS 4/13 = 839 K, el. power at 3.49 kW. L701 = 1438 mm. L 501 = -405 mm. System pressure 3 bar. Ar 6 g/s, superheated steam 2 g/s.
-2260… -2170	Pressurization of rods from 15 to 55 bar.
0	Start of transient with max electrical power increase rate.
2; 4	Electrical power 32; 43 kW.
36…58	**Sequential onset of ballooning for rods pressurized to 55 bar.**
55…87	**Sequential onset of burst for rods from inner rod #4 to peripherical rod #10.** See burst table (Table 10).
87	Switch of the electrical power from max 58.65 kW to decay heat of 3.5 kW. Initiation of rapid steam supply line (50 g/s) additionally to carrier argon (6 g/s). Switch-off of slow steam supply (2 g/s). Tmax = TFS 4/12 = 1345 K.
91	Cladding surface temperature maximum reached. Maximal hydrogen production rate. **Tmax = TFS 4/12 = 1373 K.**
91…209	Cool-down of bundle in steam. Decrease of TFS 4/12 reading from 1373 K to 1023 K.
212	Initiation of quench water supply. Switch-off of steam supply. Switch of argon to bundle top supply.
212…221	Increase of bundle temperatures to ~1073 K due to switch-off of the steam cooling.
237	Maximal quench rate (about 100 g/s) reached.
247…293	Wetting of cladding surface thermocouples (TFS) at elevations between -250 and 1350 mm at temperatures between 484 (TFS 7/1) and 858 K (TFS 7/12) (Table 12).
270…305	Maximal water evaporation rate (about 25 g/s).
351	Bundle completely filled with water (L 501 = 1307 mm)
417	Electrical power switched off. Tmax = TFS 15/15 = 333 K
1688 (12:22:20)	End of data recording. L 501 = 1289 mm

Q-L1; El. resistances of rods [mΩ] at 20°C; most sensitive parameter

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Internal circuit with 9+1 rods

rod	1	2	3	4	5	6	7	8	9	16	*Ave-rage*	*10 rods parallel*
pre-test	6.5	6.5	6.4	6.4	6.5	6.6	6.4	6.4	6.4	6.2	*6.4*	*0.64*
post-test	6.4	6.9	6.8	6.7	5.7	6.4	6.7	6.5	6.7	7.7	*6.7*	*0.66*

Note: Measured values include the resistance of slide contacts R_s=0.75 mΩ

External circuit with 11 rods

rod	10	11	12	13	14	15	17	18	19	20	21	*Ave-rage*	*11 rods parallel*
pre-test	6.3	6.4	6.2	6.2	6.2	6.3	6.2	6.2	6.5	6.2	6.3	*6.3*	*0.57*
post-test	7.8	6.8	7.1	6.5	6.8	7.7	6.7	7.4	6.8	6.5	6.7	*7.0*	*0.63*

Note: Measured values include the resistance of slide contacts R_s=0.75 mΩ

Each circuit connected to the DC generator with 4 parallel bonded cables. The resistance of each cable is R_c=1.2 mΩ. Therefore, the external (outside) resistance corresponding to each heated rod (indicated by SCDAP/RELAP as **fxwid**) is $R_{ie}=R_s+10*R_c/4$=3.75 mΩ for the inner rod group and $R_{oe}=R_s+11*R_c/4$=4.05 mΩ for the outer rod group.

Accepted Manuscript

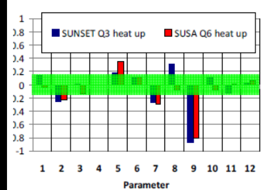
Application of Best Estimate Approach for Modelling of QUENCH-03 QUENCH-06 Experiments

