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M8 POWER CALIBRATION (M8CAL) HODOSCOPE REPORT

by

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Source: M8CAL
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ABSTRACT

TREAT test M8 will be performed to determine, for IFR fuel, the transient fuel-failure threshold and pre- and postfailure fuel movement that could lead to shutdown. The fast-neutron hodoscope, an ex-reactor instrument, measures test fuel motion in a 10-wide by 36-high array of channels. Hodoscope data—both transient and steady state—obtained in M8 power calibration tests are analyzed. Since the transient data are for an unfueled test vehicle, corrections to them are formulated to attain a constant, power-normalized reactor-background response for all channels in a transient. Corrections for axial flux tilt, detector deadtime, detector nonlinearities, and detector efficiencies are described.

Scan data are reported for both fueled and unfueled scans. The hodoscope signal-to-noise ratio is determined from scan data. Finally, both transient and scan data are used to derive a hodoscope performance estimation for test M8. One conclusion is that the smallest mass change that can be detected by the hodoscope on a 4-ms time scale is of the order of 0.55 g of fissile material per pixel, which is some 8% of the portion of the fissile mass of a fuel pin that is subtended by a hodoscope row. Systematic errors that may raise this minimum sensitivity are also evaluated.

The M8CAL data show that there is appreciable axial flux tilting as a function of control-rod position, with the variation from top to bottom of the hodoscope array approaching 20%. Rod-position changes perturb ion-chamber readings as well. Refinements of the hodoscope data-handling algorithms to compensate for those effects are described; some anomalies remain unexplained.

SUMMARY

Hodoscope data from both transient and steady-state reactor operations were analyzed.

A. Summary of Deductions from the M8CAL Transient Data

The M8CAL data show that there is appreciable axial flux tilting as a function of control-rod position, with a maximum variation over the 1.2-m (48-in.) span from top to bottom of the hodoscope array of about 15%. The maximum variation from top to bottom of an M8 pin is about 5%. Rod position perturbs ion-chamber readings as well. The hodoscope data-handling algorithms have been refined to compensate adequately for those effects: Corrections for the variations in axial flux shape have been derived, permitting rod-position corrections to ion-chamber power-monitor data, and axial-tilt corrections to the hodoscope data. The corrected ion-chamber data can now be used to indicate "local power," for accurate power normalization of each hodoscope row, and for determination of deadtimes for the individual data channels by least-squares fitting.

The least-squares process also produces an accurate set of efficiency multipliers—useful for determining preliminary efficiencies from trial transients.

For the highest-power transient in the series (it reached 260 MW), no nonlinear effect in the proportional counters (e.g., pulse-height reduction caused by buildup of space charge* in the counter gas) can be seen that is not adequately handled by a (paralyzable-model) deadtime type of correction. This is not to say that a separable space-charge effect will not be seen in transients that go to appreciably higher power.

There are indications of a delay of the order of 1.5 ms between the occurrence of a power change at the center of the TREAT core and the time it is detected by the hodoscope ion chamber, but this time adjustment is too small to affect M8 analysis. The source of this anomaly is not clear at this time.

B. Summary of Deductions from the M8CAL Scan Data

Analysis of the scan data established a fuel-signal/background ratio and provided an axial response curve for the hodoscope. From the horizontal scans, the fuel-signal/background for the M8CAL fuel was deduced to be ~ 1.15 . "Fuel shine" from neutrons scattered from structural materials near the test section was found to constitute $\sim 16\%$ of the total fuel signal.

Plots of the axial response were assembled from vertical scan data. From scans of unfueled assemblies, the axial distribution of the fast-neutron reactor background was determined,

*If a gas-filled proportional counter is in a high-radiation field, a supply of ions is continually present in the gas, consisting of electrons on their way to the central anode, and positive ions migrating to the outer cathode. The result is a reduction in pulse height, and thus of counting rate, because of partial neutralization of some of the ions created in the ionizing event. This phenomenon is referred to as a *space-charge effect*.

yielding a curve to be subtracted from the scans with test fuel present. Axial peak-to-average fuel power was determined to be 1.11, in good agreement with the radiochemical value of 1.10.

Experimental-error analysis, using the transient and scan data, along with the fissile content of the M8 test fuel, predicts a single-channel mass resolution of 0.55 g for the M8 test.

The horizontal scan data revealed that the M8 calibration test train was misaligned, making the fuel pins appear closer together than the assembly drawings specified.

C. Preparations for the M8 Test

Corrective actions that must be performed before the M8 test include replacing 25 defective detectors, and identifying and rectifying the cause of an observed anomaly in some of the axial scans. Moreover, the hodoscope data acquisition program should be modified so that the true scan positions are written with the proportional counter data.

The hodoscope parameters needed for the M8 pretest transients and scans have been determined. The first pretest hodoscope operation for M8 will be to calibrate the proportional counters, using the new axial distribution determined with the M8CAL vehicle. One horizontal and two vertical scans are recommended, both pretest and posttest. From the horizontal and vertical scans, an optimal collimator alignment can be determined. Having two vertical scans permits each pin to be optimally aligned in one of them. (The alternative, if only one scan should be feasible, is either to choose between compromising on both pins or to align directly on only one.) The horizontal scan should range ~ 456 gauge mils each side of 2160, at a vertical position of 2000 gauge mils. It should be performed before the vertical scans, and analyzed to determine the optimal fixed horizontal position for the vertical scan of each of the pins. The vertical scans should span the maximum available range.

For transient operations, the collimator will be set at the horizontal and vertical positions judged optimum on the basis of the pretransient scans.

I. INTRODUCTION

A. Plan for M8

TREAT test M8 is intended to investigate fuel pin failure mechanisms, margins to failure, and fuel movement, both pre- and postfailure, that could lead to shutdown of a reactor fueled with IFR pins. Test pins will be similar to the EBR-II, Mk-V design. The M8 test vehicle is designed so that two test pins are separately cooled, each in its own sodium flow tube. M8 will test two nominally identical pins that have HT9 cladding with U-19Pu-10Zr fuel, and are irradiated to 11.1 % burnup. One will be intentionally overcooled, so that its failure will lag that of the other pin. Figure 1 provides a plan view of the M8 test. The current plan is to fail the western pin, which is in flow tube 1, on the right as viewed by the hodoscope. Test M8 will employ a power transient with a period of ~ 30 s. This period is slow enough to promote creep rupture clad failure driven by fission-gas plenum pressure. TREAT power will be reduced as soon as possible after the first pin fails, to keep the overcooled pin from failing. Failure of the first pin will be indicated by a sudden reduction in sodium flow. This change in flow will trigger a reduction in TREAT power to a low, gradually decreasing "shelf". The purpose of this power shelf is to allow limited fuel-motion monitoring until fuel freezes.

B. Control-rod Configuration

Figure 2 shows the radial locations of the various control rods in the configuration of TREAT used for M8CAL. All the rods of a given type were operated in a ganged mode. M8 will be the first TREAT experiment to use this rod mode. For this reason, the M8CAL hodoscope analysis was much more detailed than for previous M-series tests. To run the transients, the control/shutdown rods and compensation rods were fully withdrawn, and then the reactivity was controlled with the transient rods. At the very end of the run, the reactor was scrammed, with all rods driving to their full-in position. Figure 3 shows the axial ranges of motion of the various control rods.

C. Instrument Locations

The instruments that monitor and control TREAT power for a transient are uncompensated ion chambers that are located in instrument penetrations at the corners of the reactor, near the midplane. Considering that information along with the control-rod layout in Fig. 2, one might expect that motion of the transient rods would affect the accuracy of the correlation between instrument readings and actual TREAT power.

The instruments that monitor and control TREAT power for low-power runs such as are used for scans are compensated ion chambers located in instrument penetrations near the center of the west face of TREAT (at the right in Fig. 2). At this location, the instruments would be expected to be even more sensitive to transient-rod position than instruments at the corners. Fortunately, the range of rod motion for scans is typically small. Normally, the control/shutdown rods are used to control low-level runs.

D. The Fast-neutron Hodoscope

M8 test objectives require using the fast-neutron hodoscope[2] at TREAT. This ex-core instrument can cine-radiographically measure spatially resolved fuel motion down to a millisecond time scale. It monitors test-fuel distributions within thick-walled, opaque test vehicles during TREAT power transients and steady-state runs, using a massive, multi-slotted collimator with a gas proportional counter associated with each slot. Each collimator slot has a Hornyak button detector as backup. Fast neutrons emitted by the test fuel penetrate the test vehicle wall travel through a passageway in the core and move into the collimator slots to be counted by the detectors. Each slot and its neutron detector are referred to as a single hodoscope channel. The fuel volume contributing neutrons to a particular channel's counts corresponds to a single pixel in the hodoscope image. The pixel (channel) counts are reconstructed into radiographic images related to fuel mass, and are directly used for quantitative analysis. There are 360 hodoscope channels arranged in a 10-column by 36-row array. The array views a test region that is 66 mm wide by 1245 mm high. Figure 4 shows plan and elevation views of the hodoscope at TREAT. The location of the M8 test vehicle is labeled "TEST SECTION"

in the elevation view, and appears as a small circle at the south end of the slotted elements in the plan view.

For transients, counting is done in time-resolved mode, and after data reduction, the counts are related to fuel mass. The hodoscope is also used in a scan mode before and after high-power test transients. A scan is performed with minimal reactor power (~ 80 kW) so the test fuel remains stationary. The scan mode provides increased spatial resolution compared to the transient mode. A pretest scan is useful to confirm that the test has been properly assembled and no shipping damage has occurred. Comparison of posttest and pretest scans provides the first high-resolution view of fuel rearrangement. For a scan, the collimator is stepped horizontally or vertically in small increments, and counts from every channel are measured after each step. It is this collimator movement in small steps that provides increased spatial resolution compared to fixed-collimator transient operation. Separate horizontal and vertical scans are performed.

E. Hodoscope Ion Chamber

Hodoscope analysis uses power data from the TREAT control system. There also is a hodoscope (uncompensated) ion chamber mounted on top of the rear collimator, just outside the reactor shield. This ion chamber can be used as a power monitor for transients and horizontal scans, but not for vertical scans.

F. Hodoscope Runs for M8CAL

In the course of the M8 calibration experiments in TREAT, the hodoscope was run for eight of the transients, and hodoscope scans were done in conjunction with seven low-level, steady-state (LLSS) experiments. These experiments are listed in Table I.

There was no test fuel present for any of the transients, but there was test fuel for scan Operations 20 and 21. This report summarizes results of examining the hodoscope data collected during those tests. In this report, the transients are referred to by their transient

TABLE I. M8CAL Hodoscope Experiments

Transients:

Oper. (Seq.)	Trans. No.	Hodo. Transient Specs; Slot	Type	Description	Completed	Peak Power; Total Energy
19	2811	R0206-1290-SF-00 Full	HB	Full heat-balance transient; "fueled" test train, but with no fuel	10/25/90	50 MW 655.6 MJ
21	2815	R0206-1291-SF-00 Full	Trial	8-s heat-balance transient	11/14/90	230 MW 993.5 MJ
7	2862 HB-7	R0206-1310-SF-00 Half	HB	Heat-balance transient flux- wire irradiation	9/23/92	50.7 MW 654 MJ
10	2864 M8uf-10	R0206-1311-SF-00 Half	Trial	"8-s period" transient flux-wire irradiation	10/14/92	261.5 MW 1835 MJ
23	2867 M9uf-23	R0206-1312-SF-00 Half	Trial	"30-s period" transient	10/27/92	138 MW 1908 MJ
24	2868	R0206-1312-SF-00 Half	Trial	"30-s period" transient, partial	10/29/92	1176 MJ
25	2869	R0206-1312-SF-00 Half	Trial	"30-s period" transient, partial	10/30/92	592.5 MJ
14	2873 M9uf-14	R0206-1312-SF-00 Half	Trial	M8CAL "80-s period" transient, with flux wire	11/19/92	60.7 MW 1797 MJ

Scans (Horizontal and Vertical):

Oper. (Seq.)	Expt.	Hodo. Scan Specs Slot	Type of Run	Completed	Peak Power; Total Energy
18	Bkg-18	R0206-1289-SF-00 Full	LLSS background scan without fuel	10/19/90	80 kW 667 MJ
19	Bkg-19	R0206-1309-SF-00 Half	LLSS hodoscope background measurements; unfueled	8/26/92	80 kW 576 MJ
16	BWire-16	R0206-1306-SF-00 Half	LLSS flux wire irradiation; unfueled	11/20/92	60 kW 576 MJ
20	TFuel-20	R0206-1307-SF-00 Half	LLSS fuel irradiation	1/29/93	80 kW 480 MJ
22	BWire-28	R0206-1308-SF-00 Half	LLSS unfueled	2/8/93	80 kW 480 MJ
28	BWire-28	R0206-1306-SF-00 Half	LLSS unfueled	3/2/93	80 kW 576 MJ
21	HFuel-21	R0206-1308-SF-00 Half	LLSS fuel irradiation	3/5/93	80 kW 480 MJ

number, while the scans are referred to by their operation (sequence) number. The hodoscope viewed the M8 calibration vehicle in these tests; this vehicle is neutronically similar to the M8 test vehicle. A separate report[1] describes the entire M8 power calibration series.

