Assessment of ASTEC 2.1 capability to predict reactor core behaviour at the late phase of severe accident progression based on QUENCH-12

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Abstract

The presented paper discusses capability of recently developed version 2 revision 1, patch 1 of ASTEC computer code to predict a fuel behaviour at late phase of severe accident progression. The conducted assessment is part of the ASTEC validation based on available information from performed tests in QUENCH program for these purposes. It has been selected QUENCH-12 experiment for simulation of investigated phenomena as fuel cladding, oxidation and hydrogen generation, including temperature escalation during heat up followed by quenching overheated surface fuel cladding.

The QUENCH-12 experiment was proposed by FZK together with RIAR Dimitrovgrad and IBRAE Moskow (Russia). The test was conducted at Forschungszentrum Karlsruhe on 27 December, 2006 in the frame of EC-supported ISTC program.

The selected QUENCH-12 experiment was performed to extend knowledge gathered in previous QUENCH test to fuel behaviour in other LWRs slightly different from well investigated western type PWR with squared lattice. The fuel assemblies with a hexagonal lattice and containing fuel rod claddings made of Zr1%Nb (E 110) using in the VVER reactors are investigated in the experiment.

The developed QUENCH-12 model for ASTEC code successfully predicted the entire sequence from initial heat-up to quench phase of experiment, except hydrogen generation during quenching phase at the end of transient. Keywords: Severe Accident, Reactor Core, Hydrogen production, VVER Fuel Analysis, QUENCH

1. Introduction

The aim of this research is to improve the results for oxygen consumption, temperature and hydrogen generation [1]. The main objective was to compare the bundle behaviour of an east VVER bundle during a severe accident scenario including quenching with water from the bottom. In ASTEC computer code it is used default correlation for the simulation of QUENCH-12 experiment. The QUENCH-12 test [2] as conducted successfully at KIT (Karlsruhe Institute of Technology) on 27 July 2011. The test was proposed by was proposed by FZK together with RIAR Dimitrovgrad and IBRAE Moscow (Russia), and supported by PSI (Switzerland) and the Kurchatov Institute Moscow (Russia) together with IRSN Cadarache (France).

The experiment QUENCH-12 was analysed with ASTEC computer code version 2.1 revision 1, patch 1. The code version of ASTEC 2.1.1 [3] represented the major evolution and improvements in the core region (model ICARE) [4]. The new dedicated model evaluates the creep and oxidation of Zr1%Nb alloys with the mechanical and chemical behaviour of VVER claddings. New general in-core heat transfer model based on an equivalent radiative conductivity approachable to deal with radiative exchanges in a reactor core whatever the core degradation. Implementation of a new correlation for the oxygen partial pressure in the fuel is used. During the front-end phase, CESAR calculates the thermal hydraulics in the whole test using 2D two-phase flow patterns. ICARE deals with the thermal behaviour and degradation of all vessel structures (heat-up, creep, oxidation, material relocation) from the beginning of the transient.

The experiment focussed specifically on following phenomena:
✓ The investigation of coolability and determination of the hydrogen;
✓ The provision of an extensive experimental database for the development of detailed mechanistic models;
✓ The examination of the physico-chemical behaviour of overheated fuel elements under different flooding conditions and at different stages of core degradation;
✓ The determination of cladding failure criteria, cracking of oxide layers, exposure of new metallic surfaces to steam;
✓ The investigation of the oxide layer degradation under steam starvation conditions and influence of this phenomenon on subsequent flooding;
✓ The investigation of the melt oxidation process;
✓ The determination of the hydrogen source term.

