The M8 Power Calibration Experiment (M8CAL)

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by

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IFR TECHNICAL MEMORANDUM NO. 232

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ABSTRACT

The M8 calibration experiment was a series of 23 irradiations in TREAT performed to determine the relationship between the fission power generated in the TREAT core and the fission power generated in experiment fuel located in an in-core experiment vehicle and irradiated by core neutrons. The experiment was planned to provide the essential calibration information specifically needed for planning and analysis of the M8 test (and subsequent tests similar in geometry to M8) to be performed in the post-upgrade TREAT core.

Irradiations were performed in TREAT cores loaded with a full-slotted (to optimize hodoscope performance) and with a half-slotted (to maximize energy deposition). Tests included a few selected low-power irradiations of fresh IFR-type U-Zr and U-Pu-Zr fuel pins supplemented by multiple irradiations of uranium-zirconium monitor wires ranging from low steady-state power to high-power maximal transients.

This report describes the M8CAL test hardware, measurements, analysis assumptions, and methods used to deduce power coupling between the reactor and experiment fuel--including both absolute magnitudes and axial distributions. Power coupling results are reported for fresh IFR fuel pins under high-power transient test conditions appropriate to the planned M8 transient test. In line with previous calibration data, measured dependence of power coupling on the specifics of each irradiation is also shown to correlate well with the in-core axial locations of the TREAT control rods. Estimates are made for maximal test fuel energy deposition capability in controlled transients.

I. INTRODUCTION

The principal parameter that describes the relationship between the TREAT power and the power in the test sample is the power coupling factor. In convenient units, this factor has units of test-sample power per gram of test sample per unit of TREAT power. The sample fission energy deposition is derived from postirradiation measurement of the fission density in the sample. The TREAT power is measured as a function of time by ion chambers located at the edge of the core. The value of the power coupling factor depends upon several parameters including the composition of the fuel sample, the configuration of fuel assemblies in the core, the configuration of control rods in the core, and the axial locations and movements of the absorbing portion of the control rods during irradiations. During transients the effect of the control rods is time dependent.

The power coupling is determined by first measuring the fission density distribution in fresh fuel irradiated in TREAT under very-low power conditions. Then the result is scaled to the higher-power experiment conditions using measured fission densities in fissile monitor wires irradiated under very-low power and higher-power conditions.

The M8 experimental hardware is virtually identical neutronicallly to that employed previously in experiments M5 through M7. However, upgrade of the TREAT reactor between 1988 and 1990 resulted in significant changes to the neutronic environment within the TREAT core. The M8CAL series of calibration irradiations were all performed after the reactor upgrade. Among important changes to the reactor in the upgrade, the array of transient rods and control/shutdown rods was changed from a two-ring concentric pattern to a single-ring pattern, causing changes in the neutron flux distribution at the experiment location as well as at the location of power and energy instruments at the core edge. Critical positions of the control/shutdown rods and transient rods were also changed.

Since power coupling factors are sensitive to the radial flux distribution in TREAT, they needed to be characterized in the new core. A large database of such calibration information had been developed for the pre-upgrade core configuration.[1-7] "Bridging" data were needed to allow the information obtained using the new core to be analyzed and understood on the basis of the previous database. Calibration runs were included in M8CAL specifically for that purpose.

Irradiations were also included to determine effects on power coupling and transient correction factors from changing the core loading from a full-slotted configuration as used in the M2 through M7 tests (optimizing hodoscope performance) to a half-slotted configuration (maximizing energy deposition) needed for test M8 and later tests. Additional irradiations were included to span transients whose kinetics range between the 8-s-period exponential power transient used in M2 through M7 and longer-period transients planned for M8 and future tests.

The methodology used to determine power couplings was similar to that used in past calibration experiments. Low-power irradiation of fresh fuel in a calibration vehicle is used to directly determine a test fuel-to-reactor power coupling by comparing energy release in the reactor with radiochemically measured fissions in the test fuel. Changes in power coupling due to burnup and swelling in extrapolating from fresh fuel to irradiated test fuel are calculated by neutronic analyses. Further extrapolation of measured power coupling from low-power irradiations to high-power transients are made by comparing fissions measured in a series of monitor-wire irradiations without test fuel present. These extrapolations of power coupling from low-power to transient irradiations assume a constant ratio of fissions in test fuel to fissions in a monitor wire.

The M8CAL irradiations were performed in two campaigns. The first comprising six irradiations in October and November 1990 was performed using a TREAT core loaded with a full-lateral slot through the core in line with the Fast Neutron Hodoscope. The second, comprising 17 irradiations between August 1992 and March 1993, was performed using a half-lateral slot extending only from the hodoscope to the test vehicle. Most of the samples irradiated were enriched-uranium flux monitor wires. Two irradiations each used a pair of fresh fuel pins similar in design to pins that are expected to be used in M8 and later tests. The composition of uranium-zirconium test fuel were included containing 0, 19, and 28 wt.% of plutonium.

The Fast Neutron Hodoscope was operated during many of the irradiations to collect reference information on signal and background strengths as well as neutron scattering effects in the experiment vehicle that will be useful in planning hodoscope operations for M8 and future experiments in the new core. Results from the hodoscope operations will be reported separately.[8]

All fuel irradiations were performed in the half-slotted core. Extrapolation of the results to the full-slotted core was accomplished by neutronic analyses and comparison of monitor-wire irradiations. M8CAL also extends the notion, developed previously, [9] that the transient effects on power coupling may be correlated to control rod position. It is shown that a common correlation adequately describes rod position effects in data taken from both full-slotted and half-slotted TREAT cores.

II. DESCRIPTION OF THE CALIBRATION HARDWARE

A. Calibration Vehicle

Mark-IIIC test vehicles were used for all M-series loop experiments. Accordingly, the M2CAL, M7CAL and the M8CAL experiments were conducted in a neutronic mockup of the Mark-IIIC vehicle (the M2CAL vehicle, Drawing No. RO236-0094). 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, itself, put together with parts taken from previous TREAT test calibration vehicles. A straight spool piece was substituted for the pump leg on the LO4/LO5 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 fabricated and banded in place around the test section of the LO3 calibration vehicle. The modified LO3 calibration vehicle test section was then inserted into the modified LO4/LO5 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 aluminum sleeve and the 0.062-in. (0.157 cm) thick stainless-steel sleeve were added to the Mark-IIIA LO3 calibration vehicle test section to simulate the neutronic effects of the 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

DIMENSIONS IN inches

G1001a

Fig. 1. Axial Dysprosium Shaping Collar Configuration

Fig. 2. Cross-sectional View of the Calibration Test Loop Including the Fueled Calibration Test Train

TABLE I. Radial Dimensions of the Calibration Train and the M8 Test Train

	Calibration Train				M8 Test Train			
	O.D. (in.)	I.D. (in.)	Wall (in.)	Area (in. ²)	O.D. (in.)	I.D. (in.)	Wall (in.)	Area (in. ²)
Outer Tube	1.250	1.120	0.065	0.242	1.375	1.255	0.060	0.248
Shield Tubes Along Fuel Pins	---	---	---	---	0.625	0.585	0.020	0.038
Mockup Tubes Along Fuel Pins	0.375	0.259	0.058	0.058	---	---	---	---
Flowtubes Along Fuel Pins	---	---	---	---	0.348	0.311*	0.0185	0.019
Shield Tubes Below Fuel Pins	---	---	---	---	0.625	0.585	0.020	0.038
Mockup Tubes Below Fuel Pins	0.464	0.334	0.065	0.081	---	---	---	---
Flowtubes Below Fuel Pins	---	---	---	---	0.437	0.367	0.035	0.044
Fuel Pins	0.230				0.230			

* Before dimpling.

Note that the cross-sectional areas between the calibration train and the M8 test train compare favorably:

	<u>Cross-sectional Area (in.²)</u>	
	<u>Calibration Train</u>	<u>M8 Test Train</u>
Outer Tube	0.242	0.248
Shield/Flow Tubes Along Fuel Pins	0.058	0.057
Shield/Flow Tubes Below Fuel Pins	0.081	0.082

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.

The shaping collar configuration, identical to that on the test loops themselves, was selected on the bases of 2D diffusion calculations[10] to produce an axial power distribution that would lie midway between the axial profile of a full-scale reactor (~1.2 peak/average) and the axial profile of the smaller EBR-II core (1.10 peak/average). This was done in the interest of generating a profile that would represent either (or both) profiles reasonably well.

B. Fueled Calibration Train (FCT)

The test train is a removable insert (within the test vehicle) that contains the test fuel pins. For M8CAL, a mockup fueled calibration test train (Drawing No. RO289-0007) with the capability of containing up to two fuel pins in individual flow/shield tubes was used for the fuel pin irradiations (Fig. 2). 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.

The fueled calibration test train was sealed at the top of 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 low-level, steady-state (LLSS) irradiations. After the irradiations the valve was used to sample the plenum gas to test for failed fuel pins (unlikely).

C. Unfueled Calibration Train (UCT)

An unfueled calibration test train was used to position U/Zr flux monitor wires during irradiation. Two U/Zr wire compositions were used: high- and low-enriched uranium (Sect. III.B). The wires were inserted (one in each irradiation) into one of two monitor-wire-holder assemblies (one filtered, Drawing No. RO288-0005, the other unfiltered, Drawing No. RO280-0006).

Both holder assemblies contained a stainless-steel wire sheath of inside diameter 0.072-in. (0.183 cm) which was centered within a 1-in. (2.54 cm) diameter wire holder. The filtered assembly, surrounded by a 0.015-in. (0.038 cm) thick dysprosium filter, was used during irradiations of high-enriched uranium wires primarily to eliminate the possibility of wire melting.

III. DESCRIPTION OF THE CALIBRATION FUEL AND MONITOR WIRES

A. Calibration Fuel

Four fuel pins were required in the experiment. Two of these were used previously in LLSS irradiations during the M7CAL experiment (April 1987): fuel pin T-433, a U-10 wt.% Zr pin and pin T-462, a U-19 wt.% Pu-10 wt.% Zr pin. These two pins (having been in storage for about six years prior to M8CAL) were considered as "fresh" fuel.

The other two pins were "rejects" made for EBR-II subassembly X-489: fuel pin H-307, a U-10 wt.% Zr pin and pin H-316 a U-28 wt.% Pu-10 wt.% Zr pin. (These pins were rejected because of incorrect top end plugs but were quite suitable for use as calibration fuel.[11])

Table II describes the three pins. All pins were fabricated with sodium bonding (Fig. 3). The wire wraps, normally associated with the fuel pins, were removed from the pins for this experiment. The midplane of the active test fuel column was located at the midplane of the TREAT reactor core.

