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Effects of Burnup on Fuel Pin Thermal Performance*

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Abstract

The development of models for analyzing the thermal performance of fast reactor mixed-oxide fuel pins throughout life is presented. The models provide a capability for examining the interrelationship between the various kinetic phenomena occurring in fuel pins. Emphasis is placed on gap conductance behavior. The factors which influence thermal behavior as burnup proceeds are discussed. Preliminary application of the models to fast reactor operating conditions are presented. The results reveal the competing effects on thermal performance of fission gas dilution of the bond gas, fission gas pressure, gap closure rates and restructuring kinetics. The importance of a restraint-dependent fuel swelling model to thermal behavior was also revealed by these studies.

EFFECTS OF BURNUP ON FUEL PIN THERMAL PERFORMANCE

INTRODUCTION

Fuel pin thermal performance characteristics vary with burnup due to changes in the chemical and physical properties and the physical state of the fuel. Changes in fuel-clad interactions also affect thermal performance. The accumulation of fission products within the fuel pin degrades thermal performance by decreasing the fuel melting or solidus temperature and the fuel and bond gas thermal conductivities. The effect of migration of fuel constituents also is expected to be detrimental to thermal performance, but only to a minor extent. Improvements in heat transfer with burnup result from gap closure, the development of fuel-clad stresses and continued pore migration and restructuring of fuel. Fuel pins which are tested in EBR-II to high burnups at high, calculated, beginning-of-life linear powers (16-17 kw/ft) normally have two major factors which are favorable to thermal behavior. These are a) development of significant fuel-clad stresses resulting in high fuel-clad gap conductances and, b) significant reduction in linear power with burnup. LMFBR fuel pins also will undergo a reduction in linear power with burnup but to a lesser extent. However, the major item which can contribute to improvement of thermal performance with burnup, that is fuel-clad mechanical interaction, will be minimized in LMFBR fuel pins by design and as a result of the high flux levels. The high flux levels increase the cladding swelling and irradiation creep rates, compared to EBR-II tests, and thus reduce fuel-clad interaction stresses. In fact, most presently available fuel pin behavior codes indicate that no stresses are developed under steady-state LMFBR conditions.^(1,2)

Under these circumstances, the effects of changes in fuel properties can be appreciable and a detailed analysis is required to develop a thorough understanding of thermal behavior throughout life. A good description of the thermal state of the fuel at any point in lifetime is required to a) ensure that the present criteria of no fuel melting at 10-15% overpower conditions is satisfied b) provide an adequate basis for transient analysis and c) improve upon the understanding of fuel-clad mechanical interaction.

In order to analytically model thermal performance, the factors outlined above must be considered in some detail if a reasonable simulation of fuel pin behavior is to be achieved. Some of the factors are only known qualitatively and therefore their contribution to an analytical approach must be estimated based on limited information. Experimental fuel pin data represent the integration of many effects and can be utilized only by making assumptions about specific variables in order to isolate others. Fuel conductivity and gap conductance fall in this category.

This paper describes the development of a set of models for analyzing and correlating test fuel pin data and predicting the thermal performance of LMFBR fuel pins. Emphasis is placed on describing the gap conductance models. Other major parameters involved in the total thermal analysis, such as fuel and gas conductivities, fuel melting point and pore migration are briefly described. Preliminary application of the models to high burnup LMFBR fuel pins, studies of beginning-of-life conditions and the effects of plutonium migration are also presented.

GAP CONDUCTANCE

One of the major parameters encountered in evaluating fuel pin thermal performance is the conductance across the fuel-clad gap. The model developed in this study describes gap conductance as the sum of conductances through the gas gap and contact points.

$$h_{\text{total}} = h_{\text{gas}} + h_{\text{contact}} \quad (1)$$

When the fuel and clad surfaces are not in contact the only contribution is from conductance through the gas gap. When fuel and clad surfaces come in contact a finite but discontinuous gas gap still exists due to surface roughness. Thus the total conductance is the sum of conductances through the finite gap and the contact points.

