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COMPARISONS BETWEEN PREDICTED AND MEASURED FUEL PIN PERFORMANCE

F. J. Homan, C. M. Cox, and W. J. Lackey

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CONTENTS

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ABSTRACT

The FMODEL computer code is being developed to predict and analyze the irradiation performance of stainless steel clad $(U,Pu)O_2$ LMFBR fuel pins in terms of thermal and mechanical performance. Detailed comparisons were made between predicted and measured fuel pin performance in terms of cladding deformation, oxide fuel restructuring, and fuel temperatures. Reasonable agreement was obtained in each of these comparisons without resorting to the use of artificially adjusted parameters to fit the data. It is concluded that, while added sophistication will improve the performance predictions, the current version of FMODEL is a reliable tool for design analysis and interpretation of irradiation tests.

INTRODUCTION

This paper compares fuel pin performance predicted by the FMODEL computer code with that measured both during and after irradiation of LMFBR type fuel pins. Such computerized models vastly facilitate analysis of the combined effects of numerous fabrication and operation variables and thus serve a useful purpose in fuel pin design and evaluation.

Measured performance of fuel pins irradiated under fast flux conditions is presently limited to what can be observed during postirradiation examination. This is because instrumentation is very limited in EBR-II, the only fast reactor in this country in which a substantial number of mixed oxide pins have been irradiated. In-test data can be obtained from irradiation tests in several thermal flux facilities. Although it is recognized that thermal flux tests are generally unsuitable for proof tests of fast reactor fuel elements, such tests can be valuable for understanding certain aspects of fuel performance. Pending the availability of instrumented test data from fast reactors, we have utilized thermal flux test data to test the accuracy of our thermal performance models. Fast flux test data were used for the comparison between predicted and measured diametral expansion.

Comparisons between predicted and measured performance are divided into the four areas (1) diametral expansion of the pins, (2) fuel radial porosity distributions, (3) diameters of central void, columnar, and equiaxed-grain regions, and (4) fuel center-line temperatures.

DESCRIPTION OF THE FMODEL CODE

Since the objective of this work is to compare predicted and measured fuel pin performance, the description of the analytical model will be deliberately brief. A list of references concerning individual models and materials data included in FMODEL can be found in a recent report[1] concerning solutions to a round-robin exercise.

FMODEL utilizes a finite difference technique to determine the stress distribution in the cladding.[2] A generalized plane strain assumption is required for this method. Temperature distributions in both fuel and cladding are determined by numerical integration of the Fourier equation for steady-state heat conduction in a cylindrical body with an internal heat source. Fuel restructuring is assumed to occur continuously throughout the irradiation lifetime of the pin by pore motion due to a vaporization-condensation mechanism.[3] Cladding creep is considered to occur both by thermal[4] and irradiation-enhanced[5] mechanisms, while creep of the fuel is calculated from out-of-reactor data[6,7] for UO_2. The creep equation for the fuel material indicates a significant influence of grain size. Accordingly, Lackey's[8] equation for in-reactor grain growth of $(U,Pu)O_2$ is employed in the code. The fuel-cladding mechanical interaction is influenced by the fuel cracking model.[9] Briefly, this model assumes that the root of radial fuel cracks is determined by out-of-reactor data describing the rupture strength of UO_2. Fuel outside the crack, whose radius changes with time, is assumed to transmit forces directly from the crack root to the cladding once mechanical contact is obtained. Cladding swelling due to void formation is calculated with published equations[5,10] and swelling of the fuel due to an accumulation of solid fission products is based on an empirical analysis[11] of published data. Formation and growth of fission gas bubbles are calculated by a modification[12] of the Greenwood-Speight model,[13] and fission gas release as a function of temperature is determined from an empirical three-zone model.[11] Porosity is assumed to accommodate fuel swelling to a degree determined by temperature and based on an empirical analysis.[14]

Substantial flexibility has been built into the FMODEL code. It is capable of simulating steady state, cycling, and transient operation of a fuel pin. Fuel-cladding mechanical interactions due to differential thermal expansion or due to fuel swelling against the cladding can be analyzed.[15,16]

FMODEL contains no adjustable parameters for artificially "fitting" predicted performance to measured performance. Agreement between prediction and measurement depends only on the fabrication data and irradiation conditions input, the thermophysical and mechanical properties of the fuel and cladding, and the validity of the models. If agreement is not satisfactory the reason is sought in erroneous data, faulty assumptions, or omission of an important factor from the model.

The physical and mechanical property data on fuel and cladding are important to predicted results. These data, along with the creep and tensile properties of the fuel and cladding materials currently used in the code, have been summarized.[1]

DIAMETRAL EXPANSION

Permanent diametral expansion of an irradiated fuel pin is due to cladding density decrease from void formation, plastic strain accumulated throughout irradiation, and elastic strain present at room temperature due to fission gas pressure and cladding swelling gradients. Predicted diametral expansions are sensitive to the assumed cladding strength and pin fabrication and operating conditions.

Figure 1 summarizes some early FMODEL analyses on diametral expansions of several pins from the General Electric F-2 series irradiation experiments[17] in EBR-II. Irradiation-enhanced creep of the cladding was not considered in the calculations reflected in this figure, and the August 1969 version of the WARD-PNL cladding swelling correlation[10] was used. Mechanical interaction on startup due to differential thermal expansion between fuel and cladding was predicted for F2Q and F2H. Notice that the greatest measured diametral expansion for both these pins occurred at the cold end (bottom), where the fuel and cladding differed most in thermal expansion.