B. Monitor Wires

Nineteen U-Zr flux monitor wires were used in the experiment. Two 8-in. (20.32 cm) long, 0.030-in. (0.076 cm) diameter high-enriched uranium wires were composed of 3.6 wt.% uranium, enriched to 93.1 wt.% U-235. The remaining 17 low-enriched uranium wires were composed of 6.0 wt.% uranium, enriched to 19.8 wt.% U-235. (The Analytical Chemistry Laboratory composition report for the low-enriched uranium wire is included in Appendix A). The low-enriched wires were 0.040 in. (0.102 cm) in diameter and all but one were 8-in. (20.32 cm) long. (The one exception

TABLE II. Nominal Design of the M8CAL Fuel Elements

<u>Parameters Common to All Elements</u>	
Element Diameter	0.230 in. (5.84 mm)
Cladding Thickness	0.015 in. (0.38 mm)
Length of Cladding	28.8 in. (732 mm)
Overall Element Length	29.5 in. (749 mm)
Fuel Slug Diameter	0.173 in. (4.39 mm)
Fuel Slug Density	15.8 g/cc (100% Theoretical Density)
Fuel-Cladding Diametral Gap	0.027 in. (0.69 mm)
Planar Fuel Smear Density	75%
Fuel Column Height	13.5 in. (343 mm)
Upper or Lower Blanket	None
Fuel-cladding Bond	Sodium
Nominal Bond (BOL* at room temp.)	0.25 in. above fuel
Plenum Length (BOL at room temp.)	14.7 in. (373 mm)
Plenum-to-Fuel Volume Ratio (BOL)	1.5
Plenum Gas	75% He + 25% Ar
Spacer Wire Diameter	0.042 in. (1.067 mm)
Wire Material	HT9
Pitch-to-diameter Ratio	1.28
Axial wire-wrap Pitch	6 in. (152 mm)
Pitch Orientation	Clockwise

Specific Differences Among the Elements

	Fuel Element Composition: wt.% (g)					
	T-433		T-462		H-316	
Fuel:	U-10 wt.% Zr		U-19 wt.% Pu-10 wt.% Zr		U-28 wt.% Pu-10 wt.% Zr	
Uranium:	89.66*	(69.98)	70.71*	(55.31)	61.98*	(50.19)
U-234	0.63	(0.44)	0.56	(0.31)	0.49	(0.25)
U-235	65.50*	(47.94)	56.88*	(31.46)	46.08*	(23.13)
U-236	0.37	(0.26)	0.32	(0.18)	0.24	(0.12)
U-238	30.50	(21.34)	42.24	(23.36)	53.26	(26.73)
Plutonium:	N/A		19.07*	(14.91)	28.02*	(22.69)
Pu-239	N/A		93.84*	(14.00)	87.26*	(19.80)
Pu-240	N/A		5.82	(0.87)	11.81	(2.68)
Pu-241	N/A		0.29	(0.04)	0.75	(0.17)
Pu-242	N/A		0.05	(0.007)	0.22	(0.05)
Zirconium	9.70*	(7.57)	9.78*	(7.65)	10.00*	(8.10)
Cladding:	HT9		HT9		HT9M	

* Reference 12.

Fig. 3. IFR Reference Metal Alloy Fuel Pin

was 60-in. (152.4 cm) long.) The high-enrichment wires contained about 0.022 g of U-235, and the low-enriched wires contained about 2 mg of U-235 per inch of wire.

Designation tags, attached to a loop at the top of the wire, were used to distinguish one wire from another (Fig. 4). Wire identifications (shown in Table III) are of the form e91-L-n, where e is the enrichment level (High or Low), L is the active length in inches, and n is the number in the series.

IV. EXPERIMENTAL PROCEDURE

A. Irradiations

1. Reactor Core Loading and Characterization Measurements

In the initial campaign, TREAT was loaded with a full-lateral slot through the core in line with the Fast Neutron Hodoscope. Figure 5 shows the Fueled Calibration Vehicle at the core

NOTE:
ALL DIMENSIONS IN inches

G10019

Fig. 4. Typical Flux Monitor Wire Assembly

G10018

Fig. 5. Cross-sectional View of the Fueled Calibration Vehicle at the TREAT Core Center

TABLE III. Summary of M8CAL TREAT Operations

Core Configuration	TREAT Transient Number	Date of TREAT Operation	Control Rod Configuration	Wire Number	Test Train	Identification	Wire Holder	TREAT Energy, MJ	Hodoscope Operation?
Full-slotted	---	10/16/90 10/17/90	B		Fueled	Low-level, steady-state (LLSS) irradiation providing background signal for the hodoscope (NO FUEL)	---	437	Yes
Full-slotted	---	10/19/90	B	L91-8-10	Unfueled	LLSS	LO3	667	Yes
Full-slotted	2811	10/25/90	B	L91-8-11	Unfueled	Full Heat Balance Transient	LO3	655.4	No
Full-slotted	2812	10/26/90	B	L91-8-12	Unfueled	Heat Balance Transient (Partial)	LO3	404.7	No
Full-slotted	2815	11/14/90	D	L91-8-13	Unfueled	8-s Period Transient	LO3	996.0	Yes
Full-slotted	2816	11/15/90	D	L91-8-14	Unfueled	8-s Period Transient (Partial)	LO3	661.8	No
Half-slotted	---	8/24/92	A	L91-60-1	Unfueled	LLSS	LO3	576	No
Half-slotted	---	8/26/92	A	---	Fueled	LLSS for hodoscope background signal measurement (NO FUEL)	---	---	Yes
Half-slotted	2858	8/31/92	C	L91-8-2	Unfueled	Heat Balance Transient (Partial)	LO3	423.1	No
Half-slotted	2862	9/23/92	C	L91-8-3	Unfueled	Full Heat Balance Transient	LO3	655.0	Yes
Half-slotted	2864	10/14/92	D	L91-8-4	Unfueled	8-s Period Transient	LO3	1868.4	Yes
Half-slotted	2867	10/27/92	D	L91-8-7	Unfueled	30-s Period Transient	LO3	1956.7	Yes
Half-slotted	2868	10/29/92	C	L91-8-8	Unfueled	30-s Period Transient (Partial)	LO3	1198.6	No
Half-slotted	2869	10/30/92	C	L91-8-9	Unfueled	30-s Period Transient (Partial)	LO3	602.1	No
Half-slotted	2871	11/10/92	D	L91-8-15	Unfueled	30-s Period Transient (with power roll-over)	LO3	1999.8	No
Half-slotted	2873	11/19/92	D	L91-8-5	Unfueled	80-s Period Transient	LO3	1797.8	Yes
Half-slotted	---	11/20/92	A	L91-8-1	Unfueled	LLSS	LO3	576	Yes
Half-slotted	---	1/29/93	A	T-433 T-462	Fueled	LLSS	---	480	Yes
Half-slotted	---	2/8/93	A	L91-8-6	Unfueled	LLSS	LO3	480	Yes
Half-slotted	---	2/12/93	A	H91-8-1	Unfueled	LLSS	M2CAL	576	No
Half-slotted	2874	2/17/93	D	H91-8-2	Unfueled	8-s Period Transient	M2CAL	1807.1	No
Half-slotted	---	3/2/93	B	L91-8-16	Unfueled	LLSS	LO3	576	Yes
Half-slotted	---	3/5/93	A	H-316 H-307	Fueled	LLSS	---	480	Yes

Notes to Table III are given on the following page.

Notes for Table III:

Control-rod Configurations:

Full-slotted:

- (B) Compensation and control/shutdown rods fully withdrawn,
Transient rods banked at approximately 18.5-in. and withdrawn as needed,
Termination with all-rod shutdown.
- (D) Compensation and control/shutdown rods fully withdrawn,
Transient rods banked at approximately 18.5-in. and withdrawn as needed,
Transient termination with "clip:" transient rods fully inserted, and remaining rods inserted 15 s later.

Half-slotted:

- (A) Compensation rods fully withdrawn,
Control/shutdown rods banked at approximately 22-in. and withdrawn as needed.
Transient rods withdrawn to approximately 40-in.,
- (B) Compensation rods fully withdrawn,
Control/shutdown rods withdrawn to approximately 48-in.,
Transient rods banked at approximately 11.5-in. and withdrawn as needed.
- (C) Compensation rods fully withdrawn,
Control/shutdown rods withdrawn to approximately 48-in.,
Transient rods banked at approximately 11.5-in. and withdrawn as needed,
Termination with all rod shutdown.
- (D) Compensation rods fully withdrawn,
Control/shutdown rods withdrawn to approximately 48-in.,
Transient rods banked at approximately 11.5-in. and withdrawn as needed,
Transient termination with "clip:" transient rods fully inserted, and remaining rods inserted 15 s later.

center. Measurements with this full-slotted core configuration were performed during October and November 1990. Following these measurements, the M8CAL Experiment was interrupted. Measurements were resumed in August 1992 in a second campaign with a TREAT core loaded with a half-slotted (slot facing toward the north). Table III summarizes the M8CAL irradiations.

In the full-slotted core loading, the calibration vehicle was loaded at the core center with dummy half-width slotted elements loaded on either side of the vehicle. In the half-slotted configuration the vehicle was again centered in the core and a half-width dummy element was placed immediately south of the vehicle. In both cores the 48 in. (121.9 cm) high Fast Neutron Hodoscope was positioned on the north face of the reactor.

Both the full- and half-slotted core configuration were "characterized" by performing the following series of tests and measurements: 1) determination of the reactor control-rod worths, 2) a reactor heat-balance test, and 3) several temperature-limited transients. (Temperature-limited transients define the maximum reactivity of the core and establish limiting safety system settings and safety limits for the core loading.) Results of the temperature-limited transients for the half-slotted core configuration (Transients 2855, 2856, and 2857) are shown in Table IV.

There are three types of reactor control rods (Fig. 6): 1) four single pneumatic compensation rods in the inner ring (during any LLSS or transient operation these are always removed from the core), 2) four pairs of pneumatic control/shutdown rods in the outer ring, and 3) four pairs of hydraulic transient rods in the outer ring. In the automatic mode (as opposed to the steady-state mode) the reactor is controlled by computer operation of the transient rods which are ganged together. (The transient rods are the only computer driven rods.) Reactivity worths of the transient and control/shutdown rods are shown in Figs. 7 and 8.[13] The total worth of the transient and control/shutdown rods in the full-slotted core are 9.02 and 7.77% respectively. Those in the half-slotted core are 8.46 and 8.83% respectively. Control-rod-poison-section locations for the control/shutdown and the transient rods are shown in Fig. 9. For the two sets of rods to be at the same elevation relative to the TREAT core, when the transient rods indicate 0.0 in. withdrawn, the control/shutdown rods must indicate a withdrawal height of 13.5 in. (34.3 cm). The maximum reactivity for experimental use is 5.8% $\Delta k/k$. Table IV shows the critical rod positions and the excess core reactivity for the two cores.

Fig. 6. Configuration of Control Rods and Instrumentation in the Half-slotted TREAT Core

TABLE IV. M8CAL Full- and Half-slotted Core Characterizations

Full-slotted Core Configuration:

Critical Control Rod Position and (Core Excess Reactivity)

	Compensation Rod Position, in.	Control/Shutdown Rod Position, in.	Transient Rod Position, in. (Excess Reactivity)
LLSS for Hodoscope Scan and Wire Irradiation	58.5	58.5	18.5 (4.2%)*

Half-slotted Core Configuration:

Critical Control Rod Position and (Core Excess Reactivity)

	Compensation Rod Position, in.	Control/Shutdown Rod Position, in. (Excess Reactivity)	Transient Rod Position, in. (Excess Reactivity)
LLSS Wire Irradiation	58.5	22.0 (6.55%)	40.0 (0.0)
Heat Balance Transient	58.5	48.7 (0.53%)	11.3 (5.89%)
Heat Balance Transient	58.5	48.9 (0.51%)	11.5 (5.83%)

() indicates reactivity contribution toward total core excess

Temperature Limited Transients**

Nominal Reactivity	Nominal Energy	Compensation Rods	Control/Shutdown Rods	Transient Rods	Total Excess Core Reactivity	Initial Core Temperature (°C)
1.8%	792	58.5	28.72 (4.84%)	26.5 (1.80%)	6.64%	26
3%	1572	58.5	33.05 (3.66%)	21.5 (3.01%)	6.67%	24
3.85%	2265	58.5	36.40 (2.79%)	18.5 (3.84%)	6.63%	25

Fully withdrawn control rod positions, in.: Compensation rods: 58.5
Control/shutdown rods: 58.5
Transient rods: 40

* Total excess reactivity of core. All rods were fully withdrawn except the transient rods which were banked at 18.5 in. The reactivity corresponding to the withdrawal of the transient rods from 18.5 in. to 40 in. is about 4.2% (See Fig. 7).

