April 29, 2004

MEMORANDUM TO: David B. Matthews, Director
Division of Regulatory Improvement Programs
Office of Nuclear Reactor Regulation

Suzanne C. Black, Director
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

FROM: Farouk Eltawila, Director ***/RA/***
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

SUBJECT: TECHNICAL SAFETY ANALYSIS OF PRM-50-76, A PETITION FOR RULEMAKING TO AMEND APPENDIX K TO 10 CFR PART 50 AND REGULATORY GUIDE 1.157

Reference: Memorandum from C. I. Grimes to F. Eltawila, "Request for Technical Support - Resolution of Petition for Rulemaking (PRM-50-76)"

The referenced memorandum requested that RES prepare a technical safety analysis of the subject PRM and recommendations for its resolution. The enclosed report satisfies that request. In particular, it is understood that this report will support a paper to the Commmision and a Federal Register Notice regarding the disposition of PRM-50-76.

Previously, at the Petition Review Board meeting of September 30, 2003 and in PRM-50-76 working group meetings, RES representatives provided information to support the denial of the petition. The enclosed report provides significantly more information to support that denial.

If you have any questions, please contact me (415-7499), Ms. Rosemary Hogan (415-7484) or Mr. Norm Lauben (415-6762).

Attachment: As stated

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Technical Safety Analysis of PRM-50-76
A Petition for Rulemaking to Amend Appendix K to 10 CFR Part 50 and Regulatory Guide 1.157

1.0 Background - A petition for rulemaking was docketed as PRM-50-76 on May 8, 2002 (Reference 1). The petitioner, Mr. Robert Leyse, requested amending those parts of Appendix K to 10 CFR Part 50 (Reference 2) and Regulatory Guide 1.157 (Reference 3) that address metal water reaction models for ECCS analysis. Mr. Leyse stated that he is aware of deficiencies in the Baker-Just equation (Reference 4) required for Appendix K ECCS analysis and deficiencies in the acceptable Cathcart-Pawel metal-water reaction data base (Reference 5) 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 (AER) opinion (Reference 6) regarding the ECCS Rulemaking Hearing. That opinion set forth 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 (Reference 7).

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 provides during the public comment period (References 8 and 9). Public comments were also received from Westinghouse (Reference 10), Nuclear Energy Institute (NEI) (Reference 11) and (Strategic Teaming and Resource Sharing (STARS) (Reference 12). These three industry comments recommended denial of the petition.

2.0 Discussion of Petitioner's Specific Issues

2.1 Inapplicability of the Baker-Just Equation

In Section 3.1 of Reference 1, the petitioner discusses the inapplicability of the Baker-Just equation (Reference 4) for calculating zirconium-water reaction rates during a LOCA. Certainly, experiments run with 40-60 mil wires at temperatures at or near the zirconium melting point (~3400°F) for 1 or 2 seconds are not typical of fuel rod cladding at temperatures in the range of 1800°- 2200°F for 50 to 400 seconds that are postulated to occur in a design basis LOCA. In Reference 4, only one data point from that study (at 3366°F) is compared to the Baker-Just equation. This data point was used to "anchor" the Baker-Just equation. Other data at more relevant conditions used in the Baker-Just derivation are described in References 13 and 14.

Correlations known at the time of the ECCS hearing included that of Lemmon (Reference 14) and Hobson and Rittenhouse (Reference 15). Those two correlations are shown in Figure 1 along with Baker-Just (Reference 4) and Cathcart-Pawel (Reference 5). The Commission in Reference 6 expressed uncertainty about the Hobson-Rittenhouse data based on the hearing record. For these reasons the Commission admonished the staff that new and better zirconium-water reaction data should be obtained (Reference 6). The Commission did recognize that the data used to develop the correlations shown in Figure 1 (with the exception of Cathcart-Pawel of course, which did not yet exist) indicated a degree of conservatism in the Baker-Just equation. Subsequent discussions in this report related to Section 3.3 of the petition will further address the conservatism of the Baker-Just equation.

Mr. Leyse appears to be concerned about the low water temperature (no greater than 599°F) in the Baker-Just experiments. This however is the saturation temperature at 1530 psia, which was the pressure for that particular experiment. While a very few degrees of liquid superheat may be possible under LOCA/ECCS conditions, the degree of non-equilibrium required for higher liquid or "bulk" temperatures postulated by Mr. Leyse is not possible. Only steam directly heated can achieve high temperatures. This of course has been observed in many ECCS tests such as those reported in Reference 7.

Mr. Leyse is also concerned about the large water volume compared to the zirconium sample size as it would relate to the quench capability of zirconium clad fuel rods. As discussed above, these experiments were atypical in that respect. Further, it should be noted that the study in Reference 4 was not at all intended to be a heat transfer study, but rather to investigate zirconium-water reaction kinetics at high temperatures.

