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Probabilistic Estimation of LMR Fuel Cladding Performance Under Transient Conditions

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Abstract

The object of this paper is the probabilistic failure analysis on the cladding performance of WPF(Whole Pin Furnace) test fuel pins under transient conditions, and analysis of the KALIMER fuel pin using the preceding analysis. The cumulative damage estimation and Weibull probability estimation of WPF test are performed. The probabilistic method was adapted for these analyses to determine the effective thickness thinning due to eutectic penetration depth. In the results, it is difficult to assume that a brittle layer depth made by eutectic reaction is all of the thickness reduction due to cladding thinning. About 93% cladding thinning of the eutectic penetration depth is favorable as an effective thickness of cladding. And the unreliability of the KALIMER driver fuel pin under the same WPF test condition is lower than that of the WPF pin because of the higher plenum-fuel volume ratio and lower cladding inner radius vs. thickness ratio. KALIMER fuel pin developed from conceptual design has a more stable transient performance for a failure mechanism due to fission gas buildup than the WPF pin.

Key Words : LMR fuel pin, cumulative damage fraction, weibull distribution, eutectic penetration, wall thinning

1. Introduction

A metallic U-TRU-Zr alloy with HT-9 cladding is considered as a potential fuel for the KALIMER(Korea Advanced LIquid MEtal Reactor). High thermal conductivity of the metallic fuel and use of the bond-sodium promote inherent safety characteristics of KALIMER core, and irradiation swelling-resistant ferritic-matensitic steel is favorable for the metallic fuel cladding because the neutron fluence in the metallic fuel core is usually higher than that in the oxide fuel core. Based on current progress in cladding material development, the cladding material is selected for the ferritic-matensitic alloys HT9. However, HT9 doesn't offer superior creep resistance for temperature range greater than approximately 640℃ compared to cold-worked Type 316 stainless steel[1]. This feature is unfavorable during off-normal temperature excursions because creep deformation is a potential cladding damage mechanism under transient conditions.

Important parameters leading to cladding rupture in metallic fuels during off-normal events are plenum pressure due to fission gas buildup, FCMI(Fuel-Cladding Mechanical Interaction) and eutectic penetration. Gas pressure loading is dominant for low burnup fuel where the fuel-cladding gap has not closed. FCMI loading of the cladding can occur under transient overpower conditions where the fuel expands into the cladding. However, this effect is minimized because of the similarities in thermal expansion coefficients between the fuel and the cladding in metal fuel[2]. Damage by eutectic penetration is caused by the interdiffusion of fuel constituents and lanthanide fission products with the cladding constituents. It was assumed that brittle zone in the cladding cause a cladding thinning for modeling purposes in this study.

Fuel-cladding compatibility was studied by FBTA(Fuel Behavior Test Apparatus) experiment[3].

The threshold temperature which FCI(Fuel Cladding Interaction) melting may occur during off-normal and the cladding penetration rate was gained from these tests. And the WPF(Whole Pin Furnace) experiment was conducted to simulate the transient accident of LMR. This test was subjected to temperature ramp and hold times representative of possible off-normal events[2].

The object of this paper is the probabilistic failure analysis for the cladding performance during transient conditions using the result of the WPF tests on irradiated fuel pins, and analysis of the KALIMER fuel pin using the preceding analysis. First, cumulative damage estimation about the WPF test data is performed by the transient failure correlation determined through the FCTT(Fuel Cladding Transient Testing) experiment and the cladding penetration data gained from the FBTA test. Then distribution of the CDF(Cumulative Damage Fraction) of the WPF data is determined by Weibull probabilistic analysis[4]. Finally, this distribution makes it possible to predict a failure of a fuel pin failure under transient conditions. Additionally, performance of the KALIMER breakeven core driver fuel pin designed by KAERI(Korea Atomic Energy Research Institute) has been estimated under the same condition as the WPF tests.

