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INSTRUMENTATION AND CONTROLS DIVISION

SUBCRITICALITY MONITORING SYSTEM EVALUATION IN SEFOR

A. R. Buhl

N. J. Ackermann, Jr., R. C. Kryter, J. C. Robinson*

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*Consultant, Nuclear Engineering Department, University of Tennessee,
Knoxville, Tennessee.

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ABSTRACT

A prototype of the ORNL subcriticality monitoring system (SMS) was successfully demonstrated on-line in the Southwestern Experimental Fast Oxide Reactor. A realistic engineering test and evaluation of the SMS was conducted to determine its performance in a hostile LMFBR-like environment (10^6 R/hr gamma, 350°F, liquid sodium coolant, and high electromagnetic noise background). Measurements were made over the full subcriticality range from critical to full shutdown for both Core I and Core II. Core I was a soft-spectrum core containing a large BeO inventory. Core II was achieved by replacing the BeO with steel, giving rise to a harder neutron spectrum. Secondary objectives achieved were (1) precise and accurate measurements of Λ/β for both cores, and (2) a limited intercomparison of reactivity values as determined by inverse kinetics rod drop and breakfrequency noise analysis methods.

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1. INTRODUCTION¹

A prototypic subcriticality monitoring system (SMS) developed at the Oak Ridge National Laboratory (ORNL) for the Liquid-Metal Fast Breeder Reactor (LMFBR) was tested and evaluated by ORNL personnel in on-line operation at the Southwest Experimental Fast Oxide Reactor (SEFOR). The main objectives of this demonstration were to determine the engineering feasibility of the SMS and whether safety and economic benefits could be derived by incorporating the system into future LMFBR designs. Another objective was to obtain a precise and accurate measurement of the prompt die-away time constant (Λ/β) for SEFOR so that the General Electric Company, operator of the reactor near Fayetteville, Arkansas, could use this information in analysis of prompt transient tests. A final objective was to obtain additional data for comparison of subcriticality values determined by the inverse kinetics rod-drop (IKRD) and breakfrequency noise analysis (BFNA) techniques so that discrepancies observed in a previous experiment² possibly could be explained.

The SEFOR was selected because of its LMFBR-like environment, specifically, a gamma field of about 10^6 R/hr, a temperature of 350°F, a liquid sodium coolant, and a high electromagnetic noise background. Measurements were made in the soft-spectrum core of SEFOR (Core I containing BeO) and in two configurations of the hard-spectrum core (Core II, stainless steel replacing the BeO).

The SMS employs the modified source multiplication (MSM) technique, calibrated near critical by either the BFNA or the IKRD technique. The neutron sensors

1. It is a pleasure to acknowledge the several persons who contributed to this work. ORNL personnel who assisted at the SEFOR and contributed measurably to the performance of the experiment were J. B. Bullock, D. N. Fry, and C. B. Stokes. The splendid cooperation of the General Electric Company, in particular R. A. Becker and his staff at SEFOR and R. Pflasterer and his staff at Sunnyvale, is appreciated. W. A. Rhoades performed the delayed-neutron data calculations and analysis and contributed to the preparation of this report.

2. R. C. Kryter, N. J. Ackermann, Jr., and A. R. Buhl, "Subcriticality Measurements in FTR-3: The Homogeneous Mockup of the Fast Test Reactor," ORNL-TM-3715 (February 29, 1972).

in the SMS are fission counters designed to withstand the extreme environment of an LMFBR. A general proof-in-principle physics evaluation of these measurement techniques in a fast reactor had been made previously;² however, this evaluation was the first application of the SMS in a power reactor environment.

2. DESCRIPTION OF SUBCRITICALITY MONITORING SYSTEM

The SMS comprises breakfrequency noise analysis (BFNA), inverse kinetics rod-drop (IKRD), and modified source multiplication (MSM) techniques. The BFNA and IKRD techniques are used to calibrate the MSM technique at a slightly subcritical condition, and the MSM technique is used to determine the subcriticality over the full range of shutdown. Errors in the conventional source multiplication technique due to normalization changes (source strength and detection efficiency) are corrected in the MSM technique by applying previously calculated factors.

2.1 Breakfrequency Noise Analysis

The derivation of subcriticality, detection efficiency, and related parameters from BFNA measurements is well established^{3,4} and will not be reiterated here except to state the working formulas. An estimate of dollar subcriticality \$ is derived from the fitted -3 dB breakfrequency (f_{break}) of the cross-power spectral density (CPSD) function measured at a series of points over a range of frequencies encompassing f_{break} by means of the point reactor relation:

$$(1 - \$) = \frac{2\pi\Lambda}{\beta} f_{\text{break}} = \frac{\Lambda}{\alpha\beta}; \quad (1)$$

3. W. Seifritz et al., "Two-Detector Cross Correlation Experiments in the Fast-Thermal Argonaut Reactor (STARK)," p. 195 in Neutron Noise, Waves, and Pulse Propagation, USAEC Symposium Series 9 (1967).

4. R. C. Kryter et al., Evaluation of the Two-Detector Cross Correlation Technique for Shutdown Margin Measurements in Power Reactors, ORNL-4255 (1968).

at delayed critical, the ratio of prompt-neutron lifetime to effective delayed-neutron fraction (Λ/β) is thus directly measured. In this expression, Λ/β is assumed to remain constant at its critical value for modest departures from critical; i.e., observed changes in f_{break} are ascribed to changes in β exclusively. Likewise, the neutron detection efficiency W , defined as the ratio of the reaction rate in the detector to the fission rate in the reactor, is derived from this inferred subcriticality and from the ratio of the amplitudes of the cross and auto-power spectra by the relationship

$$W \Big|_B^A = Q \Big|_A^B(f, \beta) \frac{\beta^2 R}{\chi_2} \left[(1 - \beta)^2 + \left(\frac{2\pi f \Lambda}{\beta} \right)^2 \right], \quad (2)$$

where subscripts A and B refer to the two detector channels, $Q(f, \beta)$ is the frequency- and reactivity-dependent ratio of fission-chain-correlated (CPSD) to uncorrelated (APSD) detector events, and other quantities are known constants having their usual noise theory meanings ($\chi_2 = 0.8$ and $R = 1$ for a pulse detector). If the Q 's are measured at frequencies well below f_{break} , then the $(1 - \beta)^2$ term in Eq. (2) will dominate, making knowledge of Λ/β unnecessary.

In practice, raw CPSD values from the ORNL instrumentation were corrected for equipment nonidealities by experimentally determined white noise correction factors and feedthrough offsets and then fitted by the least-squares method to the point reactor equation in the frequency domain, thus yielding f_{break} and, through Eq. (1), β .

Two further corrections to the data were required in estimating W from Eq. (2) when using the Q 's derived from CPSD and APSD measurements in the low-frequency region below f_{break} . First, modest counting losses due to nonzero fission counter deadtime were incurred at mean counting rates greater than $\sim 2 \times 10^5$ counts/sec. Since these losses affected the estimates of Q to the same degree as they affected the observed counting rate CR_o , the following correction was made:

$$Q_{\text{true}} = Q_{\text{obs}} (1 - CR_o \tau)^{-1}. \quad (3)$$

The second correction was for nonzero pulse-height discrimination, which also increased the observed Q values, and was made by multiplying all Q values by 1.48, a factor derived experimentally from count rate vs discriminator level (i.e., integral bias) curves extrapolated to zero discriminator level. These two corrections made W defined by Eq. (2) commensurate with the W defined theoretically by Eq. (13).

