Draft Interim Review of PRM-50-93/95 Issues Related to Conservatism of 2200 degrees F, Metal-Water Reaction Rate Correlations, and "The Impression Left from [FLECHT] Run 9573"

Disclaimer:

Public availability of this draft interim review is intended to inform stakeholders of the current status of the NRC review of the issues raised in PRM-50-93/95. This draft interim review 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 findings on PRM-50-93/95 issues will not be final until the NRC publishes a notice of final action on this petition for rulemaking in the *Federal Register*.

1.0 Issues Raised in the Petitions and Associated Comments

A petition for rulemaking was docketed as PRM-50-93 on November 17, 2009 (M. Leyse, 2009). The petitioner is requesting revisions to section 50.46 of Title 10 of the *Code of Federal Regulations* (10 CFR) "Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Power Reactors" and to 10 CFR Part 50, Appendix K "ECCS Evaluation Models," as well as associated regulatory guidance. The petitioner, Mark Edward Leyse, has alleged that several aspects of the existing regulations are non-conservative. Specifically, the petitioner claims that 1) the peak cladding temperature limit of 2200 degrees F in 10 CFR 50.46(b) is non-conservative; 2) the Baker-Just (Baker and Just, 1962) reaction rate correlation specified in Appendix K and the Cathcart-Pawel (Cathcart and Pawel, 1977) reaction rate correlation specified in Regulatory Guide 1.157 are both non-conservative for metal-water reaction rate evaluations under loss-of-coolant accident (LOCA) conditions. The petitioner also claims that stainless steel cladding heat transfer coefficients are not always a conservative representation of Zircaloy cladding behavior for equivalent LOCA conditions.

This draft interim review is the NRC staff's interim evaluation of certain assertions in the petition for rulemaking PRM-50-93/95 regarding the peak cladding temperature limit and conservatism associated with correlations specified for use in calculating the metal-water reaction rate. It also examines the petitioner's concern regarding the use of stainless steel-clad heaters rather than Zircaloy-clad heaters in deriving cladding-to-coolant heat transfer coefficients. As these items are closely related to the petition's statements concerning "the impression left from [Full Length Emergency Cooling Heat Transfer (FLECHT)] run 9573," that topic is also discussed in this draft interim review.

2.0 Peak Cladding Temperature Limit

The petitioner claims that both the Baker-Just and the Cathcart-Pawel correlations are non-conservative for metal-water reaction rate evaluations under LOCA conditions. Based on this, the petitioner asserts that the peak cladding temperature limit of 2200 degrees F in 10 CFR 50.46(b) is also non-conservative. The assumed connection (not clearly stated in the petition) between the asserted non-conservatism of the metal-water reaction correlations and the 2200 degree F regulatory criteria, is that the 2200 degree F limit helps to ensure that "autocatalytic" or otherwise excessive metal-water reaction rates do not occur. Pages 25 and 26 (M. Leyse, 2009) discuss the metal-water reaction rate and its relation to the 2200 degree F limit. The petition states, claiming reference from the "Compendium of [Emergency Core Cooling System (ECCS)] Research for Realistic LOCA Analysis" (NRC, 1988):

> Assessment of the conservatism in the [peak cladding temperature (PCT)] limit can be accomplished by comparison to multi-rod (bundle) data for the autocatalytic temperature. This type of comparison implicitly includes…complex heat transfer mechanisms…and the effects of fuel rod ballooning and rupture on coolability… Analysis of experiments performed in the Power Burst Facility, in the Annular Core Research Reactor, and in the NEILS-CORA (facilities in West Germany) program have shown that temperatures above 2200°F are required before the zircaloy-steam reaction becomes sufficiently rapid to produce an autocatalytic temperature excursion. Another group of relevant experimental data were produced from the MT-6B and FLHT-LOCA and Coolant Boilaway and Damage Progression tests conducted in the NRU Reactor in Canada. …even though some severe accident research shows lower thresholds for temperature excursion or cladding failure than previously believed, when design basis heat transfer and decay heat are considered, some margin above 2200°F exists.

