Validation of Models for the Analysis of the Transient Behavior of Metallic Fast Reactor Fuel

J. M. Kramer, T. H. Hughes, E. E. Gruber
Argonne National Laboratory, Argonne, IL USA

INTRODUCTION

The Integral Fast Reactor (IFR) concept being developed at Argonne National Laboratory has prompted a renewed interest in U-Pu-Zr metal alloys as a fuel for sodium-cooled fast reactors. Part of the attractiveness of the IFR concept is the improvement in reactor safety margins through inherent features of a metal-fueled LMR core. In order to demonstrate these safety margins it is necessary to have computer codes available to analyze the detailed response of metallic fuel to a wide range of accident initiators. Two of the codes that play a key role in assessing this response are the STARS fission gas behavior code and the FPIN2 fuel pin mechanics code.

Verification and validation are two important components in the development of models and computer codes. Verification demonstrates through comparison of calculations with analytical solutions that the methodology and algorithms correctly solve the equations that govern the phenomena being modeled. Validation, on the other hand, demonstrates through comparison with experimental data that the phenomena are being modeled correctly. Both components are necessary in order to have the confidence to extrapolate the calculations to reactor accident conditions. This paper presents the results of recent progress in the validation of models for the analysis of the behavior of metallic fast reactor fuel.

The experiments that are used for the model validation studies presented here are TREAT transient overpower tests M5, M6 (Robinson et al, 1987) and M7 (Wright et al, 1988). These experiments have been analyzed using the STARS and FPIN2 codes. In this analysis the STARS code provided the pretransient distribution of fission products; additional characterization of the EBR-II-irradiated test pins was obtained from sibling pin examinations. The thermal and mechanical response of the pins during the TREAT tests was then determined using the FPIN2 transient fuel pin behavior code.

The current status of STARS and FPIN2 are described in the first two sections of this paper. These descriptions are followed by results from the analysis of TREAT tests M5, M6 and M7.

DESCRIPTION OF THE STARS CODE

The STARS code comprises a number of models that treat the various aspects of fission gas behavior and the effects of fuel structure and geometry. These models treat the accumulation of (and swelling due to) gas within grains, on grain faces, in grain-edge porosity, and in large pores. The code also includes models of the cladding restraint to radial swelling, gas release from large

pores to the plenum, and axial swelling. Swelling due to solid fission products, bond sodium relocation (from the fuel-cladding gap to the plenum and into open porosity), and release of some of the liquid fission products (such as cesium) to the sodium, are also modeled in the present version of the code.

Steady-state behavior of fission gas depends more on the behavior of single gas atoms than on that of bubbles. Re-resolution effects dominate, at least at lower temperatures characteristic of steady-state irradiation of metallic fuels. Under these conditions, bubbles within grains remain extremely small, and the gas behavior can be modeled adequately by an extension of the Booth model (Booth, 1957). The present model for intragranular fission-gas behavior applies the work at Harwell in developing the OGRES models for oxide fuel (Wood and Matthews, 1980). This model, based on diffusion of gas from a sphere, includes the effects of trapping of gas atoms by bubbles, bubble resolution and nucleation, and the time variation of the effective diffusion coefficient. It does not include bubble migration and coalescence, which would be important for transient or high-temperature conditions.

This intragranular gas-behavior model is combined with structural considerations similar to those used in the more detailed FRAS code (Gruber and Kramer, 1987a), which was developed for transient calculations. Gas released from the grains is assumed to collect in bubbles on the grain boundaries (or other planar traps). The number density of these bubbles is assumed constant, and the bubbles grow by accumulating gas until a critical fractional coverage (taken to be 50%) of the available grain-boundary area is reached.

Any gas released from the grains in excess of the amount corresponding to boundary saturation is assumed transferred to grain-edge tunnels. These tunnels are modeled as cylindrical pipes, with cross sections modified to account for the lenticular nature of the intersections of the tunnels with the grain boundaries. The tunnel volume is determined from a balance between the gas pressure and the curvature, until the volume reaches a value characteristic of stable interconnected channels. Once this critical level of edge swelling (taken to be 5%) is reached, any additional gas is transferred to large pores.

