Failure prediction of irradiated fuel rod in nuclear reactors under reactivity-initiated accidents by means of statistical approach

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Abstract

During the last decade, RIA behavior of high-burnup fuel rod has been of great concern in nuclear safety since there is an evidence of fuel rod failures at unexpectedly low enthalpy values. A statistics-based methodology was proposed to predict failure probability of irradiated fuel rods. Based on RIA results published in literature, the failure enthalpy of irradiated fuel rod was correlated with oxide thickness, fuel burnup, and pulse width. The 'equivalent enthalpy' was introduced as a single damage parameter characterizing the cladding damage of irradiated fuel rod. The failure probability distribution was represented as a function of equivalent enthalpy applying a two-parameter Weibull statistical model. Lifetime prediction was attempted using the developed methodology to estimate the effects of corrosion, fuel burnup, peak fuel enthalpy and type of cladding materials used.

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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 PFE (peak fuel enthalpy) criteria are used as limits in the range of 200~280cal/g according to regulatory authorities. The enthalpy values of 85~200cal/g or DNB (departure from nucleate boiling) criteria are usually imposed as fuel cladding failure thresholds. 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 60cal/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 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. Special emphasis has been placed on the cladding failure mechanism and licensing limit of high-burnup fuel.

As irradiation proceeds, the microstructures of fuel pellets also change, 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 simple statistical approach to predict 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. MODELS FOR FAILURE ENTHALPY AND RELIABILITY

As burnup increase, the cladding failure mechanism would significantly differ from that of unirradiated cladding due to microstructural changes in the 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 the increased level of oxygen dissolved [3] in Zircaloy. These hydrogen and oxygen contents are closely associated with the level of water-side corrosion. Therefore, corrosion reduces fracture resistance of cladding not only by consumption of a load-bearing ligament but also by an increase of hydrogen and oxygen contents in cladding material.

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 the RIA condition. The fuel swelling caused by solid fission products and cladding creepdown leads 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 believed due to hydride-assisted PCMI failure [4].

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 [5], the heating of fuel tends to be adiabatic during narrow power pulse width of less than about 10 ms, but with the pulse width becoming broader, peak contact stress and cladding temperature at the time of maximum stress decrease owing to the heat transfer from fuel to coolant. Since the ductile brittle transition (DBT) phenomenon in high-burnup Zircaloy cladding is believed to occur [3], cladding temperature associated with pulse width is important in the cladding failure mode. Volkov [5] also demonstrated that up to around 1,000 ms of pulse width the logarithmic scale of pulse width is linearly dependent on the energy deposition.

Figures 1 (a), (b) and (c) show the effects of fuel burnup, oxide thickness and pulse width, from the RIA test results with irradiated rods that are listed in Tables I to IV [6~17]. It is evident from these figures that data scattering is quite significant in all three plots, indicating that the failure of fuel rods is not controlled by only one dominant factor but several factors likely contribute to these failures. The three main independent variables, i.e., fuel burnup, oxide thickness and pulse width were considered in this failure model development because these three variables were 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, 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.

Multiple linear regression model has been widely used in the case where various factors are involved, so that establishment of the mechanistic model is hard to be practical. An example of establishing the multiple regression model can be found elsewhere [18]. The failure enthalpy of irradiated fuel rods was modeled by applying the multiple regression method under the assumption that the oxide thickness, burnup and pulse width each independently affected the failure enthalpy. In this model, the logarithmic dependence of pulse width was assumed from Volkov's calculation [5]. Taking into account only the failed data listed in Tables I to IV, the failure enthalpy correlation was derived as follows,

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

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

Figure 2 shows the uncertainty of the failure model. Even though the variety of test conditions and slightly different types of fuel and cladding materials were included in the experimental data, the failure model proposed provides reasonable predictions of the experimental results. Fujishiro [19] reported that the failure of fresh fuel rod was generally about 240~265cal/g of the energy deposition at a pulse width range of 4~70ms. When the failure model, equation (1) is extrapolated down to an unirradiated condition, the values of failure enthalpy are predicted in the range of 174~211cal/g depending on pulse width (4~70ms), these are comparable with 192~212cal/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 were normalized by their maximum values, i.e., 64GWD/tU, 130μm and 840ms. 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 the failure enthalpy 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.

Since the Weibull distribution was 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,

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

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 [20].

