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Prediction of Failure Enthalpy and Reliability of Irradiated Fuel Rod under Reactivity-Initiated Accidents by Means of Statistical Approach

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Abstract

During the last decade, the failure behavior of high-burnup fuel rods under RIA has been an extensive concern since observations of fuel rod failures at low enthalpy. Of great importance is placed on failure prediction of fuel rod in the point of licensing criteria and safety in extending burnup achievement. To address the issue, a statistics-based methodology is introduced to predict failure probability of irradiated fuel rods. Based on RIA simulation results in literature, a failure enthalpy correlation for irradiated fuel rod is constructed as a function of oxide thickness, fuel burnup, and pulse width. From the failure enthalpy correlation, a single damage parameter, equivalent enthalpy, is defined to reflect the effects of the three primary factors as well as peak fuel enthalpy. Moreover, the failure distribution function with equivalent enthalpy is derived, applying a two-parameter Weibull statistical model. Using these equations, the sensitivity analysis is carried out to estimate the effects of burnup, corrosion, peak fuel enthalpy, pulse width and cladding materials used.

I. INTRODUCTION

It is a common practice to postulate the RIA (reactivity-initiated accident) as a design-basis accident in licensing of LWRs (light water reactors). When RIA occurs, the fuel pellet expands abruptly due to high-energy deposition in a very short period, so that fuel cladding is susceptible to failure. To prevent fuel fragmentation and loss of coolability during RIA, the radial averaged peak fuel enthalpy criteria are used as limits in the range of 200 ~ 280 cal/g according to regulatory authorities. The enthalpy values of 85 ~ 200 cal/g or DNB (departure from nucleate boiling) criteria are usually imposed as fuel cladding failure threshold. These limits were established based on the RIA test results with test rods of fresh and low burnup fuels in the early 1970s.

At the beginning of the 1990s, the high-burnup fuel rods failed at significantly reduced enthalpies as low as 30 and 60 cal/g at CABRI [1] and NSRR [2], respectively. These results have prompted extensive investigations on irradiated fuel rod behavior under RIA situations during the last decade, since the failure at low enthalpy was unexpected and could be an obstacle to the worldwide trend of burnup extension. These investigations include the additional RIA simulation tests in France, Japan and Russia, as well as reassessment of RIA in commercial reactors in the aspect of neutronic and thermal-hydraulic calculations. The special emphasis has been placed on the cladding failure mechanism and licensing limit of high-burnup fuel.

Montgomery et al. [3] employed the strain energy density (SED) approach to evaluate the cladding failure at CABRI tests. In this methodology, the failure is assumed when calculated SED, i.e., integration of stress-strain curve in response to RIA sequence, exceeds critical SED value that is function of temperature, fast fluence and hydrogen content. However, this model was originally established based on cladding axial deformation results. Therefore this approach seems difficult to use due to complexities in predicting fuel-cladding behaviors in actual RIA condition as well as the lack of a database on circumferential stress-strain response in terms of hydrogen content, neutron fluence, etc. under typical

RIA conditions including strain rate and simulation temperature of interest. Chung and Kassner [4] proposed a cladding failure model that is based on temperature-sensitive tensile properties and fracture toughness of high-burnup Zircaloy cladding. This model consists of microstructural parameters such as oxide thickness, oxygen and hydrogen contents in alpha-phase, hydride continuity constant and temperature. Even though this model seems to be basically reasonable, it is also difficult to apply because such a microstructural detail of high-burnup cladding is unavailable at present.

As irradiation proceeds, the microstructures of fuel pellets also changes, leading to an increase of the potential to cladding damage, which makes it more difficult to predict cladding failure. Nevertheless, with this situation, the number of fuel rod failures should be calculated, so that the source term, i.e., radiological doses to the public can be estimated. Therefore a statistical approach in predicting the cladding failure when an irradiated fuel rod is subject to RIA condition, is suggested in which the failure enthalpy and cladding reliability can be assessable.

II. PREDICTION MODEL FOR FAILURE ENTHALPY

II.1 Cladding Failure Mechanism

The failure of fresh fuel rods is known to be mainly caused by the melting of fuel pellets and cladding or oxidation-induced brittle fracture during DNB and subsequent fracture on quenching. The peak fuel enthalpy (PFE) above ~250 cal/g is required to cause these types of failure [5].

As burnup increase, the cladding failure mechanism would be significantly different from that of unirradiated cladding due to microstructural changes in fuel pellet as well as Zircaloy cladding. The fast neutron fluence severely degrades the cladding ductility by forming microstructural defects in the matrix. Irradiation induced dissolution of second phase particles may embrittle cladding. The other source of ductility loss in Zircaloy cladding during irradiation is resulted from hydride formation from hydrogen content increase and increased level of oxygen dissolved [4], in the alpha-phase layer of Zircaloy. These hydrogen and oxygen contents are closely associated with the level of water-side corrosion. Thereby, corrosion reduces fracture resistance of cladding not only by consumption of load-bearing ligament but also by increase of hydrogen and oxygen contents in cladding material. The fracture resistance of Zircaloy cladding might be further degraded by the stress corrosion cracking (SCC) at the inner side of the cladding primarily due to iodine released from fuel pellet as a fission product during irradiation.