** Measurements were made with the calibration vehicle (without fuel or wire) at the time of the experiment.

Fig. 7. Transient and Control/Shutdown Rod Worths in the M8CAL Full-slotted Core

Fig. 8. Transient and Control/Shutdown Rod Worths in the M8CAL Half-slotted Core

Fig. 9. TREAT Control Rod Poison Section Locations Relative to the TREAT Core

2. Experiment Operations

a. Neutron Radiography

To confirm the position of the two fuel pins with respect to the dysprosium shaping collars and to determine any misalignment of the fuel pins within the vehicle, two sets of neutron radiographs were taken of the fueled calibration train (loaded with two fuel pins) within the calibration vehicle prior to the first of the two LLSS fuel irradiations. These were performed at the TREAT radiograph facility. One set showed the length of the test section with the vehicle orientated 90° from that viewed by the hodoscope. The other set showed the vehicle as seen by the hodoscope.

The radiographs indicated a clockwise rotation of about 25° relative to the reference orientation shown in Fig. 2. (Hodoscope measurements corroborated this rotation.) Since it was believed that the rotation would not adversely affect M8CAL experimental measurements, no corrective action was taken.

Radiographs of the unfueled calibration train (UCT) were also taken.

b. Low-level, Steady-state (LLSS) Irradiations

Two LLSS fuel irradiations (both in the half-slotted core configuration) and six LLSS wire irradiations were included in the experiment (Table III). Data recorded during each LLSS irradiation included the time at power, the steady-state low-level linear power meter reading, and all compensation, control/shutdown, and transient rod positions. TREAT control-rod configurations for the LLSS irradiations are described in Sect. VII.

(1) Irradiations with Fuel

Two LLSS irradiations were performed in the half-slotted core: one with test pins T-433 and T-462 and one with pins H-307 and H-316 (Sect. III.A). In the first irradiation pin T-462 was loaded into the west "flowtube" (flowtube 1) and pin T-433 was loaded into the east "flowtube" (flowtube 2). In the second irradiation pin H-316 was loaded into flowtube

1 and pin H-307 into flowtube 2. Following the irradiations, pins T-433, T-462, and H-316 were transferred to the ANL-West Analytical Chemistry Laboratory for gamma counting and radioanalyses. (Pin H-307 was used simply to occupy one of the two positions in the two pin fueled calibration test train.)

A TREAT power level of 80 kW was maintained for 100 min (480 MJ) in both fuel irradiations. Similar energy depositions during the M7CAL experiment produced a "flowtube" wall temperature of about 200°C.[4] Prior to the fuel irradiations the volume inside the test section was evacuated and pressurized with 2 atm of helium to enhance the transfer of heat away from the fuel. The eutectic temperature of U-Pu-Zr fuel and stainless steel is given as approximately 750°C. Following each of the two fuel irradiations, the volume inside the test section was checked for xenon-133 activity, the presence of which would indicate fuel cladding failure. None of the pins failed during the M8CAL experiment.

(2) Irradiations with Monitor Wires

One flux monitor wire was used in each of six LLSS irradiations (one in the full-slotted core configuration and five in the half-slotted core). Five of the wires were 8-in. (20.3 cm) long and one was 60-in. (152.4 cm) long. The wires were located in the same position as the test fuel.

In the half-slotted core configuration, for comparison purposes, wires of different uranium enrichment were irradiated under LLSS and again under transient conditions. Both the LLSS and the transient operations used the same control-rod configuration (Table III, Half-slotted Core, Control Rod Configuration A for the LLSS operation and Configuration D for the transient operation). Also in the half-slotted core, for comparison, two low-uranium enrichment wires were irradiated with different TREAT control-rod configurations (Table III, Half-slotted Core, Control Rod Configurations A and B).

c. Transient Operations

One wire was used in each of 13 transients (four in the full-slotted core configuration each with an unfiltered-low-enriched uranium wire and nine in the half-slotted core, eight with an unfiltered-low-enriched uranium wire and one with a filtered-high-enriched uranium wire). Table III summarizes the transient operations.

In the full-slotted core full and partial heat balance and full (maximum energy) and partial power transients were performed. Partial transients have the same shape as the full transient, however they are terminated at some specified intermediate point during the transient after only a portion of the full transient energy has been released. An 8-s reactor period was maintained in the power transients.

In the half-slotted core full and partial heat balance and full and partial power transients (30-s reactor period) were performed. Full power transients having 8-, and 80-s reactor periods were also included as well as one 30-s period transient having a "power roll-over." In the latter transient once full power was attained the transient rods remained fully withdrawn until the power dropped to 105 MW (Fig. B11) at which time the transient was terminated.

d. Hodoscope Operations

The 48 in. (121.9 cm) high TREAT Fast Neutron Hodoscope was positioned on the north face of the reactor. To calibrate (measure the efficiency of) each hodoscope detector and to determine the signal/noise ratio, the hodoscope was operational during several irradiations as listed in Table III.

To enhance the signal/noise ratios in the TREAT half-slotted core configuration a dummy TREAT element rather than a fuel element was located directly behind the calibration vehicle. The dummy element was made of solid graphite with zirconium-alloy cladding.

Results from the hodoscope operations are reported in Ref. 8.

B. Radiochemical Analyses

Radiochemical measurements, described below, were performed on three fuel pins and 19 flux monitor wires.[12]

1. Fuel Samples

Initially each of the three fuel pins: T-433, T-462, and H-316 were gamma scanned to determine the top and bottom of the active fuel column within the stainless-steel cladding. The fuel cladding was then 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 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 1/2 in. (1.27 cm) long segments. Each segment was identified and weighed. All segments were gamma counted to determine their relative activity. Three segments were selected for further analysis of the absolute number of fissions per gram of fuel.

a. Gamma Scan Activity

The intact fuel pins were gamma scanned through a 1/4 in. (0.635 cm) diameter lead collimator, 8 in. (20.3 cm) in depth. The activity was obtained at 1/2 in. (1.27 cm) increments from the bottom or spade end of the fuel pin. The distance from the bottom of the spade to the active fuel column is 0.75 in. (1.91 cm).

b. Relative Activity

The 1/2 in. (1.27 cm) long fuel segments were individually counted for relative activity on a Ge(Li) gamma spectrometer. The estimated error of analysis is +/- 5%.

c. Analysis for Absolute Fission Activity

Selected fuel segments from each pin were dissolved and an aliquot taken for gamma ray analysis. The La^{140} 1.5916 MeV photopeak was counted on a Ge(Li) gamma ray spectrometer. The number of absolute fissions per gram were calculated using the equations of Ref. 14. The estimated error of analysis is +/- 2.5%.

2. Monitor Wire Samples

The wires were removed from the stainless-steel sheath (Fig. 4) and analyzed for gamma activity and absolute fissions.

a. Relative Activity

The wires were cut into segments beginning at the top or tagged end. All wires were analyzed in 1/2 in. (1.27 cm) long segments except for the top and bottom portions of the one 60-in. (152.4 cm) long wire which were analyzed in 1 in. (2.54 cm) long segments. Each segment was individually weighed and counted for relative activity on a Ge(Li) gamma spectrometer. The estimated error of analysis is +/- 5%.

b. Analysis for Absolute Fission Activity

Three segments from each wire were dissolved and an aliquot taken for gamma ray analysis. The La^{140} 1.5916 MeV photopeak was counted on a Ge(Li) gamma ray spectrometer. The number of absolute fissions per gram of wire were calculated using the equations of Ref. 12. The estimated error of analysis is +/- 2.5%.

V. AXIAL POWER DISTRIBUTIONS

A. Fuel Sample Analysis

Axial power profiles were obtained from fuel samples using two methods:[12] 1) by gamma scanning the intact fuel pin (Sect. IV.B.1.a) and 2) by shearing the fuel column into approximately 1/2 in. (1.27 cm) long segments and counting the relative fission product activity of each individual segment (Sect. IV.B.1.b). Figures 10, 11, and 12 compare the two methods for fuel pins T-433, T-462, and H-316. (These three uranium-zirconium pins have plutonium concentrations of 0, 19 and 28 wt.% respectively.)

For the individual fuel segments, the count rate per gram of segment was determined. These values were normalized to unity at the axial peak of a least-square polynomial fit through the data points within the central 7.5 in. (19.1 cm) high nondysprosium region. The normalization allowed for better intercomparison of axial shapes as well as a more accurate determination of the power coupling at the axial peak.

Absolute axial positioning of all data is somewhat uncertain (approximately 0.5 in.). Nominal axial positioning of scan data in Figs. 10, 11, and 12 has been arbitrarily shifted by a small amount to optimize alignment with data from the fuel segments.

B. Monitor Wire Analysis

An axial power profile was obtained by cutting the 60 in. (152.4 cm) long flux monitor wire (Table III, wire L91-60-1) and gamma counting the relative fission product activity from each segment (Fig. 13). Wire L91-60-1 was irradiated in the half-slotted core configuration under LLSS conditions. The count rate per gram of wire was determined for each segment, and the values were normalized to unity at the axial peak of a polynomial fit performed over the region described in Sect. V.A.

Fig. 10. Axial Power Profiles from U-10 wt.% Zr Fuel Pin T-433

Fig. 11. Axial Power Profiles from U-19 wt.% Pu-10 wt.% Zr Fuel Pin T-462

Fig. 12. Axial Power Profiles from U-28 wt.% Pu-10 wt.% Zr Fuel Pin H-316

Fig. 13. Axial Power Profile Comparisons with Full-length Flux Monitor Wires

C. Comparison of the Axial Power Profile Before and After TREAT Upgrade

Figure 13 compares the flux monitor wire axial power profile before and after the TREAT facility was upgraded. Both profiles are normalized to unity with the peak activity occurring slightly below the core midplane. The pre-upgrade high-enriched-uranium wire from the M2CAL experiment was encased axially in a full-length 0.015 in. (0.038 cm) thick dysprosium filter. The double filtering condition of the pre-upgrade wire (full-length filter plus the dysprosium shaping collar filter configuration shown in Fig. 1) compared to the single shaping collar filtering of the post-upgrade wire is believed to account for the differences in the wings of the distribution.

Data in Fig. 14 was previously reported in Ref. 4 and compares the axial power profile for various fuel compositions prior to TREAT Upgrade. The gamma activity distribution of each composition was normalized as described in Sect. V.A. The dashed curve represents a least-squares-fit fitting all the data (not just the region identified in Sect. V.A). Both the curve values and the individual fuel segment data values were re-normalized by dividing by the peak value of the fit.

Fig. 14. Axial Power Profile Comparison of Pre-TREAT Upgrade Fuel Data

Fig. 12. Axial Power Profiles from U-28 wt.% Pu-10 wt.% Zr Fuel Pin H-316

Fig. 13. Axial Power Profile Comparisons with Full-length Flux Monitor Wires

C. Comparison of the Axial Power Profile Before and After TREAT Upgrade

Figure 13 compares the flux monitor wire axial power profile before and after the TREAT facility was upgraded. Both profiles are normalized to unity with the peak activity occurring slightly below the core midplane. The pre-upgrade high-enriched-uranium wire from the M2CAL experiment was encased axially in a full-length 0.015 in. (0.038 cm) thick dysprosium filter. The double filtering condition of the pre-upgrade wire (full-length filter plus the dysprosium shaping collar filter configuration shown in Fig. 1) compared to the single shaping collar filtering of the post-upgrade wire is believed to account for the differences in the wings of the distribution.

Data in Fig. 14 was previously reported in Ref. 4 and compares the axial power profile for various fuel compositions prior to TREAT Upgrade. The gamma activity distribution of each composition was normalized as described in Sect. V.A. The dashed curve represents a least-squares-fit fitting all the data (not just the region identified in Sect. V.A). Both the curve values and the individual fuel segment data values were re-normalized by dividing by the peak value of the fit.

