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POTENTIAL FOR FUEL MELTING AND CLADDING THERMAL FAILURE DURING A PCM EVENT IN LWRs

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The primary concern in nuclear reactor safety is to ensure that no conceivable accident, whether initiated by a failure of the reactor system or by incorrect operation, will lead to a dangerous release of radiation to the environment. A number of hypothesized off-normal power or cooling conditions, generally termed as power-cooling-mismatch (PCM) accidents, are considered in the safety analysis of light water reactors (LWRs). During a PCM accident, film boiling may occur at the cladding surface and cause a rapid temperature increase in the fuel and the cladding, perhaps producing embrittlement of the zircaloy cladding by oxidation [1-3]. Molten fuel may be produced at the center of the pellets, extrude radially through open cracks in the outer, unmelted portion of the pellet and relocate in the fuel-cladding gap. If the amount of extruded molten fuel is sufficient to establish contact with the cladding, which is at a high temperature during film boiling, the zircaloy cladding may melt. The present work assesses the potential for central fuel melting and thermal failure of the zircaloy cladding due to melting upon being contacted by extruded molten UO_2-fuel during a PCM event.

In some of the PCM in-pile tests [4-7] that have been performed in the Power Burst Facility at the Idaho National Engineering Laboratory, extensive central fuel melting of up to 80% of the pellet radius and extrusion of molten fuel into the fuel-cladding gap through radial cracks in the pellet were observed, an example of which is shown in Figure 1a. Conditions for central fuel melting during a hypothesized PCM event were predicted using a steady-state heat transfer model for a cylindrical fuel rod with central melting [8]. As shown in Figure 1b, onset of fuel melting at the center of the pellet depends on the linear power of the rod and the temperature at the surface of the pellet. Increasing the reactor power increases the molten fuel radius and temperature at the center of the pellet.

A differential pressure between the central melting zone and the fuel-cladding gap (due to the fuel volume expansion upon melting, molten fuel vapor pressure, and fission gas bubble coalescence) would tend to force such molten fuel to extrude outwards through radially open cracks in the pellet and relocate in the fuel-cladding gap. Thermal failure of zircaloy cladding due to partial or complete melting upon the cladding being contacted by the extruded molten UO_2 depends on the temperatures of the fuel and the cladding at the time of contact, as well as the metallurgical composition of the inner surface of the cladding (either alpha-zircaloy, or ZrO_2). As indicated in Figure 2, which is based on an analytical model [9] for the freezing of a stagnant superheated liquid on a semi-infinite wall undergoing simultaneous

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melting, increasing either the molten fuel temperature or the initial temperature of the cladding so that the combined values are above the curves for either oxygen-stabilized alpha-zircaloy or ZrO_2, would result in fuel freezing and simultaneous melting of the inner surface of the cladding. For example, melting of oxygen-stabilized alpha-zircaloy cladding upon being contacted by molten UO_2-fuel at the fusion temperature would be initiated if the cladding temperature was ≥1660 K. If a layer of ZrO_2 exists at the inner surface of the cladding, due to a sufficient oxygen potential in the fuel, onset of melting at the cladding inner surface (the ZrO_2) would be delayed up to an initial cladding temperature of ∿2640 K. At such a temperature, the middle layers of the cladding (which may have been either oxygen-stabilized alpha-zircaloy or beta zircaloy, or both) would already be in a molten state. In those PCM in-pile tests[4-7], in which the rod peak power was about 65 kW/m and a ZrO_2 or an oxygen-stabilized alpha-zircaloy layer was present at the inner surface of the cladding, melting of zircaloy cladding upon contact with molten fuel was not observed (Figure 1a). The absence of cladding melting, in agreement with Figure 2, was due to the fact that the temperatures of the molten fuel and the zircaloy cladding were below the levels required to initiate fuel freezing and simultaneous cladding melting upon contact[8]. In summary, if molten UO_2 should be produced and extruded into the fuel-cladding gap and contact the zircaloy-cladding, the cladding temperature would have to reach a value in excess of about 1660 K before thermal failure due to a partial or complete melting of the cladding is possible.

