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Correction factor for thermal conductivity in binary (U, 10Zr) metallic fuel

Byung-Ho Lee, Chan-Bock Lee, Cheol Nam and Dong-Seong Sohn
Korea Atomic Energy Research Institute

Abstract

The model for thermal conductivity of irradiated metallic fuel has been developed to consider the effects of temperature, gas-filled porosity and sodium infiltration.
Irradiated metallic fuel can be modelled as a two component system: pores filled with fission gas and infiltrated sodium, and fuel matrix. The thermal conductivity of pores is first calculated considering the contributions of gas and sodium. And then the irradiated fuel thermal conductivity is calculated for the 100% dense fuel matrix and pores.
This model will be incorporated into a fuel performance analysis code to improve the prediction of irradiation behavior of metallic fuel.

1. Introduction

Fuel temperature has an effect on almost all the physical processes related to fast reactor fuel behavior. Since more fission gases are available for release and swelling in metallic fuel, temperature is the one of the most important controllable operating parameters. A reasonable prediction of temperature is therefore an essential requirement for the performance analysis of metallic fuel.

However, it is not available to obtain a detailed burnup dependence of the measured temperature during irradiation in fast reactor. Therefore it is difficult but very important to develop more accurate model for temperature prediction, which is determined from the thermal conductivity.

The thermal conductivity variation with irradiation is very complicated due to the generation of fission gas-filled pores, their open and interconnection, and sodium infiltration into the gas-filled pores at the irradiated metallic fuel.[1]

In the present paper, new methodology was proposed to correct the irradiated thermal conductivity of the irradiated fuel that contains the gas pores and infiltrated sodium.

2. Correction factor for thermal conductivity

High and very rapid swelling in the restructuring with constituent migration is a key feature of the metallic fuel. At the beginning of irradiation, most of the net volume increase in swelled fuel is from low-conductivity gaseous fission products accumulating in randomly distributed pores.[1] At some point in the swelling process, gas-filled pores are open and, therefore, gas is released from them into the pin plenum, and high-conductivity bond sodium is able to infiltrate the fuel through the interconnected pores. A maximum gas-filled porosity of ~23% may be reached, followed by sodium logging, which is weakly dependent on fuel type. In the progress of irradiation the gas-filled pores degrade the thermal property, while the sodium-filled pores can increase the thermal conductivity by replacing the fission gases in the pores. This variation of thermal conductivity depends on the swelling, gas-filled porosity, sodium-logged volume fraction.

Therefore, the behavior of thermal conductivity is a little complicated as shown in Fig. 1. Minimum thermal conductivity occurs at ~1.75 at. % burnup with large conductivity fluctuations between 1 and 2 at % burnup, followed by linear increase and leveling off. At the beginning of fuel life, the steady decline of conductivity with burnup corresponds closely to initial fuel swelling through the growth of gas filled porosity. As burnup increases to ~1.7 at %, typical pores continue to enlarge, overlap, and interconnect, while fuel-cladding contact becomes more extensive. The measured rise in thermal conductivity from the 1.7 at. % suggests the onset of sodium logging of the fuel pores. This implies that during initial stage of expansion, fuel reaches but does not press strongly against the cladding. Because axial transport of bond sodium seems to be very difficult once fuel-cladding gap closure is complete, the fact that 6 to 10% sodium is measured in fully restructured cross sections indicates that it is present at the initial stage of fuel expansion. The swelled fuel configuration at minimal conductivity is comprised of a gas-filled porosity of ~23% and occasional fuel-cladding contact that is largely buffered by a thin annulus of bond sodium amounting to ~6 to 10% of fuel cross section.[1]

To take into account the effects of the porosity and the sodium infiltration into the porosity, the correction factor for thermal conductivity can be approximated by the Bauer's expression.[1,2] Bauer derived for spherical gas-filled and irregular sodium-filled pores. In the case of binary fuel, for a distribution of pores filled with sodium conductivity, k_{Na} and embedded in metallic fuel of conductivity, k_{UZr} , correction factor is given by

$$f = \left\{ 1 - 3\frac{P_{Na}}{(1-P_g)} \left[\frac{\left(1 - \frac{k_{Na}}{k_0}\right)}{\frac{2}{e} + \left(3 - \frac{2}{e}\right)\frac{k_{Na}}{k_0}} \right] \right\} (1-P_g)^{3/2} , \qquad (1)$$

where

k_{Na}, k_{UZr} : thermal conductivities of sodium and unirradiated fuel, respectively

P_{Na} : sodium-filled porosity fraction

P_g : gas-filled porosity fraction

e : shape factor (1.72).