The concept of large pores existing as traps in metallic fuel is a key element in the STARS analysis. In ceramic fuels, large pores are not a major factor. Most of the fission gas generated in the unrestructured fuel is retained in the form of small intragranular bubbles and individual gas atoms. In the restructured fuel, temperatures and thermal gradients are high enough that the larger gas bubbles migrate rapidly to the central void. Microcracks also develop, enhancing the release of gas that might otherwise collect in large pores. In metallic fuels, however, large pores provide an important mechanism by which the microscopic behavior of fission products can be related to macroscopic changes in fuel dimensions. They develop and collect gas, contributing to the fuel swelling, until they interlink when the percolation threshold is reached.

The STARS code also includes a simple model for redistribution of liquid fission products. Non-gaseous fission products are assumed to occupy their atomic volumes, with solid fission products retained in the grains and contributing to the grain (or intragranular) swelling. The liquid fission products, however, are apportioned between the fuel grains and the bond sodium. The fraction dissolved in the sodium is an input parameter (taken equal to 0.5 in the present calculations). Another input parameter determines the average amount of sodium in the porosity. In the present calculations, this parameter was set equal to 20%.

Fission-gas behavior is strongly dependent on the temperature and power. Since both of these parameters vary strongly with axial location, the STARS code was extended to treat an arbitrary number of equal axial segments. The calculations

described here were carried out with 10 segments. The axial temperature and power profiles were provided by FPIN2 analyses of EBR-II irradiation conditions for each axial segment.

DESCRIPTION OF THE FPIN2 CODE

The FPIN2 computer code has been developed to analyze the complex thermal-mechanical phenomena which govern fuel and cladding behavior during fast-reactor accident transients. The analysis provides the fuel and cladding temperatures, stresses, and displacements during overpower and undercooling events. The basic program includes a group of subroutines to calculate the temperature of the fuel, cladding, coolant, and outer wall, and a separate group of subroutines to calculate the mechanical behavior of the fuel and cladding. Relevant pretransient fuel characterization parameters are input into FPIN2 based on sibling pin information or STARS and/or LIFE code calculations. The heat transfer section in FPIN2 uses an implicit finite difference algorithm, and the mechanical analysis makes use of a nonlinear finite-element procedure. A major reason for choosing the finite-element method is that it allows convenient modular coding of the fuel pin mechanics such that different models for material behavior and improvements in specific algorithms can easily be implemented into the code.

A comprehensive description of the FPIN2 code and the models used in the code to analyze the behavior of metallic fuel pins has been given previously (Hughes and Kramer, 1986). There have been several modifications to the code since the time that paper was issued. These changes reflect new information on material properties and a better understanding of the phenomenology that govern the transient response of metal-fueled pins. The following sections describe several aspects of the most recent metal-fuel version of FPIN2.

Ternary Fuel Redistribution

Postirradiation destructive examinations of ternary U-Pu-Zr fuel pins irradiated in EBR-II have revealed significant migration of plutonium and zirconium. All previous versions of FPIN2 have assumed uniform fuel composition; changes have now been made to allow for fuel composition variations. The most significant changes were brought about by the realization that, because of alloy redistribution, the initial melting of ternary fuel may not occur at the fuel centerline and, for full length pins, the molten fuel zone may not have direct access to the plenum when melting begins.

Specific models added to FPIN2 include a provision for the user to supply radial and axial variations in plutonium and zirconium weight fractions (with the remainder assumed to be uranium). These distributions are used in the fuel material properties routines to determine variations with alloy content in properties, such as the fuel solidus and liquidus temperatures.

Fission Gas Retention

For the present study fission gas retained in the fuel matrix was calculated for each FPIN2 node by using the STARS code. In FPIN2 part of this gas is assigned to grain boundary bubbles with a characteristic density of 3.2×10^{11} bubbles/cm³. The remainder of the gas is assumed to be in solution or in small bubbles within the fuel grains. In the previous FPIN2 calculations the fraction of retained gas on the grain boundaries was assumed to equal 10%. However, the STARS analysis of the fuel used in TREAT tests M5, M6 and M7 showed that this fraction increases from about 15% at 0.8 at.% burnup to 69% at 9.8 at.% burnup as more gas is released and as the plenum pressure becomes significant compared to the surface tension constraint on the grain boundary bubbles. Therefore, the fraction of retained gas on the grain boundaries is now an input parameter in FPIN2.

