REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

IRSN

The EU H2020 R2CA project: Main Outcomes

Reduction of Radiological Consequences of Accidents

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Commission européenne

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OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

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Objectives & Scope

REDUCTION OF RADIOLOGICAL CONSEQUENCES
OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

To consolidate/refine assessments of radiological consequences of explicit DBA and DEC-A accidental scenarios **in Gen II, Gen II and Gen III+ NPPs**

↓

To **improve code predictability for RC of LOCA & SGTR scenarios within DBA/DEC-A domain**

- Identify weaknesses/needs and improve models, tools & calculation chains (incl. coupling)
- **Elaborate updated methodologies for evaluation/reduction of RC in DBA/DEC-A**
- **Apply updated methodologies to** derive more realistic safety margins for LOCA/SGTR .
- Derive rationales for the optimization of EP&R actions
- Provide rationales/develop innovative measures/devices/tools for anticipated diagnosis and for the management/mitigation of these accidents
- **Provide recommendations** for harmonization of the RC evaluation methodologies

PWRs/EPR/VVERs/BWR, LOCA/SGTR, DBA/DEC-A, Radiological Consequences, Accident Management

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PWRs/EPR/VVERs/BWR, LOCA/SGTR, DBA/DEC-A, Radiological Consequences, Accident Management

Context

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **For LOCA** 3 types of modelling approaches
  - Complex modelling with (coupled) computer codes : simulations of T/H, thermo-mechanics analysis (incl. FP releases from fuel), FP transport and behavior in containment
  - Detailed T/H & thermo-mechanics but for FP release/behavior conservative assumptions
  - Detailed T/H but for thermo-mechanics conservative assumptions (i.e. entire & instantaneous release of gap content at transient start or 100% rod failure…)

- **For SGTR** various levels of modeling
  - Common features: no simulation of clad defect formation & FP retention in SG upper structures, detailed T/H in I^{ary} and to a less extent in II^{ary} circuits
  - For FP release from defective fuel rods either simple models (RING) or assumptions for I^{ary} circuit activity S.-S. & transient evolution (iodine spike) often based on NPP feedbacks
  - For FP (esp. iodine) either detailed behavior modelling (incl. gas/liquid partition, flashing, atomization) or simplified modelling (only partitioning considered)

→ *Needs for increasing model prediction/accuracy for DBA/DEC-A conditions & decreasing conservatisms (specific database was build for model V&V)* (presentation 3.2)

Main Results: LOCA modelling

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REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Improve tools for more realistic evaluations of LOCA DBA & DEC-A radiological consequences

T3.1 FP releases from I^ary circuit

AMBITION

Better evaluation of environ^t source term

DONE

- Upgraded models for FP release & transport in I^ary circuit (releases for High BU fuel…)
- Refitted models for iodine–paint interactions

T3.2 Clad burst & core modelling

AMBITION

More accurate evaluation of the number of fuel rod burst failures

DONE

- Elaboration of new clad burst criteria for Zr alloys (Zr4, E110) & updated clad creep models
- M5 phase transformation & high T creep models
- Dev^t of more detailed core modelling approaches (DRACCAR, ATHLET-CD)

T3.3 Fuel rod T/M & FP releases

AMBITION

More realistic evaluation of FP transient releases

DONE

- Impv^t of FP "mechanistic" release models (burst transient releases)
- Updated FP release-fuel T/M tools (inc. their coupling impv^t & high BU fuel formation)
- Devp^t of an Axial gas transport model in fuel gap