T. Kaliatka, A. Kaliatka, V. Vileiniskis

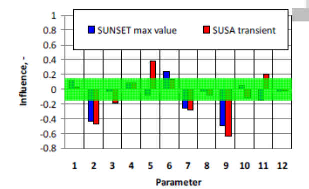
ACCEPTED MANUSCRIPT

Uncertain input parameters used in the best estimate analysis

No.	Parameter	Reference value / Deviation range
1	Quenching water flow, kg/s	
2	Steam flow, kg/s	
3	Argon flow, kg/s	
4	Quenching water temp., K	
5	Steam temp., K	
6	Argon temp., K	
7	Thermal conductivity of ZrO_2, W/m·K	
8	Specific heat of ZrO_2, J/kg·K	
9	In RELAP/SCDAPSIM code: contact resistance of sliding contacts, mΩ	
	In ASTEC code: additional resistance outside the bundle (OCR), mΩ	
10	Quencing water pressure, bar	
11	Steam pressure, bar	
12	Argon pressure, bar	



a) Heat up phase



b) Quenching (SUNSET) and transient (SUSA) phases

nfluence of uncertain parameters to the calculated cladding temperature of fuel rod imitators n outer ring at 750 mm height.

Discussion adopting KIT ASTEC- knowledge

- Perspectives (*future prospects):* **validation of the thermo-mechanical models Q-L1**

  H_2 / [kg/s]/ [kg] especially during the Q- phase

- ASTEC description of the Q -facility (meshing, nodes) & adapting specified **scenarios**–done (IDs); also the **Q-L1** trends/profiles should be consistent with the (intuitive) expectation, as it was the case of all visualized **Q-14** τ- dependences
- The newest version of the ASTECv2.1 code (still under development) will surely give us a further chance for even more accurate modeling of the quench-phenomena.
- The following important general aspects of the Q-L1 process should be modeled in a correct way at first:
- 1) the position of the hottest zone in the test bundle,
- 2) **burst times**
- 3) **T(τ)** histories-needed for finding „the H_2 prod. data" (or rates) in the different Q-L1 phases
- 4) the thicknesses of the oxide layers both over **time & height** of the **bundle .**

  In our former ASTEC modeling only the part of **outer** cladding oxide has been incorporated. the Q-L1 experiment showed relative thick **inner** oxide layers in the claddings (up to ca. 20 *μm*) in the upper elevations

  Although some differences in the validation of the Q-L1 modeling results towards exp-t occurred (higher temperatures, especially for the QUENCH phase itself) one can be optimistic looking for the next stage

→ **Band banding** and consequently the channel blockages were prototypical beginning with the Q-L3 test, so **buckling** phenomena out of scope here…

ASTEC- ID adaptation for Q-L1

The existing **QUENCH-05 ID** was used, developed by S. Melis (IRSN), & adapted in former times as Q-06 by H. Muscher.

- To change the QUENCH-ID according to the exp. conditions of Q-L1 & ASTEC v 2.1.0.3 (changes in **style/ syntax/ contents**):
- the Th-H part **done**; sophisticated **thermo-mechanic** part – still to be done
- El. power histories for both sub circuits of heated rods have been changed in accordance to experimental values, correct **time instants** incorporated etc..
- Visu: some fig-s have to be additionally produced (designed) By all these implementations, changes/ improvements in the Q-L1 IDs - especially for the new ASTECv2.1 several runs have to be performed, allowing a comparison of the results given by the older / newer ASTEC-versions

→ The specific Q-facility **geometry** is given in KIT reports - **see** according (**quick look) tables**

→ Some new quantitative results are obtained via ASTEC at KIT

→**Trends captured** were ok, but the values: not fully consistent with the (intuitive) expectation –