Fig. 14. Axial Power Profile Comparison of Pre-TREAT Upgrade Fuel Data

Figure 15 compares the curve shown in Fig. 14 to the present post-TREAT Upgrade fuel data. Data from the three M8CAL fuel pins was also analyzed and fitted in the same manner as that described above. The pre- and post-TREAT Upgrade axial power profiles are nearly identical. The fitted equation for the M8CAL fuel pins is:

$$\text{Relative Power} = 0.7183 + 1.2521(Z/L) - 1.5262(Z/L)^2 + 0.3002(Z/L)^3 \quad (1)$$

Figure 16 compares the axial power profiles as determined from the least-squares fitted curve through the M8CAL fuel data, and full-length monitor wire data in filtered and unfiltered holders (as shown earlier in Fig. 13).

Differences at the wings of the distribution are attributed in part to "end effects," whereby neutrons streaming axially up and down the test hole in TREAT induce fissions preferentially near the ends of thick fuel pins but not in thin monitor wires. Placement of dysprosium filters at the ends of the axial fuel column are designed to minimize this effect. However, in the wings of the distribution, the filtering effect of these collars also combine with self-shielding the test fuel to cause less power reduction than that in an unfiltered monitor wire. It is interesting to note that the power shapes measured in previous calibrations by monitor wires in a dysprosium filtered holder are closer to that of the test fuel. From this we conclude that with regard to axial power distributions, the filtering from the 15-mil thick dysprosium produces similar results to the self-shielding within the test fuel itself.

As shown in Figs. 15 and 16, the least-square fitted curve through the M8CAL fuel data, Eq. (1), is recommended for use as the axial power profile in M8. The ratio of axial peak to axial average is 1.10. As discussed in Sect. VI.C, we assume that the power shape applies for all irradiation power levels and control-rod positions.

Fig. 15. Axial Power Profile Comparison of Pre- and Post-TREAT Upgrade Fuel Data

Fig. 16. Comparison of Fuel and Monitor Wire Axial Power Profiles

VI. AXIAL PEAK POWER COUPLING FACTORS

A. Heat Generation Per Fission

In a small-scale TREAT test, fission heating is primarily local and based on fission fragments. The heat generated per fission is slightly different for uranium and plutonium[14,15] and is, therefore, different for fuel types having different U/Pu mixes. If H_U is the heat generated per fission of U, H_{Pu} the heat generated per fission of Pu, W_U the weight fraction of U and W_{Pu} the weight fraction of Pu then:

$$H_{Fuel} = \frac{W_U * H_U + 1.5 W_{Pu} * H_{Pu}}{W_U + 1.5 W_{Pu}} \quad (2)$$

(The factor 1.5 represents the fact that plutonium is approximately 50% more likely to fission than uranium in TREAT's thermal neutron flux.) Note that the same H_{Fuel} may be applied to irradiated fuel since relative Pu and U fractions tend to remain approximately constant. (During irradiation in EBR-II, plutonium burns up faster than uranium but the difference is made up by breeding more plutonium.) The heat generation per fission for the two monitor wires and the three fuel types are shown in Table V.

TABLE V. Heat Generation per Fission for M8CAL Fuel and Monitor Wires and Contribution from Beta Decay

Fuel/Monitor Wire Type	Fissile Density, fissile g/total g	Energy Deposition per Fission (including Beta Decay) MeV/f (J/f)
High Enriched Uranium Wire	0.0335	170 (2.72×10^{-11})
Low Enriched Uranium Wire	0.0119	170 (2.72×10^{-11})
U-10 wt.% Zr Fuel	0.618	170 (2.72×10^{-11})
U-19 wt.% Pu-10 wt.% Zr Fuel	0.584	171.7 (2.75×10^{-11})
U-28 wt.% Pu-10 wt.% Zr Fuel	0.530	172.4 (2.76×10^{-11})

Note: Fissile grams include U-235, Pu-239, and Pu-241.

Depending on the duration of the transient, a small amount of energy should also be added to the above values to account for the energy from beta decay.[15] Considering the proposed M8 transient, 2 MeV/fission will be added in this report.

A distributed and general heating of material from TREAT fuel gamma rays is estimated to be 0.03 W/g-MW-TREAT, and will also be added to power couplings in this report.[14]

B. Proportionality of Fuel and Monitor Wire Fissions

A fundamental assumption made in these (and previous) calibration measurements is that, for identical transients or LLSS irradiations in TREAT, fissions in test fuel and fissions in mock-up monitor-wire irradiations are directly proportional. The constant of proportionality is determined by the ratio of the power coupling factors measured during two similar LLSS irradiations with similar TREAT energy release: one using a fueled calibration vehicle and the other with a monitor wire in the neutronically-similar unfueled vehicle. The resulting proportionality constant may depend on core temperature and neutron spectrum,[9] but is independent of the measured TREAT power and should be only weakly dependent on the details of TREAT core loading or control-rod motion. (Provided, of course, that the same rod motion and core loading has been used for both fuel and monitor-wire irradiations.) In M8CAL we will apply this assumption principally to axial peak power couplings.

TREAT power and energy are explicitly needed for the convenient and useful "power coupling factor" concept that is emphasized in this report. However, the proportionality assumption combined with a database of monitor-wire irradiations effectively minimizes dependency on any particular TREAT power meter or its calibration. Absolute calibration and accurate measurement of TREAT energy release may be important for other purposes, but all that is required here is that the TREAT energy release, measured by any means chosen, be consistent and reproducible. In this regard, it is fundamentally advantageous to perform the reference similar fuel and monitor-wire irradiations close together in time.

The proportionality assumption allows extension of the experimental fuel power calibration database using much less expensive power coupling measurements of monitor wires. In particular,

high-power transients that would melt test fuel may be included in this database. Basically, once the power coupling ratio is measured, only a trial transient containing a monitor wire is required in order to calculate the energy deposition in test fuel undergoing that same transient. By including additional monitor wire fission measurements encompassing a wide range of transients, we may empirically determine the relationship between test fuel fissions and TREAT measured energy deposition. In effect, we correct and extend the directly-measured test fuel power coupling factor from LLSS conditions to a much wider range of irradiations.

C. Influence of Power Meters and Control Rod Position

It has been observed for some time that power coupling factors are influenced by control rod position. Referring to Fig. 6, a power coupling factor is basically a ratio of TREAT neutrons leaking into the centrally-located test hole to those leaking into power meters at the edges of the core. The two types of control rods which are used to control power during high-power and LLSS operation are located in a ring between the experiment and power meter, and their influence on the power coupling ratio is thus physically plausible. High-power operation is always controlled by the computer-controlled transient rods with control/shutdown rods banked to hold down excess reactivity. High powers are measured by instruments at the corners of the core. Low-power operation, however, may be controlled by using either the transient rods (which mimics high-power operation) or the control/shutdown rods (as preferred by TREAT operations for practical reasons). Low-power levels are measured by a different, more sensitive instrument on the west side of the core (Dedicated Information System, DIS, Linear Operating Instrument). Power couplings determined during LLSS and transient irradiations thus utilize different instruments to estimate TREAT energy release. As noted above in Sect. VI.B, there is no problem in using different power meters for different types of irradiations to determine power couplings, provided the use of each meter is consistent. (Note that both low- and high-power level instruments are calibrated to the same heat energy release measured in a LLSS heat balance operation.)

Under high-power transient conditions, power coupling changes, called "transient correction factors," have been extensively studied both in past calibration work,[4,9] and in the present effort (Sect. VII).

However, M8CAL data also demonstrates that during low-power operation, power coupling is strongly influenced by the chosen method of reactor control and the rod configuration at critical. Table VI shows configurations and results. Figure 6 indicates that, whereas the transient and control/shutdown rods are rather symmetrically located relative to the experiment at the core center and the transient power meters at the corners of the core, the transient rods are much closer to the steady-state meter situated on the west side of the reactor. Physically, the principal effect of using the control/shutdown rods instead of the transient rods to control the reactor (Configuration A instead of B) is to increase neutron flux to the steady-state power meter (the transient rods being fully withdrawn) and, consequently, decrease power couplings by the same factor. Accordingly, all LLSS results discussed below for both monitor wire and fuel irradiations must make careful note of the rod configuration.

As noted in Sect. V.C, we have assumed that axial power distributions, themselves, are not affected by control rod motion or initial critical position. No confirming measurements were made during M8CAL, since the same control rod configuration was used to irradiate the single long monitor wire and all fuel irradiations (Table III). However, monitor-wire irradiations from previous M-series calibration work[1,4] indicated no significant differences in axial power shape for rod motions ranging between LLSS conditions and maximal high-power transients.

D. Changes in Test Fuel Power Coupling From Burnup and Restructuring

The effect of burnup and restructuring on power coupling can be large for metallic fuel. Effects of isotopic depletion and changes in fuel density and radius were calculated and reported in Ref. 4. Principal results are repeated here for information and completeness.

As fuel burnup increases, depletion of fissile isotopes reduces the power coupling by a calculated amount of ~0.5% for each at.% burnup. However, the effects of fuel expansion oppose this decrease. IFR fuel expands outward to the inner cladding radius in the first few at.% of burnup with a decrease in density ~28% and an increase in fuel surface area of ~18%. Because of the large neutron flux depression in the fuel, this expansion leads to a calculated power coupling increase of about 13%.

TABLE VI. M8CAL LLSS Flux Monitor Wire Power Coupling Factors

Item	Date	Wire Identification	Core Slot	Axial Peak: Absolute (f/g) ($\times 10E13$)	Total Energy in Irradiation, MJ	Measured Coupling Factor (f/g U-235-MJ) ($\times 10E12$)	Control Rod Configuration	Approximate Initial (Critical) Rod Position, in.		Wire Holder
								Control/Shutdown	Transient	
1	10/19/90	L91-8-10	Full	1.42	667	1.79	B	Fully Withdrawn	18.5	Unfiltered
2	8/24/92	L91-60-1	Half	0.958	576	1.40	A	22	Fully Withdrawn	Unfiltered
3	11/20/92	L91-8-1	Half	0.968	576	1.41	A	22	Fully Withdrawn	Unfiltered
4	2/ 8/93	L91-8-6	Half	0.819	480	1.44	A	22	Fully Withdrawn	Unfiltered
5	2/12/93	H91-8-1	Half	0.972	576	0.503	A	22	Fully Withdrawn	Filtered
6	3/ 2/93	L91-8-16	Half	1.26	576	1.84	B	48	11.5	Unfiltered

Notes to Table VI are given on the following page.

Notes for Table VI:

* Control-rod Sequence Description:

Full-slotted:	Configuration B:	Compensation and control/shutdown fully withdrawn, Transient rods banked at about 18.5-in. and withdrawn as needed.
Half-slotted:	Configuration A:	Compensation rods fully withdrawn, Control/shutdown rods banked at about 22-in. and withdrawn as needed, Transient rods withdrawn to about 40-in. (i.e., fully withdrawn)
	Configuration B:	Compensation rods fully withdrawn, Control/shutdown rods withdrawn to about 48-in., Transient rods banked at about 11.5-in. and withdrawn as needed.

* Computation notes:

The low-enriched uranium wires (L) are 6 wt.% U enriched to 19.8 wt.% U-235 or $(0.06)(0.198) = 0.01188$ g U-235 per gram of wire.

The high-enriched uranium wires (H) are 3.6 wt.% U enriched to 93.1 wt.% U-235 or $(0.036)(93.1) = 0.03352$ g U-235 per gram of wire.