In addition to the test data cited in the above passage, the petition goes on to list and discuss other data in which it is asserted that an autocatalytic reaction occurred below 2200 degrees F. The previously-referenced section from the petition is incomplete, as it leaves out some important information from the "Compendium of ECCS Research for Realistic LOCA Analysis." The Compendium section discusses conservatism in the regulatory criteria, and provides some justification. In the same section, for example, the data discussed previously was evaluated with the following findings:

> The MT-6B test conducted in June 1984 showed that at cladding temperatures of 2200°F (1204°C) the zircaloy oxidation rate was easily controllable by adding more coolant. In the FLHT-test, completed in March 1985, 12 ruptured zircaloy-clad rods were subjected to an autocatalytic temperature excursion. From the measurements made on the full-length rods during the test, the autocatalytic reaction was initiated in the 2500 – 2600°F (1371 – 1427°C) temperature region.

In effect, the Compendium notes that in several multi-bundle experiments if an autocatalytic reaction occurred it was at a temperature well above 2200 degrees F.

The staff concludes, then, that the autocatalytic reactions have not occurred at temperatures less than 2200 degrees F. Accordingly, the 2200 degree F regulatory limit is sufficient provided the correlations used to determine the metal-water reaction rate below 2200 degrees F are suitably conservative such that excessive reaction rates do not occur below that value. The two correlations cited by the petition, Baker-Just and Cathcart-Pawel, are discussed in the following two sections.

3.0 Baker-Just Correlation

One of the concerns of the petition is that the Baker-Just correlation is non-conservative. That is, the petition claims that the Baker-Just correlation underpredicts the metal-water reaction rate (and thus would underpredict the heatup, heatup rate, or maximum temperature of the cladding during a LOCA). The technical evaluation by the staff in the denial of PRM-50-76 (NRC, 2004), however, carefully examined the metal-water (oxidation) rates as predicted by the Baker-Just correlation, and found that the Baker-Just correlation was clearly conservative for prediction of the amount of oxidation.

The petition did not take into account Westinghouse's metallurgical analyses performed on the cladding for all four FLECHT Zircaloy clad experiments reported by Cadek et al. (1971). Westinghouse applied the Baker-Just correlation to these experiments, which had the "complex thermal hydraulic phenomena" deemed important by the petition. This application of the correlation to the metallurgical data clearly demonstrates the conservatism of the Baker-Just correlation to 21 typical temperature transients. The NRC (NRC, 2004) independently applied the Baker-Just correlation to the FLECHT Zircaloy experiments with nearly identical results, thus providing a check on the Westinghouse calculations.

Numerous other studies have found the Baker-Just correlation to be conservative. A report prepared by Argonne National Laboratory (Billone, 2002) examined steam-oxidation kinetics for a variety of zirconium alloys and performed a literature review of existing studies. They concluded:

> The Baker-Just correlation is specified in Appendix K of 10CFR50.46 for calculation of the heating rate due to oxidation, hydrogen generation and the Effective Cladding Reacted (ECR) because it was available in 1973. However, this correlation has the least significant database and justification of all those reviewed. Oxidation kinetics studies on a variety of zirconium alloys conducted since 1962—particularly in the 1970s—have demonstrated that the Baker-Just correlation over-predicts weight gain and zirconium consumed by as much as 30% at the peak cladding temperature (1204 C) allowed by 10CFR50.46.

A recent State of the Art report by the Organisation for Economic Cooperation and Development (OECD) (OECD, 2009) also confirms this long-standing finding that the Baker-Just correlation overpredicts the reaction rate between 1330 K and 1700 K. Based on the evaluation by the NRC, and confirmed by independent studies such as those by Billone et al. and the OECD, the staff concludes that the Baker-Just correlation is conservative.

4.0 Cathcart-Pawel Correlation

Conservatism and adequacy of the Cathcart-Pawel correlation was also considered in detail in the staff's technical evaluation of PRM-50-76. The NRC applied the Cathcart-Pawel oxygen uptake and ZrO_2 thickness equations to the four FLECHT Zircaloy experiments, confirming the best-estimate behavior of the Cathcart-Pawel equations for large break LOCA reflood transients. The NRC applied the Cathcart-Pawel oxide thickness equation to 15 of their transient temperature experiments. The equation was conservative or best-estimate for 13 experiments and non-conservative for the remaining two. Regulatory Guide 1.157, which provides guidelines for best-estimate calculations for loss-of-coolant accidents, is correct, then, in permitting the use of Cathcart-Pawel. Since "best-estimate" in effect requires uncertainty to be accounted for, the possibility that Cathcart-Pawel may not bound all applicable experimental data must be addressed.