Main Results: LOCA modelling

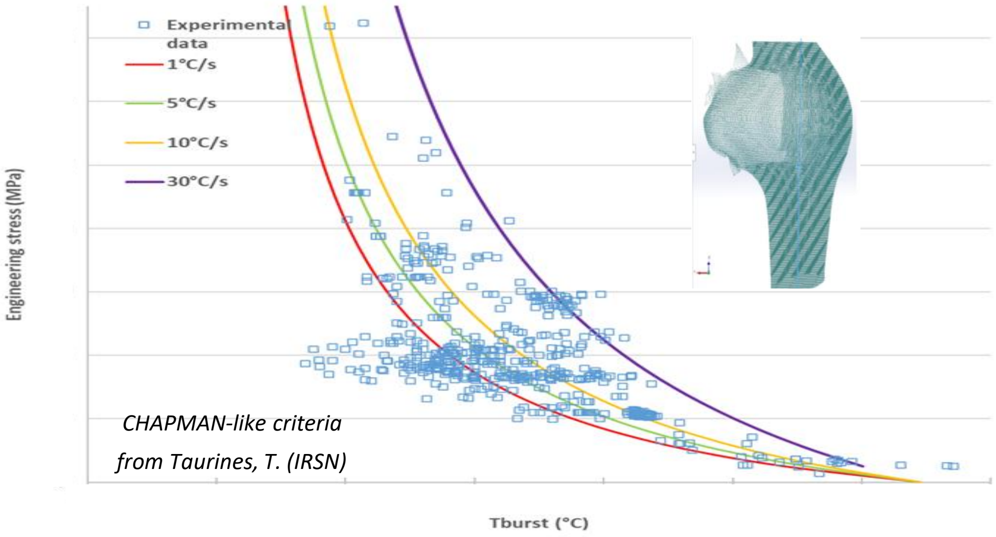
AMBITION

More accurate evaluation of fuel rod burst failures

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Existing clad burst criteria & core modelling not relevant to predict number of failed rods in LOCA DBA

• Clad burst

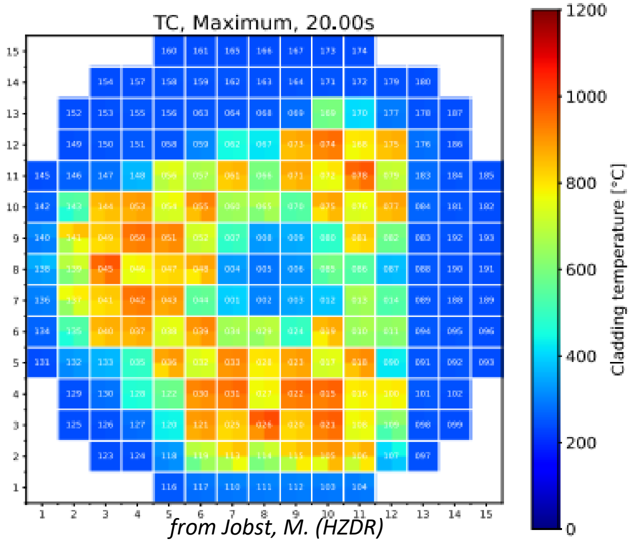


– Devp^t of new burst criteria (engineering or true stress based) for Zr4

– Less conservative but based on scattered burst exp. data (remaining uncertainties)

(presentation 3.6)

• Core modelling



– Devp^t of a 3D detailed core approach with 3D T/H model & eq. Rod(s)/FA : i.e. in ATHLET-CD

– Promising for core T/H non symetric simulations & non homogenous distribution of FA characteristics but CPU times challenging

(presentation 3.5)

