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TREAT TESTS M2 AND M3:
EXPERIMENT INFORMATION AND PRETEST ANALYSIS

by

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ABSTRACT

The purpose of TREAT tests M2 and M3 is to obtain early information on metal-alloy fast reactor fuel during transient overpower conditions. Three EBR-II driver fuel elements of near fresh, medium, and high burnup are to be tested with margin to cladding failure and axial extrusion of foremost interest. Test fuel, hardware, and conditions are described. Pretest predictions of test results as well as the motivation and reasoning behind the chosen test conditions are also given.

1.0 INTRODUCTION

Metal fuels were the first fuels used in sodium cooled fast reactors. The early choice of these fuels was based on their excellent breeding performance and their ease of fabrication. During the late 1960's, design objectives of high burnup and high sodium outlet temperature eliminated the consideration of metal fuels because fuel swelling and ultimately fuel cladding failure during burnup severely limited the length of time the fuel could operate in the reactor. Recently, fuel pins designed to allow for fuel volume expansion of approximately 33% inside the cladding have led to considerably higher fuel burnups. Because of the important design changes incorporated in these high performance pins, the results obtained from previous TREAT tests on the behavior of metal fuel pins of the earlier designs are in most respects not directly applicable to current fuel design. Basic empirical information on the transient behavior of current and advanced fuel designs needs to be obtained to confirm the inherent features of the metal fuel and to guide the modeling and analysis of fuel behavior in the Integral Fast Reactor (IFR) system design.

The purpose of TREAT tests M2 and M3 is to obtain early information on metal-alloy fast-reactor fuel behavior during transient-overpower (TOP) reactor conditions. Specifically, data from these and subsequent loop tests will provide information relevant to the prediction of pressure assisted eutectic penetration of cladding and to the prediction of reactivity feedback due to axial fuel extrusion. This information is needed to confirm key safety features of the IFR. The objectives of the experiments are then (1) to measure axial in-pin fuel extrusion prior to fuel cladding failure, (2) to measure the extent of fuel-cladding eutectic formation and pressure-assisted penetration during TOP conditions and (3) to monitor the initial post-failure fuel motion. The two tests will envelope the domain of pin failure in three pins with different burnup.

Both tests will use a Mark-III TREAT Integral Sodium Loop which is described in the document, Mark-III Systems Design Description [1-1]. The test train configuration is capable of holding three fuel pins, each thermally isolated in its own orificed coolant flow channel. The M2/M3 experiments will use U-5Fs (uranium-5 w/o fissium) EBR-II Mark-II driver fuel elements with a different burnup level pin in each of the flowtubes.

The M2/M3 test transient is to simulate a TOP accident in the range of 1 β /s to 10 β /s reactivity insertion. The overpower burst generated by TREAT will achieve nearly five times nominal power rising on a period of 8 seconds. The M2 transient will be terminated at either a flow reduction scram signal indicating at least one failed fuel pin or at the time when the transient rods reach their fully withdrawn positions, whichever occurs first. The flows in the three flow tubes in M3 will be appropriately orificed and the M3 transient conditions will be altered to obtain results which complement those obtained in M2, i.e., fail those pin types that did not fail and leave intact those types that did fail in M2. Details of the selected transient conditions are given in Section 4.

During the tests, the fuel temperature will slowly increase and weaken the fuel to the point of self-extrusion. Further temperature increase will provide full opportunity for potential in-pin dispersion, ensure substantial

eutectic penetration into the cladding wall and eventually to breach the cladding.

The 1.2-m TREAT fast-neutron hodoscope will be used to measure pre- and postfailure fuel motion. The test section and pump legs of the loop are so oriented that both are in line with the the full slot through the TREAT core. The fully-slotted core is used in order to reduce the neutron background noise to the hodoscope thereby increasing the signal-to-noise ratio and enhancing the resolution of the axial fuel motion.

2.0 DESCRIPTION OF THE M2/M3 LOOP AND APPARATUS

2.1 The M2/M3 Loops

The M2/M3 Loops are well-tested Mark-IIIC Integral Sodium TREAT test vehicles [1-1]. The only major difference between these loops and the loops used for previous tests is the absence of sodium expansion tanks on the pump leg of the loop. The loop, shown in Fig. 2-1, contains one Annular Linear Induction Pump (ALIP).

The axial midplane of the active fuel column is at the midplane of the TREAT core. An asymmetric configuration of dysprosium neutron-flux-shaping collars (Fig. 2-2) was chosen [2-1] to achieve an axial power profile lying within desired limits [2-2]. Details of the fuel axial profile produced by this configuration are discussed in Section 3.2. Except for these shaping collars, the loops are unfiltered.

2.2 The M2/M3 Test Trains

The primary function of the M2/M3 test trains when installed in the test section of the loop is to hold three preirradiated EBR-II fuel pins, each thermally isolated in its own orificed coolant flow channel. As a secondary function, the test train provides a support structure within the loop for instrument sensors in the sodium flow and adjacent to the test fuel.

Figure 2-1 shows a cross section of the test section of the loop along with the locations of the thermocouples attached to the test train. The M2 and M3 tests will have three EBR-II Mark-II driver fuel pins located in individual stainless steel flowtubes at a triangular pitch of 1.32 cm. A spiral wire wrap separates the fuel from its flow tube. Sodium flows upward between the fuel pin and the flowtube.

