Nuclear Engineering and Design 330 (2018) 524–537

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Simulation of the OECD/NEA Sandia Fuel Project Phases I & II ignition tests with DRACCAR

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ABSTRACT

This paper describes simulations of two ignition tests performed at full power in the frame of the Sandia Fuel Project (SFP) with the thermo-mechanical code DRACCAR v2.3.

The OECD/NEA Sandia Fuel Project was built on an agreement between 12 countries from OECD, the Nuclear Energy Agency (NEA) and the US-NRC for the characterization of thermal-hydraulic and zirconium fire phenomena in pressurized-water reactor (PWR). The experimental program was split in two phases to focus at first on axial heating and burn propagation in one prototypic fuel assembly (Phase I), and then on axial and radial heating and burn propagation in 1 × 4 fuel assemblies (Phase II).

DRACCAR is a simulation tool, developed at IRSN, for fuel assembly mechanical behavior and coolability assessment during a LOCA transient. The flexibility of DRACCAR allows the modeling of many kinds of geometries. Because the code is based on a 3D non-structured meshing, it can be used to model any non-axisymmetric geometry, like the 1 × 4 fuel assemblies geometry of the Phase II of the SFP program.

In order to check the consistency of the modeling, we have optimized the code options to get best results for the Phase I, and applied the same options to the Phase II. Most of the DRACCAR results have been successfully checked against experimental ones, using additional code improvements. Air oxidation and breakaway modeling of the zircaloy claddings were successfully tested against the experimental results. Nevertheless parts of the experimental results of Phase II have been difficult to reproduce. As many causes could be involved in these difficulties, such as detailed evolution of the air convective loop, radiative heat transfers in the bundles, and the modeling of additional reactions of zirconium with nitrogen in places where oxygen is lacking, there is still room for improvement in the work of interpretation and modeling of the SFP tests.

1. Introduction

Prior to 2001, the US-NRC performed an evaluation of the potential accident risk in a spent fuel pool at decommissioning plants in the United States (Collins and Hubbard, 2001). Some of the assumptions in this evaluation were known to be conservative. Spent fuel pool accident research was carried out with computer codes to predict the severe accident progression following various postulated accident initiators. Various modeling and phenomenological uncertainties prompted a need for experimental confirmation.

From 2003 to 2012, the US-NRC undertook an experimental program to address thermal-hydraulic conditions and zirconium fire propagation during a complete loss of coolant accident in a boiling-water reactor (BWR) spent fuel pool (Lindgren and Durbin, 2013a,b). In that program, two kinds of tests series were performed. A first test series was performed with a single, full-length highly prototypic fuel assembly inside a prototypical pool rack cell, corresponding to a uniform spent fuel pool pattern of recently discharged, high-powered assembly (Fig. 1). It was followed by a second test series corresponding to five short assemblies (1/3 length) contained in a 3 × 3 pool rack and corresponding to a 1 × 4 loading pattern.

These experiments demonstrated that BWR fuel assemblies can lead to ignition which further propagates axially and radially in the pool rack during a complete loss of coolant accident.

In the meantime, code calculations for pressurized-water reactor (PWR) assemblies were also performed, leading to ignition prediction

Abbreviations: CA, Central Assembly; DRACCAR, Déformation et Renoyage d'un Assemblage de Crayons Combustibles pendant un Accident de Refroidissement (Deformation and reflooding of a fuel rods assembly during a LOCA accident); FR, Flow Rate; HT, Heat Transfer; IRSN, Institut de Radioprotection et de Sûreté Nucléaire; KIT, Karlsruhe Institute of Technology; LOCA, Loss Of Coolant Accident; US-NRC, US Nuclear Regulatory Commission; PA, Peripheral Assembly; PBR, Pilling and Bedworth Ratio; SFP, Sandia Fuel Project

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https://doi.org/10.1016/j.nucengdes.2018.01.047
Received 5 September 2017; Received in revised form 23 January 2018; Accepted 27 January 2018
Available online 20 March 2018
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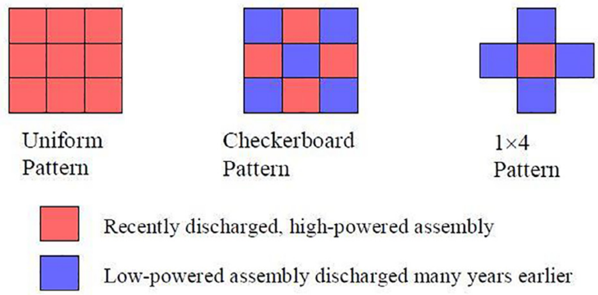

Fig. 1. Loading patterns (NUREG 7143).

and complete fuel degradation for assemblies. However, experimental and qualified data obtained in representative fuel configurations were needed to confirm these results. In May 2009, 12 countries from OECD, the Nuclear Energy Agency (NEA) and the US-NRC signed an agreement to perform experiments focused on thermal-hydraulic and zirconium fire phenomena in a PWR spent fuel pool. This program lasted from 2009 to 2013. Similarly to the previous BWR study, the Sandia Fuel Project was split in two parts in order to first study the zirconium fire propagation in one assembly alone, and then to look out for the propagation of the fire from the central assembly to the neighboring assemblies, simulating a 1 × 4 loading pattern. The SFP series used full-length commercial fuel assemblies' mockup. A benchmark was performed between the partners after each ignition test, for code comparison and improvement. The results of the first benchmark have been published (Adorni et al., 2016) leading to similar results among the partners, insofar as hydraulics has been properly described due to the availability of accurate hydraulics data in the test series.