Hodoscope data for some of the transients were evaluated for axial flux tilt, detector dead-time, and detector nonlinearities. Determination of the data-reduction parameters necessary to produce a uniform (flat ratio of detector count rate to reactor power) for the unfueled M8 calibration transients was made. Application of these parameters to the M8 test data will accurately reveal the test-fuel signal above the reactor-background signal. The count rate from a typical detector in the M8 calibration series is used to predict the single-channel mass resolution.

Scan data were obtained from both fueled and unfueled operations. The scan data were evaluated to determine the ratio of fuel signal to reactor background, the fuel shine, the horizontal separation of the fuel pins, and the vertical hodoscope response function. A signal-to-background ratio was determined from the horizontal scans, and used to determine the single-channel mass resolution. "Fuel shine" refers to test-fuel neutrons scattered into the hodoscope from structures near the test fuel. Shine causes systematic errors in the hodoscope data.

The horizontal scan data revealed that the M8 calibration test train was misaligned, making the fuel pins appear closer together than the assembly drawings specified.

A vertical hodoscope response function, assembled from the scan data, can be used to improve pretest calibration of the hodoscope detectors. It also provides an easily interpretable axial fuel distribution.

A performance prediction for the M8 test can be stated as the anticipated single-channel mass resolution. This prediction, based on examination of the experimental error, indicates that a mass change as small as 0.55 g of fissile material in a channel can be detected. The time scale for this mass loss is 4.36 ms, the anticipated hodoscope resolution interval for the M8 test. Systematic errors in the hodoscope data are discussed.

II. ANALYSIS OF M8CAL TRANSIENT DATA

A. Overview of the Transients

In analyzing the M8CAL transient data, we concentrate on transients 2864, 2867, and 2873 (see Table I). In that series, the peak power is halved in going from one transient to the next, while the total energy remains approximately constant (with the result that the range of transient-rod motion is about the same in the three tests), and the power profiles are typical of what is expected in an M8 test. Thus, the three transients are well suited to an investigation of the effects of deadtime, space-charge induced nonlinearity, and rod-induced axial flux tilting. For comparing the three transients in this report, our policy will be to proceed from the lowest-power run to the highest—i.e., the sequence of transients will be: 2873, 2867, 2864.

Figures 6 through 8 contain plots of the TREAT power, energy, and transient-rod position as seen by the TREAT instrumentation. Note that in each case, when the desired energy has been reached, the power is "clipped" by a partial rod insertion, producing a 15-s "shelf" before scram. The purpose of the shelf is to maintain counting statistics for a while, so the hodoscope can monitor the posttest fuel configuration.

The average counting rate of the hodoscope detectors (the "array average") has frequently been used to indicate TREAT power, although it was known to be distorted somewhat by dead-time and other nonlinearities. Figures 9 through 11 contain semilog plots of TREAT power as represented by the hodoscope array average and the ion chamber.

At any given time there usually are a few malfunctioning channels in the hodoscope array. The bad channels for Operation 20 are shown in Fig. 5.

B. Response of the Uncompensated Ion Chamber

Figures 12 and 13 extend the time frame covered by Figs. 10 and 11, showing a stretch of about 400 s following scram. The array average, which is highly insensitive to gammas,

falls off more-or-less as one would expect of the delayed-neutron intensity. The ion chamber, however, almost levels off after scram—as one would expect for a detector that has significant sensitivity to gamma rays as well as neutrons. The discrepancy is more clearly illustrated in Figs. 14 and 15, which contain plots of the ratio of the array average to the ion chamber. We note that the drop-off for the high-power run continues longer than for the other run, even though the integrated powers were about the same (the lower-power run went to about 4 % more energy); this is not understood.

We conclude that an uncompensated ion chamber (such as the TREAT instruments used to monitor reactor power during a transient) cannot provide accurate power data following full scram. This, however, does not prevent construction of fuel mass distributions following full scram.

C. Axial Tilting

1. Counting Data vs Time

The hodoscope data from the M8CAL tests show that as the transient rods are withdrawn (see Figs. 2 and 3), the axial power distribution in TREAT changes. With the rods extending below the reactor fuel (which the transient rods cannot quite do) or all the way out, one would expect the flux to be symmetrical about the midplane. As the rods rise, the flux near the bottom of the reactor should increase first more rapidly, then less rapidly than the flux higher up. Because M8 is the first TREAT test to be performed with ganged transients rods, particular attention was given to study of possible axial flux tilt effects.

For the at-power and shelf segments of the three transients, the correlation between the ion chamber and the hodoscope detectors at various axial positions was investigated. The hodoscope field of view was divided into four equal axial zones of nine rows each, and the average ratio for each zone was plotted as a function of time. Figures 16 through 18 show the results. Qualitatively, at least, the divergences and gross trends are in the directions that one would predict. Being on top of the collimator, the ion chamber would be expected to follow

the flux in the upper half of the core, and the curves for the two top zones do tend to be closer to horizontal than the two lower ones.

The shallowness of the slopes of the curves at scram, in this group of three figures and the next group, is deceptive, being an artifact of the large averaging intervals that were needed to get good statistics.

As mentioned above, the hodoscope array average has often been used as a surrogate for the actual TREAT power, substituting for the ion chamber. It too is affected by rod-induced flux tilts, but in a somewhat different way. Figures 19 through 21 correspond to the preceding three figures, this time using the array average as the reference.

2. Axial Profiles

A more direct way to look at the flux tilts is by means of axial profiles, as in Fig. 22, where the data are averaged over columns 2 through 9. To produce this figure, for each transient the time at power was divided into six equal time slices, and then the axial profile for each slice was calculated. (This is equivalent to choosing approximately the same rod positions.) The curves for the last time slice are constrained to be approximately flat because that is the approximate time interval that was used to determine the efficiency multipliers for the individual data channels. The actual ordinate values of the various curves are not significant, since each curve is vertically positioned to illustrate the correlation in tilt from transient to transient.

The axial tilt (zero, by definition, for the first time slice) is seen to change progressively as time passes—i.e., as the transient rods rise. The fact that the curves in each set of three track each other confirms that the tilt is primarily a function of rod position rather than power level.

Figure 23 is a similar set of three curves, for the trailing 15-s power shelf. Again, considering the counting statistics, the agreement is reasonably good.

For a more careful correlation with rod position, time slices were selected that centered around the same rod positions. The results for the at-power times are presented in Figs. 24 through 26. (Normalizing to the ion chamber does not affect the shape of the individual curves, but merely serves to group them on the graph.)

D. Deadtime

All counting circuits have a deadtime—a period after a pulse during which additional events are not counted. The subtleties of deadtime correction can be complex, and we will not go into them here. For counting rates that are not too high, the correction is not sensitive to the details of the deadtime model used. For the record, we used the *paralyzable model*. Traditionally, and with some experimental basis, a deadtime of $0.5\ \mu\text{s}$ has been used for the hodoscope system. The M8CAL transients give us an opportunity to test this, because we have, for the same transient-rod position, a very-low-power shelf and a relatively high-power time during the transient. Also note that the actual counting rates are considerably higher for the detectors near TREAT midplane than for the ones at the top and bottom. Work with the M8CAL data confirmed that $0.5\ \mu\text{s}$ was indeed reasonable, but that $0.7\ \mu\text{s}$ was a slightly better average value.

Deadtime and (for proportional counters) space-charge effects are functions of counting rate that depress the counting rate nonlinearly as counting rate increases. Thus, it might be expected that a "deadtime" correction derived from counting-rate data would necessarily include at least partial compensation for space-charge effects. In this report the terms "nonlinearity" and "space-charge effects" apply only to any residual counting-rate-dependent effects that are not adequately handled by "deadtime" corrections.

Figure 27 shows the axial profiles for the lowest-power transient (2873), for the shelf (upper two curves) and the at-power time for the same rod position, with no deadtime corrections applied. The curves are relatively close to each other at the ends, but deviate in the middle, where the counting rates are higher. Applying a $0.7\text{-}\mu\text{s}$ deadtime leads to Figs. 28

through 30. Those plots show that $0.7\ \mu\text{s}$ does about as well as one could expect from applying the same deadtime to every detector in the array. More-accurate, individual deadtimes are derived later.

E. Tilt Corrections

The result of applying the four fundamental corrections to a set of hodoscope data—deadtime, nonlinearity (space charge for proportional counters and supralinearity* for Hornyak buttons), flux tilt, and efficiency—is to be a field that remains flat if there is no test fuel, and, if there is fuel, remains constant prior to fuel motion.

The tilt correction will consist of a multiplier (or divisor) that is a function of hodoscope row and transient-rod position. It must be normalized somewhere, and we arbitrarily decide that it will be unity for all rod positions at row 18, and unity (zero tilt) for all rows at rod position 16.4 in. Given that deadtime effects are small for the low-power transient 2873, and on the assumption that space-charge effects are negligible, the tilt corrections can be derived from that transient. Figure 31 shows quadratic fits derived from the axial profiles. Although cubic fits are somewhat better, the quadratic ones seem to be accurate to within a percent or so, which is adequate and probably all that is justified within the experimental error.

Figure 32 shows linear fits vs rod position of the coefficients from Fig. 31. A first-degree fit is satisfactory in each case.

We can now go through the algebra of correcting for flux tilts. We will use the following symbols:

*In working with Hornyak buttons, it has been observed that the counting rate increases more rapidly than the incident flux. This *supralinearity effect* is ascribed to an increase in photomultiplier multiplication due to changed voltages in the divider string.

- C = counting rate corrected for tilt,
T = position of transient rods,
Q = "relative counting rate" (ordinate) in the axial profiles of Fig. 31,
R = observed counting rate (corrected for deadtime, and possibly nonlinearity, but not necessarily for efficiency), before correcting for tilt, and
W = hodoscope row.

The quadratic fits in Fig. 31 have the form

$$Q(W) = aW^2 + bW + c, \text{ where } Q(18) = 1. \quad (1)$$

The linear fits in Fig. 32 are

$$a = gT + h, \text{ } b = iT + j, \text{ and } c = kT + m, \quad (2)$$

where a, b, and c are the coefficients in Eq. (1), and the values of g,h,i,j,k, and m are given in Fig. 32. Equation (1) becomes

$$Q(T,W) = (gT+h)W^2 + (iT+j)W + (kT+m), \quad (3)$$

and the corrected counting rate C is given by

$$C = R/Q(T,W). \quad (4)$$

When this correction is applied to the data plotted in Fig. 24 (and 31) for the low-power run, Fig. 33 results. The flatness of these curves is acceptable.

Figures 34 and 35 show the results of tilt-correcting the data from the two higher-power transients. For transient 2864 (Fig. 35), in particular, although the tilt is largely corrected (compare Fig. 26), the data get progressively more uneven as the transient proceeds; at least

in part, this is due to problems in correcting the data for multiple overflows in some channels (the counting interval for these transients was 28 ms).

Figures 36 through 38 are the tilt-corrected versions of Figs. 27 through 30. The tilt for the high-power and low-power profiles at the same rod position is seen to be similar.

F. Development of a Power Reference

There is considerable channel-to-channel variation in effective deadtime, so for analyzing hodoscope data it is necessary to determine for each channel an individual deadtime (along with, possibly, a correction for sublinearity due to the space-charge effect). This can be done by requiring that, in the absence of fuel motion, the counting rate for each scaler track the neutron flux to which the viewed pixel is exposed—which we will call the *local power*; it varies from row to row because of the changing tilt in the axial flux. Thus, a valid local-power reference is needed for each row of detectors.

In principle, an ion chamber makes an excellent power monitor, since the ion current is not subject to the deadtime and space-charge problems that can afflict a counter. We develop here a method for using an ion chamber—either the one on the hodoscope or one of the TREAT instruments—as an instrument to track the local power.

The method involves (a) using data from a low-power transient (2873), where deadtime effects are small enough that first-order deadtime corrections are accurate, along with the hodoscope tilt adjustments derived above (normalized to row 18), to determine a tilt-corrected hodoscope array-average signal as a function of time; (b) plotting the ratio of ion-chamber signal to that array average as a function rod position; (c) determining a correction multiplier $f(T)$ (where T is rod position) that causes the ion chamber to track the array average; and (d) applying the hodoscope tilt correction (function of row and rod position) to the corrected ion-chamber signal.

Figure 39 is a flow chart depicting the calculational steps, involving the hodoscope data-processing program DGL and a plotting package, leading to the function $f(T)$ for correcting the

ion-chamber data for rod position. The resulting data and least-squares quadratic fit are shown in Fig. 40. The data cover the complete time span from the start of the test until scram, which includes the trailing, low-power shelf, the points for which are at 25–26 in.