One interesting feature of the Baker-Just report is the heat and mass transfer analysis of an example case analyzed to examine the processes limiting the reaction rate. In this severe case, a 0.21 cm zirconium sphere at its melting point was dropped into water. Mr. Baker and Mr. Just were concerned that the reaction could be limited by gas phase diffusion of steam through a film of steam and hydrogen. This appears to be similar to the concern expressed by Mr. Leyse. As explained in Reference 4, water cannot stay in contact with the hot metal and a vapor film immediately forms around the sphere. Figure 15 in Reference 4 shows that vapor phase diffusion is the limiting steam transport process for less than 0.2 seconds, while a slight film of oxide is forming on the surface of the sphere. After that the parabolic rate equation, e.g., Baker-Just, becomes limiting. The figure also shows that the gas phase diffusion is far less temperature sensitive than the parabolic rate law. Certainly at lower temperatures more typical of a LOCA, the parabolic law would be even more limiting than gas phase diffusion as long as the reaction is not steam starved.

Regarding Baker-Just then, it is acknowledged that it is not the best equation especially when compared to more recent data. However, it has been shown to be conservative. A significant example of this will be described in Section 2.3.

2.2 Inapplicability of Cathcart-Pawel Equation

Mr. Leyse states that the limited test conditions described in the Cathcart-Pawel report (Reference 5) obviates the use of that data for LOCA calculations. Mr. Leyse further states that:

> "The Zircaloy-4 specimens were not exposed to LOCA fluid conditions. Only steam was applied, steam was applied at only very low velocities for the main test series. There was no documented heat transfer from the zircaloy surface to the slow-flowing steam, and the conditions of the very small scale laboratory tests were thus not typical of the complex thermal-hydraulic conditions that prevail during a LOCA."

Mr. Leyse suggests that without liquid water present in the tests, the tests are invalid. On the contrary, the presence of liquid water would invalidate the tests. Accurate steady flow measurement would be extremely difficult. The droplets or liquid film would most surely complicate the achievement of relatively constant sample temperatures so necessary in these reaction kinetics tests. However, adequate steam flow is a concern. If the flow is too low, the reaction becomes steam starved. Other than that, having steam flow typical of LOCA/ECCS conditions is not necessary. These are not heat transfer tests. Once a reaction rate model is developed using data from experiments like these, then model should be validated against transient tests under LOCA conditions, such as the four Zircaloy tests described in Reference 7 and the transient tests described in Reference 5.

With respect to adequate steam flow, calculations were performed to assure that this was the case for the MiniZWOK experiments used to derive the Cathcart-Pawel correlation (Reference 5). The Cathcart-Pawel total oxygen consumption equation was applied to the MiniZWOK apparatus for a range of equivalent cladding reacted (ECR) for those particular tube specimen dimensions. The variable calculated was the stoichiometric steam flow required for the calculated reaction rate at the particular sample temperature and ECR. The results shown in Figure 2 indicate that for an ECR as small as 1 micron, at a sample temperature of 2400°F, the applied steam flow (0.5 gm/sec.) is 100 times greater than the stoichiometric requirements. Calculations using the Cathcart-Pawel correlation for the transient temperature oxidation experiments in Reference 5, indicate that an ECR as small as 1 micron exists for less than 3 seconds even for temperatures as low as 1700°F. Obviously the reaction would be steam starved at any applied flow rate less than the calculated value, but some steam starvation could occur if the flow is not in close proximity to the sample surface. In this apparatus the channel width around the sample is about 0.75 in. Anything that increases the ECR, which happens throughout any transient, will reduce the reaction rate and thus the steam flow requirements. Figure 2 shows that for temperatures as high as 200°F above the current 50.46 limits, the steam flow used in the MiniZWOK experiments was at least two orders of magnitude more than would be needed to avoid stoichiometric steam starvation.

Perhaps the most convincing arguments regarding the absence of steam starvation is how the isothermal Cathcart-Pawel MiniZWOK experiments give consistent results that support the parabolic/Arrhenius behavior. Each isothermal experiment exhibits parabolic behavior as a function of time. This behavior is consistent with diffusion of gas through a solid. The authors have shown that the theory works for oxide formation, α phase zirconium growth, and total oxygen uptake. When the data set is plotted as an Arrhenius equation, e.g., reaction rate constant vs. 1/T, the data matches the Arrhenius reaction rate model. Once again this is true for oxide, α phase and total oxygen. If the reaction were steam limited or "mass transfer" limited the experimental behavior would not match parabolic/Arrhenius behavior.

Mr. Leyse states that the steam velocity in the MiniZWOK sample section is "erroneously" reported as 3 ft/sec, whereas he states that it was only about 1 ft/sec. Unfortunately, the exact thermodynamic conditions are not reported in Reference 5. They were also not reported in the available monthly progress reports. Reference 5 states that the steam entering the reaction chamber was superheated. There are indications that the temperature may have been about 200°C (392°F). If that was the case, the steam velocity was about 2 ft/sec. If there was no superheat the velocity was about 1½ ft/sec. However, whether the velocity is 1,1½, 2 or 3 ft/sec is not important. Based on the 30 g/min (0.5 g/sec) reported steam flow rate and the parabolic/Arrhenius exhibited behavior, the experiments were not steam limited, nor was the reaction rate controlled by steam "mass transfer" from the flowing stream.

