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*Multi-physics modeling in the frame of the
DRACCAR code development and its
application to spent-fuel pool draining
accidents*

Lecture outline

- DRACCAR presentation
- Validation of Thermal-mechanical modeling (within manuscript)
 - Single rod computation: comparison with **CAST3M XPERT** (finite element codes)
- Influence of channel blockage conditions on core coolability
 - Coupling with the two phase flow thermal hydraulic module CESAR and simulation of the **FEBA** tests
- Application to spent-fuel-pool draining accident
 - Coolability of assemblies in situation of complete LOCA in case of non axis-symmetrical heat exchanges configuration
 - OECD **Sandia Fuel Project Phase II** presentation (no results but qualitative presentation because SFP open to 12 partners only)

DRACCAR: a simulation tool for fuel assembly deformation and coolability assessment during LOCA (1/2)

■ DRACCAR objectives

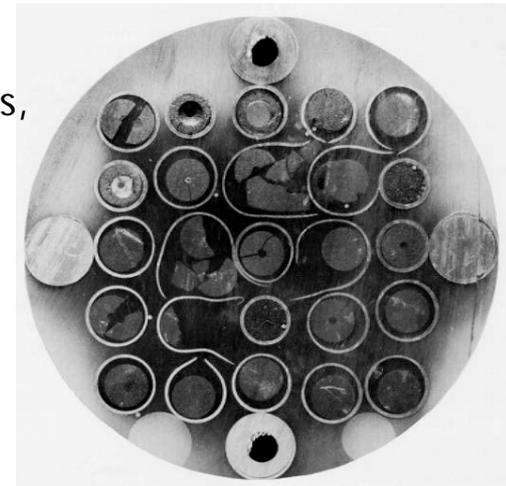
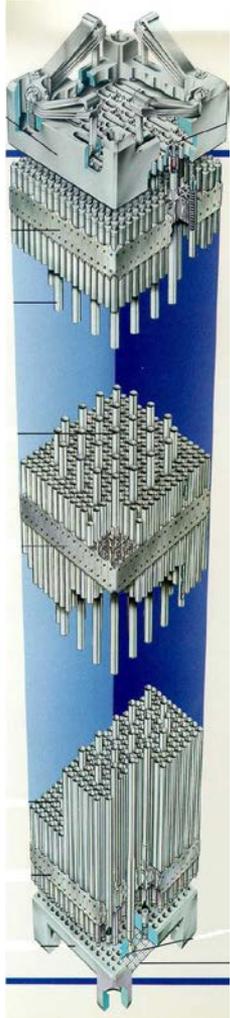
- Simulation of the 3D thermo-mechanical deformation and reflooding of a fuel rod assembly during a LOCA transient
 - Structure embrittlement before and after reflooding (with DIFFOX)
 - Coolability of a fuel rod assembly during a LOCA
- Flexible enough to adapt easily to different types of fuel assembly, experimental geometry, and to future technologies
- Efficient direct coupling with the thermal hydraulic module CESAR of ASTEC

■ Application fields

- Any LOCA transient
- From a single rod to a full fuel assembly (control rods, guide tubes, grids, shroud,...)
- Any kind of fuel, cladding material and burn-up
- In-pile or out-of-pile experiments, NPP transients

■ DRACCAR state of development

- 2006: start of the DRACCAR project
- 2008: Version 1.0
- 2010: Version 2.0
- January 2013: the latest version, version V2.1
- Use of DRACCAR to perform safety assessment studies by 2015

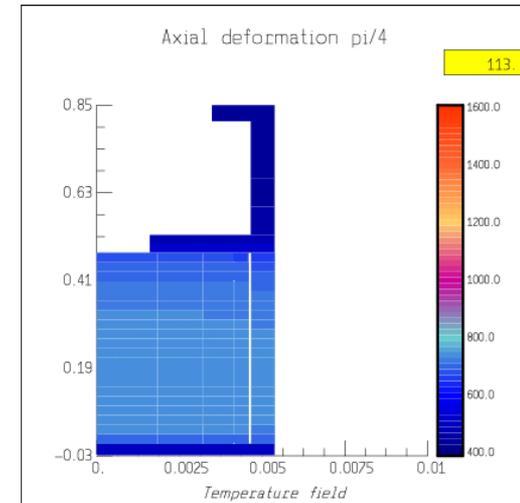


PHEBUS LOCA test

DRACCAR presentation (2/2)

