R2CA Newsletter

Issue 3

31/10/2022

What's new in R2CA

The third year of the project was mainly focused on the R&D work where several model improvements in various codes and new calculation methodologies were initiated both for LOCA and SGTR scenarios.

The main outcomes of this still on-going R&D work are highlighted in this newsletter. It concerns for LOCA the progresses made towards a better evaluation of the number of failed rods in a core and the associated fission product releases. For SGTR the main advances are related to the modelling of the increase activity release from a defective fuel rod during a power transient (i.e., the so-called iodine spike) and of the secondary clad hydriding phenomena in normal operation potentially further weakening its integrity.

Some of the main advances can be summarized as follows:

- **For failed rod number evaluation:** best-estimate exponential true stress models developed and updated correlations for clad creep, new core modeling approaches proposed (incl. 3-D fine meshing or increased number of fuel sections)
- **For fuel rod transient behavior:** revised models for high burn-up structure formation and growth proposed, fuel performance and fission product release code coupling
- **For fission product releases (**from defective fuel rod under transients): updated correlations for iodine (cesium) spiking activity and for iodine gas/liquid partitioning, developments of detailed models for gap releases in normal and transient conditions initiated
- **For clad secondary hydriding** (in defective rods)**:** new H_2-uptake tests performed (on Zr4/E110), models developed for axial gas transport in fuel gap, clad secondary hydriding (incl. H_2 in-clad radial re-distribution, hydride precipitation)

In parallel, results from the first set of reactor calculations were analyzed and the main lessons learned.

All these advances will be reported in a special issue of ANE scheduled for the end of 2022.

Nathalie Girault, IRSN

Mobility program

The mobility actions in R2CA are now on the starting block. The COVID-19 caused delays, but now seven Master of Science students, Ph.D. students, and PostDoc are looking forward to working in hosting institutions within the project. The envisaged activities concern modelling and simulation, with developments towards code improvements. In detail:

- three mobility actions will focus on the coupling between the fission gas/fission product behavior code SCIANTIX and different fuel performances used in R2CA (i.e., TRANSURANUS and FRAPCON/FRAPTRAN);
- one mobility will target the use of TRANSURANUS/SCIANTIX to complement CATHARE and MELCOR calculations.
- one mobility will evaluate the improved capabilities of the TRANSURANUS/MFPR-F code in predicting fission product release from high burnup structure.
- the last two mobilities will address the FP transport during the SGTR transient and the optimization of accident management. Via these mobilities, it is possible to speed up code development by giving direct access to software, data, and expertise to young researchers, which positively propagates into the education and training outcome of the project.

E. Luzzi, POLIMI

Main outcomes of first set of reactor calculations

About 48 accidental scenarios (both **LOCA and SGTR**) were calculated on different kinds of reactor designs (**VVERs, PWRs, EPR and BWR**), covering both **DBA and DEC-A** conditions.

Various methodologies based on different modelling computer codes or process assessments were used by the R2CA partners based on their own experience, commonly used methods in their countries, and existing modelling codes.

For **LOCA** three types of modelling approaches can be distinguished:

1. Detailed simulations of all phenomena were performed (incl. thermal-hydraulic, fuel thermo-mechanics, fission product release, transport and behaviour in both primary circuit and containment) using complex coupled and detailed computer codes.
2. Detailed thermal-hydraulic and thermo-mechanical analyses were provided. However, conservative/empirical assumptions for the FP releases and behaviour were made.
3. Only thermal-hydraulic analysis was provided, and assumptions made for fuel failures. Taking them into account, the FP behaviour was then simulated using computer codes.

Noble gas releases (especially Xe) via containment design leakages mostly dominated the environmental activity, but iodine depending on the considered scenarios (in particular containment spray actuation) also played a significant role. Environmental activities were found to differ by two orders of magnitude for VVERs and PWR reactors both for DBA and DEC-A cases. Apart from differences in the approaches used for calculating the containment design leakages and differences in containment vessel designs, several other factors play an important role such as containment inventories, fission product distribution between the containment liquid and gas phases and iodine chemistry consideration.