Main results: LOCA modelling

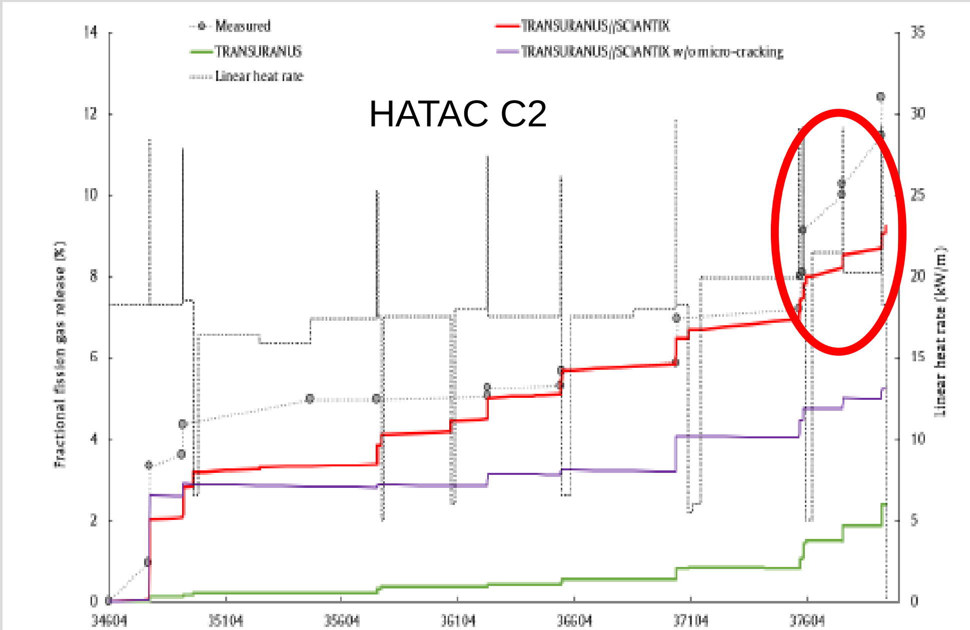
AMBITION

Refined evaluations of FP release amount & kinetics from fuel

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

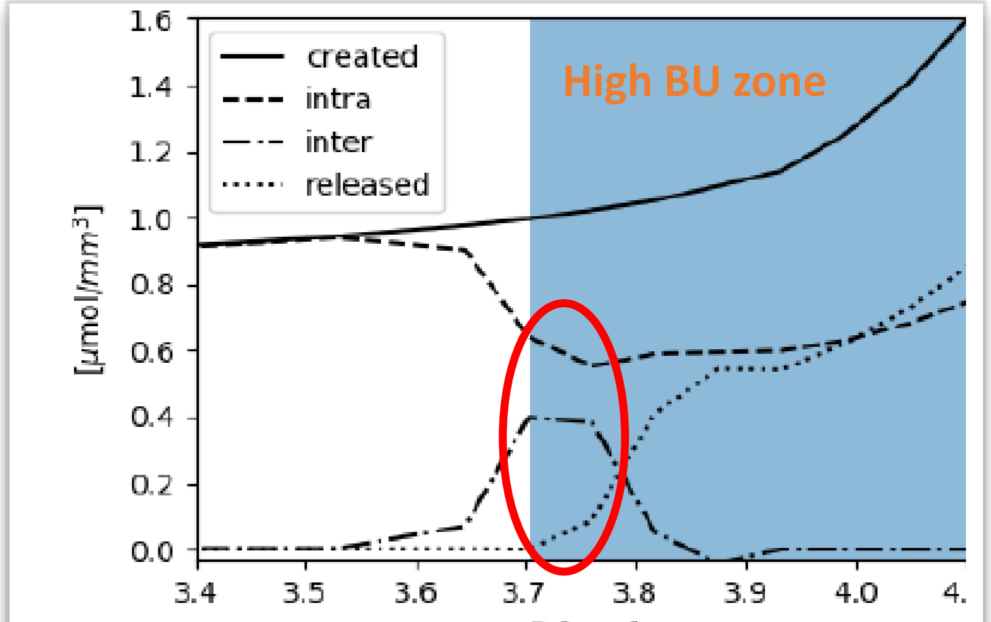
Existing FG release modelling don't simulate properly transient FP releases & higher release from HBS

• FG releases



from Pizzocri D. and al. (POLIMI)

• FG releases from High BU fuel



from KREMER, F. (IRSN)

– Impt of FG release tools and their coupling with fuel performance code

– Dynamics of releases & evolution during irradiation well reproduced in constant/transient conditions (presentation 2.6 & 3.7)

– Improved modelling for FG releases from HBS (≠ EOS added →transient intergranular pore overpressurisation)

Main Results: SGTR modelling

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Improve tools for more realistic evaluations of SGTR DBA & DEC-A radiological consequences

T4.1 FP releases from I^{ary} circuit

AMBITION

Better evaluation of environ^{t} source term

DONE

- New functionalities in tools (Iod. flashing) from existing models
- Model refinements (Iod. partitioning..)

T4.2 FP releases from leaking rod

AMBITION

More accurate evaluation of I^{ary} circuit activity in NO & transients

DONE

- Imp^{ts} of mechanistic models for FP transient burst releases
- Dev^{t} of a prelim. Simplified model for gap-to-coolant escape in leaking rods (wo gap axial transport….)
- Reffiting of empirical correlations for iodine spike predictions

T4.3 Clad II^{ary} hydriding & failure

AMBITION

Evaluation of the risks of defective fuel rod failure

DONE

- New experim^{ts} for H_2 uptake by Zr at low T (~300°C)
- Dev^{t} of an integral model for clad II^{ary} hydriding (inc.H_2 uptake/diffusion & blister formation

