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Simulation of REBEKA 6 with DRACCAR v2.1

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HIGHLIGHTS

- A simulation of REBEKA 6 with the code DRACCAR v2.1 is presented.
- The thermo-mechanical impact of a non-heated central rod on its neighbors is assessed.
- Code predictions are encouraging although some trends cannot be reproduced.
- Tertiary creep models or empirical models could be added for balloon size predictions.

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ABSTRACT

This document presents a simulation of the test REBEKA 6 with the thermo-mechanical code DRACCAR v2.1, carried out in the framework of the NURESAFE SP3. The analysis focuses on the impact of the non-heated central rod on its neighbors: various results, including azimuthal temperature differences, cladding creep in different directions, overall deformation profiles and the occurrence of rupture are assessed and compared to experimental data.

Overall, the DRACCAR results are encouraging and most trends seem plausible although the experimental data cannot always be reproduced accurately. Several suggestions for future developments are provided, including the addition of a model dedicated to tertiary creep in order to obtain a more accurate assessment of the size of post-rupture balloons.

1. Introduction

1.1. Background

In the framework of the NURESAFE SP3, AREVA contributes by providing an assessment of DRACCAR's predictive capabilities against the REBEKA-6 test.

A first comparison of DRACCAR's predictions against REBEKA 6 data has already been performed in Lamare. This paper presents temperatures histories, fluid temperatures, internal rod pressures and deformation profiles obtained in a highly-simplified 4*1/4 rod geometry where the non-heated central rod was not considered. In order not to duplicate this analysis, it is suggested to focus here on another aspect of REBEKA 6: the impact of a non-heated rod on its neighbors and DRACCAR's ability to predict the resulting azimuthal temperature field and its mechanical consequences on deformation and rupture. DRACCAR does indeed support an azimuthal meshing of the rods, together with radiation heat transfer, which makes the code suitable for such an analysis. Besides, the REBEKA 7 test is essentially a duplication of REBEKA 6 in which the central rod was pressurized and heated, which provides additional experimental data for a comparison of the central rod's impact.

The objective of this work is to assess the accuracy of the predictions provided by DRACCAR and the plausibility of the code's models. Correctly calculating swelling and rupture of the rods in an asymmetrical thermal environment is indeed relevant to safety analyses since it determines how well the rods will be cooled and hence the peak temperatures that are to be expected in the bundle.

1.2. Content of the document

A quick description of the REBEKA 6 test is given in Section 2.1, followed by an overview of DRACCAR's setup in Section 2.2.

In Section 3, the impact of the non-heated rod on the azimuthal temperature field is analyzed. This includes an assessment of the "Hot Side Straight Effect" model, which enables the code to decenter the cladding during deformation on the basis of the temperature field. Sections 4 and 5 investigate the deformation of the

Abbreviations: HSSE, Hot Side Straight Effect; KfK, Kern Forschungszentrum Karlsruhe; KIT, Karlsruher Institut für Technologie; LB LOCA, Large Break Loss of Coolant Accident; Zy, Zircaloy.

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cladding, both locally (at a given elevation) and globally i.e. over the entire rod length. Section 6 provides a comparison of the internal rod pressures, which also gives some information on the kinetics of rod creep. Finally, Section 7 focuses on rod rupture: rupture orientation, time of rupture and rupture elevation are analyzed.

DRACCAR's predictions are systematically compared to experimental data whenever it is available. All the experimental data was retrieved from KfK (Kern Forschungszentrum Karlsruhe) reports (Wiehr and Harten, 1986, 1987; Wiehr, 1988).

2. The REBEKA 6 test and its simulation with DRACCAR

2.1. The REBEKA 6 test

The REBEKA (REaktortypische Bündel Experimente Karlsruhe) tests were conducted in Karlsruhe by KfK (KIT: Karlsruher Institut für Technologie) from 1973 to 1986. The purpose of these tests was to assess the behavior of a rod bundle following a Large Break Loss of Coolant Accident (2A LB LOCA), an accident in which rod swelling and bursting may occur. More specifically, the purpose of the tests was to determine the extent of flow blockage induced by swelling/bursting and if this blockage could hinder core cooling. The possible propagation of ruptures in the bundle was also a point of interest when the tests were designed.

2.1.1. Test rig and experimental procedure

The REBEKA 6 test rig (see Fig. 1) is composed of a 7*7 electrically-heated rod bundle. Each rod is composed of concentric layers of various materials, including an Inconel layer (in which the heating power is dissipated), a gap filled with He and an outer Zy-4 cladding. The rods are 3.9 m long and are held in place by 8 grids evenly positioned along the rods. The entire rig is pressurized at around 4 bar.

