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Development of a Simplified Fuel-Cladding Gap Conductance Model for Nuclear Feedback Calculation in 16X16 FA

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Abstract

The accurate determination of the fuel-cladding gap conductance as functions of rod burnup and power level may be a key to the design and safety analysis of a reactor. The incorporation of a sophisticated gap conductance model into nuclear design code for computing thermal hydraulic feedback effect has not been implemented mainly because of computational inefficiency due to complicated behavior of gap conductance. To avoid the time-consuming iteration scheme, simplification of the gap conductance model is done for the current design model. The simplified model considers only the heat conductance contribution to the gap conductance. The simplification is made possible by direct consideration of the gas conductivity depending on the composition of constituent gases in the gap and the fuel-cladding gap size from computer simulation of representative power histories. The simplified gap conductance model is applied to the various fuel power histories and the predicted gap conductances are found to agree well with the results of the design model.

I. Introduction

The heat transfer from the fuel pellet to the cladding is important not only for fuel performance analysis but also for the nuclear design and safety analysis in maintaining the fuel integrity during steady-state and transient operation of a nuclear reactor. Since the characteristics of heat transfer can be represented by fuel-cladding gap conductance, the accurate determination of the gap conductance as functions of individual rod burnup and power level may be a key to the best-estimated design and safety analysis of a reactor. However, incorporation of a sophisticated gap conductance model into the nuclear design code for the calculation of thermal hydraulic feedback effect has not been implemented mainly because of computational inefficiency associated with the complicated behavior of gap conductance and partly because of its week sensitivity to the core average nuclear parameter.

Therefore, the prediction of the gap conductance as a function of burnup is commonly done by a computer code. However, it may take somewhat longer computing time because numerous iteration is often necessary to determine the gap conductance as the size and the physical properties of the gap are continuously changing with burnup. For the purpose of rapid analysis of the fuel temperature and the associated Doppler coefficient of reactivity, a simplified model for the gap conductance is developed from the sophisticated current model in FATES fuel performance analysis computer code [1, 2].

The simplified model eliminates the iteration scheme in calculating the gap conductance, and thus greatly reduces the computational time without compromising the accuracy of nuclear feedback calculation. And the model takes into account only the heat conductance contribution to the gap conductance, which is governed by the gas conductivity and the fuel-cladding gap size. The gas conductivity is dependent upon the composition of the constituent gases and the temperature of the gap for a given rod burnup and power level. The gas composition is determined by taking the fission gas release to the cold fuel rod void volume into consideration. The variation of the gap distance is determined from the computer simulation of the fuel performance analysis code by taking into account representative fuel power histories and associated burnup allowed in the steady-state PWR operating conditions. The performance code used is FATES for the CE type 16X16 fuel assembly.

2. Description of the Model

2.1 Gap Conductance

The fuel-cladding gap conductance consists of many components, such as heat conductance, contact conductance and radiation heat transfer. Since the component of the heat conductance is taking more than 95 % of the heat transfer in the PWR fuel element, the heat conductance alone is dealt with in this work.

The heat conductance is expressed in the following way:

$$H_{gap} = K_g / D_{gap} \qquad (1)$$

where K_g is the conductivity of the constituent gases and D_{gap} is the gap distance for heat conductance calculation between the fuel pellet and the clad. D_{gap} is expressed as follows:

$$D_{gap} = (R_{ch} - R_{ph}) + j + C(R_{cs} + R_{ps}) \qquad (2)$$

where R_{ch} and R_{ph} are the hot clad inner radius and the hot pellet outer radius, j is the temperature jump distance, C is a profile factor for the gap conductance, R_{cs} and R_{ps} are the surface roughness of the clad and the pellet, respectively.

The temperature jump distance is often incorporated to accommodate the temperature jump effect [1], which is the apparent discontinuity in temperature at a solid-gas boundary when heat is flowing across the interface of surfaces in near contact. Because of the small magnitude of the jump distance, it is neglected in calculating the gap distance in this work.

