Fission Induced Swelling of U-Mo/Al Dispersion Fuel

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Abstract

Fission-induced swelling of U-Mo/Al dispersion fuel meat was measured using microscopy images obtained from post-irradiation examination. The data of reduced-size plate-type test samples and rod-type test samples were employed for this work. A model to predict the meat swelling of U-Mo/Al dispersion fuel was developed. This model is composed of several submodels including a model for interaction layer (IL) growth between U-Mo and Al matrix, a model for IL thickness to IL volume conversion, a correlation for the fission-induced swelling of U-Mo alloy particles, a correlation for the fission-induced swelling of IL, and models of U-Mo and Al consumption by IL growth. The model was validated using full-size plate data that were not included in the model development.

1. Introduction

U-Mo fuel particle dispersion in an inert Al matrix, designated as U-Mo/Al hereafter, in plate geometry is a primary fuel form of interest that is extensively studied worldwide for the conversion of HEU-fueled research and test reactors to LEU fuel. The Mo content in the U-Mo alloy has a range of 7 – 10 wt%. The U-Mo alloy particles, typically spherical, are produced by a method called atomization [1]. To fabricate fuel plates the U-Mo particles are dispersed in an Al matrix, and then this fueled zone is bonded to an Al alloy cladding. The fueled zone of a dispersion fuel is also termed ‘meat.’ An alternative design to dispersion fuels uses a thin U-Mo foil directly bonded to cladding. This fuel type is called monolithic fuel (see **Fig. 1** for comparison).

During irradiation U-Mo fuel particles undergo fission-induced swelling, caused by fission product formation. The fuel particle swelling is manifested in increased plate thickness in plate-type fuel, and increased cross-section area in rod-type fuel. No dimensional changes occur in the other dimensions due to higher constraints. The increase in plate thickness, or rod cross-sectional area, can be used to determine the performance of a test fuel, where a smaller increase is indicative of a better performing fuel.

For monolithic fuel plates, U-Mo fuel swelling can be quantified by measuring the plate thickness before and after irradiation, because the Al alloy cladding does not change dimensions under irradiation [2]. Conversely, if U-Mo fuel swelling is known, plate thickness swelling can be calculated by multiplying the U-Mo fuel swelling by the ratio of as-fabricated foil thickness to

as-fabricated plate thickness. For a dispersion fuel plate, however, plate thickness swelling cannot be directly correlated to U-Mo fuel swelling. The volume of the U-Mo fuel particle increases due to fission-induced swelling and simultaneously decreases due to the reaction between the U-Mo fuel and the Al matrix. It is not uncommon during PIE (post-irradiation examination) that the U-Mo fuel volume remains nearly unchanged from the as-fabricated state because the fission-induced swelling and the consumption of the fuel by the U(Mo)-Al reaction approximately cancel each other. Another important factor is that because the interaction layer (IL) contains uranium, fission also occurs there, in addition to within the fuel. Hence, the IL is also subject to considerable fission-induced swelling. Therefore, except for the cases having negligible IL growth, the application of U-Mo swelling obtained using the correlation for monolithic U-Mo fuel, such as the one available in Ref.[2], to dispersion cases in an attempt to calculate plate thickness swelling can lead to inaccurate results. For the dispersion cases, fuel meat swelling must be applied instead; which is composed of U-Mo particle swelling, IL growth, and consumption in the U-Mo and Al matrix by IL growth. Plate thickness swelling can then be calculated by multiplying U-Mo/Al fuel meat swelling by the ratio of as-fabricated fuel meat thickness to as-fabricated plate thickness.

In this study, we measured fuel meat swelling of dispersion fuel samples using optical microscopy (OM) images taken during post-irradiation examination (PIE). We also developed a model to predict fuel meat swelling of U-Mo/Al for both plate type and rod type test samples. The validity of the developed model was examined by comparing the model predictions for full-size plates with the measured data. The model predictions matched closely with the measured data.

2. Irradiation tests and post-irradiation examination

U-Mo/Al dispersion fuel plates from miniplate tests RERTR-4, -5, -6, -7, and -9 were analyzed. Several rod-type samples from KAERI's KOMO-3 and -4 tests were also included. The RERTR miniplates were irradiated at 81 – 154 °C and KOMO samples were irradiated at 167 – 194 °C [3]. Due to this temperature difference, the KOMO test samples experienced much thicker IL growth than the RERTR test samples at about the same fission density.

Two types of Mo composition were adopted, i.e., 7 and 10 wt% for the RERTR tests, but only 7 wt% Mo was tested in the KOMO tests. The matrices were composed of pure Al or Si-added Al, with the Si content varying in the range of 0.2 – 5 wt%. Both LEU, where U-235 enrichment is limited to less than 20%, and HEU fuels were used.

The RERTR miniplates were sub-sized test plates 100 mm x 25 mm x 1.40 mm in size, with fuel meat dimensions of 81.3 mm x 18.5 mm x 0.64 mm. The fuel meat was composed of U-Mo fuel particles dispersed in an Al matrix metallurgically bonded with Al-6061 cladding.

The KOMO test samples were rods 7.92 mm in diameter x 760 mm in length and the fuel meat was composed of U-Mo fuel particles dispersed in an Al matrix directly bonded to Al-1060 cladding by a co-extrusion method. The meat dimensions were 6.4 mm in diameter x 200 mm in length, located in the upper part of the rod (see **Fig. 2**). The cladding for the KOMO test rods was 0.76 mm thick and was finned (see Fig. 3 of Ref. [4] for more details). The KOMO test rods had higher constraints than the plate type samples, which is advantageous for suppressing pore

formation in the meat, and possibly also reducing fission gas bubble swelling in U-Mo particles. The detailed irradiation test data of the samples are summarized in **Table 1**.

The RERTR miniplates were cut at their axial mid-plane for PIE (see **Fig. 2**). Meat swelling was measured using micrographs taken at the center in the width direction. For the KOMO test samples, metallography was performed at the peak burnup location, at the bottom of the test rods.

3. Measurement of U-Mo/Al fuel meat swelling

Fuel meat swelling was measured using optical micrographs taken during PIE for RERTR miniplates. Creep and mass relocation occurring in the plate-type fuel meat at the meat edges can additionally increase the meat thickness [8], which augments false meat swelling. To avoid the complexity of dealing with this situation, we selected the measurement location at the center of the plate width, away from the regions affected by creep.

