Technical Safety Analysis of PRM-50-93/95
A Petition for Rulemaking to Amend 10 CFR 50.46 and
Appendix K to 10 CFR Part 50

1.0 Background

A petition for rulemaking (PRM) was docketed as PRM-50-93 on November 17, 2009 (M. Leyse, 2009). The petition 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" (10CFR, 2007), and to 10 CFR Part 50, Appendix K, "ECCS Evaluation Models" (NRC, 1974) as well as associated regulatory guidance. The petitioner, Mark Edward Leyse, has alleged that several aspects of the existing regulations are nonconservative. Specifically, the petition claims that the peak cladding temperature limit of 2,200 degrees Fahrenheit (F) (1,204 degrees Celsius (C))[1,478 Kelvin (K)] in 10 CFR 50.46(b) is nonconservative, and the Baker-Just (Baker, 1962) reaction rate correlation specified in Appendix K and the Cathcart-Pawel (Cathcart, 1977) reaction rate correlation specified in Regulatory Guide 1.157 (NRC, 1989) are both nonconservative for metal-water reaction rate evaluations under loss-of-coolant accident (LOCA) conditions. The petition also requested that a new regulation for minimum reflood rates in the event of a LOCA be implemented. The petition states that, if implemented, the amendments proposed in the petition would improve public and plant-worker safety.

On October 27, 2010, NRC published for public comment a notice of consolidation of petitions for rulemaking (NRC, 2010). The PRMs consolidated were PRM–50–93 (M. Leyse, 2009) discussed above filed by Mark Edward Leyse on November 17, 2009, and PRM–50–95 (NEC, 2010) filed on June 7, 2010, by Mark Edward Leyse and Raymond Shadis, on behalf of the New England Coalition. PRM–50–95 was docketed by the NRC on September 30, 2010. The Leyse/Shadis 2010 petition was initially submitted as a petition under 10 CFR 2.206 for enforcement action against Vermont Yankee. Because the licensee was in compliance with existing regulations, enforcement action was not appropriate and the 2.206 petition was denied. In that the petition asserted the inadequacy of certain NRC regulations, the NRC decided to consider the petition's technical issues as a petition for rulemaking under 10 CFR 2.802. In PRM–50–95, the petition requested that NRC order Vermont Yankee Nuclear Power Station (Vermont Yankee) to lower the licensing basis peak cladding temperature in order to provide a necessary margin of safety in the event of a loss-of-coolant accident (LOCA). The NRC considered PRM–50–95 in conjunction with existing PRM–50–93 that the NRC was reviewing on the same issues, and reopened the public comment period to consider the matters raised by PRM–50–95.

Thirty-two total comments were received on the combined petition PRM-50-93/95 including 12 from the petitioner Mark Leyse for the New England Coalition (NEC). Four comments were received from Robert Leyse. Two comments were received from the Nuclear Energy Institute (NEI), one from Exelon, one from the Union of Concerned Scientists (UCS), one from Beyond Nuclear, and eleven comments were received from individuals. The comments were considered with the related issues of the petition.

In order to keep the public informed during the staff's review of the issues in this petition, the staff provided four draft interim review reports. These interim reports were intended to provide an initial draft response and enable the staff to address significant safety issues rapidly had any been identified. These draft interim review reports contain additional details beyond the summary information in this report. However, this document is intended to serve as the official technical basis for the staff's evaluation. The additional details in the draft interim review reports are considered supplementary information that is not necessary to justify the staff's position. Section 2 discusses the main petition issues and Section 3 provides more detailed technical information on the main petition issues. The staff identified three main issues that were specifically pointed out in the petition and were possible causes for rulemaking, while related technical issues were items the petition or comments cited as technical concerns only.

1.1 Similar Petition Previously Considered by NRC (ML041210109)

A petition for rulemaking was docketed as PRM-50-76 on May 8, 2002 (R. Leyse, 2002). The petitioner, Mr. Robert Leyse, requested amending those parts of Appendix K to 10 CFR Part 50 (NRC, 1974) and Regulatory Guide 1.157 (NRC, 1989) that address metal water reaction models for ECCS analysis. Mr. Leyse stated that he is aware of deficiencies in the Baker-Just equation (Baker, 1962) required for Appendix K ECCS analysis and deficiencies in the acceptable Cathcart-Pawel metal-water reaction data base (Cathcart, 1977) described in Regulatory Guide 1.157 for best-estimate ECCS analysis. In both cases he states that the models do not include any consideration of complex thermal hydraulic conditions during a LOCA including the potential for very high fluid temperatures. Further, Mr. Leyse quotes a portion of the Atomic Energy Commission (AEC) opinion (AEC, 1973) regarding the ECCS Rulemaking Hearing. That opinion was set forth in the ECCS rule on December 28, 1973 and was noticed in the Federal Register on January 4, 1974. The petition quotation states: "It is apparent, however, that more experiments with Zircaloy cladding are needed to overcome the impression left from run 9573."

Run 9573 refers to one of four Zircaloy Clad Full Length Emergency Core Heat Transfer (FLECHT) experiments performed in 1969 and reported in WCAP-7665 (Cadek, 1971). In Section 3 of the petition, Mr. Leyse describes in detail his concerns regarding Baker-Just, Cathcart-Pawel and the need to consider experiments like FLECHT Run 9573. Mr. Leyse provided further explanation as comments provided during the public comment period (R. Leyse, 2002a and 2002b). Public comments were also received from Westinghouse (WEC, 2002), Nuclear Energy Institute (NEI) (NEI, 2002) and (Strategic Teaming and Resource Sharing (STARS) (STARS, 2002). These three industry comments recommended denial of the petition.

The staff's position on PRM-50-76 was that Appendix K of 10 CFR Part 50 and existing guidance on best estimate ECCS Evaluation Models are adequate to assess ECCS performance for U.S. LWRs using Zircaloy clad UO_2 at burnup levels currently permitted by regulations.

Each of the petition's key presumptions was investigated. As a result, no technical basis was found in the petition (R. Leyse, 2002) for the assertion that Appendix K or Regulatory Guide 1.157 are flawed and present a significant safety concern. The Baker-Just correlation (Baker, 1962) using the current range of parameter inputs is conservative and adequate to assess Appendix K ECCS performance. Virtually every data set published since the Baker-Just correlation was developed has clearly demonstrated the conservatism of the correlation above 1,800 degrees Fahrenheit (982 degrees Celsius). Parabolic/Arrhenius behavior of the Cathcart-Pawel isothermal experiments (Cathcart, 1977) confirmed that there was adequate availability of steam. An NRC analysis confirms that the ORNL/ANL assessment that the Cathcart-Pawel isothermal experiments were not steam starved by at least two orders of magnitude.

NRC has continued to study complex thermal hydraulic effects on ECCS heat transfer processes during accident conditions related to LOCAs (NRC, 1988) consistent with Commission direction. The NRC funded more than 50 Zircaloy clad bundle reflood experiments at the NRU reactor (Mohr, 1981, and Thurgood, 1982). The petition did not take into account Westinghouse's metallurgical analyses performed on the cladding for all four FLECHT Zircaloy clad experiments reported in WCAP-7665. He also appeared to have ignored the Westinghouse application of 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 also applied the Baker-Just correlation to the FLECHT Zircaloy experiments with nearly identical results, thus providing a very good check on the application in WCAP-7665.

For the development of oxidation correlations limited by oxygen diffusion into the metal, well - characterized isothermal tests are more useful than the complex thermal hydraulics tests as suggested by the petition. This enables researchers to focus on phenomena more suitable for correlation development. The use of complex thermal hydraulic conditions would be a detriment in reaction kinetics tests. It is quite proper and important to apply the developed correlations to more prototypic transients to verify that the proposed phenomena embodied in the correlations are indeed limiting. This is what was done by Westinghouse in WCAP-7665, Cathcart-Pawel in ORNL/NUREG-17 (Cathcart, 1977) and by the NRC in its evaluation of the petition (NRC, 2004).

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 nonconservative for the remaining two. Additionally, RG 1.157 requires that applicants consider the uncertainty in the correlation and account for that uncertainty in the statistics for a best-estimate analysis. A "best-estimate" correlation such as Cathcart-Pawel is not intended to be a bounding approach. Its results should generally represent the mean of the data. Cathcart-Pawel results that are conservative for 13 cases and nonconservative for two are reasonable for this particular set of data in concluding that the calculation is at the very least on the conservative side of best-estimate. Therefore in SECY-05-0113 dated June 29, 2005 (NRC, 2005), the staff recommended that the Commission deny PRM-50-76.

On August 5, 2005, the Commission denied the petition for rulemaking (Commission, 2005).

2.0 Discussion of Petition's Main Issues and Staff Response

2.1 Peak Cladding Temperature Limit is Nonconservative

The petition states that that the current peak cladding temperature limit of 2,200 degrees F (1,204 degrees C) contained in 10 CFR 50.46(b)(1) is nonconservative. The 2,200 degrees F (1,204 degrees C) limit was selected to ensure that "autocatalytic" or otherwise excessive metal-water reaction rates do not occur. Pages 25 and 26 of the petition (M. Leyse, 2009) discuss the metal-water reaction rate and its relation to the 2,200 degrees F (1,204 degrees C) limit. The petition states, referring to 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 2,200 degrees F (1,204 degrees C). However, the staff notes some additional important information from the "Compendium of ECCS Research for Realistic LOCA Analysis," which was not cited by the petition. Specifically, the referenced Compendium section also discusses conservatism in the regulatory criteria, and provides justification. For example, the data discussed previously was evaluated and resulted in 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 that if an autocatalytic reaction occurred, it was at a temperature well above 2,200 degrees F (1,204 degrees C). The staff concludes, then, that the autocatalytic reactions have not occurred at temperatures less than 2,200 degrees F (1,204 degrees C). Accordingly, the 2,200 degrees F (1,204 degrees C) regulatory limit is sufficient provided the correlations used to determine the metal-water reaction rate below 2,200 degrees F (1,204 degrees C) are suitably conservative such that excessive reaction rates do not occur below that value. (NRC, 2011a)

Further, the petition and a comment submission states:

> … when taking into account data from the CORA experiments and other severe fuel damage experiments conducted with Zircaloy assemblies more than a decade after the Zr2K test, it is clear that the Zr2K test-which had cladding-temperature increases of several hundred degrees Fahrenheit within approximately 20 seconds, at some locations of its assembly, after cladding temperatures reached between approximately 2100 and 2200°F-incurred an autocatalytic oxidation reaction. (M. Leyse, 2010a, p. 42); and
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> …data from such experiments indicates that the 10CFR 50.46(b)(1) PCT limit of 2200ºF is nonconservative. (M, Leyse, 2009, p. 11)

The staff has reviewed the data from the CORA and other severe accident tests cited in the petition and its associated comments. 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 behavior of temperatures in the CORA experiments is consistent with prior NRC understanding and expectations on oxidation rate at temperatures below 2,200 degrees F (1,204 degrees C)[1,478K]. No locations with temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K] with heatup rates suggesting an autocatalytic reaction were identified. The heatup rates below 2,200 degrees F (1,204 degrees C)[1,478K] do not indicate a presence of an exothermic "autocatalytic" reaction. The results of CORA do not suggest that the current peak cladding temperature limit of 2,200 degrees F (1,204 degrees C)[1,478K] contained in 10 CFR 50.46(b)(1) is nonconservative. The assertions made by the petition with regards to the peak cladding temperature limit are not substantiated by the CORA data.

