HIGH TEMPERATURE DEFORMATION MODEL FOR ZIRCALOY CLAD BULGING UNDER LOCA CONDITIONS

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SUMMARY

During the hypothetical design base loss-of-coolant accident (LOCA), the coolant depressurization and reduced coolant flow causes a pressure differential across the fuel clad and high cladding temperatures. Cladding deformations and the potential for clad bulging must be evaluated for these conditions. This paper presents a plastic-creep deformational model for the zircaloy cladding for application under prototypic LOCA environmental conditions. The plastic contribution to deformation is based upon fuel clad burst test data for temperatures below 780°C (1435°F) and on rapid heatup burst test data above this temperature. The relation obtained for the plastic deformation, $\varepsilon_p$, is

$$\varepsilon_p = 0.194 \times (\sigma/\sigma_f)^{4.012}$$

where the true circumferential stress, $\sigma$(psi), is divided by the temperature dependent stress factor

$$\sigma_f = \exp\left(7.79856 - \frac{15042.8}{T_A} + \frac{35.67994 \times 10^6}{T_A^2}\right) T_A > 1895 R$$

$$= 65470 + 35.852 \times T_A - 0.032146 \times T_A^2 T_A > 1895 R$$

The creep contribution to deformation is based upon high temperature creep rupture data to determine the activation energy and upon constant pressure heatup cladding burst tests conducted in steam and air to determine the creep rate coefficient and the bulging strain stability criterion. The relation obtained for the creep deformation rate is,

$$\dot{\varepsilon}_c = \exp\left[-0.4247 - (Q/R)/T_A\right] \cdot \sigma^{4.012}$$

where

$$Q/R = 77050$$

$$= 72800 + 10.5 \times (T_A - 2150) T_A < 2150 R$$

and the strain stability criterion is 0.1514.

The empirical fit of creep rate coefficient and strain stability criterion was obtained with the SIMPLEX parameter search and a quadratic error surface minimization technique. Resultant standard deviation estimates of the creep rate and strain stability criterion were 0.0138 and 0.00017, and the multiple correlation coefficient was 0.894. The resultant model correlated with data where bulge failure temperatures ranged between 760°C (1400°F) and 1260°C (2300°F). This material model is used in a time incremental computer code (BULGEX) to evaluate clad deformations and the onset of bulging for both BWR and PWR LOCA conditions.
1. Introduction

Safety studies for light water reactors in the U. S. A. require evaluation of the effects of a loss-of-coolant accident (LOCA) on the cooling capability of the core. During the hypothetical design base LOCA, the coolant depressurization and reduced coolant flow causes a pressure differential across the fuel clad and high cladding temperatures. Cladding deformations occur which affect the gap conductance during the blowdown phase of the accident, and clad bulging may occur which could affect the oxidation rate, radiation heat transfer, and coolant flow during reflooding. Rapid coolant depressurization and temperature increases may occur during part of the LOCA while in other portions the pressure differential may be approximately constant, and the rate of temperature rise will decrease. Both plastic and creep deformational processes must be considered to represent the full range of conditions encountered by the fuel cladding. This paper describes how experimental data from a variety of material tests were used to evaluate a plastic-creep deformational model and a stability criterion for the onset of bulging for zircaloy cladding under prototypical LOCA environmental conditions.

The evaluation procedure is based upon assuming functional forms for the deformation processes based on the general deformational processes observed in zircaloy. Parameters are adjusted in the assumed deformational behavior using statistical and parametric adjustment techniques. The onset of clad bulging is assumed to be a plastic instability that can be empirically evaluated as a strain limit. The test data [1-15] used for empirical evaluation were all collected on pressurized tubular geometries which simulates the loading conditions of the cladding during a LOCA and allows the circumferential stresses and strains to be directly related to test measurements without the use of generalized stress criteria and flow rules. The stress-strain relations are expressed in terms of true stress and true strains so that the large deformation processes can be realistically represented.

2. Material Model Evaluation

Data from four test conditions [1-15]—inert atmosphere rapid heatup burst tests, constant temperature burst tests, creep burst tests, and steam atmosphere heatup burst tests—were used to evaluate the material deformation model. The sequence used for evaluating the material model was to: (1) evaluate the plastic deformation with rapid heatup burst test and constant temperature burst test data, (2) evaluate the temperature dependence of creep deformation model with creep burst test data, and (3) adjust the creep coefficient and strain stability criterion with heatup burst test data obtained in steam and air atmospheres.