The boundaries between meat and cladding are typically uneven as shown in **Fig. 3**. Therefore, the meat thickness is difficult to measure, which invites uncertainties. To overcome this uncertainty, the plate thickness was measured and converted the plate thickness data to meat swelling using the following expression:

$$\left(\frac{\Delta V}{V_0} \right)_m = \left(\frac{t_p - t_{p,0}}{t_{p,0}} \right) \left(\frac{t_{p,0}}{t_{m,0}} \right) \quad (1)$$

where t_p is the post-irradiation plate thickness, $t_{p,0}$ is the as-fabricated plate thickness, $t_{m,0}$ the as-fabricated meat thickness. As-fabricated data are given by nominal values, which may vary from the actual plate values. Since Al does not change dimensions by irradiation, it is reasonable to assume that the plate thickness away from the fueled zone is the same as the as-fabricated plate thickness. We measured the plate thickness at the location as shown in **Fig. 3** and used it as the as-fabricated plate thickness.

For the KOMO rod samples, meat swelling induces an increase in the meat radial cross section area. Overwhelming constraints in the axial direction inhibits swelling along the axis during irradiation. The meat diameter change on the radial cross section before and after irradiation was obtained using optical micrographs made available during PIE. To remove any uncertainty in sphericity, several radial measurements at different circumferential locations were made and then the average was taken. Fuel meat swelling was then calculated from:

$$\left(\frac{\Delta V}{V_0} \right)_m = \frac{D_m^2 - D_{m,0}^2}{D_{m,0}^2} \quad (2)$$

Here D is the meat diameter. The subscripts m and 0 stand for the meat and the as-fabrication value, respectively.

The measured meat swelling data are given in **Table 1** for both plate- and rod-type fuels. The IL thickness was also measured at the location where the meat swelling was measured and included in the table. The IL thickness data were obtained using the same method described in Ref. [3].

No additional correction such as stereoscopic effects was considered.

Measurement errors were caused mainly by uncertainties in the as-fabricated meat thickness for the RERTR test plates and as-fabricated meat diameter for the KOMO test samples. The estimated errors in the measurement data are also included in **Table 1**. The measurement errors were due to uncertainty in as-fabricated meat thickness for the plate samples and meat diameter in rod type samples and fuel particle distribution in the meat. The error bands were calculated using the minimum and maximum values measured for the samples. The RERTR-4, -5, and -6 plates had as-fabricated meat thicknesses close to the nominal value, 0.64 mm, but RERTR-7, and -9 plates appeared to have quite irregular meat thicknesses. For some samples from RERTR-7 and -9, the meat thickness at the width center was measured using OM images and then the as-fabricated meat thickness was estimated by removing the meat swelling by applying the following equation:

$$t_{m,0} = \frac{t_m}{1 + \left(\frac{\Delta V}{V_0} \right)_m} \quad (3)$$

where $\left(\frac{\Delta V}{V_0} \right)_m$ is the fractional meat swelling.

A close examination of the data given in **Table 1** revealed that the measured meat swelling t is generally dependent upon fission density, which is similar to the case for the monolithic fuel data that showed fuel swelling is a function of fission density [2]. However, a slight difference is also found that fuel meat swelling in a dispersion fuel meat is reliant on not only fission density, but also IL growth and U-loading (or U-Mo volume fraction in meat).

The effect of the IL on meat swelling was examined by plotting the meat swelling data as a function of the IL thickness (**Fig. 4**). Only data for plates with 6 gU/cm^3 loading were included to eliminate the effect of U-loading. Plates with 6 gU/cm^3 loading were selected for comparison because this loading had the most samples available. To exclude the effect of fission product-induced swelling by the fuel particles, a function of fission density, three data groups with relatively tight ranges of fission densities were selected. The RERTR-4, -5 and -6 data are for plates with pure Al matrix and the RERTR-7 data are for plates with Si addition in the matrix. The RERTR-7 data have higher meat swelling than the RERTR-5 and -6 data due to the higher fission densities although the ILs are in the similar range. Commonly for all three data groups, meat swelling clearly increases as IL thickness increases, which shows the measurable contribution of IL growth in meat swelling.

4. Modeling of U-Mo/Al fuel meat swelling

4.1 U-Mo fuel particle swelling

As was discussed in Ref.[2], it is convenient to use monolithic U-Mo samples to obtain fission-product-induced fuel swelling because the effect of IL formation can be avoided. Fission-product-induced fuel swelling of U-7Mo in monolithic fuel plates in the RERTR-6 was measured and the results are plotted in Fig. 5. The model prediction for U-10Mo foil, previously documented [2], is also included for comparison. The plotted data for U-7Mo fuel swelling are systematically higher than the line representing U-10Mo. Fuel swelling data for U-7Mo appear to be on average about 22% higher than that of U-10Mo. Because fuel swelling due to solid fission

products should be similar for both alloys [2], the augmentation is probably due to fission gas bubble (FGB) swelling.

FGB swelling is known to be closely dependent on grain subdivision (also known as recrystallization) kinetics [9],[10]. As grain subdivision progresses, additional grain boundaries are formed. Intergranular FGB nucleate and grow on the existing grain boundaries [9],[10], so increased grain boundary density enhances fuel swelling by FGB formation.

Fig. 6 shows grain subdivision kinetics as a function of fission density (FD). Kim showed that fuel grain subdivision increases as a sigmoidal function of FD [10]. It is also noticeable that the alloy with a lower Mo content tends to have faster kinetics and a shorter incubation time, which may be due to enhanced diffusion along the grain boundaries due to reduced Mo content. **This also holds for monolithic U-Mo foil fuel.**

The data fit and consideration of the observations discussed previously result in a correlation for U-7Mo fuel particle swelling as a function of FD as follows:

$$\left(\frac{\Delta V}{V_0}\right)_f = 0.05f_d, \quad \text{for } f_d \leq 2.0 \times 10^{21} \text{ fissions/cm}^3 \quad (4)$$

$$\left(\frac{\Delta V}{V_0}\right)_f = 0.1 + 0.067(f_d - 2.0) + 0.0058(f_d - 2.0)^2, \quad \text{for } 2.0 \times 10^{21} \text{ fissions/cm}^3 < f_d \quad (5)$$

where fuel swelling is expressed as a fraction and f_d is fission density in 10^{27} f/m³ fuel. The model for U-7Mo assumes a transition at 2.0×10^{21} f/cm³ fuel, compared to 3.0×10^{21} f/cm³ for U-10Mo. **This value was tentatively selected that fits the data** shown in **Fig. 5** and grain subdivision behavior shown in **Fig. 6**, following the same method described in Ref.[2]. As was

stated previously, the earlier transition is due to the earlier initiation of grain subdivision for U-7Mo because of the effect of lower Mo content. In **Fig. 6**, grain subdivision starts at 1.5×10^{21} f/cm³. Hence, the transition FD of 2.0×10^{21} f/cm³ appears to be reasonable considering some delay in FD for measurable FGB swelling. The obtained model is, however, considered tentative as it was developed based on limited data **that include uncertainties due to the inhomogeneity of the Mo content in the monolithic fuels.** Therefore, the data obtained for the U-7Mo monolithic foil plates data This is true for monolithic and certainly dispersion fuel. The validity of the model is tested later in this study by a comparison with measured meat swelling data.