Two of the pins shown in Fig. 1, F2Z and F2H, were included in the modeling round-robin exercise.[1] A more detailed comparison of the measured and predicted diametral expansion for these pins is shown in Figs. 2 and 3. Calculations performed with the data provided for this exercise resulted in far better agreement between prediction and measurement for F2Z than for F2H. However, we have noted[1] that both the heat rate and neutron fluence provided in the round-robin data package were below those reported in the literature for F2H. These effects account for part of the bias between observed and predicted diametral expansion for this pin.

Figure 4 compares predicted and measured diametral expansions for fuel pin F2S. This pin is particularly interesting because the fabricated smear density and heat rate were high, the fuel was axially

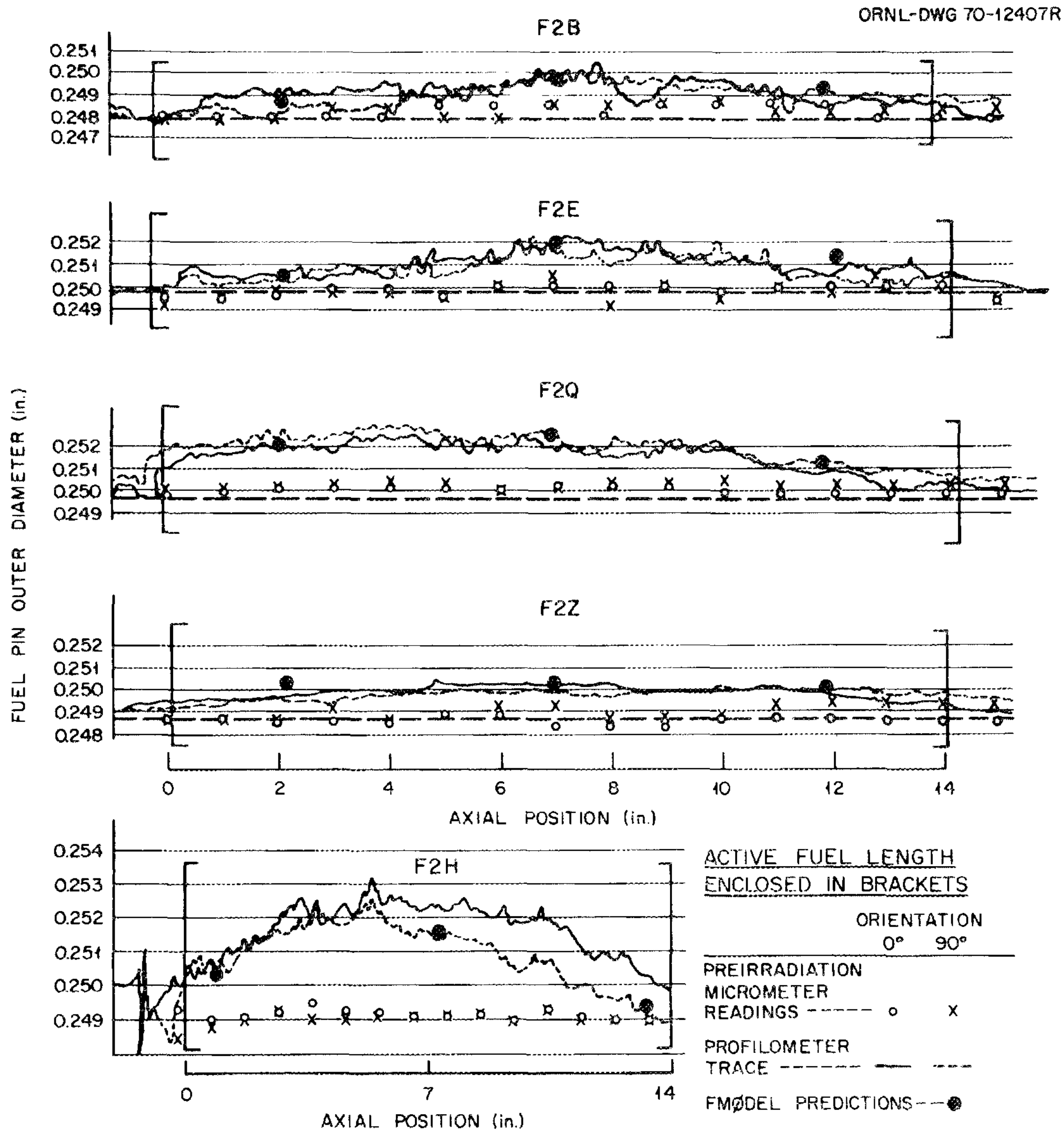

Fig. 1. Postirradiation Profilometer Traces for Five Fuel Pins from General Electric F-2 Series.

