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SUBCRITICAL REACTIVITY SURVEILLANCE PROCEDURES FOR THE FAST FLUX TEST FACILITY

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MASTER

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AEC-RL RICHLAND, WASH.

SUBCRITICAL REACTIVITY SURVEILLANCE PROCEDURES FOR THE FAST FLUX TEST FACILITY

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SUBCRITICAL REACTIVITY SURVEILLANCE
PROCEDURES FOR THE FAST FLUX TEST FACILITY

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ABSTRACT

Current development efforts to formulate reliable subcritical reactivity measurement procedures for FFTF are described. Emphasis is placed on problems anticipated with the transfer of techniques developed in the zero power critical facility to high power conditions in FTR. Discussions of interfaces with existing FTR instrumentation and operating procedures are given. Appended to the report are more detailed presentations of preliminary calculations of the steady-state and dynamic response of the FTR to reactivity changes in the source range.

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1. INTRODUCTION

A set of Reactivity Surveillance Procedures is being formulated for the Fast Flux Test Facility (FFTF). The objective of this development effort is to provide an information processing package which will interpret the existing reactor process signals to indicate the reactivity state of the Fast Test Reactor (FTR). The range of interest spans from the full shutdown condition to full reactor power. Reactivity surveillance requirements for the high power and subcritical regions are necessarily different, thus providing a natural division for the related development efforts. This report deals with the development of subcritical reactivity surveillance procedures for FFTF operation.

In the source range, the countrate signals from the three Low Level Flux Monitors (LLFM's) are the only available indication of the core reactivity state. However, these signals are not only sensitive to the reactivity but also to the reactor core configuration, control rod settings, etc. Once the system is initially calibrated, the problem becomes one of interpreting changes in the LLFM countrates. The method to be used is a refined version of the source multiplication technique which utilizes calculated corrections to account for nonuniform detector responses. This procedure is referred to as Modified Source Multiplication (MSM).

The end product of the development of subcritical reactivity monitoring procedures will be a prepared reactor operator guide which provides a reliable procedure for converting the LLFM countrates to reactivity. The procedure will be capable of insuring a minimum shutdown margin of 15$ with a precision of 3$ during all stages of refueling.

2. SUMMARY

Procedures for monitoring the reactivity of the FTR while in a subcritical state have been proposed and analyzed in detail. The procedures center around the Modified Source Multiplication (MSM) method, coupled with a reactivity calibration procedure. The suggested calibration procedure involves an inverse kinetics/rod drop to be initiated with the FTR close to critical.

The feasibility of the MSM method has been demonstrated by critical experiments testing. FTR calculations indicate, however, that the configuration factors, which are applied to the source multiplication results, are strongly dependent upon the relative proximity of the control rods and the detectors. In some cases, the configuration factors correct the source multiplication data in a nonconservative direction, i.e., prior to applying the correction factors, the reactor appears to be closer to critical than is actually the case. Consequently, the operational procedures and use of the MSM method must be carefully coordinated.

A series of critical experiments has been designed to test the subcritical reactivity monitoring procedures proposed for the FTR in the ZPR-9 critical facility at ANL. The data from this experiment will serve as the basis for determining the final configuration factor calculational model, and as a result, the accuracy and sensitivity of the method will be better established.

Practical applications of the MSM method will require that there be a method for inferring configuration factors from a finite precalculated base set. This problem can be separated in the sense that changes in the effective

source, due to fuel exchanges and heavy isotope buildup, and changes in detection efficiency, due to flux distortions brought about by material changes in the core, are more or less independent. While these problems are well identified, they require additional extensive investigation.

The effect of background noise signals on subcritical reactivity measurements was studied for both static and dynamic modes. While the nonlinearities induced by a background signal can be minimized for the dynamic inverse kinetics calibrations, the effects on far subcritical source multiplication measurements are severe. Furthermore, attempts at direct measurement of background signals in a loaded reactor through the use of known reactivity changes are subject to large errors.

Simulated FTR inverse kinetics measurements with the LLFM system have been investigated. Based on these studies it would appear that the LLFM is adequate for recording the required rod drop measurements and, therefore, for source multiplication calibration. However, a combination of rod drop and rod run-in measurements may be required to infer accurate control rod worth profiles.

The interface with FTR operating procedures was investigated. The required source multiplication calibrations can be meshed into the normal operating scheme without significant effect on the reactor plant availability. Following inadvertent scrams from high power, reactivity monitoring will be based on calibrations made on the previous approach to critical. Special methods for monitoring the initial approach to critical must be developed, and it is likely that configuration factor schemes will be part of this procedure.

3. SUBCRITICAL REACTIVITY MONITORING

3.1 Proposed Method for Monitoring Subcriticality in FTR

Given the proper conditions, the subcritical reactivity (ρ) in a reactor with a neutron source can be simply related to the counting rate (CR) in a neutron detector, through the use of the point kinetics equations. The derivations are well known, but are reproduced in Appendix A for completeness and for the proper definition of terms.

The equation can be written in the familiar form

$$\rho = -\frac{Q}{CR} \quad (1)$$

where Q is determined experimentally at some initial condition and presumed to remain constant throughout the course of the experiment.

Intuitively, however, one suspects that Q does not remain constant; and if the particular characteristics of the FFTF are considered, i.e., the placement of the Low Level Flux Monitors (LLFM's), the mode of achieving reactivity changes, and the high inherent neutron source strength in the PuO_2-UO_2 fuel, one would indeed be surprised if Q did not change significantly over the course of a given shutdown and refueling cycle. Once the components of Q are defined specifically, the nature of these changes becomes more apparent.

$$Q = \frac{\varepsilon S}{\nu} \quad (2)$$

ε = counts in detector per fission in the reactor

S = effective source neutrons per sec

ν = average number of neutrons produced per fission in the reactor.

(See Appendix A for the detailed discussions of these equations.)

To postulate a few conditions which would lead to changes in Q, consider the following circumstances:

- Movement of a control rod, safety rod or peripheral shim rod: A change of this nature severely perturbs the spatial distribution of the lower energy flux. Since the neutron detectors primarily detect lower energy neutrons, the detection efficiency may change drastically depending upon the relative proximity of the detector and the absorber assembly being moved.

- Replacement of a high exposure fuel element with fresh fuel: During the course of irradiation, mixed oxide fuel will generate trace quantities of ^{242}Cm and ^{244}Cm isotopes. Each of these has a sufficiently high (α,n) and spontaneous fission activity, that they may overshadow the neutron source due to the plutonium isotopes in fresh fuel. Replacement of exposed fuel with fresh fuel will cause significant changes in the effective source term in Equation (2).

These arguments are not meant to be comprehensive, but rather are intended to illustrate reasons for not relying on Equation (1) as a reliable means of monitoring the reactor subcriticality.

In considering alternatives to the use of Equation (1) for measuring the subcriticality of fast reactors, one finds, again, that rather ideal conditions are required for their application. Several recent publications deal with this subject[1,2,3], but in all cases, the difficulty of applying these alternate techniques in the far subcritical region with existing FFTF flux monitor equipment is apparent.

Difficulties with source multiplication measurements became apparent early in the FFTF critical experiments program performed in the ANL zero power critical facilities. Prior to the recent wave of interest which has generated the more reliable noise analysis and inverse kinetics methods of measuring reactivity in zero power fast reactors, subcritical reactivity was measured using the source multiplication method (Equation (1)). This presented the reactor analyst with the problem of interpreting a variety of reactivity values from several neutron detectors. An early version of what is now referred to as the Modified Source Multiplication Method (MSM), i.e., calculated corrections to the source multiplication measurements, was developed for that purpose[4].

In terms of Equation (1), this method can be summarized as

$$\rho_i = - \frac{Q_o}{CR_i} F_i'$$

where the i subscript denotes the configuration of interest, the prime indicates a calculated quantity, and the o subscript refers to a calibration configuration. F_i', the configuration factor, can be defined in many ways

$$F_i' = \frac{Q_i'}{Q_o'} = \frac{CR_i'\rho_i'}{CR_o'\rho_o'} = \frac{\nu_o' S_i' \varepsilon_i'}{\nu_i' S_o' \varepsilon_o'} \qquad (3)$$

each indicating the ratio of calculated parameters intended to remove the nonuniformity in the detector response. Obviously, an independent assessment of the configuration factor must be made for each detector location in the assembly.

In order to appropriately apply this method to FFTF, the following conditions must be met:

1) A reliable and inexpensive method of calculating the configuration factors must be available.
2) A reliable method for directly measuring the reactivity of a calibration configuration, ρ_0, must be available.
3) A method for inferring configuration factors must be determined so that not all configurations need be calculated directly.
4) An adequate detection system, without significant drift and unaccountable spurious background noise signals, must be available to measure the subcritical countrates.

The balance of this report describes the development program which is being carried out to assure that a viable subcritical reactivity monitoring package, using this method, is available for FFTF operations. To the extent that more effort has been directed at the first two points listed above, more emphasis will be placed on those areas. However, at least brief discussion of each of the points will be given.

3.2 Calculation of Configuration Factors

3.2.1 Critical Experiments Testing to Date

The development of methods for arriving at configuration factors has centered upon multigroup reactor source calculations. At HEDL, the

FFTF nuclear design methods and models have been employed for this purpose. In order to establish the feasibility of this approach, a series of special critical experiments was performed, as part of the FTR-3 critical experiments program[5], in ZPR-9 at Argonne National Laboratory.

The experiments consisted of measuring the reactivity of successively further subcritical reactor core configurations. Starting with an initial core containing no poison assemblies, the reactor was made subcritical mainly by the insertion of control rods in the first row of the reflector in a manner similar to the FFTF reference control system design at that time. Countrates from several detectors were recorded for each configuration. Reactivities in the 0-4$ subcritical range were measured directly, while those further subcritical were inferred from well established experimental control rod worth data.

Reactivities and countrates were calculated using the 2DB[6] code in the source mode, and configuration factors were inferred for three detectors in each reactor configuration. A discussion of this analysis has been reported earlier[7]. The results for one of the detectors are shown in Figure 3-1. Source multiplication and modified source multiplication are plotted against the core reactivity. The arrows indicate the magnitude and direction of the change in the source multiplication value due to the configuration factors.

Figure 3-2 describes modified source multiplication results for the three detectors investigated in this analysis. In all cases, the

DETECTOR NO. 2

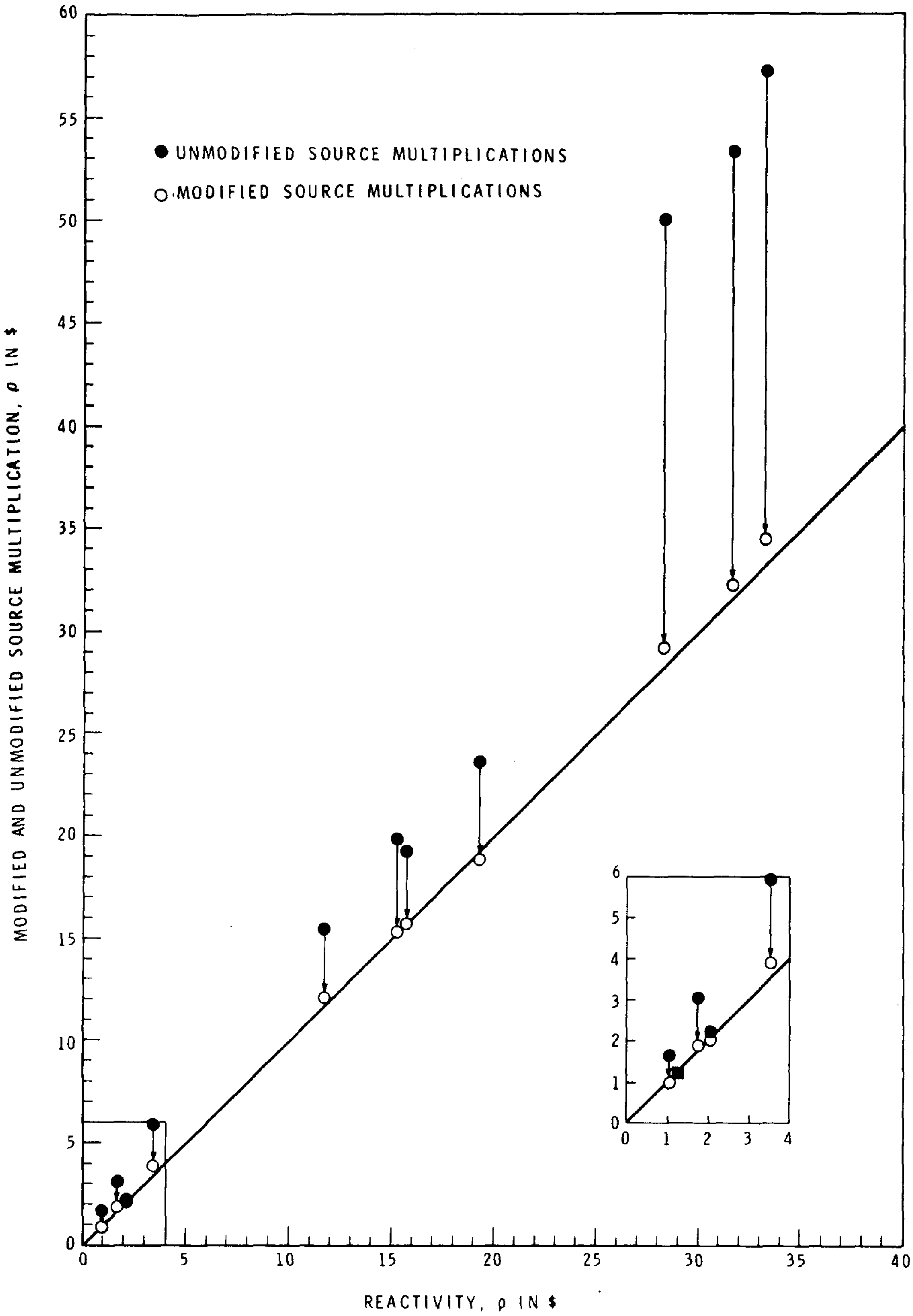


FIGURE 3-1. FTR-3 MSM Calculations.

