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Fuel Rod Failure During Film Boiling

(PCM-1 Test in the PBF)

W. F. Domenico
C. J. Stanley
A. S. Mehner

The Power-Cooling-Mismatch (PCM) Test, PCM-1 was conducted in the Power Burst Facility (PBF) in March of 1978. The PCM Test Series[1-7] is being conducted at the Idaho National Engineering Laboratory by EG&G Idaho, Inc., under contract to the USNRC and is designed to characterize the behavior of nuclear fuel rods operating under conditions of high power or low coolant flow or both leading to departure from nucleate boiling. The PCM-1 test was performed to provide in-pile data for a "worst case" PCM incident. The objective of this experiment was to study the behavior of a single pressurized water reactor (PWR) fuel rod subjected to a high-power and low flow environment which would result in cladding failure at full power. The "worst case" conditions established for the experiment consisted of a rod peak power of 78.7 kW/m and a coolant mass flux of 1356 kg/s.m^2. Fuel temperatures at the stipulated operating conditions were such that a significant volume of molten fuel was present when failure occurred which produced a high probability of molten fuel-coolant interaction (MFCI) with the possibility of a vapor explosion.

The single fuel rod used for PCM-1 was nominally of a 15 x 15 PWR design with the exceptions of enrichment (20 wt % U^{235}) and fuel stack length (0.91 m). The fuel rod cladding was unirradiated, zircaloy-4. The rod was backfilled to 2.54 MPa with a mixture of helium and argon (77.7% He). The test rod was positioned within a circular, zircaloy flow shroud with a rod-to-shroud diametral clearance of 5.6 mm. The fuel rod was instrumented for measurement of internal (plenum) gas pressure, cladding elongation, and cladding surface temperature at four axial locations.

The transient portion of the PCM-1 experiment consisted of ramping the fuel rod peak power up to 78.7 kW/m while maintaining the pre-established coolant conditions of 600 K inlet temperature, 15.2 MPa pressure, and a mass flux of 1356 kg/s.m^2. The critical heat flux was surpassed during the power ramp and stable film boiling was established along a 0.6-m section of the middle and upper portions of the fuel rod. The highest cladding temperature measured was approximately 2000K, well into the β-zircaloy temperature regime.

The fuel rod was operated in high temperature film boiling conditions for about 15 minutes. Following eight minutes of film boiling operation, cladding failure was detected by high activity levels in the coolant. The failure was apparently caused by the high thermal and mechanical stresses generated by the heavy oxidation of the zircaloy cladding. Calculations of equivalent cladding reacted to oxide indicate that more than 21% of the zircaloy was oxidized at the time of failure. This value is higher than the present licensing failure criterion of 17% equivalent oxide thickness. No coolant pressure peaks were detected at failure as would be expected if a violent MFCI (vapor explosion) had occurred. The fuel rod plenum pressure did not increase at the time of failure. The lack of a plenum pressure increase indicates that the cladding collapse onto the fuel stack between the plenum region and the failure location was sufficiently tight to eliminate liquid or gas communication along the fuel rod.

Following the failure, the rod continued to operate in the high temperature condition for 7 additional minutes with no apparent change in fuel rod response. After a total of 15 minutes of film boiling operation the reactor was scrammed to end the test and the hot portion of the fuel rod disintegrated as shown in Figure 1. A 0.4-m section of completely oxidized, embrittled cladding fragmented during the high stress situation of cooldown. Fuel and cladding debris from the fuel rod wedged between the rod and the flow shroud substantially blocking the coolant flow path. No MFCI pressure peak was detected even though fuel particles and possibly molten fuel had entered the coolant. The rod plenum pressure went to system pressure at reactor shutdown indicating that the collapsed fuel-cladding gap had reopened during the rod cooldown.

The PCM-1 test was performed at more severe conditions than would occur in a power reactor and, even so, the fuel rod operated 8 full minutes prior to cladding failure and following failure continued to operate for an additional 7 minutes with no apparent change in fuel rod response. The test results indicate that the 17% oxidation criterion is conservative for these test conditions. Even though 90% of the fuel diameter (estimated from posttest metallographic results) was molten, no MFCI vapor explosion occurred. The test results also indicated that cladding collapse onto the fuel was sufficiently hard to prevent pressure communication or gas flow between the plenum and the lower portions of the rod until the rod cools and the fuel-cladding gap opens.

