REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

| | |
|---|---|
| WP: | **WP 6 – Knowledge dissemination** |
| Task: | Core modelling approaches for failed fuel assessment during LOCA |
| Speaker: | Sébastien Belon |
| Affiliation: | IRSN |
| Event: | Short Course DBA and DEC-A for Light Water Reactors |
| When: | July 5th 2023 |
| Where: | Bologna (Italy) |

Commission européenne

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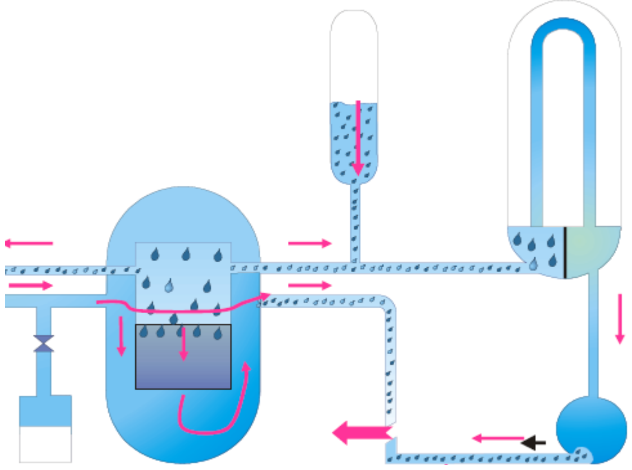
# Core modelling for failed fuel rod assessment

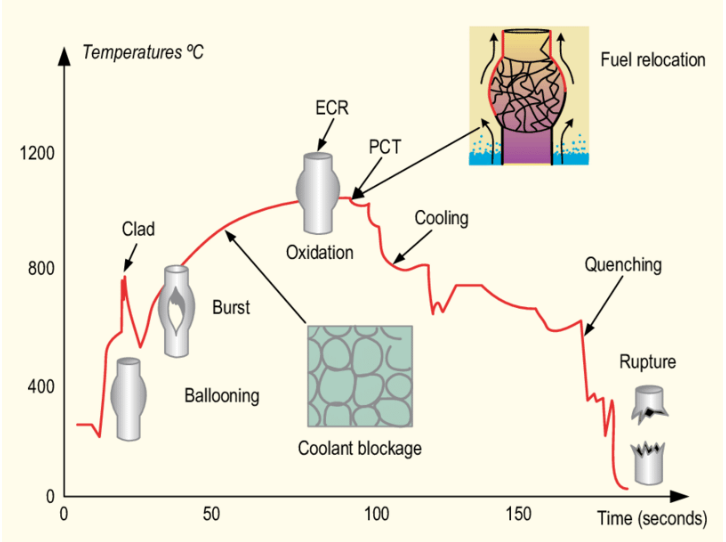
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Scope: LOCA in LWR
  - Loss-of-coolant initiator = Break on primary circuit
  - Fast depressurization of reactor coolant system (RCS)
  - Loss of primary coolant inventory ➔ partial or full core uncovery
  - Need of Emergency Core Cooling System (ECCS) to reflood the core




*List of Acronyms*

| | |
|---|---|
| DBA | Design basis accident |
| DEC-A | Design Extension Conditions without core melt |
| LOCA | Loss-of-coolant accident |
| PCT | Peak cladding temperature |
| ECR | Equivalent cladding reacted parameter(s) |
| RBR | ratio of bursting rods |
| BU | Burn-up |
| RC | Radiological consequences |
| RIP | Rod internal pressure |
| ST | Source Term |
| T/H | Thermal Hydraulics |
| T/M | Thermal Mechanics |




Source: Rudling, Peter & Garzarolli, Friedrich. (2011). New PWR/VVER Zr Alloys for HIgh Burnups - Figure 5-1

# Why developing new core model in the frame of R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **Objective: Quantification of the radiological consequences during LOCA on PWR**

- **Discriminate fuel assembly (FA) behaviors during LOCA to evaluate respective potential for burst of each fuel rod**

RBR evaluation ← Predicting the burst risk of each fuel rod in the core

*Few modeling issues*

~150 to 250 FAs in the core

~40000 to 65000 fuel rods

Multi-physics simulation + 3D effects

Thermalhydraulics ←→ Thermalmechanics

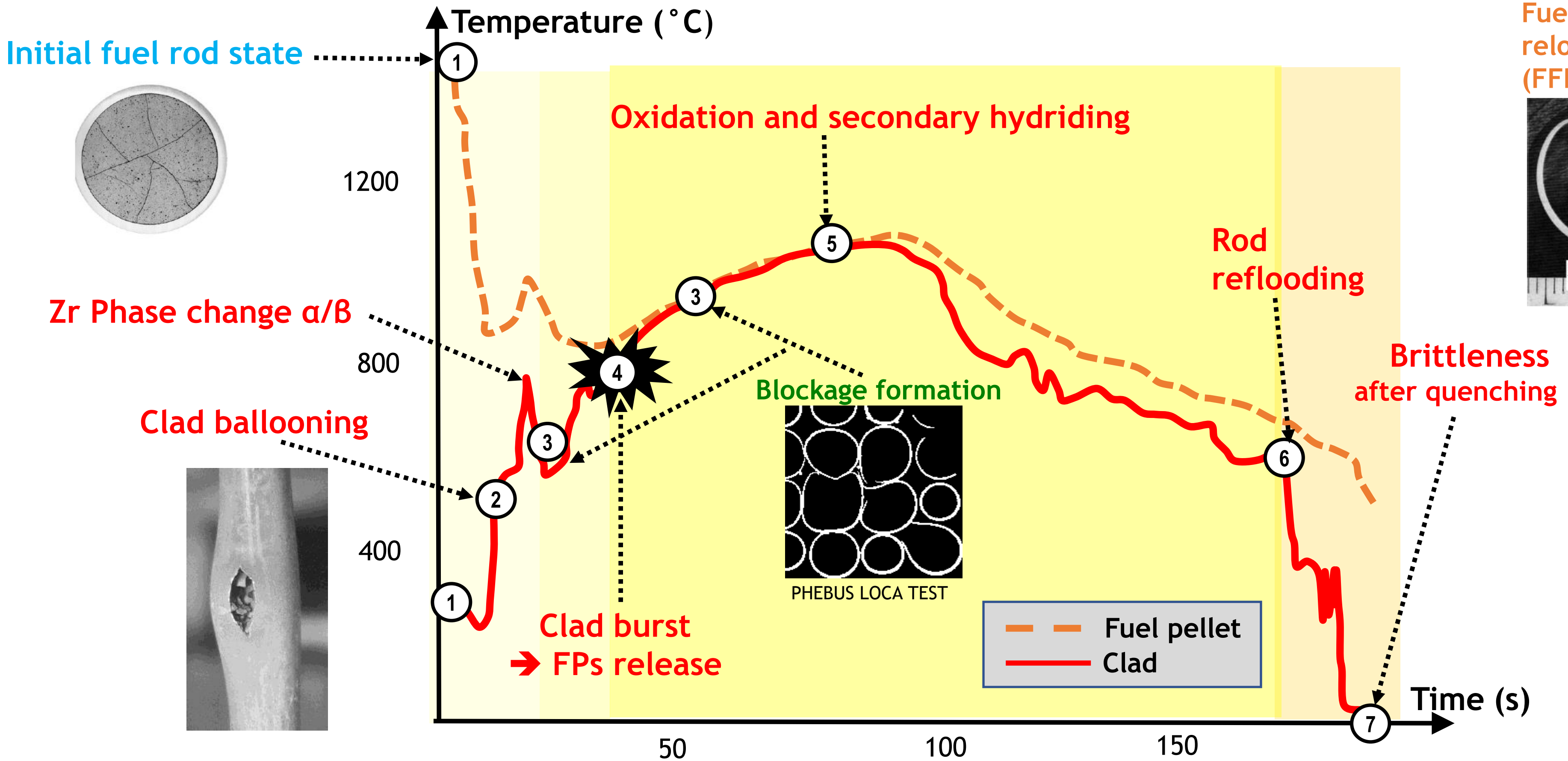
- **Burst risk for each fuel rod during LOCA is influenced by many parameters:**
  - **Plant design: RCS, standard and safety systems, …**
  - **Core and fuel design: fuel type and materials (IFBA, PuOx), core management and loading map,...**
  - **Initial state: neutron power before accident, irradiation history, burn-up (RIP, FG, conductivity, oxidation,…),…**
  - **Parameters and hypotheses associated to scenario: break size and location, availability of safety systems,…**

# Core modelling for failed fuel rod assessment

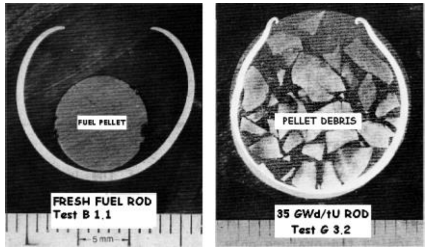
*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

- Scope: LOCA in LWR – consequences on fuel rod during LOCA
  - **Rod heat-up due to core uncovery ➔ $T_{clad}$ ↗**
  - **[ Rod internal pressure (RIP) - coolant pressure ] ↗**

} Creep of the cladding, Zr $\alpha/\beta$ phase change } Risk of burst & FPs release in containment



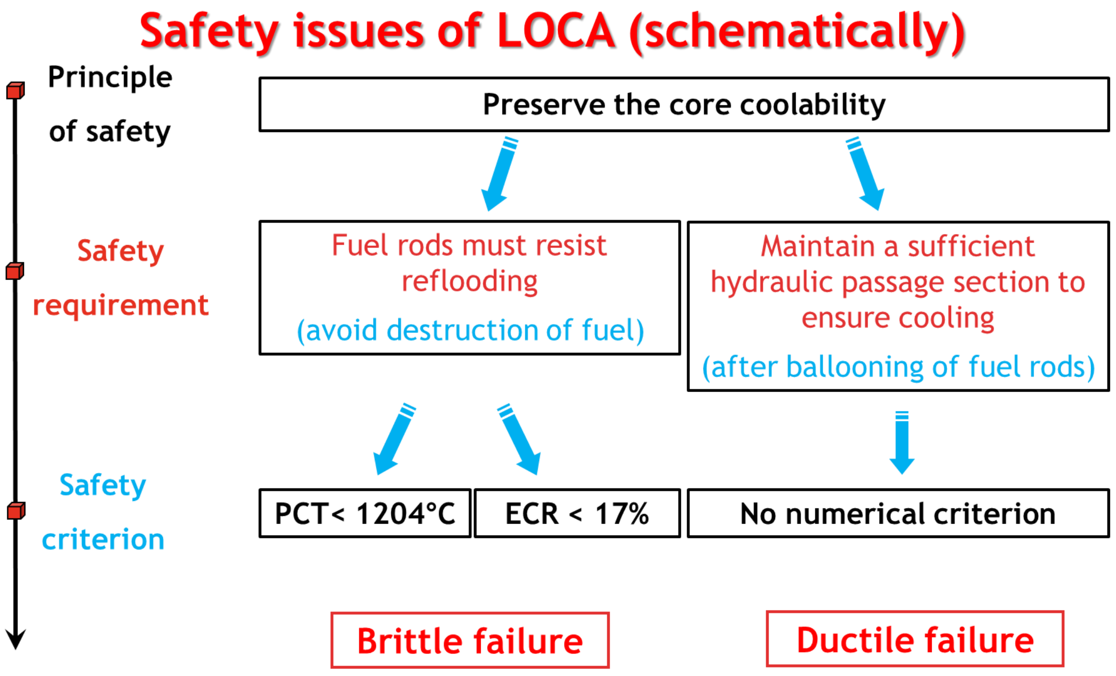

Fuel fragmentation, relocation and dispersal (FFRD)