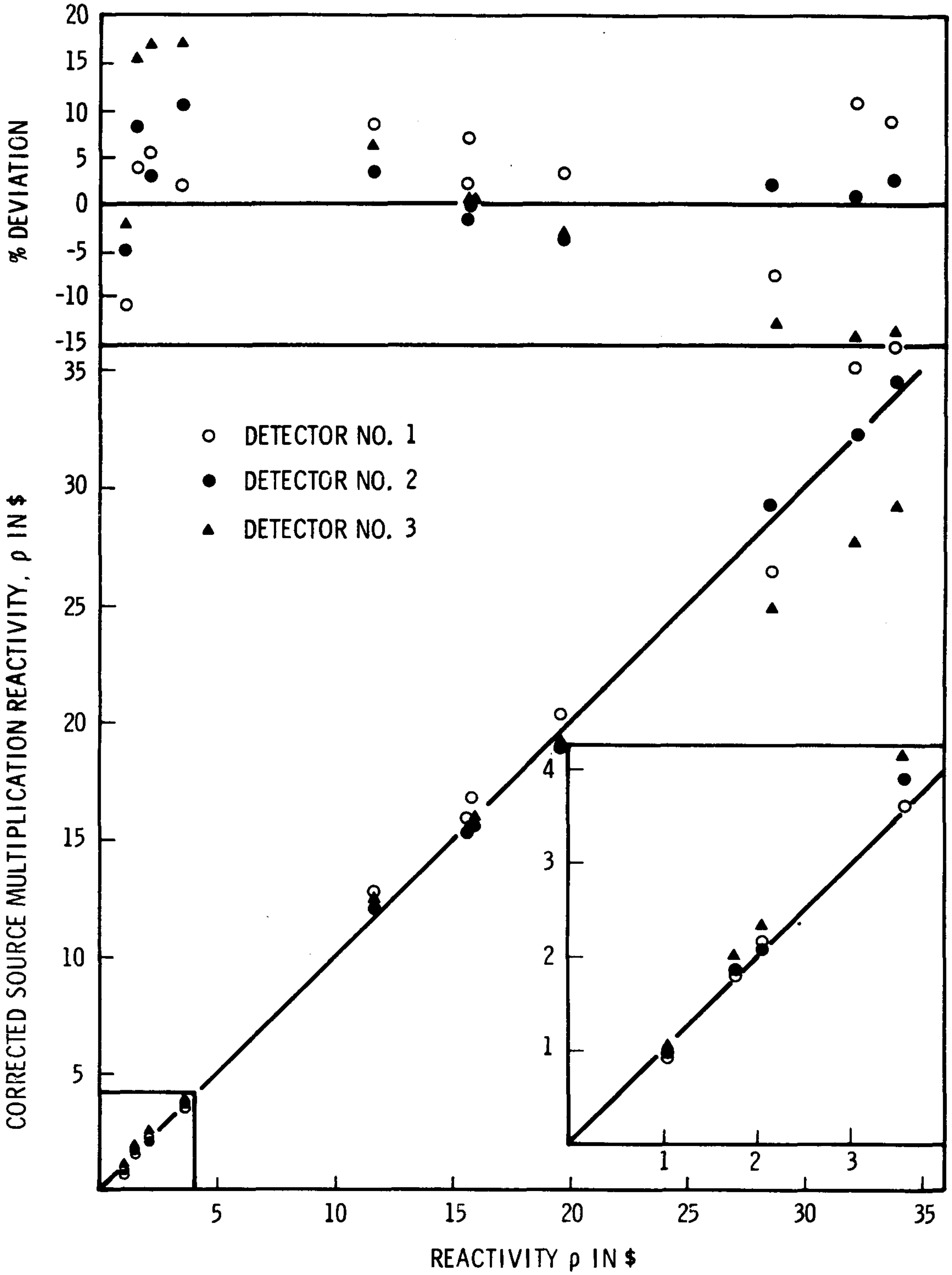


FIGURE 3-2. Composite FTR-3 Experimental Results.

modified source multiplication value falls well within ±20% of the core reactivity.

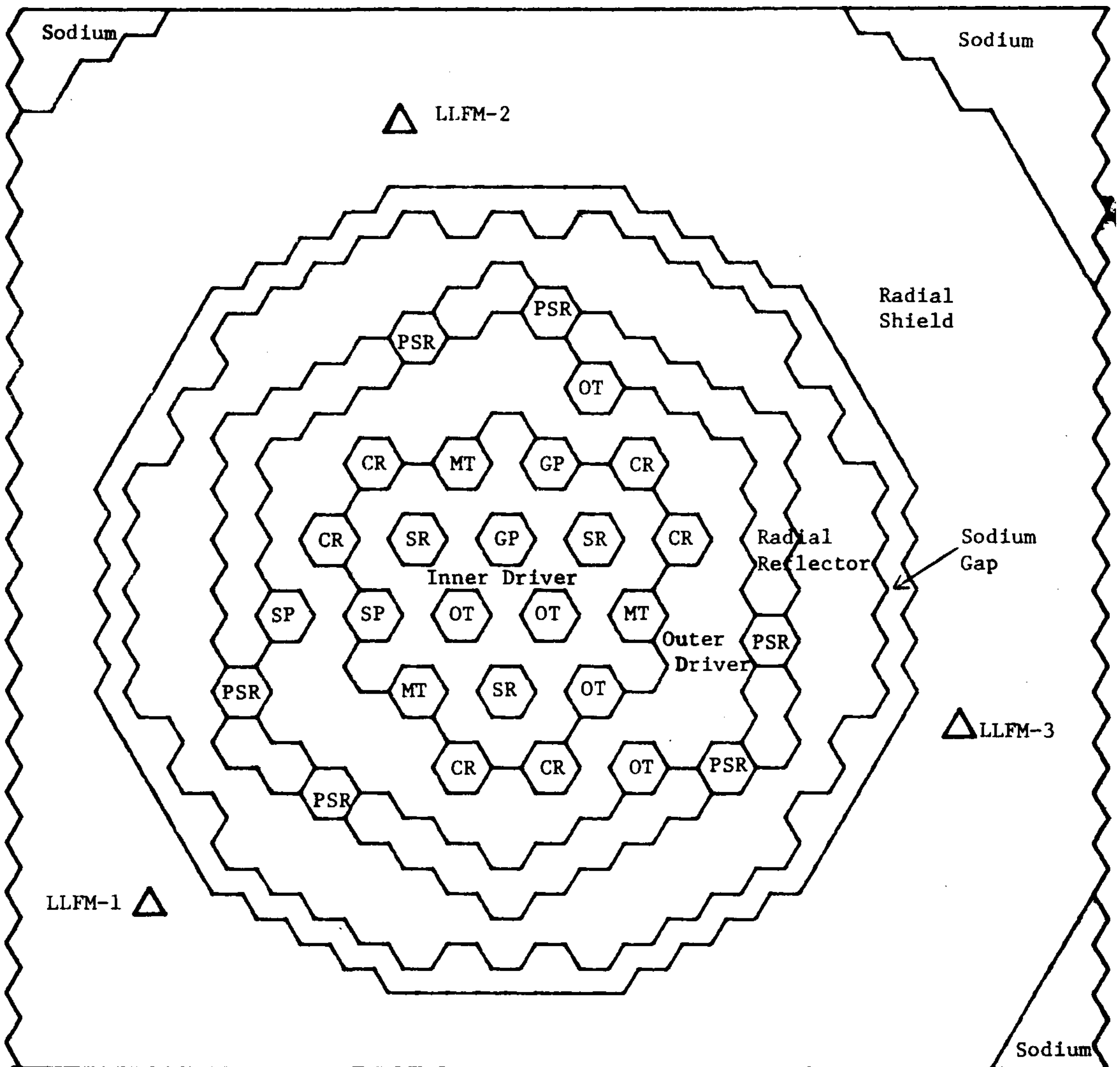
An independent analysis of these experiments was performed by ORNL[8]. This analysis employed two-dimensional transport theory and different cross section data. However, and perhaps somewhat surprisingly, the results are very much the same. Whereas the results are not directly comparable because different detector locations were analyzed by ORNL, the characteristics of source multiplication corrections are very much similar to those calculated by HEDL.

Part of the MSM development effort involves a careful comparison of calculational techniques, reactor models, and cross section data. This work is a joint effort between HEDL and ORNL.

3.2.2 FTR Configuration Factor Calculations

MSM calculations have been performed for a series of FTR reactor configurations which represent a planned reactor shutdown from critical. Reference FTR nuclear design methods were used in these calculations. The geometric reactor model is shown in Figure 3-3 and further details of the calculations are given in Appendix B.

Figures 3-4 and 3-5 show the calculated source multiplication results for each of the LLFM's for symmetric and asymmetric calibration configurations, respectively. The symmetric calibration configuration was near critical with all rods represented at 50% density. The asymmetric configuration was $\sim$ 1$ subcritical with one control rod fully in-



PSR = Peripheral Shim Rod
OT = Open Test Position
CR = Control Rod
MT = Material Test

GP = General Purpose Closed Loop
SP = Special Purpose Closed Loop
SR = Safety Rod

FIGURE 3-3. FTR Subcritical Configuration Factor Calculational Model.

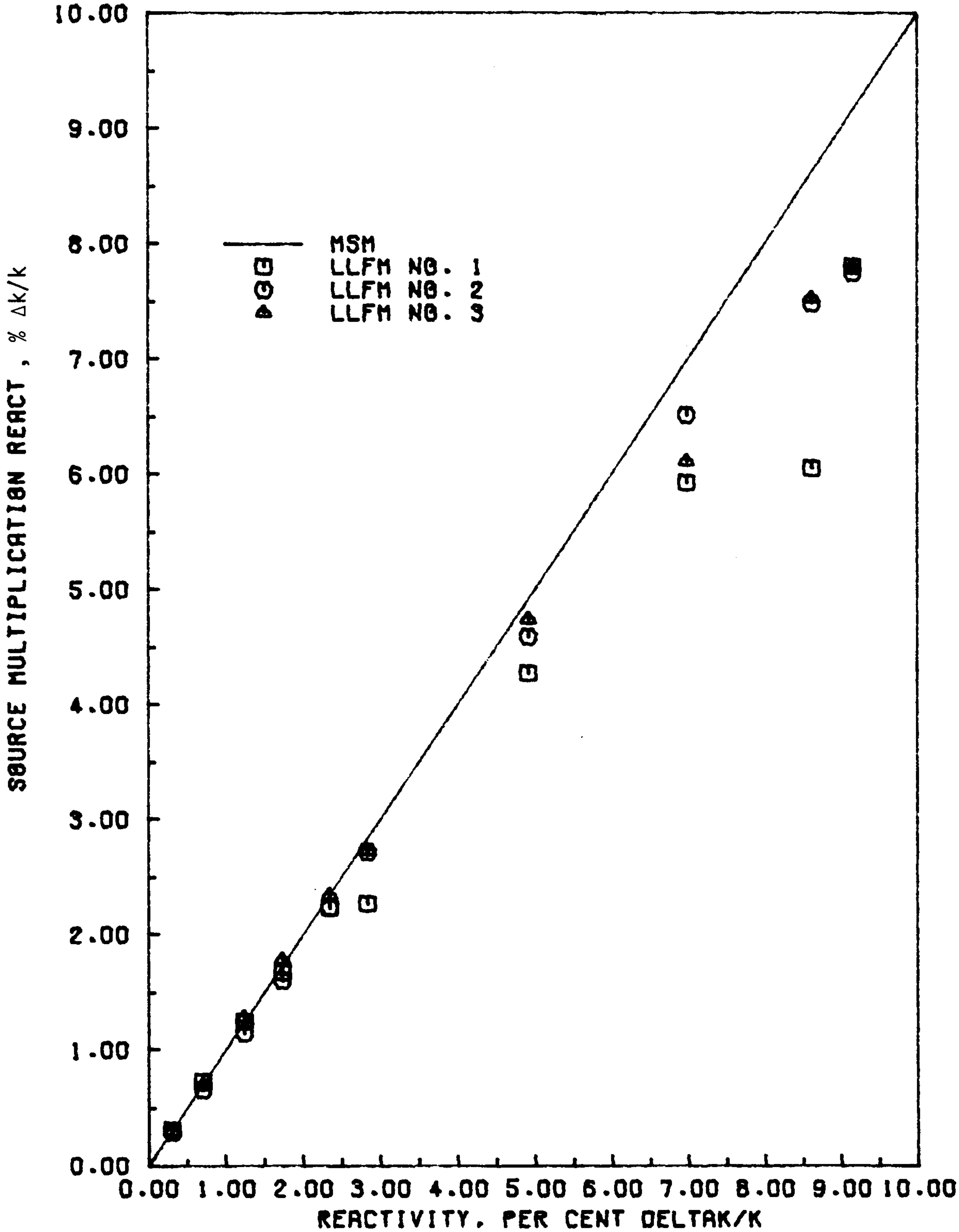


FIGURE 3-4. Source Multiplication Symmetric Calibration Configuration.

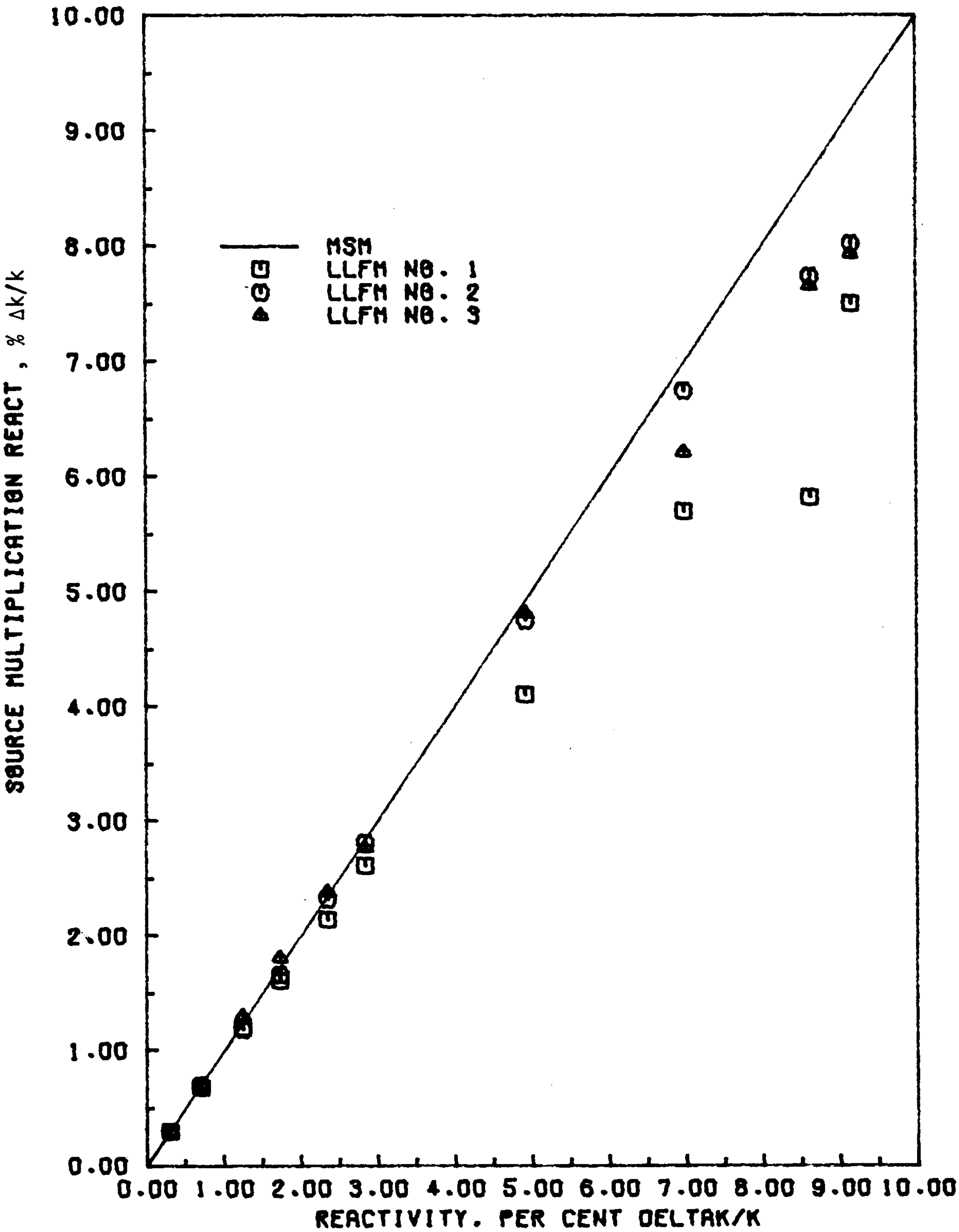


FIGURE 3-5. Source Multiplication Asymmetric Calibration Configuration.

serted and the remaining five represented at 50% density. Since these figures represent idealized comparisons, application of the correction factors will give exact agreement between MSM and the core reactivity. However, the remarkable difference between these plots and similar ones for the FTR-3 experiments warrants some discussion.

As noted earlier, FTR-3 reactivity changes involved primarily the movement of control rods located in the reflector. Moreover, the detectors used in the FTR-3 experiments were located in close proximity to the rods. On the other hand, the current FTR design utilizes control rods in the fifth fuel row and the Low Level Flux Monitors are located well into the radial shield. This change in rod-detector proximity is largely responsible for the difference in the source multiplication response.