Transient Swelling of Solid Fuel

The earlier FPIN2 solid fuel swelling model assumed that the fission gas bubble pressure remains in equilibrium with the surface tension and the mean (hydrostatic) component of the local fuel stress tensor. Fuel therefore expands or contracts instantaneously in response to changes in gas bubble temperature. However, this simple equilibrium model also greatly increases the fuel compressibility. When hot fuel is constrained by the cladding or by regions of colder fuel, the equilibrium swelling model predicts less axial growth than that due to normal thermal expansion. This is caused by bubbles tending to compress as rapidly as the fuel matrix expands. Such behavior is obviously unrealistic because time is required for fission gas bubbles to grow, unless the overpressure becomes so great that dislocation loops are punched out from the bubble surface.

We have concluded from our study of gas-bubble growth mechanisms in metallic fuel (Gruber and Kramer, 1987b) that transient swelling of metallic fuels is dominated by diffusive growth of grain boundary bubbles. A grain boundary bubble swelling model based on this work has been implemented into FPIN2 and was used in the present analysis of the TREAT tests.

Cladding Axial Constraint

Fuel that is in contact with the cladding is assumed to be locked axially to the cladding, either by metallurgical bonding or by friction, at temperatures below a critical temperature for slip. In this case the increments in axial strain in the fuel are equal to the increments in axial strain in the cladding. The FPIN2 finite-element algorithm solves for the resultant fuel and cladding axial forces by combining the fuel and cladding stiffness matrices in a non-iterative procedure.

At temperatures above the critical temperature the fuel and cladding are assumed to slip freely because of liquids that form at the fuel-cladding interface. The current release temperature of 988K (715°C) is based on the eutectic temperature in the iron-uranium phase diagram. In plutonium bearing U-Pu-Zr fuels this temperature may be somewhat lower. Small changes in the critical temperature for release would not significantly change the results presented here except near the point where slip begins. At this point there is a discontinuous change in the axial stress as the fuel expands slightly in the axial direction and contracts in the radial direction due to elastic recovery.

Extrusion of Molten Fuel into the Plenum

The molten fuel cavity in FPIN2 is located by the axial and radial extent to which the fuel has reached its solidus temperature. In previous versions of FPIN2 this boundary was found by interpolating the fuel temperatures such that the boundary moved smoothly in time through the finite elements. Preliminary studies exploring how to handle ternary fuel that did not begin melting at the centerline showed that the cavity volume could increase stepwise in time as each element reached the solidus without adversely affecting the mechanics routines. Elements inside the cavity boundary which may not have reached their solidus are assumed to be in a hydrostatic state of stress equal to the cavity pressure. These elements occupy a volume in proportion to their density and contribute to the mass and volume balance iteration which determines the cavity pressure. In addition, the transient plenum pressurization has been decoupled from the molten fuel cavity pressurization for analyzing cases where the fuel melt front does not extend to the fuel-plenum interface. Once melting reaches this interface the two pressures as assumed to equilibrate and the cavity and plenum pressure-volume equations are coupled and solved together to give the common pressure and amount of axial molten fuel motion (extrusion) into the plenum. Unlike oxide fuels, large central cavity pressures are not calculated

for metallic fuels because of their higher porosity, much lower expansion on melting and because the peak fuel temperatures occur near the top of the fuel column so that the melt front reaches the fuel-plenum interface early in the transient.

Cladding Failure

Information on temperatures, stresses and strains is available within the FPIN2 analysis to calculate cladding rupture using a variety of failure criteria. For the high temperatures of interest to safety analysis, creep-rupture criteria based on accumulated effective plastic strains or on life fractions are most appropriate. In the present calculations we have used life fraction criteria.

An additional complication for metallic fuel pins is that a low melting point eutectic exists between the fuel and the cladding which can contribute to cladding failure during transient overheating events. Liquids which attack the cladding wall form at about the uranium-iron eutectic of 988K (715°C). The rate of penetration of these liquids has been correlated by Bauer (Bauer, Fenske and Kramer, 1987) using the results of U-Fe cladding dipping tests. The correlation was validated by comparing measured and calculated failure times for tests where irradiated EBR-II driver pins were heated in a furnace. These calculations indicate that the primary effect of the liquid eutectic on cladding failure is wall thinning and the liquid does not further damage the remaining cladding tendon by mechanisms such as liquid metal embrittlement.

