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The Effect of Uncertainties on the Operating Temperature of U–Mo/Al Dispersion Fuel

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1. Introduction

As the development of low-enriched uranium (LEU) fuels has been pursued for research reactors to replace the use of highly-enriched uranium (HEU) for the improvement of proliferation resistance of fuels and fuel cycles [1], U-Mo particles dispersed in an Al matrix (U-Mo/Al) is a promising fuel for conversion of the research reactors that currently use HEU fuels to LEU-fueled reactors due to its high density and good irradiation stability [2].

Thermal conductivity is an important parameter in determining the operational temperature of the fuel plate and this property influences available reactor safety margins. The thermal conductivity of dispersion fuel is primarily dependent upon the thermal conductivity of the matrix material itself, porosity that forms during fabrication of the fuel plates, and upon the volume fraction of the dispersed fuel phase [1]. Several models have been developed for the estimation of the thermal conductivity of U–Mo fuel, mainly based on the best fit of the very few measured data without providing uncertainty ranges. The purpose of this study is to provide a reasonable estimation of the upper bounds and lower bounds of fuel temperatures with burnup through the evaluation of the uncertainties in the thermal conductivity of irradiated U-Mo/Al dispersion fuel.

2. Operational temperature evaluation of U-Mo fuel

To calculate the operational temperature of fuel meat (T_m), equation (1) is used [1]:

$$T_m = T_c + q''\left(\frac{a}{2\lambda_e} + \frac{b}{\lambda_c} + \frac{c}{\lambda_o}\right) \ldots (1)$$

where:

- T_m: fuel meat operational temperature (^oC)
- T_c: the outer surface of the fuel plate cladding temperature (^oC) (calculated from equation (2)).
- q'': the surface heat flux (W/cm^2)
- a: the half thickness of the fuel meat (cm)
- b: the thickness of the cladding on one side (cm)
- c: the oxide layer thickness.
- λ_e: the effective thermal conductivity of the fuel meat (W/m-K).
- λ_c: the thermal conductivity of the cladding (The thermal conductivity of as-manufactured Al 6061 cladding matrix is 165 W/m-K) [3] .
- λ_o: the oxide layer thermal conductivity (constant at 1.85 W/m-K) [3].

To obtain the value of T_c in equation (1), Newton's law of cooling is used as described by equation (2) [1]:

$$q'' = h\,(T_c - T_b) \ldots (4)$$

where:

- h: the heat transfer coefficient, which was assumed to be constant at 3.03 W/cm^2-K [1].
- Tb is the coolant temperature, assumed to be 40^oC.

In order to use equation (1) and equation (2) for the determination of the operational temperature of U-Mo/Al fuel, several parameters and equations have to be obtained.

2.1 Uncertainty of fuel meat thermal conductivity

The thermal conductivity uncertainty can be obtained by calculating the combined uncertainty from the respective uncertainty values of specific heat capacity, density, and thermal diffusivity.

The thermal conductivity of U-Mo/Al fuel can be obtained from the simple thermal conductivity model utilizing the three major parameters: density, thermal diffusivity, and specific heat capacity through the following equation [4]:

$$k = \alpha\, C_p\, \rho \ldots (3)$$

where:

- k: thermal conductivity (W/m-K)
- α: thermal diffusivity (mm^2/s)
- Cp: specific heat capacity (J/g-K)
- ρ: density (g/cm^3).

Measurement uncertainties of specific heat capacity, density, and thermal diffusivity are adopted from the uncertainties of U-Mo/Al fuel as well as UO_2 fuel that are available in the literature. By combining the uncertainty values of the three parameters, the thermal conductivity uncertainty is obtained.

According to UO_2 fuel thermal properties database, the heat capacity uncertainty is ±2% from 298.15 to 1800 K [4].

An AccuPyc 1300 gas expansion pycnometer was used for density determination of U-Mo fuel samples. The density uncertainty according to PNNL-24135 document [5] and UO_2 fuel thermal properties database [4] is considered acceptable if the measured values of the standard weights were within ±1% of the standard values for the entire temperature range.

