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Power Coupling in TREAT M-Series: New Experimental Results from M7CAL and Updated Analyses

by W. R. Robinson
and T. H. Bauer

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POWER COUPLING IN TREAT M-SERIES: NEW EXPERIMENTAL RESULTS FROM M7CAL AND UPDATED ANALYSES

by

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POWER COUPLING IN TREAT M-SERIES:
NEW EXPERIMENTAL RESULTS FROM M7CAL AND UPDATED ANALYSES

by

W. R. Robinson and T. H. Bauer

ABSTRACT

Experiments and methods used to determine power coupling of test fuel to the TREAT reactor during six recent metal-fueled sodium loop tests (M2-M7) are described. Previously reported calibration work on a three-pin test configuration with uranium-fissium fuel is updated (M2CAL). Additional results on a two-pin test configuration with the Integral Fast Reactor (IFR) reference fuel (uranium-zirconium and uranium-plutonium-zirconium) are reported (M7CAL).

The peak axial low-level, steady-state (LLSS) fresh fuel pin power coupling factors for the IFR fuel compositions were determined from radiochemical analysis of fuel segments. A large data base of uranium-zirconium neutron flux monitor wire measurements were complied to extend the fuel measurements to high-power transient conditions by comparing the measured power couplings from high and low-power wire irradiations. Power coupling results were obtained in both a full-slotted and a half-slotted TREAT core configuration.

Relative power coupling measurements are compared to calculations for the three different types of fuel; U/Fs, U/Zr and U/Pu/Zr. Estimates of power coupling including corrections accounting for the effect on the power coupling of isotopic depletion and fuel swelling as the fuel undergoes burnup are presented for planning and analysis of tests M5, M6 and M7.

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1. INTRODUCTION

In every TREAT experiment heat generated by test fuel pins is related to the power generation measured in the TREAT reactor through "power coupling factors". To support the analysis and planning of M-Series experiments on metallic fuel a number of independent experimental measurements and neutronic calculations have been performed to estimate these power couplings. Measurements include separate "calibration experiments" on fresh fuel and monitor wires at low power levels, as well as high-power transient irradiations of monitor wires performed at the time of the transient experiment itself. Neutronic analyses have been used to account for test fuel burnup including corrections for isotopic depletion and fuel swelling. Early calibration results were reported for the EBR-II driver fuel first tested (Refs. 1, 2 and 3). The purpose of this report is to update information on M-Series power coupling factors, in particular to present new experimental results and analyses pertaining to advanced U/Pu/Zr and U/Zr fuel tested in TREAT tests M5-M7.

By way of background, since 1984, six tests (M2 through M7) have been conducted in sodium loops in the TREAT facility on metal fuel in support of the Integral Fast Reactor (IFR) program (Refs. 2, 3 and 4). U/Fs fuel of a wide burnup range (up to 8 at.%) was chosen for initial testing, in tests M2-M4, since it was readily available. Later tests, M5-M7, used U/Pu/Zr and U/Zr IFR reference concept fuel. As irradiated IFR fuel became available, the highest burnup fuel was chosen for each test: 0.8 and 1.9 at.% U/Pu/Zr fuel for M5 (August 1986), 1.9 and 5.3 at.% U/Pu/Zr fuel for M6 (February 1987) and a 9.8 at.% U/Pu/Zr pin along with a 2.9 at.% U/Zr pin for M7 (October 1987).

A total of 15 pins have been overpower-tested so far. Specifically, M2-M4 each tested three 0.174 in. (0.44 cm) diameter EBR-II Mark-II uranium-5 wt.% fissium* driver fuel pins. M5 and M6 each tested two uranium-19 wt.% plutonium-10 wt.% zirconium fuel pins and M7 tested one U-19Pu-10Zr pin and one uranium-10 wt.% zirconium pin. Test fuel pins for M5-M7 were all 0.230-in. (0.58 cm) in diameter. The U/Fs pins were clad in 316 stainless

* Fissium (Fs) is a mixture of metals representing an equilibrium concentration of solid fission products that are formed during irradiation.

steel, the U/Pu/Zr pins in D9 cladding and the U/Zr pin in HT9 cladding. The power coupling of each fuel type needs to be determined.

During a calibration experiment, fuel can only be irradiated at low power levels, but U/Zr monitor wires can be irradiated at both high and low power levels. Extending measurements to high power transient irradiations is accomplished by comparing power couplings of measured "high-power" and "low-power" U/Zr monitor wires. In applying this method, careful measurements of the ratio of test fuel to monitor wire fissions were made under low-power (LLSS) conditions, and representative high-power transient irradiations of U/Zr flux monitor wires were performed at the time of each M-series experiment.

The first calibration experiment in this series, "M2CAL" (the M2 Power Calibration Experiment), was conducted in TREAT in September 1984 to directly measure power coupling of U/Fs test fuel. It consisted of a series of irradiations in a neutronic "mock-up" of an M-series test loop, one irradiation with a three-pin geometry of fresh U/Fs fuel and several irradiations with U/Zr flux monitor wires. The LLSS coupling factor was obtained from radiochemical analysis of the fresh U/Fs fuel (Ref. 1).

In April 1987, as described in this report, "M7CAL" (the M7 Power Calibration Experiment) extended the measurements of power coupling to U-10Zr and U-19Pu-10Zr fuel pins in a two-pin test geometry. The M7CAL experiment included a number of features in addition to those described above:

1) power coupling measurements for both a full-slotted and a half-slotted TREAT core configuration. (The full-slot option optimizes the quality of the TREAT fast neutron hodoscope data during an experiment and was used during M2-M7. The half-slot option maximizes energy deposition and could be used in future tests),

2) the irradiation of a pre-irradiated fuel pin (irradiated in EBR-II) with a burnup of 2.9 at.% along with a fresh fuel pin to allow the hodoscope to determine the effect of in-pin radial swelling on the power coupling factor,

3) several irradiations to provide data for improving hodoscope measurements of pin-to-pin coupling factor ratios,

4) a comparison of hodoscope signal-to-noise ratios from a test vehicle in both the half-slotted and the full-slotted TREAT core configuration. This comparison would indicate the effect of the increased noise background (from fuel elements located behind the test vehicle in the half-slotted configuration) on the hodoscope results.

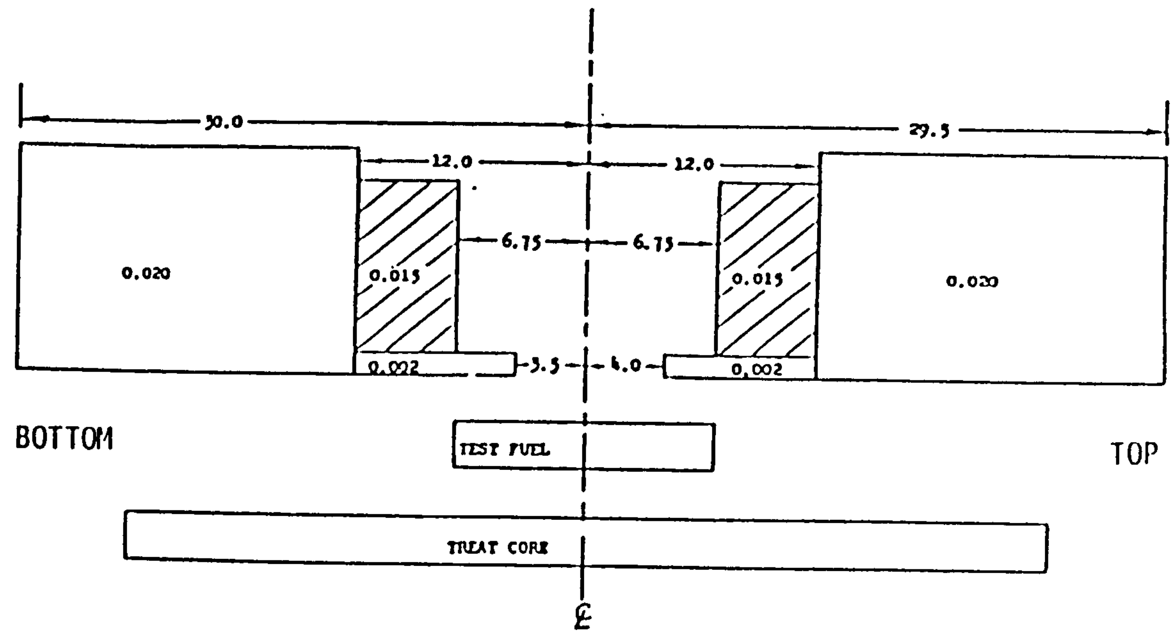
The remainder of this report describes the M7CAL experimental apparatus, LLSS irradiations, high-power monitor wire irradiations, and the analytical procedures used to obtain power coupling factors suitable for use in experiment analyses. Both axial peak values and axial distributions are included in the discussion. Analytic corrections for fuel-pin burnup are also described. Where neutronic calculations have been performed to obtain power couplings for the U/Fs, U/Pu/Zr and U/Zr fuel types, appropriate comparisons are made with measured results from M2CAL and M7CAL.

Results of the M7CAL hodoscope sensitivity and performance measurements (items 2-4 above) have not been fully analyzed and will be reported at a later date.

2. M7CAL EXPERIMENTAL APPARATUS

Mark-IIIC test vehicles were used for tests M2 through M7. Both the M2CAL and M7CAL experiments were conducted in a neutronic mockup of the Mark-IIIC vehicle (the M2CAL vehicle). The M2CAL vehicle was also used for trial transients and appropriate U/Zr monitor wire irradiations prior to tests M2 through M7.

The M2CAL vehicle was put together with parts taken from previous TREAT test calibration vehicles. A straight spool piece was substituted for the pump leg on the L04/L05 calibration vehicle. The only accessory on this spool piece was a neutronic mockup of the flowmeter magnet at the top of the pump leg. A new dysprosium axial shaping collar configuration (Figs. 1 and 2) including the associated stainless steel shims and dummy heaters, was



(Note : Dimensions in inches)

Fig. 1. Axial Dysprosium Shaping Collar Configuration

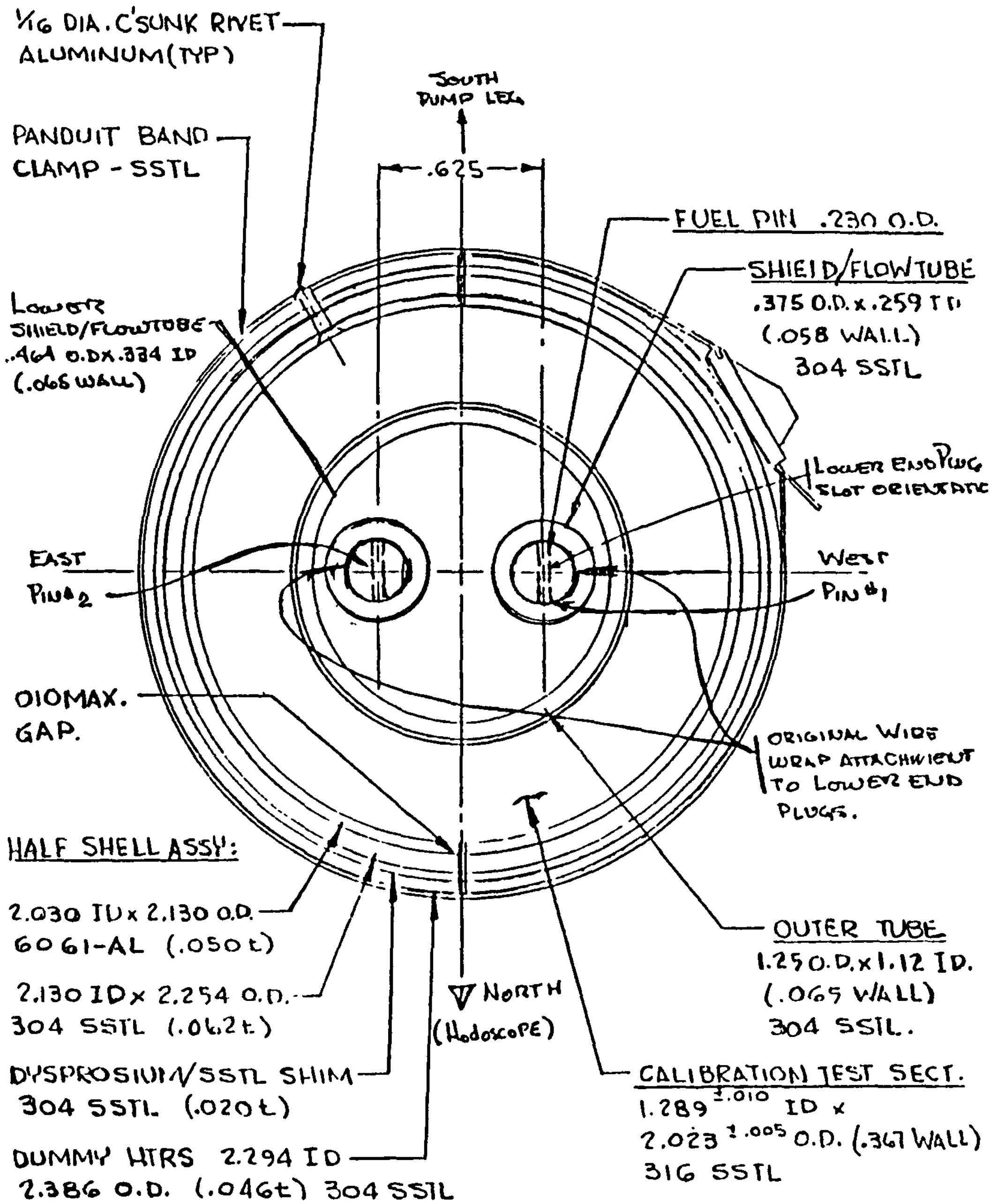


Fig. 2. Cross-Sectional View of the Calibration Vehicle including the Fueled Calibration Test Train (looking down)

fabricated and banded in place around the test section of the L03 calibration vehicle. The modified L03 calibration vehicle test section was then inserted into the modified L04/L05 calibration vehicle frame.