To demonstrate this point, one of the peripheral shim rods (PSR) nearest the No. 1 LLFM was removed from the shutdown configuration. Before the removal, the configuration factor was 1.173. Following the removal, the configuration factor jumped to 1.424. In other words, the perturbation effect of that single PSR, worth $\sim$ 1$ in reactivity, was equal to the perturbation effect of the total incore control system, worth approximately 30$ in reactivity. This effect is displayed graphically in Figure 3-6, on which iso-configuration factor lines are plotted for this reactivity adjustment. The influence of the removed PSR is evident from this figure. It is only reasonable to assume that if the reactor shutdown were achieved with peripheral rods, the FTR con-

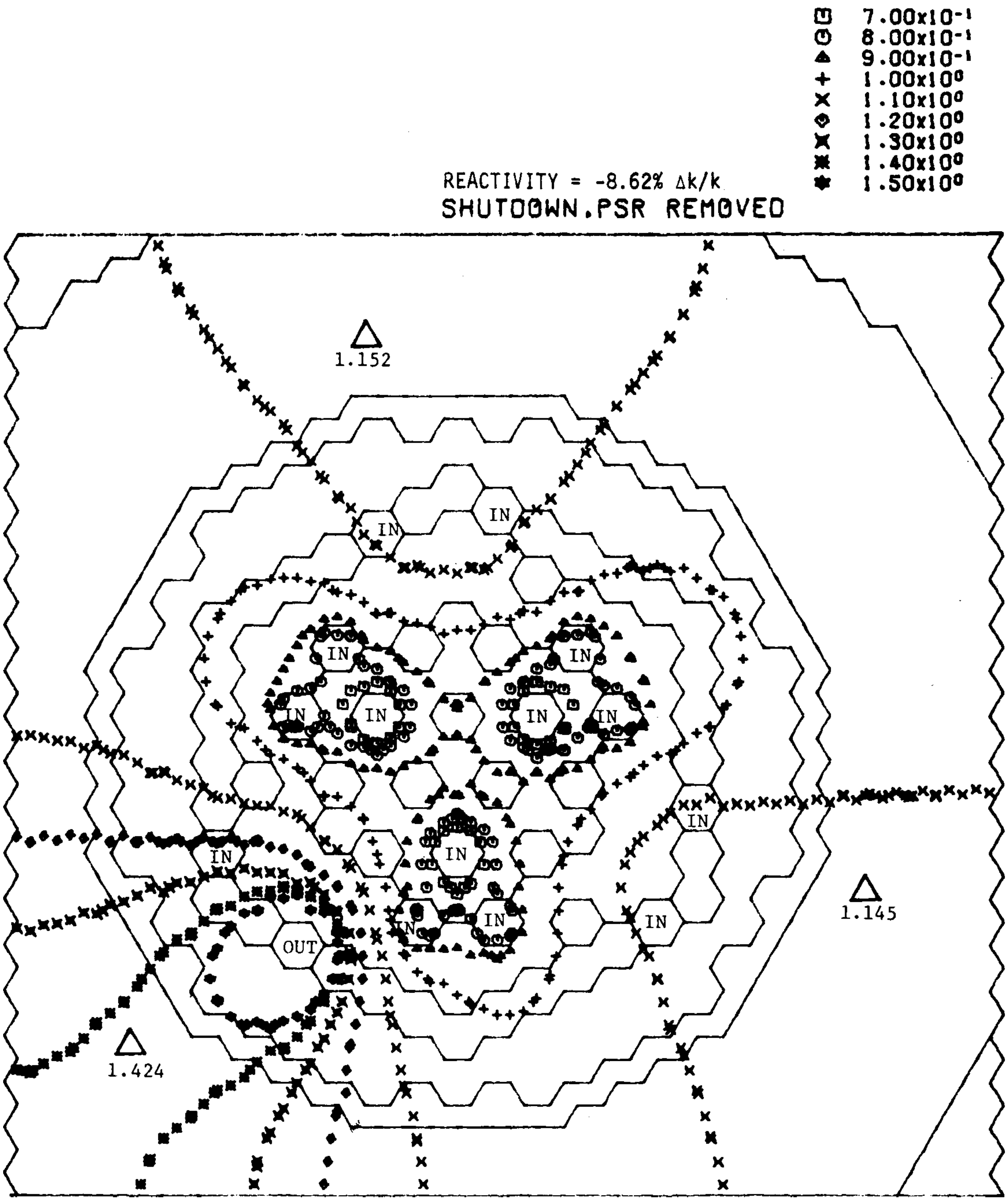


FIGURE 3-6. FTR Subcritical Configuration Factors.

figuration factors would be similar to those measured in FTR-3. In fact, large corrections similar in both magnitude and direction to those measured in FTR-3 could be caused in FTR by the insertion of many PSR's for shimming purposes during the refueling sequence.

Plots similar to Figure 3-6 for each of the shutdown sequence configurations are given in Part 3 of Appendix B. These plots display graphically the flux tilts and perturbations introduced by the control rods during a planned reactor shutdown.

The fact that FTR configuration factors appear to react differently than those measured in FTR-3 is some cause for concern. This would imply that when the configuration factor is applied to the source multiplication equation, the resultant reactivity will be further subcritical than the uncorrected value; certainly a nonconservative correction. However, as the above discussions would indicate, one can postulate refueling schemes which would affect corrections to be applied in either direction. The conservative or nonconservative nature of this method will be determined by the calibration configuration and the particular reactor loading sequence to be monitored.

These features present some interesting problems when applying the method to FTR. It is most likely that both unmodified source multiplication and MSM calculations will be carried out during the refueling process. The more conservative of the two would perhaps be best used for compliance with operating safety limits, while the MSM data would provide the best quantitative check on the reactivity changes encountered during the reloading sequence. Certainly, the behavior of FTR configuration factors warrants continued investigation, and additional critical experiments evaluation is discussed in the following section.

3.2.3 Additional Critical Experiment Testing

A joint experimental effort among HEDL, ORNL and ANL has been pursued for the purpose of performing a comprehensive evaluation of a number of reactivity measurement methods under similar experimental conditions in the FFTF Engineering Mockup Critical[9,10,11]. These experiments will involve detailed comparisons of the various noise analysis and inverse kinetics reactivity measurement methods in a zero power assembly quite similar to the FFTF. Such comparisons of direct measurement techniques will lend themselves not only to establishing a practical means for calibration of the source multiplication method in FTR, but also to the more fundamental investigations of the accuracy, range, and speed of direct measurement techniques for general LMFBR program applications. Moreover, these experiments will provide the opportunity to investigate the reference FFTF source multiplication methods with the current design control rod arrangement using at least one detector prototypic of the FTR-LLFM.

The experiment will begin with a critical configuration that approximately simulates the FTR at the beginning of the first cycle. The assembly will be progressively shut down by sequentially inserting the control rods. All reactivity measurement techniques will be used with various detection systems located throughout the assembly until the lower extent of the reactivity range of each combination is established.

The shutdown will continue with the sequential insertion of the safety rods until the full shutdown condition is achieved. At that time, typical refueling moves will be simulated. Source multiplication data for all the detectors will be recorded for each of the subcritical configurations.

Data from the experiment will be used for the following FTR-related development efforts:

- Establishing the anticipated accuracy and sensitivity of the MSM method in FTR.
- Establishing a reference source multiplication calibration procedure for FFTF using the LLFM's.
- Making systematic comparisons of diffusion and transport calculations of configuration factors in cooperation with ORNL.
- Testing procedures for calculating countrates in the LLFM's.
- Testing schemes for inferring configuration factors without direct calculation for each configuration.
- Testing the sensitivity of MSM to refueling reactivity changes.
- Determining the feasibility of using reactivity measurement techniques with special instrumentation during FFTF startup and physics testing.

While the experiment will not provide solutions to all subcriticality monitoring development problems for the FFTF, it is expected to furnish a data set which will prove invaluable for investigating many of the related technical problems.

3.3 Other Development Areas

3.3.1 Heavy Isotope Source Effects

As the FTR-mixed oxide fuel is exposed to high neutron flux levels for long periods of time, the build-up of trace quantities of heavy isotopes will occur. Of particular interest are the isotopes ^{242}Cm and ^{244}Cm because of their extremely high spontaneous fission and (α,n) activity. These isotopes build up according to the production chains:

$$^{242}Pu + n \rightarrow (^{243}Pu - \beta) \rightarrow {}^{243}Am + n \rightarrow (^{244}Am - \beta) \rightarrow {}^{244}Cm$$

$$(^{241}Pu - \beta) \rightarrow {}^{241}Am + n \rightarrow (^{242}Am - \beta) \rightarrow {}^{242}Cm$$

Approximate calculations indicate that the inherent neutron source rate in an FFTF driver after full exposure will be approximately five times larger than that of a fresh driver fuel element. The total core source rate at the end of three cycles of operation prior to refueling will be approximately three times that at the beginning of life(12). When light water reactor plutonium, with higher concentrations of ^{241}Pu and ^{242}Pu is used, possibly as early as FFTF cores 3 and 4, the problem becomes significantly worse.

Reliable means of accounting for large effective source changes are available provided the source changes are well known. Certainly, the reference methods for calculating configuration factors will be designed to accommodate changes in the spatial distribution of the inherent neutron source; however, as yet untested are more approximate means to estimate changes in the effective source. Such schemes might involve adjusting the effective source with approximate adjoint weighting factors.

Continued development in this area will require more accurate calculations of the spatial distribution of heavy isotope buildup in FTR as a function of core life. Additional sensitivity calculations will be performed to determine approximate methods for making source adjustments as part of the operating procedure for monitoring subcriticality in the FFTF.

3.3.2 Configuration Factor Interpolation

While the feasibility for calculating configuration factors was well established in the FTR-3 experiments, general methods for inferring configuration factors from a finite precalculated base set have been only superficially investigated to date. The degree to which one must pursue this issue is somewhat dependent upon the sensitivity of the method to actual fuel loading changes. For example, if interest is restricted to perturbations induced by control and safety rods, then symmetry considerations can be used to reduce the required number of configuration factor calculations as discussed below.

In Table 3-1 the configuration factor results for the calculations discussed in Section 3.2.2 and Appendix B are given. In all cases, the

Table 3-1

FTR Configuration Factors with Symmetric and Asymmetric Calibration Configurations

ρ	Symmetric Calibration Configuration Factors			Asymmetric Calibration Configuration Factors		
% Δk/k	LLFM #1	LLFM #2	LLFM #3	LLFM #1	LLFM #2	LLFM #3
0	*	*	*	-	-	-
- 0.298	.961	1.035	1.016	*	*	*
- 0.700	.959	1.064	1.008	1.028	.988	.992
- 1.242	.996	1.082	.968	1.037	1.046	.953
- 1.729	1.032	1.077	.970	1.074	1.040	.955
- 2.346	1.051	1.048	1.001	1.094	1.009	.985
- 2.834	1.042	1.042	1.038	1.085	1.007	1.022
- 4.917	1.150	1.070	1.037	1.197	1.034	1.021
- 6.980	1.177	1.071	1.142	1.225	1.035	1.124
- 9.159	1.173	1.182	1.174	1.221	1.142	1.155
- 8.620	1.424	1.152	1.145	1.482	1.114	1.127

*Calibration configuration.

ratios among the configuration factors for the various detectors in symmetric configurations remain constant within one percent. This is true even when the calibration configuration is asymmetric. Since this is the case, interpolation on this ratio is less sensitive to error than actual interpolations on the configuration factor.* Under these assumptions, configuration factors for all three detectors can be inferred for reactor configurations in which the control rod insertion pattern is shifted 120°. This reduces significantly the number of calculations required to assess control rod effects. For example, the number of calculations required to assess configuration factors for full-in-full-out control and safety rod combinations can be reduced by a factor of 2.5.

To the extent that peripheral rods, fissile fuel loading changes, and partially inserted control rods invalidate this rather simplistic approach, more sophisticated approaches must be investigated, and critical experiment data will be of value for testing proposed methods. Significant additional effort must be applied in this area.

3.3.3 LLFM Background Signal Effects

For the sake of simplicity, discussions of the MSM procedures up to this point have neglected the presence of any possible background in the LLFM signals. It is expected, however, that background will exist at

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*Since the configuration factor is really the ratio of two Q's (see Equation 3, Section 3.1), and the denominator, Q_0', is fixed for a given sequence of experiments, interpolation is required to infer values for Q_i' which in turn are used to calculate configuration factors.

initial startup and that it may vary with time, i.e., with power history of the FTR. Preliminary investigations indicate that at initial startup the LLFM sensor background will be between zero and approximately 100 cps as suggested by recent SEFOR and EBR II experience, respectively. Source calculations on the FTR at shutdown condition (∿-30$) yield an LLFM countrate of ∿120 cps, which, when corrected for detector efficiency and pulse height discrimination losses, reduces to ∿40 cps. Hence, background countrates as large as 100 cps would prove to be troublesome for subcritical reactivity assessments.

Table 3-2 demonstrates the effect of a background signal on the source multiplication evaluation. Assume, for simplicity, that the inverse multiplication law is followed, and an undetected background of 10 cps exists in the system; the reactivities of 1$ (calibration point), 15$, and 30$ show up as 1$, 14.5$ and 24.2$, respectively. If one attempts to correct for the background and for some reason overcorrects, the consequence is nonconservative since the source multiplication indicates that the reactor is further subcritical than it is in reality. In the event that the background is variable, unknown changes will appear as unexplainable reactivity changes that will not vanish until the reactor approach-to-critical is made.

Simulated FTR kinetics studies (Appendix C) indicate that the presence of a constant background does not affect the final reactivity inferred from inverse kinetics rod drops, but does bias the corresponding initial reactivity. By posing the rod calibration procedure such

Table 3-2

Effect of Background on Source Multiplication

True Reactivity	True Countrate	Background	Source Multiplication
$	cps	cps	$
1	1200	10	1.0*
15	80	10	13.5
30	40	10	24.2

*Calibration point

that the initial reactivity is very small, large fractional errors in this quantity will not significantly affect the measured rod worth. This point is well demonstrated in Appendix C. The source multiplication can be calibrated accurately by using the final reactivity from the rod drop. However, the background will continue to affect the source multiplication measurements unless it can be routinely measured and subtracted from the measured countrate.

In principle, one can infer the background in the presence of a neutron signal from known subcritical states. Using Equation (1), re-written to reflect the background,

$$\rho_i = - \frac{Q}{CR_i - B}$$

where, as before, ρ_i is the subcritical reactivity, Q is the calibration constant, and CR_i is the countrate including background B, such that CR_i-B is the true neutron signal.

If two known subcritical states, ρ_1 and ρ_2, are achieved by insertion of calibrated rods, one can show that

$$B = \frac{\rho_2 CR_2 - \rho_1 CR_1}{\rho_2 \quad \rho_1}$$

If we assume that the uncertainties in the measured reactivities are much larger than the error in the countrates, then the uncertainty in the background, S_B, can be written simply as

$$S_B = \sqrt{2}\ \frac{Q}{\Delta\rho}\ (\frac{S_\rho}{\rho})$$

where $\frac{S_\rho}{\rho}$ is the fractional uncertainty (assumed to be equal) in the ρ_i's.

Using values of Q = 1200 and $\Delta\rho$ = 3\$, then $S_B \simeq 566\ (\frac{S_\rho}{\rho})$ for FTR. If we assume that the reactivities can be measured with a precision of 1-5%, then the uncertainty in the background signal inferred from this measurement would range from ~6 - 30 cps. These values indicate that an accurate inference of background in the presence of a neutron signal in FTR will be difficult at best and that every effort must be made to eliminate the possibility of noise pick-up in the LLFM system.