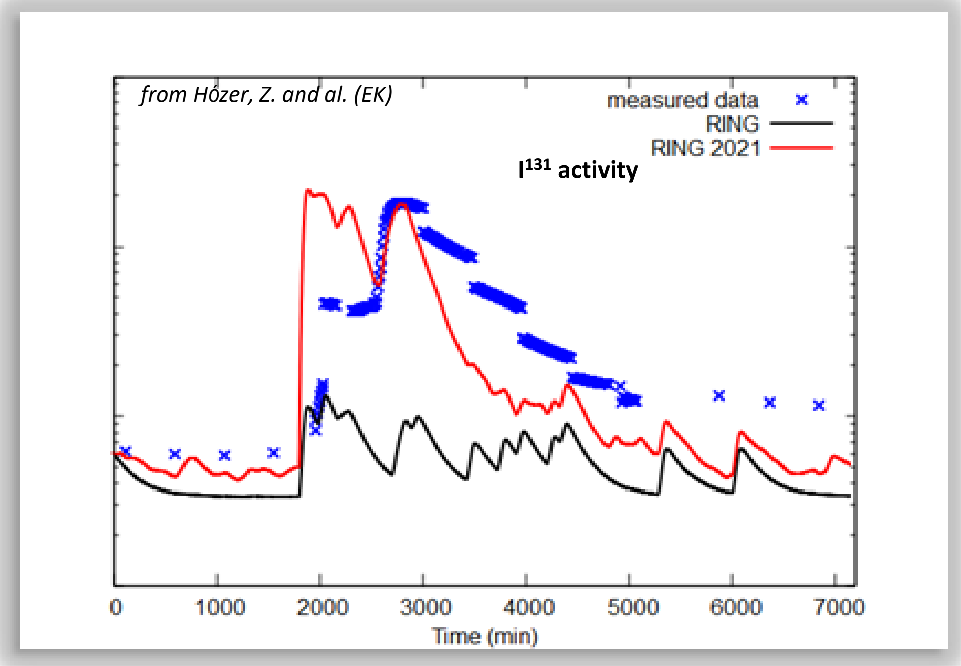
Main results: SGTR modelling

AMBITION
Best estimate evaluation of Iary circuit activity in NO & transient

Existing correlations for iodine spike are empirical & underestimate iodine activity releases in primary circuit

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Iodine spike

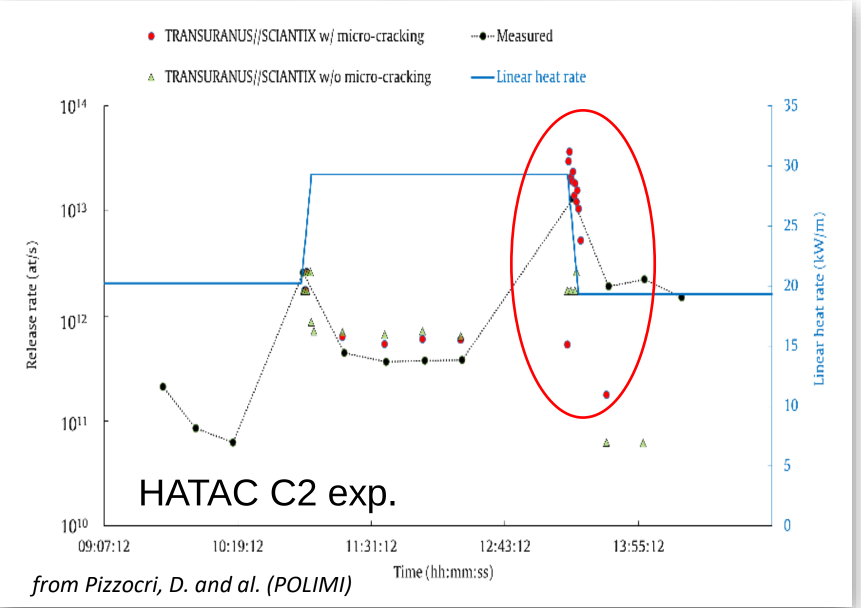


– Updated correlations for Iodine spike due to **reactor power, primary pressure and H_3BO_3 conc.** changes from new NPP data (presentation 3.9)

$$S^n = 1 + a_1 \frac{\Delta Q^n_{core}}{Q^{nom}_{core}} + a_2 \frac{\Delta P^n}{P^{nom}} + a_3 \frac{\Delta c^n_{bor}}{c^{nom}_{bor}}$$

Burst transient FP release

Xe^{133} R/B ratio evolution during power transients (HATAC C2)



– Devt of mechanistic modelling (coupling fuel performance/FP codes for transient spike releases (due to power decrease & stress variations) (presentation 2.3 & 3.7)