The sodium conductivity k_{Na} [4] is given by

$$k_{Na} = 93 - 0.0581(T - 273.15) + 1.173\times10^{-5}(T - 273.15)^2 \quad \text{(W/m-K)}, \ (2)$$

where T is in Kelvins.

The thermal conductivity k_{UZr} [3] of unirradiated binary fuel is a known function of temperature by

$$k_{UZr} = 17.5\frac{(1-2.23W_{Zr})}{(1+1.61W_{Zr})} + 1.54\times10^{-2}\frac{(1+0.061W_{Zr})}{(1+1.61W_{Zr})}T + 9.38\times10^{-6}T^2 \quad \text{(W/m-K)}, \ (3)$$

where W_{Zr} is the zirconium weight fraction, and T is in Kelvins. Fig. 2 shows the variations of thermal conductivity of sodium and (U, 10Zr) fuel as a function of temperature. It is notable that the thermal conductivity of (U, 10Zr) fuel increases with temperature, while that of sodium decreases less steeply.

However, the Bauer's expression contains the empirical shape factor that depends on the empirical and experimental data. Therefore, instead of Bauer's expression, the generally applicable thermal conductivity correlation for metallic fuels irradiated larger than 1.7 at % burnup was derived. In general, the dependence of thermal conductivity on porosity can be evaluated from the following expression[5],

$$f = \left\{1 - a\cdot P^{\frac{2}{3}}\cdot\left[1 - \frac{1}{1+\frac{1}{a}\cdot P^{\frac{1}{3}}\cdot(n-1)}\right]\right\}, \quad (4)$$

where

n = $\frac{k_0}{k_P}$

k_0 = thermal conductivity of the fully dense material (W/m-K)

k_P = thermal conductivity of the pore (W/m-K)

P = porosity (volume fraction of the porous phase)

a = anisotropy factor (a=1 means isotropic pore distribution).

The thermal conductivity is first calculated by applying Eq. (4) to metallic fuel media that contains gas-filled and sodium-infiltrated pores such as Fig. 3. The pores are assumed that their shapes are spherical and they contain the sodium and fission gas uniformly. After obtaining the corrected thermal conductivity for the pore, the correction factor can be obtained for the irradiated fuel that consists of pore and fully dense metallic fuel media.

First, for the case of pore, the following approximate equation results from Eq. (4) under the assumption of $n \to \infty$ (which means that the thermal conductivity of sodium is very larger than that of fission gas) and an isotropic pore distribution $a = 1$:

$$f^{subsystem} = 1 - P^{2/3} \ , \qquad (5)$$

where P is gas-filled fraction of pore. So the thermal conductivity for the pore is given by

$$k_{Na-g} = f^{pore} \cdot k_{Na} \ , \qquad (6)$$

where k_{Na-g} is thermal conductivity for the pore. Fig. 4 shows the variation of correction factor as a function of gas-filled porosity in the pore. Fig. 4 exactly describes that if the pore is filled with only sodium, the corrected thermal conductivity is equal to the sodium thermal conductivity.

From the thermal conductivity of pore, the correction factor on the irradiated binary fuel can be obtained by,

$$F = \left\{1 - a \cdot P_{MAX}^{\frac{2}{3}} \cdot \left[1 - \frac{1}{1 + \frac{1}{a} \cdot P_{MAX}^{\frac{1}{3}} \cdot \left(\frac{k_{UZr}}{k_{Na-g}}\right)}\right]\right\}, \qquad (7)$$

where P_{MAX} is maximum porosity produced until 1.7 at % burnup. Finally, the thermal conductivity of irradiated binary metallic fuel can be obtained by

$$k_{IRR} = F \cdot k_{UZr} \qquad (8)$$

3. Recommendation for thermal conductivity of irradiated metallic fuels

In summary, thermal conductivity of irradiated metallic fuel is affected by

- Fuel temperature
- Gas-filled porosity
- Sodium infiltration

Based on the analytical expressions describing these effects, thermal conductivity of irradiated metallic fuel can be expressed by