3.4 Source Multiplication and Control Rod Calibrations with Inverse Kinetics Methods

The use of the MSM technique requires a reactivity calibration which will most likely be done in the near critical range. Of the two most likely calibration techniques, noise analysis and inverse kinetics, the latter has several advantages. The suitability of the noise methods is highly dependent upon the frequency response, detection efficiency, and placement of the neutron detection system. By comparison, inverse kinetics techniques can be performed with minimum restrictions on the flux detection system. Hardware requirements include individual rod scram and drive capability and a computing system with on-line data sampling capabilities. The measurement is rapid and the result will most likely be known before the system is returned to the pre-experiment condition. Other advantages include the option for obtaining a detailed rod worth profile from a rod run-in experiment and the fact that the method does not require a critical calibration.

Several perturbations to an early inverse kinetics technique proposed by Carpenter[13,14], have been suggested but the technique remains essentially the same. In Appendix C the inverse kinetics measurements are described and simulated FTR control rod and safety rod calibrations are given. Based on these studies, it would appear that the LLFM is adequate for recording the rod drop measurements and, therefore, for source multiplication calibration. However, a combination of rod drop and rod run-in measurements may be required to infer accurate control rod worth profiles.

The ZPR-9 subcritical experiments discussed in Section 3.2.3 will provide substantial data for evaluating the LLFM with regard to these applications. Included in the list of proposed experiments is a series of rod drops in the 0.5$ to 6$ range designed to test directly the response of a simulated LLFM to inverse kinetics calibrations similar to those that will be performed in the FFTF.

3.5 Interface With FFTF Hardware Systems

3.5.1 The Low Level Flux Monitor (LLFM) System

The LLFM system is relied upon to provide data on the neutronic state of the subcritical FTR. There are no other FFTF sensor systems designed to monitor the neutron flux during shutdown. The system consists of three ^{235}U fission counters located about 120° apart azimuthally and 113 cm from the FTR centerline (Figure 3-3). When the reactor is shut down, the LLFM's are positioned on the midplane of the reactor core and are withdrawn from that position when the power level is sufficient to be monitored by the ex-vessel sensors. The three sensors feed three separate and identical electronic systems, and hence produce three distinct signals.

The subcritical reactivity surveillance procedures will utilize the signals from the LLFM to (1) ensure that the FTR is below the shutdown margin of -15$ during the refueling process, (2) monitor the approach to critical, and (3) provide the dynamic reactivity calibrations required for FFTF operations. To accurately and efficiently provide these functions, three LLFM channels were provided. The provision of three LLFM channels allows for the requirement that two out of three channels be verified as operational during subcritical operations.

In appraising this interface between subcritical reactivity surveillance procedures and the LLFM system, several facts stand out. First, to meet the requirements, the neutron flux signal must have sufficient accuracy. This means that the linear LLFM countrate data must be used, not the logarithm of the signal. Second, noise on the LLFM signal will be a potential problem. The noise or background magnitude may be of the same order of magnitude as the neutron signal for the fully shutdown FTR. The noise level may not be time invarient; it may be dependent upon FFTF equipment in operation; and it may well be different for each LLFM channel. Third, fission counter sensors and their electronics are known to sometimes fail in a manner not distinguishable from flux changes. Finally, two modes of operation or use of the LLFM signal have already been described. That is, both static and dynamic data retrieval will be required, as the LLFM signals are used for both MSM reactivity determinations and dynamic kinetics calibrations.

A means of correcting for background signals and electrical noise was investigated above (Section 3.3.3), and it is apparent that efforts must be made wherever possible to reduce the noise level in the LLFM signal. The LLFM design effort has addressed the problem[15,16,17] and a summary of significant design criteria is given below.

- Only one connector between the detector and the preamplifier is being used and that is at the preamplifier input. The detector has an integral cable lead.
- The detector shield can, the outer cable sheath, and the preamplifier shield can form an outer shield insulated from the inner high-quality signal ground.
- A triaxial cable system is being used.
- Lead lengths between the sensors and preamplifiers are being minimized to the extent possible.

In addition, an effort will have to be exerted during installation and operation to eliminate sources of signal contamination.

Figure 3-7 shows a portion of the LLFM system design. Shown are the block diagrams of the instrumentation for one of the three channels,

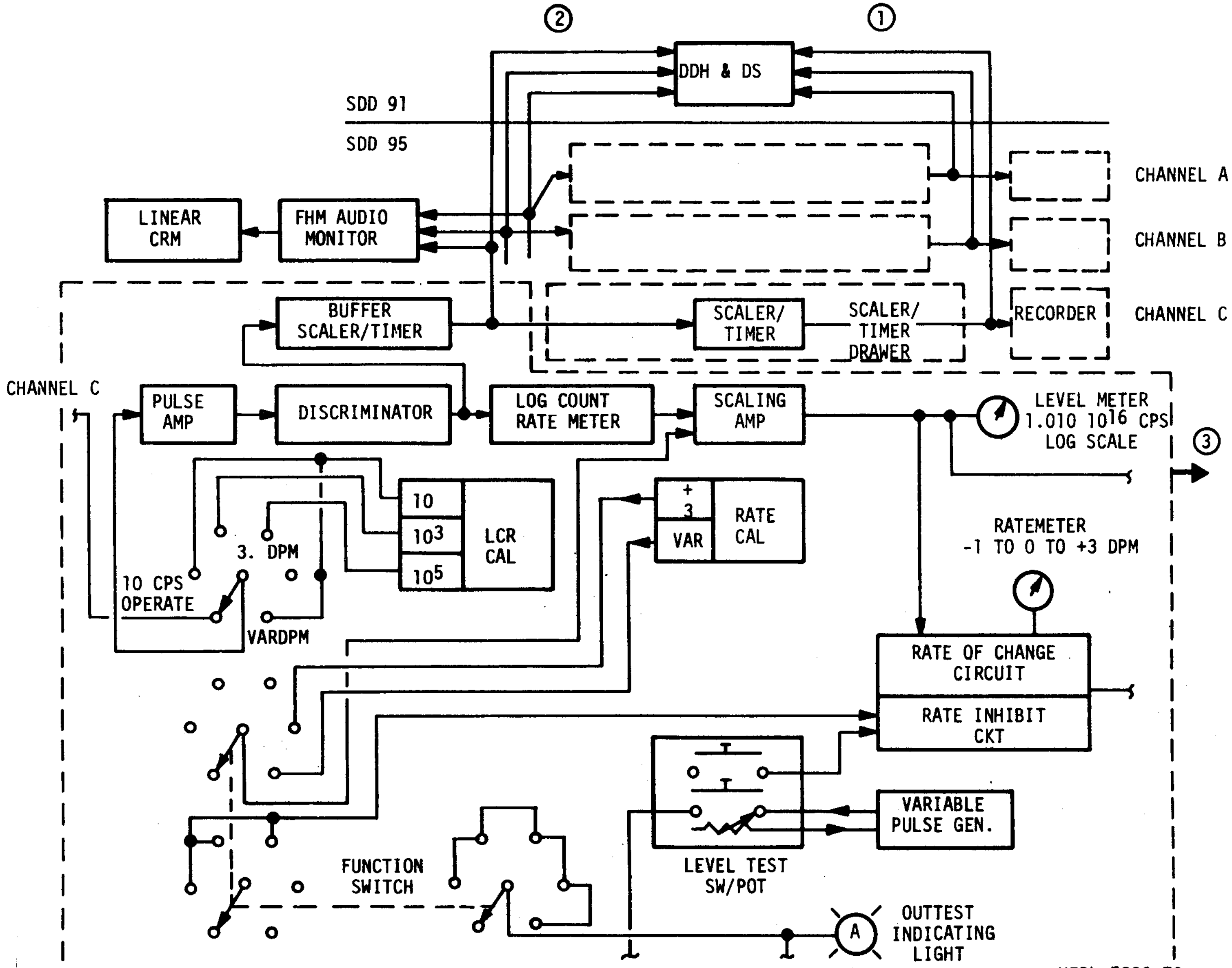

FIGURE 3-7. LLFM Instrumentation System - Block Diagram.

channel C. The pulse signal from the fission counter (not shown) is amplified and passes through the discriminator. After the discriminator, the signal branches to the log countrate meter and also to the scaler/timer. The signal available from the scaler/timer is the linear signal suitable for reactivity measurements. The other signal that is routed to the level meter is proportional to the logarithm of the countrate. For this signal, the precision at the upper end of the countrate is very poor. For example, the percent precision at 10^6 cps would be six times larger (poorer) than at 1 cps - assuming a perfect logarithm relationship.

Shown in Figure 3-7, in phantom outline, are scaler/timer units for the other two channels. The present design does not call for three scaler/timers but for one which could be switched between the three channels. Three scaler/timers would provide for simultaneous reading of the linear countrate and for simultaneous data logging of the linear countrate by the DDH and DS. The proposal to provide three scaler/timer units with three connections to the DDH and DS is presently under investigation. The benefits of such a system can be enumerated. First, large operational time savings accrue from simultaneously recording the control rod drop (or run-in) calibrations with each of the LLFM sensors. The alternative is to conduct the calibration repetitively, each time switching to a different LLFM signal. Second, the total counting time for source multiplication measurements will be reduced by a factor of three with simultaneous counting capability. This may amount to large time savings during the initial load to critical when counting times may be extremely long. Third, if other plant equipment must be turned off during LLFM counting periods, operation time and plant availability will be improved. Finally, the three inputs to the DDH and DS would allow for LLFM system diagnosis, which would be unavailable otherwise.

3.5.2 Digital Data Handling and Display System (DDH and DS)

The subcritical reactivity monitoring plans call for developing an operational procedure which is not dependent on the availability of the DDH and DS. Hence the base line procedure will be an MSM-based operators guide. The DDH and DS will provide an accurate backup procedure for MSM reactivity determinations. In particular, it is envisioned that the DDH and DS could play a valuable role in the interpolation effort (Section 3.3.2). The dynamic mode of using the LLFM data - i.e., for the inverse kinetics calibration procedures - does require rapid on-line data taking capability. The DDH and DS can provide this capability and the additional feature of on-line data analysis.

Shown in Figure 3-7 are alternate connections (1), (2), and (3), between the LLFM and the DDH and DS. As explained in Section 3.5.1 above, the connection pattern indicated by (1) is under investigation. It represents the best interface arrangement since no special input devices would be required by the computer system. An alternate arrangement for routing the signals to the computer is labeled by (2). This arrangement takes the pulse trains and routes them to the DDH and DS. A special set of electronic input devices, equivalent to the counter in the scaler/timer electronics, would be needed. Route (2) should be considered as an alternative if route (1) becomes infeasible due to the use of only one scaler/timer. The present design shows the log signal routed to the DDH and DS, shown by (3). As explained above, such a signal does not have sufficient accuracy to be useful for computer processing.

3.6 Interface With FTR Operations

3.6.1 Normal Operating Conditions

Under normal operating conditions, the subcritical reactivity monitoring procedures will readily integrate with the normal operating procedures. Detailed reference procedures for plant operation have been proposed[18,19]. However, detailed procedures for the source multiplication calibration have not been developed and, therefore, are not as yet reflected in the current procedures. However, a general description of the suggested operation can be made.

With the current descent from power procedures, the reactor is eventually stabilized at a power level of 10-20 MW with 75% flow. From this condition, the secondary rods (control rods) will be sequentially inserted to about one inch above bottom. The primary (safety) rods will then be sequentially inserted to about one inch above bottom. The rods are driven to this "hot standby condition," rather than scrammed, to maintain 75% sodium flow and permit easier control of the plant cooldown. Finally, when the temperature effects have stabilized, the rods are scrammed, thus disengaging the sodium pumps.

In order to accommodate the calibration of the source multiplication equation, the insertion procedure for the control rods must be modified slightly from the reference procedure. This will involve running the first rod in to establish a stable nuclear power level, such that the LLFM has a countrate in the range of 10^5-10^3 counts/sec (1¢-50¢ subcritical). This configuration must be held until the thermal effects are reduced to the point that the reactivity feedback will not interfere with the inverse kinetics calibration. Waiting for the thermal effects to decay in this reactor condition, as opposed to the "hot standby condition," does not affect the time required to shut down since the fission power produced is at most a few hundred watts. Once the stable temperature and power conditions are achieved, the inverse kinetics calibration can proceed by scramming a single rod. If it is desirable, this can be achieved without tripping the sodium pumps. The remaining shutdown sequence can be achieved without further restrictions imposed.

During the subsequent refueling and approach to critical, the calibration from the previous shutdown will be used to perform MSM measurements. This will require that the calculated Q values for the approach to critical adequately reflect the fuel loading reactivity effects, relocation of shim rods and test assemblies, and the change in the source level due to discharge of spent fuel. At some arbitrary time during the approach to critical, an additional calibration by inverse kinetics rod drop will be required. This procedure will likely be compatible with required control rod calibrations and have no impact on the plant availability.

3.6.2 Unplanned Reactor Scram From High Power

In the event that the reactor is inadvertently scrammed from high power, the opportunity for calibrating source multiplication is lost. If the reactor operating procedures will allow, the reactor could be returned to zero power critical for calibration purposes; however, it is unlikely that this will generally be the case, and the subcriticality monitoring procedures must allow for the circumstance in which a new calibration is not achieved. It is for this application that source multiplication calibrations are required during the routine approach to critical.

During power operation, the significant reactivity effect is due to fuel depletion. However, this is a fairly uniform change which would only slightly affect the detection efficiency in the LLFM. Certainly, estimates of this effect could be obtained. The second significant effect would be changes in the reactor source due to the build-up of curium isotopes (see Section 3.3.1). These effects would require attention and would perhaps involve large corrections to the source multiplication calibration. Methods which must be developed for adjusting source effects during routine refueling will prove valuable for this application.

All other fluence-related effects will probably not significantly influence the source multiplication measurements and it is reasonable to assume that the major effects can be treated adequately. Therefore, subcritical reactivity monitoring can likely proceed, without a large sacrifice in accuracy, with no calibration on the power descent, providing a calibration was made on the preceding approach to critical.

3.6.3 The Initial Load to Critical

During the initial load to critical, the modified source multiplication method cannot be used, per se, to determine the subcritical reactivity since there is no possible way to calibrate Equation (1). Nevertheless, configuration factors can be used to make the ordinate of the inverse multiplication curve directly proportional to reactivity, such that the resultant units will be different from the standard reactivity units only by a multiplicative constant. Consequently, data from the three LLFM's would be reasonably uniform regardless of the symmetry conditions in the core. However, because the fuel worth generally decreases as the core size increases, even the suggested approach would not be linear with mass over a wide range.

Innovative ideas for establishing linear approach to critical curves are abundant in the literature, although none has been universally accepted. Perhaps one of the most successful is the method proposed by Olson and Palmer[20].

At the end of the Phase D FFTF critical experiments, an experiment will be performed in which the core is unloaded in a way which simulates, in reverse order, the initial load to critical in the FFTF. Data from this experiment are expected to determine a satisfactory initial approach to critical procedure for the FFTF.