Individual stainless steel shield tubes surround each of the flow tubes. Spaces between the flowtubes and the shield tubes and between the shield tubes and the outer wall of the test train are filled with a thermally insulating Ar-He gas mixture. The large spacing between pins has several advantages. Each fuel pin is sufficiently separated from adjoining pins to allow nearly-uniform azimuthal power distributions by minimizing the effects of neutron self-shielding. The separation distance also allows for improved viewing of each pin by the hodoscope. Detailed dimensions of the M2/M3 test train are given in Section 2.4.

Fig. 2-1. Loop and Test Train Cross Section

Fig. 2-2. Axial Dysprosium Shaping Collars

2.3 Data Acquisition Instrumentation

Sensors provided on the M2/M3 loops for data acquisition include pressure transducers, permanent magnet flowmeters and thermocouples. The location of these sensors as well as those mounted on the test train are shown in Fig. 2-1. Two pressure transducers, one located at the test section inlet (PT-1) and one at the outlet (PT-2), have a pressure range of 0-6.89 MPa (0-1000 psig).

Three permanent-magnet type flowmeters are installed to monitor the sodium coolant flowrate. Inlet flowmeters FM-1 and FM-3 are located at the inlet to the test section (bottom of the loop) and at the top of the pump leg respectively. An outlet flowmeter (FM-2) is located at the outlet of the test section.

Seventeen thermocouples (TC-1 to TC-17) are attached to the outside of the flowtubes along the active fuel column length at locations shown in Fig. 2-1. The axial locations are chosen to minimize the effect of any periodicity in temperature rise induced by the spirally-wrapped spacer wire along the fuel pins. Each thermocouple contains conductors of approximately 0.015-cm diameter. In the intrinsic type junction used, each conductor is separately welded to the 0.037-cm thick flowtube wall. One in-sodium thermocouple (TC-18) is installed above the manifold at the outlet of the test section. All thermocouples are stainless steel sheathed, MgO insulated, Chromel-Alumel with an outside diameter of 1.016 mm.

2.4 Relevant Dimensions for Analysis

Figure 2-3 shows the dimensions and flow parameters needed for thermal-hydraulic analysis of the Mark-IIIC loop. With the exception of the modified section in the pump leg, the data are the same as those used for previous experiments in Mark-IIIC loops [2-3].

Dimensional details of the three-pin test train are shown in Figs. 2-4 and 2-5, and Table 2-1 lists some radial dimensions of the test train components. The coolant flow areas for the three single-pin flow tubes were determined from individual component specifications. The average sodium flow area in the pin/extender region is 0.234 cm² for a high burnup pin (7.9 at.%) and 0.240 cm² for fresh fuel pins. Above and below the pin/extender region the flow area is 0.406 cm². An orifice plate at the inlet to each of the tubes is used to control flowrates. For test M2, the flow in all three tubes is the same, but for M3 the orifices may be changed in order to modify the power-to-flow ratios of individual pins.

An analysis of pressure drops across various sections of the single pin flow tubes and the entire three-pin test train has been performed for a coolant flowrate of 67 cm³/s-pin at 633 K. Figure 2-6 summarizes the results of pressure drop measurements for several orifice sizes, for the full-length single-pin flow tube and the full-length 3-pin test train. In addition, calculations of the pressure drops along smaller sections of the flow tube are given in the figure.

Fig. 2-3. Loop Schematic Depicting Geometry for Use in Hydraulic Analyses

Fig. 2-4. Test Train Schematic Depicting Geometry for Test Analysis

Fig. 2-5. Test Cross Section

Δp_0 (MEASURED)	ORIFICE DIAMETER (MM)
0.00862	5.055
0.01896	4.318
0.02379	3.810
0.06033	3.302

$$\Delta p_1 = 6.895 \times 10^{-4}$$

$$\Delta p_2 = 4.426 \times 10^{-2}$$

$$\Delta p_3 = 2.875 \times 10^{-2}$$

$$\Delta p_4 = 2.137 \times 10^{-3}$$

$$\Delta p_5 = 2.068 \times 10^{-2}$$

(ALL DIMENSIONS EXCEPT
ORIFICE DIAMETER IN CM;
ALL PRESSURES IN MPA)

Fig. 2-6. Test Section Pressure Drops at 633 K Temperature and 67 cc/s-pin Flowrate

TABLE 2-1. Test Section Radial Dimensions for the M2/M3 Test Vehicle

	M2/M3 Test Vehicle		
	O.D.	I.D.	Wall
TEST LOOP:			
Dysprosium/Stainless Steel, Filters/Shims	-	-	0.508
Loop Test Section (Primary Containment)	57.15	36.50	10.32
TEST TRAIN:			
Outer Tube	34.92	31.62	1.65
Shield Tubes	13.21	11.68	0.711
Outer Diameter of Thermocouple Sheath	1.02		
Flowtubes	7.92	7.19	0.368

Note: All dimensions are in mm.

Using the data presented above, as well as the fuel pin specifications of Section 3.1, pertinent variables used by the COBRA-PI thermal-hydraulics code have been derived and are listed in Table 2-2. The flow area parameters are for a single flowtube. The duct wall thickness is an equivalent value which includes the mass of the wire wrap. The fuel smear density assumes the fuel has swelled to the inner surface of the clad for burnup levels greater than 2 at.% and for a level of 8 at.% that the clad has radially swelled by 2%.

