REDUCTION OF
RADIOLOGICAL
ACCIDENT
CONSEQUENCES

IRSN

The EU H2020 R2CA project: Main Outcomes

Reduction of Radiological Consequences of Accidents

N. GIRAULT (IRSN)

R2CA Final Open Workshop, 29-30 November, 2023

Commission européenne

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

R2CA main Achievements

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **E**xtensive dedicated experimental **database** (covering DBA & DEC-A cond.)
- **S**ignificant **"modelling"** improvements for both **LOCA & SGTR** phenomena at different levels
  - ✓ Upgrading/development/implementation of models
  - ✓ Improvements of simulation tools at different scales for most impacting processes in RN releases
  - ✓ Enhancement of tool coupling (i.e. Fuel performance and FP behaviour…)
  - ✓ Updating of calculation chains/RC evaluation methodologies
- **A**nalyses and **RC evaluations** of a large variety of **LWR** concepts/**scenarios**
  - ✓ Calculation results archived and formatted for easy database input on NPP calculation results
- **R**ecommendations **for harmonisation** of RC evaluation **methodology**
- **O**ptimisation of **AMP** (SGTR) & development of a generic numerical methodology
- **A** prototype **expert system** for early diagnosis of rod defect and location
- **E**valuation of some near-term **ATF** with updated methodologies

The R2CA database

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Fuel behaviour

FP activity release

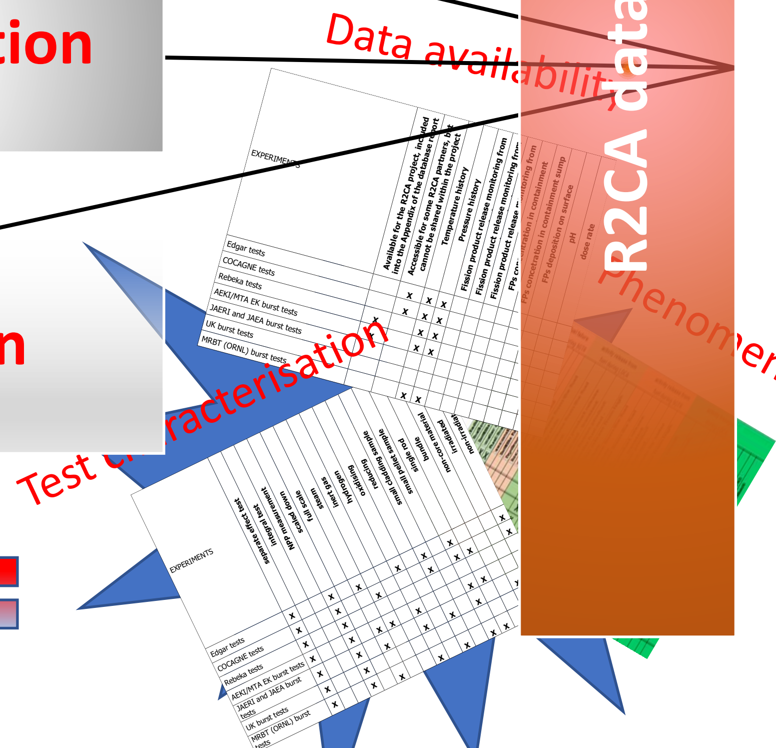
FP activity transport

Phenomena

Test characterisation

Data evaluation

R2CA database



+ 200 tests (data/reports), ~ 50 experimental series
(@ different scales + NPP data, new/legacy)

Reactor calculations (LOCA)

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Organization	Type of reactor	LOCA		SGTR	
		DBA	DEC-A	DBA	DEC-A
ARB	VVER-440;	+	+	+	+
	VVER-1000	+	+	+	+
Bel V	PWR-1000	-	-	+	+
BOKU	PWR-1300,	-	-	+	+
	VVER-1000	-	-	+	+
CIEMAT	PWR-1000	-	-	+	+
ENEA	PWR-900	+	+	-	-
HZDR	PWR-Konvoi	+	+	-	-
IRSN	PWR-900	+	+	+	-
LEI	BWR-4	[illegible]	+	-	-
EK	VVER-440	+	-	+	-
SSTC-NRS	VVER-1000	+	+	+	+
TRACTEBEL	PWR-1000	[illegible]	[illegible]	[illegible]	+
UJV NRI	VVER-1000	+	-	+	-
VTT	EPR-1600	+	-	-	-
	VVER-1000	-	+	-	-