Now we are in a position to determine the local power for each hodoscope row. Noting that the rod-position-corrected ion chamber is normalized to match hodoscope row 18 (since the array average used to determine $f(T)$ was so normalized), all we need to do is to *tilt* the corrected ion-chamber data for the row under consideration. A least-squares fitting process can then determine the deadtime for each channel.

G. Determination of Individual Deadtimes and Efficiencies

The goal of counting-rate corrections is to cause the corrected rate R_c to be a linear function of the local power P_w in the absence of fuel motion:

$$R_c = G_z + k_z \cdot P_w, \quad [\text{no fuel motion}] \quad (5)$$

where the intercept G_z is presumably very small. The coefficients G_z and k_z are to be determined in the course of a least-squares fitting process. *Note that for the trial transient (no fuel), k_z is inversely proportional to the "efficiency" multiplier if G_z is negligibly small.*

Experience with the very high counting rates in the TREAT equation-of-state (EOS) experiments showed that the paralyzable deadtime model is appropriate for the hodoscope system. The rigorous equation for the paralyzable (extendable deadtime) case is

$$R_d = R_m \cdot e^{-T_h R_d}, \quad (6)$$

where T_h is the deadtime, R_m is the measured counting rate, and R_d is deadtime-corrected.

Assuming for now the absence of space-charge nonlinearities that are distinguishable from deadtime effects, we can replace R_d with R_c in Eq. (6):

$$R_c = R_m \cdot e^{Th \cdot R_c}, \quad (7)$$

Equation (7) can not be solved analytically for R_c , so it must be solved by numerical iteration. Let $f_\theta(R_m, P_w, Th)$ be the result—i.e., $R_c = f_\theta(R_m, P_w, Th)$, which can be substituted for R_c in Eq. 5:

$$f_\theta(R_m, P_w, Th) - k_z \cdot P_w - G_z = 0. \quad (8)$$

Program NONLIN can determine, for each scaler, the least-squares values of G_z , k_z , and Th . It is also possible to constrain G_z to be zero, so that only k_z and Th are fitted; this seems to give slightly better results.

As mentioned above, k_z is the reciprocal of the efficiency multiplier, so that the least-squares process determines both deadtimes and efficiencies. The flow chart in Fig. 41 shows the logic sequence of DGL and NONLIN processing for finding the deadtimes and efficiency multipliers. Once those have been determined, they are applied in a DGL run as outlined in Fig. 42.

Figures 43 through 45 show plots of the ratio of array average to ion chamber (corrected for rod position) for the three transients, after the counting rates have been corrected for tilt and for individual deadtimes and efficiencies as determined according to the above procedure. After the initial power rise—rods above 16 in., times after 5–6 s—the fit is reasonably good.

For all three transients, however, there is an initial pronounced drop of about 20%, corresponding to the initial steep power rise. Observe, also, that in all three cases there is an isolated datum, about 2-3% low, at the time of the rod clip preceding the shelf. A possible explanation is presented in Sect. II.I.

H. Adequacy of the Corrections

We noted above [see Eq. (5)] that the data corrections should be such that

$$R_c = k_z \cdot P_w, \quad [\text{no fuel motion}] \quad (9)$$

which is Eq. (5) with G_z constrained to be zero. This can be rewritten

$$(R_c/k_z)/P_w = 1, \quad (10)$$

where R_c/k_z is the efficiency-corrected, deadtime-corrected counting rate of an individual channel. Thus, plotting R_c/k_z vs time should yield a horizontal line at the ordinate 1.00. To illustrate the adequacy of the corrections, such plots for all 36 channels in column 6 are presented in Figs. 46 through 48, for the highest-power transient. In each of those figures, the zero is suppressed, and the curves above the bottom one are successively displaced vertically by 0.1 unit. The data following scram are not plotted, because the uncompensated ion chamber does not track the reactor power in that region (see Fig. 6).

For times after 5 s (i.e., after the initial steep power jump), Eq. (10) is satisfied, considering the statistics, to within $\pm 1\%$ or so. This is taken as confirmation that the data adjustments have been correctly made.

I. Delayed Response of Ion Chamber

We called attention above to some small anomalies in the data plotted in Figs. 43 through 45—the initial drop of about 20% in the curves, corresponding to the initial steep power rise, and an isolated datum (about 2-3% low) at the time of the rod clip preceding the shelf. Three possible explanations come to mind:

- (a) The time-constant of the hodoscope ion chamber might be long enough to account for the observed effect, since the response time of the hodoscope is extremely short,

- (b) The hodoscope sees what is happening at the center of the core, and the ion chamber is outside the biological shield. If it took an appreciable time for an event in the core to manifest itself at the ion chamber, that could account for the observed effects, and
- (c) Since the ion chamber is uncompensated, one might expect it to show a finite time constant for a sizeable power step, as the gamma-ray intensity catches up with the new power.

With regard to explanation (a), information from D. M. Ray[3] indicates that the time constant of the hodoscope ion chamber is $30\ \mu\text{s}$, which is far too short to account for the effect. (However, the TREAT ion chambers have time constants that tend to be longer—from $50\ \mu\text{s}$ to 10 ms, depending on the detector and the range; this might become a factor if one of those instruments were to be used as the power reference.)

To investigate explanation (b), calculations based on Figs. 8 and 45 revealed that a delay of the order of milliseconds between the core and the ion chamber might account for part of what is observed. This was checked out by subtracting several fixed times from the time for the ion-chamber data. The subtracting was done in Program FUDGE, Figs. 49 through 51 show the results of advancing the ion-chamber time by 1.0, 1.5, and 2.0 ms (the data with no time adjustment are plotted in Fig. 45). Obviously there is no appreciable improvement for the initial power rise. For the power clip at 15 s, the best compromise is 1.5 ms, but it does not completely resolve the discrepancy: The low point is raised, but so are points just preceding the clip. In any event, this anomaly is too small to affect M8 fuel-motion analysis.

J. NONLIN Output

Program NONLIN performs the least-squares fitting of the counting rate to the local power. It is derived from, and intended to replace, the old codes SUPRA and PCA for doing nonlinearity corrections. (As of now, however, there is no demonstrated need—for determining anything beyond deadtimes and efficiencies; recall that first-order space-charge, and probably supralinearity, corrections are subsumed in the deadtime algorithm.)

TABLE II. An Example of the Printout of Input and Output Information from Program NONLIN

```

                                I/O INFORMATION
                                -----

Input:
-----

Transient No.: 2864           Date: 20-APR-94           Time: 15:34:13

DGL File: TILT.DG4C

Parameter File: TILT.PNLDG4

Store NONLIN Corrections? N


Fit Model: D           Deadtime Type: P           Power Reference: FD( 5)

Power Reference Multiplier:      1.000

Data Collection Time (msec):      28.000

Data Fitted: Scaler

Number of Averaging Slices:      3

Slice Number:      1      Slice Number:      2      Slice Number:      3
Min. Time:      0.000      Min. Time:      5.000      Min. Time:      15.000
Max. Time:      5.000      Max. Time:      15.000      Max. Time:      30.000
No. Averaged:      10      No. Averaged:      5      No. Averaged:      10

Scaler number: 195

Output:
-----

Chi**2: 0.0665      Weighted Ave. Error: 3.5884E+04

Ave. Fit Var.: 2.3867E+03

Final Fit Values and Statistics:

Parm.      Value      Fixed/Not Fixed      Std. Deviation
-----
A      0.0000E+00      Fixed      0.0000E+00
k      3.5881E-01      Not Fixed      2.1367E-05
T      8.7067E-07      Not Fixed      1.7164E-10
G      0.0000E+00      Fixed      0.0000E+00

```

TABLE III. A NONLIN Listing of the Input Data and Deviations from the Fitted Curve;
Scaler 195 (The data extend through the shelf.)

FITTING INFORMATION					

Transient No.: 2864		Date: 20-APR-94		Time: 15:34:13	
DGL File: TILT.DG4C					
Scaler number: 195					
Pt.	Time (s)	Power	Data (C/s)	Data-Fit	% Stat. Error

1	2.2380	41332.75	15109.67	452.116	0.389
2	4.7198	253522.22	85653.52	1532.047	0.446
3	5.1548	342527.13	110694.58	169.242	0.568
4	5.4351	361294.47	118228.02	2347.539	0.550
5	5.7156	376748.91	121100.95	861.195	0.543
6	5.9962	388416.78	124049.23	555.398	0.537
7	6.2769	398953.19	127451.55	1045.797	0.529
8	6.5572	408947.50	129687.64	537.508	0.525
9	6.8377	413890.25	130133.50	-355.664	0.524
10	7.1182	421837.81	131894.53	-750.703	0.520
11	7.3988	439667.59	136637.91	-819.656	0.511
12	7.6793	453173.00	141260.11	199.859	0.503
13	7.9598	466721.91	143870.47	-769.797	0.498
14	8.2403	478891.94	147222.47	-600.984	0.493
15	8.5210	490285.06	151253.59	478.938	0.486
16	8.8013	504409.19	154036.39	-371.531	0.482
17	9.0818	525669.56	159071.08	-752.375	0.474
18	9.3623	542526.69	163876.06	-174.609	0.467
19	9.6431	559431.38	167986.61	-254.250	0.461
20	9.9234	577707.38	172752.61	33.000	0.455
21	10.2039	592887.75	175024.97	-1361.563	0.452
22	10.4844	610941.50	180384.03	-318.141	0.445
23	10.7650	625210.25	184318.72	255.422	0.440
24	11.0454	639832.63	187134.41	-336.516	0.437
25	11.3259	656204.69	192397.47	1147.641	0.431
26	11.6065	673637.63	194682.00	-543.453	0.428
27	11.8870	696512.44	199305.17	-1068.234	0.423
28	12.1254	714548.94	203228.20	-1145.438	0.501
29	12.2936	726418.31	206243.13	-730.453	0.588
30	12.4339	737691.38	209438.78	13.359	0.584
31	12.5741	748651.69	210203.55	-1583.703	0.583
32	12.7144	757743.13	213295.50	-432.859	0.579
33	12.8551	768435.94	215633.17	-364.469	0.576
34	12.9949	777486.63	218521.28	626.188	0.572
35	13.1352	786675.63	219457.38	-356.000	0.571
36	13.2754	798593.63	224018.33	1730.234	0.565
37	13.4157	809321.63	224038.00	-452.844	0.565
38	13.5559	819340.63	229852.70	3320.656	0.557
39	13.6962	827699.38	227307.25	-908.656	0.561
40	13.8366	838955.31	229544.33	-930.000	0.558
41	13.9769	847480.63	232890.03	725.109	0.554
42	14.1169	857555.63	232299.50	-1852.031	0.555
43	14.2572	867215.81	237651.17	1614.500	0.548
44	14.3975	875675.50	236835.30	-834.188	0.549
45	14.5377	883720.13	241483.63	2277.469	0.544
46	14.6780	895199.63	240893.17	-507.688	0.545
47	14.8182	903568.19	242552.95	-410.078	0.543
48	14.9446	912921.69	246193.38	1484.672	0.602
49	15.1549	809416.81	220534.70	-3678.906	0.384
50	16.1509	111370.78	38222.03	-239.004	0.395
51	18.2406	73242.95	25489.33	-95.277	0.397
52	21.4805	44302.79	15800.30	186.753	0.399
53	26.6700	24336.49	8791.23	161.012	0.422

TABLE IV. A NONLIN Listing of the Moving Values of the Fitted Parameters; Scaler 195
(The data extend through the shelf.)

