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A MODEL FOR FUEL ROD AND TIE ROD ELONGATIONS IN BOILING WATER REACTOR FUEL BUNDLES

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ABSTRACT

A structural model is developed to determine the relative axial displacements of the spring held fuel rods to the tie rods in Boiling Water Reactor fuel bundles. An irradiation dependent relaxation model, which considers a two stage relaxation process dependent upon the fast fluence is used for the compression springs. The changes in spring compression resulting from the change in the length of the zircaloy fuel cladding due to irradiation enhanced anisotropic creep and growth is also considered in determining the time dependent variation of the spring forces. The time dependence of the average linear heat generation rates and their axial distributions is taken into account in determining the fuel cladding temperatures and fast fluxes for the various fuel rod locations within each of the BWR fuel bundles whose relative displacements were measured and used in this verification study.

Data from 116 relative rod length measurements on four designs of BWR fuel bundles undergoing exposures from 10 to 30 MWD/KGU are compared to predictions made with this structural model. Irradiation histories are calculated for each bundle using fuel management neutronic calculations based on reactor power level, flow conditions and control rod insertions. All the parameters in the material models are based on material property data and were not adjusted during this verification study. A sensitivity set of calculations was made for the anisotropic parameters used in the cladding creep model flow relation. The total deformations are dependent upon the anisotropic parameters (R and P factors for relative contraction) with fourty percent more deformation predicted in the tie rod for the anisotropic model than for the isotropic model, but the relative deformation variations are all less than eight percent between the two different creep model assumptions. The predicted relative rod changes using the anisotropic creep model have only a 0.063 mm bias with the mean of the data while the variation of predictions with the data had a 1.35 mm standard deviation. These verification studies support the validity of the structural and material models used in this modelling procedure.

1.0 Introduction

Relative axial displacements between the tie rods and fuel rods have been observed in BWR fuel bundles. In these bundles, the tie rods were connected to the end tie plates and the remaining fuel rods were held in place with compression springs. The primary cause of these relative displacements is presumed to be the axial forces caused by the compression springs which alter the axial stresses from the combination of the differential coolant and fill gas pressure loading and the tensile forces in the tie rods and compressive forces in the remaining fuel rods caused by the compression springs. The calculational model is presented which was used to verify that the observed deformations can be predicted if the cladding material's creep deformations are calculated using the assumed biaxial loading conditions and the variations in the axial force due to compression spring relaxation are calculated using an irradiation induced stress relaxation model.

2.0 Theoretical Model

For the verification calculational model, the relative motion of the tie plates is assumed to remain planar and without rotation for an octant of the fuel bundle. This octant contains N_i fuel rods of type R_i which elongate X_i as a function of time due to the axial compressive spring force F_i and the pressure differential across the cladding. The anisotropic creep and irradiation induced growth are the assumed deformational mechanisms active in the cladding. The compression deformations, δ_i, of the compression springs are denoted by

$$\delta_i = X_{oi} - X_T + X_{Ri} \qquad (1)$$

where

δ_i = deflection of compression spring type i
X_{oi} = initial deflection of compression spring type i
X_T = extension of the tie rod
X_{Ri} = extension of the fuel rod type i.

Figure 1 is a schematic diagram of the structural model.

The deformational increments of the fuel cladding are summed over the axial segments of the fuel length and are accumulated on a time incremental basis taking into account calculated power histories based on reported reactor control and flow conditions. Power and thermal histories, growth rates, and creep rates are assumed to remain constant over a time increment Δt_k. The thermal expansions are assumed to be instantaneous which causes changes in axial forces from the springs at the start of each time increment. The model for the spring forces accounts for the irradiation induced relaxation and the relative tie plate to fuel rod motions.

2.1 Spring Deflection-Force Model

Each spring type is represented by a Maxwell relaxation model[1] or a spring and dash pot connected in series. For this representation, the deformation rate is the sum of the spring's and the dash pot's deformation for the force F_i or

$$\dot{\delta} = \dot{F}_i/K + \eta F_i \qquad (2)$$

where

K = spring constant [lb/in]
η = viscous coefficient [in/lb-hr]

The viscous coefficient is evaluated with relaxation test data where the initial force F_o for each time increment is relaxed exponentially under a constant deformation and fast flux. To apply this model for irradiation induced relaxation, the relaxation is assumed to be non-linearly dependent on fluence instead of time dependent and based on measured relaxation data[2,3]. The effective relation for each time increment,

$$K\eta\Delta t = \ln\,(F_o(t)/F(t + \Delta t)) \qquad (3)$$

is approximated by

$$K\eta\Delta t = \exp\left(\frac{-1619}{T}\right)\left(\psi_{t+\Delta t}^{0.19} - \psi_t^{0.19}\right)$$

for the high fluence exposure and by

$$K\eta\Delta t = 2.89 * 10^{-22}\ \Delta\psi$$

for the low fluence exposure[3] where

T = spring temperature (K)
ψ = fluence (neutrons/cm^2) - E> 1 mev

The transition between the two relaxation modes is made at a fluence of $1.36 * 10^{20}$ (n/cm^2) which yields a continuous relaxation model. The axial forces on the compression springs are calculated with Equations (1) and (2) and equations for the deflections of the fuel rods based on their growth, thermal expansion, and creep.

During each time increment, the relative rod deformation rates from the creep and growth are assumed to be constant and the effective spring relaxation coefficient is also assumed to be constant. The analytical evaluation of Equation (2) using these assumptions for the spring force relation for rod i during the time Δt is

$$F_{i,k}\,(t + \Delta t_k) = F_{i,k}\,(t) \cdot \exp(-K\eta\Delta t_k) + \left(\frac{\dot{\delta}_i}{\eta}\right)\left[1 - \exp(-K\eta\Delta t_k)\right] \qquad (4)$$

where the effective $K\eta\Delta t$ are evaluated with Equations (3). The initial spring forces for each time increment are corrected for the relative thermal expansions of the tie and fuel rods due to any changing thermal conditions.

