Draft Interim Review of PRM-50-93/95 Issues Related to the CORA Tests

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Public availability of this interim report is intended to inform stakeholders of the current status of the NRC's review of the issues raised in PRM-50-93/95. This interim report may be incomplete or in error in one or more respects and may be subject to further revisions during resolution of PRM-50-93/95. The NRC is not soliciting public comments on these interim conclusions, and will not provide a formal response to any comments received. The NRC's findings on PRM-50-93/95 issues will not be final until the NRC publishes a notice of final action on this PRM in the *Federal Register*.

The CORA experiments were severe fuel damage tests performed by Kernforschungszentrum Karlsruhe (KfK) using an out-of-pile facility to provide information on the failure mechanisms of light water reactor fuel elements at high temperatures. Several small multi-rod bundles were subjected to temperature transients in a steam environment and tested to failure of the fuel and assembly components. The petition claims that experimental data from the CORA multi-rod bundle tests indicates that the current peak cladding temperature limit of 2200 degrees Fahrenheit (˚F) contained in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.46(b)(1) is non-conservative. On Page 26, the petition (Leyse, 2009) references a technical paper (Sepold et al., 2009) which states:

> The critical temperature above which uncontrolled temperature escalation takes place due to the exothermic zirconium/steam reaction crucially depends on the heat loss from the bundle; *i.e.*, on bundle insulation. With the good bundle insulation in the CORA test facility, temperature escalation starts between 1100 and 1200°C [(2012 to 2192°F)], giving rise to a maximum heating rate of 15 K/sec.

The petition goes on to claim that "a maximum heating rate of 15 K/sec indicates that an autocatalytic oxidation reaction commenced, and that when the peak cladding temperatures increased at a rate of greater than 10 K/sec in CORA an autocatalytic reaction commenced at cladding temperatures between 2012 and 2192 ˚F." The petition states that these experiments demonstrate that the runaway oxidation reaction of Zircaloy cladding occurs at temperatures far below those predicted by the Baker-Just and Cathcart-Pawel equations. Based on this information the petition concludes that this shows that the Baker-Just and Cathcart-Pawel equations are both non-conservative for calculating the metal-water reaction rates that would occur in the event of a loss-of-coolant accident (LOCA).

The petition is inaccurate in its characterization of the CORA tests. These tests were severe fuel damage tests, and conditions were designed to produce temperatures exceeding 2200 ˚F and relocation of parts of the fuel bundle. The data does show temperatures that increase at nearly 15 K/sec, however this rate of increase <u>did not</u> occur while temperatures were less than 2200 ˚F. As intended in the CORA tests, the heatup rate was initially about 1 K/sec. The rate of temperature increase did escalate as temperatures exceeded 1100 degrees Celsius (˚C) (2012 ˚F). As temperatures approached 2200 ˚F, the rate of increase was generally 3 to 4 K/sec and only a few thermocouples had a more rapid heatup. Figure 1 shows a histogram of the thermocouple heatup rate distribution obtained by an evaluation of results from CORA Tests 2, 3, 5, 7, 9, 12, 13, 15, 16, 17, and 18. This includes all of the tests specifically mentioned in the

petition and related public comments. The median heatup rate of these thermocouples was approximately 2.25 K/sec, well below the 15 K/sec rate that is suggested as evidence of an autocatalytic reaction.

The distribution in Figure 1 identified only four locations in which the heatup rate exceeded 4 K/sec. While each of these locations had heatup rates well below that which might be considered autocatalytic, these apparent outliers received additional consideration. Each outlier was found to be located in the bottom half of the rod bundle. Figure 2 shows the heatup rate as a function of elevation in the bundle. The elevations of these outliers were 350 mm or less from the bottom. Two of these outliers occurred in Test 12 at 350 mm (7.5 K/sec) and at 250 mm (5.7 K/sec). However, when the heatup rates at these locations achieved their maximum (while the temperature was below 1200 ˚C), the upper part of the bundle had already started to melt and relocate. Figures 27 and 34 from the data report (Sepold et al., 2009a) show photographs from post-test examination of the bundle. Relocated material is clearly evident at the 350 mm and 250 mm elevations. While not specifically discussed in the data report (Sepold et al., 2009), these heatup rates occurred roughly 300 seconds later than when the absorber rods relocated. Thus, relocation of molten material and "candling" are likely causes of these isolated heatup rates. The measured hydrogen production rate in Test 12 during this period is also notable. At approximately 4300 seconds when elevations 350 and 250 mm achieved their maximum heatup rates while below 1200 ˚C, the hydrogen generation rate was increasing but leveled off by 4500 seconds. If an "autocatalytic" had actually occurred, then the hydrogen generation rate would have continued to increase.