Adequacy of the Cathcart-Pawel correlations has also been established by independent studies. A series of technical papers by Schanz et al. (2004), Volchek et al. (2004), and Fichot et al. (2004) reported on recent progress in understanding high temperature zirconium oxidation kinetics and light-water reactor core degradation models. The works considered the experimental database applicable to the assessment of metal-water reaction rate correlations. Part I of the study (Schanz et al, 2004) noted that for low temperatures (T < 1800 K), the experimental data base is very large and applicability of several well-defined correlations has been established. While high temperature (T > 1800 K) cladding oxidation was the primary concern in these studies, they also considered the accuracy of the Cathcart-Pawel and other correlations for temperatures below 1800 K. In the low temperature range (T < 1800 K), the Cathcart-Pawel correlation was found to provide the best agreement with data. The Cathcart-Pawel correlation was also found to be similar to the Leistikow-Schanz formulas (Leistikow and Schanz, 1987) which were developed independently for Zircaloy oxidation. Cathcart-Pawel was in slightly better agreement with the data considered in these recent studies.

The staff therefore concludes that the Cathcart-Pawel correlation provides a sufficiently accurate determination of the metal-water reaction rate for zirconium-based alloys below the regulatory limit of 2200 degrees F. As outlined in Regulatory Guide 1.157, uncertainties in this correlation should be considered if this correlation is used as part of a best-estimate calculation.

5.0 "The Impression Left from [FLECHT] Run 9573"

The petition for rulemaking, as well as several comments, discusses FLECHT run 9573. This particular test used a Zircaloy bundle and was conducted with a nominal initial cladding temperature of 2000 degrees F and with a flooding rate of 1 inch/sec. During this test there were numerous heater element failures as temperatures exceeded 2200 degrees F. A post-test inspection of the bundle found there to be severe local damage near a Zircaloy spacer grid at the 7-ft elevation due to temperatures in excess of 2500 degrees F. Several possible causes of the high temperatures were cited, with metal-water reaction of Zircaloy being a likely candidate (Cadek et al., 1971).

Pages 8 – 13 of PRM-50-93 (M. Leyse, 2009), discuss "the impression left from run 9573" and the petitioner's concern that "it has not been empirically established that 'the impression left from run 9573' has ever been overcome by subsequent experiments with Zircaloy cladding." The petitioner further states on page 12 that:

> …"the impression left from run 9573" includes the fact that run 9573 had a low coolant flood rate; it had the lowest flood rate of the four FLECHT Zircaloy tests. It also had the lowest initial cladding temperature, before flood, of the four Zircaloy tests. Therefore, it is highly probable that run 9573 incurred autocatalytic oxidation, because it had a low flood rate.

This assertion is used as part of the petitioner's basis for claiming that the Baker-Just and Cathcart-Pawel correlations are non-conservative.

The “impression left from run 9573” refers to statements that the 1973 AEC Commissioners made due to the observation at that time that heat transfer coefficients determined from FLECHT run 9573 were lower than heat transfer coefficients from the other three Zircaloy clad tests reported in WCAP-7665 when compared to the equivalent stainless steel tests. The Commissioners believed that this anomaly could be cleared up with more experiments with Zircaloy cladding.

The “impression left from run 9573” and conditions and results of this test were also central to PRM-50-76 which was denied by the NRC (NRC, 2005). FLECHT run 9573, as well as other tests performed as part of that series of experiments and the 1973 AEC Commissioner concerns, was extensively investigated during the evaluation of PRM-50-76 (NRC, 2004). It was concluded in that investigation and NRC denial that contrary to the petitioner’s assertion there had indeed been appropriate testing to address the “impression” and other issues raised by FLECHT run 9573. No new information has been provided by PRM-50-93, PRM-50-95, or the associated comments that invalidates the NRC’s previous evaluation of FLECHT run 9573.