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APPENDIX A

DERIVATIONS OF KINETICS EQUATIONS

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DERIVATIONS OF KINETICS EQUATIONS

Listed below are definitions of the various parameters used in the following discussions.

n	=	total neutron population
$S(r,E)$	=	space and energy-dependent extraneous neutron source
S	=	extraneous effective neutron source
k	=	core multiplication
Δk	=	$k-1$
ρ	=	$\Delta k/k$ = reactivity
β_i	=	effective delayed neutron fraction for delayed group i
β	=	$\Sigma\beta_i$ = effective delayed neutron fraction
C_i	=	delayed neutron precursor density for delayed group i
λ_i	=	delayed neutron decay constant for delayed group i
$\phi(r,E)$	=	space and energy-dependent neutron flux
$\phi^*(r,E)$	=	space and energy-dependent adjoint flux
V_c	=	volume of core
V_d	=	volume of detector
$\Sigma_d(r,E)$	=	macroscopic detector cross section
$\Sigma_f(r,E)$	=	macroscopic core fission cross section
ν	=	average number of neutrons produced per fission in the reactor
$\$$	=	$\frac{\Delta k}{k\beta}$ = reactivity in dollars
N	=	number of delayed neutron groups
ℓ	=	prompt neutron lifetime
Λ	=	$\frac{\ell}{k}$ = prompt neutron generation time

1. The Source Multiplication Equation

The familiar point kinetics equations are:

$$\frac{dn}{dt} = \frac{\rho-\beta}{\Lambda} n + \sum_{i=1}^{N} \lambda_i C_i + S \tag{A-1}$$

$$\frac{dC_i}{dt} = \frac{\beta_i n}{\Lambda} - \lambda_i C_i \tag{A-2}$$

At initial conditions, in which the delayed neutron precursors are in equilibrium

$$n = n_o, \frac{dn}{dt} = 0$$

$$C_i = C_{i,o}, \frac{dC_i}{dt} = 0$$

Equations (A-1) and (A-2) become

$$\frac{\rho_o-\beta}{\Lambda_o} n_o + \sum_{i=1}^{N} \lambda_i C_{i,o} + S_o = 0 \tag{A-3}$$

$$\frac{\beta_i}{\Lambda_o} n_o - \lambda_i C_{i,o} = 0 \tag{A-4}$$

Substituting (A-4) into (A-3)

$$\frac{n_o \rho_o}{\Lambda_o} = - S_o$$

$$\rho_o = \frac{- S_o \Lambda_o}{n_o} \tag{A-5}$$

which is the source multiplication equation, also often given in the form:

$$\Delta k_o = \frac{-S_o \ell_o}{n_o}$$

The equation may be used in either form, the first assuming a constant prompt neutron generation time and the other assuming a constant prompt neutron lifetime. Time-dependent kinetic studies by ANL[21] have shown the assumption of time in variant generation time to be more likely true in reactor systems like the FTR. Moreover, since one is more comfortable dealing in reactivity terms when discussing subcriticality, Equation (A-5) has been selected as the reference source multiplication equation for use in FTR.

In general application, $S_o \Lambda_o$ is assumed to remain constant, and Equation (A-5) is written more generally as

$$\rho = -\frac{S_o \Lambda_o}{n} \qquad \text{(A-6)}$$

Since the derivation utilized above is from the point kinetics model, the parameters must be defined in the global sense

$$n = \int_{V_c} \int_E \frac{\phi(r,E)}{v} \phi^*(r,E) \, drdE$$

$$S = \frac{\int_{V_c} \int_E S(r,E) \, \phi^*(r,E) \, drdE}{\int_{V_c} \int_E \phi(r,E) \, \phi^*(r,E) \, \frac{1}{v} \, drdE}$$

Experimentally, we do not measure the total neutron population, n, but rather a detector countrate, CR, and conversion of the measured countrate is required. This conversion, for a given neutron generation, is accomplished by determining the ratio of the detection efficiency, ε

$$\varepsilon = \frac{\int_{V_d} \int_E \Sigma_d(r,E) \, \phi(r,E) \, drdE}{\int_{V_c} \int_E \Sigma_f(r,E) \, \phi(r,E) \, drdE}$$

and ν. This ratio is essentially the number of neutrons counted in the detector per neutron produced by fission in the reactor. Therefore,

$$n = \frac{\nu \; CR \; \Lambda}{\varepsilon}$$

Substituting this result into Equation (A-6)

$$\rho = - \frac{\varepsilon_o S_o}{\nu \; CR} \qquad \text{(A-7)}$$

The parameters ν_o, ε_o, and S_o can be lumped together to form the more familiar source multiplication formulation

$$\rho = - \frac{Q_o}{CR} \text{ , where } Q_o = \frac{\varepsilon_o S_o}{\nu_o} = |\rho_o \; CR_o| \; . \qquad \text{(A-8)}$$

2. Inverse Kinetics Equation

Derivation of inverse kinetics data analysis equations is included here for completeness of the discussions of rod calibration by the inverse kinetics method which are given in Appendix C.

Beginning again with the point kinetics equations, we have

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{N} \lambda_i C_i + S \qquad \text{(A-1)}$$

$$\frac{dC_i}{dt} = \frac{\beta_i n}{\Lambda} - \lambda_i C \qquad \text{(A-2)}$$

Recalling that, in general, the solution to the equation

$$\dot{x}(t) + \lambda x(t) = y(t) \text{ is}$$

$$x(t) = e^{-\lambda t} \int_0^t e^{\lambda t'} \, y(t') \, dt' + x_o e^{-\lambda t}$$

the solution to Equation (A-2) can be written

$$C_i = \frac{\beta_i e^{-\lambda_i t}}{\Lambda} \int_o^t e^{\lambda_i t'} n(t')dt' + C_{i,o} e^{-\lambda_i t} \qquad \text{(A-9)}$$

Applying the initial conditions at t = 0

$$k \equiv k_o \text{ and } \frac{dC_i}{dt}\Big|_{t=0} = 0$$

$$C_{i,o} = \frac{\beta_i n_o}{\lambda_i \Lambda} \qquad \text{(A-10)}$$

Substituting (A-10) into (A-9)

$$C_i = \frac{\beta_i}{\Lambda} e^{-\lambda_i t} \left[\frac{n_o}{\lambda_i} - \int_o^t e^{\lambda_i t'} n(t')dt'\right] \qquad \text{(A-11)}$$

Substituting (A-11) into (A-1)

$$\frac{dn}{dt} = \frac{\rho-\beta}{\Lambda} n + \sum_{i=1}^{N} \frac{\lambda_i \beta_i}{\Lambda} e^{-\lambda_i t} \left[\frac{n_o}{\lambda_i} + \int_o^t e^{\lambda_i t'} n(t')dt'\right] + S \qquad \text{(A-12)}$$

Solving for ρ we get the inverse kinetics equation

$$\rho = \beta + \frac{1}{n} \left[\Lambda \frac{dn}{dT} - \sum_{i=1}^{N} \beta_i e^{-\lambda_i t} [n_o + \lambda_i \int_o^t e^{\lambda_i t'} n(t')dt'] - S\Lambda\right] \text{(A-13)}$$

or in dollar reactivity units

$$\$ = 1 + \frac{1}{n} \left[\frac{\Lambda}{\beta} \frac{dn}{dt} - \sum_{i=1}^{N} \frac{\beta_i}{\beta} e^{-\lambda_i t} [n_o + \lambda_i \int_o^t e^{\lambda_i t'} n(t')dt'] - \frac{S\Lambda}{\beta}\right] \qquad \text{(A-14)}$$

This equation assumes that Λ is constant over the reactivity range. If ℓ is assumed constant, as in the case in most current algorithms, then

$$\$ = 1 + \frac{1}{n} \left[\frac{\ell}{k\beta} \frac{dn}{dt} - \frac{1}{k} \sum_{i=1}^{N} \frac{\beta_i}{\beta} e^{-\lambda_i t} [n_o k_o + \lambda_i \int_o^t kn(t') e^{\lambda_i t'} dt'] - \frac{\ell S}{\beta K}\right] \qquad \text{(A-15)}$$

APPENDIX B

FTR CONFIGURATION FACTOR CALCULATION DETAILS

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1. Calculational Model

A hexagonal reactor model has been developed for FTR configuration factor calculations. The model contains 3,108 triangular mesh intervals (74-X by 42-Y) which is equivalent to six triangular mesh per FTR driver subassembly. The core map is shown in Figure 3-3 of Section 3.2.2. Each fueled subassembly position is zoned individually to facilitate representing essentially any core configuration of interest. Row 7 is zoned for separate row 7 and rows 8, 9 reflector densities. The sodium gap between the reflector and shield regions has been zoned as well as possible with the triangular mesh option. The zone, as represented, will contain 71.1% sodium and 28.9% radial shield. The shield region is represented as a single zone, with a 100% sodium zone included where the model extends beyond the outer shield boundary.

The outside dimensions of this model do not represent the full extent of the FTR shield. In order to economize computer running time, the dimensions were set to preserve adequate shielding ($\sim$30 cm) around each LLFM position and minimize the required spatial mesh where possible. The model, as shown, utilizes $\sim$35% fewer spatial mesh points than would be required for full shield representation.

Number densities and physical dimensions were taken from the final FTR fuel enrichment specification[(22)]. Slight adjustments were made to account for isothermal temperature effects in going from 70°F to refueling temperatures.

The inherent neutron source strength due to spontaneous fission and (α,n) reactions was calculated to be 116.8 n/sec cm^3 and 142.9 n/sec cm^3 for fresh inner driver and outer driver fuel zones, respectively[(23)].

2. Cross Section Group Structure Comparisons

In order to investigate the effect of cross section group structure on MSM calculations, a number of cross section sets were prepared for comparison. Specifically, 42, 21, and 4-group cross sections were prepared from the Set

300-S library[24] and 30 and 15-group cross sections were prepared from the Set 300 library[25].

Two reference configurations were calculated with each cross section set. The first configuration was very nearly critical, with the row 5 control rods represented at 50% density to simulate partial insertion. The second configuration represented the FTR with all control and safety rods fully inserted, i.e., the ∿30$ shutdown condition.

In Table B-1, the calculated reactivities, countrates, source multiplication constants, Q, and configuration factors are compared, with the 42-group results used as the standard. Although there are discrepancies as large as ∿13% in the individual countrates and reactivities, all but an apparent systematic difference between Set 300 and 300-S countrates washes out when the product is taken to calculate Q. Even this systematic difference appears to vanish when the configuration factors are calculated. Therefore, one would conclude that errors on the order of a few percent in the configuration factors would be incurred by the use of fewer-group cross section data. However, one must be more careful when calculating reactivities and countrates directly. Based on these investigations, subsequent scoping studies of FTR configuration factors have utilized the 4-group Set 300-S cross section set.

TABLE B-1

COMPARISON RATIOS OF FEWER-GROUP RESULTS TO 42-GROUP RESULTS FOR CONFIGURATION FACTOR APPLICATIONS

Number of Groups	Reactor Condition	ρ/ρ_{42}	CR/CR_{42}	Q/Q_{42}	F/F_{42}
4	Critical	0.8718	1.1334	0.9882	-
	30$	0.9918	0.9817	0.9738	0.9855
15	Critical	0.9946	0.9276	0.9227	-
	30$	1.0000	0.9188	0.9187	0.9958
21	Critical	1.0117	0.9934	1.0047	-
	30$	1.0030	0.9946	1.0010	0.9965
30	Critical	0.9956	0.9204	0.9164	-
	30$	0.9984	0.9176	0.9162	0.9998

ORNL has been engaged in a comparison of various cross section data for MSM calculations in the FTR. This study involved both one-dimensional diffusion and transport calculations using cross sections prepared at HEDL, ARD, and ORNL. A document describing this study is being prepared for publication[26].

3. FTR Shutdown Sequence

The hexagonal reactor model and the 4-group cross sections were used to calculate a reactor shutdown sequence. Figures B-1 through B-9 describe each configuration in detail. Superimposed on each core map are the iso-configuration factor lines for that assembly, using the initial configuration with half-inserted rods as the calibration configuration. The plots are instructive as to the spatial distribution of the perturbation introduced by the control rods.

Table 3-1 in Section 3.3.2 of this report also lists the configuration factors for the case where an asymmetric control rod configuration, i.e., with one control rod inserted, was used for the calibration configuration.

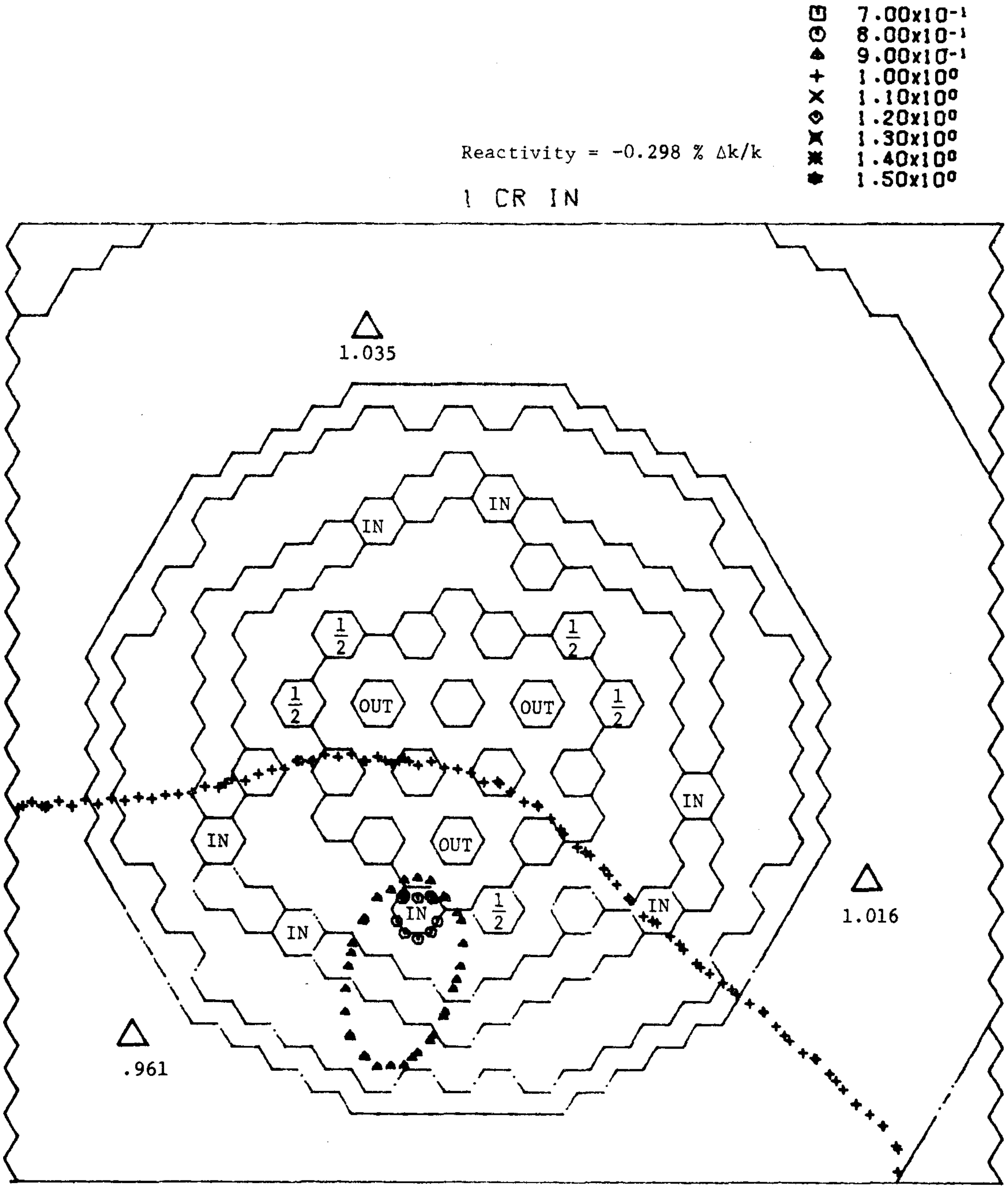

FIGURE B-1. FTR Subcritical Configuration Factors.