In the fuel pellet, the gaseous fission products are either accumulated and form gas bubbles at the grain boundary of the pellet matrix or are released into the plenum region. The more fission gas accumulated in the fuel pellet, the more the pellet-cladding mechanical interaction (PCMI) force to cladding increases during RIA condition. The fuel swelling caused by solid fission products and cladding creepdown lead to a decrease of fuel-cladding gap size, hence, the PCMI failure susceptibility increases as well. In any case, the main contributor in lowering the failure threshold of high-burnup fuel is commonly accepted to be due to hydride-assisted PCMI failure [3].

Reactor conditions such as pulse width in terms of full width at half maximum (FWHM) and coolant temperature may also have an affect on the cladding failure mode. Although the same PFE is imposed on the fuel rod, the narrow pulse width may give rise to a higher PCMI stress and lowering temperature in cladding than those of wide pulse width. According to a sensitivity assessment on pulse width [6], the heating of fuel tends to be adiabatic during narrow power pulse width less than about 10 msec, but with pulse width becoming broader, peak contact stress and cladding temperature at the time of maximum stress are decreasing owing to the heat transfer from fuel to coolant. Since ductile brittle transition (DBT) phenomenon in high-burnup Zircaloy cladding is believed to occur [4], cladding temperature associated with pulse width is important in the cladding failure mode. Volkov [6] also demonstrated that both PFE and energy deposition depend on pulse width, and his calculation results are shown in figure 1. As seen in the figure, with pulse width increasing up to around 1,000 msec, the logarithmic scale of pulse width is linearly dependent on the energy deposition in order to accommodate for the heat loss rise with pulse width broadening.

II.2 Regression Model for Failure Enthalpy

As mentioned in the previous section, complex behaviors of pellet and cladding, and various test conditions on irradiated fuel rods under RIA-simulation experiments, have made it extremely difficult to predict the cladding failure by using traditional analytical tools. In this section, a statistical regression model is employed to predict the failure enthalpy of irradiated PWR type fuel rods based upon the RIA test results observed at the worldwide research reactors in terms of fuel burnup, oxide thickness and pulse width. Most of currently available data regarding to the RIA test results with irradiated rods are listed in Tables I to IV from the literature [5, 7~18]. The thermal failures such as melting and quench embrittlement fracture are ruled out in this analysis, while only data that caused by PCMI failure are used in failure model establishment.

The plot of failure enthalpy versus fuel burnup is the conventional way of illustrating in irradiated rods under RIA tests. But Meyer et al. [7] emphasized that oxidation thickness is more dominant variable than burnup effect. Figure 2 (a), (b) and (c) show the effects of fuel burnup, oxide thickness and pulse width, respectively. From these figures, it is evident that data scattering is quite significant in all three plots. This indicates that the failure of fuel rod does not controlled by only one dominant factor, but several factors may be contribute to these failures. The three main independent variables, i.e., fuel burnup, oxide thickness and pulse width are considered in this failure model development because these three variables are presumed to cover most of factors in cladding damage. For example, it can be said that fuel burnup stands for those effects of irradiation damage, iodine-induced SCC, gap decrease and fission gas accumulation in the pellet, while oxide thickness for the consumption of load-bearing thickness, possible oxide layer spallation effect, hydrogen uptake and oxygen dissolution in Zircaloy cladding. Pulse width is representative with accident conditions such as cladding temperature and the intensity of hoop stress on cladding.

The multiple linear regression model is widely used in the case where various factors are involved in so that establishment of the mechanistic model is hard to be practical. An example of establishing the multiple regression model can be found elsewhere [19]. The failure enthalpy of irradiated fuel rod is modeled by applying the multiple regression method under assumption that each of oxide thickness, burnup and pulse width is independently affect on the failure enthalpy. Taking into account only the failed data listed on Tables I to IV, the failure enthalpy correlation is derived as follows,

$$H_f = 156.6 - 0.774 \cdot OT - 1.076 \cdot Bu + 29.41 \cdot \log(PW) \quad (1)$$

Where H_f is failure enthalpy in cal/g, OT is oxide thickness in μm, Bu is fuel burnup in GWD/tU and PW is pulse width in terms of FWHM in msec.

