Multi-physics modelling in the frame of the DRACCAR code development and its application to spent-fuel pool draining accidents

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Abstract:
To meet the simulation needs of its LOCA R&D program, the IRSN is developing a multi-pin computational tool named DRACCAR. In order to realistically describe the behavior of the reactor core during a Loss Of Coolant Accident (LOCA), modeling has to take into account many coupled phenomena such as thermics (heat generation, radiation, convection and conduction), hydraulics (multi dimensional 1-3 phase flow, shrinkage), mechanics (thermal dilatation, creep, embrittlement) and chemistry (oxidation, oxygen diffusion, hydriding,...). This paper presents several aspects of the DRACCAR code abilities: investigation of the bundle rods strain during a LOCA transient, checking of the thermalhydraulics during reflooding of a partially ballooned bundle, and application to spent-fuel-pool draining accidents in the case of a propagation of the burn front in a typical non axis-symmetrical situation for the thermal heat exchanges which are driving the accident.

1 INTRODUCTION

One of the design basis accidents (DBA) for water cooled reactors is the loss of coolant (LOCA) caused by the failure of a large coolant pipe. In order to mitigate the consequences of this break, it is necessary that the reactor has several emergency core cooling systems so that the fuel could be cooled efficiently during all phases of the DBA. This requirement naturally led to a criterion that the fuel must maintain a coolable geometry through the whole LOCA sequence and that the structural but not necessarily the hermetical integrity of the fuel rods should be maintained.
The requirement of coolable geometry and structural integrity turned out to be a very complex issue due to the particular properties of the zirconium alloys used as cladding tubes for the fuel.
During a LOCA, the metal heats up to temperatures over 1 000°C, the oxidation reaction starts to accelerate and the growth of the oxide scale becomes significant. The problem is that oxygen also embrittles the α phase of the metal and that the oxide itself is very brittle when the hot fuel rod is quenched back to low temperature. Following the temperature increase, the rate of steam-cladding oxidation could be so high that the heat can no longer be adequately dissipated by cooling, eventually leading to run-away oxidation. If run-away or autocatalytic oxidation is not arrested, cladding metal and reactor core could melt.
There are also many other detail issues which must be taken into account. When the fuel rods heat up and the external pressure is lost the rod internal pressure is large enough to cause plastic deformation of the cladding which leads to ballooning and burst, and to some pending questions:
- A first one is relative to the characterization of the relocation of irradiated fuel fragments in the balloons that had formed in the swelling/rupture phase of the claddings, mainly the filling ratio as function of the granulometry of the fragments. The fuel relocation leading to a local power increase may influence the subsequent transient behavior with regard to cooling and embrittlement of the cladding and possibly reduce the available margin with respect to safety criteria
- An other one is the characterization and the influence of the most penalizing blockage (ratio and length of maximum flow blockage) that may occur in an assembly with irradiated fuel

rods and the coolability of such a partially blocked assembly under thermal-hydraulic conditions typical of large or small break, taking account of a possible fuel relocation.
- and a last one could concern the cladding embrittlement in the ballooned areas, due to the cumulative effects of clad thinning, two-sided oxidation and secondary hydriding on the inner surface. The question is highly dependent on which type of loading to apply to the cladding in order to quantify the embrittlement: quench loads or mechanical post quench loads of various nature
The French “Institut de Radioprotection et de Sûreté Nucléaire” (IRSN) conducted an extensive State-of-the-Art- Review relative to fuel behavior under LOCA conditions, covering the aspects of clad ballooning and flow blockage [1], coolability of partially blocked assemblies [2], clad oxidation and clad resistance to quench and post quench loads [3].
To meet the simulation needs of its LOCA R&D program, IRSN has developed a new multi-physics computational tool named DRACCAR [4] .
DRACCAR is a simulation tool for fuel assembly mechanical behavior and coolability assessment during a LOCA transient. Its aim is to simulate the 3D thermomechanical deformation and reflooding of a fuel rod assembly including its coolability as well as structure embrittlement.
The DRACCAR code is based on a 3D non-structured meshing able to model a simple fuel rod, a partial or a full assembly, as well as a surrounding shroud. It is based on an axial discretization of the rod which leads to analyze quasi-independent 2D thermal mechanical problems. Important modeling such as pellet eccentricity, heat transfers (within the solid and through the fluid) or material properties evolutions (oxidation layer, phase changing,...) can thus be taken into account and the important question of the cladding integrity during a LOCA transient can be addressed even in case of contact between the structural elements. In that case, the geometry is strongly changed (flattened zone contact) as well as the loading nature (mixed stress–displacement loading) and so the rupture is more difficult to model than a threshold criteria used in most of the multi-rod codes: with DRACCAR, nonlinear geometrical effects are added to non-linear behaviour laws in the modeling.
Also important is the possibility to get a better knowledge on the system’s capability to cool structures whatever are the evolutions of the deformation of the rods and the blockage of the sub-channels. Obviously these two critical issues which are essential to treat in modeling LOCA transient effects, can only be dealt with in a realistic manner with a multi-pin code coupled to an efficient 3D thermal–hydraulic code, and that’s why DRACCAR is currently coupled to the two phase flow module CESAR of the ASTEC code [5], able to compute deformed geometry evolutions thus actualizing the coolant flow passage within the different sub-channels.
Many results have already been obtained with the DRACCAR code with respect to a substantial validation matrix (e.g. CORA 13 [7], EDGAR [8], FEBA [6], HALDEN IFA 650 [9], PERICLES, PHEBUS B9+ [10], PHEBUS 218 [11], REBEKA 6 [12], ROSCO [13], SEFLEX [14] experiments).