Much of Mr. Leyse's criticism of the Cathcart-Pawel work is related to comparison of MiniZWOK and MaxiZWOK experimental conditions. MiniZWOK was used to develop a consistent set of data for correlation development. Controlling sample temperature by adjusting heater power (MiniZWOK) was much more successful than adjusting steam flow (MaxiZWOK). As Mr. Leyse notes temperature overshoot was a problem with MaxiZWOK and at high temperatures could have led to temperature runaway. As noted above, temperature control is absolutely necessary in reaction kinetics experiments such as these. Mr. Leyse implies that the experimenters abandoned MaxiZWOK in favor of MiniZWOK. Actually, the isothermal MiniZWOK experiments were essentially complete before the MaxiZWOK experiments were begun. Results from MaxiZWOK between 1652°F and 1832°F showed good comparison with MiniZWOK data at the same temperatures. The authors of Reference 5 state:

> "The very good agreement between these two data sets is regarded as evidence that steam flow rate and steam insertion temperature do not affect significantly the kinetics of the steam oxidation of Zircaloy, at least in this temperature range."

Certainly, with steam velocities at least an order of magnitude greater in MaxiZWOK than MiniZWOK, the potential for more rapid gas phase diffusion of steam to the sample surface "mass transfer" is greater for MaxiZWOK. Clearly this is not the limiting phenomenon. This was demonstrated by the good comparison between MiniZWOK and MaxiZWOK data and the good comparison of MiniZWOK data to Parabolic/Arrhenius behavior. There is no evidence to suggest that high "mass transfer coefficients" in MaxiZWOK was the cause for temperature overshoot in MaxiZWOK at 1832°F as proposed by Mr. Leyse. It is true as Mr. Leyse suggests that:

> "It is not possible to achieve an isothermal rate of oxidation of Zircaloy-4 if the Zircaloy-4 is exposed to LOCA fluid conditions at elevated conditions."

However, it is not for the reasons postulated by Mr. Leyse. Rather, large break LOCA reflood conditions are characterized by constantly decreasing power (decay heat), and increasing heat transfer coefficients after a few seconds. Under these conditions, isothermal conditions are impossible. Reference 7 universally showed this kind of heat transfer and power behavior for all tests that were done under design basis conditions, and of course these heat transfer tests did not exhibit isothermal cladding temperature behavior.

Two sets of transient temperature oxidation experiments were performed and reported in References 5 and 16. The first six transient tests were performed to examine the effect of simple heatup and cooldown (two tests), to examine the effect of temporary temperature increases to 1400°C (two tests) and to examine the effect of more complex temperature transients typical of a double peaked large break LOCA (two tests). All six experiments were used to test the computer codes SIMTRAN and BILD5. However, neither code uses the

Cathcart-Pawel correlations. SIMTRAN uses an ideal diffusion model, and although BILD5 uses parabolic rate constants, it does not use the Cathcart-Pawel values. The values used in BILD5 were developed prior to the development of the Cathcart-Pawel correlations. Cathcart and Pawel did not apply their correlations against their transient tests. Recently, the NRC applied the Cathcart-Pawel oxide thickness equation to the six tests. Table 1 presents the measured oxide thickness for the six tests and the thickness calculated by SIMTRAN and BILD5 from Reference 5. The oxide thickness values recently calculated using the Cathcart-Pawel equations are also presented. The per cent deviation of predicted versus measured is also shown.

Table 1.
Experimental and Predicted Oxide Thickness for Transient Steam Oxidation of Zircaloy-4

			BILD5		SIMTRAN		C-P (NRC)	
Expt. No.	**Transient Type**	**Measured (μm)**	**Calc. (μm)**	**% dev.**	**Calc. (μm)**	**% dev.**	**Calc. (μm)**	**% dev.**
S-155	heat/cool	39.3	40.0	+1.8	41.0	+4.3	40.2	+2.3
S-158	heat/cool	35.8	36.7	+2.5	37.5	+4.7	37.7	+5.3
S-163	high PCT	65.2	71.0	+8.9	74.4	+14.1	70.5	+8.1
S-164	high PCT	65.8	73.6	+11.9	73.7	+12.0	70.5	+7.1
S-160	LBLOCA	45.8	48.4	+5.7	49.5	+8.1	33.2	-27.5
S-196	LBLOCA	40.2	49.7	+23.6	51.1	+27.1	35.3	-12.1

The authors of Reference 5 noted that the oxide thickness predicted by BILD5 and SIMTRAN for Test S-196 was significantly more than the measured value. It was also noted that the measured value for S-196 was less than the measured value for S-160 even though the first temperature peak was higher for S-196. On the other hand, the Cathcart-Pawel calculations by the NRC for both tests substantially underpredict the measured values.

Because of the overprediction by the ORNL codes (SIMTRAN & BILD5) and the anomalous oxidation/temperature behavior observed by the authors, it was decided that further transient experiments and analysis should be performed. In particular, stylized double peaked LOCA-like transients were performed to determine if the over prediction was attributable to the extensive temperature hysteresis associated with the monoclinic-tetragonal oxide phase transformation. Once again the authors applied BILD5 to the temperature transients and recently NRC applied the Cathcart-Pawel oxide thickness correlation. The results are shown in Table 2.