Example determination of the measured coupling for the unfiltered, low-enriched uranium wire in the full-slotted core configuration:

$$\frac{(1.42 \times 10^{13} \text{ f/g})}{667 \text{ MJ}} = 2.13 \times 10^{10} \text{ f/g of wire/MJ}$$

or (since this is a low-enriched uranium wire)

$$\frac{2.13 \times 10^{10} \text{ f/g of wire/MJ}}{0.01188 \text{ g U-235/g of wire}} = 1.79 \times 10^{12} \text{ f/g U-235/MJ}$$

* The average of the three half-slotted, low-enriched uranium, unfiltered values = 1.42×10^{12} f/g U-235/MJ

E. Radial Power Profile

Significant neutron flux depression in test fuel leads to a steep radial power profile in test fuel. Radial power shapes calculated for U-10Zr and U-19Pu-10Zr IFR fuel and recommended for use here were reported in Ref. 4.

F. Fuel at Low-level Steady State

1. Measurements

The measured peak axial LLSS fresh fuel coupling factors were obtained in the half-slotted core configuration for the three compositions of fuel as follows. Results are shown in Table VII.

1) The 13.5 in. (34.29 cm) long fuel column was sheared into approximately 1/2 in. (1.27 cm) long segments. The segments were gamma counted to obtain their relative activity (Sect. IV.B.1.b). Selected fuel segments were analyzed to determine the number of absolute fissions per gram of fuel (Sect. IV.B.1.c). For each of the selected segments the value of the absolute number of fissions per gram was divided by its respective relative gamma activity. The resulting ratios for those segments were then averaged.

2) The axial dysprosium shaping collar configuration (Fig. 1) includes a 7.5 in. (19.1 cm) dysprosium-free central region. The peak of the relative gamma activity distribution through this region was obtained by means of a polynomial fit (as described in Sect. V.A).

3) The average ratio obtained in step 1 was then multiplied by the value obtained in step 2 of the number of fissions/gram of fuel at the peak of the axial distribution. Individual ratios were used to determine the random uncertainty reported in Table VII.

4) The value in step 3 was then multiplied by the heat generation per fission (Table V) and the result divided by the TREAT energy released during the LLSS irradiation.

TABLE VII. M8CAL LLSS Fresh Fuel Power Coupling Factors

Fuel Pin Identification	Cladding	Fuel Composition	Absolute Activity (f/g) (x10E13)	Relative Activity	Average Ratio: Abs./Rel. f/g (x10E13)	Fitted Peak of Rel. Act. Distribution	Fitted Axial Peak: Absolute f/g (x10E13)	Measured Power Coupling Factor, J/g-MJ (Normalized)	Normalized Calculated Power Coupling Factors*
T-433	HT-9	U-10 Zr (65.5% Enr. U)	8.07	0.901	8.95 +/- 0.04	0.992	8.88	5.06 +/- 0.02 (1.0)	---- (1.0)
			8.87	1.000					
			8.59	0.952					
T-462	HT-9	U-19 Pu-10 Zr (57.0% Enr. U)	7.65	0.910	8.24 +/- 0.08	0.991	8.17	4.71 +/- 0.05 (0.93)	---- (0.94)
			8.13	1.000					
			7.76	0.947					
H-316	HT-9M	U-28 Pu-10 Zr (46.0% Enr. U)	6.80	0.905	7.57 +/- 0.06	0.989	7.49	4.34 +/- 0.03 (0.86)	---- (0.88)
			7.44	1.000					
			7.42	0.990					
			7.66	0.997					
			6.94	0.898					

* Calculations by R. W. Swanson, June 1993.

Example determination of the measured power coupling factor for fuel pin T-433:

$$\frac{(8.88 \times 10^{13} \text{ fissions/g}) (2.72 \times 10^{-11} \text{ J/fission})}{480 \text{ MJ}} + 0.03 \text{ Wg-MW} = 5.06 \text{ J/g-MJ}$$

$$(1 \text{ W-s/g-MW-s} = 1 \text{ J/g-MJ})$$

Uncertainties presented are statistical only and represent the standard deviation of the mean.

5) Finally, to account for the additional heat generated within the test section by gamma rays from fissions occurring in the TREAT fuel, a value of 0.03 W/g-MW was added.

2. Calculations

To compare power coupling ratios among the three fuel compositions, neutronic calculations were performed by R. W. Swanson using the 1D transport code ANISN and a 50-group neutron cross-section set. A fuel pin density of 15.8 g/cc and an intact fuel pin diameter of 0.173 in. (0.44 cm) was used in all cases.[16] Results are reported in Table VII. Differences between the measured and calculated values are within the statistics of the measured data.

G. Monitor Wires

Table VI summarizes the measured LLSS flux monitor wire peak axial coupling factors in the full- and half-slotted core configurations:

1) The central part of the wires were cut into 1/2 in. (1.27 cm) long segments. The segments were gamma counted to obtain their relative activity (Sect. IV.B.2.a). Selected segments were analyzed to determine the number of absolute fissions per gram of wire (Sect. IV.B.2.b). For each of the selected segments the value of the absolute number of fissions per gram was divided by its respective relative gamma activity and the resulting ratios averaged.

2) The axial dysprosium shaping collar configuration (Fig. 1) includes a 7.5 in. (19.1 cm) dysprosium-free central region. The peak of the relative gamma activity distribution through this region was obtained by means of a polynomial fit as described above in Sects. V.A and VI.F.1.

3) The average ratio obtained in step 1 was then multiplied by the peak value obtained in step 2. Individual ratios were used to determine reported random uncertainties.

4) Using the number of grams of U-235 per gram of wire for the low- and high- enriched wires (as given in the notes for Table VI) the power coupling factors were calculated in units of f/gram of fuel per TREAT MJ. Note that all applications of monitor wire power coupling involve only ratios. Thus, it is not necessary to convert fissions to heat energy.

Table VI shows monitor wire power coupling results for the two core configurations (described in Sect. IV.A.1), the two uranium wire enrichments (described in Sect. III.B), the two wire holder assemblies (described in Sect. II.C), and three control-rod configurations: one in the full-slotted core and two within the half-slotted core configuration. Some of the effects of these conditions can be obtained by comparing one item with another:

1) A comparison of items 2, 3, and 4 from Table VI indicates the reproducibility of measurements having the same conditions over an approximate six-month time span: half-slotted core, low-uranium enrichment wire, unfiltered wire holder and control-rod Configuration A. The average of the three values is 1.42×10^{12} f/g U-235/ TREAT MJ. The statistical uncertainty of this average is $\pm 0.75\%$.

2) The effect of the combination of uranium enrichment and wire holder filtering can be seen by comparing the average value just calculated in (1) with the value of item 5 of Table VI:

$$\frac{\text{Low-enriched uranium, unfiltered}}{\text{High-enriched uranium, filtered}} = \frac{1.42 \times 10^{12} \text{ f/g}}{0.503 \times 10^{12} \text{ f/g}} = 2.82 \quad (3)$$

This result is in reasonable agreement with earlier data comparing TREAT Transient 2704 (high-enriched uranium wire, unfiltered holder in the M5 full-slotted core) and TREAT Transient 2728 (high-enriched uranium wire, filtered holder in the M6 full-slotted core):[17] Unfiltered holder/Filtered holder = 2.65.

3) The effect of the two different control rod configurations (see Sect. VI.C) on power coupling can be seen by comparing the above average in (1) with item 6 from Table VI:

$$\frac{\text{Configuration A}}{\text{Configuration B}} = \frac{1.42 \times 10^{12} \text{ f/g}}{1.84 \times 10^{12} \text{ f/g}} = 0.77 \quad (4)$$

The result quantifies the observation made in Sect. VI.C that controlling the reactor with the control/shutdown rods (Configuration A) would decrease the power coupling factor (23% effect).

4) The measured effect of core configuration on LLSS monitor wires (half-slotted vs. full-slotted) can be seen by comparing item 6 with item 1 of Table VI:

$$\frac{\text{Half-slotted Core (Item 6)}}{\text{Full-slotted Core (Item 1)}} = \frac{1.84 \times 10^{12}}{1.79 \times 10^{12}} = 1.03 \quad (5)$$

By comparison, this same ratio reported previously in M7CAL [4] is:

$$\frac{\text{Half-slotted Core}}{\text{Full-slotted Core}} = 1.05 \quad (6)$$

H. Full-slotted Core Configuration

There were no fuel irradiations in the full-slotted core configuration during M8CAL. However, as described in Sect. VI.B, by ratioing the LLSS monitor wire power coupling factors between the half-slotted core and the full-slotted core, and applying this ratio to the LLSS fresh fuel power coupling factor obtained in the half-slotted core one can obtain the fuel coupling factor for the full-slotted core:

The Table VI ratio of item 6 to item 1 (ratio of the LLSS wire power coupling factor in the half-slotted core to that in the full-slotted core under similar control rod positions) of 1.03 gives a rough estimate. As noted in the footnote to Table VI, the control-rod configurations (Configuration B in both cores) used in the two wire irradiations to obtain the ratio (1.03) were not quite identical. Moreover, as described in Sects. VI.C and VI.G changes in control rod position can significantly influence power coupling.

VII. TRANSIENT CORRECTION FACTORS

A. Definitions and Assumptions

The power coupling between the test fuel and the reactor is directly measured in fuel that has been irradiated under LLSS conditions. In Sect. VI.G it was shown that the power coupling in TREAT depends on the particular rod configuration at LLSS. However, the power coupling under power transient conditions also shows a small but significant difference from that at LLSS conditions. As will be shown, this effect is principally correlated to the relative positions of the TREAT control rods during power transients and LLSS operations.

At any given time into a power transient, the coupling factor is related to that at LLSS conditions by the Transient Correction Factor (TCF), defined by:

$$TCF = \frac{\text{Coupling factor under transient conditions}}{\text{Coupling factor at LLSS}} = \frac{CF_T}{CF_{LLSS}} \quad (7)$$

where the coupling factor is generally expressed in terms of (J/g of fuel) per MJ of TREAT power. When integrated over the entire transient, an energy-weighted average TCF is obtained.

$$TCF = \frac{\frac{1}{E_T} \int_0^{E_T} CF dE}{CF_{LLSS}} = \frac{\overline{CF_T}}{CF_{LLSS}} \quad (8)$$

where $\overline{CF_T}$ is the energy-averaged coupling factor, and E_T is the total energy in the transient.

In order to obtain the average TCF we assume the fundamental proportionality of fuel and monitor wire fissions described in Sect. VI.B. Monitor wires are irradiated in TREAT under transient conditions and at LLSS, and their coupling factors obtained from analysis of the number of fissions that have occurred. It is then assumed that the ratio of coupling factor under transient conditions to coupling factor at LLSS for the monitor wires is the same as for the test fuel. Thus, the coupling factor for the fuel under transient conditions may be calculated from:

$$\frac{\overline{CF_T}}{CF_{Fuel,LLSS}} = \frac{CF_{Wire,Transient}}{CF_{Wire,LLSS}} \quad (9)$$

or

$$\overline{CF_T} = \frac{CF_{Fuel,LLSS}}{CF_{Wire,LLSS}} * CF_{Wire,Transient} \quad (10)$$

$$\overline{CF_T} = CF_{Fuel,LLSS} * TCF \quad (11)$$

$$\frac{\text{Half-slotted Core (Item 6)}}{\text{Full-slotted Core (Item 1)}} = \frac{1.84 \times 10^{12}}{1.79 \times 10^{12}} = 1.03 \quad (5)$$

By comparison, this same ratio reported previously in M7CAL [4] is:

$$\frac{\text{Half-slotted Core}}{\text{Full-slotted Core}} = 1.05 \quad (6)$$

H. Full-slotted Core Configuration

There were no fuel irradiations in the full-slotted core configuration during M8CAL. However, as described in Sect. VI.B, by ratioing the LLSS monitor wire power coupling factors between the half-slotted core and the full-slotted core, and applying this ratio to the LLSS fresh fuel power coupling factor obtained in the half-slotted core one can obtain the fuel coupling factor for the full-slotted core:

The Table VI ratio of item 6 to item 1 (ratio of the LLSS wire power coupling factor in the half-slotted core to that in the full-slotted core under similar control rod positions) of 1.03 gives a rough estimate. As noted in the footnote to Table VI, the control-rod configurations (Configuration B in both cores) used in the two wire irradiations to obtain the ratio (1.03) were not quite identical. Moreover, as described in Sects. VI.C and VI.G changes in control rod position can significantly influence power coupling.