In this document, a first validation of the thermal–mechanical modeling of DRACCAR for a single-rod computation is presented. Three numerical test-cases with increasing complexity have been compared with the two finite-element codes CAST3M (test cases 1-2) and XPER (test case 3).
Then the DRACCAR-CESAR coupling will be assessed with the simulation of the FEBA tests in which the influence of channel blockage conditions on core coolabilty has been tested.
A final assessment of the code capabilities will deal with the coolability of assemblies of a spent fuel pool in situation of complete LOCA, with the simulation of the Sandia Fuel Project (SFP) test program performed at Sandia National Laboratories.

2 STRESS AND STRAIN STATE VALIDATION

Three numerical test-cases performed with two finite-elements codes namely CAST3M (testcases 1 and 2) and XPER [15] (test-case 3) are presented hereafter. The purpose is to validate the thermal-mechanical modelling of DRACCAR with single-rod computations (test-case 1: axisymmetric geometry and loading ; test-case 2: azimuthal thermal gradient) and multi-pin computation (test-case 3: contact between rods). The basic input data for all these

test-cases are the following : the internal and external cladding diameters are respectively 8.36mm and 9.56mm, the height is 250mm, the pellet eccentricity is 0mm, the pin filling pressure is 2.5MPa, the overall system pressure is 0Mpa (to maximize creeping deformation) and the diametrical gradient of temperature is 100K (for test-case 2 only).
Finite-element (FE) results of CAST3M and XPER are based on two dimensional plane strain calculations (which can be considered as a conservative approach concerning the stress and strain states). The different physical couplings that can occur during a thermal transient within a bundle are not considered here. For example, we do not model the pellet stack eccentricity within the cladding, which is a major cause of azimuthal temperature difference generation, but we directly model in both the DRACCAR code and the finite-element codes an azimuthal gradient of temperature. Such separate-effect test-cases seem to be the best first step to determine if the usual thin-shell model-like is efficient in all the transient situations. This is the prior step to the validation with experimental results as expected in the IRSN CYCLADES project [16].
Concerning the large deformation of a pressurized cladding with an axi-symmetric geometry and load, there is a very good agreement between the results from the DRACCAR code and from the FE computation (Figure1, on the left). When a thermal azimuthal gradient is taken into account (test-case 2), the circular shape of the cladding is lost by differential creep strain along the perimeter. This leads to different local curvature radii and different thicknesses at each azimuthal node (Figure 1, on the right). Some bending moments can appear as the circular shape vanishes and can explain the relative differences (2%) between the DRACCAR code and the FE computations concerning the maximal diameter: indeed, the DRACCAR code does not calculate those bending moments, as a result, the cladding deformation is slightly overestimated. One can note that taking into account shear stress within the structure leads to reduce the discrepancies obtained between the discretized sectors of the DRACCAR code (by continuity of the displacements and moments).

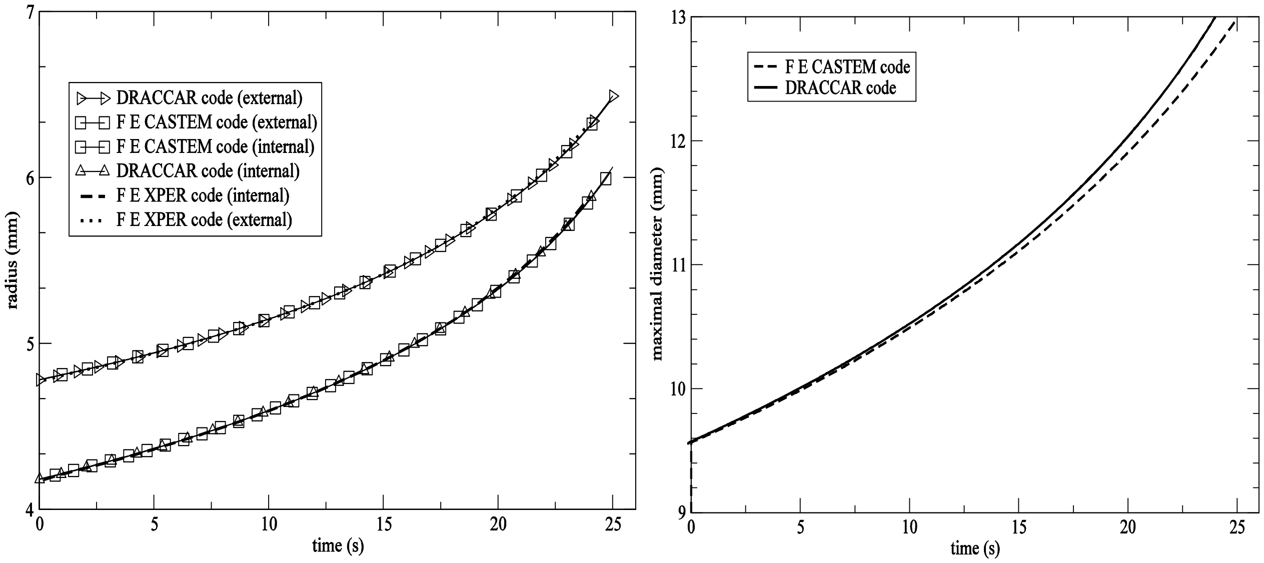

Figure 1. Numerical comparisons with FE computations. (left: test-case 1): internal and external radii evolutions for axi-symmetric loading; (right: test-case 2) : maximal diameters evolutions for azimuthal non-uniformities in temperature

As the DRACCAR code is validated for loadings that conserve more or less the transverse circular shape of claddings, we now consider the more complicated situation of contact between rods. Complication is twofold: first, geometries with large flattened contact zones are no more within the scope of the thin-shell theory, and secondly, the loading becomes mixed after pure stress loading. Then, we have to make sure that global variables like the flow blockage ratio as well as the local stress state are well approximated by the DRACCAR code computation. Discretized problems (using natural symmetries for the finite-element code), for both the DRACCAR code and the finite-element XPER code, are respectively described on the left and on the right on Figure 2.