2. The Experiments Under Transient Conditions

The FCTT system was developed to simulate reactor transient heating and loading condition in the laboratory[5]. LOF(Loss-Of-Flow) events may give rise to relatively constant temperatures for a period of time. In this case, ramp and hold tests provide a better simulation of the transient conditions to which the fuel rod is exposed. FCTT tests were conducted at ramp and hold temperature condition. All specimens were initially heated from 370℃ at 5.6 ℃/s until a preselected hold temperature was reached. The temperature dependence of stress rupture life is represented in terms of the Dorn parameter, θ, and the activation energy, Q, as follows[6].

$$t_r = \theta \exp\left(\frac{Q}{RT}\right) \tag{1}$$

$$\ln\theta = A + B\ln\left[\ln\left(\frac{\sigma^*}{\sigma}\right)\right] \tag{2}$$

where constant B is 12.47, activation energy Q is 70,170 cal/mole, hardness of the material σ^* is 730 MPa., gas constant R is 1.986 cal/mole K, σ is applied stress in MPa, T is temperature in ℃, and t_r is expected rupture time in second.

Equation 3 represents parameter A in case of hold temperature below 871℃ and equation 4 reproduces parameter A above 871℃ and below 1050℃. T_H is the hold temperature in degrees centigrade.

$$A = 24.942 - 0.153T_H + 9.488 \times 10^{-5} T_H^2 \quad (3)$$

$$A = -36.1 + 1.5 \tanh\left[\frac{(T_H - 871)}{80}\right] \quad (4)$$

FCTT testing shows that the transient behaviors of the unirradiated cladding are the same as those of HT9 cladding specimens taken from the fuel column region. That is, the rupture test data of the unirradiated and irradiated specimens had a negligible difference in transient conditions in FCTT[6].

WPF test data was used for a probabilistic estimation of transient conditions for this study. WPF facility simulates transient conditions of metal fuel by external heating, because thermal conductivities of metal fuels are so comparable to those of cladding steels, that the fuel radial temperature profile in LOF accidents at decay heat levels would also be nearly flat[5]. WPF tests were ramp and hold tests like FCTT. The fuel parameters and key variables in the WPF tests are summarized in Table 1.

3. Cumulative Damage Estimation and Weibull Analysis

Under non-stationary loading conditions, it is difficult to predict a failure time because there are different effects of stress and temperature on the different damage stages. The concept of the Cumulative damage estimation based on linear summation of creep damage is appropriate for non-stationary stress and temperature loading conditions. The creep damage represents loading time per expected rupture time at a stationary loading condition. Cumulative damage fraction is given as follows[7, 8]

$$CDF = \int \frac{dt}{t_r(\sigma, T)} \quad (5)$$

where T is the temperature, σ is the hoop stress and tr is the rupture time at constant temperature and stress. The CDF value approaching unity means less margins to the creep rupture. This criterion is based on a correlation from cladding rupture data, however CDF=1 does not mean that failure indeed would occur at this value. Virtually it indicates the most probable failure point[9]

The fuel pin performance can be predicted using rupture correlation of the fuel pin. But present lifetime correlation does not consider hazards of

Table 1. Summary of WPF Tests

	Peak fuel burnup (a/o)	Plenum/fuel vol. ratio	Hold temperature (℃)	Test duration (min.)	Eutectic penetration (% of cladding thickness)
FM1	3.0	1.0	820	67 f	64
FM2	3.0	1.0	820	112 f	67
FM3	2.2	1.4	820	146 f	65
FM4	11.4	1.5	770	68 f	24
FM5	11.4	1.5	Ramp to 780, cool	3	0
FM6	11.3	1.0	670	2160	0

f cladding breach

environmental errors and uncertain material behaviors, such as pin vs. pin interaction, pin-duct interaction, hot spots, fretting wear, handling damage, etc[10]. Weibull analysis is a powerful probabilistic method of analyzing life-test experiments and these hazards. Weibull distribution has proved to be a successful model for many failure mechanisms because it has a flexible distribution with a wide variety of possible failure rate curve shapes. The two-parameter cumulative Weibull distribution function is written by[11],

$$F(t) = 1 - e^{-(t/\eta)^{\beta}} \qquad (6)$$

where η is the characteristic life and β is the shape parameter. The characteristic life is defined as the age at which 63.2% of the units will fail. The shape parameter determines which a failure rate curve shape is. The PDF(Probability Distribution Function) shape for β=3.4 becomes normal distribution and β=1 becomes exponential distribution. The Weibull distribution can be called by generalization of exponential and normal distributions[12, 13].

One of the advantages of the Weibull analysis is that it provides a simple and useful graphical plot. This plot has special scales. The ordinate is a double natural log scale of an expression containing the "fraction failing" while the abscissa is a single natural log scale of the random variable.