TABLE 2-2. Suggested Input for Thermal-Hydraulic Analysis

	8% Burnup	Fresh
Flow Tube:		
Flow area (cm ²)	0.234	0.240
Wetted perimeter (mm)	40.65	40.40
Heated perimeter (mm)	14.16	13.88
Duct Wall:		
Wetted length (mm)	27.036	
Thickness (mm)	0.419	
Fuel Smear Density (g/cm ³)	13.225	13.150

3.0 TEST FUEL AND POWER COUPLING TO THE REACTOR

3.1 Test Fuel

Three preirradiated, sodium-bonded, EBR-II Mark-II U-5Fs driver metal fuel pins will be used in M2 and M3: one near-fresh of 0.3 at.% burnup, one medium burnup of 4.4 at.%, and one high burnup of 7.9 at.% burnup. The as-built fuel pin dimensions are shown in Fig. 3-1. The type 316 stainless steel cladding is spirally-wrapped with a 0.125-cm diameter spacer wire in a 15.24-cm (6 in.) axial pitch. The gap between the fuel and the cladding is initially filled with sodium. Table 3-1 lists the as-built fuel pin parameters.

Changes in fuel characteristics wrought by the preirradiation are estimated using various empirical correlations describing the performance and behavior of EBR-II driver fuel and reported in Refs. 3-1 and 3-2. Characteristics of most interest in this pretest analysis concern fission gas retention, swelling and pin pressurization. In brief summary: fission gas is generated at a rate of 0.00327 moles/g-fuel per at.% of burnup; for burnups less than 2 at.% fuel swells with gas accumulation at a uniform rate of about 5% of original volume for every at.% of burnup with negligible gas release; at some burnup near 2 at.%, "breakaway" swelling occurs, expanding the fuel to the full cladding diameter, and providing pathways for subsequently generated fission gas to be released to the gas plenum. For higher burnups fission gas is thus retained in the fuel at the concentrations first achieved at 2 at.% burnup with the excess leading to increases in the pin plenum pressure. After breakaway swelling some portion (perhaps 20%) of the fuel's porosity might not be simply gas-filled but logged with bond sodium.

Burnup dependent characteristics have been computed for the test fuel on a pin-average basis and summarized in Table 3-2.

3.2 Power Coupling to the Reactor

The M2 power calibration experiment [2-2] measured the test fuel pin to reactor power coupling factor by irradiating fresh EBR-II Mark-II driver fuel pins at a low-level, steady-state (LLSS) power in TREAT. Additional information concerning coupling during power transients was obtained through monitor wire irradiations at both low power and during trial transient simulations. Radial flux depression within each pin was estimated on the basis of neutronics calculations.

Fresh fuel pin power coupling factors were determined from radiochemical analysis of selected fuel segments irradiated under the LLSS conditions to determine absolute fissions per gram. Axial dependence was determined on the basis of gamma scanning all segments. Absolute fissions were multiplied by a conversion factor of 27.2 pJ/fission and divided by the appropriate TREAT energy released in the irradiation to yield a fuel-to-reactor power coupling. The factor converting fissions to heat energy was obtained on the basis of 168 MeV/fission for the U-5Fs fuel pins and an additional 1.6 MeV/fission from beta decay. Also, to account for heating by TREAT generated gammas, a value of 0.03 W/g-MW(TREAT) is included.

Fig. 3-1. M2/M3 Test Fuel Pin Specification

TABLE 3-1. Fuel Pin Parameters As-Built

Fuel	
Chemical composition, Uranium, wt%	95 ± 1
Fissium, ^a wt%	5 ± 1
Isotopic composition, ²³⁵ U, wt%	66.72 ± 0.50
²³⁴ U + ²³⁶ U + ²³⁸ U, wt%	33.28 ± 0.50
²³⁴ U + ²³⁶ U, wt%	<1.0
Form	
	Cast pin
Density, g/cm ³	17.6
Length, mm	342.90 ± 0.81
Diameter, mm	3.30 +0.10/ -0.23
Mass, g	51.7 ± 1.0
Cladding, 316 solution annealed stainless steel	
Inside diameter, mm	3.81 ± 0.01
Thickness, mm	0.31 ± 0.01
Fuel restrainer, dimple distance above fuel, mm	12.70
Fuel-cladding bond, (cold)	
	Sodium
Level, above fuel pin, mm (maximum/minimum)	(38.10/16.89)
Diametral gap, mm	0.51
Plenum	
Fill gas	Argon
Volume, hot, cm ³ , (maximum/minimum)	2.4/2.1
Plenum volume/fuel volume (maximum/minimum)	0.81/0.71
Axial insulators or reflectors	
	None
Element	
Mass, g	80
Length, mm	612.01
Spacer Wire, 316 annealed stainless steel	
Diameter, mm	1.25
Pitch, mm, right hand	152

^aFissium refers to an equilibrium concentration of solid fission products that are formed during irradiation and accumulated.