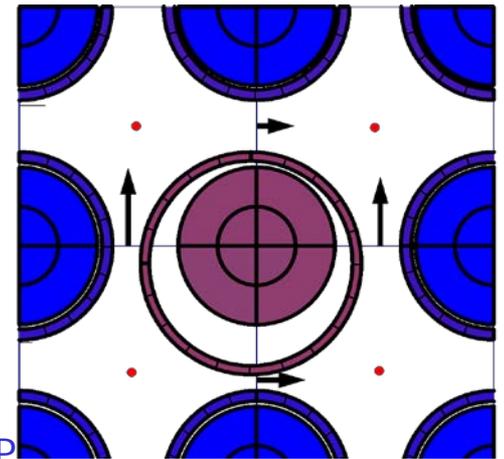
■ DRACCAR physical models

- Heat exchanges (3D conduction, convection, radiative transfers)
- Cladding embrittlement (steam and air oxidation, oxygen diffusion and hydriding with DIFFOX)
- Cladding deformation (3D creep model, 4 rupture modes, internal pressure calculation, mechanical contact, hot side straight effect)
- Fuel behaviour (fuel cracking, fuel relocation)
- Power generation (electrical or decay heat)
- Thermal-hydraulics (with a 2 phase flow T/H module)



■ DRACCAR validation

- Based on [code to code benchmarking](#)
 - CATHARE-2 and CATHARE-3 for T/H
 - Validation of models and mechanical hypotheses using [CAST3M](#) and [XPER](#) finite element codes (creep deformation, contact,...)
- Based on [experimental comparisons](#)
 - T/H, reflooding: PERICLES, ROSCO, [FEBA](#), SEFLEX,...
 - Mechanics: PHEBUS LOCA, EDGAR, HALDEN IFA,...
 - Thermics, chemistry: PHEBUS SFD B9+, CORA 13, [OECD SFP test program Phase II](#)...



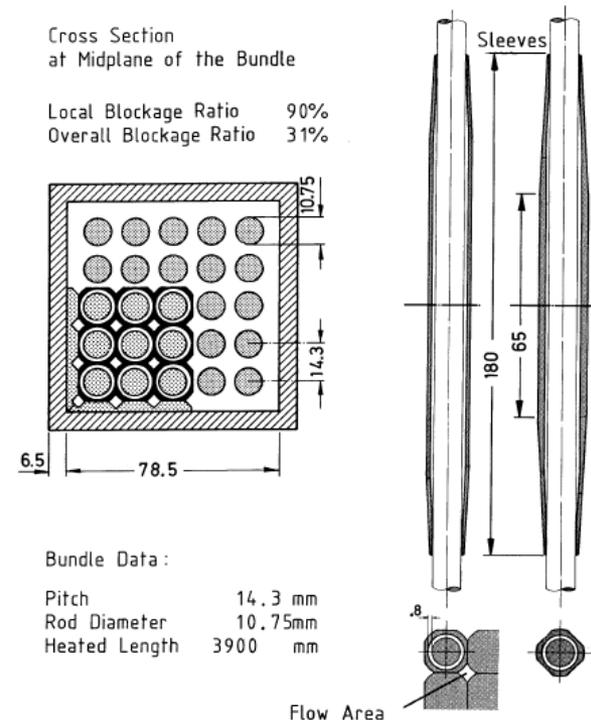
Simulation of FEBA tests (1/3)

■ Presentation

- Assess impaired coolability under channel blockage conditions due to clad ballooning
- 60 tests carried out at KIT institute (Karlsruhe Germany) in the 80's
- The test section:
 - 5x5 electrically heated rods
 - 7 or 6 spacer grids and a thick square housing made of stainless steel
 - Some rods may be equipped with hollow sleeves made of stainless steel to simulate blockage ratio of 62% and 90% with or without by-pass area
 - Blockage located in the corner to simulate a 10x10 bundle with a central 6x6 blockage
- 8 series of tests with different spacer grids and blockage arrangements

■ Experimental procedure

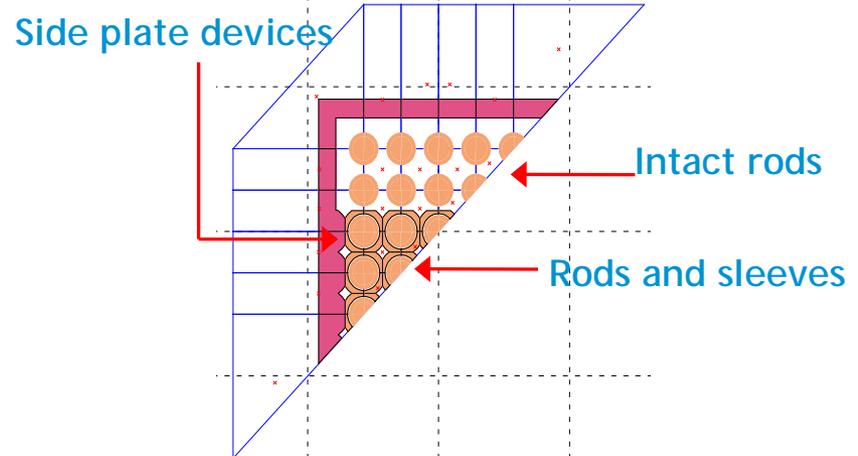
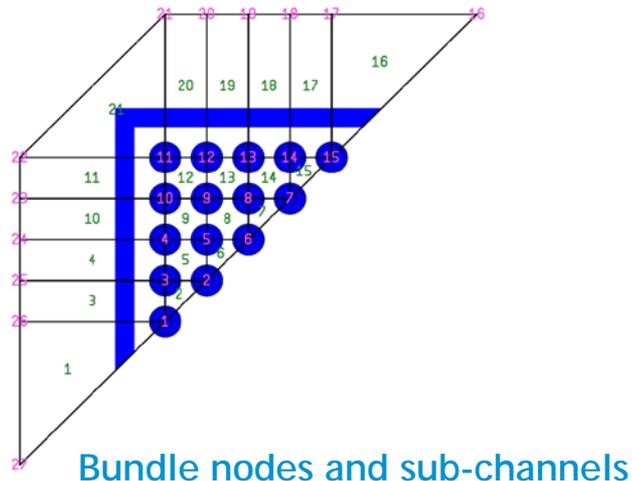
- Reaching initial steady-state operating conditions in stagnant steam with the required power to get temperature range of 600°C-800°C at bundle mid-plane
- Establishing reflood at constant forced rate with a power history defined according to the decay law ANS71 +20%, 40s after reactor shutdown.