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At any given time into a power transient, the coupling factor is related to that at LLSS conditions by the Transient Correction Factor (TCF), defined by:

$$TCF = \frac{\text{Coupling factor under transient conditions}}{\text{Coupling factor at LLSS}} = \frac{CF_T}{CF_{LLSS}} \quad (7)$$

where the coupling factor is generally expressed in terms of (J/g of fuel) per MJ of TREAT power. When integrated over the entire transient, an energy-weighted average TCF is obtained.

$$TCF = \frac{\frac{1}{E_T} \int_0^{E_T} CF dE}{CF_{LLSS}} = \frac{\overline{CF_T}}{CF_{LLSS}} \quad (8)$$

where $\overline{CF_T}$ is the energy-averaged coupling factor, and E_T is the total energy in the transient.

In order to obtain the average TCF we assume the fundamental proportionality of fuel and monitor wire fissions described in Sect. VI.B. Monitor wires are irradiated in TREAT under transient conditions and at LLSS, and their coupling factors obtained from analysis of the number of fissions that have occurred. It is then assumed that the ratio of coupling factor under transient conditions to coupling factor at LLSS for the monitor wires is the same as for the test fuel. Thus, the coupling factor for the fuel under transient conditions may be calculated from:

$$\frac{\overline{CF_T}}{CF_{Fuel,LLSS}} = \frac{CF_{Wire,Transient}}{CF_{Wire,LLSS}} \quad (9)$$

or

$$\overline{CF_T} = \frac{CF_{Fuel,LLSS}}{CF_{Wire,LLSS}} * CF_{Wire,Transient} \quad (10)$$

$$\overline{CF_T} = CF_{Fuel,LLSS} * TCF \quad (11)$$

As described in Sect. VI.B this method minimizes dependence on performance of specific power meters and their calibration. Nonetheless it is advisable that the LLSS wire irradiation be performed within a short time of the LLSS fuel irradiation in order to minimize a chance of any perturbation caused by instrument drifts and calibration changes with time.

B. Effect of LLSS Rod Positions

As described in Sect. VI.G, results reported in Table VI show the effect of the different rod motions on the power coupling factor for a monitor wire, for LLSS conditions. If the control/shutdown rods are used to control the power, with the transient rods out of the core (Rod Configuration A) there is an apparent 23% decrease in the coupling factor from the case where the transient rods control the power and the control/shutdown rods are withdrawn to 48 in. (Rod Configuration B).

From the standpoint of defining transient correction factors, it does not matter which operation is used to define LLSS conditions as long as results from the rod configuration are used consistently. It is essential, however, that the same LLSS rod configuration be used for both fuel and monitor wire irradiations.

Referring to Table III, reported TCF results utilize the LLSS monitor wire values from the irradiations on 10/19/90 for the full-slotted core, on 2/8/93 for the low-enriched uranium wires in the half-slotted core and on 2/12/93 for the high enriched wires in the half-slotted core. (In the full-slotted core the transient rods were banked and withdrawn as needed and the control/shutdown rods were fully withdrawn; whereas in the latter two irradiations the transient rods were fully withdrawn and the control/shutdown rods were banked and withdrawn as needed.)

C. Summary and Results from M8CAL Monitor Wire Measurements

As has been discussed in this report, a large number of monitor-wire irradiations were performed in TREAT during M8CAL for diverse and, in many cases, multiple purposes. These irradiations included LLSS and transients, utilizing both full- and half-slotted TREAT cores. Table VIII presents a database of summary descriptions, measured results, and deduced TCFs for all these irradiations. This Table VIII database will be used, as described below in Sect. VII.D, to correlate TCFs to control rod position. For

TABLE VIII. Summary of M8CAL Monitor Wire Irradiations

Date	Description	TREAT Transient Number	Wire Number	Energy-weighted Average Transient Rod Position, in.	Energy, MJ	Fitted Peak of Rel. Act. Distribution	Axial Peak Absolute f/g of wire ($\times 10^{13}$)	Coupling Factor, f/g _{U-235} -MJ ($\times 10^{12}$)	Transient Correction Factor	Fitted Transient Correction Factor (Peak)(d)
10/19/90	Full-slotted: LLSS	---	L91-8-10	20.5 (a)	667	0.989	1.418 +/- 0.018	1.790 +/- 0.023	1.0 (Reference)	---
10/25/90	Full-slotted: HB	2811	L91-8-11	25.2 (a)	655.4	0.999	1.372 +/- 0.007	1.762 +/- 0.009	0.984 +/- 0.014	0.972
10/26/90	Full-slotted: HB	2812	L91-8-12	23.3 (a)	404.7	1.002	0.853 +/- 0.003	1.774 +/- 0.006	0.991 +/- 0.013	0.988
11/14/90	Full-slotted: 8-s Period	2815	L91-8-13	27.8 (a)	996.0	0.997	2.004 +/- 0.003	1.694 +/- 0.003	0.946 +/- 0.013	0.952
11/15/90	Full-slotted: 8-s Period	2816	L91-8-14	25.8 (a)	661.8	1.000	1.365 +/- 0.013	1.736 +/- 0.017	0.970 +/- 0.016	0.967
8/24/92	Half-slotted: LLSS	---	L91-60-1	40.0 (b)	576	0.990	0.958 +/- 0.004	1.400 +/- 0.006	0.975 +/- 0.004	0.987
8/31/92	Half-slotted HB	2858	L91-8-2	16.4 (c)	423.1	0.993	0.882 +/- 0.009	1.755 +/- 0.018	1.222 +/- 0.010	1.231
9/23/92	Half-slotted HB	2862	L91-8-3	18.2 (c)	655.0	0.998	1.342 +/- 0.005	1.725 +/- 0.006	1.201 +/- 0.003	1.210
10/14/92	Half-slotted: 8-s Period	2864	L91-8-4	25.7 (c)	1868.4	0.995	3.583 +/- 0.023	1.614 +/- 0.010	1.124 +/- 0.006	1.134
10/27/92	Half-slotted: 30-s Period	2867	L91-8-7	26.1 (c)	1956.7	0.997	3.795 +/- 0.029	1.633 +/- 0.012	1.137 +/- 0.007	1.131

TABLE VIII. (Contd.)

Date	Description	TREAT Transient Number	Wire Number	Energy-weighted Average Transient Rod Position, in.	Energy, MJ	Fitted Peak of Rel. Act. Distribution	Axial Peak Absolute f/g of wire (x10E13)	Coupling Factor, f/g _{U-235} -MJ (x10E12)	Transient Correction Factor	Fitted Transient Correction Factor (Peak)(d)
10/29/92	Half-slotted: 30-s Period	2868	L91-8-8	22.0 (c)	1198.6	0.999	2.392 +/- 0.015	1.680 +/- 0.011	1.170 +/- 0.007	1.170
10/30/92	Half-slotted: 30-s Period	2869	L91-8-9	18.2 (c)	602.1	0.998	1.248 +/- 0.001	1.745 +/- 0.001	1.215 +/- 0.001	1.211
11/10/92	Half-slotted: 30-s Period	2871	L91-8-15	26.8 (c)	1999.8	0.996	3.807 +/- 0.016	1.602 +/- 0.007	1.116 +/- 0.004	1.125
11/19/92	Half-slotted: 80-s Period	2873	L91-8-5	25.4 (c)	1797.8	1.000	3.538 +/- 0.017	1.657 +/- 0.008	1.154 +/- 0.005	1.138
11/20/92	Half-slotted: LLSS	---	L91-8-1	40.0 (b)	576	0.999	0.969 +/- 0.047	1.415 +/- 0.007	0.985 +/- 0.005	0.987
2/8/93	Half-slotted LLSS	---	L91-8-6	40.0 (b)	480	1.000	0.819 +/- 0.006	1.436 +/- 0.001	1.00 (Reference)	---
2/12/93	Half-slotted LLSS	---	H91-8-1	40.0 (b)	576	0.991	0.972 +/- 0.007	0.503 +/- 0.004	0.988 +/- 0.008	Not Included in Fit
2/17/93	Half-slotted: 8-s Period	2874	H91-8-2	25.3 (c)	1807.1	0.980	3.685 +/- 0.028	0.608 +/- 0.005	1.194 +/- 0.008	Not Included in Fit
3/2/93	Half-slotted LLSS	---	L91-8-16	13.5 (c)	576	0.993	1.259 +/- 0.010	1.840 +/- 0.015	1.281 +/- 0.008	1.264

Uncertainties represent the standard deviation from the scatter of three measurements. Errors in TREAT energy deposition or other systematic effects are not considered. Notes for Table VIII:

Notes for Table VIII:

- (a) Compensation rods and control/shutdown rods are fully withdrawn and initially the transient rods are withdrawn about 18.5 in. During LLSS irradiations the transient rods are withdrawn about 4 in.
- (b) Compensation rods and transient rods are fully withdrawn and initially the control/shutdown rods are withdrawn about 22 in. During LLSS irradiations the control/shutdown rods are withdrawn about 4 in.
- (c) Compensation rods are fully withdrawn, control/shutdown rods are banked at approximately 48 in. and initially the transient rods are withdrawn about 11.5 in. During LLSS irradiations the transient rods are withdrawn about 4 in.
- (d) "Fitted Transient Correction Factors" were obtained from the least-square-fitted data of Fig. 26.

Example computations:

- 1) Transient correction factors for the full-slotted core configuration:
(Low-enriched uranium wires were used throughout the full-slotted core measurements)

$$\text{e.g., } \frac{1.762 \times 10^{12}}{1.790 \times 10^{12}} = 0.984 \quad (\text{full-slotted HB transient: 10/25/90})$$

- 2) Transient correction factors for the half-slotted core configuration:
(Both low- and high-enriched uranium wires were used in these measurements)

For the low-enriched uranium wires the LLSS irradiation of 2/8/93 was chosen since that irradiation is closest in time to the two fuel irradiations.

$$\text{e.g., } \frac{1.755 \times 10^{12}}{1.436 \times 10^{12}} = 1.222 \quad (\text{half-slotted HB transient: 8/31/92})$$

For the high-enriched uranium wires the TCFs are calculated assuming an approximate factor of 2.82 to convert fissions from a filtered to unfiltered monitor wire holder.

$$\frac{(2.82)(0.608 \times 10^{12})}{1.436 \times 10^{12}} = 1.194 \quad (\text{half-slotted 8-s period: 2/17/93})$$

now, the range of measured TCFs is illustrated by plots of TCF vs. average transient rod position in Figs. 17 and 18 for the full- and half-slotted cores, respectively.

Table VIII results also extends determinations of TCF's, as defined in Sect. VII.A, to LLSS irradiations. Particular LLSS irradiations which are used to calculate TCF's are labeled "reference." TCF's are calculated for all others. It will be shown in Sect. VII.D that power couplings of other LLSS irradiations may be correlated to control rod positions along with measured power couplings of transient irradiations.

We note that transient irradiations include both full and partial segments of, candidate heat balance and overpower transients for the M8 experiment. Full-scale overpower transients were designed to use the maximum reactivity available in TREAT, and in some cases included low-power tails after termination to optimize the Fast Neutron Hodoscope signal posttransient. Data from these maximal transients will be used later in Sect. VIII to estimate maximum energy deposition capability in a fueled test in TREAT.

