REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

WP:	**WP 6 – Knowledge dissemination**
Task:	Session 3 – Evaluation of failed fuel rod number: major improvements in clad creep/burst models, core modelling & calculation approaches
Speaker:	Sébastien Belon
Affiliation:	IRSN
Event:	R2CA Final Open Workshop
When:	November 30th 2023
Where:	Fontenay-aux-Roses (France)

Commission européenne

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

Why developing new core model in the frame of R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Status of methodologies associated to radiological consequences evaluation for LOCA

- **Former methodologies often various fixed amount of burst rods**
  EUR 19841 EN report: proposal for failed fuel rod fraction was to apply
  33% failed fuel rods for reactor designs with safety injection in the cold leg
  10% failed fuel rods for case with injection in both cold and hot legs

- **Current Methodology review – R2CA D2.1 report**

  - **use of deterministic conservative assumption, methodologies are mainly based on decoupled approaches**

  - **various assumption on ratio of failed rods**
    33% (IRSN), 55% (LEI) and 100% for other partners (SSTC NRS, AERB, Tractebel, BelV)

  - **agreement on the need to consider several types of FA based on irradiation and core management.**

Country	Failed rod rate for radiological assessment
Belgium	100%
Czech Republic	100%
Finland	10%
France	EPR 10% (proposed) Other PWRs 33%
Germany	SB LOCA 1% LB LOCA 10%
Hungary	SB and MB LOCA 1% (changing) LB LOCA 100% (changing)
Japan	100%
Republic of Korea	No explicit limit
Slovakia	No explicit limit
Spain	100% for American design NPPs 10% for the German design NPP
Sweden	No explicit limit
Switzerland	No explicit limit
U.K.	100%
U.S.A.	100%

Source: Report on FFRD NEA/CSNI/R(2016)16, 2016

Assumption on the Ratio of failed rods is mostly used by RC evaluation methodologies for LOCA

Approach to evaluate rod burst ratio (RBR)

- is needed to **measure gain** brought by accident management procedure, plant or fuel modification/innovation
- could be needed **to verify assumption on RBR assumed in** RC methodology

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 200 FAs in the core
~40000 to 60000 fuel rods

Multi-physics simulation + 3D effects
Thermalhydraulics ←→ Thermalmechanics

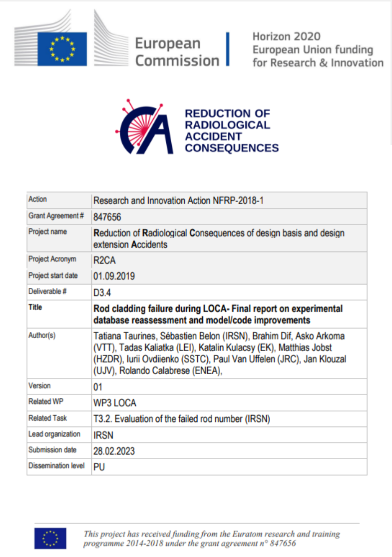
- **Burst risk during LOCA is influenced by many parameters**
  - **Plant design: RCS, standard and safety systems, …**
  - **Core and fuel design: fuel type and materials (IFBA, PuOx), core management and loading map,...**
  - **Fuel rod Initial state: power, irradiation history, burn-up (RIP, FG, conductivity,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

Rod cladding failure during LOCA within R2CA

- Some challenges associated to failed rod number prediction during LOCA investigated in the frame of R2CA project

- **Challenges related to burst prediction :**
  - **Dedicated models are needed to better evaluate the number of failed fuel rods**

    ➔ **Reassessment of experimental data** was realized to **propose new model** (to predict burst timing)
    ➔ Comparison of burst criteria and creep models were compared on validation and reactor cases


European Commission | Horizon 2020 European Union funding for Research & Innovation

REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

Action	Research and Innovation Action NFRP-2018-1
Grant Agreement #	847656
Project name	**R**eduction of **R**adiological **C**onsequences of design basis and design extension **A**ccidents
Project Acronym	R2CA
Project start date	01.09.2019
Deliverable #	D3.4
Title	**Rod cladding failure during LOCA- Final report on experimental database reassessment and model/code improvements**
Author(s)	Tatiana Taurines, Sébastien Belon (IRSN), Brahim Dif, Asko Arkoma (VTT), Tadas Kaliatka (LEI), Katalin Kulacsy (EK), Matthias Jobst (HZDR), Iurii Ovdiienko (SSTC), Paul Van Uffelen (JRC), Jan Klouzal (UJV), Rolando Calabrese (ENEA),
Version	01
Related WP	WP3 LOCA
Related Task	T3.2. Evaluation of the failed rod number (IRSN)
Lead organization	IRSN
Submission date	28.02.2023
Dissemination level	PU

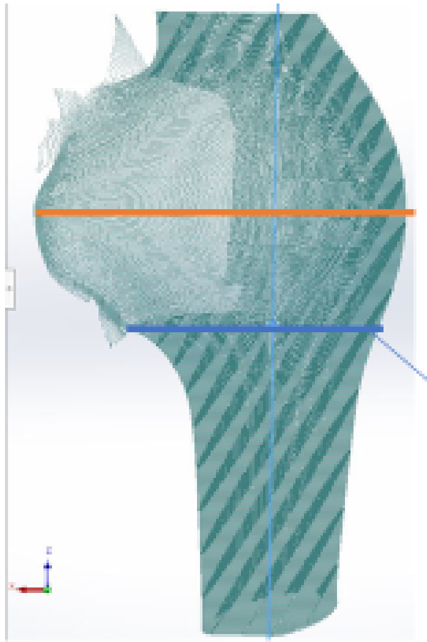
This project has received funding from the Euratom research and training programme 2014-2018 under the grant agreement n° 847656

Reassessment of experimental data for burst and creep

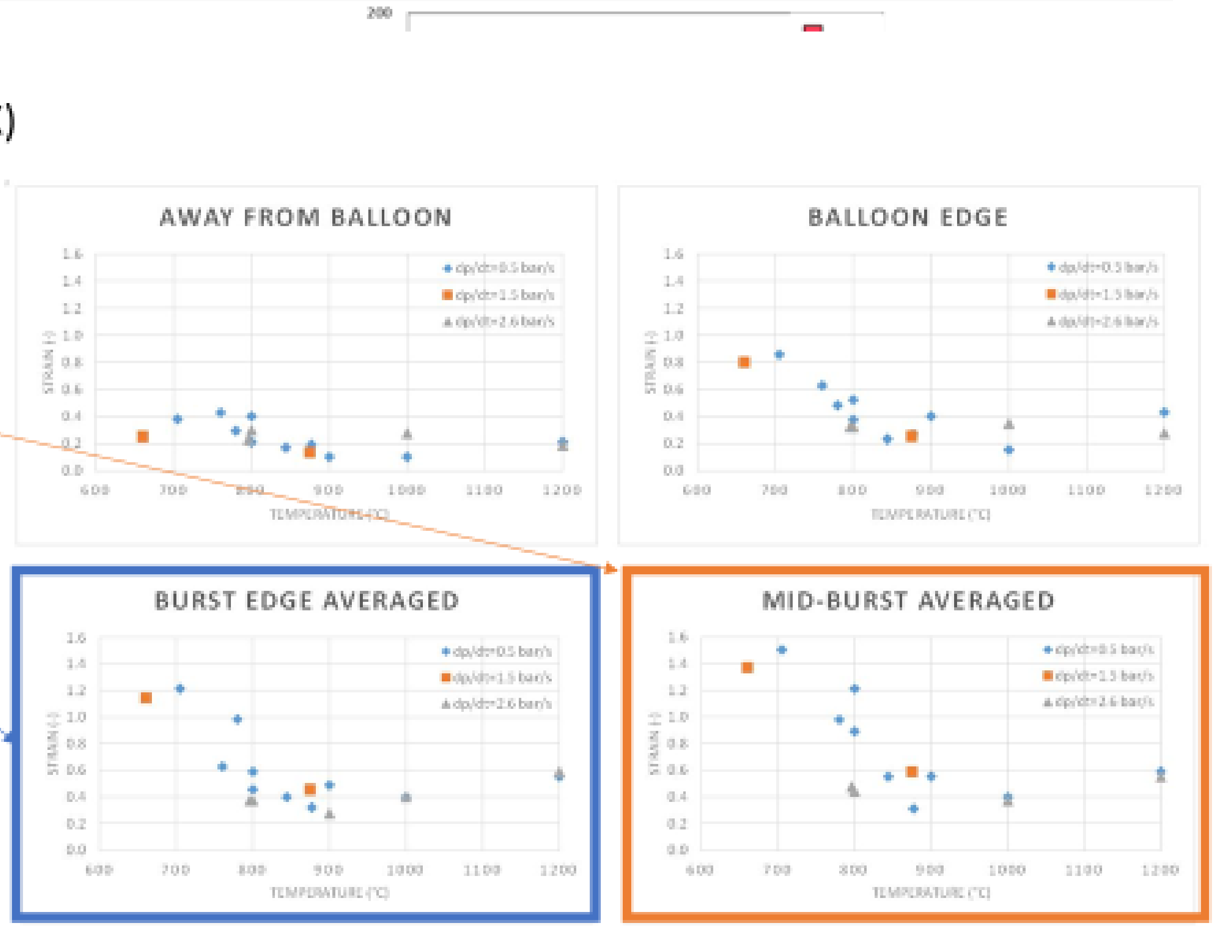
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Reassessment of experimental data for burst prediction