2.2 Gap Gas Conductivity

The composition of the gap gas is assumed to consist of the initial helium fill gas and the released gaseous fission products of xenon and krypton. Then, the conductivity of the mixture gases in the gap is expressed following the work of Brokaw [3]:

$$K_g = \frac{K_1}{1+\Psi_{12}(C_2/C_1)} + \frac{K_2}{1+\Psi_{21}(C_1/C_2)} \qquad (3)$$

where K_1 = conductivity of helium gas

K_2 = conductivity of the gaseous fission products

T = gap gas temperature (K)

$\Psi_{12} = \{[1+(K_1/K_2)^{0.5} (m_1/m_2)^{0.25}]^2 / [2^{1.5} (1+m_1/m_2)]^{0.5}\}$

$\quad \times \{1 + 2.41 [(m_1-m_2)(m_1-0.142m_2) / (m_1+m_2)^2]\}$

$\Psi_{21} = \{[1+(K_2/K_1)^{0.5} (m_2/m_1)^{0.25}]^2 / [2^{1.5} (1+m_2/m_1)]^{0.5}\}$

$\quad \times \{1 + 2.41 [(m_2-m_1)(m_2-0.142m_1) / (m_1+m_2)^2]\}$

m_1 = molecular weight of helium

m_2 = molecular weight of the mixture of xenon and krypton gases

C_1 = mole fraction of helium

C_2 = mole fraction of the gaseous fission products

The mole fractions of the constituent gases are varying as the helium gas becomes diluted due to the increase in the amount of the released fission gases. The fission gas release rate is incorporated in computing the mole fractions, C_1 and C_2, of each gas.

2.3 Fission Gas Release

The amount of the fission gas generated in an i-th axial node within the fuel rod is first determined as follows [1]:

$$V_i^{FGG} = \beta \cdot B \cdot \rho_{sh} \cdot \pi \cdot R_p^2 \cdot (L_f/N) \qquad (4)$$

where β = fission gas production rate, B = burnup (MWd/kgU), ρ_{sh} = fuel stack height density, R_p = pellet outer radius, L_f = active fuel length, N = number of axial nodes in the active fuel region

Then, the amount of the fission gas released in the i-th axial node is calculated in the following manner [2]:

$$I_{1,i} = \beta \cdot [1 - \exp(-K \cdot B^A)] / (B^{(A-1)} \cdot K) \qquad (5)$$

where A = model constant

$I_{1,i}$ = local gas inventory in a radial ring of i-th axial node at STP, in^3/gm of UO_2

$K = K_o \times \exp(-7600/T) / G_o^n$

where T = local fuel pellet temperature, G_o = initial fuel grain size (μm),

K_o, n = model constants

$$I_{2,i} = \beta \cdot B\ (1 - 0.0001 \cdot B) \quad (6)$$

where $I_{2,i}$ = inventory of i-th axial node considering knockout and recoil release contributions

Then the current inventory of the fission gases, $I_{c,i}$, is selected as a minimum value from the inventory of each release contribution, $I_{1,i}$ and $I_{2,i}$.

The percent of the released fission gas in the i-th axial node, F_i, is calculated as follows:

$$F_i = (\beta \cdot B - I_{c,i}) / (\beta \cdot B) \quad (7)$$

Finally the amount of the released fission gas in the i-th axial node and the total amount from the entire nodes become as follows:

$$V_i^{FGR} = F_i \cdot V_i^{FGG}\ ,\ in^3 \text{ at STP} \quad (8)$$

$$V_{TOTAL}^{FGR} = \sum_{i=1}^{i=N} V_i^{FGR} \quad (9)$$

The resultant mole fractions in the equation (3) can be obtained by converting the V_{TOTAL}^{FGR} into the number of moles in the fuel rod void volume considered. The number of the moles of the initial helium fill gas is determined to be 1.038 moles. The number of the moles of the released fission gas becomes $n_{FG} = 0.03\ V_{TOTAL}^{FGR}$.

