Conf. 751101-15

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July 1975

Work performed for
Energy Research and Development Administration
Idaho Operations Office
Under Contract AT (10-1) - 1375

Aerojet Nuclear Company

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The thermal behavior of fuel rods during simulated accident conditions is extremely sensitive to the heat transfer coefficient which is, in turn, very sensitive to the cladding surface temperature and the fluid conditions. This paper summarizes the development of a semianalytical, lumped-parameter fuel rod model which is intended to provide accurate calculations, in a minimum amount of computer time, of the thermal response of fuel rods during a simulated loss-of-coolant accident. The results show good agreement with calculations from a comprehensive fuel-rod code (FRAP-T) currently in use at Aerojet Nuclear Company.

As an alternative to detailed nodalization of the fuel rod (generally 15 or more radial nodes are required in a purely numerical model such as FRAP-T) an analytical solution for the surface temperature of the fuel may be used to improve the accuracy of a lumped-parameter fuel rod model while retaining its computational simplicity. In order to derive the analytical solution, the usual assumptions are made that the thermal properties of the fuel are independent of temperature and position, azimuthal symmetry exists, and axial conduction can be neglected. Then the thermal diffusion equation can be written as;

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{Q}{k} = \frac{1}{\kappa} \frac{\partial T}{\partial t} \quad (1)$$

with the nomenclature given at the end of text. The solution to Equation (1) for a prescribed heat flux history may be found by superposition techniques. The exact solution has two infinite series terms which have been approximated

by the first two terms in each series. The solution to Equation (1) can then be written in quadrature form as

$$\begin{aligned}
 T_2(t+\Delta t) = & \left\{ 4k_f T_2(t) + 4k_f Q(t) \Delta t / \rho_f C_f \right. \\
 & + 2k_f B \left[\exp[-\alpha_1^2 t / R_2^2] - \exp[-\alpha_1^2 (t+\Delta t) / R_2^2] \right] \\
 & - 8\kappa q_2''(t) \Delta t / R_2 + R_2 q_2''(t) + k_G T_1(t) \ln(R_1/R_2) \\
 & + 2k_G \ln(R_1/R_2) \left[R_2 q_2''(t) - Rh[T_1(t) - T_f(t)] \right] \Delta t \\
 & / \rho_C C_C (R^2 - R_1^2) + 8R_2^3 q_2''(t) \left[\exp[-\alpha_1^2 \kappa t / R_2^2] \right. \\
 & - \exp[-\alpha_1^2 \kappa (t+\Delta t) / R_2^2] \bigg] / \alpha_1^4 + \left[\exp[-\alpha_2^2 \kappa t / R_2^2] \right. \\
 & \left. \left. - \exp[-\alpha_2^2 \kappa (t+\Delta t) / R_2^2] \right] / \alpha_2^4 \right\} / \left\{ [4k_f + k_G \ln(R_1/R_2)] \right\} \quad (2)
 \end{aligned}$$

The energy equations for the gas gap and cladding can also be written in quadrature form as:

$$q_2''(t+\Delta t) = [T_2(t+\Delta t) - T_1(t+\Delta t)] (k_G/R_2) \ln(R_1/R_2) \quad (3)$$

and,

$$\begin{aligned}
 T_1(t+\Delta t) = & T_1(t) + 2 \left\{ q_2''(t) R_2 - Rh[T_1(t) - T_f] \right\} \Delta t \\
 & / \rho_C C_C (R^2 - R_1^2) \quad (4)
 \end{aligned}$$

Equations (2) through (4) make up a complete set of finite difference equations which can be used directly with heat transfer correlations and fluid boundary conditions to estimate cladding temperatures during rapid transients.

The computed results obtained from the semianalytical rod model, a previous lumped parameter rod model ⁽¹⁾, and FRAP-T are shown in Figure 1. The boundary conditions for all three models are calculated by an advanced

Figure 1: Surface temperature response to a cold-leg break in a test reactor predicted by three rod models.

core hydrodynamics code for a simulated cold-leg break. The heat transfer and CHF correlations are given in Reference 2. The agreement between results from the semianalytical model and the results obtained using FRAP-T appears to be quite good considering that the semianalytical model presently neglects the effects of thermal property variation and a varying gap conductance.

In conclusion, a simplified, fuel rod, conduction model has been developed for use with advanced core hydrodynamics codes. The model provides more nearly accurate surface temperature calculations for the fuel rods than previous lumped-parameter models.

NOMENCLATURE

C	-----	specific heat
J_0	-----	0^{th} order Bessel function of the first kind
k	-----	thermal conductivity
q''	-----	heat flux
Q	-----	power generation per unit volume
r	-----	radial coordinate
R	-----	outside radius of the cladding
R_1	-----	inside radius of the cladding
R_2	-----	fuel radius
t	-----	time
T	-----	temperature

GREEK

α_n	-----	n^{th} root of $J_1(\alpha) = 0$
Δ	-----	change in variable in one time step
∇^2	-----	Laplacian operator
ρ	-----	density
κ	-----	thermal diffusivity

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1	-----	evaluated at R_1
2	-----	evaluated at R_2
C	-----	cladding
f	-----	fuel
G	-----	gap

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