  - **IRSN/EK/VTT:**
  - Experimental data reassessed (EK)



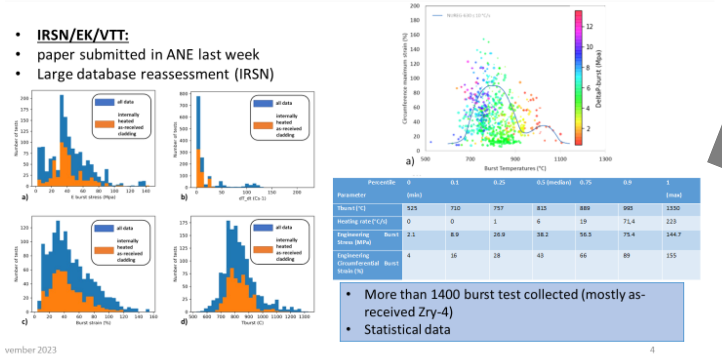
3D scanning by computer tomography



Reassessment of experimental data for burst and creep

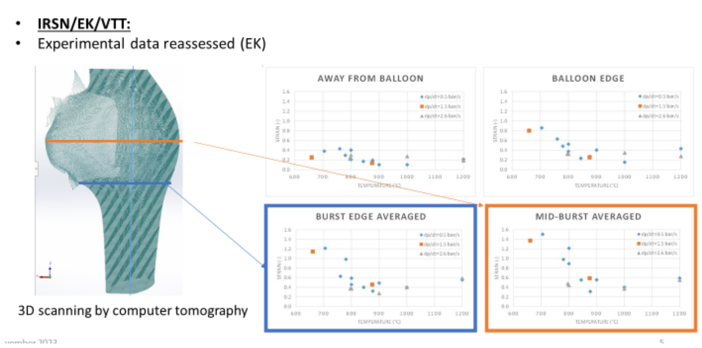
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Reassessment of experimental data for burst prediction & burst criteria development

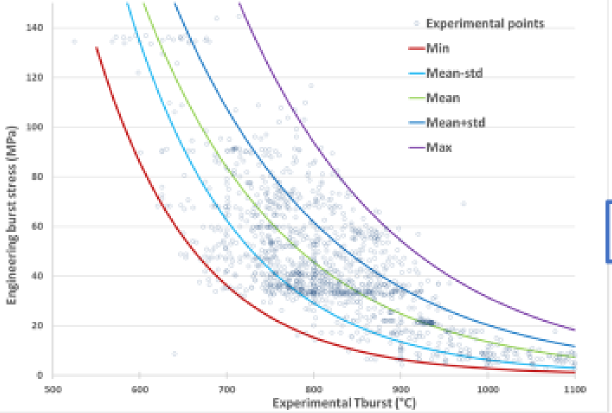


Percentile / Parameter	0 (min)	0.1	0.25	0.5 (median)	0.75	0.9	1 (max)
Tburst (°C)	525	710	757	815	889	993	1330
Heating rate (°C/s)	0	0	1	6	19	71,4	223
Engineering Burst Stress (MPa)	2.1	8.9	26.9	38.2	56.5	75.4	144.7
Engineering Circumferential Burst Strain (%)	4	16	28	43	66	89	155

- More than 1400 burst test collected (mostly as-received Zry-4)
- Statistical data



- **IRSN/EK:**
- Burst criteria proposal



Engineering burst stress versus experimental burst temperature and exponential models for statistical parameters

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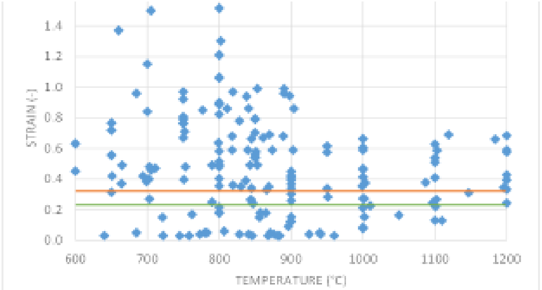
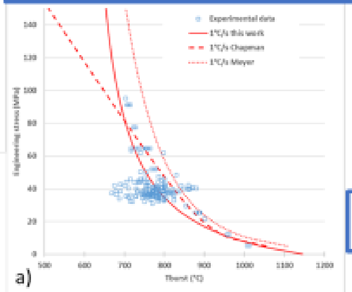


Strain versus burst temperature : average mean-value 35%, proposed conservative limit 21%



Burst temperature versus engineering stress

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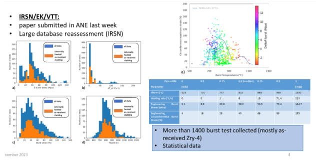
Several criteria proposed for burst prediction
(burst true & engineering stresses, burst temperature, burst strain)

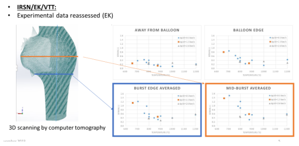
Not suitable for core coolability assessment

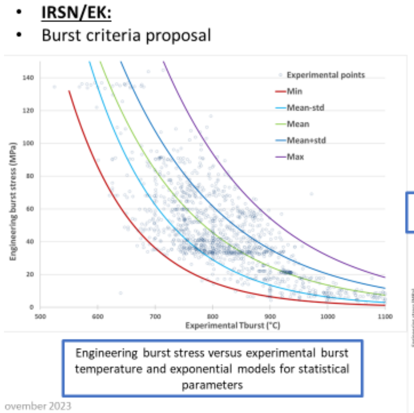
Reassessment of experimental data for burst and creep

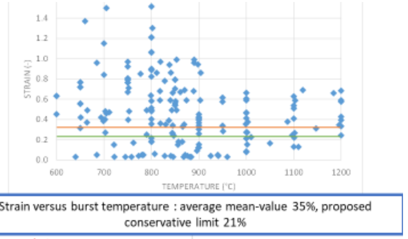
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