On pages 5 – 9 of Mr. Leyse’s comment dated March 15, 2010 (M. Leyse, 2010a), additional comments were made by the petitioner regarding FLECHT run 9573. The comments discuss the negative heat transfer coefficients near the mid-plane elevation in FLECHT run 9573 and that, as pointed out in the data report (Cadek et al., 1971), this occurred at approximately the time when heater rods began to fail in the bundle and the cladding temperatures were 2200 – 2300 degrees F. The comments also noted that heat transfer coefficients in this test were lower than those in other FLECHT tests with Zircaloy cladding. The petitioner, however, failed to recognize or acknowledge that this aspect of FLECHT run 9573 was addressed in the NRC technical evaluation of PRM-50-76 where this anomaly was attributed to the data reduction process. (See page 7 of NRC, 2004.)

The effect of the facility housing is discussed on pages 26 – 27 of Mr. Leyse’s comment dated April 12, 2010 (M. Leyse, 2010b). For all of the FLECHT tests, and run 9573 in particular, the stated concern is that the housing wall acted as a “cold spot.” The commenter infers that this is relevant in proving that “in FLECHT Run 9573, an autocatalytic oxidation reaction commenced at a temperature lower than what both the Baker-Just and Cathcart-Pawel equations would predict.” In another comment dated April 28, 2010 (M. Leyse, 2010c), meant as clarification, the petitioner claims, “In no section of PRM-50-93, and in no section of Petitioner's comments on PRM-50-93, does Petitioner state that a zirconium-water autocatalytic reaction was reached at temperatures below 2200 [degrees F] in FLECHT Run 9573.”

Based on these statements, the NRC concludes that petitioner is not identifying anything about FLECHT run 9573 that invalidates the use of Baker-Just or Cathcart-Pawel below 2200 degrees F. If an autocatalytic reaction did occur, it was at cladding temperatures above 2200 degrees F and therefore not relevant to the design basis criteria of 10 CFR 50.46. The fact that the housing is relatively “cold” compared to the heater rods is likewise not important to validation of the Baker-Just or Cathcart-Pawel correlations. In FLECHT run 9573 there were three thermocouples that registered temperatures greater than 2200 degrees F at a time of 18 seconds. (After 18 seconds, the data is considered suspect due to heater rod failures.) These were thermocouples numbered 3D3, 2D2, and 4E3. Each of these three thermocouples was on the interior of the bundle and shielded from the housing by at least one row of heater rods. Because of the low thermal radiation view factor, the housing is not expected to have had a large influence on local heat transfer coefficients on the interior of the bundle.

Pages 29 – 34 of Mr. Leyse's comments dated November 23, 2010 (M. Leyse, 2010d), contain a discussion on the negative heat transfer coefficients that were obtained for several thermocouples near the bundle mid-plane elevation in FLECHT run 9573. In addition, pages 18 – 22 of Mr. Leyse's comments dated November 23, 2010 (M. Leyse, 2010e), discuss these negative heat transfer coefficients, the "impression left from run 9573," and the cladding materials used in the FLECHT series of tests. These issues were considered in the NRC's technical evaluation of PRM-50-76. As pointed out in that study, heat transfer coefficients are not directly measurable quantities. They are calculated using an inverse heat conduction technique that uses the measured temperatures, the rod power and properties of the materials involved to estimate the heat transfer coefficient. Reflood of the bundle in FLECHT run 9573 was initiated after cladding had exceeded 1900 degrees F (1311 K). At this temperature a significant, but not autocatalytic, exothermic metal-water reaction is expected. For Zircaloy cladding at high temperatures, some estimate must also be made of the metal-water reaction rate which complicates the data reduction and adds uncertainty to the results. The anomaly of lower than expected heat transfer coefficients, including a short period of negative heat transfer coefficients, was attributed to this data reduction process. This was also pointed out in the NRC's denial of PRM-50-76, in which the same claim was made. The staff has reviewed PRM-50-76 and the basis for denial and has reaffirmed its original conclusion regarding FLECHT run 9573. Lower than expected heat transfer coefficients, and even reverse heat transfer (from the cladding to an interior thermocouple) does not indicate by itself that an autocatalytic reaction occurred while the cladding was below 2200 degrees F (1478 K). It generally indicates that the local steam temperature is higher than the cladding temperature due to the axial power profile in the rod bundle. Negative heat transfer coefficients were also obtained in other FLECHT tests with stainless steel cladding, which shows that conditions other than an exothermic metal-water reaction can cause negative heat transfer coefficients. An example of this is FLECHT test 8975 in Figure 3-105 of WCAP-7665 (Cadek et al., 1971) which shows negative heat transfer coefficients for a bundle with stainless steel cladding. Thus, the petition fails to provide sufficient justification based on this "impression left from run 9573" that the regulatory criteria should be revised.