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 2,200 degrees F (1,204 degrees C)[1,478K] and relocation of parts of the fuel bundle. The data does show temperatures that increase at nearly 15 K/s, however this rate of increase did not occur while temperatures were less than 2,200 degrees F (1,204 degrees C)[1,478K]. As intended in the CORA tests, the heatup rate was initially about 1 K/s. The rate of temperature increase did escalate as temperatures exceeded 2,012 degrees F (1,100 degrees C)[1,373 K]. As temperatures approached 2,200 degrees F (1,204 degrees C)[1,478K], the rate of increase was generally 3 to 4 K/s and only a few thermocouples had a more rapid heatup. Maximum heatup rates for CORA tests when thermocouple temperatures are less than 2,200 degrees F (1,204 degrees C)[1,478K] was 8 K/s. This is based on 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 petition cites as a basis for the proposed rule change a reconsideration of the BWR FLECHT Zr2K Test performed in 1968-1970 "in light of data from the CORA experiments and other severe fuel damage experiments conducted with Zircaloy assemblies." The petition claims that the Zr2K test "had cladding-temperature increases of several hundred degrees Fahrenheit within approximately 20 seconds, at some locations of its assembly, after cladding temperatures reached between approximately 2,100 degrees F (1,149 degrees C)[1,422 K] and 2,200 degrees F (1,204 degrees C)[1,478K] and that the information from the CORA tests (and other tests) which were conducted after Commission consideration of the BWR FLECHT Zr2K test makes it "clear that the Zr2K test … incurred an autocatalytic oxidation reaction."

GEAP-13197, "Emergency Cooling in BWR's Under Simulated Loss-of-Coolant Conditions," (BWR-FLECHT Final Report) (GEAP, 1971) describes the results of the BWR FLECHT program. The FLECHT program was designed to further investigate the significant heat transfer mechanisms during the emergency cooling phase of the postulated BWR loss-of-coolant accident. The effect of thermal transients on Zircaloy cladding was investigated for the first time in this test program. The program was funded by the Atomic Energy Commission. Testing and analysis of test results were accomplished by the General Electric Atomic Power Equipment Department in San Jose, California.

The BWR FLECHT test program and its results were considered in detail during the ECCS hearings that concluded with the issuance of the peak cladding temperature (PCT) and cladding oxidation limits currently prescribed in 10 CFR 50.46(b). The testimony included arguments regarding the importance of the metal water reaction rate on the peak cladding temperature. In particular, discussion of test Zr2K and the temperature data noted in the petition ("temperature increases of several hundred degrees Fahrenheit within approximately 20 seconds") was specifically included in the testimony.

The petition provided no data from the FLECHT program that was not considered in the Commission deliberation. Rather, the petition argues that information from test programs that occurred after the ECCS hearings (including CORA) shows that a different conclusion (from that reached by the Commission) regarding the role of metal water reactions in the Zr2K test is indicated. Specifically the petition concludes that "after cladding temperatures reached between approximately 2100 and 2200°F… the Zr2K test incurred an autocatalytic oxidation reaction."

During the formal public hearings that led to the current ECCS acceptance criteria, the Commission considered in detail the data from the BWR FLECHT program, including the Zr2K test. The petition provided no new data from the Zr2K test. The staff also reviewed data from subsequent severe accident tests cited in the petition that used Zircaloy fuel assemblies. In none of the tests did the staff find temperature escalation rates demonstrating the occurrence of "runaway" or autocatalytic oxidation at temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K]. Therefore, the assertion that data from subsequent severe fuel damage experiments conducted with Zircaloy assemblies shows that the BWR FLECHT Zr2K test incurred an autocatalytic reaction at temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K] is not supported.

The staff has reviewed the data and information from Materials Test 6B, CORA, PHEBUS B9R and the FLECHT program as well as information from other severe accident tests cited in the petition. In none of these tests did the staff find temperature escalation rates demonstrating the occurrence of "runaway" or autocatalytic oxidation at temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K]. Thus the staff does not agree with the petition that consideration of test information developed after the FLECHT program indicates that the Zr2K test incurred autocatalytic oxidation at temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K]. As a result, no technical basis was found in the petition (Leyse, 2009) for the assertion that the regulations at 10 CFR 50.46(b)(1) to require a calculated maximum fuel element cladding temperature limit of less than 2,200 degrees F (1,204 degrees C)[1,478K] are nonconservative and present a significant safety concern. (NRC, 2011a)

2.2 Baker-Just and Cathcart-Pawel Equations are Nonconservative

One of the concerns of the petition is that the Baker-Just and Cathcart-Pawel correlations are nonconservative. That is, the petition claims that these correlations under predict the metal-water reaction rate and thus would under predict the heatup, heatup rate, or maximum temperature of the cladding during a LOCA. The petition uses two main arguments for the basis of this claim. First, the petition states that data from multi-rod (assembly) experiments indicates that the Baker-Just and Cathcart-Pawel equations are both nonconservative for use in analyses that calculate the temperature at which an autocatalytic (runaway) oxidation reaction of Zircaloy would occur in the event of a LOCA. In addition, the petition states that the Baker-Just and Cathcart-Pawel equations were not developed to consider how heat transfer would affect zirconium-water reaction kinetics in the event of a LOCA.

The petition's basis for the first claim is based upon a comparison of experimental test data to RELAP5 calculations performed by the NRC. The petition claims that analysis using the Baker-Just correlation calculates autocatalytic (runaway) oxidation to occur when cladding temperatures increased above approximately 2,600 degrees F (1,427 degrees C)[1,700 K] while Cathcart-Pawel calculates autocatalytic oxidation to occur when cladding temperatures increased above approximately 2,700 degrees F (1,482 degrees C)[1,755 K]. The petition then claims that experimental test data from multiple test facilities shows autocatalytic (runaway) oxidation occurs at much lower temperatures than predicted by these RELAP5 calculations. The petition does not specifically identify the time period or measurements that show these reportedly lower temperature autocatalytic oxidation rates. Test facilities/tests referenced in the petition and considered by the staff for assessing conservatism of Baker-Just and Cathcart-Pawel included:

- Power Burst Facility (PBF) Severe Fuel Damage Tests
- The NRU Reactor Transition Test
- NRU Reactor Full-Length High-Temperature Test
- LOFT LP-FP-2
- CORA Experiments
- PHEBUS B9R Test
- QUENCH-04 Test
- FLECHT Run 9573

In PRM 50-95, the petition discusses data from these tests and compares the experimental data to NRC staff calculations of hypothetical LOCAs reported in Research Information Letter 0202 (RIL 0202, 2002). In the more than 50 LOCA sensitivity calculations performed using RELAP5, the highest peak cladding temperature observed without runaway oxidation using the Baker-Just equation was about 2,600 degrees F (1,427 degrees C)[1,700 K]. When the temperature went above this value, it continued to the melting point without turning around at some peak value. This indicated that runaway temperatures could not be prevented above about 2,600 degrees F (1,427 degrees C)[1,700 K] for the parameters used in these calculations. The highest peak cladding temperature without runaway oxidation observed in corresponding calculations with the Cathcart-Pawel equation was about 2,700 degrees F (1,482 degrees C)[1,755 K]. The petition claims that these temperature values are the exact temperatures at which Baker-Just and Cathcart-Pawel predict runaway oxidation. The staff believes this assumption is inaccurate because there is no specific temperature at which autocatalytic "runaway" oxidation begins because it is strongly dependent on heat transfer to/from the fuel rods.

As an example, the petition states that in the Power Burst Facility Severe Fuel Damage tests 1-1, 1-3 and 1-4, rapid temperature excursions occurred at either approximately 2,420 degrees F (1,327 degrees C)[1,600 K] or approximately 2,600 degrees F (1,427 degrees C)[1,700 K] as a result of the exothermic Zircaloy-water reaction and that the Baker-Just and Cathcart-Pawel correlations are nonconservative because they predict this occurs at higher temperatures. The petition appears to equate "rapid" with "autocatalytic" or an uncontrolled temperature escalation, and uses a heatup rate exceeding 18 °F/s [10 K/s] (petition sometimes uses 27 °F/s [15 K/s]) as an indication that an autocatalytic reaction occurred. Regardless of if or when an autocatalytic oxidation reaction occurred, the staff finds that it is inappropriate to make comparisons between a specific test and these RELAP5 calculations as those calculations were not intended to simulate this test facility (exact geometry, heat losses, coolant flow rate, etc.). As stated in the description of the RELAP5 calculations, the temperatures predicted were “for the parameters used in these calculations,” and not generic to all situations.

Therefore, the staff does not agree that a comparison of specific tests to RIL 0202 calculated temperatures is a valid method for demonstrating the conservatism or non-conservatism of metal water reaction rate correlations for calculating the temperature at the onset of autocatalytic reactions. The staff therefore does not agree that the Baker-Just or Cathcart-Pawel correlations have been shown to be nonconservative for use in licensing basis LOCA models.

The second argument made by the petition is that the Baker-Just and Cathcart-Pawel equations were not developed to consider how heat transfer would affect zirconium-water reaction kinetics in the event of a LOCA. The staff evaluated assertions in the petition regarding experimental measurements of oxidation kinetics. One issue raised was related to oxidation measurements with inductive heating and radiative heat losses with respect to the Baker-Just correlation. The petition contends that the experiments did not replicate reactor LOCA behavior of cladding because of the radiative heat losses from the sample inherent in using inductive heating, and so proposes that the Baker-Just correlation is nonconservative.

The staff has evaluated the petition's contention that the Baker-Just oxidation kinetics correlation is nonconservative because it is partly derived from experimental data asserted to be not representative of reactor LOCA behavior. NRC determined that the questioned data are similar to data obtained by other methods, and so the heat losses are not relevant in correlating the data. The metal-water reaction rate constant correlation is a function of temperature only, and must be used in conjunction with system-level thermal hydraulic models in order to determine the instantaneous cladding temperature. The induction heating method described by Lemmon (Lemmon, 1957) was examined by the staff, and it was concluded that the specific method of heating does not affect the metal-water reaction. Therefore, use of the data from Lemmon did not result in a nonconservative correlation of the data by Baker and Just.

There are many other studies that conclude the Baker-Just and Cathcart-Pawel correlations are conservative as noted below. Additionally, the technical evaluation by the staff supporting the denial of PRM-50-76 (NRC, 2004) also carefully examined the metal-water (oxidation) rates as predicted by the Baker-Just and Cathcart-Pawel correlations, and found that the correlations were conservative for prediction of the amount of oxidation.

As described in WCAP-7665 (Cadek, 1971), Westinghouse performed metallurgical analyses on the cladding for all four FLECHT Zircaloy clad experiments. Westinghouse applied the Baker-Just correlation to these experiments, which had the “complex thermal hydraulic phenomena” considered important by the petition. This application of the correlation to the metallurgical data 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.

A report prepared by Argonne National Laboratory (Billone, 2002) examined steam-oxidation kinetics for a variety of zirconium alloys and included a literature review of existing studies. It concluded:

> The Baker-Just correlation is specified in Appendix K of 10 CFR 50.46 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 10 CFR 50.46.

A more recent report by the Organization for Economic Cooperation and Development (OECD) (OECD, 2009) also confirms this long-standing finding that the Baker-Just correlation over predicts the reaction rate between 1,934 degrees F (1,057 degrees C)[1,330 K] and 2,600 degrees F (1,427 degrees C)[1,700 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. The NRC also 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 the transient temperature experiments. The equation was conservative or best-estimate for 13 experiments and nonconservative for the remaining two. These results confirmed that the Cathcart-Pawel correlation provides reasonably accurate estimates of the oxide thickness and thus can be considered best-estimate.

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, 2004) noted that for low temperatures (T < 2,780 degrees F (1,527 degrees C)[1,800 K]), the experimental data base is very large and applicability of several well-defined correlations has been established. While high temperature (T > 2,780 degrees F (1,527 degrees C)[1,800 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 2,780 degrees F (1,527 degrees C)[1,800 K]. In the low temperature range (T < 2,780 degrees F (1,527 degrees C)[1,800 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, 1987) which were developed independently for Zircaloy oxidation. Cathcart-Pawel was in slightly better agreement with the data considered in these recent studies. (NRC, 2011c)

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 2,200 degrees F (1,204 degrees C)[1,478K]. 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.

