Draft Interim Review of PRM-50-93/95 Issues Related to the LOFT LP-FP-2 Test

Disclaimer:

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 is 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*.

This report is the NRC staff's interim evaluation of certain assertions in the Petition for Rulemaking PRM-50-93/95 [1] regarding results of testing at the Loss of Fluid Test Facility (LOFT). The LOFT facility was used to simulate numerous large break loss-of-coolant accidents (LOCAs), small break LOCAs, and other transient events before being used for several severe accident experiments. The LOFT facility was unique in that it had a nuclear core composed of several part-height (5.5 foot) rod bundles. In particular, the LOFT LP-FP-2 experiment extended severe accident experience into the realm of a large break LOCA. It permitted measurements of core melt progression phenomena under low system pressure in a decay-heat driven bundle, and of fission product transport through a scaled upper plenum and a simulated low pressure injection system line. LOFT test LP-FP-2, conducted on July 9, 1985, was the second fission product release and transport test performed at the LOFT facility. It was also the final test performed at the facility. The LP-FP-2 test was designed to provide information on the release, transport and deposition of fission products resulting from severe core damage.

Petition for rulemaking PRM-50-93/95 asserts that experimental data from LOFT Test LP-FP-2 indicates that the current peak cladding temperature limit of 2200 ºF contained in 10 CFR 50.46(b)(1) is non-conservative. The petition in several locations (such as in the footnote on page 5) asserts that:

> *Data from multi-rod (assembly) severe fuel damage experiments (e.g., the LOFT LP-FP-2 experiment) indicates that the Baker-Just and Cathcart-Pawel equations are both non-conservative for calculating the temperature at which an autocatalytic (runaway) oxidation reaction of Zircaloy would occur in the event of a LOCA. This, in turn, indicates 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 LOCA.*

Central to the petitioner's assertion, is that both the Baker-Just [2] and Cathcart-Pawel [3] equations predict autocatalytic reaction rates to occur well above 2200 ºF(1477 K), however the petition asserts that experimental data show autocatalytic reactions occur well below 2200 ºF. Put another way, if experimental data show the existence of autocatalytic reaction rates well below 2200 ºF, then these correlations must be incorrect and non-conservative. The petition defines heatup rates exceeding 15 K/sec (27 ºF/sec) as evidence that an autocatalytic reaction is taking place.

While LOFT LP-FP-2 did show rapid temperature increases as regions of the core approached and exceeded 2200 ºF, neither the data from this experiment nor the information put forth by the petition provide evidence that either the Baker-Just or the Cathcart-Pawel equation is non-conservative for calculating cladding oxidation rates. The petition is inaccurate in its characterization of the test results. This section discusses the claims regarding LOFT Test LP-FP-2 and results from the test.

It is important to note the significant differences in the core configuration for Test LP-FP-2 and a typical light-water reactor core. The core for this experiment consisted of four square 15x15 design fuel assemblies and four triangular peripheral fuel assemblies. The central fuel assembly was reduced to an 11x11 array to permit enclosure in a thick zirconium oxide shroud to protect the surrounding fuel assemblies from damage during the experiment. This shroud also prevented cross-flow from the surrounding assemblies, which acted to "starve" the central bundle of coolant. This was intentional, in order to achieve the high temperatures that were part of the test objectives. Flow was supplied to the central assembly only to provide enough coolant so that there was sufficient steam for the metal-water reaction. In addition, the fuel rods in the central assembly were enriched to 9.744 wt% U^{235} (the U.S. enrichment limit is 5 wt% for commercial facilities). The central fuel assembly was irradiated to a pre-transient burnup of 448±25 MWD/MTU. The transient phase of the experiment was terminated when the outer surface temperature of the shroud reached 1517 K (2271 ºF).

The primary objective for Test LP-FP-2 was to obtain peak center fuel module temperatures in excess of 2100 K (3321 ºF) for at least three minutes while maintaining the outside shroud temperature below 1517 K (2271 ºF) and the peripheral bundle fuel rods below 1390 K (2043 ºF).

LOFT Test LP-FP-2 has previously been evaluated in detail. The Quick Look Report [4] carefully examined the cladding heat up rates for the fuel rods in Bundle 5, which was the central bundle, and the guide tubes. The earliest rapid temperature increase was observed to occur at a guide tube. The Quick Look Report notes that:

> *The first recorded (and qualified) rapid temperature rise caused by the exothermic reaction between the steam and the zircaloy is at about 1430 s on guide tube thermocouple TE-5H08-027. (Thermocouple TE-5EII-027 was judged to have failed at 1311 s, but the mode of failure suggests that temperatures reached 1800 K (2780 °F) at some location in the core by 1381 s.) The rapid temperature rise began from approximately 1400 K (2060°F). (These figures must necessarily be approximate because there is no abrupt change to characterize the start of the reaction).*

The evaluation notes that the rapid temperature rise began at approximately 1400 K (2060 ^{o}F) but does not conclude that this was due to an "autocatalytic" reaction. The petition appears to equate "rapid" with "autocatalytic" or an uncontrolled temperature escalation, and uses a heatup rate exceeding 15 K/sec as an indication that an autocatalytic reaction occurred. In fact, a closer examination of thermocouple TE-5H08-027 as it reached a temperature of 1400 K shows that the rate of temperature increase was approximately 5.1 K/sec. This is well below the 15 K/sec rate of temperature increase that the petition claims is autocatalytic. Later in time (approximately 1447 sec) and while at a higher temperature, this location did achieve a heatup rate greater than 15 K/sec. The report goes on to explain why this high rate of temperature increase may have occurred, and notes that TE-5H08-027 seems to be an exception to the pattern of thermocouple response.