Combined use of CDF and Weibull analyses can provide a useful tool to the core designer and reactor operator for the evaluation and qualification of element designs[10]. To get failure distribution function, CDF values of failure point were applied to the age parameter of the Weibull distribution in this paper.

4. Analysis Results of WPF Tests and KALIMER Fuel Pin

4.1. Cumulative Damage Estimation of WPF Tests

To calculate the CDF of the fuel pin, above all, hold temperature, plenum pressure at EOL(End of Life) and eutectic penetration depth should be known. Plenum pressure was calculated by fission gas release, which was estimated by a MACSIS(A Metallic Fuel Performance Analysis Code for Simulating In-Reactor Behavior under Steady-State Conditions) code developed by KAERI[9]. However, it hasn't been able to estimate how much eutectic penetration depth affects cladding thinning up to now. In this study, the effective thickness concept was introduced[3]. The CDF of fuel pin was calculated from 100% cladding thinning to 60% cladding thinning due to eutectic penetration. 100% cladding thinning means that a brittle layer made by eutectic reaction didn't completely contribute to cladding strength

A calculation of the CDF was conducted by the Fortran code, what estimates increase in hoop stress as a function of cladding thickness thinning and determines the CDF values using transient correlation of the FCTT tests. Table 2 and figure 1

Table 2. CDF of WPF Data

WPF test	100%*	90%*	80%*	70%*	60%*
FM1	17.1068	7.7018	4.1131	2.4687	1.6122
FM2	54.8702	20.4489	9.5645	5.1955	3.1355
FM3	2.1138	1.0362	0.5863	0.3663	0.2460
FM4			7.7816		

*cladding thinning due to eutectic penetration depth

Table 3. Rupture Time of WPF Data

WPF Test	Rupture time (min.)					
	Present analysis			FPIN code		Test
	100%*	90%*	80%*	A**	B***	
FM1	33.96	37.43	41.70	36	-	67
FM2	39.47	43.63	48.76	42	-	112
FM3	110.44	143.46	203.96	93	108	146
FM4		8.74		4.4	16	68