TABLE 3-2. Burnup Dependent Fuel Characteristics

Fuel Pin Burnup (at.%)	Retained Gas (moles/g-fuel)	Plenum Pressure (Mpa- room temp.)	Diametral Fuel/Clad Gap (mm)
0.3	3.6 E-6	0.1	0.48 +0.1/-0.2
4.4	2.04 E-5	2.2 ± 0.5	nil
7.9	2.04 E-5	4.4 ± 0.5	nil

The array-averaged, axial-peak power coupling factor was determined by these techniques to be 5.90 J/g-MJ (fresh fuel and LLSS conditions). An uncertainty of 3 to 5% should be included in any use of this result. Significant difference in coupling by pin-array position was not expected, and measured differences did indeed fall within these uncertainty bounds; so this array-averaged value is recommended for use with all pin positions.

Fuel burnup reduces fresh fuel coupling factors. For M2 and M3, based on calculations [3-3], this coupling is expected to be reduced by factors of 1.0, 0.98, and 0.96 for the near-fresh, 4, and 8 at.% burnup pins, respectively. Further, the power coupling factor during a reactor transient differs slightly from that measured under LLSS conditions by a transient correction factor (TCF), which is defined as follows:

$$TCF = \frac{\text{fissions/g-MJ(TREAT): Transient conditions}}{\text{fissions/g-MJ(TREAT): LLSS conditions}} .$$

The ratio in the TCF is obtained from flux monitor wire irradiations (one under transient conditions and one under LLSS conditions) and is assumed to be the same as it would be for fuel irradiations. Although the TCF is defined for the peak value of the axial distribution, little axial dependence of the TCF has been noted. A transient correction factor was obtained for an approximation of the final transient during the calibration experiment. The TCF for this transient was observed to be 0.95, and a similar result is expected for the actual transients used in M2 and M3. While the TCF is a measurement made over a whole transient, the time-dependence of the underlying effects is estimated from an empirical correlation [3-4] called the "rod shadowing factor" (RSF). By construction the RSF averages to 1.0 over the whole transient, and, based on trial transients, the RSF is expected to vary from 0.9 on the power flattop to 1.1 near peak power. The resulting axial peak coupling factors, including the TCF (but excluding any time-dependent RSF) are listed in Table 3-3.

The measured axial power profile as obtained from a fresh fuel pin during the LLSS fuel irradiation (gamma counting) is shown in Fig. 3-2. The arrangement of dysprosium neutron filter/shaping collar configuration which helped produce this profile has been shown in Fig. 2-2. It is anticipated

Fig. 3-2. Measured Test Fuel Axial Power Profile

that this profile will apply throughout the experiments. The ratio of axial-peak/axial-average was measured to be 1.10.

TABLE 3-3. Axial Peak Fuel Pin Coupling Factors Expected in the Final Transient

Position	Burnup (at.%)	Coupling Factors (W/g-MWT) (Approximate M2/M3 Transient)	
1	0.3	5.59	} $\pm 5\%$
2	4.4	5.46	
3	7.9	5.35	

Figure 3-3 shows a radial power profile computed for the test fuel in M2 and M3 [2-1]. The three pins in the array are sufficiently separated that no significant azimuthal power variation is expected within the pins. The surface to centerline ratio is computed to be 2.9 with an estimated uncertainty of about 15%. This radial power dependence can be summarized (approximately) in closed form as proportional to: $I_0(b \cdot R/R_0)$, where I_0 is a hyperbolic Bessel function; R is the radial position; and R_0 is the fuel outer radius. The shape parameter, b , is found to be 2.27.

4.0 DESCRIPTION OF TRANSIENT CONDITIONS FOR M2 AND M3

Desired transient conditions to be imposed on the test fuel involve a slow ramp rate overpower transient starting from conditions simulating steady-state operation of an IFR. Proposed IFR starting conditions involve a peak heating rate of about 38 kW/m and a temperature rise in the coolant channel of about 150 K, which are about 50% higher (in both conditions) than during test fuel irradiation in EBR-II. During the overpower portion of the transient power levels of around 4.5 times this IFR-nominal level may be required to fail the cladding. The actual power transient produced in the test fuel is restricted by energy deposition limits of the TREAT reactor. For M2 and M3 total energy deposited in the test fuel is limited to little more than 30 full-power (IFR) seconds. Thus for purposes of test design, compromises must be made limiting both the length of time at steady power and the "slowness" of the overpower burst if both steady-state and peak-overpower power levels are to be achieved.

The same power transient has been chosen for both M2 and M3, differing only in the timing and possibly the mode of termination. The longest-running version of this transient is shown in Fig. 4-1. Commencing from a low level, power quickly rises to steady-state level and holds for 1.5 s. Following this, power rises exponentially in accord with a constant, 8-s e-fold period. In M2 the power rise is to be terminated on the first sign of a significant cladding failure in at least one of the pins, as evidenced by a significant reduction of inlet flow. So as not to respond too soon to a mild, early failure of defective or damaged cladding, the power rise will not be terminated before about 3.8 times IFR-nominal is reached. In the (unlikely)

RADIUS	POWER	RADIUS	POWER
*****	*****	*****	*****
0	.62647	.525	.75592
.025	.62374	.575	.78995
.075	.62176	.625	.83036
.125	.6244	.675	.87908
.175	.63024	.725	.93757
.225	.63893	.775	1.01
.275	.65043	.825	1.1023
.325	.66474	.875	1.2266
.375	.68192	.925	1.3973
.425	.7025	.975	1.654
.475	.72704	1	1.8013

Fig. 3-3. Computer Test Fuel Radial Power Profile (Ref. 2-1)

Fig. 4-1. Full Length M2/M3 Power Transient

event that no cladding failure occurs or that failure is not detected, the power rise will terminate, as shown in Fig. 4-1, after the TREAT transient rods are fully withdrawn, at a power level of about 4.7 times IFR-nominal. The indicated power levels apply specifically to the high burnup pin but in fact apply within a reasonable 5% margin of error to all three.