2.2 Inverse Kinetics Rod Drop

In the IKRD technique, the transient behavior of the neutron population accompanying a rod drop is adequately described by the generation time, point model formulation:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^M \lambda_i C_i + S, \quad (4)$$

and

$$\frac{dC_i}{dt} + \lambda_i C_i = \frac{\beta_i}{\Lambda} n, \quad (5)$$

for $i = 1, 2, \dots, M$. The total number of delayed groups is represented by M, the source term is S, and all other symbols are standard. The observed count rate (CR) is related to the neutron population by

$$CR = \frac{Wn}{\nu\Lambda}, \quad (6)$$

where ν is the average number of neutrons produced per fission. Substituting Eq. (6) into Eq. (4) and solving for the reactivity in dollar units

$$(\$ = \rho/\beta) \quad (7)$$

yields

$$\$ = \frac{1}{CR} \left[\frac{d(CR)}{dt} \right] + 1 - \frac{1}{CR} \sum_{i=1}^M \psi_i + \frac{1}{CR} \left(\frac{WS}{\nu\beta} \right), \quad (8)$$

where

$$\psi_i(t) = \frac{\lambda_i W C_i(t)}{\beta \nu} \quad (9)$$

The solution for $\psi_i(t)$ is obtained from Eqs. (5) and (9):

$$\frac{d\psi_i}{dt} + \lambda_i \psi_i = \lambda_i \frac{\beta_i}{\beta} CR(t). \quad (10)$$

The term $\psi_i(t)$ is obtained as a function of time from the solution of Eq. (10), using the observed $CR(t)$. (The detection efficiency is assumed to be constant throughout the rod drop transient.) The system is at steady state prior to the rod drop. From the observed $CR(t)$ and the computed $\psi_i(t)$, the reactivity $\$$ is obtained from Eq. (8) (the inverse kinetics equation) at any desired time if the source S and efficiency W are known. The constant $(WS)/(\nu \beta)$ is determined from the observed $CR(t)$. This is accomplished by a least-squares fit of Eq. (8) for the parameters $\$$ and $(WS)/(\nu \beta)$ to the observed $CR(t)$ and computed $\psi_i(t)$'s over an interval of time in which $\$$ is constant (nominally 1/2 sec after the initiation of the rod drop to 4 min after the rod drop). After the parameter $(WS)/(\nu \beta)$ is established, Eq. (8) is solved for the reactivity $\$$ vs time. From this information, some diagnostic analyses are made by comparison of $(WS)/(\nu \beta)$ from the various rod drops, behavior of $\$$ vs time, and comparison of directly calculated CR vs time (using the fitted parameters in the point model equations) with the observed $CR(t)$. These diagnostics allow the experimenter to test the IKRD results for validity of the model and assumptions.

2.3 Modified Source Multiplication

We have proposed that a somewhat generalized variant of the neutron source multiplication technique be employed as the primary, wide-range subcriticality measurement method in an LMFBR. In the conventional source multiplication measurement, the observed steady-state count rate of a detector in a reactor is presumed to be related to the dollar subcriticality by

$$CR = \frac{N}{(-\$)}, \quad (11)$$

where N is a calibration constant which is assumed, once determined, to be invariant. However, it is well known that such an assumption of constancy is valid only under restrictive conditions. Although experimenters have attempted to arrange source-detector geometrical conditions to strengthen the validity of this assumption, designers of power reactors have little latitude in prearranging or postadjusting the source-detector geometry and, hence, must acknowledge the nonconstancy of N from the outset.

We have proposed⁵ that, instead of Eq. (11), the following less restrictive relationship be used for interpreting neutron source multiplication measurements:

$$CR = \frac{WS}{\nu\beta(-\rho)} \quad (12)$$

In an LMFBR, ν and β are expected to remain essentially constant over an entire shutdown, but W and S might not. The reasoning for these expectations is as follows.

W is calculated from the following equation:

$$W = \frac{\int_{V_d} \int_{\text{all } E} \Sigma_d(r, E) \phi(r, E) dr dE}{\int_{V_c} \int_{\text{all } E} \Sigma_f(r, E) \phi(r, E) dr dE} \quad (13)$$

where $\Sigma_f(r, E)$ and $\Sigma_d(r, E)$ are the macroscopic fission and detection cross sections, and V_d and V_c are detector and core volumes, respectively. Obviously, W is sensitive to local perturbations in the flux, because the numerator of Eq. (13) is integrated only over the volume of the detector, but the denominator is integrated over the entire reactor core. Local flux (and thus W) perturbations will almost certainly be encountered during an LMFBR shutdown (e.g., control rod insertions after calibration, or nearby fuel element or control rod extraction).

5. N. J. Ackermann, Jr., "Subcriticality Measurements in an LMFBR," Nucl. Safety **12**(6), 587 (1971).

Changes in S may also occur during refueling of an LMFBR because the source [spontaneous fission and (α, n) reactions of PuO_2] is distributed in the fuel; however, in general, these source changes are expected to be relatively small.

In principle, changes in W and S from their calibrated values will be accounted for properly in the interpretation of neutron source multiplication by Eq. (12). Changes in W will be determined through the numerical solution of Eq. (13), and changes in S will be determined by analytical calculations or by monitoring the fuel elements before insertion and after extraction from the core. The overall plan is as follows:

1. With the reactor slightly subcritical for the MSM calibration, either BFNA or IKRD and steady-state count rate measurements will be made, thus giving $\$ _o$ and $CR _o$;
2. Equation (12) will be solved for the calibration factor, using $\$ _o$ and $CR _o$ to calculate

$$K = \frac{W _o S _o}{\nu \beta} = (CR _o) (-\$ _o); \quad (14)$$

3. The subcriticality at any subsequent reactor condition will be measured by determining the steady-state count rate and using Eqs. (12) and (14) to give

$$-\$ = \frac{KR _w R _s}{CR}, \quad (15)$$

where $R _w$ is the detection efficiency ratio $W/W _o$, $R _s$ is the source ratio $S/S _o$, and the unsubscripted W and S refer to the subsequent state in question.

3. EXPERIMENTAL APPARATUS

The equipment for the SEFOR investigations (Fig. 1) comprised four subsystems: detectors, wideband pulse electronics, a cross-power spectral density analyzer, and an IKRD data logger.

3.1 Detectors

Since in-vessel neutron detectors were required for measurement of subcriticality, the detectors and their cable assemblies were designed to operate in an LMFBF environment. Inasmuch as a fission counter is the only detector able to perform under these conditions, two modified, Reuter-Stokes, model RSN-10A counters were encased in a 0.275-in.-thick sleeve of lead to reduce the gamma flux (Appendix, Sect. 8.4) and placed in a stainless-steel drywell. The counters were modified as follows: (1) they were filled with 95% Ar-5% CO₂ gas at 1 atm to give a faster pulse collection time (~80 nsec) than could be obtained with the manufacturer's gas filling, and (2) 99.9% ²³⁵U (calutron separated) to increase the sensitivity to neutrons and to reduce the ²³⁴U alpha background.

A high temperature connector, Reuter-Stokes, model RSE-16-1, joined each detector to 15 ft of special, high-temperature, quartz-fiber insulated, low-noise coaxial cable (Sante Fe Textile Company, model SF-388, modified to have an internal shield of three layers of copper braid for improved electrical noise rejection). Each 15-ft cable was joined near the top of the drywell to 30 ft of RG-233/U coaxial cable which had an internal shield of two layers of copper braid. Both of these 50-Ω cable types were further covered by a secondary electrical interference shield (a single layer of copper braid) that was electrically isolated from the primary internal shields of the cable. This shield system provided excellent noise rejection with the primary shields connected to the high-quality (preamplifier signal return) ground and the secondary shields connected to building ground at several points along the cable. Repeated 500-sec background counting tests, performed with a normal (plateau) discriminator setting of 24 units and with the detectors installed in the SEFOR core, consistently gave zero counts, demonstrating no pickup noise. The integral bias response of the detection system taken while in the SEFOR is shown in Fig. 2.