5.1 Consideration of Complex LOCA Hydraulics

On pages 51 – 54 of PRM-50-93 (M. Leyse, 2009), the petitioner asserts that "What the NRC does not consider is that under the complex thermal-hydraulic conditions that would occur in the event of a LOCA, heat transfer would affect zirconium-water reaction kinetics." and that neither the Cathcart-Pawel nor Baker-Just correlations are conservative "because they were not developed to consider how heat transfer would affect zirconium-water reaction kinetics."

The petitioner is not correct. It is important to recognize that the Baker-Just and Cathcart-Pawel correlations are reaction rate correlations that are functions of temperature only. In licensing analyses these reaction rate correlations must be used in an integrated system analysis model that includes appropriate heat transfer models. It is the integrated system model that must be demonstrated to be conservative relative to the 2200 degree F criterion. The discussion in the following section demonstrates how an integrated system model uses Baker-Just and Cathcart-Pawel in such an analysis.

Furthermore, while PRM-50-93 takes issue and disagrees with parts of the NRC's evaluation of petition PRM-50-76, it fails to consider that in the NRC evaluation there were calculations of oxygen uptake and ZrO_2 thickness for the four FLECHT Zircaloy experiments (Cadek et al., 1971). The calculations showed Cathcart-Pawel to be best-estimate and Baker-Just to be conservative. These tests did, in fact, simulate "complex thermal-hydraulic conditions that would occur in the event of a LOCA." Because of the initial high temperature in FLECHT run 9573, the conditions exceeded design basis LOCA conditions and were more typical of a severe accident test.

The three part study by Schanz et al. (2004), Volchek et al. (2004), and Fichot et al. (2004) is also relevant to metal-water reaction correlations and the complex thermal-hydraulics that occurs in a rod bundle following a hypothetical LOCA. As part of their assessment of several correlations, multi-rod bundle test data from PHEBUS B9+ and QUENCH-06 were used. In simulation of tests, the Cathcart-Pawel correlation was used and is apparently adequate for cladding in the low temperature range (T < 1800 K).

5.2 TRACE Simulation of FLECHT Run 9573

A TRAC/RELAP Advanced Computational Engine (TRACE) simulation was made of FLECHT run 9573 in order to examine the conservatism in the Baker-Just and Cathcart-Pawel correlations and to demonstrate the adequacy of these expressions when used for complex thermal-hydraulics. Three separate calculations were made. The base case assumed no metal-water reaction. The second and third calculations used the Cathcart-Pawel and Baker-Just correlations for metal-water reaction rate, respectively.

FLECHT run 9573 was a low-reflood rate experiment. The reflood rate was held constant at 1.1 inch/sec (0.02794 m/sec) at an inlet temperature of 140 degrees F (333.15 K). Power was applied to the rods until the temperature exceeded 1970 degrees F (1349.8 K) after which time coolant was injected to the bundle. During the test, heater element failures started at 18.2 seconds. By 30 seconds, sixteen elements had failed and all but nine of the forty-two heater elements had failed when power was shut off at 55.5 seconds. The TRACE simulations were run for the first 18 seconds of the experiment, since after that time the data is not considered valid for thermal-hydraulic assessment.

Results for the TRACE simulations are listed in Table 1, which shows the cladding temperatures at five elevations 18 seconds into the transient. The data listed in the table are the average of the available thermocouple measurements at a particular elevation.

Elevation Index	Elevation, m (ft.)	Data, K	No Metal-Water Reaction, K	Cathcart-Pawel, K	Baker-Just, K
1	3.05 (10)	1015.1	1022.3	1023.4	1025.9
2	2.44 (8)	1403.4	1366.3	1417.6	1432.7
3	1.83 (6)	1513.5	1464.3	1554.2	1598.4
4	1.22 (4)	1286.8	1292.2	1324.9	1330.3
5	0.70 (2)	841.0	884.2	884.2	884.2

Table 1. TRACE Results at 18 sec. with Various Metal-Water Reaction Options.

