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AN ASSESSMENT OF MOLTEN DEBRIS FREEZING IN A SEVERE RIA IN-PILE TEST

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An understanding of the freezing of molten debris on cold core structures following a hypothetical core meltdown accident in a light water reactor (LWR) is of importance to reactor safety analysis. The purpose of the present investigation was to analyze the transient freezing of the molten debris produced in a severe reactivity initiated accident (RIA) scoping test, designated RIA-ST-4,[1] which was performed in the Power Burst Facility and simulated a BWR control rod drop accident.

In the RIA-ST-4 experiment, a single, unirradiated, 20 wt% enriched, UO_2 fuel rod contained within a zircaloy flow shroud was subjected to a single power burst which deposited a total energy of about 700 cal/g UO_2. This energy deposition is well above what is possible in a commercial LWR during a hypothetical control rod drop (BWR) or ejection (PWR) accident. However, the performance of such an in-pile test has provided important information regarding molten debris movement, relocation, and freezing on cold walls.

The test rod failed approximately 33 ms after the initiation of the burst at a total energy deposition of about 370 cal/g UO_2. The average fuel temperature at the time of failure was estimated to be approximately 3500 K, about 400 K above the melting point of UO_2. Extensive amounts of molten UO_2 fuel and zircaloy cladding were produced and expelled axially and radially within the flow shroud upon fuel failure. The molten debris that was ejected upward froze and formed a complete flow blockage at the exit of the flow shroud. The inner surface of the shroud wall was completely coated with a frozen debris layer having a thickness of 0.7 mm. However, the inner surface of the shroud wall did not melt upon being contacted by the molten debris. The amount of molten debris deposited on the inner surface of the shroud wall was about 380 g, which represented 57% of the total mass of UO_2 fuel and zircaloy cladding present in the test fuel rod.

A physical model, shown in Figure 1, was developed to study the transient freezing of the molten debris layer deposited on the inner surface of the shroud wall during the RIA-ST-4 experiment. The shroud wall had a thickness of 3.05 mm and was cooled along its outer surface by coolant bypass flow. The governing equations were solved using a one-dimensional finite element code (SINGLE) based on the method of weighted residuals,[2] and considering the conditions of finite wall thickness, convective cooling at the shroud wall outer surface,

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radiation cooling at the surface of the molten debris layer, temperature dependent thermophysical properties, and internal heat generation in the molten debris. A parametric analysis was performed[3] to evaluate the effects of molten debris temperature, radiation cooling, initial wall temperature, and zircaloy volume ratio within the debris on the transient freezing of the molten debris layer and the potential erosion of the shroud wall due to melting. The molten debris is treated as a homogeneous mixture of UO_2 fuel and zircaloy cladding with volume ratios equivalent to those of the test fuel rod before the burst (≃13% zircaloy and 87% UO_2).

The freezing of the molten fuel debris is completed through two successive stages. In the first stage, the molten UO_2 freezes as the temperature of the molten debris descends below the melting point of UO_2 fuel (3113 K). Following that, the molten zircaloy within the UO_2 fuel crust (which froze in the first stage) freezes when the temperature in the crust drops below the melting point of zircaloy (2100 K). As shown in Figure 1, two moving fronts with a change-of-phase are formed within the debris layer. The first front represents a temperature isotherm corresponding to the melting point of UO_2 fuel and the second front corresponds to the melting point of zircaloy.

As shown in Figure 2, the freezing of the molten debris layer is governed mainly by the transient heat conduction through the shroud wall, with the radiation cooling at the surface of the molten debris layer influencing the freezing process. Analysis[3] indicated that increasing the zircaloy volume ratio within the debris accelerates the freezing process of the molten debris layer, because an increase in the zircaloy volume ratio significantly improves the effective thermal conductivity of the debris. Melting of the inner surface of the shroud wall upon being contacted by the molten debris would occur only if the initial wall temperature at the time of contact was in excess of about 1000 K. The melting process in the wall would be unstable under such conditions; that is, a molten layer would grow into the wall until it reached a maximum thickness (less than the initial thickness of the wall), and then the molten layer would become thinner due to freezing and would eventually disappear.

It is concluded that the shroud wall did not melt upon contact with the molten debris in the RIA-ST-4 experiment because of the initial low temperature in the wall (538 K), the small thickness of the wall (3.05 mm), and the continuous cooling at the wall outer surface during the test.