Fig. 1. Conceptual diagram of the ORNL subcriticality monitoring system.

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Fig. 2. Response of the detection system at SEFOR.

3.2 Pulse-Mode Electronics

The 50- Ω coaxial cable system described in Sect. 3.1 was connected to two wideband, current-mode preamplifiers installed immediately outside the reactor containment cell. These ORNL, model Q-5095-1, field-mounted preamplifiers were fabricated to RDT Standard C15-3T, subsection BG.⁶ These units were connected to standard commercial pulse amplifiers, discriminators, and scalers as indicated in Fig. 1. The instruments for the two independent detector channels were contained in separate NIM bins to preclude interchannel cross talk through the NIM power supply.

The three pulse amplifiers in each channel were LeCroy, model 107F, dual wideband (> 100 MHz) amplifiers connected in cascade through differentiating and integrating passive networks, all having an equal time constant of 27 nsec. The pulse height discriminators were variable level, nonparalyzing, EG&G model T-105/N. A common high-voltage stabilized power supply (John Fluke) polarized the chambers of both channels at 200 V.

Two separate 50- Ω outputs from each integral discriminator drove a dual 100-MHz pulse counting scaler (TSI model 1535) and a dual RC time-constant unit (ORNL Q-3136). The scaler served two functions: (1) when electrically gated on and off with a 10-sec timer, it accurately measured the average counting rate of each detector under static conditions; and (2) when electrically gated by a special logic circuit (Sect. 3.4), it served as a zero-deadtime time analyzer for measuring the rapidly varying counting rate of one detector following a reactor control reflector drop. The dual time-constant unit had a pair of passive parallel RC networks, each with an e -folding time constant of $1.5\mu\text{sec}$; it low-pass filtered the 50-nsec-wide discriminator output pulses and thereby generated, for input to the

6. RDT Standard C15-3T, "Current Pulse Preamplifiers for Fission Counters," U. S. Atomic Energy Commission, Division of Reactor Development and Technology, (1971).

CPSD analyzer (Sect. 3.3), a pair of semicontinuous analog waveforms having a bandwidth (20 kHz) commensurate with the frequency range required to determine the transfer function of the SEFOR.

3.3 CPSD Analyzer

This instrument, designed and built at ORNL (model Q-4305), efficiently extracted and statistically averaged the fission-chain-related portions of the two RSN-10A detector signals so as to yield the characteristic neutron transfer function of the reactor, from which the prompt die-away time constant (or breakfrequency) could be derived and related to the SEFOR subcriticality by means of the point reactor model. The analyzer calculated the CPSD over a frequency range from 50 Hz to 40 kHz by the analog method of bandpass filtration, cross-multiplication, and exponentially weighted time integration of the instantaneous signal products.

The one-third-octave continuous filter banks were General Radio, model 1925, active six-pole Butterworth designs yielding 30 filtered outputs in parallel. Any ten of these outputs could be selected on a patchboard for simultaneous analysis by ten multiplier-time-average NIM modules (ORNL Q-3128). Time-averaged (100-sec RC) estimates of the CPSD were read out each 100 sec by a data logging system consisting of a sequential scanner and a teletypewriter that produced both printed copy and punched paper tape for further digital computer analysis (application of corrections and least-squares fitting to a point model) on a phone-linked, time-shared commercial system.

The frequency response of this CPSD analyzer system was nominally "flat" from its lower frequency limit to ~ 25 kHz, with a correction of about 4% for multiplier rolloff required at 40 kHz. However, deviations ($\sim 10\%$) in the response of the individual filters within the banks had to be corrected for by white-noise calibration runs, wherein noise having a known and constant spectral density function over the range of the CPSD equipment was analyzed in the same manner as reactor data, and the resulting answers were forced to a constant value through application of correction factors in the data handling computer program referred to previously.

System stability for the few hours' duration of a typical experiment was $\sim 2\%$, although long-term drift of the analog filter banks necessitated periodic tuneup for best performance. The accurate signal processing dynamic range of the CPSD analyzer was $\sim 4 \times 10^3$, and thus it could extract subcriticality information from signals having a signal-to-noise ratio as small as 10^{-3} . The basic limitation to the dynamic range of an analyzer of this design is nonideality of the analog multipliers, which is called "feed through"; corrections for this nonideality were also applied in the data handling digital computer program.

Further information concerning the equipment contained within the Q-4305 system and the calibration and error correction techniques may be found in ref. 2.

3.4 IKRD Data Logger

This instrument, which consisted of a custom constructed integrated circuit logic unit (ORNL Q-5104-1), a Teletype BRPE-11 paper-tape punch, and a 30-V dc punch-driver power supply, was used with the TSI, model 1535, dual six-decade scale. Together, these devices formed a fixed-channel-width, multichannel time analyzer for gathering and recording transient count-rate data from one of the two neutron detector channels following a reflector drop. The resulting data were subsequently analyzed for subcriticality by inverse solution of the point kinetics equations formulated in the time domain (Sect. 6.2.2). This somewhat unconventional, though wholly adequate, method of recording counts occurring during a preselected time interval as a function of elapsed time was chosen for its expediency, because it was relatively simple to implement and inexpensive (the BRPE-11 punch was available on loan).

The punch served both as the final storage medium and as the master timing source that fixed the time channel widths. The rotational speed of the synchronous motor that drove the punch mechanism was such that ~ 18 , six-character numbers could be punched per second in the paper tape, and, fortuitously, this was commensurate with the data acquisition rates required in IKRD experiments, since the rate of change of the neutron population is governed by the time constants (~ 0.1 to

40 sec) of the delayed-neutron precursors. Accordingly, a magnetic pickup synchronizing pulse from the punch flywheel was shaped and used for the master time base. The control logic, synchronized by the timing pulses, caused neutron pulses from a single detector channel to be routed to and accumulated by scaler channels A and B in an alternating (buffered) fashion; the control logic also was arranged to force the contents of one channel to be punched out and then reset while the other channel simultaneously accumulated counts. The result was that five decimal digits and a space character were punched serially in the paper tape in standard ASCII format, the counting time (individual channel width) being 54.55 msec (on 60-Hz ac power) with a precision better than 0.05%. Counting in each of the two scaler channels on alternate cycles resulted in a zero deadtime, contiguous channel analyzer (i.e., all pulses from the detector were accumulated without loss) with no limit to the number of total readings recorded.

Because the output format was limited to five decimal characters, input pulse rates greater than $(10^5/0.05455) \sim 1.8 \times 10^6$ per second caused the most significant digit to be truncated on the output paper tape. However, this minor deficiency was easily discernible and corrected by the IKRD data processing program (Sect. 6.2.2).

4. EXPERIMENTAL PROCEDURES AND SCHEDULE

4.1 Core Configurations

A general description of the SEFOR core structure and components is given in ref. 7. We made measurements in SEFOR Core I and in two configurations of Core II: Assemblies I-P, II-A, and II-C (Figs. 3, 4, and 5, respectively). The core loadings for each assembly are also listed in the figures.

7. R. A. Meyer, A. B. Reynolds, S. L. Steward, M. L. Johnson, and E. R. Craig, Design and Analysis of SEFOR Core I, GEAP-13598, (June 1970).