$k_{IRR} = f_g \cdot k_{UZr}$ for BU ≤ 1.7 at %

$k_{IRR} = \left\{1 - P_{MAX}^{\frac{2}{3}} \cdot \left[1 - \frac{1}{1 + P_{MAX}^{\frac{1}{3}} \cdot \left(\frac{k_{UZr}}{\left[f^{pore}\right] \cdot k_{Na}}\right)}\right]\right\} k_{UZr}$ for 1.7 at% < BU ≤ 2.0 at %

$$k_{IRR} = \left\{1 - P_{MAX}^{\frac{2}{3}} \cdot \left[1 - \frac{1}{1 + P_{MAX}^{\frac{1}{3}} \cdot \left(\frac{k_{UZr}}{f_{\max}^{pore} \cdot k_{Na}} - 1\right)}\right]\right\} k_{UZr} \quad \text{for BU > 2.0 at\%}$$

where f_g is the gas-filled fraction at the irradiated fuel and f^{pore} is correction factor of thermal conductivity of pore obtained from Eq. (3). And $f_{\max}^{pore}$ is the correction factor when the pore is filled with the maximum sodium. Fig. 5 shows the variation of thermal conductivity in the temperature range of 1200 to 1500K of metallic fuel. Compared with Fig. 1, the developed thermal conductivity model for irradiated metallic fuel well predicts the measured values.[1]

4. Conclusion

The model for the thermal conductivity of irradiated metallic fuel has been developed to consider the effects of temperature, gas-filled pore fraction and sodium infiltration. The calculated thermal conductivity of irradiated fuel showed minimum value at 1.7 at % burnup and saturates after 2.0 at % burnup in the temperature range of 1200~1500K. This behavior of thermal conductivity is consistent with the measured data.

This model will be incorporated into a fuel performance code to improve the predictions of metallic fuel irradiation behavior.

Acknowledgements

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Reference

1. T.H. Bauer and J.W.Holland, "In-pile measurement of the thermal conductivity of irradiated metallic fuel," Nuclear Technology, 110, 407 (1995).
2. T.H. Bauer, "A general approach toward the thermal conductivity of porous media," Int. J. Heat Mass Transfer, 36, 4181 (1993).
3. A.M. Yacout, W.S. Yang, G.L.Hofman, and Y. Orechwa, "Average irradiation temperature for the analysis of in-pile integral measurement," Nuclear Technology, 115, 61 (1996).
4. G.H. Golden and J.D. Tokar, "Thermophysical properties of sodium," ANL-7323, Argonne National Laboratory, (1967).
5. H. Kampf and G. Karsten, "Effect of different types of void volumes on the radial temperature distribution of fuel pins," Nuclear Application and Technology, 9, 288 (1970).