Several reliability assessments using Weibull statistics on fuel rod failures in nuclear reactor were reported, putting the response parameter as fuel burnup [21] or cumulative damage fraction (CDF) of cladding [22]. As a matter of fact, it has been often explained in that the PFE was the sole contributor to cladding damage when a fresh fuel was subjected to an RIA condition. However, in the 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 the intensity of cladding damage, was introduced for irradiated fuel rods under RIA. We named it 'equivalent enthalpy', H_{eq} that was defined as,

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

where H_{exp} is the experimental PFE or failure enthalpy that is given in an RIA-simulation test or hypothesized RIA situation. As analyzed before, the increase of burnup and oxide thickness or decrease of pulse width significantly reduces the failure resistance of cladding in the manner that is 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 enthalpy equivalence values. For that reason, the three factors were 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 an irradiated fuel rod is equivalent to an increase in the experimental PFE of an unirradiated one. Therefore the equivalent enthalpy becomes a single damage parameter under RIA pulse for an irradiated fuel rod that corresponds to the state of a fresh fuel rod condition.

Figure 3 shows the equivalent enthalpy versus experimental enthalpy. The figure indicates the threshold failure enthalpy by means of H_{eq} is around 110cal/g. On the other hand, some rods above that equivalent enthalpy 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 was treated as 'suspended' data in determining Weibull parameters. The Weibull distribution function was derived in terms of reliability (1- P_f) in figure 4 together with its 95% confidence interval, and it can be written as a following formula.

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

Figure 5 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 32.9cal/g, 180cal/g and 46.8%, respectively.

III. LIFETIME PREDICTION

A sensitivity analysis of high-burnup fuel was 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 (40~60GWD/tU burnup) were carried out in order to simulate the RIA reactor conditions in detail [6]. Their results have shown that the PFE and pulse width are reached in the range of 20~100cal/g and 30~75 ms, respectively. On the basis of these results, the typical RIA conditions such as 60cal/g and 50ms of PFE and pulse width were selected and kept constant in this analysis. Also the high-burnup fuel rod conditions (60GWD/tU burnup and 80 μm oxide thickness) were assumed and fixed.

To evaluate the effect of corrosion, induced by the difference of cladding material used, the typical oxidation thickness of standard Zircaloy-4 and low tin Zircaloy-4 claddings in PWR reactors [23] was used in this sensitivity analysis as input values. Based on the correlation between burnup and oxide thickness, the sensitivity of failure probability was estimated in accordance with fuel burnup extension under typical RIA conditions in PWRs, and is shown in figure 6. The standard Zircaloy-4 and low tin Zircaloy-4 cladding materials would maintain their integrity up to the burnup of ~40 and ~45GWD/tU, respectively, having negligible failure probability (~1% failure) under a typical RIA situation. At 60GWD/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 most of PWR fuel rods. The reliability of the Zircaloy-4 versus PFE under typical PWR RIA conditions is plotted in figure 7 with fuel burnup. The 50% of failure probability is expected when 20, 40, 60 and 80GWD/tU burned fuel rods encounter the RIAs having PFEs of 201, 154, 104 and 55cal/g, respectively.

IV. 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. The failure enthalpy was correlated with these factors and it was revealed that the impact on failure potential is decreased by the sequence of oxide layer, pulse width and fuel burnup. Based on the failure enthalpy correlation, a concept of 'equivalent enthalpy' was introduced in order to calculate fuel rod reliability by regarding the effects of peak fuel enthalpy and three primary factors as a 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 lifetime forecast for high-burnup fuel rods under RIAs.

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Table I. RIA results tested at PBF and SPERT reactor in USA [6]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, ms	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 [7~9]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, ms	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 [10~14]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, ms	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 [15~17]

Test ID	Burnup, GWD/tU	Oxide Thickness, μm	Pulse Width, ms	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.