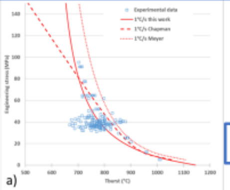
- **Reassessment of experimental data for burst prediction & burst criteria development**

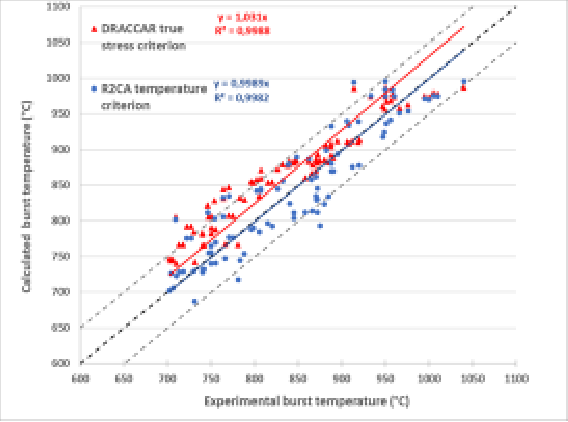




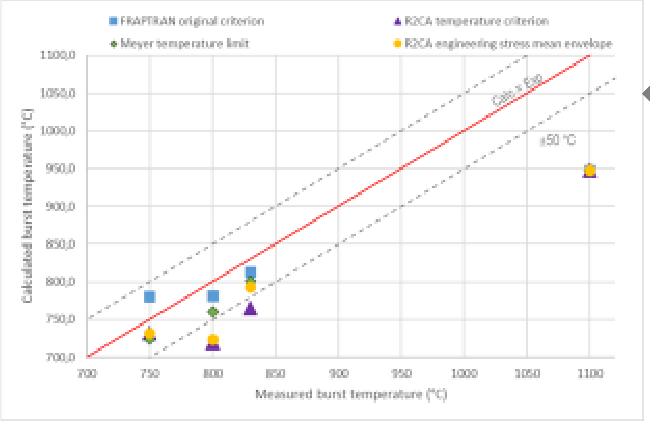








Calculated burst temperature versus experimental temperature on EDGAR test on Zry-4 with DRACCAR true stress criterion and R2CA temperature criterion and linear fitting (y=ax). Gray dashed lines correspond to ±10%



Calculated versus experimental burst temperature for the simulated validation cases. Dashed lines correspond to ±50°C from the bisector line.

VTT, IRSN:
Implementation of the criteria in codes (FRAPTRAN, DRACCAR)

Comparison of response obtained on validation cases

DRACCAR reactor applications for R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- New burst criteria were tested in reactor demonstrative LOCA cases

ENEA and IRSN compared burst true stress criteria envelopes proposed in R2CA and burst temperature on DBA and DEC-A scenario demonstrative case

Main burst criterion	Max. clad hoop strain (%)	Number of failed fuel rods (% of the total)	Time of first cladding failure (min)
True stress BE-exponential	40	66.88 (*)	35.86
True stress Mean	40	66.88 (*)	35.86
True stress Min	40	**71.97**	33.93
True stress Max	40	66.88 (*)	35.86
R2CA Temperature	40	**66.88**	34.64

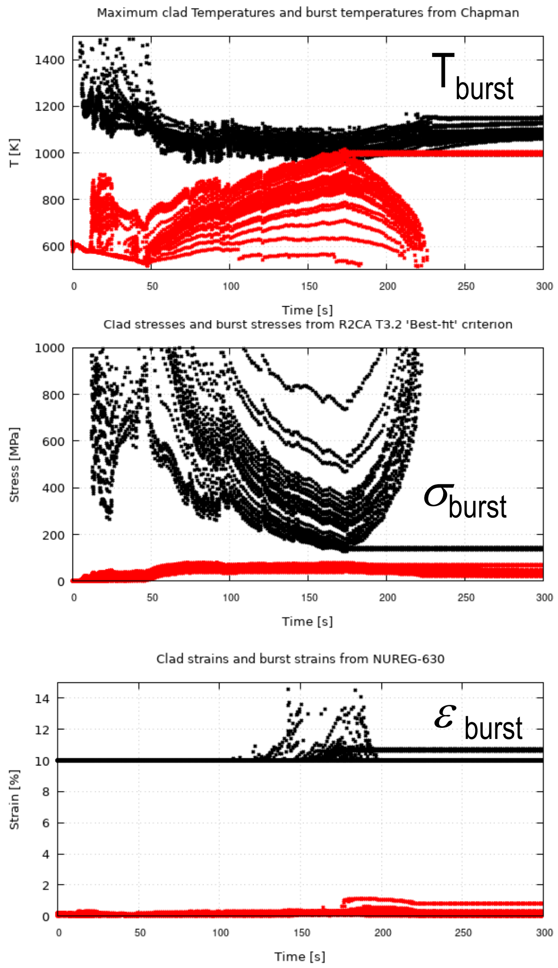
(*) Failure triggered by the fulfilment of maximum allowed hoop strain.

Comparison of burst criteria with ASTEC on DEC-A demonstrative case
Source: S. Ederli (IRSN), Individual final report R2CA WP2 T2.5

➔ **True stress min envelope and burst temperature seems more penalizing than other criteria including classical one (NUREG0630)**

➔ **Choice of burst criteria is of first order when evaluating RBR and uncertainty associated to these criteria remains huge**

➔ **Recommendation is to test a large panel of burst criteria for RBR evaluation**



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

Reassessment of experimental data for burst and creep

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

• Reassessment of experimental data for burst prediction

- **<u>ENEA and JRC</u> : new M5^{TM} models for TRANSURANUS**

  - ☑ Crystallographic phase transition model
  - ☑ Creep model
  - ☑ Papers presented at NENE2021 and NENE2022*

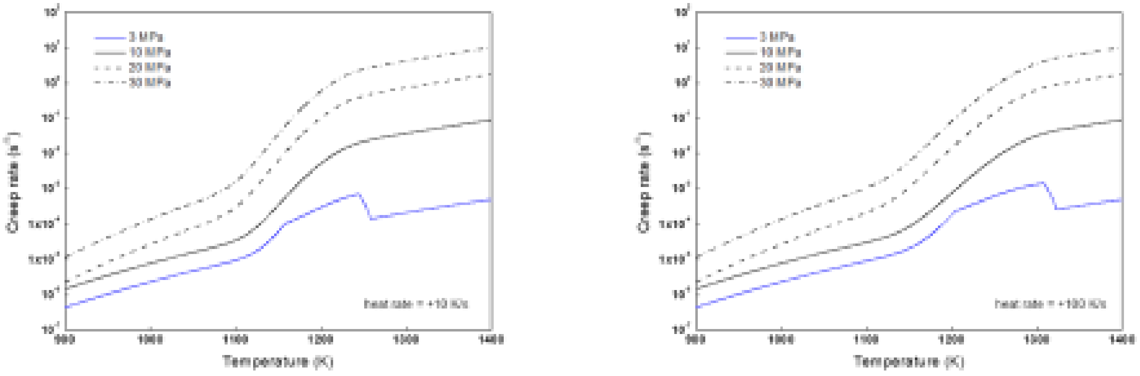
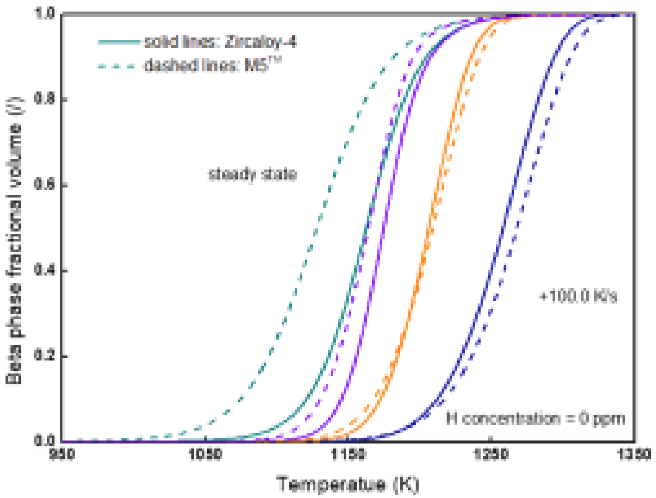