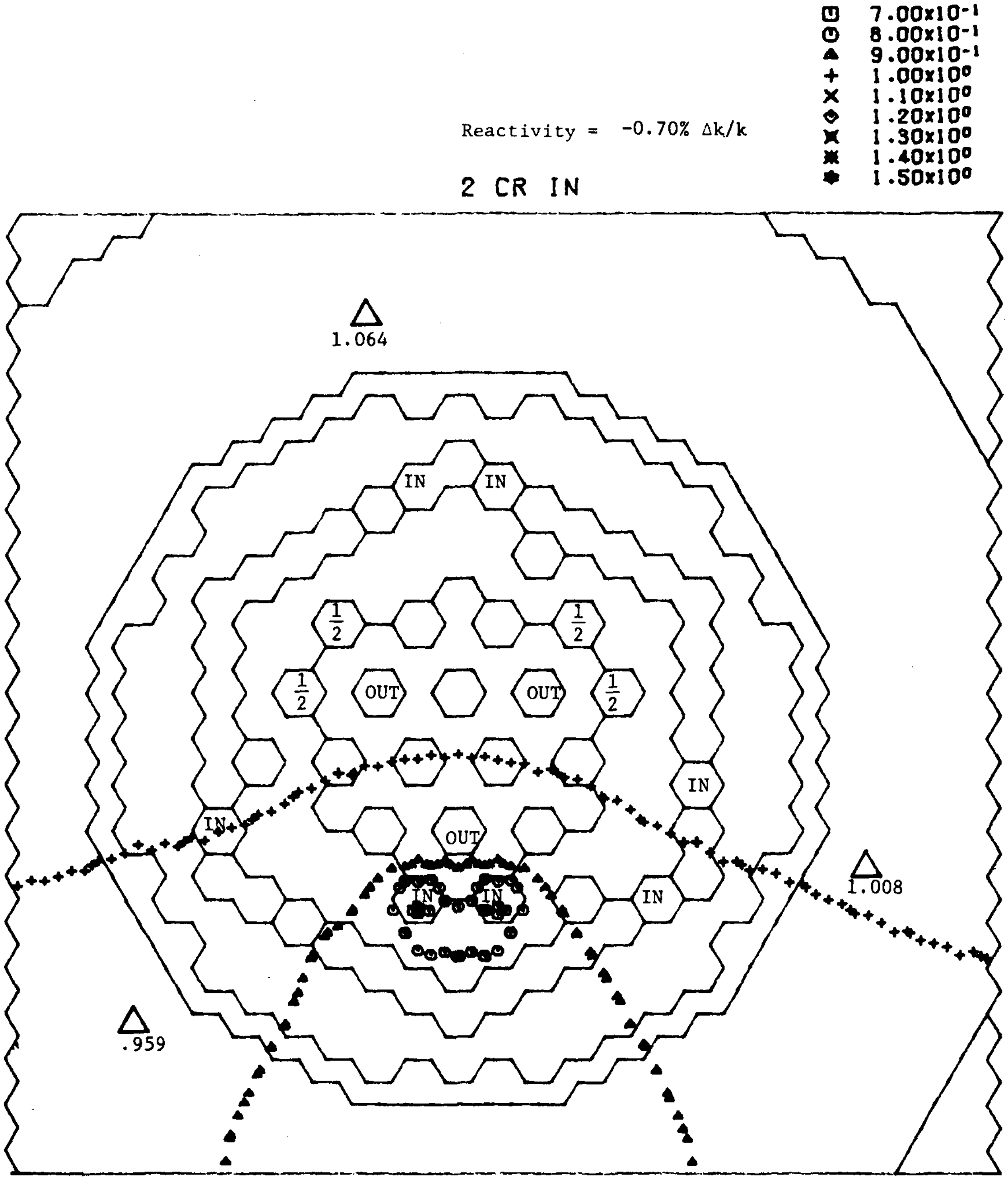

FIGURE B-2. FTR Subcritical Configuration Factors.

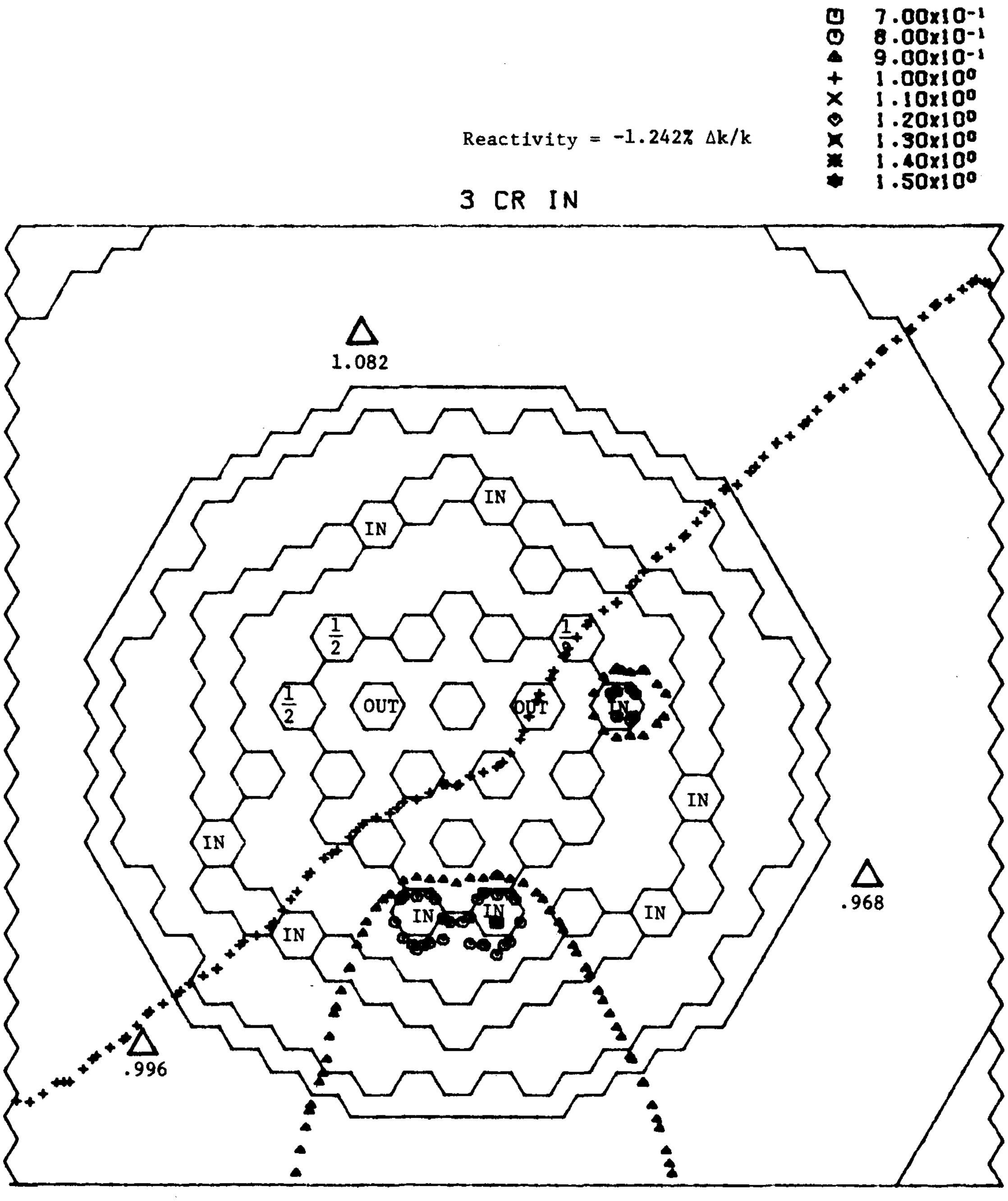

FIGURE B-3. FTR Subcritical Configuration Factors.

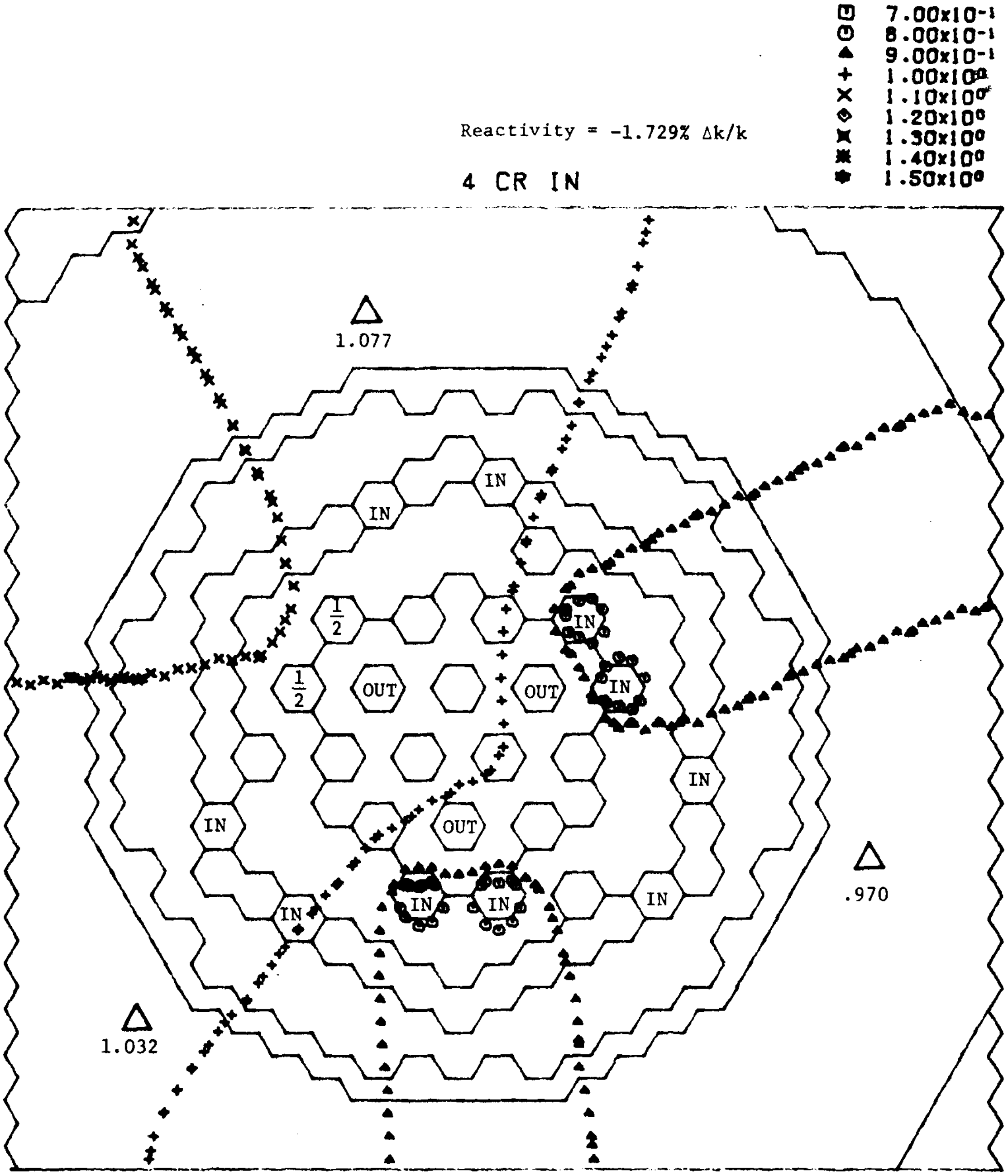

FIGURE B-4. FTR Subcritical Configuration Factors.

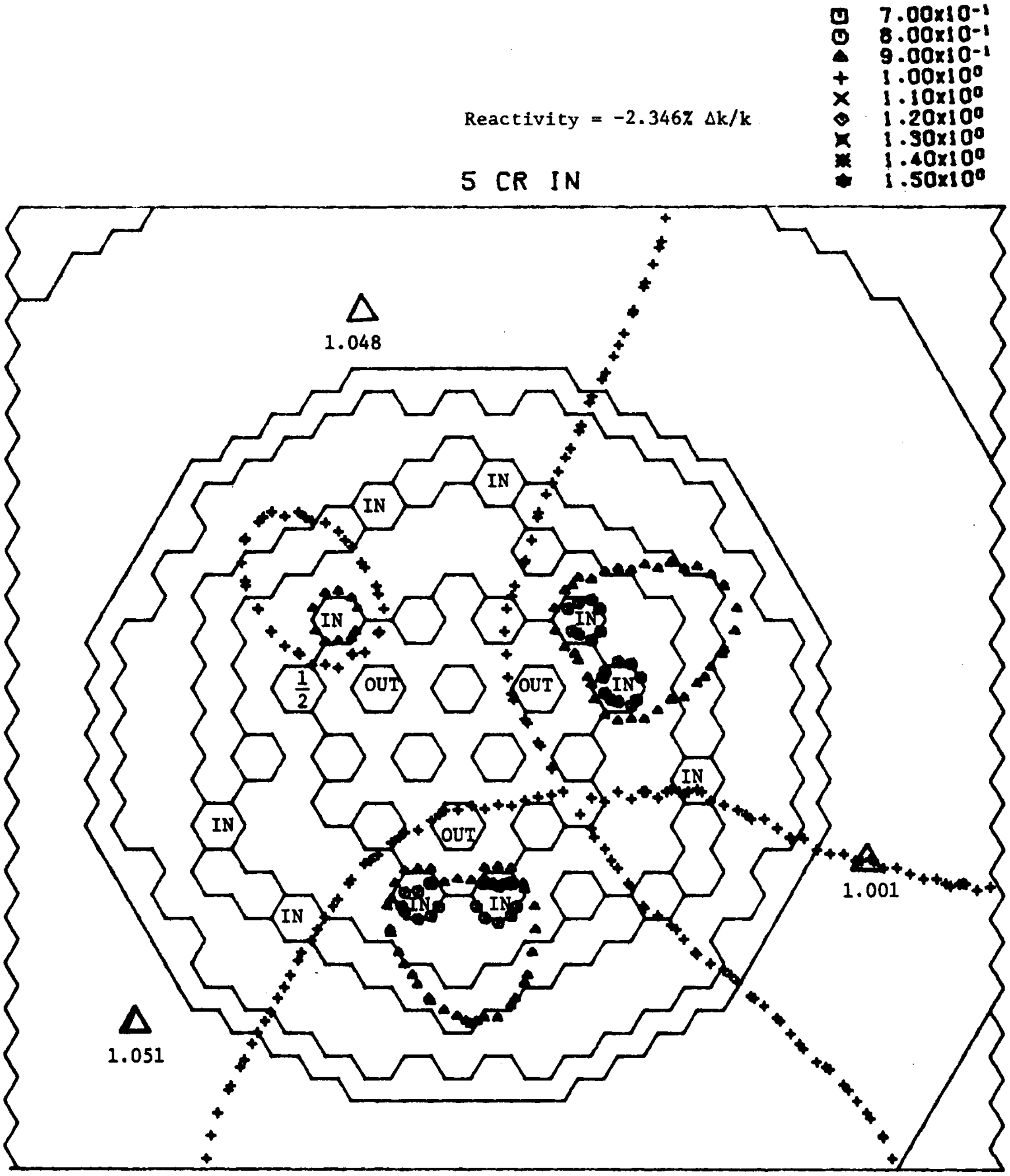

FIGURE B-5. FTR Subcritical Configuration Factors.