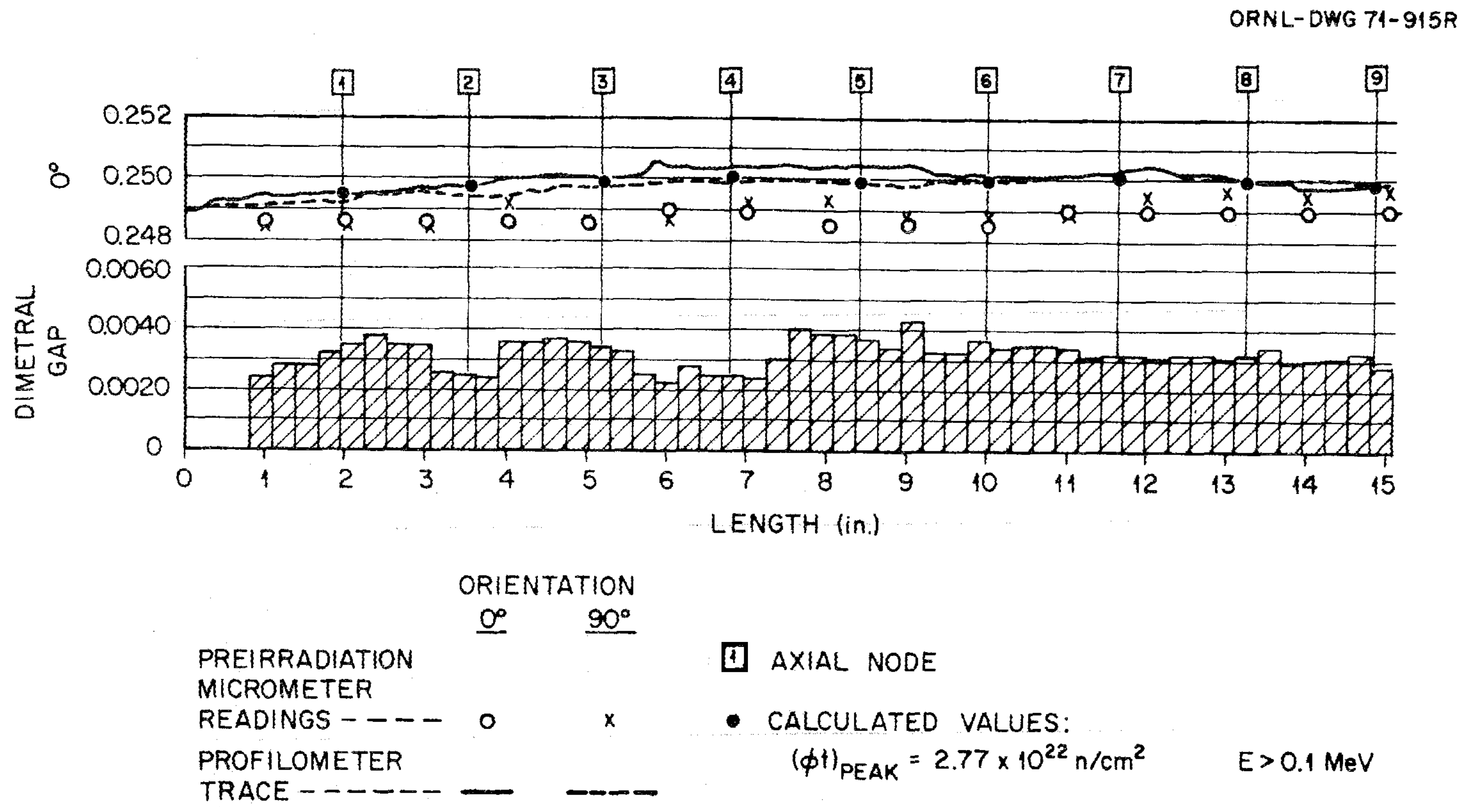

Fig. 2. Comparison of Predicted and Measured Diametral Expansions for Pin F2Z.

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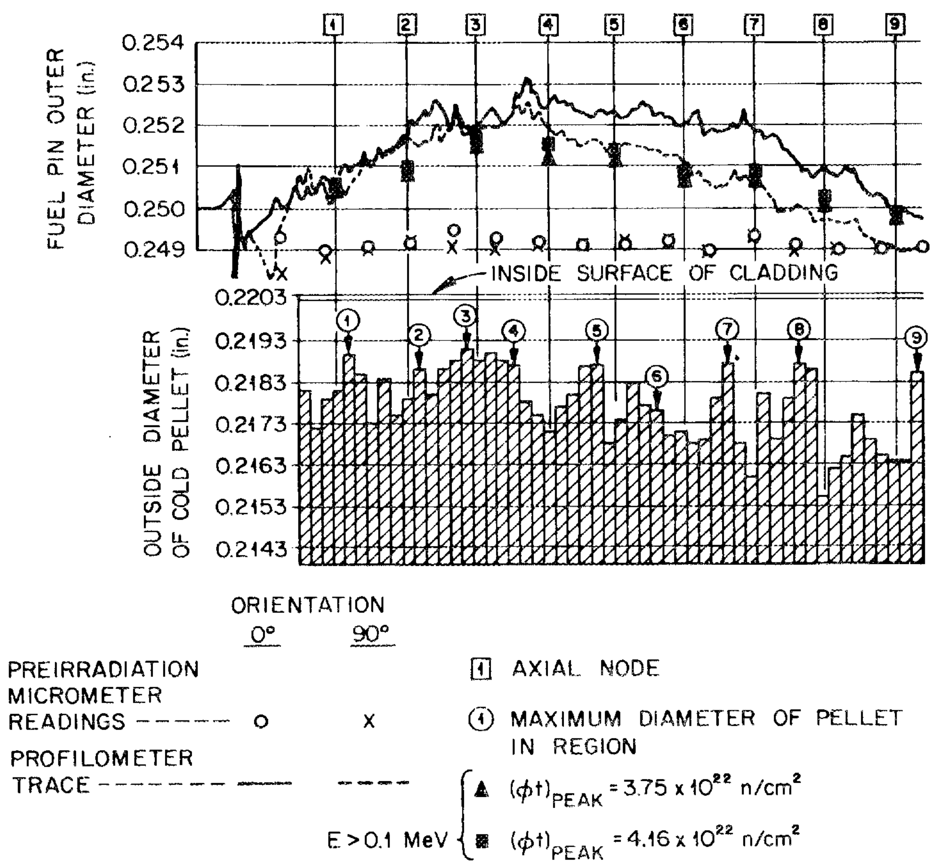

Fig. 3. Comparison of Predicted and Measured Diametral Expansions for Pin F2H.