For U-10Mo alloy, similar correlations were documented previously [2], and the following is a repetition taken from Ref. [2] for the purpose of comparison.

$$\left(\frac{\Delta V}{V_0} \right)_f = 0.05 f_d, \quad \text{for } f_d \leq 3.0 \times 10^{21} \text{ fissions / cm}^3 \quad (6)$$

$$\left(\frac{\Delta V}{V_0} \right)_f = 0.15 + 0.063(f_d - 3.0) + 0.0033(f_d - 3.0)^2, \quad \text{for } 3.0 \times 10^{21} \text{ fissions / cm}^3 < f_d \quad (7)$$

where fuel swelling is expressed as a fraction and f_d is in 10^{21} f/cm³ fuel.

For alloys with Mo content other than 7 or 10 wt%, an interpolation is recommended between U-7Mo and U-10Mo.

Inhomogeneity in the Mo content in U-Mo alloys is one of the sources of error and is implicitly included in the error bars. Because the present modeling follows the average behavior, we excluded this effect in this work.

4.2 Volume expansion by interaction layer growth

Interaction layer (IL) growth and its effect on fuel meat swelling behavior during irradiation distinguishes the behavior of dispersion fuel meat from monolithic fuel. The presence of the IL renders the phenomenological description of the dispersion fuel meat swelling more complex than that of monolithic fuel.

4.2.1 Interaction layer growth

IL growth during irradiation has extensively been studied and several models are available to predict growth kinetics (see Ref. [3] and references therein). The empirical correlation reported in Ref. [3] to predict IL thickness is as follows:

$$Y^2 = 2.6 \times 10^{-8} \dot{f}^{0.5} \exp\left(-\frac{3850}{T}\right) t f_{Si} f_{Mo} \quad (8)$$

where Y is IL thickness in μm , $\dot{f}$ is fission rate in $\text{f}/(\text{cm}^3 \text{ s})$, T temperature in K, t time in s. f_{Si} and f_{Mo} are factors representing the effect of Si addition to the matrix and the effect of the Mo content in U-Mo, respectively. The method for calculating these factors follows.

The addition of Si to the Al matrix is known to suppress the IL growth rate by reducing Al diffusion to U-Mo [3]. The IL growth rate for the matrix with Si addition was dealt with in the model by the factor f_{Si} :

$$f_{Si} = (1.201 - 0.00062 T) \exp\left[-(10.333 - 0.021 T) W_{Si}\right] + (0.00062 T - 0.201) \exp\left[-(0.00081 T - 0.302) W_{Si}\right] \quad (9)$$

where T is the fuel meat temperature in K (≤ 473 K) and W_{Si} is the Si content in the matrix in wt% (≤ 8 wt%). f_{Si} is in the range $0.02 \leq f_{Si} \leq 1$. The minimum occurs for a Si content of 8 wt%, whereas the maximum occurs for pure Al, for Si content between 0 and 8 wt%. Although no in-pile data are available, Si content greater than 8 wt% would further decrease the IL growth rate. However, the practical limit for Si content from the fabrication technology point of view seems to be about 8 wt%.

The effect of Mo content on IL growth is to decrease IL growth linearly with the Mo content in the range of 6 – 10 wt%. The following formula was installed in the model reported in Ref. [3]:

$$f_{Mo} = 1.35 - 0.05W_{Mo} \quad (10)$$

where W_{Mo} is the Mo content in fuel particles in wt%. f_{Mo} varies between 0.85 (at 10 wt% Mo) and 1.05 (6 wt% Mo). A Mo-content beyond 10 wt% is not considered in the US RERTR program.

The correlation given in Eq. (8) is an empirical fit to the PIE data. Therefore, the IL thickness and the corresponding IL volume include both fission induced swelling occurring in the IL, and possible volume expansion during IL formation because of the density difference between the reactants and IL.

4.2.2 Conversion from IL thickness to IL volume

Once IL thickness is known, the corresponding IL volume can be calculated using the model given in Ref. [3] that assumes uniform U-Mo particle size and U-Mo particle distribution in an FCC array. Focusing on a U-Mo particle with radius of r , the fuel volume is

$$V_f = \frac{4\pi r^3}{3} \quad (11)$$

The IL volume, i.e., the time-dependent IL volume per U-Mo particle, was calculated by

$$V_{IL} = \frac{4\pi R^3}{3} - \frac{4\pi r^3}{3} - 12(V_c - 2v_c) \quad (12)$$

where $R = r + Y$. Y is the IL thickness. V_c and v_c are overlapping volumes with neighboring particles. The number on the last term of the right hand side of Eq. (12) indicates that there are 12 neighboring particles interacting with the particle in question. The overlapping zone volumes are given by

$$V_c = \frac{1}{3}\pi h^2(3R - h) \quad (13)$$

where

$$h = Y - \left(\frac{1}{\sqrt{8}} \sqrt[3]{\frac{16\pi}{3} \frac{1}{v_f}} - 1 \right) r \quad (14)$$

and

$$v_c = \frac{1}{3}\pi g^2(3R - g) \quad (15)$$

where

$$g = \frac{1}{2} \left[Y - \left(\frac{1}{\sqrt{2}} \sqrt[3]{\frac{16\pi}{3} \frac{1}{v_f}} - 2 \right) r \right] \quad (16)$$

and v_f is the fuel volume fraction in the meat.

4.3 U-Mo and Al consumption by IL growth

During irradiation, U-Mo fuel particles are consumed by IL growth. The consumed U-Mo volume is proportional to the produced IL volume. If the densities of U-Mo and IL are known, the consumed U-Mo volume per U-Mo particle can be calculated as follows:

$$V_f^{c'} = \frac{\rho_{IL}}{\rho_f} \frac{M_f}{M_{IL}} V_{IL} \quad (17)$$

where ρ_f is the U-Mo density, ρ_{IL} is the IL density, M are molecular weights, and V_{IL} is the IL volume obtained in Eq. (12).

The IL volume has contributions not only from consumption of the fuel and matrix, but also from fission-induced swelling. This contribution to the IL volume must be removed in order to determine the volume of U-Mo fuel and Al matrix consumed by IL formation. It was assumed that the swelling rate of the IL was approximately the same as that of UAl_x in the absence of swelling data for the IL. This assumption can be justified if the effect of a small amount of Mo included in $U(Mo)Al_x$ does not considerably alter swelling of UAl_x . The swelling kinetics for UAl_x is available in the literature [12] as follows:

$$\left(\frac{\Delta V}{V_0} \right)_{IL} = 0.064 f_d \quad (18)$$

where the swelling is in fraction and f_d is fission density in 10^{21} f/cm^3 . As was discussed in Ref. [12], the swelling kinetics given in Eq. (18) includes an additional contribution from oxide inclusions in the UAl_x . The oxide inclusions originate from the powder production process. The ILs formed between U-Mo and Al during irradiation, however, are free of such oxides.