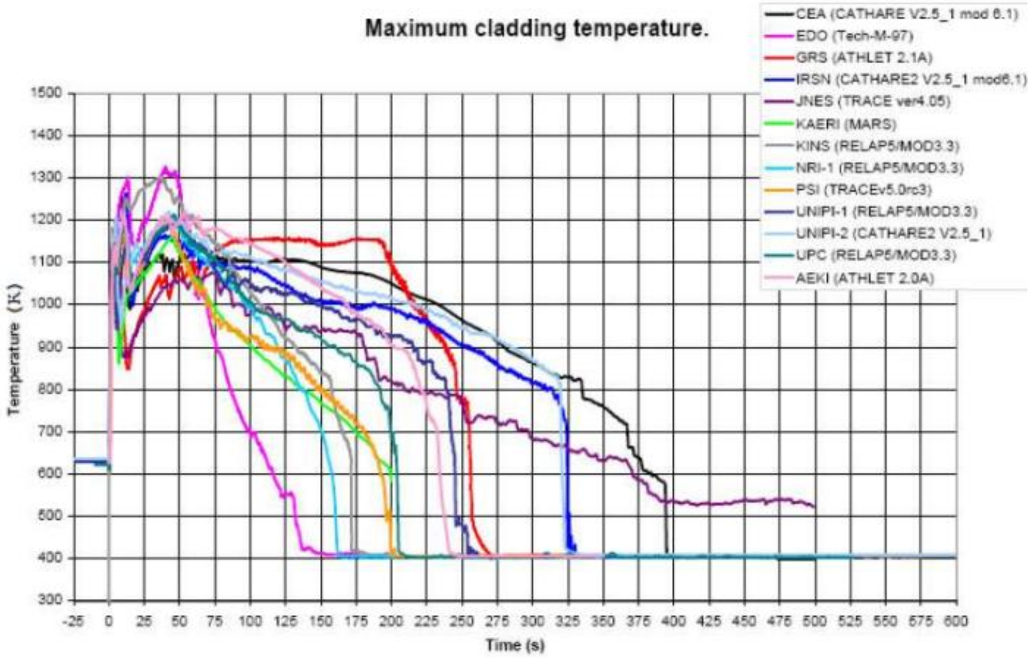


# Why developing new core models in the frame of R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- “Classical” DBA model cannot be used to predict “Failed rod number” under LOCA conditions
  - Coolability and rod integrity demonstration based on the hottest rod PCT and the maximum channel blockage
  - Idealized model (non-realistic architecture) & Assumptions targeted in DBA maximize PCT and flow blockage
  - Burst criteria in use for coolability assessment are mainly focused on burst

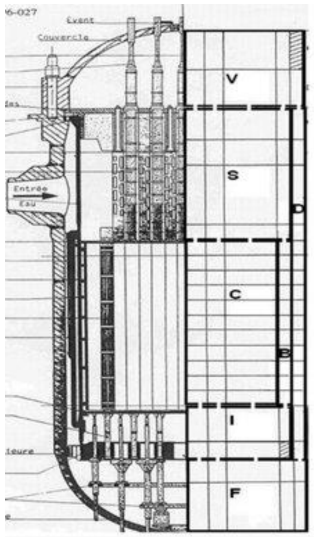


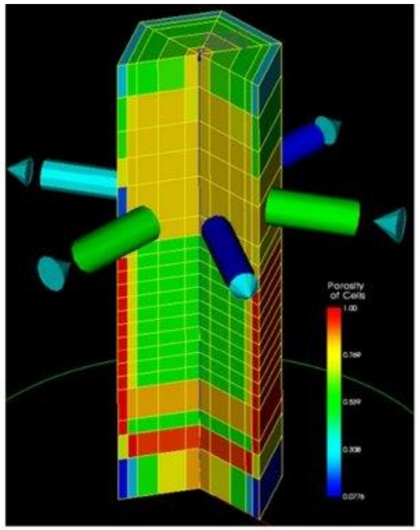

Source: NEA (2008), BEMUSE Phase IV Report: Simulation of a LB-LOCA in Zion NPP – Main report, OECD Publishing, Paris

# Why developing new core models in the frame of R2CA

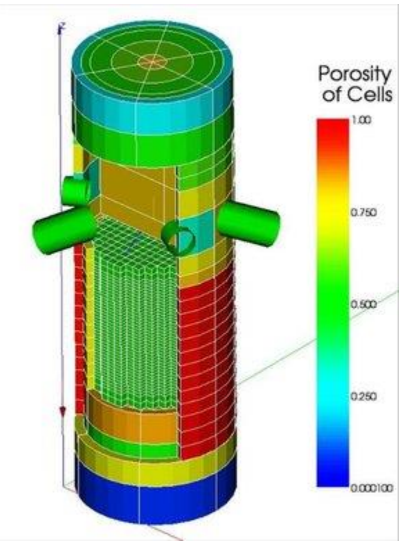
- "Classical" DBA model cannot be used to predict "Failed rod number" under LOCA conditions
  - **Coolability and rod integrity demonstration based on the hottest rod PCT and the maximum channel blockage**
  - **Idealized model & Assumptions targeted in DBA maximize PCT and flow blockage**
  - **Burst criteria tends to maximize deformation**



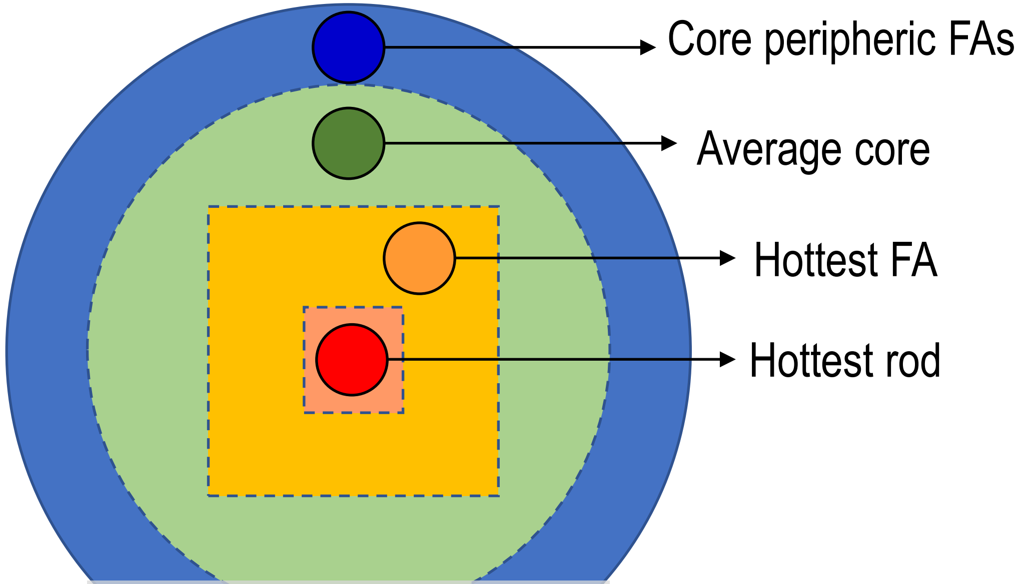
PWR vessel



CATHARE-2
3D model




CATHARE-3
3D model




Schematic core model
for LOCA DBA analysis

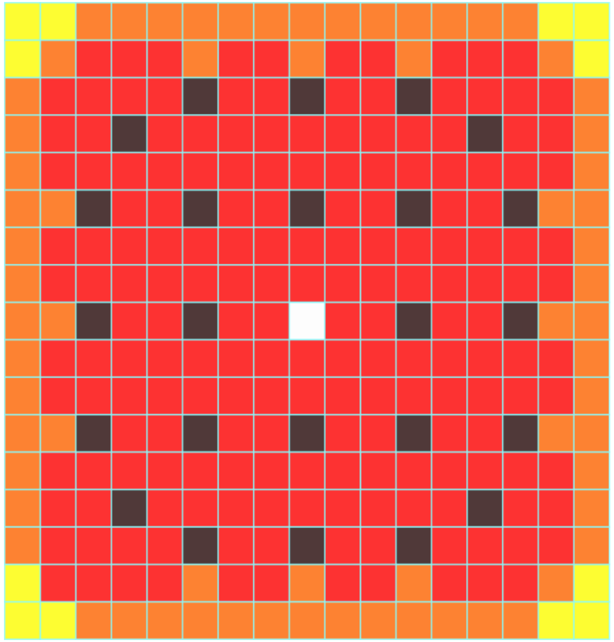
Source: Préa R. & al. - CATHARE-3 V2.1: The new industrial version of the CATHARE code. ATH'20 – 2020
https://www.ans.org/pubs/proceedings/article-49142/

# Why developing new core models in the frame of R2CA



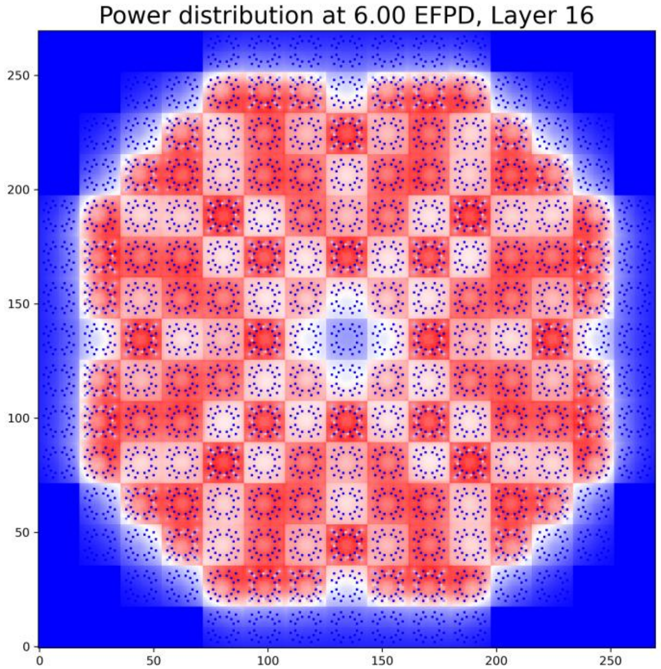
- Example of core loading map and fuel assembly design

➔ Heterogeneities of PWR core loading map and FA compositions



- 1 instrumentation tube
- 24 guide tubes & control rods
- 12 low Pu enriched fuel rods
- 68 mid Pu enriched fuel rods
- 184 high Pu enriched fuel rods

Typical PWR 17x17 MOX configuration




Example of core power distribution
source: M. Jobst (HZDR), final report R2CA WP3.2

**FA and core maps are clearly 3D with significant variations of power, BU and RIP**

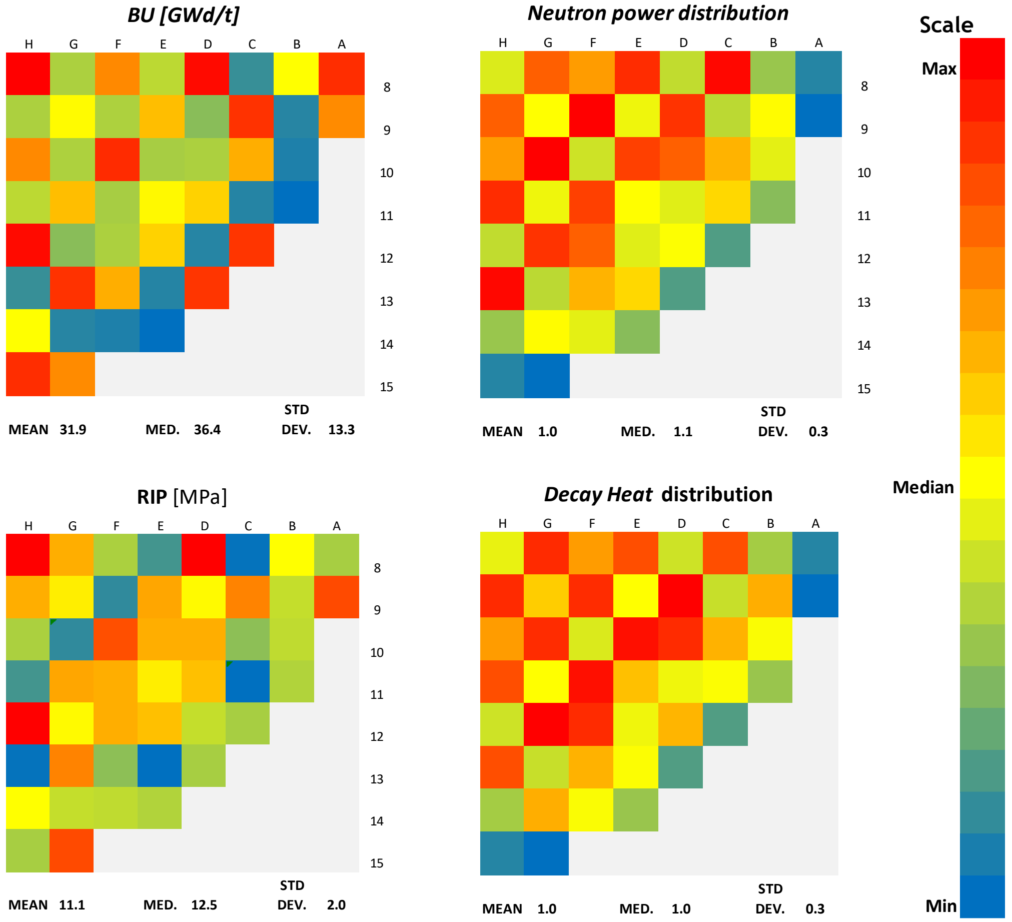
**➔ Need to represent each FA as it should behave differently from its neighbors under LOCA conditions**

