DRACCAR: a multi-physics code for computational analysis of multi-rod ballooning and fuel relocation during LOCA transients

Part Two: Assessment of modeling capabilities

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Abstract

Computational predictions concerning ballooning of multiple fuel pin bundles during a loss of coolant accident with a final reflooding phase are now more than ever of interest in the framework of light water reactor nuclear safety. To carry out these studies, two difficulties have to be overcome. First, the modeling has to take into account many coupled phenomena such as heat transfer (heat generation, radiation, convection and conduction), hydraulics (multidimensional 2-phase flow, blockage), mechanics (thermal expansion, creep, embrittlement) and chemistry (oxidation, hydriding). Secondly, there are only a few experimental investigations that can help to validate such complex coupled modeling. Over several years, IRSN has developed the 3D computational tool DRACCAR to investigate rod bundle strain during LOCA transients including prediction of the reflooding phase. The DRACCAR code is dedicated to study complex configurations such as the deformation and possible contact between neighboring rods and the associated blockage of thermalhydraulic channels in the ballooned zone of the fuel assembly. To accompany the development of DRACCAR, efforts have been devoted to the validation of the coupling between the thermo-mechanics and thermalhydraulic models - including reflooding - through a comparison to integral experiments dedicated to LOCA. The DRACCAR capabilities and validation status are depicted for the version DRACCAR V2.3.1. DRACCAR provides an interesting insight on LOCA by simulating multi-rod and fluid interaction which cannot be investigated with a classical single rod approach. As a conclusion, some prospects regarding the development and validation of the future version DRACCAR V3 are mentioned. In particular significant evolutions are expected regarding the cladding rupture prediction, the contact simulation and the assessment of the coolability of deformed geometries. These evolutions will be based on the knowledge acquired through the R&D project PERFROI, a project dedicated to LOCA, launched by IRSN in association to other partners and supported by the French National Research Agency (ANR).

Keywords: LOCA - DRACCAR - validation - modeling

1. Introduction

1.1. Background and Context

With respect to the possible consequences of Loss Of Coolant Accident (LOCA) occurring on a light water nuclear

reactor, these accidents were largely investigated through research and development activities in the frame of nuclear safety. To contribute to the safety assessment or to design the emergency safety systems, the evaluation of important parameters such as the peak cladding temperature and its comparison to the safety criteria are done mainly using two types of modeling : single rod based modeling or more recently multi-rod model-

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ing. If the first category was and is still largely used for safety assessment, the second one offers some interesting evolutions. Multi-rod approaches can deal with the complex 3D thermo-mechanical behavior inside a fuel rod bundle associated with appropriate 3D thermalhydraulics modeling. It allows to describe contact between deformed rods, blockage of thermalhydraulic channels and its impact on the coolability. In the frame of its LOCA R&D programme, since 2009, IRSN is developing the DRACCAR platform which aims to describe the ballooning and the oxidation of a fuel assembly and to simulate the 3D thermalhydraulic flow within the bundle during a LOCA transient including the reflooding phase. This article belongs to a set of articles which aims to present DRACCAR code. The first part was dedicated to physical modelling description ([Glantz et al. \(2018\)](#)). The present paper corresponds to the second part which describes the validation status of DRACCAR code. It concludes on the prospects to improve DRACCAR predictive capability. First, a description of DRACCAR platform will be briefly recalled in this paper. Then the validation process associated with the DRACCAR software will be generally presented in section 2. In addition, details are provided about the validation on separate effect tests for thermal-chemistry (section 3), hydraulics (section 4) and on integral LOCA tests (section 5). Selected illustrations on the validation reflects the code predictive capability and some remaining challenges. As the validation of a code is strongly coupled to the reliability of the experimental data and therefore to the uncertainties of the measurements or test conditions, an example that includes such aspects in the frame of DRACCAR validation is given in section 6.

1.2. DRACCAR overview

DRACCAR is dedicated to the analysis of multi-rod ballooning in LOCA conditions for light water nuclear power reactors. It describes :

- the thermo-mechanical behavior of fuel rods (creep and burst of cladding, fuel relocation within balloon),

- the thermo-chemistry (oxidation of Zircaloy by steam or air),
- the thermalhydraulics in the fuel bundles (3D thermalhydraulics in deformed geometries) as well as in the circuit (1D-model for the reactor primary loops and secondary circuit).

DRACCAR is a platform that couples its thermo-mechanical code describing the core structures, ICARE3D, to different thermalhydraulics : the CATHARE-3 code (developed by CEA, ([Emonot et al. \(2011\)](#)), financed by AREVA, CEA, EDF and IRSN) and CESAR module (from the severe accident code ASTEC developed by IRSN, [Chatelard et al. \(2016\)](#)). The coupling method as well as the details on physical modeling are largely described in [Glantz et al. \(2018\)](#). Only few elements are recalled to provide enough context for the following section. DRACCAR is a multi-physics code involving mechanics, heat transfer, chemistry and hydraulics. As a consequence, individual descriptions of phenomena use simple models and complex phenomena are often described using semi-empirical laws. It results that its verification against theoretical solution cannot cover completely the applicability domain and that experiments are needed to validate the code for its final application : the assessment of thermo-mechanical behavior and coolability of fuel assemblies during LOCA transients. To answer this challenge, IRSN is operating the PERFROI research programme promoted by the French National Research Agency (ANR) dedicated to LOCA (ANR project ref. 11-RSNR-0017, programme detailed in [Repetto et al. \(2017\)](#)).