As an OECD partner, IRSN participated only to the Phase II of that program using the ASTEC (Chatelard, 2016) and DRACCAR (Glantz et al., 2017) codes. The main physical effects were related to thermal hydraulics, cladding oxidation kinetics and heat exchange within cells and between adjacent cells, in a non-axisymmetric geometry. The argument of non-axi-symmetry was decisive for running the DRACCAR code in the post-test recalculations. However, because of a rather complex geometry of the Phase II tests, a more cautious approach has been chosen to firstly recalculate the simpler geometry of the Phase I tests.

DRACCAR is a multi-physics code for computational analysis of multi-rod ballooning and fuel relocation during LOCA transients. The main features of rod ballooning and fuel relocation of the code have not been used, but we have taken advantage of the unstructured meshing capability of the code to reproduce the exact geometry of the 1 × 4 loading pattern cells assemblies.

This paper will deal with DRACCAR calculations for both test series. A best data set will be worked out for the Phase I and applied for the Phase II calculations, thus illustrating the good consistency within the code modeling to calculate two different sets of geometries with the same code options.

The simulation of the whole accident sequence was challenging, leading to several code improvements and to a better understanding of the whole experimental sequence.

2. Sandia Fuel Project

2.1. OCDE/SFP experimental program

The program was conducted in two phases. The Phase I (Durbin et al., 2016a) focused only on axial heating and burn propagation, while the Phase II (Durbin et al., 2016b) addressed both axial and radial heating and burn propagation, including effects of fuel rod ballooning. Each part of the program included many tests: unheated flow tests, pre-ignition tests, and a final destructive ignition test. In this paper, we will focus on the final destructive part of each test.

The test assemblies were fully instrumented to get various measurements: the inlet flow rates, the thermal responses of the rods throughout the assembly, and the amounts of nitrogen, oxygen, and argon in the exhaust stream directly above the test bundle.

Phase I looked at a single PWR fuel assembly within a storage cell at commercially available sizes. The single test assembly was completely insulated to model boundary conditions representing a "hot neighbor" loading pattern ("Uniform pattern" Fig. 1), which is a typical bounding scenario. The heated fuel rods were filled with compacted magnesium oxide (MgO) powder with a thermal mass (ρCp) similar to that of uranium dioxide (UO2), making MgO powder an excellent surrogate for spent fuel. This phase gave experimental insights for ignition timing and burn propagation in a single 17 × 17 PWR assembly.

Phase II was composed of five full-length assemblies placed in a 3 × 3 pool rack, with the central cell being the only heated assembly. These boundary conditions experimentally represent a "cold neighbor" situation ("1 × 4 pattern" Fig. 1) that completes the bounding scenario covered by Phase I. All mockup fuel assemblies were constructed with zirconium alloy cladding and prototypic structural components.

The central assembly used the same heated design as the one used in Phase I. The unheated peripheral fuel rods were filled with high-density MgO ceramic pellets, sized to precisely match the thermal mass of real spent fuel rods. Two of the four peripheral assemblies were pressurized with argon gas (at different pressures), so that these fuel rods would balloon when the zirconium-alloy cladding reached a high enough temperature. The two peripheral assemblies without pressurized rods were used to compare and evaluate the effects of ballooning.

2.2. Main test outcomes

2.2.1. SFP Phase I results

The final ignition test was conducted in March 2011 at a simulated decay power of 5.0 kW, equivalent to offload duration of approximately 17 months. The first detection of the ignition temperature (1200 K) of the Zircaloy claddings within the assembly happened at 12.66 h after the test onset, near the top of the rods at 3.302 m. The test assembly continued to react for several days after the first ignition event, leading to the final destruction of the assembly due to the very high temperature level being reached.

At these high temperatures, zirconium readily reacts with oxygen to form a zirconium dioxide product layer, with a highly exothermic reaction. During the burn phase, the oxygen concentration dropped to zero (starvation) due to the zirconium oxidation reactions, converting 14% of the initial bare zirconium to ZrO_2.

Additional mechanisms come into play when nitrogen is present in the gas phase. The nitrogen reacts with zirconium to produce ZrN in a spot wise manner. According to the exhaust gas analysis, 20% to 40% of the zirconium in the assembly was converted to ZrN. These results indicate that the hot "oxygen starved" environment remaining after the passage of the burn front is ideal for significant zirconium nitride formation.

2.2.2. SFP Phase II results

The final ignition test was conducted in June 2012 at a simulated decay power of 15.0 kW for the central assembly, representing a three-month-offload assembly (at 45 GWd/MTHM burnup).

The first ignition temperature event of the Zircaloy claddings was observed after 6.31 h in the central fuel assembly, at a similar level to the one of the Phase I test (at 3.302 m). The cladding fire propagated transversely into the peripheral assemblies at 7.08 h and 3.150 m. The progression of the ignition front across the entire cross section of all of the peripheral assemblies was detected at 8.74 h. The thermal-hydraulic behavior of assemblies with ballooned rods did not appear to be much different from the unpressurized assemblies, leading us to not consider any cladding deformation modeling in the calculations.

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