Table 2.
Experimental and Predicted Oxide Thickness for
Stylized LBLOCA Transient Steam Oxidation of Zircaloy-4

Expt. No.	T-min/ T-plateau °C/°C	Measured (μm)	BILD5 Calc. (μm)	BILD5 % dev.	C-P (NRC) Calc. (μm)	C-P (NRC) % dev.
S-224	650/1050	12.2	25.2	+106.6	23.9	+95.9
S-225	650/1050	12.6	27.2	+115.9	26.3	+108.7
S-226	650/1200	36.3	38.8	+6.9	36.4	+0.3
S-227	650/1400	50.2	52.9	+5.4	51.6	+2.8
S-228	650/1400	54.0	56.7	+5.0	52.8	-2.2
S-229	1200/1200	49.7	51.7	+4.0	49.3	-0.8
S-230	1200/1200	48.4	50.0	+3.3	51.4	+6.2
S-238	1050/1050	29.4	28.4	-3.4	27.8	-5.4
S-239	650/1090	10.5	28.2	+168.6	28.1	+167.6

As can be seen in Table 2, the oxide thickness calculated by Cathcart-Pawel is very similar to that calculated using BILD5. Both analytical methods substantially overpredicted the oxide thickness for three tests (S-224, S-225 and S-239). The Reference 5 authors noted that:

> "Common to all three of these experiments were the facts that (1) each was a "two-peak" transient, (one in which the specimen was cooled significantly between heating cycles), and (2) the temperature of the second peak was less than 1200°C (2192°F).

The Reference 5 authors compare the experimental transient characteristics to the known oxide phase transformation temperature hysteresis. Ultimately they conclude that:

> "Clearly, however, the problem of transient temperature oxidation predictions deserve further study."

This would seem to be especially true since for two temperature transients in the first data set presented, Cathcart-Pawel appears to under predict the data, whereas SIMTRAN and BILD5 do not. This is indeed puzzling, since for the other 13 transients the comparisons between BILD5 and Cathcart-Pawel calculations were good.

Mr. Leyse implies that the Reference 5 authors' statement that scoping tests on the effect of steam pressure that was in progress is an admission of inapplicability of their work. There is no evidence to support such an inference. That work was completed and subsequent work by others has also been undertaken to examine pressure effects. The idea proposed by Mr. Leyse that the authors' statement regarding ongoing work somehow applies to very low steam velocities is also unsupported.

Work in this area did not end in 1977. The NRC, foreign partners and the industry are currently conducting and evaluating experimental and analytical programs on fuel cladding behavior. Being investigated are issues such as the effects of fuel relocation, various types of zirconium based cladding, high burnup, mixed oxides, ZrO_2 phase change hysteresis, and system pressure. An important purpose of this work is to evaluate the adequacy of current 50.46 oxidation criteria and models. An important link to the current work is the extensive research reported in Reference 5.

2.3 Relevance of Zircaloy Clad ECCS Transient Test Data Reported in WCAP-7665

As noted in the introduction, the petitioner quotes from Reference 6 that:

> "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 (Reference 7). The "impression" that the 1973 AEC Commissioners refer to appear to be the fact that Run 9573 indicates lower "measured" heat transfer coefficients than the other three Zircaloy clad tests reported in WCAP-7665 when compared to the equivalent stainless steel tests. They believed that this anomaly could be cleared up with more experiments with Zircaloy cladding. Some of the anomaly can probably be explained due to a deficiency in the data reduction process.

Heat transfer coefficients are not directly measurable quantities. They must be calculated from measured temperatures, known heat sources and known thermal properties. Reference 7 describes the heat transfer data reduction process using the DATAR code. For these experiments, the decay heat simulation was well known, as was the time of heater failure. However, the heat source due to zirconium water reaction had to be estimated in some way. The Baker-Just correlation was used for that purpose. Because of the conservatism of the Baker-Just correlation, this overestimates the amount of reaction and the associated heat generation rate. At 21 locations on 19 rods among the four Zircaloy tests, post-test oxide thickness measurements were made. Westinghouse applied the Baker-Just correlation to each temperature transient measured at or very near to each oxide thickness measurement. The comparison between predicted and measured oxide thickness was presented in Figure B-12 of Reference 7. Figure 3 of this report is a representation of Figure B-12 with the X and Y axes inverted. As can be seen from Figure 3, the Baker-Just calculated oxide thickness is about 1.6 times the measured value. Thus for this data set, the Baker-Just correlation over-predicts the data by about 60%, which is quite conservative.

The NRC obtained tabular time/temperature data from Westinghouse for 19 of the 21 locations analyzed by Westinghouse for the four Zircaloy FLECHT tests. The Baker-Just correlation was applied to these 19 data sets as a check on the analysis in Reference 7. The Cathcart-Pawel oxide thickness correlation was also applied to the 19 available data sets. The predicted vs. measured points for these two applications are shown in Figure 4. The regression line for the 19 point Baker-Just application is shown along with the predicted = measured line. The Baker-Just regression line and data points in Figure 3 and Figure 4 are nearly identical, indicating a good check of the Baker-Just application in Reference 7. As can be seen in Figure 4, the data points for the Cathcart-Pawel application lie close to the predicted = measured line, indicating that Cathcart-Pawel is a good fit to this data set. The 2σ variances of the points of the Baker-Just applied points about the Baker-Just regression line in Figure 4 is 0.38 mils. The 2σ variances of the Cathcart-Pawel applied points about the predicted = measured line is only 0.27 mils. Therefore, not only does the Cathcart-Pawel correlation provide a better representation of typical LOCA transient oxidation data, the variance of the applied correlation is also better.

Mr. Leyse states that:

> "Unfortunately, a detailed thermal-hydraulic analysis of Run 9573, including evaluation of the heating from Zircaloy-water reactions, was never performed."