COEFFICIENT INFORMATION						

Transient No.: 2864		Date: 20-APR-94		Time: 15:34:13		
DGL File: TILT.DG4C						
Scaler number: 195						
Pt.	Time (s)	Power	A (xE-6)	k	Th (xE-6)	G

6	5.9962	388416.78	0.0000	0.3710	1.0245	0.00
7	6.2769	398953.19	0.0000	0.3699	1.0038	0.00
8	6.5572	408947.50	0.0000	0.3711	1.0264	0.00
9	6.8377	413890.25	0.0000	0.3747	1.0932	0.00
10	7.1182	421837.81	0.0000	0.3782	1.1538	0.00
11	7.3988	439667.59	0.0000	0.3803	1.1870	0.00
12	7.6793	453173.00	0.0000	0.3774	1.1410	0.00
13	7.9598	466721.91	0.0000	0.3777	1.1456	0.00
14	8.2403	478891.94	0.0000	0.3768	1.1324	0.00
15	8.5210	490285.06	0.0000	0.3734	1.0782	0.00
16	8.8013	504409.19	0.0000	0.3723	1.0621	0.00
17	9.0818	525669.56	0.0000	0.3718	1.0533	0.00
18	9.3623	542526.69	0.0000	0.3700	1.0262	0.00
19	9.6431	559431.38	0.0000	0.3686	1.0056	0.00
20	9.9234	577707.38	0.0000	0.3671	0.9819	0.00
21	10.2039	592887.75	0.0000	0.3675	0.9885	0.00
22	10.4844	610941.50	0.0000	0.3665	0.9738	0.00
23	10.7650	625210.25	0.0000	0.3652	0.9541	0.00
24	11.0454	639832.63	0.0000	0.3646	0.9461	0.00
25	11.3259	656204.69	0.0000	0.3631	0.9228	0.00
26	11.6065	673637.63	0.0000	0.3630	0.9215	0.00
27	11.8870	696512.44	0.0000	0.3632	0.9244	0.00
28	12.1254	714548.94	0.0000	0.3633	0.9269	0.00
29	12.2936	726418.31	0.0000	0.3631	0.9231	0.00
30	12.4339	737691.38	0.0000	0.3623	0.9130	0.00
31	12.5741	748651.69	0.0000	0.3628	0.9192	0.00
32	12.7144	757743.13	0.0000	0.3625	0.9149	0.00
33	12.8551	768435.94	0.0000	0.3622	0.9110	0.00
34	12.9949	777486.63	0.0000	0.3615	0.9022	0.00
35	13.1352	786675.63	0.0000	0.3613	0.9003	0.00
36	13.2754	798593.63	0.0000	0.3604	0.8885	0.00
37	13.4157	809321.63	0.0000	0.3604	0.8887	0.00
38	13.5559	819340.63	0.0000	0.3591	0.8730	0.00
39	13.6962	827699.38	0.0000	0.3594	0.8766	0.00
40	13.8366	838955.31	0.0000	0.3597	0.8797	0.00
41	13.9769	847480.63	0.0000	0.3594	0.8764	0.00
42	14.1169	857555.63	0.0000	0.3599	0.8822	0.00
43	14.2572	867215.81	0.0000	0.3594	0.8761	0.00
44	14.3975	875675.50	0.0000	0.3596	0.8782	0.00
45	14.5377	883720.13	0.0000	0.3589	0.8712	0.00
46	14.6780	895199.63	0.0000	0.3591	0.8727	0.00
47	14.8182	903568.19	0.0000	0.3592	0.8737	0.00
48	14.9446	912921.69	0.0000	0.3587	0.8689	0.00
49	15.1549	809416.81	0.0000	0.3588	0.8708	0.00
50	16.1509	111370.78	0.0000	0.3588	0.8706	0.00
51	18.2406	73242.95	0.0000	0.3588	0.8706	0.00
52	21.4805	44302.79	0.0000	0.3588	0.8706	0.00
53	26.6700	24336.49	0.0000	0.3588	0.8707	0.00

The type of output that can be obtained from NONLIN is illustrated in Tables II through IV and Figs. 52 and 53, which are for scaler 195 (row 20, column 5). In these figures, the symbol A is reserved for a future nonlinearity parameter, and k, t, and G are, respectively, the k_z , T_h , and G_z used in Eqs. (5) through (8). Figure 52 is a plot of rate/power, after rate has been corrected for the deadtime derived in the process. This plot is equivalent to those of Figs. 46 through 48, but plotted against power rather than time, and with the time cut off just before the power clip. Figure 52 is plotted from the data for the first 48 points listed in Table III.

As a user option, NONLIN can calculate the "moving values" of the fitted parameters—that is, the values as determined from the first six points, the first seven points, the first eight points, and so on, permitting one to observe the evolution of the values as the power increases. Such data are listed in Table IV and the deadtime values through point No. 48 are as a function of power in Fig. 53. We see that the deadtime settles down eventually to a value of $0.87 \mu s$, after an early rise to almost $1.2 \mu s$. Other channels show similar behavior. The initial high values are probably due to the delayed response of the ion chamber, commented on above.

III. SCAN DATA

A. Scan Overview

Table I lists the seven M8 calibration scans. These scans are referred to by their operation number. Thus, Operation 20 refers to the fueled scan performed on January 29, 1993. Operations 18 and 21 are not discussed in this report. Separate horizontal and vertical scans were performed for each operation. Appendix C describes how the scan data are processed. Separate scan data are attained from each functional channel. Row-averaged horizontal scan data are also assembled from each row. The row averaged data are less noisy and view a wider portion of the test region.

A scan proceeds by sweeping the collimator a fixed distance to new position, counting neutrons at this position for a fixed time, and sweeping the collimator on to the next position.

The horizontal scan is usually done before the vertical scan. A horizontal scan proceeds by scanning the test vehicle from left to right as viewed from the hodoscope—i.e., from east to west. Vertical scans proceed by scanning the test vehicle from top towards the bottom.

Scan step sizes are indicated by separate transducers (gauges) for horizontal and vertical scans. Both transducers report a scan step size in units of gauge mils. The relation between the gauge mils and the collimator sweep at the test plane is different for the horizontal and vertical scans. For M8CAL, the horizontal scans moved 12 gauge mils between positions; this swept the field of view in steps of 0.6881 mm at the test fuel. For the vertical scans, the step size was 98 gauge mils, which corresponds to 1.874 mm at the test fuel.

The collimator pivot points for horizontal and vertical scans are located at different distances from the test fuel. There is a mechanical pivot point for the horizontal scans, while for vertical ones there is no mechanical pivot—two motors located underneath the collimator act in unison to vertically pan the collimator about a virtual pivot located between the test vehicle and the collimator, at the center of the front collimator (see Fig. 2).

It is important to note the scan step positions recorded on the proportional-counter data tapes only reflect the initial position and the desired step size. Actual step sizes from the position transducers are input to the Hornyak-button tape. The Hornyak buttons are a backup to the proportional counter array, and were inoperable for the M8 calibration. In Fig. 2, the Hornyak-button neutron-counter array is labeled as the neutron/gamma array. Before the M8 test is performed, the hodoscope data acquisition system should be programmed so that the actual transducer positions are written to the proportional-counter data tape.

B. Horizontal Scan

1. Signal-to-background Ratio and Fuel Shine

The hodoscope signal-to-background ratio (S/B) is one of the determinants of the fuel-mass resolution. The total S/B ratio, composed of both unscattered and shine components, was

used to estimate the fuel-mass resolution. Scan results were used to determine S/B for M8. Unscattered fast neutrons from the test fuel detected by a channel aligned with the fuel enter into the unscattered S/B ratio. Fast neutrons also can originate in the test fuel and be scattered by the test structure into channels not aligned with the test fuel. These scattered neutrons are referred to as fuel shine, and a S/B ratio can be estimated for shine.

Figure 54 shows the averaged scan data used to determine S/B. Scan data from row 20 were chosen because that row is near the peak axial power. Both the vehicle with the fuel (Operation 20) and the so-called "fueled vehicle" without fuel (Operation 19) are shown. Data from the vehicle with fuel consist of signal and background counts. The fueled vehicle without fuel represents background counts. These scans have 148 data values, as indicated by the abscissa. This corresponds to a scan distance of 101.3 mm (3.98 in.) at the test plane.

Signal-to-background was determined from the data in Fig. 54. First, the unfueled data were renormalized to make the averages of the first 35 data values for both data sets are identical. This renormalization corrects for slight day-to-day differences in the channel efficiencies. Then the S/B ratio was calculated as the fueled minus the unfueled data divided by the unfueled data.

Figure 55 shows the S/B ratio as a function of scan position. Both shine and an unscattered component of the signal are readily apparent. The shine component for a channel directly aimed the axial center of a fuel pin can be estimated: Figure 55 also shows a least-squares fit that estimates shine for channel positions that are directly viewing fuel. This least-squares fit was determined from the scan data on either side of the fuel-pin peaks. These side counts are solely from shine. Specifically, the coefficients of the parabolic least-squares fit are determined from positions 47 to 75 and positions 115 to 142.

Figure 56 illustrates the S/B ratios for a stationary collimator. It is assumed that the collimator is aimed so that column 5 is directly aligned with the axial center of one of the calibration fuel pins. Figure 56 is derived from Fig. 55 data, scan increment, and channel separation. Each scan increment at the test fuel spanned 0.68881 mm, and the interchannel

separation is 6.25 mm. Therefore, a distance of 9.07 steps in Fig. 55 corresponds to the distance between channels.

Table V contains data from Fig. 56 for columns 4 through 8. The two fuel pins are nominally aligned with columns 5 and 7, respectively. Because one pin is chosen to be perfectly aligned with column 5, the other pin is not optimally aligned with column 7, since the pin separation was 15.875 mm and the separation of columns 5 and 7 is 12.50 mm. Therefore, the pin aligned with column 5 has a higher S/B than the one nominally aligned with column 7, which is directly viewed by column 6 as well as by column 7. Total S/B ratios are 1.15 and 0.87 for columns 5 and 7, respectively. The fraction of shine S/B to total S/B is 0.16 and 0.20 for columns 5 and 7, respectively. Since the calibration pins were closer together than the test pins will be (see Sect. III.B.2), the shine fractions for M8 may not be quite as large. However, the test fuel is 15% wider than the calibration fuel. This effect would slightly increase the test shine fraction.

TABLE V. Signal-to-background from M8 Calibration

Column	Total S/B	Shine S/B	(Shine S/B)/(Total S/B)
4	0.21	0.17	0.81
5	1.15	0.19	0.16
6	0.57	0.19	0.33
7	0.87	0.17	0.20
8	0.16	0.14	0.87

Shine is undesirable because it lends systematic uncertainty to the fuel mass resolution. Consider the removal of all the fuel optically aligned with a channel. In a two-pin test like M8, shine neutrons from the adjacent fuel pin would still be detected by this channel. Even in a single-pin test, removal of all the fuel optically aligned with a channel does not remove all the signal—some neutrons from fuel in the field of view of adjacent axial channels are scattered in. Sect. III.C.5 discusses axial shine.

2. Fuel-pin Separation

Evaluation of the hodoscope scan data shows the pin-to-pin horizontal centerline separation was less than the nominal distance specified in the assembly drawings for the calibration test vehicle. Deconvolution of the scan data confirmed the narrow separation. Maximum-likelihood deconvolution of hodoscope scan data[4] was first reported for New Production Reactor (NPR) calibration fuel. The NPR fuel had two large concentric cylinders; this is the first time data from two small fuel pins have been deconvoluted. The pretest neutron radiographs also show a narrow separation.

Drawings of the calibration test train indicate a nominal pin-to-pin centerline distance of 15.88 mm (0.625 in.). Figure 57 presents the averaged scan data and its maximum-likelihood deconvolution for Operation 20, row 18. The pin-to-pin centerline separation from both the scan data and their deconvolution is 10.32 mm (0.406 in.) for row 18. Table VI lists the pin-to-pin centerline separation from both the scan and its deconvolution for rows 14 to 23. All the rows show a narrow separation. The average separations from the scan data and its deconvolution are 10.60 mm (0.417 in.) and 10.53 (0.415 in.), respectively. Since the calibration fuel is unirradiated, the two fuel castings could move in the sodium bond towards each other to be no closer than 15.2 mm (0.598 in.), so that such movement cannot explain the narrow separation.

As a check on the test fuel scan increment of 0.6881 cm for a 12 gauge-mil collimator movement, the M7 pretest scan data and their deconvolution for row 17, column 5 are plotted in Fig. 58. The measured separation is 15.8 mm (0.623 in.) which is consistent with the nominal distance of 15.9 mm (0.625 in.). Note the irradiated M7 test fuel filled the gap inside the cladding, so there is no ambiguity about horizontal movement within the sodium bond, as there is with the unirradiated M8 calibration fuel. Therefore, the M7 scan data confirm that the separation of the M8 calibration pins as viewed by the hodoscope was too narrow. The likely explanation is that the test train was rotated some 25-35° from its nominal position; see Ref. 1 for a fuller discussion.

TABLE VI. M8CAL Pin-to-pin Centerline Separation by Row

Row	Scan Data		Deconvolution	
	Number of Positions Between Maxima	Distance (mm)	Number of Positions Between Maxima	Distance (mm)
14	16	11.01	16	11.01
15	16	11.01	16	11.01
16	15	10.32	15	10.32
17	15	10.32	14	9.63
18	15	10.32	15	10.32
19	14	9.63	15	10.32
20	15	10.32	15	10.32
21	15	10.32	15	10.32
22	16	11.01	15	10.32
23	17	11.70	17	11.70
Average	15.4	10.60	15.3	10.53

C. Vertical Scan

1. Axial Response Function of the Hodoscope

In the course of analyzing the M8CAL scan data, we have established a new method that describes a normalized, axial, fast-neutron response for the hodoscope. Earlier work done by manual alignment of M6 data suggested that the approach is feasible. For any given column, the individual axial responses of the rows can be joined in a smooth curve, making use of the row-to-row overlap. Figure 59(a) shows the unprocessed data from column 3 in an unfueled scan (Operation 19). Note the discontinuities at the row boundaries, due to the differing counting efficiencies. Only the nonoverlapping scan points are shown in Fig. 59(a). Since adjacent rows overlap (view the same part of the test region) over a small range of scan positions, the ratio of the overlap-point averages for adjacent rows is used to adjust adjacent row efficiencies to form a smooth curve. Figure 59 is from Operation 19, column 3, and is chosen as the most appropriate data for three reasons: First, Operation 19 is free of anomalies, as

discussed in Sect. III.C.4. Secondly, column 3 was aligned with the center of the test vehicle. Finally, there were no malfunctioning channels in column 3 for this scan.