Sodium coolant flow is chosen to produce a temperature rise of 150 K at IFR-nominal power, which, for M2, will be about 60 g/s-pin. Small adjustments (possibly by changing orifices at flowtube inlets) may be made in this value for individual flowrates in M3, based on M2 posttest results and Section 6 analyses, to assure that the pin types which failed in M2 will not fail in M3 and vice versa. Inlet coolant temperature is to be set at 633 K. To suppress any sodium boiling prior to cladding failure, the loop plenum pressure will be set at 4 atm-abs. at operating temperature.

In both cases the power rise will be terminated by driving the TREAT transient rods into the core as rapidly as possible with the aim of preserving materials and geometry in the time domain of early failure. Figure 4-1 includes a calculated time dependence for this shutdown. Upon shutdown, power will drop rapidly to a non-zero slowly-decaying "tail" at or below 10% of IFR-nominal. The tail will be held for about 15 s to facilitate fast neutron hodoscope analysis of fuel remains after which the power will be brought to zero.

The above specifications were formulated on the basis of calculations and results to be described in Section 6. Because thermal time constants in a metal-fueled system are so short, temperatures very close to steady-state values will be achieved in both fuel and coolant after only 1.5 s at steady power. (However, the same assurance cannot be given concerning mechanical or solid-solid phase changes within the fuel.) Thermal behavior of the test fuel should simulate corresponding behavior during the same overpower transient in an IFR fairly well for a time frame of about 10 s. Cladding failures in all three pins are expected to occur at power levels both within the "window" open to generate a shutdown signal and within about 5% of one another. On the other hand, transient shutdown will be sufficiently rapid that intact pins are expected to remain intact after shutdown. Thus, a very good possibility exists that a flowrate-generated shutdown in M2 will result in both just-failed and almost-failed pins.

5.0 CALCULATIONAL METHODS USED IN PLANNING AND ANALYSIS

5.1 Concepts

In line with the objectives of M2 and M3 to study fuel pin failure and axial extrusion, proposed underlying mechanisms and models which were used in experiment planning and which will be later used in posttest analyses are summarized here. To help fulfill the broad objectives of providing knowledge useful to the IFR program the tested concepts are intended to be applicable to ternary (U-Pu-Zr) fuel proposed for an IFR as well as the EBR-II fuel tested in M2 and M3. Ultimately, validation of these concepts will be through comparison of predicted consequences with posttest results of M2 and M3 as well as other experiments performed both in and out of pile.

5.1.1 Cladding Failure

While the cladding of metallic fuel under accident conditions should respond to temperature and stress transients in ways similar to well-studied oxide fuel cladding, failure in metal fuel is augmented by a low temperature eutectic that penetrates and, effectively, thins the cladding. Analysis in this report uses a rather simple correlation for cladding melt rate that depends only on the temperature of the fuel-cladding interface. Time-to-failure is then estimated using a plastic strain to rupture criterion developed in the UK for 316-SS and successfully used for failure analysis in recent TREAT tests of oxide fuel. All calculations employ stresses appropriate to thinned cladding. In most respects these modeling concepts should apply to ternary as well as to the EBR-II fuel that was used in their development.

The correlation for cladding melt rate, based on data from fuel pins (both fresh and irradiated) as well as phenomenological studies, has been reported in Ref. 5-1. There is good evidence that cladding melt rates are fairly universal, at least within uncertainties important to accident analysis, and that the specific fuel/cladding material is reflected principally in a melting threshold temperature. Within the time frame of accident transients (10's of seconds), cladding meltthrough proceeds very slowly until a fuel-cladding contact temperature of about 1350 K is achieved, when high melt rates of up to 1 mm per second are likely. With melt rates of this magnitude cladding would completely melt through in less than 1 s without regard to any details of a failure model. Detailed computations correlate rate of plastic strain to cladding stress and cladding temperature [5-1, 5-2]. Cladding stress is calculated assuming the fuel is sufficiently weak that the cladding is under load only from internal gas pressure, i.e., by: $(P_{int} - P_{ch}) * R / t$, where P_{int} and P_{ch} are the internal pin and adjoining coolant channel pressures, R is the mid-clad radius, and t is cladding thickness (subject to thinning). Failure is inferred when integrated plastic strain is approximately 2%.

5.1.2 Fuel Extrusion

Fuel swelling and axial extrusion calculated in this report make use of a simple gas bubble expansion-to-equilibrium model developed in Ref. 5-3. The basic idea is that all fission gas retained by fuel is to be found within individual bubbles which are in equilibrium with the pressure in the pin gas plenum. Fuel swelling data indicates a bubble size of about 0.1 micron radius under normal, steady-state reactor operating conditions. The gas pressure in these small bubbles can be quite large when surface tension pressure (about 20 MPa) is added to the pin gas plenum pressure exerted on the bubble. Transient swelling is calculated by adjusting gas bubble size in accord with changing fuel temperature and gas plenum pressure while maintaining mechanical equilibrium. The number and gas content of individual bubbles are assumed fixed. Neither bubble coalescence (which would augment swelling) nor gas release (which would reduce swelling) is included in this picture.