Simulation of FEBA tests (2/3)

■ DRACCAR modelling

- Half a bundle for partially blocked bundles, 1/8th for intact bundles as well as for totally blocked bundles
- Heating length height
- 2 BC at the inlet and outlet



■ DRACCAR procedure

- Rods and housing initial temperatures at the beginning of reflooding are initialized using data available in the experimental report
- Heating power law and reflooding are initiated at the same time

Simulation of FEBA tests (3/3)

■ DRACCAR simulation results for tests #282 series V

- Comparison with experimental results and with CATHARE 2 results (from validation data decks) for information purposes.

■ CATHARE results

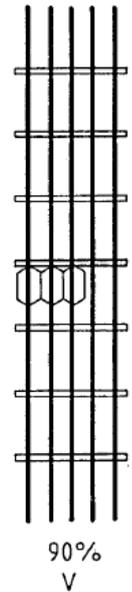
- In the BP, good results during the first 50s of the transient, PCT well predicted, quenching far too early.
- Within the blockage, strong overestimation of PCT, quenching far too early.

■ DRACCAR results

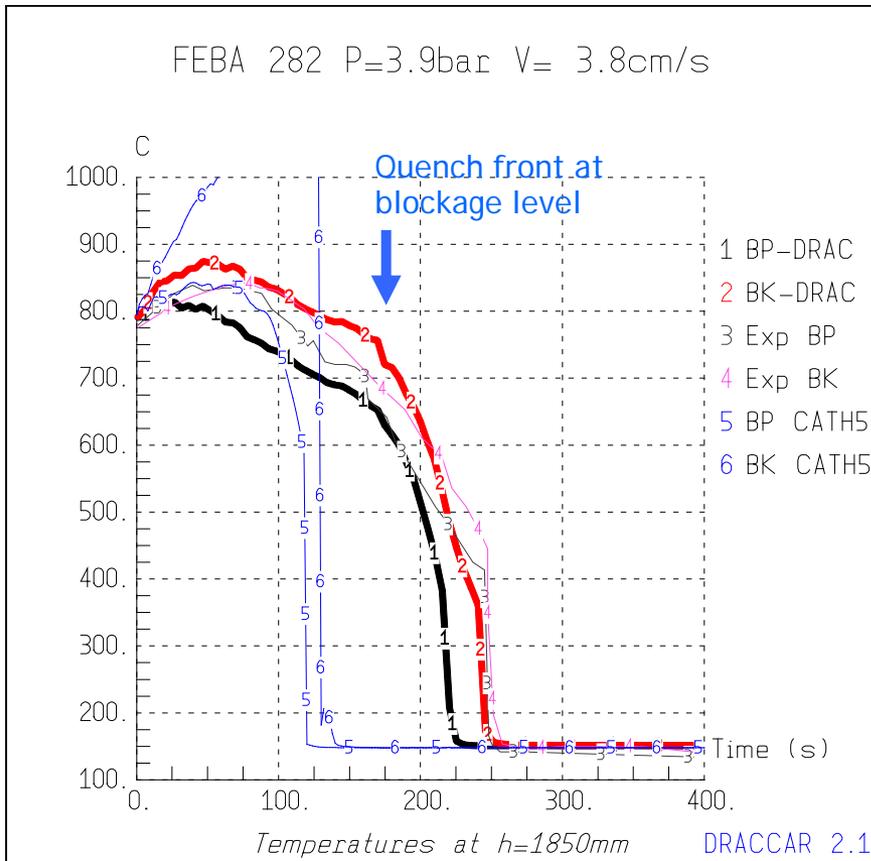
- In the BP, PCT slightly underestimated, quenching a little too early.
- Within the blockage, T° slightly overestimated, quenching well predicted.