Then, the mole fractions of the constituent gases are computed in the following way:

$$C_1 = n_{He} / (n_{He} + n_{FG}) \quad (10)$$

$$= 1.038 / (1.038 + 0.03\ V_{TOTAL}^{FGR})$$

$$C_2 = 1 - C_1 \quad (11)$$

2.4 Gap Distance

The variation of the gap distance with burnup and power is simulated by the fuel performance analysis codes, FATES [1, 2] for the 16X16 fuel rod. The various power histories possible for the steady-state PWR operating conditions are analyzed. The gap distance varying according to the fuel power change alone is computed as follows:

$$D_{gap}(B_o, q'_o + \Delta q') = D_{gap}(B_o, q'_o) + (\partial D_{gap} / \partial q')_{B_o} \times \Delta q' \quad (12)$$

where $(\partial D_{gap}/\partial q')_{B_o}$ = variation of the gap distance at a constant burnup (B_o) due to

the instantaneous change in power from q'_o to $q'_o+\Delta q'$

Figures 1 and 2 show the variation of the gap distance with the instantaneous change in power alone.

The burnup-dependent gap distance is calculated at constant linear heat rates (q'_o) from 2 to 12 kw/ft with a step-wise increase of 2 kw/ft as follows:

$$D_{gap}(B_o+\Delta B,\ q'_o) = D_{gap}(B_o,\ q'_o) + (\partial D_{gap}/\partial B)_{q'_o=2,\dots,12kw/ft} \times \Delta B \qquad (13)$$

where $(\partial D_{gap}/\partial B)_{q'_o}$ = variation of the gap distance at a constant power (q'_o) due to the

increase in burnup from B_o to $B_o+\Delta B$

Figure 3 shows the variation of the gap distance at constant powers with burnup. Further adjustment is made for the final expression of the slope, $(\partial D_{gap}/\partial B)$, according to a axial power peaking factor and the current gap size from which the slope starts to deviate from the initial value. Then the gap distance at the burnup step, $B_o+\Delta B$, with the power, $q'_o+\Delta q'$, can be predicted in the following way:

$$D_{gap}(B_o+\Delta B,\ q'_o+\Delta q')=D_{gap}(B_o,\ q'_o)+ (\partial D_{gap}/\partial q')_{B_o} \times \Delta q'+ (\partial D_{gap}/\partial B)_{q'_o+\Delta q'} \times \Delta B \qquad (14)$$

For a burnup range at which the gap distance becomes less than the minimum gap distance of $2.5\mathrm{x}(R_{cs}+R_{ps})$, the gap distance calculated from the equation (14) is adjusted to be the minimum distance of $2.5\mathrm{x}(R_{cs}+R_{ps})$.

3. Results and Discussion

The results of the simplified gap conductance model are compared with the FATES code for the fuel rod of the YGN Units 3 and 4. The fuel rod powers would represent the common behavior of rods from the first to the last loading in the reactor. The test cases 1 and 2 represent power histories for the typical fuel loading patterns. The test case 3 represents somewhat randomly varying power history. With these test cases, the FATES and the simplified gap conductance calculations are done for the rod having axial nodes of 20.

Figures 4, 5 and 6 show the variation of the gap conductance at three representative axial nodes as a function of burnup. It is seen that the calculated H_{gap} of the middle node gives excellent results compared to the FATES results. It can also be seen that when the fuel powers are decreasing for each test case the calculated gap conductances are in good agreement with the FATES results.

The maximum deviation of the gap conductance in the middle node takes place in the test case 2 at a burnup of 14 MWd/kgU and it is estimated to be 22 %. It is noted that the test case 2 is selected to simulate the fuel loading from the low power region to very high power region. Although the increase in power with large quantity results in the minimum gap distance and it is well predicted by the simplified model, the gap gas conductivity results in rather high value.

As shown in Figures 4, 5 and 6, the calculated gap conductances of the bottom node follow fairly well the FATES results except the test case 2. In the case 2, the deviation starts to be observed at the burnup of 8 MWd/kgU and becomes greater with the increase in burnup. It is mainly due to the fact that the calculated gap distance deviates steadily from the FATES results. This fact would suggest that the simplified gap conductance model may be restricted in applying to the case of the increase in power with very great magnitude.