Consequently, the application of Eq. (18) to IL swelling may lead to a slight over-prediction ($\sim 1\%$ per 10^{21} f/cm³), as the oxide is known to have higher FGB swelling [13].

Adopting Eq. (18) was justifiable, and gave accurate results whether the oxide effect was considered or not because the contribution of fission-induced swelling in the IL to meat swelling is insignificant. Although it appears to be comparable with that of U-Mo, the fission-induced swelling in the IL is minor because the fission density in the IL is small due to a low fissile uranium concentration. The fission density in IL is related to that in U-Mo by

$$(f_d)_{IL} = \frac{\rho_{IL}}{\rho_f} \frac{M_f}{M_{IL}} (f_d)_f \quad (19)$$

where $(f_d)_f$ and $(f_d)_{IL}$ are fission densities for U-Mo and IL, respectively, and ρ and M are described in Eq. (17). For example, the fission density of IL (U-10Mo)Al₄ is about 0.26 of that in U-Mo.

By subtracting the fission-induced swelling from the IL volume, the real consumed U-Mo volume can be found as follows:

$$V_f^c = \frac{\rho_{IL}}{\rho_f} \frac{M_f}{M_{IL}} V_{IL} \left[1 - \left(\frac{\Delta V}{V_0} \right)_{IL} \right] \quad (20)$$

where $\left(\frac{\Delta V}{V_0} \right)_{IL}$ is the fission-induced swelling of IL obtained in Eq. (18).

Similar to the U-Mo particle case, the Al consumption by IL growth per U-Mo particle can be found by

$$V_{Al}^c = \frac{\rho_{IL}}{\rho_{Al}} \frac{x M_{Al}}{M_{IL}} V_{IL} \left[1 - \left(\frac{\Delta V}{V_0} \right)_{IL} \right] \quad (21)$$

where x is the atomic ratio of Al to U+Mo in the IL, which is frequently expressed as $U(Mo)Al_x$ although the IL is amorphous [15],[16].

The remaining U-Mo volume was calculated by subtracting the consumed U-Mo volume from the as-fabricated U-Mo volume. To determine fission-induced swelling in the fuel particle equations (4) – (7) were used. Then, the time-dependent U-Mo fuel volume per particle was calculated as follows:

$$V_f = (V_{f,0} - V_f^c) \left[1 + \left(\frac{\Delta V}{V_0} \right)_f \right] \quad (22)$$

where V_f^c is given by Eq. (20), and $V_{f,0}$ is the as-fabricated volume of a U-Mo particle, which can be expressed as

$$V_{f,0} = \frac{4\pi r_0^3}{3} \quad (23)$$

where r_0 is the as-fabricated fuel particle radius. Similarly, the time-dependent Al volume per fuel particle is

$$V_{Al} = V_{Al,0} - V_{Al}^c \quad (24)$$

where V_f^c is given by Eq. (21), and $V_{Al,0}$ is the as-fabricated Al matrix volume per U-Mo particle, which can be calculated by

$$V_{Al,0} = \left(\frac{1}{v_{f,0}} - 1 \right) V_{f,0} \quad (25)$$

where $V_{f,0}$ is given in Eq. (23) and $v_{f,0}$ is the as-fabricated fuel volume fraction in the meat. $v_{f,0}$ is fixed by the given fuel loading (or the uranium density in the meat) and fuel alloy density. For example, $v_{f,0}$ for a fuel loading of 8 gU/cm^3 with U-10Mo particles was calculated as $v_f = 8/17.1/(1-0.1) = 0.52$ using a U-10Mo density of 17.1 g/cm^3 (**Table 2**). In this calculation, as-fabricated porosity in the meat is neglected because it is negligible for the test samples used in this study. As uranium-loading increases for full size plates, however, the meat porosity tends to be higher (such as up to $\sim 5.7\%$ for the full-size plate with 8 gU/cm^3 [17]).

4.4 U-Mo/Al meat swelling

The time-dependent meat volume is composed of U-Mo volume, Al volume and IL volume:

$$V_m = V_f + V_{Al} + V_{IL} \quad (26)$$

V_f is given by Eq. (22), V_{Al} by Eq. (24), and V_{IL} by Eq. (12). As a result, the fractional meat swelling is

$$\left(\frac{\Delta V}{V_0} \right)_m = \frac{V_f + V_{Al} + V_{IL}}{V_{f,0} + V_{Al,0}} - 1 \quad (27)$$

Once the meat swelling is known, the plate thickness swelling can be calculated by

$$\left(\frac{\Delta t}{t_0} \right)_p = \left(\frac{\Delta V}{V_0} \right)_m \left(\frac{t_{m,0}}{t_{p,0}} \right) \quad (28)$$

where t is plate thickness and 0 denotes the as-fabricated state.

5. Model prediction and discussion

5.1 IL densities

The IL density is a required model parameter. However, no measured data for the IL density was available in the literature. The effective IL densities that provided the best fit for the measured meat swelling data are summarized in **Table 1**.

The test samples were classified into two categories in terms of matrix composition: pure Al and Al with Si addition. The Si content varies across the samples from zero to 8wt%. Although there is no clear boundary, the samples with Si content below 1 wt% showed approximately the same behavior as those with a pure Al matrix. The samples with higher than 1wt% Si showed contrastingly different behavior in terms of fuel meat swelling. The samples with Si addition in the matrix exhibited generally lower meat swelling. This suggests that the IL formed in these samples likely have different characteristics; for example, density.

An out-of pile test found that the IL is composed of $U(Al, Si)_3$, $U_4Mo_6Al_{43}$ and UAl_3 [18],[19]. Crystallinity is lost in in-pile test samples in which the ratio (x) of Al to U+Mo in the IL is substantial. Several EPMA (electron probe micro-analysis) studies are available that measured x for the ILs of in-pile test samples. The ratio was lower for Al matrices with Si addition ($x = 3 - 4$ [20]-[23]) than that reported for the pure Al matrix ($x = 3 - 7$ [22],[24]). However, if the Si atoms are included in the ratio, x values, where $x = (Al+Si)/(U+Mo)$, become similar for both cases. A reasonable fit was found when the x value was set equal to 4 for cases with and without Si addition.