The FPIN2 analysis of cladding failure in TREAT tests M5, M6 and M7 used the Bauer correlation to calculate the change in cladding wall thickness for temperatures above 988K. Below 988K the penetration rate was assumed to be zero. The hoop stress in the cladding tendon was then calculated from the thin-shell equations used in developing the life fraction correlations. The life fraction over time increment dt was calculated from the rupture time t_r for the instantaneous average cladding temperature T and hoop stress σ . Life fractions were summed in the usual way so that cladding failure was predicted to occur when the life fraction reached 1.0.

PRETRANSIENT FUEL CHARACTERIZATION

Prior irradiation of fast reactor fuel pins influences their thermal and mechanical response during accident transients. The pretransient features that appear to be most important for metallic fuels are: fuel geometry; fission product, alloy and porosity distributions; fuel elongation; and the effects of fast neutron fluence on transient cladding properties. The philosophy used in the validation of the transient models discussed in this paper is that the steady-state fuel characterization forms the initial conditions from which the transient calculations begin. For the analysis of TREAT tests M5, M6 and M7 much of this information was directly available from sibling pin examinations. However, as discussed below, the fission gas distributions were obtained from STARS code calculations.

As-Fabricated Fuel

All six of the fuel pins used in the TREAT experiments discussed in this study were of the lead IFR design shown in Fig. 1. The pins were irradiated in the EBR-II reactor at Argonne's Idaho facility. Five of the pins were fabricated with U-19Pu-10Zr fuel and austenitic D9 cladding. The remaining pin contained U-10Zr fuel with ferritic alloy HT9 cladding. Other relevant fabrication data and burnup information for the test pins are given in Table I.

Fission Gas Distributions

Fission gas plays an important role in transient fuel pin response. Gas that is

retained in the fuel during steady-state irradiation provides a source for expansion of both solid and liquid fuel during overheating. The quantity of fission gas in the plenum is also important because the plenum pressure is a major contributor to cladding loading and, therefore, to cladding failure.

A reasonable amount of data for gas in the pin plenum and, to a lesser extent, gas retained in the fuel is available from destructive examination of U-19Pu-10Zr and U-10Zr pins that were siblings to those used in TREAT tests M5-M7. The STARS computer code is also available to determine fission gas distributions in metallic fuels based on analytical models. These STARS results give a detailed self-consistent picture of the distribution of the gas between the fuel matrix, grain boundaries, edge tunnels, large pores and the plenum. Since such details can be important to the transient response of metallic fuels, we have chosen in this paper to use STARS results for input to the transient thermal-mechanical analyses of the TREAT tests.

Figure 2 shows the gas partitioning between the fuel, the pores, and the plenum, as a function of peak burnup for 19% Pu ternary fuel. These results were obtained by summing the results for the individual axial segments. Initially, all of the generated gas remains in the fuel, either within grains or in grain-boundary or grain-edge porosity. As these fission-gas traps saturate, near 0.5% peak burnup, gas begins to collect in large pores.

When the gap closes at the first segment (axial segment 6, just above the midplane, at 0.62% peak burnup), the model permits gas release to the plenum to begin. As the plenum pressure increases, more gas collects in the fuel and in the porosity. However, the gas in the fuel is already at a relatively high pressure, because of surface tension in the relatively small bubbles. As a result, the amount of gas in the fuel increases by a factor of 2.5 while the plenum pressure increases by a factor of about 30. The gas in the pores also increases less rapidly than the gas in the plenum; the reason for this difference is the diminishing volume available to the large pores, due to solid fission-product swelling.

In order to compare the calculated retention to measured results, it is necessary to consider how much of the gas in the large pores would contribute to measured gas retention. In comparing STARS results with data from small samples cut from sibling pins it was assumed that all of the gas in large pores would be released during sample preparation. The retained gas then includes only gas in the grains, on grain faces, and in edge porosity. Figure 3 shows calculated results for 19% Pu ternary fuel, along with measured results, at three levels of burnup. Agreement is good at low burnup, although the calculations indicate greater retention at the bottom of the pin than observed. The discrepancy becomes more evident, however, as burnup increases. The differences are most likely due to gas retained in some of the large pores. This pore gas is also accounted for separately in FPIN2; the number of grams of pore gas per unit volume is calculated from the input porosity distributions and the plenum pressure.

The burnup dependence of gas released to the plenum for three levels of plutonium in M5, M6 and M7 sibling pins are shown in Fig. 4. The corresponding plenum pressures at a plenum temperature of 741K are shown in Fig. 5. It appears that measured results vary somewhat less than the calculations would predict. The results do indicate the tendency for higher plutonium concentrations to cause the fuel to release more gas, and to commence the release a little earlier. However, the release for U-10Zr fuel is uniformly underpredicted.