Figure 4: Creep rate of M5™ as a function of temperature and heat rate: +10 K/s (left) and +100 K/s (right)



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Review of M5™ Cladding Models Relevant for LOCA Simulation with the TRANSURANUS Code, R. Calabrese et al. NENE 2021
Crystallographic phase transition of zirconium alloys: new models for the TRANSURANUS code, , R. Calabrese, NENE 2022

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Reassessment of experimental data for burst and creep

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- ## Main achievements regarding burst and creep models

- New burst criteria were proposed for Radiological Consequences evaluation
- These criteria were implemented in simulation tool (ASTEC, DRACCAR, FRAPTRAN,…)
- New M5 thermomechanical models were implemented in TRANSURANUS

- ## Status and further needs

- Classical and newly proposed criteria cannot predict with accuracy burst timing and burst strain.
- Due to experimental data scattering, the uncertainty associated to burst cirterion remains high.

➔ Need of data in more prototypic conditions (internal heating, O/H content and irradiated fuel rods, influence of impaired gas communication)

➔ New material data and models are needed (ATF)

Rod cladding failure during LOCA within R2CA

European Commission | Horizon 2020 European Union funding for Research & Innovation

REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

Action	Research and Innovation Action NFRP-2018-1
Grant Agreement #	847656
Project name	Reduction of Radiological Consequences of design basis and design extension Accidents
Project Acronym	R2CA
Project start date	01.09.2019
Deliverable #	D3.4
Title	**Rod cladding failure during LOCA- Final report on experimental database reassessment and model/code improvements**
Author(s)	Tatiana Taurines, Sébastien Belon (IRSN), Brahim Dif, Asko Arkoma (VTT), Tadas Kaliatka (LEI), Katalin Kulacsy (EK), Matthias Jobst (HZDR), Iurii Ovdiienko (SSTC), Paul Van Uffelen (JRC), Jan Klouzal (UJV), Rolando Calabrese (ENEA),
Version	01
Related WP	WP3 LOCA
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Lead organization	IRSN
Submission date	28.02.2023
Dissemination level	PU

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REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **Some challenges associated to failed rod number prediction during LOCA investigated in the frame of R2CA project**

- **Challenges related to burst prediction :**
  - **Dedicated models are needed to better evaluate the number of failed fuel rods**
    - ➔ **Reassessment of experimental data** was realized to **propose new model** (to predict burst timing)
    - ➔ Comparison of burst criteria and creep models were compared on validation and reactor cases
  - **LOCA simulation with full core described pin by pin at subchannel scale coupled to 3D thermalhydraulics is not achievable** due to computational-time cost
    - ➔ **New approaches were investigated with integral tools** (ASTEC, ATHLET-CD and DRACCAR) by realizing some compromise on description and software capabilities
    - ➔ Development of new core nodalizations and demonstration on reactor cases

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

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

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)

Different approaches investigated for RBR evaluation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Approach chaining RCS simulation 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: RBR evaluation imposing T/H results to single fuel rod transient simulations

- Widely used by R2CA partners for reactor cases :
  EK (ATHLET/FRAPTRAN), LEI (ASTEC/TRANSURANUS), SSTC-NRS (RELAP5/TRANSURANUS), UJV (ATHLET/ TRANSURANUS), VTT (APROS/GENFLO+FRAPTRAN)

Main advantages:

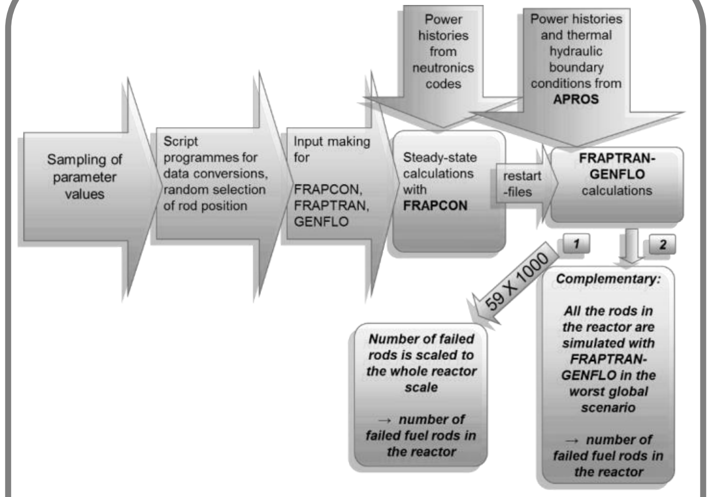
Reduce cost of single rod computation ➔ large number of simulations can be run

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

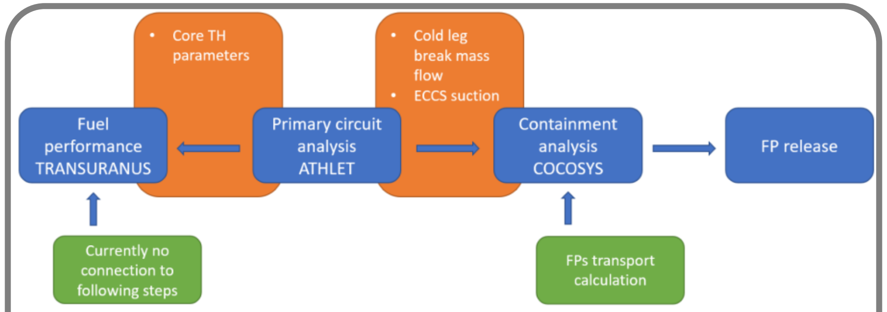
Possible issues:

Feedback of thermomechanics on thermalhydraulics

Average T/H system response imposed as boundary conditions at sub-channel scale in fuel channel – use of hot rod core modeling



Approach at VTT to evaluate the RBR during a LOCA
Source: A. Arkoma (VTT), final report R2CA WP2 T2.5



Approach at UJV to RBR and RC during a LOCA
Source: A. Kecek & al (UJV), final report R2CA WP2 T2.5

Different approaches investigated for RBR evaluation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Approach chaining LOCA system simulation 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: RBR evaluation imposing T/H results to single fuel rod transient simulations

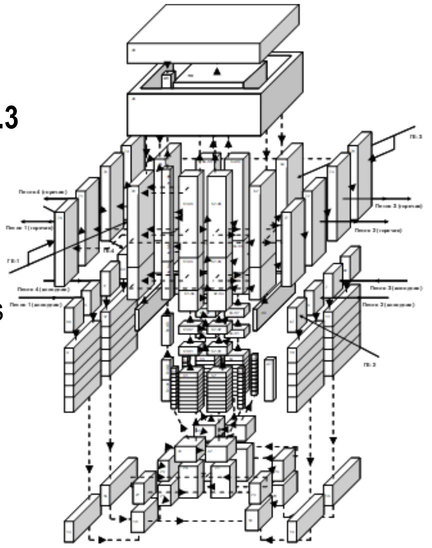
- Updated simulation of reactor cases proposed by partners