The failure data from heatup burst data run in inert atmospheres with heating rates greater than 100°F/sec. were analyzed with a linear regression subroutine to correlate the log of the failure stress with a second order polynomial of the reciprocal absolute failure temperature. The correlation obtained from this statistical fitting procedure was:
\[
\sigma_f = \exp \left( 7.79856 - \frac{15042.8}{T_A} + \frac{35.67994 \times 10^6}{T_A^2} \right) \tag{1}
\]

\(\sigma_f\) = instantaneous bulging stress (psi),

\(T_A\) = absolute failure temperature (R) \(\geq 1895R\) or (1053K)

The plastic deformations were assumed to be a power function of true stress[10] with an exponent of 4.012. An average uniform strain limit value of 0.194 was obtained from deformations measured [12] adjacent to cladding bulges and this value was used for the true strain corresponding to \(\sigma_f\). The rod heatup test data were limited for highly pressurized rod data and the correlation for the instantaneous bulging stress extrapolated to very high values for temperatures below 780°C (1435°F). Thus, constant temperature burst test data [4,5] were used to obtain the relation for the instantaneous bulging stress at temperatures below 780°C (1435°F). These data indicated that the burst stress was dependent upon the pressurization rate; hence, only the rapidly pressurized tube burst data were used to obtain the instantaneous bulging stress relation for the lower temperature regime. The relation obtained using data from tubes pressurized at a rate greater than 50 psi/sec. is:

\[
\sigma_f = 65470 + 35.852 \times T_A - 0.032146 \times T_A^2 \tag{2}
\]

for \(T_A < 1895R\) or (1053K). The correlations of eqs. (1) and (2) and the experimental data used to obtain these correlations is presented in Figure 1. The resultant relation used for the plastic component of circumferential strain, \(\varepsilon_p\), is

\[
\varepsilon_p = 0.194 \left(\sigma/\sigma_f\right)^{4.012} \tag{3}
\]

where \(\sigma = \) true circumferential stress (psi) and \(\sigma_f\) is given by eqs. (1) and (2).

The data from high temperature creep burst tests conducted in an inert atmosphere [10] were used to evaluate the activation energy and power dependence of the creep rate relation. The creep strain was determined by subtracting the plastic strain calculated with eq. (3) from the measured strain. This creep strain was then divided by the time to reach this strain and by the factor \(\exp (-Q/R_A) \times 0.012\). The activation energy term, \(Q/R\), was temperature adjusted to obtain a rate that did not show any temperature bias. Initially a constant activation energy [8] was used for the temperature adjustment. The resultant correlation for the log of this adjusted rate with temperature showed sharp breaks at the \(\alpha + \beta\) to \(\beta\) phase boundary and a temperature bias at high temperatures. The temperature adjustment for the activation energy terms, \(Q/R\), that resulted in an improved correlation for a constant creep rate coefficient was

\[
Q/R = 77050 \quad T_A < 2150R \tag{4}
\]

\[
= 72800 + 10.5 \times (T_A - 2150) \quad T_A \geq 2150R \text{ or (1194K)}
\]

Variations of the power stress dependence were also made about the reference value of 4.012. The suggested value [8,9] of 4.012 was very near to that which yielded the lowest variance with the data, and the creep rate coefficient was correlated using this value.
The deformation of zircaclay at high temperatures in steam atmospheres alters the creep rates and uniform ductility limit. Thus, correlations of data from steam and air atmosphere tests cannot be made directly with material properties determined in inert atmospheres but must be correlated with data from prototypic test atmospheres. The creep rate coefficient $A$ in the relation

$$
\dot{\varepsilon}_C = \exp \left[ A - (Q/R)/T_A \right] \cdot \sigma^{4.012} 
$$

