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ON A VAPOR EXPLOSION IN THE RIA-ST-4 Experiment

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A concern in assuring the safety of commercial light water reactors (LWRs) is whether core overheating, during which molten fuel is produced, can lead to massive vaporization of the coolant and shock pressurization of the system due to an energetic molten fuel-coolant interaction (MFCI). The possibility of such an MFCI occurring in a nuclear reactor during a hypothetical core meltdown accident (CMA) has not been ruled out.[1-3] The purpose of this paper is to present and briefly discuss the results obtained from the RIA-ST-4 experiment, described below, with respect to the ongoing discussion of the thermal interaction mechanisms of molten UO_2 fuel with water.

The RIA-ST-4 experiment was one of four scoping tests in the Reactivity Initiated Accident (RIA) Test Series, which is being conducted in the Power Burst Facility (PBF) to define an energy deposition failure threshold and to determine modes and consequences of fuel rod failure during a postulated boiling water reactor (BWR) control rod drop accident. These RIA tests are being performed at typical BWR hot-startup conditions (coolant pressure of 6.45 MPa, coolant temperature of 538 K, and coolant flow rate of 0.085 ℓ/s). The objective of the RIA-ST-4 experiment was to quantify the magnitude of potential pressure pulses as a result of fuel rod failure. The fact that high pressures and temperatures were recorded in this experiment, in addition to the fine fragmentation of the molten fuel debris, is of interest to the current safety analysis of LWRs with regard to the potential for energetic MFCI during a hypothetical CMA.

The RIA-ST-4 experiment was composed of a single, unirradiated, 20 wt% enriched, UO_2 fuel rod having a cold internal pressure of 3.79 MPa. The test rod, contained in a zircaloy flow shroud, was subjected to a single power burst, depositing a total energy of approximately 700 cal/g UO_2. A reactor peak power of 15.9 GW was achieved aproximately 30 ms after the initiation of the burst which lasted about 76 ms. The test fuel rod failed 3 ms after the peak power occurred at a total energy deposition of about 370 cal/g UO_2. The generation of coherent pressure pulses up to 35 MPa indicated rod failure. The coolant pressure recorded during the test at the inlet of the flow shroud is shown in Figure 1. The average fuel temperature at the time of failure is estimated to have been about 3500 K, at which temperature the contribution to the pressure by the UO_2 fuel vapor was negligibly small, about 0.05 MPa. Due to the high internal

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pressure in the test rod at the time of failure, extensive amounts of molten fuel and cladding were expelled within the flow shroud. A molten debris layer having a thickness of 0.7 mm was deposited along the inner surface of the shroud wall. The shroud outside diameter was enlarged from 25.4 to approximately 27.66 mm. This deformation was apparently caused by the pressure generated within the shroud upon fuel rod failure, together with the induced overheating in the shroud wall due to the deposition of the molten debris on the inner surface of the wall. The coolant temperature at the exit of the flow shroud reached a value in excess of 940 K after approximately 500 ms from the initiation of the burst.

Severe fuel fragmentation occurred, as evidenced by the particles collected from within the shroud and the upper particle filter. (A few unmelted chunks of UO_2 fuel were observed in the debris, indicating that the fuel pellets at the extreme ends of the active fuel stack did not melt completely before rod failure.) About 155 g of molten debris were fragmented upon contact with water (Figure 2). Approximately 58% of this amount (90 g) was fragmented into fine particles 38 to 2000 μm in diameter, characteristic of particle sizes generally observed in MFCI events[4,5]. As shown in Figure 2, the typical appearances of the fuel particles are spherical or round with relatively smooth surfaces, indicating that the fragmentation process occurred when the UO_2 fuel was molten. The fragmentation of the molten fuel debris may have been caused by the violent release of dissolved gases and entrapped water vapor from within the molten drops[6,7], or by a film boiling collapse mechanism,[8,9] or both. Such fragmentation mechanisms[6-9] may explain why some fragments (Figure 2) appear to be ruptured or voided in the center and ballooned.

