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Operating Temperature Evaluation of U–Mo/Al Dispersion Fuel and the Effect of Uncertainties

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1. Introduction

As a large number of the operating research reactors still use highly-enriched uranium (HEU) as fuel to provide high neutron fluxes that are superior for their applications. However, apprehensions on the use of HEU and concerns over the enhanced proliferation resistance of fuel cycles simultaneously increase. Therefore, the development of low-enriched uranium (LEU) fuels for research reactors has been commenced to replace the use of HEU. U-Mo/Al plate-type dispersion fuel is a promising candidate for this replacement without significant impacts on performance, fuel cycle costs, or safety [1].

Uncertainties of key parameters may influence a significant impact on the fuel temperature since fuel performance, represented by swelling, fission gas release, and interaction layers formation, is affected by fuel temperature and vice versa.

In this paper, the uncertainty ranges of the reactor operation conditions, fuel fabrication, fuel properties, and the dynamic changes of fuel during irradiation, such as the thermal conductivity of irradiated fuel, oxide layer thickness and pH value uncertainties, are used to determine the probable fuel temperature ranges. The combined uncertainty effect of these parameters on the fuel temperature range is also determined using the propagation of uncertainty. These analyses may provide technical advantages in the fuel performance evaluation and safety analyses.

The authors' previous work [2] has shown the effect of the uncertainties of some of the important parameters on the operating temperature of the fuel using reported fission density steps and a nominal heat flux profile from ATR irradiation summary report. These results are discussed in following sections and they are applicable to ATR case. In this work, additional, high influence parameters taken from mainly ATR or IAEA documents and AFIP-1 data of RERTR program have been included. A realistic heat flux profile and new fission density steps have been used for the temperature evaluation to demonstrate the validation of the proposed method herein to learn how much influence of each uncertainty on the fuel temperature and fuel performance.

2. Operational temperature evaluation of U-Mo fuel

To calculate the operational temperature of fuel meat (T_m), equation (1) is used [3]:

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

where:

- T_m: fuel meat operational temperature (°C)
- T_c: the outer surface of the fuel plate cladding temperature (°C) (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) [4] .
- λ_o: the oxide layer thermal conductivity (constant at 2.25 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) [3]:

$$q'' = h\,(T_c - T_b) \quad \dots (2)$$

where:

- h: the heat transfer coefficient, which was assumed to be constant at 3.03 W/cm^2-K [3].
- T_b is the coolant temperature, assumed to be 55 °C and 61 °C for the low heat flux and high heat flux profiles, respectively [3].

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 considered in the following sections have to be obtained.

3. Values of Parameters and their Uncertainties

To calculate the operational temperature of U-Mo/Al fuel and evaluate the effect of uncertainties, the value or the profile of the parameter and its uncertainty must be obtained and specified.

Eight parameters and their uncertainties are required for the calculations; fuel meat thermal conductivity, fuel meat thickness, heat transfer coefficient, surface heat flux profile, oxide layer thickness and its thermal conductivity, pH value and the effect of swelling.

3.1 Fuel meat thermal conductivity

The thermal conductivity of UO_2 fuel is obtained using laser flash analysis, differential scanning calorimetry, and pycnometry to access thermal diffusivity, specific heat capacity, and density, respectively [5]. These analysis methods have been also used to get the thermal conductivity of U-Mo/Al fuel [3]. Due to the lack of measurement data of the thermal conductivity of U-Mo/Al fuel and the high reliability of UO_2 thermal conductivity data base and uncertainties, the uncertainty value of the measured UO_2 thermal conductivity is used as the measurement uncertainty of U-Mo/Al fuel.

It is reported that the uncertainty of UO_2 thermal conductivity, based on scatter in data and data deviation from the recommended equation, is ±10% within the temperature range of 298-2000 K [6].

Since the measured thermal conductivity data of U-Mo/Al fuel as a function of fission density (burnup) is scarce, the measured values by Burkes [3] and Huber [7] alongside with the calculated thermal conductivity values of the fuel have been used for the operating temperature calculations.

3.2 Fuel plate dimensions

The standard fuel plate dimensions are obtained from NUREG-1313 document [8]. The nominal fuel meat thickness is 0.51 mm and the nominal cladding thickness is of 0.38 mm. There are fabrication uncertainties regarding fuel meat thickness and uranium density variation due to in-homogeneity of uranium particles distribution 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.