FPIN2 ANALYSIS OF TREAT TESTS M5, M6 AND M7

FPIN2 code calculations were performed for each of the fuel pins in TREAT tests

M5, M6 and M7. A considerable quantity of detailed information is available from these calculations on the thermal and mechanical response of the pins during the transient overpower tests. For the purposes of this paper, we have concentrated on selected results for which a direct comparison with experimental data can be made. These comparisons include flowtube temperatures, cladding failure time and location, and fuel extrusion.

Description of the Tests

TREAT tests M5, M6 and M7 were performed to study the behavior of U-Pu-Zr and U-Zr fuel pins under transient overpower conditions that are sufficiently severe to cause extensive fuel damage and/or fuel pin failure. Each test contained two EBR-II irradiated fuel pins in separate flow tubes within a Mark-IIIC sodium loop. The characteristics of these pins that are relevant to the present analysis were given above.

All of the tests were designed to subject the pins to an 8s period exponential power rise at full flow. The overpower transient was preceded by a short flattop in the power history which was designed to achieve initial temperatures that simulate fuel operating conditions at 12 kW/ft and a 150K coolant temperature rise. The transient was to be terminated at or near cladding failure with an anticipated overpower of 3.5 to 4.5 times the simulated steady-state conditions. All of the TREAT tests achieved this goal with failure occurring in two of the six pins. However, in TREAT test M5 it was necessary to subject the pins to two transients because the first transient was prematurely terminated at 3.3-3.4 times nominal power, about 10% less than desired. The two M5 transients are referred to as M5-F1 and M5-F2 (Final-1 and Final-2) to distinguish them from low power M5 heat balance tests that were also run in TREAT prior to the final transients. In the FPIN2 calculations given in the present paper, the M5-F1 and M5-F2 transients are treated as separate tests with the assumption that there was no effect of the M5-F1 transient on the subsequent M5-F2 fuel pin response.

Flowtube Temperatures

Thermocouples were mounted to the outside of the flowtubes in each of the TREAT tests. Measured flowtube temperatures for one of the tests, M7, are shown in Figs. 6 and 7. Also shown on the figures are predicted flowtube temperatures from the FPIN2 base-case calculations. Agreement between the measured and calculated flowtube temperatures is good. However, the oscillations in the temperatures indicate that the pins moved relative to the flowtubes causing significant deviations from ideal annular flow. These effects are complex and difficult to quantify and are not modeled in fuel pin codes such as FPIN2. The approach taken here is that the deviations in the flow geometry result in uncertainties in the flow rate. The sensitivity of the calculated fuel pin failure to these uncertainties is addressed separately below.

Cladding Failure

Cladding failure was calculated in the FPIN2 analyses of the TREAT tests by using the life fraction method. As discussed previously, the effect of molten eutectic penetration was modeled by calculating the instantaneous cladding hoop stress based on the amount of thinning of the cladding wall. The location of the failure is then the first cladding segment to reach a life fraction of 1.0. For all of the tests where failure was predicted, the failure location was at the top of the fuel column, in agreement with the experimental data. Calculated cladding failure times are compared with measured failure times in Table II. It can be seen from this table that neither of the M5 transients were severe enough to fail the cladding, in agreement with the experiments. The essentially zero damage to the cladding during the M5-F1 transient also supports the approach we have taken here in neglecting the effects of the M5-F1 transient

on the M5-F2 results.

Fuel pin failure did occur in the TREAT M6 and M7 experiments. In test M6 the 5.3 at.% pin failed at 13.240 s. The FPIN2 base-case results given in Table II did not predict this failure although the peak life fraction reached 0.4, which is probably within the one sigma-error band for the data upon which the life fraction correlation is based. In addition, sensitivity analyses were performed where the power was increased by 5% or the flow was decreased by 5%, which are within the experimental uncertainty. Cladding failure was predicted for both cases at about 13.2 s, which is near the measured failure time of 13.240 s. We therefore conclude that the FPIN2 cladding failure models are capable of correctly predicting the results for pin 2 in TREAT test M6 within the experimental uncertainties.