Gap Conductance

Heat transfer through the gas gap depends primarily on the thermal conductivity of the gas, the gap size and the accommodation effect at the solid-gas interface. The temperature drop through the gas gap is schematically shown in figure 1. The total temperature drop across the gap is the sum of the drop due to the temperature jump effect at the surface and the drop across the gas. The theory of temperature jump effect has been adequately described.^(3,4) The apparent temperature discontinuity at the solid gas interface is described in terms of the accommodation coefficient which is defined as

$$a = (T_i - T_r)/(T_i - T_s) \quad (2)$$

where T_i and T_r are the temperatures of the incident and reflected gas streams from a solid surface at the temperature T_s . Only limited data on accommodation coefficients are available^(5,6) therefore causing some uncertainty in calculations. Based on the available data a value of 0.05 was used in this study. Higher accommodation coefficients would increase the calculated conductance. The temperature drop through the gas is calculated using the Fourier equation. The pertinent equations are

$$\Delta T = \Delta T_{\text{jump}} + \Delta T_{\text{gas}} \quad (3)$$

$$h_{\text{gas}} = \frac{q'}{\Delta T} \quad (4)$$

$$= \frac{1}{\frac{2-a}{a} \cdot \frac{2}{v+1} \cdot \frac{9v-5}{4} \cdot \frac{L}{K_g} + \frac{X}{K_g}} \quad (5)$$

ΔT = Temperature drop

h = conductance

q' = Heat flux per unit area

a = accommodation coefficient

v = ratio of C_p to C_v

K_g = Conductivity of the gas

L = Mean free path of the gas

X = Radial gap width

Determination of the thermal conductivity of the gases is based on the data of Ubisch, Hall & Strivastav.⁽⁷⁾ An empirical fission gas release model has been developed for calculating the gas composition. This model is described later. Assuming continuous gas release and perfect mixing of the gases, composition and pressures are calculated. These results are then used for calculating thermal conductivities of the gas mixtures.

A sensitivity analysis of the model to fission gas dilution, pressure, temperature and gap size is shown in Figures 2, 3 and 4. Figure 2 shows the significant effect of reduction in gas conductivity due to fission gas release and also shows the effect of gap size on conductance. Figure 3 illustrates the effect of pressure on conductance for three gap sizes. These results demonstrate that conductance is highly sensitive to gas pressure, particularly at small gap widths. In a fuel pin, the increase in gas pressure due to fission gas release will partially offset the effects of the concomitant reduction in thermal conductivity. Figure 4 shows that although the sensitivity of conductance to temperature is relatively small, it cannot be neglected and, as is the case of gas pressure, it is emphasized at small gap width.

Contact Conductance

When two surfaces are in contact, only a small portion of the total available surfaces actually mate with each other because of surface roughnesses. The number of contact points and the area of contact depend on the surface roughnesses, hardness, yield strength and contact pressure. Heat is transferred through the contact areas by solid conduction. Several workers have theoretically analyzed these factors under idealized surface conditions,^(8,9,10) but their results are of limited application under conditions prevailing in a fuel pin. A simpler approach, which is normally taken, is to employ out-of-reactor experimental results which relate contact conductance to the principal parameters, surface roughness, hardness and contact pressure. Some of the relevant experimental work has been carried out by Ross & Stoute⁽¹¹⁾ and Rapier, Jones & McIntosh.⁽¹²⁾ In the present study a modified Ross & Stoute model is used. The surface roughnesses for cold-drawn stainless steel tubes was assumed to be of the order of 20-40 μ in. and that for oxide pellet of the order of 150 μ in.

MATERIAL PROPERTIES AND BEHAVIOR

Validity of the fuel pin thermal analysis depends on the accuracy of available material properties and their dependence on temperature. Further, in this work, attention has also been given to their variability during fuel burnup. The material properties and models developed to describe the behavior are briefly discussed.