The other heatup rates that appeared to be outliers occurred in Test 16 (7.8 K/sec) at 150 mm and in Test 13 (5.8 K/sec) at 350 mm. The results from Test 16 are described by Sepold et al., 2009b and Test 13 by Firnhaber et al., 1993. As with Test 12, the maximum heatup rates at these elevations occurred several hundred seconds following the time at which melt and relocation was initiated in the upper part of the bundle. Post-test examinations confirmed the relocation of material to the lower parts of the bundle. The increased heatup rates are likely due to the relocation of molten material at these elevations. Again, as in Test 12, the hydrogen generation rates showed no signs of an autocatalytic reaction when the maximum heatup rates were observed. The hydrogen generation rates in Test 16 and 13 did <u>not</u> show evidence of an autocatalytic reaction at these times.

It is also important to note that the test conditions for the CORA experiments were not representative of those expected during a LOCA. In the CORA tests, power was ramped upwards such that the average rod power was several times that expected in a design basis LOCA. A low flow rate of steam and argon was injected to the bundle, and as a result the convective cooling was lower than that expected in the core during a LOCA as well. Neither of these conditions (inordinately high power and low flow rate) necessarily dismiss the CORA tests for consideration of important phenomena below the regulatory limit of 2200 ˚F. However, by lacking some of the appropriate range of conditions, the CORA tests are less suitable than others for rod bundle thermal-hydraulics.

Another aspect of the petitioner's claim is that the oxidation rate equation is non-conservative. The participants in the CORA program were very careful in the testing and subsequent analyses to look at whether there were any mechanisms to produce fresh (unoxidized) cladding surface during the experiments when temperatures were high. Such mechanisms would require special treatment by LOCA analysis codes in using the oxidation rate equations. The following text describes why such mechanisms are not active or pertinent at design basis accident conditions.

The petition makes specific reference to a conference paper (Ott, 1991) that states that for Test 16, "cladding oxidation was not accurately predicted by available correlations." Ott also reports that cladding oxidation for Test 17 was accurately predicted by the available correlations. The paper did not identify which correlations were examined, nor did it report if the predictions were non-conservative for Test 16, only that they were inaccurate, e.g. time delay. The paper noted that cladding strain could be a factor and that cladding strain and significant oxidation occurred simultaneously. The paper provided an analytical adjustment that improved the timing prediction with respect to the measured temperatures.

In the mid 1980s, NRC sponsored an assessment of zircaloy oxidation that provides an explanation for possible enhanced oxidation observed under conditions with cladding strain. NUREG/CR-4412 (Williford, 1986) explained that under **certain** conditions ballooning and deformation of the cladding can increase the available surface area for oxidation, thus enhancing the apparent oxidation rate. The mechanisms causing this enhancement are highly unlikely to occur for typical pre-pressurized rods, which will deform and rupture before the oxidation rate is significant. Likewise, the CORA experimenters were also concerned with mechanisms that might produce fresh (unoxidized) cladding surfaces when temperatures were high. Therefore as part of the CORA program a study was conducted (Hofmann, 1997) to investigate the generation of new metallic surfaces in Zircaloy cladding tubes and their influence on oxidation was reviewed. The Hofmann report describes results of tests in a small-scale test rig which quenched single short pre-oxidized Zircaloy fuel rod segments by water and steam. The concern is that in an environment with low heat losses, as in the core of a nuclear reactor, the additional oxidation on crack surfaces could increase the cladding temperature thus leading to a further enhanced oxidation. The report shows that, for oxide thickness less than 120 microns, specimens cooled from temperatures below 1400 ˚C had no oxide cracking and thus no fresh surfaces for increased oxidation. The current NRC regulation in 10CFR 50.46 restricts cladding oxidation to 17%. A surface with 17% oxidation of cladding with a manufactured wall thickness of 685 microns (27 mils) would produce an oxide layer of less than 100 microns. Therefore, the generation of new metallic surface area is not a concern for design basis accident conditions. The petition's reference to the finding by Ott is inadequate as a basis to revise regulations or invalidate the use of Baker-Just or Cathcart-Pawel for design basis calculations of oxidation.