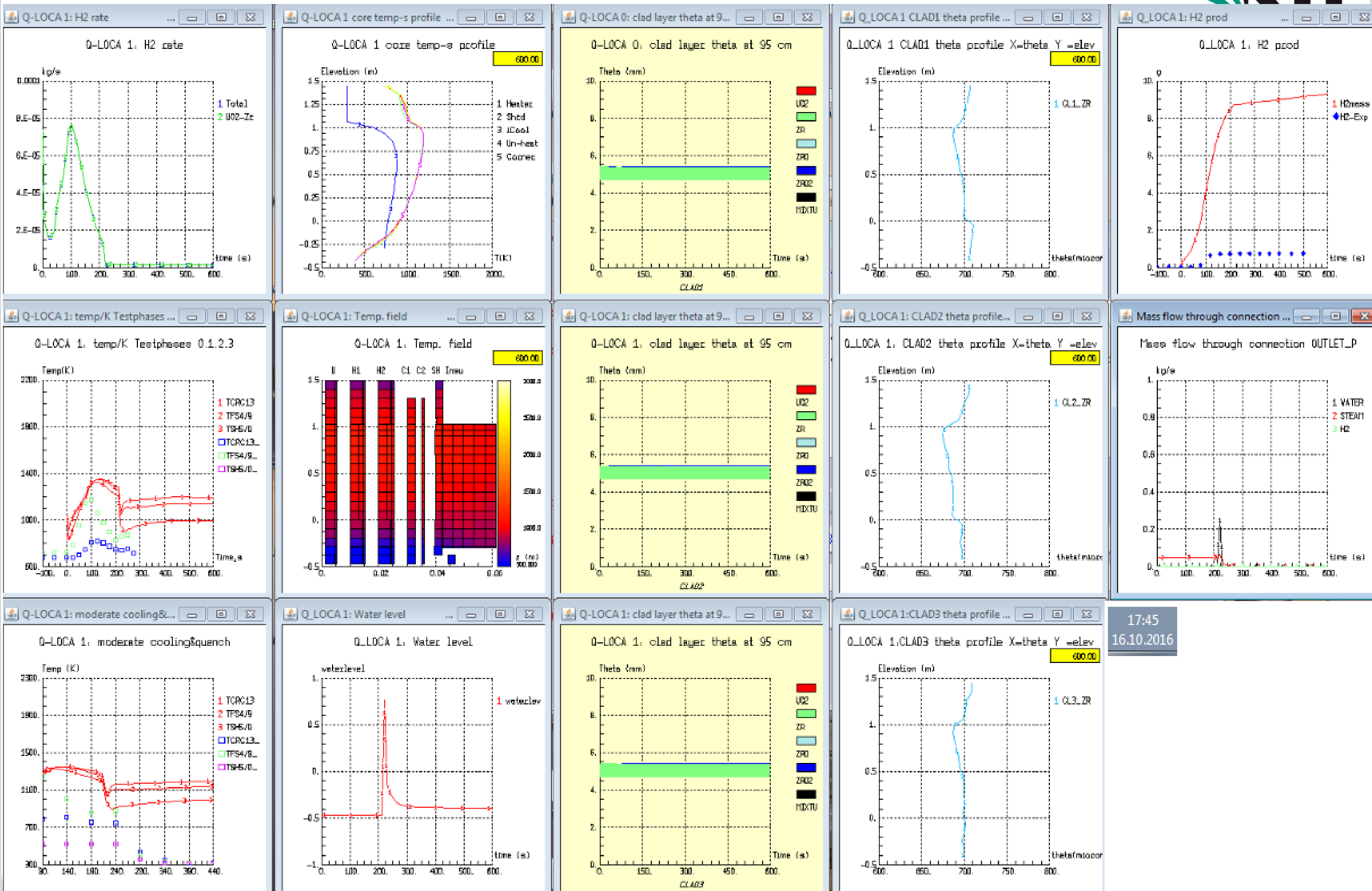
Temperatures given by ASTEC where somewhat too high, resulting in a higher H_2 data as in QL1

Feasibility study: “the codes (SOCRAT, ATHLET) were feasible to examine the QUENCH-L-1”: applying the 38% strain –criterion for burst;

“BARC- PT CREEP” – uses similar approach, for calandria tubes, but generally the results are (strongly) dependent on imposed BC, IC…

Further QL1- ASTEC work – is to be continued using the **new ASTEC: instead of V2.0-rev3p4 now v2.1.0.4 (Nov 2016)**