■ Overall DRACCAR simulation results

- Satisfying results / experiment
- Improvements of reflooding phenomena in the vicinity of blockages expected by overcoming limitations of the T/H module on droplets behavior to increase heat exchanges in the ballooned zone.



90%
V



#282: within the maximum flow blockage,
100mm upstream of the mid-plane.

SFP (Spent Fuel Pool) program objectives

■ Experimental phase

- To get experimental data following a complete instantaneous draining of a pool in a spent fuel building
 - Link with the September 11 2001 attacks
 - US NRC program in collaboration with OECD and 12 international partners, conducted at Sandia National Laboratories (SNL)
 - Integral tests on prototypic LWR fuel assemblies
- Major role of Air
 - Air oxidation
 - Zircaloy cladding oxidation burn front
 - Zirconium-nitrogen reactions
- Possible propagation of oxidation reactions from a hot assembly towards “cold” neighbor assemblies ?



■ Validation of severe accident computer codes

- MELCOR, ATHLED-CD, ASTEC, DRACCAR, etc in these experimental conditions

Simulation of SFP Phase II (1/3)

2009-2013 OECD SFP test program on PWR 17×17 assembly

- **Phase I:** single test assembly of full length, electrically powered, within a pool rack cell (stainless steel) and completely isolated to model "hot neighbor" loading pattern. Cooled by natural air flow at bottom
- Ignition test conducted in 2011 at a power representative of a typical time offload.

➤ Zirconium ignition temperature reached
➔ self-sustaining zirconium fire in the bundle

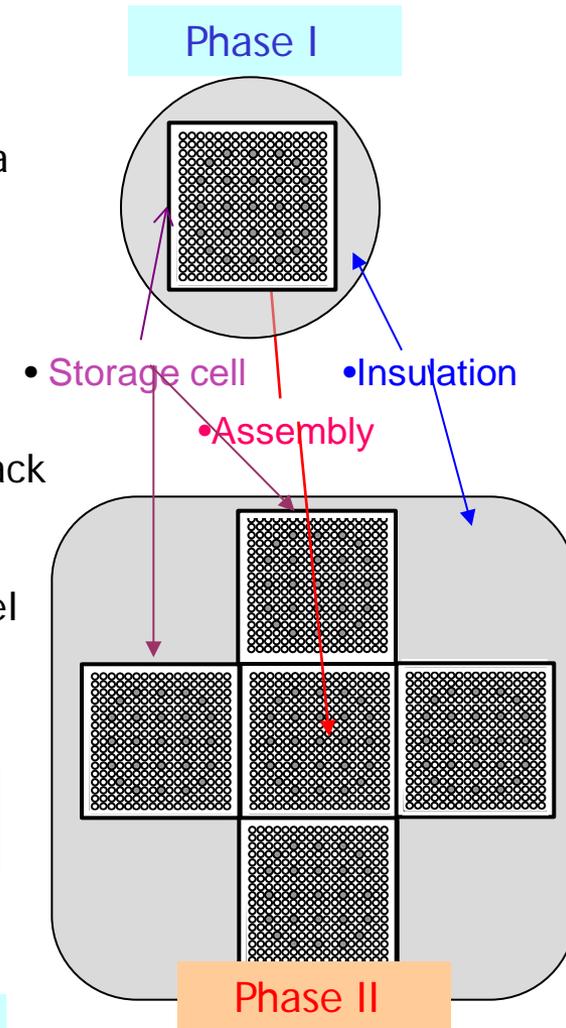
- **Phase II:** transverse heating and burn propagation in 1×4 configuration. Five full-length assemblies arranged in a pool rack with electrically heated assembly in the center cell to model "cold neighbor" situation.

- Two cold assemblies pressurized with Argon to mimic spent fuel pressure at cladding rupture
- Ignition test conducted in 2012 at power representative of a typical time offload

➤ Zirconium ignition temperature reached in central cell
➔ self-sustaining zirconium fire in the five assemblies

- Significant nitrogen removal by zirconium nitride formation observed in both test Phases