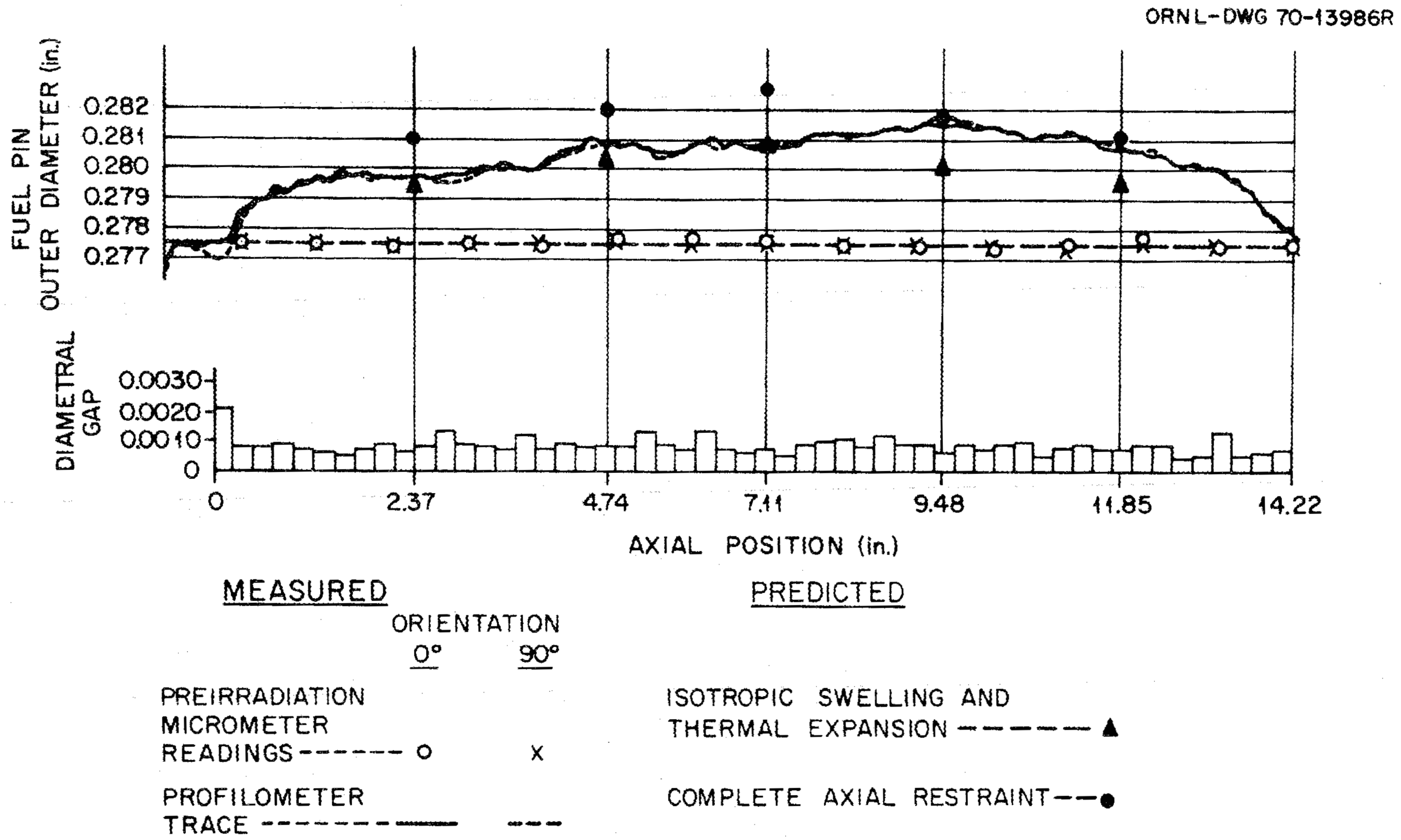

Fig. 4. Comparison of Predicted and Measured Diametral Expansion for Pin F2S as a Function of Axial Position.

restrained, and the cladding was 30 mils thick. The postirradiation profilometer trace for F2S indicates a greater diametral expansion at the hot end of the pin than at the cold end. Recall that this is opposite to the observations made for F2H and F2Q. It has been suggested[18] that the axial restraint at the top of F2S prevented any axial movement of fuel in that portion of the pin, whereas the fuel at the bottom of the pin, being more remote from the restraint, may have been freer to move axially. Our analysis supports this hypothesis. Two sets of assumptions were made in calculating the predictions plotted in Fig. 4. First we assumed that thermal expansion and swelling of the fuel occurred isotropically; then we assumed that there was complete axial restraint in all regions of the pin. Good agreement between prediction and measurement was achieved at the bottom of the pin using the isotropic assumption and at the top of the pin using the axial restraint assumption.

All comparisons between predicted and measured fuel pin diametral expansion are summarized graphically in Fig. 5. Each point of the plot represents one axial position for the pin indicated. The measured values are the average of the 0 and 90° profilometer traces. The predicted values are those plotted on the previous figures, with the exception of F2S. The predicted values for this pin were based on the isotropic assumption at the bottom of the pin and the axial restraint assumption at the top of the pin. With the exception of pin F2H, where the actual operating conditions were uncertain, agreement is excellent. Even in this case the agreement was within 30%. Exact agreement for any pin must be considered fortuitous since the cladding density changes