ASTEC- ID adaptation for Q-L1/ preliminary results



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KIT – IAM

ASTEC- ID adaptation for Q-L1/ *for illustration purposes only*

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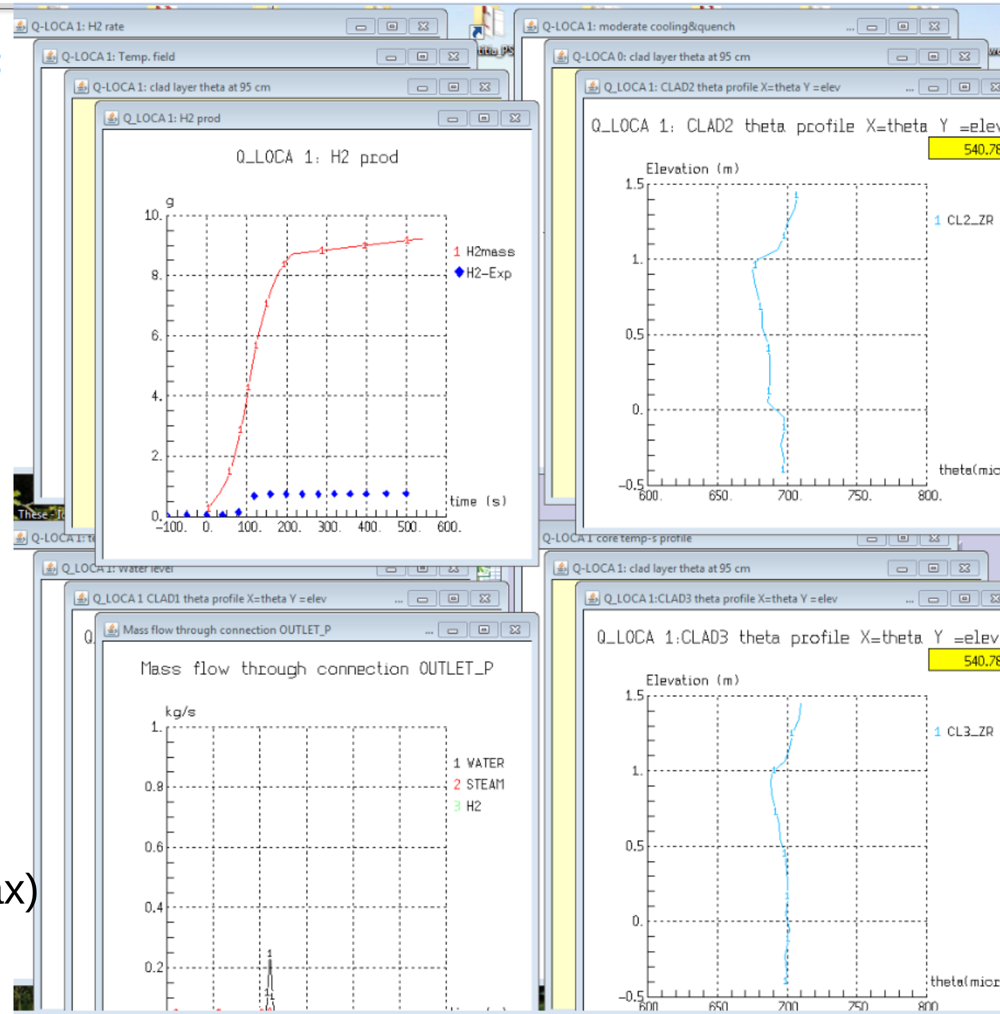
% OF CREEP IN MACRO-COMPONENTS (as Log(R/R0) :

CLAD1	GAP PRESSURE (BAR) 6.90006E+01				
	0.00	0.00	0.00	0.00	0.00
	0.00	0.03	0.16	0.44	1.00
	2.14	3.83	4.72	8.17	10.30
	10.24	8.13	4.36	0.88	0.03
CLAD2	GAP PRESSURE (BAR) 6.90007E+01				
	0.00	0.00	0.00	0.00	0.00
	0.00	0.03	0.18	0.48	1.06
	2.23	3.97	4.88	8.32	10.43
	10.30	8.13	4.37	0.90	0.03
CLAD4	GAP PRESSURE (BAR) 6.90007E+01				
	0.00	0.00	0.00	0.00	0.00
	0.00	0.05	0.21	0.53	1.14
	2.34	4.10	5.03	8.41	10.38
	10.15	7.93	4.22	0.86	0.03
CLAD5	GAP PRESSURE (BAR) 6.90007E+01				
	0.00	0.00	0.00	0.00	0.00
	0.00	0.04	0.20	0.51	1.10
	2.28	4.00	4.87	8.28	10.22
	9.93	7.71	4.03	0.80	0.02