Significant metal-water reaction rates are only expected at the middle three elevations since the top and bottom elevations remain below 1800 degrees F (1255 K). At the lowest elevation (0.70 m), TRACE predicted a cladding temperature of 884.2 K regardless of the selection for metal-water reaction rate. At the 1.83 and 2.44 m elevations, TRACE was found to underpredict the cladding temperatures if the metal-water reaction rate was not included in the calculations.

At the 1.83 m elevation, which was the peak power location in the bundle, TRACE underpredicted the data by approximately 49 K without metal-water reaction being simulated.

If the metal-water reaction rate is calculated using the Cathcart-Pawel correlation, the cladding temperatures predicted by TRACE exceeded the experimental values at each of the three elevations where significant metal-water reaction rates occurred. At the high power elevation (1.83 m), TRACE overpredicted the cladding temperature by approximately 41 K (74 degrees F). Thus, the TRACE calculation when using the Cathcart-Pawel correlation is seen to conservatively predict the cladding temperatures for a test with Zircaloy-clad rods where complex convective heat transfer and metal-water reaction phenomena occur simultaneously.

When the Baker-Just correlation was used for the metal-water reaction rate, the TRACE results were found to be even more conservative. At the peak power elevation (1.83 m), TRACE overpredicted the experimental measured values by nearly 85 K (153 degrees F). Except for the lowest elevation, where metal-water reaction did not occur, calculations with the Baker-Just correlation predicted cladding temperatures greater than those predicted using the Cathcart-Pawel correlation, and significantly greater than the measured temperatures. Thus, the TRACE calculation when using the Baker-Just correlation is seen to provide significant conservatism when used to predict the cladding temperatures for a test with Zircaloy-clad rods where complex convective heat transfer and metal-water reaction phenomena occur simultaneously.

Finally, it should be noted that over the first 18 seconds of FLECHT run 9573 the heatup rate was below the 15 K/sec that is considered in the petition to be an indication of an “autocatalytic reaction” rate. Table 2 compares the measured and predicted cladding heatup rates from the TRACE simulations. The value for the data represents the average of the available thermocouple measurements at each elevation at 18 seconds.

Elevation Index	Elevation, m (ft.)	Data, K/s	No Metal-Water Reaction, K/s	Cathcart-Pawel, K/s	Baker-Just, K/s
1	3.05 (10)	4.8	4.4	4.5	4.6
2	2.44 (8)	8.6	7.8	10.7	11.5
3	1.83 (6)	11.4	8.7	13.7	16.1
4	1.22 (4)	6.7	6.5	8.4	8.7
5	0.70 (2)	0.74	2.4	2.4	2.4

Table 2. Heatup Rate Results with Various Metal-Water Reaction Options.

At the elevations where cladding oxidation was significant (1.22, 1.83, and 2.44 m), both the Cathcart-Pawel and the Baker-Just correlations resulted in an overprediction of the measured heatup rate. Heatup rates with the Baker-Just correlation were greater than those obtained with the Cathcart-Pawel correlation, and were significantly greater than the heatup rates observed in the experimental data. At the peak power elevation (1.83 m), the heatup rate using the Baker-Just correlation exceeded the experimental value by 41 percent. The only elevation at which the heatup rate in the data is greater than in the TRACE simulations is at the 3.05 m (10 ft.) elevation. This is due to a slight overprediction in the heat transfer prediction, as indicated by the “no metal-water reaction” case. At 3.05 m (10 ft.), the cladding temperature at 18 seconds was 1015.1 K (1368 degrees F), which is well below the temperature at which metal-water reaction rates become significant.

The TRACE simulations demonstrate how the Baker-Just and Cathcart-Pawel reaction rate correlations are used in an integrated system model that accounts for the complex thermal hydraulic phenomena that occur during a LOCA and is then compared against the 2200 degree F acceptance criterion. Furthermore, it is noted that the experimental data from FLECHT run 9573 do not show evidence of an "autocatalytic reaction" below 2200 degrees F (1478 K), in spite of its low reflood rate.