2. DRACCAR validation strategy and status

2.1. DRACCAR validation strategy

In this article, the term validation corresponds to the comparison of the code predictions to experimental data. Thus, validation will not deal with comparison to analytical solutions or numerical test cases which are therefore tasks linked to the verification process out of the scope of this paper. The application domain of DRACCAR code and the capabilities of software

to simulate LOCA were described in a state of the art review (Grandjean (2005) and Grandjean (2006)). This review highlighted the remaining needs regarding experimental data necessary for code validation. The validation of DRACCAR is based on the main experiments devoted to phenomena involved in LOCA and includes several level of observation, from separate effect tests to large-scale experiments.

The validation aims to verify that the retained physical description (models, meshing) implemented in the software to describe the real phenomena is adequate enough and provides reliable results compared to experimental observations. Experiments provide a reflection of reality and code to experiment comparison allows to judge the accuracy of the code to simulate LOCA and predicts margins with respect to the safety criteria (peak cladding temperature, equivalent cladding reacted, ...). According to the discussion and classification of the numerous experiments dedicated to LOCA done by Grandjean (2006), relevant experiments were selected for the validation matrix of DRACCAR taking care of the associated experimental uncertainties and the availability of experimental data. Validation is as well as verification a continuous process which accompanies code development and evolutions since the start of the DRACCAR project. Part of this validation work has been already presented for previous code version (Bascou et al. (2015)).

A peculiarity of DRACCAR platform is related to its coupling to existing thermalhydraulic codes (CATHARE-3 (Emonot et al. (2011)) or CESAR (Chatelard et al. (2016)) codes). That strategy was chosen to save time in the development and the validation of a thermalhydraulic predictive tool within DRACCAR. Indeed, this choice gives a first level of confidence on the system thermalhydraulic simulation provided by the verification and validation status of the coupled reference codes CATHARE-3 (Valette et al. (2011)) and ASTEC (Bandini et al. (2010)). Of course, the validation of DRACCAR has to deal with the coupling and interaction of the thermalhydraulics and the thermo-mechanical models in the DRACCAR context (3D meshing, LOCA conditions including reflooding).

2.2. Validation matrix

According to a building block approach, the validation of DRACCAR models is achieved using experiments with different levels of complexity - from the simpler consisting in separate effect tests to the more complex one regrouping the so called integral tests. Table 1 presents the separate-effect tests selected for the mechanical, chemical and hydraulic validation. The first level of validation corresponds to the separate effect experiments which study one physical or chemical phenomenon for instance Zircaloy oxidation, cladding creep and burst or reflooding of fixed geometries. One can notice the numerous experiments dedicated to the reflooding in intact geometries (PERICLES, ROSCO) and in fixed deformed geometries (FEBA, SEFLEX, THETIS and ACHILLES). It shows the importance to simulate this phase of the accident which involves complex flow configurations and heat exchanges and whose success is clearly associated with the nuclear safety criteria (peak cladding temperature, equivalent cladding reacted).

In our terminology, the integral tests correspond mainly to large-scale experiments which couple most of the phenomena involved during LOCA and therefore which are representative of these accidents. Of course regarding only thermalhydraulics, reflooding experiments such as PERICLES or FEBA would have been considered as integral tests (as complex heat transfer with two-phase flow are involved). However according to the objectives of DRACCAR, these experiments are not considered as integral in our classification because the coupling between heat transfer, thermalhydraulics and the deformation or damage of the fuel rods were not investigated.

In addition to LOCA integral tests, the initial phase of severe accident tests corresponding to heat-up phase until damage and melt of materials complete the validation domain regarding the heat transfer and oxidation models and coupling. The table 2 summarizes the integral LOCA or severe accident tests selected for the validation of DRACCAR.

Field	Name	Overview	Ref.
Mechanics	EDGAR	Single rod creep and burst tests	
Thermo-hydraulics	PERICLES ROSCO	Intact bundles reflooding	
	FEBA SEFLEX THETIS ACHILLES	Bundle blockage impact on reflooding	
	BETHSY 6.2TC CEGB PSBT	6 inches LOCA Aeraulic tests Void fraction distribution	
Thermal-chemistry	PHEBUS SFD B9+ MARGO-R	Zry-4 steam oxidation	ISP 28

Table 1: Separate effect experiments composing the validation matrix of DRACCAR V2.3.1

Name	Overview	Ref.
CORA-13	Out-of-pile severe fuel damage test on 25 rods (only the early phase is validated)	ISP 31
PHEBUS FPT1	Severe fuel damage in-pile test on 20 rods (only the early phase is validated)	ISP 46
PHEBUS LOCA 215R	In-pile LOCA test on 25 fresh fuel rods	ISP 19
PHEBUS LOCA 218	In-pile LOCA test on 25 fresh fuel rods	
NRU MT-3	In-pile LOCA test on 32 full-length fuel rods	ISP 14
REBEKA-6	Out-of-pile LOCA test on 49 electrically heated full length simulators	
REBEKA-7	Out-of-pile LOCA test on 49 electrically heated full length simulators	
HALDEN IFA-650 SFP	In pile single rod tests on irradiated fuel Ignition of zirconium fire and bundle degradation during a Spent Fuel Pool drain-down	

Table 2: Integral experiments composing the validation matrix of DRACCAR V2.3.1

3. Thermal/chemistry validation

During a LOCA transient, the high temperatures and steam environment can lead to materials degradation. A few experimental tests concerning thermal/chemistry are included in the DRACCAR validation matrix. These tests are used to validate thermal models (heat transfers by convection, conduction, radiation, ...) and chemical models (oxidation of a cladding under steam or air atmosphere).