The sequence of events leading to the recorded pressure pulses in the RIA-ST-4 experiment may be explained by the pressure detonation model of Board, Hall, and Hall.[10] They suggested that in a large-scale thermal interaction (vapor explosion), the rapid energy transfer from the hot liquid to the cold volatile one is initiated by a shock front in a manner similar to a chemical detonation. The shock front propagates through the coarse mixture of the two liquids causing fine fragementation and rapid energy transfer. The expansion of the volatile liquid sustains the shock front propagation. Such a thermal explosion (chemical-like detonation) will only propagate in a highly constrained geometry.[11] In the RIA-ST-4 experiment, the molten UO_2 fuel and zircaloy cladding ejected within the flow shroud probably coarsely intermixed with the coolant (liquid and vapor) under the effect of a pressure wave induced by the release of the hot, pressurized gases from within the test fuel rod upon failure. The preexistence of water vapor, due to the occurrence of film boiling at the cladding surface before failure, probably resulted in an efficient intermixing process[12] and increased the velocity differential between the molten drops and the coolant[13] because of the large difference in densities. This shock wave traveled through the mixture and the relative velocity differential may have induced hydrodynamic instabilities which, with other mechanisms,[6-9] caused the fine fragmentation of the molten drops. The resulting rapid vaporization of the coolant, together with the surrounding constraints by the flow shroud wall, caused the recorded pressure pulses.

In conclusion, the pressure pulses recorded in the RIA-ST-4 experiment were caused by an energetic MFCI that may be viewed in light of the Board et al., pressure detonation model.[10] However, further investigation of the fragmentation mechanisms and the effects of fuel failure and system pressure[9] are necessary before a final conclusion can be drawn.

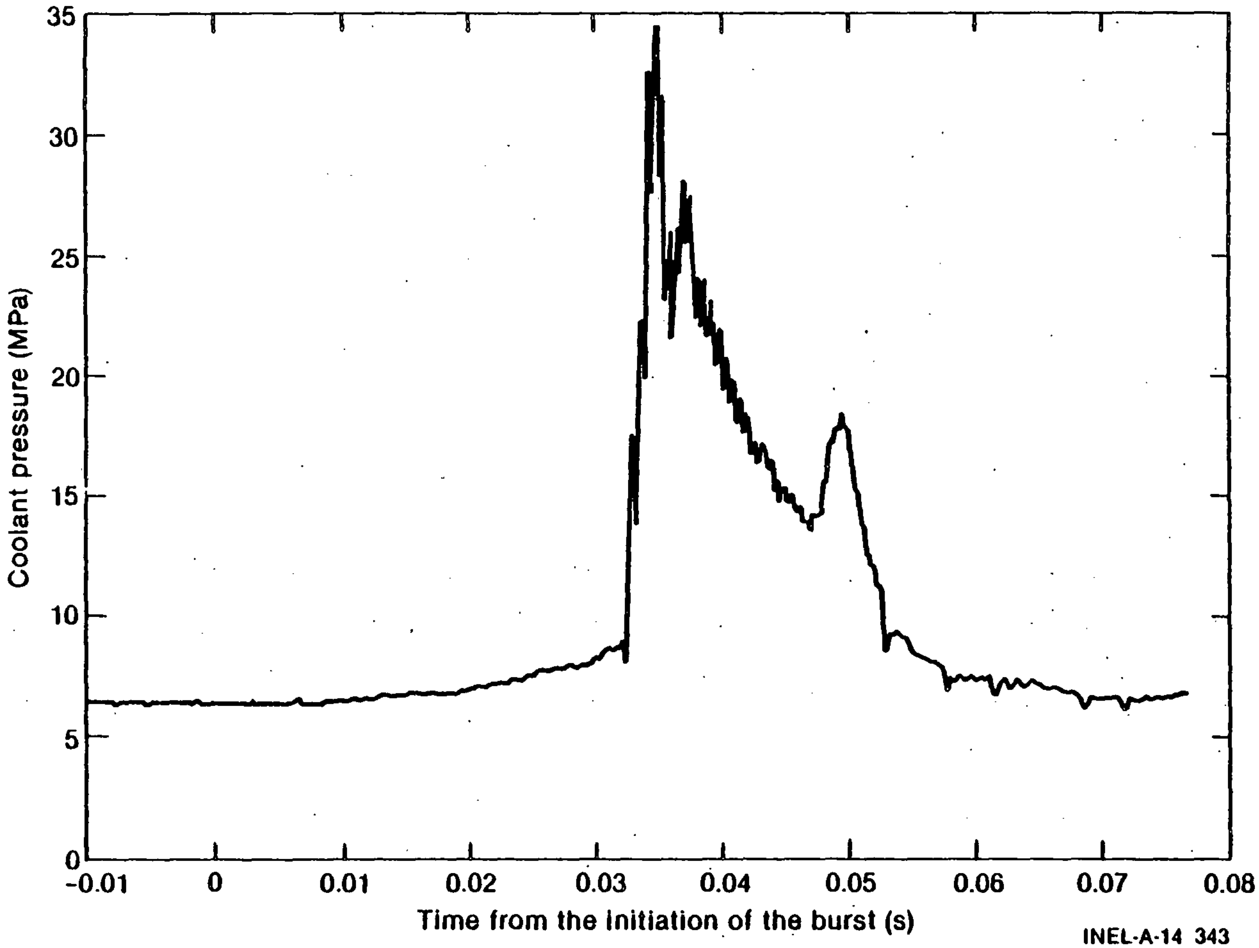

Figure 1. Coolant pressure measurements at the test shroud inlet.

