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Aerosol release from Silver Indium Cadmium control rod

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In nuclear reactor severe accident, radioactive fission products as well as structural materials are released from the core by evaporation, and the released gases form particles by nucleation and condensation. In addition, aerosol particles may be generated by droplet formation and fragmentation of the core. In pressurized water reactors (PWR), a commonly used control rod material is silver-indium-cadmium (SIC) covered with stainless steel cladding. The control rod elements, Cd, In and Ag, have relatively low melting temperatures, and especially Cd has also a very low boiling point (about 1040 K). Therefore, control rods are likely to fail early on in the accident affecting fuel rod degradation as well as aerosol source term to the environment in the event of containment failure (Petti, 1989; Haste and Plumecocq, 2003).

The QUENCH experimental program at Forschungszentrum Karlsruhe investigates phenomena associated with reflood of a degrading core under postulated severe accident conditions but where the geometry is still mainly rod-like and degradation is still at an early phase. QUENCH-13 test was the first in this program to include a SIC control rod of prototypic PWR design (Birchley et al., 2008). The effects of the control rod on degradation and reflood behaviour were examined under integral conditions, and for the first time the release of SIC aerosols following control rod rupture was measured.

To characterize the extent of aerosol release during the control rod failure, aerosol particle size distribution and concentration measurements in the off-gas pipe of the QUENCH facility were carried out. The aerosol concentration and size distribution released from the core were determined using Electrical Low-Pressure Impactor (ELPI), and Berner Low-Pressure Impactors (BLPI). The sampling system was isolated from the facility before core cooling by quench. A second aerosol sampling system with 10 impactors was used also during the quench phase of the test.

Two aerosol particle modes were generated, fine mode with $D_{ae} = 0.1 - 2$ µm generated by vaporization and subsequent nucleation, condensation and coagulation, and coarse particle mode with $D_{ae} > 3$ µm generated by droplet release and fragmentation. These findings indicate that the commonly used modeling of aerosol formation from control rod rupture by evaporation from molten material surface would need to be refined to include aerosol generation by mechanical processes, such as droplet formation and fragment entrainment.

The aerosol generation during QUENCH-13 test can be divided into five phases: 1) Transient phase: A small but steady aerosol concentration increase presumably due to release of Sn from the Zircaloy. 2) First significant aerosol release at peak bundle temperature 1560 K is thought to have been caused by a small crack in the control rod cladding. The particles contained mainly Cd as an oxide. 3) A very large, but short aerosol burst presumably due to a massive failure of the control rod contained particles rich in Cd and In, with some Ag in the fine mode particles. 4) Steady aerosol release followed the large burst at bundle peak temperature increase from 1650 to 1800 K. The particles were rich in Cd and In, and the amount of Ag increased with time. At this stage, molten control rod material was relocated downwards, and aerosol was released from molten material surface. 5) Particles released during bundle cooling by quench were mainly irregular, coarse particles containing Zr, Sn and W, along with varying amounts of Cd and In. Ag and Fe were present in some distinct particles.. The particles were presumably generated from the molten material, and by fragmentation of the Zircaloy cladding and heater elements due to thermal shocks.

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