In this model, the logarithmic dependence of pulse width is assumed as a result of the enthalpy characteristics shown in figure 1. The proportional constant for pulse width is found to be 29.4, which is reasonably consistent with, but slightly higher than the slopes in figure 1. The higher proportional constant of pulse width compared to the slopes in figure 1 may be explained as a cladding temperature rise induced by pulse width broadening that further increases the failure enthalpy.

Figure 3 shows the uncertainty of the failure model. Even though the variety of test conditions and a little different type of fuel and cladding materials are included in the experimental data, the failure model proposed provides reasonable predictions of the experimental results. Fujishiro [20] reported that the failure of fresh fuel rod was generally about 240 ~ 265 cal/g of the energy deposition at pulse width range of 4 ~ 70 msec. When the failure model, equation (1) is extrapolated down to an unirradiated condition, the values of failure enthalpy are predicted in the range of 174 ~ 211 cal/g depending on pulse width (4 ~ 70 msec), these are comparable with 192 ~ 212 cal/g of PFE values converted from the energy deposition of 240 ~ 260 cal/g.

To compare the relative significance among burnup, corrosion and pulse width on failure enthalpy, the input data for model derivation are normalized by their maximum values, i.e., 64 GWD/tU, 130 μm and 840 msec. In this case the proportional constants of burnup, oxide thickness and pulse width appeared to be –68.8, –100.6 and +86.0, respectively. This indicates the three primary factors affect on failure enthalpy in comparably, and among them the increase of water-side corrosion is the most detrimental factor in reducing the failure enthalpy of fuel rods under RIAs.

III. RELIABILITY ANALYSIS BY WEIBULL STATISTICS

Since the Weibull distribution proposed in the early 1950s, this methodology has been widely used in the area of life-time prediction under fatigue and fracture loads. The two-parameter cumulative Weibull distribution function is expressed as,

$$P_f(x) = 1 - \exp\left[-\left(\frac{x}{\eta} \right)^{\beta} \right] \quad (2)$$

where P_f is cumulative failure probability, x is the response parameter, η is characteristic life and β is shape parameter. The η implies 63.2% failure expectation at $P_f(\eta)$. The β controls the width of frequency distribution such that the higher the β, the narrower the probability density distribution. The details of Weibull statistics and derivation methods of Weibull parameters can be found elsewhere [21,22].

The several reliability assessments using Weibull statistics on fuel rod failures in nuclear reactor were reported, putting the response parameter as fuel burnup [23] or cumulative damage fraction (CDF) of cladding [24]. As a matter of fact, it has been often explained in that the PFE was a sole contributor on cladding damage when a fresh fuel was subjected to RIA condition. However, in case of high-burnup fuel, this assumption would lead to highly uncertain results, because the burnup and corrosion might significantly alter the failure enthalpy. To resolve this problem, a new concept that represents intensity of cladding damage, is introduced for irradiated fuel rod under RIA. We name it 'equivalent enthalpy', H_{eq} that is defined as follows,

$$H_{eq} = H_{\exp} + 0.774 \cdot OT + 1.076 \cdot Bu - 29.41 \cdot \log(PW) \quad (3)$$

where H_{exp} is experimental PFE or failure enthalpy that is given at a RIA-simulation test or hypothesized RIA situation. As analyzed in the previous section, the increase of burnup and oxide thickness or decrease of pulse width significantly reduces the failure resistance of cladding in the manner that shown in equation (1). In other words, the reduction of failure enthalpy implies the increase of peak fuel enthalpy encountered during RIA when expressing the influence of three main factors as the enthalpy equivalence values. For that reason, the three factors are incorporated into equivalent enthalpy correlation by reversing the signs of proportional constants in equation (1). The argument made for deriving equation (3) from equation (1) assumes the dependence of OT, Bu, and $\log(PW)$ is linear so that a decrease in the failure enthalpy of irradiated fuel rod is equivalent to an increase in the experimental PFE of unirradiated one. Therefore the equivalent enthalpy becomes a single damage parameter under RIA pulse for irradiated fuel rod that corresponds to the state of fresh fuel rod condition.

Figure 4 shows the equivalent enthalpy versus experimental enthalpy. The figure indicates the threshold failure enthalpy by means of H_{eq} is around 110 cal/g. On the other hand, some rods above that equivalent enthalpy are survived without failing. Thus, a failure distribution function is needed for reliability assessment by reflecting both the data set of the failed and the survived.

The intact data set is treated as 'suspended' data in determining Weibull parameters. The Weibull distribution function is derived in terms of reliability (1- P_f) in figure 5 together with its 95% confidence interval, and it can be written as a following formula.

$$P_f(H_{eq}) = 1 - \exp\left[-\left(\frac{H_{eq}}{193.4} \right)^{6.383} \right] \quad (4)$$

Figure 6 illustrates the failure probability and its failure probability density as a function of equivalent enthalpy. In this figure, the statistical parameters such as standard deviation, mean failure enthalpy in terms of equivalent enthalpy and failure probability at mean equivalent, are found to be 32.9 cal/g, 180 cal/g and 46.8%, respectively.

