THE RERTR-2007 INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS
September 23 – 27, 2007
Hotel Diplomat
Prague, Czech Republic

POST IRRADIATION ANALYSIS AND PERFORMANCE MODELING OF DISPERSION AND MONOLITHIC U-Mo FUELS

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ABSTRACT

We analyzed fission product swelling of post-irradiation U-Mo fuels from the early RERTR tests to the recent RERTR-8 test. We found that the gas bubble swelling of the fuel-swelling model was overestimated. From the recent tests, RERTR-7A and 8, we could also collect a considerable amount of fuel swelling data from monolithic U-Mo fuel plates. The fuel swelling data from the monolithic fuel plates are considered more reliable because the interaction layer growth between the fuel and matrix in dispersion fuel, which obscures fuel swelling, does not exist. The swelling correlation comparison to the Si-added dispersion fuel data and monolithic fuel data suggested that a modification of the existing model was necessary. We also developed an interaction layer growth model for U-Mo/Al dispersion fuel plates with a Si-added matrix. PLATE code calculations with the new PIE data analysis results were performed. The updated versions predict with better accuracies for both monolithic fuel plates and dispersion fuel plates. In this paper, we present the results of fission product swelling characterization. In addition, the interaction layer growth model for U-Mo/Al with a Si-added matrix is presented.

1. Introduction

Addition of 2 wt% silicon to the Al matrix in U-Mo/Al dispersion fuel has proven to effectively reduce interaction layer (IL) growth, as demonstrated by the port-irradiation results of the RERTR-6 (~40 at% U-235) test and the RERTR-7A (~100 at% U-235 LEU equiv.) test [1,2]. Fuel swelling by Fission products is now considered the major factor that increases plate thickness in dispersion fuel plates as well as monolithic fuel plates. We analyzed fission gas bubble development in order to better characterize this part of the swelling kinetics. We also

obtained total fuel swelling data by analyzing plate thickness data for monolithic fuel plates from RERTR-6 and 7A tests. The fuel swelling correlation developed for dispersion fuel data has been re-evaluated to match the new data.

Since our report in the last RERTR conference [2] that Si addition in the Al matrix in U-Mo/Al dispersion fuel decreased the interaction layer (IL) by an exponential function of the Si-content in Al, we have collected more IL thickness data from RERTR-6 and -7A confirming the effect of Si-addition. As a result, a new activation energy (*Q*) and a pre-exponential constant (*A*) were obtained for the IL growth correlation.

In this paper, we present the results of fuel swelling analysis and IL growth correlation for Si-added U-Mo/Al dispersion fuel plates. PLATE code [3] update results are also presented.

2. Fuel fission product swelling analysis

2.1 Total fission product swelling

The fuel swelling is composed of two components, viz., swelling by gas bubbles and fuel matrix swelling by solid and gaseous fission products not confined in the bubbles. The total yield of fission gases, i.e., Xe and Kr, is ~0.25 per fission. A majority of fission gas atoms remain in the fuel matrix particularly at low burnup. These fission gas atoms contribute to fuel matrix swelling. Total fuel swelling can be expressed as follows:

$$\left(\frac{\Delta V}{V_0}\right)_{total} = \left(\frac{\Delta V}{V_0}\right)_g + \left(\frac{\Delta V}{V_0}\right)_s \tag{1}$$

where the first term of the right hand side is for swelling by gas bubbles and the second term is for fuel matrix swelling. The latter is also called as solid swelling. The suffix “0” on V denotes initial volume.

U-Mo swelling is known has two distinct rates: slow at low burnup and much faster at high burnup. The phenomenon underlying in the transition is grain refinement or “recrystalization” of the γ U-Mo. After this transition, gas bubble agglomeration accelerates. SEM observations from RERTR-3, 4, and 5 indicate that the transition burnup depends weakly on the Mo content: the lower the Mo content, the earlier the transition tends to take place with a range 35 - 50 at%U-235 burnup, or 2.5 - 3.5x10^{21} f/cm^3. The transition fission density of 3.0x10^{21} f/cm^3 fits the data for U-10Mo from RERTR-6 and 7. For other Mo content fuel, we presently lack the monolithic fuel data at high burnup necessary to model a relationship between the transition fission density and fuel swelling.