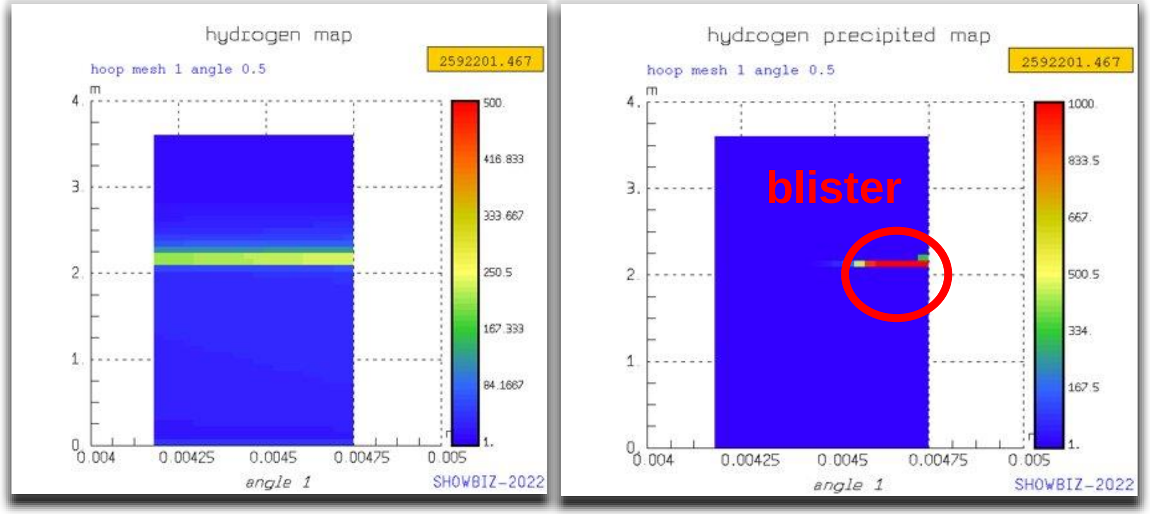
Main Results: SGTR modelling

AMBITION
Evaluation of the risks of defective fuel rod failure

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Existing studies for clad II^{ary} hydriding focussed on LOCA (i.e. @ higher T) overpredicts H_{upt} @400°C

- **Clad Secondary Hydriding (in N.O.)**

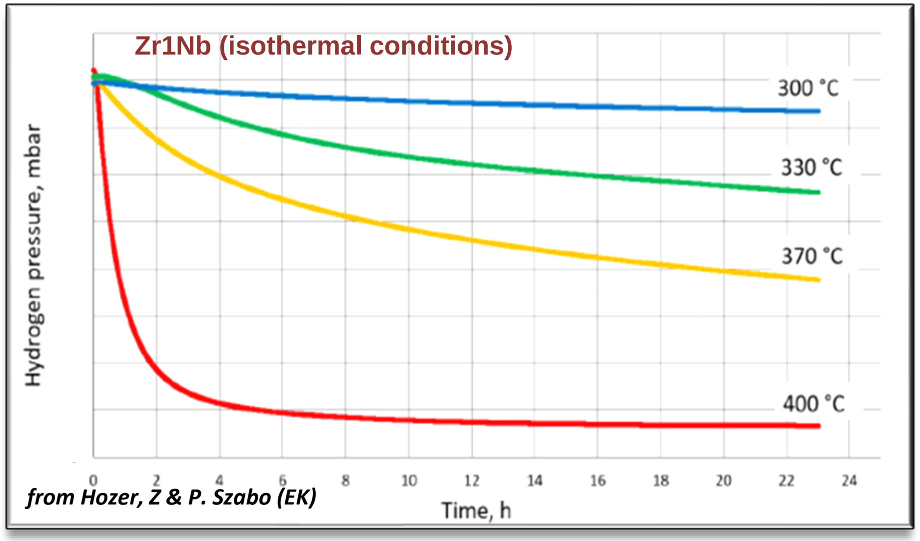


from Leclere C. (IRSN)

– Devpt of an integral model for clad II^{ary} hydriding in defective rods from water ingress to blister formation

– Simple failure criterion proposed from blister depth & mechanical analyses of remaining clad thickness

- **H_2 uptake measurts @300-400°C**



– Reffited solubility parameters in SIEVERT law ($H_{sol.}$= f(pH_2 & O_2 content)

Main results: Accident Management & Prevention

AMBITION

Analyse values of operating parameters plants to optimize their safety

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **Optimisation of Accident Management Procedures** (presentation 3.3)
  - Use **of Downhill-SIMPLEX Method** to find a functional dependency between AM parameters and Iodine activity threshold release to reduce iodine spike phenomenon impact

- **Elaboration of an expert system for early diagnosis of defective fuel rods**
  - Devept of a physical model for activity release from fuel rod to coolant
    - Isotope transmutation and transport equations considered
  - Generation of a sample dataset from the developed model (2000 samples generated)
    - Determination of the most influential parameters
  - Design of 2 artificial Neural Networks for 1) coolant activity 2) defect formation predictions
    - ANNs trained on generated data: 2000 samples split in training (80%) and testing (20%)

Physical model

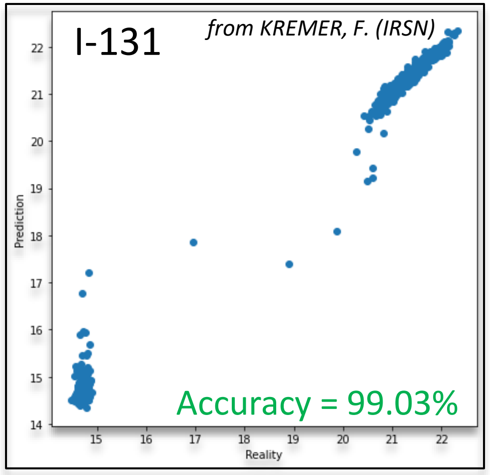
PELLET	GAP	COOLANT
Source : **fission** Loss : **diffusion & recoil**	Source : **release from pellet** Loss : **escape through defect**	Source : **release from gap & tramp uranium** Loss : **purification systems**