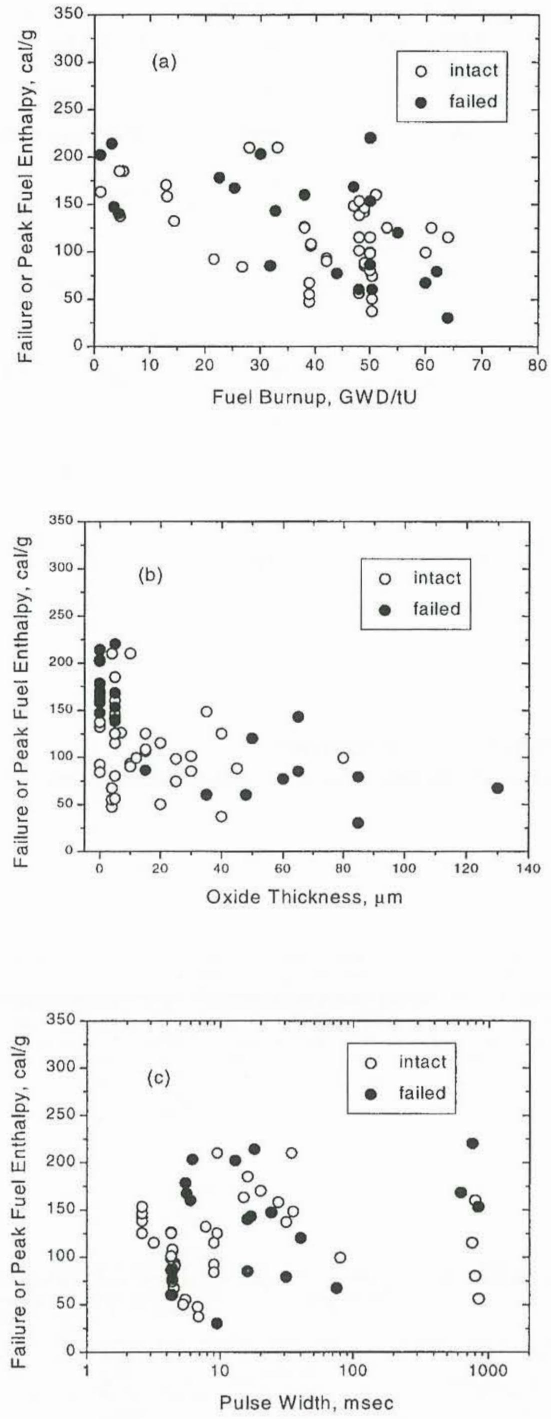

Figure 1. Influence of (a) fuel burnup, (b) oxide thickness, and (c) pulse width on the failure or peak fuel enthalpy of irradiated fuel rods.

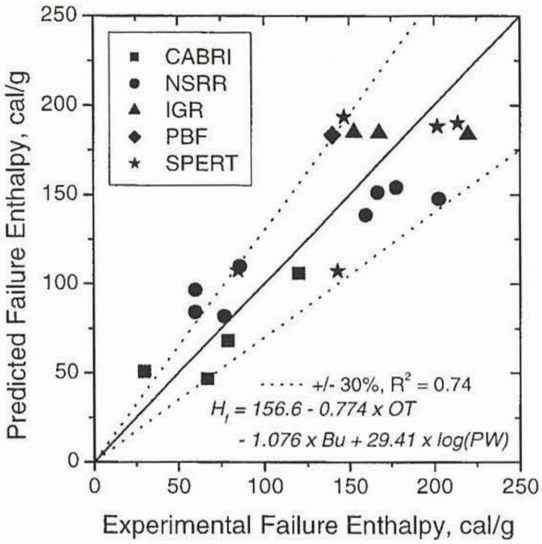

Figure 2. Comparison of the failure enthalpy between experimental data and the model predicted.

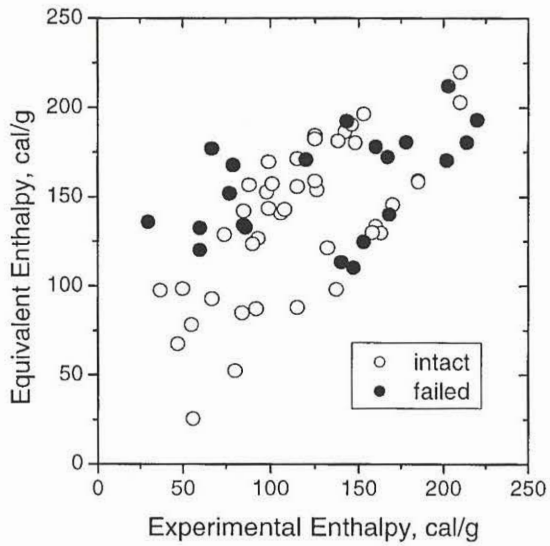

Figure 3. Calculation results of equivalent enthalpy along with the experimental enthalpy.