Thermal Conductivity

Extensive studies have been carried out on the thermal conductivity of unirradiated UO_2 .⁽¹³⁾ Limited data are available on mixed oxide fuel thermal conductivity. However, the in-reactor variation of thermal conductivity is still not well defined. Thermal conductivity variations occur under operating conditions primarily due to

- . pore migration and columnar grain formation
- . fission product dispersion
- . migration of fuel constituents

From the available in and out-of-reactor data⁽¹⁴⁻¹⁹⁾ the following thermal conductivity correlation was derived using the least square regression technique:

$$k = \frac{1}{A + BT} + CT^3 \quad (6)$$

where T is in °K and k is the thermal conductivity in watts/cm-°K

The analysis for 95 percent theoretical density hypo-stoichiometric mixed oxide fuel (U, 20-25 w/o Pu) $\text{O}_{1.98}$ yielded values for the coefficients A, B, and C as shown in Figure 5. In-pile oxygen migration effects were accounted for in this analysis.

Expansion of the above equation to include as-fabricated fuel densities and in-pile restructuring, was carried out using the modified Maxwell⁽²⁰⁾ equations yielding:

for $.85 \leq \rho \leq .95$

$$K = (1 - 2.1\rho + \rho^2) \left[-\frac{1}{0.288 + 0.00252T} - 5.83 \times 10^{-12} T^3 \right], \quad (7)$$

and for $.95 \leq \rho \leq 1.00$

$$K = (3\rho - 1) \left[\frac{1}{5.75 + 0.0503T} + 2.91 \times 10^{-13} T^3 \right], \quad (8)$$

Associated integrated thermal conductivity equations are:

for $.85 \leq \rho \leq .95$

$$\int_{\rho}^{T_2} K_p dT = (1 - 2.1\rho + \rho^2) [-397 \ln (3.11 + 0.0272T) - 1.46 \times 10^{-12} T^4] \quad (9)$$

and for $.95 \leq \rho \leq 1.00$

$$\int_{\rho}^{T_2} K_p dT = (3\rho - 1) [19.87 \ln (3.11 + 0.0272T) + 6.79 \times 10^{-14} T^4] \quad (10)$$

It can be seen from Figure 6 that the calculated $\int K dT$ values from the above equations are in good agreement with experimentally determined values.

Fission Gas Release

Fission gas release significantly influences the gap conductance. An empirical model⁽²¹⁾ describing this phenomena was developed based on experimental data.⁽²²⁻²⁴⁾ The data showed a significant dependence of release on burnup. The fractional release is given by

$$f(B) = 1 - \frac{A(1 - e^{-\alpha_1 B})}{\alpha_1 B} - (1 - A) \frac{1 - e^{-\alpha_2 B}}{\alpha_2 B}$$

where B is the burnup in a/o. The parameters α_1 , α_2 and A depend on the density of fuel and were obtained by fitting the experimental data to this equation.

Figure 7 is an example of how well the model correlates the data. Using this model dilution of the gap gas due to fission gases was calculated and is shown in Figure 8.

Melting Point

Melting points (solidus) of unirradiated mixed oxide fuel have been measured by a number of investigators. The effects of stoichiometry also have been determined.⁽²⁵⁾ Only limited data⁽²⁶⁾ are available on effects of burnup on melting points. The available data, however, show a decrease in melting point with burnup which should be included in thermal analysis. Figure 9 shows the correlation of the decrease with burnup derived from a statistical analysis of the data.

Fuel Swelling and Restructuring

An area of significant uncertainty is fuel swelling. Fuel swelling is essentially due to solid fission products and fission gas. Available data indicate that swelling rate depends on temperature, burnup and restraint. However, these dependencies are not yet well established. For this work empirical estimates are used for parametric studies with the assumption that unrestrained swelling rates are high. Restructuring kinetics are based on Nichol's void migration model.⁽²⁷⁾ Pore mobility and subsequent velocity are determined as a function of local temperature and thermal gradient. Restructuring is then inferred from the distribution of the fabricated voids and thus is dependent upon the power history and thermal behavior of the fuel pellet.

THERMAL AND MECHANICAL ANALYSIS

The interaction between the fuel models and properties described was obtained from the CYGRO-F code. This code provides a mechanical analysis of the fuel pin by calculating stresses and strains in a cross section of fuel and clad. Details of this code have been previously presented.⁽¹⁾ A multi-ring $\int k dT$ type temperature calculation provides the thermal analysis of fuel and clad. Gamma heating in the cladding is neglected. The burnup effect on thermal conductivity is simulated by assuming a fraction of fuel swelling contributes to the total porosity. The integrated models, called THOR, thus provide a means of continuously determining fuel temperature as burnup proceeds and provide the capability of investigating the interrelationship between the various kinetic phenomena occurring in a fuel pin.