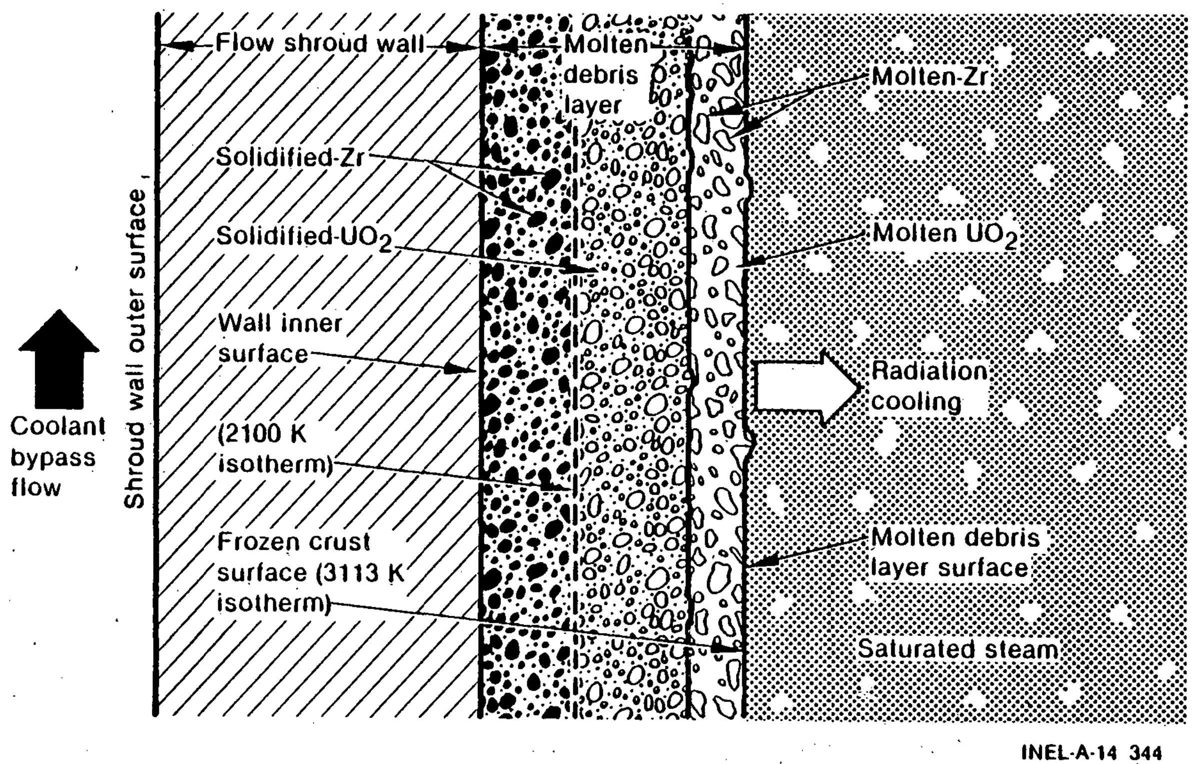

Figure 1. Physical Model.

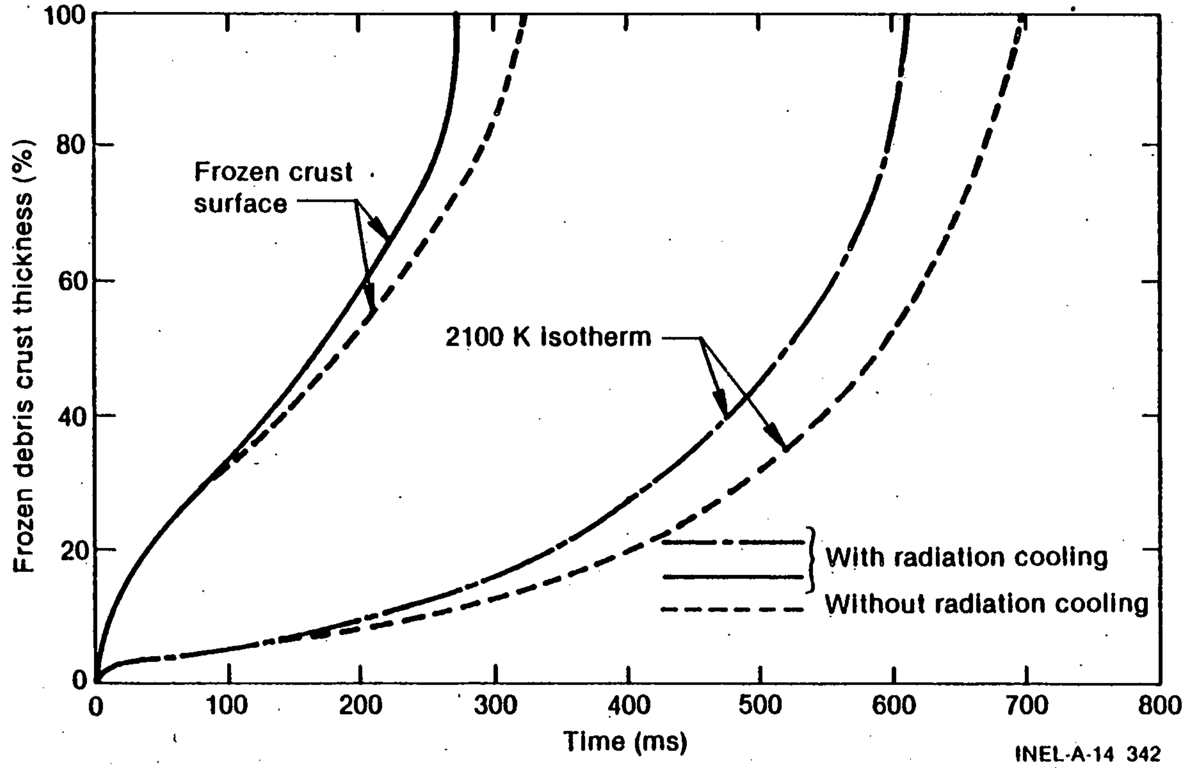

Figure 2. Transient freezing of the molten debris layer on the inner surface of the test shroud wall.

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