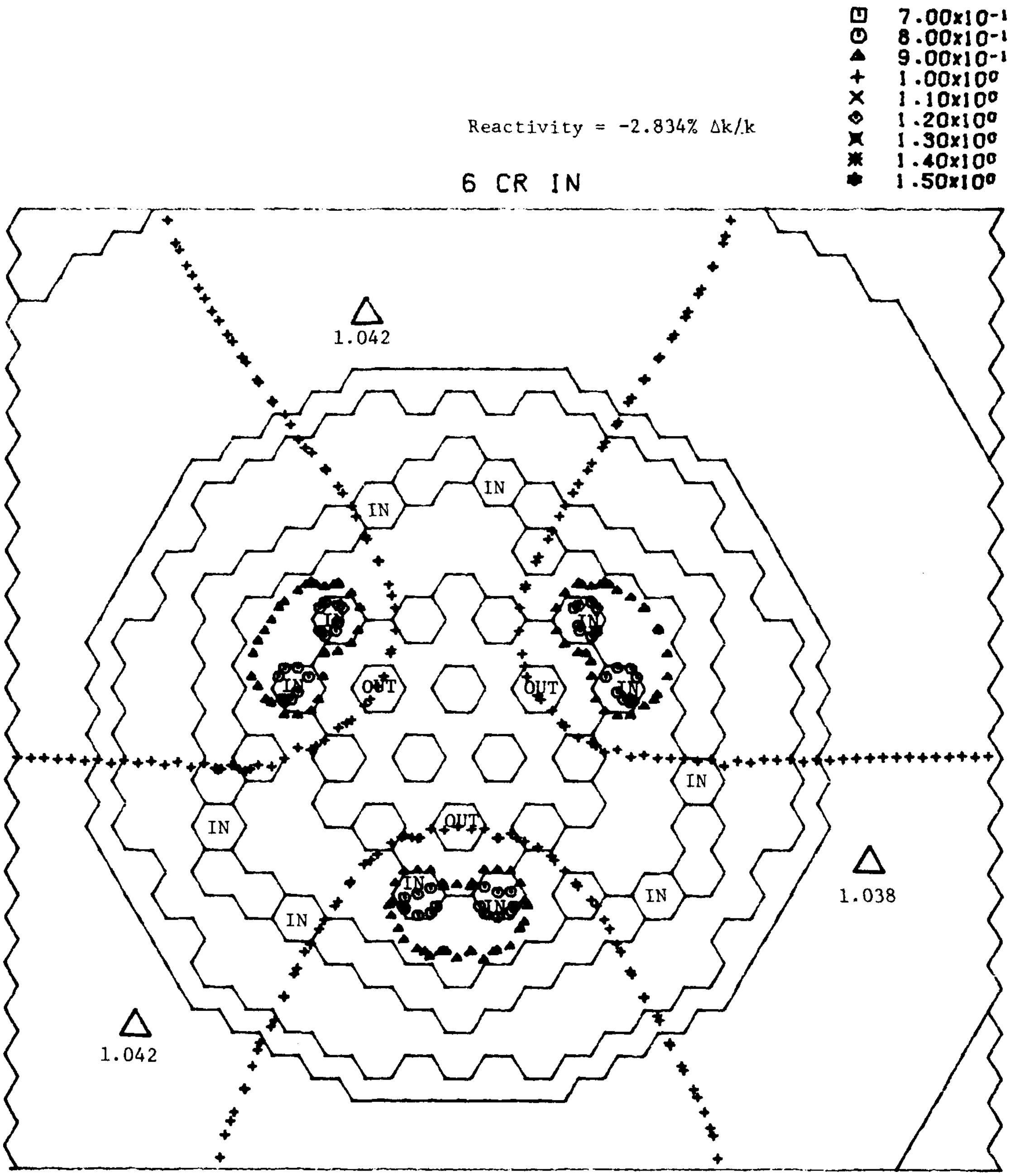

FIGURE B-6. FTR Subcritical Configuration Factors.

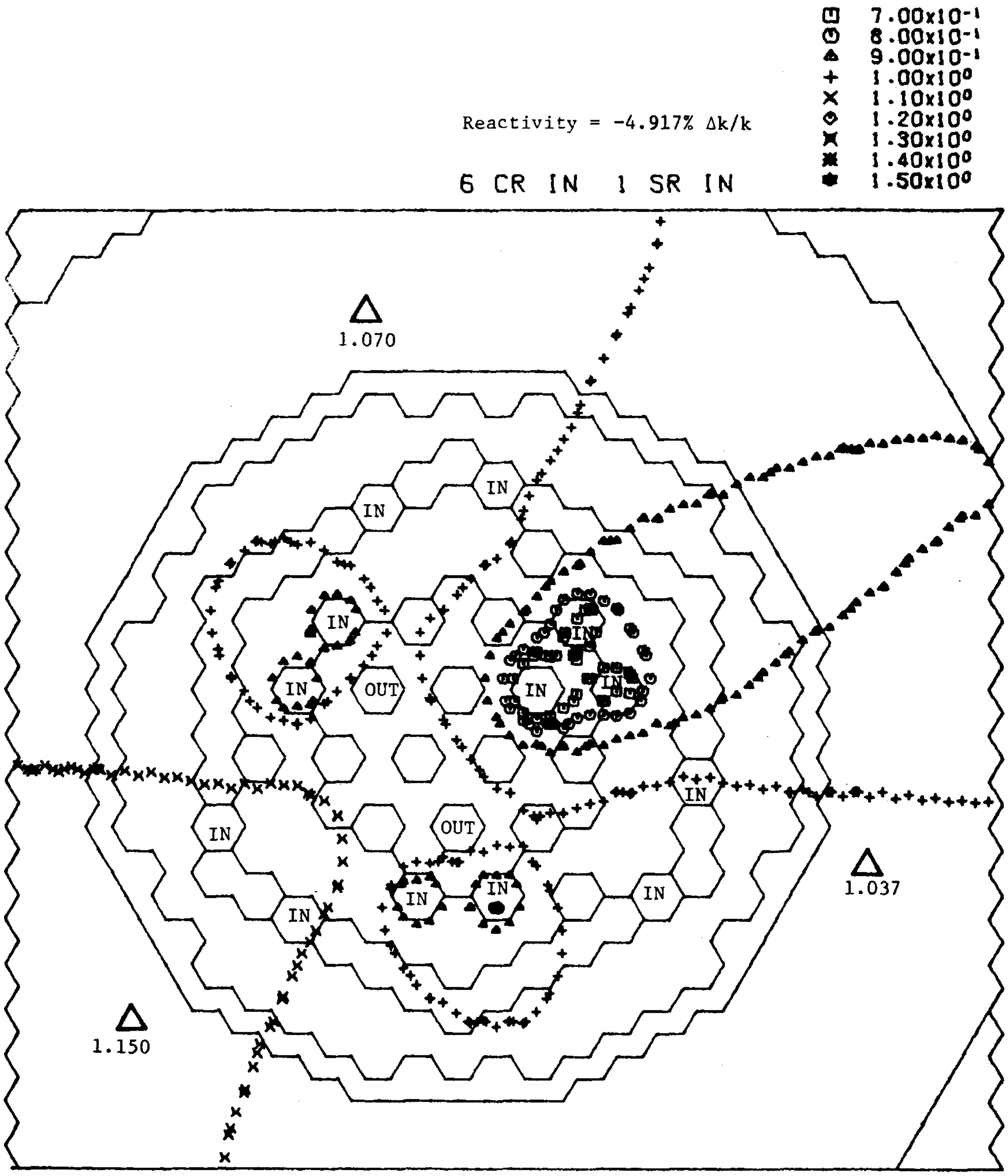

FIGURE B-7. FTR Subcritical Configuration Factors.

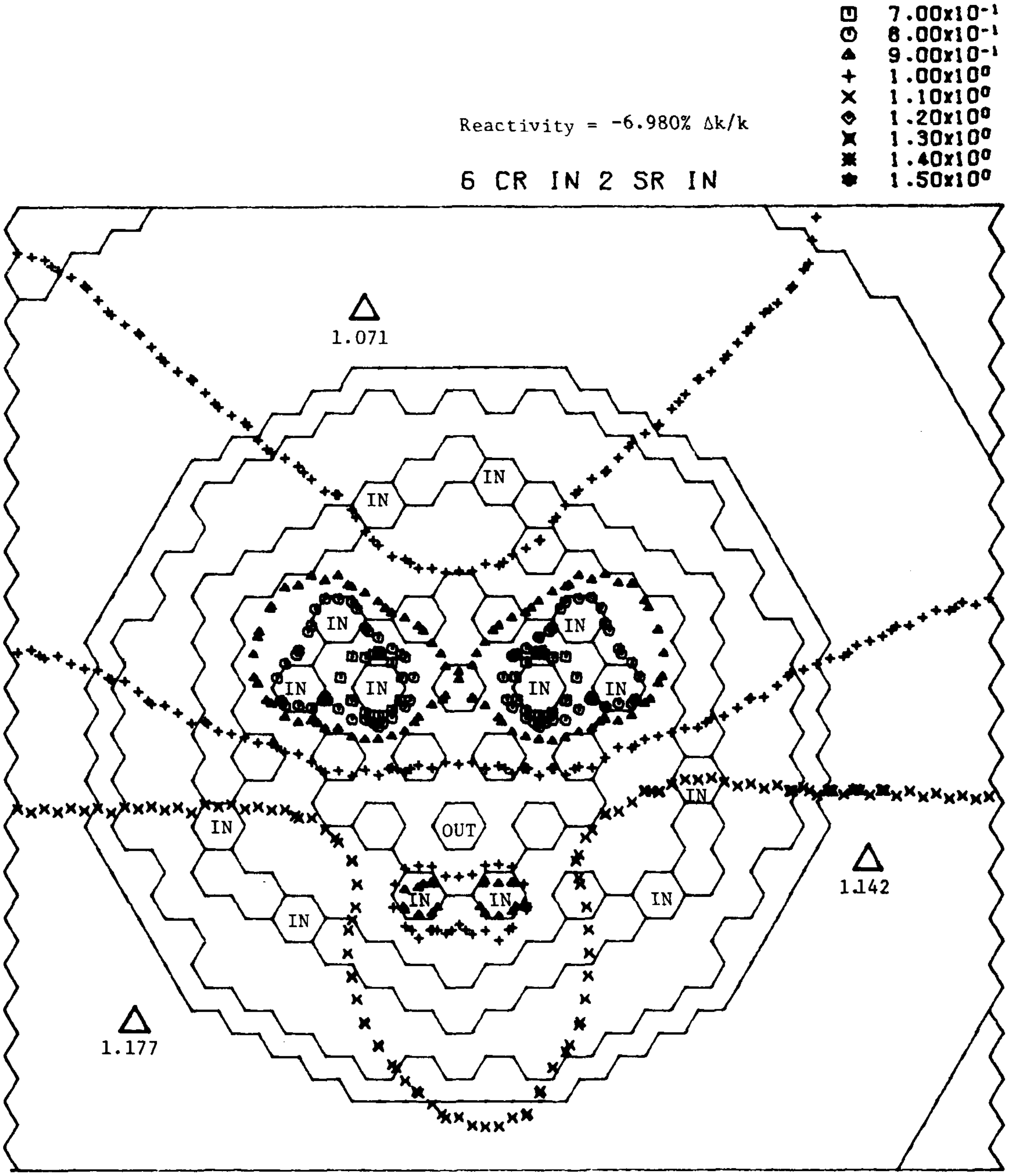

FIGURE B-8. FTR Subcritical Configuration Factors.

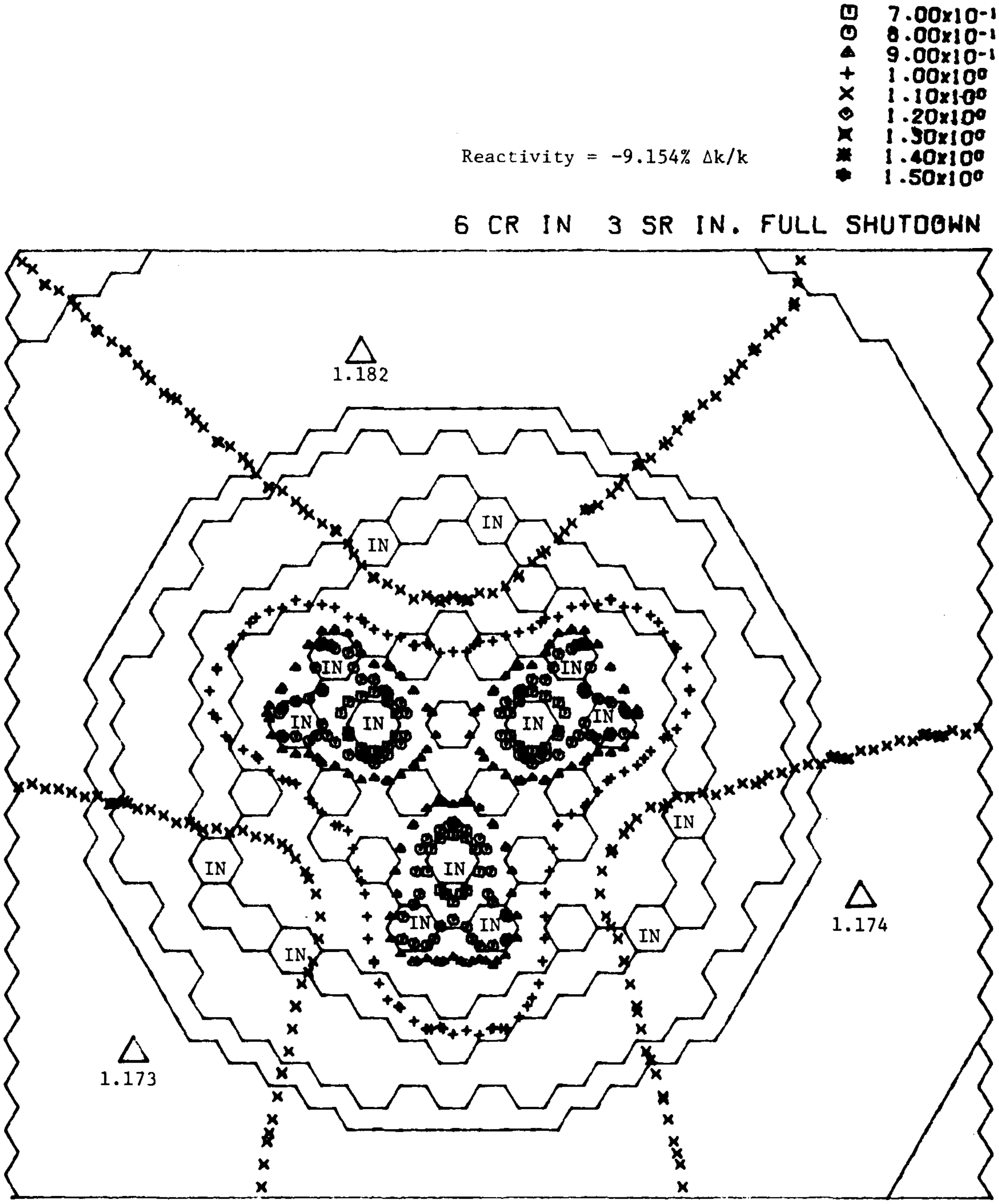

FIGURE B-9. FTR Subcritical Configuration Factors.

APPENDIX C

ZERO POWER INVERSE KINETICS MEASUREMENTS IN FTR

APPENDIX C

ZERO POWER INVERSE KINETICS MEASUREMENTS IN FTR

An inverse kinetics measurement is initiated by allowing the delayed neutron precursors to establish equilibrium at a constant subcritical power level. From this condition, a reactivity change is made (we shall assume by rod motion), and the neutron flux is recorded continuously as it dies away, in the case of a negative reactivity change, or rises in the case of a positive one. The data-taking process continues until sufficient data have been collected for the analysis. The reactivity in dollars, \$, neutron density, n, and effective neutron source, S, are related as a function of time according to the equation

$$\$ = 1 + \frac{1}{n}\left[\frac{\Lambda}{\beta}\ \frac{dn}{dt} - \sum_{i-1}^{N} \frac{\beta_i}{\beta} e^{-\lambda_i t}\ [n_o + \lambda_i \int_0^t e^{\lambda_i t'}\ n(t')dt'] - \frac{S\Lambda}{\beta}\right] \qquad \text{(A-14)}$$

which is derived in detail in Part 2 of Appendix A. In the equation, both the effective source, which we shall assume is constant as a function of time, and the reactivity are unknown. However, since the reactivity was constant before and after the rod motion, by iterating on the effective source value until the reactivity time trace following the rod motion fits a least-squares line with zero slope, the correct source term, and therefore the correct reactivity time trace, can be determined.