2.2 Fuel Rod Axial Deformations

The axial deformations for each fuel type are summed up over the axial increments. Actual fuel management and reactor control and operational records are used to create bundle and fuel rod exposure histories for each axial region for each fuel rod type. The cladding temperatures, equivalent creep and growth rates and cladding thermal expansions are evaluated with the calculational routines used in the RODEX program.[4] The internal gas pressure in the fuel rod is based on the initial fill gas pressure adjusted for the changes in the calculated plenum temperature. An anisotropic creep model is included for the determination of creep elongations of the cladding. When the stress axes are the principal axes of the anisotropic structural orientation, the deformation process is mainly irradiation enhanced creep where no twinning occurs (no difference between compressive and tensile loadings) and the deformational process is constant volume, the general anisotropic formulation[5] is equivalent to Hills' flow relation[6] for orthogonal symmetry.

This formulation is the same as that previously applied for zircaloy[7,8] where the axial creep increment is evaluated with the relation

$$(\Delta\varepsilon_z)_c = \dot{\varepsilon}_c\Delta t \frac{\partial\sigma_e}{\partial\sigma_z} = \left(\frac{\varepsilon_c\Delta t}{\sigma_e}\right)\cdot\left(\sigma_z - \frac{R\sigma_\theta}{R+1} - \frac{\sigma_r}{R+1}\right), \qquad (5)$$

The radial stress is assumed to be the mean of the internal and external pressure, the circumferential stress is the equilibrating stress for the pressure loadings, and the axial stress is the equilibrating stress for the pressure and spring force loadings.

$$\sigma_z = \frac{P_i}{\left[\left(R_o^2/R_i^2\right) - 1\right]} - \frac{P_o}{\left[1 - \left(R_i^2/R_o^2\right)\right]} - \frac{F_i}{\pi\left(R_o^2 - R_i^2\right)} \qquad (6)$$

The calculated stresses are used to evaluate the creep strain increments for each axial segment of each rod type with Equation (5). The spring forces in Equation (6) are evaluated using the relaxed spring forces calculated with Equation (4). The evaluations are made using an incremental calculation procedure.

3.0 Model Verification

Relative fuel rod elongations have been measured on a number of BWR fuel bundles. Both 7x7 and 8x8 fuel bundle arrays have been measured[9] after exposures ranging from 10 to 30 MWD/KGU. Relative rod length changes were measured on photographs of the upper tie plate area. Significant random variations in the measurements could be expected due to measurement error and variations in the initial conditions of fuel rod length, spring length, and spring characteristics encountered due to normal fabrication tolerances. For the verification study, actual histories for the bundles were generated using the fuel management records and established procedures for determining fuel rod power histories.[10] The spring constants and initial spring deflections were set at their nominal values for each fuel type.

The anisotropic parameters R and P were varied as part of a sensitivity study. The predicted relative displacements between tie rods and the other fuel rods did not significantly depend upon these anisotropic parameter values although the total fuel rod length changes were dependent on the anisotropic parameters. The maximum predicted elongation for the tie rods was fourty percent greater for the anisotropic creep parameters of $R = 1.5$ and $P = 2.25$ than for the isotropic case. For the verification analyses, these values of anisotropic parameters were used. Only relative fuel and tie rod elongations were measured, thus verification of the anisotropic dependence could not be made with these data.

The verification results were based on studies of ten different structural and power conditions for four different fuel types with one hundred and sixteen observations of relative elongations. The fuel rods had different diameters for the 7x7 and 8x8 fuel bundles and different cladding thicknesses were used in two of the 7x7 bundle designs. Figure 2 shows the comparison between the predicted and averaged observation for each rod type modelled and observed. An analysis of variance of these calculations and data yielded a bias of - 0.063 mm, a standard deviation of within fuel type measurements of 1.35 mm, and a standard deviation of between fuel type measurements of 0.81 mm. These values are within the range of initial fuel rod length variations permitted by fabrication and the bias in the predictions is very small with respect to the observational variations. Since the model evaluation procedure did not empirically adjust any model parameters, the fit of the data to the measurements indicates that over the exposure range and design parameter range of these fuels, the assumptions employed in this model were applicable.

4.0 Acknowledgment

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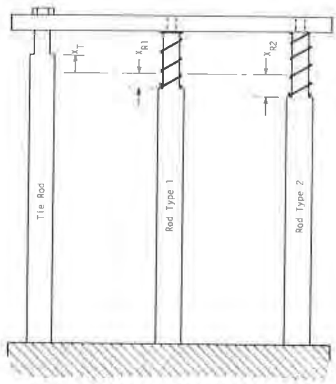

Figure 1 Schematic Diagram of the Structural Model For Rod Length Changes

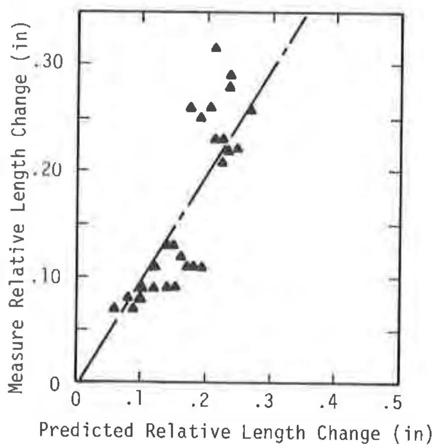

Figure 2 Comparison of Predicted and Measured Relative Length Changes Between Tie Rods and Fuel Rods