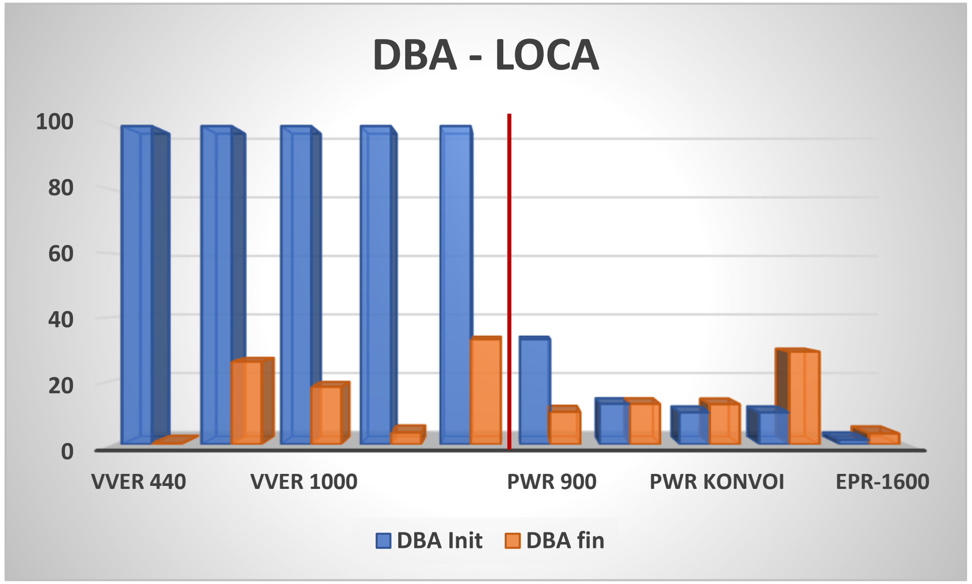
- 8 different LWR designs (7 for LOCA)
- 4 different kinds of scenarios
- ~70 reactor calculations (~ 30 for LOCA)
- no benchmarking
- RC evaluations (simple radiological tool)
- Calculated twice

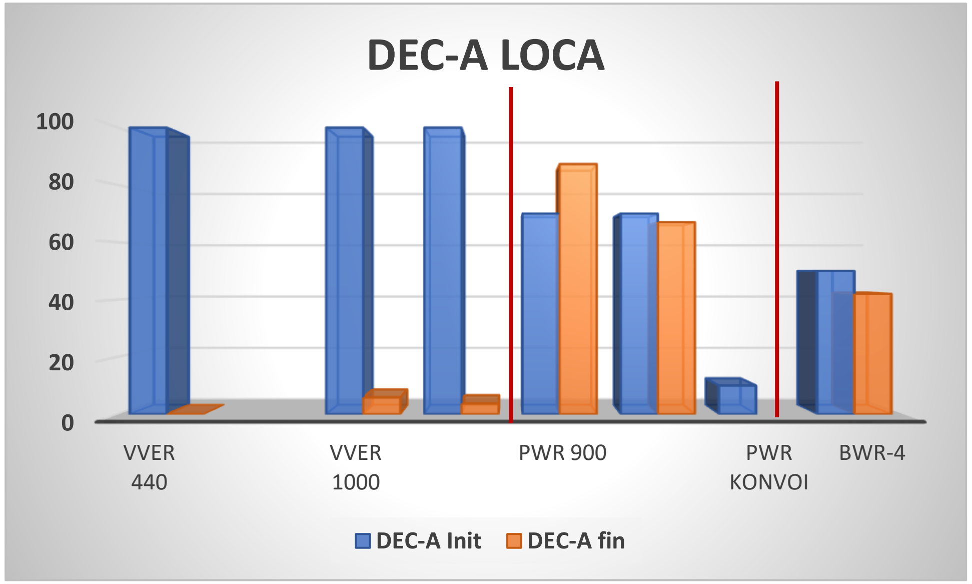
Reactor type	LOCA Scenario DBA (Initial event + failures)	LOCA Scenario DEC-A (Initial event + failures
VVER 440	DEGB in CL LOOP Failure of DG-1	DBA+CSS failure
	DEGB in CL $^{2}/_{3}$ LPIS available	
VVER 1000	DEGB in CL LOOP Failure of DG-1	DBA+CSS failure
	DEGB in CL LOOP	DBA+CSS failure
	DEGB in CL $^{3}/_{4}$ HA available $^{1}/_{3}$ HPIS & LPIS available	
PWR 900	IB in CL LOOP Failure of ½ DG	SB in HL Failure of ECCS Manual start of SIS + delay
PWR Konvoi	DEGB in CL LOOP	DBA + ECCS failure
EPR 1600	DEGB in CL LOOP Delay of DG start	
BWR-4		DEGB in main recirculation pipe Failure of ECCS Except LPCI

- Scenarios: mostly cat 4 in DBA (DEGB in CL + 1 single failure (often LOOP) for PWRs), for DEC-A mostly ~DBA + 1 add. failure (excpt 2 cases with ≠ scenarios from complementary domain)
- Initial conditions: mostly conservative (some nominal) in DBA (in line with Safety Analysis methods of DBAs regarding RC), and more realistic for DEC-A