The MARGO-R program, performed by IRSN, was used to

validate the DIFFOX module, which calculates oxygen diffusion through the cladding. This program aimed to study the impact of a pre-oxide layer on the steam high temperature (1173-1473 K) oxidation behavior of Zircaloy-4 cladding tubes (Duriez et al. (2011)).

To illustrate the validation status of DRACCAR concerning thermal and chemical models, the simulation of PHEBUS B9+ test and of the Sandia Fuel Project (SFP) experiments are described hereafter.

3.1. PHEBUS SFD B9+

In the eighties, the PHEBUS B9+ test has been performed by the French IPSN (current IRSN) at Cadarache nuclear center. This experiment belongs to the PHEBUS SFD programme which investigated the damage mechanisms acting on an uncovered PWR core up to very high temperatures typical of severe accidents. This test was widely evaluated with other codes throughout the International Standard Problem #28 (Adroguer et al. (1992)). Only the early phase of the accident is simulated with DRACCAR.

The main objectives of this experiment were to study:

- Cladding oxidation,
- The mechanical behavior of a variable thickness of the external zirconia layer of the cladding containing molten zircaloy,
- The dissolution of UO_2 and ZrO_2 by molten Zircaloy,
- The relocation of the melt.

The PHEBUS SFD facility mainly consists of the PHEBUS driver core supplying the test fuel with nuclear power and a SFD (Severe Fuel Damage) loop reproducing the thermalhydraulic conditions relatively close to what would exist in a PWR under beyond design basis conditions. The PHEBUS B9+ test section consists of 21 PWR fresh fuel rods (5x5 arrangement, the four corner rods being removed) with a 0.8m total fissile height.

The test transient can be divided into three phases. First an oxidation phase was performed with a constant pure steam flow and three different power plateau leading to peak cladding temperatures of 1000, 1350 and 1600K. The second phase, under

pure helium, leads to temperatures about 2750K. Finally, the power was reduced to slowly cool the bundle.

The PHEBUS SFD B9+ bundle is modeled with DRACCAR taking into account symmetries in order to speed-up the calculation (1/8th of the whole test section is modeled - figure 1). The rods with internal heat generation and the shroud (with a helium layer) are modeled. Only the first phase with imposed steam flow is modeled since material melting is beyond the scope of the DRACCAR simulation.

Figure 1: PHEBUS SFD B9+ bundle modeling with DRACCAR

Figure 2: PHEBUS SFD B9+ test - Rod 3 cladding temperature

A comparison between experiment and calculation is presented on figure 2 for cladding temperatures and on figure 3 for fuel temperatures of rod number 3. There is a good agreement between calculation and measured temperatures. It illus-

Figure 3: PHEBUS SFD B9+ test - Rod 3 fuel temperature

trates the validation of heat transfer modeling in DRACCAR. Of course, the target phenomena of these experiment (e.g. the dissolution and the relocation of fuel) are out of the scope of the code and are therefore not described by its physical models.

3.2. Spent Fuel Pool applications

The DRACCAR simulation tool has been extended to Spent Fuel Pool accidents. DRACCAR cannot answer to the whole problematic of spent fuel pool accidents involving complex natural convective exchanges within the pool and with the atmosphere of the building. Nevertheless, DRACCAR modeling offers advantages such as its 3D-unstructured grid suitable for non-axisymmetric configurations and its physical models such as zircaloy oxidation in steam and air atmosphere as explained in chapter 7 of [OECD/NEA \(2015\)](#) dedicated to simulation tools and in [Bascou et al. \(2015\)](#). The validation of DRACCAR for such application is based on the Sandia Fuel Project (SFP) programme promoted from 2009 to 2013 by OECD/NEA and the U.S.NRC. This project addressed thermalhydraulic conditions and zirconium fire propagation during a complete loss of coolant for spent PWR fuel assemblies. That experimental program was divided into two parts. The first one was dedicated to the study of the axial heating and burn propagation in a single PWR assembly under oxygen, nitrogen and argon atmospheres ([Durbin et al. \(2016a\)](#)). The second one was focused on radial heating and burn propagation of one fuel assembly enclosed in

4 colder neighbouring fuel assemblies (Durbin et al. (2016b)). In addition to the test, benchmark involving partners with different simulation tools such as severe accident codes as well as CFD simulation tools showed that the measurements provides enough accuracy on the hydraulic for code validation and improvement (Adomi et al. (2016)).

The validation of DRACCAR on the tests phase I and phase II is largely described by Deluze et al. (2018). That work highlighted the different evolutions of the modeling that were necessary to depict the phenomenology involved in SFP accidents such as the axial radiative heat exchanges, the oxidation of cladding in steam or air atmosphere as well as a simple parametric model for nitriding of zircaloy cladding. Results obtained for the phase I demonstrate that DRACCAR captures the onset and the axial propagation of the ignition front which is clearly influenced by nitriding (figure 4). The good results obtained with DRACCAR on this test are well depicted by the accurate prediction of the temperature evolution (figure 5).