IV. SENSITIVITY ANALYSIS

In this section, a sensitivity analysis of high-burnup fuel with respect to PFE, pulse width, oxide thickness and fuel burnup is attempted as a basis of the failure model and failure probability function derived in the previous sections. Recently, some neutronics code calculations for the high-burnup fuel (40 ~ 60 GWD/tU burnup) were carried out in order to simulate the RIA reactor conditions in detail [7]. Their results have shown that the PFE and pulse width are reached in the range of 20 ~ 100 cal/g and 30 ~ 75 msec, respectively. On the basis of these results, the typical RIA conditions such as 60 cal/g and 50 msec of PFE and pulse width are selected and kept constant in this analysis. Also the high-burnup fuel rod conditions (60 GWD/tU burnup and 80 μm oxide thickness) are assumed and fixed.

Figure 7 shows the sensitivity results that are calculated from equations (3) and (4) in which only one variable is considered and three remaining factors are kept constant. As expected, the increase of burnup, oxide thickness and PFE gradually raises the susceptibility to cladding failure, while the pulse width up to 20 msec drastically decreases the failure probability as it increases.

To evaluate the effect of corrosion, inducing by the difference of cladding material used, the typical oxidation thickness of standard Zircaloy-4 and low tin Zircaloy-4 claddings in PWR reactor [25] is used in this sensitivity analysis as input values. Based on this simple correlation between burnup and oxide thickness, the sensitivity of failure probability is estimated in accordance with fuel burnup extension under typical RIA conditions in PWRs, and is shown in figure 8. The standard Zircaloy-4 and low tin Zircaloy-4 cladding materials would maintain their integrity up to the burnup of ~40 and ~45 GWD/tU, respectively, having negligible failure probability (~1% failure) under typical RIA situation. At 60 GWD/tU burnup, the failure probabilities of standard and low tin Zircaloy-4 cladding are calculated as 34% and 11%, respectively. These failure probability differences are only caused by their corrosion rate differences. Accordingly, it is instructive that highly corrosion resistant cladding material development is necessary for the purpose of the high burnup extension of fuel rod.

At present, the low tin Zircaloy-4 cladding is being used in the most of the PWR fuel rods. Thus its reliability versus PFE under typical PWR RIA conditions is plotted in figure 9 in variations with fuel burnup. In this prediction, 50% of failure probability is expected when 20, 40, 60 and 80 GWD/tU burnups of the fuel rods are subjected to PFEs of 201, 154, 104 and 55 cal/g, respectively.

The proposed concept of the equivalent failure enthalpy and related reliability function in this paper allows one to predict failure probability of fuel rods and may be of value in giving some insight into licensing criteria on RIA conditions for high-burnup fuels. For instance, if a licensee or a source term requirement limits 95% reliability (5% failure probability) with the upper bound 95% confidence level in RIA situation, then a fuel designer may meet that by showing the equivalent enthalpy is less than a certain level, in this case 120 cal/g from figure 5. Moreover in this case, if fuel burnup and oxide thickness were expected to be 60 GWD/tU and 80 μm, respectively, the accidental PFE should have not exceeded 43 cal/g when predicted pulse width is 50 msec that may be given from reactor core analysis.

V. CONCLUSIONS

The primary factors that control the failure susceptibility of Zircaloy cladded PWR type fuel rods under RIA have been identified as cladding corrosion, fuel burnup and pulse width. Using the worldwide RIA-simulation test results, the failure enthalpy was correlated with these factors and revealed that the impact on failure potential is decreased by the sequence of oxide layer, pulse width and fuel burnup. Based on failure enthalpy correlation, a new concept of ‘equivalent enthalpy’ was introduced in order to reflect the effects of peak fuel enthalpy and three primary factors into single damage parameter. Furthermore, the failure distribution function in response to equivalent enthalpy was derived by applying two-parameter Weibull statistics. This methodology might give some insight into failure forecast and licensing criteria adjustment for high-burnup fuel rods under RIAs.

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Table I. RIA results tested at PBF and SPERT reactor in USA [5,7]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, msec	Peak Fuel Enthalpy, cal/g	Fuel/Clad Type
802-1	5.2	5	16	185	UO_2/Zry-4
802-2	5.1	5	16	185	UO_2/Zry-4
802-3	4.4	5	16	Failed at 140	UO_2/Zry-4
802-4	4.5	5	16	185	UO_2/Zry-4
CDC-571	4.6	0	31	137	UO_2/Zry-2
CDC-568	3.5	0	24	Failed at 147	UO_2/Zry-2
CDC-567	3.1	0	18	Failed at 214*	UO_2/Zry-2
CDC-569	4.1	0	14	Failed at 282**	UO_2/Zry-2
CDC-703	1.1	0	15	163	UO_2/Zry-2
CDC-709	1.0	0	13	Failed at 202*	UO_2/Zry-2
CDC-685	13.1	0	27	158	UO_2/Zry-2
CDC-684	12.9	0	20	170	UO_2/Zry-2
CDC-756	32.7	65	17	Failed at 143	UO_2/Zry-2
CDC-859	31.8	65	16	Failed at 85	UO_2/Zry-2

*Peak fuel enthalpy is used since failure enthalpy is unknown.
**Excluded from analysis because this rod was failed through melting mechanism.