The staff concludes that the behavior of temperatures in the CORA experiments is consistent with prior understanding and expectations on oxidation rate at temperatures below 2200 ˚F. No locations with temperatures less than 2200 ˚F with heatup rates greater than 10 K/sec were identified. The heatup rates below 2200 ˚F do not indicate a presence of an exothermic "autocatalytic" reaction. The results of CORA do not suggest that the Cathcart-Pawel or Baker-Just correlations are non-conservative. The assertions made by the petition with regards to Cathcart-Pawel and Baker-Just are not substantiated by the CORA data.

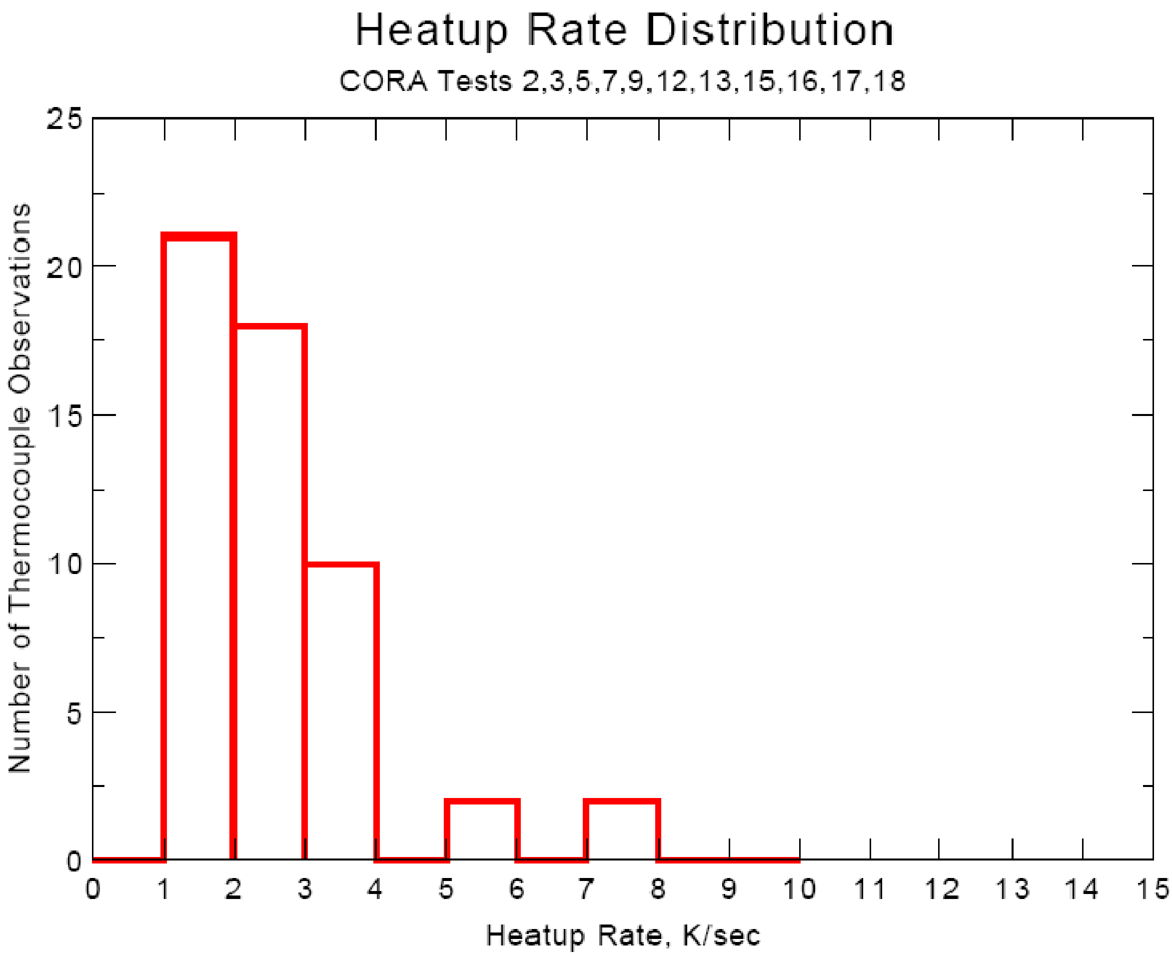

Figure 1. Distribution of maximum heatup rates for CORA Tests when thermocouple temperatures are T < 1200 C.