Contrary to Mr. Leyse's assertion, not only was an evaluation of the heating from Zircaloy-water reaction performed for Run 9573, it was done for all four Zircaloy tests. Unfortunately, by using the conservative Baker-Just correlation to estimate the zirconium-water heat release, the derived heat transfer coefficients are overestimated. Thirty five years later, it would be difficult to replicate the DATAR code, substitute a better metal-water model and rederive the heat transfer coefficients. This would be a minimum requirement before considering the expense of high temperature Zircaloy tests, which would have marginal benefit in terms of increased understanding of LBLOCA heat transfer and metal-water reaction kinetics. Current programs at Pennselvania State University (PSU), Argonne National Laboratory (ANL) and elsewhere are far more cost-effective.

At this time we know that high temperature tests similar to run 9573 would require rod bundle powers well outside the range of operation of any current or proposed PWRs. Also, no realistic transient experiments or analyses have indicated cladding temperatures at the beginning of reflood anywhere near the 1970°F achieved in run 9573. If run 9573 were repeated the results would probably be the same, the high temperatures and high power would quickly catapult the cladding into the severe metal-water reaction regime, destroying the bundle and producing very little useful heat transfer information.

Mr. Leyse states that:

> "Petitioner is aware that more experiments with Zircaloy cladding have not been conducted on the scale necessary to . . . overcome the impression left from run 9573."

In the early 1980's, the NRC through Pacific Northwest Laboratories (PNL) contracted with National Research Universal (NRU) at Chalk River, Ontario, Canada to run a series of LOCA tests in the NRU reactor. More than 50 tests were conducted to evaluate the thermal-hydraulic and mechanical deformation behavior of a full length 32-rod nuclear bundle during the heatup, reflood and quench phases of a large break LOCA. Two tests were initially selected (References 17 and 18) for COBRA/TRAC (Reference 19) simulation to assess the applicability of that code. The NRC is reviewing the data from this program to determine the value of using it to assess the current generation of codes such as TRAC-M (Reference 20), now renamed TRACE.

In assessing the need for further experiments like the Zircaloy clad FLECHT tests, it is important to understand the past and current role of rod bundle reflood heat transfer tests. In the late 1960s a mechanistic understanding of reflood heat transfer did not exist. In order to develop heat transfer models as expeditiously as possible, the PWR FLECHT program was cooperatively developed with the AEC, Westinghouse and Electric Power Research Institute (EPRI). The principle purpose was to determine reflood heat transfer coefficients as a function of key initial and boundary conditions, rod elevation and time after the beginning of reflood, and to develop empirical correlations based on that dependency. As long as a sufficiently large matrix of tests performed with full scale rod bundles, the need was much less for a comprehensive mechanistic understanding. The key parameters were:

A. Pressure
B. Peak power
C. Decay power
D. Flooding rate
E. Inlet sub-cooling
F. Initial temperature
G. Bundle size
H. Cladding material
I. Housing temperature

When nuclear plant behavior and design conditions are outside the envelope defined by these test parameters or the design of the experimental system, there is no basis for extrapolation, since the derived heat transfer models are not necessarily based on the physical models governing the reflood heat transfer processes. Also, for the very empirical process used in the early FLECHT experiments, a great deal of effort was not expended obtaining data needed for development of mechanistic physical models. It would be impractical to obtain sufficient Zircaloy heat transfer coefficient data for the empirical process used with the early FLECHT experiments.

As the FLECHT program and other rod bundle reflood heat transfer programs have progressed over the last 30 years, more information appropriate for mechanistic model development has been obtained. As better mechanistic models are developed, careful extrapolation has a better chance of success, and the role of experiments like FLECHT has shifted from model development to developmental assessment. In fact many of the FLECHT-SEASET experiments are used to assess the new code models. As mentioned above, the NRC is attempting to obtain the NRU Zircaloy clad nuclear fuel bundle test results for further code assessment.

3. Conclusions - The following conclusions support the position 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 petitioner's key presumptions was investigated. As a result, no technical basis was found in the petition (Reference 1) for the assertion that Appendix K (Reference 2) or Regulatory Guide 1.157 (Reference 3) are flawed and present a significant safety concern.

The Baker-Just correlation (Reference 4) 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 1800°F.

Parabolic/Arrhenius behavior of the Cathcart-Pawel isothermal experiments (Reference 5) 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 (Reference 21) consistent with Commission direction. The NRC funded more than 50 Zircaloy clad bundle reflood experiments at the NRU reactor (References 17 and 18).

The petitioner did not take into account Westinghouse' metallurgical analyses performed on the cladding for all four FLECHT Zircaloy clad experiments reported in Reference 7. He also ignored the Westinghouse application of the Baker-Just correlation to these experiments, which had the "complex thermal hydraulic phenomena" deemed important by the petitioner. 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 Reference 7.

For the development of oxidation correlations, limited by oxygen diffusion into the metal, well - characterized isothermal tests are more important than the complex thermal hydraulics suggested by the petitioner. His suggested 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 Reference 7, Cathcart-Pawel in Reference 5 and by the NRC for this report.

The NRC applied the Cathcart-Pawel oxygen uptake and ZrO_2 thickness equations to the four FLECHT Zircaloy experiments, confirming the best-estimate behavior of the Cathcart-Pawel equations for large break LOCA reflood transients. The NRC applied the Cathcart-Pawel oxide thickness equation to 15 of their transient temperature experiments. The equation was conservative or best-estimate for 13 experiments and non-conservative for the remaining two.