PRELIMINARY RESULTS AND DISCUSSION

The present status of the models, although requiring further development, is adequate to examine the relative behavior of some key aspects of fuel rod thermal performance. The models have been applied to typical EBR-II and LMFBR fuel pin operating conditions in order to examine the early-in-life and high burnup thermal behavior and the potential effects of plutonium migration.

The early-in-life (up to ~ 1 a/o) gap conductance and central temperature behavior have been the subject of considerable speculation. In-reactor gap conductances have generally been estimated from test fuel pin results. This is accomplished by identifying fuel temperature isotherms such as columnar grain growth⁽²⁸⁾ or melting boundaries⁽²⁹⁾ in the fuel structure and calculating fuel surface temperatures. This method is subject to considerable error and results are usually highly scattered. None the less, this method has provided the major basis for establishing in-reactor gap conductances. Because of the scatter, conservative values are normally selected for design. The above method neglects the kinetics of grain growth and the fact that gap conductance during this period of life may be varying since it is dependent on the competition between gap closure rate and the dilution rate of the bond gas by fission gases. The models described in this paper can be used to examine these factors.

Figure 10 shows the effects of three gap closure rates on gap conductance behavior early-in-life for a 6 mil cold diametral gap. Relatively rapid closure rates were obtained by using high, constant values of fuel swelling to represent unrestrained swelling rates. This method cannot be used for late-in-life studies because of the unrealistic high stresses that develop upon gap closure. The rapid gap closure rate shown in Figure 10 on start-up is due to differential thermal expansion; when full power is reached closure is due to swelling. The results indicate that if gap closure occurs within ~ 0.7 a/o burnup the gap conductance, after attaining its full power value, continues to rise slowly up to the point of closure. For closures at 1 to 1.5 a/o, the full power gap conductance value of 1100 B.T.U./Hr.-FT²-°F slowly drops (due to fission gas

dilution) to minimum values of 950 and 875. Preliminary unrestrained fuel swelling models indicate that closure should occur within 1 a/o. Thus, for the conditions studied, the assumption of a constant value of gap conductance during short-term irradiation tests (to 1 a/o) may be a reasonable one. It is interesting to note that our evaluation of short-term EBR-II fuel pin tests with 6 mil cold diametral gaps, using the columnar grain growth isotherm technique, showed minimum values of 1,000 B.T.U/Hr-Ft²-°F. (30)

Figure 11 shows a similar study as above, but with a 7.5 mil cold diametral gap. The same general trend is observed as in Figure 10. For gap closures within 1 a/o, a minimum value of 825 B.T.U/Hr-Ft²-°F is calculated. It should be noted that these results depend on several assumptions, such as, continuous fission gas release, and the selection of an accommodation coefficient. Further analysis of sensitivity to assumptions and correlation with short-term fuel pin data are being conducted. Figure 11 also illustrates the temperature profile early-in-life. The results demonstrate the importance of fuel restructuring kinetics. The restructuring counteracts the effects of the slowly dropping gap conductance and results in a relatively rapid lowering of central temperature as burnup proceeds.

Application of the model to a typical high burnup EBR-II test pin is presented in Figure 12. Gap closure in this case occurs on start-up and yields a high gap conductance. This increases slowly up to mid-life because of increasing fuel-clad mechanical interaction as analyzed by the CYGRO-F code. This demonstrates why many of the high burnup EBR-II test pins will not reveal thermal degradation effects.