For **SGTR** two types of modelling were used:

1. For iodine release in the primary coolant from a defective rod (i.e., iodine spiking modelling) where either simple model with fitting parameters or empirical assumptions for primary circuit activity increases based on NPP feedbacks were used.
2. For iodine behaviour in the failed steam generator from gas/liquid partitioning only to a more detailed simulation also including iodine flashing and atomisation.

Environmental activity releases strongly differ. They strongly depend on scenarios (whether steam generator overflows or not), on the level of modelling details (partitioning/flashing /atomisation) and on whether only iodine or a more complete list of fission products is considered. The most impactful parameters and hypotheses for activity (esp. iodine) release predictions are the primary coolant steady-state and transient (spiking) activity and the partition between liquid and gas phase in the faulted steam generator.

T. Kaliatka (LEI), M. Salmaoui (TE), N. Girault (IRSN)

Fuel failures during Loss-Of-Coolant Accidents and releases -1

Better evaluating the number of failed rods in a core during a Loss-Of-Coolant Accidents is one of a key challenging issue towards a best estimate evaluation of their consequences. Several ways to reduce the uncertainties in code failed rod predictions are investigating within the R2CA project, whose **clad burst criteria, and core meshing refinement**.

The definition of burst criteria is often made difficult by the large experimental strain and stress data scattering, greatly contributing to code calculation uncertainties. For the reduction of these uncertainties which helps the establishment of new burst criteria, several solutions are under study. One of them consists in the refinement of the measurements of ballooned and burst test sample geometries. **Cladding burst failure models in several different codes such as FRAPTRAN & DRACCAR were also reviewed**. To re-assess the burst criteria in this latter, a large burst database from legacy experimental tests was built.

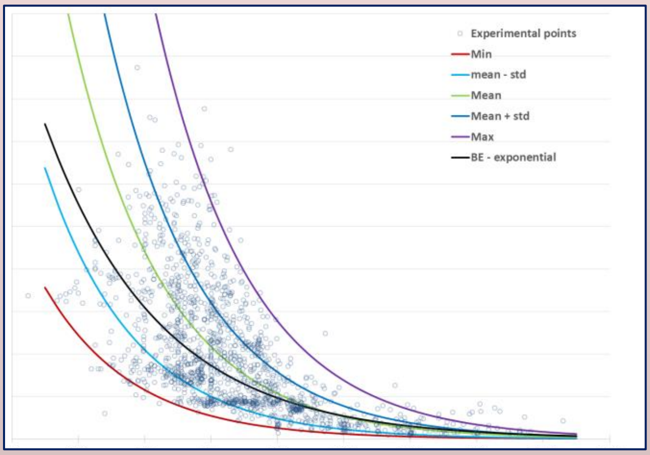


Figure 1: True burst stress versus experimental burst temperature, best estimate model and exponential models for statistical parameters (X & Y axis values are not shown).

More than **1400 burst tests** from about 20 experimental programs were thus collected, most of the tests were run on **Zy-4** cladding under **temperature ramp tests**. Best Estimate Chapman type models on engineering and true burst stresses as well as exponential models with and without the impact of the heating rate were adjusted. Finally, different exponential models were adjusted in order to obtain minimum, maximum, mean, mean ± std **correlations on true burst stress**. These correlations can now be used for sensitivity analysis to evaluate the number of failed rods during a LOCA.

Core meshing strategy is also a key issue to assess the extent of core damage and the failed rod number during a Loss-Of-Coolant Accident. Several methodologies to model the core more realistically, are also under investigation within the R2CA project.

The **statistical approach** to the fuel failure quantification using the TRANSURANUS code was further tested where both code models and fuel rod parameters were sampled with their uncertainty range. The bounding envelope of the rod powers (i.e., peak linear heat-rate) as a function of burn-up was thus determined and the non-burst threshold determined.

Fuel failures during Loss-Of-Coolant Accidents and releases - 2

Besides, **new approaches for core meshing** were developed **in both ATHLET-CD and DRACCAR** codes**.** The **DRACCAR code capabilities** were thus **extended by mixing different modelling scales** with fined assembly description at sub-channel scale as well as coarser 3D core meshing with lumped volumes and using at least one equivalent representative rod per fuel assembly. Both scales are intended to be used to predict the whole core response to a Loss-Of-Coolant Accident with the **3D detailed meshing** used to assess the fuel rod burst potential for each fuel assembly accounting for their location in the core and characteristics (i.e. power and initial state before the accident) as well as the presence of cold/hot spots in the fuel assembly associated to thermal field (guided tubes, local power) and 3D flow distribution between fuel rod sub-channels (influenced by clad deformations).