Figure 4: SFP phase I - Evolution of the ignition front against elevation axis in experiment (blue markers) and for DRACCAR simulations (with nitriding model (green solid line) and without (red solid line))

The phase II involves more complex phenomena and it appears that even if DRACCAR is able to predict a propagation to neighboring fuel assemblies, the thermal state of cells, prior or after ignition cannot be well estimated (figure 6). This is mainly linked to the difficulties to predict correct flow distri-

Figure 5: SFP phase I - Evolution of the temperature at elevation 3.30m in the experiment (blue dashed line) and for DRACCAR simulations (with nitriding model (green solid line) and without (red solid line))

bution within bundles which are noticeably driven by the temperature inside cells. Improvements regarding 3D-flow prediction in DRACCAR seems to be necessary to predict correctly the behavior on these tests. Airflow tests planned in COAL experimental programme (belonging to PERFROI) could lead to extend the capability of DRACCAR to simulate complex 3D configurations. Therefore, it would be interesting to re-evaluate the code predictions on these experiments. Regarding the zircaloy oxidation and nitriding phenomena in air or steam/air mixed atmosphere, IRSN pursues its effort to propose adequate models (Lasserre et al. (2013)) which would be implemented in the DRACCAR code. In the frame of the DENOPI experimental programme, supported by the French National Research Agency (ANR reference 11-RSNR-0006), IRSN operates experiments which will produce new knowledge on the phenomenology of these accidents and that will feed the development of models.

Figure 6: SFP phase II - Evolution of the temperature at elevations 3.32m (red), 2.62m (orange) and 2.52m (blue) in the experiment (dashed line) and for DRACCAR simulations (with nitriding model (solid line))

4. Thermalhydraulic / reflooding validation

The reflooding of the core is the last phase of a typical LOCA transient during which all the fuel rods have to be cooled-down in order to bring back the reactor to a safe state. The thermalhydraulic conditions (pressure, liquid temperature, ...) depend on many parameters of the LOCA scenario such as the break size or the availability of several safety systems. The assemblies state (power, rod deformations, burst, ...) may have an impact on the reflooding progress, this state being the consequence of the fuel rod composition and history (burn-up).

One of the main objectives of the DRACCAR code is to predict the temperature evolution of the cladding during LOCA including the reflooding phase. It needs to describe well all phenomena involved in the reflooding phase of a LOCA, for all possible type of thermalhydraulic conditions and assembly states. That is why the code has been largely experienced on this topic as indicated in Table 1. In fact, the validation database on the subject is composed of nearly 100 tests on 6 different facilities. These tests allow coverage of almost all assemblies' states and thermal-hydraulic conditions in the core which could be encountered during a LOCA.

In general, the reflooding procedure is quite the same in all

these experiments, that is to say that the considered bundle is composed of electrically heated rods which are heated up to a desired temperature at a constant pressure. Then, liquid water is injected at the bottom of the test section with a constant flowrate and a constant temperature. Experiments end when the whole test section is refilled.

The PERICLES programme (Veteau and Digonnet (1989)) has been carried out in the 1980s by the French Commissariat à l'Energie Atomique (CEA). Two different test sections have been studied in the PERICLES facility, the first one being cylindrical and composed of 368 unballooned rods and 25 guide tubes simulating a typical 17x17 French PWR assembly. This first test section was designed to study the influence of all thermalhydraulic conditions (pressure, rod power, injected liquid flowrate and temperature) characteristic of the reflooding phase during a LOCA. The second test section is rectangular and is composed of 3 bundles of 17x7 unballooned rods. It was dedicated to the study of the expected 2D effects during the reflooding phase caused by the different powers developed by adjacent fuel assemblies in a reactor core (Veteau and Digonnet (1985)). All the experiments performed within the PERICLES facility have been simulated with DRACCAR in order to develop and to validate its reflooding model (Glantz et al. (2018)).

The ROSCO programme (Bazin (1995)) has been carried out between 1992 and 1994 by the CEA. The tests in the ROSCO facilities are particularly relevant for the DRACCAR validation because the heater rods used in ROSCO are more realistic (bundle 4x4 using Zircaloy cladding, sintered boron nitride pellets, and a 50 μm wide gas-filled gap) than those used in the PERICLES facility. Moreover, reflooding in oscillating flow rate conditions has been studied in the ROSCO programme and therefore can extend the DRACCAR validation to such reflooding conditions.

The FEBA (Flooding Experiments with Blocked Arrays) programme (Ihle and Rust (1984)) has been carried out in the early 1980s by the German Kernforschungszentrum Karlsruhe (KfK, now KIT). It is series of separate effect tests under forced reflooding conditions performed on bundles composed of 25

electrically heated rods. Its purpose is to assess the effectiveness of the emergency core cooling system of a pressurized water reactor under channel blockage conditions due to rod cladding ballooning. The effect of the blockage ratio, the balloon position in the bundle (co-planar or not), and the number of ballooned rods have been studied in the FEBA programme. Some of these tests have been simulated with DRACCAR in order to validate its reflooding model in ballooned bundles.

The SEFLEX programme (Ihle and Rust (1987)) has been also carried out in the 1980s by KfK in order to complete the conclusions obtained in the FEBA programme. In particular, as for ROSCO programme, more realistic rods with Zircaloy cladding and gas filled gap have been used. The interest of this programme for DRACCAR is to validate its reflooding model on more realistic unblocked and blocked bundles.

The THETIS programme (Pearson et al. (1984)) has been carried out in the 1980s by the United Kingdom Atomic Energy Authority at the Winfrith Atomic Energy Establishment (AEE). The THETIS test programme investigated the heat transfer and rewetting processes in a fuel rod cluster composed of 49 full-length rods. On 16 of these rods, long co-planar swellings were simulated by attaching preformed balloons in order to form an idealized 80% partial flow blockage. THETIS tests have been simulated with DRACCAR in order to extend the validation database of the code to other ballooned geometries and flow blockages.

The ACHILLES programme (Dore and Pearson (1991)) has been carried out in the early nineties by the AEA Winfrith Technology Center and have the same objectives of the previous programmes, investigating the emergency core cooling of a PWR during a LOCA. In the ACHILLES experiments, unballooned clusters and 80% blocked bundles have been studied with particular attention paid to the grid impact on the reflooding and the droplet behavior. The DRACCAR database includes two ACHILLES tests. The first one focuses on pure steam flow and is used to validate the grid modeling of DRACCAR. The second one is dedicated to the forced reflooding of a ballooned cluster.