Figure 59(b) shows the result of removing the efficiency differences. Because these data are from an unfueled scan, they represent the axial fast-flux profile as perturbed by the M8 vehicle and as viewed by the hodoscope. Other examples of axial hodoscope response are presented in this report, including the response of a column with test fuel, showing the axial distribution of the fuel. A complete specification of the response curve program is given in APPENDIX D, which also discusses the validity of the program.

2. Comparison with Other Axial Responses

a. Monitor-wire Comparison

It is useful to compare the fast-flux distribution from the response curve with monitor wire data. The monitor-wire data used for this comparison were taken pre-upgrade as part of the LO1 calibration test. The monitor wire was placed in the cooling channels two TREAT fuel elements from the test vehicle, to keep it away from the influence of the experimental flux-shaping collars. Rod movement was chosen to be as far from the wire as feasible. This wire provides the best estimation of the TREAT axial power profile and is believed to be valid for the upgraded core.[5] M8CAL monitor wires provide a poor comparison because the axial flux shaping collars perturb the wire data. Figure 60 compares this LO1 monitor wire with the M8 calibration response curve. The M8CAL response is derived from the same data as Fig. 59(b). The datum for each row in Fig. 60 is the average of 18 scan points, renormalized to peak at one, as is the monitor-wire curve.

Generally, agreement between the axial response and the wire is very good, and the disagreement can be explained. Both plots peak slightly below the core centerline. Both plots have larger values near the bottom of the core (-24 in.) than at the top (+24 in.). The plots overlap closely from about 432 mm (17 in.) below center to about 305 mm (12 in.) above center. Near the core extremes, the monitor-wire data are greater than the hodoscope response.

These differences in response are attributed mainly to differences between the axial shapes of the thermal and fast fluxes. The monitor-wire data are from thermal neutron fissions. However, the hodoscope response curve is for fast neutrons in the test-vehicle position. Thermal neutrons are scattered back into the core by TREAT's graphite reflector. There is no effective fast-neutron reflection at the ends of the test vehicle, so the fast flux falls off more rapidly than the thermal flux near the core extremes.

There is also another effect[5] that can help explain why the hodoscope response is lower than the wire near the core top and bottom. The hodoscope uses cross-focused optics (Fig. 2), so the top and bottom channels are viewing the background behind the test at different axial levels than at the test plane. For example, a channel viewing the top of the core at the test plane has some background from a region behind the test plane that is out of the core. Agreement is better near the center of the core because the hodoscope channel cross-focusing effect there is smaller.

b. Comparison with Present Calibration Response

The hodoscope counting rates are periodically calibrated to match approximately the axial fast flux distribution as measured in an unfueled test vehicle. Figure 61 shows the proportional-counter calibration curve used currently. It was derived several years ago[6] from Hornyak-button data. Agreement with the M8CAL response curve is fairly good. However, the M8 response curve is slightly higher than the calibration curve in the top half of the core.

We recommend that the M8CAL response curve (open circles in Fig. 61, which are derived from the lower curve in Fig. 59) be used for calibrating future tests. The present calibration curve disagrees with both the monitor wire and the M8 response curve above the core center. Table VII presents row-averaged response values from the new response curve. These values will be used for the M8 pretest proportional counter calibration.

TABLE VII. New Calibration for Proportional Counters

Row	Response	Row	Response	Row	Response
1	0.243	13	0.889	25	0.945
2	0.298	14	0.920	26	0.934
3	0.374	15	0.936	27	0.904
4	0.450	16	0.954	28	0.871
5	0.515	17	0.975	29	0.836
6	0.574	18	0.989	30	0.799
7	0.636	19	0.998	31	0.759
8	0.683	20	1.000	32	0.698
9	0.729	21	0.998	33	0.637
10	0.772	22	0.986	34	0.562
11	0.813	23	0.978	35	0.470
12	0.857	24	0.964	36	0.400

3. Response in Fueled Columns

Figures 62 and 63 present axial responses for fueled columns 2 and 4, respectively, in Operation 20. Fueled rows rise above the reactor background at sharp discontinuities. Points about halfway up these discontinuities are marked, and fuel column lengths of 342.12 mm (13.469 in.) are calculated as the distances between the marked points. For each channel scanning an end of a fuel column, a point marked at the halfway location is aligned with the end of the fuel because this is the midpoint of the vertical channel umbra. The marked lengths show excellent agreement with the nominal length, 342.9 mm (13.5 in.), of EBR-II fuel.

Note that rows 7 and 22 in Fig. 62 and row 30 in Fig. 63 are plotted as straight lines. These channels were malfunctioning. The response program interpolates a straight line for such channels; the slope of the line is the average of the slopes of the adjacent rows.

From the data in Fig. 62, a test fuel peak-to-average fission ratio of 1.11 is derived. APPENDIX D illustrates how this ratio is obtained. This peak-to-average ratio from the response curve is in excellent agreement with the radiochemistry peak-to-average ratio of 1.10, reported in Ref. 1. From Fig. 62, the peak-to-top and peak-to-bottom fission ratios are 1.34

and 1.54, respectively. Radiochemistry indicates the peak-to-top and peak-to-bottom fission ratios are 1.33 and 1.39, respectively.

Figure 63 does not show even an approximately correct axial response for the fuel in column 4. The reason is that this column was poorly aligned for the axial scan, which was performed at a fixed horizontal gauge position of 1900 mils. From the horizontal scans, columns 2 and 4 are optimally aligned with the fuel pins at 1928 and 1955 gauge mils, respectively. Therefore, column 4 is more out of alignment than column 2, and this misalignment is responsible for the axial response for column 4.

4. Axial Scan Anomaly in Operations 20, 22, and 28

Figures 62 and 63, from Operation 20 (low power, steady state, with fuel), show a steep, concave, axial response starting in row 28 and continuing to row 36. This contrasts with the shape shown in Fig. 64 from Operation 19, and is referred to here as an anomaly. All the columns in Operation 20 reveal this anomaly. The vertical scans from Operations 22 and 28, both low-power unfueled, also showed the same anomaly in all the columns. However, the scans from Operations 19 and 16 did not show the anomaly in any of the columns. The hodoscope scan specifications (horizontal position, range above and below horizontal) were identical for all operations. Furthermore, the shape of the anomaly is not consistent with occlusion by an object between the test section and the collimator. The cause of the anomaly is at present unknown.

It is reassuring to note from Table I that the dates of anomaly-free Operations 19 and 16 bracket the dates of the most important M8CAL transients analyzed for this report. However, Operations 20, 22, and 28 are among the most recent scans, so there is concern that the source of the anomaly still is present. Figures 64 through 68 show the response from column 7 of Operations 19, 16, 20, 22, and 28, respectively. These figures are presented in chronological order. Column 7 is selected because it had few or no malfunctioning detectors in these operations. This column is also far enough from the fuel in Operation 20 to be only

slightly affected by it. This anomaly should be resolved before M8, because it may indicate some kind of occlusion beginning about three rows above the top of the test pin.

5. Fuel Shine

"Shine" refers to neutrons from the test fuel scattered by the test structure into columns not directly aligned with the fuel. Section III.B.1 evaluates horizontal fuel shine. As is the case for horizontal scans, it is possible to subtract an unfueled scan from a fueled scan to reveal axial fuel shine. Indeed, in Appendix D, the scan subtraction results are used as partial validation of the axial response program. Before subtraction is performed, the unfueled response is normalized so that its mean for the first 100 data points starting in row 1 equals the mean of the first 100 fueled-scan data points. One 100 points give good statistics, but only cover the range to row 6, which is far from the top of the fuel (row 14).

Figure 69 shows the result of such a subtraction for column 7; the unfueled data of Operation 20 are subtracted from the fueled data of Operation 22. The result is a peak centered at row 19, which is aligned with the midplane of the fuel column. Therefore, the peak in Fig. 69 is due to test fuel neutrons scattered into column 7. Recall that the test fuel was aligned with columns 2 and 4 in Operation 20.

D. Fuel Position

The hodoscope must be aligned vertically and horizontally to optimize sensitivity to expected fuel motion. Final alignment of the hodoscope for the M8 test must be determined from the pretest scan. However, the M8CAL scans can be used to specify the M8 pretest scan limits.

All M8CAL horizontal scans were conducted about a central position of 1900 gauge mils. A fixed horizontal position of 1900 gauge mils was also used for all M8 calibration vertical scans. This position aligned the hodoscope so that the fuel was in columns 2 and 4 for the vertical scans. A better horizontal central position would have been 2160 gauge mils, which

would have aligned the hodoscope so that column 5 was positioned between the fuel pins. A horizontal central gauge mil of 2160 mils is recommended for the pretest scan for M8.

The M8CAL vertical scans were conducted about a vertical gauge reading of 2000 mils. This is the position for a horizontal collimator, and was the fixed vertical position during all the horizontal scans. The axial response information can be used to determine an optimal vertical alignment for the M8 test. For example in the M8 calibration, the top and bottom of the fuel columns were at row positions 13.9 and 24.6, respectively (see Fig. 62). The maximum axial response (vertical umbra of the channel response) for row 14 extends from row position 13.87 to 14.13. Therefore, a vertical gauge reading of 2000 almost perfectly aligns row 14 to detect the inception of the expected axial fuel column swelling. Of course, the optimal M8 alignment will be different because the irradiated fuel columns are slightly longer. The pretest axial scans for M8 will be used to determine the optimal vertical alignment.

It is important that the fixed horizontal position of the collimator be set in the M8 transient so that the pin expected to fail is optimally aligned with a hodoscope column. As discussed in Sect. III.B.1, this results in a maximum signal-to-noise ratio for the pin expected to fail. The M8 pretest horizontal scan will establish this position. For pretest and posttest vertical scans, it is impossible to optimally scan both pins with a fixed horizontal position. A recommendation is made in Sect. IV.C to perform two M8 pretest vertical scans, each scan providing optimal horizontal alignment for a specific pin. This will ensure that the axial response information is optimized. The poor axial response to the fuel shown in Fig. 63 for column 4 in fueled Operation 20 emphasizes the need for an optimal fixed horizontal position for vertical scans.

IV. PERFORMANCE PREDICTION

A. Scope

The most important M8 test objective is to measure the timing and extent of axial fuel motion. This section addresses hodoscope performance with respect to this test objective. Prediction of hodoscope performance can be addressed in several ways. The simplest prediction is the single-channel mass resolution, which can be determined from an experimental error analysis. Additional fuel movement information can be determined if multiple adjacent channels are involved in a correlatable fuel motion event. Systematic errors also affect the hodoscope performance and are discussed. An exhaustive analysis of hodoscope performance is contained in Appendices VI through IX of Ref. 2.

B. Single-channel Mass Resolution

APPENDIX E presents a derivation of the mass-resolution formula and calculates the mass resolution to be expected in the M8 test. The result is a single-channel mass-resolution uncertainty of 0.55 g fissile, or 8% of the fissile fuel viewed by a single hodoscope channel. This is an experimentally determined, one-sigma uncertainty based upon average count statistics for a single channel in the 30-s period part of the transient. The data resolution interval (DRI) for this mass resolution is 4.36 ms. This DRI is the same as the data collection interval (DCI) for the M8 test, so it is the shortest possible DRI. The DCI is determined by the transient length, the capacity of the data-storage disk, and the time to write all 360 channels to the disk.

One should appreciate that lower count rates in the post pin-failure power shelf cause either a higher fissile-mass uncertainty for the same DRI or a larger DRI than 4.36 ms for the same mass resolution. Single-channel mass resolution is important because it is independent of any specific type of fuel motion. The M8CAL results were used to determine the signal-to-background ratio and background count rate—the quantities that determine the mass resolution.

C. Correlated Fuel Motion

If fuel motion is correlated over several channels, the hodoscope provides additional information. The event is correlated if count-rate gains in one region are matched with count-rate losses in a contiguous region of channels.

In order to discuss correlated fuel movement in M8, it is useful to consider axially correlatable fuel motion events from similar tests M5, M6, and M7, as reported in Ref. 7. These tests also were transient overpower tests on IFR fuel. Two types of correlated fuel motion were observed in M5, M6, and M7: prefailure fuel-column expansion and postfailure axial fuel ejection from a cladding breach near the top of the fuel column. Prefailure expansion was determined by correlating losses in rows at and just below the top of the pretest fuel column with gains in contiguous rows just above the pretest top of the fuel. Upon fuel failure, molten fuel was ejected from the pin into the coolant channel and swept upward by sodium flow. The failure event was over an extensive axial region in which fuel losses and gains were related.

Similar correlatable axial motion is expected to occur in M8. However, it may not be as abrupt because M8 will have a lower heating rate. Tests M5, M6, and M7 had 8-s TREAT power periods, while M8 will have a 30-s period. Heating rate for M5, M6, and M7 at failure was ~ 100 C/s. The heating rate of M8 near the expected failure time is ~ 25 C/s. The lower heating rate in M8 may cause the pin to fail by pressure-assisted creep rupture. Pin failure in M5, M6, and M7 was by eutectic clad penetration.