The petition asserts that data from such experiments as the LOFT LP–FP–2 experiment indicates that the Baker-Just and Cathcart-Pawel equations are both nonconservative for calculating the temperature at which an autocatalytic (runaway) oxidation reaction of Zircaloy would occur in the event of a LOCA. The petition states that these experiments demonstrate that the autocatalytic oxidation reaction of Zircaloy cladding occurs at temperatures far below those predicted by the Baker-Just and Cathcart-Pawel equations. The petition concludes that this, in turn, indicates that the Baker-Just and Cathcart-Pawel equations are both nonconservative for calculating the metal-water reaction rates that would occur in the event of a LOCA.

Although LOFT LP-FP-2 did show rapid temperature increases as regions of the core approached and exceeded 2,200 degrees F (1,204 degrees C)[1,478K], the heatup rates do not suggest that an “autocatalytic” oxidation reaction occurred while cladding temperatures were below 2,200 degrees F (1,204 degrees C)[1,478K]. While cladding temperatures remain below 2,200 degrees F (1,204 degrees C)[1,478K], heatup rates were less than 15 K/s 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 the central rod bundle in LOFT Test LP-FP-2 is consistent with prior understanding of oxidation rates at temperatures below 2,200 degrees F (1,204 degrees C)[1,478K]. A close examination of thermocouple data for LOFT LP-FP-2 found that the heatup rates below 2,200 degrees F (1,204 degrees C)[1,478K] do 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 nonconservative. 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. (NRC, 2011b)

The staff evaluation again confirms that the Cathcart-Pawel and Baker-Just correlations are appropriately conservative for metal-water reaction rate evaluations under loss-of-coolant accident (LOCA) conditions.

2.3 Need for a Minimum Allowable Reflood Rate

The petition requests that the NRC promulgate a regulation that will stipulate minimum allowable core reflood rates in the event of a LOCA. The petition (M. Leyse, 2009) states that it can be extrapolated from experimental data that in the event of a LOCA, a constant core reflood rate of approximately one inch per second or lower would not, with high probability, prevent Zircaloy fuel cladding from exceeding the peak cladding temperature limit of 2,200 degrees F (1,204 degrees C)[1,478 K] if, at the onset of reflood, the cladding temperature was 1,200 degrees F (649 degrees C)[922 K] or higher.

The petition cites as a basis for the proposed rule change the FLECHT Test 9573. This particular test used a Zircaloy bundle and was conducted with an initial maximum cladding temperature of 1,970 degrees F (1,077 degrees C)[1,350 K]. The flooding rate was nominally 1.1 inch/s. A post-test inspection of the bundle found there to be severe local damage near a Zircaloy spacer grid at the 7-foot elevation due to temperatures in excess of 2,500 degrees F (1,371 degrees C)[1,644 K]. Several possible causes of the high temperatures were cited, with metal-water reaction of Zircaloy being a likely candidate (Cadek, 1971).

The petition states on page 12:

> Petitioner believes that the “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.

The petition further states:

> It would be reasonable to postulate that if run 9573 were repeated—with the same or a lower coolant flood rate, yet with lower initial cladding temperatures (that in the event of a LOCA, would occur at the beginning of reflood at current and/or proposed PWRs) and a lower power level (within the operational range of current and/or proposed PWRs)—that the fuel assembly would still incur autocatalytic oxidation and be destroyed, because run 9573 had the lowest flood rate of the four Zircaloy tests. Furthermore, it is likely that such a test would produce valuable heat transfer information.

As additional support for the request for a limit on the reflood rate, the petition further cites results from NRU tests (page 18 of the petition). The petition notes that NRU tests with reflood rates less than or equal to 1.0 inch/s had large temperature increases. The peak cladding temperatures in those tests remained below 2,200 degrees F (1,204 degrees C)[1,478K], but these tests started with relatively low initial cladding temperatures. The petition hypothesizes that if these tests had started with higher initial cladding temperatures, these assemblies “with high probability, would have incurred autocatalytic (runaway) oxidation, clad shattering, and failure —like FLECHT run 9573.”

There are several parameters that are known to have an important effect on reflood in a light water reactor (LWR). Experimental studies such as FLECHT (Lilly, 1977), FLECHT-SEASET (Lee, 1982), Achilles (Pearson, 1989), NRU (Mohr,1981) and RBHT (Hochreiter, 2012) have each demonstrated that the peak cladding temperatures and behavior of reflood hydraulics depends on several parameters including reflood rate, coolant subcooling, and pressure. In addition, initial and boundary conditions due to geometry and operation also affect LOCA behavior. These include but are not limited to the rod bundle design, bundle power, power shape and power decay rate.

The parametric effects of many of these parameters were considered in the evaluation by Lee et al. (1982). Reflood rate was found to be an important parameter, with peak cladding temperatures increasing as the reflood rate decreases. However, other parameters were also found to have significant effects on the peak cladding temperature or quench time of the rod bundle. Initial cladding temperature and initial rod power likewise were found to have important effects. Peak cladding temperatures increased with increasing initial temperature or initial power. Other parameters, such as pressure and coolant subcooling were found to have a relatively weak influence on peak cladding temperature, but could have important effects on the bundle quench time (which may influence the duration of time over which significant metal-water reaction occurs).

Because numerous parameters have an effect on reflood hydraulics, no single parameter completely controls the peak cladding temperature for a particular transient. Basing a conclusion on any single parameter can be misleading. Part of the basis for the petition's request for a limit on reflood rate, is the significant temperature increases observed in the NRU reflood tests. Starting from initial cladding temperatures less than 1,000 degrees F (538 degrees C)[811 K], several NRU tests produced temperature increases of over 1,000 degrees F (556 degrees C)[556 K]. The petition cites NRU test 127 and 130 as examples. The petition appears to imply that similar temperature increases would occur if the initial cladding temperatures had been 1,200 degrees F (649 degrees C)[922 K] or more. This is not correct, however. Thermal radiation becomes more important in transferring heat away from hot spots, and as rod temperatures increase the temperature difference between the cladding and the coolant increases. Figure 3-23, "Initial Clad Temperature Effect of Temperature Rise and Quench Time," in Lee et al. (1982), shows the effect of initial cladding temperature on temperature rise from tests in three experimental facilities. As the initial cladding temperature increases, the overall temperature rise <u>decreases</u>. Linear extrapolation of initial cladding temperatures to predict final cladding temperature is inappropriate due to the increased radiative cooling at higher temperatures. Thus, contrary to the claim made by the petition, "extrapolation" of data does <u>not</u> show "with high probability" that peak cladding temperatures will exceed 2,200 degrees F (1,204 degrees C)[1,478K].

To examine the effect of initial cladding temperature on reflood where metal-water reaction is a concern, the NRC staff performed a sensitivity study using TRACE[1] which simulated the FLECHT Test 9573 and compared the TRACE output to available experimental data. As noted previously, FLECHT Test 9573 had a forced reflood rate of 1.1 inch/second (0.02794 meter/second). Since that test initiated with an initial cladding temperature of 1,970 degrees F (1,077 degrees C)[1,350 K], temperatures quickly exceeded 2,200 degrees F (1,204 degrees C)[1,478K], damaging the bundle. The TRACE simulation of Test 9573 showed reasonable agreement with available data (Cadek, 1971), with TRACE-generated cladding temperatures exceeding the measured FLECHT maximum cladding temperature 18 seconds into the test. (After 18 seconds, thermocouples began to fail and the data is suspect.) At the 6-foot (1.83-meter) elevation, the measured cladding temperature was 2,265 degrees F (1,241 degrees C)[1,514 K]. TRACE predicted 2,338 degrees F (1,281 degrees C)[1,554 K] for the peak cladding temperature using the Cathcart-Pawel (1977) correlation for metal-water reaction.

The sensitivity of peak cladding temperature to initial temperatures was investigated by simulating FLECHT Test 9573 with TRACE. The initial axial cladding temperature profile was scaled to data in order to obtain the desired maximum initial cladding temperature at the start of the simulation.
The reflood rate was assumed to be 1.1 inch/second, consistent with Test 9573. At maximum initial cladding temperatures less than approximately 1,200 degrees F (649 degrees C)[922 K], typical of those expected following the blowdown period of a LOCA, the TRACE simulation showed that the

[1] TRACE or Transient Reactor Analysis Code/Reactor Excursion and Leak Analysis Program (TRAC/RELAP) Advanced Computational Engine is NRC's advanced, best-estimate reactor system code used to model and analyze the thermal-hydraulic performance of nuclear power plants.

peak cladding temperature remained below 1,800 degrees F (982 degrees C)[1,255 K]. It also showed that the predicted peak cladding temperature did not exceed 2,200 degrees F (1,204 degrees C)[1,478 K] unless the maximum initial cladding temperature was greater than 1,600 degrees F (871 degrees C)[1,144 K]. This is significantly higher than the initial temperatures that are expected to occur following the blowdown and refill periods of a LOCA.

The reflood rate simulated in the TRACE calculations was 1.1 inch/second, to be consistent with the rate used in the actual experiment. Clearly, if coolant is denied to a rod bundle during reflood, the cladding will increase in temperature rapidly. The rate at which the cladding temperature increases depends on several parameters, as does the peak cladding temperature that is attained during a transient. As discussed previously, the peak cladding temperature depends on numerous other parameters including the rod power, coolant temperature, and pressure. This is because the temperature at a particular location on a rod depends on an energy balance. Ultimately the peak temperature depends on the local heat generation (decay heat from the fuel and metal-water reaction heat) and heat removal mechanisms (conduction away from the hot spot, convection to the coolant, and thermal radiation to the coolant or colder structures). Indeed, it is possible to cool a bundle and prevent the peak cladding temperature from exceeding 2,200 degrees F (1,204 degrees C)[1,478K] with a zero reflooding rate if sufficient cooling is provided by other means.

An additional simulation was performed with TRACE using the model of the FLECHT bundle assuming an initial temperature profile with a maximum temperature of 1,200 degrees F (649 degrees C)[922 K] and with no liquid injection but with steam-only cooling of the bundle. With a steam-only mass flow rate of 0.114 kg/s through the bundle, the peak cladding temperature obtained was 1,927 degrees F (1,053 degrees C)[1,326 K]. No liquid injection can be interpreted as a reflooding rate of 0.0 in/s. In this case, cooling was accomplished not by reflood of the bundle, but by convective cooling to the steam. The results were that cladding exceeded 1,832 degrees F (1,000 degrees C)[1,273 K], and thus metal-water reaction became a significant source of heat. Nevertheless, the peak cladding temperature remained below 2,200 degrees F (1,204 degrees C)[1,478K] and an “autocatalytic” (runaway) oxidation did not occur.

The steam-only TRACE cooling calculation demonstrates that it is possible to cool a Zircaloy-clad bundle without reflooding. Adequate cooling could be obtained by alternative heat transfer mechanisms. This indicates that specification of a minimum reflood rate, as requested by the petition, is not necessary. As long as sufficient cooling by the Emergency Core Cooling System (ECCS) is maintained, the peak cladding temperature can remain below the regulatory limit of 2,200 degrees F (1,204 degrees C)[1,478K].

The staff’s TRACE simulation of steam cooling of a Zircaloy bundle (mass flow rate of 0.114 kg/s, saturated steam at 0.42 MPa.) demonstrates that the argument central to the petition’s request, that a minimum reflood rate be specified as noted above, is false.

The TRACE calculations showed that if FLECHT Test 9573 were repeated with the same power level, the bundle would not have been destroyed as long as adequate steam cooling was maintained. The reflood rate is irrelevant. Thus, the results of the calculations also demonstrate that the following petition’s claim is false:

> “it can be extrapolated from experimental data that, in the event a LOCA, a constant core reflood rate of approximately one inch per second or lower (1 in/s or lower) would not, with high probability, prevent Zircaloy fuel cladding, that at the onset of reflood had cladding temperatures of approximately 1,200 degrees F (649 degrees C)[922 K] or greater, from exceeding the 10 C.F.R. § 50.46(b)(1) PCT limit of 2,200 degrees F (1,204 degrees C)[1,478K].”