  EK (ATHLET/FRAPTRAN), LEI (ASTEC/TRANSURANUS), SSTC-NRS (RELAP5/TRANSURANUS), UJV (TRANSURANUS/ATHLET), VTT (APROS/GENFLO+FRAPTRAN)

Initial assessment of RBR & RC in task 2.3 proposed by SSTC-NRS chains RELAP to TRANSURANUS

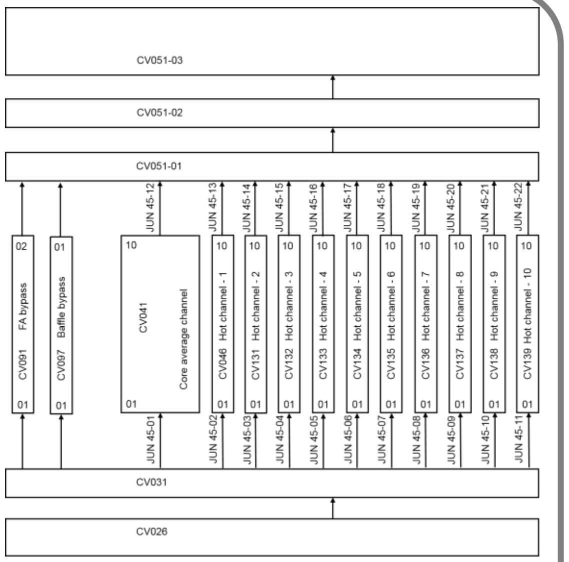
RELAP RPV model for VVER 1000
4 sectoral core with cross-flow connections

In each sector:
1 average channel
1 hot rod channel



Re-assessment of RBR & RC in task 2.5 proposed by SSTC-NRS

Evolution of T/H core model
by introducing 10 hot rod channels respectively to clustering of rods



Evolution of the core thermalhydraulic RELAP model proposed by SSTC NRS to evaluate RBR and RC for VVER1000
Source: Y. Vorobyov, O. Kotsuba (SSTC-NRS), final individual reports for R2CA WP2 Task 2.3 and Task 2.5

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 as an initial approach for evaluation of RBR - T2.3 (IRSN, ENEA, LEI)

Main advantages:

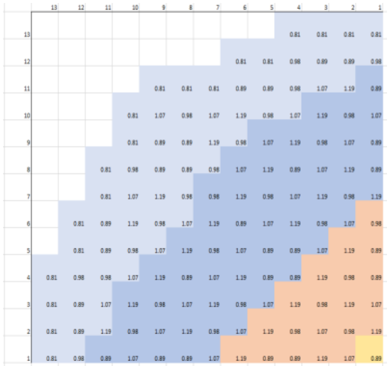
Integral simulation with multi-physics capabilities coupling T/H & T/M

ASTEC manages FPs transport and behavior in circuit and containment within the same LOCA simulation

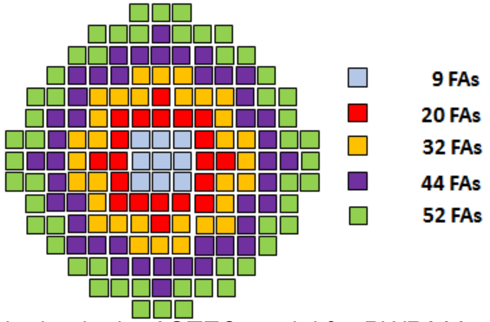
Possible issues:

Difficulty to represent core heterogeneities due to core nodalization

T/H system response averaged by rings and applied to different FA



Core partitioning in the ASTEC model for BWR-4 considered in R2CA demonstrative case
Source: T. Kaliatka (LEI),
Final individual report R2CA WP2 T2.3



Core partitioning in the ASTEC model for PWR900 considered in R2CA demonstrative case
Source: S. Ederli (ENEA),
Final individual report R2CA WP2 T2.3

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

- ENEA proposed an updated ASTEC core model

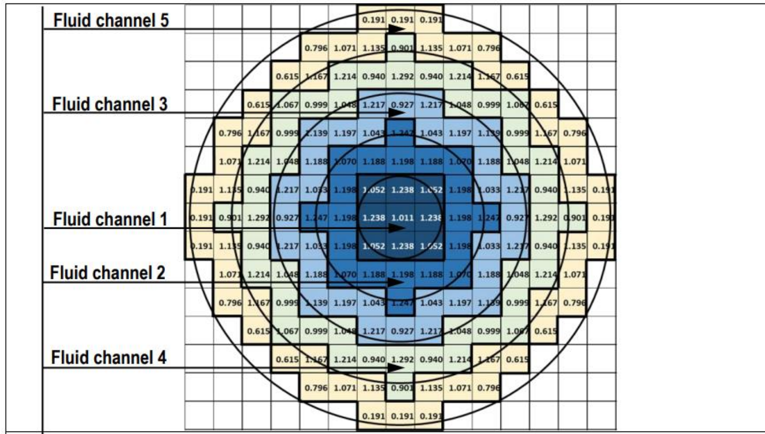
Basic principle of the core model update:

T/H nodalization is unchanged
Increase of the number of represented rods in T/H rings according to FA power
Initial model: 5 rep. fuel rods → Updated model: 20 rep. fuel rods

Main results:

Updated core model predicted burst for only a fraction of fuel rods located in a ring channel in a DEC-A case (due to high difference in rod decay heat)

T/M response of rods was observed to be driven by T/H conditions in the ring channel.
➔ Homogeneous response of rods located in the same channel was observed.



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

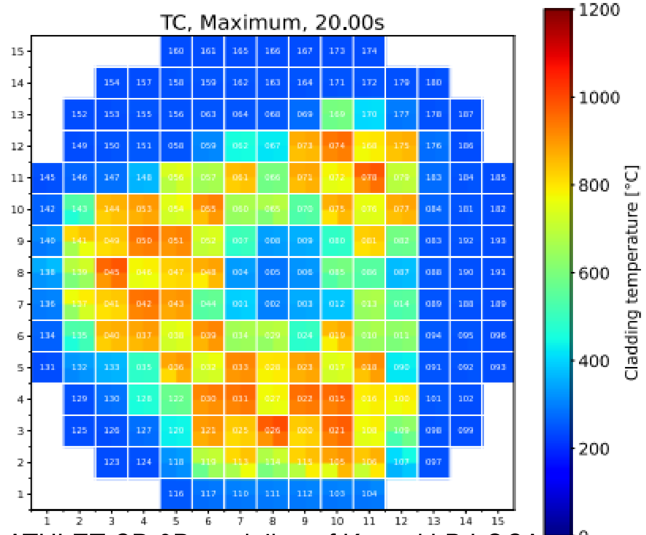
Description tends to “realistic” simulation based on 3D model (core map description, crossflow between neighboring core channels)

Possible issues:

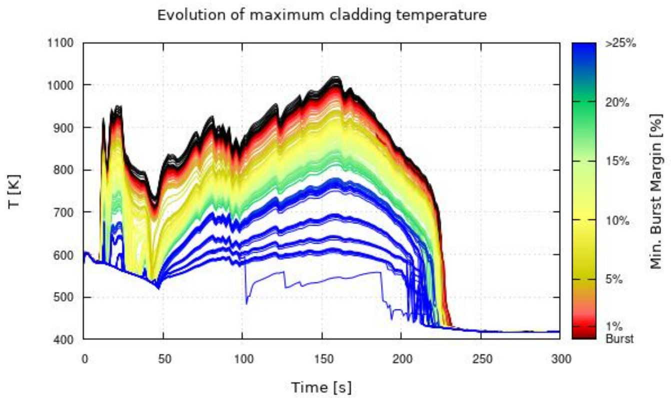
CPU cost

Validation status of 3D core or RPV model

Use of 2D (r,z) lumped rods instead of detailed 3D FAs modeling at sub-channel scale