The high burnup pin in TREAT test M7 is predicted to fail at a time very close to the measured failure time. The FPIN2 calculations indicate that the failure was primarily due to pressure loading and not eutectic attack. However, the FPIN2 results predict that the low burnup U-10Zr HT9-clad pin in test M7 should have failed even earlier due to excessive eutectic attack, which was not observed. The predicted Pin 2 failure time of 17.075 s is so early that one cannot explain the observed absence of failure in terms of uncertainties in the power or flow. In fact, the measured flowtube temperatures of nearly 1300K shown in Fig. 7 almost certainly require that the inner cladding temperature exceeded the assumed threshold for rapid eutectic penetration of 1353K (Bauer, Fenske and Kramer, 1987). The lack of agreement therefore suggests that there is a deficiency in the modeling when applied to U-10Zr fuel and/or HT9 cladding since Pin 2 of Test M7 was the first of this fuel type tested in TREAT. We postulate here that this deficiency may be in the assumption that the rapid eutectic attack, where the penetration rates in the dipping tests increased by three orders of magnitude, may require a reservoir of molten fuel. Since the ternary U-19Pu-10Zr fuel solidus is nominally 1325K, by the time the fuel-cladding interface reaches the 1353K threshold gross fuel melting has begun. On the other hand, the solidus temperature for U-10Zr is at 1455K, which is above the threshold. In order to test our hypothesis, we re-ran the FPIN2 analysis of pin 2 assuming no acceleration in penetration rate. Cladding failure in this case was not predicted to occur, in agreement with the experiment.

Extrusion of Molten Fuel

Transient fuel motion and fuel relocation in TREAT tests M5, M6 and M7 were measured using the fast neutron hodoscope (Robinson et al, 1987). Under the assumption of minimal density change in the fuel, these hodoscope results can be used to derive the axial extrusion of molten fuel into the plenum prior to pin failure. Earlier TREAT tests on surrogate U-Fs metallic fuel showed elongations up to 18% of the initial fuel column length. Such a large extrusion would contribute a significant amount of negative reactivity to a severe reactor transient. However, TREAT tests M5, M6 and M7 on U-Pu-Zr and U-Zr fuels showed much less extrusion with maxima of only about 2-5% (Robinson et al, 1987). The STARS code calculations discussed earlier show that the reason for this difference is due to the lower gas retention in the M5, M6 and M7 pins caused by higher operating temperatures during their irradiation in EBR-II and higher diffusion coefficients and finer grain structures in plutonium bearing fuels. With the small amount of intragranular and grain boundary gas retained in the U-Pu-Zr and U-Zr fuel the FPIN2 code predicts only from 2 to 4.5% extrusion for TREAT tests M5, M6 and M7. As an example, the FPIN2 results for the 2.9 at.% burnup and 9.8 at.% burnup pins in test M7 show a peak axial elongation of 2.5% and 2.0%, respectively, compared to the hodoscope-measured 3% and 2.1%. Furthermore, almost all of this extrusion was due to the gas trapped in the large pores; sensitivity analyses with FPIN2 where zero intragranular and grain boundary gas retention was assumed for the 9.8 at.% burnup pin resulted in identical extrusion to that given above. Since all of the fuel pins in tests

M5, M6 and M7 had nearly the same total porosity it is, therefore, not surprising that they showed about the same amount of extrusion.

CONCLUSIONS

New models for the behavior of U-Pu-Zr fuels have been incorporated into the STARS and FPIN2 codes. These models have been validated by comparison of calculated results with measurements from EBR-II irradiation and transient testing of six pins in TREAT tests M5, M6 and M7. The STARS code was used to determine the steady-state fission gas distributions in the test pins. Transient thermal and mechanical analyses of the pins were performed using the FPIN2 code. Results of code calculations were compared with experimental data. The sensitivities of some of the calculated results to uncertainties in experiment conditions were also discussed. In general the agreement between calculations and measurements was good, with the exception of the predicted failure time of the U-Zr binary fuel pin. The postulated reason for this discrepancy is that the high melting temperature of the binary fuel delays the onset of rapid eutectic penetration.