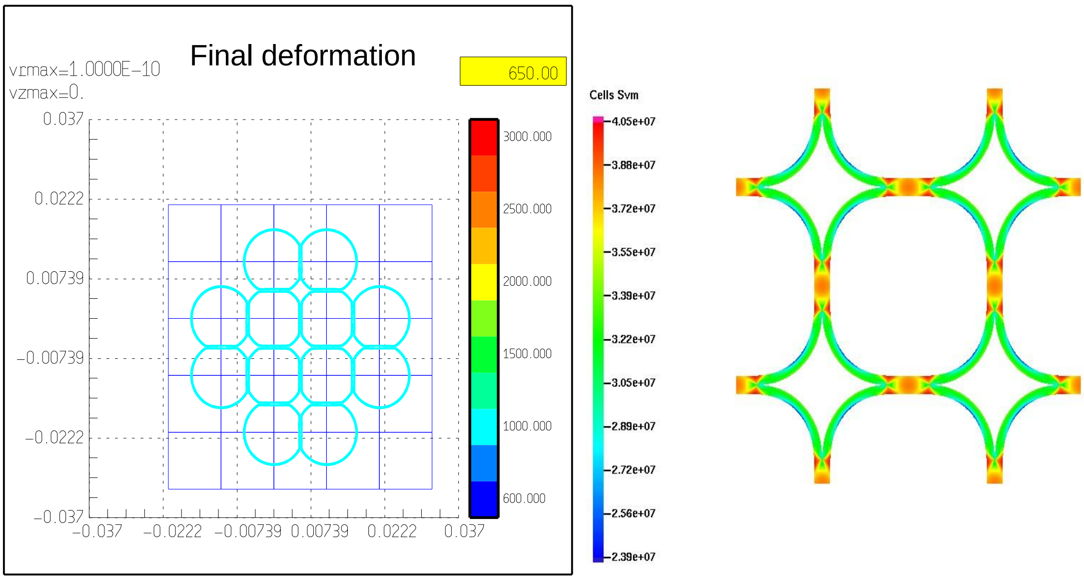

Figure 2. Test-case 3: left: DRACCAR view of the deformed bundle; right: the equivalent stress iso-values computed by the XPER code

Results presented on Figure 3 are computed on the center of the bundle (in the central subchannel of the left hand graph of Figure 2 concerning the flow blockage ratio, and at the polar node of one of the neighbouring cladding concerning the hoop stress). The left hand graph on Figure 3 shows a good agreement between the DRACCAR code and the XPER code concerning the flow blockage ratio even for large values (up to 88% blockage). The right hand graph on Figure 3 represents the hoop stress evolution in the rod cladding plotted against the angle in radian. As shown on the graph, the hoop stresses calculated by the XPER code really differs between the inner face and the outer face of the cladding, this is especially the case on the free polar node due to bending stresses that acts like an additional tensile stress on the outer face and like an additional compression stress on the inner face ; and on some nodes of the contact zone where bending of the last node in contact relaxes the stress on the former contact zone by creating a kind of lever arm.

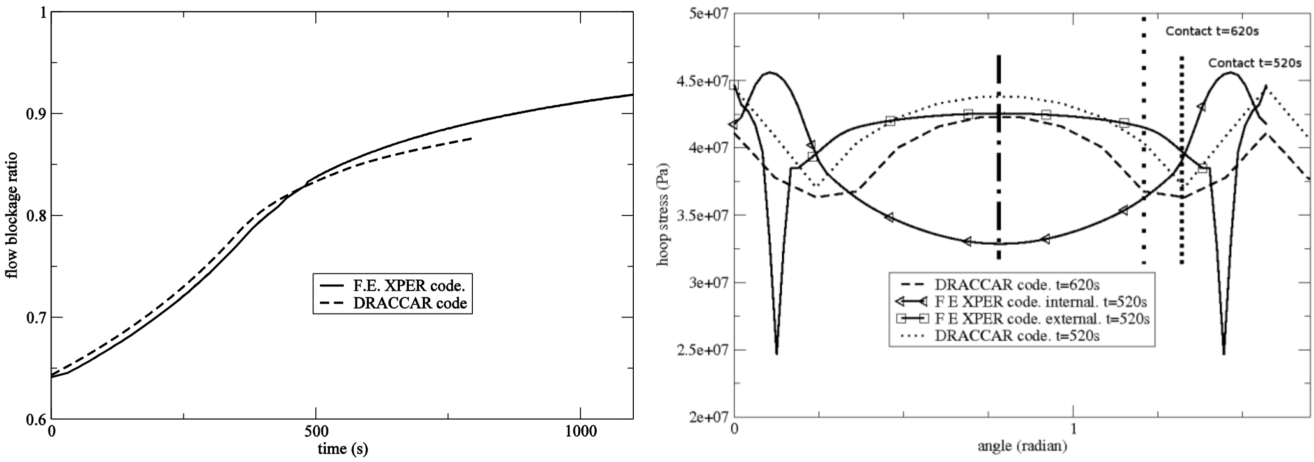

Figure 3. Test-case 3: comparison between DRACCAR and XPER results. On the left : flow blockage ratios evolutions ; on the right : hoop stresses evolutions along one quarter of the cladding perimeter.