Table II. RIA results tested at CABRI reactor in France [8 ~ 10]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, msec	Peak Fuel Enthalpy, cal/g	Fuel/Clad Type
Na-1	64	85	9.5	Failed at 30	UO_2/Zry-4
Na-2	33	4	9.5	210	UO_2/Zry-4
Na-3	53	40	9.5	125	UO_2/Zry-4 (Low Tin)
Na-4	60	80	80	99	UO_2/Zry-4
Na-5	64	20	9.0	115	UO_2/Zry-4
Na-6	47	35	35	148	$UPuO_2$/Zry-4
Na-7	55	50	40	Failed at 120	$UPuO_2$/Zry-4
Na-8	60	130	75	Failed at 67	UO_2/Zry-4
Na-9	28	10	34	210	$UPuO_2$/Zry-4 (Low Tin)
Na-10	62	85	31	Failed at 79	UO_2/Zry-4

Table III. RIA results tested at NSRR reactor in Japan [11 ~ 15]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, msec	Peak Fuel Enthalpy, cal/g	Fuel/Clad Type
MH-1	38.9	4	6.8	47	UO_2/Zry-4
MH-2	38.9	4	5.5	55	UO_2/Zry-4
MH-3	38.9	4	4.5	67	UO_2/Zry-4
GK-1	42.1	10	4.6	93	UO_2/Zry-4
GK-2	42.1	10	4.6	90	UO_2/Zry-4
OI-1	39.2	15	4.4	106	UO_2/Zry-4
OI-2	39.2	15	4.4	108	UO_2/Zry-4
HBO-1	50.4	48	4.4	Failed at 60	UO_2/Zry-4
HBO-2	50.4	40	6.9	37	UO_2/Zry-4
HBO-3	50.4	25	4.4	74	UO_2/Zry-4
HBO-4	50.4	20	5.3	50	UO_2/Zry-4
HBO-5	44	60	4.4	Failed at 77	UO_2/Zry-4
HBO-6	49	30	4.4	85	UO_2/Zry-4
HBO-7	49	45	4.4	88	UO_2/Zry-4
TK-1	38	7	4.3	126	UO_2/Zry-4 (Low Tin)
TK-2	48	35	4.3	Failed at 60	UO_2/Zry-4 (Low Tin)
TK-3	50	12	4.3	99	UO_2/Zry-4 (Low Tin)
TK-4	50	25	4.3	98	UO_2/Zry-4 (Low Tin)
TK-5	48	30	4.3	101	UO_2/Zry-4 (Low Tin)
TK-6	38	15	4.3	125	UO_2/Zry-4 (Low Tin)
TK-7	50	15	4.3	Failed at 86	UO_2/Zry-4 (Low Tin)
JM-1	21.6	0	9	92	UO_2/Zry-4
JM-2	26.8	0	9	84	UO_2/Zry-4
JM-3	14.4	0	7.8	132	UO_2/Zry-4
JM-4	22.6	0	5.5	Failed at 178*	UO_2/Zry-4
JM-5	25.4	0	5.6	Failed at 167*	UO_2/Zry-4
JM-14	38	0	6	Failed at 160*	UO_2/Zry-4
JMH-3	30	0	6.2	Failed at 203*	UO_2/Zry-4

* Peak fuel enthalpy is used since failure enthalpy is unknown.

Table IV. RIA results tested at IGR and BIGR reactor in Russia [16 ~ 18]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, msec	Peak Fuel Enthalpy, cal/g	Fuel/Clad Type
H1T	51	5	800	160	UO_2/Zr-1Nb
H2T	50	5	760	Failed at 220*	UO_2/Zr-1Nb
H3T	50	5	820	Failed at 265**	UO_2/Zr-1Nb
H4T	50	5	760	115	UO_2/Zr-1Nb
H5T	50	5	840	Failed at 153*	UO_2/Zr-1Nb
H6T	50	5	800	80	UO_2/Zr-1Nb
H7T	47	5	630	Failed at 168*	UO_2/Zr-1Nb
H8T	48	5	850	56	UO_2/Zr-1Nb
RT No1	49	5	2.6	142	UO_2/Zr-1Nb
RT No2	48	5	3.2	115	UO_2/Zr-1Nb
RT No3	48	5	2.6	138	UO_2/Zr-1Nb
RT No4	61	5	2.6	125	UO_2/Zr-1Nb
RT No5	49	5	2.6	146	UO_2/Zr-1Nb
RT No6	48	5	2.6	153	UO_2/Zr-1Nb

*Peak fuel enthalpy is used since failure enthalpy is unknown.
**Excluded from analysis because this rod was failed through melting mechanism.