# Why developing new core models in the frame of R2CA

*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

- Example of core loading map considered in task 2.5 by IRSN

➔ “PWR 900MW like” data for reactor case simulation = “realistic” approach




- “PWR900-like” core with 2 types of fuel $UO_2$ and MOX
- Control rods located in some FAs
- Wide range of BU
- Small differences between neutron power (fission) and DH distributions (same as FP distribution)
- Rod internal pressure (RIP) > 10 MPa at nominal power and varying according to BU and fuel type

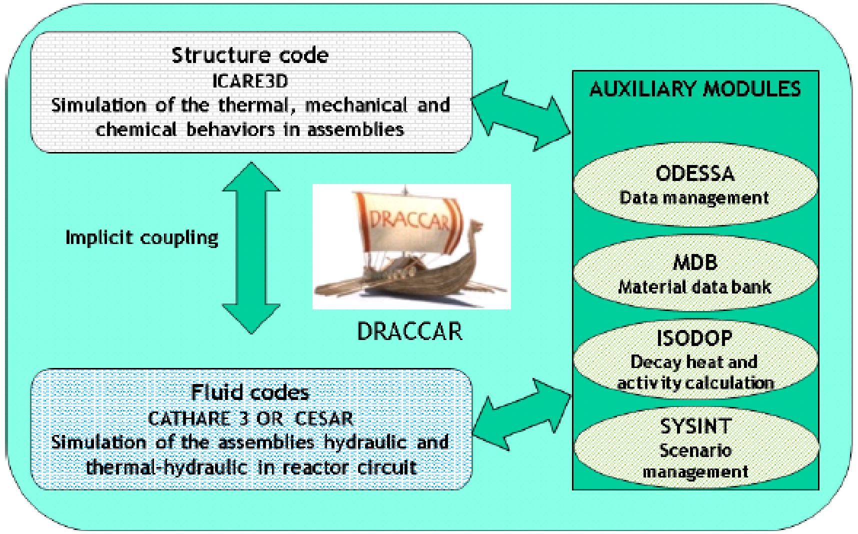
**Core map is clearly 3D with significant variations of power, BU and RIP**

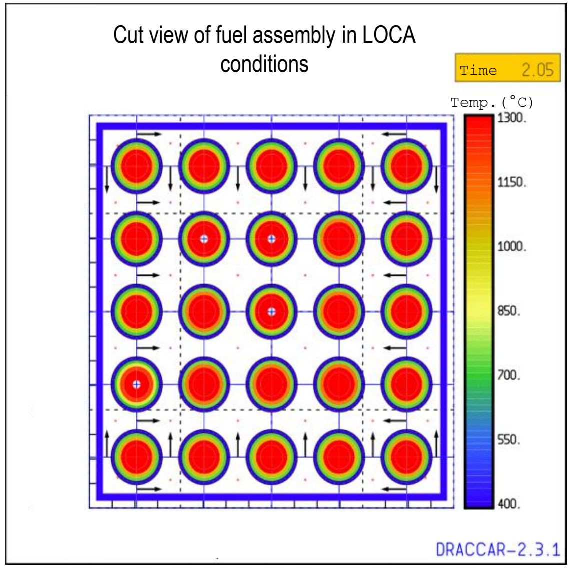
**➔ Need to represent each FA as it should behave differently from its neighbors under LOCA condition**

# Different approaches investigated for RBR evaluation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Several types of tools can deal with phenomena involved during a LOCA
  - Detailed tools specialized in a field e.g. Mechanics using finite elements : CAST3M(CEA), ASTER(EDF),…
  - Fuel performance code : FRAPCON(USNRC/PNNL), CYRANO3(CEA), COPERNIC(FRAMATOME),…
  - System thermalhydraulic tools : CATHARE(CEA), TRACE(US-NRC), RELAP(INL), ATHLET(GRS), SPACE(KAERI),…
  - Multi-physics single fuel rod tools : FRAPTRAN(USNRC/PNNL), TRANSURANUS(JRC), ALCYONE(CEA), BISON(INL),…
  - Severe accident integral tools : ASTEC(IRSN), ATHLET-CD(GRS),…
  - Multi-physics and multi-rods tools : DRACCAR(IRSN), MATARE(JRC/IC),…



# Different approaches investigated for RBR evaluation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## Various approaches selected by partners in the frame of R2CA for LOCA reactor applications

| Partner | System model (core+RCS) | | | Fuel perfomance modelling | |
|---|---|---|---|---|---|
| | Thermo-hydraulic modelling | Thermo-hydraulic Code | Core nodalization | Thermo-mechanical modelling | Code |
| **Fuel performance code chained to T/H code** | | | | | |
| **SSTC** | 2D Axi-symetric | RELAP5 | Groups | 2D Axi-symetric | TRANSURANUS |
| **UJV** | 2D Axi-symetric | RELAP5 | Groups | 2D Axi-symetric | TRANSURANUS |
| **Integral system approach** | | | | | |
| **LEI** | 2D Axi-symetric | ASTEC | 4 Groups (rings) | 2D Axi-symetric | ASTEC |
| **HZDR** | 3 D | ATHLET-CD | Rings + azimuthal sub-division | 2D Axi-symetric | ATHLET-CD |
| **IRSN** | 3 D | DRACCAR | at least 1 / FA | 2,5 D | DRACCAR |

***Approaches selected by partners for Task 2.5 LOCA reactor applications***

**Chain T/H system code → Fuel performance code**
EK (ATHLET/FRAPTRAN)
SSTC-NRS (RELAP5/TRANSURANUS)
UJV (ATHLET/TRANSURANUS)
VTT (APROS/GENFLO+FRAPTRAN)

**Integral approach + Fuel performance code**
LEI (ASTEC/TRANSURANUS)

**Integral approach**
ENEA (ASTEC)
HZDR (ATHLET-CD)
IRSN (DRACCAR)

Source: D3.4 T3.2 Final report – R2CA H2020 EC project

# Different approaches investigated for RBR evaluation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## Approach chaining LOCA system simulation results to single fuel pin simulations

- Basic principle of the approach
  - 1st step: Simulation of T/H response of NPP to LOCA scenario using T/H system code
  - 2nd step: Evaluating RBR by simulating core response using single fuel rod transient simulations

- Widely used by R2CA partners in T2.5: EK (ATHLET/FRAPTRAN), LEI (ASTEC/TRANSURANUS), SSTC-NRS (RELAP5/TRANSURANUS), UJV (TRANSURANUS/ATHLET), VTT (APROS/GENFLO+FRAPTRAN)

Main advantages:

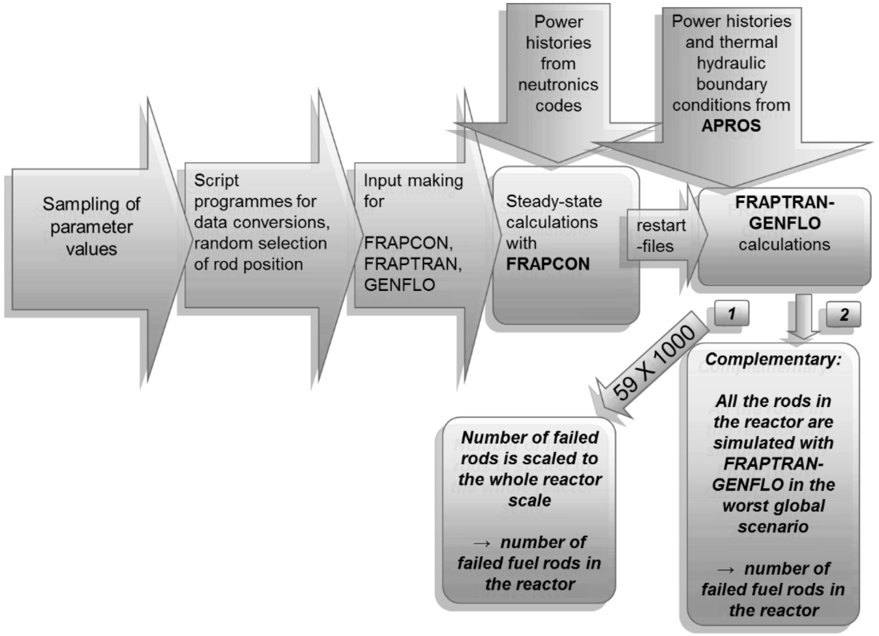
Reduce cost of single rod computation ➔ large number of simulations can be run

Level of details on fuel behavior brought by the transient single fuel rod code

Possible issues:

Feedback of thermomechanics on thermalhydraulics

Average T/H system response imposed as boundary conditions at sub-channel scale in fuel channel




Approach at VTT to evaluate the number of failing fuel rods in a reactor during a LOCA
Source: A. Arkoma (VTT), final report R2CA WP2 T2.5

# Different approaches investigated for RBR evaluation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## Approach based on severe accident simulation using classical core ring model

- Basic principle of the approach
  - Integral simulation with 2D- axisymmetric nodalization of the core and representative rods
- Illustrated by partners in T2.3 (IRSN, ENEA, LEI) and updated in T2.5 (ENEA)

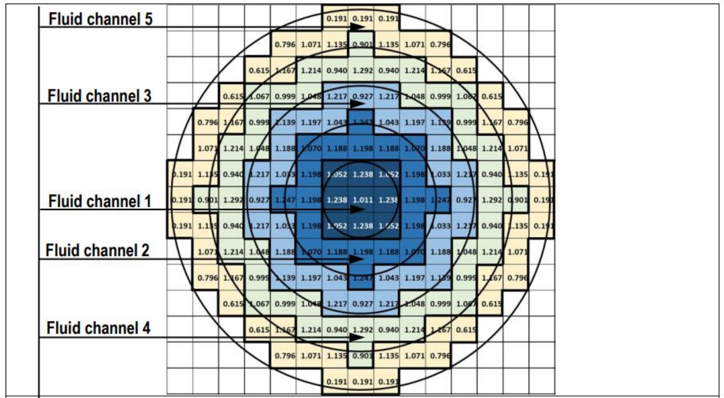
### Main advantages:

Integral simulation with multi-physics capabilities coupling T/H & T/M as well as FPs transport and behavior in circuit and containment

### Possible issues:

Difficulty to represent core heterogeneities due to core nodalization

Average T/H system response in rings applied to different FA




| Fluid Channel | Representative fuel rod | Weight (N° of FA) | Decay heat factor | Neutronic power factor | Internal pressure (room temperature) |
|---|---|---|---|---|---|
| 1 | ROD11 | 4 | 1.238 | 1.130 | 30 bar |
| | ROD12 | 4 | 1.052 | 1.130 | 30 bar |
| | ROD13 | 1 | 1.011 | 1.130 | 30 bar |
| | 3 Rep. Rods | 9 FAs | | | |
| 2 | ROD21 | 4 | 1.247 | 1.180 | 30 bar |
| | ROD22 | 12 | 1.195 | 1.180 | 30 bar |
| | ROD23 | 4 | 1.070 | 1.180 | 30 bar |
| | 3 Rep. Rods | 20 FAs | | | |
| 3 | ROD31 | 8 | 1.217 | 1.120 | 30 bar |
| | ROD32 | 12 | 1.175 | 1.120 | 30 bar |
| | ROD33 | 8 | 1.038 | 1.120 | 30 bar |
| | ROD34 | 4 | 0.927 | 1.120 | 30 bar |
| | 4 Rep. Rods | 32 FAs | | | |
| 4 | ROD41 | 4 | 1.292 | 1.060 | 30 bar |
| | ROD42 | 8 | 1.214 | 1.060 | 30 bar |
| | ROD43 | 20 | 1.032 | 1.060 | 30 bar |
| | ROD44 | 8 | 0.940 | 1.060 | 30 bar |
| | ROD45 | 4 | 0.901 | 1.060 | 30 bar |
| | 5 Rep. Rods | 44 FAs | | | |
| 5 | ROD51 | 8 | 1.167 | 0.780 | 30 bar |
| | ROD52 | 8 | 1.135 | 0.780 | 30 bar |
| | ROD53 | 8 | 1.071 | 0.780 | 30 bar |
| | ROD54 | 16 | 0.706 | 0.780 | 30 bar |
| | ROD55 | 12 | 0.191 | 0.780 | 30 bar |
| | 5 Rep. Rods | 52 FAs | | | |
| Total N° of Rep. Rods = 20 | | Total N° of FA = 157 | | | |