5.3 Zircaloy and Stainless Steel Test Bundles

On pages 65 – 71 of PRM-50-93 (M. Leyse, 2009), the petition discusses heat transfer coefficients obtained from tests with stainless steel-clad rods compared to those obtained from tests with Zircaloy-clad rods. The petition notes that in three of the four FLECHT tests with Zircaloy-clad rods the heat transfer coefficients were higher than those obtained from stainless steel rods. In the other test, FLECHT run 9573, the heat transfer coefficients were lower. The petition later makes the statement:

> So Appendix K to Part 50—ECCS Evaluation Models I(D)(5)—which states that "reflood heat transfer coefficients shall be based on applicable experimental data for unblocked cores, including [the] FLECHT results [reported in "PWR FLECHT Final Report"]"—is erroneously based on the assumption that stainless steel cladding heat transfer coefficients are *always* a conservative representation of Zircaloy cladding behavior, for equivalent LOCA conditions.

The NRC staff disagrees with this statement. Heat transfer coefficients in FLECHT run 9573 were lower than expected. However, this in itself does not invalidate the use of data from stainless steel rod data for the development of heat transfer models.

The TRACE simulations presented in Section 5.2 demonstrate that it is possible to develop heat transfer models based on data obtained primarily from stainless steel rods and conservatively simulate FLECHT run 9573. When either the Cathcart-Pawel or Baker-Just correlations are used to determine the metal-water reaction rate, TRACE was found to conservatively predict the cladding temperatures at each elevation. The TRACE simulations further show that it is therefore not necessary to take into account the effect of heat transfer on zirconium-water reaction kinetics, as the petition suggests (page 51 of PRM-50-93 (M. Leyse, 2009)). The staff concludes that there is nothing in the petition that use of stainless steel clad rod data is inaccurate or insufficient for development of heat transfer models. While new experimental data is beneficial, the staff does not consider it necessary for tests to be conducted with Zircaloy cladding as a means of improving heat transfer models.

6.0 Summary and Conclusions

The petition for rulemaking PRM-50-93/95 requests revisions to 10 CFR 50.46 "Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Power Reactors" and to 10 CFR Part 50, Appendix K "ECCS Evaluation Models," as well as associated regulatory guidance. Specifically, the petition claims that 1) the peak cladding temperature limit of 2200 degrees F in 10 CFR 50.46(b) is non-conservative; 2) the Baker-Just reaction rate correlation specified in Appendix K and the Cathcart-Pawel reaction rate correlation specified in Regulatory Guide 1.157 are both non-conservative for metal-water reaction rate evaluations under LOCA conditions. The petition makes numerous references to FLECHT run 9573 and claims that it was "highly probable that run 9573 incurred autocatalytic oxidation, because it had a low flood rate."

This draft interim evaluation has evaluated both issues and has re-examined FLECHT run 9573. The staff concludes that the aspects of the petition discussed in this draft interim review fail to provide sufficient information to justify revisions to 10 CFR 50.46. The petition makes numerous statements regarding the Baker-Just and Cathcart-Pawel correlations, claiming that they are non-conservative for predicting metal-water reaction rates. The review provided in this draft interim review, as well as the review of these correlations in the staff's technical evaluation of PRM-50-76 (NRC, 2004), conclude that both the Baker-Just and the Cathcart-Pawel correlations are acceptable for calculating metal-water reaction rates for cladding at temperatures below 2200 degrees F (subject to the provisions in section 3.2.5.1 of Regulatory Guide 1.157). Information examined in this draft interim review, and elsewhere by the NRC staff, has indicated that any "autocatalytic reaction" that might occur would only do so at cladding temperatures well above 2200 degrees F (1478 K). FLECHT run 9573 is no exception. This draft interim review found no evidence of an excessive or "autocatalytic" metal-water reaction when the cladding temperatures were below 2200 degrees F (1478 K). High rates of metal-water reaction are believed to occur in FLECHT run 9573 and were the cause of severe damage to the bundle. However, these high metal-water reaction rates occurred well above 2200 degrees F (1478 K), and, thus, the fact that FLECHT run 9573 was conducted with a low reflood rate is irrelevant to the regulatory limit. The staff concludes then that information related to FLECHT run 9573 in the petition provides no information that sufficiently justifies a revision of the peak cladding temperature limit of 2200 degrees F. Finally, the staff concludes that the petition fails to show that the use of Zircaloy is necessary for deriving heat transfer coefficients.