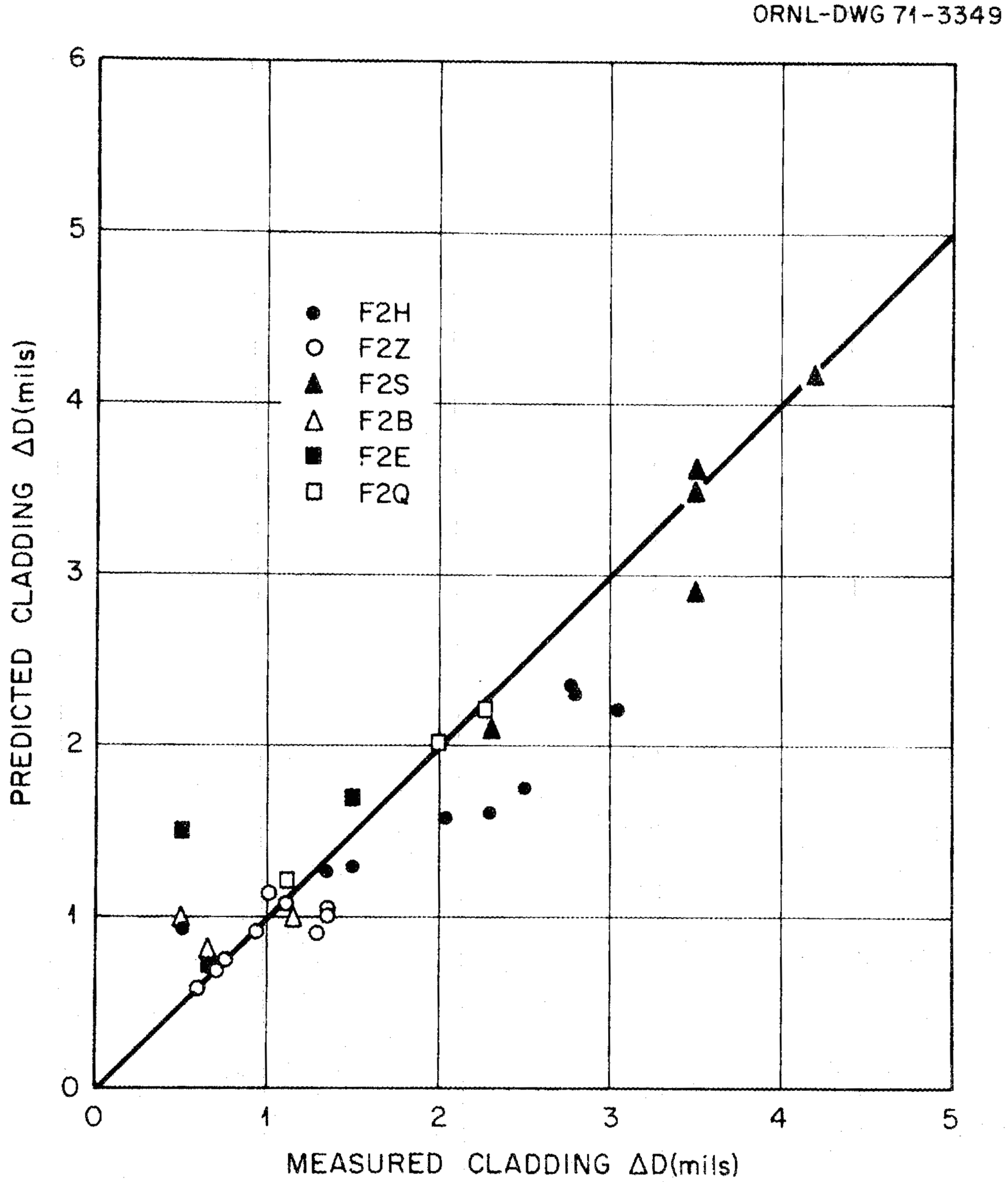

Fig. 5. Summary of Comparison Between Predicted and Measured Cladding Diametral Expansions.

generally accounted for at least half the predicted diametral expansions, and the data from which the swelling correlations were derived have a wide scatter band.

FUEL RADIAL POROSITY DISTRIBUTION

FMODEL utilizes a continuous, time-dependent fuel restructuring model adapted[3] from Nichols' equation[19] for pore motion by a vaporization-condensation mechanism. One measure of the validity of such a model is the comparison of predicted and measured void diameters and diameters of the columnar and equiaxed-grain regions. However, a difficulty with such comparisons is that axial movement of fuel will influence the measured diameters and thus distort the comparison. In addition, columnar and equiaxed grains are not exact indicators of the porosity present in a given fuel region. Therefore, actual comparison of predicted and measured radial porosity distributions in the fuel provides a much sounder basis for judging the usefulness of this model. Unfortunately, few systematic measurements of radial porosity distributions of pins irradiated under fast flux conditions are reported in the literature. Lackey and Kegley[20] measured the radial porosity distribution for a Sphere-Pac fuel pin operated at 13.6 kW/ft to about 0.7% FIMA in the Engineering Test Reactor (ETR). Their data are shown in Fig. 6 along with two predicted radial porosity distributions for this pin at the end of life. The two curves are based on different assumptions. In one case we assumed that all porosity was of the open type and thus connected to the gas plenum. An alternate assumption was that porosity in regions of less than 90% density was open to the plenum, but porosity