Reactor calculations: LOCA main results

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS





FAILED FUEL FRACTION

- Calculated activity released generally lower in updated evaluations, mostly related to decrease Failed Fuel rod Fraction
  - ✓ High decrease in VVERs from 65-100% (higher in DEC-A vs DBA) due to conservatisms & decoupling factors in initial calc.
  - ✓ Low decrease in PWRs 900 DBA strongly dependent on core modelling (concentric rings vs 3D), slight increase of FFF in DEC-A for 3D core modelling due to better differentiating FAs)

    calc. highlights core ring model limitations due to averaged T/H
  - ✓ Low increase (but remaining low) in PWR Konvoi & EPR DBA: resp. 10 & 1% to 12 & 3% (new core modeeling approach, R2CA new criteria)

Reactor calculations: LOCA main outcomes

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

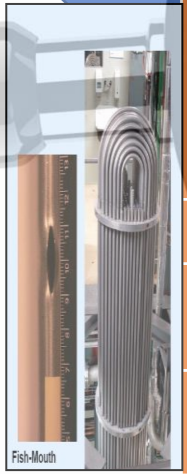
- Significant improvements in model/tool/calc. schemes (i.e. stronger T/H-T/M coupling)
- Key points in calculation improvements :
  - ✓ New clad burst models/criteria (T, stress, strain) more appropriate for DBA/DEC-A conditions (lower clad deform), less conservative + updated clad deformation models
  - ✓ Detailed 3D T/H core modelling (RPV) coupling T/H-T/M: differentiation of FA characteristics (power distribution), 4 to 6 equivalent fuel rods per assembly
  - ✓ More refined calculations of fuel gap inventory (3D burn-up)
- Most detailed calc. evidenced FBR dependence on rod int pressure/power distribution, local cooling variations implying needs for better estimation of fuel axial gas transport, FA characteristics (burn-up, location…) and whole 3D T/H core modelling (increased CPU)
- For all, uncertainty management recommended (input model parameters, initial/boundary conditions (RIP, core loading), burst criteria…) requiring to reduce CPU (necessary compromise with description details vs computational effort) and use of specific methods
- Additional improvements still needed to further refine the source term (FP multi-gap inventory, increased number of equivalent FR & associated T/H channels, FA assembmy modelling at sub channel scale (rod/rod interaction), reduce CPU of 3D T/H resolution …)

Reactor calculations (SGTR)

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Organization	Type of reactor	LOCA		SGTR	
		DBA	DEC-A	DBA	DEC-A
ARB	VVER-440;	+	+	+	+
	VVER-1000	+	+	+	+
Bel V	PWR-1000	-	-	+	+
BOKU	PWR-1300,	-	-	+	+
	VVER-1000	-	-	+	+
CIEMAT	PWR-1000	-	-	+	+
ENEA	PWR-900	+	+	-	-
HZDR	PWR-Konvoi	+	[illegible]	[illegible]	-
IRSN	PWR-900	+	+	+	-
LEI	BWR-4	-	+	-	-
EK	VVER-440	-	-	+	-
SSTC-NRS	VVER-1000	+	+	+	+
TRACTEBEL	PWR-1000	-	-	+	+
UJV NRI	VVER-1000	+	-	+	-
VTT	EPR-1300	+	-	-	-
	VVER-1000	-	+	-	-

- 8 different LWR designs (5 for SGTR)
- 4 different kinds of scenarios
- ~70 reactor calculations (~ 45 for SGTR)
- no benchmarking
- RC evaluations (simplified radiological tool)
- Calculated twice