REFERENCES

- Bauer, T. H., Fenske, G. R. and Kramer, J. M. (1987). Cladding Failure Margins for Metallic Fuel in the Integral Fast Reactor. Transactions of the 9th International Conference on Structural Mechanics in Reactor Technology, Lausanne, Vol. C, pp. 31-38.
- Booth, A.H. (1957), A Method of Calculating Fission Gas Diffusion from UO_2 Fuel and Its Application to the X-2-f Loop Test, AECL Report No. 496.
- Gruber, E. E. and Kramer, J. M. (1987a), Modeling Fission-Gas Behavior in Metallic Fuels. Journal of the American Ceramic Society, Vol. 70 [10], pp. 699-703.
- Gruber, E. E. and Kramer, J. M. (1987b). Gas-Bubble Growth Mechanisms in the Analysis of Metal Fuel Swelling. American Society for Testing and Materials, STP 955, pp. 432-444.
- Hughes, T. H. and Kramer, J. M. (1986), The FPIN2 Code - An Application of the Finite Element Method to the Analysis of the Transient Response of Oxide and Metal Fuel Elements, Proceedings of the BNES/ENS/ANS Conference on the Science and Technology of Fast Reactor Safety, Guernsey, pp. 427-432.
- Robinson, W. R., Bauer, T. H., Wright, A. E., Rhodes, E. A., Stanford, G. S. and Klickman, A. E. (1987). First TREAT Transient Overpower Tests on U-Pu-Zr Fuel: M5 and M6. Transactions of the American Nuclear Society, 55, p. 418.
- Wood, M. H. and Matthews, J. R. (1980), A Simple Operational Gas Release and Swelling Model. I. Intragranular Gas. Journal of Nuclear Materials, 91, pp. 35-40.
- Wright, A. E., Bauer, T. H., Lo, R. K., Robinson, W. R., and Palm, R. G. (1986), Recent Metal Fuel Safety Tests in TREAT, Proceedings of the BNES/ENS/ANS Conference on the Science and Technology of Fast Reactor Safety, Guernsey, pp. 59-64.
- Wright, A. E., Bauer, T. H., Robinson, W. R., Kraft, D. A. and Klickman, A. E. (1988). The IFR Overpower Test M7 in TREAT. Transactions of the American Nuclear Society, 56, pp. 383-384.

ACKNOWLEDGMENTS

The authors would like to thank Ms. Lois Miller for preparing the manuscript.

Work supported by the U.S. Department of Energy, Office of Technology Support Program, under Contract W-31-109-Eng-38.

Table I. Characterization of TREAT Test Pins

	<u>M5-Pin 1</u>	<u>M5-Pin 2</u>	<u>M6-Pin 1</u>	<u>M6-Pin 2</u>	<u>M7-Pin 1</u>	<u>M7-Pin 2</u>
Fuel Alloy	U-19Pu-10Zr	U-19Pu-10Zr	U-19Pu-10Zr	U-19Pu-10Zr	U-19Pu-10Zr	U-10Zr
Cladding Alloy	D9	D9	D9	D9	D9	HT9
Peak Burnup, at. %	0.8	1.9	1.9	5.3	9.8	2.9

Table II. Comparison of Measured and Calculated Cladding Failure Times for Base-Case Power and Flow Conditions.

<u>Test Number</u>	<u>Pin Number</u>	<u>Burnup at. %</u>	<u>Measured Failure Time, s</u>	<u>Calculated Failure Time, s</u>	<u>Peak Life Fraction</u>
M5-F1	1	0.8	No Failure	No Failure	0.000
	2	1.9	No Failure	No Failure	0.002
M5-F2	1	0.8	No Failure	No Failure	0.000
	2	1.9	No Failure	No Failure	0.015
M6	1	1.9	No Failure	No Failure	0.040
	2	5.3	13.240	No Failure	0.412
M7	1	9.8	17.719	17.741	1.000
	2	2.9	No Failure	17.075	1.000

Fig. 1.
As-Fabricated Geometry

Fig. 2.
Fission Gas Partitioning
in the Fuel, Pores, and
Plenum.

Fig. 3.
Gas Retention in 19% Pu
Ternary Fuel. Data given
by symbols. STARS calcula-
tions by curves.

Fig. 4.
Dependence of Gas Release to
the Plenum on Pu Concentration.
Data given by symbols. STARS
calculations given by curves.

Fig. 5.
Dependence of Plenum Pressure
at 741K on Pu Concentration.
Data given by symbols. STARS
calculations given by curves.

Fig. 6.
Measured (curves) and
FPIN2-Calculated Flowtube
Temperatures for Pin 1 in Test M7.

Fig. 7.
Measured (curves) and
FPIN2-Calculated Flowtube
Temperatures for Pin 2 in Test M7.