(presentation 3.4)

ANN

Physical parameters + Time of defect → ANN 1 → Isotopes activities

Results

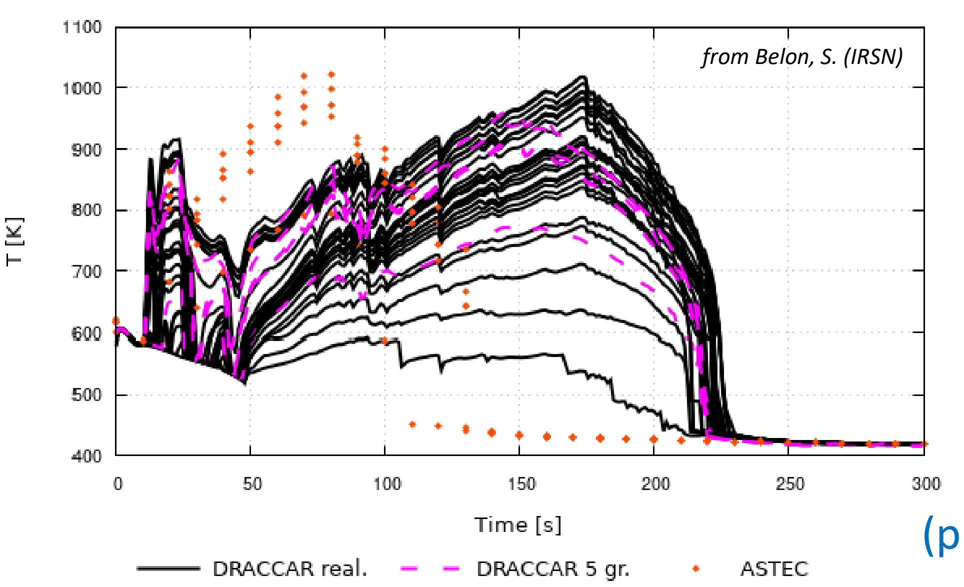


Impact: Updated LOCA Reactor Calculations

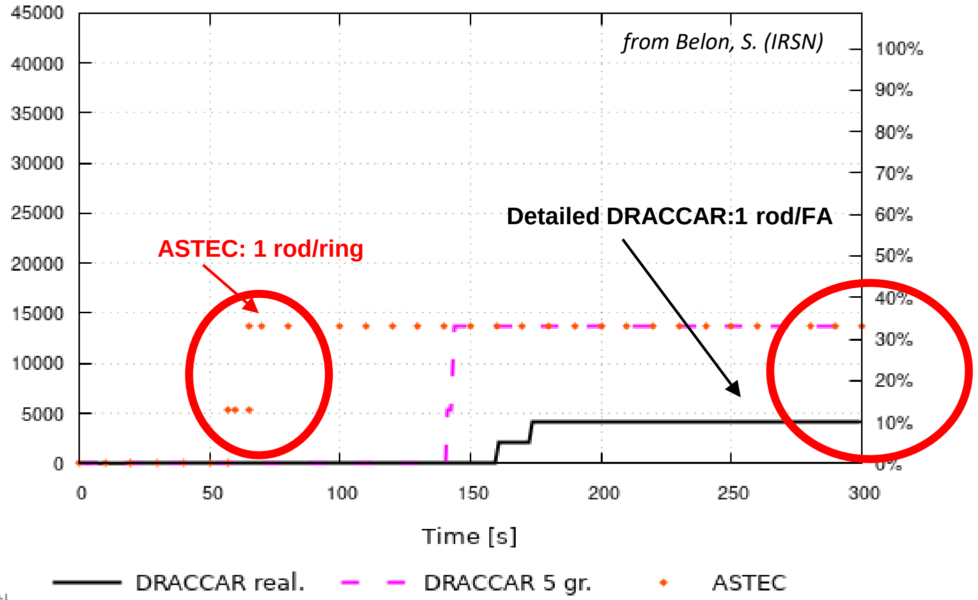
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- PWR LOCA DBA: DRACCAR/ASTEC calc. of IB (16,3'' in CL) + LOOP + ½ DG
  - Improvements made:
    - New DRACCAR core modelling approach (1/8th of core ⇔ 26 FAs): average 2D model (at least 1 equivalent rod/FA, 2D(r,z) thermal meshing, 2.5 D (Θ,z) for clad contour/creep) with contact detection, 3D-2-phase model for core T/H (1 channel/FA+ 1 D T/H in RCS)
    - New burst criteria specific to burst risk assessment
    - Chaining of ASTEC FP modules with DRACCAR + Gap release of FP evaluated for each FA