The U-Mo fuel swelling model currently employed in the RERTR program was developed based chiefly on dispersion fuel data from the RERTR-3, 4, and 5 tests [4]. The fuel swelling data derived from dispersion plates contain a number of uncertainties associated with the IL growth between fuel and matrix. The data measured for monolithic plates do not have such disadvantages. The IL growth at the fuel-cladding interface during irradiation is less than 2 μm, which is ~0.2% of the as-fabrication plate thickness. In general, fuel swelling data from

monolithic plates can be obtained from fuel plate thickness measurement without major adjustments.

RERTR-6 and 7A were the first tests that irradiated monolithic miniplates. We estimated fuel swelling from the plate thickness data [5] by using the conversion factor from plate thickness to fuel foil thickness. Only monolithic plates fabricated by the friction stir welding method (FSW) [6] were used. The ILs at the fuel-cladding interface fabricated by FSW were typically very thin and uniform, improving the reliability of the plate thickness measurements.

Figure 1 shows the measured data and the swelling correlations for total fuel swelling as a function of fuel burnup. Dispersion fuel data were also included for comparison. The old and new correlations are actually rather similar. The major difference, however, lies in the transition fission density. In the new correlation, the transition occurs at $3x10^{21}$ fissions/cm^3 whereas that of the old correlation occurs at $2x10^{21}$ fiss/cm^3. It is remarkable that the old correlation, developed chiefly with dispersion plates at relatively low burnup predicts reasonably well at high burnup.

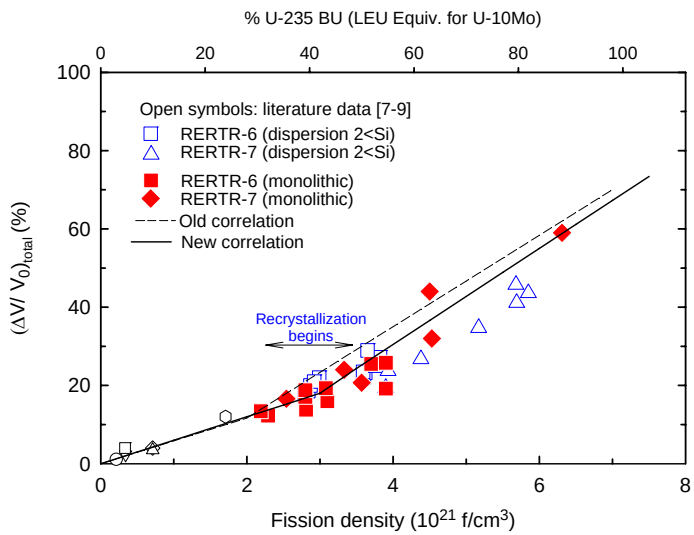


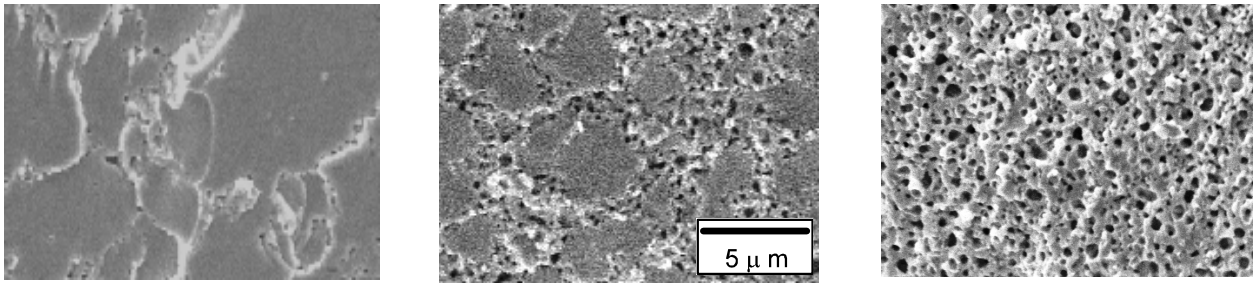
Fig. 1 Comparison between the measured data and model predictions for U-Mo swelling from plate thickness measurements. All measured data are for U-10Mo except RERTR-7 dispersion data with U-7Mo.