Table I lists the loop and test section radial dimensions for the calibration vehicle and the two-pin test train. The 0.050-in. (0.127 cm) thick aluminium sleeve and the 0.062-in. (0.157 cm) thick stainless steel sleeve were added to the Mark-IIIA L03 calibration vehicle test section to simulate the enlarged Mark-IIIC test section. Sodium was not required neutronically in the calibration vehicle, and it was not used. Aside from the axial dysprosium shaping collars there were no other filters on the loop. The completed calibration vehicle was neutronically representative of the Mark-IIIC Integral Sodium Loop, in materials and geometry overall and was intended to be especially accurate within 29.5-in. (74.9 cm) above and 40-in. (101.6 cm) below the midplane of the TREAT core midplane (Ref. 5).

The shaping collar configuration, identical to that on the test loops themselves, was selected on the bases of 2-D diffusion calculations (Ref. 6) to produce an axial power distribution that would lie midway between the axial profile of the design concept of the Integral Fast Reactor (1.23 peak/average) and the axial profile of EBR-II (1.10 peak/average). This was done in the interest of generating a profile that would represent either (or both) profiles reasonably well.

For M7CAL, a mockup fueled calibration test train with the capability of containing up to two fuel pins in individual flow/shield tubes (Fig. 2) was used for the fuel pin irradiations. In the calibration hardware the flow and shield tubes were represented by a single tube. A 0.375-in. (0.95 cm) long x 0.25-in. (0.64 cm) diameter stainless steel reference marker was welded to flow/shield tube number 1 (west side of test train) to facilitate identification of the test train orientation during radiography.

Also unique to M7CAL was the one thermocouple (TC) attached to each flow/shield tube to monitor the temperature during LLSS fuel pin irradiations; however, only the TC on flow/shield tube number 1 on the west side was operational during the experiment. The TC's were stainless steel sheathed, MgO insulated, Chromel/Alumel with an outside diameter of 0.040-in. (1.016 mm). Inside the sheath were two conductors of approximately 0.006-in. (0.152 mm) diameter. An intrinsic type junction was used where each conductor is

Table I. Radial Dimensions of the Fueled Calibration Test Train and the M7 Test Train

<table>
<tr><th rowspan="2"></th><th colspan="4">Calibration Test Train</th><th colspan="4">M7 Test Train</th></tr>
<tr><th>O.D. (in.)</th><th>I.D. (in.)</th><th>Wall (in.)</th><th>Area (in.2)</th><th>O.D. (in.)</th><th>I.D. (in.)</th><th>Wall (in.)</th><th>Area (in.2)</th></tr>
<tr><td>Outer Tube</td><td>1.250</td><td>1.120</td><td>0.065</td><td>0.242</td><td>1.375</td><td>1.255</td><td>0.060</td><td>0.248</td></tr>
<tr><td>Shield Tubes Along Fuel Pins</td><td rowspan="2">0.375</td><td rowspan="2">0.259</td><td rowspan="2">0.058</td><td rowspan="2">0.058</td><td>0.625</td><td>0.585</td><td>0.020</td><td>0.038</td></tr>
<tr><td>Flowtubes Along Fuel Pins</td><td>0.348</td><td>0.311</td><td>0.0185</td><td>0.019</td></tr>
<tr><td>Shield Tubes Below Fuel Pins</td><td rowspan="2">0.464</td><td rowspan="2">0.334</td><td rowspan="2">0.065</td><td rowspan="2">0.081</td><td>0.625</td><td>0.585</td><td>0.020</td><td>0.038</td></tr>
<tr><td>Flowtubes Below Fuel Pins</td><td>0.437</td><td>0.367</td><td>0.035</td><td>0.044</td></tr>
<tr><td>Fuel Pins</td><td>0.230</td><td></td><td></td><td></td><td>0.230</td><td></td><td></td><td></td></tr>
</table>

separately welded to the 0.058-in. (1.473 mm) thick flow/shield tube wall. The TC's were located axially one-inch above the test fuel centerline and azimuthally 30 degrees off the line joining the centers of the two flow/shield tubes, on the outward-facing side of each tube.

Six fresh fuel pins and one preirradiated pin were required in the experiment. All fuel pins were fabricated with sodium bonding the fuel slug to the stainless steel cladding (Fig. 3). The wire wraps, normally associated with the fuel pins, were removed from the pins for this experiment. Table II describes the particular fuel pins. The midplane of the active test fuel column was located at the midplane of the TREAT reactor core.

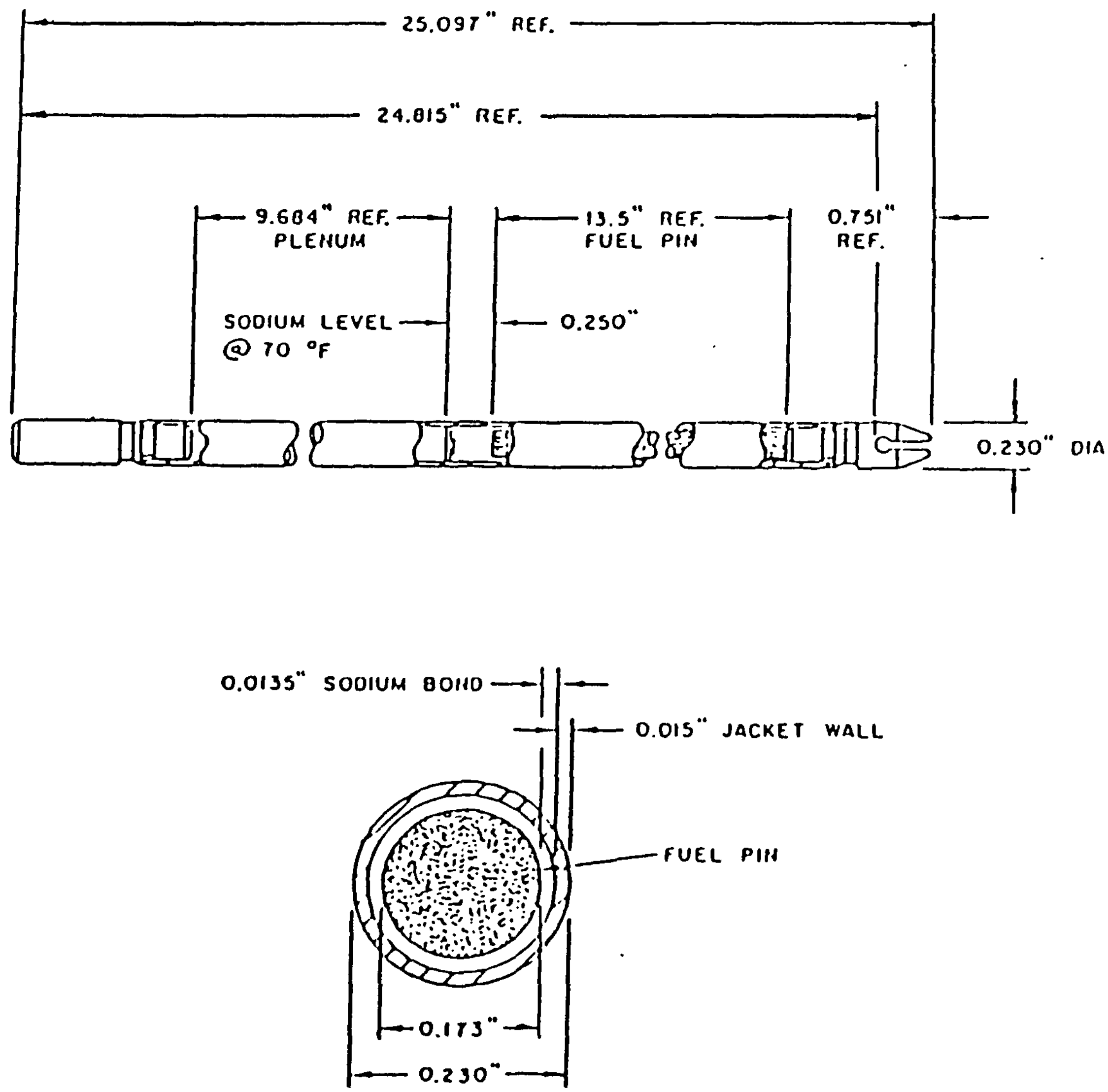
The fueled calibration test train was sealed at the top to the loop test section. After the train was loaded into the test section, a valve at the top of the test train permitted the volume within the test section to be evacuated and pressurized with He to aid in transferring heat away from the fuel during the LLSS irradiations. After the irradiations the valve was used to sample the plenum gas to determine the likelihood of any failed fuel pins.

An unfueled calibration test train was used to irradiate the two U/Zr flux monitor wires. Each wire was 15-in. (38.10 cm) long and 0.030-in. (0.076 cm) in diameter. The wires each contained 3.6 wt.% U enriched to 93 wt.% U-235 (about 0.04 grams of U-235) and were inserted into a stainless steel sheath which ran the length of the fuel region along the test section centerline. The sheath had an inner diameter of 0.072-in. (0.183 cm). A 0.015-in. (0.038 cm) thick dysprosium filter surrounded the 1-in. (2.54 cm) diameter monitor wire holder to prevent the wire from melting during high power transient measurements.

3. EXPERIMENTAL PROCEDURE

3.1 TREAT Operations

Table II summarizes the low-level, steady-state calibration irradiations. The initial core loading for M7CAL was the loading that had been used for all the tests in the M2-M6 series (the M6 test had immediately



Note: Wire Wrap removed for calibration experiment

Fig. 3. IFR Reference Metal Alloy Fuel Pin

Table II. M7 Calibration Irradiation Summary

TREAT Irradiation Identification Number	1987 Date	Core: Slot-Configuration	Notes	"Flowtube" Number	Fuel Pin & Wire Number	Material Composition (wt. %)	Batch Number	BU (at.%)	Fuel/Wire Weight (grams)	Active Length (inches)	Test Train Rotation (degrees)	Total Run (min.)	TREAT Power Level (kW)	TREAT Energy (MWs)	Peak Temperature (degrees F)
2	3/30	FULL	(3)	---	NONE	-------	--	----	----	---	0	261	80	1253	---
7	3/31	FULL	(2,8)	---	15-17	U-96.4Zr	--	----	1.19	15.0	0	120	78	562	---
1	4/3	FULL	(1,6,7,8)	1 2	T-410 T-460	U-10Zr U-19Pu-10Zr	204 006	Fresh Fresh	78.72 77.53	13.515 13.552	0	126.5	78	592	---
3	4/6	FULL	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	0	124	80	595	379
4	4/7	FULL	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	55	133	80	638	287
6	4/8	FULL	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	305	124	80	595	288
4R	4/9	FULL	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	55	130	80	624	286
5	4/10	FULL	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	180	146	80	701	293
6R	4/13	FULL	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	305	171	80	821	302
2R	4/14	FULL	(3)	---	NONE	-------	--	----	----	---	0	129	80	619	---
9	4/17	HALF	(3)	---	NONE	-------	--	----	----	---	0	222	80	1066	---
8	4/20	HALF	(1,6,7,8)	1 2	T-428 T-463	U-10Zr U-19Pu-10Zr	204 006	Fresh Fresh	78.12 77.71	13.514 13.525	0	136.8	76.8	630	399
12	4/21	HALF	(2,8)	---	15-18	U-96.4Zr	--	-----	1.19	15.0	0	120.2	80	577	---
10	4/22	HALF	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	55	183	77	845	313
11	4/23	HALF	(4,6,7,8)	1	T-433	U-10Zr	204	Fresh	78.05	13.516	305	206	77	952	321
13	5/14	FULL	(5,6,7,8)	1 2	T-183 T-462	U-19Pu-10Zr U-19Pu-10Zr	36 006	2.9 Fresh	78.31 78.21	13.7 13.562	0	129	80	619	TC Non-operational

Table II. M7 Calibration Irradiation Summary (Cont'd)

Notes:

1) Irradiations 1 and 8 provided the LLSS absolute number of fissions/gram at the midplane of the active fuel region in both U/Zr and U/Pu/Zr fuel types in both the full-slotted and half-slotted core configurations.