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

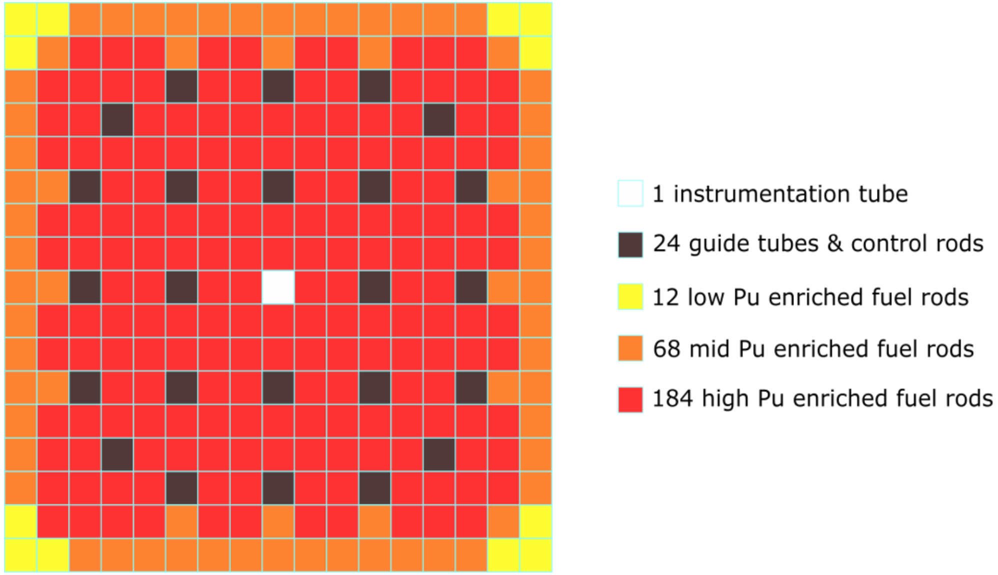


PCT obtained with DRACCAR 3D PWR model with 1 channel per FA and 6 eq. rods per FA
source: S. Belon (IRSN), D3.4 final report R2CA WP3.2

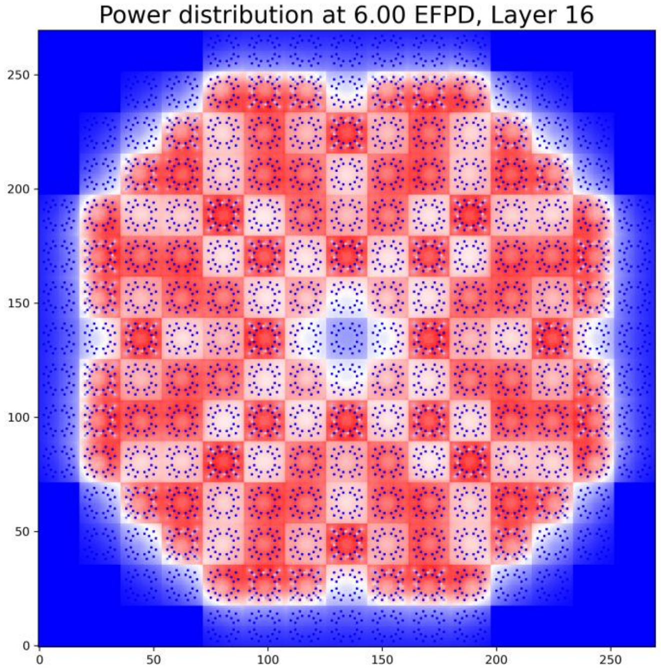
Why developing new core models in the frame of R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Example of core loading map and fuel assembly design
  ➔ Heterogeneities of PWR core loading map and FA compositions



Typical PWR 17x17 $(U,Pu)O_2$ FA configuration



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

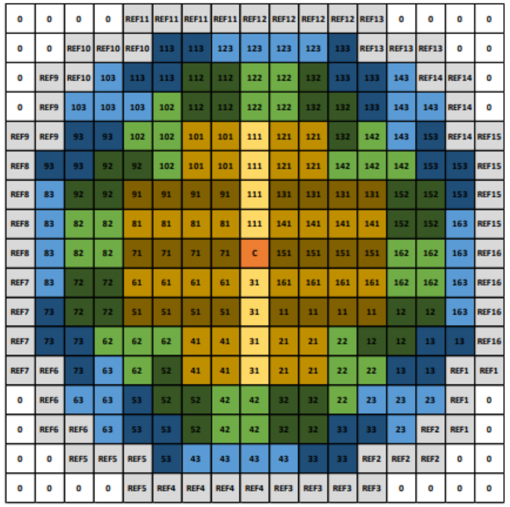
FA and core maps are clearly 3D
with significant variations of power, BU and RIP

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

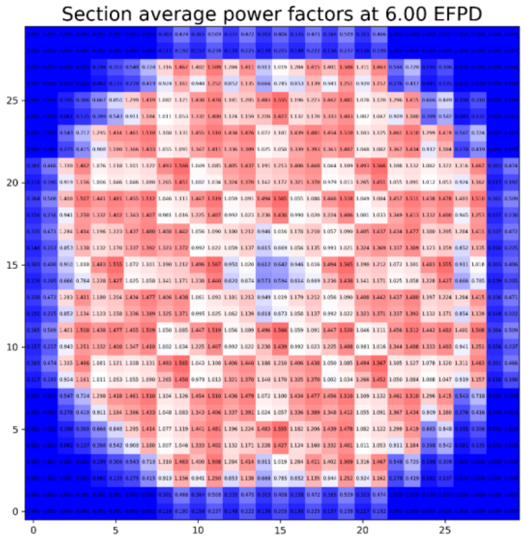
3D RPV & core modeling approach with ATHLET-CD

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

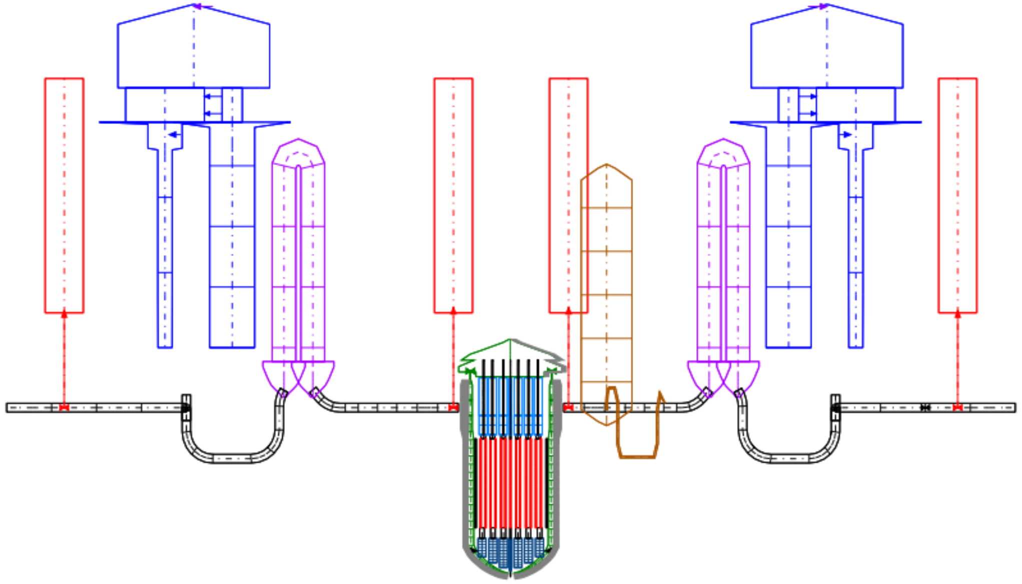
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