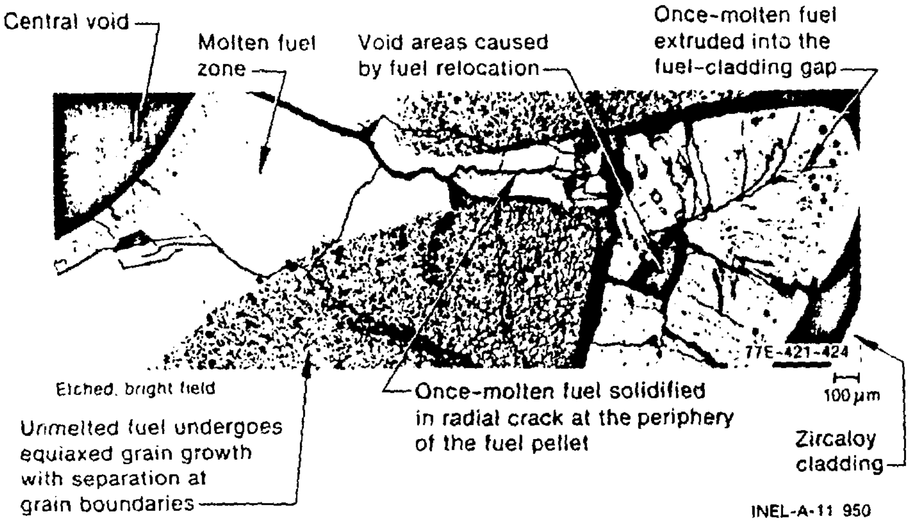

Fig. 1a Central fuel melting, radial extrusion and relocation in the fuel cladding gap, observed in PCM in-pile test[5].

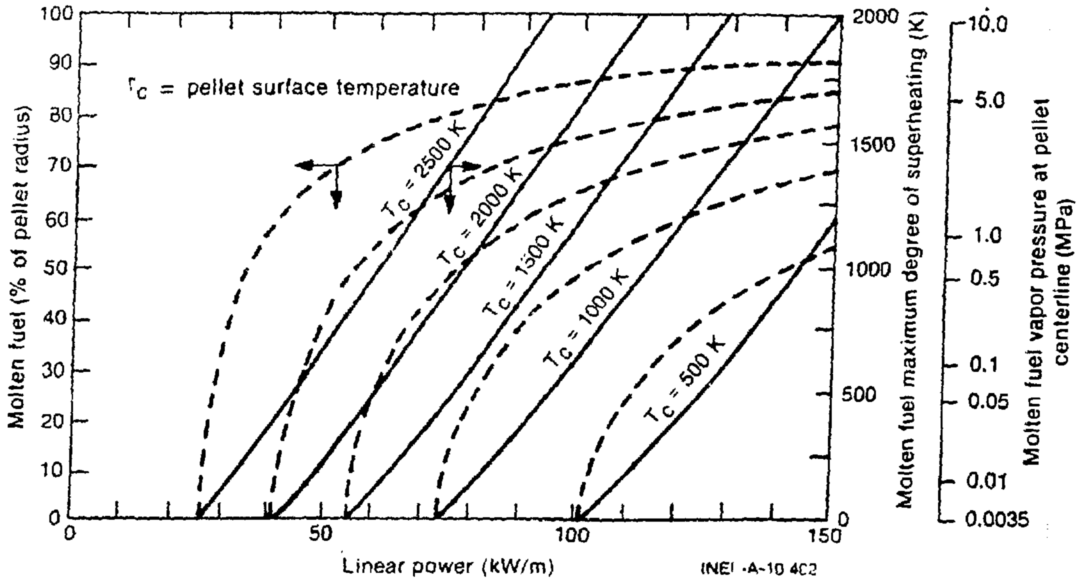

Fig. 1b Percentage fuel melting and superheating as function of linear power and pellet surface temperature.