Updated ASTEC core ring model using 5 T/H channels and 20 representative rods
Source: S. Ederli (ENEA), final report R2CA WP2 T2.5

# Different approaches investigated for RBR evaluation

*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

## 3D core approach with detailed core model

- Basic principle of the approach
  - Represent core thermal-hydraulics with 3D model and depicting each FA with representative rods (average, hot rod, …)
  - Core T/H + system T/H coupled to thermalmechanical behavior of fuel rods
- Applications developed by partners HZDR (ATHLET-CD) and IRSN (DRACCAR)

Main advantages:

Multi-physics capabilities coupling T/H & T/M

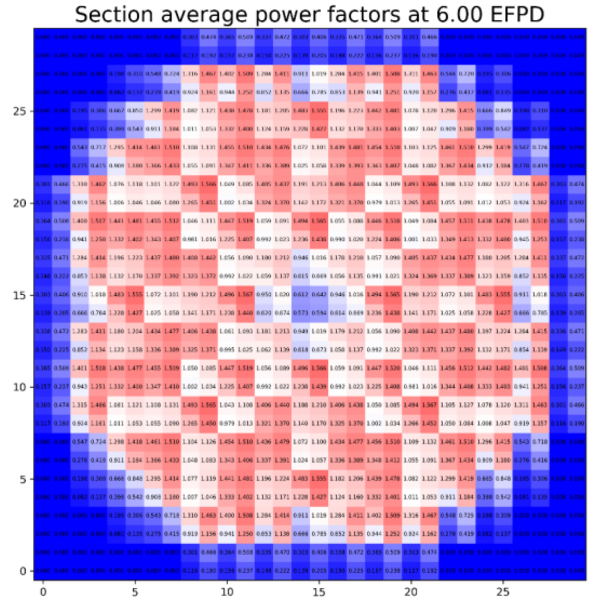
Description tends to “realistic” simulation based on 3D model

Possible issues:

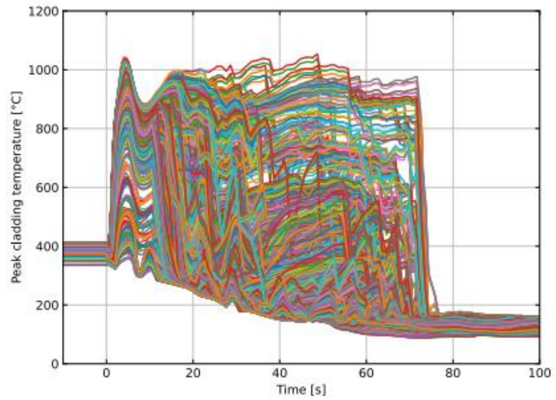
CPU cost

Validation of 3D core model

Use of representative rods instead of detailed 3D FAs modeling




ATHLET-CD 3D model with 1 channel per FA and 4 eq. rods per FA
source: M. Jobst (HZDR), D3.4 final report R2CA WP3.2

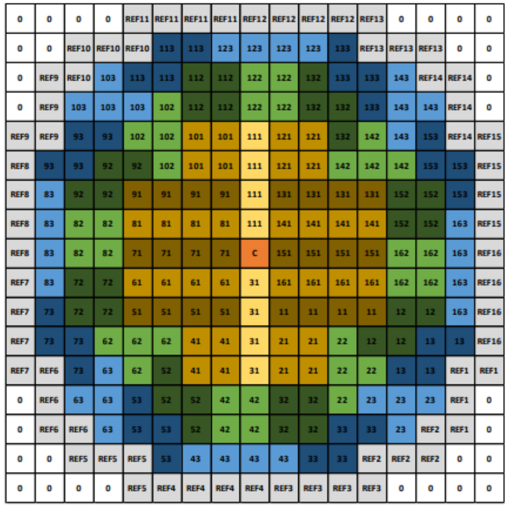



PCT obtained for 772 representative fuel rods with ATHLET-CD
source: M. Jobst (HZDR), D3.4 final report R2CA WP3.2

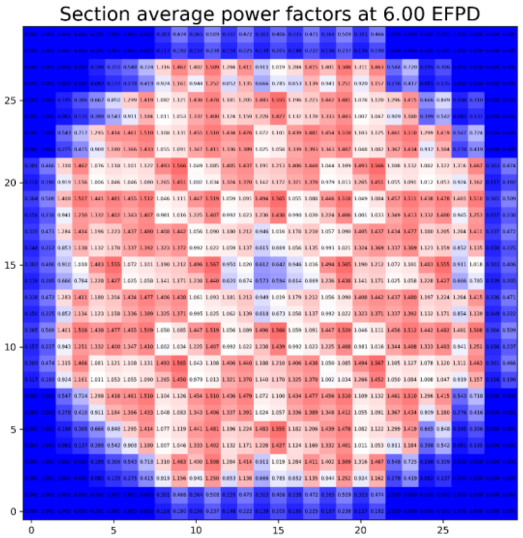
# 3D RPV & core modeling approach with ATHLET-CD

*source: M. Jobst (HZDR) D3.4 final report R2CA WP3.2*

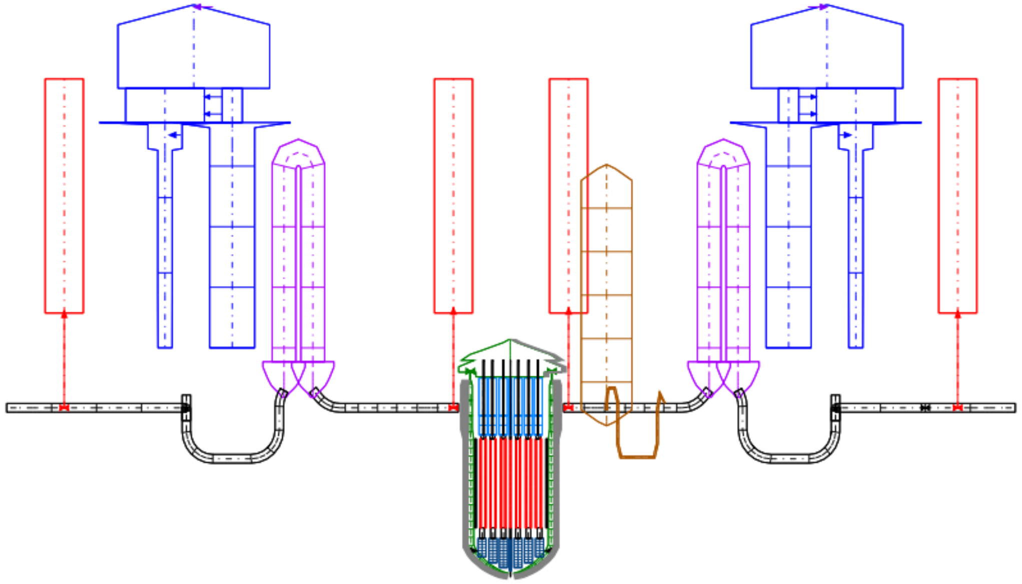




ATHLET-CD 3D connections of 193 FA channels to 49 lower/upper vessel plenums channels




ATHLET-CD 3D model with 1 channel per FA and 4 eq. rods per FA



ATHLET-CD circuits nodalization for generic Konvoi PWR

**HZDR proposes 3D approach for RBR evaluation with ATHLET-CD** (developed by GRS)

**3D RPV model** with **3D Core T/H using 1 channel/FA** with cross flows between neighboring channels

**Connected to 1D T/H in RCS (primary loops.SG...)**

**3D Full core model with 193 FAs** :

Each FA is partitioned in four groups of fuel rods represented by quartiles Q1,Q2,Q3,Q4 on rod power

Each fuel group is represented by an equivalent rod ➔ 4 equivalent rod / FA

# Multi-physics core modeling approach with DRACCAR

*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

**NPP initial state +**
**LOCA transient assumptions**
(initiator. normal/safety systems)

**Fuel rod initial state + Power dist.**
At least computed per FA
Irradiation ($T_{2D}$.RIP.BU.oxide...)
Neutronics (Power.DH.FPs)

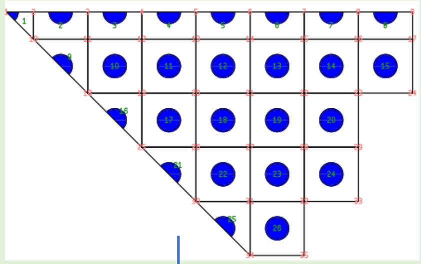
**FRAPCON**[PNNL/US NRC]
**VESTA**

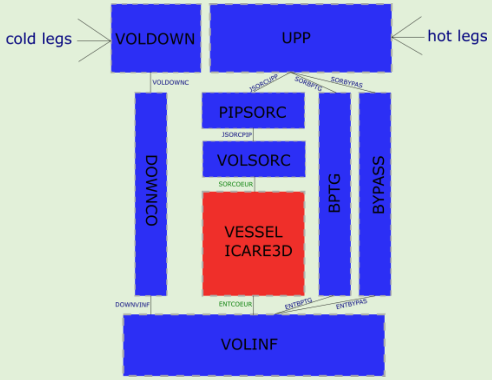
**Core data and initial state**
Core loading map. irradiation program. fuel spec. . plant operation conditions

**REQUIRED INPUT DATA**

## DRACCAR LOCA core T/H and T/M simulation

Various core model possible - minimum core model = **1/8$^{th}$ of the core**
Simulate at least 1 response per FA = 1 average equivalent rod for 1 FA
= 26 FAs using 2D meshed equivalent fuel rods
**3D Core T/H using 1 channel/FA + 1D T/H in RCS (primary loops.SG...)**



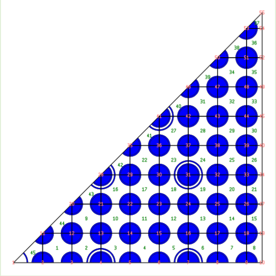



FA channel T/H BC

RPV DRACCAR model

## DRACCAR detailed FA T/H and T/M simulation

Study singular specificities of fuel rods in a FA (power.comp.location)
→PCT. strain and burst are evaluated for each rod of FA
1/8th of FA modelled using 3D T/H and T/M models
45 3D meshed rods with 39 fuel rods
3D FA T/H using sub-channels + T/H BC



**MIXED SCALE DRACCAR CORE MODELING APPROACH**

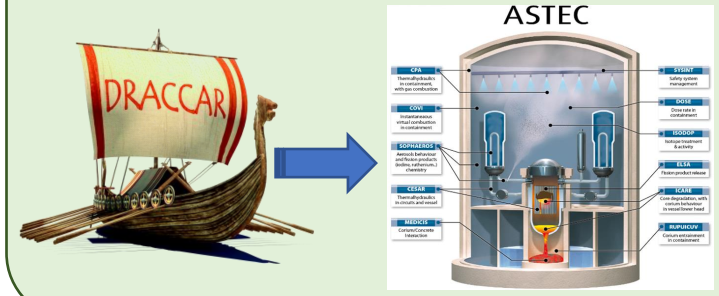
# Multi-physics approach to evaluate LOCA radiological consequences with DRACCAR & ASTEC (developed by IRSN in T2.5)

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## WP2.5 Development of chained application DRACCAR/ASTEC:

***FO**ster the **RE**actor **C**oolant **A**ccident and **S**ource **T**erm **S**imulations*

FORECASTS




- Update the ASTEC V2.2.0 modules embedded in DRACCAR
  - ELSA for fission gas release (FP released in RCS at burst)
  - ISODOP for isotopes decay and computation of decay heat

- Development of interface to chain sequentially DRACCAR results to ASTEC FP simulation

Step 1: DRACCAR stand-alone simulation to produce T/H conditions in RCS during accident and rod failure computation with associated FGR (from ELSA)

Step 2: Chain DRACCAR results to ASTEC input data by reading the DRACCAR results (T/H in all RCS and FP source at core junctions) and formatting as ASTEC inputs