It must be mentioned that contrary to the XPER modelling, the DRACCAR one does not allow to calculate separate stresses on the internal face and the external one since it is a thin wall equilibrium that is considered. In order to correctly describe the cladding behaviour emphasized by the XPER code, two modifications have been implemented in the DRACCAR code. First, a bending stress has been added to the stress computed on nodes located next to the contact zone, using the analytical formulation for beam bending. This modification is responsible for the inverted v-shape revealed by the DRACCAR curve “t=520s” in the last part of the graph. Secondly, in order to take into account the evolution of the stress field in the contact zone, an empirical stress relaxation formula has been introduced and is applied whenever a new node enters the contact zone. The effect of this modification can be noticed by comparing the hoop stresses computed by the DRACCAR code at times 520s and 620s.

3 SIMULATION OF THE FEBA TESTS

3.1 Experiment Presentation

The FEBA program (Flooding Experiments with Blocked Arrays) is a series of separate effect tests under forced reflooding conditions [6]. 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 FEBA program has been carried out in the early 80’s at the German nuclear research center of Karlsruhe. A total of 60 tests were performed. This paragraph focuses on eight series of tests carried out on a full length bundle of 5x5 electrically heated rods.

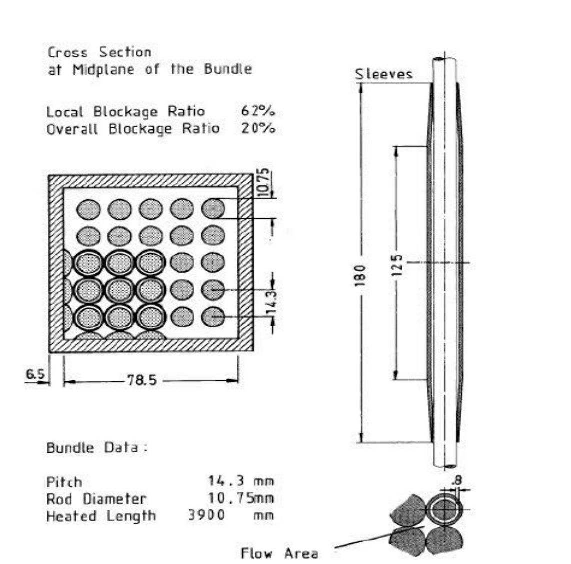

Figure 4. Sectional view of the test section and sleeves geometry for the 62% blockage ratio [6].

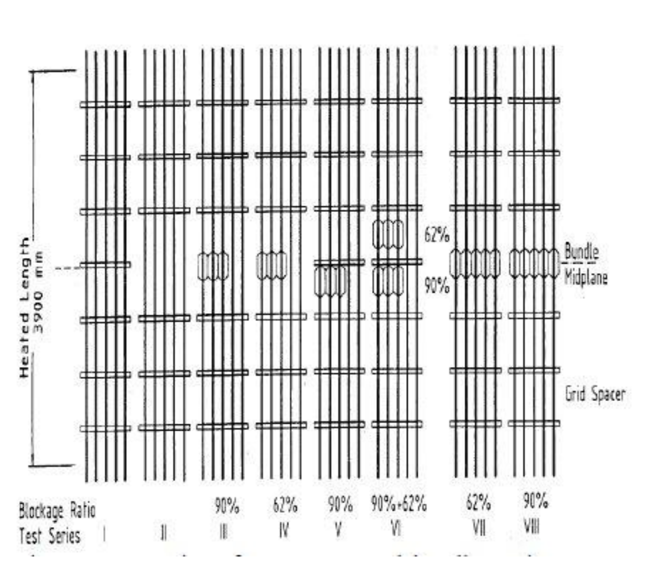

Figure 5. Geometries of FEBA 5x5 rod bundle, series I to VIII [6].

The test rig consists of: a 5x5 bundle with solid type fuel rods (10,75mm across, 3,9m high), 7 grid spacers positioned at different axial levels and a thick square housing (6,5mm thick) made of stainless steel. Rods consist of a spiral heating element, embedded in a magnesium oxide insulator surrounded by a nichrome cladding without gap. Heater rods are equipped or not with hollow sleeves made of stainless steel to simulate the shape of ballooned rods. Sub-channels blockage ratios of 62% and 90% have been investigated, the blockage area in a 3x3 rod bundle is located in the left hand corner of the square housing thus letting the sixteen other rods form a by-pass area (Figure 4). This layout is supposed to simulate one quarter of a 10x10 rod bundle featuring a central 6x6 blockage. For that reason, the sub-channels between sleeve blockages and housing were blocked by side plate devices.

Tests are divided into eight series of tests with different grid spacers and blockages arrangements (Figure 5). Every test is characterized by: the blockage geometry, the flooding velocity, the system pressure, the feedwater temperature and the initial temperatures of rod claddings and of the housing (see Table I).

Series	Test number	Flooding velocity cms^{-1}	Pressure bar	Feedwater temperature (°C)		Heat flux at t=0s kW
				0-30s	End	
I	216	3,8	4,1	48	37	200
II	229	3,8	4,1	53	38	200
III	239	3,8	4,1	49	37	200
IV	263	3,8	3,9	61	43	200
V	282	3,8	3,9	77	45	200
VI	276	3,8	3,9	73	43	200
VII	324	3,8	4,1	56	42	200
VIII	337	3,8	4,0	57	42	200

Table I: FEBA tests simulated with DRACCAR

Every test is carried out following the same operational procedure. About two hours prior to reflooding, fuel rod simulators were heated-up using a low rod power until the rod claddings reach the desired temperature. In the meantime the housing is passively heated up by radiation from the rods. Reflooding was initiated by closing valves, and the bundle power was stepped up to the decay heat ANS71+20% 40s after shutdown.

3.2 DRACCAR modeling

We choose to simulate the bundle on a height equivalent to the rods heating length, with the square housing. One boundary condition at the inlet and one at the outlet of this portion close the system. Taking into account the symmetry of the test sections, half a bundle is modeled for series III to VI and 1/8th of a bundle for series I, II and VII to VIII (Figure 6).