Thermal diffusivity measurements can be performed using a Netzsch LFA 457 MicroFlash® Laser Flash Apparatus [5]. The instrument was considered in calibration if the iron standard measurements were within ±5% of the expected values.

The uncertainty propagation of the three parameters in equation (3) provides the thermal conductivity uncertainty that is obtained from this equation [6]:

$$\frac{u(k)}{k} = \sqrt{\left(\frac{u(\alpha)}{\alpha}\right)^2 + \left(\frac{u(C_p)}{C_p}\right)^2 + \left(\frac{u(\rho)}{\rho}\right)^2} \ldots (4)$$

The results of uncertainty calculations reveal that the thermal conductivity uncertainty is ±5.48%. These results are used to determine the possible operation temperature ranges of U-Mo dispersion fuel.

2.2 Fuel plate dimensions

The standard fuel plate dimensions are obtained from NUREG-1313 document [7]. The nominal fuel meat thickness is 0.51 mm and the nominal cladding thicknesses of 0.38 mm. There are fabrication uncertainties regarding fuel meat thickness and uranium density in the fuel meat. The minimum allowable thickness of the cladding is 0.25 mm; the fuel meat thickness range is 0.51 ± 0.26 mm. The acceptable uranium density variations of fuel meat are ± 16%; the uranium density range is 8.0 ± 1.28 g/cm^3 [7].

2.3 Heat transfer coefficient and heat generation (surface heat flux)

The heat transfer coefficient used in equation (2) is assumed to be constant at 3.03 W/cm^2-K. According to a reference by W.L Woodruff [8], the heat transfer coefficient uncertainty fits within a band of ± 20% for any of the single phase correlations commonly used.

W.L Woodruff [8] stated that since there were no available data for the uncertainties of power and power density, it was assumed that the uncertainty in the power measurements is ± 5% and the uncertainty in power density is ± 10%.

Since there is no open data about the fission density as well as the surface heat flux of a research reactor core using U-Mo/Al fuel, it is assumed that the surface heat flux has multiple values ranging between 100 W/cm^2 to 400 W/cm^2 with uncertainty of ±10% that is used for the combined uncertainty study of the operational temperature of U-Mo/Al fuel.

2.4 Outer cladding temperature

By modifying equation (2) to be a function of T_c, using the uncertainties of q’’ (± 10%) and h (± 20%) stated in the previous section, using T_b as 40^{o}C and applying equation (4). Multiple values of the cladding surface temperature are obtained based on the surface heat flux used, ranging from 73^{o}C at 100 W/cm^2 surface heat flux to 172^{o}C at 400 W/cm^2.

The uncertainty of the outer cladding temperature is obtained by combining the uncertainties of heat flux and the heat transfer coefficient using the same method used for thermal conductivity uncertainty (equation (2) and (4)). The resulting uncertainty of the outer cladding temperature is ± 22%.

2.5 Thermal conductivity of fuel meat as a function of fission density

The data available in ref [1] and ref [9] of the fuel meat (U-7Mo/Al with 8 g-U/cm^3) were used to obtain the thermal conductivity of irradiated U-Mo/Al dispersion fuel as a function of burnup. As can be seen in ref [1], the thermal conductivity of U-Mo/Al dispersion fuel decreases down to approximately 10 W/m-K at the fuel meat fission density of 3.5E+21 when the heat flux is in the range of 200-270 W/cm^2 and the calculated beginning-of-life fuel temperature is in the range of 180-210^{o}C [1].

2.6 Oxide layer thickness growth with burnup

Aluminum alloy cladding experiences oxidation layer growth on the surface during the reactor operation [3]. The oxide growth model developed by Kim and Hofman, et al. [10] which uses a variable rate-law power in a function of irradiation time, temperature, surface heat flux, water pH, and coolant flow rate, was used for estimating the oxide film thickness as a function of burnup. The predicted oxide thickness is sensitive to water pH, and it is assumed that water pH will be evenly distributed in the range of 5.5 ~ 6.2 [3].