As noted in Sect. VI.B, absolute knowledge of TREAT energy release is not needed to convert between measured monitor wire fissions and predicted fuel fissions. However, reasonably consistent estimates of relative TREAT energy release among different irradiations in the database are needed to (1) express results in terms of the practical and useful power coupling factor and (2) correlate power coupling results to rod position (or any other parameter which characterizes these irradiations).

1. Energy Deposition in Low-level, Steady-state Irradiations

The amount of energy released during a LLSS irradiation was determined by multiplying the DIS Linear Operating Instrument measured power by the time at power. The DIS instrument is used only to compare relative energy deposition in LLSS operations.

Fig. 17. Transient Correction Factors in the M8CAL Full-slotted Core

Fig. 18. Transient Correction Factors in the M8CAL Half-slotted Core

now, the range of measured TCFs is illustrated by plots of TCF vs. average transient rod position in Figs. 17 and 18 for the full- and half-slotted cores, respectively.

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Fig. 17. Transient Correction Factors in the M8CAL Full-slotted Core

Fig. 18. Transient Correction Factors in the M8CAL Half-slotted Core

2. Transient Energy Deposition

Accuracy of measured transient correction factors depends critically on knowing relative amounts of energy released in transients. For transient operations in the upgraded TREAT the Automatic Reactor Control System (ARCS) Linear instrument (Power I) provides the best overall determination of the total energy released during the transient. This is because the Power I is a multi-range instrument and is accurate over a wide range of powers. [Other available power instruments (Reactor Trip System, RTS, Transient Linear, A, B, and C) are set on the highest range (or on a high range) and remain on that range throughout the transient.] The Power I instrument has both a monitor node and a control node, each with its own analog-to-digital converter.

Determining energy deposition during M8CAL power transients was complicated by the fact that the power-time history recorded by the Power I monitor node contained small, but unphysical discontinuities at powers associated with the automatic range changes. Fortunately, the control node power trace is continuous and is used as the basis of power determination until a "shutdown" command terminates the control node power signal. Figures B1 through B13 in Appendix B show the power and energy (from the Power I, control node instrument) and the transient rod motion for the M8CAL transients.

Table C1 in Appendix C shows how the total energy for each transient was determined. First the energy from the control node was recorded (energy throughout the transient up until the "shutdown" command) e.g., 1187.3 MJ for TREAT Transient 2868 (Fig. B9). Next the energy from the time of the "shutdown" command to the end of the transient was determined from the monitor node, e.g. 11.3 MJ. The sum of the two values ($1187.3 + 11.3 = 1198.6$ MJ) represents the total transient energy.

Some of the transients (2815, 2864, 2867, 2871, 2873, and 2874) were terminated by first driving the transient rods into the core (creating a slowly decreasing power tail) and then waiting 15 s before inserting the remaining rods. Since the power in these transients was very near zero at the time of the "shutdown" command the contribution from the monitor node is small (Table C1). The contribution from the monitor node is largest in those "partial" transients (2816, 2868, and 2869) where the "shutdown" command occurred at a high intermediate power.

3. Fractional Reactivity Control Rod Worth vs. Rod Position

The effect that control rod position within the core has on power coupling will be quantified in terms of relative reactivity. To this end, a dimensionless "fractional reactivity" is defined at any rod position by dividing the rod worth at a particular position by the total rod worth. Fractional rod worth is rod position expressed in terms of inserted reactivity. It highlights the importance of rod motion in the central region of the core. Control rod worth as a function of position was supplied by TREAT (Figs. 7 and 8[13]) for transient and control/shutdown rods in both full- and half-slotted cores. Fractional reactivity vs. rod position results are shown in Figs. 19 and 20.

It is interesting to note that full and half-slotted fractional reactivity results are nearly identical for both sets of control rods. By contrast, absolute values are quite different. Total reactivity worth of the transient rods are 8.46% for the full-slotted core and 9.02% for the half-slotted core. Total reactivity worth of the control/shutdown rods are 7.77% for the full-slotted core and 8.83% in the half-slotted core.

D. Correlation of TCFs with Control Rod Positions

1. Method

The first TCF correlation study was presented in Ref. 9, which demonstrated that variation of power coupling during transient operations could be correlated to the changing position of control rods. Correlations similar to Ref. 9 for an extensive set of M-series transients performed prior to TREAT Upgrade were reported in Ref. 4. Indeed, for the actual test transients in tests M2 through M7, these correlations and the measured rod motion were used to calculate an empirically-based average TCF and a time-varying power coupling in actual transients. The correlation study presented here extends previous studies to the TREAT Upgrade M-series core by including (1) the entire set of LLSS irradiations, (2) both transient and control/shutdown rods, and (3) TCF data from both full- and half-slotted cores in the same correlation.

Fig. 19. Comparison of Fractional Worth vs. Transient Rod Position for the M8CAL Full- and Half-slotted Cores

Fig. 20. Comparison of Fractional Worth vs. Control/Shutdown Rod Position for the M8CAL Full- and Half-slotted Cores

Following the basic approach of Ref. 9, we empirically model power coupling of test fuel to the reactor as a product of factors. The first, and most important, depends on the test fuel, test hardware, and the makeup of the TREAT core. Two other significant, but less important, factors depend on the positions of each set of control rods. To assure that each effect studied enters as a multiplicative factor, we will fit measured TCF's to the exponential form:

$$\text{TCF} = e^{(a+bT+cC)} \quad (12)$$

where T and C are the fractional worths of the transient and control/shutdown rods, respectively, as defined in Sect. VII.C.3. Dimensionless parameters, a , b , and c are to be fit by the data of Table VIII. Because Table VIII TCF's are averaged over an irradiation, T and C are also based on energy-weighted average rod positions during that irradiation. Practical fits of data take the logarithm of Eq. (12), which allows the parameters: a , b , and c to be fit by linear regression techniques to the form:

$$\ln \text{TCF} = a + bT + cC \quad (13)$$

The fitted parameter, a lumps together the important effects of test fuel, test hardware, and the makeup of the TREAT core. Each unique experiment configuration, e.g., full- and half-slotted core data, requires a different reference LLSS irradiation to define a TCF and a different fitted constant, a . Effects of different power meters or the particular rod configuration used in reference irradiations are also included in the fitted constant, a (Sects. VI.C and VII.B).

The fitted values of b and c describe the rod position dependence of principal interest in this section. Because the effect of changing rod position is not expected to be large, the parameters, b , and c represent the lowest-order terms of a linear expansion in terms of fractional rod worth. Our approach to these parameters will be empirical, but if, as discussed in Sect. VI.C, rod position influences power coupling principally by altering the leakage flux to nearby external power meters (see Fig. 6), fits to parameters, b and c may be approximately universal.

2. Correlations

The database of Table VIII has been used for three separate but interrelated correlation studies.

The first study (I) used only data from the full-slotted core. Since all irradiations in this configuration were performed with the control/shutdown rods fully withdrawn, only the parameters, a and b were fitted. Results are shown in Figs. 21 and 22. The typical deviation between measured and fitted TCF is about 1%. Fitted values of a and b are: -0.085 and 0.23.

The second correlation study (II) used only data from the half-slotted core. While all transients were performed with the control/shutdown rods fully withdrawn, LLSS irradiations were performed with this configuration as well as one where the transient rods fully withdrawn. Thus there was sufficient data to fit for all three parameters: a , b , and c . Results are shown in Figs. 23 and 24. Because conversion from filtered to unfiltered monitor wire holders is approximate, results from "bridging" irradiations using high-enrichment monitor wires are shown on Fig. 23 figures but were not included in the fits. The typical deviation between measured and fitted TCF is less than 1%. Fitted values of a , b , and c are: 0.065, 0.29, and -0.115. In agreement with expectations of "universality," the fitted parameters, b from fits (I) and (II) seem quite consistent.

The third study (III) included data from both full- and half-slotted cores. Two a parameters: a_{fs} and a_{hs} were fit separately from the data of each core. However, to test the hypothesis of rod-dependence "universality", a common parameter b and c were fitted using all the data. (As above, high-enrichment monitor wire data was excluded.) Results are shown in Figs. 25 and 26. The typical deviation between measured and fitted TCF is again less than 1%. Fitted values of a_{fs} , a_{hs} , b , and c are: -0.099, 0.068, 0.28, and -0.12. We note the quality of this combined fit (III) is excellent and commensurate with that from the individual core loadings (I and II). Moreover, fitted values of b and c in (III) are quite consistent with those found in (I) and (II). TCFs calculated from this combined fit are reported in the last column of Table VIII.

VIII. TREAT TEST SAMPLE ENERGY DEPOSITION CAPABILITY

Energy deposition capability in test fuel has been estimated without reference to any TREAT energy measurement using the proportionality of fuel monitor wire fissions discussed in Sect. VI.B. Estimates were made in all cases (pre- and post-TREAT Upgrade) where monitor wires were irradiated in maximal controlled transients. Specifically Table IX computes and compares the maximum energy generation (J/g) in fresh fuel under controlled transient conditions for three

Fig. 21. Correlation of Transient Correction Factors in the Full-slotted M8CAL Core

Fig. 22. Comparison of Measured and Fitted Transient Correction Factors in the Full-slotted M8CAL Core

Fig. 23. Correlation of Transient Correction Factors in the Half-slotted M8CAL Core

Fig. 24. Comparison of Measured and Fitted Transient Correction Factors in the Half-slotted M8CAL Core

Fig. 25. Correlation of Transient Correction Factors: Combined M8CAL Full- and Half-slotted Data

Fig. 26. Comparison of Measured and Fitted Transient Correction Factors: Combined M8CAL Full- and Half-slotted Data

TABLE IX. TREAT Test Sample Energy Deposition Capability in a Controlled Transient

TREAT Core Configuration	TREAT Core Reactivity	Maximum Energy Generation in Fresh Fuel, J/g		
		Fuel Composition, wt.%		
		U-10 Zr	U-19 Pu-10 Zr	U-28 Pu-10 Zr
M7CAL Full-slotted	4.6%	6932	6459	---
M8CAL Full-slotted	4.15%	5663	5268	4846
M8CAL Half-slotted	5.8%	9321	8670	7975

TREAT configurations: full-slotted core prior to the TREAT Upgrade and full- and half-slotted core following the upgrade. The number of J/g of fuel was determined in each case by multiplying the following three quantities:

- 1) The absolute number of fissions/g (f/g) from a monitor wire irradiated in a "maximal energy type transient." The transient proceeded from an initial critical rod configuration with all rods either fully withdrawn or banked to the condition of complete withdrawal of the transient rods. The absolute number of fissions/g of monitor wire was determined by radiochemistry. (If the transient included a "power tail"* as in TREAT transient number 2867, Fig. B8, the total number of fissions/g was reduced by the ratio of the energy at the time of the initial rod drop divided by the total energy released in the transient.)
- 2) The ratio of the number of fissions/g per TREAT MJ in fresh fuel divided by the number of fissions/g per TREAT MJ in a monitor wire during a corresponding LLSS irradiation. (The monitor wire in this item has the same composition as the wire in item 1 above, the same control rod configuration is used for both the LLSS fuel and the LLSS wire irradiation, and the two LLSS irradiations were performed within a short time of each other minimizing the effect of a shift in reactor power instrument calibrations; see Sect. VI.B.)

* Transient termination with a "power tail" involves full insertion of the transient rods followed by insertion of the compensation and control/shutdown rods after a 15-s delay.

- 3) The heat generation/fission (J/f) for the specific fuel composition (Sect. VI.A).