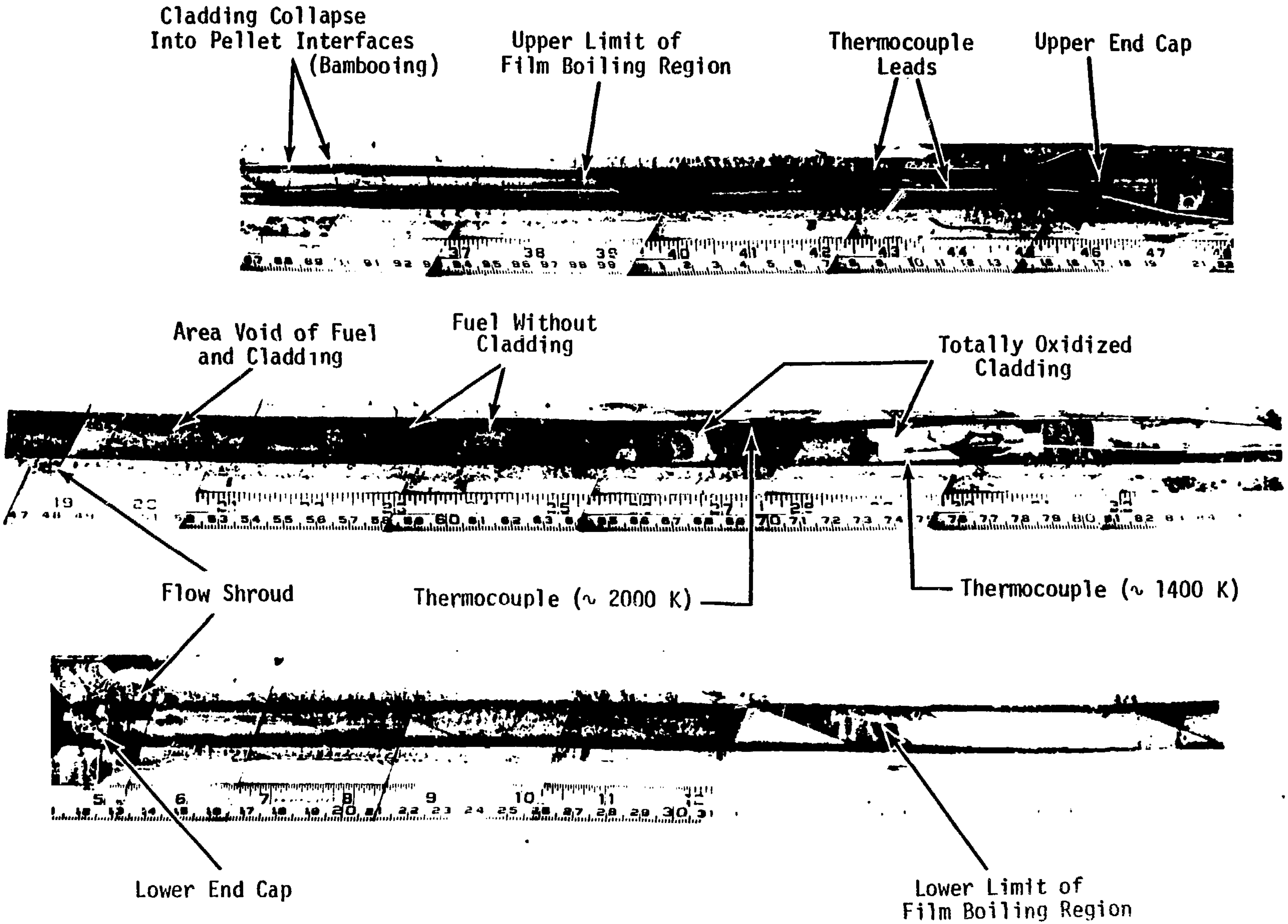

Figure 1 Posttest photograph of the PCM-1 fuel rod and flow shroud.

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