3.3 Heat transfer coefficient

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 [9], the heat transfer coefficient uncertainty fits within a band of ±20% for any of the single phase correlations commonly used.

3.4 Surface heat flux profile

In the authors' previous work [2], it was assumed that the surface heat flux has multiple values ranging between 100 W/cm^2 to 400 W/cm^2 with uncertainty of ±10%. In this work, a realistic fitted heat flux profile has been used from the beginning of life (BOL), maximum, and end of life (EOL) heat flux values of the Advanced Test Reactor (ATR) for low and high heat flux profiles [10].

The uncertainty of the surface heat flux is a result of the uncertainty of two major parameters, the variation of uranium density (homogeneity) in the fuel meat (uranium density uncertainty) and the neutron flux uncertainty through the following equation [11]:

$$q'' = \frac{G\,\rho\,N_A\,\sigma_f\,\phi_n\,V}{M_w\,A} \quad \ldots (3)$$

where:

- q'': surface heat flux (W/cm^2)
- G: energy produced per fission (MeV)
- $\boldsymbol{\rho}$: uranium density (g/cm^3)
- N_A: Avogadro's number
- σ_f: fission microscopic cross-section (barns)
- ϕ_n: neutron flux ($neutron/cm^2$)
- M_w: molecular weight
- V and A are the volume and the surface area of the fuel element, respectively.

The uncertainties of uranium density and neutron heat flux are ± 16% [8] and ± 10% [12], respectively. Combining the uncertainties of the two parameters results in the uncertainty of the surface heat flux of about ±19%.

3.5 Oxide layer thickness and thermal conductivity

Aluminum alloy cladding experiences oxidation layer growth on the surface during the reactor operation [3]. The oxide growth model developed by Kim et al. [13] 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 reported that water pH is in the range of 5.0 ~ 5.7 for ATR [10].

The oxide layer thickness at zero burnup is assumed to be 5 μm since some claddings have a pre-film of a protective oxide layer [3] [4]. The oxide layer thickness growth as a function of burnup (fission density) is obtained by using Kim's model and the uncertainty of the oxide layer thickness growth is ± 10% [13].

The oxide layer thermal conductivity value is reported by J.C. Griess et al. [14] ,considering 21 measurement sets to be the most reliable, to be 1.3 Btu hr^{-1} ft^{-1} $(°F)^{-1}$ (2.25 W/mK) with a standard deviation of ±0.2 (±15.4 %).

To obtain the oxide layer thermal conductivity uncertainty, a common statistical approach using the confidence interval of 1.96 standard deviations was used. The resulting oxide layer thermal conductivity is 30%.

3.6 pH value

The effect of the pH value uncertainty is reflected on the operational temperature of U-Mo/Al fuel through the sensitivity of the oxide layer thickness on the pH value. This parameter's uncertainty is a reactor dependent. As mention previously, for ATR, the pH value range is between 5.0 and 5.7.

3.7 Swelling

As the fuel gets irradiated, swelling starts to take place. As swelling increases as the fission density and the interaction layer (IL) formation increases [15], the thickness of the fuel meat increases that leads to a significant increase in the fuel operational temperature.

The swelling in the fuel particle has been obtained using the following equations [15]:

$$\left(\frac{\Delta V}{V_0}\right)_f = 0.05\, f_d, \quad for\ f_d \leq 2.0\ \times\ 10^{21}\ \frac{fissions}{cm^3}$$

$$\left(\frac{\Delta V}{V_0}\right)_f = 0.1 +\ 0.067\,(f_d - 2.0) + 0.0058\,(f_d - 2.0)^2,$$
$$for\ f_d > 2.0\ \times\ 10^{21}\ \frac{fissions}{cm^3} \ldots (4)$$

Where f_d is fission density in 10^{27} fissions/m^3 fuel.

To minimize the formation of IL, silicon additions have been used to make the interaction layer growth thinner and denser. According to Kim et al. [15], if the silicon addition is greater than 0.5 wt%, it is valid to assume that the IL growth does not have influence on the meat swelling or the IL formation reaction does not yield volume expansion.