2) The purpose of irradiation numbers 7 and 12 was to obtain the LLSS absolute number of fissions/gram at the midplane of the active fuel region in flux monitor wires in both the full-slotted and the half-slotted core configurations.

3) Irradiations 2 and 9 utilized the test hardware only, that is the M2CAL test section, frame and the two pin "fueled calibration test train" (but without fuel). These irradiations provided the background signal for the hodoscope measurements.

4) Irradiations 3, 4, 5, 6, 10 and 11 provided hodoscope data to aid in determining pin-to-pin coupling factor ratios. In these irradiations the test train was rotated a specific number of degrees from the reference rotation of 0.0 degrees shown in Fig. 2. Rotations were in the clockwise direction (looking down).

5) Irradiation 13 allowed the hodoscope to compare the signal from a preirradiated fuel pin to that from a fresh fuel pin in order to determine the effect of radial fuel swelling on the power coupling factor.

6) All fuel pins have HT9 stainless steel cladding except for pin T-183 which has D9 stainless steel cladding.

7) The as-fabricated length is shown for all pins except for pin T-183 for which the length after the EBR-II irradiation is indicated.

8) Batch data:

wt.%	Wire	006	204	36
Uranium	3.6	70.71	89.66	71.45
U-234	-	0.56	0.63	0.41
U-235	93.	56.88	68.50	56.99
U-236	-	0.32	0.37	0.26
U-238	-	42.24	30.50	42.34
Plutonium	-	19.07	--	18.83
Pu-239	-	93.84	--	93.83
Pu-240	-	5.82	--	5.70
Pu-241	-	0.29	--	0.39
Pu-242	-	0.05	--	0.07
Zirconium	96.4	9.78	9.70	10.41

preceded M7CAL). This core loading contained a full north-south slot and the test vehicle was oriented as shown in Fig. 2.

Beginning with irradiation identification number 9 in Table II on April 17, 1987 the core was changed to a half-slotted core loading. (Note that the TREAT irradiation identification numbers are as they appeared in the original data package, Ref. 7). The half-slotted core loading was specified to contain the highest possible reactivity achievable with a half slot to the north and a dummy element placed immediately south of the calibration vehicle. Finally, the TREAT core was returned to the original full north-south loading for the last irradiation, number 13. The slots in both configurations were 48-in. (121.92 cm) high.

Neutron radiographs were taken of the calibration vehicle at two different times during the experiment, 1) with two fresh pins in the fueled calibration test train at the start of the experiment and 2) with a preirradiated and a fresh pin in the vehicle at the end of the experiment. The purpose of the first set of radiographs was to ascertain that the fuel pins were centered on the dysprosium shaping collar configuration. The second set was taken to confirm a suspected unplanned 13 degree clockwise rotation of the fuel pins relative to the reference orientation (the reference orientation is shown in Fig. 2). Hodoscope measurements corroborated this rotation.

Following all but the last fuel pin irradiation the gas in the test section was checked for xenon-133 activity, the presence of which would indicate fuel cladding failure. None of the fuel pins failed during the experiment.

Prior to each fuel pin irradiation, the volume inside the test section was successively evacuated and pressurized with helium and a final pressure of two atmospheres (absolute) was established. The high thermal conductivity of helium allowed the fuel to withstand several hours of low-level, steady-state operation with fuel temperatures reaching a maximum of only about 205°C.

Using the one operational TC, the flow/shield tube temperatures were periodically recorded during each fuel pin irradiation except for the last irradiation when an open junction developed in the TC circuit. Two typical measured temperature-time profiles are shown in Fig. 4 along with a conservative (convection and radiation effects were not considered) THTB

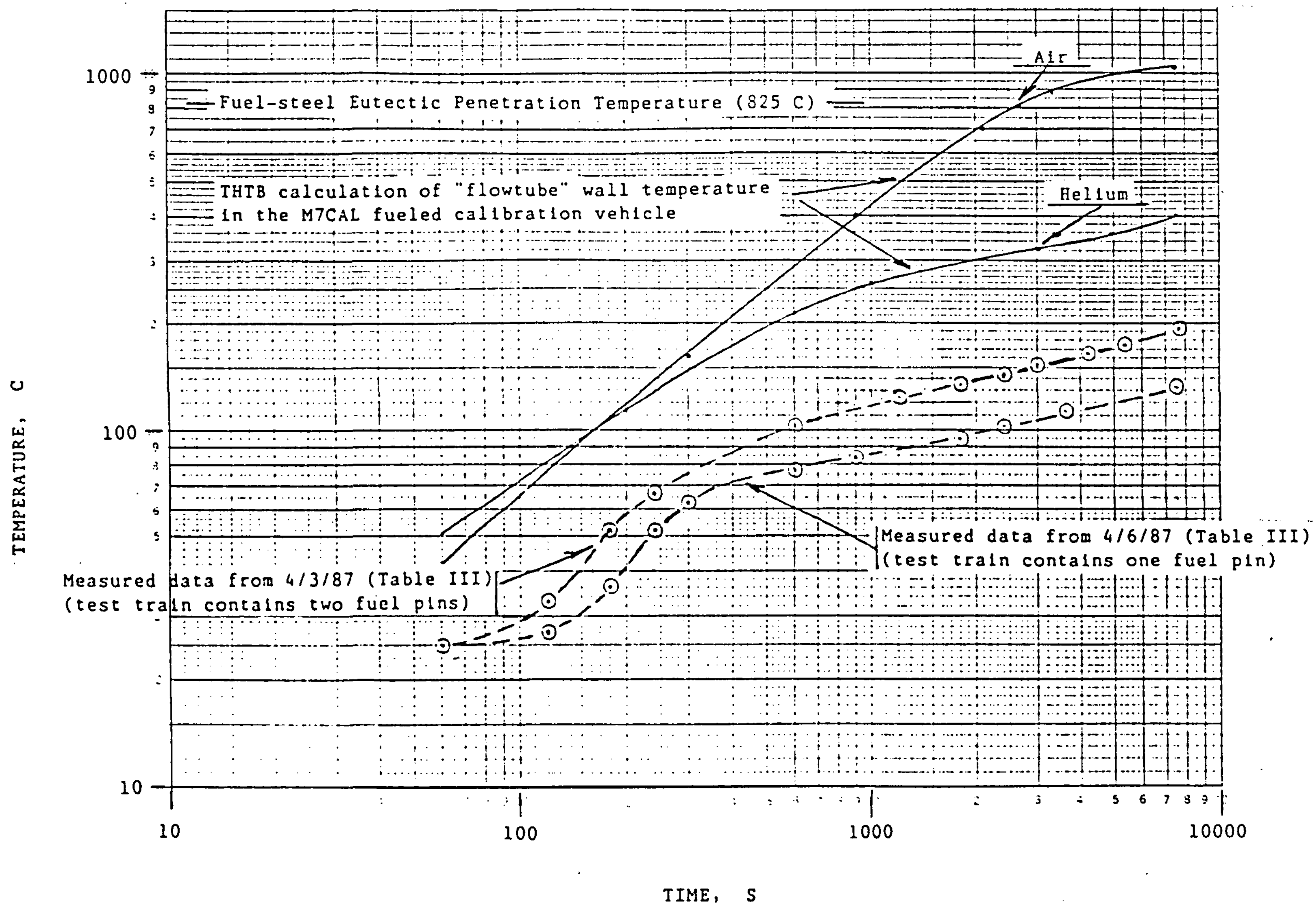


Fig. 4. Computed and Measured Temperature Histories

calculation (Ref. 7). For the calculations a conservative power coupling factor of 6.0 was assumed. Flow/shield tube temperatures during the experiment were kept far below the eutectic temperature for U/Pu/Zr fuel and stainless steel which is given as 825°C (Ref. 8).

Flux monitor wires were also loaded at TREAT. The wires were loaded into the unfueled test train and then the train was loaded into the test section.

Control of TREAT low-power irradiations and high-power transients are accomplished using both an inner ring and an outer ring of rods (Fig. 5). The inner ring contains three pneumatic control rods and one hydraulic rod pair, (T-1). The outer ring contains three pneumatic control rods and one hydraulic rod pair, (T-2). The length of poison material in both rod types is identical. When the hydraulic rods indicate 0.0 in., the pneumatic rods must be set at 13.5 in. (34.3 cm) to be at the same elevation relative to the TREAT core.

For the LLSS fuel-pin and wire irradiations, the entire inner ring of rods was fully withdrawn and the entire outer ring of rods banked and raised during the irradiation to maintain a constant power level. The low-level linear power meter was used to establish the specified power level. For transient operation, the inner pneumatic rods were always fully withdrawn, the outer pneumatic rods banked and the two hydraulic rods used to accomplish the desired transient.

An accurate average power level was obtained for the two wire irradiations and the two fuel pin irradiations that contained two fresh pins by digitizing the power trace and performing numerical integration.

Special shielding was constructed at TREAT to handle the fuel pins and test hardware between irradiations. Examples of radiation levels encountered during the experiment were 1) fuel pin T-433, 18 hours after the last of six irradiations in the full-slotted core loading had an activity greater than 20 R/hr at two inches, 2) at the same time the activity of the fuel pin holder itself was 3 R/hr at two inches and 3) nine days later pin T-433 emitted 6 R/hr at two inches.

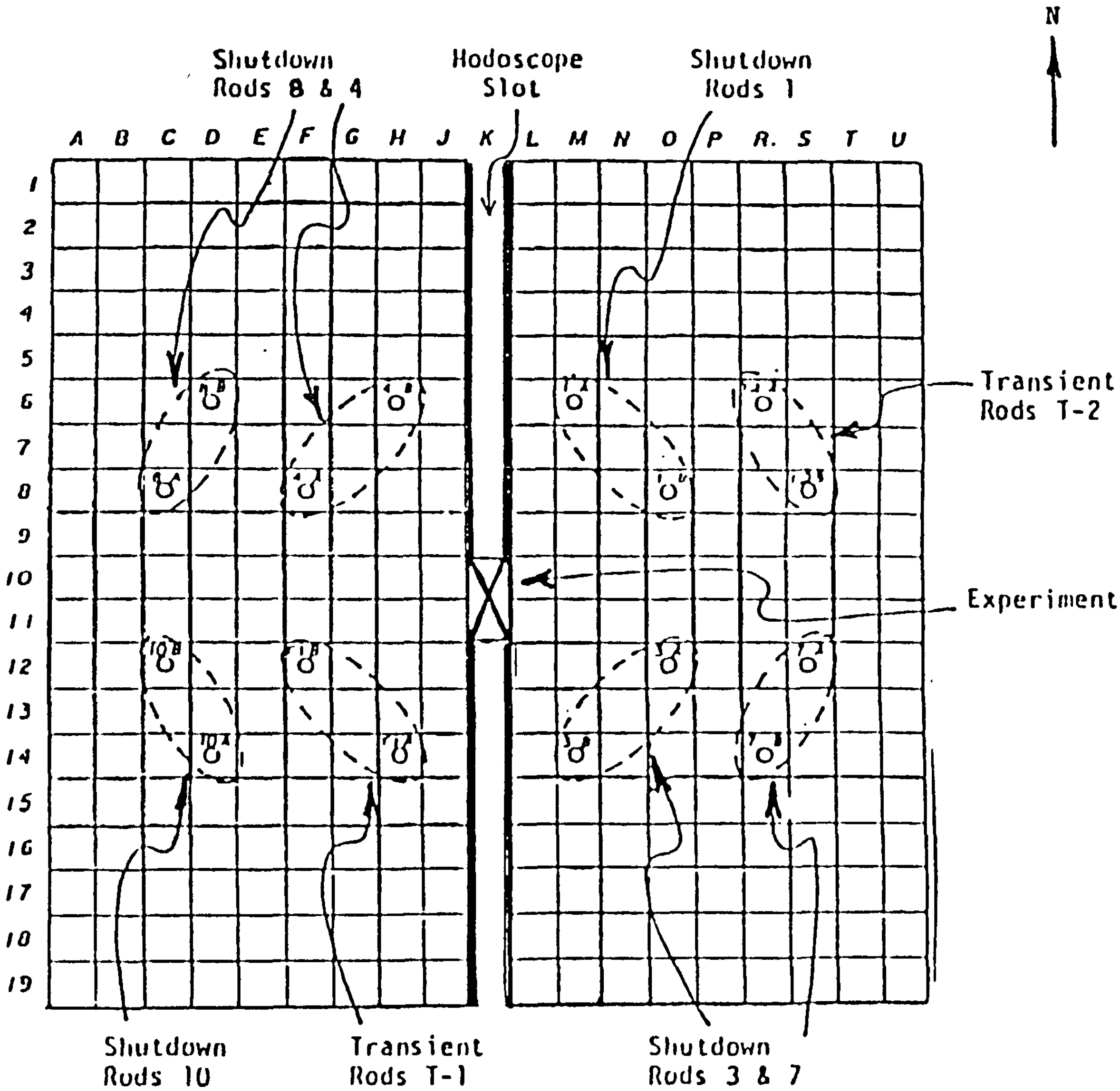


Fig. 5. TREAT Reactor Core - Plan View showing Full-slotted Core Configuration

3.2 HFEF Operations

The amount of radioactivity and the potential for the release of fission products from the 2.9 at. % burnup, preirradiated, fuel pin (used in TREAT irradiation identification number 13) precluded its handling at TREAT. Consequently this pin along with the one fresh pin for that irradiation were loaded into the test train, and the train into the vehicle, at HFEF. The vehicle was then transferred to TREAT. After irradiation number 13, the vehicle was transferred back to HFEF for unloading.