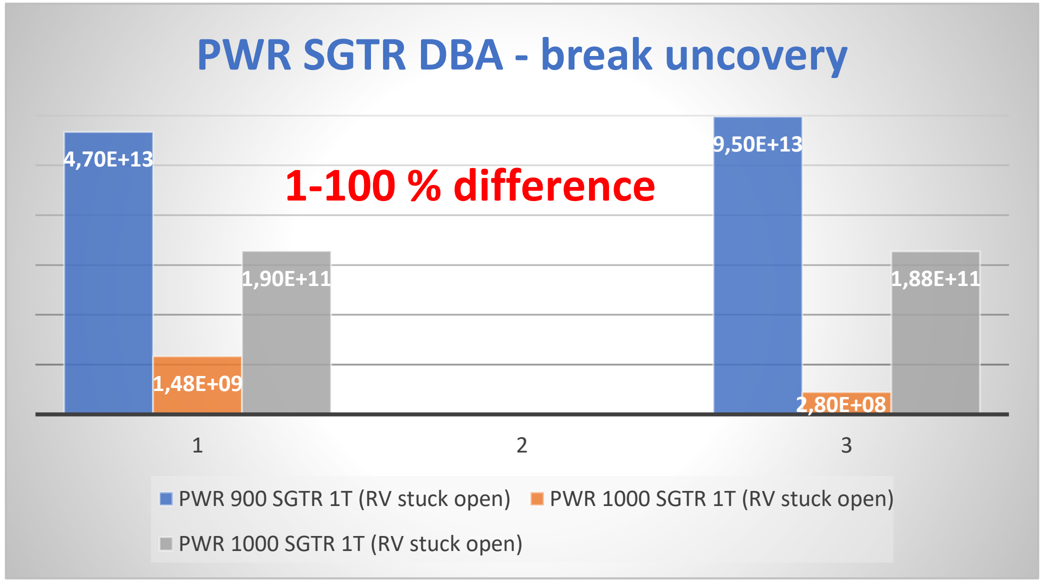


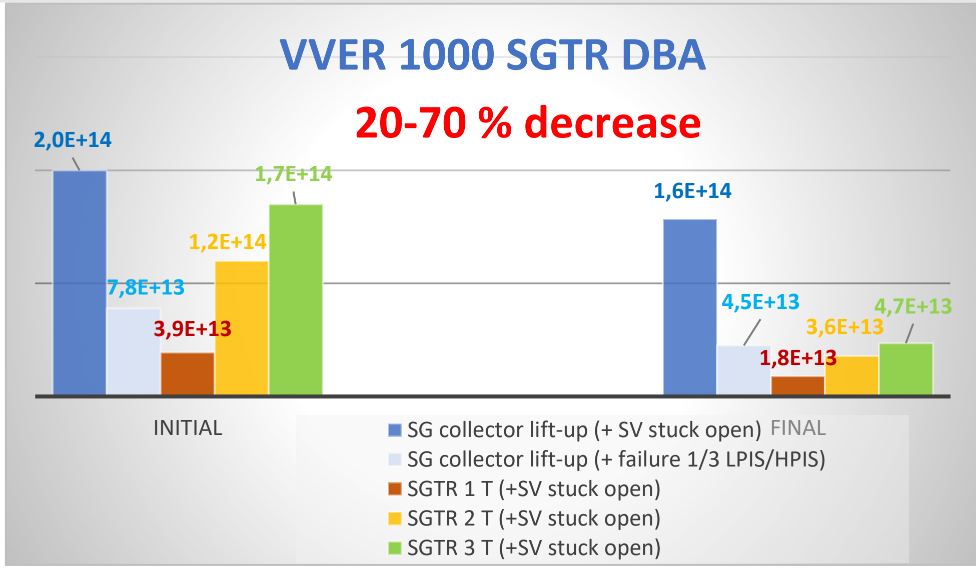
Reactor type	SGTR Scenario DBA (Initial event + failures)	SGTR Scenario DEC-A (Initial event + failures)
VVER 440	SG SV stuck open LOOP SG collector lift-up	SG SV+RV stuck open LOOP SG collector lift up
	SG SV stuck open LOOP SGTR 1, 2 or 3 tubes	SG SV+RV stuck open LOOP SGTR 1, 2 or 3 tubes
	DEGB (3 tubes)	
	SG Collector lift-up	
VVER 1000	SG SV stuck open LOOP SG collector lift-up	SG SV+RV stuck open LOOP SG collector lift up
	SG SV stuck open LOOP SGTR 1, 2 or 3 tubes	SG SV+RV stuck open LOOP SGTR 1, 2 or 3 tubes
	SG collector lift up LOOP failure of $^1/_3$ HPIS + LPIS	SG collector lift up + RV stuck open LOOP failure of $^1/_3$ HPIS + LPIS
	SG hot collector lift-up all active safety systems of one loop not available	SG hot collector lift up +SG RV stuck open Failure of HPIS
PWR 900	DEGB (1 tube) SG RV blocked open	
PWR 1000	DEGB (1 tube) SG RV stuck open	DEGB (3 tubes) + SLB LOOP
	DEGB (1 tube) SG RV stuck open	DEGB (3 tubes) + SLB LOOP
PWR 1300	DEGB (1 tube) Failure of 2/4 HPIS/LPIS pumps and 2/4 EFW	DEGB (1 T) + SG RV stuck open Failure of LPIS/EFW of affected SG

- Scenarios: mostly 1 tube DEGB + 1 single failure (RV stuck open) in PWRs, + for VVERs collector lift-up + LOOP. For DEC-A mostly ~DBA + 1 additional failure (for PWRs 1 aggravating factor also considered: 3 T DEGB)
- DBA/DEC-A initial conditions mostly similar with maximum (or penalized) primary coolant activity in NO