The axial meshing takes into account the axial power profile discretization and the sleeve geometries (for series with blockages). The meshes height never excess 80mm. Grids are not physically modeled, but the corresponding pressure losses are taken into account.

During the experimental heat up phase vapor was fed into both the upper and the lower plenum but flow-rates are not specified in the experimental documentation, as a result, rods and housing initial temperatures are initialized using the experimental temperature axial profile given for base case test #216, after normalization it has been applied to all the other tests. In the end, the simulated procedure consists in activating the heating power and reflooding at the same time.

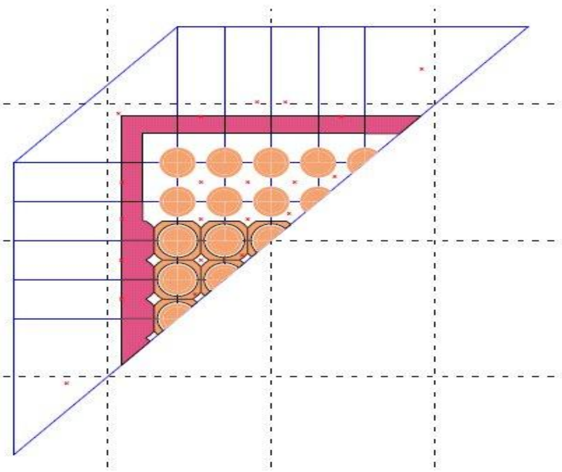

Figure 6. Modeling of half a FEBA test section with DRACCAR

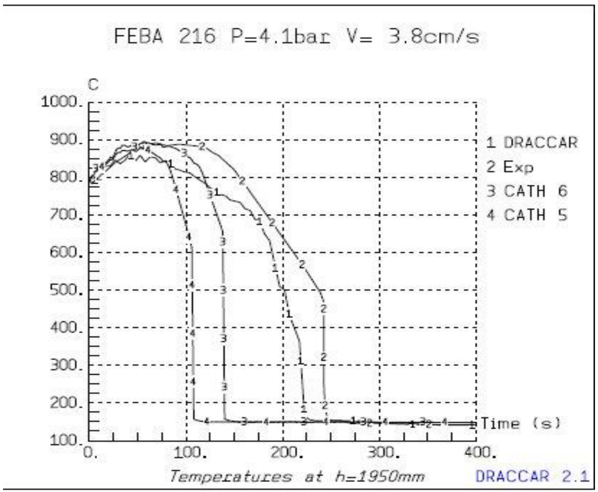

Figure 7. Rod cladding temperature evolutions at z=1.95m for test #216, experiment/DRACCAR/CATHARE comparison.

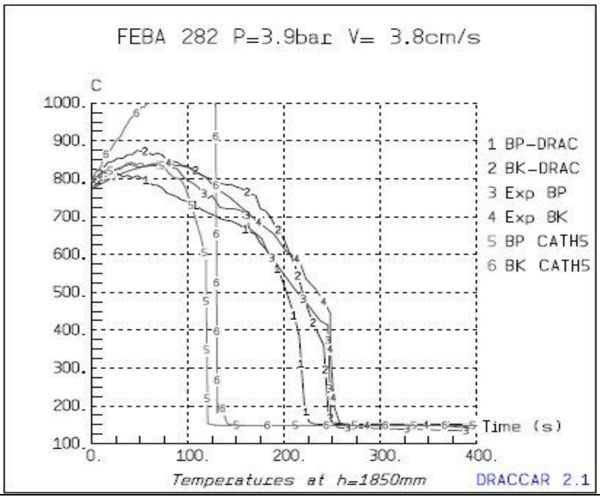

Figure 8. Rod cladding temperature evolutions at z=1.85m for test #282, experiment/DRACCAR/CATHARE comparison. :

3.3 Simulation results

The Figures 7 and 8 present results from DRACCAR V2.1 simulations, and are compared to experimental data. Also presented for information purposes are CATHARE 2 V2.5_2 [17] results run from its validation data decks. Results presented below are from base case test #216, series I with an intact geometry and test #282, series V with a 90% partial blockage 100mm upstream of the bundle mid-plane (within the maximum flow blockage).
In the figures, “BP” stands for by-pass region, “BK” for blocked region, “Exp” for experimental results and “CATHi” for CATHARE results in mesh “i” (generally two elevations are given to enclose the experimental measurement point elevation since CATHARE meshes are 390mm high).
Concerning CATHARE results, temperatures in the by-pass region are well described during the first 50s of the transient and the maximum cladding temperature is quite well predicted. However, temperature drops are predicted far too sharp and too early. Within the blockage the CATHARE code strongly overestimates the cladding temperature and quenching is also predicted far too early.
This is mainly due to the fact that the thick housing surrounding the bundle is not modeled, as a consequence the effect of its inertia is not taken into account, i.e. lowering of the maximum cladding temperature reached and cooling slow down.
In by-pass regions, DRACCAR slightly underestimates the maximum cladding temperature reached and quenching is predicted a little too early. Within the blockage, temperature is slightly overestimated and quenching is quite well predicted. Overall DRACCAR simulated temperature evolutions are satisfying compared with the experimental results. However a closer look at the various simulations results have shown that phenomena observed at the vicinity of blockages such as cooling improvements within and downstream of a partial 62% blockage due to an increased dispersed flow cooling or just below a partial 90% blockage probably due to water entrainment and breaking-up of droplets at the leading edge of the blockage are not always correctly predicted by the CESAR code.
More generally, droplets entrainment by vapor, their interception by flow obstacles, their dispersion or reentrainment, as well as their fall back due to gravity into regions of reduced vapor velocity is of most importance since it plays a role in the cooling phenomenon. A significant task is currently underway to improve the actual thermal-hydraulics module

CESAR (transition from 5 to 6 equations). Its goal is to reach a description level of droplets behavior de-correlated from the vapor behavior necessary since it takes an important place in these transients. A coupling between the DRACCAR code and CATHARE 3 [18] is also being made possible.