4. Conclusions

(1) The calculation of gap conductance with fuel powers at each axial node is done. In three representative axial nodes, the calculated H_{gap} of the middle node shows excellent results compared to the FATES results. When the fuel powers are decreasing for each test case the calculated gap conductances are generally in good agreement with the FATES results.

(2) The maximum deviation of 22 % in the gap conductance of the middle node takes place in the test case 2 at a burnup of 14 MWd/kgU, which showed the increase in power with very large quantity resulting in higher gap gas conductivity.

(3) The calculated gap conductance of the bottom node follows fairly well the FATES results except the test case 2. The deviation starts to be observed at the burnup of 8 MWd/kgU and becomes greater with the increase in burnup. This fact would suggest that the simplified gap conductance model may be limited in applying to the case of the increase in power with very great quantity.

5. References

[1] "C-E Fuel Evaluation Model Topical Report", CENPD-139-P-A, Combustion Engineering, Inc., July 1974.

[2] "Improvements to Fuel Evaluation Model", CEN-161(B)-P, Supplement 1-P-A, Combustion Engineering, Inc., January 1992.

[3] R. S. Brokaw, "Alignment Charts for Transport Properties, Viscosity, Thermal Conductivity and Diffusion Coefficients for Nonpolar Gases and Gas Mixtures at Low Density", Lewis Research Center, NASA-TR-R-81, 1960.

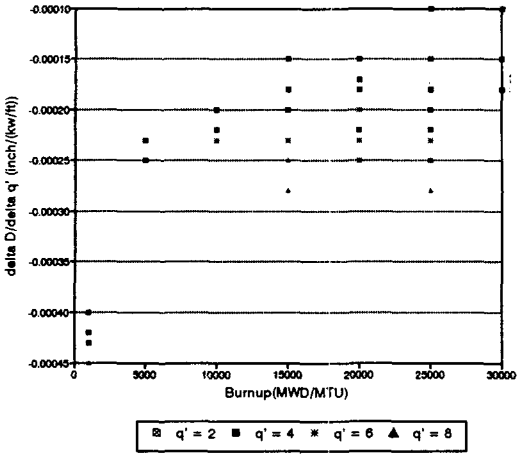

Figure 1. Variation of the gap distance with instantaneous increase in power.

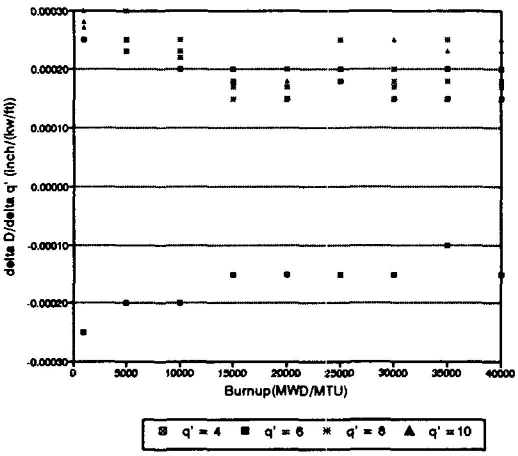

Figure 2. Variation of the gap distance with instantaneous decrease in power.

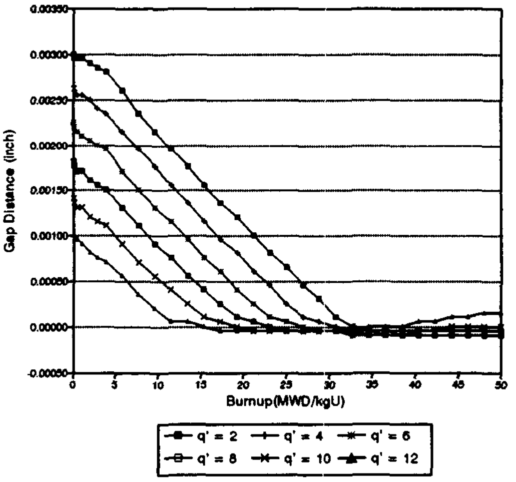

Figure 3. Variation of the gap distance with burnup at constant power.