It is expected that there will be less molten fuel at failure in M8. This may result in less prefailure axial expansion and less fuel being ejected into the coolant channel. However, the failure location is still expected to be near the top of the fuel column, resulting in fuel being swept upward into rows that had no fuel, so the hodoscope is expected to observe the failure event.

The main question is sensitivity of the hodoscope to a smaller prefailure axial expansion. Sensitivity to prefailure axial fuel movement will be optimized by carefully aligning the

hodoscope as described in Sect. III.D. The vertical scan mode is very sensitive to small changes in fuel length in the pin that does not fail. It is expected that the axial scan response curves will increase capability of the hodoscope to observe small fuel column length changes.

We recommend two pretest and two posttest vertical scans; the additional vertical scans would optimize the sensitivity of the hodoscope to axial fuel-distribution changes in both test pins. In the first pretest or posttest scan, a channel would be directly aligned with the pin expected to fail. For the second scans, a channel would be directly aligned with the pin not expected to fail.

D. Systematic Errors

1. Fuel Self-shielding Error

The specific fission rate (expressed in fissions/[s-g-MW_{TREAT}]) changes as the fuel geometry evolves during the test. Self-shielding error refers to changes in the specific fission, and this is the largest systematic error. To a first-order approximation, the mass balance imposed during data reduction corrects for changes in specific fissions.

Hodoscope data can be used to predict the reactivity change ("worth" change) to be expected in a power reactor that undergoes fuel motion of the type observed in a test. The calculation makes use of the observed changes in the axial fuel distribution, by multiplying the transient axial fuel distribution by a cosine-squared axial worth distribution approximate to EBR-II, and integrating axially. The process is described in Ref. 8.

The predicted reactivity change is affected by the fuel self-shielding error. Reactivity losses reported for axially dispersive events in M5, M6, and M7 result in an underestimate of loss due to self-shielding error. Therefore, any loss reported for similar axial fuel motion in test M8 is expected to be a conservative reactivity-loss underestimate.

2. Fuel Shine Error

As discussed in Sect. III.B.1, fuel shine represents only 16% of the total S/B for a channel directly aligned with the pin. For channels adjacent to either side of the aligned channel, Table V shows that the respective fuel shines are 33% (for a channel towards the other pin) and 81% (for a channel away from the other pin). These percentages, however, are far greater than the shine-caused fuel-relocation error, since (to a first approximation) the signal from relocated fuel will simply be superimposed on the shine. Still, the shine is a source of uncertainty, since relocation of fuel is accompanied by changes to shine. The importance of the shine-related error will depend on the details of the observed fuel motion. Since only one pin is expected to fail in M8, shine from the unfueled pin will be relatively constant. It would be possible to reduce the shine uncertainty by performing scans with one pin or, possibly, by doing neutronic calculations to determine the shine contribution from one pin.

V. CONCLUSIONS

Procedures for analyzing hodoscope data from TREAT transients have been refined to correct more accurately for the effects of control-rod position on both the axial flux tilt and ion-chamber power reading. It was found that the tilt corrections can approach 20%. Corrected ion-chamber data are used for a more accurate power normalization for each row of channels. Hodoscope data-processing algorithms have been modified to compensate for these rod-position effects. The end result is a constant, power-normalized, response for all channels in the unfueled M8CAL tests. An improved analysis, with increased sensitivity to movement of the test fuel, minimally affected by control rod position, is expected for the M8 test.

Two major improvements to the information provided by scans have resulted from work with the M8CAL hodoscope data. First, computer methods were developed to form an axial response curve from vertical scan data. For unfueled scans, this response depicts the axial distribution of the fast-neutron background; this background will be used to perform an improved detector calibration for the M8 test. With fueled test assemblies, the fuel distribution

is accurately revealed by a suitable analysis of the axial response. A direct comparison of axial response with the radiochemical axial fission distribution yielded excellent agreement for one of the calibration pins. The importance of optimizing the fixed horizontal collimator position for a vertical scan to obtain an accurate axial response is emphasized by the M8 calibration results. A comparison of properly aligned pretest and posttest axial responses should provide a highly sensitive means to observe axial fuel rearrangement in the M8 test.

Second, horizontal scan data have been analyzed to determine quantitatively the fuel-shine contribution to the signal-to-noise ratio. Quantification of fuel shine contributes to the systematic error analysis.

In examining the hodoscope data from the M8CAL tests, some of the techniques for analyzing transient and scan data have been improved to provide maximum sensitivity. In light of comparison of the specifications for M8 and for previous tests for which the hodoscope performance is known, the sensitivity of the hodoscope is more than adequate to determine the location and extent of pin failure and significant axial fuel motion in M8. Careful alignment of the hodoscope must be performed to ensure maximum sensitivity to prefailure axial fuel movement.

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APPENDIX A

CODES FOR PROCESSING TRANSIENT DATA

Data for the M8CAL tests were received from TREAT on 10.5-in. magnetic tapes. Program FUDGE read the data from the tape and then corrected each scaler for lost bits. In the correction process, FUDGE keeps a running average of the five collection intervals before the interval being checked and five intervals after. If in the interval a scaler is outside of a predetermined range centered on the running average, it is corrected. In theory such a deviation is due to a dropped bit, which can be replaced without statistical bias. FUDGE corrects scalers by adding or subtracting bits until the count falls within the proper range. If either of two bits will bring the count within the specified range, the bit bringing the count closest to the running average will be used. Any timer errors in the data set are corrected here, along with scaler overflows. Since the disk-data retrieval system was inoperable during the M8 calibration tests, the tape had to be used, which made the counting interval a very lengthy 28 ms. Since the counting interval was so long, scaler overflows were a problem requiring special coding in the FUDGE program. When finished, FUDGE wrote the revised data sets to the Microvax hard disk.

Next the data were read by Program DGL (Diglites), which processes the data from FUDGE. At this point no efficiency, space charge, or deadtime corrections were made. The data were averaged using the NTOTAL option in order to maintain uniform counting statistics. Under the NTOTAL option there is a preset minimum number of counts in an averaging interval. Collection intervals are summed until this limit is passed. The counting time is then adjusted accordingly. A maximum and minimum number of collection intervals to be summed can also be set. The data were averaged by this method, and files were then written to the disk in DGL output format.

The DGL files were then read by program FPLOTT. FPLOTT is a plotting package for hodoscope transient data. Plots were made to examine the hodoscope data for erratic or

nonfunctioning scalers. Each scaler was normalized to the ion chamber, and 12 scalers at a time, from a column, were plotted on the screen, without hard copies. A list of bad scalers was compiled for each data set. Then Diglites wrote a new file to the disk with the same averaging but with the bad scalers deleted.

Next, program EFFI calculated efficiency multipliers for the hodoscope data. From the power profile, a time slice early in the power ramp was chosen. The efficiency multipliers were calculated for this slice and written to the disk in ASCII format. The efficiency file was edited and any efficiencies that had been marked with an X (for deletion) were unmarked and changed to one. The data were again examined using FPLOT, to determine the quality of the efficiencies. If a multiplier was unsatisfactory, it was changed in the efficiency file and checked again. Once a satisfactory set of multipliers was obtained, DGL was run once again. The deleted scalers were then smoothed,* and the efficiencies just generated were incorporated into the new file. At this point, the desired averaging was applied to the file—perhaps no averaging, constant averaging, or averaging slices. Various deadtime corrections were made to the transients analyzed. These specialized DGL files were made for plotting in FPLOT and DeltaGraph, the latter being a commercial plotting program from Deltapoint, Inc., Monterey, California.

Axial profiles were desired, so DGL files were prepared with a few well-chosen averaging slices, for known rod positions, using the averaging-slice option in Diglites. These files, with efficiency and deadtime corrections included, were run through either Program TILT, which makes profiles relative to row 20, Program TILTOI, which makes profiles relative to the hodoscope ion chamber, or Program TILT18, which makes profiles relative to row 18. These profile files are in ASCII format, including the time, with each of the 36 rows averaged over some suitable number of columns. These files were then transferred to the PC and plotted by DeltaGraph.

*"Smoothing" consists of replacing the data in a malfunctioning data channel with the average of the adjacent channels.

APPENDIX B

RELATION OF MONITOR-WIRE DATA TO HODOSCOPE INTEGRATED COUNTS AND TREAT POWER

Transient 2867 of the M8 Calibration tests, which had a 30-s period, is expected to be the transient most like the M8 test. Transients 2868 and 2869 were clipped transients run for integrated powers of one half and one quarter, respectively, of the integrated power of 2867. For each of these an 8-in.-long monitor wire was centered in the TREAT core. High-precision radiochemistry was done on three half-inch segments of each of the wires. From the average of these three segments, the relative fissions per gram were determined. The relative fissions per gram in the monitor wire is a measure of the integrated flux of the TREAT core. In principle, assuming that the fast and thermal fluxes are directly proportional, the integrated counts for rows near the center of the hodoscope array should also measure the integrated flux. In addition, the TREAT integrated-power monitors should measure the integrated flux. These are uncompensated ion chambers located at three corners of the core about a foot above the core centerline. Since the monitor wire, hodoscope, and integrated power are all a measure of the same thing, each should track the other for increasing reactor power. So if one compared the relative change in these three measures of TREAT reactor integrated flux for increasing power, they should be roughly equal.

Thus, an experiment was devised to test how well the monitor wire, integrated hodoscope counts, and integrated TREAT power tracked each other. Data on relative fissions per gram existed from monitor wires in the 2869, 2868, and 2867 transients. Integrated TREAT power was also available for these transients. The hodoscope was run only for transient 2867, the full 30-s period transient. So counts were averaged up to the integrated power of 2869, 2868, and 2867 from the 2867 transient for several rows viewing the center of the reactor core. The raw data are contained in Table B1. The data from the monitor wire, hodoscope, and TREAT integrated power monitors were then ratioed to the quarter transient, transient 2869 to provide an

indication of relative change, with rising power, of each measure of the integrated flux (see Table B2).

TABLE B1. Data from the TREAT Integrated Power Monitor, Monitor Wire, and Hodoscope Row 20 for the Quarter (2869), Half (2868), and Full (2867) 30-s-period Transients

Transient Number	Time of Integration(s)	Integrated Power (MJ)	Relative Fissions per g ($\times 10^{13}$)	Integral Count ($\times 10^6$) $\theta = 0 \mu s$	Integral Count ($\times 10^6$) $\theta = 0.5 \mu s$
2869	10.32	602.1	1.21	6.732	7.1905
2868	15.41	1198.6	2.33	12.50	13.44
2867	35.0	1956.7	3.71	19.45	20.85

TABLE B2. Data Relative to the Quarter Transient for the TREAT Integrated Power Monitor, Monitor Wire, and Hodoscope Row 20 for the Quarter (2869), Half (2868), and Full (2867) 30-s-period Transients

Transient Number	Time of Integration(s)	Integrated Power	Relative Fissions per g	Integral Counts, $\theta = 0 \mu s$	Integral Counts, $\theta = 0.5 \mu s$
2869	10.32	1	1	1	1
2868	15.41	1.991	1.926	1.857	1.865
2867	35.0	3.250	3.066	2.889	2.893

As is evident from Table B2, each measure of the integrated flux increases with increasing power, as expected. The rates of increase, however, are somewhat different. The relative rise of the integrated power is the greatest, followed by the monitor wire. The hodoscope counts rise the least, but the application of a deadtime causes the hodoscope counts to approach the rate of increase of the monitor wire. If a deadtime were applied to the relative hodoscope counts for transient 2867 (2.889) to make it equal to the relative monitor wire fissions per gram (3.066), the deadtime would be $22.125 \mu s$, a physically unrealistic value. Therefore, the

difference in increase must be caused by a phenomenon other than detector deadtimes. As can be seen, the integrated power is supralinear compared to the monitor wire and integral hodoscope counts. The integrated power monitors, however, reside outside the TREAT core and about a foot above the core centerline. Since the integrated-power detector views an axial location above that of the monitor wire and hodoscope row 20, the relative tilts should cause it to be supralinear. Also, the integrated power monitors view the core through the banked transient rods, emphasizing the tilts even more.

As can also be seen, the integral hodoscope counts are sublinear to the monitor-wire fissions per gram. Each views the same axial location of the core, so tilts cannot be the cause for the discrepancy. As mentioned above, deadtimes cannot account for the sublinearity either. One possible explanation lies in the difference in the fluxes each views. The monitor wire responds to the thermal flux, the hodoscope to the fast flux. If these did not react identically to the rod positions, the discrepancy might be explained. In any event, the magnitudes of these discrepancies are acceptable.

APPENDIX C

SCAN-DATA PROCESSING

The first code used to process the scan data is SCAN2, which reads the TREAT tape to the Microvax disk. Next an iterative combination of CLSC (a.k.a. Clean-scan), RJCONA (a.k.a. reject and consolidate), and SPLOT are used to determine which channels are functional. After the channels are evaluated, SPLOT is used to prepare an ASCII data set of all the data for the 360 channels. Horizontal scan data are adjusted for small variations in reactor power during the scan, but at this stage the vertical scan data were not yet adjusted for power variation. Zeros are written for the nonfunctional channels.