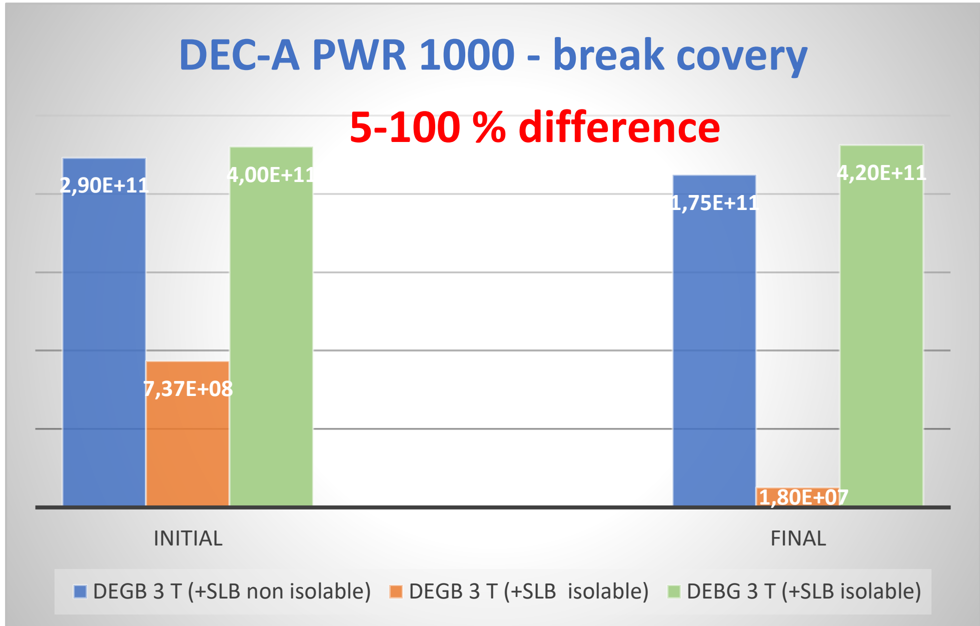
Reactor calculations: SGTR main results

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS





- Activity generally lower in updated evaluations (impvts of iodine spike, RN transport/dilution, releases from SR valves, EOPs …) except for some cases
- Increased iodine release calculated for break uncovery with an improved modelling of flashing (iod. speciation) or partitioning (T)
  - ✓ Importance of the different phenomena for iodine release function of scenario & iodine speciation in primary



Reactor SGTR calculations: main outcomes

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Significant improvements made mostly concerning FP modelling (fuel releases, transport, PRISE transfer, gas-liquid distribution in SGs)

- Key points in modelling improvements :
  - ✓ Primary circuit contamination, spike transient releases from defective fuel rod gap beneficial for all kinds of SGTR scenarios (w/wo SG overflowing)
  - ✓ Iodine flashing (depend. on speciation) & atomisation for uncovery break scenarios, iodine partitioning

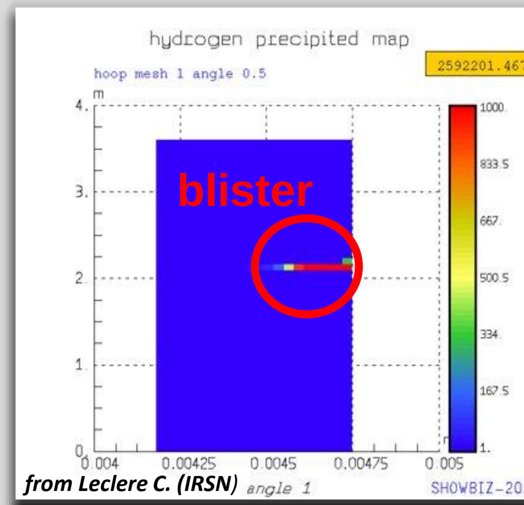
- Additional improvements still needed at different levels to further refine the source term (i.e. use of more mechanistic models for informing iodine-spike correlations, retention in SG upper part...)

Other main modelling improvements

- Additional developments made (generally more mechanistic) which will be of benefit in future reactor calculations
- Main developments/upgrades concern

Clad long-term integrity of defective fuel rods in N.O.

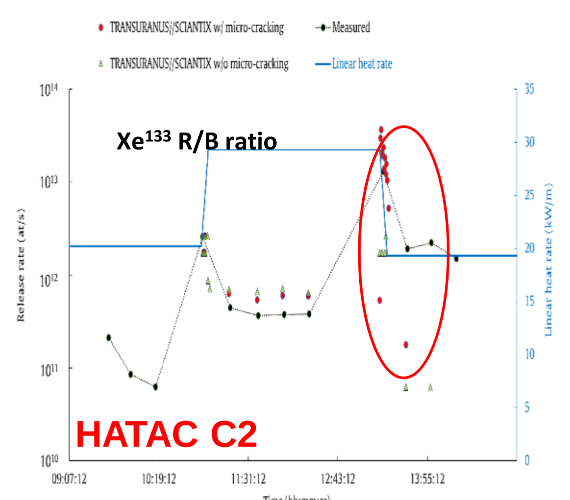
✓ Devpt of an integral model for internal clad secondary hydriding from water ingress to blister formation



from Leclere C. (IRSN)

FP releases from fuel (gap building inventory & RIP)

✓ Refinement of models in FP detailed codes for transient releases (power/stress variations in fuel)
✓ Additional models in FPCode for fuel oxidation & impact on FP thermochemistry/diffusion
✓ Improved High Burn-up Structure mechanistic modelling
✓ Devpt of model for axial gas communication in fuel rod free volumes



from Pizzocri, D. and al. (POLIMI)