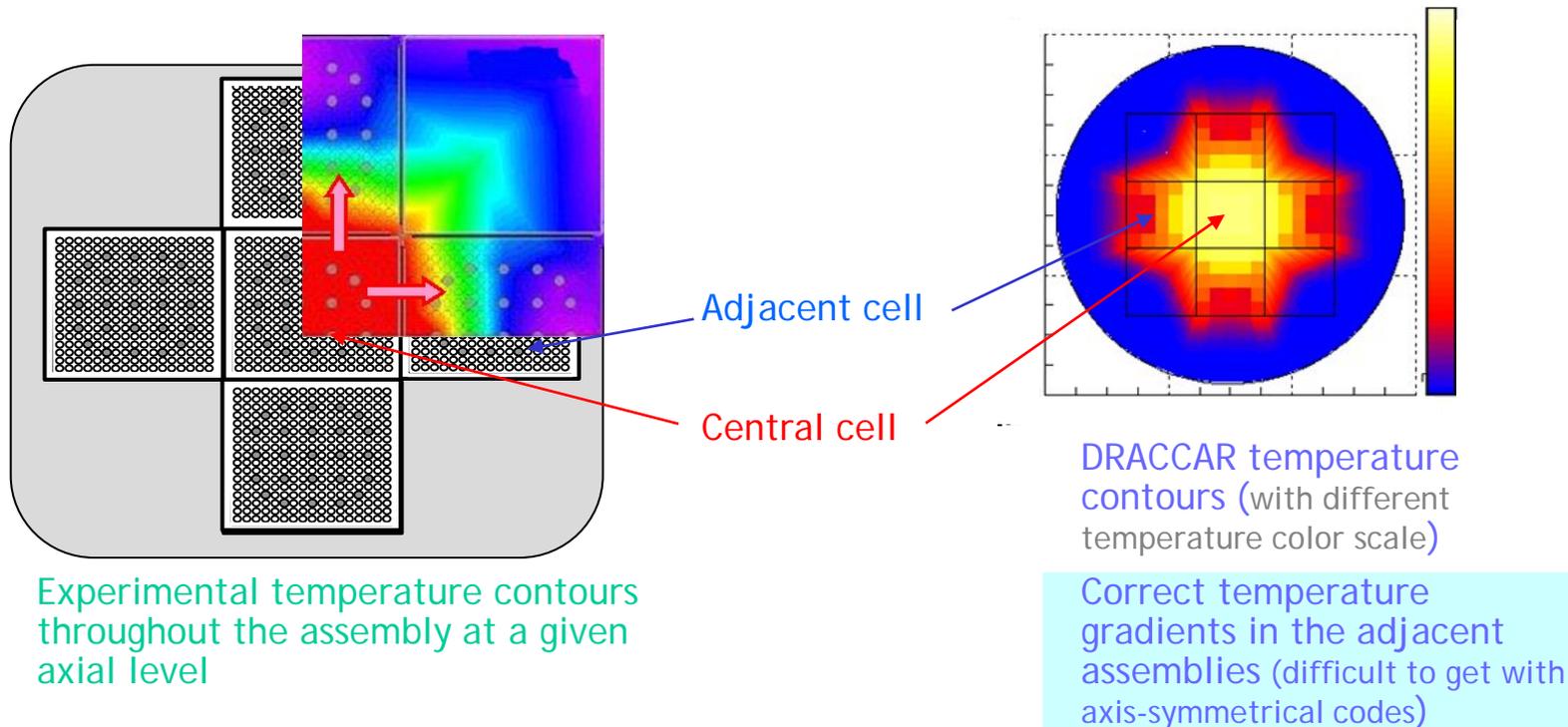
□ **Main instrumentation:** thermocouples, oxygen sensors (O_2 starvation), hot wire anemometers (naturally induced flow rates), residual gas analyzer (nitrogen reactions).



Simulation of SFP Phase II (2/3)

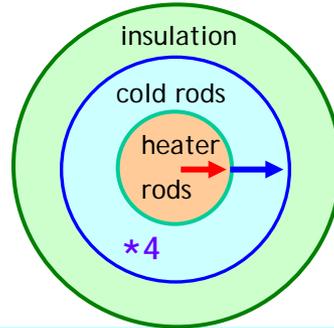
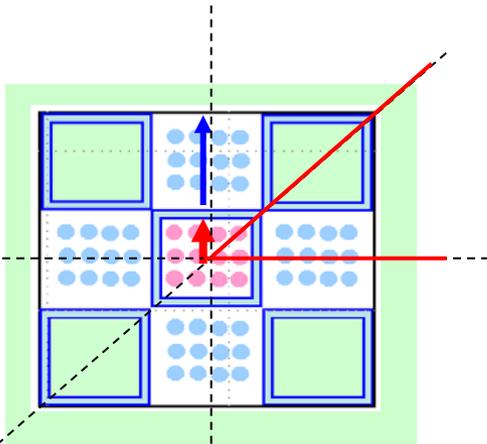
Difficulty to model non symmetrical heat exchanges with axis-symmetrical codes

- Most of severe accident codes are axis-symmetric (MELCOR, ASTEC, ..)
 - Ignition: electrical power stopped shortly after ignition → bundle degradation is still continuing due to large sustained oxidation power in the bundle
 - Central cell: axis-symmetrical codes can be used to simulate central cell burn front evolution (with standard heat transfer (HT) code modules)
 - Peripheral cells: non axis-symmetrical temperature gradients are difficult to simulate, except for mean temperatures and ad hoc tuning coefficients for HT.