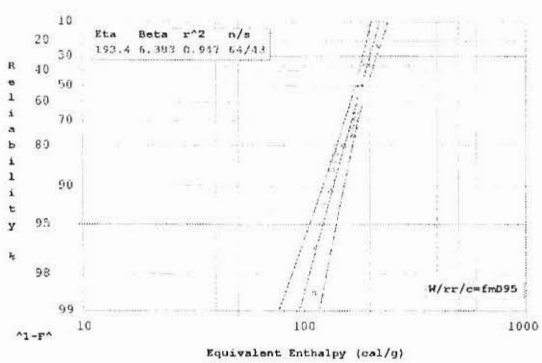

Figure 4. Determination of Weibull parameters with 95% confidence level.

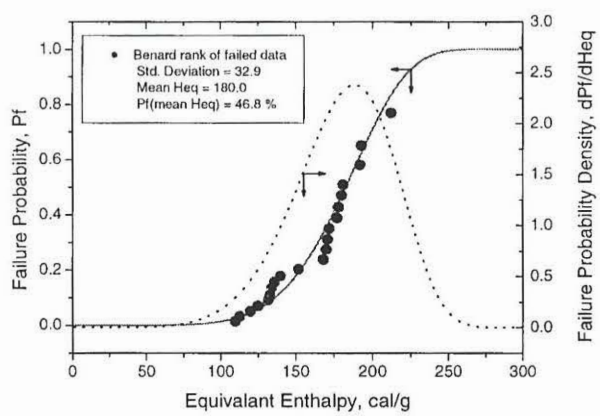

Figure 5. Plot of failure probability and its probability density with respect to the equivalent enthalpy.

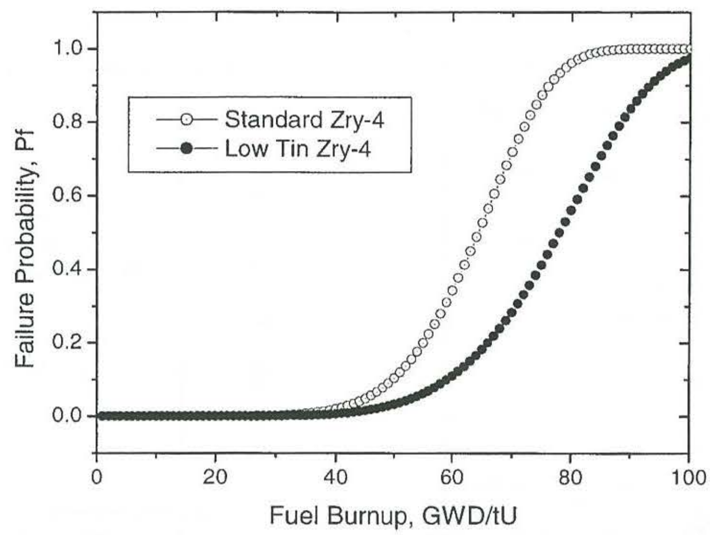

Figure 6. The predicted failure probability with fuel burnup in accordance with cladding materials under typical RIA conditions (PFE = 60cal/g, pulse width = 50ms).

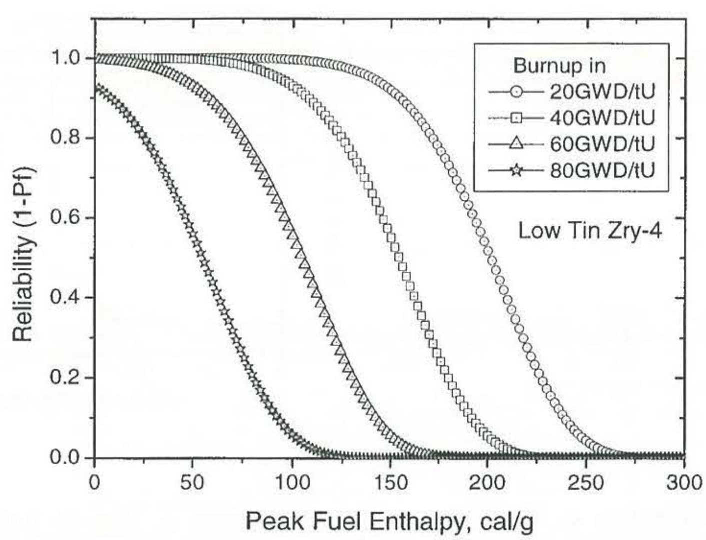

Figure 7. The predicted reliability with PFE in accordance with fuel burnup under 50ms of power pulse.