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618 STANDARD FUEL RODS
 12 IFA FUEL RODS
 102 STANDARD BeO TIGHTENER RODS
 6 BeO IFA TIGHTENER RODS
 10 B₄C RODS
 6 GUINEA PIG RODS
 1 STAINLESS STEEL ROD
 1 FOIL HOLDER ROD

○○○ INSTRUMENTED FUEL ASSEMBLY (IFA)
 ● B₄C ROD
 ○ GUINEA PIG ROD
 ⊙ STAINLESS STEEL ROD

Fig. 3. Core I loading for Assembly I-P.

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617 STANDARD FUEL RODS	● B ₄ C RODS
12 IFA FUEL RODS	⊙ IFA's
97 STANDARD STAINLESS STEEL
TIGHTENER RODS	○ VACANT FUEL LOCATIONS
6 IFA BeO TIGHTENER RODS	⊕ VACANT TIGHTENER ROD LOCATIONS
7 B ₄ C RODS	◉ GUINEA PIG RODS
2 GUINEA PIG RODS	

Fig. 4. Core II loading for Assembly II-A.

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620 STANDARD FUEL RODS

12 IFA FUEL RODS

9 B₄C RODS

6 GUINEA PIG RODS

1 STAINLESS STEEL ROD

102 STAINLESS STEEL TIGHTENER RODS

6 BeO IFA TIGHTENER RODS

○ ○ ○ IFA's

⊕ STAINLESS STEEL (SS) RODS

● B₄C RODS

○ GUINEA PIG RODS

Fig. 5. Core II loading for Assembly II-C.

The Core I (Assembly I-P), "partially reflected" configuration, contained 102 BeO tightener rods that served to soften the neutron spectra which enhanced the Doppler coefficient. Criticality was achieved with three reflectors down (removed). Runs numbered N1 to N13 (BFNA and MSM) and RD1 to RD15 (IKRD) were performed in Core I.

A "fully reflected" configuration of Core II (Assembly II-A) was achieved by replacing 1 fuel rod and 96 BeO rods with stainless-steel rods. Criticality was achieved with only 1-1/2 reflectors removed. Runs N21 to N33 and RD16 to RD28 were performed in this configuration.

A "partially reflected" configuration of Core II (Assembly II-C) was achieved by adding three standard fuel rods, four special test rods (guinea pig rods), and six steel rods to the reflected configuration. Criticality was achieved with two reflectors removed. Runs N41 to N46 and RD29 to RD31 were performed in this configuration.

Measurements were made in the Core II configurations primarily to investigate the sensitivity of the prompt die-away time constant to reflector conditions.

4.2 Experimental Schedule

The SEFOR data were collected over two time periods in 1971: September 23-25 and October 8-11. The first period was for Core I and the second for Core II investigations.

An outline of the experimental schedule is given in Tables 1 to 3 where the labels $N(i)$ and $RD(i)$, $i = 1, 2, 3$, etc., used in the tables denote the i th BFNA and IKRD measurements, respectively. MSM measurements were made for all $N(i)$.

5. ANALYSIS OF DATA

5.1 Calculation of Detection Efficiency

W was calculated for Cores I and II for the fully reflected and partially reflected configurations of SEFOR. The system was mocked up in R-Z geometry, using

Table 1. Experimental schedule for CRNL measurements on SEFOR Core I (Assembly I-P)

Run No.	Date (Sept.)	Time	Nominal Reactor Condition ^a	Subcriticality Monitoring Techniques	Comments
N1	23	1805	Full shutdown	None	White noise calibration of CPSD instrumentation; count rate $\sim 1.25 \times 10^5 \text{ sec}^{-1}$.
N2	23	1950	Full shutdown	BFNA	Preliminary measurement of neutron detector efficiency.
N3	23	2330	Approaching critical	BFNA, MSM	Counting loss measurements; near-critical breakfrequency determination.
N4	24	0250	Approaching critical	BFNA	APSD portion of run N3.
N5	24	0900	Critical	MSM	Counting loss too great to allow correlation measurements; run discontinued.
N6	24	1000	Critical	BFNA, MSM	Indicated count rate $\sim 2.2 \times 10^6 \text{ sec}^{-1}$; losses tolerable.
RD1	24	1515	Critical to ~ 1.35 subcritical	IKRD	Dropped reflector 7 from critical.
RD2	24	1530	Critical to ~ 1.35 subcritical	IKRD	Repeat of run RD1.
RD3	24	1550	Critical to ~ 1.35 subcritical	IKRD	Repeat of run RD2.
N7	24	1610	~ 1.35 subcritical	BFNA, MSM	Indicated count rate, $\sim 5.4 \times 10^5 \text{ sec}^{-1}$.
RD4(a)	24	1945	~ 1.35 to ~ 2.40	IKRD	Dropped reflector 2 from previous condition, but reactor scrambled.
RD4(b)	24	2145	~ 1.35 to ~ 2.40	IKRD	Repeat of RD4(a), following unexpected reactor scram.
N8	24	2335	~ 2.40 subcritical	BFNA, MSM	Indicated count rate $\sim 5.4 \times 10^5 \text{ sec}^{-1}$.
N9	25	0330	~ 0.50 to ~ 2.40	BFNA, MSM	Indicated count rate $\sim 9.4 \times 10^5 \text{ sec}^{-1}$.
RD5	25	0650	~ 0.50 to ~ 2.40 subcritical	IKRD	Dropped reflectors 2 and 7 simultaneously, but reactor scrambled owing to low hydraulic pressure; run discontinued.
RD6	25	0845	~ 0.50 to ~ 2.40 subcritical	IKRD	Repeated RD5, but reactor scrambled again owing to low hydraulic pressure in reflector drive system.
RD7	25	1015	~ 0.50 to ~ 1.35	IKRD	Removed only reflector 7.
RD8	25	1022	~ 1.35 to ~ 2.40	IKRD	Removed reflector 2, additionally.
RD9	25	1035	~ 0.50 to ~ 1.35	IKRD	Repeat of RD7.
RD10	25	1045	~ 1.35 to ~ 2.40	IKRD	Repeat of RD8.
RD11	25	1110	~ 2.40 to ~ 3.00	IKRD	Removed reflector 4, additionally.
RD12	25	1120	~ 3.00 to ~ 3.50	IKRD	Removed reflector 6, additionally.
RD13	25	1130	~ 3.50 to ~ 4.00	IKRD	Removed reflector 9, additionally.
N10	25	0735	Not used	None	White noise calibration of CPSD instrumentation using pseudorandom generator.
N11	25	1245	~ 4 subcritical	BFNA, MSM	Indicated count rate $\sim 1.3 \times 10^5 \text{ sec}^{-1}$.
N12	25	1600	Critical	BFNA, MSM	Indicated count rate $\sim 2.6 \times 10^6 \text{ sec}^{-1}$.
RD14	25	1840	~ 0.15 to ~ 1.35	IKRD	Repeat of RD1.
RD15	25	1900	~ 1.35 to ~ 2.40	IKRD	Repeat of RD4.
N13	25	1920	Full shutdown	None	White noise calibration of CPSD instrumentation; count rate $\sim 1.0 \times 10^5 \text{ sec}^{-1}$.

^aAll subcriticality values are expressed in dollars.