In order to obtain stabilized initial conditions, 11.5 g/s of steam at ~140 °C is fed into the bottom of the test section and flows upwards along the rods, before exiting from the top of the test section. When the temperature inside the bundle is stable, the rods are pressurized with helium at 60 bar and a heating power of ~7.8 kW/rod is applied to the rods (cosine power profile).

The steam flow along the rods is not sufficient to cool the rods, which are therefore subjected to a temperature ramp of about ~7 K/s.

When the rod temperature at mid-elevation reaches 765 °C, the steam supply is turned off, the power generation in the rods is reduced to 6.6 kW/rod and water is fed into the bottom of the test section to start the quenching phase. The water supply ensures a quenching front upward velocity of about 3 cm/s. The test proceeds until the top of the rods are quenched.

In REBEKA 6, the central rod is neither pressurized nor heated which makes it a "cold" spot for all neighboring rods.

2.1.2. Instrumentation

NiCr/Ni thermocouples are positioned on most rods at various elevation along the bundle. These thermocouples are either soldered inside the rods or welded to the surface of the Zircaloy cladding. The latter make it possible to compare temperature predictions for the cladding to experimental data. Finally, thermocouples dedicated to the measurement of fluid temperatures are positioned along the non-heated central rod, on several grids and along the shell surrounding the bundle.

The pressure inside each pressurized rod is measured by means of a dedicated manometer. This makes it possible to determine the time of rupture for each rod. The pressure in the test section is also measured with a dedicated manometer. Differential pressure sensors are also included in order to assess the position of the quench front during reflooding.

2.1.3. Post-test results and examination

Data acquisition during the test and post-test examination provided the following information:

- The temperature histories of all rods at various elevations, see Section 3.
- Sectional cuts of the bundle, see Section 4.
- The deformation of the rods as a function of elevation, see Section 5.2.
- The pressure histories of the rods, see Section 6.
- The rupture elevations and orientations, see Sections 7.1 and 7.3.

2.1.4. Additional information retrieved from other REBEKA tests

Although REBEKA 6 is the main focus of this paper, two other REBEKA tests will be briefly mentioned in this paper because they provide interesting information:

- The REBEKA 7 test is essentially a duplication of REBEKA 6. The main difference is that the central rod was heated and pressurized in this test and that the two rods which were only pressurized at 5 bar in REBEKA 6 were fully pressurized in REBEKA 7 (60 bars). The underlying idea was to make sure that all conditions leading to maximal blockage of the bundle were met. A comparison of REBEKA 6 and 7 therefore makes it possible to assess the impact of a cold/hot (central) rod on its neighbors. This information will be helpful when investigating the orthoradial deformation and the burst orientation of the rods surrounding the central rod.
- The REBEKA 4 test was carried out with a smaller 5*5 bundle, in which only the innermost 8 rods were pressurized (the outer rows were only heated). As in REBEKA 6, the central rod is neither pressurized nor heated. The power profile dissipated in the rods was step-shaped instead of cosine-shaped but the heating ramps were similar (~7 K/s). The test sequence is similar to REBEKA 6 but, prior to quenching, the steam flowed downwards (from top to bottom of the test section) instead of upwards.
  REBEKA 4 provides interesting data because a rod located next to the unheated central rod is equipped with two thermocouples: one thermocouple faces the central non-heated rod whereas the second thermocouple faces a heated rod in the opposite direction. The temperature difference between both sides of the rod is therefore available. This provides an order of magnitude of the orthoradial temperature difference that should be expected.

2.2. DRACCAR v2.1 simulation characteristics

2.2.1. Coupled DRACCAR-CESAR simulation

DRACCAR relies on a 3D non-structured meshing, which makes it possible to simulate the 3D thermo-mechanical deformation of a fuel rod. In this application, it is coupled to the two-phase flow module CESAR. The combination of DRACCAR and CESAR enable the modelling of various phenomena including: heat transfer within solids and to the fluid, material property evolution (growth of an oxidic layer, phase change), contact between structures and cladding integrity (De Luze et al.). DRACCAR has already been validated against several test programs including ACHILLES, THETIS, OECD SFP (De Luze et al.).

This paper will take advantage of the fact that DRACCAR's 3D mesh can provide information on the orthoradial temperature field within the cladding of a rod facing structures at different temperatures.

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