Later PCT : 170 (DRACCAR) vs 65 s (ASTEC)



Lower failed rod number : 10 (16 FA) vs 33 %



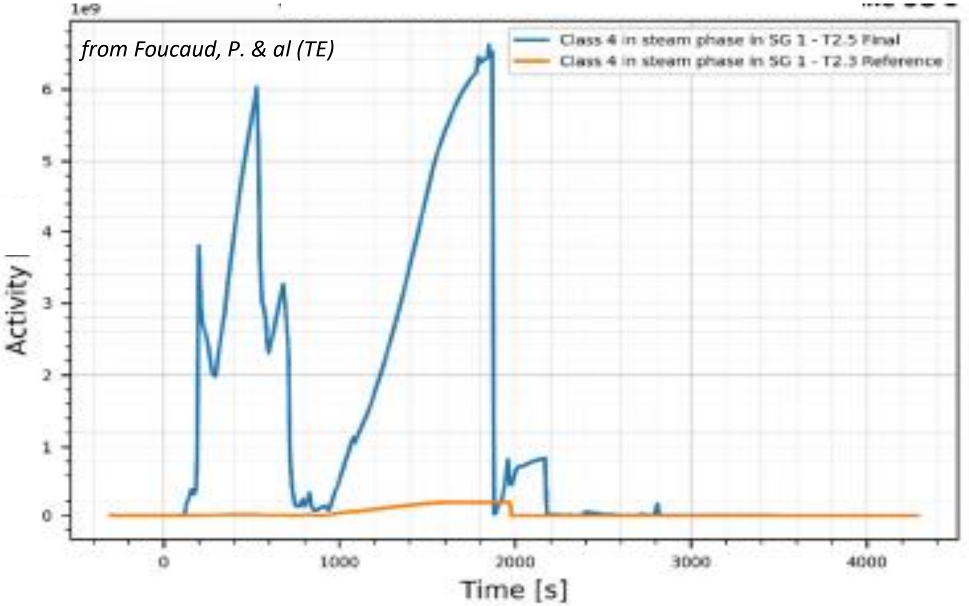
(presentation 3.5)

Impact: Updated SGTR Reactor Calculations

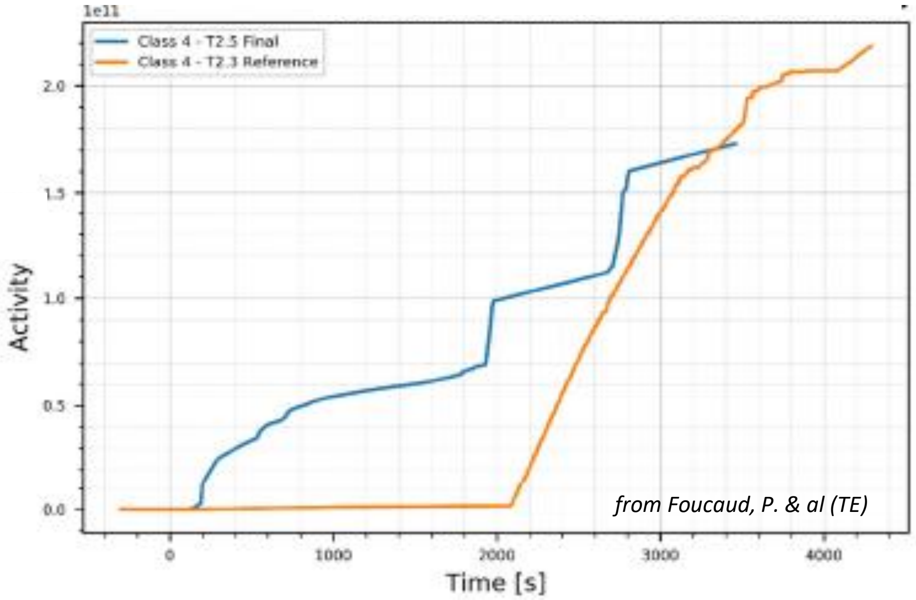
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- PWR SGTR DEC-A: SGTR +SLBOUT
  - Improvements made:
    - Optimization of EOPs : faster controlled RCS depressurization to reduce break mass flow rate and releases into environment + earlier HPSI pump trip
    - Refinement of iodine partitioning model in SG taking into account increase with T, and evaporating conditions

higher iodine activity in gas phase



early higher iodine activity release in env^t



BUT finally lower activity released in env[t] and RC incl. for iodine (eq. thyroid doses)