An attempt has been made to apply this expansion-to-equilibrium swelling concept as realistically as possible to computations of axial extrusion. Present calculations limit swelling rates to be consistent with measured secondary creep rates in accord with a formalism presented in Ref. 5-4. When

realistic creep rates for metal fuel [5-5] are used, little expansion is computed before reaching the fuel solidus, when the expansion rate is no longer assumed to be restrained. If the volume fraction occupied by retained fission gas is totaled up and compared with observed porosity, it is evident that a considerable excess exists when fuel has swelled out to the cladding (at burnups greater than required for breakaway swelling). This excess volume fraction is termed open porosity to distinguish it from the volume formed by the closed, gas-retaining bubbles. As the expansion of the "closed" gas bubbles increases the total fuel volume, existence of open porosity permits expansion in the radial as well as the axial direction. When fuel is free to slip within the cladding, 2/3 of the computed fractional volumetric expansion acts to close open porosity in the fuel cross section with 1/3 producing axial extrusion. If fuel-cladding interface temperatures are below the melting threshold, medium and high burnup fuel is considered stuck to the cladding and all swelling acts only to close open porosity.

5.1.3 Effect of Burnup on Fuel Thermal Conductivity

Computation of fuel extrusion depends strongly on computed fuel temperature which in turn depends on fuel thermal conductivity. The principal effect that burnup would have on conductivity is thought to be through swelling and the creation of a distribution of porosity. The porosity (around 25% when fuel is swollen out to the cladding) could be either filled with low-conductivity gas or partly logged with sodium. Current calculations estimate [5-6], partly empirically and partly theoretically, the effect of fuel porosity on its thermal conductivity, including the likely possibility that some fraction, perhaps 20%, of the porosity is logged with bond sodium. For medium to high burnup fuel without sodium logging the effective thermal conductivity is reduced in calculations to about 0.4 that of fresh fuel. Logging some of the porosity with sodium restores conductivity to about 0.6 times that of fresh fuel.

5.2 Computer Codes

Two major computer codes were used in the planning and analysis of tests M2 and M3. COBRA-PI [5-7] performs thermal-hydraulic modeling of an actual test bundle prior to any pin failures or sodium coolant boiling. SAS4A [5-8] is the developmental version of the principal US tool for accident analysis.

An important reason for the parallel development of metal fuel features in the two codes was to verify the performance of SAS4A during prefailure times with the above modifications. COBRA-PI provides a detailed description of the fuel pin and flow tube, while SAS4A is a basic pin in a pipe model within the test section. SAS4A integrates prefailure thermal analysis, coolant boiling and postfailure fuel and coolant motions. SAS4A will be used in the posttest analysis of fuel motion in M2 and M3, and these pretest comparisons with COBRA-PI will show that channel conditions at failure are being correctly calculated by SAS4A. The PRIMAR-4 capabilities of SAS4A can model the entire loop, including the three individual flow tubes with different flowrates joining in a common plenum. This three channel capability has not been used in current analyses but will be incorporated into the analysis in the near future.

The M2/M3 geometry consists of three single pins in separate channels with little azimuthal dependence expected either in power generation or temperatures. (The swirling effect of the fuel pin wire-wraps is not explicitly modeled by either code and not included in the analysis.) By design, no coolant boiling is anticipated in the test prior to cladding failure. Both tests are also slated to terminate in the time domain of cladding failure. Thus, both SAS4A and COBRA-PI should be useful in modeling these current tests that involve essentially intact fuel pin geometry. Future experiments are likely to investigate postfailure behavior of more complex, multi-pin bundles. COBRA-PI calculations will be then most useful in explicit prefailure analyses of complex test sections, whereas SAS4A calculations will emphasize analysis of postfailure material motion.

The concepts described in Section 5-1 have been incorporated into the COBRA-PI and SAS4A analyses largely through the addition of specially written routines that compute eutectic penetration into cladding, cladding failure, and fuel extrusion. In the case of COBRA-PI, computed fuel and cladding temperatures along with user-supplied properties of irradiated fuel, such as fission gas retention and plenum pressure, are supplied to a routine, EXP (EXtrusion and Penetration). EXP performs calculations which are "auxiliary" in the sense that no modification of the original COBRA-PI analysis takes place.

The implementation of the eutectic formation and extrusion concepts discussed above were incorporated into the SAS4A code through a modification of an existing subroutine FAILUR. This subroutine is called once at each main time step to check various input criteria to determine if cladding failure has occurred. Once failure has occurred, this subroutine is no longer called, which imposes two limits on its usefulness. One, any extrusion potential beyond clad failure cannot be calculated with this version. Second, the clad rip cannot be propagated based on eutectic penetration of nodes adjoining the original failure site. The capabilities of this modified FAILUR subroutine will be incorporated into a future version of the DEFORM module, allowing full interaction with other subroutines to follow extrusion after failure and extend the clad rip more correctly.

Other developmental analyses are also proceeding with SAS4A. Appendix A describes an analysis using PINACLE, which models explicitly the relocation of in-pin molten fuel prior to failure.