Finally, in **ATHLET-CD** the possibility to **sub-divide the core into a user-defined number of sections** located within an x-y coordinate system was implemented**.** This refined meshing offers the possibility to model the PWR Konvoi core with up to 1737 active core sections (i.e. with a subdivision of each fuel subassembly in the core). The extended ATHLET code capabilities means that several different groups of fuel rods within one sub-assembly can be distinguished as a function of their power and/or burn-up and the highest-power fuel rods assessed separately thus refining at the end the failed rod number prediction.

Finally, regarding the fission product releases **a refined two-way coupling of the TRANSURANUS fuel performance code with the mechanistic chemistry code MFPR-F and the 0D grain-scale code SCIANTIX,** tailored for fission gas behavior modelling, was performed.

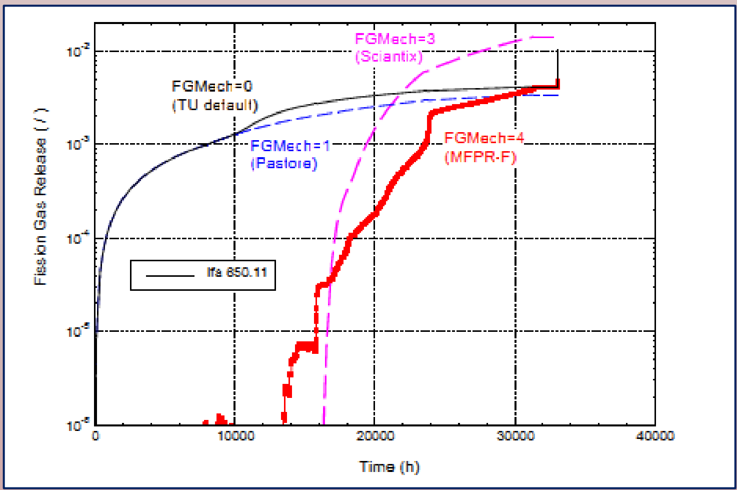


Figure 2: Total fission gas release in IFA 650-11 (56 MWd/kgU) during the base irradiation with different options of the latest TRANSURANUS version.

The improvements are a better description of the fission gas distribution within the fuel and the modelling of the **high-burnup structure (HBS)**, with the final goal of improving the description of pellet-cladding mechanical interaction. Considerable differences in both kinetics and total fission gas releases however still requires further analysis.

Defective fuel rod behaviour during normal operation and transients - 1

During a steam generator tube rupture (SGTR) event the system parameters will change, and activity release associated with iodine spiking is expected from defective fuel rods. The amount of released activity from those fuel rods must be estimated as, in containment by-pass accidental scenarios (such as SGTRs), it can lead directly to activity releases in the environment.

Improvements of the iodine spiking model and extension to the modelling of caesium isotopes were performed both in the RING and MAAP code. In the latter case**,** new coefficients for iodine and cesium linear activity increases in primary circuit after scram were added and validated on NPP experimental measurements and by comparisons with the reference code COSAQUE.

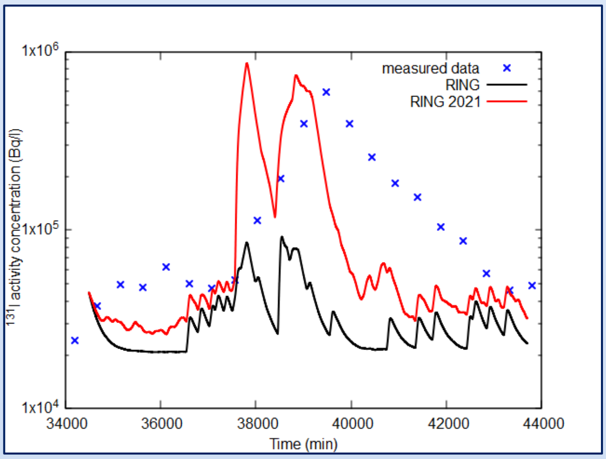


Figure 2: Measured and calculated coolant ^{131}I activity concentrations using the original (RING) and improved (RING 2021) code versions

Fitting of the new coefficients of the spiking model in the RING code was performed using reactor shutdown, power change and startup transients of a VVER-440 NPP. The results showed that the effect of power change was underestimated by the previous version of the code. The introduction of the new cesium spiking model was based on available measured data. The correlations for ^{134}Cs and ^{137}Cs are like that of ^{131}I, and take into account the effects of power, pressure, and boric acid concentration changes during the transient.