Simulation of SFP Phase II (3/3)

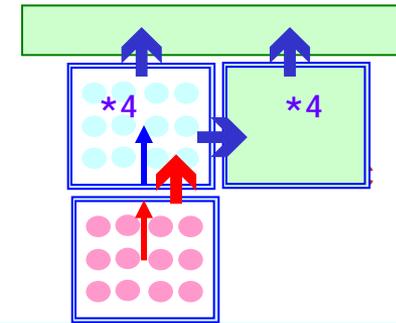
Different models for non symmetrical heat transfers (HT) with axis-symmetrical codes



\neq Cells \rightarrow \neq rings (Melcor, Astec)

- ΔT_{radial} correct
- \neq exchange surfaces
- not real geometry

\rightarrow adjust HT to exp. results

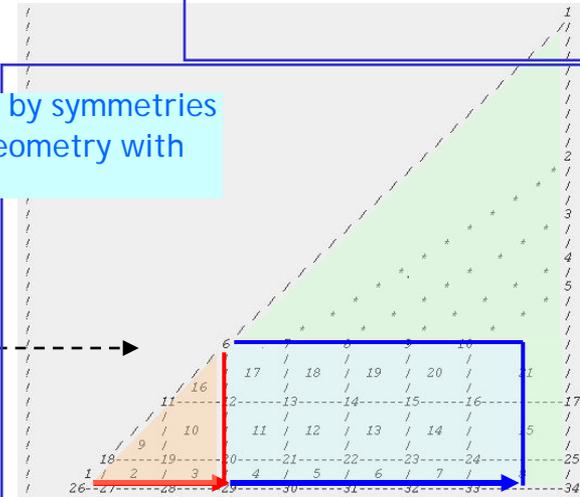


Separate Cells and coolants (Astec)

- ΔT_{radial} not correct for Periph. cells
- \rightarrow ΔT between Cells not correct
- \neq exchange surfaces
- Cell exchanges by GAP exchange

\rightarrow adjust HT to exp. results

- ✓ Reduction of meshing by symmetries
- ✓ Meshing of the real geometry with rods inside meshes



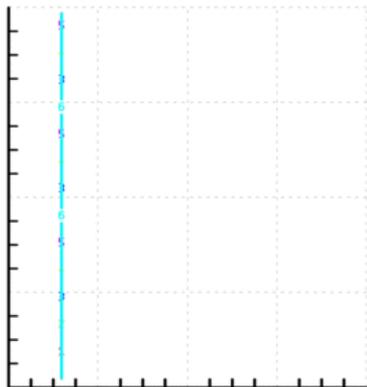
Real geometry with symmetries (Draccar)

Central Cell (1/8) Peripheral Cells (1/2)

- ΔT_{radial} correct. Same exchange surfaces
- Rods defined in meshes with weights (only 3 radial meshes / 5 rings in Astec)

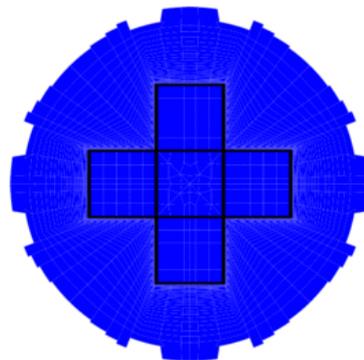
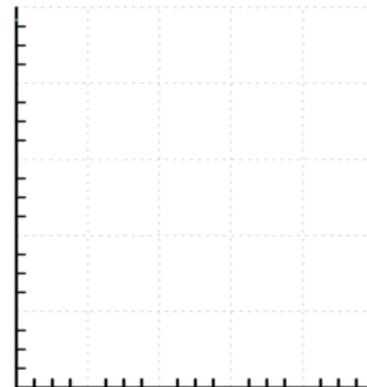
\rightarrow no adjustment of heat transfers coefficients

cladding Temperature profile, central cell

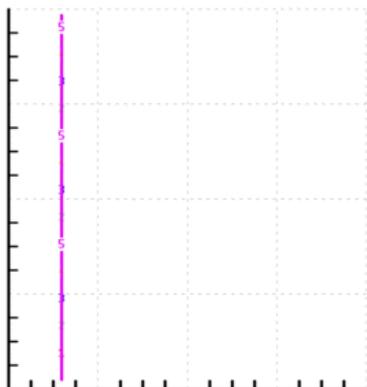


- 1 c1
- 2 c2
- 3 c3
- 4 c9
- 5 c10
- 6 c16

Center cladding Temperature evolution

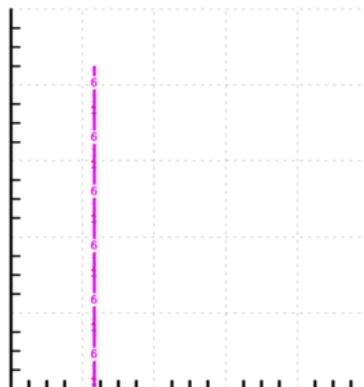


peripheral Temperature profile, hottest rank

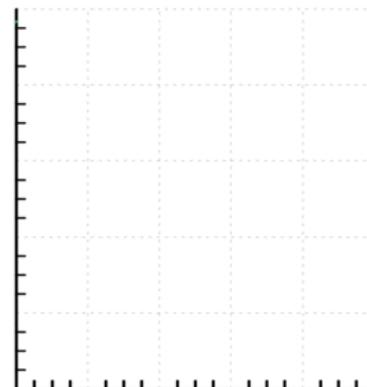


- 1 c4
- 2 c5
- 3 c6
- 4 c7
- 5 c8

oxygen fract profile center:



hottest cladding peripheral assembly



Conclusion and prospects

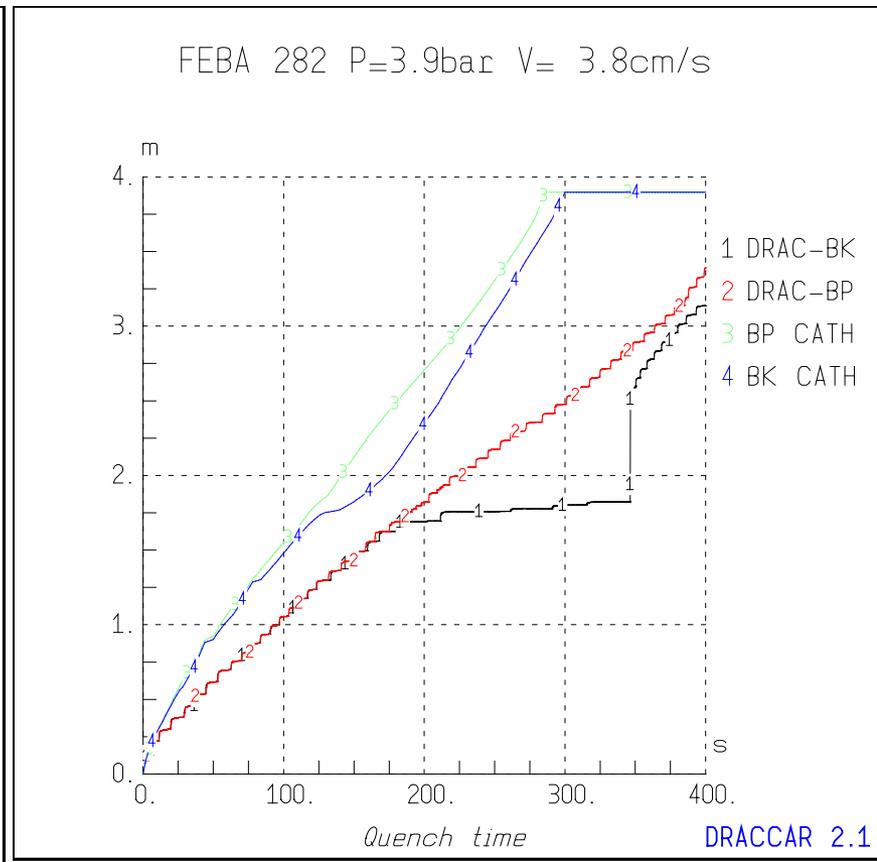
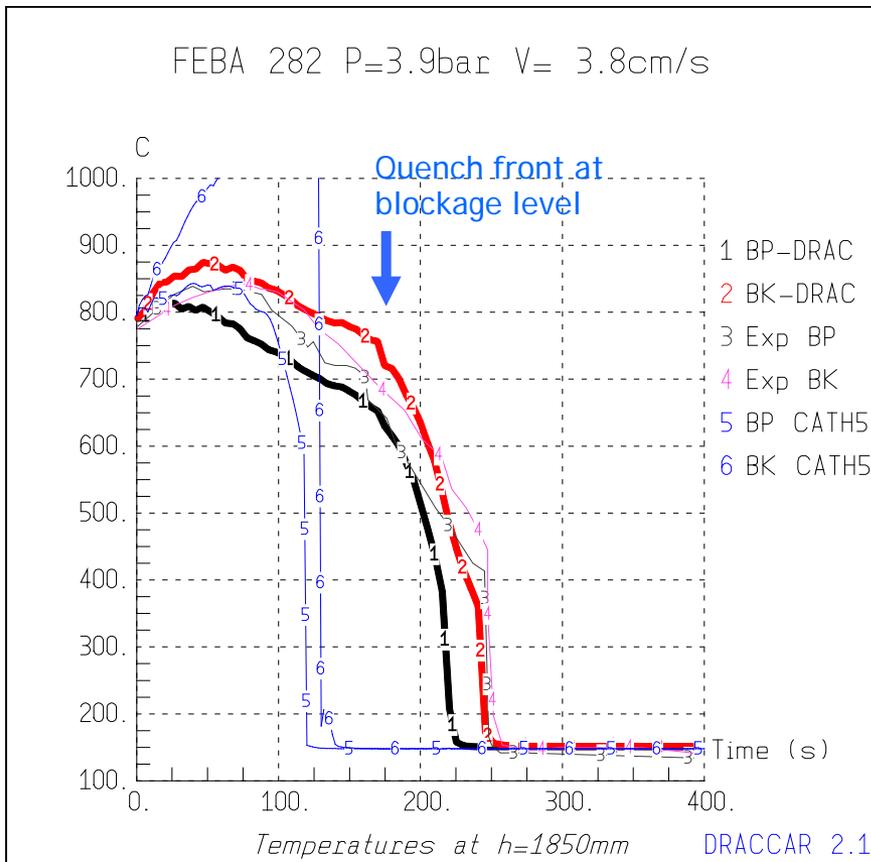
- Coupled T/H and T/M codes CESAR-DRACCAR are necessary to correctly describe and understand the complex and diversified phenomena that occur in LOCA and post LOCA transients
 - The DRACCAR code results in predicting the T/H behavior of a bundle even in case of partial blockage are satisfying
 - In the frame of spent-fuel-pool draining accident, ignition and propagation of zircaloy cladding fire inside a 1×4 assemblies configuration (typically non axis-symmetrical) have been correctly reproduced
- Code development is a long term task, the DRACCAR code takes into account a growing number of aspects
- **Ongoing developments** such as:
 - the development of a 6 equations version of the T/H module (FEBA),
 - the modeling of Nitrogen kinetics in oxygen starvation conditions (SFP)**are a further step to reach better simulation skills**
- **Ongoing experimental programs** such as:
 - **COAL test series** within the PERFROI program at IRSN
[**CO**olability of a fuel **A**ssembly during **L**oca]