6.0 RESULTS OF THE PRETEST ANALYSIS

6.1 Thermal Performance

Thermal performance of the test fuel under the transient conditions described in Section 4 is illustrated by results of SAS4A and COBRA-PI analyses presented in Figs. 6-1 to 6-4. These calculated results indicate both dependence on time (see Fig. 4-1) and axial height. As mentioned in Section 4, thermal profiles are nearly fully developed by the end of the flattop. Thermal behavior of all three pin types were computed to be similar. Allowing for plausible differences in power and flow, computed temperatures in both fuel and coolant fall within about 50 K of one another

Fig. 6-1. SAS4A Computed Time Dependence of Selected Temperature - Low Burnup Pin

Fig. 6-2. SAS4A Computed Time Dependence of Selected Temperatures - High Burnup Pin

Fig. 6-3. COBRA-Computed Axial Dependence of Selected Temperature for the High Burnup - End of Flattop (5.6 s)

Fig. 6-4. COBRA-Computed Axial Dependence of Selected Temperatures for the High Burnup Pin - Near Failure (16.8 s)

for all three pin types. (Decreases in power coupling with burnup are partly offset by decreases in both thermal conductivity and channel flow area due to swelling.) The thermal effect of the experiment radial power dependence is to lower peak fuel temperatures by about 100 K at cladding failure time from what would be the case with uniform power.

Calculated results for medium and high burnup pins generally assumed a fuel thermal conductivity calculated on the basis of 20% of the total porosity being logged with liquid sodium. This assumption had a maximal impact on calculations just prior to fuel melting where peak fuel temperatures were computed to be about 50 K lower than if all pores were empty. Above fuel melting the same thermal conductivity was used in all analyses.

Some difference in thermal performance between the M2/M3 test fuel and fuel ternary may be noted owing to a significantly lower fuel melting threshold in the test fuel. Solidus and liquidus temperatures are taken to be 1283 K and 1373 K with heat of fusion 81.6 kJ/kg for the test fuel in contrast to about 1420 K and 1520 K with heat of fusion 47.1 kJ/kg for ternary fuel.

6.2 Fuel Performance and Cladding Failure

Computed results concerning fuel performance and cladding failure from SAS4A and COBRA-PI are summarized in Table 6-1. All failures are computed to be at the top of the fuel. When the computed cladding failure threshold for the three fuel types is examined, it is found that only the high burnup pin fails before a significant fraction of cladding is melted. In essence, the failure of the low and medium burnup pins occurs shortly after a fuel-cladding interface temperature of at least 1350 K, at which point the cladding melt rate accelerates rapidly. On the other hand, very high plenum pressure coupled to a very high mid-clad temperature determines the time of failure in the high burnup pin.

The same cladding failure modes should apply to ternary fuel under similar transient conditions. The low threshold temperature for the formation of fuel-cladding eutectic in EBR-II fuel should not affect failure threshold under present transient conditions since the rate of melting at these low temperatures is also very low. Also, because fuel-cladding interface and cladding temperatures are of primary importance, the lower fuel melting point of EBR-II fuel is not expected to strongly influence the nature of cladding failure.

6.3 Axial Fuel Extrusion

Amounts of axial extrusion expected at the cladding failure threshold are indicated at the bottom of Table 6-1. The time dependence of axial fuel extrusion as computed by COBRA-PI for the three fuel types is shown in Fig. 6-5 relative to the failure time. In these analyses it has been assumed that the test transient terminates immediately upon cladding failure (according to the shutdown rate shown in Fig. 4-1). If a shutdown trigger is not detected and the test transient were continued beyond pin failure to its maximum length as shown in Fig. 4-1, fuel would continue to extrude to COBRA-calculated maximum values of 0.7 (low), 1.9 (medium), and 2.1 (high) cm in each pin type before shutdown.

TABLE 6-1 Summary of Calculated Test Fuel Performance

Pin type	0.3 at.%	4.4 at.%	7.9 at.%
Onset of fuel melting (s)	13.9 (SAS) 14.6 (COB)	12.4 (SAS) 13.6 (COB)	12.6 (SAS) 13.6 (COB)
Computed pin failure (2% plastic strain):			
Time (s)	17.1 (SAS) 17.1 (COB)	17.0 (SAS) 17.1 (COB)	16.7 (SAS) 16.7 (COB)
Power (kW/m)	166 (SAS) 166 (COB)	161 (SAS) 166 (COB)	153 (SAS) 153 (COB)
Pin plenum pressure (Mpa)	1.2 (SAS) 0.4 (COB)	10.9 (SAS) 9.6 (COB)	18.5 (SAS) 18.5 (COB)
Fraction of fuel above solidus-			
hottest node:	1.0 (SAS) 1.0 (COB)	1.0 (SAS) 1.0 (COB)	1.0 (SAS) 1.0 (COB)
whole pin:	0.5 (SAS) 0.5 (COB)	0.6 (SAS) 0.7 (COB)	0.6 (SAS) 0.6 (COB)
Fraction of cladding molten at failure site	1.0 (SAS) 1.0 (COB)	0.5 (SAS) 0.5 (COB)	0.02 (SAS) 0.02 (COB)
Axial extrusion (cm)-			
before failure:	0.6 (SAS) 0.6 (COB)	1.0 (SAS) 0.9 (COB)	0.8 (SAS) 0.6 (COB)
after failure:	0.6 (COB)	1.3 (COB)	1.0 (COB)