* cladding thinning due to eutectic penetration depth

** 6% cladding strain criterion based on transient plastic flow law

*** Transient creep-rupture correlation

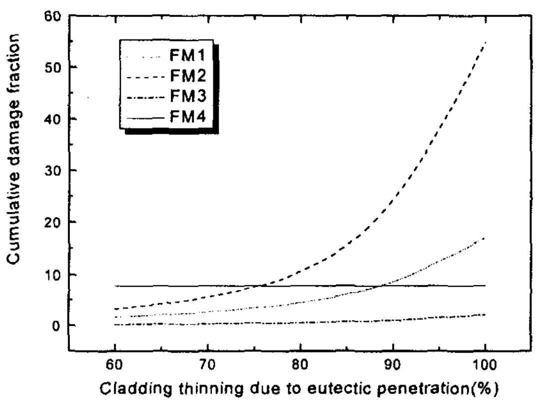

Fig.1. Calculated CDFs of WPF Rod According to Cladding Thinning

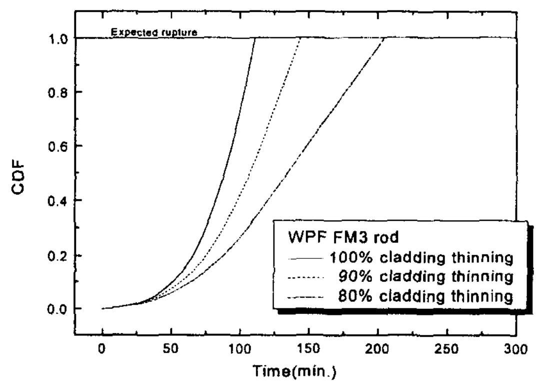

Fig. 3. Time-dependent CDF Values in FM3

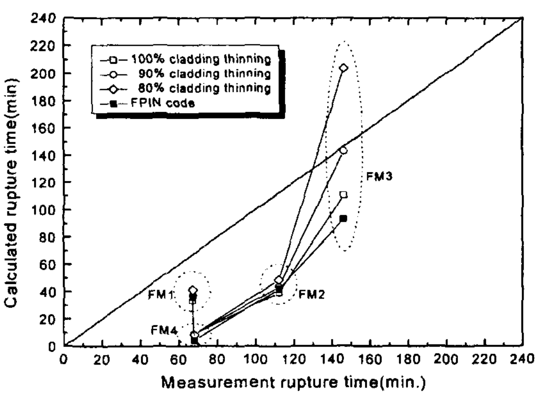

Fig.2. Calculated Rupture Time of WPF Rod According to Cladding Thinning

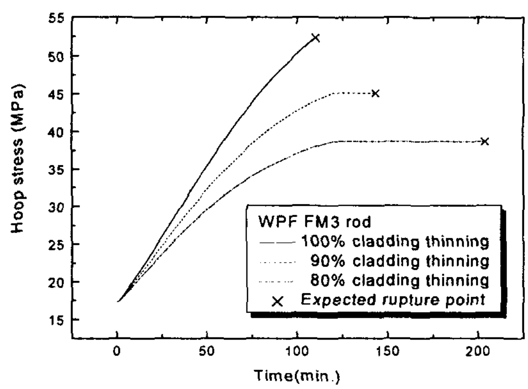

Fig. 4. Time-dependent Hoop Stress in FM3

shows the calculated the CDF at failure point of the WPF data. And Table 3 compares the predicted rupture time with the measurements from the tests and the estimated value of the FPIN code[2]. In case of 100% and 90% fractions of cladding thinning, the present determined rupture time has a similarity to the FPIN code analysis results. Also, calculated rupture times(CDF=1) of FM3 relatively are in reasonable agreement with the measurement more than the others and, the results of FM3 have the largest difference according to the cladding thinning fraction despite of large plenum-fuel volume ratio and low burnup as shown in figure 2.

While FM2 makes the greatest difference between the CDF values according to the cladding thinning fraction due to the eutectic penetration depth because it has a longer test rupture time than FM1 despite of similar low-burnup test circumstances, therefore cumulative creep damage is more sensitive to the cladding thinning fraction. This represents that the calculated rupture time is sensitive to the cladding-thinning fraction nearby CDF=1.

There was mismatch of calculated rupture time and CDF tendency with increasing the fraction, because most of damage accrues in a relatively short time late in life as shown in figure 3.

Figure 4 shows tendency of time-dependent hoop stress increase in FM3. Because of this tendency, the increment rate of CDF is higher with increasing time. For that reason, the calculated CDF has several decades, but the predicted rupture time has half of the measurements.

As a result of the CDF estimation, determining the fraction is considered as a primary contributor to the failure prediction of the low burnup pins.

4.2. Probabilistic Consideration of the Fraction of Cladding Thinning Due to Eutectic Penetration Depth

When a CDF distribution of the failure condition is estimated using a correlation, this distribution shape is variable with failure mechanisms, because uncertainties of the stress rupture correlation have a difference in each failure mechanism. The Weibull parameter, which determines this shape, is the shape parameter, β. However, though failure mechanisms of the cladding are different from each other so that each shape parameters have unequal values, if it is assumed that unity of CDF means 50% unreliability related to the correlation from the data and two mechanism are estimated by the same correlation, the standard failure values of the age parameter(50% unreliability) should be same. That is, two distributions that have a difference of failure mechanism should have the same value of median. The rupture correlation used in the effective thickness concept was identical with the correlation that estimates rupture time due to only gas pressure buildup in this paper.

The following consideration is the probabilistic method of determining the fraction of cladding

Table 4. Weibull Parameter

	100%*	90%*	80%*	70%*	60%*
β	0.587	0.639	0.681	0.716	0.745
η	27.44	11.20	5.581	3.179	1.991
Mean	42.49	15.59	7.254	3.941	2.385
Median	14.70	6.313	3.259	1.905	1.217

*cladding thinning fraction due to eutectic penetration depth thinning.

- To determine the fraction as distributions that consist in the CDF calculated by each failure mechanism having the same median values.

4.3. Weibull Analysis of CDF

The data sets of CDF and unreliability were used for making a point on Weibull paper. Then, we linearly fitted the data sets by rank regression method. Table 4 shows estimated Weibull parameter as the cladding thinning fraction due to eutectic penetration, and each probabilistic distribution on Weibull paper is shown in figure 5. This represents the failure distribution function shifts to the right side on the paper as the cladding thinning fraction increases.