In summary, the petition makes numerous references to FLECHT Test 9573, and claims that it was “highly probable that run 9573 incurred autocatalytic oxidation, because it had a low flood rate.” Based primarily on this test and on the expectation that the NRU tests, if repeated, might behave similarly, the petition requests "that the NRC make a new regulation stipulating minimum allowable core reflood rates, in the event of a loss-of-coolant accident ('LOCA')."

The staff has evaluated the claims in the petition related to specification of a minimum reflood rate using TRACE simulations of a Zircaloy clad bundle with a geometry and design as was used for FLECHT Test 9573. Those calculations show the petition's claims to be false. Calculations with steam-cooling through TRACE simulations only showed that likewise, cladding temperatures in a Zircaloy clad bundle could be maintained within the regulatory limit. Cooling of a rod bundle depends on several parameters and heat transfer mechanisms, and not simply on the reflood rate. The staff thus concludes that the petition did not provide sufficient information to justify revisions to 10 CFR 50.46 that would stipulate a minimum allowable core reflood rate. (NRC, 2013)

3.0 Staff Evaluation of Related Technical Issues

This section addresses technical issues raised in the petition that weren't related to potential changes in NRC regulations. However, to be responsive to the petition, the staff evaluated these additional issues.

3.1 Issues Related to National Research Universal (NRU) full-length high-temperature (FLHT) In-reactor Tests

The petition raised several issues in PRM-50-93 related to the NRU thermal-hydraulic tests. The NRU facility was used to simulate conditions in a 12-rod bundle of full-length fuel rods during hypothetical, small-break LOCAs. On pages 31-38 of PRM-50-93, the petition derives 2,275 degrees F (1,246 degrees C)[1,519 K] as the onset of autocatalytic oxidation for NRU FLHT-1 based on an 18 second time discrepancy in the report and a definition of the onset of autocatalytic oxidation as >10 K/s. The petition then points to test data to show that autocatalytic oxidation has been observed at temperatures lower than 2,600 degrees F (1,427 degrees C)[1,700 K] or 2,700 °F (1,482 degrees C)[1,755 K]. Therefore, the petition concludes, Baker-Just and Cathcart-Pawel are both nonconservative for calculating the cladding temperatures at which an autocatalytic oxidation reaction would occur in the event of a LOCA. The petition cites NRU FLHT-1 test as an example of autocatalytic oxidation that occurred below 2,600 degrees F (1,427 degrees C)[1,700 K] or 2,700 °F (1,482 degrees C)[1,755 K]. The petition argues it occurred at 2,275 degrees F (1,246 degrees C)[1,519 K].

The data from the experiments however do not support such an assumption nor do they show that an autocatalytic reaction was in progress at temperatures significantly below 2,600 degrees F (1,427 degrees C)[1,700 K]. This can be seen by a closer examination of the data shown in Figure 4.2 of NUREG/CR-5876 (Lombardo, 1992) which the staff used for its analysis (NRC, 2016a). This figure is an alternative representation of the data from Petition Reference 96 (Rausch, 1993). A time of 4,800 seconds in Figure 4.2 corresponds to a time of 17:10:00 reported in Petition Reference 96. The actual data as shown in Figure 4.2 show that when temperatures are below 2,200 degrees F (1,204 degrees C)[1,478K], the rate of temperature increase is approximately 1.6 K/s; temperature between 2,240 degrees F (1,227 degrees C)[1,500 K] and 2,420 degrees F (1,327 degrees C)[1,600 K] correspond to a heat-up rate is approximately 2 – 3 K/s and the average heat-up rate between 2,420 degrees F (1,327 degrees C)[1,600 K] and 2,600 degrees F (1,427 degrees C)[1,700 K] is approximately 5 – 6 K/s. These rates were determined by estimating the slopes on an enlarged copy of the figure. Furthermore, since the temperature in the range of interest (i.e., after 4,500 s) is monotonically increasing throughout the range and the average over the two ranges is significantly less than 10 K/s, it is clear that at no time when the temperatures were below 2,420 degrees F (1,327 degrees C)[1,600 K] did the heat-up rate reach 10 K/s. Above 2,420 degrees F (1,327 degrees C)[1,600 K], the increasing slope on the figure may indicate the rate of temperature rise may exceed 10 K/s. However, since the average rate of temperature rise between 2,420 degrees F (1,327 degrees C)[1,600 K] and 2,600 degrees F (1,427 degrees C)[1,700 K] is only 5 – 6 K/s, it is unlikely that a rate of 10 K/s is reached significantly below

2,600 degrees F (1,427 degrees C)[1,700 K]. Thus, the petition assumption does not seem to be supported.

On pages 34 and 35 of the petition (M. Leyse, 2009), the petition states:

> How can it be explained that after the coolant flow rate was increased—when cladding temperatures reached approximately 1475°K (2200°F)—that the cladding temperatures were able to increase by 225°K (400°F)? Why would the test conductors have not been able to terminate the cladding-temperature rise, as they did earlier in the test when cladding temperatures reached 1450°K (2150°F)? And how can it be explained that the test conductors did not have enough time to increase the coolant flow rate back up to 18 kg/hr. (40 lb/hr.), as they did when cladding temperatures reached 1450°K (2150°F), earlier in the test?

The following statement appears on page 32 of the comment submission dated December 27, 2010 (M. Leyse, 2010b):

> Clearly, the fact that in the FLHT-1 test, the test conductors were not able to prevent runaway oxidation by increasing the coolant flow rate when peak cladding temperatures reached approximately 2200°F, is another piece of evidence that indicates that the 10 C.F.R. § 50.46(b)(1) 2200°F PCT limit is nonconservative.

The comment submission is indicating that during the NRU FLHT-1 experiment, when cladding temperature reached 2,150 °F [(1,177 degrees C)[1,450 K], the cladding heat-up rate associated with cladding oxidation was sufficiently slow that operators were able to terminate the temperature rise using the level control system. Yet at 2,200 degrees F (1,204 degrees C)[1,478 K] the heat-up rate associated with cladding oxidation was so rapid that operators were unable to terminate the temperature rise using the same level control system. The assertion is then made that this is evidence that the 2,200 degrees F (1,204 degrees C)[1,478 K] limit is nonconservative.

A footnote on page 12 of NUREG/CR-5876 (Lombardo, 1992) explains the behavior noted in the petition. The footnote reads:

> The FLHT-1 experiment operation differed from the sequence described above. The test plan called for a 16-step reduction in bundle inlet flow until a peak cladding temperature of 2150 K was attained; this was to be followed by test termination. However, no means existed for heating the components above the bundle region (i.e., plenum, closure, and vertical outlet piping) and the limited superheat of the steam generated in the bundle region was insufficient to keep those surfaces above the saturation temperature. Consequently, condensate formed and fell back into the bundle region, making the bundle liquid level difficult to control. Operator adjustments to obtain higher steam superheat to heat the plenum caused the liquid level to fall below the Level-80 (2.0-m) elevation for a sustained period. Autocatalytic oxidation of the cladding eventually occurred resulting in temperatures reaching 2300K. The test was terminated coincident with the oxidation excursion.

The footnote indicates that an unanticipated condition was experienced in the NRU FLHT-1 test that complicated test execution and resulted in a loss of level control. The unanticipated condition was that condensation formed on the components above the bundle region and the condensation fell back into the bundles. The design of the level control system apparently did not properly account for such a condition. As a result, the operators experienced level control difficulties. The loss of level control resulted in sustained low liquid levels in the fuel bundle. Sustained low liquid levels would be expected to result in reduced heat transfer and heat up in the upper (uncovered) portions of the test bundle. The temperature excursion noted by the petition's comment is consistent with this expectation. However, as demonstrated by the data discussed above, excessive heat-up rates were not experienced during this excursion until temperatures exceeded 2,420 degrees F (1,327 degrees C)[1,600 K]. Thus the referenced results do not support the petition's assertion that the 2,200 degrees F (1,204 degrees C)[1,478K] limit is nonconservative. Additionally, the lack of level control in the NRU FLHT-1 test is not considered relevant with regard to the onset of autocatalytic oxidation and conservatism in the 2,200 degrees F (1,204 degrees C)[1,478K] cladding temperature limit. The operators in NRU FLHT-1 were attempting to control the level so that cladding temperatures remained high. The control system and ability to control conditions in the NRU FLHT were dissimilar to those for an operating commercial reactor where emergency operating procedures and safety systems would result in rapid shutdown.

The staff notes that it is well established that at temperatures above 2,200 degrees F (1,204 degrees C)[1,478 K] the Zircaloy oxidation rate increases rapidly as temperature increases (Meyer, 2013). The observation given above does not provide any new information in this regard. Cladding oxidation as a function of temperature up to 2,200 degrees F (1,204 degrees C)[1,478 K] is explicitly included in approved ECCS evaluation models. Finally, as discussed above, the data from the NRU FLHT-1 experiment are consistent with the staff position that heat-up rates associated with runaway oxidation only occur at temperatures well above the 2,200 degrees F (1,204 degrees C)[1,478 K] limit.

To emphasize that autocatalytic oxidation occurs only above the 2,200 degrees F (1,204 degrees C)[1,478 K] licensing limit, the staff also notes that the NRU FLHT report, NUREG/CR-5876 (Lombardo, 1992) defines in several places the following statements:

> "…temperatures were too low (below ~1700 K) to initiate autocatalytic oxidation." (page 15)
>
> "Shortly after this time, at temperatures near 1700 K autocatalytic oxidation behavior was recorded." (page 18)
>
> "The downward progression occurred as a result of the developing axial temperature profiles in the lower axial levels reaching autocatalytic reaction temperatures of 1600 to 1700 K." (page 31)

The staff notes that the report never uses the term "runaway."

A review of the data shown in the references as described above does not support the assertion that there is a high probability that cladding temperature heat-up rates during the initial coolant boilaway in the NRU FLHT tests reach autocatalytic values when the temperature reaches 2,275 degrees F (1,246 degrees C)[1,519 K]. Further, it is important to note that the NRU FLHT tests were conducted in a manner to evaluate damage progression when temperatures exceed 3,140 degrees F (1,727 degrees C)[2,000 K]. Therefore, coolant levels in the NRU FLHT bundles were not typical of coolant levels expected during design basis small-break LOCAs.

Another petition issue with NRU FLHT tests is related to the reflood rate. Specifically, the petition states:

> …it can be extrapolated from experimental data that, in the event a LOCA, a constant core reflood rate of approximately one inch per second or lower (1 in/s or lower) would not prevent Zircaloy fuel cladding, that at the onset of reflood had cladding temperatures of approximately 1200°F or greater, from exceeding the 10 C.F.R. § 50.46(b)(1) PCT limit of 2200°F.
>
> The NRU Thermal-Hydraulic Experiment 1 ("TH-1") tests illustrate that low reflood rates do not prevent Zircaloy cladding temperatures from having substantial increases.

The petition then goes on to present temperature increases and peak cladding temperatures for several NRU tests with different reflood rates. The petition then states that if these results are extrapolated to some hypothetical set of conditions, that the PCT would exceed the 2,200 degrees F (1,204 degrees C)[1,478 K] limit.

Another petition issue related to the NRU tests is use of the Baker-Just and Cathcart-Pawel metal-water reaction equations. The petition makes a comparison between the data from NRU TH-1 test 128 and a sample code prediction (using the Baker-Just correlation) from Westinghouse's “PWR FLECHT Final Report.” Based on results of this comparison, the petition states:

> …it is evident that analyses using the Baker-Just correlation under-predict the amount of heat generated by Zircaloy oxidation in TH-1 test no. 128.
>
> So with similar parameters (but with a lower fuel rod power) TH-1 test no. 128 had an overall PCT increase that was more than 100°F greater than the overall PCT increase predicted in the UO2 Zircaloy fuel assembly example discussed in “PWR FLECHT Final Report.” This indicates that analyses using the Baker-Just correlation under-predict the amount of heat that Zircaloy oxidation generated in TH- 1 test no. 128, a thermal hydraulic experiment simulating LOCA conditions.