The total fuel swelling data of dispersion fuels at high burnup shown in Fig. 1 are generally lower than those of the model correlation. The possible reason is that swelling of the ILs are lower than fuel.

2.2 Fission gas bubble swelling

Post irradiation U-Mo fuel cross sections show the characteristic bulk bubble morphology for several burnup levels, as shown in Fig. 2. Fission gas bubbles first appear on the grain boundaries (shown in (a)). There are virtually no bubbles in the interior of the grains. As burnup increases to ~40-50 %U-235, the bubble population increases on the grain boundaries and additional bubbles progressively spread to the interior regions (shown in (b)). This is the stage

where recrystallization takes place, and the fuel swelling shifts to a faster rate. Eventually at higher burnup, gas bubbles emerge uniformly over the entire fuel cross section (shown in (c)).



(a) 35 %U-235 BU V6018G from RERTR-5 | (b) 65 %U-235 BU V6001M from RERTR-4 | (c) 80 %U-235 BU V6022M from RERTR-4

Fig. 2 SEM photos of irradiated U-Mo fuels from RERTR-4 and 5. The samples shown in this figure were fabricated with the same batch of atomized fuel particles and irradiated at similar temperatures.

Gas swelling at low burnup

Gas bubble volume fractions at burnup below the transition were measured on SEM micrographs for plates from RERTR-1, 2, 3, and 5. The fuel temperature range of the plates was 70 – 190°C. The results are shown in Fig. 3. The bubble volume fractions appear to be a function of the fission density possibly with a short incubation period.

Gas swelling at high burnup

Gas bubble volume fractions in high burnup fuels from the RERTR-4, 7A, and 8 tests were measured on polished optical micrographs by using the image analysis method [10]. The measured values were assessed for fuel initial volumes. The results are given in Table 1.

Table 1 Bubble volume fraction measurement for high burnup fuels

	Fission density 10^{21} f/cm^3	$(\Delta V/V)_g$, % (measured)	$(\Delta V/V)_s$ %	V_0	$(\Delta V/V_0)_g$ %
S6006C RERTR-4	6.7	18	33	0.82/1.33=0.62	29
R2R040 RERTR-7A	5.7	16	29	0.84/1.29=0.65	25
H1P02B RERTR-8	8.3	24	41	0.76/1.41=0.54	44

In Fig. 4, the low burnup data from Fig. 3 are compared to the high burnup data from Table 1. Guided lines are also included to show the difference in the slopes between the low burnup data and high burnup data. The steeper slope observed for the high burnup data is attributed to recrystallization in the fuels.

The pre-transition gas bubble swelling for the data in Fig. 3, which is the same as the solid line shown in Fig. 4 is

$$\left(\frac{\Delta V}{V_0}\right)_g = 1\times10^{-21}\, f_d\,, \quad \text{for } f_d \le 3\times10^{21}\ \text{f/cm}^3 \tag{2}$$

where the gas bubble swelling is given in % and f_d is fission density in fissions/cm^3.