Enhanced coupling of FPCs with meso/grain scale FP codes

Extension of code capabilities for ATFs

What about uncertainties quantification

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **I**dentification of uncertainty sources for LOCA and SGTR within DBA/DEC-A conditions
- **P**roposal of a global uncertainty approach combining uncertainty of single calculations when used in a coupled mode

  BUT no systematic uncertainty analyses performed within R2CA

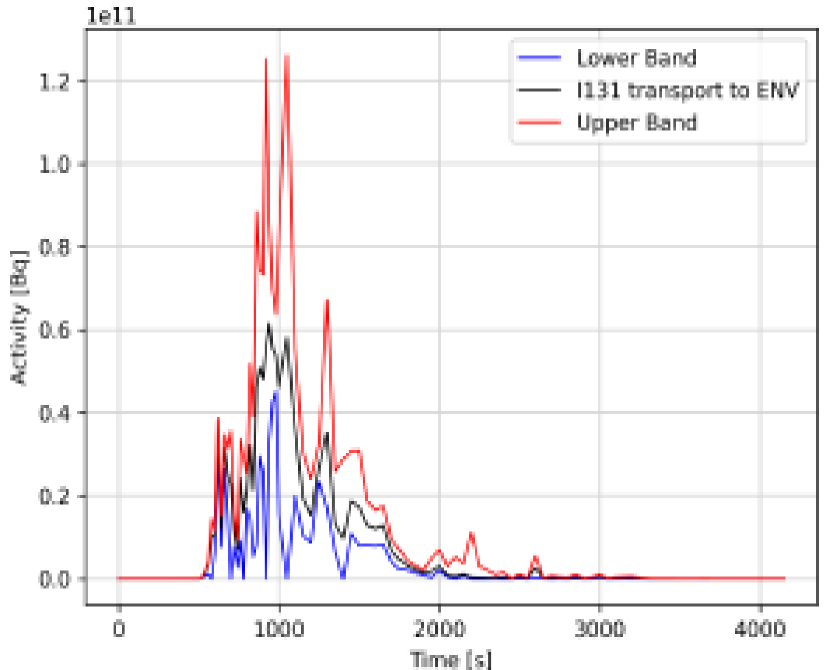
- **E**xploratory extended application **of CIAU** methodology (Pisa University) on DEC-A SGTR in VVER1000 for determination of uncertainty on I-131 releases in environment

  - Standard procedure applied on 3 T/H parameters (boundary variations of these parameters + time identified)

  +

  - Uncertainties relevant for environmental releases (secondary pressure, void fraction at relief valve)

  → very pronounced uncertainty on I-131 release (> factor 2)



What about uncertainties quantification

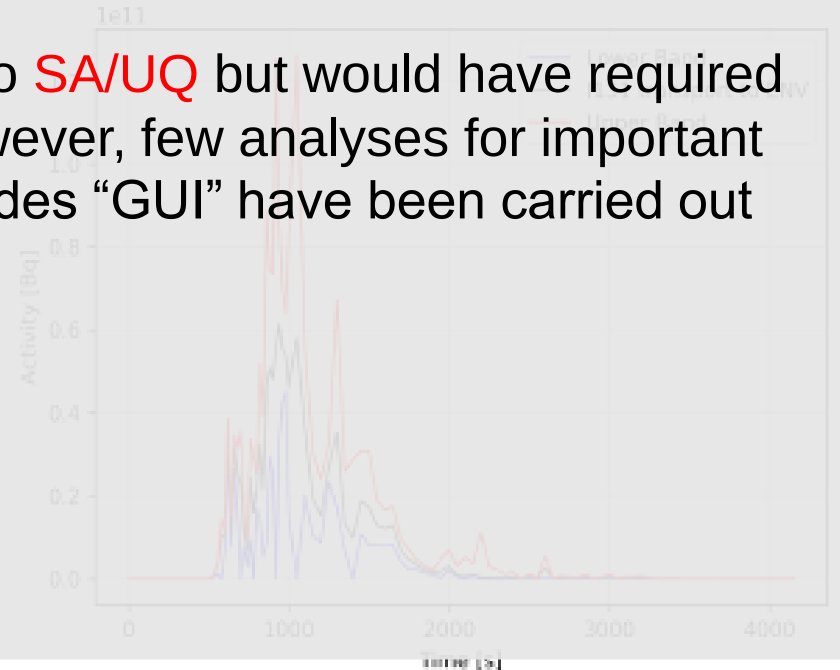
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Overview of existing uncertainty evaluation approaches
- Identification of uncertainty sources for LOCA and SGTR within DBA/DEC-A conditions
- Proposal of a global uncertainty approach combining uncertainty of single calculations when used in a coupled mode

BUT no systematic uncertainty analyses performed within R2CA

- Exploratory extended application **of CIAU** methodology (Pisa University) on DEC-A SGTR in VVER1000 for determination of uncertainty on I-131 releases in environment
  - Standard procedure applied on 3 T/H parameters (boundary variations of these parameters + time identified)
  - (secondary pressure, void fraction at relief valve)

very pronounced uncertainty on I-131 release (> factor 2)