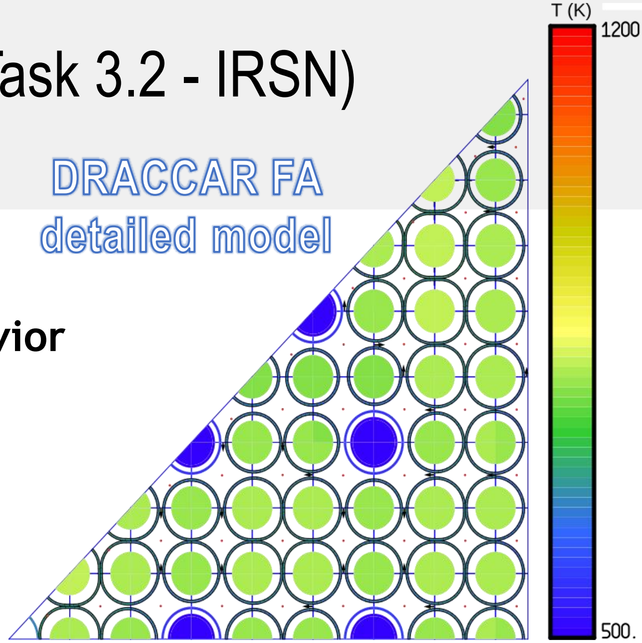
Step 3: Performing ASTEC ST stand-alone simulation using ISODOP.SOPHAEROS.CPA simulation to compute FPs transport and behavior

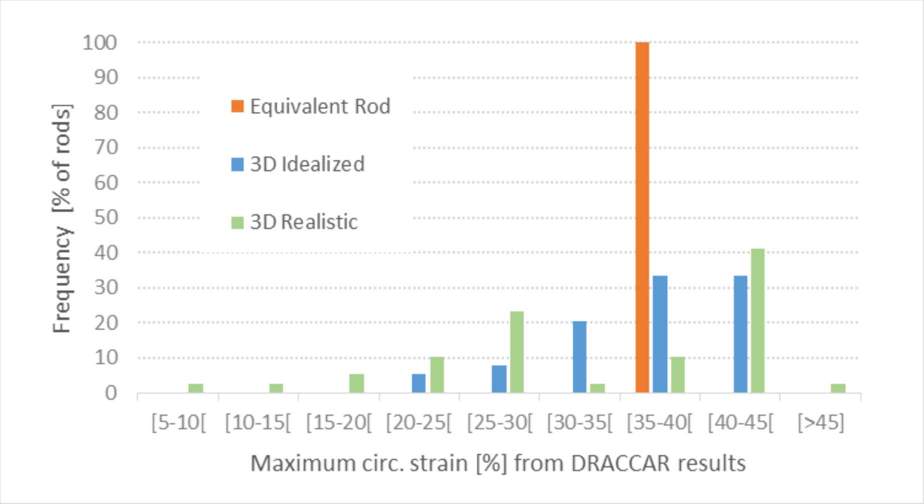
FORECASTS allows chained DRACCAR→ASTEC simulations for source term evaluation during LOCA using new core model and updated approach for rod failure prediction (WP3.2)

# Learnings from LOCA "like" case studies (Task 3.2 - IRSN)

## • Detailed fuel assembly model vs Equivalent rod model

- Equivalent rod model does not capture local details and non axisymmetric behavior
- DRACCAR FA 3D meshed model can provide focus on fuel rod behavior



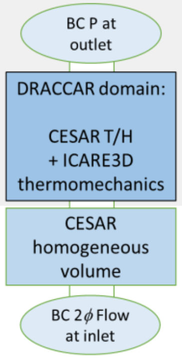

| Main DRACCAR results | Unit | 3D detailed & realistic modeling | Single equivalent rod |
|---|---|---|---|
| Maximum circumferential strain | % | 9 to 47 | 35 |
| Mean of max. circ. strain ± std deviation (over all modelled rods) | % | 34 ± 10.5 | |
| PCT | °C | 664 to 713 | 692 |
| Mean PCT± std deviation (over all modelled rods) | °C | 690 ± 13 | |

**Average PCT are well in agreement between detailed model and equivalent rod model but large deviation on strain is obtained with 3D model**

**3D FA meshing gather details (cold/hot spots) and non axisymmetric behavior which cannot be captured using equivalent rod model.**

**Methodology using equivalent rod model should still incorporate conservatism in order to compensate lack of modeling**

# Learnings from LOCA "like" case studies (Task 3.2 - IRSN)



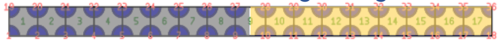

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **FA to FA interaction during LOCA – 1D DRACCAR case study using PWR configuration**
  - DRACCAR case: slice 1D of 17 subchannels = studying two half of neighboring FAs
    - Selected FA: Max difference of power factors ; PWR900 like data (FRAPCON,VESTA,...)

| Characteristics | Fuel Group 1 | Fuel Group 2 |
|---|---|---|
| Power factor | 0.98 | 1.21 |
| BU [GWd/t] | ~25 | ~50 |

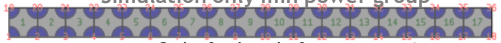
  - 3 simulations :

Simulation with 2 neighboring FAs



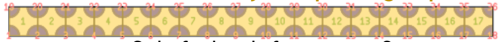
Fuel rods from group 1 Fuel rods from group 2

Simulation only min power group



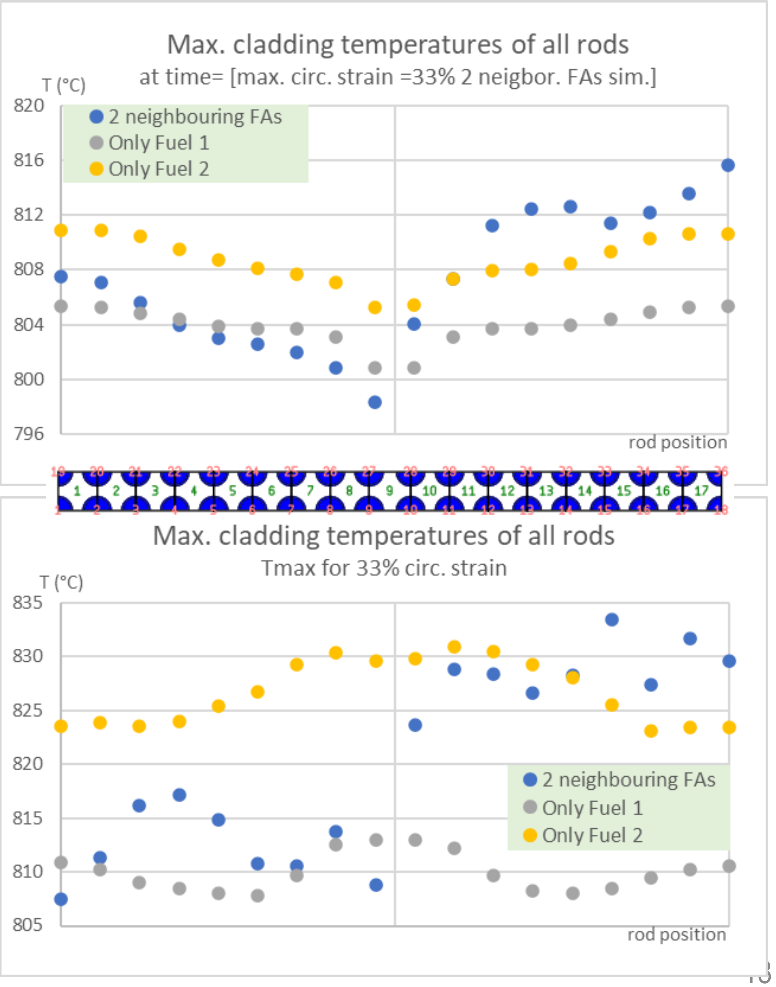
Only fuel rods from group 1

Simulation only max power group



Only fuel rods from group 2

  - Imposed BC for T/H flow condition at bottom representative of IBLOCA




**1D simulation case shows that the influence of hottest FA on colder FA remains limited**

**Flow distribution is influenced by blockage and induces temperature variations = only captured by 3D sub-channel meshing**

**FA to FA interactions seem mostly driven by T/H**

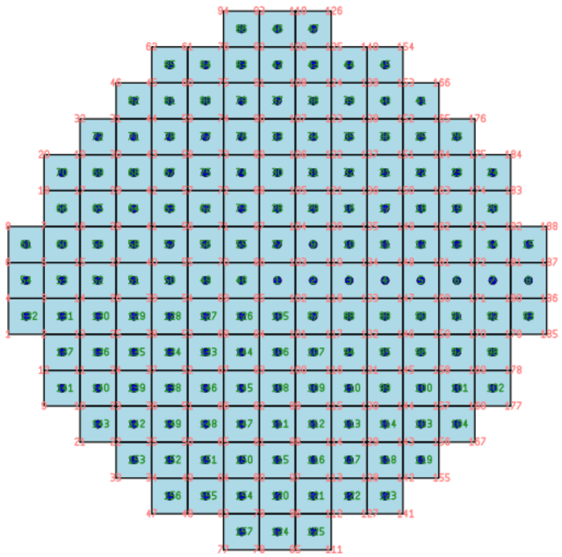
# DRACCAR new core model development



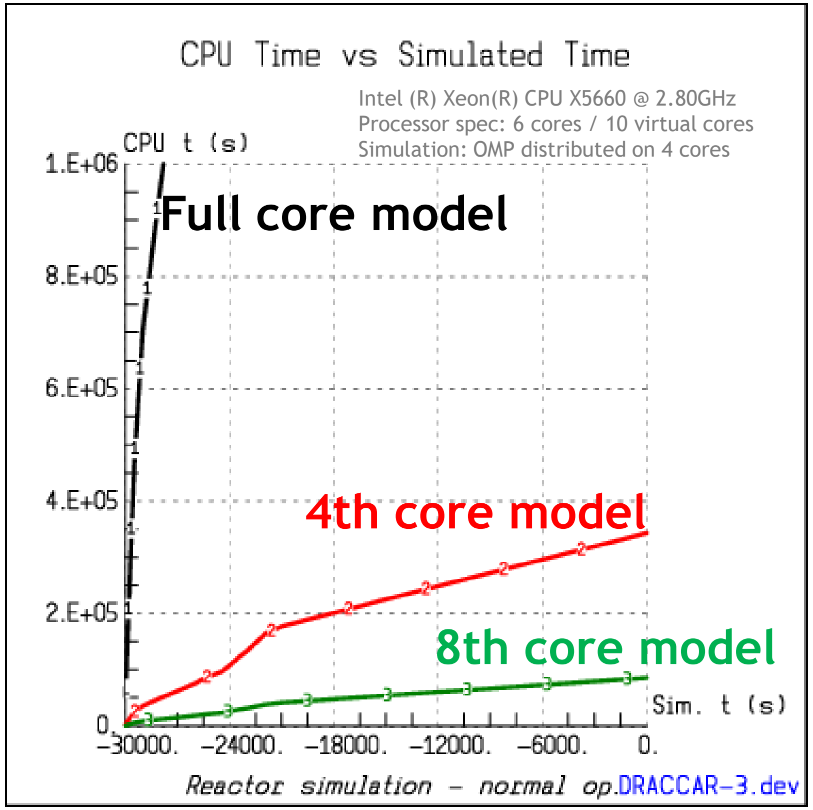
- Selecting a meshing for DRACCAR core model (IRSN)

LOCA analysis for burst risk assessment requires to cover a wide panel of core configurations and to manage source of uncertainties (input, model)
➔ number of simulations that can be run is influenced by model performance

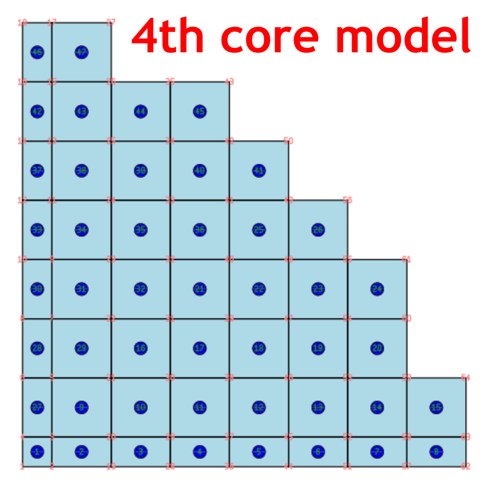
Choice of the meshing = compromise between accuracy and computational effort
Ex: DRACCAR Full core model is ~20 times more costly than 8th of core model