In the next paragraph, a focus is done on two experiments be-

longing to the DRACCAR validation matrix: one test from the SEFLEX programme and the other one from the ACHILLES facility.

4.1. SEFLEX

The SEFLEX programme (Fuel Rod Simulator Effects in Flooding Experiments) was aimed at providing some elements to answer issues raised by the FEBA programme (Flooding Experiments with Blocked Arrays) in terms of techniques used to simulate fuel rods and channel blockages. The purpose is to answer the following question : how fast are fuel rods realistically cooled down under given reflooding conditions compared to swaged heater rods. In order to represent more closely existing features in the actual fuel rod design, fuel rod simulator made of alumina pellets and Zircaloy claddings with a gas-filled gap in between were used in SEFLEX experiments. The DRACCAR validation matrix includes several SEFLEX experiments. Test number 5, presented hereafter, deals with the reflooding of an unballooned bundle. In this experiment, the test section was made up of 25 fuel rods arranged in a square array using 8 spacer grids of prototypic design and assembled within a rectangular stainless steel shroud vessel. The rod diameter and pitch were respectively 10.75mm and 14.3mm. The reflooding scenario consisted of a heating phase during which the clad temperature reached 650°C at the hottest point. During the second phase, the bundle power which was set to 200kW at the initial time is decreased following the decay heat law ANS71+20. At the same time, liquid water at 40°C was injected at 3.8cm/s in order to cool down the bundle.

The SEFLEX test section is modeled with DRACCAR accounting for symmetry considerations (1/8 of the whole test section is modeled - figure 7) in order to speed-up the calculation. The heating rods as well as the grids are represented with DRACCAR using a fine meshing (6273 structure meshes and 402 fluid meshes have been used). Concerning the scenario simulation, only the reflooding phase has been reproduced because the experimental data are not sufficient to calculate with enough accuracy the heating phase.

Figure 7: SEFLEX bundle modeling with DRACCAR

Figure 9: SEFLEX test - clad temperature evolution

at 0.115m (curve 1), 0.66m (c. 2-3), 1.205m (c. 4-5) and 1.75m (c.6-7)

A comparison between experiment and calculation is presented in figure 8 for the quench front evolution and in figure 9 for the clad temperature evolution of a rod located in the middle of the test section. The general trend is that DRACCAR simulation shows a good agreement with the experiment on the clad temperatures and quench front evolution. The main differences between the experiment and calculations can be explained by the experimental uncertainties on the measurements of the boundary and initial conditions such as the liquid inlet temperature and flow rate for example (see section 6).

Figure 8: SEFLEX test - quench front progression

4.2. ACHILLES

The ACHILLES experimental programme has been carried out to investigate the heat transfer in the core of a pressurized water reactor during the reflooding phase of a large break loss of coolant accident. Several tests performed on the ACHILLES facility have been used to validate the DRACCAR code, in particular the test A2R038 dedicated to the reflooding of a ballooned cluster (80% flow blockage) under forced and constant flow rate conditions. In this test, the test section was made up of 69 fuel rods assembled in a square array using 8 spacer grids of prototypic design. The bundle was surrounded by a circular stainless steel shroud vessel. The rod diameter and pitch (9.5mm and 12.6mm) were typical of a PWR. 16 of the 69 rods were fitted with ballooned sleeves which simulate clad deformation.

The experimental procedure is composed of two phases. During the first phase, the test section is heated until the clad temperature at the hottest point reaches 650°C. During the second phase, the bundle reflooding is performed by injecting liquid water at a constant flowrate of 0.15kg/s and at 24°C. During all the test, the pressure is kept constant and equal to 2.1 bar. These conditions are typical of LOCA conditions in a PWR.

Considering the symmetry of the device, only half of the whole test section is modeled with DRACCAR (figure 10) in

order to speed-up the calculation. Rods as well as the grids are represented using a fine meshing (32370 structure meshes and 1558 fluid meshes have been used). Concerning the scenario simulation, only the reflooding phase has been reproduced because the experimental data are not sufficient to well evaluate the heating phase.

Figure 10: ACHILLES bundle modeling with DRACCAR

A comparison between experiment and calculation is presented on figure 11 for the quench front evolution and on the figure 12 for the clad temperature profile of a ballooned rod. The DRACCAR results are in a relatively good agreement with the experimental measurement and except uncertainty studies, no real way of improvement was identified.

Figure 11: ACHILLES test - quench front progression

Figure 12: ACHILLES test - clad temperature profile

4.3. Prospects on thermohydraulic validation of DRACCAR

The previous examples of validation against reflooding experiment demonstrates that the knowledge on these valuable past programmes (from the 1980s) is sometimes insufficient (due to lack of available measurements) to achieve a satisfactory code to experiment comparison. This epistemic uncertainty limits the possible ways of improvement of the code. Moreover, the inference to the real application from the experimental results obtained through these programmes can be subject to discussion as the increase of power and thermal inertia in the balloon due to fuel relocation was not represented by the rod simulators and power profiles used. This issue will be addressed by the COAL out-of-pile experiment ([Repetto et al. \(2015\)](#)) designed by IRSN that should bring updated results on the reflooding of a deformed bundle in LOCA configuration with local overheating representative of fuel relocation and significant blockage rate.