The petition also discusses TH-1 test 130. The petition states:

> …the reactor shutdown when the PCT was approximately 1850°F; and after the reactor shutdown, cladding temperatures kept increasing becaue of the heat generated from the Zircaloy-steam reaction (of course, there would have also been a small amount of actual decay heat) and the peak measured cladding temperature was 2040°F. So the peak cladding temperature increased by 190°F after the reactor shutdown, because of the heat generated from the Zircaloy-steam reaction.
>
> It is highly unlikely that analyses using the Baker-Just and Cathcart-Pawel correlations would predict a peak cladding temperature increase of 190°F in TH-1 test no. 130, after the reactor shutdown.
>
> So data from thermal hydraulic experiments indicates that the Baker-Just and Cathcart-Pawel correlations are not adequate for use in ECCS evaluation calculations that calculate the metal-water reaction rates that would occur in the heat transfer conditions of loss-of-coolant accidents.

The staff examined the NRU thermal hydraulic tests for issues related to reflood and the metal-water reaction. In the case of reflood, the petition claims through extrapolation that a high temperature at the start of reflood along with a low reflood rate will result in a large temperature rise. This extrapolation was shown to be invalid as the temperature increase declines as the temperature at the start of reflood increases due to effects not considered by the petition.

For the metal-water reaction, the petition argues that the Baker-Just correlation is nonconservative based on comparison of the NRU TH-1 test no. 128 against some PWR FLECHT code calculations. The petition was making an indirect comparison by comparing code results from one test facility (used for a specific purpose) to experimental results from a specific test in another facility. Staff compared NRU TH-1 test no. 128 against PWR FLECHT test 4129 and found only a small difference in PCT between the test with stainless steel rods and with Zircaloy rods, demonstrating that the metal-water reaction is not significant at temperatures below 2,000 degrees F (1,093 degrees C)[1,366 K]. The PWR FLECHT code calculations were then compared against PWR FLECHT test 4225 and showed excellent agreement for stainless steel rods. When Zircaloy rods were simulated in the code, the PCT increased by 27 degrees F (mainly due to the metal-water reaction). A comparison between TH-1 test no. 128 (with Zircaloy cladding) and PWR FLECHT run no. 4129 (with stainless steel cladding) showed a 15 degrees F difference in temperature rise with the Zircaloy rods, demonstrating that the metal-water reaction is not significant at these temperatures. Based on these comparisons, there is no evidence that the Baker-Just metal-water reaction correlation is nonconservative.

The petition argues that the experimental data from TH1 test no. 130 demonstrates that the Zircaloy-steam reaction is substantial below 1,900 degrees F (1,038 degrees C)[1,311 K]. The petition claims that the peak cladding temperature increased 190 degrees F after the reactor was tripped. TH1 test no. 130 was examined and it was determined that the reactor was not tripped at a peak cladding temperature of 1,850 degrees F (1,010 degrees C)[1,283 K] as the petition claims, rather the 1,850 degrees F (1,010 degrees C)[1,283 K] trip setpoint is based on a time lagged average of the guard fuel rods. In addition, there is an approximately 0.75 second delay after the initiation of trip before the power begins to decline as seen in Figure 9.3 of NUREG/CR 1208.[2] While the exact peak cladding temperature at the time reactor power begins to decline is unknown, it is by definition higher than the 1,850 degrees F (1,010 degrees C)[1,283 K] trip setpoint, therefore, there is no basis for the statement that the peak cladding temperature increased 190 degrees F after the reactor was tripped. There is also no justification or evidence provided by the petition to substantiate the claim that autocatalytic oxidation would have occurred had the reactor not been tripped (NRC, 2016a).

The staff disagrees with the conclusions drawn in the petition with regard to the NRU tests. The staff concludes that there is nothing in the NRU data as cited by the petition that invalidates the use of the Cathcart-Pawel or Baker-Just correlations, or necessitates a change to existing regulations.

3.2 Eutectic Behavior at Temperatures below 2,200 degrees F (1,204 degrees C)

One of the concerns of the petition in PRM-50-95 is that liquefaction of fuel assembly components at low temperatures is “a significant nuclear power safety issue.” The petition cites information regarding the eutectic reactions between various fuel assembly components including the cladding, control rods (also called absorber rods) and spacer grids. A eutectic reaction in this context is one where two materials in contact with one another at relatively high temperatures can liquefy at a temperature that is lower than the temperatures of the two individual materials.

The staff evaluated the significance of the eutectic reactions on the potential for a reduction in safety margins for the following types of materials interactions: (1) degradation of boiling water reactor (BWR) control blades due to eutectic reaction of boron carbide (B_4C), stainless steel and Zircaloy, (2) degradation of pressurized water reactor (PWR) cladding due to eutectic reaction between Inconel grids and Zircaloy cladding, and (3) degradation of PWR control rods that contain silver (Ag), indium (In) and cadmium (Cd).

Details of the staff’s evaluation of the eutectic behavior of the various fuel assembly components are provided in the following sections. Although in summary, the staff concludes that the eutectic behavior of control rod, grid, and cladding materials would not have a significant effect on the margin of safety with respect to material behavior in a design-basis loss-of-coolant accident (LOCA). Test results and analytical simulations have shown that insignificant material interactions occur for times and maximum temperatures assumed in a design-basis LOCA.

Boron Carbide – Stainless Steel Interaction

PRM-50-95 (NEC, 2010) includes the following statement on page 62:

> And, clearly, data from the CORA-16 experiment—*i.e.*, the B_4C-stainless steel reaction beginning at approximately 1000 °C (1832 °F) and the stainless steel cladding of the B_4C absorber material liquefying very quickly above 1200 °C (2192 °F)—is further evidence that [Vermont Yankee Nuclear Power Station]’s [licensing basis peak cladding

[2] Section 9.7 of NUREG/CR-1208 describes the trip logic.

temperature] of 1960 °F for GE14 fuel would not provide a necessary margin of safety to help prevent a partial or complete meltdown, in the event of a LOCA.

The control blades used in BWRs consist of boron carbide (or B_4C) powder or pellets contained inside stainless steel tubes arranged within a stainless steel cruciform. The blades are positioned in the spaces between four BWR fuel assemblies, and the four fuel assemblies plus the control blade are positioned inside a square Zircaloy (Zr) channel box. The DF-4 test (Sandia, 1993) and out-of-pile tests (e.g., CORA-16) have shown that the B_4C reacts with the stainless steel to cause blade failure and liquid phase formation, as described by the petition. Further, these tests show that the liquid attacks and penetrates the Zircaloy channel box walls and reacts with the zircaloy clad fuel rods. Separate effects tests found the reaction kinetics between B_4C and stainless steel to be rapid at temperatures around 2,240 degrees F (1,227 degrees C)[1,500 K], the temperature at which this interaction was observed to initiate in the CORA-16 test.

Hofmann's research (circa 1989), cited in the petition (Leyse, 2010b), has shown that the chemical interactions of B_4C with stainless steel can be described by parabolic rate laws and that melting will occur above 2,192 degrees F (1,200 degrees C)[1,473 K] with rapid liquefaction above 2,281 degrees F (1,249 degrees C)[1,523 K]. Liquefaction occurs below the melting points of the individual B_4C and steel components due to eutectic interactions (Hofmann, 1990).

In the CORA program, 16 out of 19 tests were performed with absorber rods. Nine tests with (Ag, In, Cd) absorber material investigated the damage behavior in PWR-type reactors. In PWR reactors the (Ag, In, Cd) absorber, the stainless steel of the absorber cladding and the Inconel of the spacer grids react eutectically with Zircaloy. For investigation of BWR-type behavior, seven tests with B_4C and stainless steel control blades were performed. In BWR reactors, the B_4C powder of the control blade forms eutectic alloys with the stainless steel of its cladding. The liquefied stainless steel reacts with the Zircaloy. In both reactor types, the liquefaction of macroscopic regions of the bundle starts at about 2,192 degrees F (1,200 C) [1,473 K]. The eutectic temperatures of the different reactions are partially below 1,832 degrees F (1,000 degrees C) [1,273 K], but it takes some time until the diffusion of the initially separated materials start the process on a macroscopic scale (Hagen, 1996 and Sepold, 2009).

The issue of control blade degradation in a LOCA or severe accident can be addressed by considering code calculations of the phenomena seen in experiments. Codes such as MELCOR, a computer code which models severe accident behavior including core melting phenomena, considers the spatial effects of temperatures and integrate results of numerous experiments. MELCOR has been used to model the in-pile DF-4 damaged fuel experiment performed in the Annular Core Research Reactor. The DF-4 experiments provided data for early phase melt progression in BWR fuel assemblies, particularly for phenomena associated with eutectic interactions in the BWR control blade and zircaloy oxidation in the fuel assembly canister and fuel cladding (Sandia, 1993).

Section 5.4.2 of the report SAND93-1377 (Sandia, 1993) describes stainless steel-B_4C eutectic interaction temperatures. One of the most important models affecting control blade temperature and relocation behavior in DF-4 was the materials interactions model in MELCOR. This model accounts for the liquefaction of B_4C and stainless steel at a temperature well below the melting temperature of either constituent, as well as interactions between other materials. The melting temperature of steel is 2,600 degrees F (1,427 degrees C) [1,700 K] in MELCOR, and for pure B_4C, it is about 4,220 degrees F (2,327 degrees C) [2,600 K]. However, the B_4C-steel eutectic reaction is at 2,276 degrees F (1,247 degrees C) [1,520 K] by default in MELCOR but was changed to 2,366 degrees F (1,297 degrees C) [1,570 K] in the base case model. In the sensitivity study, the eutectic temperature of the B_4C-stainless steel mixture was varied by ±50 K from its default value. The results of the sensitivity study showed little effect on core melting and relocation or hydrogen production.

Models that allow failure of the control blade absorber tubes at a different temperature than the control blade sheath were implemented in the ORNL computer code BWR/DF4. Simulations resulted in good agreement between the observed and calculated control blade response. For these simulations, failure of the absorber tubes and outer sheath occurred at 2,250 degrees F (1,232 degrees C) [1,505 K] (Ott, 1997).

Staff notes that this eutectic temperature is above the LOCA regulatory limit of 2,200 degrees F (1,204 degrees C) [1,478K], and well above the Vermont Yankee calculated LOCA peak cladding temperature of 1,960 degrees F (1,071 degrees C) [1,344 K]. Also, the temperature in the channel where the control blade sits would be lower than the peak cladding temperature. (NEI, 2010). The petition (Leyse, 2010b) agreed with this NEI position. Because of the 2,200 degrees F (1,204 degrees C) [1,478K] regulatory limit, the petition's concern regarding the B_4C-stainless steel eutectic melting temperature as a source for decrease safety margin is inconsequential.

Inconel – Zircaloy Interaction

The staff also examined the petition's claims regarding the loss of safety margin with respect to the degradation of PWR cladding due to a eutectic reaction between Inconel grids and Zircaloy cladding during a design-basis LOCAs.

Page 40 of "Response to the U.S. Nuclear Regulatory Commission's notice of solicitation of public comments on PRM-50-93 and PRM-50-95; NRC-2009-0554" (Leyse, 2010b), has the following statement:

> It is significant that grid spacers would effect [sic] the progression of damage in a reactor core during a LOCA if temperatures were to reach approximately 2012°F; and significant that experiments have revealed chemical interactions between Inconel and Zircaloy occur at temperatures as low as 1832°F.