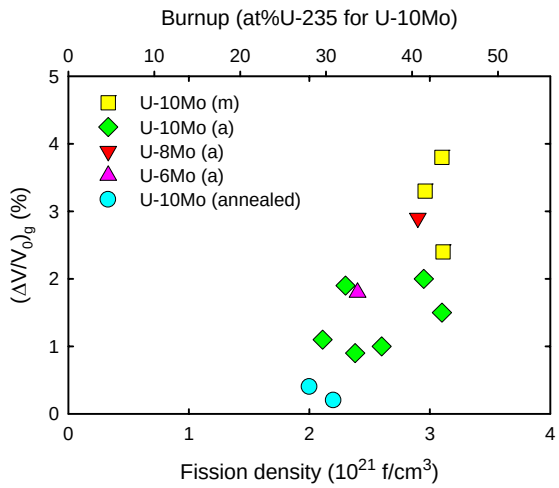


Fig. 3 Gas bubble swelling measured for RERTR-1,2,3, and 5 plates.

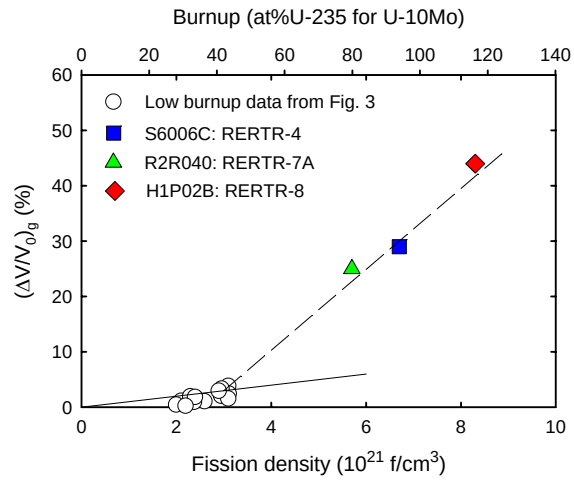


Fig. 4 Gas bubble swelling measured for RERTR-4, 7A, and 8 plates, combined with data from Fig. 3.

The gas bubble swelling in Eq. (2) is only 40% of the existing correlation. Because the gas swelling data for U-Mo fuel had not been available, the current correlation used U-Zr data from EBR-II tests [11]. However, there are differences between U-Zr fuel irradiated in the EBR-II and U-Mo fuel from the RERTR tests in terms of fission gas swelling. In U-Mo fuel, fission gas is not released whereas in U-Zr EBR-II fuel fission gas forms bubbles and is released as the fuel is irradiated in much higher temperatures. The majority of fission gas in U-Mo, ~90 %, remains in the fuel matrix. In this situation, most of the fission gas behaves similarly to solid or liquid fission products.

The post-transition gas bubble swelling shown as the dashed line in Fig. 4 can be described as

$$\left(\frac{\Delta V}{V_0}\right)_g = 3 + 7.3\times10^{-21}\left(f_d - 3\times10^{21}\right), \quad \text{for } f_d \ge 3\times10^{21}\ \text{f/cm}^3 \tag{3}$$

There is no discernable temperature effect on the swelling data. And our current understanding of the underlying swelling mechanism supports an athermal behavior for the temperature range below ~300°C. Therefore, we rejected the incorporation of a temperature dependence in the correlations.

The effect of the Mo-content in fuel alloy is modeled as in the old model [3]. Although the effect of the Mo-content in fuel swelling is not obvious from Fig. 3, this does not suggest that the effect can be excluded completely. Until we collect enough data for more detailed modeling, we tentatively use a weak dependence on the Mo-content by using a linear function of

f(x)=1+0.025x where x is the weight percent deviation in the Mo-content from U-10Mo. f(x) is to be multiplied with the fuel swelling.

The plates with γ-phase annealed powders have much lower gas bubble swelling than the plates with as-fabricated powers. The γ-annealed powder particles have much higher grains and the grain boundaries are much thinner than the as-fabricated powder particles. This suggests that γ-annealing is a very effective method to reduce fission gas swelling although this observation is based on a limited number of cases and no high burnup data exist.