The values of the parameters needed to calculate the oxide layer thickness growth as a function of burnup are KJRR data that are listed in ref. [11]. And the conversion of units of burnup was adopted from ref. [12].

Table 1 shows the oxide layer thickness growth as a function of burnup (fission density), which is obtained by using Kim’s model [10]. To obtain the data, assumptions have been used which are average pH value, average heat flux and average cladding surface temperature. Linear interpolation is used to match the burnup steps with the thermal conductivity steps for operational temperature calculations.

Table 1: The oxide layer thickness as a function of burnup (fission density).

Fission density (fission/cm^3)	Oxide Layer Thickness (μm)
0	0.00
1.49E+20	5.56
2.35E+20	7.19
3.34E+20	8.73
4.37E+20	10.37
5.33E+20	11.57
9.44E+20	15.76
1.34E+21	18.49
1.65E+21	20.21
1.92E+21	21.26
2.24E+21	22.24
2.56E+21	22.93
2.83E+21	23.48
3.12E+21	23.93
3.36E+21	24.22
3.50E+21	24.29

The oxide layer thickness at zero burnup is assumed to be zero (no oxide layer formation before operation), although some claddings have a pre-film of the protective oxide layer (of around 5 μm) [1].

The data is obtained at outer cladding temperature of 110^{o}C and a heat flux of 200 W/cm^2. The uncertainty of the oxide layer thickness growth is ± 10% according to ref [10].

2.7 Operational temperature of fuel meat calculations

After obtaining all the required parameters and values for the operational temperature calculations of fuel meat, equations (1) and (2) were used to calculate the operational temperature at different surface heat flux ranging from 100 W/cm^2 to 400 W/cm^2. The results of temperature calculations as a function of burnup (fission density) are shown in Fig. 1.

3. Combined uncertainty in fuel temperature

The final goal of this work is to get the temperature distribution of upper and lower bounds based on the values of uncertainty of thermal conductivity of fuel, heat flux, heat transfer coefficient, fuel meat thickness and the oxide layer thickness.

To evaluate the combined effect of all these parameters on the operational temperature distribution, the root of sum of squares (RSS) method is used since these parameters are changing independently [13].

RSS is used and acceptable to combine uncertainties that are independent from each other, and after studying the effect of each parameter on the operational temperature, RSS method is valid to be used assuming that the parameters are independent.

The root of sum of squares (RSS) method, represented as follows [13]:

$$P = P_{base} + Root\left(\sum_i (P_i - P_{base})^2\right) \quad \ldots (5)$$

where:

- P: The combined uncertainty effect of all parameters.
- P_{base}: Operational temperature value of the base model.
- P_i: Operational temperature value after changing a parameter.

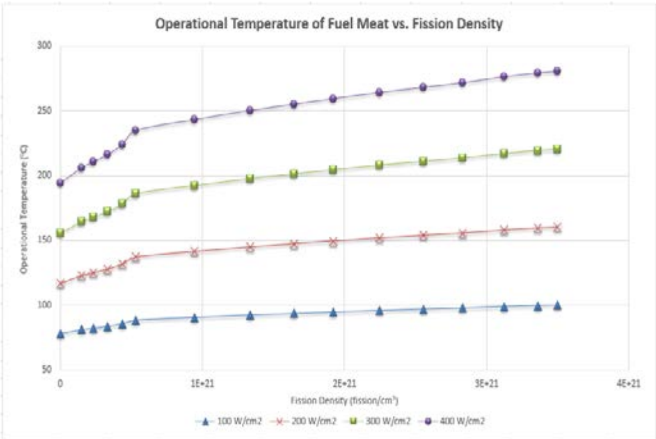

Fig. 1: Operational Temperature of U-Mo/Al Fuel as a function of fuel meat fission density.

Fig. 2 shows the operational temperature distribution as a function of burnup when applying the upper and lower bounds with respect to the base case operational temperature of the fuel meat.