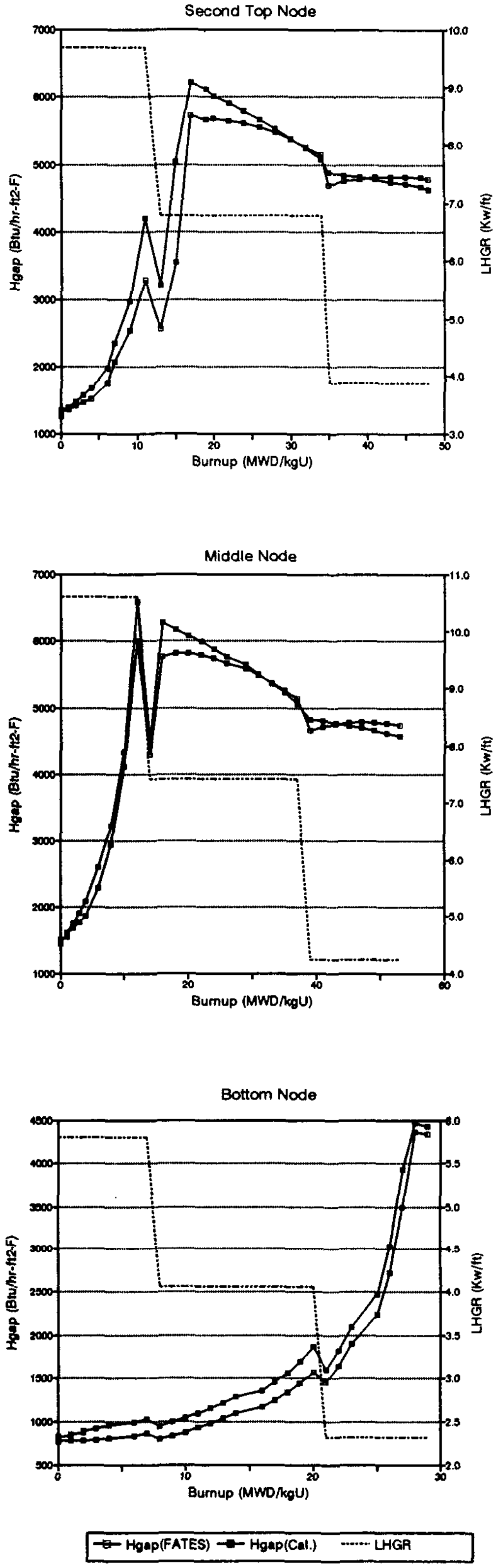

Figure 4. Comparison of the calculated gap conductance to the FATES results in the test case 1.