2.3 Solid fission product swelling

This part of fuel swelling is caused by solid and liquid phase fission products and a major part of fission gas atoms that also behave like solid fission products. The solid swelling is proportional only to burnup; it is independent of temperature and alloying conditions such as the Mo content and fabrication method. The difference between the total swelling (shown in Fig. 2) and the gas bubble swelling (shown in Fig. 4) is the solid swelling. It is a linear function of burnup

$$\left(\frac{\Delta V}{V_0}\right)_s = 5\times 10^{-21} f_d \tag{4}$$

where the solid swelling is in percent and f_d is the fission density in fissions/cm^3. As the gas swelling increases at higher burnup, more gas atoms are collected in gas bubbles. The resulting solid swelling may have to be lowered proportionally. We did not attempt to model this in detail due to the lack of the accuracy in measurement. This area is a subject of a future study.

3. Interaction-layer-growth correlation for U-Mo/Al-Si plates

The IL thickness data of the plates with the Si-added Al matrix were available from RERTR-6 and 7A. The IL growth kinetics of plates with 2wt% or more Si in the Al matrix was drastically lower than the pure-Al matrix plates. We assumed that the correlation has the same functional form as for pure-Al matrix plates with different fitting constants [2].

$$Y^2 = A\ F_r^{\ 0.5}\ \exp\left(-\frac{Q}{RT}\right) t \tag{5}$$

where Y is the IL thickness in cm, F_r the fission rate in f/cm^3-s, T temperature in K, and t time in s.

Fitting the measured data from RERTR-6 and 7A was performed in the PLATE code [3] by iteration. As a result, A=7.5x10^{-18} and Q=8000 cal/mol were obtained. This compares the pure-Al matrix plates, for which A=5x10^{-17} and Q=7000 cal/mol [12].

In Fig. 5, PLATE prediction results for R2R040 and R3R050 from the RERTR-7A test are compared with the measured. The predictions and the measured data are consistent.

In order to examine the predictability of the PLATE code, PLATE runs were made for R2R010 (C3), R2R010 (B2), and R3R030 (B5) from the RERTR-6 test. The results were placed in comparison with the measured data at the plate-center and 7th and 9th node locations, as shown in

Fig. 6. The comparison between the predictions and the measured for R2R040 (B2) and R3R050 (C7) from the RERTR-7A is also included in Fig. 6. For the plate center regions, minor overpredictions can be seen whereas for the plate hot side, generally slight underpredictions are observed.

The PLATE predictions assume uniform meat thickness across the fuel plates. Optical micrographs of fuel cross section for RERTR-7A plates revealed clear non-uniformities in meat thickness. The cross section of R3R050 from the RERTR-7A test is compared with R2R020 from the RERTR-6 test in Fig. 7. We speculate that the larger fuel particles of RERTR-7A plates are harder to distribute evenly in the meat than RERTR-6 plates. This may be the reason why more frequent discrepancies between the predicted and the measured are observed for RERTR-7A plates.

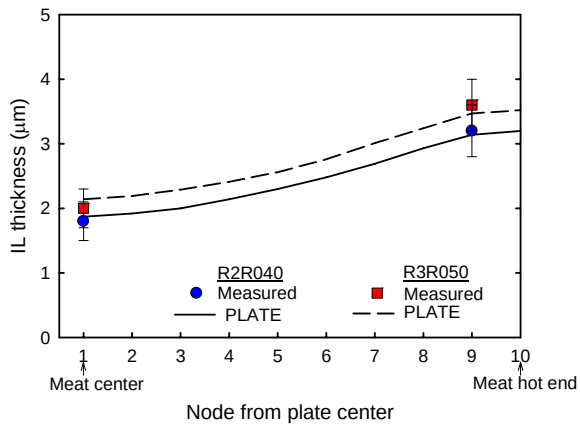


Fig. 5 Comparison of PLATE predictions with the measured IL thicknesses of R2R040 and R3R050 from RERTR-7A across the half-plate width.