Figure 6 compares the median values of FM1 ~ FM3 Weibull distribution responding to the fractions of the wall thinning effect, with CDF of FM4 in which only the gas loading mechanism worked. The match point is 93% wall thinning due to eutectic penetration. The median value is 7.95 at 93%. Figure 7 shows Weibull distribution of 93% including FM4. The characteristic life is 12.75 and the shape parameter is 0.812 in the distribution. The low shape parameter results from small sample size and excess extrapolation of the transient correlation. For more accurate probabilistic distribution, more test data need to be secured. The Weibull paper made by the methods mentioned previously has an important roll of a useful probabilistic performance analyzer. The failure distribution function of WPF test data is considered as follow,

$$F(t) = 1 - e^{-(t/\eta)^{\beta}} \quad (7)$$

The CDF value(7.7816) of FM4 test is in position between 100% and 90% cladding

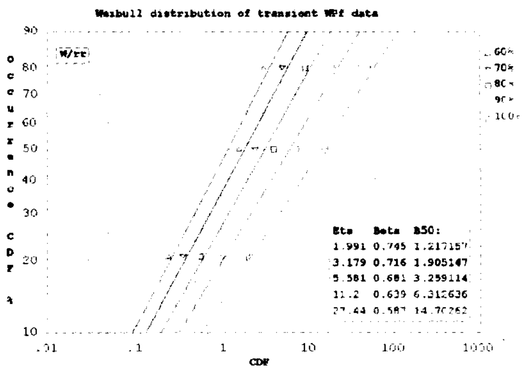

Fig. 5. Probabilistic Distribution of WPF Test Data on Weibull Paper

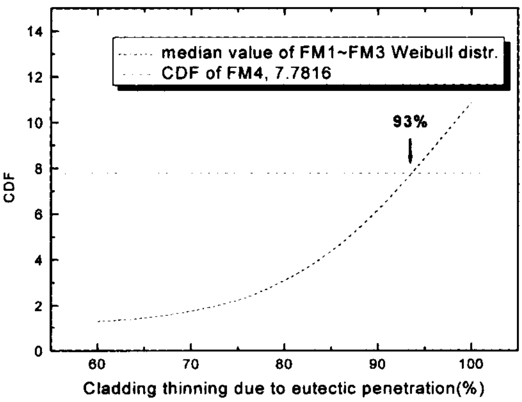

Fig. 6. Comparison Between Median of FM1~FM3 Weibull Distribution and CDF of FM4

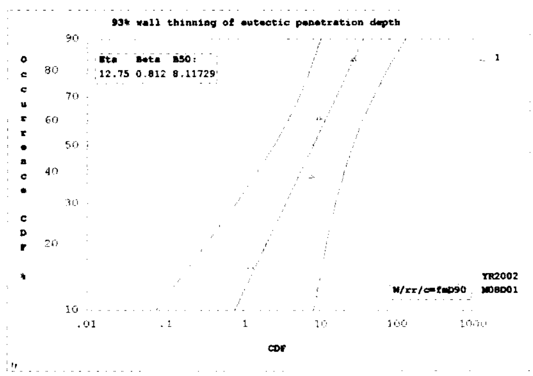

Fig. 7. Weibull Distribution of 93% Cladding Thinning Due to Eutectic Penetration Depth Including CDF of FM4

Table 5. Key Pin Parameters for WPF Tests and KALIMER

	Fuel type	Cladding type	Plenum fuel vol. ratio	Smear density (%)	Cladding outer diameter (mm)	Cladding thickness (mm)	Fuel diameter (mm)
KALIMER	U-30TRU-10Zr	HT9	1.75	75	7.4	0.55	5.46
FM-1	U-10Zr	HT9	1.0	75	5.84	0.38	4.39
FM-2	U-19Pu-10Zr	HT9	1.0	75	5.84	0.38	4.39
FM-3	U-26Pu-10Zr	HT9	1.4	75	5.84	0.38	4.39
FM-4	U-19Pu-10Zr	HT9	1.5	75	5.84	0.38	4.39