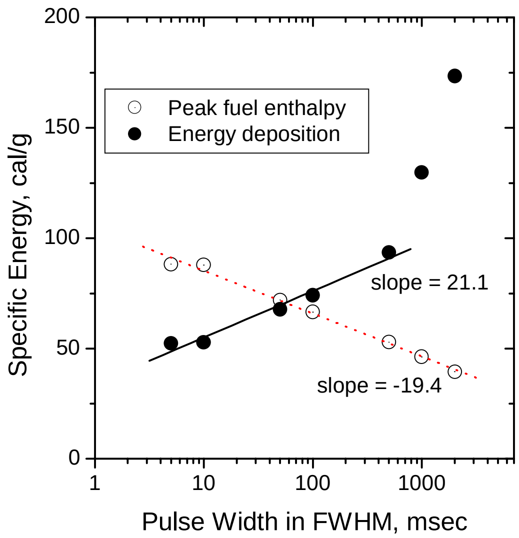

Figure 1. Variations of PFE for the same energy deposition of 70 cal/g and energy deposition for the same PFE of 70 cal/g, respectively, at a burnup condition of 60 GWD/tU [6].

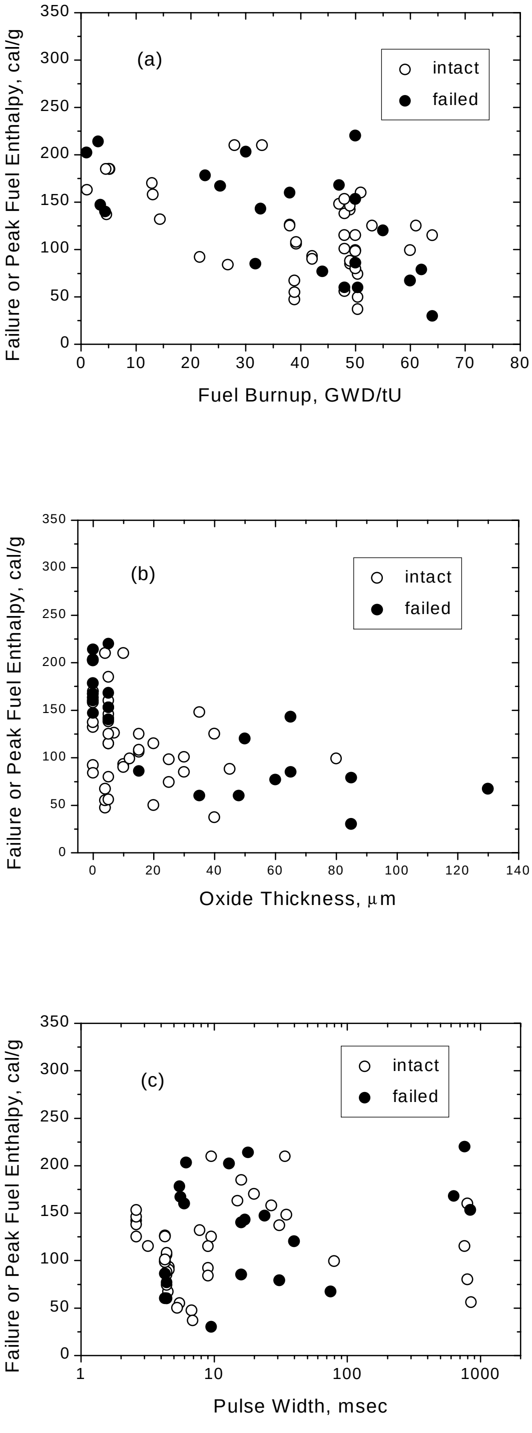

Figure 2. Influence of (a) fuel burnup, (b) oxide thickness, and (c) pulse width on the failure or peak fuel enthalpy of irradiated fuel rods.