to go beyond FEBA results on impaired coolability due to fuel accumulation in the ballooned region **are a further step to reach better understanding**

Simulation of FEBA tests (3/3)

■ DRACCAR simulation results for tests #282 series V

- Comparison with experimental results and with CATHARE 2 results (from validation data decks) for information purposes.



#282: within the maximum flow blockage,
100mm upstream of the mid-plane.

Appendix

■ FEBA

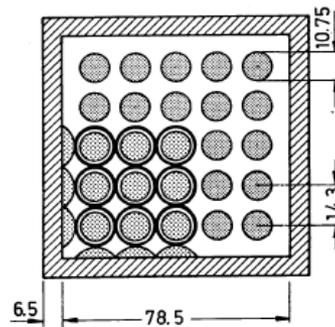
- P. IHLE, K. RUST, FEBA -Flooding Experiments with Blocked Arrays - Evaluation report, KfK 3657.

Series	Test number	Flooding velocity $cm.s^{-1}$	Pressure bar	Feedwater temperature ($^{\circ}C$)		Heat flux at $t=0s$ kW
				0-30s	End	
I	216	3,8	4,1	48	37	200
II	229	3,8	4,1	53	38	200
III	239	3,8	4,1	49	37	200
IV	263	3,8	3,9	61	43	200
V	282	3,8	3,9	77	45	200
VI	276	3,8	3,9	73	43	200
VII	324	3,8	4,1	56	42	200
VIII	337	3,8	4,0	57	42	200

Tests simulated using the DRACCAR code.

Cross Section at Midplane of the Bundle

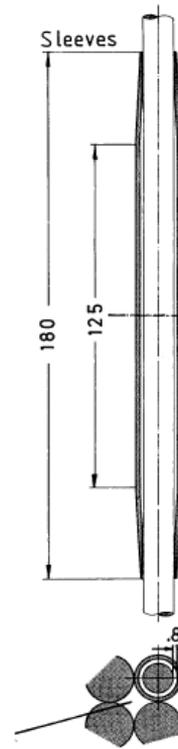
Local Blockage Ratio 62%
Overall Blockage Ratio 20%



Bundle Data :

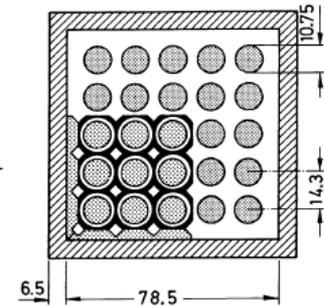
Pitch 14.3 mm
Rod Diameter 10.75mm
Heated Length 3900 mm

Flow Area



Cross Section at Midplane of the Bundle

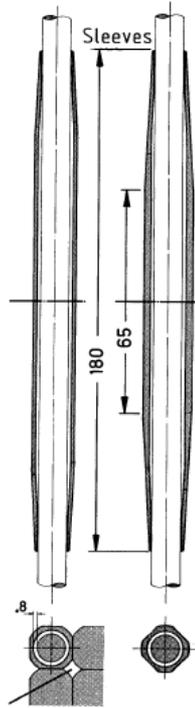
Local Blockage Ratio 90%
Overall Blockage Ratio 31%



Bundle Data :

Pitch 14.3 mm
Rod Diameter 10.75mm
Heated Length 3900 mm

Flow Area



Sectional views of the FEBA test sections and sleeves geometry for 62% and 90% blockage ratio.