Impact: ATF evaluation

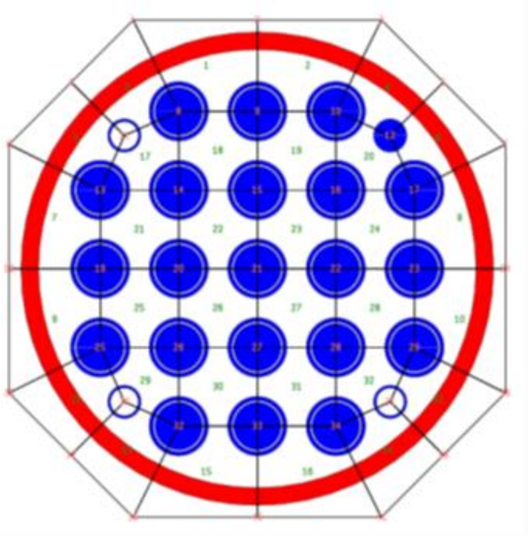
AMBITION

Evaluate advanced fuel-rod concepts that better withstand accidents

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

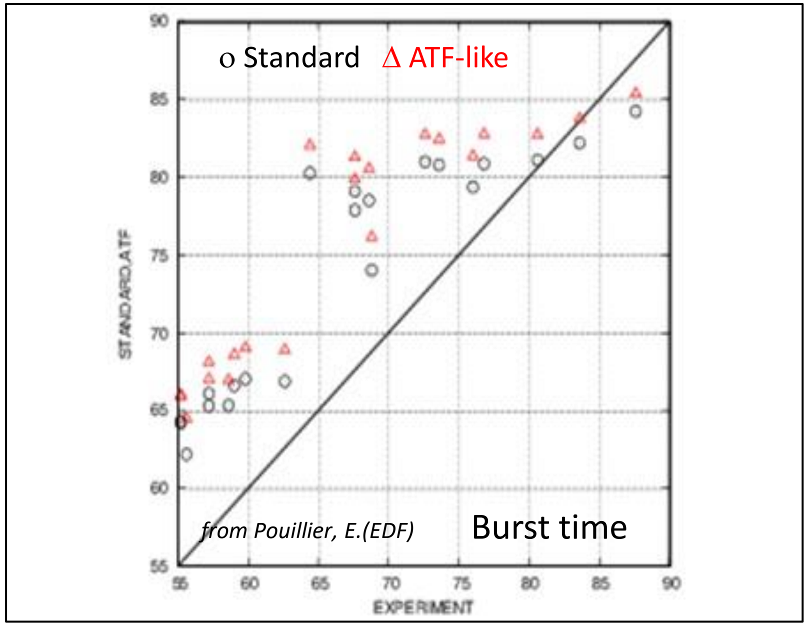
New evaluations of some ATF concepts using updated calc. chains, code extension capabilities with various ATF properties, uncertainty & sensitivity studies on relevant parameters

● Cr-coated Zr evaluation in LOCA (QUENCH L1 test)



DRACCAR modelling

Total number of fluid/structure meshes : 1632/12720



- Detailed DRACCAR modelling of QUENCH L1 test with Cr-coated Zr-4 rod bundle and decreased creep rate indicating a delayed rod burst (consistent with burst occurrence @ higher P/T)
- ATF-like burst criterion & oxidation not considered

(presentation 3.8)

Summary

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **D**ifferent kinds of improvements made for both LOCA & SGTR calculations
  - ✓ Updated approach of core modelling & nodalisation
  - ✓ Enhanced tool coupling, use of mechanistic models to improve low-informed tool prediction
  - ✓ Upgraded simulation tools/models at different levels of details for most impacting processes regarding environmental radioactive releases

  ↪ new validated numerical tools in support to the integration of DBA/DEC-A accident risks (ST evaluation) in design phase of future NPP concepts

- **P**rovided updated calculation chains lead to less conservative assessments of RC in LOCA/SGTR sequences within DBA/DEC-A conditions in different concepts of NPPs.

- **M**eans/actions to reduce RC (i.e. timing, operator's actions, accident management procedures optimization & early defect detection tools (incl. use of Neural Network) were proposed

- **N**ear-term ATFs were evaluated through updated methodologies & Sensitivity Analyses

Thank you!

- Presentations in Conference (2021/22): NENE, SNE, TOPFUEL, NURETH19…
- Journal papers (Nucl. Eng and Tech.)
- 1 ANE special issue expected for the end of 2023
- All public deliverables will be archived in Zenodo (R2CA project community) & R2CA public website (https://r2ca-H2020.eu)

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