4 SANDIA FUEL PROJECT (SFP) PHASE II TEST PROGRAM

The US Nuclear Regulatory Commission (NRC), in collaboration with the Organization for Economic Co-operation and Development (OECD), and 12 international partners, conducted an experimental program to obtain experimental data for the characterization of hydraulic and ignition phenomena of prototypic light water reactor fuel assemblies in a spent fuel pool under complete loss of coolant accidents for validation of severe accident computer codes. The experimental program was conducted in two phases at Sandia National Laboratories.

Since the OECD SFP programme is open only to 12 partners, only a general qualitative presentation of its results in relationship to the DRACCAR capabilities will be given.

4.1 Apparatus and procedures

4.1.1 SFP Phase I: a hot neighbor loading pattern

A single test assembly of a full-length commercial 17x17 PWR fuel bundle was constructed using prototypic, commercial components with heater rods made from zirconium alloy tubing supplied by an industrial vendor. The fuel assembly contains the core skeleton including eleven spacers permanently attached to twenty-five guide tubes and 264 fuel rods which pass through the spacers and are held captive in the assembly by the top and bottom nozzles (see Figure 9). The assembly was placed into two different size pool racks during the testing. The test assembly was completely insulated to model boundary conditions representing a “hot neighbor” loading pattern. The test assembly was fully instrumented including hot wire anemometers (flow rate), oxygen sensors, gas chromatograph (Ar and N2 quantification), quartz light pipes (visual observation), laser Doppler anemometer (velocity), pressure transducers and thermocouples.

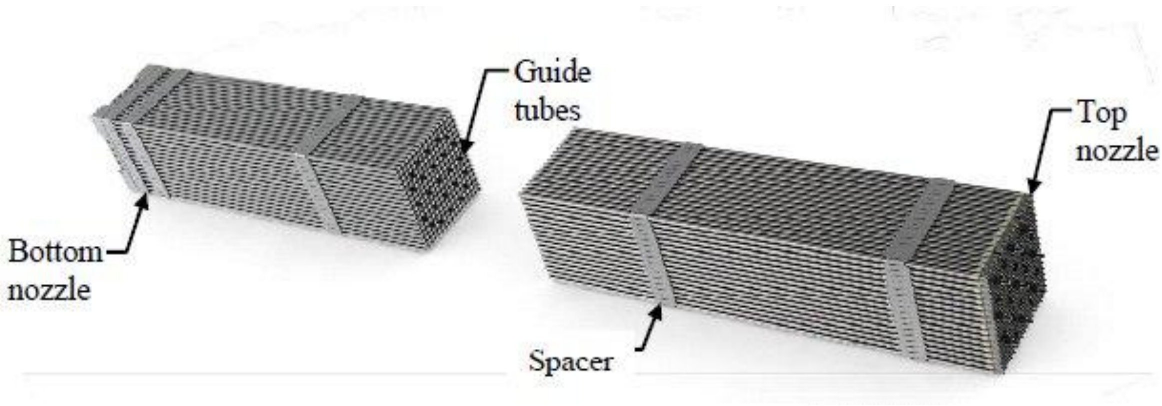

Figure 9. Various components in a typical 17×17 PWR fuel assembly

Separate effects tests were performed to investigate the assembly hydraulic response. For these tests, the assembly was unheated, and flow was forced into the assembly covering the expected range of flow rates. Tests were performed and these values were computed for

both pool rack cell sizes. The experimental data for flow rate and pressure drop was used to compute both the frictional and inertial flow resistance coefficients
Pre-ignition tests were conducted using a uniform axial power profile with electrically heated rods to simulate decay powers. The key parameters for these non-destructive tests are temperatures throughout the fuel assembly and inlet mass flow rate.
The ignition test was conducted at a maximum power level, representative of an assembly after a typical time offload. With such a power, and with a natural convection cooling by the surrounding air, the zirconium ignition temperature has been reached, leading to a self-sustaining zirconium fire. Power to the assembly was lost shortly after ignition occurred.

This phase of the program demonstrated that most of the axi-symmetrical severe accident computer codes could accurately simulate ignition timing and axial location, and burn propagation in a single 17x17 PWR assembly under complete loss of coolant conditions [19].

4.1.2 SFP Phase II: a cold neighbor 1×4 arrangement

Phase II focused on transverse heating and burn propagation in five full-length assemblies [20]. The fuel assemblies were arranged in a pool rack with the heated assembly in the center cell (see Figure 10). The four peripheral fuel assemblies each shared a cell wall with the center assembly and were unheated, representing older spent fuel. All mock fuel assemblies were constructed with zirconium alloy cladding and prototypic structural components. The center assembly was constructed with electrically resistive heaters. The thermal mass of the compacted MgO powder used to make the electric heater is an excellent match to spent fuel as demonstrated in the previous BWR study [21]. The peripheral assemblies were loaded with MgO pellets in order to closely match the thermal mass of spent fuel. Two of the four peripheral assemblies were pressurized with argon to simulate ballooning of the fuel clad during the ignition test.