An example of the ICARE **stru CREEP**, syntax)

Peculiarities of ASTEC / ICARE got from the guidelines

- Axial extension (LP, UP, plugs) → is **outside the** ICARE **domain**
- Strong sensitivity of **burst τ** on that volumes (**LP, UP**); low heating rates (<0,5K/s) problematic
- Max **hoop strain** recommended as **~40%** for PWR-like systems to prevent unrealistic deformations of the cladding
- Surprising results, if **no early burst τ** is detected by CREE **rubric**
- However, embrittlement not treated by CREE, this should be done by VESSEL/ INTE through defining **criteria** to be fulfilled **<u>simultaneously</u>**
- Fuel rod "loss of integrity": let us substitute inadequate **temp/ θ** [μm] criteria by:

\- **embrittlement** criteria *(having large influence on the sim. results)*

\- as well as **steam flow rate per <u>heated rod</u>** and **<u>length unit</u>**

- CH blockages: highly influenced by ballooning/ creep progress
- Chronology of these blockages might become inconsistent in ASTEC
- ASTEC *(similar to other codes)* recommends ***limit deformation EPMX <35% -*** *that is crucial*
  - **α →β phase transition** may be affected by EPMX **user value** = const
  - CROX- only allowed at high internal rod Δp
  - <u>Loss of integrity</u> can occur even t rather low T/K due to thermal shocks ("thermal runaway")
  - or **<u>fast cooling</u>** (quenching)

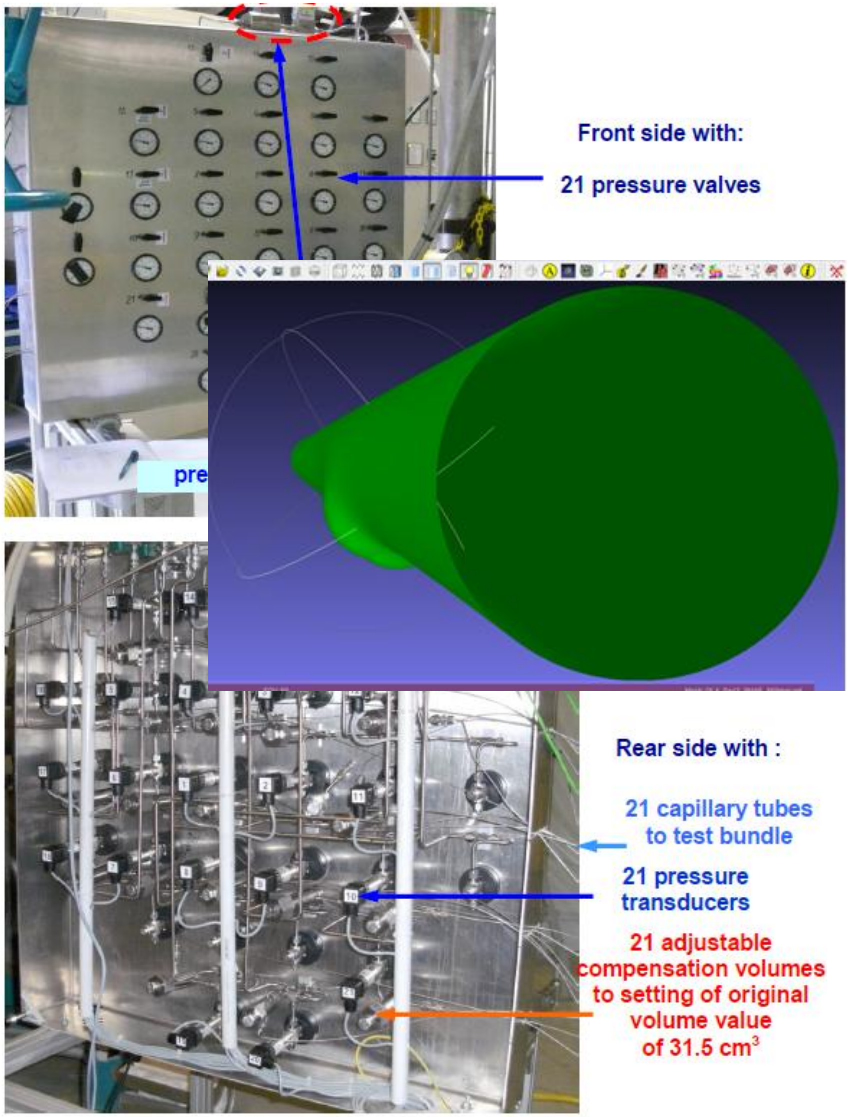
Peculiarities of ASTEC / ICARE from the guidelines, *ff.,*