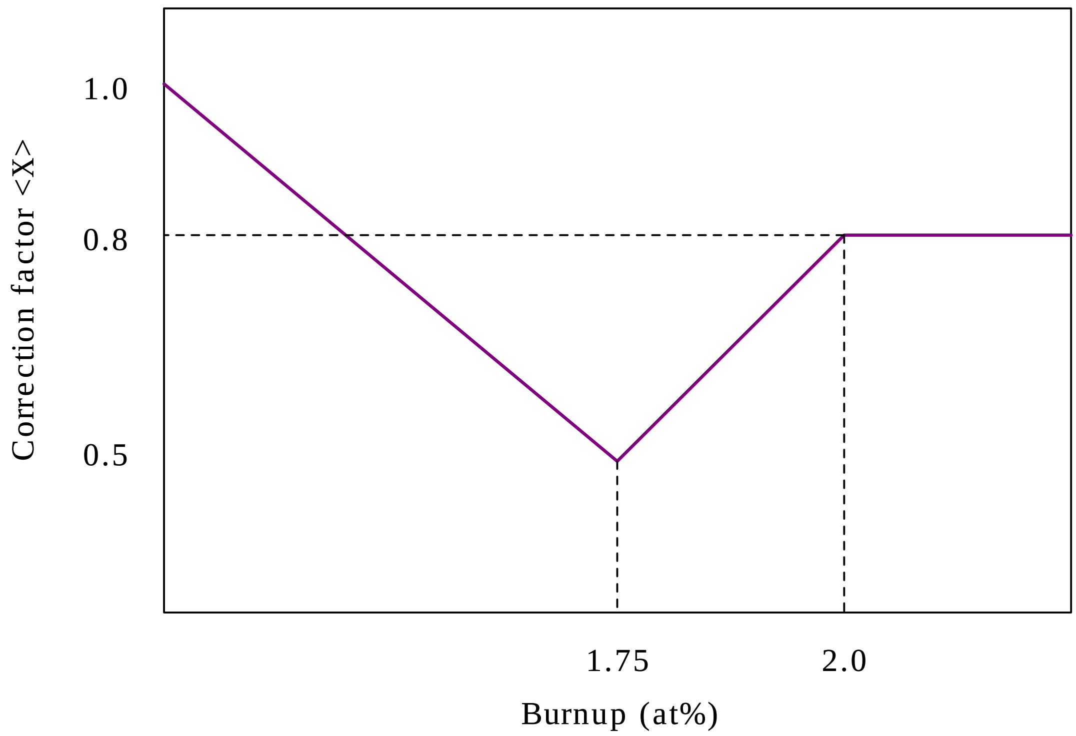

Fig. 1 Schematic variation of thermal conductivity as a function of burnup.

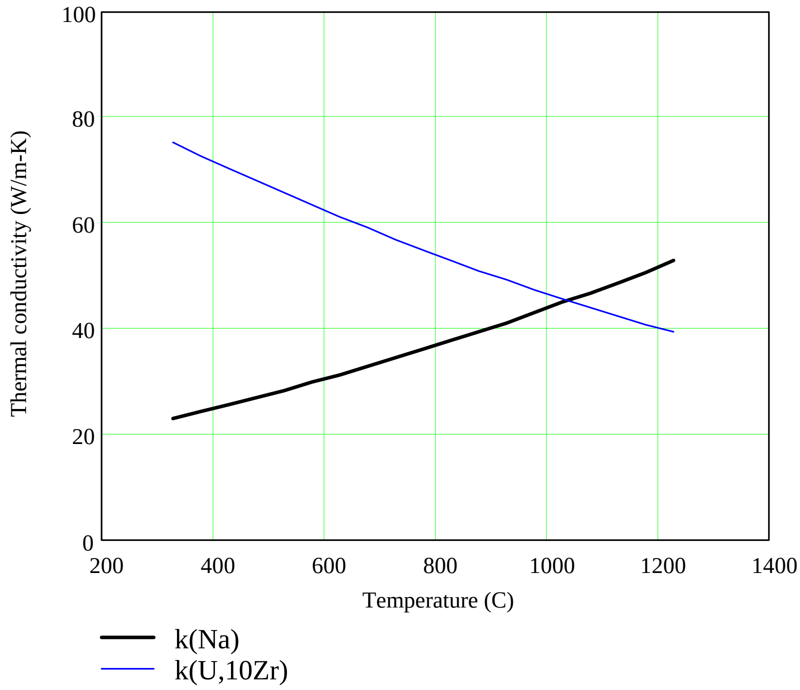

Fig. 2 Thermal conductivity of sodium and unirradiated (U, 10Zr) fuel.

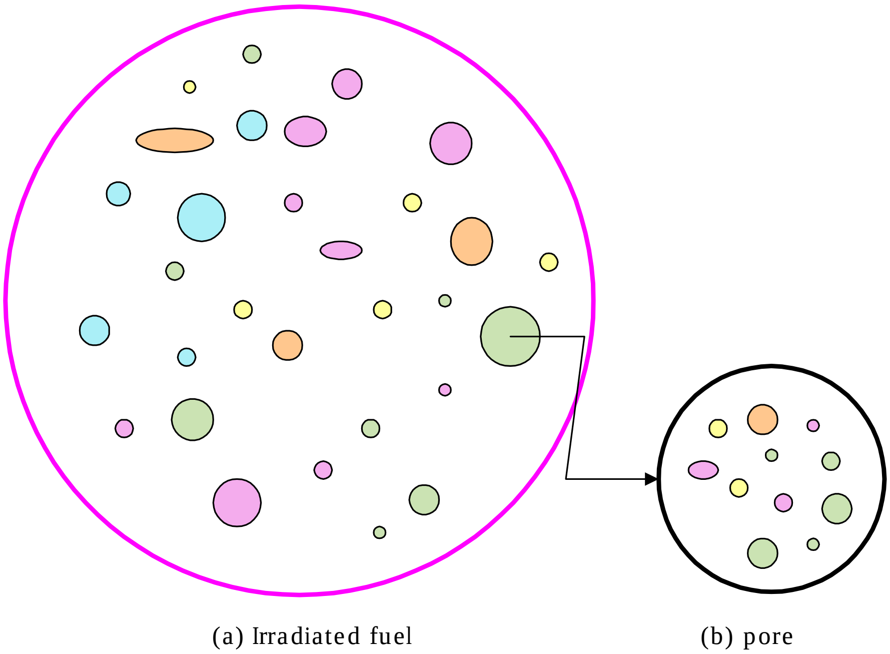

Fig. 3 Pore and irradiated metallic fuel.