Table 2. Experimental schedule for ORNL measurements on SEFOR Core II (Assembly II-A)

Run No.	Date (Oct.)	Time	Nominal Reactor Condition ^a	Subcriticality Monitoring Techniques	Comments
N21	8	0700	Full shutdown	None	White noise calibration of CPSD instrumentation.
N22	8	1430	Approaching critical	BFNA, MSM	Power level drift due to temperature changes; run discontinued.
N23	8	1630	Critical	BFNA, MSM	Indicated count rate $\sim 2.2 \times 10^6 \text{ sec}^{-1}$; reactor held steady by jogging reflector 3.
N24	8	2005	Critical	BFNA, MSM	Repeat of N23, but with count rate lowered by higher discriminator threshold.
N25	8	2235	Critical	BFNA, MSM	Repeat of N23, but with count rate lowered by lower reactor power.
RD16	9	0200	Critical to ~ 1.35	IKRD	Removed reflector 7 from critical.
RD17	9	0228	Critical to ~ 1.35	IKRD	Repeat of RD16.
N26	9	0250	~ 1.35 subcritical	BFNA, MSM	Indicated count rate $\sim 3.2 \times 10^4 \text{ sec}^{-1}$.
RD18	9	0530	~ 1.35 to ~ 2.40	IKRD	Removed reflector 2, additionally.
N27	9	0600	~ 2.40 subcritical	BFNA, MSM	Indicated count rate $\sim 1.45 \times 10^4 \text{ sec}^{-1}$.
N28	9	1000	~ 0.50 subcritical	BFNA, MSM	Indicated count rate $\sim 7.5 \times 10^4 \text{ sec}^{-1}$.
RD19	9	1340	~ 0.50 to ~ 1.35	IKRD	Removed reflector 7 from its critical position.
RD20	9	1403	~ 1.35 to ~ 2.40	IKRD	Removed reflector 2, additionally
RD21	9	1500	~ 0.50 to ~ 1.35	IKRD	Repeat of RD19.
RD22	9	1520	~ 1.35 to ~ 2.40	IKRD	Repeat of RD20.
RD23	9	1540	~ 2.40 to ~ 3.00	IKRD	Removed reflector 4, following final condition of RD22.

^aAll subcriticality values are expressed in dollars.

Table 3. Experimental schedule for ORNL measurements on SEFOR Core II (Assembly II-C)

Run No.	Date (Oct.)	Time	Nominal Reactor Condition	Subcriticality Monitoring Techniques	Comments
N41	10	2245	Critical	BFNA, MSM	Indicated count rate $\sim 6.8 \times 10^5 \text{ sec}^{-1}$.
N42	11	0135	Critical	BFNA, MSM	Indicated count rate $\sim 1.0 \times 10^6 \text{ sec}^{-1}$.
N43	11	0500	Critical	BFNA, MSM	Indicated count rate $\sim 2 \times 10^5 \text{ sec}^{-1}$.
RD29	11	0740	Critical to ~ 1.35	IKRD	Removed reflector 8 from its critical position.
N44	11	0805	~ 1.40 subcritical	BFNA, MSM	Indicated count rate $\sim 2.5 \times 10^4 \text{ sec}^{-1}$.
N45	11	1105	~ 0.50 subcritical	BFNA, MSM	Indicated count rate $\sim 8.0 \times 10^4 \text{ sec}^{-1}$.
RD30	11	1350	~ 0.50 to ~ 1.35 subcritical	IKRD	Removed reflector 8.
RD31	11	1400	~ 1.40 to ~ 2.40	IKRD	Removed reflector 7, additionally.
N46	11	1500	Shutdown	MSM	Final counting rate measurement.

25 regions (Fig. 6). An S_4P_3 quadrature and expansion and 30-group cross sections were used in the calculations.⁸ The number densities of each region are given in Table 15 (Appendix, Sect. 8.2).

Efficiencies were computed from the multigroup fluxes for a ^{235}U fission counter in terms of W per gram of ^{235}U in the counter:

$$W = \frac{A}{M} \frac{\sum_{\text{all } g} \phi_{ig} \sigma_g}{\sum_{\text{all } i, \text{ all } g} \phi_{ig} \Sigma f_{ig}}, \quad (16)$$

where

- A = Avogadro's number,
- M = molecular weight (235),
- ϕ_{ig} = multigroup flux at space point i for energy group g ,
- σ_g = microscopic fission cross section for ^{235}U for energy group g ,
- Σf_{ig} = macroscopic fission cross section at space point i for energy group g .

These W values can be compared directly with experimental values by multiplying them by the number of grams of active material and accounting for the nonzero pulse height setting in the detection system.

Calculated radial traverses of W are shown in Fig. 7 for cross sections along the A, B, and C axial positions shown in Fig. 6 for the reflected SEFOR configuration. Figure 8 shows the effect of removing the reflectors. Axial traverses are shown along the core center for the reflected and unreflected core in Fig. 9.

Since all measurements were made with the detectors at the center of the core, the changes in W were less than 4% throughout these experiments. The ratio of W for the unreflected core to W for the fully reflected core at the core center is 1.039; that is, W increased at the detector location when the reflectors were removed to achieve the full shutdown condition. If the detectors had been in the reflector region, W would have decreased considerably (see Fig. 8).

8. F. R. Mynatt, A User's Manual for DOT, a Two-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering, K-1964 (1969).

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Fig. 6. SEFOR zone configuration for R-Z calculations.

Fig. 7. Detection efficiencies in two-dimensional SEFOR model as a function of the radial distance from the center of the core.

Fig. 8. Calculated effect of reflectors on detection efficiencies in SEFOR.

Fig. 9. Detector efficiencies in two-dimensional SEFOR model as a function of the axial distance from the bottom of the Na grid plate.

The measured W for the RSN-10A detectors in SEFOR was 3.32×10^{-6} count/fission in the core. The calculated W per gram was 3.05×10^{-6} . The RSN-10A counters contained 1.69 g of ^{235}U each, and the plateau extrapolation from a pulse height selector setting of 0 to 24 gave a factor of 1.48, or a 32% reduction for comparative purposes; hence, the comparable calculated value would be 3.05×10^{-6} times (1.69/1.48), or 3.48×10^{-6} .

5.2 Calculation of Delayed-Neutron Data

The SEFOR geometry described in Sect. 5.1 was used for calculation of the effective delayed-neutron yield by delay group and by fissile species. The k -eigenvalue problems for flux (ϕ) and importance (ϕ^*) were solved using the APC-II code.⁹ This code performed a consistent leakage R-Z calculation in which two one-dimensional problems were coupled by an artificial absorption term determined by the leakage in the alternate direction. Heterogeneities in the direction of calculation were treated explicitly in each problem, but transverse heterogeneities were removed by a linear perturbation method. The individual problems within the APC-II code were resolved by a discrete ordinates module based on the ANISN¹⁰ code. A 30-group cross-section library was prepared for the SEFOR geometry, using the XSDRN¹¹ code. The cross-section source was the 123-group ORNL library labelled ENDF-VII-GRP123 · SIGMAS · T293.¹²

Self-shielding was calculated using the XSDRN Nordheim integral treatment, with input parameters determined for a typical SEFOR cell geometry.

9. W. A. Rhoades, ORNL, unpublished notes.

10. W. W. Engle, Jr., A User's Manual for ANISN - A One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering, K-1693 (March 30, 1967).

11. N. M. Greene and C. W. Craven, Jr., XSDRN: A Discrete Ordinates Spectral Averaging Code, ORNL-TM-2500 (July 1969).

12. J. L. Lucius, J. D. Jenkins, and R. Q. Wright, The Index Data System, An Index of Nuclear Data Libraries Available at ORNL, ORNL-TM-3334 (March 29, 1971).

These calculations yielded ϕ , ϕ^* , and the rates of fission and neutron production due to each nuclide. From these the fission fractions were calculated for four configurations (Tables 16 and 17, Appendix, Sect. 8.2):

$$f_n = \frac{F_n}{\nu \sum F_n}, \quad (17)$$

where f_n is the fission from n th nuclide per fission neutron produced, F_n is the relative fission rate from n th nuclide, and ν is the overall ratio of neutron production to fission rate.