2. Description of QUENCH facility

The scheme of the QUENCH facility is presented on Figure 1. The test bundle is approximately 2.5 m long and is made up of 18 heated and 13 unheated fuel rod simulators, each with a length of approximately 2.5 m. The test section is enclosed by safety containment; it is a shroud of Zr2.5%Nb (E125) with a 37 mm thick ZrO\textsubscript{2} fiber insulation extending from the bottom to the upper end of the heated zone and a double walled cooling jacket of stainless steel over the entire length. Heating is electric by 4 mm diameter tungsten heaters installed in the rod center and the heated length is 1024 mm. Heated rods were filled with Ar5%Kr and unheated test rods, including the central one, were filled with He, in each rod at a pressure of approx. 0.22 MPa. The annulus between shroud and cooling jacket is filled (after several cycles of evacuation) with stagnant argon of 0.22 MPa. The 6.7 mm annulus of the cooling jacket is cooled by an argon flow. Both the absence of a ZrO\textsubscript{2} insulation above the heated region and the water cooling of the bundle head are to avoid overheating in that bundle region. The main contribution of the radial heat losses is due to radiation. The tungsten heaters are connected to electrodes made of molybdenum and copper at each end of the heater. The molybdenum and copper electrodes were joined by high frequency/high-temperature brazing under vacuum using an AuNi 18 powder (particle size <105 μm). For electrical insulation the surfaces of both types of electrodes were plasma-coated with 0.2 mm ZrO\textsubscript{2}. To protect the copper electrodes and the O-ring-sealed wall penetrations against excessive heat they are water-cooled (lower and upper cooling chambers filled with demineralized water). The copper electrodes are connected to the DC electric power supply by means of special sliding contacts at the top and bottom.

The fuel rod simulators are held in position by grid spacers at seven levels, all made of Zr1%Nb with 20 mm length. The bundle geometry and clad material correspond to Soviet VVER-type with respect to material and dimensions (Zr1%Nb) on the Figure 2. In radial direction the QUENCH fuel rod bundle is composed of an unheated rod at center position, a ring of 6 heated rods connected to an electric power supply, a middle ring with 13 unheated rods and an outer ring of 12 heated rods connected to another electric power supply system, and a set of 6 corner rods at the vacant rod positions.
3. Boundary conditions and the test phase of QUENCH-12

Table 1 summarizes the main boundary conditions for QUENCH-12 for each test phase as well as the main times and temperatures.

| Phase   | Description |
|---------|-------------|
| Phase I | Pre-oxidation started with an application of electrical bundle power of ca. 3.5 kW, ramped step-wise to 9.9 kW over approx. 2300 s to achieve the bundle pre-oxidation temperature of 1473 K to of 6000 s with 3.3 g/s flow of steam and Ar. |
| Phase II| During the transient phase the bundle power was ramped at a rate of 5.1 W/s to reach increasing of maximum bundle temperature of 2073 K. |
| Phase III | Quenching of the bundle by a water flow of 48 g/s |

Stabilization the initial bundle temperature at 873 K.

The electrical power input during the QUENCH-12 test corresponds completely to the values calculated up to reflood phase (see Figure 3). The experiment started with an electrical bundle power about 3.5 kW, which was ramped step-wise to 9.9 kW over approx. 2300 s to achieve the pre-oxidation temperature at bundle. Pre-oxidation continued to the test time of 6000 s. The power was then ramped at a rate of 5.1 W/s to cause a temperature increase until the desired maximum temperature before quench was reached. The electrical power was reduced to 4 kW during the reflood phase [5].
4. Description of ASTEC QUENCH facility input model

ASTEC computer code version 2.1 revision 1, patch 1 has been used to simulate the experiment QUENCH-12. The new model of computer code ASTEC 2.1.1 [6] has been developed at INRNE-BAS. The new input deck for QUENCH - 12 test, was adapted to new version of the code of at the baseline input deck [7] with the same initial and boundary conditions.