3.3 ANL-W Radiochemistry Operations

Radiochemical measurements were performed on two flux monitor wires and four fuel pins (Ref. 9).

3.3.1 Flux monitor wires

The wires were removed from the stainless steel sheath and cut into approximately one-half inch long increments beginning at the top of the wire. Each segment was weighed and gamma counted to determine its relative activity. Three segments from each wire were dissolved and counted for La-140 activity to determine the absolute number of fissions per gram.

3.3.2 Fuel pins

Each of the four fuel pins were gamma scanned to determine the top and bottom of the active fuel column within the stainless steel cladding. The fuel cladding was cut at the junction between the spade end plug and the fuel column. The upper end was also cut to allow the sodium to more readily flow out of the cladding upon heating. The fuel slug was removed from the cladding and the sodium dissolved in butyl cellosolve. Beginning at the bottom, the slug was then sheared into approximately one-half inch long segments and each segment identified and weighed. All segments were gamma counted to determine their relative activity and three segments were selected to be dissolved and counted for absolute fissions.

3.4 Analysis and Results

Experimental results from both fuel and monitor wire measurements are presented in Sections 4, 5, and 6 to follow. Section 4 describes the determination of the axial-power profile and, in particular, axial-peak values near the centerline of the TREAT core. Further analyses of power coupling in Sections 5 and 6 refer chiefly to axial peak values. Section 5 compares calculations and measurements of the relative power couplings of the three different fuel types and two different core loadings. Section 6 describes in some detail the corrections and methods for obtaining power coupling factors for use in experimental analysis.

Tables III-VI summarize principal results of expriments and analyses of axial peak power couplings. In particular Table V provides a comprehensive summary of results of all M-series calibration irradiations, at both low and high power, performed with fuel and monitor wires.

4. AXIAL AND RADIAL POWER DISTRIBUTIONS

4.1 Axial Power Profiles

Axial power profiles were obtained by gamma counting the relative fission product activity from the two segmented monitor wires, the two segmented U/Zr fuel pins and the two segmented U/Pu/Zr fuel pins. The count rate per gram of wire or fuel segment was determined for each segment, and the values were normalized to unity at the axial peak of a polynomial fit performed over the central 7.5 in (19.1 cm) high region not under the dysprosium shaping collars. This normalization allows for better intercomparison of axial shapes as well as more accurate determinations of power coupling at the axial peak. Distributions from the two wires and from the four fuel pins are shown in Figs. A1-A3 of the Appendix.

In the wire distributions one or two abnormally high points are observed just below the midplane of the distribution. Radiographs of the monitor wire holder within the calibration vehicle show an approximate 0.13 in. (0.33 cm) gap in the 0.015-in. (0.038 cm) thick axial dysprosium filter at about the same axial location (Ref. 1). The gap evidently allowed a local neutron flux peak. Data points from this questionable region are indicated in Fig. A1 and were excluded from the fitting procedure.

The axial distributions from the wires and different fuel types are consistent within a 3% scatter of the data as shown by Figs. 6, 7 and 8. Figure 6 shows the measured normalized axial distributions for U/Fs, U/Pu/Zr and U/Zr fuel in the full-slotted core configuration. The solid curve represents a least squares fit through all the data (not just the region identified earlier used to fit the peak). The U/Fs data is from the M2CAL experiment. Figure 7 compares the same fitted curve to the measured normalized axial distributions for U/Pu/Zr and U/Zr fuel in the half-slotted configuration and Fig. 8 compares the fitted curve to the four LLSS monitor wire distributions in the full-slotted core configuration (from M2CAL, M6, M7CAL and M7). The ratio of axial peak to axial average is 1.095 for the curve shown in Figs. 6, 7 and 8.

4.2 Radial Power Profiles

For completeness, the calculated test fuel radial power profiles from Ref. 10 for both U/Zr and U/Pu/Zr fuel are shown in Fig. 9. The profiles were determined by one-dimensional transport theory using the assumption that the two pins (in the two-pin geometry of metal fuel tests beginning with test M5) were sufficiently separated so that a single pin analysis would be adequate.

5. POWER COUPLING COMPARISON OF METAL FUEL TYPES: CALCULATIONS AND MEASUREMENTS

The peak axial LLSS fresh fuel coupling factors were obtained from the M7CAL irradiations of 4/3 and 4/20/87 in the full-slotted and the half-slotted TREAT core configurations respectively (Table II). The axial peak of the distribution was determined using a polynomial fit to the activity measurements within the central 7.5-inch (19.1 cm) high non-dysprosium filtered axial region.

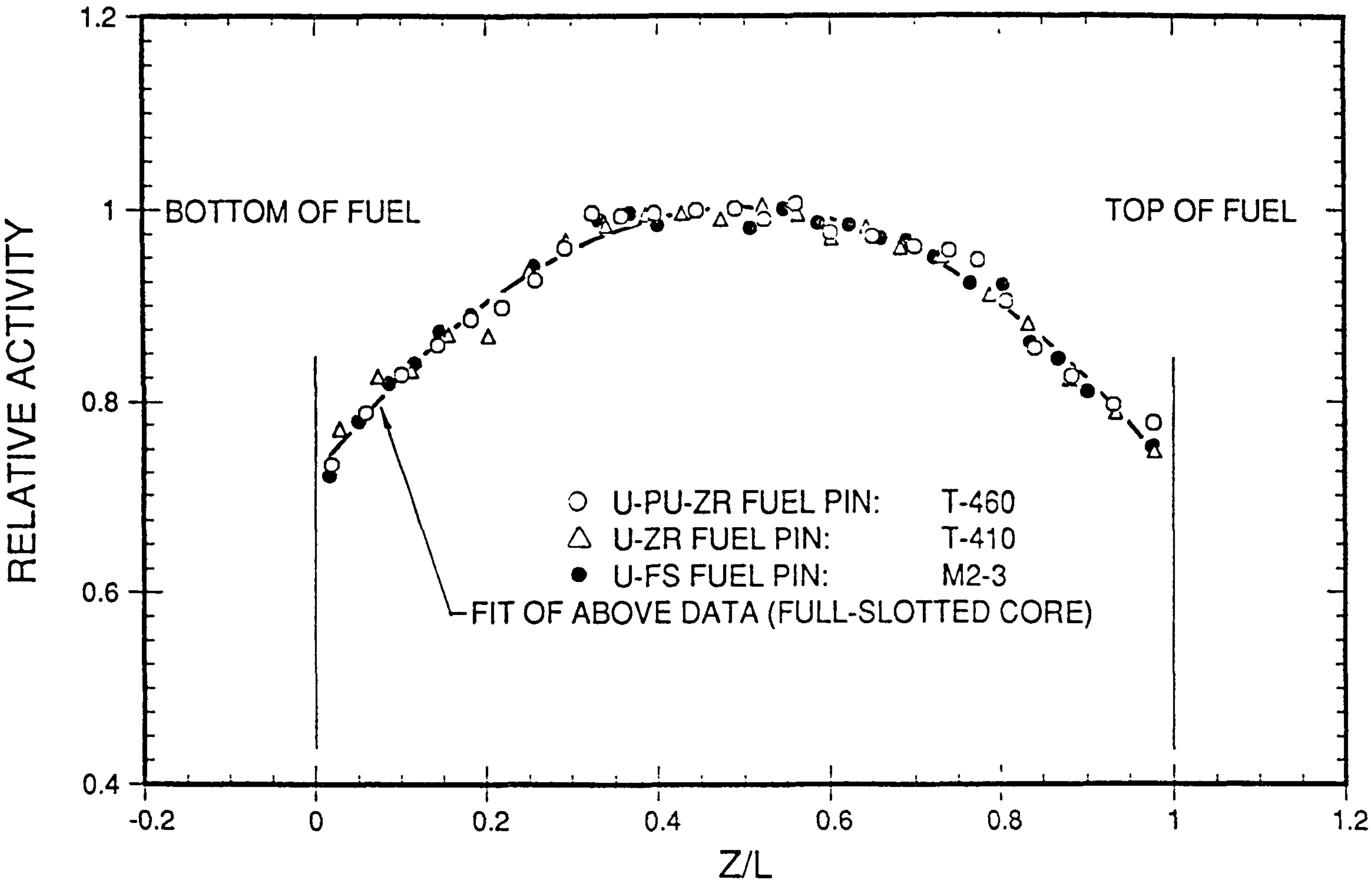


Fig. 6. Measured Axial Power Profiles in the Full-slotted TREAT Core from U-Fs, U-Pu-Zr and U-Zr Fuel Pins

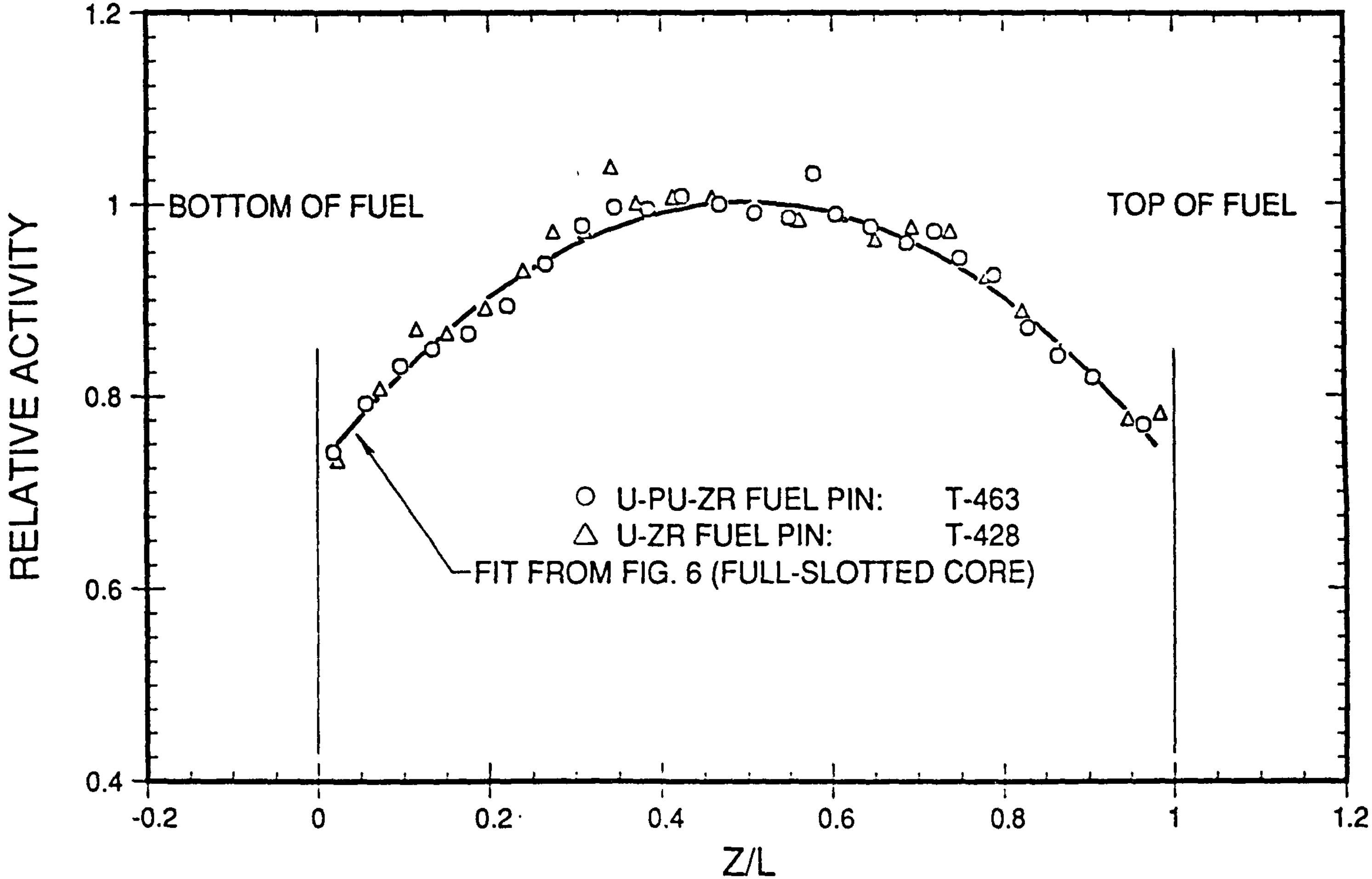


Fig. 7. Measured Axial Power Profiles in the Half-slotted TREAT Core from U-Pu-Zr and U-Zr Fuel Pins