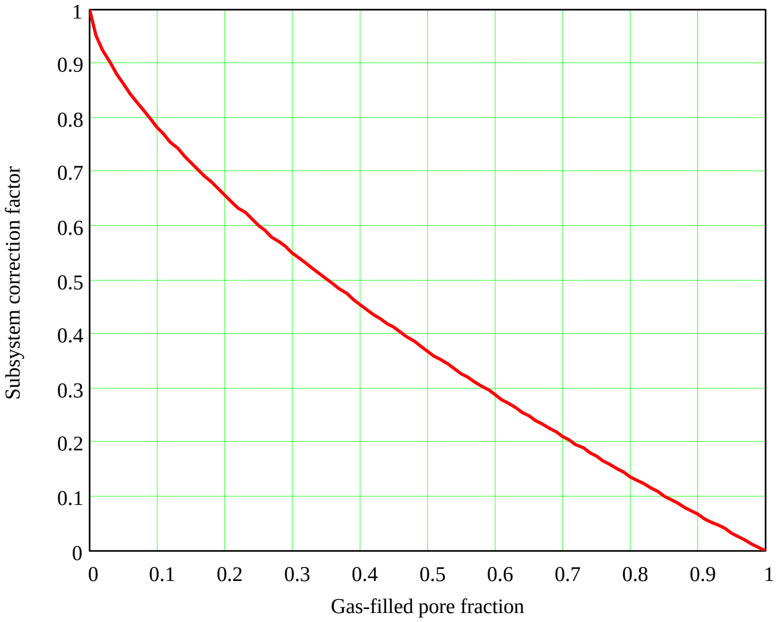

Fig. 4 Correction factor for the pore that consists of gas and sodium.

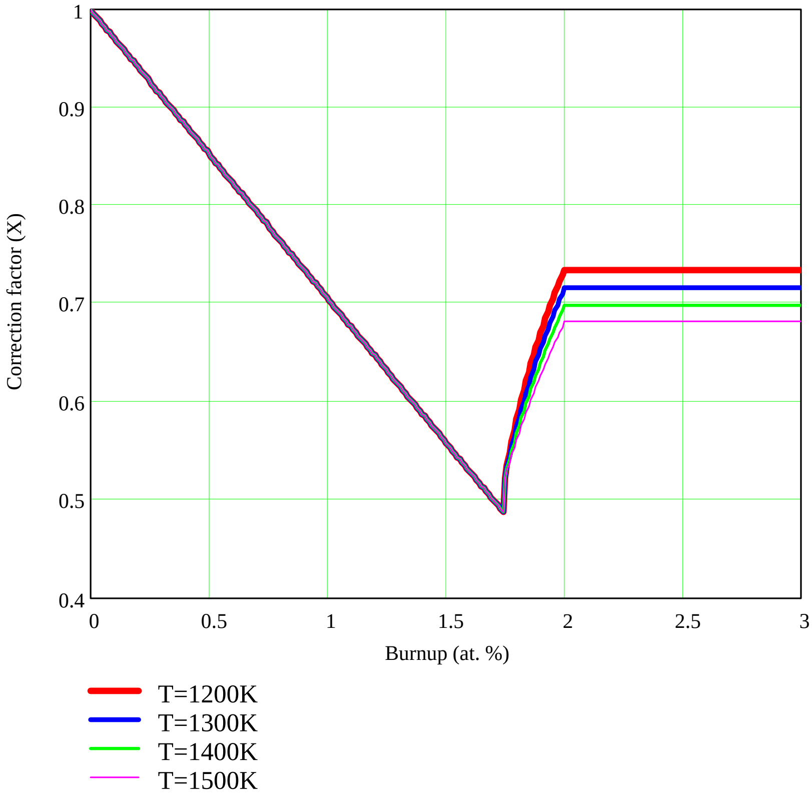

Fig. 5 Correction factor for the irradiated (U, 10Zr) fuel.