A complete set of measurements was available for two of the three TREAT configurations: the pre-upgrade full-slotted core and the post-upgrade half-slotted core. There were no fuel irradiations performed in the post-upgrade full-slotted configuration. To determine the energy generation in the post-upgrade full-slotted core it was assumed that the ratio of the number of fissions/gram of fuel to the number of fissions/gram of monitor wire was the same in both full- and half-slotted cores, and hence this ratio could then be applied to the maximal transient (Table III, Transient 2815) from the full-slotted core. There were no maximal transients performed in the pre-upgrade half-slotted configuration.

In assessing these results for energy deposition capability, it should be pointed out that upper limits of energy deposition and reactivity available for transient control can be either physical or administrative in nature. Typically, in the full-slotted M-series core maximum reactivity is physically limited. Maximum reactivity available to run a transient was 4.6% pre-upgrade. A less-reactive core (4.15%) was used in the full-slotted M8CAL core: not all of the available core fuel positions were loaded with fuel elements. In the M8CAL half-slotted core a reactivity of 6.5% was available physically but only 5.8% permitted administratively (to conform with TREAT operating specifications).[18] We note that upper limits of TREAT energy release in a controlled transient are somewhat transient-dependent but principally determined by available reactivity and independent of the TREAT core loading. In particular, available reactivities 4.15%, 4.6%, and 5.8% correspond to maximal TREAT energy depositions of 1000, 1600, and 1900 MJ, respectively.

IX. CONCLUSIONS

M8CAL has extended the database of TREAT power coupling measurements to the post-upgrade M-series core configurations. Focusing on tests M8 and beyond, measurements concentrated on the half-slotted core. Power coupling measurements were performed on three fuel types including first measurements on high-Pu-fraction fuel. Measured axial peak power coupling factors were within several percent of pre-upgrade values, and their relative values were in reasonable agreement with analytical expectations. Many M8CAL power coupling results are

extensions of and similar to those reported in earlier reports, but a number of new findings will be highlighted in this concluding section.

Axial power profiles were measured by several techniques, including new measurements with low-enrichment monitor wires. It was found that gamma scans of intact irradiated fuel pins agreed well with the axial power profile obtained destructively by counting measurements on individual segments. The measured axial power shape was determined to be the same for each of the three fuel types measured and the same as measured pre-upgrade in the full-slotted core.[4] On the other hand, the axial power profile measured by low-enriched monitor wires drops off more rapidly near the ends, deviating from that measured directly in fuel. It is believed that low-enriched monitor wires without dysprosium filtering gives an accurate axial distribution of thermal neutron flux, but that fuel data is influenced by "end effects," neutron filtering from shaping collars, and fuel self-shielding. Interestingly, in older monitor wire measurements of axial power shape, higher-enrichment wires in filtered holders yielded results that agreed well with fuel.[4] Thus, we conclude that both a monitor wire holder with a 15-mil thick dysprosium filter and the self-shielding of the test lead to similar axial power shapes at the wings of the distribution.

Using a standard assumption concerning the proportionality of test fuel and monitor wire fissions, an extensive series of monitor-wire irradiations were undertaken to empirically determine the dependence of power coupling on control rod position. (Control rod position was significantly changed in the course of TREAT Upgrade.) M8CAL results extended previous studies by (1) including low-level steady-state (LLSS) irradiations with different rod configurations, (2) including movement of transient as well as control/shutdown rods, and (3) correlating data from both full and half-slotted cores. Good correlation between power couplings (TCFs) and control rod position were found. These showed (1) LLSS power coupling depends importantly on whether transient or control/shutdown rods are used to control the reactor and (2) the dependence of power coupling on control rod position is essentially the same for the full- and half-slotted core.

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REFERENCES

1. W. R. Robinson, "Power Calibration Experiment for TREAT Test M2," Argonne National Laboratory Report, ANL-IFR-8 (April 1985).
2. W. R. Robinson, et al., "IFR Safety Tests M2 and M3 in TREAT: Data and Analysis," Argonne National Laboratory Report, ANL-IFR-18 (June 1985).
3. T. H. Bauer, et al., "Update of Safety Testing in TREAT on U-5Fs Fuel: Data from M4 and Combined Analyses of Tests M2, M3, and M4," Argonne National Laboratory Report, ANL-IFR-69 (May 1987).
4. W. R. Robinson and T. H. Bauer, "Power Coupling in TREAT M-Series: New Experimental Results from M7CAL and Updated Analyses," Argonne National Laboratory Report, ANL-IFR-86 (February 1988).
5. T. H. Bauer, et al., "First Overpower Tests of Metallic IFR Fuel in TREAT: Data and Analysis from Tests M5, M6, and M7," Argonne National Laboratory Report, ANL-IFR-124 (December 1989).
6. 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).
7. T. H. Bauer, et al., "Behavior of Modern Metallic Fuel in TREAT Transient Overpower Tests," Nucl. Technol., **92**: 325 (December 1990).
8. R. G. Palm, G. S. Stanford, S. D. Kovaleski, J. P. Regis and C. E. Dickerman, "M8 Power Calibration (M8CAL) Hodoscope Report," Argonne National Laboratory Report in preparation.
9. G. Klotzkin, R. W. Swanson, P. Hart, and L. J. Harrison, "Time Dependence of Test Fuel Power Coupling During Transient Reactor Test Facility Irradiation Experiments," Nucl. Sci. Eng., **86**: 206-18 (1984).

10. G. Klotzkin and R. W. Swanson, Argonne National Laboratory-West, unpublished information (1984).
11. G. Batte, Argonne National Laboratory-West, unpublished information (1992).
12. J. O. Young, Argonne National Laboratory-West, unpublished information (1993).
13. R. W. Swanson, Argonne National Laboratory-West, unpublished information (1993).
14. T. H. Bauer, Argonne National Laboratory-East, unpublished information (1980).
15. J. P. Unik and J. E. Grindler, "A Critical Review of the Energy Released in Nuclear Fission," Argonne National Laboratory Report, ANL-7748 (March 1971).
16. R. W. Swanson, Argonne National Laboratory-West, unpublished information (1993).
17. W. R. Robinson, Argonne National Laboratory-East, unpublished information (1992).
18. "Guide for Irradiation Experiments in TREAT," (June 7, 1991).

APPENDIX A

COMPOSITION OF THE U-ZR ALLOY FLUX MONITOR WIRES AS DETERMINED
BY THE ANALYTICAL CHEMISTRY LABORATORY

ANALYTICAL CHEMISTRY LABORATORY
Argonne National Laboratory
Argonne, IL 60439

REPORT OF ANALYTICAL RESULTS

Sample Material: U-Zr Alloy

Date Received: 10/23/89

Submitted by: D. Kraft

Date Reported: 10/26/89

Your Number	Our Number	SPM BATCH # 140-020-08420-04079				
		Isotopic Analyses, Wt. %				
		<u>U233</u>	<u>U234</u>	<u>U235</u>	<u>U236</u>	<u>U238</u>
M8-1	90-0033-01	<0.0005	0.1114	19.823	0.1378	79.928
M8-2	-02	<0.0005	0.1113	19.840	0.1380	79.911
M8-3	-03	<0.0005	0.1114	19.836	0.1379	79.915
		<0.0005	0.1114	19.833	0.1379	79.918
			± 0.0005	± 0.005	± 0.0005	± 0.005
		Quantitative Analyses by Mass Spec. Isotope Dilution, Wt. %				
M8-1	90-0033-01	6.006 ± 0.006				
M8-2	-02	6.011 ± 0.006				
M8-3	-03	6.006 ± 0.006				

APPENDIX B

GRAPHICAL DATA FROM THE M8CAL TRANSIENTS SHOWING POWER, ENERGY AND TRANSIENT ROD MOTION

- Fig. B1. Transient 2811: Full-slot Core, Heat Balance
- Fig. B2. Transient 2812: Full-slot Core, Heat Balance (Partial)
- Fig. B3. Transient 2815: Full-slot Core, 8-s Reactor Period
- Fig. B4. Transient 2816: Full-slot Core, 8-s Reactor Period (Partial)
- Fig. B5. Transient 2858: Half-slot Core, Heat Balance (Partial)
- Fig. B6. Transient 2862: Half-slot Core, Heat Balance
- Fig. B7. Transient 2864: Half-slot Core, 8-s Reactor Period
- Fig. B8. Transient 2867: Half-slot Core, 30-s Reactor Period
- Fig. B9. Transient 2868: Half-slot Core, 30-s Reactor Period (Partial)
- Fig. B10. Transient 2869: Half-slot Core, 30-s Reactor Period (Partial)
- Fig. B11. Transient 2871: Half-slot Core, 30-s Reactor Period with Power "Roll-over"
- Fig. B12. Transient 2873: Half-slot Core, 80-s Reactor Period
- Fig. B13. Transient 2874: Half-slot Core, 8-s Reactor Period

Fig. B1. Transient 2811: Full-slot Core, Heat Balance

Fig. B2. Transient 2812: Full-slot Core, Heat Balance (Partial)

Fig. B3. Transient 2815: Full-slot Core, 8-s Reactor Period

Fig. B4. Transient 2816: Full-slot Core, 8-s Reactor Period (Partial)

Fig. B5. Transient 2858: Half-slot Core, Heat Balance (Partial)

Fig. B6. Transient 2862: Half-slot Core, Heat Balance

Fig. B7. Transient 2864: Half-slot Core, 8-s Reactor Period

Fig. B8. Transient 2867: Half-slot Core, 30-s Reactor Period

Fig. B9. Transient 2868: Half-slot Core, 30-s Reactor Period (Partial)

Fig. B10. Transient 2869: Half-slot Core, 30-s Reactor Period (Partial)

Fig. B11. Transient 2871: Half-slot Core, 30-s Reactor Period with Power "Roll-over"

Fig. B12. Transient 2873: Half-slot Core, 80-s Reactor Period

Fig. B13. Transient 2874: Half-slot Core, 8-s Reactor Period

APPENDIX C

METHOD OF DETERMINING THE TOTAL ENERGY RELEASED IN THE M8CAL TRANSIENTS

TABLE C1. Determination of TREAT Transient Energy

Core Configuration	Transient	Description	Transient End Time, s	Control Node Energy at Time of "Shutdown Command", MJ	Monitor Node Energy at Time of "Shutdown Command", MJ	Remaining Monitor Node Energy, MJ	Total Energy in Transient, MJ
Full-slotted	2811	HB	16.940	650.0	650.2	$655.6 - 650.2 = 5.4$	655.4
	2812	HB Partial	11.856	399.9	399.9	$404.7 - 399.9 = 4.8$	404.7
	2815	8-s	27.104	994.9	992.4	$993.5 - 992.4 = 1.1$	996.0
	2816	8-s Partial	10.344	649.5	645.9	$658.2 - 645.9 = 12.3$	661.8
Half-slotted	2858	HB Partial	12.400	418.4	417.8	$422.5 - 417.8 = 4.7$	423.1
	2862	HB	17.000	649.9	649.3	$654.4 - 649.3 = 5.1$	655.0
	2864	8-s	30.256	1867.2	1833.7	$1834.9 - 1833.7 = 1.2$	1868.4
	2867	30-s	34.830	1955.6	1906.7	$1907.8 - 1906.7 = 1.1$	1956.7
	2868	30-s Partial	15.330	1187.3	1164.7	$1176.0 - 1164.7 = 11.3$	1198.6
	2869	30-s Partial	10.250	593.7	584.1	$592.5 - 584.1 = 8.4$	602.1
	2871	30-s Roll-over	35.390	1998.8	1954.0	$1955.0 - 1954.0 = 1.0$	1999.8
	2873	80-s	53.264	1797.2	1796.5	$1797.1 - 1796.5 = 0.6$	1797.8
	2874	8-s	29.808	1805.9	1774.0	$1775.2 - 1774.0 = 1.2$	1807.1

* At this time power has dropped to zero and energy does not change.