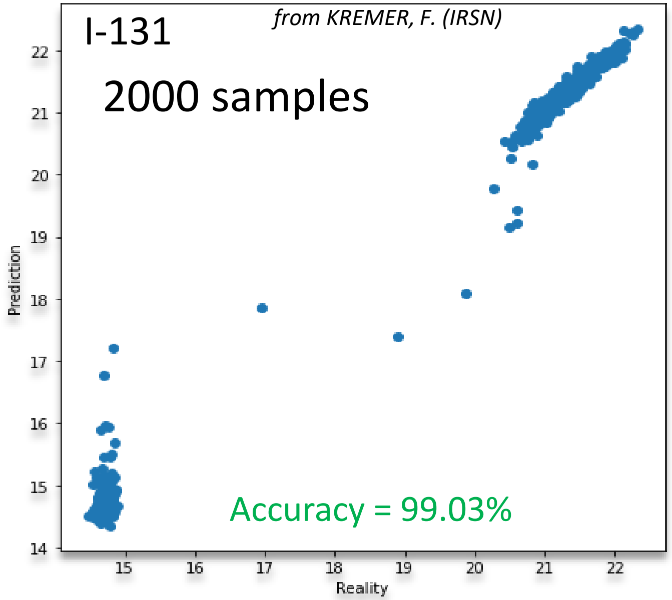


More realistic evaluations need to be associated to SA/UQ but would have required much more time/effort than devoted in R2CA. However, few analyses for important parameter identification & specific extension of codes “GUI” have been carried out

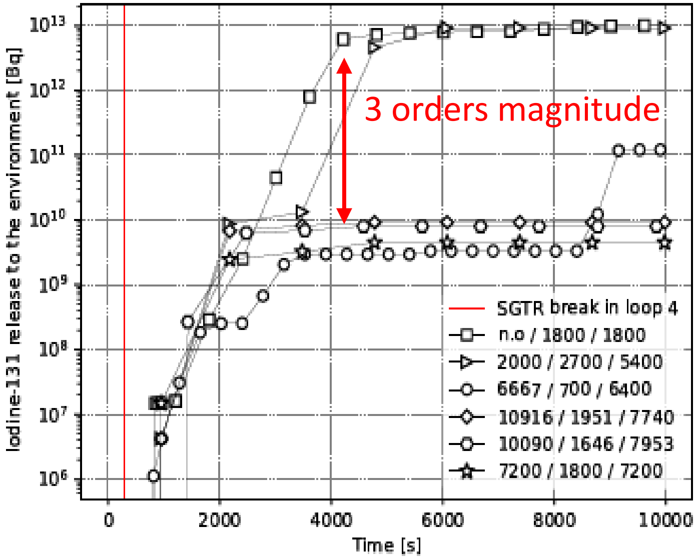
Accident Prevention & Management: main outcomes

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **E**laboration of a prototype of an expert tool for early diagnosis of defective fuel rods
  - Devpt of a physical model for FP releases from a defective rod (generation of a computational database for ANN training/testing)
  - Design of **Artificial Neural Networks** predicting 1) coolant activity & 2) defect formation/onset



- **O**ptimisation of **A**ccident **M**anagement **P**rocedures
  - Use of **Downhill-SIMPLEX** Method (optimization algorithm, event-based) to determine best timing of operator's actions & reduce RN releases in SGTR (interesting when data are scarce)

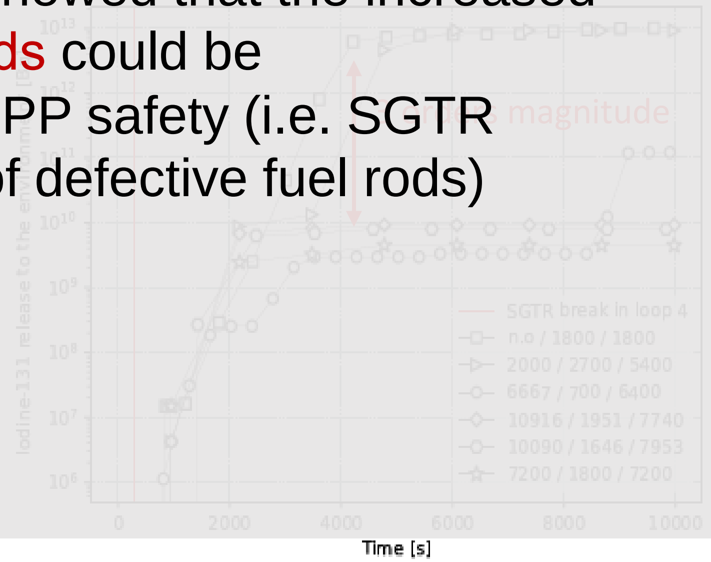


Accident Prevention & Management: main outcomes

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Elaboration of an expert tool for early diagnosis of defective fuel rods
  - Devpt of a physical model for FP releases from a defective rod (generation of a computational database for ANN training/testing)
  - Design of **Artificial Neural Networks** predicting 1) coolant activity & 2) defect formation/onset