With that assumption, the fuel meat swelling can be obtained by the following equation [15]:

$$\left(\frac{\Delta V}{V_0}\right)_m = \left(\frac{\Delta V}{V_0}\right)_f v_{f,0}\ \ldots (5)$$

Where $v_{f,0}$ is the as-fabricated volume fraction of fuel particles in the fuel meat.

The uncertainty of swelling measurements depends on four major parameters [16]: the plate thickness measurements, oxide layer thickness measurements, cladding thickness, and fuel loading volume fraction. As a result, the uncertainty of the scatter in the local fuel swelling data is ±10% [16].

Table 1 shows the parameters used for the operational temperature calculation and their uncertainties.

4. Fuel Operational Temperature Calculations

After obtaining all the required parameters values for the operational temperature calculations of fuel meat with their uncertainties, equations (1) and (2) were used to calculate the operational temperature for high and low heat flux profiles. The results of temperature calculations as a function of fission density are shown in Fig. 1.

5. Combined uncertainty in fuel temperature

The first goal of this work is to obtain the temperature distribution of upper and lower bounds based on the values of uncertainty of the eight parameters discussed previously. Several parameters are interdependent or interrelated but their uncertainties and the sources of uncertainties are independent. To evaluate the combined effect of all these parameters on the operational temperature distribution, the root of sum of squares (RSS) method is used.

Table 1: Parameters and their uncertainties.

Parameter	Uncertainty
Fuel meat thermal conductivity	±10%
Fuel meat thickness	±51% (±0.13 mm)
Heat transfer coefficient	±20%
Surface heat flux profile	±19%
Oxide layer thickness	±10%
Oxide layer thermal conductivity	±30%
pH value	5.0 - 5.7
Swelling	±10%

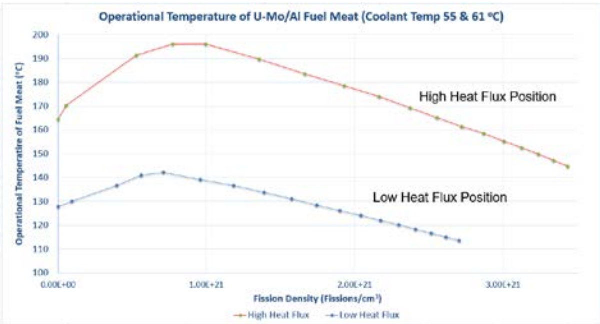

Fig. 1: Operational temperature calculations of U-Mo/Al fuel as a function of fuel meat fission density for low and high heat flux profiles.

The root of sum of squares method, represented as follows [17]:

$$P =\ P_{base} + Root\ (\textstyle\sum_i (\ P_i -\ P_{base})^2) \ldots (6)$$

where:

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

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 (calculated using nominal values) operational temperature of the fuel meat.

It is worth mentioning again here that some parameters are interdependent and related to each other. However, the first goal of this study is to evaluate the effect of each parameter independently taking into account the independency of the uncertainty sources. The effect of interdependency and correlation is addressed in the conclusion section and requires additional analysis.

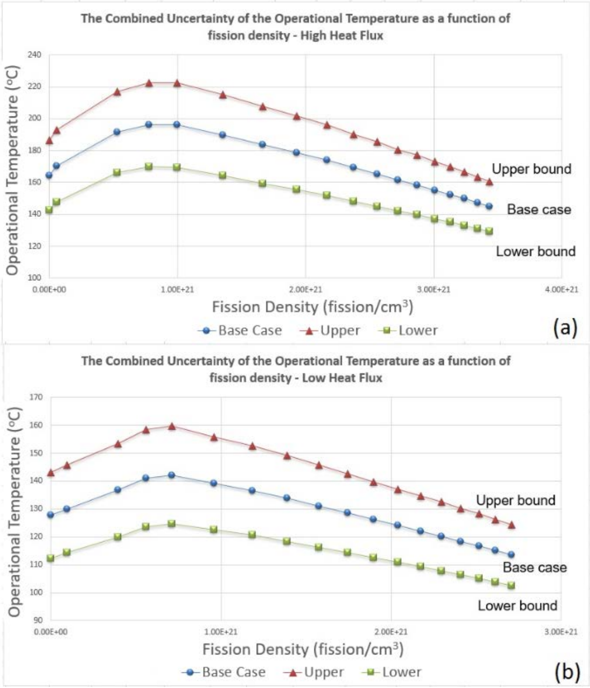

Fig. 2: Operational temperature variations of U-Mo/Al fuel as a function of fuel meat fission density when applying the upper and lower uncertainty bounds compared to the base case (a) high heat flux (b) low heat flux.