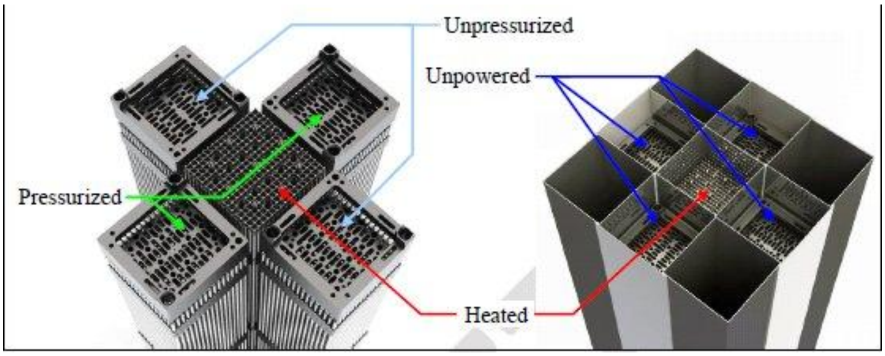

Figure 10. Layout of the Phase II test assembly

A series of pre-ignition tests were similarly conducted to build a high-fidelity database of the thermal hydraulic response of fuel below ignition temperatures.
For the ignition test, a significant power, representative of several months after offload, has been applied to the center assembly. Ignition of the Zircaloy claddings within the center assembly was first observed. At test end, all five fuel assemblies were completely consumed as a result of the Zircaloy cladding fire. The thermal-hydraulic behavior of the fuel assemblies was monitored during the ignition test as well as the timing of the ballooning of the pressurized rods. Finally, the depletion of oxygen and nitrogen in the exhaust stream were also directly measured.

4.2 DRACCAR modeling of SFP Phase II

For the simulation of the Phase II, the issue is not in the modeling of the heat transfers mechanisms within each cell (as in Phase I), but rather in the modeling of the thermal heat exchanges between the central cell and the peripheral ones. The difficulty lies in the fact that the test is typically non axis-symmetric and that most of the severe accident codes which participated to the program were axis-symmetric codes (MELCOR, ASTEC).

A snapshot of the temperature contours throughout the assemblies after the ignition of the central one illustrates this fact. In Figure 11 (left), we can observe that the gradients of temperature in the peripheral assemblies go from the hot cell wall (close to the central cell) to the cold outer cell wall (in contact with insulation material), and that all the peripheral cells are only heated from one face only.

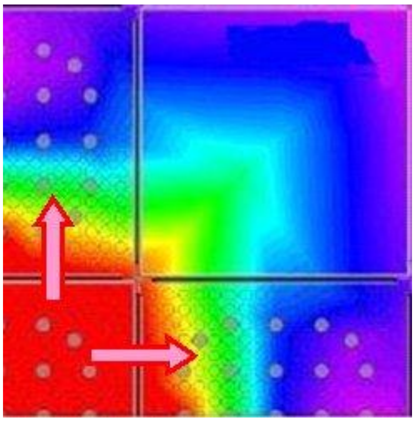	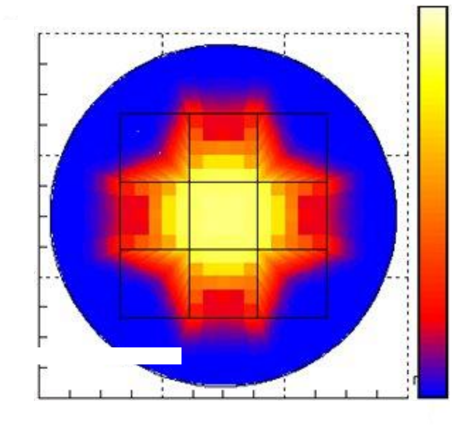
Figure 11 left. Experimental temperature contours throughout the assembly at a given axial level	Figure 11 right. DRACCAR temperature contours

This specific geometry can be modelled using axis-symmetric codes but at the cost of some simplifying hypotheses to reproduce at best average experimental values. However, in order to get some “correct“ code results, parametric tunnings are necessary to fit at best the experimental results.
A correct calculation can reproduce the central cell temperature up to ignition, but the following events (ignition of the peripheral cells, burn front evolution in the whole assembly) could be more difficult to reproduce because they are linked to the oxidation reactions of the zircaloy claddings cooled by natural convection. These reactions are very temperature dependant, and the peripheral temperatures calculated with axis-symmetric codes are not correct.
The Figure 12 illustrates some possible ways to model the Phase II using axis-symmetric codes and DRACCAR:

- One possiblity is to model the different cells with different rings of heated rods (Figure 12 up left). In that case, the temperature gradients in the rings are correct, but the exchange surfaces are different and the real geometry is not reproduced. Some adjustments in the heat transfer (HT) coefficients are necessary to reproduce the experimental results.
- With the ASTEC code [5] it is possible to model independant cells with independant cooling flows, each cell being modelled with standard values for the HT coefficients (Figure 12 up right). The interest of this modeling in comparison to the previous “rings“ modeling is in the more realistic description of the HT within a cell, but as the heat exchange between the cells is concerned, symmetrical considerations lead to false statements for the heat exchanges. Similar adjustments for the HT coefficients are necessary too.