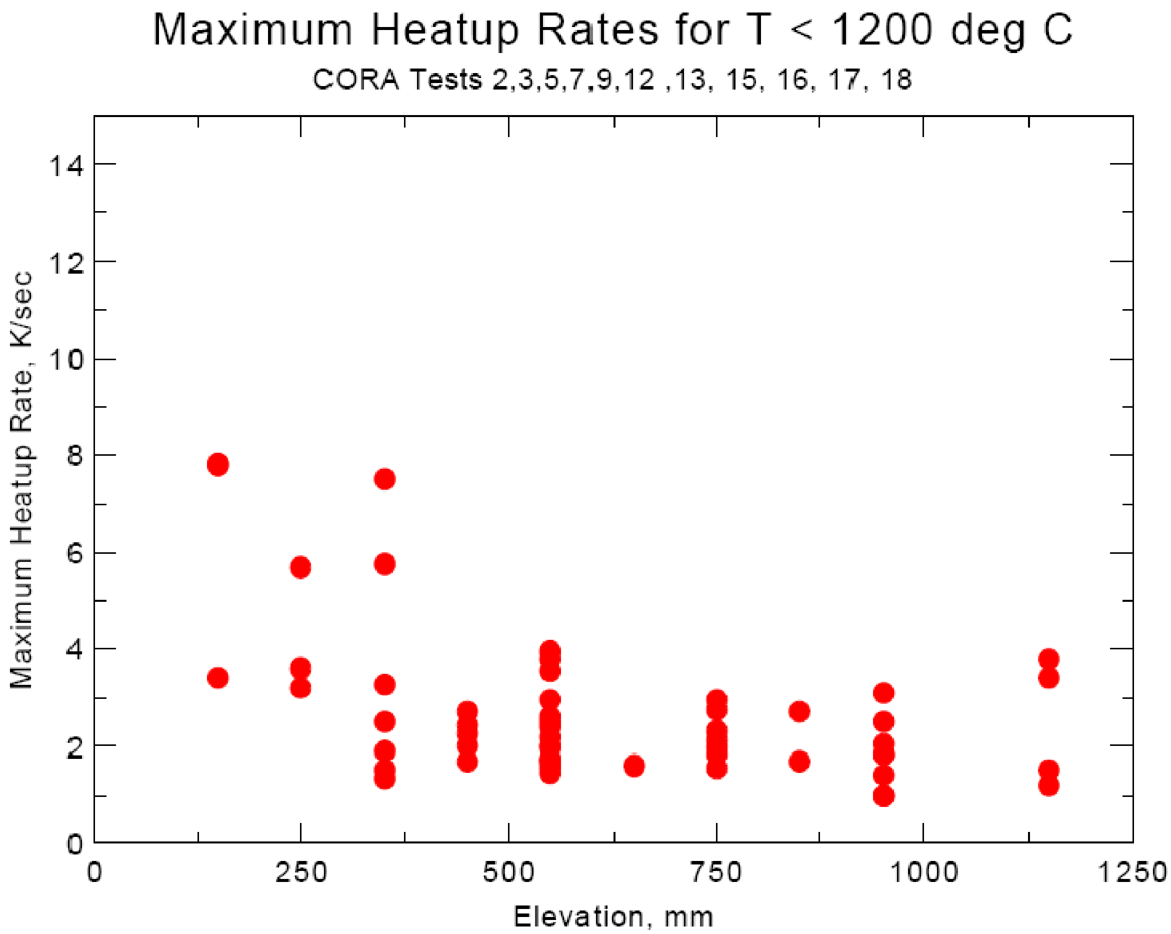

Figure 2. Maximum heatup rate in CORA tests with elevation.

References:

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