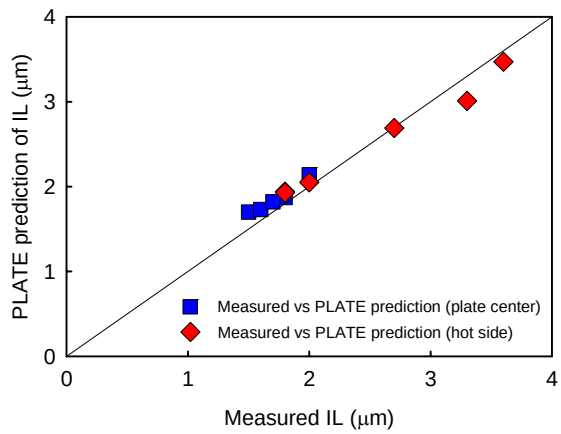
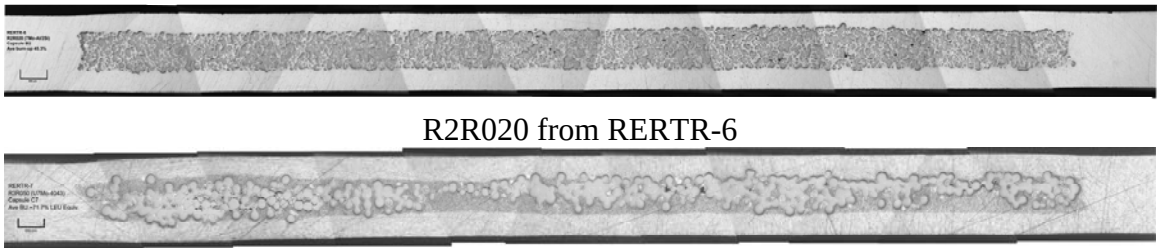


Fig. 6 Comparisons of PLATE predictions with PIE data from RERTR-6 and 7A.

The below average loading at the fuel mid-region results in an overprediction of the fuel temperature and IL thickness in the PLATE calculations. Conversely, the above average loading at the hot side of the plates causes underpredictions of the fuel temperature and IL thickness. This type of prediction error is inevitable for PLATE. A more uniform fuel loading is the only solution to the discrepancies.



R2R020 from RERTR-6

R3R050 from RERTR-7A

Fig. 7 Cross sections of example plates from RERTR-6 and 7A [1]. U-Mo particles are relatively uniformly loaded in RERTR-6 plates than RERTR-7A plates. The particle size is also larger in the RERTR-7A test than the RERTR-6 test.

4. Monolithic version PLATE modeling

The monolithic version of PLATE was updated with the new fuel swelling model. A comparison between the PLATE predictions and the measured for several monolithic plates from the RERTR-6 test and RERTR-7A test is shown in Fig. 10.

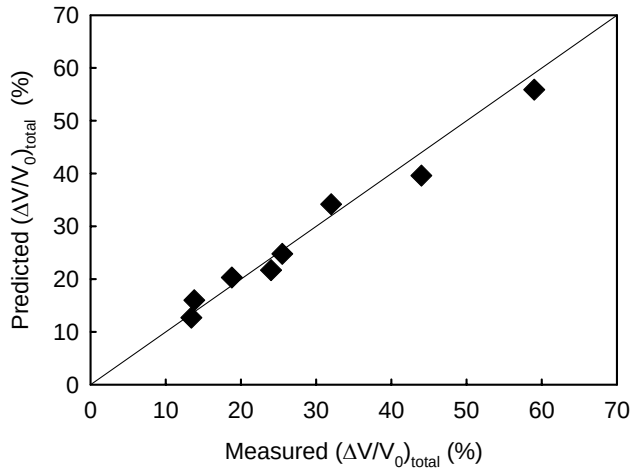


Fig. 10 Comparison of fuel swelling between PLATE predictions and measured data for monolithic fuel plates from RERTR-6 (L1F040 and L2F030) and RERTR-7A(L1F140 and L1F160).