The staff notes that some grid spacers or the grid clips used in PWRs prior to 2000 were made from Inconel metal containing nickel. PWR designs generally limit nickel-based grid components at the top and bottom of a fuel assembly. These relatively lower power regions will experience a more benign temperature relative to the interior of the core. Also, BWR designs have more liberal use of nickel-based grid components. Hofmann's research (Hofmann, 1989) in Germany, cited by the petition (Leyse, 2010b), has shown that the chemical interactions of Inconel with Zircaloy can occur at temperatures below 2,200 degrees F (1,204 degrees C)[1,478K] due to the nickel content. Testing (Hofmann, 1989) has shown that the eutectic reaction (at LOCA relevant temperatures) will be impeded by presence of zirconium oxide layer (which forms within days of operation).

The results of these German single-effect tests are in agreement with results of integral tests (i.e., CORA experiments) where fuel rod bundles were heated to temperatures of about 3,600 degrees F (2,000 degrees C) [2,273 K]. In all cases damage to the bundle was initiated by Zircaloy–Inconel interactions. Localized liquefaction of the components started at around 2,200 degrees F (1,204 degrees C)[1,478K]. Thin oxide layers on the Zircaloy surface delay liquid phase formation and reduce the rates of reaction, but cannot prevent the chemical interaction. In experiments of short durations (minutes), the oxide layers shift the liquefaction temperature to higher values and the oxide dissolution period depends on the initial oxide layer thickness and on the temperature (Hofmann, 1995). Time-at-elevated temperature (above 1,832 degrees F (1,000 degrees C) [1,273 K])) for a large break LOCA is limited and generally less than 100 seconds.

At temperatures below 1,832 degrees F (1,000 degrees C) [1,273 K], the cladding might balloon and burst, so it is degraded though expected to maintain some structural rigidity. The small lines of contact at some grid tips that might later undergo eutectic melting at higher temperatures would not significantly add to the structural degradation.

Only when the cladding temperatures exceeded 2,192 degrees F (1,200 C) [1,473 K] did the oxidation rate begin to increase. In the range of 2,192 degrees F (1,200 C)[1,473 K] to 2,552 degrees F (1,400 degrees C) [1,673], Haste et al. (2015) summarized the process noting that in this range of temperature there is the "Start of rapid Zr oxidation by steam leading to uncontrolled temperature excursion and extensive hydrogen production; liquefaction of Inconel grid spacers and absorber rod materials due to chemical interactions, giving metallic melts which initiate core melt progression (localized fuel rod and control rod damage)."

The staff evaluated the petition's assertion that eutectic behavior of cladding and Inconel grid materials would have a significant effect on the margin of safety with respect to core degradation behavior in a design-basis LOCA. Although the onset of liquefaction can occur at or near the 2,200 degrees F (1,204 degrees C) [1,478K] regulatory limit, test results have shown that only insignificant material interactions occur for times and maximum temperatures anticipated in a design-basis LOCA. Additionally the contact surface area is limited and hence any potential damage due to a eutectic reaction is limited. It is recognized that cladding integrity during postulated LOCA is not guaranteed. However, any limited damage due to an eutectic reaction does not constitute loss of coolable geometry, nor challenge the input to bounding radiological consequence assessment.

Silver – Indium – Cadmium Interaction

In a comment submission (M. Leyse, 2010c), a similar concern was raised for PWR control rods that contain silver (Ag), indium (In) and cadmium (Cd). As mentioned before, in the CORA program nine tests were conducted with (Ag, In, Cd) absorber material to investigate the eutectic reaction in PWR reactors. The CORA experiments show that the degradation of PWR bundles is strongly influenced by interactions of the absorber materials with the other components of the fuel element. With increasing temperatures under loss-of-coolant conditions, the materials in contact are no longer chemically stable with each other. This concern was further studied by the PWR Owner's Group in 2007 (PWROG, 2007). As a result of the staff's review of the PWROG report, NRC concluded that this type of PWR control rod would survive design basis LOCAs.

The staff evaluated the petition's assertion that eutectic behavior of control rod, grid, and cladding materials would have a significant effect on the margin of safety with respect to several types of eutectic behavior in a design-basis LOCA. The staff has reviewed the currently available experimental information and it does not support the petition's claims. No information that shows loss of a coolable geometry at temperatures below 2,200 degrees F (1,204 degrees C) [1,478K] was identified. The liquefaction is either (well) above 2,192 degrees F (1,200 C) [1,473 K] or the amount of liquefaction is insignificant. Both the staff's and ORNL's MELCOR calculations show negligible materials interaction below 2,192 degrees F (1,200 C) [1,473 K], and eutectic interactions are taken into account in those calculations. Test results and analyses have shown that insignificant eutectic reactions occur for times and maximum temperatures assumed in a design-basis LOCA.

3.3 TRACE simulation of FLECHT run 9573

The staff performed a TRAC/RELAP Advanced Computational Engine (TRACE) code calculation simulating the 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. Thermocouple measurements were taken at five elevations (references to elevation are from the top). Significant metal-water reaction rates are only expected at the middle three elevations since the top and bottom elevations remain below 1,800 degrees F (982 degrees C)[1,255 K]. At the lowest elevation, TRACE predicted a cladding temperature of 1,131 degrees F (611 degrees C)[884 K] regardless of the selection for metal-water reaction rate. At the second and middle elevations, TRACE was found to underpredict the cladding temperatures if the metal-water reaction rate was not included in the calculations. At the middle 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 middle elevation, TRACE overpredicted the cladding temperature by approximately 74 degrees F [41 K]. 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 153 degrees F [85 K]. 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.

Additionally, it was noted that over the first 18 seconds of FLECHT run 9573 the heatup rate was below the 15 K/s that is considered in the petition to be an indication of an “autocatalytic reaction” rate. At three middle elevations where cladding oxidation was significant, 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 middle elevation, 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 top elevation. This is due to a slight overprediction in the heat transfer prediction, as indicated by the “no metal-water reaction” case. At the top elevation, the cladding temperature at 18 seconds was 1,368 degrees F (742 degrees C)[1,015 K], which is well below the temperature at which metal-water reaction rates become significant.

The staff’s 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 2,200 degrees F (1,204 degrees C)[1,478 K] acceptance criterion. Furthermore, it is noted that the experimental data from FLECHT run 9573 do not show evidence of an “autocatalytic reaction” below 2,200 degrees F (1,204 degrees C)[1,478 K], in spite of its low reflood rate. (NRC, 2012)

3.4 Selection of Core Damage Temperature

The petition states that the peak cladding temperature limit of 2,200 degrees F (1,204 degrees C)[1,478K] contained in 10 CFR 50.46(b)(1) is nonconservative. There is not a universal definition of core damage so the staff has selected appropriate definitions when needed. As explained in NUREG-1953 “Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models—Surry and Peach Bottom” (NUREG-1953, 2011), that because no universal definition of core damage exists, the definition used was the temperature at which the transition occurs in the Urbanic-Heidrick zirconium/water reaction correlation (i.e., a peak cladding temperature (PCT) of approximately 2,876 degrees F (1,580 degrees C)[1,853 K] to 2,912 degrees F (1,600 degrees C)[1,873

K]. This is the point at which the reaction becomes more energetic, and significant oxidation of the cladding is more likely.

A number of potential surrogates that have traditionally been used in PRAs, several of which are called out in the PRA standard (Section 2-2.3) (ASME/ANS, 2009) were considered in the NUREG. These included various parameters associated with collapsed reactor vessel water level, peak core exit thermocouple temperature, and PCT. MELCOR calculations were performed to investigate these surrogates. The time that the proposed surrogate (e.g., 2,200 degrees F (1,204 degrees C)[1,478K] was reached was compared to the time that the zirconium/water transition temperature range (1,580 degrees C to 1,600 degrees C) was reached.

In all MELCOR cases but one (the surrogate representing a core exit thermocouple temperature greater than 1,200 degrees F plus a 30-minute offset), the proposed surrogate was reached before the oxidation transition temperature. The MELCOR analyses showed that a PCT of 2,200 degrees F (1,204 degrees C)[1,478K] achieves all of the following characteristics:

- It always precedes oxidation transition.
- It is not overly conservative.
- It is equally applicable for both PWRs and BWRs.
- The timing between 2,200 degrees F (1,204 degrees C)[1,478 K] and oxidation transition is relatively similar among the different sequences analyzed.
- It is consistent with the criteria contained in Title 10 of the Code of Federal Regulations (10 CFR) 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors" (10 CFR, 2007).

With regard to the latter bullet, the conservatism (i.e., safety margin) in 10 CFR 50.46 is due to uncertainty in large-break loss-of-coolant accident (LBLOCA) thermal-hydraulic analysis. For PRA usage, the margin has, in part, a different reason: the desire to have a specific criterion that can be used for all sequences combined with overall analysis uncertainty. For the reasons stated above, a PCT of 2,200 degrees F (1,204 degrees C)[1,478 K] is an appropriate surrogate used to define core damage for MELCOR analyses.

3.5 Stainless Steel and Zircaloy Heat Transfer Coefficients

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 petition makes no request for a revision to the 10 CFR 50.46 acceptance criteria or Appendix K based on this observation. 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. Models for convective heat transfer are not dependent on material properties of the surface, but on the properties of the fluid, and thus heat rod material is irrelevant in correlation of the data.

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.

3.6 Issues Related to the PHEBUS B9R Test

The petition discussed on pages 45-46 the PHEBUS B9R test as part of the basis for the assertion in the petition (M. Leyse, 2009) that the autocatalytic oxidation reaction occurs at temperatures below 2,200 degrees F (1,204 degrees C)[1,478 K]. The petition refers to rapid temperature excursions and autocatalytic oxidation, often implying that these are equivalent.

Specifically, the petition cited references that stated:

1. "During the B9R-2 test, an unexpected strong escalation of the Zr-water reaction occurred at mid-bundle elevation during the steam injection. Considerable heatup rates of 20 to 30 K/s were measured in this zone with steam starved conditions at upper levels." (NUREG/CP-0126, Vol. 2, 1993);

2. "…. the B9R-2 test had an unexpected high oxidation escalation in the upper bundle zone (20 to 30 K/s)" (Haste, 1996).

The petition asserts that "a graph of the cladding-temperature values (from NUREG/CP-0126, Vol. 2, 1993) at the 0.6 meter "hot-level" indicates that the autocatalytic oxidation reaction began when cladding temperatures were below 2,200 degrees F (1,204 degrees C)[1,478K]".

The NRC staff examined the references cited above and notes that neither reference specifies the temperature at which the unexpected escalation of the Zirconium-water reaction begins. The staff therefore examined the graph of cladding temperature specifically cited by the petition (i.e., "Sensitivity Calculation on the B9R Test: Temperature Escalation at the Hot Level (0.6 m)" from NUREG/CP-0126, page 312). The staff digitized the graph and calculated the temperature ramp rate to be less than 5 K/s [9°F/s] at temperatures below 2,200 degrees F (1,204 degrees C)[1,478 K]. This rate is below the 10 to 15 K/s [18 to 27°F/s] that the petition describes as autocatalytic.

Licensing basis calculations of peak cladding temperature are limited to temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K]. Temperature ramp rates of approximately 5 K/s [9°F/s] at temperatures near 2,200 degrees F (1,204 degrees C)[1,478K] are consistent with data from the body of integral experiments on this subject.

The staff therefore concludes that the data from the PHEBUS B9R test cited by the petition does not demonstrate that the autocatalytic reaction occurs at temperatures below 2,200 degrees F (1,204 degrees C)[1,478K]. A need for rulemaking is not indicated by the cited information from the PHEBUS B9R test.