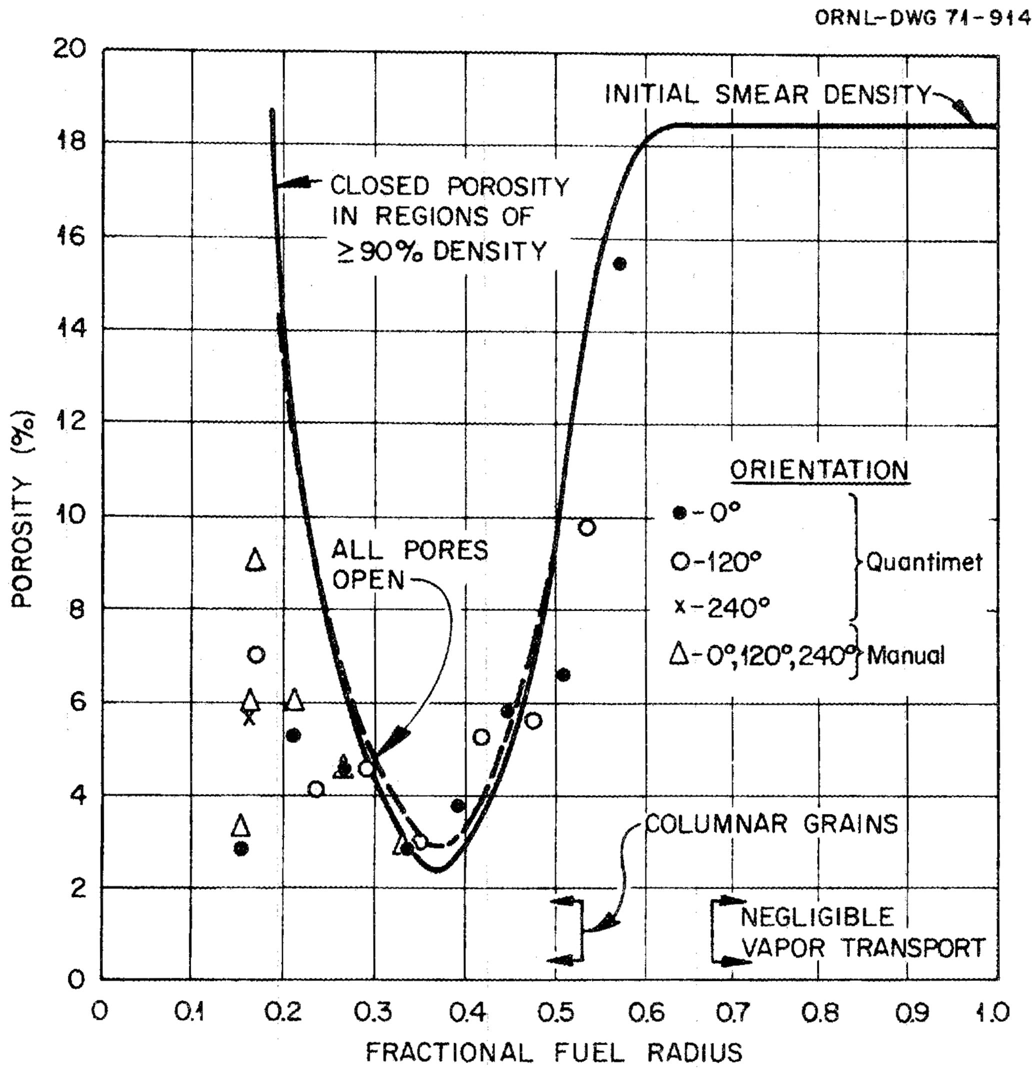

Fig. 6. Comparison of Calculated and Measured Radial Porosity Distribution for $U_{0.85}Pu_{0.15}O_2$ Irradiated at 13.6 kW/ft to 0.7% FIMA.

in the regions of greater than 90% density was closed. The results plotted in Fig. 6 show that the predicted radial porosity distribution is insensitive to this assumption for this pin with very low burnup.

Examination of Fig. 6 indicates that agreement between prediction and experiment is good, except for fractional fuel radii less than 0.3. In this central region the temperature gradient was considerably less steep than in the outer fuel regions, and the vaporization-condensation model may be oversimplified. We investigated, with negative results, the possibility that, for the region near the fuel center with the low temperature gradient, the dominant mechanism for pore migration might be surface or volume diffusion rather than vaporization-condensation. This is not likely since the increase in pore velocity for a unit increase in temperature is larger for the vaporization-condensation mechanism than for either surface or volume diffusion.[21]

DIAMETERS OF CENTRAL VOID, COLUMNAR, AND EQUIAXED-GRAIN REGIONS

As mentioned earlier, another measure of the validity of any fuel restructuring model is the comparison between predicted and measured void diameters and diameters of the columnar and equiaxed-grain regions. Although this comparison is not as useful as one between predicted and measured radial porosity distributions, considerably more data are available. A summary of predictions with measurements reported[17] for General Electric F2 series irradiations is plotted in Fig. 7. The beginning-of-life heat rates for the pins considered ranged from 9.7 to 17.4 kW/ft, and the fabricated fuel densities ranged from 83.8 to 98.2% of theoretical. It should be emphasized that FMODEL does not predict