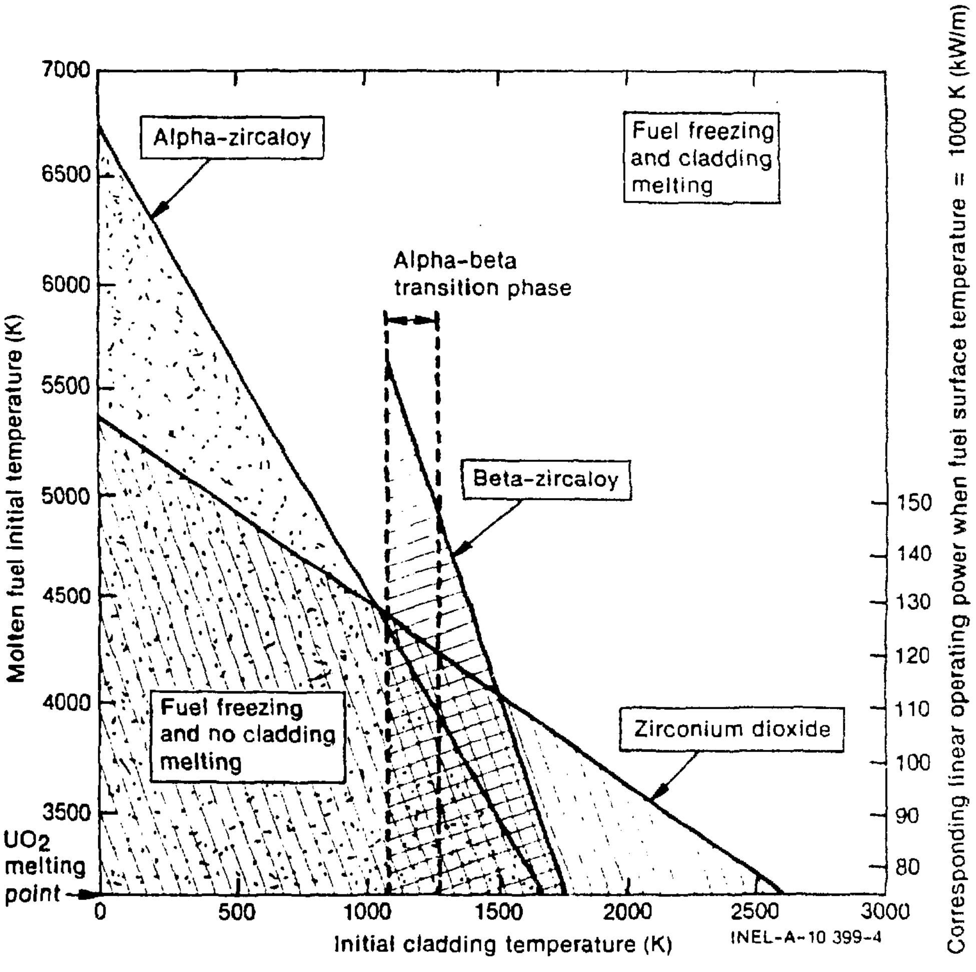

Fig. 2 Temperature map for initially molten UO_2 contacting initially solid zircaloy cladding.

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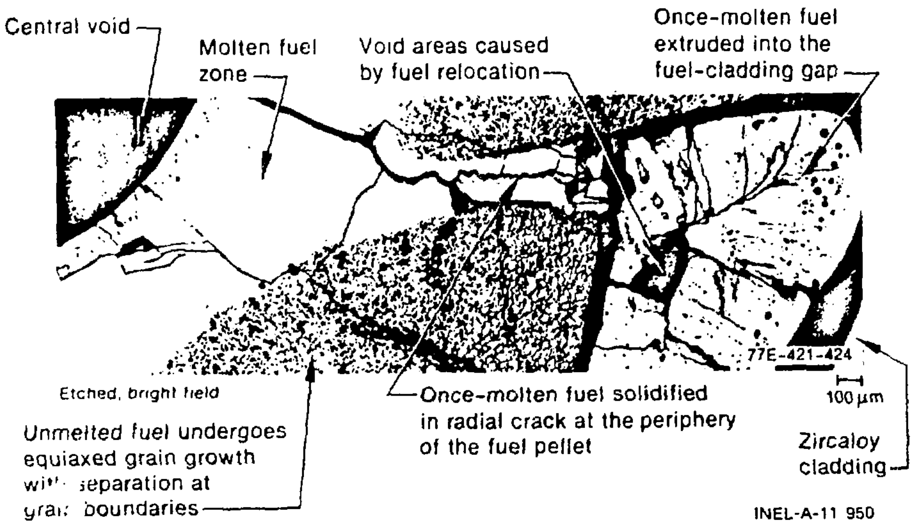