6. Results and Discussion

The operational temperature calculations of the base case show that the maximum temperature of the fuel reaches 196.18 ^{o}C at fission density of around 1.00E+21 and 142.21 ^{o}C at 7.09E+20 for high heat flux and low heat flux profiles, respectively.

The uncertainty analysis results show that the parameter that has the highest impact on the operational temperature of the fuel is the heat transfer coefficient, due to its high uncertainty and its direct relation with the cladding outer temperature. ΔT of the heat transfer coefficient, which is the difference between temperatures when applying the upper and lower bounds, is the highest among all the parameters (37.76 ^{o}C and 28.11 ^{o}C at maximum heat flux for high and low heat flux profiles, respectively).

Surface heat flux uncertainty has the second highest influence among the parameters with a ΔT of 17.65 ^{o}C and 8.05 ^{o}C upon applying the upper and lower bounds of uncertainty for high and low heat fluxes.

The pH value uncertainty gives a higher influence on the operational temperature than the fuel thickness and swelling for the high heat flux profile. The pH value uncertainty shows a maximum ΔT of 15.53 ^{o}C, higher than those from the oxide layer thermal conductivity, the fuel thickness, and swelling uncertainties for the high heat flux position. The fuel meat thickness and swelling uncertainties give a maximum ΔT of 10.08 ^{o}C while the oxide layer thermal conductivity uncertainty shows a maximum ΔT of 11.67 ^{o}C. For the low heat flux profile, the oxide layer thermal conductivity, the fuel thickness, and swelling uncertainties show higher influences. The ΔT for the fuel meat thickness and swelling uncertainties is 4.69 ^{o}C while ΔT is 4.16 ^{o}C for the oxide layer thermal conductivity when compared to a ΔT of 3.03 ^{o}C for the pH value uncertainty. Therefore, as the heat flux increases, the effect of the pH value on the operational temperature increases (which is reflected through the increase formation of the oxide layer).

In addition, the thermal conductivity uncertainty of the fuel shows a higher influence than the oxide layer thickness for the studied case of AFIP-1. As the effect of the thermal conductivity uncertainty increases with burnup, it shows a small effect as ΔT is 5.6 ^{o}C and 2.47 ^{o}C at a fission densities of 3.50E+21 and 2.71E+21 fission/cm^3 for high and low heat flux profiles, respectively.

The parameter that has the lowest impact on the operational temperature is the oxide layer thickness. It has a maximum ΔT of 3.54 ^{o}C and 1.26 ^{o}C at the highest burnup values for high and low heat fluxes.

The combined uncertainty results show that when applying all the parameters' uncertainties, the maximum overall influence on the value of the operational temperature is 27.47 ^{o}C for high heat flux profile and 17.67 ^{o}C for low heat flux case (a maximum temperature of 223.65 ^{o}C and 159.89 ^{o}C for high and low heat fluxes, respectively). As a result, these parameters and their uncertainties 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.

7. 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 of eight high-influence parameters were considered (see Table 1).

After obtaining all the uncertainty values of the required parameters, the operational temperature of fuel meat was calculated as a function of the fission density for high and low heat flux profiles.

The combined uncertainty study using the RSS method evaluated the effect of applying the selected key uncertainty values of the parameters on the operational temperature of U-Mo/Al fuel. The maximum overall influence on the operational temperature is 27.47 ^{o}C and 17.67 ^{o}C for high heat flux and low heat flux profiles, respectively. These values represent the difference between the upper (and lower) bound of the temperature and the base case when using the nominal values.

Further studies are needed including the use of other statistical and propagation of uncertainty methods that can be used to validate the results in this work, such as Monte Carlo simulation, these studies are important to take into account the interdependency and correlation effects of parameters. In addition, new parameters and their uncertainties can be added to evaluate their effect on the operational temperature of the fuel and its behavior more accurately.

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