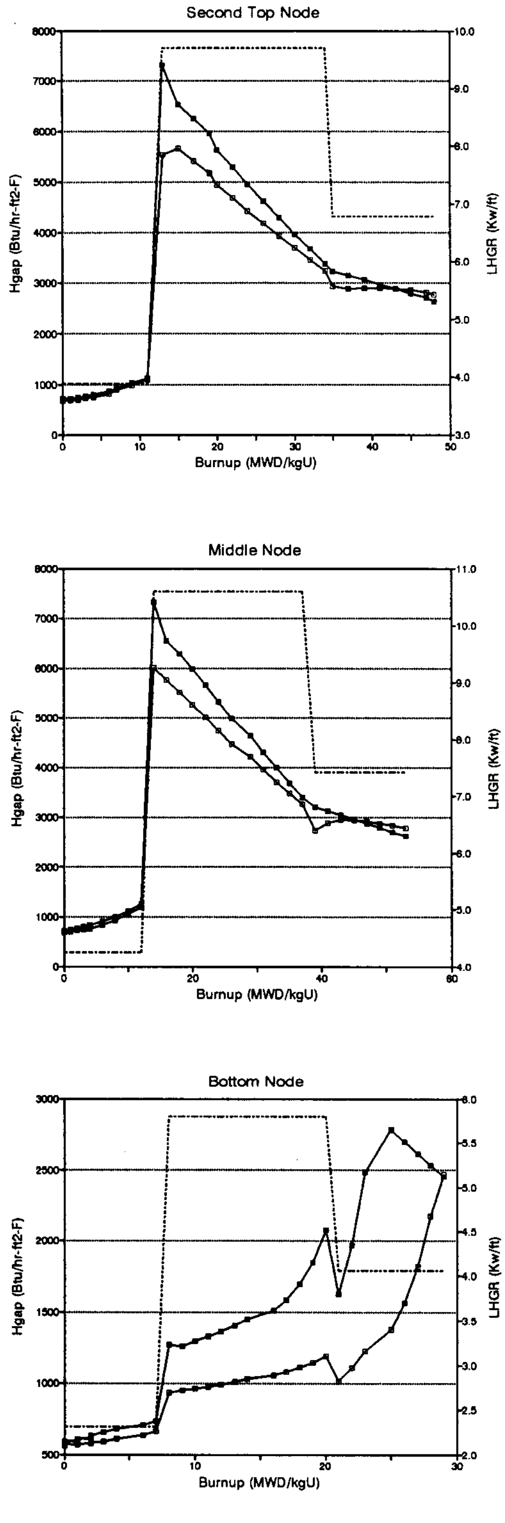

Figure 5. Comparison of the calculated gap conductance to the FATES results in the test case 2.

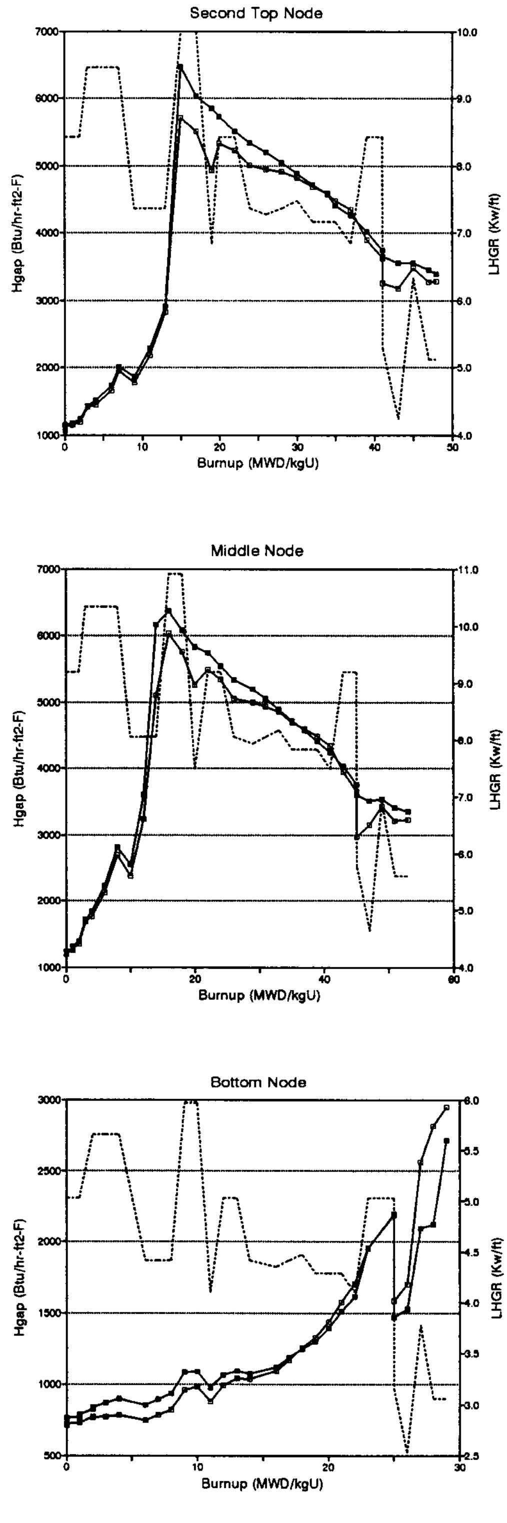

Figure 6. Comparison of the calculated gap conductance to the FATES results in the test case 3.