7.0 References

Baker Jr., L., and Just, L. C., Studies of Metal-Water Reactions at High Temperatures, III. Experimental and Theoretical Studies of the Zirconium-Water Reaction, ANL-6548, ADAMS Accession No. ML050550198, May 1962.

Billone, M. C., Chung, H. M., and Yan, Y., "Steam Oxidation Kinetics of Zirconium Alloys," ADAMS Accession No. ML021680052, June 2002.

Cathcart, J. V. et al, Zirconium Metal-Water Oxidation Kinetics IV. Reaction Rate Studies, ORNL/NUREG-17, ADAMS Accession No. ML052230079, August 1977.

Cadek, F. F., Dominicis, D. P., and Leyse, R. H., "PWR FLECHT (Full Length Emergency Cooling Heat Transfer) Final Report," WCAP-7665, ADAMS Accession No. ML070780083, April 1971.

Fichot, F., Adroguer, B., Volchek, A., and Zvonarev, Yu., "Advanced treatment of zircaloy cladding high-temperature oxidation in severe accident code calculations Part III. Verification against representative transient tests," Nucl. Eng. Des., 232, 97-109, 2004.

Leistikow, S., and Schanz, G., "Oxidation kinetics and related phenomena of zircaloy-4 fuel cladding exposed to high temperature steam and hydrogen-steam mixtures under PWR accident conditions," Nucl. Eng. Des. 103, 65-84, 1987.

Leyse, M. E., Petition for Rulemaking (Docketed as PRM 50-93) ADAMS Accession No. ML093290250, November 17, 2009.

Leyse, M. E., “Comments on PRM-50-93; NRC-2009-0554,” Memorandum to Annette L. Vietti-Cook, ADAMS Accession No. ML100820229, March 15, 2010a.

Leyse, M. E., "Comment of Mark Edward Leyse on Petition for Rulemaking PRM-50-93", ADAMS Accession No. ML101020564, April 12, 2010b.

Leyse, M. E., "Comment of Mark Edward Leyse on Petition for Rulemaking PRM-50-93", ADAMS Accession No. ML101230118, April 28, 2010c.

Leyse, M. E., "Comment of Mark Edward Leyse on New England Coalition PRM-50-95," ADAMS Accession No. ML103340249, November 23, 2010d.

Leyse, M. E., "Comment of Mark Leyse on New England Coalition PRM-50-95," ADAMS Accession No. ML103340248, November 23, 2010e.

Nuclear Regulatory Commission, “Compendium of ECCS Research for Realistic LOCA Analysis,” NUREG-1230, ADAMS Accession No. ML053490333, December 1988.

Nuclear Regulatory Commission, “Technical Safety Analysis of PRM-50-76, A Petition for Rulemaking to Amend Appendix K to 10 CFR Part 50 and Regulatory Guide 1.157,” ADAMS Accession No. ML041210109, April 29, 2004.

Nuclear Regulatory Commission, “Denial of a Petition for Rulemaking to Revise Appendix K to 10 CFR Part 50 and Associated Guidance Documents (PRM-50-76),” SECY-05-0113, ADAMS Accession No. ML050250359, June 29, 2005.

Organisation for Economic Cooperation and Development, “Nuclear Fuel Behaviour in Loss-of-coolant Accident (LOCA) Conditions, State-of-the-Art Report,” ISBN 978-92-64-99091-3, 2009.

Schanz, G., Adroguer, B., and Volchek, A., “Advanced treatment of zircaloy cladding high-temperature oxidation in severe accident code calculations Part I. Experimental database and basic modeling,” Nucl. Eng. Des., 232, 75-84, 2004.

Volchek, A., Zvonarev, Yu., and Schanz, G., “Advanced treatment of zircaloy cladding high-temperature oxidation in severe accident code calculations Part II. Best-fitted parabolic correlations,” Nucl. Eng. Des., 232, 85-96, 2004.