5. LOCA integral validation

5.1. REBEKA 6

The validation of DRACCAR code regarding LOCA integral tests covered most of the out of pile integral experiments such as REBEKA-6. This test belongs to the REactor typical Bundle Experiment Karlsruhe (REBEKA) experimental program performed in the 1980s at Kernforschungszentrum Karlsruhe (KfK

known nowadays as KIT). This program was composed of single rod test rigs and of bundle tests loop such as REBEKA-6. That test was selected as an OECD/NEA International Standard Problem under reference ISP 14 (Karwat et al. (1985)). The test REBEKA-6 consisted of a 7x7 bundle out of pile configuration with flooding condition. The test was designed to study the influence of heat transfer and flow direction on the cooling of a deformed rod bundle during a LOCA accident. Even if realized with fuel rod simulators and out of pile, REBEKA bundle tests with reflood were considered to be the most realistic LOCA experiments performed up to 1986 Grandjean (2006). It allows to observe the interaction between thermo-mechanical and thermohydraulic phenomena (in the configuration and the conditions representative of a real LOCA with significant deformation and flow blockage). The device is composed by electrically heated fuel rods with Zry-4 cladding organized in a bundle with spacer grids reproducing a PWR fuel assembly (figure 13). The active heated part is at full scale (3.9m height). The test is divided into two phases. The first one corresponds to a heat-up phase in steam atmosphere (injection of 11.5g/s of steam at 4 bars and 150°C with constant power (7.8kW/rod) leading to a temperature ramp of +7°C/s representative of the quasi-adiabatic heating subsequent to the blow-down occurring during a LOCA. The second phase is initiated when the rod temperature at the elevation 1.85m reaches 765°C. During that phase, the power is decreased to 6.6kW/rod and water at 130°C is injected to quench the bundle with a velocity of 3cm/s.

Regarding the main results, the general trends concerning the thermal behavior and the mechanical deformation are well captured by the code. In comparison to previous validation work (Fargette (2017)), significant improvements especially regarding the reflooding phase were obtained with current version of the code, DRACCAR V2.3.1 (figure 14). Moreover, the presence of grids has been taken into account in the model. The deformation simulated by DRACCAR is in good agreement with the experiment except in the rupture zone (figure 13). It is mainly due to the creep law and rupture models used which are not able to predict the deformation during the rupture in-

stability. As a consequence, the simulation under-estimates the deformation at the rupture locations. The presence of a non-heated rod (index TF on figure 13) which creates an azimuthal temperature gradient - that impacts deformation - is well reproduced by the code. The use of Hot Side Straight Effect model (HSSE) was investigated in Fargette (2017). Nevertheless, this phenomena could not be studied in details according to the lack of available measured data. The blockage of the thermohydraulic channel is well reproduced (figure 15). Concerning the reflooding phase, the main trends of the reflooding phase are captured. In this phase, it was identified that the modeling which takes advantages of the symmetry of the test was not able to reproduce the scattering of temperatures observed during the reflooding (as illustrated by the quenching timings in figure 14). As a conclusion, this simulation has demonstrated that DRACCAR is able to predict a plausible deformation and thermal behavior of the rods. The prediction of rupture remains a difficult task. Concerning prospects, further analysis including sensitivity to the models and parameter could lead to fruitful discussion on the accuracy of the results. It could be completed by taking into account the uncertainties related to the measured data or test conditions. This challenge is clearly some of key concern in the frame of ELFE experiments (belonging to the PERFROI program). Fargette (2017) also highlighted some perspectives concerning the improvement of the evaluation of the deformation during the rupture instability using empirical approaches.

5.2. PHEBUS LOCA 218

The PHEBUS facility was a pool-type reactor with a nuclear core composed of 1576 0.8m-long fuel rods which provided a linear power up to 57kW/m. In the center of the PHEBUS core, a cavity allowed to introduce a vertical test cell. This test cell was able to house a test device where a fuel bundle composed of 25 0.8m-long fuel rods were loaded. The test device is connected to a pressurized water loop that reproduces the in-core steady conditions (pressure: 15.5 MPa, fluid temperature: 320°C, fluid velocity in the test section: 5m/s) as well as

Figure 13: Schema of REBEKA-6 bundle from Karwat et al. (1985) (a), - only colored part is represented in DRACCAR simulation - and REBEKA-6 cut view of the bundle at 116s simulated with DRACCAR (b)

Figure 14: REBEKA-6 test, ISP14 - Evolution of the rod temperature (for rod index, please refer to 13 (a)), MaxTC and MinTC corresponds to fuel rod temperature extremum measurements

Figure 15: REBEKA-6 test, ISP14 - Axial profile of the average blockage of the test section at the final time

LOCA transient conditions similar to those expected in a PWR (blow-down, refill and reflooding phases) by opening 'blow-down' valves and operating the safety injection system.

The objectives of the PHEBUS-LOCA test 218 were to investigate phenomena occurring inside a bundle of fresh fuel rods under LOCA representative conditions with a two peaks temperature history. The test was performed at Cadarache Nuclear Center (France) by the French Institut de Radioprotection et de Sûreté Nucléaire in July 1984. This experiment is an International Standard Problem referenced as OCDE/NEA ISP 19.

The rod bundle introduced in the PHEBUS core for the test 218 is made of 25 fresh fuel rods maintained by 4 grids. A rod is composed of UO_2 pellets and a Zircaloy clad.

The main goals of PHEBUS test 218 are:

- to reproduce the clad temperature evolution characteristics representative of the one obtained during the simulation of large break loss of coolant accident in a PWR;
- to obtain clad burst at the beginning of the transient;
- to obtain significant clad oxidation before the core reflooding.