5.0 References

1. PRM-50-76, Petition for Rulemaking to Amend Commission Regulations and Guidance Concerning Evaluation of Emergency Core Cooling Systems, Robert H. Leyse, May 1, 2002.

2. Appendix K to 10 CFR Part 50 - ECCS Evaluation Models, January 4, 1974 as amended.

3. Regulatory Guide 1.157, Best Estimate Calculations of Emergency Core Cooling System Performance, May 1989.

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

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

6. Opinion of the Commission, In the Matter of: Rulemaking Hearing on Acceptance Criteria for Emergency Core Cooling Systems for Light Water Cooled Nuclear Power Reactors, December 28, 1973.

7. F. F. Cadek, D. P. Dominicis, R. H. Leyse, PWR FLECHT (Full Length Emergency Core Heat Transfer) Final Report, WCAP-7665, April 1971.

8. R. H. Leyse, Petitioner's First Response to Commission's Request for Comment, September 11, 2002.

9. R. H. Leyse, Petitioner's Responses to Comments by Westinghouse and NEI, December 14, 2002.

10. H. A. Sepp, Westinghouse Electric Co., Letter to Annette Vietti-Cook, Secretary of the Commission, "Comments of the Westinghouse Electric Company regarding The Petition for Rulemaking Published in federal Register 51783" October 22, 2002.

11. Anthony R. Pietrangelo, Nuclear Energy Institute, Letter to Annette Vietti-Cook, Secretary of the Commission, "NEI Comments on the Robert H. Leyse Petition for Rulemaking (Ref. 67 Fed. Reg. 51783, dated August 9, 2002), October 25, 2002.

12. D. R. Woodlan, Chairman, Integrated Regulatory Affairs Group, STARS, Letter to Annette Vietti-Cook, Secretary of the Commission, "Strategic Teaming and Resource Sharing (STARS) Comments on Petition for Rulemaking Regarding Emergency Core Cooling Systems (ECCS) Evaluation Models and Associated Guidance (67 FR 51783)," October 24, 2002.

13. W. A. Bostrum, The High Temperature Oxidation of Zircaloy in Water, WAPD-104, March 1954.

14. A. W. Lemmon, Studies Relating to the Reaction Between Zirconium and Water at High Temperature, BMI-1154, January 1957.

15. D. O. Hobson and P. L. Rittenhouse, Embrittlement of Zircaloy-Clad Fuel Rods by Steam During LOCA Transients, ORNL-4758, January 1972.

16. R. E. Pawel, J. V. Cathcart and R. A. McKee, “Anomalous” Oxide Growth During Transient-Temperature Oxidation of Zircaloy-4, Oxidation of Metals, Vol. 14, No.1, 1980.

17. C. L. Mohr, et al., “Prototypic Thermal-Hydraulic Experiment in NRU to Simulate Loss-of-Coolant Accidents,” PNL-3681 NUREG/CR-1882, Pacific Northwest Laboratory, 1980.

18. C. L. Mohr, et al., “Loss of Coolant Accident Simulations in the National Research Universal Reactor, Safety Analysis Report.” PNL-3093 NUREG/CR-1208, Pacific Northwest Laboratory, 1981.

19. M. J. Thurgood, et al., “COBRA/TRAC - A Thermal-Hydraulics Code for Transient Analysis of Nuclear Reactor Vessels and Primary Systems, Developmental Assessment and Data Comparisons.” PNL-4385 NUREG/CR-3046, Volume 4, Pacific Northwest Laboratory, 1982.

20. R. G. Steinke, et al., “TRAC-M/FORTRAN 90, (Version 3.0) User’s Manual." NUREG/CR-6722, Los Alamos National Laboratory, May 2001.

21. “Compendium of ECCS Research for Realistic LOCA Analysis.” NUREG-1230, December 1988.