In the radial direction, the whole test section is modelled including shroud up to the inner cooling channel showing on the Figure 4. An ASTEC V2.1.1.1 model of the QUENCH-12 test includes three fluid channels top represent the test section. In channel 1, a central rod (CLAD 1) representing the unheated simulator rod and six heated simulator rods (CLAD 2). In channel 2, 12 unheated simulator rods are represented and divided into two sections since their radial distances to center is different. In channel 3, six corner rods and 12 heated simulator rods (CLAD 3). In axial direction the nodalization starts from -0.47 m and end at 1.5 m elevation, as given in Figure 5. Only the lateral connection to the gas-off pipe could not be simulated adequately. The test bundle is modelled with a central unheated rod; surrounded by two rings of independently heated rods, the ring with unheated rods between heated rings, the six Zircaloy corner rods, and a shroud up to the inner cooling jacket. The three of corner rods are modelled as a tube structures, the other three are modelled as a solid structure. The ZrO$_2$ fiber insulation is modelled from the bottom of lower plenum to the end of heated zone at 1.024 m elevation. The pipes that connect with the test section are not modelled. The boundary conditions are given in structure CONNECTY. The uses materials are VVER type. The bundle heated section is divided into 9 axial levels each one 0.10 m long and two with 0.062 m length.

The following heat transfer mechanisms are considered: conduction, convection at the external surface of the elements facing the channels (i.e. fuel rods, corner rods, grids and shroud), radiation among the FR$S$s, the corner rods, the shroud and the cooling jacket.

Cladding or shroud failure occurs if the cladding temperature is greater than 2300 K and if the ZrO$_2$ layer thickness is lower than 300 µm. Upon this condition, the inner molten material is released into the core channels and relocates according to the 2-D MAGMA model. The shroud is not allowed to fail and relocate, since it could induce massive blockage formation in the core channels, and excessive heat-up of the ascending fluid. Therefore, steam entrainment into the annular gap of the shroud is not considered. Oxidation of molten material outside the cladding is also taken into account.

As for the chemical interactions, oxidation of solid Zircaloy-4 and molten Zircaloy-4 within the cladding in steam is calculated with the “Best-fit correlation”.

Figure 3 Electrical power generated
5. Analysis of the results

On the Figure 6 is shows the maximum bundle temperature. The test started with bundle temperature stabilization at 873 K. The maximal bundle temperature compare to experimental data has slightly low temperature at elevation 950 mm. In the next phase of the test is the pre-oxidation phase, which continues to 6000 s. The comparison of calculated temperature (figure 7) is slightly overpredicted compare with experimental data [8]. The axial temperature predicted by ASTEC code for the bundle is shown on figure 8. The evolution of both predicted and measured temperatures are close to each, which means that ASTEC predicts very well the overall trends [9].

Figure 4 Radial nodalization scheme of ASTEC Quench facility

Figure 5 Axial nodalization scheme of ASTEC Quench facility

Figure 6 Maximal bundle temperature at elevation 1250 mm

Figure 7 Maximal bundle temperature at elevation 950 mm
The total hydrogen generation is shown in Figure 9. The calculations have given a closer prediction on the time when the hydrogen started to be generated (during the heat-up phase). The hydrogen generation during reflood is underestimated compare with experimental data. The total hydrogen production is 58 g during the whole test [10], [11]. In case of an accident with failure of the main and emergency cooling systems, core dry-out can lead to core degradation and even to core meltdown. Due to the dry-out and available steam, the fuel rods oxidise. It is concluded that a large amount of hydrogen previously absorbed in the metal is released additionally to the hydrogen produced by the strong oxidation during temperature escalation and at the beginning of the reflood phase, respectively.

Oxidation of zircaloy depends on the time, temperature, gas composition and cladding alloys. The comparisons of the oxidation thickness profile for the 6 and 12 heated rods are shown in figure 10 and figure 11. The cladding oxidation is detected in the experiment at approximately 700 s, when the
maximal bundle temperature is approximately 1100 K. The flooding with water increases the amount of steam, which can lead to crack formation and break-up of the oxide layer of the fuel rods [12], [13].

6. Conclusions

The developed QUENCH-12 model for ASTEC code successfully predicted the entire sequence from initial heat-up to quench phase of experiment, except hydrogen generation during quenching phase at the end of transient. The hydrogen generation during reflood is underpredicted. It could be explained with using of significantly high initial temperature for Zircaloy oxidation and used oxidation correlations.

Despite the all assumptions, ASTEC code is able to predict temperatures reasonably and analyse many phenomena like oxidation and chemical processes.

7. References

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