- ICARE analysis **w/o** accounting **for** the presence of [O] in the β–Zr phase
- ICARE "surely not adapted to handle the embrittlement of Zry claddings in the **quench-phase**" – since the **ductility of the β-Zr** play a key role here
- **Shattering:** SHAT – a sudden exposition of free surfaces ("spalling of scales" – temp. escalation is to **modeled via VESSEL/ OPTI** (NMIX as a parameter is to be changed)
- Rod loss of integrity: (simulation trick is, to modify mats properties, *since lack of models has to be compensated somehow)*
- ICARE2: not yet designed for **detailed rod analysis** under DBA conditions → **not** "**best-estimate"** studies possible yet, but only (=just) **exploratory** ones".
- UZRO as such has not to be applied at low temperatures
- For **DBA** analysis (LOCA) it is **mandatory** to **select ZROX - activating** the **ZROX/CREE line,** *although tight UZRO/ DROX coupling was recommended* for the quench phase
- **Pre-hydrided** claddings can be accounted only by CREE *(in a simplest way)*
- The fuel column in case of **very high pressure** scenarios (>15 MPa) – **not accounted for** by ICARE2.

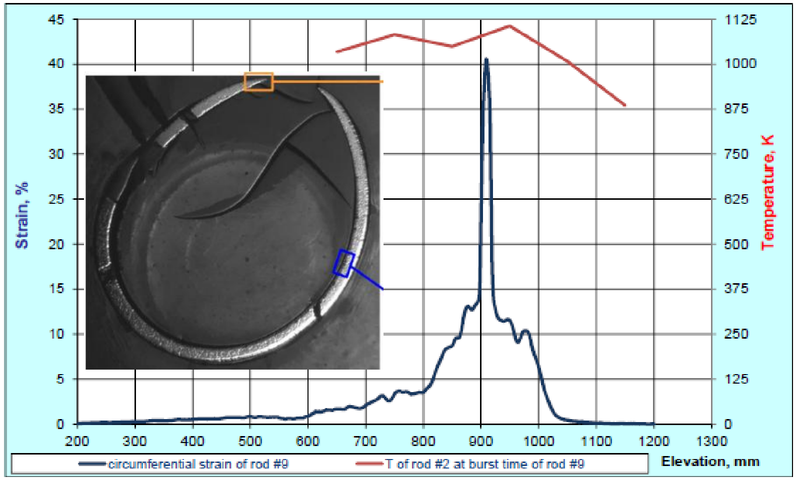
(for comparison- see: BARC/ their PT CREEP)