The scenario of test 218 can be separated into several phases:

- Phase 1: The water loop depressurization and emptying are performed by opening two breaks (located on pipes connected respectively to the inlet and to the outlet of the bundle). As a consequence, the clad temperatures increase and lead to fuel rod deformation and burst;
- Phase 2: An adiabatic rise of the clad temperature increase occurs during the first part of this phase (no fuel cool down). Then the fuel power is controlled in order to maintain the clad temperature constant. As a consequence, clad oxidation occurs. At the same time, a partial water loop refill (up to the bundle inlet) is proceeded. This refill has no impact on clad temperature;
- Phase 3: In this phase, the water loop located below the fuel rods is full of water and the bundle reflooding is performed.

DRACCAR modeling concerns the test device including the fuel bundle and the pressurized water loop. The bundle of 25 fuel rods is simulated in 3D using a fine meshing composed of 7200 structure meshes and 360 fluid meshes. The water loop is modeled using typical 1D elements of the thermalhydraulic code CESAR : 179 meshes have been used to describe the fluid in the water loop pipes and 154 meshes for the wall of these pipes. The whole scenario of the test 218 have been simulated with DRACCAR.

DRACCAR results and their comparison to the experimental measurements are depicted on the figures 16 to 20. The calculation results are globally in good agreement with the experimental results. Indeed, from thermalhydraulic point of view, DRACCAR is able to estimate well the water loop depressurization (figure 16). It can be noticed that some differences between calculation and experiment exist concerning the fluid circulation in the water loop during the depressurization phase (figure 17). This discrepancy is probably due to a bad initialisation in the calculation of the fluid temperature in several parts of the water loop which correspond to dead zones. Unfortunately, those parts were not instrumented and feed into the epistemic uncertainties.

This discrepancy between experiment and calculation on hy-

Figure 16: PHEBUS LOCA test - pressure evolution

Figure 17: PHEBUS LOCA test - core inlet flowrate

draulic behavior has an impact on the clad temperature prediction during the depressurization phase (figure 16). Nevertheless, rod temperature evolutions are well estimated by DRACCAR during the whole test (figure 19).

From mechanical point of view, rod deformations and bursts are directly dependant on the clad temperature evolutions. Therefore, the discrepancies observed on the temperatures explain the difference between the experimental and calculated rod deformations and bursts (figure 20).

Regarding oxidation phenomena, the code is in good agreement with the experiment. For example, the zirconia layer created on rod 12 during the test 218 has a thickness experimentally included between 40 and 64 μm at the elevation 315 mm

Figure 18: PHEBUS LOCA test - rod temperature evolution during the depressurization phase

Figure 19: PHEBUS LOCA test - rod temperature evolution

from the bottom of the core (close to the clad burst). In the calculation, for the same elevation, this thickness is included between 49 and 57 μm .

As a conclusion, DRACCAR is able to simulate all the phases of this loss of coolant accident replicated in the PHEBUS facility and especially the fuel behavior (temperature evolution, ballooning, rupture and clad oxidation). Further analysis should focus on the impact of fluid conditions in the dead zones and on the uncertainty of measurements through sensitivity studies.

Figure 20: PHEBUS LOCA test - Deformations and bursts observed in experiment(a) and obtained with DRACCAR (b)

6. Uncertainty studies

6.1. Principle and objectives

Uncertainty studies are performed for some experiments of the DRACCAR database and will be progressively extended in a near future to the whole validation matrix. These studies address distinctively uncertainties from experimental parameters and from physical model parameters. The main goal of these studies is to quantify the impact of input uncertainties on DRACCAR results. The method consists in the propagation of known input uncertainties, through DRACCAR calculations, to obtain the output uncertainties. The main three steps of the method are:

- The data sampling (or uncertainty modeling): the discrete values of input uncertainties are generated by DRACCAR from parameters defined by the user in the input deck. These parameters are the interval of variation of the input, the corresponding distribution function and the total number of values N that will be used to discretize the interval of variation. Those values are stored in a test matrix, where each column corresponds to an explanatory input and each row to a set of values taken by these variables inside the user defined uncertainty band.
- The uncertainty propagation: DRACCAR is run repeatedly for all the N values of each uncertain parameters. At

the end of this phase a sampling on the output parameters of interest is obtained.

- The statistical analysis of the results: the output sample is then used to get any typical statistics of the code response and to determine the cumulative distribution function.

6.2. Example of uncertainty analysis within the frame of the DRACCAR validation on SEFLEX experiment

The selected test of the DRACCAR database for the uncertainty study is the reflooding test SEFLEX 05 performed on an intact bundle and already presented in section 4.1. The considered uncertainties concern the experimental measurements which are used to set the boundary and/or initial conditions in DRACCAR. It corresponds to the incoming flooding velocity and associated feedwater temperature, the system pressure inside the facility and the power supplied to the bundle. The first step of the uncertainty method is the data sampling. For each parameter are known a reference value (the measured one) and its limits (the minimum and maximum values bounds the uncertainty of the measure). So, from the knowledge of the reference, the minimum and the maximum values, the sampling composed of 61 quadruplets can be determined by a random selection following a triangular probability law. The number of quadruplets was chosen according to the Wilk's formula, to

obtain the values of the output in the 95th percentile with the probability 0.95. Table 3 presents the reference values of each parameters and the considered uncertainty.