Because of the relatively few locations in the center fuel module at which the fuel rod cladding temperatures are measured, it is considered unlikely that the first occurrence of the rapid reaction between steam and the zircaloy occurred at a thermocouple location. Once the reaction has begun in some location, however, the resultant high temperatures will influence nearby surfaces by radiation and conduction, thus causing an increase in the rate of temperature rise. It is almost certainly this effect that is being measured in the center fuel module.

The course of the rapid reaction between the zircaloy and the steam can be tracked by noting the times at which indicated cladding temperatures exceed 1800 K (2780 °F), that being a reasonable indication that the rapid reaction has occurred. The results, for those thermocouples which had not failed by that temperature, are shown in Table E-l. The reaction probably started between the 0.64-m (27-in.) and the 1.07-m (42-in.) elevations. The reaction then spread across the entire center fuel module at the 1.07-m (42-in.) elevation between 1480 and 1530 s, and then across the 0.69-m (27-in.) elevation. The few thermocouples at the 0.69-m (27-in.) elevation that reacted early (TE-5H08-027 and TE-5H06-027) seem to be exceptions to the pattern. There is no evidence of a rapid temperature rise due to the reaction between steam and zircaloy at the ten-inch elevation.

That is, the high heatup rate observed by TE-5H08-027 appears to have been due to thermal radiation and conduction from rods immediately above it. Rod thermocouples at the 42-inch elevation began to exceed 1477 K (2200 ºF by 1455 seconds. The Quick Look Report, which speculates that high reaction rates began between the 27-inch and 42-inch elevations, therefore suggests that regions in the bundle between the 27-inch and 42-inch elevations had exceeded 1477 K and were thus the source of a high thermal radiation heat flux. All other nearby thermocouples at this elevation failed, most likely due to the high temperature in the upper parts of the central bundle.

With regards to other guide tube thermocouples, the Quick Look Report notes that at approximately 1500 seconds, an "event" had occurred in the test. This event was attributed to be the rupture of control rod cladding and relocation of absorber material. Thus, the rapid heatup rates at the guide tube thermocouple locations were attributed to precursory heating by nearby regions that had greatly exceeded 2200 ºF (1477 K) and/or by those locations being influenced by relocated absorber material.

Table E-1 of the Quick Look Report provides additional insight to the sequence of events in the central bundle of LOFT Test LP-FP-2. This Table lists the thermocouples that did not fail during the test. At the 42-inch elevation, there were six surviving thermocouples. Table 1 below lists these thermocouples and their temperatures and heatup rate just prior to rapid escalation and also at 1477 K (2200 ºF). The table also lists the time to 1800 K (as obtained from Table E-1 of the Quick Look Report).

Table 1. LOFT Test LP-FP-2 Central Bundle Thermocouples at the 42 Inch Elevation

Thermocouple Identifier	Temperature at 1430 sec, K	Heatup Rate at 1430 sec, K/sec	Time to 1477 K, sec.	Heatup Rate at 1477 K, K/sec	Time to 1800 K, sec.
TE-5L09-042	1413	2.1	1455	3.2	1491
TE-5I12-042	1422	2.4	1456	2.6	1487
TE-5I04-042	1415	1.7	1460	2.8	1488
TE-5C07-042	1265	1.5	1481	10.3	1495
TE-5M09-042	1290	2.0	1490	5.3	1513
TE-5D13-042	1254	1.2	1513	11.9	1529

The 42-inch thermocouples in the upper third of the central bundle can be segregated into two groups based on similar behavior. The first three listed in Table 1; TE-5L09-042, TE-5I12-042, and TE-5I04-042 were positioned one row away from the shroud. These three thermocouples each have a temperature greater than 1413 K (2084 ºF) at 1430 seconds and are the first rods to reach 1477 K. When these rods do reach 1477 K, the heatup rates are low; 3.2 K/sec or less. The second group is TE-5C07-042, TE-5M09-042, and TE-5D13-042. Each of these was located on the outermost row of the central bundle directly adjacent to the shroud.