Fig. 6-5. COBRA-Computed Time Dependence of Axial Extrusion

The time-dependence shown in Fig. 6-5 illustrates a number of general features of the extrusion model. Extrusion due to expansion of retained fission gas does not play a significant role in these calculations until significant fuel melting takes place. Prior to this there is only thermal expansion, as evidenced by comparison to the near-fresh, low burnup case. Once significant melting takes place extrusion catches up to where it would have been had it not been limited by creep rate. When cladding failure occurs, pin plenum pressure is assumed to rapidly drop to that of the coolant flow channel. Thus at failure, bubbles retaining fission gas expand rapidly to achieve a new equilibrium condition, and the computed extrusion "jumps" as indicated in the figure. In the extrusion model bubble expansion is reversible, and upon shutdown bubbles contract to achieve equilibrium at lower temperature and pressure. If cladding failure has taken place, a net positive extrusion will still be computed after a return to initial temperature because of the depressurization of the pin plenum.

Most of these features of the extrusion analysis apply equally to ternary and the current test fuel. A possible exception lies in computing the rate of extrusion when the fuel is solid. The lower melting point of the test fuel could lead to earlier extrusion. If solid fuel turns out to be significantly weaker than indicated by creep rate data, then extrusion rates could turn out to be similar. In either case steady-state or peak values of extrusion should not be strongly affected.

Further results obtained from developmental analyses using SAS4A are described in Appendix A.

7.0 CONCLUSIONS

Tests M2 and M3 should provide useful information concerning the safety-related performance of metallic fuel under slow ramp rate overpower conditions. Between the two tests, close study of the time domain of cladding failure threshold for low, medium, and high burnup fuel should be possible. Analysis indicates that under nominal test conditions all three pins will simultaneously fail or will be near failure. If test termination is made on the basis of a flow perturbation, test shutdown should be rapid enough to retain any just-failed/about-to-fail distribution among the pin types.

These conclusions are in part based on models of pin failure and fuel axial extrusion which have been developed for metal fuel. Measurements of these quantities by test instrumentation and hodoscope analysis should aid in the validation and further development of these analytical models.

Finally, it is tentatively concluded, on the basis of the phenomenology used to estimate pin failure and axial extrusion, that the Uranium-Fissium, EBR-II fuel tested is a suitable substitute for ternary fuel in M2 and M3. This conclusion is valid provided that features of steady-state performance relevant to safety behavior, such as gas retention, swelling, and porosity interconnection, remain essentially the same. Other differences in properties between the two fuel types have been identified where analysis might be affected, but these are not expected to affect the safety-related fuel behavior in a strong way.

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APPENDIX A ANALYSIS WITH SAS4A/PINACLE

A pretest analysis of the M2/M3 metal fuel experiments was performed using the SAS4A code system and the PINACLE module. PINACLE is a new model included in SAS4A, which allows the calculation of prefailure, in-pin axial fuel relocation.

As part of PINACLE validation, an analysis of a recent oxide fuel experiment was recently completed and has shown agreement between the PINACLE results and the experimentally observed prefailure in-pin fuel relocation. Results presented here represent the first use of PINACLE with a metal-fueled transient test calculation.

The pretest analysis of the high burnup test pin was performed using the SAS4A input deck described in Sections 5 and 6 and using the PINACLE modules in addition to the modules available in the last release version of SAS4A. DEFORM was not used in this calculation and the axial extrusion in the solid fuel pin was calculated using the model described in Section 5. Two runs were performed where PINACLE was initiated when the molten fuel fraction reached 0.1 and 0.3 at any axial location. At the time of PINACLE initiation, $t=13.79$ s, the axial extrusion in the solid fuel pin is discontinued and only the relocation of the molten fuel is calculated. It is expected that the solid fuel extrusion will be calculated by DEFORM IV, when the metal fuel version of this code module becomes available.

However, it is expected that once the molten fuel motion is initiated, its effect will dominate the effects of any solid state extrusion that might still be occurring. This is substantiated by Fig. A-1 which shows the height of the fuel column above the original location of the fuel pin as a function of time. A clear increase in the slope of this curve is observed at the time when PINACLE is initiated. A similar curve showing the mass of fuel relocated above the original fuel is shown in Fig. A-2. The mass of fuel relocated due to hydrodynamic effects increases rapidly after the initiation of PINACLE and then continues to increase at a steady rate until the time of pin failure. An estimate of changing fuel worth is shown in Fig. A-3, and a final prefailure calculated fuel distribution is shown in Fig. A-4.

As expected, the rate of fuel relocation calculated by PINACLE exceeds the rates calculated using the solid state extrusion model, because the liquid relocation is driven by the pressure in the central cavity, where the temperature is higher than the average pin temperature used in the solid fuel extrusion calculations. However, this leads to a more rapid pressurization of the plenum and an earlier pin-failure.

Pretest Analysis of the M2-Test High Burnup Pin Using PINACLE and SAS4A Fuel Melt Fraction of PINACLE Initiation = 0.1 —, = 0.3

Fig. A-4. Fuel Distribution in the M2 Test (High Burnup Pin) at Time $t=15.95$ s (just prior to pin failure) as Calculated by PINACLE/SAS4A in a Pretest Analysis
 Fuel Melt Fraction at PINACLE Initiation = 0.1