The emergent energy spectrum for delayed neutrons was available for each of the conventional six delay groups (Table 18, Appendix, Sect. 8.2), except that groups five and six were combined into a single spectrum.¹³ Nuclide-dependent spectra, which would allow direct calculation of β for each nuclide and group, were not available, and so an indirect "effectiveness" approach was used. An effectiveness (e_d) was calculated for each delay group:⁹

$$e_d = \frac{1}{\sum_g \chi_{d,g}^D} \frac{\sum_i V_i \sum_{g'} \phi_{g',i} [\nu \sigma^F]_{g',i} \sum_g \phi_{g,i}^* \chi_{d,g}^D}{\sum_i V_i \sum_{g'} \phi_{g',i} [\nu \sigma^F]_{g',i} \sum_g \phi_{g,i}^* \chi_g^T} \quad (18)$$

where

- e_d = effectiveness of delayed neutrons, d th delay group;
- $\chi_{d,g}^D$ = number of delayed neutrons in g th energy group, d th delay group, per fission neutron produced;
- χ_g^T = number of neutrons in g th energy group per fission neutron produced;
- V_i = volume, i th spatial interval;
- $\phi_{g',i}$ = flux, g th energy group, i th spatial interval;

13. J. T. Mihalcz, Y-12 Plant, unpublished notes.

- $\phi_{g,i}^*$ = importance, $\underline{g}$ th energy group, $\underline{i}$ th spatial interval;
- $[\nu\sigma^F]_{g',i}$ = fission-neutron production cross section, $\underline{g'}$ th energy group, $\underline{i}$ th spatial interval.

This evaluation was performed by the COMPOZ code.⁹

Values of the delayed-neutron yield per delay group for each of the nuclides of interest are available from Keepin.¹⁴ Newer values of the total yields for ²³⁵U, ²³⁸U, and ²³⁹Pu were taken from Evans and Thorpe,¹⁵ and Keepin's data for those nuclides were renormalized accordingly (Table 19, Appendix, Sect. 8.2). Finally, the yield from each nuclide, with the appropriate effectiveness correction, was found by

$$\beta_{d,n} = \gamma_{d,n} f_n,$$

$$\beta_{d,n}^* = e_d \beta_{d,n}$$

where

$\beta_{d,n}^*$ = effective yield, delayed neutrons in $\underline{d}$ th delay group from $\underline{n}$ th nuclide fission per 100 fission neutrons born;

$\beta_{d,n}$ = actual yield corresponding to $\beta_{d,n}^*$;

$\gamma_{d,n}$ = yield, delayed neutrons in $\underline{d}$ th delay group per 100 fissions from $\underline{n}$ th nuclide.

The significant parameters and results are listed in Table 4. A comparison of P_0S_2 and P_3S_6 (Table 4 vs Table 30) showed that P_0S_2 is quite adequate for these calculations.

14. G. R. Keepin, Physics of Nuclear Kinetics, Addison-Wesley, 1965, Ch. 4.

15. A. E. Evans and M. M. Thorpe, "Revised LASL Delayed-Neutron Yield Data," paper presented at the American Nuclear Society, Reactor Physics Division Informal Session, Las Vegas, Nevada, June 20, 1972.

Table 4. Delayed neutron yields for SEFOR cores

Delay Group	^{235}U	^{238}U	^{239}Pu	^{240}Pu	$\frac{\sum \beta_{d,n}^*}{\sum \beta_{d,n}}$
A. For Partially Reflected Core I (Assembly I-P)					
1	0.000209 ^a 0.000179 ^b	0.001848 0.001579	0.007230 0.006179	0.000140 0.000120	0.8547
2	0.001175 0.001037	0.019555 0.017267	0.053018 0.046815	0.001342 0.001185	0.8830
3	0.001036 0.000907	0.023113 0.020228	0.040969 0.035856	0.000945 0.000827	0.8752
4	0.002244 0.001996	0.055358 0.049241	0.062357 0.055467	0.001722 0.001523	0.8895
5	0.000704 0.000638	0.032106 0.029008	0.019581 0.017691	0.000623 0.000571	0.9035
6	0.000143 0.000129	0.010702 0.009669	0.006627 0.005987	0.000140 0.000126	0.9035
Total	0.00551 0.00488	0.14268 0.12699	0.18978 0.16800	0.00492 0.00436	0.8872
B. For Fully Reflected Core II (Assembly II-A)					
1	0.000202 ^a 0.000173 ^b	0.001841 0.001579	0.007224 0.006197	0.000147 0.000126	0.85786
2	0.001133 0.001007	0.019477 0.017317	0.052978 0.047103	0.001407 0.001251	0.88911
3	0.000998 0.000879	0.023030 0.020283	0.040937 0.036053	0.000991 0.000873	0.88070
4	0.002163 0.001936	0.055136 0.049359	0.062309 0.054876	0.001806 0.001617	0.89523
5	0.000678 0.000617	0.031977 0.029115	0.019566 0.017815	0.000663 0.000604	0.91050
6	0.000138 0.000126	0.010659 0.009705	0.006622 0.006029	0.000147 0.000134	0.91050
Total	0.00531 0.00474	0.14212 0.12736	0.18964 0.16807	0.00516 0.00460	0.89055
C. For Partially Reflected Core II (Assembly II-C)					
1	0.000197 ^a 0.000169 ^b	0.001921 0.001645	0.007192 0.006159	0.000152 0.000130	0.85633
2	0.001108 0.000982	0.020321 0.018022	0.052740 0.046720	0.001459 0.001292	0.88586
3	0.000977 0.000858	0.024028 0.021095	0.040754 0.035779	0.001028 0.000902	0.87792
4	0.002116 0.001888	0.057526 0.051340	0.062030 0.055359	0.001873 0.001672	0.89246
5	0.000664 0.000602	0.033363 0.030256	0.091478 0.017664	0.000687 0.000623	0.90688
6	0.000135 0.000122	0.011121 0.010085	0.006593 0.005979	0.000152 0.000138	0.90688
Total	0.00520 0.00462	0.14828 0.13242	0.18879 0.16766	0.00535 0.00476	0.89022

^a $\beta_{d,n}$ = neutrons in d th delayed group from n th nuclide per 100 fission neutrons.

^b $\beta_{d,n}^*$ = effective $\beta_{d,n}$.

5.3 Counting Loss Corrections

The inherent neutron source present both for Core I and for Core II was quite large, and, hence, a severe counting loss was observed at the near-critical state and a considerable loss at the subcritical states. To interpret the MSM and IKRD measurements, it was necessary to accurately determine the counting loss for each experiment.

An experiment was performed at ORNL in the Pool Critical Assembly (PCA) to establish the counting loss characteristic of the RSN-10A detectors over the full range of counting rates experienced at SEFOR. A diagram of the experiment is shown in Fig. 10. The two detection systems used at SEFOR were also used for these measurements.

The experimental procedure at the PCA was to simultaneously take counting rates from fission counters 1 and 2 at very low power levels, such that neither counter experienced a significant counting loss, and then successively increase the reactor power in small increments until the counting rate (CR) of the fission counter near the core was slightly greater than the maximum counting rate in SEFOR. At each of these steps, the counting rate of counter 2 was the true counting rate CR_1 , and the counting rate of counter 1 was the observed CR_O . At some point, of course, counter 2 could have experienced some counting loss; however, this could be corrected using the counting loss information obtained during the early part of the experiment when the counting rates of counters 1 and 2 were much lower.

