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Track 4: Transient Fuel Behavior and Fuel Performance Methodologies and Test Facilities

Behavior of Zr1%Nb Fuel Cladding under Accident Conditions

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EXTENDED ABSTRACT

Introduction

The zirconium-steam reaction under LOCA conditions results in oxidation of the fuel cladding and intensive hydrogen production. The oxidation causes the mechanical deterioration and the embrittlement of the cladding. The formed hydrogen is partly absorbed by the Zr alloy. However the hydrogen uptake is not only the accompaniment of cladding oxidation. It contributes to the cladding brittleness, which can lead to the fragmentation of the fuel rods under thermal and mechanical loads. In order to avoid severe core damage, the safety regulations limit the maximum cladding temperature and the extent of the local cladding oxidation in design basis accidents (DBA) at the levels of 1200°C and 17%, respectively. Since a hydrogen-rich atmosphere can evolve under accident conditions, the cladding may absorb hydrogen from the gaseous environment, as well. This means that the cladding can become brittle at a lower oxidation level. Therefore, our purpose was to re-evaluate the cladding ductility of Zr1%Nb oxidized in hydrogen rich steam.

The cleaning tank incident at the unit 2 of Paks NPP (2003) resulted in severe fuel damage of 30 assemblies. The zirconium components suffered heavy oxidation. Full cross section break of the fuel assemblies was observed. H-rich atmosphere could have been formed in the closed cleaning tank. New experimental programme has been initiated at AEKI to understand what kind of processes took place during the Paks-2 incident and improve knowledge on the behaviour of Zr fuel cladding oxidized in H rich steam. Furthermore to support model development, paying special attention to the role of hydrogen uptake on cladding embrittlement.

The test programme included small scale tests and large scale tests with electrically heated 7-rod bundles in the CODEX (Core Degradation Experiment) facility.

Small scale tests

The main objectives of the small scale tests can be summarized as follow: to study the effect of oxygen and hydrogen content on the mechanical behavior and to investigate the ductile-brittle transition of Russian E110 type fuel cladding. The small scale experiments consisted of the following testing procedures: oxidation tests, mechanical tests and post test investigations. The oxidation was carried out at three different temperatures (900, 1000, 1100^{o}C) in a constant flow of steam-hydrogen mixture. At each temperature several samples were oxidized during different times in order to achieve different oxidation ratios. The extent of the oxidation was measured through the weight gain of the specimens. The mechanical tests covered ring compression tests, tensile tests and ballooning experiments. The post test investigations included visual observations, metallographic analysis, SEM analysis and measurement of hydrogen content in the cladding by hot extraction method.

The ductile-brittle transition of Zr1%Nb cladding was assessed through the analysis of ring compression tests' data. The ring compression tests were performed at room temperature with pre-oxidized specimens. The specific energy at failure was used for the evaluation of the cladding ductility, since it can be easily determined as the quotient of the integral of the force and the ring height. According to our earlier studies in pure steam, 50 mJ/mm specific energy was chosen as a boundary value for the categorization of the ring specimens. The ductile-brittle transition was expressed as a function of temperature and time.

On the basis of the test results the hydrogen uptake strongly reduced the ductility of the cladding. Considering this ductility limit, the embrittlement of Zr-1Nb cladding is expected at a hydrogen content above ~ 500 wppm. The experimental data demonstrated that the correlation for the ductility limit of E110 is valid in hydrogen rich steam atmosphere, as well.

Large scale tests

During the large scale tests the main conditions of the incident were reconstructed. The new facility included a 7-rod VVER-440 type bundle with alumina pellets. Surrounding heaters were applied to reach high temperature in the cleaning tank model. Inlet and outlet junctions were located in the bottom and perforations were used to establish bypass flow. In order to simulate the spent fuel storage pool an expansion tank was connected.

On-line data recording included: temperature measurements, flowrates, water levels, pressures, hydrogen concentration, hydrogen volumetric flow and video recording.

After the experiment many similarities were found in bundle state with the assemblies of Paks-2 incident. The upper part of the rods was almost fully oxidized, while the bottom part – cooled by water during the experiment – remained intact. The middle and upper sections were broken into several pieces. The material was very brittle, further fragmentation took place during the handling of fuel rods. The post-test examination indicated high hydrogen content (several thousands ppm) in the Zr cladding and shroud.

The simulation of the cleaning tank incident provided valuable information on the probable scenario of the real incident. The data will be used for model development and code validation.