This model will allow us to estimate the activity release according to the specific power and pressure histories of the two events more precisely.

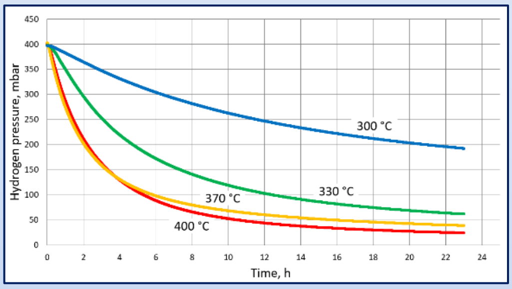
From LWR operational feedbacks, the risk of fuel defect occurrence during its entire lifetime, though reduced, cannot be completely eliminated. The main modes of fuel failure are due to debris fretting or debris-induced failures. The main indicator of a fuel failure is an increase of the primary coolant activity, but the fuel failure may not be noticeable enough. In case not and if no measures are taken, the fuel primary defect can further lead to an increased clad embrittlement through secondary hydriding in normal operation and, in case of power transients, to a spike in primary coolant activity.

Evaluation of secondary hydriding phenomena were both addressed through the performance of new H_2- uptake experiments and model improvements. The measurement of the hydrogen uptake by two Zr alloys in the range of 300-400 °C, representative of defective fuel rod cladding temperatures under normal conditions, was thus carried out. The investigated cladding materials were Zircaloy-4 and sponge based E110.

The experimental set-up consisted mainly of an electrically heated three-zone tube furnace with a quartz tube put in it containing the sample holder and can be evacuated or filled up with argon or hydrogen gas.

Defective fuel rod behaviour during normal operation and transients - 2

The hydrogen content of the samples could be estimated both from the continuous on-line measurement during approximately one day of the hydrogen pressure decrease during the tests (Fig. 2) and from the sample gain in weight evaluated after the tests. The experimental data showed the increase of hydrogen uptake and the temperature. The hydrogen uptake of the two tested alloys was found to be significantly different.



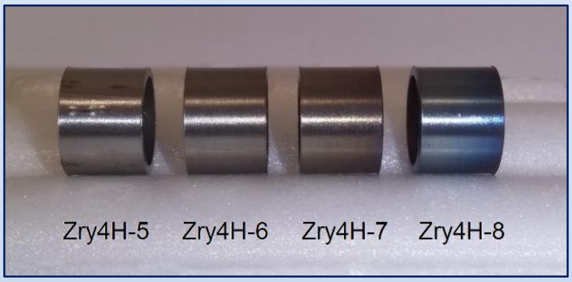


Figure 2: The hydrogen pressure during the experiments with Zircaloy-4 samples at different temperatures (left) and view of the samples after the hydrogen uptake test at 400 °C (right).

Meanwhile, several models were developed to better simulate the clad secondary hydriding with FRAPCON and SHOWBIZ codes. More especially, for in-clad hydrogen redistribution, a new 1D-model was derived from the literature review for the hydrogen performance across the cladding thickness and coupled with FRAPCON fuel performance code. This new model considering a faster precipitation rate results in a slower mobility of absorbed hydrogen within the cladding thickness, giving rise in turn to a localized accumulation/precipitation of hydrides.

Z. Hòzer, EK

WP6

Among the various dissemination activities developed along the year, a **Special Issue in Annals of Nuclear Energy Journal has been proposed.** The R2CA special issue will be focused on the mid-term results of the project. Several papers about the project results are under preparation.