Table 6. KALIMER Driver Fuel Performance Under WPF Test Condition

Transient condition	KALIMER Driver fuel rod			WPF test fuel rod		
	CDF* time(min.)	Rupture time(min.)	Unreliability (%)	CDF**	Calculated Rupture	Test(min.)
FM1	0.1672	191	2.92	9.5796	36.31	67
FM2	0.4673	161	6.59	26.7166	42.29	112
FM3	0.1635	534	2.86	1.2605	131.18	146
FM4	0.7451***	91	9.48	7.7816***	8.47	68

* at failure time of WPF test

** at 93% cladding thinning due to eutectic penetration

*** not including cladding thinning effect

thinning. This means that the brittle zone caused by eutectic penetration would contribute strength of cladding more or less. Through Weibull probabilistic analysis, the effective thickness is expected at about 90% cladding thinning. But uncertainty of the cladding thinning estimation is large because of a small sample size. The present estimation gives a hint of conservative estimation tendency of 100% cladding thinning.

4.4. Prediction of KALIMER Fuel Pin Performance Under Transient Condition

The key parameters of the WPF test pin and the KALIMER breakeven core driver fuel pin are summarized in table 5, and table 6 shows the KALIMER driver fuel pin performance under the same WPF test's temperature condition. It was assumed that the eutectic reaction of the KALIMER fuel pin is the same as the WPF pins because there is no test data of the KALIMER fuel pin concerning eutectic penetration. The cladding thinning due to eutectic penetration depth has a considerable influence on the increase of hoop stress, which is a key factor of the failure mechanism of the cladding under transient conditions.

CDF values of the KALIMER pin are below 1.0. The unreliability of high burnup(11.4a/o) fuel pin is 9.48% in FM4 condition and, is higher than that of a low burnup fuel pin. Figure 8 represents the WPF test point and calculation point of the KALIMER driver fuel pin in the Weibull distribution predetermined by the WPF test data.

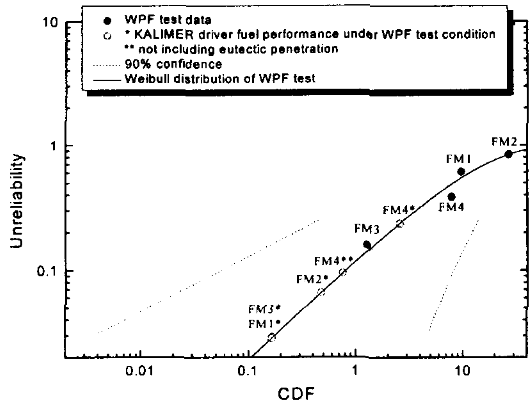

Fig. 8. KALIMER Driver Fuel Pin Performance in Weibull Distribution

Except FM4 condition, the CDF values of the KALIMER driver fuel pin in a lower bound of 90% confidence does not exceed median value of the Weibull distribution, because plenum-fuel volume ratio(1.75) of the KALIMER pin is higher than that of WPF test pin. The larger this ratio is, the lower the plenum pressure is at the end of life.

Also, the cladding inner radius vs. thickness ratio of KALIMER pin is 5.73, and the ratio of WPF pin is 6.68. The hoop stress is proportional to this ratio in the case of the same plenum pressure. That is, the KALIMER fuel pin developed from conceptual design has a more stable transient performance for a failure mechanism due to fission gas buildup than the WPF pin.

5. Conclusions

The probabilistic estimation methods of the CDF reflect uncertainty of correlation and over-estimation tendency, so it is concluded that this method has a higher reliability than estimation only by a correlation.

To estimate the cladding-thinning fraction due to eutectic penetration, the proposed method is to let the distributions of each failure mechanism have the same median value. This method makes it possible to quantify an unknown failure mechanism.

The CDF value(7.7816) of FM4 test is in median values of FM1 ~ FM3 Weibull distribution between 100% and 90% cladding thinning. The match point is 93%. This result shows that eutectic penetration layer may not completely lose the strength. That is, 100% cladding thinning is considered to be conservative, and there is need to test the verification of strength of the eutectic penetration layer.

The failure probability of the KALIMER driver fuel pin under the same WPF test condition is lower than that of the WPF pin because of a higher plenum-fuel volume ratio and lower cladding inner radius vs. thickness ratio. If we have more transient data points of the LMR fuel pin, we will set more accurate probabilistic design criteria, which will be applied to the LMR pin design.

Acknowledgements

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