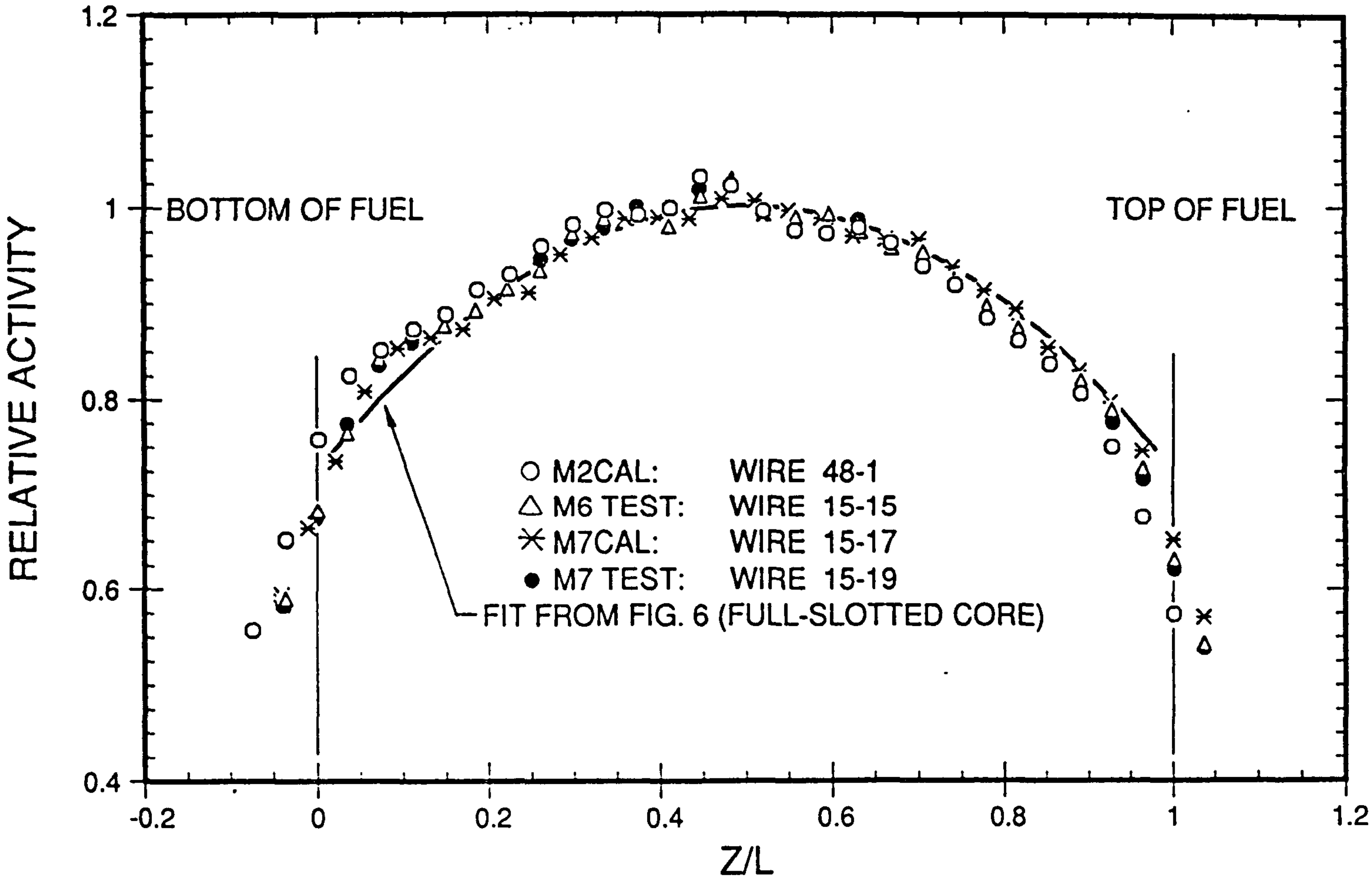


Fig. 8. Measured Axial Power Profiles in the Full-slotted TREAT Core from Flux Monitor Wires

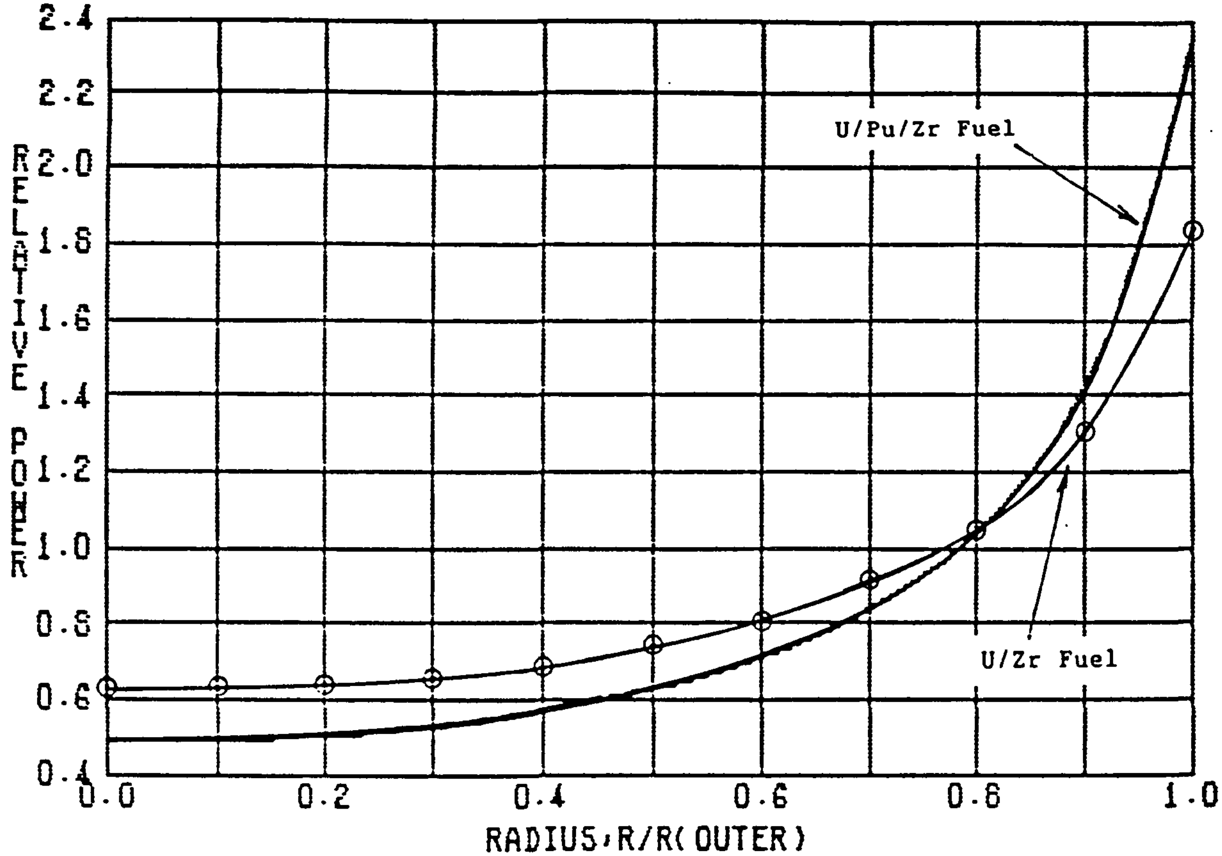


Fig. 9. Calculated Radial Power Profiles for U/Zr and U/Pu/Zr Fuel with 0 at.% Burnup (Reference 10)

This section compares neutronic calculations with measurements of power coupling factors for three different fuel types; U/Fs, U/Pu/Zr and U/Zr. The comparisons are summarized in Table III. Details of the determinations are given below in Sections 5.1 and 5.2.

In general, agreement is good and consistent with quoted levels of uncertainties. The greatest discrepancy exists between U/Fs fuel and U/Pu/Zr fuel where a difference of about 7% is noted.

5.1 Calculations

Reference 10, using a combination of Monte Carlo and one-dimensional transport theory calculations and assuming the same core loading and ion chamber instrument calibration, predicted the steady state power coupling for fresh U/Pu/Zr fuel to be 96% of that for fresh U/Fs fuel. For U/Zr fuel the coupling was calculated to be the same as that of U/Fs. The coupling values were given a one-sigma statistical uncertainty of 3.5%.

Monte Carlo calculations provided the ratio of the fresh (unirradiated) two-pin U/Pu/Zr or U/Zr power coupling to that of the three-pin U/Fs power coupling. Transport calculations determined the change in power coupling as a function of irradiation history.

These calculations, however, used parameters (fuel density and radii) from Refs. 11 and 12 which were appropriate to fuel that had swelled out to the inner wall of the cladding. To adjust these as-calculated values to the as-fabricated conditions of the fuel used in the M2CAL and M7CAL irradiations so that comparisons between calculations and measurements could be made, it was necessary to reduce the calculated power couplings for a particular fuel type by the appropriate factor that accounted for the change in pin density and radius between the as-calculated condition and the as-fabricated condition (Ref. 13). Further application of this effect has been made in correcting the test fuel power couplings (Section 6.4). Table IV lists the correction factors for the three fuel types and shows the origins of the relative computed power couplings reported in summary Table III.

Table III. Comparison of Calculated and Measured Power Coupling Factors

	Calculations (approx. +/- 4%)	Measurements (approx. +/- 4%)
1. Comparing fresh U/Fs fuel data from the M2CAL Experiment with fresh U/Pu/Zr and U/Zr fuel data from the M7CAL Experiment:		
U/Fs	1.0 (ref.)	1.0 (ref.)
U/Pu/Zr	0.91	0.85
U/Zr	0.96	0.92
2. Direct fresh fuel comparisons during the M7CAL Experiment:		
U/Zr	1.0 (ref.)	1.0 (ref.)
U/Pu/Zr	0.95	0.92[a] 0.95[b]

[a] Full-slotted TREAT core configuration
[b] Half-slotted TREAT core configuration

Table IV. Calculated Effect of Fuel Density and Radius on Power Coupling

Fuel Type	Density, g/cc[a] In-calculation/As-fabricated	Radius, cm[b] In-calculation/As-fabricated	Computed Power Coupling Correction Factor from the In-calculation to the As-measured M2CAL and M7CAL Conditions	Normalized Relative Computed Power Coupling Factors
U/Fs	13.5 /17.6	0.191 /0.165	$(1.07)^{-1}$	1.0
U/Pu/Zr	11.25 /15.4	0.254 /0.216	$(1.13)^{-1}$	0.91
U/Zr	11.25 /15.4	0.254 /0.216	$(1.12)^{-1}$	0.96

Notes: a) Density of the In-calculation U/Pu/Zr and U/Zr fuel supplied by Ref. 9, that of U/Fs fuel supplied by Ref. 10.

b) Radius of the In-calculation U/Pu/Zr and U/Zr fuel supplied by Ref. 9, that of U/Fs fuel supplied by Ref 10.

5.2 Measurements

Specifics of the various irradiations are given in Table V. From the irradiation of three U/Fs fuel pins in the full-slotted core configuration on 10/2/84, (M2CAL experiment) the average absolute, peak-axial, LLSS, fresh fuel fissions/gram value was 7.77E12 fissions/gram from a TREAT energy release of 36 MJ or 2.16E11 fissions/gram/MJ.

From the irradiation in the full-slotted core configuration on 4/3/87, (M7CAL experiment) the absolute, peak-axial, LLSS, fresh fuel fissions/gram value from U-19Pu-10Zr fuel pin T-460 was 105.8E12 fissions/gram for a TREAT energy release of 592 MJ or 1.79E11 fissions/gram/MJ.

In using these results, it is preferable to compare fuel fissions to wire fissions rather than fuel fissions to TREAT MJ. This takes account of any shift in the calibration of the low-level power meter.

The LLSS wire irradiation during M2CAL (9/17/84) is compared to that from M7CAL (3/31/87). From M2CAL, 9.00E12 fissions/gram from a TREAT energy release of 540 MJ (90 kW for 100 minutes) or 1.67E10 fissions/gram/MJ; from M7CAL, 9.17E12 fissions/gram from a TREAT energy release of 562 MJ (78 kW for 120 minutes) or 1.63E10 fissions/gram/MJ. Therefore in order to compare measurements made in M7CAL with those made in M2CAL, the M7CAL values will be increased by 2.4%.

The measured comparison between U/Pu/Zr fuel and U/Zr fuel is therefore (1.024)(1.79E11) fissions/gm/MJ compared to 2.16E11 fissions/gm/MJ. The measured U/Pu/Zr coupling factor is therefore 0.85 times that of the U/Fs fuel.