Exploratory work on AMPs performed within the project showed that the increased capabilities of numerical tools and use of “Expert” methods could be advantageously used to fill the data gaps and increase NPP safety (i.e. SGTR accident management optimisation and early diagnosis of defective fuel rods)



Communication & Dissemination: Few Figures

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Presentations at conferences

18

Articles in Scientific journal

6 (+)

ANE special issue:

18 open-access (joint) papers

19 public technical reports

+

4 Newsletters

in Zenodo & R2CA public website

(https://r2ca-H2020.eu)

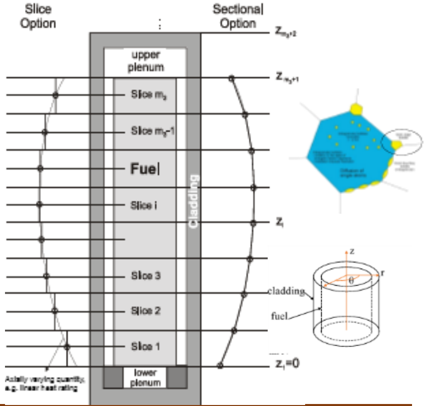
Education & Training

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- 3 specific code training courses
- 1 summer school

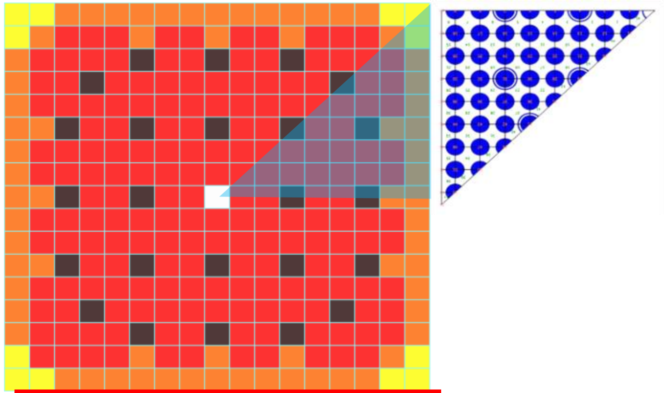
Sciantix

POLITECNICO MILANO 1863



Transuranus

JRC EUROPEAN COMMISSION



Draccar 3D

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DBA & DEC-A for LWRs

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

ENEA

Final remarks

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- Built-up of an extensive dedicated experimental **database**
- Significant **"modelling"** improvements for both LOCA & SGTR phenomena at different levels
  - Updating of calculation chains/RC evaluation methodologies
- Analyses and **RC evaluations** of a large variety of **LWR** concepts/**scenarios**
- Recommendations **for harmonisation** of RC evaluation **methodology** issued
- Optimisation of some **AMPs** for SGTR, test of (develpt of a generic numerical methodology)
- A prototype **expert system** for early diagnosis of rod defect and location was elaborated
- Evaluation of near-term **ATF** with updated methodologies & Sensitivity Analyses

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- **Updated validated numerical tools** in support to a more realistic evaluation of DBA/DEC-A accident risks (ST evaluation) in design phase of future NPP concepts (incl. evaluation of some ATFs & new AMPs)
- **Significant improvements** made in LOCA/SGTR modelling (refinement/development of models or external functions, built of new calculation chains…) decreasing the level of conservatisms, then Radiological Consequences, but not eliminating all
- Though there is still large room for additional improvements, comparisons between initial/final calculations allowed to provide **some recommendations for SGTR/LOCA RC evaluations**

Some issues for the future

- **Database extension (**exp. data too sparse for some phenomena (FP chemistry), or to be completed for more prototypical conditions (clad burst) or few new types of materials (ATF …)
- **Missing Phenomena, partially or not well modelled (**FP chemistry in fuel/primary circuit, retention in SG UP, liquid-gaz distribution, others for DEC-A?…)
- **Calculation schemes** (multi-physics/multi-scale code coupling, CPU optimisation…)
- **Systematic SA/UQ** (influent parameters & uncertainty bounds) for **BEPU** evaluations
- **Methodology extension/application** to other kinds of fuel (**MOX, high burn-up, ATFs…**) & to foreseen innovative NPP technologies (LW-**SMRs**…)
- **Harmonisation** of RC evaluation methodology in a context where national regulations vary greatly from one country to another
- **Advanced technology** (devices, procedures) for improved transient **diagnosis/prognosis** (i.e early realistic estimation of ST…) to better prevent/reduce their consequences
- …..

дякуємо

Danke

Gracias

Köszönöm

Thank you!

Merci!

Grazie

Kiitos

Děkuji

Ačiū

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