3.7 Issue Related to Whether Runaway Oxidation Temperatures Start at 1100°C (2012°F)

In several submissions on PRM-50-93 and 50-95 (Leyse, 2010a, NEC, 2010), there was reference to an OECD/NEA document (OECD, 2000) titled, "Degraded Core Quench: Summary of Progress 1996-1999." The sentence of concern in the OECD document is: "A notable feature of the experiments was the occurrence of temperature excursions starting in the unheated region at the top of the shroud, from temperatures of 750-800°C, which is more than 300 K lower than excursion temperatures associated with runaway oxidation by steam." (Leyse, 2009, page 47). In the March 15, 2010 submission (Leyse, 2010a), the petition acknowledged that: "It was later concluded that the thermocouple readings at the top of the shroud in the QUENCH experiments were erroneous, because of cable routing through hot zones of the QUENCH bundles." However the petition indicated that the first quote above is "still highly significant, because it states that 'excursion temperatures associated with [the] runaway oxidation [of Zircaloy] by steam are higher than 1050°C to 1100°C (1922°F to 2012°F) (page 32)."

The petition seems to be concluding from the OECD report that excursion temperatures associated with runaway oxidation are 1050°C to 1100°C (1922°F to 2012°F). That is, the petition seems to derive 1050°C to 1100°C by adding 300°C to 750°C and 800°C. The relevant wording of the OECD report is: "…temperatures of 750-800°C, which is more than 300 K lower than excursion temperatures associated with runaway oxidation by steam."

This quote could be interpreted as in the petition. However, the petition did not identify any specific data in the report that supports the stated interpretation, and the thermocouple readings of 750-800°C were acknowledged to be erroneous as stated in the OECD report. The staff therefore examined the OECD report for data and context to interpret the phrase. No data were found to support a determination that runaway oxidation occurs at cladding temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K] for tests simulating design basis accident conditions. Furthermore, the context for the test results being reported is probably that the tests were for beyond design basis conditions.

Given the body of data regarding oxidation rates for design basis configurations and the other severe accident tests discussed elsewhere in this petition response, the staff does not agree that the OECD report indicates the 2,200 degrees F (1,204 degrees C)[1,478K] limit is nonconservative with regard to protection against runaway oxidation.

3.8 Multi-Rod (Assembly) Severe Fuel Damage Tests Conducted in the Power Burst Facility

The petition discussed the Power Burst Facility (PBF) Severe Fuel Damage (SFD) tests as part of the basis for the assertion that the zirconium-water reaction equations (Baker-Just and Cathcart-Pawel) are both nonconservative for calculating the temperature at which an autocatalytic (runaway) oxidation reaction of Zircaloy would occur in the event of a LOCA. Specifically the petition states:

> "In the SFD 1-1, 1-3, and 1-4 tests, it is significant that rapid temperature excursions occurred at either approximately 1600°K (2420°F) or approximately 1700°K (2600°F)--as a result of the exothermic Zircaloy-water reaction--because the Baker-Just equation calculates that autocatalytic oxidation occurs at approximately 2600°F and the Cathcart-Pawel equation calculates that autocatalytic oxidation occurs at approximately 2700°F." (Leyse, 2009)

The petition refers to rapid temperature excursions and autocatalytic oxidation, often implying that these are equivalent. The petition also noted some differences between cited references on the arrangement of the test bundles. The petition discusses only three of the four SFD tests performed in the PBF.

Section C.1.a. of the petition (Leyse, 2009) discusses data from the PBF-SFD tests and compares the data to NRC staff calculations of hypothetical LOCAs reported in Research Information Letter 0202 (RIL 0202, 2002). The petition argues that data from the PBF-SFD tests shows that a rapid temperature excursion occurred at either 2,420°F (1,327 degrees C)[1,600 K] or 2,600 degrees F (1,427 degrees C)[1,700 K] as a result of the exothermic zirconium-water reactions. The petition then compares these temperatures with the results of calculations performed by the NRC staff using the RELAP5/Mod3 code for the postulated LOCA scenarios in RIL 0202. In the referenced NRC calculations, the onset of autocatalytic oxidation is estimated to occur at about 2,600 degrees F (1,427 degrees C)[1,700 K] (when the Baker-Just correlation is used in the RELAP model), and 2,700 degrees F (1,482 degrees C)[1,755 K] (when the Cathcart-Pawel correlation is used in the RELAP model). The logic of the argument presented in the petition seems to be that a conservative calculation of the temperature at which autocatalytic oxidation occurs should be a lower temperature than the actual (measured) temperature at which autocatalytic oxidation occurs. Since the temperature estimated in the NRC RIL 0202 calculation for the onset of autocatalytic oxidation is higher than the temperature data from PBF test for the onset of rapid temperature excursions, the petition concludes that this is evidence that, "..the Baker Just and Cathcart-Pawel equations are both nonconservative for calculating the temperature at which an autocatalytic (runaway) oxidation reaction of Zircaloy would occur in the event of a LOCA (Leyse, 2009)." The petition then concludes that, because the Baker-Just and Cathcart-Pawel correlations are nonconservative for estimating the temperature at the onset of autocatalytic oxidation, the correlations "are both nonconservative for calculating the metal-water reaction rates that would occur in the event of a LOCA (Leyse, 2009)."

The staff disagrees with the petition conclusion that either the Baker-Just or the Cathcart-Pawel equations are "nonconservative for calculating the metal water reaction rates that would occur in the event of a LOCA (Leyse, 2009)" for a number of reasons. First, the staff does not agree that a comparison of specific tests to RIL 0202 calculated temperatures is a valid method for demonstrating the conservatism or non-conservatism of metal water reaction rate correlations for calculating the temperature at the onset of autocatalytic reactions. Second, the calculational model used for estimating PCT in LOCA analyses (or severe accident analyses) is a complex integration of numerous empirical thermal hydraulic and chemical correlations (one of which is the metal-water reaction correlation) developed from a variety of separate effects and integral tests. Accordingly, a simple comparison of the PCT measured in a test to a calculational model (code) prediction for that test does not in itself demonstrate the conservatism or non-conservatism of any one equation or submodel used in the code even for the particular test, much less globally. Thus, even if a code included a model with a perfect, first principles correlation for the zirconium-water reaction, there is no guarantee of the accuracy of the prediction of the actual (measured) PCT at the onset of autocatalytic oxidation reaction for any particular integral systems test because of the dependencies of the PCT on the other submodels and assumptions used in the analyses.

The analyses performed for RIL 0202 was not intended to assess the response of the PBF-SFD tests nor did it include a specific model of the PBF-SFD test configuration. Rather, the RIL 0202 analyses were stylized reactor LOCA calculations intended to show a comparison of the effect on estimated PCT when using the Baker Just correlation relative to other metal-water reaction correlations.

Secondly, the staff disagrees with a conclusion relevant to this section of the petition that is presented in the petition cover letter: "Data from such experiments also indicates that the Baker-Just and Cathcart-Pawel equations are both nonconservative 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 nonconservative for calculating the metal-water reaction rates that would occur in the event of a LOCA (Leyse, 2009)."

This argument implies that an autocatalytic (runaway) oxidation reaction may occur in the event of a LOCA, and therefore, it is *necessary* that a LOCA calculational model have the ability to determine the temperature at which autocatalytic reactions occur. Thus the basis for the petition assertion that "the Baker-Just and Cathcart-Pawel equations are both nonconservative for calculating the metal-water reaction rates that would occur in the event of a LOCA" is that they do not meet this *necessary condition* (i.e., that the model be capable of conservatively calculating the temperature at which autocatalytic oxidation initiates).

However, as discussed throughout this petition response, data from the referenced tests does not indicate that an autocatalytic reaction would occur at temperatures less than 2,200 degrees F (1,204 degrees C)[1,478K]. Therefore, because autocatalytic reactions are only indicated at cladding temperatures above 2,200 degrees F (1,204 degrees C)[1,478K], and cladding temperatures during a LOCA are limited to 2,200 degrees F (1,204 degrees C)[1,478K] or less, it is not a *necessary condition* for LOCA evaluation models to have the ability to calculate the temperature at which an autocatalytic reaction occurs. Therefore, whether or not the calculational model is conservative or nonconservative for calculating the temperature at which autocatalytic oxidation initiates is of no consequence for licensing basis calculations of the peak cladding temperature. Accordingly, the assertion presented in the petition that, “the Baker-Just and Cathcart-Pawel equations are both nonconservative for calculating the metal-water reaction rates that would occur in the event of a LOCA,” which appears to be based upon the premise that the “Baker–Just and Cathcart Pawel equations are both nonconservative for calculating the temperature at which an autocatalytic (runaway) oxidation reaction of Zircaloy would occur in the event of a LOCA,” is not supported.

The most important aspect of PBF-SFD test result is that, consistent with the data from other severe accident experiments, autocatalytic reactions are not indicated below 2,200 degrees F (1,204 degrees C)[1,478K]. Specifically, runaway oxidation was not observed in the PBF-SFD tests until temperatures are several hundred degrees above the regulatory limit for design basis LOCAs (Cook, 1986). Therefore, the conservatism or non-conservatism of the models used for predicting the onset of runaway oxidation in this elevated temperature regime is not relevant to design basis LOCA considerations.

The staff does not agree that a comparison of the PBF-SFD tests to RIL 0202 calculated PCTs is a valid method for demonstrating the conservatism or non-conservatism of metal water reaction rate correlations for calculating the temperature at the onset of autocatalytic reactions. Further, the staff does not agree that the ability to calculate the temperature at the onset of autocatalytic reactions is necessary for design basis LOCA models. The staff therefore does not agree that the Baker-Just or Cathcart-Pawel correlations have been shown to be nonconservative for use in licensing basis LOCA models.

3.9 Experimental Methods Used to Derive the Baker-Just Metal-Water Oxidation Reaction Correlation

The staff evaluated certain assertions in the PRM-50-93/95 (Leyse, 2009) regarding experimental measurements of oxidation kinetics. One of the submissions (pages 12-14 of Leyse, 2010d) raised the issue of oxidation measurements with inductive heating and radiative heat losses with respect to the Baker-Just correlation (Baker, 1962). The petition contends that the experiments did not replicate reactor LOCA behavior of cladding because of the radiative heat losses from the sample inherent in using inductive heating, and so proposes that the Baker-Just correlation is nonconservative.

The staff observed that the questioned data are similar to data obtained by other methods, and so the radiative heat losses are not relevant in correlating the data. A recent paper by French experts (Vandenberghe, 2012) on cladding behavior shows that the heating mode (resistance furnace heating and induction heating) does not affect the oxidation behavior at a temperature near 1,832 degrees F (1,000 degrees C)[1,273 K]. Oxide layer thickness measurements were quite similar for each heating mode, thus showing oxidation kinetics is similar.

Additionally, the petition asserts the following:

> So the radiative heat losses of the zirconium specimens in Bostrom and Lemmon's induction heating experiments would have affected the oxidation kinetics that Bostrom and Lemmon measured. Bostrom and Lemmon's experiments certainly did not replicate the oxidation kinetics that would occur in a nuclear power plant's core, in the event of a LOCA.”

With respect to radiative heat losses, the staff notes the following considerations:

1) The Bostrom data (Bostrom, 1954) were obtained for temperatures at and above 2,372 degrees F (1,300 ºC)[1,573 K], which is above the NRC allowed peak cladding temperature. So this data is not pertinent for consideration.
2) The Lemmon data (Lemmon, 1957) at 2,012 degrees F (1,100 degrees C) [1,373 K] and 2,192 degrees F (1,200 degrees C)[1,473 K], although reasonable, have been superseded by numerous measurements which show that autocatalytic oxidation does not occur below 2,200 degrees F (1,204 degrees C).

3) The crucial aspect of oxidation measurements is knowing the temperature of the oxidizing surface and having adequate steam. Heat losses are only important to the extent that they affect temperature control, or are so large that the sample has significant temperature gradients.