The PLATE code calculates fuel thermal conductivity internally. As fuel porosity increases due to fission gas bubble formation and growth, the fuel thermal conductivity decreases. In Fig. 11, the fuel thermal conductivity as a function of fission density is given. PLATE predictions of fuel temperature and swelling at the plate axial centerline are shown in Fig. 12.

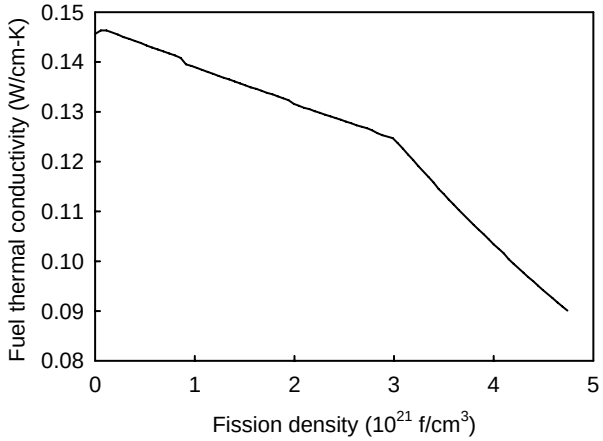


Fig. 11 PLATE prediction of fuel thermal conductivity at peak power node for L1F160 from RERTR-7A.

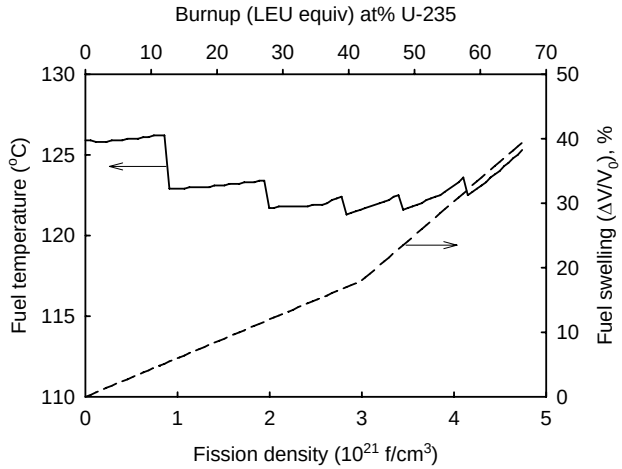


Fig. 12 PLATE predictions of fuel temperature and swelling at peak power node for L1F160 from RERTR-7A.

5. Conclusions

1. The gas bubble swelling characterization revealed that measured gas swelling values were generally lower than the calculated ones by the existing empirical correlation used in the PLATE code. The solid swelling needs to be increased by 40% to compensate for the reduced gas swelling. The transition of the slow swelling rate at low burnup to the faster swelling rate at high burnup needed to be shifted to a fission density of $3x10^{21}$ f/cm^3. This modification results in a slight reduction in the total swelling after the transition.
2. The interaction layer growth correlation for U-Mo/Al dispersion plates with 2wt% or more Si added in the matrix was developed. The new correlation has the same form used for U-Mo/Al dispersion fuel plates with a pure-Al matrix, but the pre-exponential factor and activation energy are different. The fitting constants for the new correlation are $A=7.5x10^{-18}$ (IL thickness in cm) and Q=8000 cal/mol.
3. The PLATE code was updated to install the most recent performance models. The PLATE predictions for interaction layer thickness in dispersion fuel plates and fuel swelling and plate thickness expansion for monolithic fuel plates were consistent with the PIE data.

Acknowledgments

Thanks are due to Mr. M.R. Finlay from ANSTO for his PIE results during his stay at INL that we used for our analyses.

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