For the pure Al matrix cases, the density of the IL was estimated by extrapolating from that of UAl_4 . The density of UAl_4 is available in the literature as 6.06 g/cm^3 [25]. Although it is not directly applicable for $(\text{U-Mo})\text{Al}_4$, the density of UAl_4 may be used as base information in the parametric study. Because the Mo atoms replace the U atoms to form $(\text{U-Mo})\text{Al}_4$, the IL density was reduced proportionately in this study. The density of the IL for U-10Mo dispersion in Al was determined to be 5.56 g/cm^3 , and 5.71 g/cm^3 for U-7Mo dispersion in Al. However, these values resulted in overpredictions for meat swelling due to the over-estimated volume expansion by IL formation. Considering that Mo atoms have a smaller atomic volume when they substitute U atoms, a volume contraction must also be reflected. Hence, a slight increase in the previously determined IL density was considered. Using this information, the IL densities were determined by fitting the meat swelling data in Table 1. The best fit IL densities found in this manner are summarized in **Table 2**.

For the cases where Si was added to the Al matrix, the effect of the Si addition on the IL density had to be assessed. To do that, we used an analogy of $\text{U}(\text{Al,Si})_3$ studied by Dwight [26]. Dwight found a volume contraction when Si was added to UAl_3 . From this information, an increase in the IL density by 1% was tried in the parametric study. The IL densities found are given in Table 2.

As discussed for the pure Al matrix case, the IL is amorphous during irradiation, so the ratio (x) is not indicative that the IL is a compound. From the microscopic point of view, the increase in IL density can be a result of Si diffusion and reaction with U atoms to form a U-silicide that has

a much higher density than the IL [22],[27],[28]. Because this phase is also a part of the IL, the overall IL density increases.

The volume change from the IL formation reaction is

$$\left(\frac{\Delta V}{V} \right)_{IL} = \frac{\frac{M_{IL}}{\rho_{IL}}}{\frac{M_{U-Mo}}{\rho_{U-Mo}} + \frac{x M_{Al}}{\rho_{Al}}} - 1 \quad (29)$$

where M are molecular weight and ρ are densities and x is the ratio of Al to U+Mo. Using the data in Table 2 and IL density, the volume expansion involved during IL formation in the pure Al matrix case was calculated to be 8.5% and 7.5% for the Al-Si matrix case. The smaller volume expansion in the Al-Si matrix case may be the reason why the Si added plates show lower meat swelling and in general improved performance.

5.2 Model prediction procedure

The procedure employed to calculate meat swelling in the model is described below. The calculations are performed for a U-Mo particle, for which the average particle size and number of particles per unit meat volume are specified by uranium loading in the meat in the as-fabricated data. For a time interval Δt , the following procedure is used.

- 1) Calculate IL thickness (Y) with Eq. (8).
- 2) Convert the IL thickness to IL volume with Eq. (12).
- 3) Calculate the consumed fuel and Al matrix volumes with Eqs. (20) and (21), respectively.

The input data including the Al/(U+Mo) ratios and IL densities used in the present study are collected in **Table 2**.

- 4) Calculate U-Mo fuel swelling with Eqs. (6) and (7) for U-10Mo, and with Eqs. (4) and (5) for U-7Mo.
- 5) Calculate U-Mo fuel volume with Eq. (22).
- 6) Calculate Al matrix volume with Eq. (24).
- 7) Calculate meat swelling with Eq. (27).
- 8) Move to the next time step.

5.3 Model prediction and comparison with measured data

The model developed in this study was used to calculate fuel meat swelling of the test samples listed in **Table 1**.

Fig. 7 compares model predictions with the measured data for samples with a pure Al matrix. Some samples with a small Si addition of less than 0.5 wt% were also included, based on the observation that samples with low Si content behave similar to the pure Al cases. Considering measurement uncertainties, the predictions were consistent with the measured values. The comparison also confirmed that the IL densities parametrically obtained in sect. 5.1 are valid for the present model. The effect of IL volume expansion during IL formation was examined calculating meat swelling with and without IL volume expansion during IL formation for four samples and the results are included in **Table 3**. Except for V6001M and 557-SD1 that have substantial IL growth and low U-loading in the meat, the effect of IL formation on meat swelling was insignificant considering the measurement errors given in **Table 1**.

One noteworthy observation was that the KOMO test data were mostly over-predicted, although not significantly. We suspect the rod geometry may have suppressed meat swelling by reducing FGB swelling in the U-Mo particles due to higher constraints, which was not considered in the model.

A comparison for the samples with Si addition greater than 0.5 wt% is given in **Fig. 8**. The predictions compare well with the measured data. In general, the test samples with Si addition greater than 0.5 wt% showed lower fuel meat swelling than the samples with Si addition of less than 0.5 wt%. The reduction in swelling is clear evidence of the advantageous effect of high Si addition suppressing IL growth in the meat.

5.4 Fuel particle swelling estimation

When U-Mo fuel swelling for dispersion fuel plates is desired to know, the following estimation method is employed by using the fuel meat swelling.

$$\left(\frac{\Delta V}{V_0}\right)_f = \left(\frac{\Delta V}{V_0}\right)_m \frac{1}{v_{f,0}} \quad (30)$$

where $v_{f,0}$ is the as-fabricated volume fraction of fuel particles in the fuel meat. If there is no IL formation as in a monolithic fuel sample, this method is reliable. In other words, meat swelling can be predicted by using fuel swelling calculated by Eqs. (4) and (5) for U-7Mo dispersion or by Eqs. (6) and (7) for U-10Mo dispersion without having to consider IL growth [17],[29],[30], i.e.,

$$\left(\frac{\Delta V}{V_0}\right)_m = \left(\frac{\Delta V}{V_0}\right)_f v_{f,0} \quad (31)$$

In case there is substantial IL formation, however, this method has to assume that IL growth does not have influence on the meat swelling or the IL formation reaction does not yield volume expansion.

In order to examine the validity of this method, we estimated fuel swelling by using Eq. (30) and compared with the values calculated by the fuel swelling correlations in Eqs. (4) – (7). **Fig. 9** shows the estimated fuel swelling using Eq. (30) plotted as a function of FD. In **Fig. 9(a)**, the data for U-7Mo/Al dispersion are shown. The estimated data are generally higher than the predictions obtained by using Eqs. (4) and (5). It is counter intuitive that the relatively consistent fuel swelling estimates with the predictions for KOMO-3 and -4 samples as these samples have much thicker ILs. One possible reason may be due to the low fuel loading and low IL volume fractions because of the use of the large fuel particles, $\sim 255\text{ }\mu\text{m}$ on average much larger than RERTR test samples having fuel particle size of $\sim 70\text{ }\mu\text{m}$. For U-10Mo/Al dispersion, a similar comparison was made in **Fig. 9(b)**. The fuel swelling estimates are generally higher than the predictions obtained by using Eqs. (6) and (7), which is similar to the observation for the U-7Mo dispersion in **Fig. 9(a)**.