Along the 3rd R2CA annual progress meeting, **15 participants belonging to 7 different organizations participated to the DRACCAR software short training.** This training was proposed by IRSN and hosted by ENEA in Bologna. As an introduction, the IRSN FUEL+ platform was presented to R2CA partners, it regroups a set of software focused on fuel behavior at different scales and in different contexts – RIA, LOCA, storage & transport. Then during the training, the scope of the DRACCAR software and its specific modeling dedicated to LOCA simulation were described. In particular, the meshing allowing to represent 3D multi-rod configurations and the strong coupling between thermo-mechanic and thermohydraulic in LOCA conditions were demonstrated using simulation cases. As an extent to this training, specific developments and extensions of DRACCAR software are developed by IRSN in the frame of R2CA and regularly presented to R2CA partners during technical meetings. It mainly concerns the new core methodology development in WP3.2 and the evaluation of radiological consequences during LOCA using new DRACCAR/ASTEC chained simulations in WP2.5. This training and communication on DRACCAR software participate directly to the knowledge dissemination by highlighting the simulation advances to evaluate radiological consequences during LOCA.

Events of interest for the R2CA community:

- 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20), August 20–25, 2023, Washington, D.C. (USA) (Abstract Deadline: October 1st, 2022)
- TopFuel 2022 Light Water Reactor Fuel Performance Conference, October 9–13, 2022, Raleigh, NC (USA)
- New Horizon Euratom projects kick-off meetings: **SEAKNOT** (October 3rd – 5th, 2022, Madrid, Spain), **SASPAM-SA** (October 12th – 13th, 2022, Bologna, Italy), **ASSAS** (November 28th – 30th, Aix-en-Provence, France)

Participants to the DRACCAR software short training hosted in Bologna (September 19th-20th 2022)

Dissemination activities

[1] Zimmerl, R., Anzengruber, L., and Mueller, N., "*Code to experiment comparison of a steam generator hot header break at PSB-VVER Test Facility with RELAP5/SCDAP 4.1 Thermal Hydraulic System Code*", the 19th International Topical Meeting on Nucklear Reactor Thermal Hydraulics, NURETH-19, Burssels, Belgium, March 6 – 11, 2022.

[2] T. Kaliatka T. Kacegavicius, P. and A. Kaliatka, "*Analysis of LOCA Accident for BWR-4 under DEC-A conditions using ASTEC code*", the 10th European Review Meeting on Severe Accident Research (ERMSAR2022), Akademiehotel, Karlsruhe, Germay, May 16-19, 2022.

[3] R. Iglesias, L. E. Herranz, "*Extension of the MELCOR code to DEC-A SGTR scenarios*", 47th Annual Meeting of the Spanish Nuclear Society, 28-30 September, Cartagena, Spain.

[4] R. Calabrese, "*Crystallographic phase transition of zirconium alloys: simulation of LOCA accidents with the TRANSURANUS code*", 31st International conference Nuclear Energy for New Euorope, NENE2022, Portoroz 12-15 September 2022.

[5] P. Van Uffelen, A. Schubert, Z. Sosti, "*Assessing the effect of some ATF material and uncertainties on their properties under normal conditions by means of the TRANSURANUS code*", PBNC 2022, Chengdu, China, October 30 – November 4, 2022.

R2CA Members

17 Organizations (11 Countries)

Duration

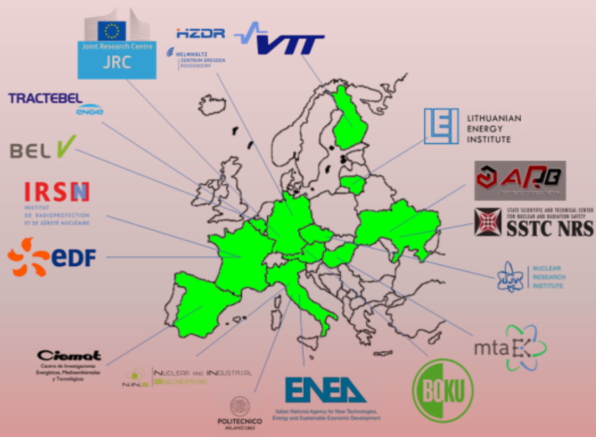
01.09.2019 – 31.08.2023

Commitment

522 person/months

Overall Budget

€ 4.2 M€ (~ ¾ funded by EU)



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