The staff has evaluated the petition's contention that the Baker-Just oxidation kinetics correlation is nonconservative because it is partly derived from experimental data asserted to be not representative of reactor LOCA behavior. The metal-water reaction rate constant correlation is a function of temperature only, and must be used in conjunction with system-level thermal hydraulic models in order to determine the instantaneous cladding temperature. The staff's evaluation of data and the induction heating method described in the Lemmon report (Lemmon, 1957) does not support the petition's assertion that use of such data by Baker and Just resulted in a nonconservative correlation. (NRC, 2016b)

3.10 Issues Related to Cladding Oxidation and Hydrogen Production

The staff reviewed a concern from a comment submission (Leyse, 2011a) based on a quote from an OECD/NEA report (OECD, 2001) titled, “In-Vessel and Ex-Vessel Hydrogen Sources.” The sentence of concern to the commenter is, “The available Zircaloy/steam oxidation correlations were not suitable to determine the increased hydrogen production in the few available tests (CORA, LOFT LP-FP-2).”

To address the commenter’s concern, staff considered that tests such as CORA and LOFT LP-FP-2 are conducted to better understand severe accident behavior. In such experiments, when the test bundle is overheated, reflooding with water can lead to increased oxidation (metal-water reaction) of the Zircaloy cladding which in turn increases hydrogen production. On page 8 of the cited OECD report, the text reads, “Nevertheless, it is commonly agreed that prediction of the hydrogen source rate, typically about 0.2 kg/s for a 1000 MWe PWR, is sufficiently accurate as long as the core geometry remains intact.” The NRC regulation 10 CFR 50.46 requires that peak cladding temperature and cladding oxidation both be limited following a loss-of-coolant accident (LOCA) such that a coolable core geometry is maintained. Therefore, the commenter’s concern regarding the OECD report and increased hydrogen production is not relevant in determining the suitability of Baker-Just or Cathcart-Pawel oxidation correlations when used in calculations of cladding temperatures below the regulatory limits.

On page 9 of the OECD report, immediately following the sentence of concern, the text reads

> “At FZK, the QUENCH programme was started, using electrically heated test bundles to investigate relevant phenomena like cracking and fragmentation of the oxygen-embrittled cladding due to thermal shocks, which leads to the generation of new metallic surfaces and to enhanced oxidation and hydrogen generation.”

More than one dozen German QUENCH tests have been performed (see for example FZKA-7368 (2008) or Steinbruck (2010). These tests have produced data from which computer code models to calculate specific severe accident behavior have been improved. Underestimating enhanced hydrogen production occurs only for conditions where the bundle is quenched after cladding temperatures have substantially exceeded the regulatory limit of 2,200 degrees F (1,204 degrees C)[1,478K]. (Fichot, 2004)

The comment assertion refers to oxidation and hydrogen production for scenarios beyond design-basis LOCA cases (i.e., outside regulatory limits). The staff thus concludes that the petition fails to provide sufficient information to justify revisions to 10 CFR 50.46 that would change the applicability of oxidation correlations.

3.11 Issues Related to the FRF Tests Conducted in the TREAT Reactor

In a comment to the original petition (M. Leyse, 2010c), the petition provides information from the “Final Report on the First Fuel Rod Failure Transient Test of a Zircaloy-Clad Fuel Rod Cluster in TREAT,” and the 1971 Indian Point Unit 2 Licensing Hearing. The petition specifically states:

> So, as stated in PRM-50-93, neither Westinghouse nor NRC applied the Baker-Just correlation to metallurgical data from the locations of run 9573 that incurred autocatalytic oxidation; furthermore, NRC did not apply the Cathcart-Pawel oxygen uptake and ZrO_2 thickness equations to metallurgical data from the locations of run 9573 that incurred autocatalytic oxidation. And, as stated above, it is reasonable to assume that--as in the CORA-2 and CORA-3 experiments--during FLECHT run 9573, the violent oxidation essentially consumed the available steam, so that time-limited and local steam starvation conditions, which cannot be detected in the post-test investigation, would have occurred.
>
> Therefore, Dr. Jack Roll's conclusion that the metallurgical data from the four Zircaloy PWR FLECHT tests reaffirmed the use of the Baker-Just correlation for evaluating the Zircaloy-steam reaction in the conditions of a loss-of-coolant accident is incorrect.

The staff has reviewed the information provided in the petition (M. Leyse, 2009), and associated comments (M. Leyse, 2010c, M. Leyse, 2011b), related to the FRF-1 experiment in the TREAT facility. The information provided by the petition related to the First Fuel Rod Failure Transient Test (FRF)-1 experiment in the TREAT facility was addressed in the 1971 Indian Point Unit 2 Licensing Hearing and does not need to be reconsidered here. New information provided by the petition states that neither Westinghouse nor NRC applied the Baker-Just correlation to metallurgical data from the locations of run 9573 that incurred autocatalytic oxidation. While assumptions can be made about what might have been found if Westinghouse had examined metallurgical data from locations of FLECHT run 9573 (or others) that incurred autocatalytic oxidation, the fact is that this data does not exist as Westinghouse did not obtain data at these locations. Additionally, there have been many subsequent experiments cited elsewhere in the staff's response that have shown that autocatalytic oxidation does not occur below 2,200 degrees F (1,204 degrees C).

In summary, the staff finds that lack of available data does not form a valid basis for the assertion that the Baker-Just or Cathcart-Pawel correlations are nonconservative.

3.12 Issues Raised at the Public Commission Meeting in January 2013

A comment letter (Leyse, 2013) repeated and clarified claims already made in PRM-50-93 and PRM-50-95 and previously submitted comment letters (NRC, 2011a, NRC, 2012). The only new issues raised are the following.

An NRC document, "Perspectives on Reactor Safety (NRC, 2002, pp. 3.7-4, 3.7-5, 3.7-29)," states that in a postulated station blackout scenario at Grand Gulf, runaway zirconium oxidation would commence at 1,832 degrees F (1,000 degrees C)[1,273 K]. This statement is made in the petition to support the assertion that runaway (autocatalytic) zirconium-steam reactions have commenced when fuel-cladding temperatures were lower than the 2,200 degrees F (1,204 degrees C)[1,478K] PCT limit. However, NRC staff notes that a station blackout is a severe accident, not a design basis accident. With minimal water addition, cladding temperatures climb continuously at a temperature ramp rate less than 2 °F/s between 2000 and 2500 °F in upper portion of Figure 3.7-5.

An OECD report titled, "Best Estimate Prediction for OECD LOFT Project Fission Product Experiment LP-FP-2" (OECD, 1985), regarding best-estimate predictions for LOFT LP-FP-2 experiments states that runaway oxidation would commence if fuel-cladding temperatures were to start increasing at a rate of 3.0 K/s. This statement is used to support the assertion that runaway (autocatalytic) zirconium-steam reactions have commenced when fuel-cladding temperatures were lower than the 2,200 degrees F (1,204 degrees C)[1,478 K] PCT limit. The comment pointed to the data presented in the NRC's September 2011 draft interim review (NRC, 2011b) which showed heatup rates of 10.3 K/s and 11.9 K/s at 2,199 degrees F (1,204 degrees C)[1,477 K].

The NRC staff notes the following statements from the OECD report:

> On page 35, "The temperature rise rate in the center bundle was calculated to be 3.0 K/s (5.4 F/s) at the fuel cladding temperatures below 1200 K (1700 F), and 1.5 K/s (2.7 F/s) between 1200 and 1850 K (1700 and 2870 F)"
>
> On page 38, "The calculation showed runaway oxidation beginning at 1650 K (2870 F) and causing the fuel rod to heatup at a maximum rate of 3.0 K/s (5.4 F/s)"
>
> On page 40, "The calculation showed runaway oxidation beginning at 1650 K (2870°F) and causing the fuel rod to heatup at a maximum rate of 5.5 K/s (9.9°F)"

From this information, The staff observes that the runaway oxidation is initiated because of the high temperatures 2,870 degrees F (1,577 degrees C)[1,650 K] not because of the heatup rate. Therefore, the staff concludes that there is no basis for the assertion that runaway (autocatalytic) zirconium-steam reactions have commenced when fuel-cladding temperatures were lower than the 2,200 degrees F (1,204 degrees C)[1,478K] PCT limit.

4.0 Conclusion

Each of the petition's key presumptions was investigated in detail. No technical basis was found in petition (M. Leyse, 2009) for the assertion that 10 CFR 50.46(b)(1), Appendix K (NRC, 1974) or Regulatory Guide 1.157 (NRC, 1989) are flawed and present a significant safety concern. The petition fails to provide any new information that supports a rule change. The NRC staff does not agree with the petition's assertions, and concludes that revisions to 10 CFR 50.46, Appendix K, or other related guidance are not necessary.

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6.0 Abbreviations and Acronyms

Numerals

10 CFR — Title 10 of the *Code of Federal Regulations*

A

ADAMS — Agencywide Documents Access and Management System (NRC)
AEC — Atomic Energy Commission
Ag — silver
ANL — Argonne National Laboratory
ANS — American Nuclear Society
ASME — American Society of Mechanical Engineers

B

B_4C — boron carbide
BWR — boiling-water reactor
B&W — Babcock & Wilcox

C

C — Celsius
Cd — cadmium
CFR — Code of Federal Regulation
CODEX — COre Degradation EXperiment
CORA — German experimental facility
CSNI — Committee on the Safety of Nuclear Installations

D

DBA — design-basis accident
DRACCAR — French computer code for analyzing fuel performance during a LOCA
DSA — RES Division of Systems Analysis

E

ECCS — emergency core cooling system
ECR — equivalent cladding reacted

F

F — Fahrenheit
FLECHT — full length emergency cooling heat transfer
FLECHT-SEASET — U.S. experimental reflood heat transfer tests performed by Westinghouse
FLHT — full-length high-temperature
FR — Federal Register
FRF — U.S. fuel rod failure experiments in TREAT reactor at INEL
FzK — Forschungszentrum Karlsruhe (formerly KfK) German experimental facility

G

GEAP — General Electric Atomic Power

H

hr — hour

I

In — indium
INEL — Idaho National Engineering Laboratory

J

K

K — Kelvin
KfK — see FzK
K/s — Kelvin per second

L

LB-LOCA — large-break loss-of-coolant accident
LOCA — loss-of-coolant accident
LOFT — U.S. loss-of-fluid test facility at INEL
LWR — light-water reactor

M

m — meter
MELCOR — U.S. computer code for analyzing severe accidents

N

NEA — Nuclear Energy Agency
NEC — New England Coalition
NEI — Nuclear Energy Institute
NIELS — German experimental facility
NRC — U.S. Nuclear Regulatory Commission
NRR — Office of Nuclear Reactor Regulation
NRU — National Research Universal
NUREG — NRC technical report

O

OECD — Organization for Economic Co-operation and Development
ORNL — Oak Ridge National Laboratory

P

PANDA	passive non-destructive assay of nuclear materials
PBF	U.S. power burst facility at INEL
PCT	peak cladding temperature
PHEBUS	French research facility
PRM	petition for rulemaking
PWR	pressurized-water reactor
PWROG	Pressurized-Water Reactor Owners' Group

Q

QUENCH	German fuel experimental program

R

RCS	reactor coolant system
REBEKA	German research facility
RELAP	reactor excursion and leak analysis program
RES	Office of Nuclear Regulatory Research
RG	regulatory guide
RIL	Research Information Letter

S

SEASET	separate effects and systems effects tests
SEFLEX	simulator effects in flooding experiments
SFD	U.S. severe fuel damage experiments in Power Burst Facility at INEL
SNL	Sandia National Laboratories
SRM	staff requirements memorandum (Commission direction to NRC staff)
SS	stainless steel
STARS	Strategic Teaming and Resource Sharing

T

TRAC	transient reactor analysis code
TRACE	U.S. TRAC/RELAP advanced computational engine code for thermal-hydraulic analysis
TREAT	U.S. transient reactor test facility at INEL

U

UCS	Union of Concerned Scientists
UO_2	uranium dioxide

V

VVER	Russian pressurized water reactor

W

WCAP	Westinghouse Commercial Atomic Power
WEC	Westinghouse Electric Corporation

Z

Zr	Zircaloy
ZrO_2	zirconium dioxide
Zr2K	German research reactor at Karlsruhe