From the same 4/3/87 irradiation the absolute, peak, axial, LLSS, fresh fuel fissions/gram value from U-10Zr fuel pin T-410 was 114.8E12 fissions/gram from a TREAT energy release of 592 MJ or 1.94E11 fissions/gram/MJ. The measured comparison between U/Zr fuel and U/Fs fuel is therefore (1.024)(1.94E11) fissions/gm/MJ compared to 2.16E11 fissions/gram/MJ. The U/Zr coupling factor is thus 0.92 times that of the U/Fs fuel.

Direct comparisons may be made between U/Pu/Zr fuel and U/Zr fuel using data from the LLSS fuel irradiations of 4/3 and 4/20/87 in the full-slotted

Table V. Summary of M-series Fuel and Monitor Wire Irradiations

TREAT Test (Fuel)	Date	Treat Transient Number	Monitor Wire or (Fuel Element) Identification	Energy (MJ)	Peak Absolute Activity (f/gram XE12)	T1 (cm)	T2 (cm)	RB (cm)	TCF	TCF-Fit	Notes*
M2CAL	9/14/84	2576	----	1390							(1,15)
(U/Fs)	9/17	LLSS	48- 1	540	9.00						(12)
	9/18	2577	48- 2	543	8.78	44.3	70.2	70.8	0.97	0.947	(2,15)
	9/19	2578	----	1498							(3,15)
	9/20	2579	48- 3	1488	22.91	42.1	78.8	115.6	0.92	0.919	(3,15)
	9/21	2580	48- 4	206	3.02	21.6	32.8	115.6	0.88	0.850	(3,15)
	9/24	2581	48- 5	408	5.97	20.9	44.0	115.6	0.88	0.864	(3,15)
	9/25	2582	48- 6	812	12.39	23.3	64.6	115.6	0.92	0.892	(3,15)
	9/26	2583	48- 7	1117	17.16	30.3	73.1	115.6	0.92	0.906	(3,15)
	10/ 2	LLSS	(M2-1: U-5Fs)	36	7.66						
			(M2-2: U-5Fs)		7.90	Average = 7.77					(13)
			(M2-3: U-5Fs)		7.76						
M2	3/11/85	2591	48- 8	549	8.63	46.4	67.9	70.8	0.94	0.945	(4,15)
(U/Fs)	3/13	2592	48- 9	1080	16.08	28.3	68.8	115.6	0.89	0.900	(5,15,16)
	3/14	2593	48-10	1219	17.98	32.4	71.2	115.6	0.89	0.904	(5,15,16)
	3/14	2594	----	1494							(5,15,16)
M3 (U/Fs)	4/ 5	2597	48-11	1147	17.48	30.1	65.7	115.6	0.91	0.896	(5,15,16)
M4	12/18	2676	15- 2	548	8.45	50.1	69.3	70.8	0.93	0.948	(6,15)
(U/Fs)	12/19	2677	15- 3	1469	23.05	43.5	71.6	115.6	0.94	0.910	(7,15,16)
	1/ 3/86	2678	15- 4	959	14.21	26.8	63.9	115.6	0.89	0.893	(7,15,16)
	1/ 6	2679	15- 5	1123	16.48	31.6	66.8	115.6	0.88	0.898	(7,15,16)
	1/ 7	2680	15- 6								(7,15,16)
	1/ 8	2681	15- 7	1398	20.62	40.5	71.4	115.6	0.89	0.908	(7,15,16)
M5	7/21	2704	15- 8	1505							(8,15,16)
(U/Pu/Zr)	7/22	2705	15- 9	656							(9,15)
	7/23	2706	15-10	910							(8,15.16)
	7/24	2707	15-11	1211							(8,15,16)
	7/25	2708	15-12	205							(8,15.16)
	7/28	2709	15-13	656	9.14	25.7	54.8	115.6	0.86	0.880	(9,15)
	7/29	2710	15-14	958	13.52	29.1	63.0	115.6	0.87	0.892	(8,15,16)
M6	1/21/87	LLSS	15-15	498	7.91						(12,)
(U/Pu/Zr)	1/22	2728	15-16	1580	23.78	41.0	76.9	115.6	0.92	0.916	(10,15,16,23)
	1/23	2729	8- 2	694	10.01	23.1	55.8	115.6	0.88	0.880	(11,15,16,23)
	1/26	2730	8- 3	408	5.61	22.5	43.1	115.6	0.84	0.864	(11,15)
	1/27	2731	8- 4	980	14.12	21.0	69.2	115.6	0.88	0.897	(10,15,16)
	1/28	2732	8- 5	1147	16.86	26.4	72.1	115.6	0.90	0.903	(10,15,16)

Table V. Summary of M-Series Fuel and Monitor Wire Irradiations (Cont'd)

M7CAL	3/31/87	LLSS	15-17	562	9.17						(12)
(U/Zr)	4/ 3	LLSS	(T-410: U-10Zr)	592	114.8						(13)
(U/Pu/Zr)			(T-460: U-19Pu-10Zr)		105.8						
	4/20	LLSS	(T-428: U-10Zr)	630	131.0						(13)
			(T-463: U-19Pu-10Zr)		124.5						
	4/21	LLSS	15-18	577	9.89						(12)
M7	9/28/87	LLSS	15-19	926	15.45						(12)
(U/Pu/Zr)	9/29	2769	8-1	689	9.74	22.5	56.9	115.6	0.87	0.882	(11,15,22,23)
(U/Zr)	9/30	2770	15-20	1585	23.71	41.0	77.3	115.6	0.92	0.916	(10,15,16,22,23)
	10/ 2	2771	8-6	1016	15.18	22.7	70.6	115.6	0.92	0.899	(10,15,16,22)
	10/ 3	2772	8-7	1198	17.91	27.6	73.3	115.6	0.92	0.905	(10,15,16,22)
		2769		642		22.5	56.9	115.6	0.93	0.946	(22)
		2770		1478		41.0	77.3	115.6	0.98	0.983	(22)
		2771		947		22.7	70.6	115.6	0.98	0.965	(22)
		2772		1117		27.6	73.3	115.6	0.98	0.971	(22)

* Notes 14, 17-21 are applicable to all irradiations.

Table V. Summary of M-Series Fuel and Monitor Wire Irradiations (Cont'd)

Notes:

1) Transient 2576 consisted of a 4 s flattop at about 28 MW followed by a power burst with a 19 s period.

2) Transient 2577 was a heat balance of about 22 MW for about 24 s.

3) Transients 2578 through 2583 consisted of a 4 s flattop at about 28 MW followed by a power burst with a 12 s period.

4) Transient 2591 was a heat balance of about 26 MW for about 21 s.

5) Transients 2592, 2593, 2594 and 2597 consisted of a 1.4 s flattop at about 47 MW followed by a power burst with an 8 s period.

6) Transient 2676 was a heat balance of about 26 MW for about 21 s.

7) Transients 2677 through 2681 contained a "jump in" point of 65 MW (no flattop) followed by an 8 s period. Transient 2680 was terminated in an unplanned mannor and analysis of the flux monitor wire was omitted.

8) Transients 2704, 2706, 2707, 2708 and 2710 contained a "jump in" point of 43 MW followed by an 8 s period.

9) Transients 2705 and 2709 were heat balance transients of about 40 MW for about 16 s.

10) Transients 2728, 2731, 2732 and 2770-2772 contained a "jump in" point of about 75 MW followed by an 8 s period.

11) Transients 2729, 2730 and 2769 were heat balance transients of about 45, 50 and 50 MW respectively.

12) The power levels and time durations for the low-level, steady-state (LLSS) wire irradiations were as follows: during M2CAL (9/17/84), 90 kW for 100 minutes, during M6 (1/21/87), 83 kW for 100 minutes, during M7CAL 3/31/87 and 4/21/87, 80 kW for 120 minutes and during M7 (9/28/87), 80 kW for 193 minutes. During the irradiations the inner control rods were fully withdrawn and the outer rods banked and raised as needed.

13) The power levels and time durations for the LLSS fuel irradiations were: during M2CAL (10/2/84), 24 kW for 25 minutes, and those during M7CAL; on (4/3/87), 80 kW for 125 minutes and on (4/20/87), 77 kW for 137 minutes. During the LLSS irradiations the inner control rods were fully withdrawn and the outer rods banked and raised as needed.

14) All fuel and wire irradiations and all wire transients utilized the M2CAL monitor wire holder except transients 2704 through and including 2708 which inadvertently used the L03 holder. The M2CAL holder has a 15-mil thick dysprosium axial filter whereas the L03 holder has none. Consequently analysis of the flux monitor wires were omitted from transients 2704 through 2708.

Table V. Summary of M-Series Fuel and Monitor Wire Irradiations (Cont'd)

15) The transient rod sequence for all non-heat balance transients was T2 followed by T1. For heat balance transients 2577, 2591 and 2676 transient rod pair T-1 was solely used. For heat balance transients 2705, 2709, 2729, 2730 and 2769 transient rod pair T-2 was the only pair used.

16) All non-heat balance transients beginning with transient 2591 were terminated with a power "shelf" whereby transient rod pairs T-1 and T-2 (T-1 only for transients 2728, 2731, 2732, 2770, 2771 and 2772) were driven in at their maximum rates. All remaining rods were scrammed after a delay of 15 seconds.

17) The transient energy was obtained from the Integral Number 1 Energy Meter. For the LLSS irradiations the low-level power meter was used. The energy of a transient was defined at the time the power went to zero (if a power "shelf" was not present) otherwise the energy was defined at the end of the power "shelf" (see item 16).

18) The monitor wires were cut into half-inch long segments during tests M2CAL, M6 and M7 and into one-inch long segments during all other tests. Except for the wires from M2CAL, all wires were analyzed beginning at the top or tagged end of the wire. The first number in the wire identification indicates the total length of the wire in inches.

19) The normalized peak activity was obtained from a least-squares-fit (using 4 coefficients) of the wire data within the central 7.5-in-high axial unfiltered region (the region devoid of dysprosium shaping collars).

20) Transient Correction Factors (TCFs) for tests involving U-Fs fuel are based on the low-level, steady-state (LLSS) wire data from 9/17/84. TCFs for tests involving U-Pu-Zr and U-Zr fuel are based on the LLSS wire data from 3/31/87.

21) A full-slotted core configuration was in place for all metal fueled tests except during the M7CAL experiment. During the M7CAL experiment, a full-slotted core configuration was in place for the measurements on 3/31 and 4/3/87 and a half-slotted configuration was in place during the measurements on 4/20 and 4/21/87.

22) For test M7, transients 2769 through 2772 are listed twice. The energy and the TCF in the first set have been multiplied by the factor 1.073 to acount for meter renormalization. In the second set the actual energy and measured TCF are listed and the TCF-Fit value has been multiplied by the factor 1.073.

23) Two transients taken during the M6 test (2723 and 2729) were repeated prior to test M7 (2769 and 2770) respectively. The repeated transients were nearly identical in rod motion, core temperature and measured monitor wire fissions.

and the half-slotted core configurations respectively during the M7CAL experiment.

Full-slotted core: (4/3/87) U/Pu/Zr = 105.8E12 and U/Zr = 114.8E12 fissions/gram, hence the measured U/Pu/Zr coupling is 0.92 times that of U/Zr.

Half-slotted core: (4/20/87) U/Pu/Zr = 124.5E12 and U/Zr = 131.0E12 fissions/gram, hence the measured U/Pu/Zr coupling is 0.95 times that of U/Zr.

Expressing these results to highlight differences in core configuration, we find:

For U/Zr fuel: 2.08E11 fissions/gram/MJ in the half-slotted core (4/20/87 irradiation) and 1.94E11 fissions/gram/MJ in the full-slotted core, thus a reduction of 7% in the power coupling from the half to the full-slotted core.

For U/Pu/Zr fuel: 1.98E11 fissions/gram/MJ in the half-slotted core and 1.79E11 fissions/gram/MJ in the full-slotted core or a reduction of 10%.

The LLSS wire irradiation in the half-slotted core configuration (4/21/87) yielded an axial peak fissions/gram/MJ value of 1.71E10 which was about 5% greater than the 1.63E10 value from the full-slotted core configuration (3/31/87).

6. AXIAL PEAK POWER COUPLING FACTORS FOR M5-M7

Power coupling factors for the M-series tests were obtained by first measuring the peak axial, low-level steady-state (LLSS), fresh fuel power coupling factor and then applying measured and calculated correction factors. This section describes in detail the steps taken to obtain a power coupling factor. Table VI lists the fresh fuel coupling factors and the measured and calculated correction factors that were used to obtain the power coupling factors for the test fuel in tests M5, M6 and M7.

6.1 Peak Axial, Low-level Steady-state (LLSS), Fresh Fuel Power Coupling Factors

For each fuel type, the peak axial, absolute fissions/gram per MJ value from Section 5.2 was multiplied by the appropriate Joules/fission conversion factor (Ref. 14 taking into account the fuel composition) to obtain 4.91 and 5.27 J/g-TREAT MJ for U/Pu/Zr and U/Zr fuel respectively.

An additional 0.03 W/g-MW was added due to gamma-heating making the total peak axial, LLSS, fresh fuel power coupling factors 4.94 and 5.30 W/g-TREAT MW.