Program SPLOT can be used to average the data from each row of detectors, to minimize the statistical fluctuations. Averaged scan data are then output into an ASCII data set for each row. All ASCII data sets are sent to Foton (see Appendix D) where they are imported into Speakeasy (Speakeasy Computing Corp., Chicago, Illinois). For this report, the plots, deconvolutions, etc., pertaining to scan data were made with Speakeasy.

Program COUNT-READER provides true counts (with small power adjustments) counts rather than relative count rates. True counts are necessary for maximum-likelihood deconvolution, which relies upon Poisson counting statistics.

APPENDIX D

AXIAL-RESPONSE PROGRAM AND VALIDITY CHECK

A. Description of Axial-response Program

A program that calculates the axial response has been written in the Speakeasy language (Speakeasy Computing Corp., Chicago, Illinois). This program runs on the Reactor Engineering Sun Sparkstation named Foton. A single axial scan-data set with all scan positions for the 360 channels is supplied from Reactor Engineering's Microvax hodoscope data analysis program SPLOT as described in Appendix C.

Every channel is reviewed on the Microvax. Malfunctioning channels have zeros written to all scan positions. It is also very important that the vertical scan data not be normalized to the hodoscope power monitor. The flux at this power monitor, which is located on top of the collimator, is progressively more occluded as the collimator moves upward in doing a vertical scan, and is, therefore, not a useful indicator of TREAT power during a vertical scan. A partial correction for TREAT power variation is made by the axial response program. The SPLOT data set is sent to the Sparkstation by FTP (File Transfer Protocol).

All the vertical scans analyzed for this report had 28 positions, covering a total scanning range of about 1.5 rows. Because in doing a vertical scan it pivots about a point at the center of the front collimator (Fig. 2), the rear collimator moves upward as it scans by tilting progressively downward; each pixel moves downward about a row and a half in the course of a vertical scan. Each data set was imported into Speakeasy as a 360 by 28 matrix. The Speakeasy program assumed that the matrix had already been created prior to program execution.

Both the collimator's horizontal position and the number of scanning positions between channel centers are needed for the program. Another data set of scan positions in gauge mils

is supplied from SPLOT. This data set specifies the scan position when the collimator is horizontal, as well as the number of positions between adjacent channel centers at the test plane. The collimator tilt is measured by a linear position gauge. The collimator is horizontal at 2000 gauge mils, which is position 18 for all scans. A vertical sweep of 1794 gauge mils scans the distance between the centers of adjacent channels at the test plane. All the scans analyzed had 98 gauge-mil steps, so there are exactly 18 scan positions between channel centers for these scans.

The following steps are performed by the response program:

- (1) For the detector column of interest, form a 36-row by 28-column matrix. Data from the detector in row 1 are in the first row of the matrix. The first scan position is in the first column of the matrix. Normalize for TREAT power variation by dividing each datum in column j by the sum of the data in column j .
- (2) Execute a 35-increment loop to determine the efficiency-adjusted axial responses for rows 2 through 36. The loop index n is equal to the number of the row being efficiency adjusted.
- (3) Check the n th row sum in the 36 by 28 matrix. If it is greater than zero the channel is good; proceed to Step 4. If the sum is zero the channel was malfunctioning; proceed to Step 5.
- (4) Determine the mean of the 19th through 28th data values in row $n-1$. Also determine the mean of the first ten data values in row n . These data ranges correspond to overlapping scan positions (they sweep the same area at the test plane). Calculate efficiency-adjusted data for row n by multiplying the scan data in row n by the ratio of the overlap means: row $n-1$ / row n . In the 36 by 28 matrix, replace the row n data with the efficiency adjusted data for row n . Go to Step 6.

- (5) Missing data must be estimated from the data in rows $n-1$ and $n+1$. By a linear least-square fit determine the slope of the row $n-1$ data from the 10th through 28th data values in this row. These data are for scan positions near the beginning of row n . Also, determine the slope of row $n+1$ by a linear least-square fit of the first through 19th data values in this row. These data values are for scan positions near the end of row n . Average the row $n-1$ and row $n+1$ slopes to determine a slope for row n . Using the 18th position in the least-squares fit for row $n-1$ as the intercept value for row n , calculate the synthesized data for row n . Go to Step 4.
- (6) Go to Step 2 unless n is 36.
- (7) Execute a 36-increment loop to assemble the unnormalized 648-position axial-response array. This array is composed of the central 18 positions in the efficiency-adjusted 36 by 28 matrix created above. The collimator's horizontal position is at scan position 18, so the central 18 scan positions are in the 10th through 27th columns of the data matrix.
- (8) Determine the maximum value of the response array. Normalize the 648-position array to this maximum value.

B. Validity of the Axial-response Program

The strongest indication of the validity of the axial response is accuracy in determining the fuel column lengths in Operation 20.

In an additional check using the data from column 2 (Operation 20), the response shape was found to agree with radiochemistry. Radiochemistry is used to make a determination of the axial distribution of thermal-neutron fissions. Unscattered fast neutrons from the fuel are proportional to this thermal neutron distribution. The axial distribution of unscattered fast neutrons can be calculated from Fig. D1. The axial-response data in Fig. D1 and the end positions of the fuel column are from Fig. 62.

The axial distribution of unscattered fast neutrons from the test fuel was determined from the difference of two least-squares fits. The first of those fits was for the sum of the unscattered (test fuel), shine (test fuel), and background (reactor) responses. Figure D1 indicates the range for determining the coefficients of this parabolic least-squares fit. This range corresponds to the portion of the scan where the entire umbra of the channel response function is viewing fuel. A definition of the channel response is provided in Ref. 2. This least-squares fit is extrapolated to the ends of the fuel column. In Fig. D1, the marked fuel-column ends correspond to the scan positions where half of the channel response umbra is viewing fuel

The second least-squares fit was for the shine and background responses. Two ranges were used for determining the coefficients of this parabolic fit. The ranges were on either side of the test fuel region, situated so that only test-fuel shine and reactor background contributed to the axial response. This least-squares fit was then extrapolated through the axial region where unscattered test fuel neutrons also contributed to the total response. The shine-plus-background fit was subtracted from the unscattered-plus-shine-plus-background fit to yield an unscattered fit between the ends of the fuel column.

The unscattered fit has a peak-to-average ratio of 1.11. Peak-to-average from radiochemistry is 1.10. The peak-to-top and peak to-bottom ratios determined from the unscattered fit are 1.34 and 1.54, respectively. Peak-to-top and peak-to-bottom from radiochemistry are 1.33 and 1.39, respectively.

It should be appreciated that column 2 is not optimally aligned with the axis of the test fuel, and that there were two nonfunctioning channels in this column. It is probable that the hodoscope's axial response would more closely match the radiochemistry if the alignment is optimized and all channels are functional.

Efficiency ratios, lack of a physical pivot, and only approximate scan positions lend uncertainty to the calculated axial response. The axial-response program normalizes the efficiency of each channel to that of the preceding channel, starting with row 1. Thus, the efficiency adjustment of row 36 is determined by the preceding string of 35 ratios of means. Each of

these means is determined from only 10 data values. These mean ratios must be fairly accurate or row 36 is not placed in the proper relation to row 1.

In addition, the collimator pivots about a virtual rather than a physical pivot point. Pivoting is provided by two motors at the bottom of the collimator. The motors are driven to provide the necessary tilt about a virtual pivot point at the narrowest opening in the front collimator.

Furthermore, the scan positions on the list provided with the proportional-counter data only approximate the true scan positions. This list is generated from a starting point and a scan increment. The actual scan-position values are written with the Hornyak-button data, but Hornyak-button data were not taken for the M8CAL scans.

A further test that shows the validity of the response technique is made from scan subtraction, a process that addresses all the uncertainties—and also shows the importance of normalizing to TREAT power (Step 1 in the program). The next eight figures illustrate the process of subtracting an unfueled scan (Operation 22) from a fueled scan (Operation 20). Before subtraction, the unfueled response is renormalized so that the mean of the first 100 data points, starting in row 1, is the same as the mean of the first hundred fueled-scan data points. One hundred points (~ 5.5 rows) is chosen to provide good statistics but still to be far away from the top of the test fuel.

Figures D2 through D5 show axial-response subtractions for columns 2, 3, 4, and 7, respectively, calculated without TREAT power normalization. Note the offset between the top and bottom channels. Figures D6 through D9 show axial-response subtractions for columns 2, 3, 4, and 7, respectively, made with TREAT power normalization. Note there is little or no offset between the top and bottom channels. The lack of an offset indicates the importance of power normalization. It also indicates that the 35 ratios used to adjust row 36 relative to row 1 are reasonably accurate. Furthermore, the lack of an offset shows the scan position and the pivot-point uncertainties are not large effects.

APPENDIX E

DERIVATION AND CALCULATION OF MASS RESOLUTION

A. Overview

The purpose of this appendix is to derive the one-sigma uncertainty for hodoscope fuel resolution, and to apply this formula to predict the mass resolution to be expected in the M8 test.

B. Derivation of the Mass-resolution Formula

Terms:

b	=	background counts/DRI per pixel
	=	(DRI is the data resolution interval)
B	=	total background counts: $B = dpb$
c	=	total counts/DRI per pixel: $c = Fb$
C	=	total counts: $C = dpc = dpFb$
ΔC	=	change in C due to fuel motion
d	=	number of DRIs
F	=	inverse relative background: $F = C/B = c/b = (1 + s/b)$
m	=	mass of fuel viewed by a central pixel
Δm	=	change in m due to fuel motion
p	=	number of pixels
r	=	fractional error in S: $R = U_s/S$
s	=	signal counts/DRI per pixel: $s = c-b$
S	=	total signal counts: $S = C-B = dpb(F-1)$
U_m	=	uncertainty in Δm
U_B, U_C, U_S	=	uncertainty in B, C, and S. $U_B = \text{sqrt}(B)$, etc.
V_B, V_C, V_S	=	variance in B, C, and S:
		$V_B = U_B^2 = B = dpb$; $V_C = U_C^2 = C = dpFb$

The experimental data consist of B, C, d, m, and p. However, the assumed basic data for this calculation consist of b, d, F, m, and p, permitting the calculation of U_m .

Signal is: $S = C-B$, with a variance $V_s = V_c + V_B = C+B$.

The fractional error in S is given by:

$$r = U_s/S = \sqrt{C+B}/(C-B) = \sqrt{dpb(F+1)}/[dpb(F-1)].$$

This corresponds to a mass uncertainty of r times m.

A change in the mass viewed by a pixel is indicated by a count-rate change $\Delta C = C_1 - C_2$. The variance in ΔC is $V_{c1} + V_{c2} = C_1 + C_2 = \sim 2C = 2dpbF$. Equation (E1) corresponds to a mass-change uncertainty U_m of $m \times \sqrt{2dpb(F+1)}/S$. U_m is the mass resolution.

$$U_m = m \times \sqrt{2dpb(F+1)}/[dpb(F-1)] \quad (E1)$$

C. Calculation

Calibration transient 2867 approximates the M8 test transient. In transient 2867, the count rate is $\sim 100,000/s$ near peak power. A data-collection interval of 0.00436 s is appropriate for the a test with the duration of M8. Therefore, the shortest data-resolution interval (DRI) will be 0.00436 s. The background count rate (b) in this interval is:

$$100,000/s \times 0.00436 \text{ s/DRI} = 436/\text{DRI}$$

The fissile fuel mass for the M8 calibration pin is 75.97 g (56.88 g U^{235} + 19.07 g Pu^{239} + 0.02 g Pu^{241}). The estimated burnup for the M8 test pin is 11.1 %, so there are 67.5 g fissile

in each M8 test pin. This fuel column is nominally 342.9 mm (13.5 in.) long. The axial domain of each channel is 33.74 mm, so the fissile mass m subtended by a single channel is:

$$67.5 \text{ g} \times 33.74 \text{ mm}/342.9 \text{ mm} = 6.64 \text{ g}$$

From Sect. III.B.1 in the body of this report, the signal-to-background ratio S/B for the M8 calibration pin is 1.15. Swelling of irradiated fuel and burnup are two opposing effects that must be considered in using S/B from the M8 calibration to estimate S/B for the M8 test. Power-coupling information on a similar M7 test pin was used to estimate these effects for the M8 pin. This estimation assumes power coupling and S/B to be linearly related. The swollen M8 test fuel has a larger diameter than the M8 calibration fuel, which increases the test S/B compared to the calibration S/B . Neutronic calculations for a similar M7 test pin indicate that swelling increases the S/B by 13%.