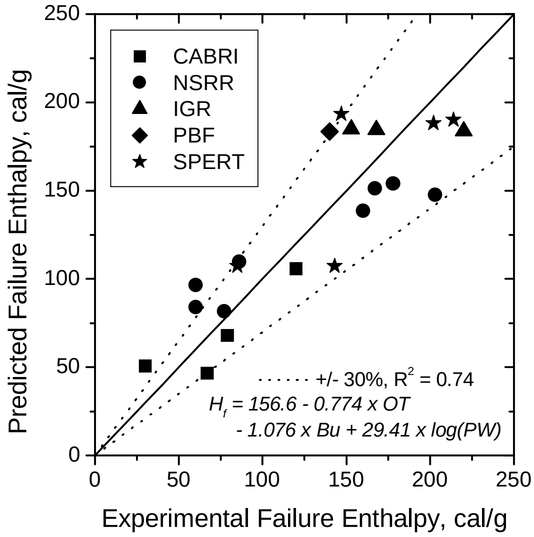

Figure 3. Comparison of the failure enthalpy between experimental data and the model predicted.

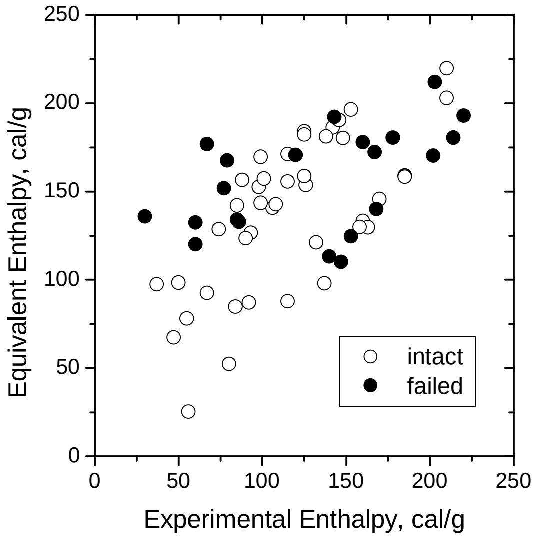

Figure 4. Calculation results of equivalent enthalpy along with the experimental enthalpy

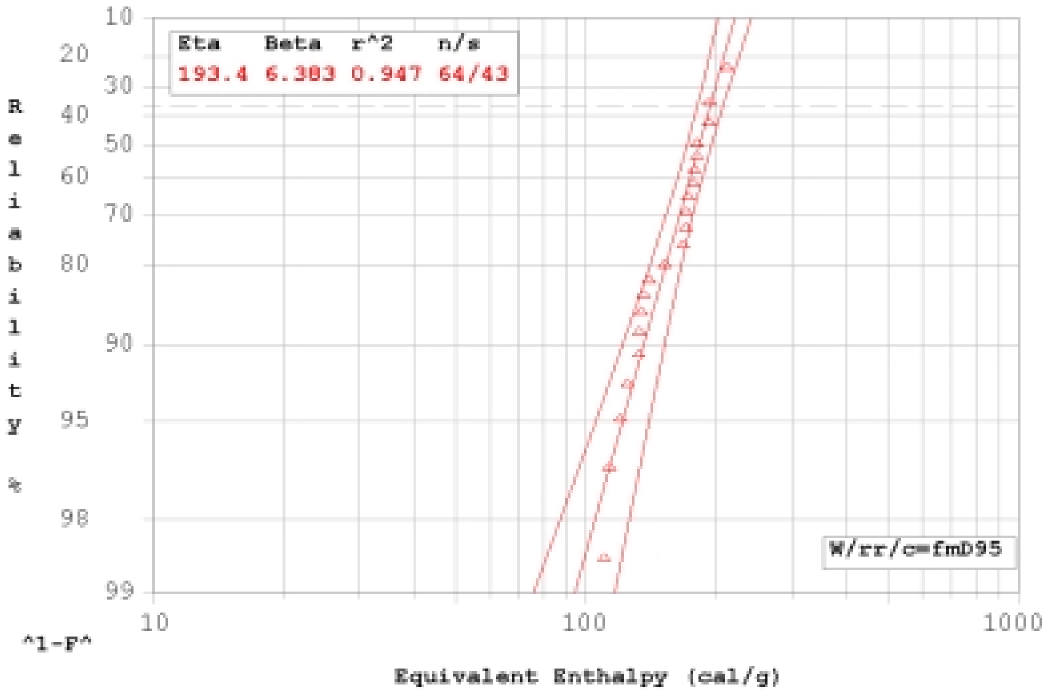

Figure 5. Determination of Weibull parameters with 95% confidence level

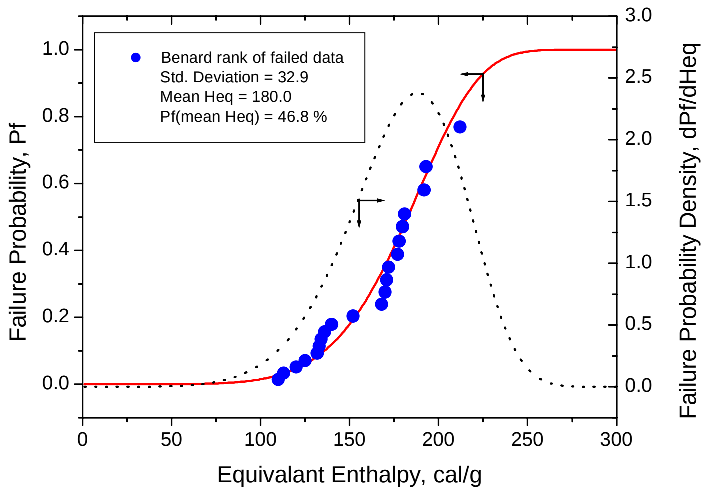

Figure 6. Plot of failure probability and its probability density with respect to the equivalent enthalpy