6.2 Measured Transient Correction Factors

Because the test fuel and TREAT ex-core reactor power meters are physically far removed from one another some dependence of power coupling on rod motion, core temperature, etc. is to be anticipated. The transient correction factor (TCF) relates the time-averaged power coupling of test fuel during a power transient to that which applies at a low-level, steady-state (LLSS) power condition in TREAT. Data for determining TCF's are obtained from U/Zr monitor wires irradiated both with low power and trial transients. The TCF value is found by dividing (a) the coupling of U/Zr monitor wire fissions to reactor energy observed in high power transients by (b) the corresponding coupling for a LLSS irradiation.

The transients used in the M-series TCF database span a wide range of control rod motion and reactor energy. All transients in the database were performed with the same core loading (with full north-south slot) and the same test vehicle (M2CAL calibration vehicle). The database spans about three years with many intermediate core changes between the M-series tests along with changes in the instrument calibrations.

The axial peak absolute wire activity and coupling to reactor energy were obtained by the following procedure:

Table VI. Power Coupling Factors for Tests M5, M6 and M7

Test	Fuel Type (wt. %)	Fuel Pin Burnup (at.%)	Peak Axial, Fresh Fuel, LLSS Coupling Factor (W/g-MW) (approx. +/-4%)	Calculated Burnup Correction Factor	Calculated Fuel Density Change Correction Factor	Peak Axial, LLSS Coupling Factors[a] (W/g-MW)	Measured Transient Correction Factor[b]
M5	U-19Pu-10Zr	0.8	4.94[c]	0.996	1.06	5.22	0.89
	U-19Pu-10Zr	1.9	4.94	0.991	1.13	5.53	0.89
M6	U-19Pu-10Zr	1.9	4.94	0.991	1.13	5.53	0.90
	U-19Pu-10Zr	5.3	4.94	0.973	1.14	5.48	0.90
M7	U-10Zr	2.9	5.30[d]	0.983	1.12	5.84	0.92
	U-19Pu-10Zr	9.8	4.94	0.946	1.13	5.28	0.92

[a] Corrected for isotopic depletion and fuel restructuring due to fuel burnup.

[b] TCF-Fit value from Table V corresponding to the energy release in the final test transient. This multiplicative factor corrects the LLSS coupling factor to that appropriate for the final test transient conditions.

[c] {(105.8E12 fissions/g)(27.5 pJ/fission)/(592 MJ)} + 0.03 W/g-MW = 4.94 W/g-MW
Heat generation per fission value from Ref. 14 accounting for the fuel composition.

[d] {(114.8E12 fissions/g)(27.2 pJ/fission)/(592 MJ)} + 0.03 W/g-MW = 5.30 W/g-MW
Heat generation per fission value from Ref. 14 accounting for the fuel composition.

1) dividing each of the three wire segment determinations of the absolute number of fissions per gram by their respective relative gamma activity (Section 3.3.1) and averaging the three ratios,

2) determining the axial peak relative activity by means of a polynomial fit to the relative gamma activity measurements within the central 7.5-inch (19.1 cm) high non-filtered axial region. (Excluded from these fits were data from the axial location where the gap was inadvertently left in the neutron filter that was placed on the wire holder as mentioned above),

3) multiplying the results from item one by the results from item two. Little axial dependence of the TCF has been noted in past measurements and none is assumed in this report.

Table V summarizes the irradiations and transients, the reactor energies, normalized peak absolute wire activations, averaged rod positions and both the measured and fitted transient correction factors.

Table V lists four LLSS wire irradiations in the full-slotted core configuration: 9/17/84, 1/21/87, 3/31/87 and 9/28/87. The axial peak fissions/gram/TREAT MJ values from these four irradiations were 1.67E10, 1.59E10, 1.63E10 and 1.67E10 respectively. Their consistency attests to the general consistency of LLSS data. Since it is assumed that the ratio of wire fissions to fuel fissions is invariant, to compute a TCF that minimizes effects of meter drift or re-calibration it is optimal to use the LLSS value obtained at the same time as the calibration of fuel and to use the high-power trial transient obtained at the same time as the appropriate experiment. Measured TCF's from M2CAL through M4 were determined using the 9/17/84 M2CAL LLSS value (1.67E10 fissions/gram/TREAT MJ) whereas TCF's for M5, M6 and M7 were determined from the 3/31/87 M7CAL LLSS value (1.63E10 fissions/gram/MJ).

Fitted TCF's (in the next-to-last column in Table V) are calculated from a linear correlation of measured TCF's to the average (power-weighted) positions of rod pair T-1, T-2 and the outer pneumatic rod bank (RB) as given in Table V. (See Section 3.1 for details of relative rod locations.) The inner pneumatic rod bank was always fully withdrawn. Since the transient energy increases as control rods are withdrawn, dependence on reactor energy or core temperature is implicit. The correlation procedure is described in greater detail in Ref. 3, but the fit reported here includes the entire database of M-series monitor wire transients from M2-M7. The calculated standard deviation of an individual, measured TCF from the fit is about 2%, and the random standard error in "TCF-fit" is estimated to be about 1%. If the effect of transient power meter recalibration between M6 and M7 is taken into account*, these fits demonstrate excellent consistency of data.

The fitted TCF values are shown in Table V and are recommended for use with the final M5, M6 and M7 transients. As long as the fits to the database are good, the fitting process minimizes random error and effectively interpolates within the trial transient database.

6.3 Calculated Effect of Isotopic Depletion on Power Coupling

Power coupling is affected by isotopic depletions due to fuel burnup. Calculated corrections were made to account for this effect (Ref. 10). The corrections were made on the basis of depleting fissile isotopes U-235 and Pu-239 by equal amounts until the specified heavy metal loss fraction was achieved. This simple prescription has been verified subsequently by more sophistical analysis (Ref. 15). Because of significant radial neutron flux depression in the test fuel in TREAT's thermal neutron flux, assumptions concerning fuel density and radial distribution of materials are important to these analyses. However, a uniform distribution of isotopes is assumed throughout.

Interpolated isotopic depletion correction factors from the tables of Ref. 10 are listed in Table VI for the specific test fuel pins of M5-M7. Estimated relative uncertainties in these estimates are +/- 0.1% for fuel burnups less than 10 at.% and +/- 1% for fuel burnups greater than 10 at.%

*Identical transients (identical in rod motion, core temperature rise, and measured monitor wire fissions) performed both during M6 and M7 time frames. However, 7% less reactor energy deposition was recorded during M7. Between M6 and M7, a transient meter re-calibration of this magnitude and sign was reported. A 7% increase was, therefore, made to the calculated M7 TCF's.

(Ref. 16). To a good approximation, for every 1 at.% burnup the power coupling is calculated to decrease by 0.5%.

6.4 Calculated Effect of Fuel Density and Radius on Power Coupling

High-swelling IFR metal fuels undergo significant physical change in the first few at.% burnup as fuel expands outward to the inner cladding radius. Even if no axial elongation takes place, the fuel surface area increases by about 18% and the density decreases by about 28% (for fuel initial diameters of 0.170 in. (0.43 cm) as in tests M5-M7). The large neutron flux depression in the fuel implies significant power coupling increases with fuel swelling. Therefore, calculated correction factors were obtained as a function of fuel density and radius (Ref. 13). The tables of Ref. 13 were used to obtain the calculated correction factors for the specific fuel pins used in tests M5, M6 and M7. Two key assumptions were made in these estimates:

1) fuel density and distribution of fissile isotopes are both uniform,

2) axial swelling was ignored because the net effect on whole-pin coupling might be small. It has been estimated that any local coupling factor increase from fuel density being further reduced would be offset by losses due to heavy shielding of any fuel above the nominal fuel height.

The correction factors are listed in Table VI. Uncertainties in these calculated correction factors are difficult to estimate because of the idealized nature of assumptions 1 and 2, above.

7. CONCLUSIONS

M7CAL results extend the base of power coupling measurements to fresh IFR-type U/Pu/Zr and U/Zr fuel. Measured power coupling differences among the fuel types tested, including U/Fs fuel measured in M2CAL, were in general agreement with the expectation from neutronic computations.

New monitor wire data obtained for both LLSS and transients were quite consistent with earlier data. This indicates a consistency in transient and LLSS data from TREAT lasting through several years and multiple core changes.

Correcting measured power couplings for burnup was not simple, largely because such corrections are large and present calculations have used idealized assumptions as to uniformity of pin density and isotopic composition. Further evaluation should be done in this area, including:

1) analysis of hodoscope data directly comparing fresh and irradiated fuel,

2) identification of non-uniformity in density and isotopic composition in fuel of various burnups, and

3) evaluation of the significance of any such nonuniformity to both power coupling and hodoscope data.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. W. R. Robinson, "Power Calibration Experiment for TREAT Test M2," ANL-IFR-8 (April 1985).

2. W. R. Robinson, et al., "IFR Safety Tests M2 and M3 in TREAT: Data and Analysis," ANL-IFR-18 (June 1985).

3. T. H. Bauer, et al., "Update of Safety Testing in TREAT on U-5Fs Fuel: Data from Test M4 and Combined Analyses of Tests M2, M3 and M4," ANL-IFR-69 (May 1987).

4. W. R. Robinson, et al., "Integral Fast Reactor Safety Tests M2 and M3 in TREAT," Trans. Am. Nucl. Soc., 50, 352 (1985). T. H. Bauer, et al., "Behavior of Metallic Uranium-Fissium Fuel in TREAT Transient Overpower Tests," Trans. Am. Nucl. Soc., 53, 306 (1986). W. R. Robinson, et al., "First TREAT Transient Overpower Tests on U-Pu-Zr Fuel: M5 and M6," Trans. Am. Nucl. Soc., 55, 418 (1987).

5. H. J. Myers, unpublished information (1984).

6. G. Klotzkin and R. W. Swanson, unpublished information (1984).

7. W. R. Robinson, unpublished information (1987).

8. B. R. Seidel and L. C. Walters, "Status of Performance and Fabrication of Metallic U-Pu-Zr Fuel for the Integral Fast Reactor," ANL-IFR-1 (November 1984).

9. J. O. Young, R. E. DiFelici, and J. F. Berg, unpublished information (1987).

10. R. W. Swanson and G. Klotzkin, unpublished information (1985).

11. A. E. Wright, unpublished information (1985).

12. A. E. Wright, unpublished information (1984).

13. R. W. Swanson, unpublished information (1987).

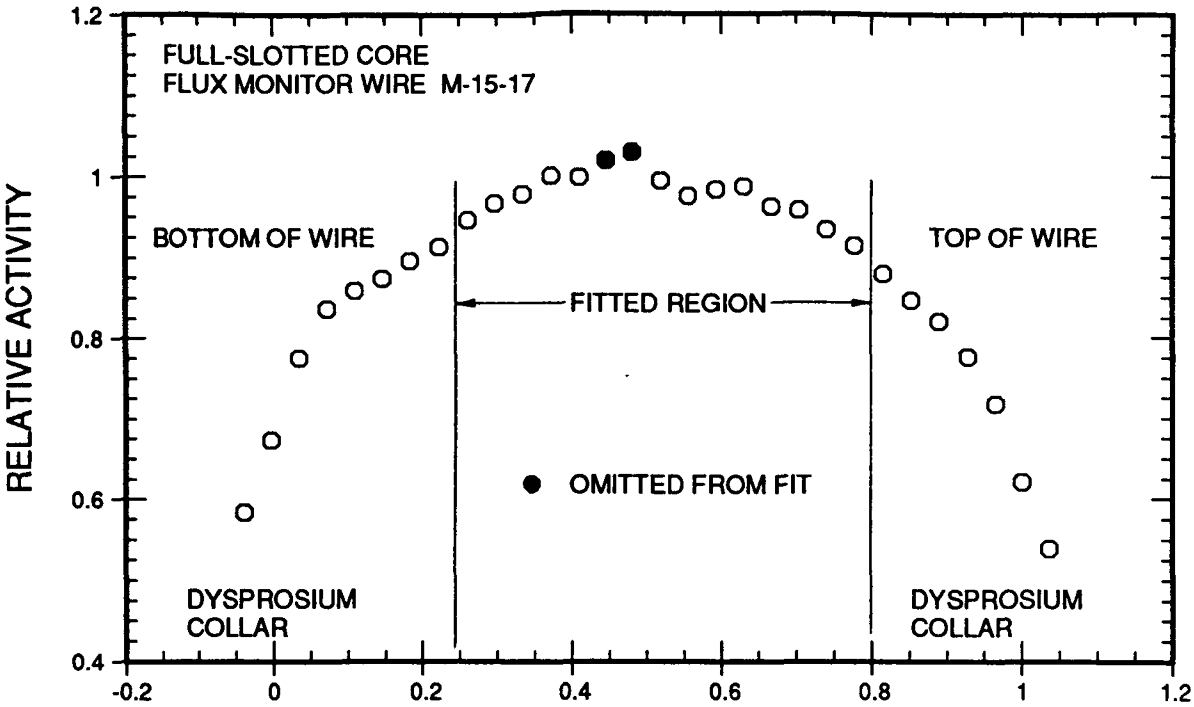
14. T. H. Bauer, unpublished information (1980).