and the strain stability coefficient $\varepsilon_B$ were evaluated with the data obtained from heatup or multi-rod burst tests run in prototypic air-steam atmospheres with heating rates lower than 50°F per second. Final fitting of the parameters was accomplished by using the SIMPLEX [16,17] parameter fitting search technique. The SIMPLEX search technique is based on evaluation of a function at points in the parameter space. For this application, the function was the sum of squares of the measured failure temperatures minus the failure temperatures calculated using a model for heatup tests with the proposed deformation model, eqs. (1) - (5), and the parameters were the creep rate coefficient $A$ and the strain stability coefficient $\varepsilon_B$. The particular search program used to perform this parameter fitting also included an additional adjustment of passing a quadratic surface through the final SIMPLEX parameter fit by numerically evaluating the first and second derivatives of the sum of squares with respect to the parameters and solving for the minimum of this surface. If the determinant of the second derivative matrix is positive, then the inverse of this matrix times twice the variance of estimation is the large sample estimator of the variance matrix of the parameters. This relation follows from the maximum likelihood estimation procedure [19] assuming that both the sample deviations and parameter deviations are from a multivariate normal distribution. An independent check of the numerical evaluation of derivatives of the function surface and parameter variance estimation was made using a function and data from the literature [16] and the resultant variance estimation was found to agree within 10% of that obtained by an analytical derivative evaluation of the likelihood function. The numerical SIMPLEX and quadratic surface technique was applied to data from references[2, 6, 7, 9, 10, 12, and 14](85 data points). The SIMPLEX was initially selected as quite large and then refined. Initial runs were made with time increments equivalent to a 10°F change in temperature and on the final fit reduced to a 2°F change. The resultant minimization yielded $A = -0.4247$, eq. (5), and $\varepsilon_B = 0.1514$. The variance of $A$ was $1.92 \times 10^{-4}$ and of $\varepsilon_B$ was $2.90 \times 10^{-5}$ with a cross variance of $9.23 \times 10^{-6}$. (Standard deviations of $A = 0.0138$ and $\varepsilon_B = 0.00017$ and a correlation coefficient of 0.124.) The variance of the data was $2.88 \times 10^4$, and the variance $R^2$ the fit was $5.80 \times 10^3$ which results in a coefficient of multiple determination of $R^2 = 0.7986$ or a multiple correlation coefficient of $R = 0.894$. The final correlation of the predicted failure temperatures versus the measured failure temperature is presented in Figure 2.
A one-way analysis of variance was also performed to check the sources of data to see if the source of data was a controlling factor on the resultant correlation. The sources were established by testing site, multi-rod test, and test atmosphere with the four classifications as:

Set 1 = References 2, 9
Set 2 = References 6, 7, 10
Set 3 = Reference 14
Set 4 = Reference 12

The analysis of variance with respect to data source indicated that the deviations within tests were ~73°F and between tests were ~22°F. Thus, the correlation was not controlled by the test data source.

3. Application of the Deformation Model

The deformation model defined by eqs. (1) - (5) was incorporated into a computer program BULGEX [20] which evaluates internal pressure in a fuel rod and the history of cladding deformations. The axial distribution temperature history of the cladding is used in a time incremental calculational procedure determining the axial distribution of the cladding deformations. Thermal expansions of the fuel pellet stack and cladding as well as the cladding mechanical deformations are used to determine the free volume for the fill and released fission gases. The gas is assumed to be at equilibrium in all the free volumes at the temperatures associated with each free volume. The BULGEX code has been used to determine cladding deformation conditions for both BWR and PWR conditions. The deformational model presented in this paper and used in the BULGEX code has yielded consistent predictions over a wide range of conditions. Representative of these predictions are those presented in Figure 3 for a sensitivity study of effects of initial free gas content and rate of temperature variation for bulging of a BWR fuel geometry. The reference temperature history varied approximately parabolically (a continual decrease in rate of temperature change) between 1200°F and 2200°F in ~300 seconds. The time scale of this temperature history was contracted to 150 seconds for the fast temperature history. The axial temperature variation of the cladding and gas in the gap and dish volumes varied with an axial power factor of 1.57. Other reference conditions used in these calculations were:

- Cladding outer diameter: 0.567 inch
- Cladding thickness: 0.0355 inch
- Nominal gap: 0.004 inch
- Active fuel length: 144 inches
- Dish volume fraction: 0.02
- Effective plenum length: 9.081 inches
- Plenum temperature: 275°F
- Coolant pressure: 15 psia

The BULGEX calculation predicts reasonable bulging temperatures over the entire range of conditions and shows the rate dependence of the deformational processes. This calculational procedure also finds general application for both BWR and PWR loss-of-coolant accident conditions.


FIGURE 1: FAILURE TEMPERATURE - INSTANTANEOUS BULGING STRESS FOR RAPID HEATUP TUBE BURST TESTS AND HIGH PRESSURIZATION RATE BURST TESTS
FIGURE 2: COMPARISON OF CALCULATED VERSUS MEASURED FAILURE TEMPERATURES OF RAPID HEATUP BURST TESTS IN STEAM AND AIR ATMOSPHERES

FIGURE 3: EFFECT OF TWO TEMPERATURE HISTORIES OF BULGING OF TYPICAL BWR CLADDING UNDER LOCA CONDITIONS