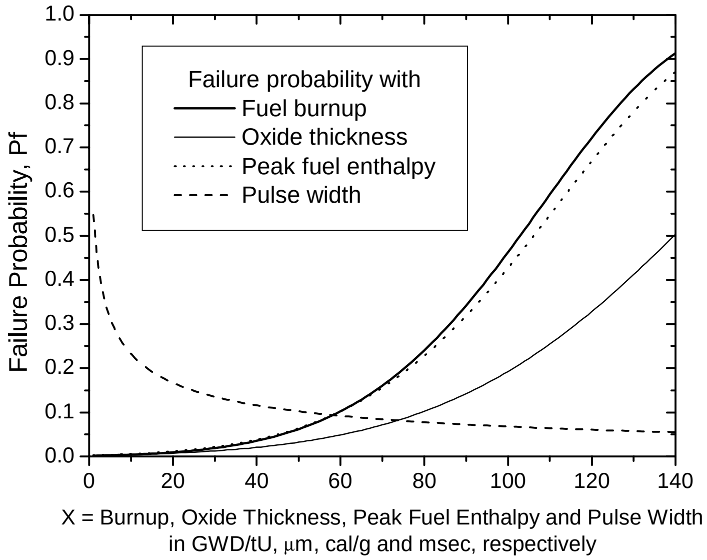

Figure 7. The failure probability trend of a fuel rod in variations with burnup, oxide thickness and accident conditions under RIA in LWR.

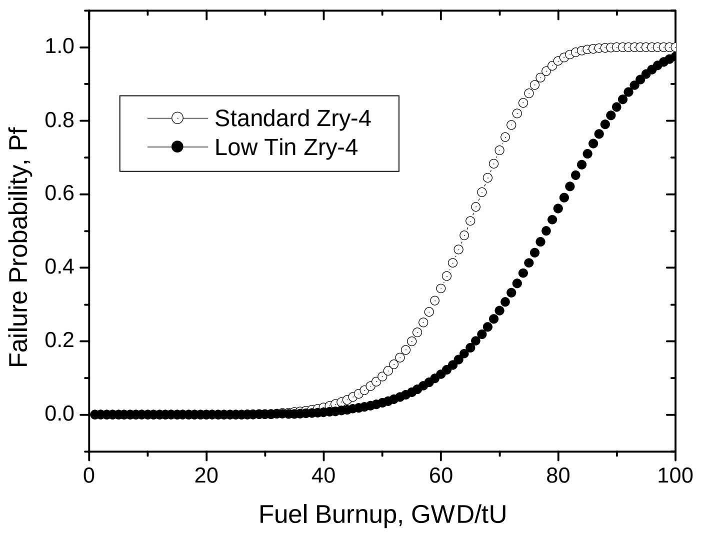

Figure 8. The predicted failure probability with fuel burnup in accordance with cladding materials under typical RIA conditions (PFE = 60 cal/g, pulse width = 50 msec)

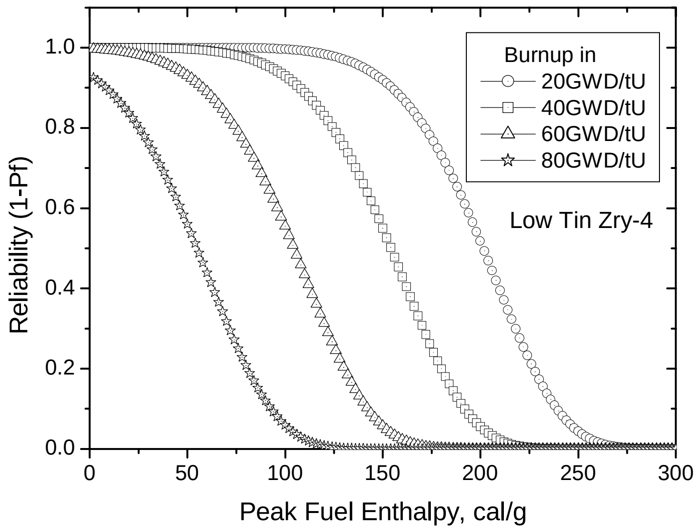

Figure 9. The predicted reliability with PFE in accordance with fuel burnup under typical 50 msec of power pulse.