Figure 1. Parabolic Rate Constants for Oxygen Consumption

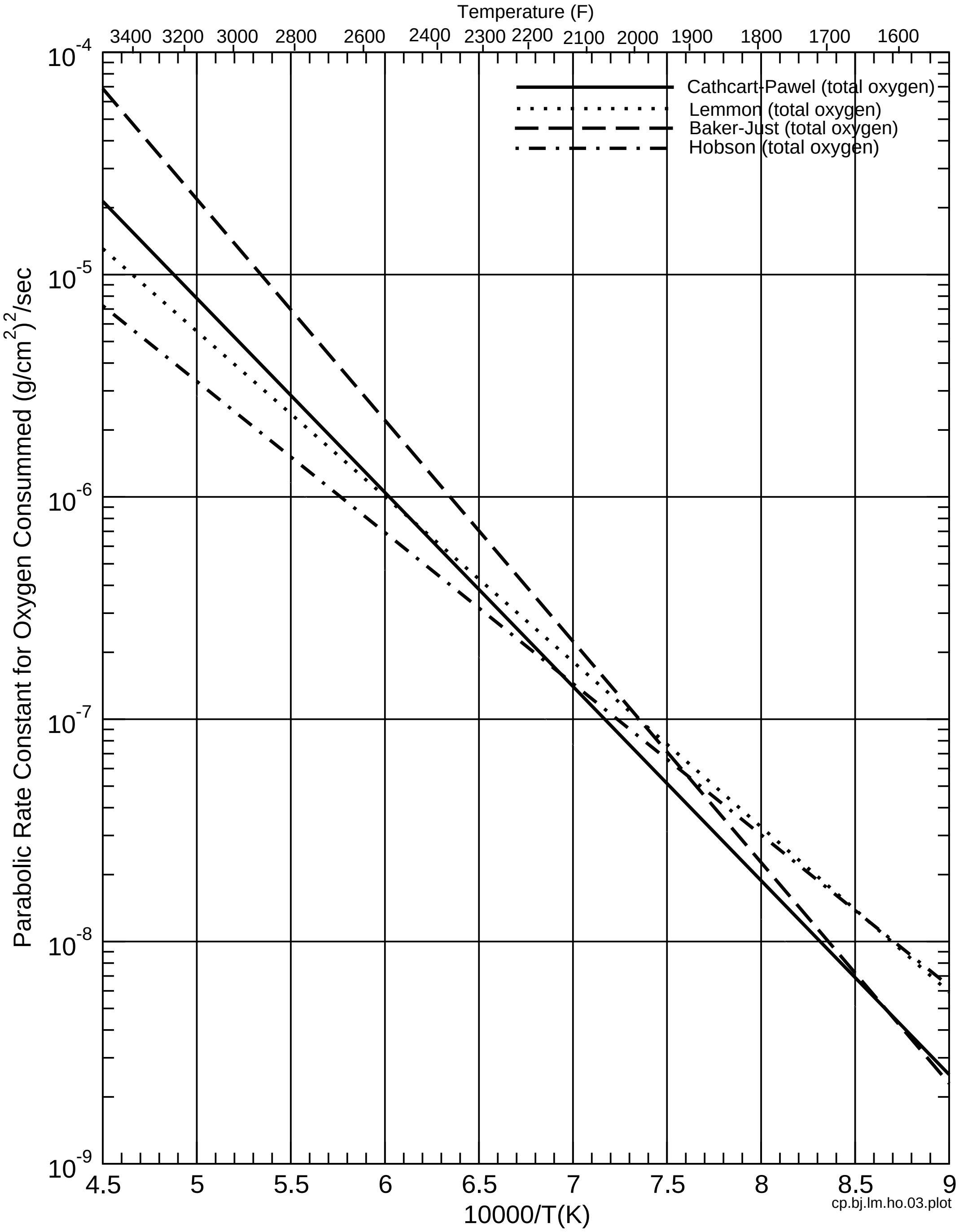

Figure 2. Stoichiometric Steam Flow for MiniZWOK

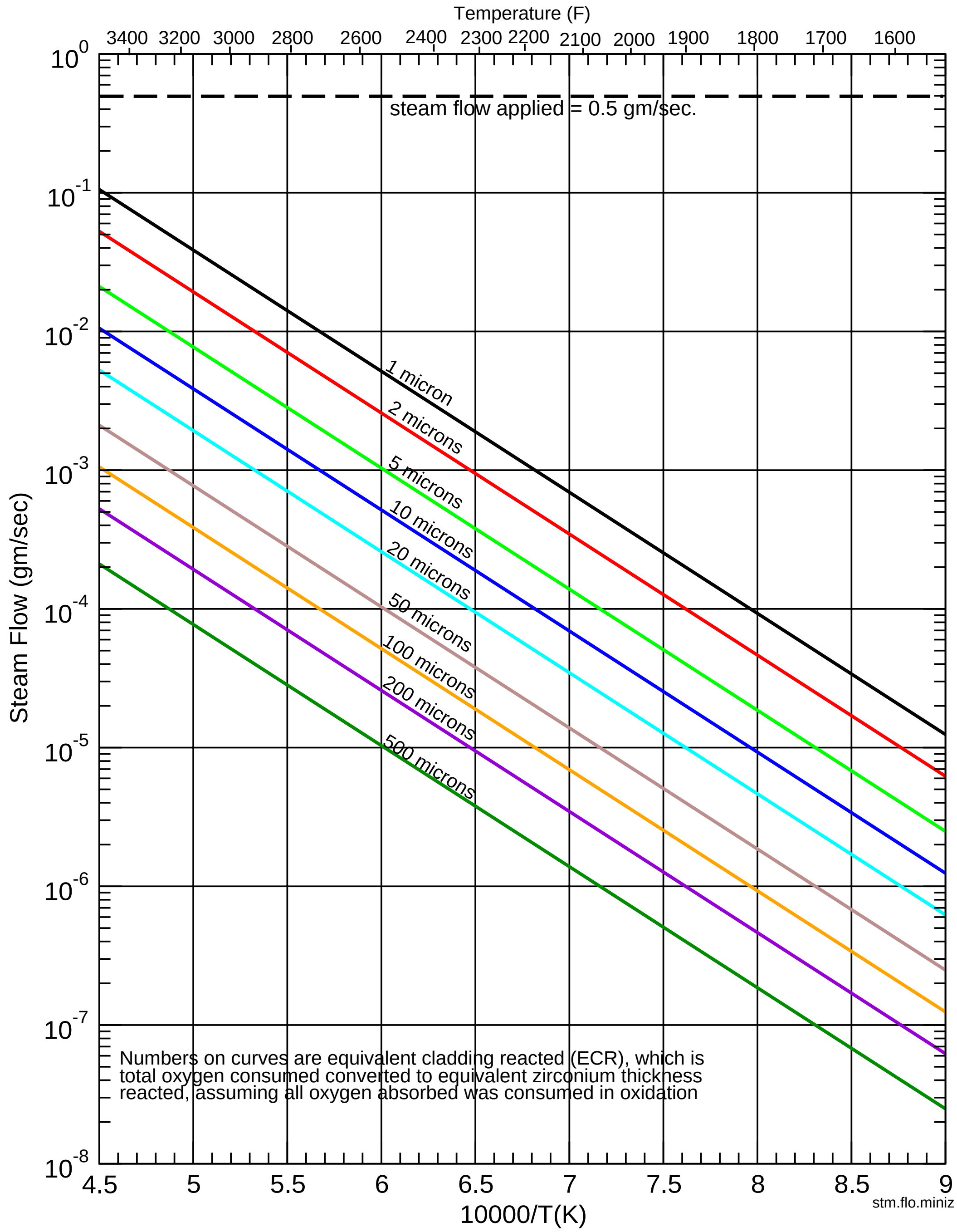