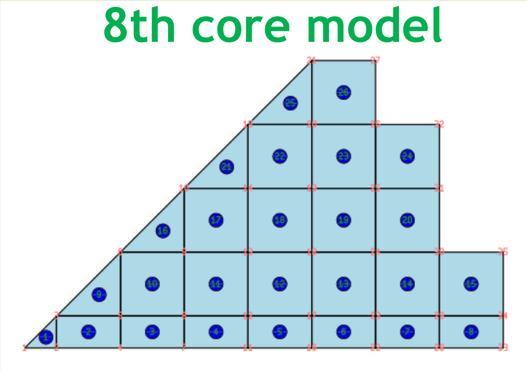


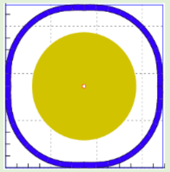
Full core model




Recommended DRACCAR core models



DRACCAR 2D eq. rod model updated in task 3.2

# 3D core models for RBR evaluation

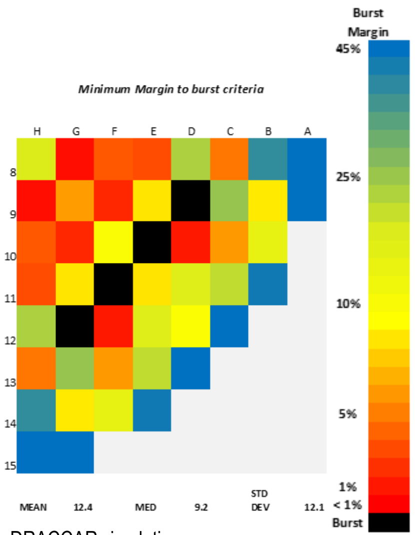
*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

## Demonstration in R2CA of 3D core approach

- T/H core model details
  - 2 phase-flow 3D model allowing cross-flow between channels = 1 T/H channel per fuel assembly interconnected in 3D core model
  - Demonstrative cases : HZDR (ATHLET-CD) = Full 3D RPV + 1D loops      IRSN (DRACCAR) = 3D core + 1D circuits (vessel plenum + loops)

- Interests of 3D descriptions for prediction capabilities

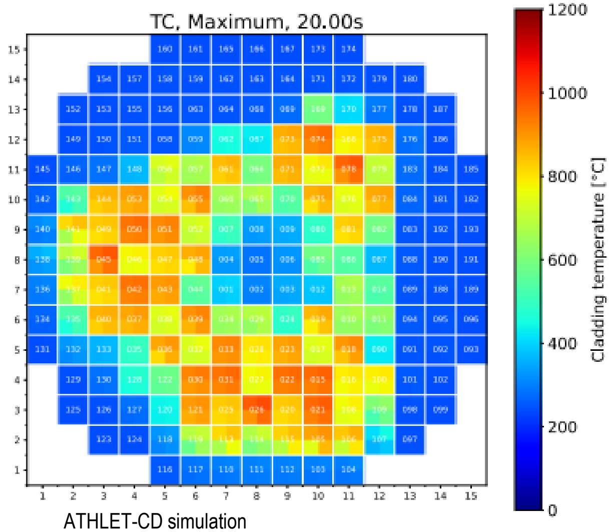
More representative than rings model as T/H conditions changes due to FA characteristics




DRACCAR simulation

source: S.Belon (IRSN), final report R2CA T2.5

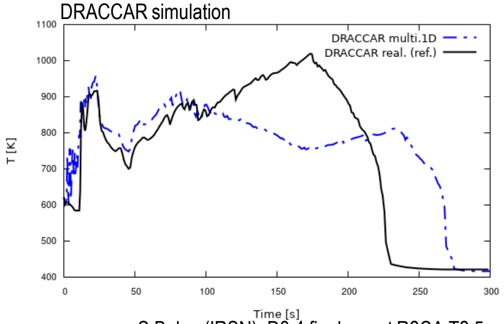
3D RPV model highlights non symmetric behavior of the core during LOCA



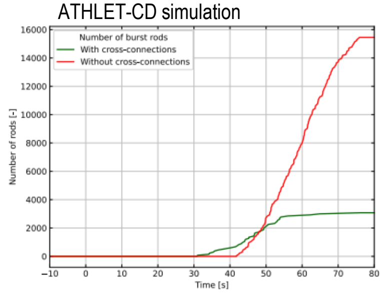

ATHLET-CD simulation

source: M. Jobst (HZDR), D3.4 final report R2CA WP3.2

Results obtained on 3D core model strongly differs from core rings model or multi-1D channels




source: S.Belon (IRSN), D3.4 final report R2CA T2.5




source: M. Jobst (HZDR), D3.4 final report R2CA WP3.2

**Use of Multiphysics 3D core or full RPV model are promising but need validation**

# DRACCAR reactor applications for R2CA

IRSN

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- RBR evaluation depends highly on burst criteria selection

**Specific burst criteria in the frame of the project were proposed for RBR evaluation which are different from criteria adapted to core coolability assessment**

Please refer to IRSN contribution from T. Taurines to D3.4 final report WP3 T3.2

$$T_{burst}(°C) = A - \frac{B\,\sigma_{e,\theta}}{1 + \frac{\min\left(\frac{dT}{dt}, 38\right)}{C} + D\,\sigma_{e,\theta}}$$

with A=1145.2°C, B=188.5 ksi$^{-1}$, C=16,5°C/s and D=0.335 ksi$^{-1}$

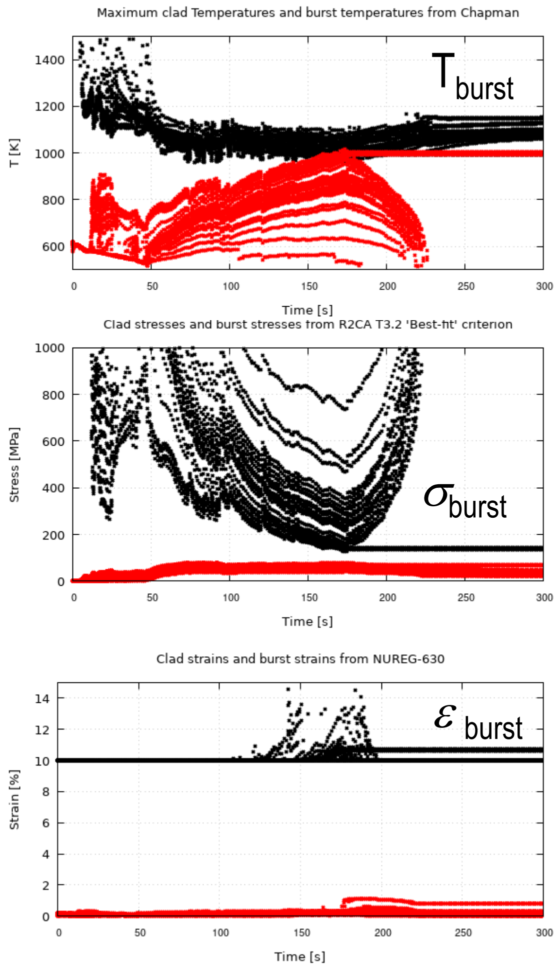
**Task 3.2 & 2.5 investigated the influence of burst criteria selection on RBR**

➔ Choice of burst criteria is of first order when evaluating RBR

➔ For Zr alloy, no criterion was found to fit both burst strain and burst timing

**Due to large scattering of burst results within experimental database regrouping data for Zr-alloy cladding and which are used to build criterion,**

➔ burst criterion correlations remain uncertain



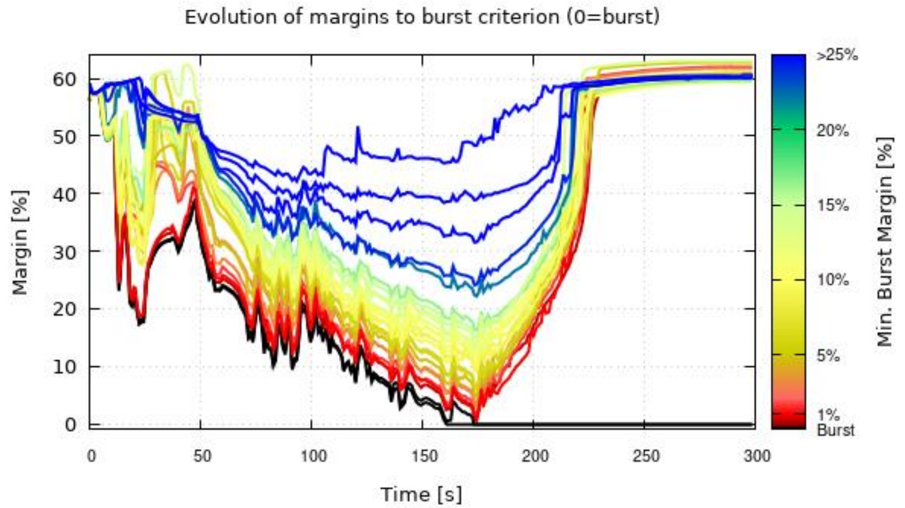

Burst criteria (black) and rod responses (red) to DBA transient evaluated with DRACCAR 8th of core model
Source: S. Belon (IRSN), final report R2CA WP2 T2.5

# DRACCAR reactor applications for R2CA



## • On the need to consider a single simulation with care

**A single simulation provides rod responses to LOCA transient and a value of RBR**



DRACCAR LOCA DBA simulation results
Source: S. Belon (IRSN), final report R2CA WP2 T2.5

For DBA scenario, DRACCAR reference simulation leads to predict a RBR of 10%

A single simulation does not account for input/model uncertainties and in particular of burst criterion

**What's the accuracy of this RBR prediction ?**

Whatever core model and burst criteria selected, **the uncertainties identification and propagation should be included within a RBR evaluation methodology**

Inspiration could be taken from BEPU approaches widely used for coolability assessment for LOCA

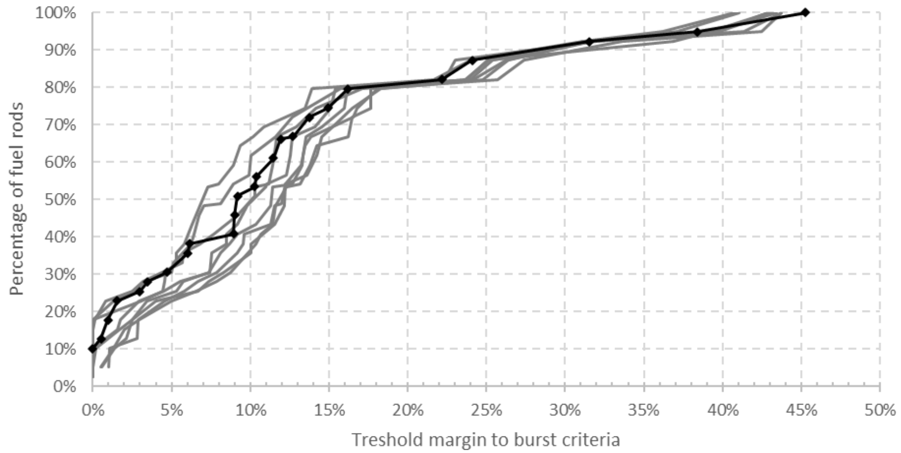


Illustration of the scattering of results from DRACCAR LOCA DBA simulations
Source: S. Belon (IRSN), final report R2CA WP2 T2.5

# Conclusion and prospects

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- In the frame of R2CA

  - Partners demonstrated several approaches to evaluate RBR with the goal to quantify RC
  - It can be summarized by two general approaches
    - Chaining system application (mainly T/H system code) to fuel performance code with transient capabilities
    - Using an integral code coupling thermalhydraulics to thermal mechanics description
  - The selection of burst criteria capable to predict with confidence the burst was underlined from work in WP3 T3.2 and highlighted by sensitivity of RBR assessment to criteria choice
  - Two partners developed specific 3D core applications (ATHLET-CD for HZDR and DRACCAR for IRSN) with integral code
    - Benefits = realistically represent core in comparison to ring model or coarse core model
      Better account for heterogeneities: core loading map, core channel responses to LOCA
    - Coupling of physics allow feedbacks of T/M on T/H (crossflow)
  - RBR evaluation methodology requires a specific management of uncertainty (identification, propagation) in order to provide a confidence level associated to results
  - Remaining challenges
    - No approach deals properly with FA behavior at sub-channel scale (rod-to-rod interaction, guide tubes)
    - No available criterion to predict with confidence both the burst strain and the burst timing
    - Modeling initial FP inventory associated to each rod or FA and evaluating FPs release in LOCA conditions
    - Calculation effort associated to 3D approach to manage uncertainties in RBR evaluation methodology