Sufficient counts were collected for each measurement to insure a counting error within $\pm 0.1\%$. The ratio of CR_1 to CR_2 with no counting loss was 37.3. Deviation from a constant ratio implied that counter 1 had begun to lose counts. The average counting rate (counts/sec) of multiple measurements at each reactor power level are listed in Table 5 along with the ratio of CR_1 to CR_2 . In the linear range, the true counting rate CR_T was 37.3 times CR_2 and is also listed in Table 5. As seen in the table, the maximum value of CR_2 was 1.457×10^5 counts/sec, which indicates that the reference count rate had about a 3% counting loss (see reactor condition 3 in Table 5).

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Fig. 10. Conceptual diagram of the counting loss experiment.

Table 5. Results of counting loss experiment

PCA Power Condition	Count Rates (counts/sec)			$\frac{CR_1}{CR_2}$	$\frac{CR_T}{CR_O^c}$
	CR_1^a	CR_2^a	CR_T^b		
1	$5.838 + 4^d$	$1.580 + 3$	$5.893 + 4$	36.9	1.009
2	$9.249 + 4$	$2.520 + 3$	$9.400 + 4$	36.7	1.016
3	$1.493 + 5$	$4.144 + 3$	$1.546 + 5$	36.0	1.034
4	$2.185 + 5$	$6.103 + 3$	$2.276 + 5$	35.8	1.042
5	$2.791 + 5$	$7.902 + 3$	$2.947 + 5$	35.3	1.056
6	$3.485 + 5$	$9.835 + 3$	$3.668 + 5$	35.4	1.053
7	$4.284 + 5$	$1.231 + 4$	$4.592 + 5$	34.8	1.072
8	$4.791 + 5$	$1.394 + 4$	$5.200 + 5$	34.4	1.085
9	$5.429 + 5$	$1.594 + 4$	$5.946 + 5$	34.1	1.095
10	$6.052 + 5$	$1.797 + 4$	$6.703 + 5$	33.7	1.108
11	$6.529 + 5$	$1.978 + 4$	$7.378 + 5$	33.0	1.130
12	$7.916 + 5$	$2.432 + 4$	$9.071 + 5$	32.5	1.146
13	$9.154 + 5$	$2.875 + 4$	$1.072 + 6$	31.8	1.171
14	$1.074 + 6$	$3.496 + 4$	$1.304 + 6$	30.7	1.214
15	$1.181 + 6$	$3.918 + 4$	$1.461 + 6$	30.1	1.237
16	$1.413 + 6$	$4.982 + 4$	$1.858 + 6$	28.4	1.315
17	$1.616 + 6$	$5.964 + 4$	$2.225 + 6$	27.1	1.377
18	$1.822 + 6$	$7.147 + 4$	$2.666 + 6$	25.5	1.463
19	$2.029 + 6$	$8.430 + 4$	$3.144 + 6$	24.1	1.550
20	$2.276 + 6$	$1.044 + 5$	$3.894 + 6$	21.8	1.710
21	$2.477 + 6$	$1.244 + 5$	$4.640 + 6$	19.9	1.873
22	$2.648 + 6$	$1.457 + 5$	$5.435 + 6$	18.2	2.052

^aA minimum of 10^4 total counts was collected for all measurements.^bTrue counting rate.^cObserved counting rate.^dNumber is read as $5,838 \times 10^4$.

The results shown in Table 5 were plotted in Figs. 11 and 12 and fitted to a straight line and an exponential curve, respectively. The low counting loss data where $CR_T/CR_O < 1.12$ are shown in Fig. 11 fitted to the following form:

$$\frac{CR_T}{CR_O} = \frac{1}{1 - CR_O \tau} \quad (19)$$

where $\tau = 155$ nsec. The data in Fig. 12 were fitted to an exponential form.

The data in Figs. 11 and 12 can be used to convert an observed counting rate in SEFOR to the true counting rate. The observed counting rate is located on the abscissa of Fig. 11 or 12, and the corresponding value along the ordinate is multiplied by CR_O to produce CR_T . The results of applying these data to the SEFOR measurements are shown in Table 6 for Core I and two configurations of Core II. These counting loss data must be properly incorporated into all data analysis methods in order to present a bias in final estimates of subcriticality.

5.4 Source Adjustments

Because the SEFOR had been operated for a long time at 10 MW prior to the subcriticality experiments, a time varying reactor neutron source caused by the $BeO(\gamma, n)$ reaction to the decaying fission product inventory was present in addition to the constant spontaneous fission and oxide sources inherent in the core.

To derive correct subcriticality values from the observed counting rates by means of the MSM algorithm [Eq. (15)], correction factors R_s for the source decay were applied.

Source decay curves were generated for the three core conditions by plotting deadtime-corrected counting rates vs elapsed time for the subcriticality conditions that were repeated once or more often during the experiments. The magnitudes of elapsed time employed in this procedure ranged from about 18 hr (Assembly II-C) to nearly 60 hr (Assembly I-P); the data are shown in Figs. 13 through 15.

Fig. 11. Counting loss correction factors for low counting rates.

Fig. 12. Counting loss correction factors for high counting rates.

Table 6. Counting loss corrections for SEFOR cores

Run No.	Average CR (counts/sec)		CR_T/CR_O	Corrected CR (counts/sec)	
	Instrument Channel	Instrument Channel		Instrument Channel	Instrument Channel
	A	B		A	B
A. For Partially Reflected Core I (Assembly I-P)					
N1	1.239 + 5 ^a	1.280 + 5	1.020	1.264 + 5	1.306 + 5
N2	1.230 + 5	1.280 + 5	1.020	1.255 + 5	1.306 + 5
N3	7.189 + 5	7.201 + 5	1.127	8.102 + 5	8.116 + 5
N4	7.201 + 5	7.218 + 5	1.127	8.116 + 5	8.135 + 5
N5	--	--	--	--	--
N6	2.323 + 6	2.133 + 6	1.710	3.972 + 6	3.647 + 6
N7	5.582 + 5	5.206 + 5	1.094/1.086	6.107 + 5	5.654 + 5
N8	2.680 + 5	2.732 + 5	1.043/1.044	2.795 + 5	2.852 + 5
N9	9.334 + 5	9.495 + 5	1.175/1.180	1.097 + 6	1.120 + 6
N10	--	--	--	--	--
N11	1.290 + 5	1.324 + 5	1.020	1.316 + 5	1.350 + 5
N12	2.607 + 6	2.506 + 6	1.955/1.860	5.097 + 6	4.661 + 6
B. For Fully Reflected Core II (Assembly II-A)					
N23	2.300 + 6 ^a	2.212 + 6	1.70/1.64	3.191 + 6	3.617 + 6
N24	6.435 + 5	5.084 + 5	--	--	--
N25	5.964 + 5	5.920 + 5	1.100	6.560 + 5	6.512 + 5
N26	3.145 + 4	3.238 + 4	1.005	3.161 + 4	3.254 + 4
N27	1.451 + 4	1.474 + 4	1.000	1.451 + 4	1.474 + 4
N28	7.446 + 4	7.510 + 4	1.011	7.528 + 4	7.593 + 4
N29	5.797 + 3	6.143 + 3	1.0	5.797 + 3	6.143 + 3
N33	5.796 + 4	5.899 + 4	1.009	5.851 + 4	5.955 + 4
C. For Partially Reflected Core II (Assembly II-C)					
N42	1.024 + 6 ^a	1.026 + 6	1.196	1.225 + 6	1.227 + 6
N43	1.946 + 5	1.992 + 5	1.046/1.047	2.036 + 5	2.086 + 5
N44	2.478 + 4	2.533 + 4	1.004	2.488 + 4	2.543 + 4
N45	7.992 + 4	8.173 + 4	1.006	8.040 + 4	8.222 + 4

^aNumber is read as 1.239×10^5 .