It is interesting to note that the samples with Si addition shown in **Fig. 10** revealed a better comparison than the pure Al matrix samples in **Fig. 9**, attributed to the generally thinner IL growth in the Si-added samples and the possible formation of denser IL. A similar trend was observed with data from RERTR-9 samples, where plates with thicker ILs tending to fall further from the curve. Another possible cause may be due to an unknown reason such as U-silicide formation by Si diffusion [22],[27],[28] that has different fuel swelling behavior. **Because their**

samples had either very thin ILs due to the use of coated fuel particles or Si addition in the matrix, the observation by Leenaers et al. [29] that the fuel swelling data calculated as a function of fission density neglecting the formation of ILs is consistent with that of monolithic fuel data may be due to the same reason.

Nevertheless, a possible conclusion from these analyses would be that unless the IL volume fraction is small, fuel swelling estimated by using meat swelling yields overestimation in general. Therefore, using Eq. (31) to estimate fuel meat swelling, and in turn to obtain plate thickness swelling, is limited only to low IL growth cases.

5.5 Model validation with full-size plate data

In order to examine the validity of the model, the model was applied to predict the meat swelling of two AFIP-1 full-size plates. The AFIP-1 plates [31],[32] were remarkable due to the following differences from the miniplates. First, the plate dimensions were much larger. The plate and meat dimensions are 571 mm x 58 mm x 1.3 mm and 526 mm x 43 mm x 0.51 mm, respectively. Second, the fuel temperatures were higher, particularly at the peak power locations. The two AFIP-1 test plates were loaded such that the plates were axially welded together and the axial (length) midplane of the combined plates received the maximum neutron flux. This produced high temperatures in the bottom plate because of the downward coolant flow. The life-averaged temperatures were estimated to be ~170 °C for the top plate (1T2) and ~180 °C for the bottom plate (1B5) at their respective peak power locations. The extensive IL growth for both plates that had Si-modified Al matrixes was attributed to the high temperatures at the peak power locations.

The model predictions were performed at the peak power locations. The IL growth of 1B5 was slightly lower than that of 1T2, although the temperature was substantially higher, due to higher Si content in the matrix for the former (see **Table 4**). As can be seen in **Table 4**, both plates show virtually the same measured fuel meat swelling. The prediction results are consistent with the measured, which confirms that the model developed based predominantly on reduced-size plate data together with rod sample data also accurately predicts for full-size plates.

6. Conclusions

Fission-induced swelling of U-Mo/Al dispersion fuel meat was measured. The measurement data could be interpreted as indicating that dispersion meat swelling is dependent on burnup (or fission density), interaction layer (IL) growth, and meat fabrication data including uranium loading in the meat and U-Mo particle size. The measured data also indicated that a net volume expansion occurred during IL formation, despite being small in magnitude.

A model to predict U-Mo/Al dispersion meat swelling was developed. The fuel meat swelling model is composed of submodels such as IL growth correlation, IL thickness to IL volume conversion model, fission-induced swelling correlation for U-Mo, fission-induced swelling correlation for IL, and models of U-Mo and Al consumption by IL growth.

The model predictions were compared with the measured meat swelling data of full-size plates.

The comparison showed that the model predictions were in accord with the measured data. The consistent comparison result also confirmed that the IL densities and Al/(U+Mo) ratio for IL

parametrically obtained in this study and used in the model predictions were reliable although approximated.

Plate thickness swelling can be obtained by using the meat swelling prediction and as-fabricated plate and meat thickness data.

Fuel swelling calculated by using meat swelling and fuel volume fraction in the fuel meat tended to be higher than the prediction by the fuel swelling correlations. In other words, a direct conversion of fuel swelling predicted by the fuel swelling correlations to meat swelling without considering the presence of IL volume yielded underprediction. In order for this method to be accurate, IL volume fraction must be considerably small in the meat. The accuracy of this method was increased when applied to Si-added samples.

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References

- [1] C.K. Kim, J.M. Park, H.J. Ryu, Nucl. Eng. Technol. 39 (2007) 617.
- [2] Yeon Soo Kim, G.L. Hofman, J. Nucl. Mater. 419 (2011) 291.
- [3] Yeon Soo Kim, G.L. Hofman, H.J. Ryu, J.M. Park, A.B. Robinson, D.M. Wachs, Nucl. Eng. Technol. 45 (2013) 827.

- [4] Yeon Soo Kim, G.L. Hofman, A.B. Robinson, D.M. Wachs, H.J. Ryu, J.M. Park, J.H. Yang, J. Nucl. Mater. 427 (2012) 233.
- [5] Yeon Soo Kim, G.L. Hofman, A.B. Robinson, D.M. Wachs, Nucl. Technol. 184 (2013) 42.
- [6] H.J. Ryu, J.M. Park, Y.J. Jeong, K.H. Lee, Y.S. Lee, C.K. Kim, and Yeon Soo Kim, Nucl. Eng. Technol. 45 (2013) 847.
- [7] J.M. Park, J.M. Park, H.J. Ryu, Y.S. Lee, B.O. Yoo, Y.H. Jung, C.K. Kim, Yeon Soo Kim, Trans. Intern. Topical Mtg. on Research Reactor Fuel Management (RRFM), Mar. 2 -5, Hamburg, Germany. Available at <http://www.euronuclear.org/meetings/rrfm2008/index.htm>
- [8] Yeon Soo Kim, G.L. Hofman, J.S. Cheon, A.B. Robinson, D.M. Wachs, J. Nucl. Mater. 437 (2013) 37.
- [9] J. Rest, J. Nucl. Mater. 346 (2005) 226.
- [10] Yeon Soo Kim, G.L. Hofman, J.S. Cheon, J. Nucl. Mater. 436 (2013) 14.
- [11] A. Leenaers, Surface-engineered low-enriched Uranium-Molybdenum fuel for research reactors, Ph.D. Thesis, University of Ghent-SCK•CEN, 2014.
- [12] Yeon Soo Kim, Uranium Intermetallic Fuels (U–Al, U–Si, U–Mo), In: Comprehensive Nuclear Materials, R.J.M. Konings, (ed.), volume 3, p 391-422, Amsterdam, Elsevier (2012).
- [13] G. L. Hofman, Nucl. Technol. 77 (1987) 110.
- [14] J. Rest, Yeon Soo Kim, G.L. Hofman, M. Meyer, S. Hayes, U-Mo Fuels Handbook, ANL-09/31, Argonne National Laboratory, 2009.
- [15] H.J. Ryu, Yeon Soo Kim, G.L. Hofman, J. Nucl. Mater. 385 (2009) 623.
- [16] S. Van den Berghe, W. Van Renterghem, A. Leenaers, J. Nucl. Mater. 375 (2008) 340.
- [17] S. Van den Berghe, P. Lemoine, Nucl. Eng. Technol., 46 (2014) 125.
- [18] M.I. Mirandoua, S.F. Aricó, S.N. Balart, L.M. Griboaud, Mater. Charact. 60 (2009) 888.
- [19] J. Allenou, H. Palancher, X. Iltis, M. Cornen, O. Tougait, R. Tucoulou, E. Welcomme, Ph. Martin, C. Valot, F. Charollais, M. Anselmet, P. Lemoine, J. Nucl. Mater., 399 (2010) 189.
- [20] H.J. Ryu, J.M. Park, C.K. Kim, Yeon Soo Kim, Proc. Int. Mtg. Reduced Enrichment for