Figure 13 shows application of the model to typical LMFBR hot pin conditions. For these conditions, the mechanical analysis with the present CYGRO-F swelling models (actually these represent highly restrained swelling rates) show that no fuel-clad stresses developed, i.e. no gap closure, up to 10 a/o. To simulate the effects of a fuel cracking-restraint-dependent swelling model, a hot gap size which is equivalent to the sum of the root mean square surface roughness of the fuel and clad (0.17 mils, identified as curve A), was used from the beginning-of-life. This assumes that essentially unrestrained fuel growth closes the gap early

and always maintains fuel-clad contact at some low interfacial pressure. This is consistent with the data of Ritzman et.al.⁽³¹⁾ A preliminary assessment of these data suggest that an interfacial pressure of ~500 psi will be maintained. The results show that after fuel-clad contact is made, and no further development of stress occurs, the dilution of the bond gas by fission gases significantly reduces the gap conductance. However, this effect, as well as the slow degradation of fuel thermal conductivity, is partially balanced by continued growth of the central void and the central temperature increases at only a low rate.

Further, we have also considered the potential effect of fuel fission creep on deformation of the fuel asperities at the fuel-clad interface. In-reactor creep of fuel has been amply established⁽³²⁾ although results vary greatly. Although the average interfacial stress we have assumed is small (500 psi), stress concentrations at the asperities are high. Thus, the contact points must slowly deform with time in the reactor. This reduces the hot gap size and enhances conductance through the asperities. A detailed model relating this deformation due to fission creep to out-of-pile results, such as those of Ross and Stoute, is being developed. A preliminary assessment of this mechanism indicates that a reduction in the average contact gap size from 0.17 to 0.1 mils can occur within 1 a/o. The gas conductance for this case is also shown in Figure 12 as curve B. The conductance through the contact points, presently estimated as 200-300 B.T.U/Hr-ft²-°F for the case examined, has not been included in these studies. The more detailed model will include this contribution. Continued in-pile deformation of fuel due to fission creep can potentially yield an additional conductance of 1700 Btu/hr-ft²-°F.

Another burnup effect which can influence thermal performance is plutonium migration. The potential effect of this phenomena is shown in Figure 14. The plutonium distribution, expressed as F(q) in the Figure, represents the maximum migration to the center based on the limited available data. The effect on central temperature is relatively small, indicating a penalty of approximately 50°F. Additional migration data are needed to satisfactorily predict this effect.

SUMMARY AND CONCLUSIONS

The development of models for analyzing and predicting LMFBR fuel pin thermal behavior was described. The major properties and behavior of the fuel required as input were presented and areas requiring further development and data were identified. Sensitivity studies showed the importance of including fission gas pressure effects on the gas gap conductance.

Application of the models to beginning-of-life behavior showed the interrelation of gap closure rate, fission gas dilution and restructuring kinetics. For gap closures within 0.7 a/o burnup, results indicated that the gap conductance is essentially constant with burnup until closure occurs. For gap closures at 1 to 1.5 a/o burnup, the gap conductance decreases but competing restructuring effects result in a continual decrease in fuel center temperature.

Application of the model to high burnup LMFBR conditions where only low fuel-clad stresses are developed, showed the significant effect of fission gas dilution on gap conductance. However, continued pore migration counteracts this dilution effect to some extent and center temperatures rise only slowly with burnup. Fission creep of the fuel at the fuel-clad interface can significantly enhance gap conductance and a detailed examination of this effect is necessary.

The beginning-of-life and high burnup analysis is strongly dependent of fuel swelling models. Detailed assessment of this area is also required.

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SCHEMATIC REPRESENTATION OF TEMPERATURE DROP ACROSS THE FUEL - CLAD GAP

Figure
1

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EFFECT OF FISSION GAS DILUTION ON GAS CONDUCTANCE

Figure
2

4/1 FMT 1479

EFFECT OF GAS PRESSURE ON GAS CONDUCTANCE

Figure
2

EFFECT OF GAS TEMPERATURE ON CONDUCTANCE

Figure
4

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Figure
5

Figure
6

Figure
7

Figure
8

DILUTION OF BOND GAS DUE TO FISSION GAS RELEASE

Figure
9

Figure
10

EFFECT OF GAP CLOSURE RATE ON BOL CONDUCTANCES

Figure
11

EFFECT OF GAP CLOSURE RATE ON BOL CONDUCTANCES

APPLICATION OF MODEL TO TYPICAL EBR-II FUEL PIN

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Figure

12

APPLICATION OF MODEL TO LMFR HOT PIN CONDITIONS

Figure

Figure
14