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 :

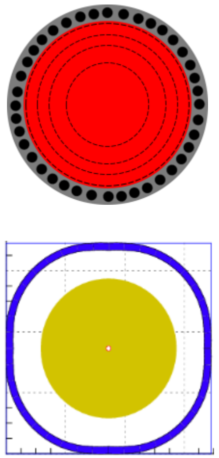
Each FA is partitioned in four groups of fuel rods represented by quartiles Q1,Q2,Q3,Q4 on rod power

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

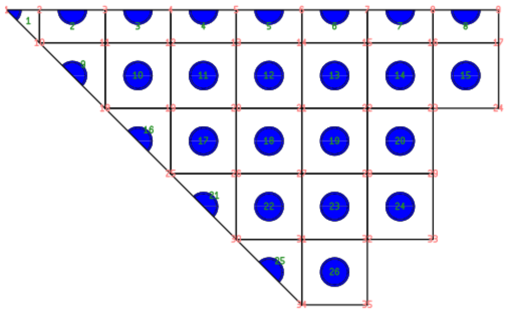
3D core and RCS modeling approach with DRACCAR

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

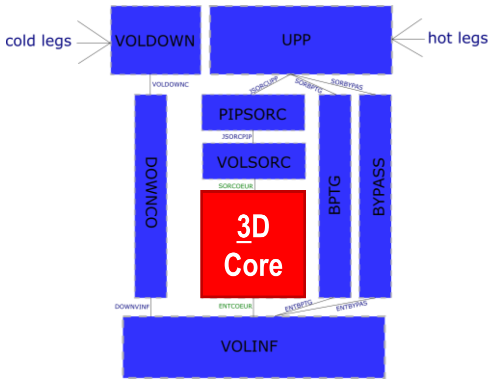
- 3D core modeling approach with DRACCAR proposed within R2CA



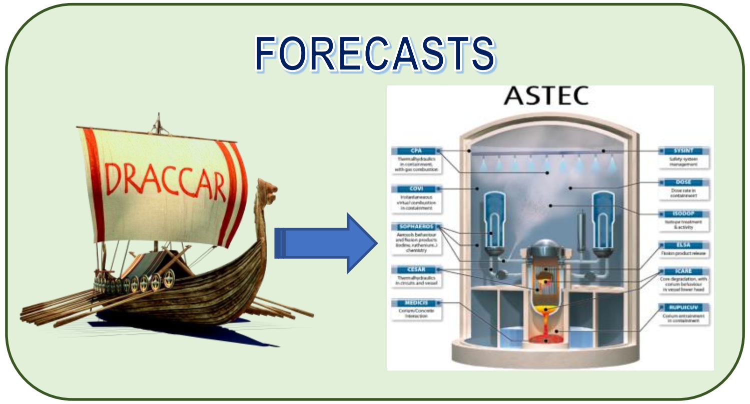
DRACCAR 2D (r,z) rods
meshed clad contour
Non-cylindrical shape



DRACCAR core model
1/8th of core
with 1 channel per FA
and several 2D rods per FA



Full RCS DRACCAR model
1D/0D volumes for RCS
3D core domain (= 8 x 1/8th core)



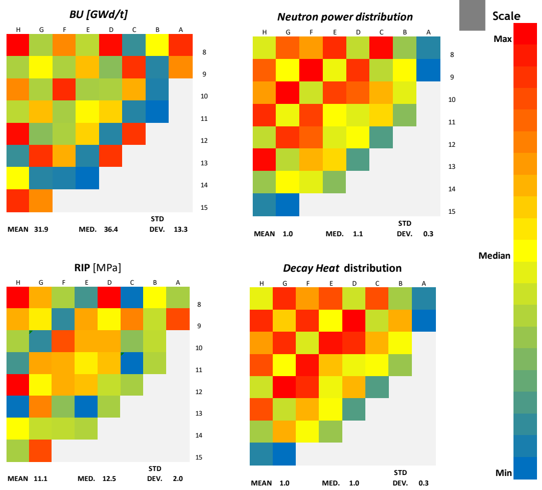
Specific chain for ST evaluation from DRACCAR to ASTEC
Applications share same modules:
T/H=> CESAR, FP=> ISODOP and RCS nodalization

IRSN proposes 3D approach for RBR evaluation with DRACCAR
3D core 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...)
Various core model possible - minimum core model **= 1/8th of the core** to speed up computation
Each FA is described by several eq. rods using 2D (r,z) meshed contour
Specific chain sharing FP releases and T/H from DRACCAR to ASTEC FP transport and behavior PWR model

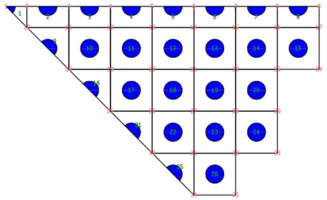
New core models in the frame of R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Example of 3D core approach with DRACCAR for demonstrative "PWR like"



Mixed oxide PWR "like" core
Fuel rod initial state and FPs inventory from simulations
FRAPCON PNNL/US NRC & VESTA IRSN
Irradiation (T_{2D}.RIP.BU.oxide...)
Neutronics (Power.DH.FPs)

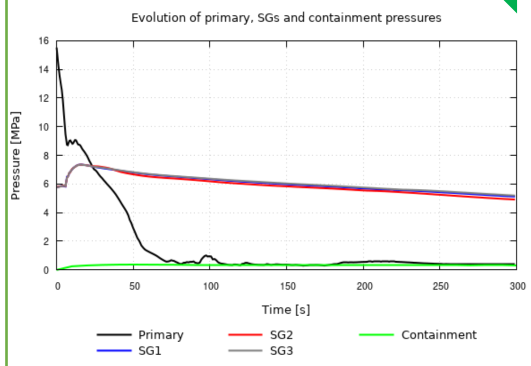


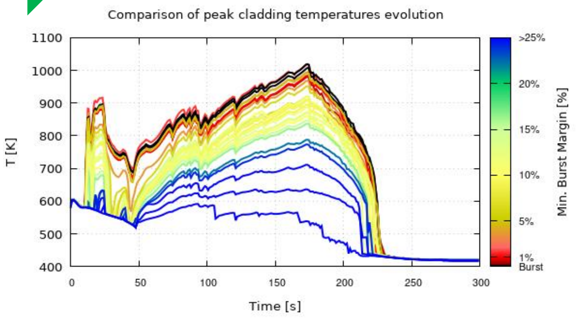
DRACCAR core
+ RCS model

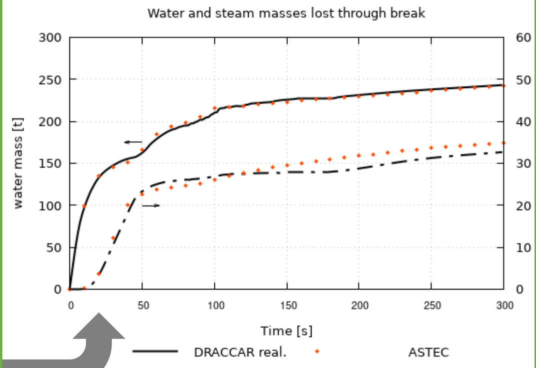
+

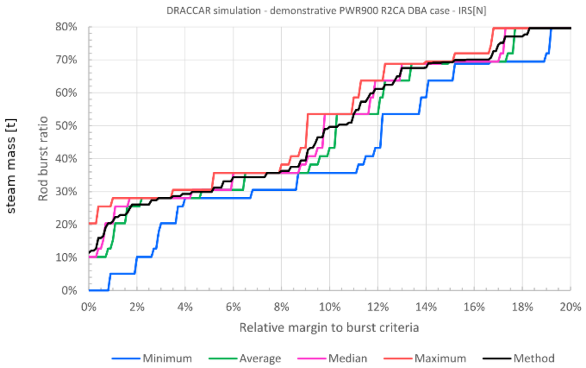
Scenario:
IBLOCA Demonstrative case with penalized assumptions