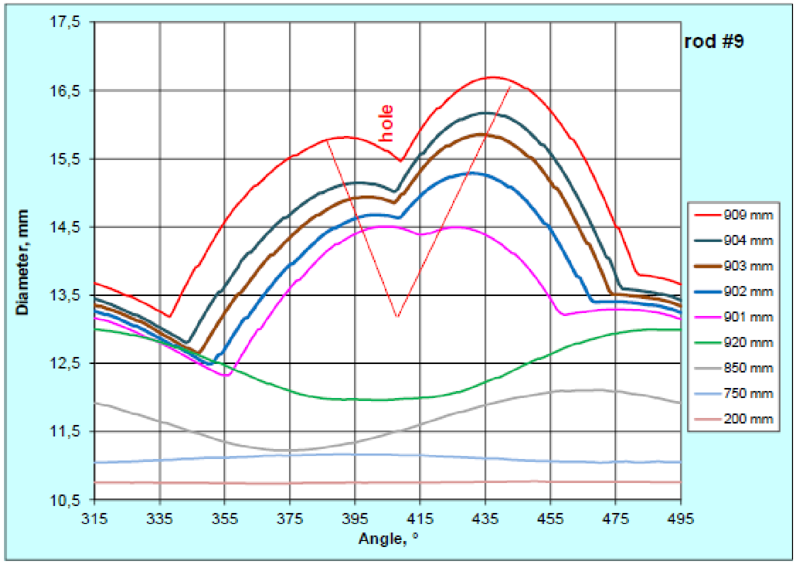
QL1: profilometry of pressurized tubes → Mesh Lab recovery;

Outlook: **future ASTEC work** *together maybe with IRSN/ INR*



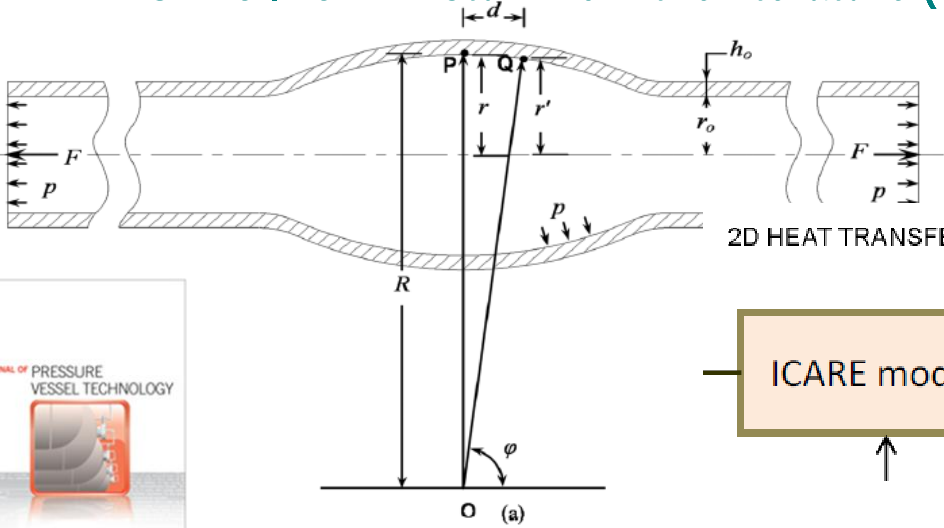
QUENCH-L1; Rod pressure control and measurement panel.





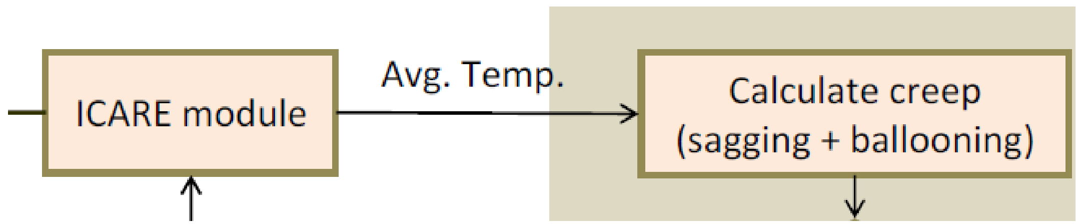
QUENCH-L1, Rod #9; longitudinal circumferential strain changing (top); azimuthal diameter changing downwards from burst (bottom).