15. R. W. Swanson, unpublished information (1987).

16. R. W. Swanson, private communication (1987).

APPENDIX A

AXIAL POWER PROFILES FROM THE M7CAL POWER CALIBRATION EXPERIMENT



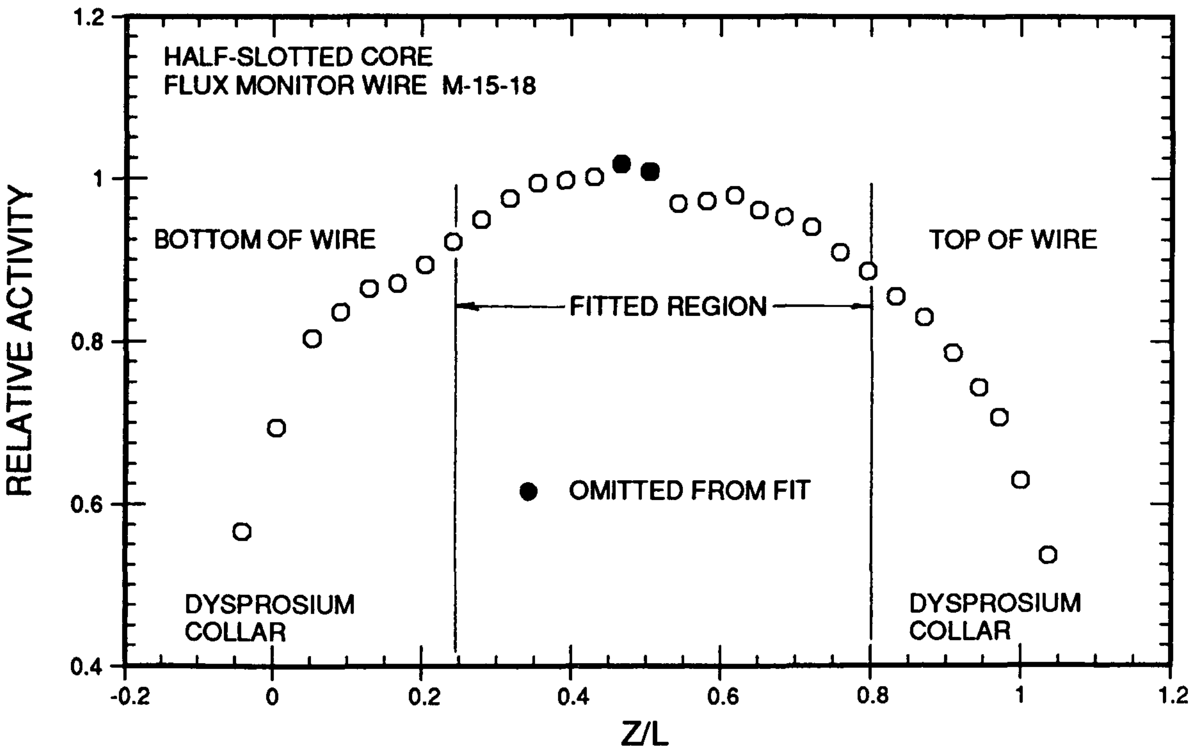
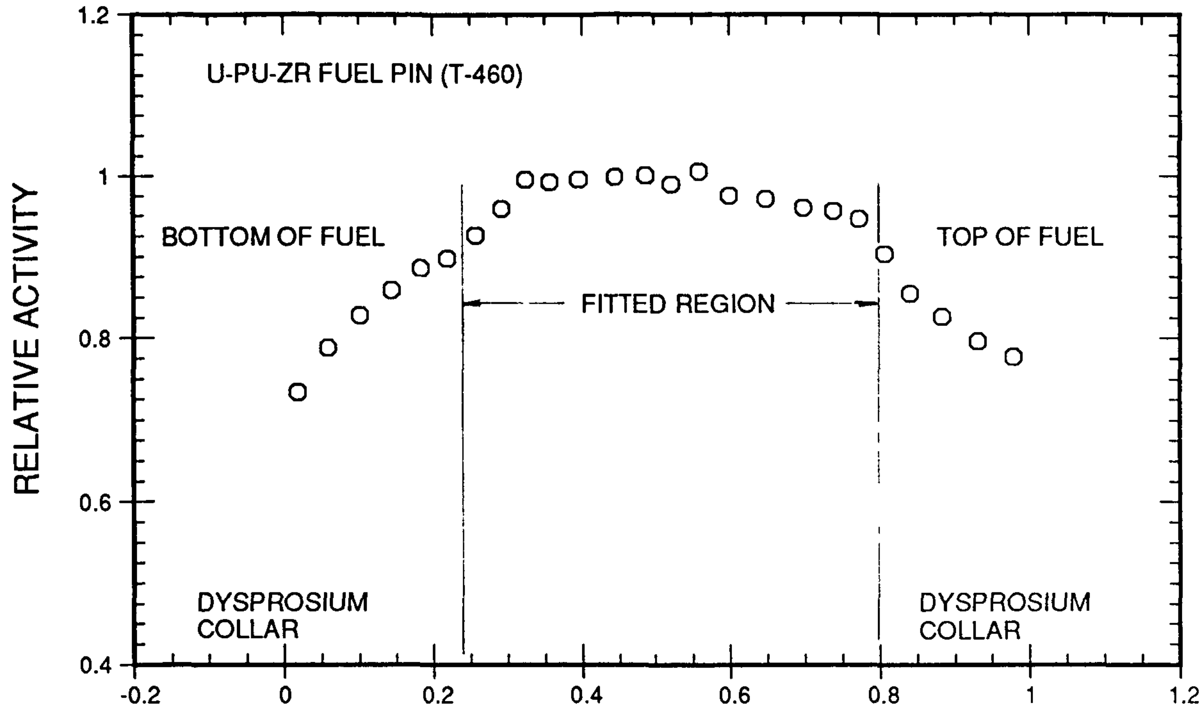


Fig. A1. Measured Axial Power Profiles from Flux Monitor Wires



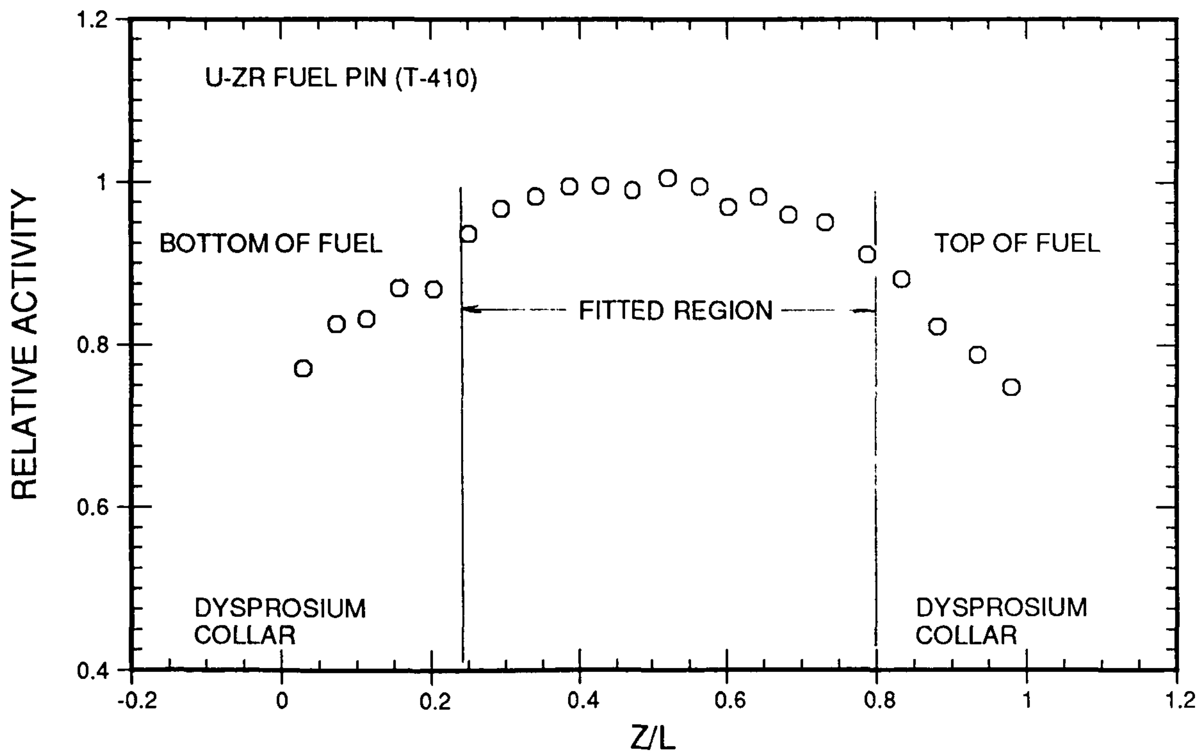


Fig. A2. Measured Axial Power Profiles in the Full-slotted TREAT Core

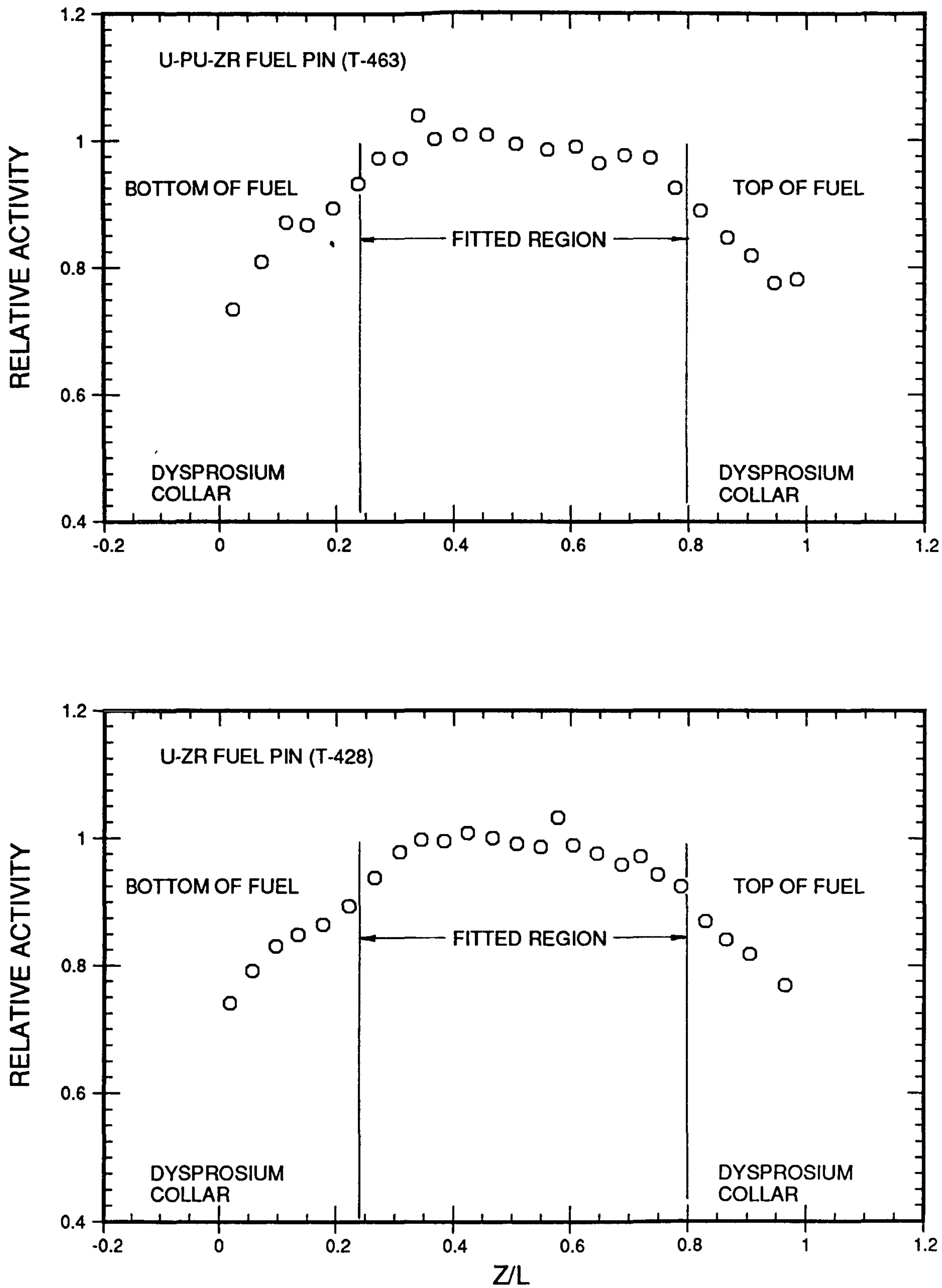


Fig. A3. Measured Axial Power Profiles in the Half-slotted TREAT Core