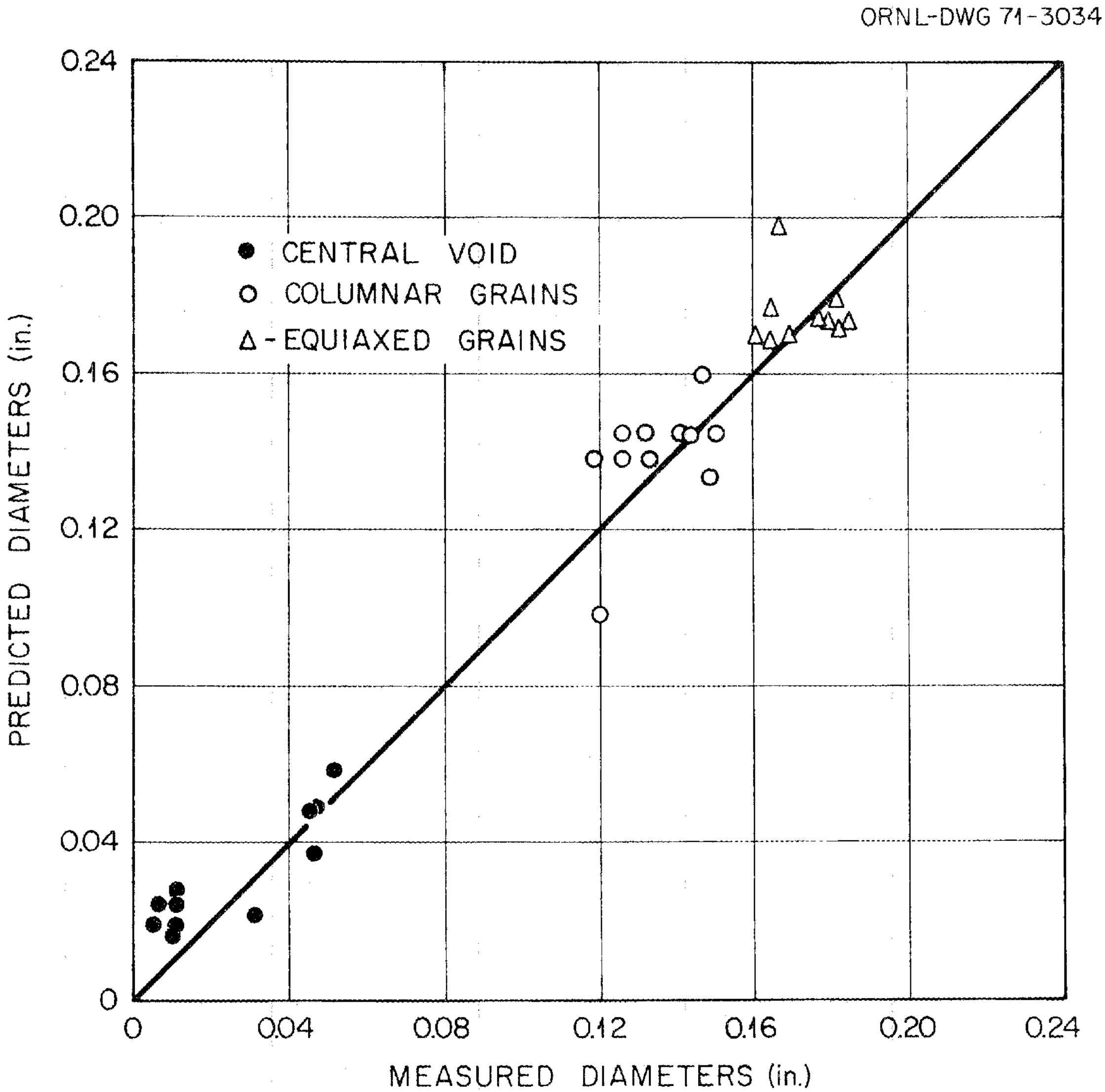

Fig. 7. Summary of Comparisons Between Predicted Diameters for Central Void, Columnar, and Equiaxed-Grain Regions.

columnar and equiaxed regions as such. Rather, it predicts porosity distributions. The columnar region has been arbitrarily assigned as any portion of the fuel with less than 2% porosity. Similarly, the equiaxed region has been arbitrarily assigned as the region between the columnar region and the region of as-fabricated density.

The results presented in Fig. 7 indicate that FMODEL somewhat over-predicts fuel restructuring. This conclusion is reached through the observation that most of the plotted points lie above the diagonal line. In contrast, the discussion and results presented in the section on radial porosity distributions suggest that under-prediction of the restructuring should be more likely because the vaporization-condensation model appears to predict less pore movement in the columnar grain region than is actually occurring, based on the comparison between predicted and measured porosity distributions for one pin.

Although it is not yet perfected, we feel that the present model is a significantly better approximation of fuel restructuring than the three-zone empirical model that we have used in the past.[11] The ability to predict fuel restructuring on a time-dependent basis is particularly necessary when related to the need to determine fuel-cladding mechanical interactions due to differential thermal expansion during startup. Using the earlier three-zone model we would assume that restructuring occurred "instantaneously" and would thereby underestimate the thermal expansion of the fuel and plastic deformation of the cladding.

FUEL CENTER-LINE TEMPERATURES

Irradiation experiments in which fuel center-line temperatures are measured have not yet been conducted with $(U,Pu)O_2$ fuel pins in the limited instrumented facilities available in EBR-II. Therefore, we have used thermal reactor data to test the heat generation and transfer portion of the FMODEL code. Fitts[22] recently completed irradiation in the ORR of an instrumented capsule that contained 82% smear density $(U,Pu)O_2$ Sphere-Pac and pellet fuel pins in tandem. Variable heat rates were achieved by moving the capsule to different flux positions within the ORR poolside facility. Fuel center-line temperatures, cladding surface temperatures, and fuel pin heat generation rates were continuously measured and recorded during the 109 days in-reactor.

Data points representing the entire range of heat rates from 0 to 16 kW/ft were selected randomly for each pin. Using the measured cladding surface temperatures and a radial power distribution predicted by the ANISN[23] neutron transport code, fuel center-line temperatures were calculated with FMODEL for both the Sphere-Pac and pellet pins. A value of 0.73 W cm^{-2} $(°C)^{-1}$ was used for the heat transfer coefficient across the fuel-cladding gap in the pellet pin, and a value of 1.93 W cm^{-2} $(°C)^{-1}$ was used for the Sphere-Pac pin.[24] Calculated and measured fuel center-line temperatures are compared in Fig. 8.