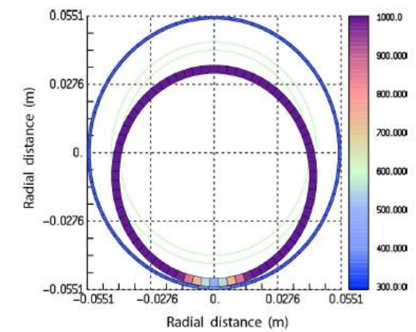
ASTEC / ICARE stuff from the literature (illustration of feasibility)

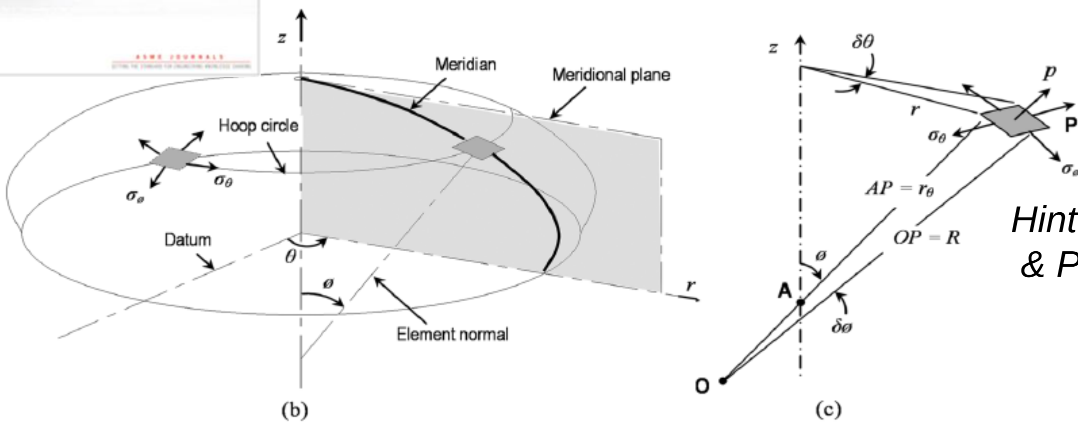


2D HEAT TRANSFER ELEMENT

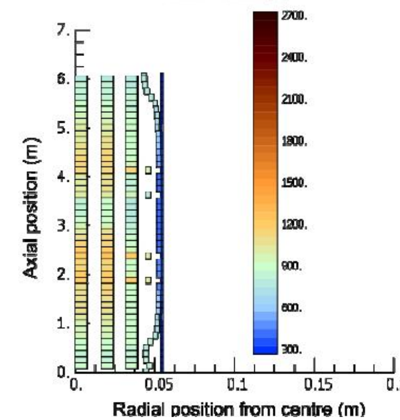
PHWR module







Hint: Results of Wright & Prassana Majumdar



Schematic diagram of clad tube undergoing ballooning deformation (*b*) an axisymmetric thin revolution shell (*c*) stresses on infinitesimal element on shell surface (Wright [8])

PHYS/STRU CREE	Name of creep model	EDGAR	CHAPMAN
CRACK/ STRU CREE	Extent of crack (axial extension of the cracking after clad burst)	0.5	0.3

Conclusions

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•We still believe that ASTEC has the potential to sim. the Q-L1 (to be approved, see guidelines)

→**concerning mechanics** „CLADDING BALOONING; CREEP & BURST“- with **CREE not CROX**

- A new Q- L1-ID inclusive **more advanced** thermo-**mechanics** should be adopted, however...
- the according parts of ICARE-guidelines were carefully studied & well understood (embrittlement, loss of geometry, pellets fragmentation…hydriding, etc).

•Tables, figures & **standardized** spread sheets with the **Q-L1 results** and the QL1 ID will be submitted at the next stage (→ CESAM & FUMAC communities, March 2017)

✓ **base case Q-L1 work** regarding **T, Δp** transients (is still to be continued for a complete bundle test) **; runs are ongoing**/ work on advanced ID **not completed yet** Fulfilling the complete set of recommendations latest in 03/2017. Being mandatory !

➢ (I expect new **plots similar to outputs** presented at the **12th QWS**, but now not for a SVECHA-single rod, but for a complete **bundle** test)

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Thank you all.