The burnup correction lowers the S/B . The 11.1%-burnup M8 fuel is comparable to the 9.8%-burnup M7 fuel. A burnup correction of -5.4% is calculated for the irradiated M7 fuel compared to unirradiated fuel. For the 11.1%-burnup M8 test fuel, a linear extrapolation results in a 6.1% decrease in S/B compared to the fresh calibration fuel. Therefore, the M8 test S/B can be estimated as 1.22 ($1.15 \times 1.13 \times 0.939$). The estimated M8 test inverse relative background $F \times (1 + S/B)$ is 2.22.

Equation (E1) gives the one-sigma mass uncertainty in interpreting a count-rate change. Assuming a single pixel ($p=1$) and single DRI ($d=1$), the following input values apply:

$$b = 436 / \text{DRI}$$

$$m = 6.64 \text{ g}$$

$$F = 2.22$$

$$p = 1$$

$$d = 1$$

Substituting these values in Eq. (E1) gives 0.55 g for U_m , which is $\sim 8\%$ of the fissile mass. This can be regarded as the limit of sensitivity. With a signal change of this magnitude or less, confirmation from several adjacent channels is necessary before much confidence can be placed in the observation.

Fig. 1. Plan View of M8 Test

Fig. 2. M8CAL Half-slotted TREAT Reactor Core. (This plan view shows the half-slot, the Mk-III calibration vehicle at the center of the core, and the locations of the instruments and control rods.)

Fig. 3. Axial Range of Transient and Control/Shutdown Rods. (For each set of rods, zero displacement corresponds to its full-in position. Note that full-in for the transient rods is not the same as full-in for the compensation and control/shutdown rods.)

Fig. 4. Plan and Elevation Views of Fast Neutron Hodoscope at North Face of TREAT Reactor

		Column										
		10	9	8	7	5	4	3	2	1		
Row											Row	
01											01	
02	E										02	
03											03	
04											04	
05										E	05	
06											06	
07									E	E	07	
08											08	
09									E		09	
10											10	
11	E										11	
12											12	
13											13	
14											14	
15									E		15	
16											16	
17											17	
18											18	
19			E	E						X	19	
20											20	
21	E						E				21	
22	E						X				22	
23	E										23	
24	E										24	
25	E										25	
26	E										26	
27	E										27	
28						X					28	
29											29	
30							X				30	
31											31	
32											32	
33			E								33	
34											34	
35	E										35	
36	X					E					36	

E= Erratic Signal
X= Zero Signal

Fig. 5. Nonfunctional Channels in Operation 20

Fig. 6. Power, Energy, and Axial Position of the Control Rods as a Function of Time for Transient 2873

Fig. 7. Power, Energy, and Axial Position of the Control Rods as a Function of Time for Transient 2867

Fig. 8. Power, Energy, and Axial Position of the Control Rods as a Function of Time for Transient 2864

Fig. 9. Array Average and Ion Chamber for Transient 2873, from 0 to 100 s. (Peak power was 60.7 MW.)

Fig. 10. Array Average and Ion Chamber for Transient 2867, from 0 to 40 s. (Peak power was 138 MW.)

Fig. 11. Array Average and Ion Chamber for Transient 2864, from 0 to 40 s. (Peak power was 261.5 MW.)

Fig. 12. Array Average and Ion Chamber for Transient 2867, from 0 to 500 s. (Peak power was 138 MW.)

Fig. 13. Array Average and Ion Chamber for Transient 2864, from 0 to 500 s. (Peak power was 261.5 MW.)

Fig. 14. Ratio of the Array Average to the Ion Chamber for the Medium-power Transient 2867, from 0 to 500 s

Fig. 15. Ratio of the Array Average to the Ion Chamber for the High-power Transient 2864, from 0 to 500 s

Fig. 16. Ratio of Counting Rate to Ion Chamber for Transient 2873, from 0 to 60 s. (Columns 2 through 8 are averaged together.)

Fig. 17. Ratio of Counting Rate to Ion Chamber for Transient 2867, from 0 to 40 s. (Columns 2 through 8 are averaged together.)

Fig. 18. Ratio of Counting Rate to Ion Chamber for Transient 2864, from 0 to 40 s. (Columns 2 through 8 are averaged together.)

Fig. 19. Ratio of Counting Rate to Array Average for Transient 2873, from 0 to 100 s. (Columns 2 through 8 are averaged together.)

Fig. 20. Ratio of Counting Rate to Array Average for Transient 2867, from 0 to 100 s. (Columns 2 through 8 are averaged together.)

Fig. 21. Ratio of Counting Rate to Array Average for Transient 2864, from 0 to 100 s. (Columns 2 through 8 are averaged together.)

Fig. 22. Axial Profiles Averaged Over Several Time Intervals during the Power Ramp, for Transients 2864, 2867, and 2873. (The curves are at times of roughly equal energy, with time increasing from top to bottom of the figure; the times given are for Transient 2964.)

Fig. 23. Axial Profiles Averaged Over the Trailing Power Shelf, for Transients 2864, 2867, and 2873

Fig. 24. Axial Profiles in the Power Ramp of Transient 2873 (peak power 60.7 MW). (Deadtime $0.7 \mu\text{s}$. "Efficiencies" to flatten the 16.4-in. profile. The ordinate is logarithmic.)

Fig. 25. Axial Profiles in the Power Ramp of Transient 2867 (peak power 138 MW). (Deadtime $0.7 \mu\text{s}$. "Efficiencies" to flatten the 16.4-in. profile. The ordinate is logarithmic.)

Fig. 26. Axial Profiles in the Power Ramp of Transient 2864 (peak power 261.5 MW). (Deadtime $0.7 \mu\text{s}$. "Efficiencies" to flatten the 16.4-in. profile. The ordinate is logarithmic.)

Fig. 27. Axial Profiles, Same Rod Position, for a Time Slice in the Power Ramp and Two Slices in the Power Shelf, Low-power Transient 2873. (Efficiencies; no deadtimes.)

Fig. 28. Axial Profiles, Same Rod Position, for a Time Slice in the Power Ramp and Two Slices in the Power Shelf, Low-power Transient 2873. (Efficiencies; deadtime $0.7 \mu\text{s}$.)

Fig. 29. Axial Profiles, Same Rod Position, for a Time Slice in the Power Ramp and Two Slices in the Power Shelf, Medium-power Transient 2867. (Efficiencies; deadtime $0.7 \mu\text{s}$.)

Fig. 30. Axial Profiles, Same Rod Position, for a Time Slice in the Power Ramp and Two Slices in the Power Shelf, High-power Transient 2864. (Efficiencies; deadtime $0.7 \mu\text{s}$.)

Fig. 31. Parabolic Fits to the Relative Axial Profiles in the Power Ramp of the Low-power Transient 2873. (Profiles normalized to unity at row 18. A, B, and C are for correcting for axial flux tilt. See Fig. 32.)

Fig. 32. Linear Fits, with Respect to Rod Position, of the Coefficients A, B, and C Derived from the Low-power Transient 2873 (Fig. 31). (The linearity of the fits shows that tilt corrections to the data can be made by means of simple analytical functions of rod position.)

Fig. 33. Axial Profiles for Power Ramp of Transient 2873 (peak 60.7 MW). (Tilt-corrected. Deadtime $0.7 \mu\text{s}$. "Efficiencies" to flatten the 16.4-in. profile. Compare Figs. 24 and 31.)

Fig. 34. Axial Profiles for Power Ramp of Transient 2867 (peak 138 MW). (Tilt-corrected. Deadtime $0.7 \mu\text{s}$. "Efficiencies" to flatten the 16.4-in. profile. Compare Fig. 25.)

Fig. 35. Axial Profiles for Power Ramp of Transient 2864 (peak 261.5 MW). (Tilt-corrected. Deadtime $0.7 \mu\text{s}$. "Efficiencies" to flatten the 16.4-in. profile. Compare Fig. 26.)

Fig. 36. Axial Profiles, Same Rod Position, for a Time Slice in the Power Ramp and Two Slices in the Power Shelf, Low-power Transient 2873. (Tilt-corrected. Efficiencies. Deadtime $0.7 \mu\text{s}$. Compare Fig. 28.)

Fig. 37. Axial Profiles, Same Rod Position, for a Time Slice in the Power Ramp and Two Slices in the Power Shelf, Medium-power Transient 2867. (Tilt-corrected. Efficiencies. Deadtime $0.7 \mu\text{s}$. Compare Fig. 29.)

Fig. 38. Axial Profiles, Same Rod Position, for a Time Slice in the Power Ramp and Two Slices in the Power Shelf, High-power Transient 2864. (Tilt corrected. Efficiencies. Deadtime $0.7 \mu\text{s}$. Compare Fig. 30.)

Fig. 39. Logic Flow for Finding a Function to Correct Ion-chamber Data for Rod Position

Fig. 40. Ratio of Ion Chamber to Array Average vs Rod Position, with No Ion-chamber Corrections, Showing the Least-squares Quadratic Fit. Low-power Transient 2873. (In determining the array average, a deadtime of $0.7 \mu s$ was applied to all scalars.)

Fig. 41. Logic Flow for Finding Deadtimes and Efficiency Multipliers by Least-squares Fitting to Ion-chamber Data. (Assumes no separate space-charge or supralinearity corrections are needed.)

Fig. 42. Logic Flow for Using DGL to Apply the Corrections for Flux Tilt, Efficiency, and Deadtimes to the Hodoscope Data, and Rod-position Corrections to the Ion-chamber Data

Fig. 43. Ratio of Array Average to Ion Chamber vs Time, for the Low-power Transient 2873. (Note that the ion chamber is now in the denominator.)

Fig. 44. Ratio of Array Average to Ion Chamber vs Time, for the Medium-power Transient 2867

Fig. 45. Ratio of Array Average to Ion Chamber vs Time, for the High-power Transient 2864

Fig. 46. Time Plots of Rate/Ion Chamber for Rows 1 through 12 of Column 6, Transient 2864. (The ion chamber data have been adjusted for rod position, and the counter data have been corrected for tilt and for individual deadtimes and efficiencies as determined by least-squares fitting.)

Fig. 47. Time Plots of Rate/Ion Chamber for Rows 13 through 24 of Column 6, Transient 2864. (The ion chamber data have been adjusted for rod position, and the counter data have been corrected for tilt and for individual deadtimes and efficiencies as determined by least-squares fitting.)

Fig. 48. Time Plots of Rate/Ion Chamber for Rows 25 through 36 of Column 6, Transient 2864. (The ion chamber data have been adjusted for rod position, and the counter data have been corrected for tilt and for individual deadtimes and efficiencies as determined by least-squares fitting. The data for row 35 [Scaler 346, second from bottom] have been synthesized from neighboring channels, since channel 256 was not functioning.)

Fig. 49. Ratio of Array Average to Ion Chamber vs Time, for the High-power Transient 2864, with a 1.0-ms Delay in the Ion-chamber Time. (Compare with Fig. 45.)

Fig. 50. Ratio of Array Average to Ion Chamber vs Time, for the High-power Transient 2864, with a 1.5-ms Delay in the Ion-chamber Time

Fig. 51. Ratio of Array Average to Ion Chamber vs Time, for the High-power Transient 2864, with a 2.0-ms Delay in the Ion-chamber Time

Fig. 52. Corrected Rate/Power vs Power for Scaler 195, as Plotted by NONLIN

Fig. 53. A NONLIN Plot of the Moving Deadtimes from Table IV; Scaler 195. (The data used stop just before the shelf.)

Fig. 54. Averaged Scan Data from Row 20

Fig. 55. Signal-to-background Ratio for Row 20

Fig. 56. Signal-to-background Ratio for Collimator Directly Aimed at Left Pin

Fig. 57. Averaged Scan Data and Its Deconvolution for Row 18, M8 Calibration

Fig. 58. Scan Data and Its Deconvolution, M7 Pretest,
Row 18, Column 5

Fig. 59. Unfueled Axial Scan, Column 3, Operation 19 (a) Scan Data; (b) Axial Response

Fig. 60. Comparison of Response Curve with Monitor Wire

Fig. 61. Comparison of M8 Calibration Response with Present Proportional Counter Calibration

Fig. 62. Fueled Column 2 Response from Operation 20

Fig. 63. Fueled Column 4 Response from Operation 20

Fig. 64. Axial Response in Operation 19, Column 7

Fig. 65. Axial Response in Operation 16, Column 7

Fig. 66. Axial Response in Operation 20, Column 7

Fig. 67. Axial Response in Operation 22, Column 7

Fig. 68. Axial Response in Operation 28, Column 7

Fig. 69. Axial Fuel Shine Peak in Column 7

Fig. D1. Unscattered Neutron Axial Distribution for Column 2

Fig. D2. Response Subtraction, No Power Normalization, Column 2

Fig. D3. Response Subtraction, No Power Normalization, Column 3

Fig. D4. Response Subtraction, No Power Normalization, Column 4

Fig. D5. Response Subtraction, No Power Normalization, Column 7

Fig. D6. Response Subtraction, Power Normalization, Column 2

Fig. D7. Response Subtraction, Power Normalization, Column 3

Fig. D8. Response Subtraction, Power Normalization, Column 4

Fig. D9. Response Subtraction, Power Normalization, Column 7