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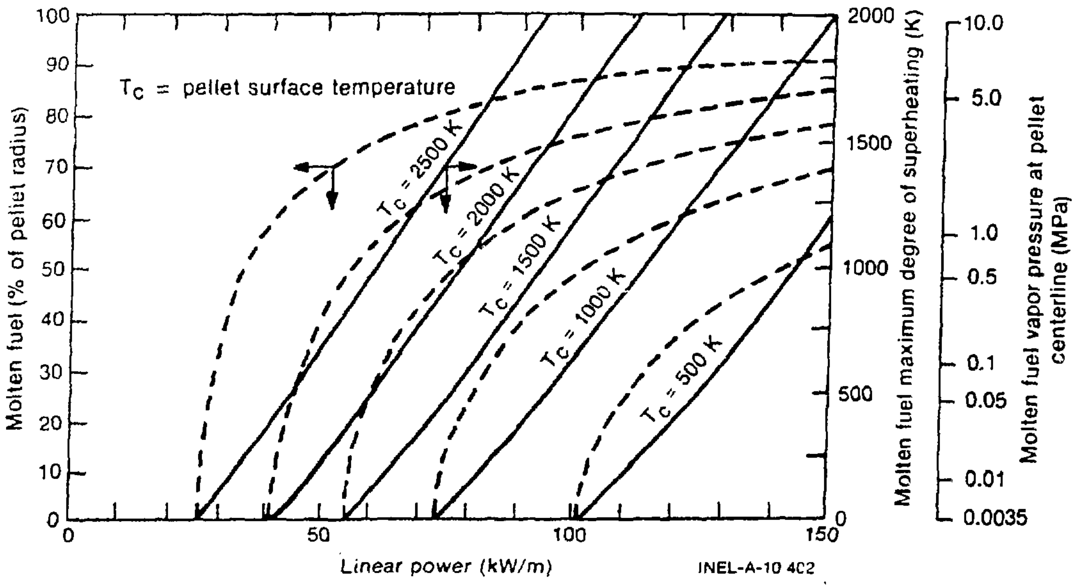

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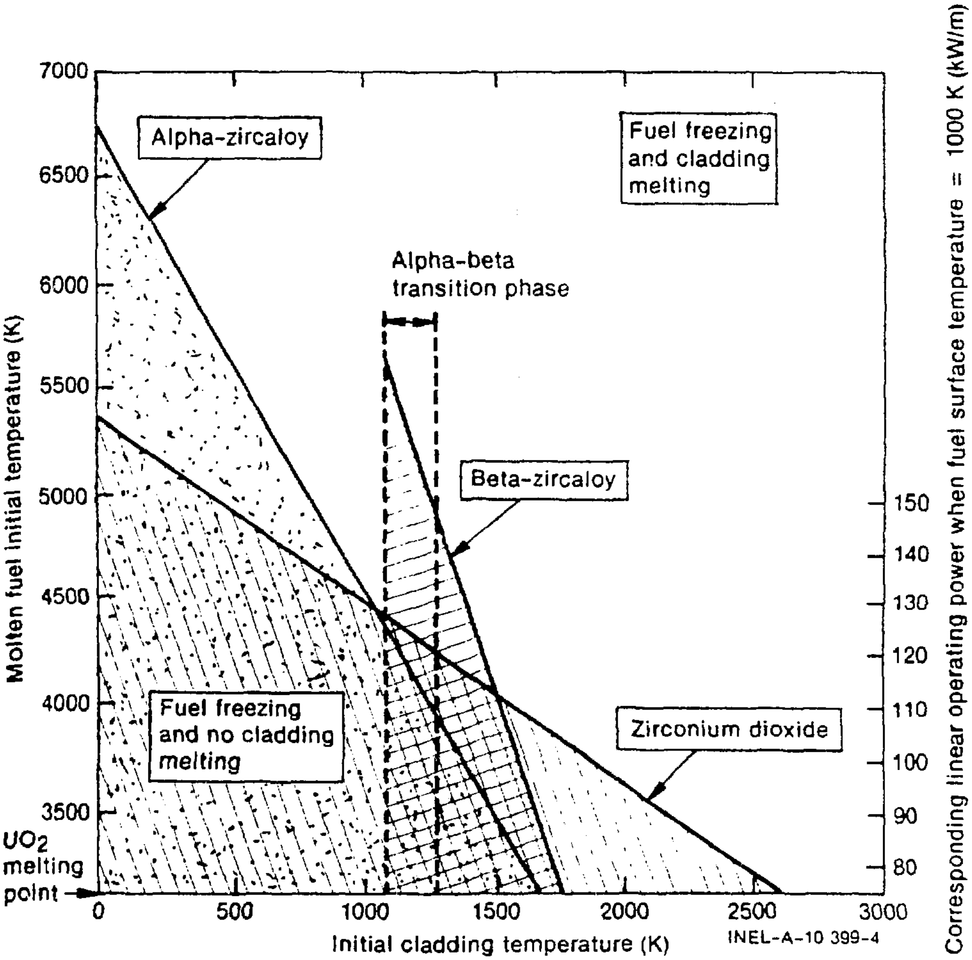

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