In order to test the feasibility of this method for

- calibrating the integral worth of control rods by rod drop,
- measuring control rod worth profiles by rod run in,
- calibrating source multiplication

simulation studies were undertaken. In these studies, an inverse kinetics algorithm developed by ANL[27] was used to analyze rod drop data generated from the point kinetics model. All experiments were initialized at a counting rate of 10^5 counts/sec. (This countrate maximizes the dynamic range of the LLFM detectors without introducing significant counting loss.) This corresponds to an initial subcriticality of approximately 1¢. Cases were run with noise-free data and with pseudo-random gaussian noise superimposed (standard deviation = square root of the counts collected over a sampling interval).

Initially, three cases were investigated. The first was a simulated 3$ rod drop to test the method for measuring integral control rod worths. The sampling time for this measurement was 0.1 sec. The second was identical to the first, except that the rod dropped was worth 6$ to simulate a safety rod calibration. The third case simulated a slow rod run-in (9 in./min) for a 3$ control rod. The sampling time for this case was 0.2 sec.

The results of the analyses for noisy and noise-free cases are summarized in Table C-1. The time histories of the input countrates and the reactivity results (inhours) for the 3$ drop, 6$ drop and 3$ profile (rod motion between 15 and 255 sec) are given in Figures C-1 through C-3, respectively. In each case, the effect of the deteriorating counting statistics is apparent from the reactivity plot.

TABLE C-1

RESULTS OF SIMULATED INVERSE KINETICS CALIBRATIONS

	Noise-Free Countrates		Noisy Countrates	
3$ Drop	Initial $	Final $	Initial $	Final $
0 CPS Background	- 0.0101	- 3.0289	- 0.008	- 3.032
10 CPS Background	- 0.0104	- 3.0289		
100 CPS Background	- 0.0131	- 3.0289		
6$ Drop				
0 CPS Background	- 0.0101	- 6.1181	- 0.008	- 6.135
10 CPS Background	- 0.0107	- 6.1182		
100 CPS Background	- 0.0161	- 6.1182		
3$ Calibration				
0 CPS Background	- 0.014	- 3.025	- 0.007	- 2.769

These results indicate that for 3$ and 6$ rod drops, sufficient data have been accumulated before the countrate statistics interfere significantly with the data analysis. However, for the rod profile analysis, by the time the rod

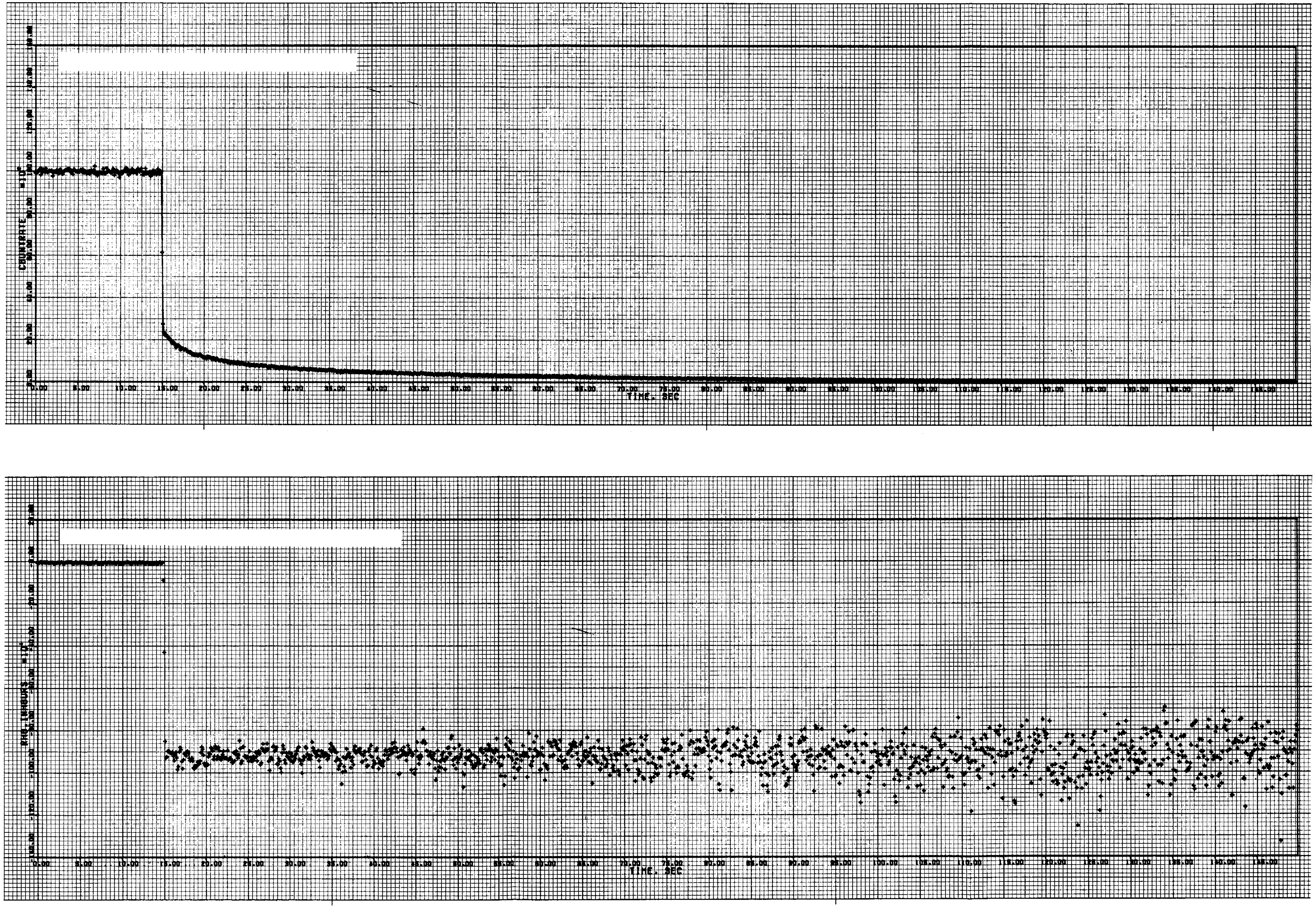

FIGURE C-1. Simulated Rod Drop 1¢ to 3$.

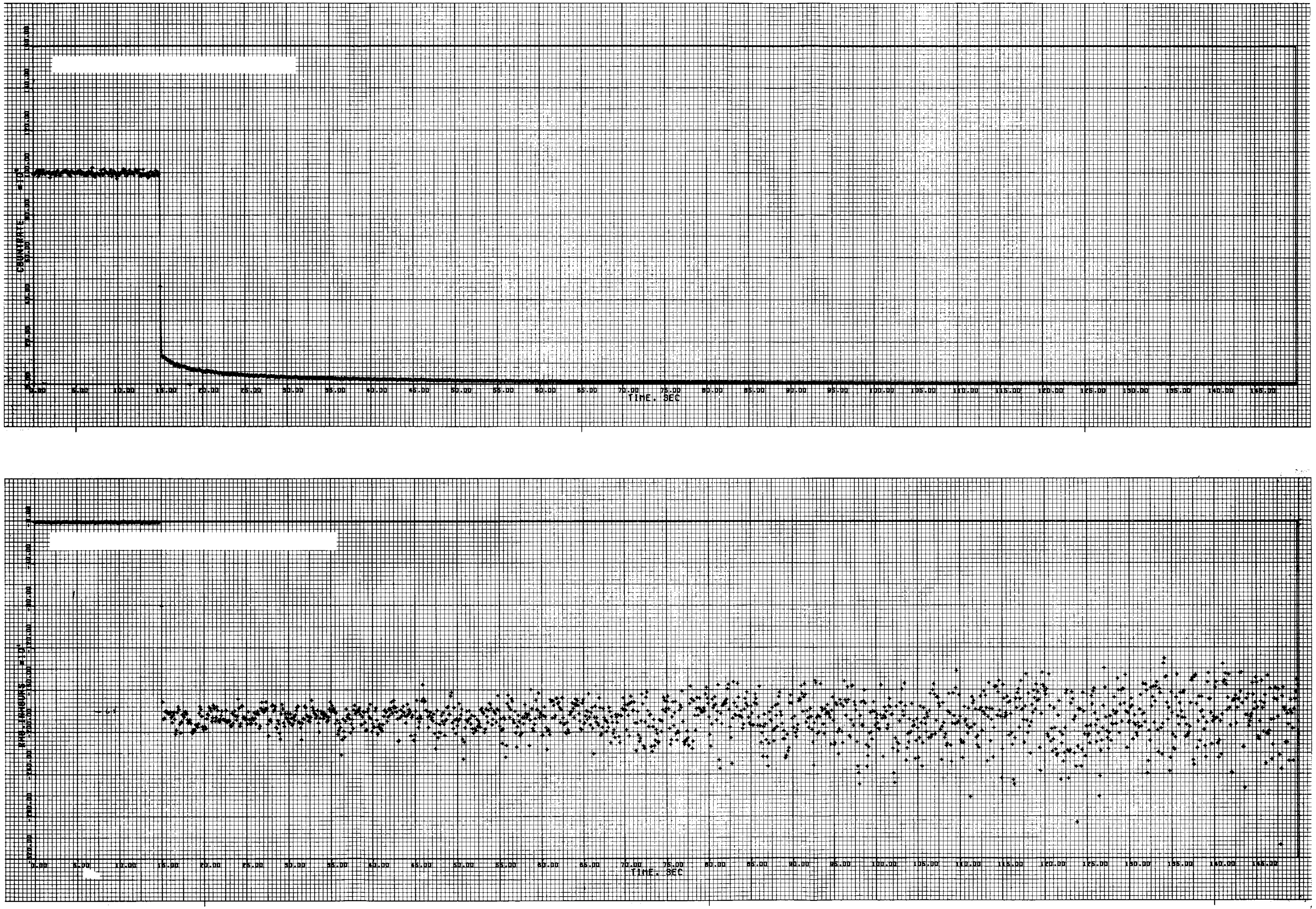

FIGURE C-2. Simulated Rod Drop 1¢ to 6$.

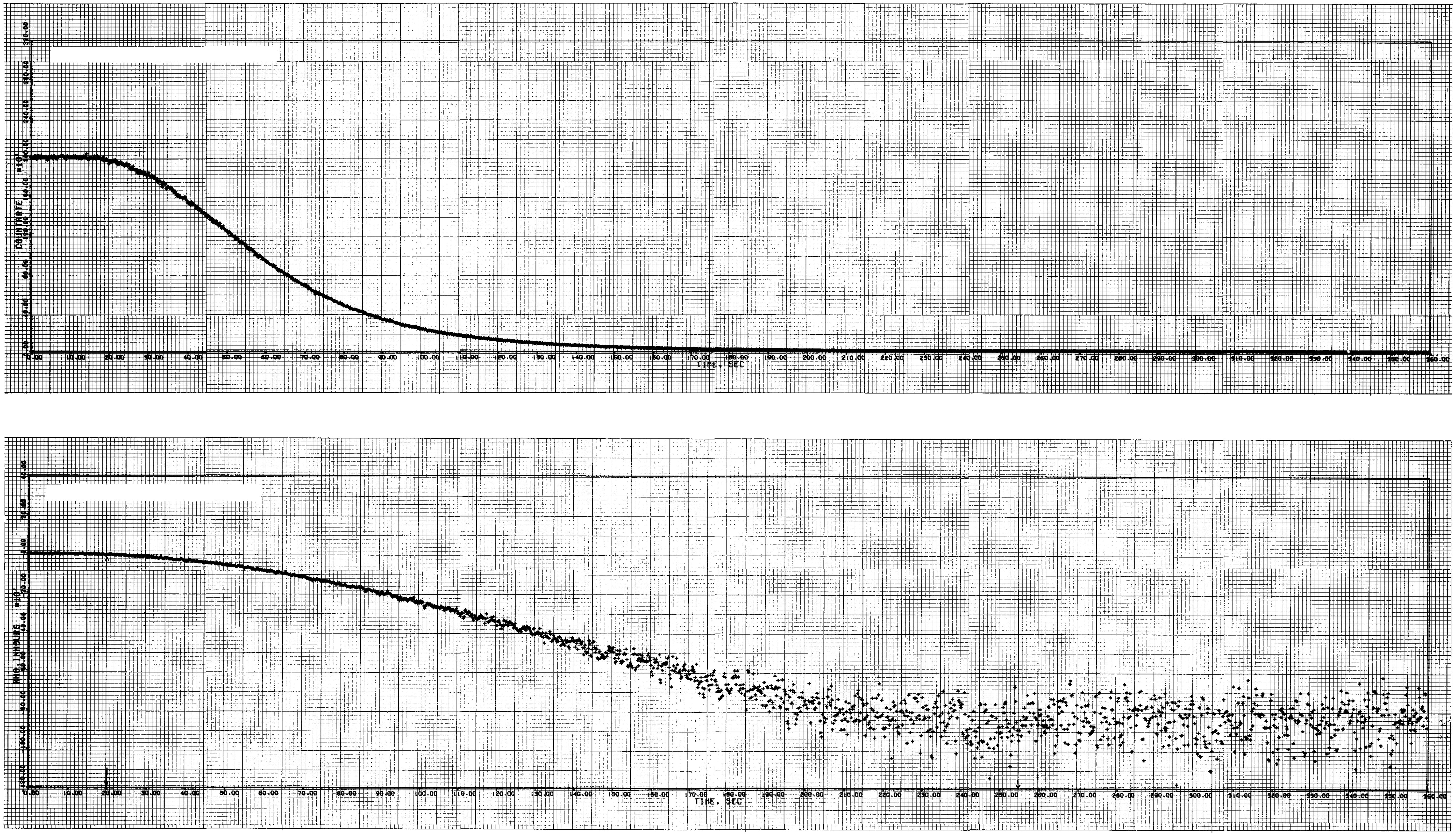

FIGURE C-3. Simulated 3$ Rod Calibration.

is completely in, the countrate has fallen to the level that counting statistics interfere with the source search. A suggested way to avoid this problem would involve first, doing a rod drop to determine the effective source term. Then, return to the original reactor configuration and repeat the experiment doing a rod run-in. Analyze the data from the second experiment with the source term from the first, thus eliminating the need for the source search on the run-in experiment. The latter part of the worth profile will be poorly defined; however, it is the well-defined upper portion of the curve which is used for power operation and reactivity anomaly detection.

To assess the effect of a constant noise background in the LLFM system on the inverse kinetics rod drop results, additional cases were studied. Constant background signals of 10 CPS and 100 CPS were added into the 6$ and 3$ rod drop power traces. The results are also given in Table C-1.

In summary, the background does not significantly affect the inferred final reactivity, since background is accommodated as part of the effective source term in the kinetics equation. However, the background signal is unmultiplied and, therefore, when the source term determined from the calibration is applied to the pre-drop countrate, the initial reactivity is incorrectly determined. By making the initial reactivity very small, as was done in these examples, the worth of a control rod can be measured quite accurately in the presence of a background signal. In addition, accurate calibration of the source multiplication can be achieved in the post-drop equilibrium condition. However, the presence of an unknown background signal interferes with subsequent source multiplication reactivity determinations. This subject is dealt with in Section 3.3.3.

Care should be taken lest too much stock be placed in simulated kinetic studies of this form; for, at the very best, they are idealized. However, using these data as a guideline, one would conclude that rod worth measurements can be made to a precision of nominally a few percent, and the rod profile can be determined to approximately the same precision over the important range with existing FTR instrumentation. Critical experiment testing of the FTR reference subcritical reactivity measurement methods (see Section 3.2.3) will provide substantial data for testing the adequacy of the LLFM for inverse kinetics calibrations.

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