- Research and Test Reactors (RERTR), October 5–9, 2008; <http://www.rertr.anl.gov>.
- [21] A. Leenaers, S. Van den Berghe, M. Anselmet, J. Noirot, P. Lemoine, A. Röhrmoser, W. Petry, Proc. Int. Mtg. Reduced Enrichment for Research and Test Reactors (RERTR), October 5–9, 2008; <http://www.rertr.anl.gov>.
- [22] A. Leenaers, S. Van den Berghe, W. Van Renterghem, F. Charollais, P. Lemoine, C. Jarousse, A. Röhrmoser, W. Petry, J. Nucl. Mater. 412 (2011) 41.
- [23] Yeon Soo Kim, G.L. Hofman, J. Nucl. Mater. 410 (2011) 1.
- [24] J.M. Hamy, P. Lemoine, F. Huet, B. Guigon, C. Jarousse, J.L. Emin, Trans. Intern. Topical Mtg. on Research Reactor Fuel Management (RRFM), Mar. 21-24, 2004, Munchen, Germany. Available at <http://www.euronuclear.org/meetings/rrfm2008/index.htm>
- [25] R. Kiessling. In Proc. Intern. Conf. Peaceful Uses Atomic Energy, Geneva, Switzerland, Vol. 9, p 69, 1956.
- [26] A.E. Dwight, ANL Report, ANL-82-14, 1982.
- [27] J. Jue, D.D. Keiser, Proc. Int. Mtg. Reduced Enrichment for Research and Test Reactors (RERTR), October 5–9, 2008; <http://www.rertr.anl.gov>.
- [28] D.D. Keiser, A.B. Robinson, J. Jue, D.M. Wachs, M.R. Finlay, J. Nucl. Mater. 393 (2009) 311.
- [29] A. Leenaers, S. Van den Berghe, E. Koonen, V. Kuzminov, C. Detavernier, J. Nucl. Mater. 458 (2015) 380.
- [30] S. Van den Berghe, Y. Parthoens, F. Charollais, Yeon Soo Kim, A. Leenaers, E. Koonen, V. Kuzminov, P. Lemoine, C. Jarousse, H. Guyon, D.M. Wachs, D.D. Keiser, A.B. Robinson, J.G. Stevens, G.L. Hofman, J. Nucl. Mater. 430 (2012) 246.
- [31] A.B. Robinson, Proc. Int. Mtg. Reduced Enrichment for Research and Test Reactors (RERTR), October 10-14, 2010; <http://www.rertr.anl.gov>.
- [32] D.M. Perez, M.A. Lillo, G.S. Chang, G.A. Roth, N.E. Woolstenhulme, D.M. Wachs, AFIP-1 Irradiation summary report, INL/EXT-11-22045, Idaho National laboratory, 2011.

Table captions

Table 1 Fabrication and irradiation characteristics of the samples used in this study and post-irradiation meat swelling and IL thickness measurement data

Table 2 Material property data and IL densities obtained in this study

Table 3 Effect of IL volume expansion during IL formation on fuel meat swelling

Table 4 As-fabricated data, PIE measurement data and predicted meat swelling results of AFIP-1 full-size plates

Figure captions

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Table 1 Fabrication and irradiation characteristics of the samples used in this study and post-irradiation meat swelling and IL thickness measurement data [3],[5],[6],[7]

Test	Plate ID	Meat composition	Average U-Mo particle size (μm)	U-loading (gU/cm^3 meat)	Enrichment (%U-235)	Test time (EFPD)	Fission density (10^{21} f/cm ³) #	IL thickness (μm)	Measured meat swelling (%)
RERTR-4	V6001M	U-10Mo/Al *	65	6	19.5	257	4.51	15	14.5 ± 1.5
RERTR-4	V6022M	U-10Mo/Al	65	6	19.5	257	5.27	18	17.0 ± 1.5
RERTR-4	V6015G	U-10Mo/Al	65	6	19.5	257	5.52	21	15.3 ± 1.5
RERTR-4	V8006B	U-10Mo/Al	65	8	19.5	257	5.38	22	16.0 ± 2.0
RERTR-4	R6003F	U-7Mo/Al	65	6	19.5	257	5.90	23	24.6 ± 2.5
RERTR-5	V8005B	U-10Mo/Al	65	8	19.5	116	2.39	12	10.7 ± 2.0
RERTR-5	R8002E	U-7Mo/Al	65	8	19.5	116	2.89	17	12.3 ± 2.0
RERTR-5	R6007F	U-7Mo/Al	65	6	19.5	116	2.41	13	8.6 ± 1.5
RERTR-6	V0R010	U-10Mo/Al	65	6	19.2	135	2.89	7	6.1 ± 1.5
RERTR-6	V1R010	U-10Mo/Al-1Si *	65	6	19.2	135	3.03	4	11.1 ± 1.5
RERTR-6	R1R010	U-7Mo/Al-1Si	65	6	19.5	135	2.90	2	5.5 ± 1.5
RERTR-6	R5R010	U-7Mo/Al-0.2Si	65	6	19.1	135	3.04	11	9.6 ± 1.5
RERTR-6	R2R020	U-7Mo/Al-2Si	65	6	19.7	135	3.07	2	5.5 ± 1.5
RERTR-6	R3R030	U-7Mo/Al-5Si	65	6	19.1	135	2.99	2	7.2 ± 1.5
RERTR-6	R5R020	U-7Mo/Al-0.2Si	65	6	19.1	135	3.14	12	12.3 ± 2.0
RERTR-7	V5R050	U-10Mo/Al-0.2Si	65	6	58.2	90	4.56	4	11.1 ± 2.0
RERTR-7	R2R040	U-7Mo/Al-2Si	75	6	58.2	90	4.16	3	12.3 ± 1.5
RERTR-7	R0R010	U-7Mo/Al	140	6	58.1	90	4.22	9	12.1 ± 1.5
RERTR-7	R3R050	U-7Mo/Al-5Si	135	6	58.2	90	4.21	3	10.5 ± 1.5
RERTR-7	R0R020	U-7Mo/Al	135	6	58.1	90	6.02	14	14.7 ± 3.0
RERTR-7	R2R050	U-7Mo/Al-2Si	90	6	58.2	90	4.32	10	15.3 ± 1.5
RERTR-9B	R2R088	U-7Mo/Al-2Si	50	8.5	58.1	115	5.65	9	25.6 ± 2.0
RERTR-9B	R6R018	U-7Mo/Al-3.5Si	50	8.5	58.1	115	5.50	7	21.9 ± 2.2
RERTR-9A	R3R108	U-7Mo/Al-5Si	50	8	44.4	98	3.70	4	11.6 ± 1.5
RERTR-9A	R2R078	U-7Mo/Al-2Si	50	8	44.4	98	3.78	5	18.4 ± 1.5
RERTR-9A	R4R018	U-7Mo/Al-2Si	50	8	44.4	98	3.68	7	15.0 ± 1.5
KOMO-3	557-SD1	U-7Mo/Al	158	4.5	19.5	206	4.80	36	12.0 ± 1.5
KOMO-3	557-MD1	U-7Mo/Al	255	4.5	19.5	206	4.60	40	10.4 ± 1.7
KOMO-3	557-LD1	U-7Mo/Al	363	4.5	19.5	206	4.90	38	10.6 ± 1.7
KOMO-3	557-HS1	U-7Mo/Al-2Si	255	4.5	19.5	206	4.80	24	8.1 ± 1.7
KOMO-4	557-SD3	U-7Mo/Al	158	4.5	19.5	132	3.80	15	8.1 ± 1.7
KOMO-4	557-MD3	U-7Mo/Al	255	4.5	19.5	132	4.00	27	7.3 ± 1.7
KOMO-4	557-LD3	U-7Mo/Al	363	4.5	19.5	132	4.10	28	6.0 ± 1.7
KOMO-4	557-2S1	U-7Mo/Al-2Si	255	5	19.5	132	3.90	30	7.0 ± 1.7
KOMO-4	676-5S1	U-7Mo/Al-5Si	255	5	19.5	132	3.60	8	6.4 ± 1.7
KOMO-4	676-8S1	U-7Mo/Al-8Si	255	5	19.5	132	3.50	7	7.2 ± 1.7