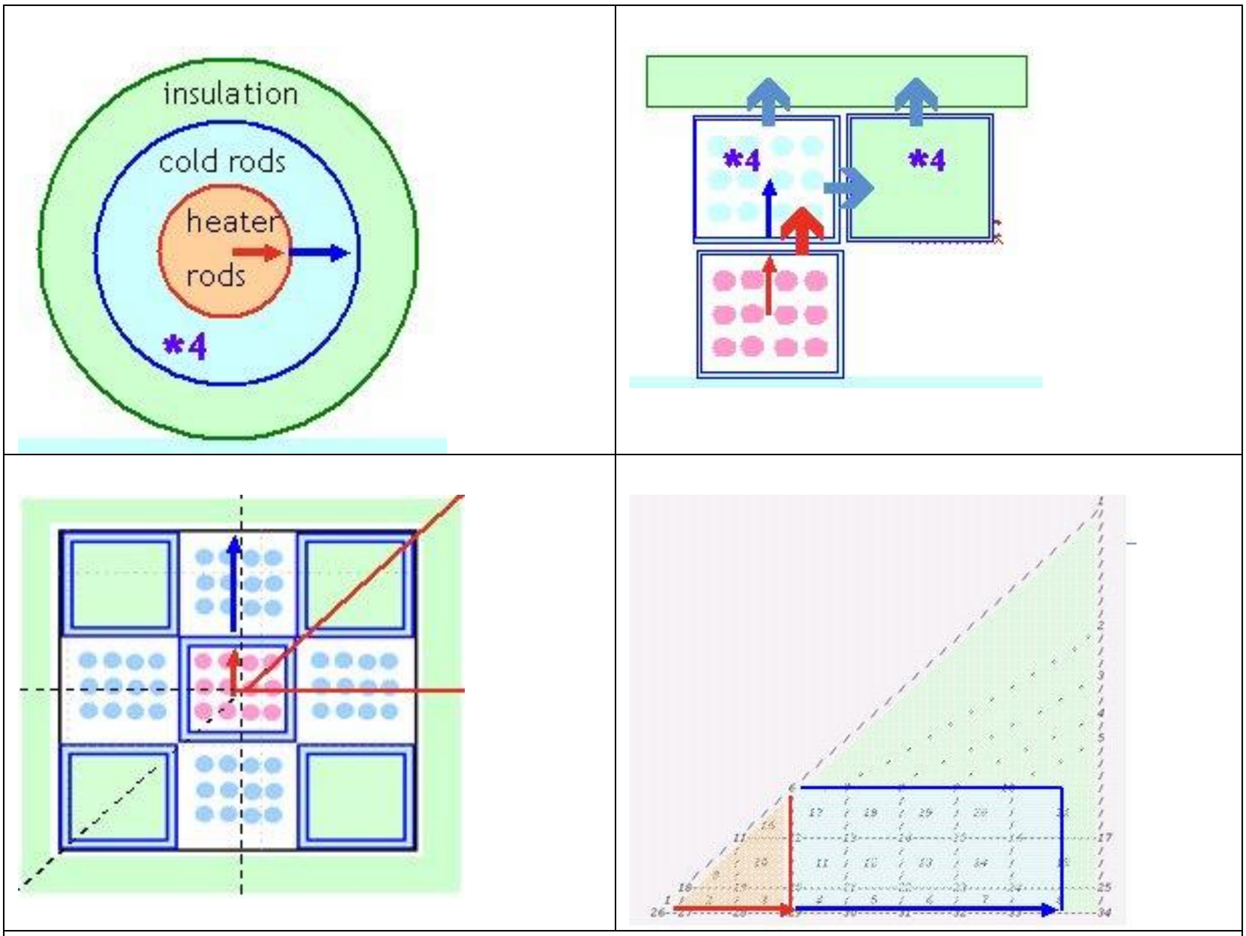

Figure 12. (**up**:left: rings, right:separate cells), (**down**: left:SFP-II, right:DRACCAR)

- With DRACCAR, an exact representation of the geometry can be defined (Figure 12 down). A reasonable target (in terms of time calculation) for fuel assembly computations is to model an eighth fuel assembly including fuel rods, control rods or guide tubes and with some limits, spacer grids. Each structure has its own thermal–mechanical behaviour but can also interact with neighbours by thermal radiation or mechanical contact. Applied to SFP Phase II geometry, a DRACCAR calculation simulates 1/8 of the central cell with six meshes (and weighted heated rods inside),and ½ of a peripheral cell with 15 meshes (and weighted cold rods inside). With this modeling, the temperature gradients in the cells are correct and the exchange surfaces and the geometry also. In this case no adjustments of the HT coefficients are made necessary, and the code results can be trusted as just as those from the substantial validation matrix.
  On the Figure 11 right a snapshot of the calculated temperature in the assemblies at the same time and axial location than the experimental ones (Figure 11 left) is shown. The temperature color code is different, but we can see that the temperature gradients in the cells with DRACCAR are very close to the experimental results. In that case, a more exact calculation of the oxidation front (ignition and propagation) in the peripheral cell can be performed.

5 CONCLUSION

A multi-pin code has been developed that describes the thermal–mechanical behaviour of rods under LOCA transients. The model accounts for creep, burst of cladding and also some coupling with other phenomena (oxidation, fragmented fuel relocation, etc.). It has been assessed against a large set of experimental data (dealing with bundle deformations, clad oxidation, water reflooding, etc.). The mechanical modeling appears to perform well with comparison to some numerical benchmarks with finite-element codes. The thin-shell modeling associated with some bending moments computed on the contact zone allows good upper bound stress fields on the whole cladding to be obtained.

Reflood phase of LOCA transients have been calculated to check the physical behaviour resulting from the efficient coupling between sub-channel thermal–hydraulics and rod thermal–mechanics of the DRACCAR code. Overall DRACCAR simulated temperature evolutions are satisfying, but better results are expected with the improvement of the actual thermal-hydraulics module CESAR to de-correlated droplets behavior from the vapor behavior, which play a role in the cooling phenomenon.

In the frame of spent-fuel-pool draining accidents, the Phase II of the Sandia Fuel Project experimental program has been simulated. Ignition and propagation of zircaloy claddings fire inside a 1×4 PWR assemblies configuration have been correctly reproduced, underlining the code flexibility to model any type of fuel assembly without the inevitable axis-symmetrical conditions usualy imposed in most of the severe accident codes.

6 REFERENCES

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