	V_{water}	T_{water}	Pressure	Power
Reference value	3.81×10^{-2} m/s	40°C	2.12×10^5 Pa	200 kW
Uncertainty	$\pm 3\%$	-3°C to +10°C	$\pm 10^4$ Pa	$\pm 1.5\%$

Table 3: SEFLEX05 input test conditions and associated uncertainty

Then the uncertainty propagation with DRACCAR and a statistical analysis have been performed. Some results are illustrated on the figure 21 presenting a rod temperature evolution (rod 18 at elevation 1.75m which was also presented on figure 9). The uncertainty band (defined by the minimum and maximum values of the uncertainty interval) is plotted in grey, the results of the reference simulation in black and the experimental results in red. As already discussed in section 4.1, the numerical results of the reference case are in good agreement with the experimental measurements. Moreover, it appears that the experimental results are included in the uncertainty band determined from the experimental input parameter variations. From that study, it was concluded that DRACCAR simulation of the test 5 from SEFLEX programme is predicted with enough accuracy with respect to measurement uncertainties and that no real way of improvement could be identified.

This example presents an analysis which addresses the experimental uncertainty. Such studies provide an alternative insight on the code to experiment comparisons and on the acceptance of the accuracy of the code prediction. It helps to determine how accurate the simulated results are compared to the experimental data. It is a necessary tool to conclude on the validation status and possible prospects to improve the code response. It should also be completed by the assessment of physical models uncertainties through sensitivity studies to the model parameters. These approaches should be generalized in the assessment of complex phenomena such as reflooding of deformed fuel assembly and are going to be widely generalized to revisit progressively the validation matrix of DRACCAR.

Figure 21: SEFLEX test - temperature evolution of the rod 18 in experiment (red curve) and DRACCAR simulations (black curve and grey band)

7. Perspectives

As a conclusion, DRACCAR capabilities were illustrated through various validation studies. Considering the continuous verification process and the wide validation matrix (covering thermal, mechanical, thermalhydraulic and chemical phenomena involved in LOCA accidents), DRACCAR has reached a satisfactory level and is able to predict the main trends of LOCA using a multi-rod description. The code can be used to provide an interesting insight on the behavior of multi-rod ballooning and coolability during LOCA in comparison with other tools using the single rod approach. Nevertheless, some remaining gaps must be filled concerning complex phenomena such as the cladding rupture, the contact between neighbouring rods and the reflooding of deformed geometries. All these topics are investigated by IRSN in the frame of the experimental programme PERFROI (composed of ELFE, COCAGNE and COAL experiments and promoted by ANR and detailed in Repetto et al. (2017)).

Regarding the rupture modeling, as illustrated by the validation on REBEKA-6, the development and validation of the DRACCAR code faces multiple challenges. The first one, and probably the most important, is to describe the rupture instability progression with simple models - that could be used in a multi-physics code like DRACCAR. The most advanced perspective

is to harness the ELFE experimental results to build a semi-empirical model. Another difficulty for the code validation is related to the industrial proprietary of cladding material properties and testing which is linked to the competitive development of innovative fuel rods. Indeed, numerous experiments exist or are on-going but are most of the time not shared between designers and research institutes. Therefore, results are not available for code development and validation.

Concerning the contact between neighbouring rods, the validation status of DRACCAR is insufficient and its improvement needs to collect experimental data. Contact was observed in several integral experiments (REBEKA, PHEBUS LOCA) but the extension of contact was not measured on-line. To answer this issue, IRSN has designed the COCAGNE experiment in the frame of PERFROI programme. This experiment investigates the behavior of a heating rod surrounded by heated neighbours (simulated by guards). The first results were obtained at the end of year 2017 and new data will be collected in the next years.

The last main challenge concerns the reflooding of deformed fuel bundles. As mentioned in section 4, the reflooding of intact and deformed geometries was largely studied through different experimental programmes since the 1980s. But the extrapolation from the experiments to the real case is somehow incomplete for the reflooding of deformed fuel bundles as in the past programmes, the power profile and the thermal inertia were not strictly representative of ballooned fuel rod with fuel relocation. The COAL experiment belonging to the PERFROI experimental programme will investigate this issue.

DRACCAR development is also influenced by other on-going OECD/NEA projects dedicated to LOCA (such as HALDEN or SCIP).

Another topic which influences the DRACCAR development concerns spent fuel pool accidents. DENOPI, the on-going IRSN programme (also promoted by ANR) dedicated to these accidents is organised in three different research axes. The first one focuses on spent fuel pool accidents and is based on a large scale experiment MIDI. That experiment will allow to observe the heat exchanges - especially convective loops - in case of

homogeneous or heterogeneous power distribution and organisation of fuel assemblies. The second axis aims at studying the uncovering of a fuel assembly and its possible mitigation by a spray system. This axis is based on the MEDEA and the ASPIC experiments which are designed to represent phenomena at the scale of a fuel assembly. The last axis is focused on the oxidation of cladding samples in mixed atmosphere (O_2, N_2 and H_2O) using separate effect tests. The DENOPI programme will provide knowledge at different scale for the understanding and simulation of Spent Fuel Pool accident phenomenology.

Concerning the prospects, it is expected in the next years that PERFROI and DENOPI programmes will bring new knowledge valuable for code development and safety assessment. The improvements of DRACCAR code through the development of DRACCAR V3 are on-going and are therefore strongly linked to these programmes. Validation process will accompany the development of this new version which could set DRACCAR as a reference tool for multi-rod LOCA simulation.

Acknowledgements The work described in the present paper has been performed in the continuity of many years of development of the DRACCAR code at IRSN with the support of Electricité de France (EDF). The authors are thankful to the former or current colleagues from IRSN for their fruitful contribution to the physical modeling. In particular, thanks are due to Sophie Bascou, François Lamare, Jean-Marc Ricaud and Tim Haste. Some valuable contributions to the code improvement and validation have been provided by Stefano Ederli from ENEA as well as by members from CS-SI company involved both in the code maintenance and development.

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