The Quick Look Report concluded that rapid oxidation of zircaloy started at approximately 1480 seconds. The first group of thermocouples at the 42-inch elevation confirm this, as these exceed 1477 K (2200 ºF) by 1460 seconds. Between 1481 and 1513 seconds, temperatures in the second group exceeded 1477 K. As they reach 1477 K, the heatup rates are increasing but remain below 15 K/sec. That the heatup rates in this second group are higher than the first group is consistent with the explanation in the Quick Look Report. That is, the elevated heatup rate is due partly to metal-water reaction, but also due to thermal radiation and conduction from other locations that have greatly exceeded 2200 ºF. Note that the first group of thermocouples at the 42-inch elevation reach 1800 K (2780 ºF) between 1487 and 1491 seconds, which is roughly the time period when the second group was reaching 2200 ºF. Therefore, the heatup rate in the second group was influenced by the very high temperatures elsewhere in the central bundle.

On page 40 of the petition, the claim is made:

> *Therefore, after the onset of rapid oxidation—after a heating rate of ~1°K/sec.—peak cladding temperatures increased from approximately 1400°K (2060°F) to 2100°K (3320°F) within a range of approximately 35 seconds; in other words, after the onset of rapid oxidation, cladding temperatures increased at an average rate of approximately 20°K/sec. (36°F/sec.).*

In a subsequent comment on the petition [5], (see page 32) this statement is corrected and clarified:

> *(It is noteworthy that in PRM-50-93, on page 40, Petitioner erroneously states that "Thermal-Hydraulic Post-Test. Analysis of OECD LOFT LP-FP-2 Experiment" states that the peak measured cladding temperature reached 2100 K (3320°F) within approximately 35 seconds and that after the onset of rapid oxidation, cladding temperatures increased at*

an average rate of approximately 20 °K/sec. (36°F/sec.); according to the paper average rate was approximately 10°K/sec. (18°F/sec.). However, according to other reports the heat up rate was between 10°K/sec and 20 °K/sec.)

The statements are misleading. The rate of temperature increase was not uniform. It gradually increased with temperature. This can be seen from the information presented in Table 1 above. The rate of temperature increase when the temperature is less than 2200 ºF (1477 K) is considerably less than the rate of increase above that temperature and significantly less than the 15 K/sec heatup rate that the petition claims is an indication of an autocatalytic reaction rate. Table 2 lists the average rate of temperature increase for the time periods above and below 2200 ºF (1477 K). The average heatup rate is large (i.e. suggesting an accelerated metal-water reaction rate) only when the cladding temperature exceeds 2200 ºF (1477 K).

Table 2. LOFT Test LP-FP-2 Central Bundle Heatup Rates at the 42 Inch Elevation

Thermocouple Identifier	Heatup Rate from 1430 sec until T = 1477 K, K/sec	Heatup Rate from 1477 K to 1800 K, K/sec
TE-5L09-042	2.56	8.97
TE-5I12-042	2.11	10.42
TE-5I04-042	2.07	11.54
TE-5C07-042	4.16	23.07
TE-5M09-042	3.12	14.04
TE-5D13-042	2.69	20.19

Therefore, although LOFT LP-FP-2 did show rapid temperature increases as regions of the core approached and exceeded 2200 ºF, the heatup rates do not suggest that an “autocatalytic” oxidation reaction occurred while cladding temperatures were below 2200 ºF (1477 K). While cladding temperatures remain below 2200 ºF (1477 K), heatup rates were less than 15 K/sec and are not considered autocatalytic. The staff notes that neither the Baker-Just nor Cathcart-Pawel correlations by themselves can predict heatup rates, though they are inputs to the prediction of heatup rates. The staff concludes that the behavior of central rod bundle in LOFT Test LP-FP-2 is consistent with prior understanding of oxidation rates at temperatures below 2200 ºF (1477 K). A close examination of thermocouple data for LOFT LP-FP-2 found that the heatup rates below 2200 ºF did not indicate presence of an exothermic “autocatalytic” reaction. The results of LOFT Test LP-FP-2 do not therefore suggest that the Cathcart-Pawel or Baker-Just correlations are non-conservative. The assertions made in PRM-50-93/95 with regards to Cathcart-Pawel and Baker-Just are not substantiated by the results of this LOFT test.

References:

[1] Leyse, M. E., Petition for Rulemaking, Submitted Pursuant to 10 CFR 2.802, ADAMS ML093290250, November 2009.

[2] Louis Baker, Jr. and Louis C. Just, Studies of Metal-Water Reactions at High Temperatures III. Experimental and Theoretical Studies of the Zirconium-Water Reaction, ANL-6548, ADAMS ML050550198, May 1962.

[3] J. V. Cathcart, R. E. Pawel, et.al, Zirconium Metal-Water Oxidation Kinetics IV., Reaction Rate Studies, ORNL/NUREG-17, ADAMS ML052230079, August 1977.

[4] Adams, J. P., et al., “QUICK LOOK REPORT ON OECD LOFT EXPERIMENT LP-FP-2,” OECD LOFT-T3804, ADAMS ML071940358, September 1985.

[5] Leyse, M. E., “Comment (14) of Mark Edward Leyse, on Petition for Rulemaking PRM-50-93, regarding "NRC revise its regulations based on data from multi-rod (assembly) severe fuel damage experiments," ADAMS ML101020564, April 12, 2010.