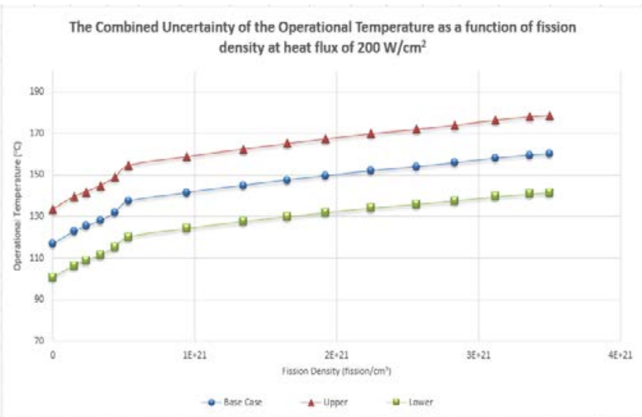

Fig. 2: Operational Temperature Variations of U-Mo/Al Fuel as a function of fuel meat fission density when applying the upper and lower uncertainty bounds compared to the base case.

4. Results and Discussion

The uncertainty analysis results show that the parameter that has the highest impact on the operational temperature of the fuel is heat transfer coefficient, due to its high uncertainty and its direct relation with the cladding outer temperature, ΔT of applying the upper and lower bounds is the highest among all the parameters (27.51°C) and it is constant with increasing burnup.

Fuel meat thickness has the second highest influence among the parameters with a ΔT of 13.05 °C upon applying the upper and lower bounds of uncertainty. In addition, Heat flux uncertainty shows a higher influence than the oxide layer thickness and the thermal conductivity of fuel as they increase with burnup, the oxide layer thickness has a small effect as ΔT is 4.32 at a fission density of 3.50E+21 fission/cm^3.

The parameter that has the lowest impact on the operational temperature is the thermal conductivity of the fuel. It has a ΔT of 2.81°C at the highest burnup value of 3.50E+21 fission/cm^3.

The combined uncertainty results show that when applying all the parameters' uncertainties, the influence on the value of the operational temperature is 16.58°C at the beginning of life and it increases as the burnup increases to reach 18.74°C at a fuel meat fission density of 3.50E+21 fission/cm^3. As a result, these parameters can be used to evaluate the performance of U-Mo/Al fuel depending on which parameter has a high impact on the operational temperature. Fig. 2 shows the results of the combined uncertainty calculations of all the parameters.

Other parameters uncertainties can also be included to evaluate the performance more accurately such as the interaction layer (IL) thermal conductivity, heat flux dependent thermal conductivity and heat flux dependent oxide layer thickness studies.

5. Conclusions

In this study, uncertainty and combined uncertainty studies have been carried out to evaluate the uncertainty of the parameters affecting the operational temperature of U-Mo/Al fuel. The uncertainties related to the thermal conductivity of fuel meat, which consists of the effects of thermal diffusivity, density and specific heat capacity, the interaction layer (IL) that forms between the dispersed fuel and the matrix, fuel plate dimensions, heat flux, heat transfer coefficient and the outer cladding temperature were considered.

After obtaining all the uncertainty values of the required parameters, the thermal conductivity of fuel meat as a function of burnup has been used alongside with the oxide layer growth to evaluate the operational temperature of fuel meat.

The combined uncertainty study using RSS method evaluated the effect of applying all the uncertainty values of all the parameters on the operational temperature of U-Mo/Al fuel. The overall influence on the value of the operational temperature is 16.58°C at the beginning of life and it increases as the burnup increases to reach 18.74°C at a fuel meat fission density of 3.50E+21 fission/cm^3.

Further studies are needed to evaluate the behavior more accurately by including other parameters uncertainties such as the interaction layer thermal conductivity. Other uncertainties related to heat flux dependent thermal conductivity owing to interaction layer growth, pH dependent oxide layer thickness and higher burnup studies, will give more detailed and accurate results for the evaluation of the operational temperature of U-Mo/Al fuel.

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