* Numbers in front of Mo and Si stand for Mo content in U-Mo in wt% and Si content in Al matrix in wt%, respectively.

Fission density in U-Mo including fissions by Pu bred during irradiation.

Table 2 Material property data and IL densities obtained in this study

U-7Mo	Unit	Value	Ref.
Molecular weight of U-7Mo	g/mol	215.2	[12]
U-7Mo density	g/cm ³	17.7	[12]
Molecular weight of Al	g/mol	27	P
Al density	g/cm ³	2.7	p
x = Al/(U+Mo) in IL for Al matrix		4	p
Corresponding IL density	g/cm ³	5.71	p
Molecular weight of IL	g/mol	323.3	p
x = Al/(U+Mo) in IL for Al-Si matrix		4	p
Corresponding IL density	g/cm ³	5.77	p
Molecular weight of IL	g/mol	323.3	p

U-10Mo	Unit	Value	Ref.
Molecular weight of U-10Mo	g/mol	206.9	[12]
U-10Mo density	g/cm ³	17.1	[12]
x = Al/(U+Mo) in IL for Al matrix		4	P
Corresponding IL density	g/cm ³	5.56	p
Molecular weight of IL	g/mol	314.9	p
x = Al/(U+Mo) in IL for Al-Si matrix		4	p
Corresponding IL density	g/cm ³	5.62	p
Molecular weight of IL	g/mol	314.9	p

p: present study

Table 3 Effect of IL volume expansion during IL formation on fuel meat swelling

Plate ID	Fuel meat composition	Fission density ($\times 10^{21}$ f/cm ³)	IL thickness (μ m)	Measured meat swelling (%)	Predicted meat swelling with volume expansion during IL formation (%)	Predicted meat swelling without volume expansion during IL formation (%)	Difference between column 5 and column 7 (%)
V6001M	U-10Mo/Al	4.51	15	14.5	13.6	8.4	6.1
V5R050	U-10Mo/Al-0.2Si	4.56	4	11.1	12.2	10.9	0.2
R0R010	U-7Mo/Al	4.22	9	12.1	12.5	11.2	0.9
R2R040	U-7Mo/Al-2Si	4.16	3	12.3	12.0	11.1	1.2
557-SD1	U-7Mo/Al	4.8	36	12.0	12.3	7.7	4.3

Table 4 As-fabricated data, PIE measurement data and predicted meat swelling results of AFIP-1 full-size plates *

Plate ID	1T2	1B5
Fuel meat composition	U-7Mo/Al-2Si	U-7Mo/Al-5Si
U-loading (gU/cm ³ -meat)	8	8
Enrichment (%U-235)	19.5	19.5
Average U-Mo size (μm)	65	65
Irradiation time (EFPD)	158.2	158.2
Fission density (10 ²¹ f/cm ³) ^p	6.42	6.45
Measured IL thickness (μm)	20	16
Measured IL volume fraction (%)	46	34
Measured U-Mo volume fraction (%)	51	60
Measured Al matrix volume fraction(%)	0	4
Measured porosity (%)	3	2
Measured meat swelling (%)	31 ± 1.5	30 ± 1.5
Predicted meat swelling (%)	29.5	30.1

* Analyses performed at the peak power location

p: At peak power location in length (axial) direction. For 1T2, 110 mm from the bottom of the plate, and for 1B5, 478 mm from the bottom of the plate.

(a) Dispersion fuel

(b) Monolithic fuel

Fig. 1 Schematics showing cross sections of monolithic and dispersion fuel forms discussed in this study.

Fig. 2 Schematic of sample cutting location for PIE and meat swelling measurement location.

Fig. 3 Optical micrograph of cross section showing dispersion fuel meat and cladding.

Fig. 4 Meat swelling versus IL thickness for the samples with U-loading of 6 gU/cm³-meat. The numbers next to the data points are fission densities in 10²¹ f/cm³-fuel.

Fig. 5 U-Mo fuel swelling vs fission density showing the effect of the Mo content. The solid line shows prediction using the correlation for U-10Mo foil reported in [2].

Fig. 6 Mo content effect on grain subdivision kinetics. The guiding lines are also added.

(a) U-10Mo/Al

Fig. 7 Comparison of U-Mo/Al meat swelling between model predictions and measured data for Al matrix with Si addition less than 0.5 wt%.

Fig. 7 Comparison of U-Mo/Al meat swelling between model predictions and measured data for Al matrix with Si addition less than 0.5 wt%.

Fig. 8 Comparison of U-7Mo/Al meat swelling between model predictions and measured data for Al matrix with Si addition greater than 0.5 wt%.

(a) U-7Mo/Al. p denotes prediction by Eqs. (4) and (5).

Fig. 9 Fuel swelling estimated using Eq. (30) for Al matrix samples.

(b) U-10Mo/Al. p denotes prediction by Eqs. (6) and (7).

Fig. 9 Fuel swelling estimated using Eq. (30) for Al matrix samples.

Fig. 10 Fuel swelling estimated using Eq. (30) for U-7Mo/Al with Si addition greater than 0.5wt%. p indicates prediction by Eqs. (4) and (5).