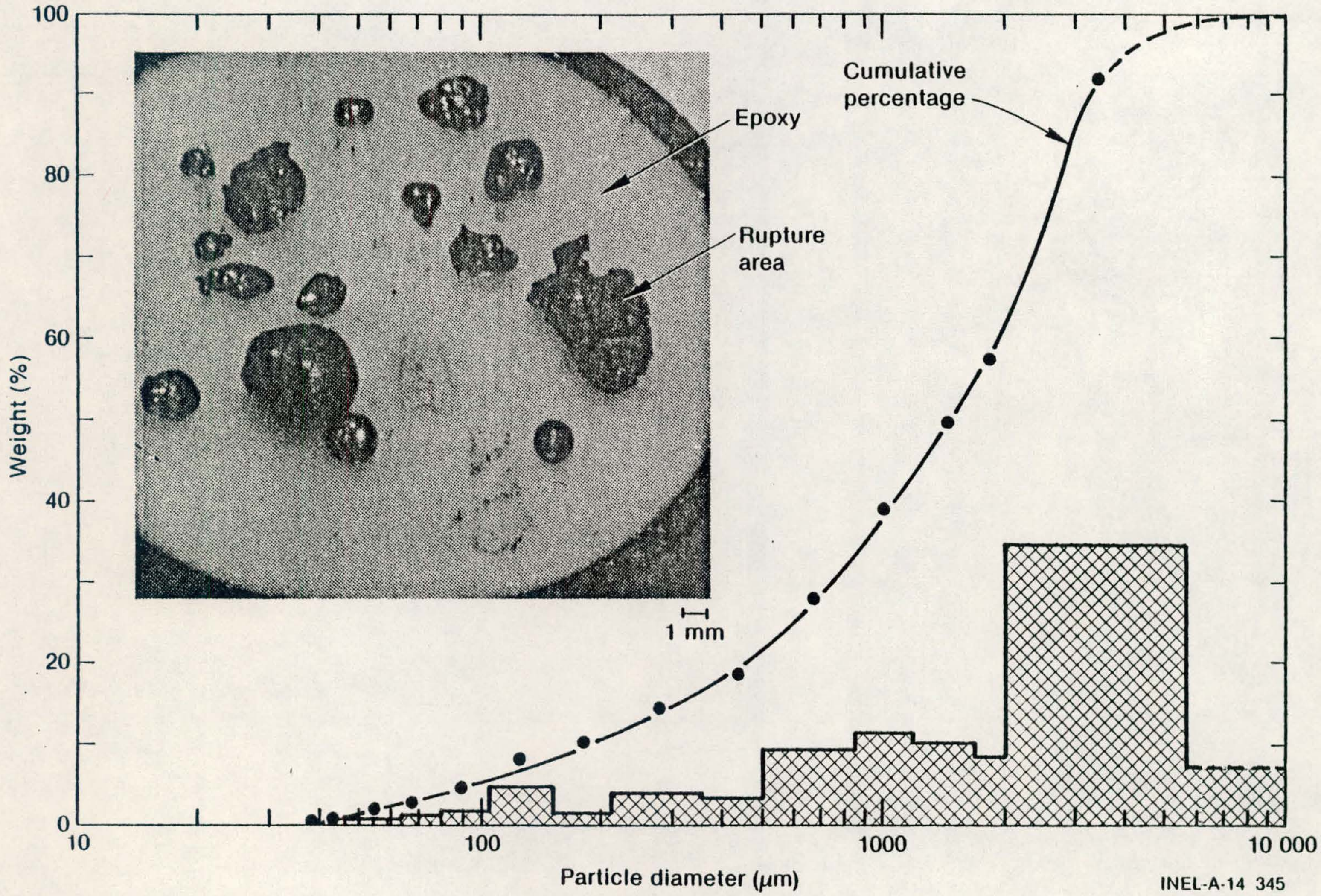

Figure 2. Fragmented fuel particles in the RIA-ST-4 experiment.

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