Examination of Fig. 8 reveals that, in general, good agreement between predicted and measured fuel center-line temperatures was achieved for the Sphere-Pac fuel. However, several measured data points between 14 and 16 kW/ft appear to be low on the temperature scale. Fitts[25] suspects that one or more of the four calorimeter thermocouple

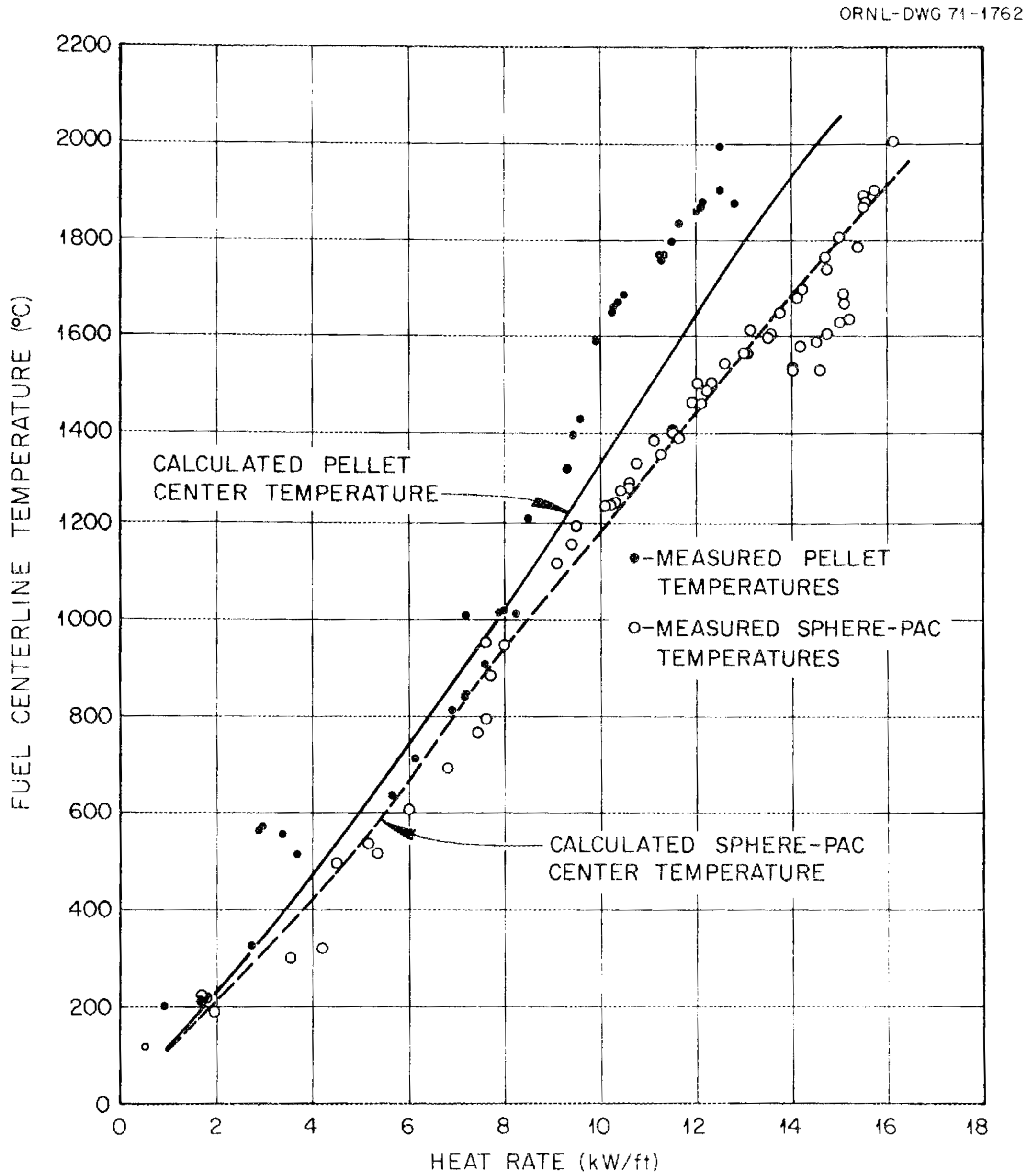

Fig. 8. Comparison Between Predicted and Measured Fuel Center-Line Temperature Variation with Heat Rate for Pellet and Sphere-Pac Pins in Capsule SG-3.

pairs used to measure the heat generation rate may have been giving erroneous readings in this range and thereby affecting the average heat generation rates plotted. He is statistically analyzing the data to see if any of the calorimeter readings can be justifiably discarded. The same discussion applies to the pellet data above 9 kW/ft. As shown in Fig. 8, the agreement between measured and calculated fuel centerline temperatures for the pellet fuel in this heat rate range is poor. An alternate explanation for this poor agreement for the pellet pin is that the heat transfer coefficient across the fuel-cladding gap may be substantially lower than the value used for these calculations.

SUMMARY AND CONCLUSIONS

The agreement between experimental observations and FMODEL predictions of fuel pin irradiation performance is sufficiently good to give confidence that FMODEL is a useful analytical tool for design of irradiation experiments and interpretation of their results. Although there is substantial room for improvement of the code, improvements and added sophistication must be guided by the results of comparisons such as those previously presented. One difficulty encountered in making such comparisons is the lack of precision with which fabrication data and irradiation conditions are reported. For instance, the peak heat rate for fuel pin F2H is reported differently in three different sources,[26–28] with values ranging from 16.5 to 17.2 kW/ft. The value given[1] in the modeling round-robin data package was 15.1 kW/ft. In addition, the axial variation in cladding surface temperatures is seldom published. Often, experimenters report only peak cladding temperatures and give no mention of the axial location of the peak cladding temperature. Therefore, axial temperature profiles of the cladding surface must be estimated, introducing the possibility of errors of 25 to 50°C. Errors of this magnitude can strongly influence cladding swelling predictions as well as fuel temperature profiles. Uncertainty in the fast neutron exposure for a given fuel pin contributes considerable uncertainty to predictions of cladding swelling.

These difficulties notwithstanding, the FMODEL code has been useful in our LMFBR fuels development program, and with added sophistication and improved operating data we feel that the comparisons between measured and predicted fuel pin performance can be improved significantly.

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