# Thank you for your attention!

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

# BACK – UP for questions

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

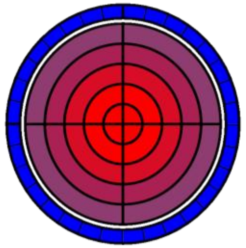
# New core modeling approach

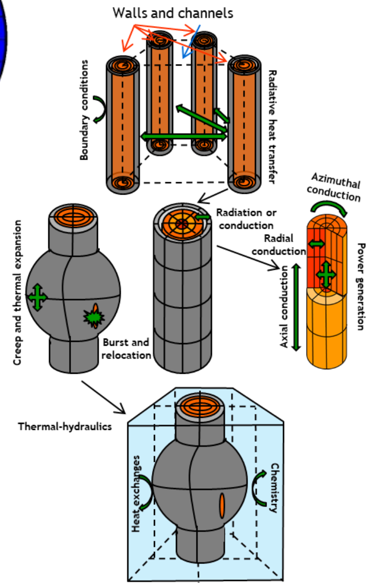
- Physical modeling available in DRACCAR code from IRSN FUEL+ platform for LOCA core simulation

### Heat exchanges and Power generation

- Heat exchange in fuel rod (3D conduction + radiation)
- Radiative exchanges between rods
- Wall to fluid convective exchanges ( 2-phase flow + reflooding model)
- Axial. radial power profile definitions in each fuel (user or FRAPCON)
- Decay heat (user or deduced from isotopes core average inventory)

Fuel meshing






### Cladding deformation and burst (detailed 3D rod model)

- Rod internal pressure calculation (uniform / gas transport / parametric law FGR)
- creep model at each axial level (based on Norton-like creep law + assumptions)
- Burst: several empirical criteria (stress. strain – local. circumferential …)
- Mechanical contact between rods or rod/grid
- Fuel relocation in balloon zone ( user parameters such as filling ratio )

### Cladding oxidation

- Oxidation of Zr by steam (parabolic laws – Arrhenius)
- Specific focus using coupled simulation with SHOWBIZ code from FUEL+ platform for oxygen diffusion

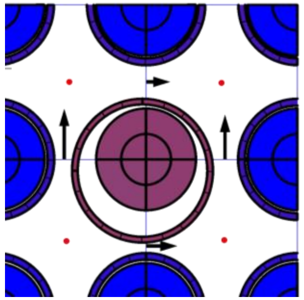
### Material properties computed via the IRSN MDB material database

- Standard wall properties (density. conductivity. emissivity. enthalpy…)
- Mechanical (creep and burst) and oxidation laws

### 3D two phase flow predicted by coupled T/H code: CESAR or CATHARE-3 CEA. EDF. FRAMATOME. IRSN

- Account for progressive blockage of channels due to ballooning and modification of wall to fluid heat exchange surface

Sub-channel meshing



# Learnings from LOCA "like" case studies

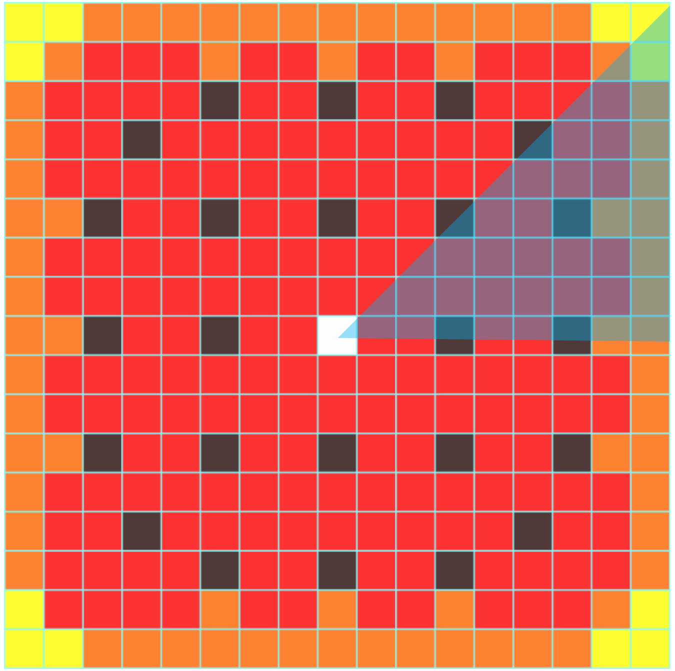
*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

- Selecting a meshing for DRACCAR core model

  - For the same CPU cost reasons, full detailed FA model (17x17 rods) as it requires 322 T/H channels (~12880 T/H meshes)

  - Recommand stand-alone DRACCAR 1/8th FA model with 3D meshed fuel rods
  - T/H from the core model can be used as boundary conditions for FA channels

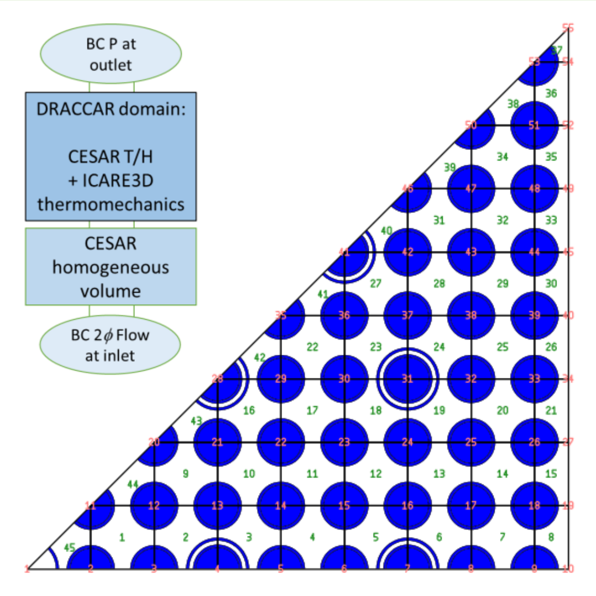
    ➔ Focus on specific fuel assembly or rod-to-rod interaction



- 1 instrumentation tube
- 24 guide tubes & control rods
- 12 low Pu enriched fuel rods
- 68 mid Pu enriched fuel rods
- 184 high Pu enriched fuel rods

Typical PWR 17x17 MOX configuration

## DRACCAR 3D meshed 1/8th FA model




1/8th of FA modeled using 3D T/H and T/M models

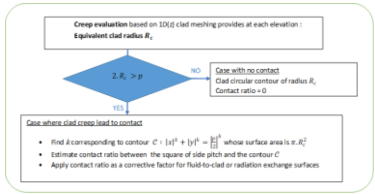
45 3D-meshed rods with 39 fuel rods

3D FA T/H using sub-channels + T/H BC

# Development of new core modeling approach

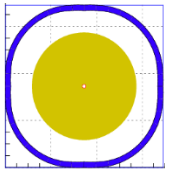


- Improving DRACCAR code from IRSN FUEL+ platform for LOCA core simulation



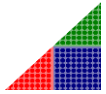

  - **Initial state of the rod before LOCA transient :**
    - Chained FRAPCON[PNNL / US NRC] to DRACCAR = transfer irradiation results as an input for DRACCAR
      Initialize PWR 900 reactor simulation gathering data for each FA (target for WP2.5) from VESTA

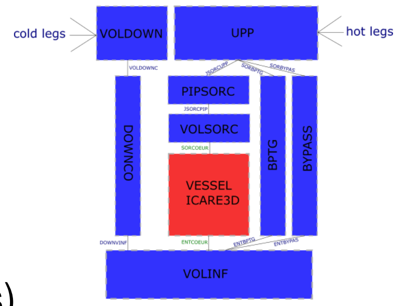
  - **Allow mixed application using detailed meshed and equivalent rods** (such as in ASTEC or TH codes)
    - Restrict equivalent rod deformation to the bundle pitch (in order to simulate contact with neighbors)
    - Manage the use of mixed meshing with equivalent rods



- Developing DRACCAR core and FA applications

  - **Single FA case simulations representative of PWR900 to study influence on rod responses**
    - Initial rod state (irradiation: RIP. BU. Pu conc.). distance to guided tubes. local rod power
    - Comparison of modeling: Single equivalent fuel rod model / 3D FA sub-channel model



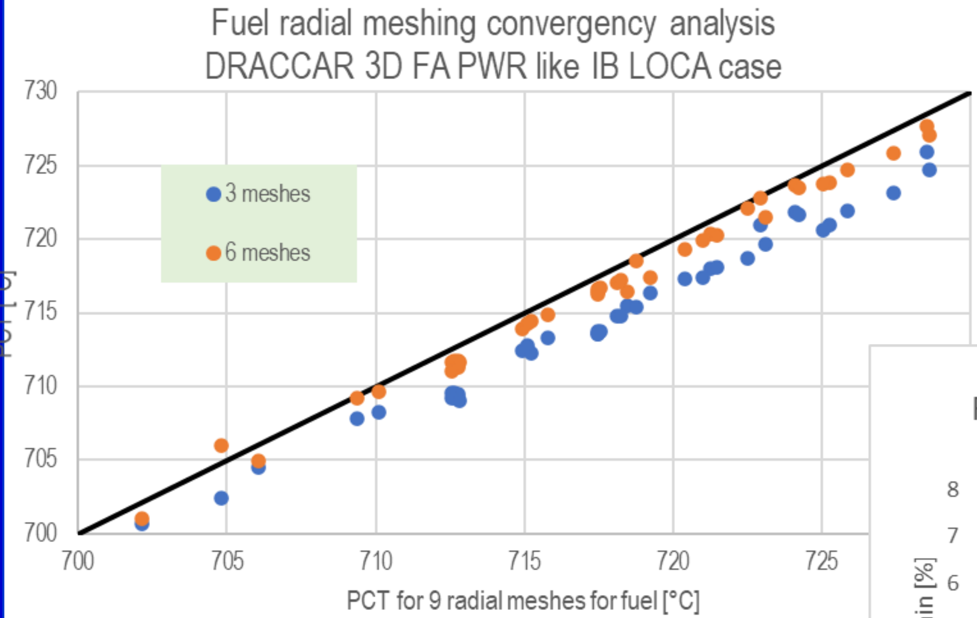


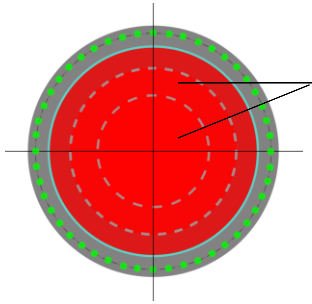

  - **Develop DRACCAR PWR900-like using 8th of core with equivalent rods** (such as in ASTEC or TH codes)
    - Develop PWR900 DRACCAR model based on ASTEC model for RCS and a new specific RPV modeling
    - Simulation with different core meshings (as a full 3D core detailed model is not reachable due to CPU time limitations)

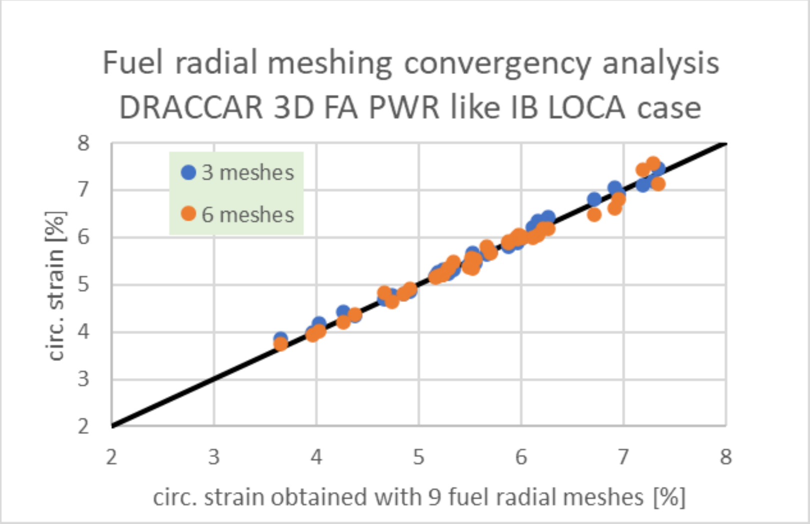
# Learnings from LOCA "like" case studies

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Impact of fuel radial meshing
  - Fuel radial discretization sensitivity analysis based on DRACCAR 3D FA model on PWR-like IBLOCA case



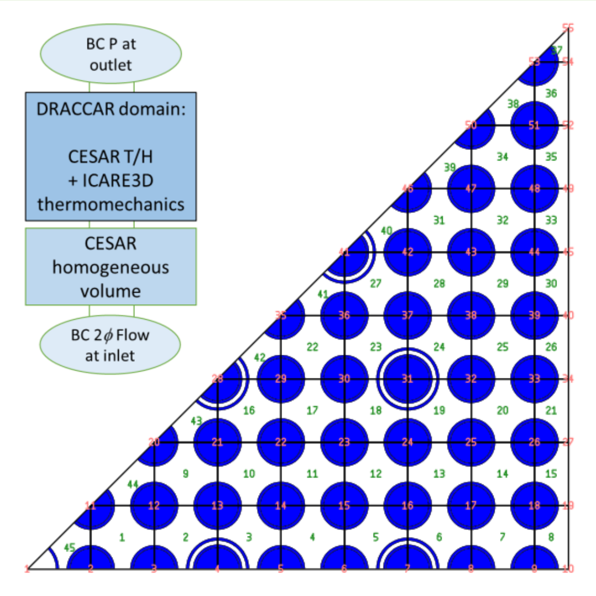




convergency on PCT
=> recom. 9 fuel radial meshes

Conclusion not so clear regarding circ. Strain (to pursue…)