T/Hydraulics & T/Mechanics









FA behavior with several rod response can be evaluated with average thermalhydraulic in FA channel interconnected in 3D T/H core model

3D core models for RBR evaluation

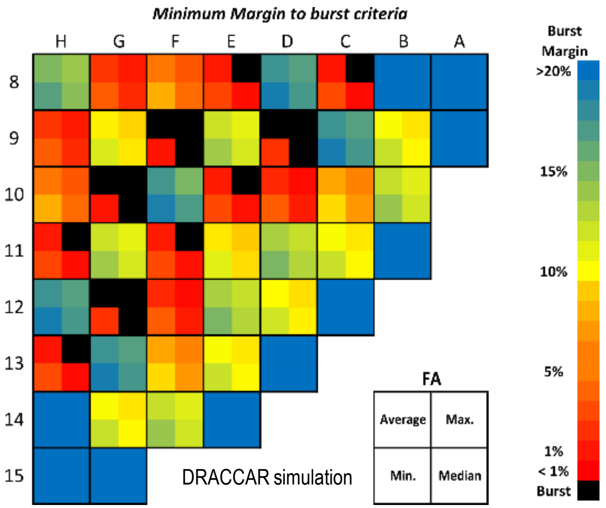
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Demonstration in R2CA of 3D core approaches

- 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)

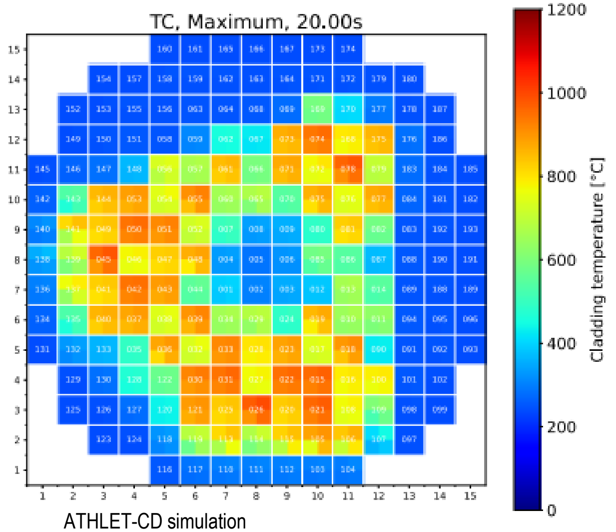
- Interests of 3D descriptions for prediction capabilities

More representative than ring model as T/H channel is solved at FA scale



source: S.Belon (IRSN) – R2CA WP2 T2.5 démonstrative case

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

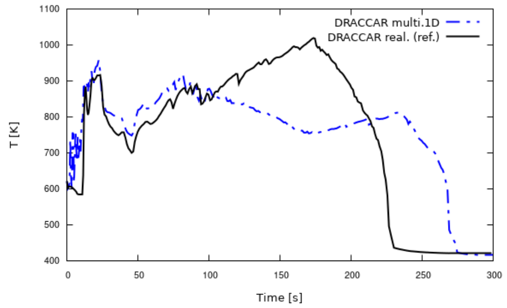


ATHLET-CD simulation

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

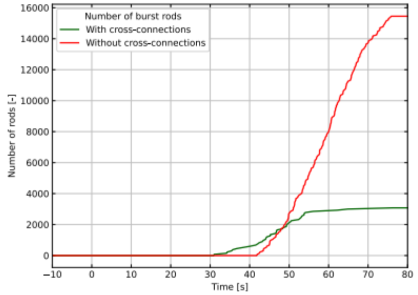
Results obtained on 3D core model strongly differs from core rings model or multi-1D channels

DRACCAR IBLOCA PWR demonstrative case



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

ATHLET-CD Demonstrative Konvoi LB LOCA simulation



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

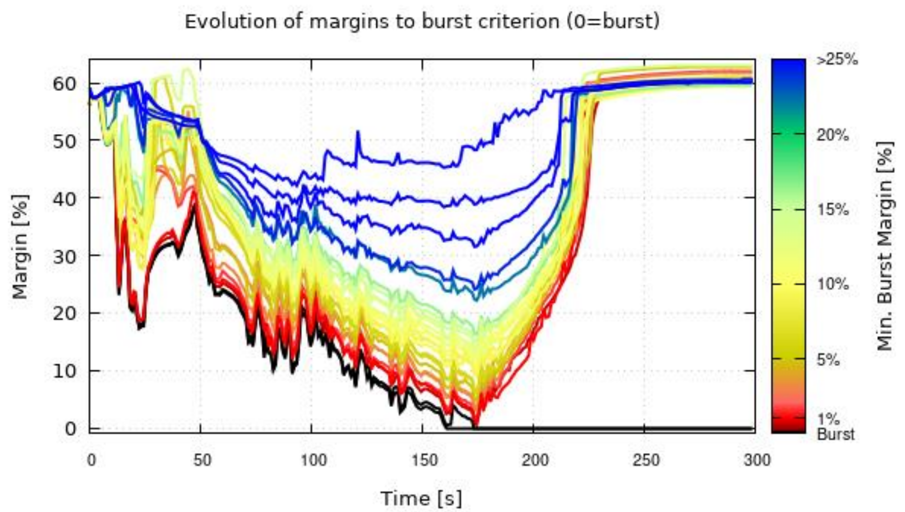
Use of Multiphysics 3D core or full RPV model are promising but still need validation

DRACCAR reactor applications for R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

• 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 ?

When using simulation approach, 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

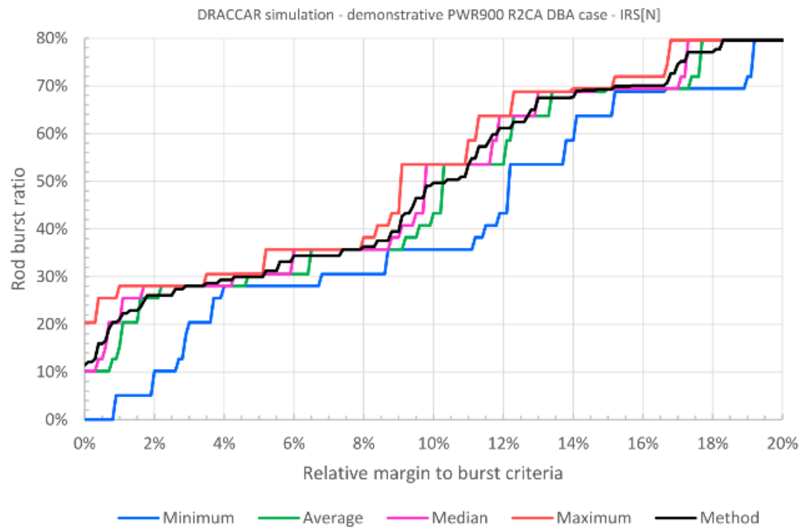


Illustration of the relative margin between burst criteria and clad temperature
Source: S. Belon (IRSN), final report R2CA WP2 T2.5

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 timing was underlined and highlighted by sensitivity of RBR assessment to criteria choice
  - 3D core applications with integral code were developed
    - Benefits = more realistic core description in comparison to "ring" model or "hot rod" model
  - RBR evaluation 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
  - Some modeling limitations were identified for each approach and require further validation/development
  - Computational cost associated to 3D approach to manage uncertainties in RBR evaluation methodology

Thank you for your attention!

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