Figure 3. FLECHT Measured vs. Predicted Oxide Thickness

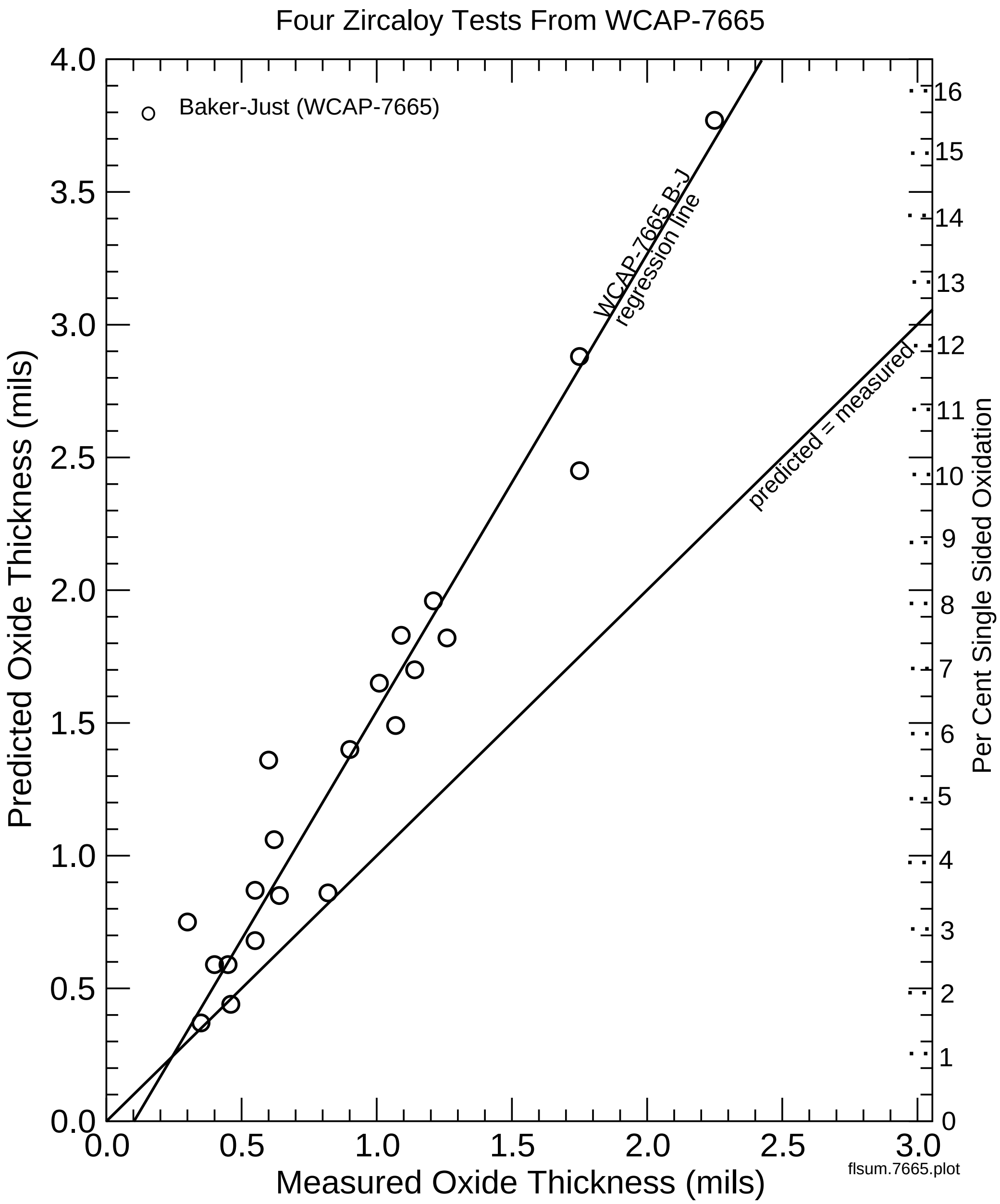

Figure 4. FLECHT Measured vs. Predicted Oxide Thickness

Four Zircaloy Tests From WCAP-7665