## DRACCAR 3D meshed 1/8th FA model

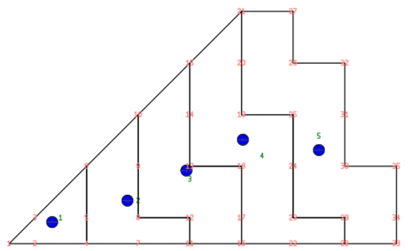


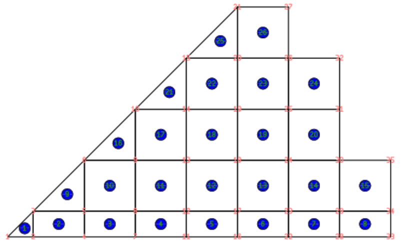

1/8th of FA modelled using 3D T/H and T/M models

45 3D-meshed rods with 39 fuel rods

3D FA T/H using sub-channels + T/H BC

# New core modeling approach


DRACCAR 5T/H core channels


DRACCAR 26T/H core channels

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## WP2.5 LOCA simulation vs WP2.3 LOCA simulation

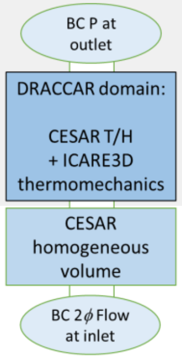
***FO**ster the **RE**actor **C**oolant **A**ccident and **S**ource **T**erm **S**imulations*

- Two demonstration cases: DBA / DEC-A already simulated using ASTEC V2 in frame of WP2.3
  - PWR900 5 core ring model ; User assumption initial fuel rod state
  - All ASTEC modules enabled with modeling of RCS and containment systems

- Main issue : How to compare WP2.3/WP2.5 simulations
  New core model approach implies modification of assumptions, core meshing, FA description and initialization from WP2.3→WP2.5

- IRSN WP2.5 simulations for WP2.3 comparison using ASTEC "like" core and fuel rod assumptions
  - ASTEC "like" core and fuel rod assumptions
  - DRACCAR uses ASTEC-like core channels = 5 T/H channels core model and 5 eq. fuel rods
  - DRACCAR new core model (1 T/H channel per FA) = 26 core T/H channels and 26 eq. fuel rods

# Learnings from LOCA "like" case studies (Task 3.2 - IRSN)





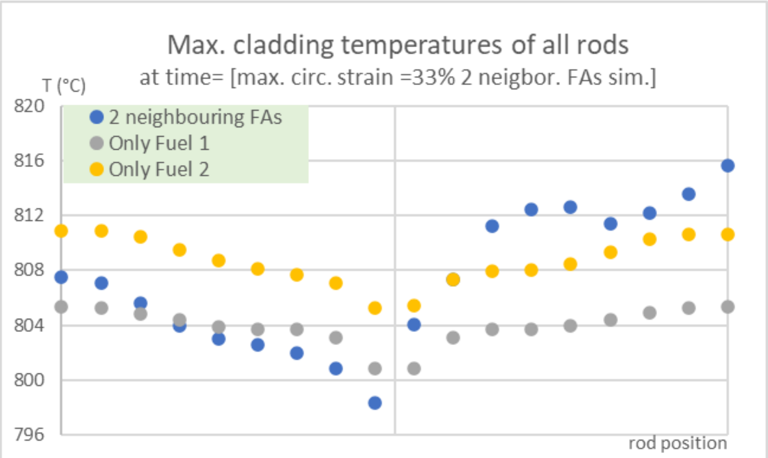

## • FA to FA interaction during LOCA – 1D DRACCAR case study using PWR configuration

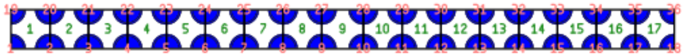
- DRACCAR case: slice 1D of 17 subchannels = studying two half of neighboring FAs
  - Selected FA: Max difference of power factors ; PWR900 like data (FRAPCON,VESTA,…)

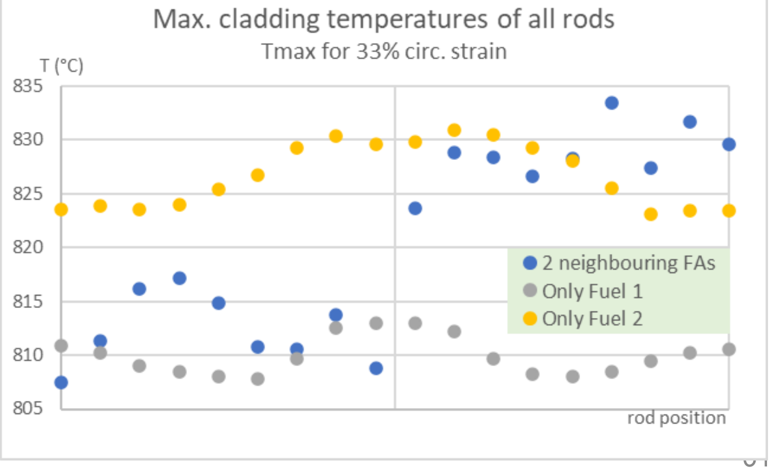
| Characteristics | Fuel Group 1 | Fuel Group 2 |
|---|---|---|
| Power factor | 0.98 | 1.21 |
| BU [GWd/t] | ~25 | ~50 |

  - 3 simulations :


  - Imposed BC for T/H flow condition at bottom representative of IBLOCA



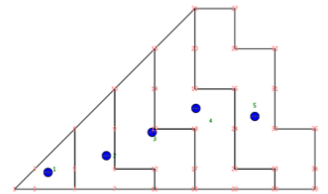



**1D simulation case shows that the influence of hottest FA on colder FA remains limited**

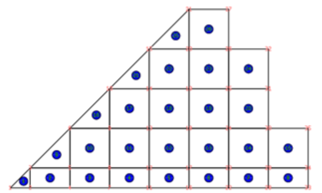
**Flow distribution is influenced by blockage and induces temperature variations = only captured by 3D sub-channel meshing**

**FA to FA interactions seem mostly driven by T/H**

# New core modeling approach



DRACCAR 5T/H core channels



DRACCAR 26T/H core channels

## WP2.5 LOCA simulation vs WP2.3 LOCA simulation

***FO**ster the **RE**actor **C**oolant **A**ccident and **S**ource **T**erm **S**imulations*

*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

- **Reminder on DBA scenario:**
  - 16.3'' IBLOCA in cold leg of loop 2
  - 104% of nominal power
  - LOOP at SCRAM with supply by emergency diesel generators
  - Safety injection starts with 33s delay and Loss of 1 HPIS and 1LPIS injection pumps
- **ASTEC V2.1 vs DRACCAR 5 T/H core channels:**
  - Small differences on RCS steady state
  - Main differences on pressure head loss coefficient in core by-pass as RPV modeling is different
- **DRACCAR 5 T/H vs 26 T/H core channels:**
  - No significant changes in RCS steady state associated to core model changes

| RCS parameters | Relative Difference % | |
|---|---|---|
| | **DRACCAR 5channels - ASTEC** | **DRACCAR 26 - 5 channels** |
| Core power | -0.037 | 0.000 |
| Primary mass inventory | 0.203 | **-0.005** |
| Secondary mass inventory | -0.025 | 0.000 |
| Primary pressure | -0.003 | 0.000 |
| Cold leg temperature | -0.023 | 0.000 |
| Hot leg temperature | -0.020 | 0.000 |
| Pressurizer heaters power | 0.099 | 0.000 |
| Max diff on SG pressure | 1.364 | 0.000 |
| Max diff on SG main FWS flowrate | -0.064 | 0.000 |
| Max SG recirculation rate | 0.570 | 0.000 |
| Downcomer flowrate | 0* | 0* |
| Total primary flowrate (from 3 loops) | 0* | 0* |
| Core external bypass | 0* | 0* |
| Core bypass within guide tubes | 0* | 0* |
| Head loss coefficient in bypass | **-56.8** | 0.000 |
| Head loss coefficient in core bypass within guide tubes | **-34.1** | **0.059** |
| Head loss coefficient in by-pass to upper head | **-76.4** | 0.000 |
| Max diff primary loop flowrate | 0.133 | 0.000 |

# Evaluating LOCA radiological consequences

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## WP2.5 Development of chained application DRACCAR/ASTEC: FORECASTS

***FO**ster the **RE**actor **C**oolant **A**ccident and **S**ource **T**erm **S**imulations*

- Update the ASTEC V2.2.0 modules embedded in DRACCAR software
  - ELSA for fission gas release (FP released in RCS at burst)
  - ISODOP for isotopes decay and computation of decay heat
-

# New core modeling approach

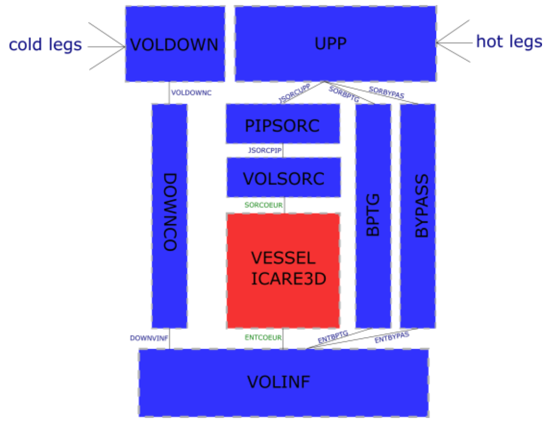
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## WP2.5 LOCA simulation vs WP2.3 LOCA simulation

- Comparison of results between ASTEC WP2.3 and DRACCAR WP2.5 “ASTEC-like” is on-going

  - ASTEC V2.1 vs DRACCAR 5 T/H core channels comparison is on-going to identify source of discrepancies

Primary parameters in transient are not consistent
(e.g. the break mass flowrate extraction)

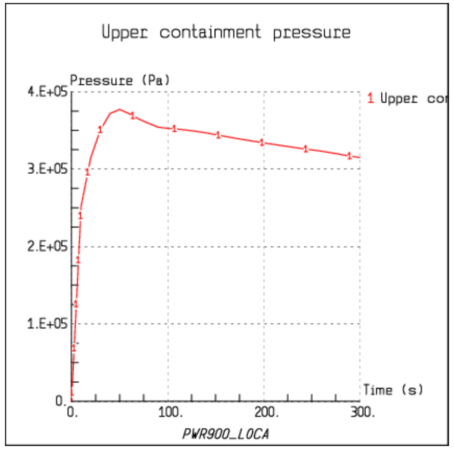



DRACCAR

### Possible origin of discrepancies :

Modeling of RPV is different in ASTEC and DRACCAR model
More safety injection flowrate is driven to the break in DRACCAR

Other possible differences linked to containment pressure
user imposed in DRACCAR simulation to 1 bar
Calculated by CPA module in ASTEC V2.1




ASTEC

# New core modeling approach

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

## WP2.5 Updated reactor simulation using DRACCAR/ASTEC application = FORECASTS

***FO**ster the **RE**actor **C**oolant **A**ccident and **S**ource **T**erm **S**imulations*

- **Two demonstration cases: DBA / DEC-A already calculated using ASTEC V2 in frame of WP2.3**
  - PWR900 5 core ring model ; User assumption initial fuel rod state
  - All ASTEC modules enabled with modeling of RCS and containment systems

- **Target : Highlight new core model approach and FORECASTS chain using "realistic" assumptions. FA description and initialization on PWR900 "like" LOCA**

- IRSN WP2.5 simulations using new FORECASTS approach and "realistic" assumptions
  - DRACCAR new core model (1 T/H channel per FA) = 26 equivalent fuel rods = 1 / FA
  - VESTA results provide Power. FPs and BU distribution among FA
  - FRAPCON$^{PNNL/US\ NRC}$ results provide rod state for each FA (geometry. RIP. T field)
  - ISODOP average core FP isotopes inventory evaluate DH and FP inventory evolution
    Average values are distributed in each FA according to FP distribution factors