Fig. 13. Source adjustments for SEFOR Core I partially reflected (Assembly I-P).

Fig. 14. Source adjustments for SEFOR Core II fully reflected (Assembly II-A).

Fig. 15. Source adjustments for SEFOR Core II partially reflected (Assembly II-C).

Except for Core I, the reactor effective source decay appeared to be nearly linear with time, although this could not be completely substantiated owing to considerable scatter of the data, an inconstant reactor temperature, and variable gain stability of the counting system electronics. Nonetheless, there was no difficulty in deriving the required R_s values from these data, because the time spans over which corrections were required were always relatively short, and, hence, the correction factors were never far from unity. The R_s values were determined from the following relations for Assemblies I-P, II-A, and II-C, respectively:

$$R_s = 1 - \frac{\Delta t}{223}, \quad (20)$$

$$R_s = 1 - \frac{\Delta t}{510}, \quad (21)$$

and

$$R_s = 1 - \frac{\Delta t}{740}, \quad (22)$$

where Δt is time lapse expressed in hours.

6. RESULTS AND COMPARISON OF TECHNIQUES

6.1 Extrapolation of β/Λ

Since counting loss was a serious problem in Core I and somewhat of a problem in the two configurations of Core II, β/Λ was inferred by extrapolation from several near-critical measurements. The procedure to infer β/Λ was to couple BFNA and MSM for several sets of runs. The MSM algorithm is

$$|\$| = \frac{WS}{\nu \beta (CR)}. \quad (23)$$

The ratio for two near-critical, but different $\$$ is

$$\frac{\$1}{\$2} = \frac{[CR]_2}{[CR]_1} \frac{S_1}{S_2}, \quad (24)$$

where $W/\nu\beta$ are assumed constant and cancel [see Eq. (12)].

In a similar way, the BFNA algorithm gives a ratio of breakfrequencies BF in terms of $\$2$ and $\$1$ as

$$\frac{BF_2}{BF_1} = \frac{1 - \$2}{1 - \$1}. \quad (25)$$

Solving Eq. (25) for $\$2$ and substituting $\$1$ in terms of $\$2$ from Eq. (24) results in

$$\$2 = \left[\frac{BF_2}{BF_1} - 1 \right] / \left[\frac{BF_2 [CR]_2 S_1}{BF_1 [CR]_1 S_2} - 1 \right], \quad (26)$$

and

$$\$1 = \$2 \frac{[CR]_2 S_1}{[CR]_1 S_2}. \quad (27)$$

In these expressions, all CR are assumed to be corrected for counting loss and all source terms appear as ratios which can be determined more readily than absolute values (Sect. 5.4). Once $\$2$ and $\$1$ are known, β/Λ can be determined from

$$BF = \frac{\beta}{\Lambda} (1 - \$). \quad (28)$$

The data obtained by applying Eqs. (26)–(28) to the results of partially reflected Core I, fully reflected Core II, and partially reflected Core II are shown in Table 7. The extrapolated values of $\$$ for Core I are consistent. For example, coupling run 4 with 6 and 12 gives $\$$ values of 0.82 and 0.85, respectively.

Table 7. Extrapolation of β/Λ for SEFOR cores

Run No.	Measured			Extrapolated		
	$[CR]_i$	BF_i (Hz)	S_1/S_2	BF_{crit} (Hz)	$-\beta$	Λ/β (μsec)
A. For Partially Reflected Core I (Assembly I-P) ^a						
N4	$8.102 + 5^b$	2225	1.045	1223	0.820	130.1
N6	$3.972 + 6$	1418			0.160	
N6	$3.972 + 6$	1418	1.028	1225	0.157	129.9
N7	$6.107 + 5$	2445			1.00	
N12	$5.097 + 6$	1343	0.8361	1204	0.117	132.3
N4	$8.102 + 5$	2225			0.850	
N12	$5.097 + 6$	1343	0.9455	1226	0.0957	129.8
N9	$1.097 + 6$	1802			0.470	
B. For Fully Reflected Core II (Assembly II-A) ^c						
N26	$3.161 + 4$	1498	1.014	1069	1.23	148.9
N28	$7.528 + 4$	1613			0.510	
N26	$3.161 + 4$	1498	1.0	1132	1.11	140.6
N33	$5.851 + 4$	1779			0.573	
N25	$6.560 + 5$	1174	1.0	1169	0.052	136.2
N28	$7.528 + 4$	1613			0.447	
N25	$6.560 + 5$	1174	1.0	1163	0.047	136.8
N26	$3.161 + 4$	1613			0.97	
N25	$6.560 + 5$	1174	1.0	1168	0.056	136.3
N33	$5.851 + 4$	1779			0.603	
C. For Partially Reflected Core II (Assembly II-C) ^d						
N42	$1.225 + 5$	1249	1.014	1217	0.027	130.8
N45	$8.040 + 4$	1705			0.40	
N42	$1.225 + 5$	1249	1.010	1212	0.031	131.3
N44	$2.488 + 4$	3034			1.50	

^a $(\Lambda/\beta)_{avg} = 130.5 \pm 0.6 \mu\text{sec}$, and $BF_{crit} = 1220 \pm 5.2 \text{ Hz}$.

^bNumber is read as 8.102×10^5 .

^c $(\Lambda/\beta)_{avg} = 139.8 \pm 2.2 \mu\text{sec}$, and $BF_{crit} = 1140 \pm 18 \text{ Hz}$.

^d $(\Lambda/\beta)_{avg} = 131 \pm 4.3 \mu\text{sec}$, and $BF_{crit} = 1215 \pm 37 \text{ Hz}$.

The extrapolated values of β for Core II fully reflected and partially reflected are not as consistent owing to statistics in the measurements of the breakfrequencies, thus giving rise to a larger uncertainty in the estimate of $(\Lambda/\beta)_{\text{avg}}$. However, the precision associated with $(\Lambda/\beta)_{\text{avg}}$ is sufficient in all cores for SMS evaluation. It is surprising that the β/Λ values are nearly identical for all three core configurations.

6.2 Determination of Subcriticality

6.2.1 Breakfrequency Noise Analysis

Twenty BFNA measurements of subcriticality were made in the SEFOR (seven in Core I, eight in Core II reflected, and five in Core II partially reflected). The spectra for experiments 6 and 8 from Core I are shown in Figs. 16 and 17, respectively, to illustrate the basic data.

The data from all 20 BFNA measurements were fitted to the point reactor model to obtain the various breakfrequencies (BF_i). The reference critical breakfrequency (BF_{crit}) for each core configuration was determined by the extrapolation method discussed in Sect. 6.1 (Table 7). The subcriticality was obtained from

$$(-\beta) = \frac{\text{BF}_i}{\text{BF}_{\text{crit}}} - 1, \quad (29)$$

and the standard deviation was determined by standard error propagation

$$\sigma_{\beta} = \left[\left(\frac{\sigma_{\text{crit}}}{\text{BF}_{\text{crit}}} \right)^2 + \left(\frac{\text{BF}_i}{\text{BF}_{\text{crit}}} \sigma_i \right)^2 \right]^{1/2}, \quad (30)$$

where σ_{crit} and σ_i are in Hertz units and were determined by the model-fitting procedure.

The results for each core configuration are given in Table 8. A dip in the CPSD at low frequencies and a tail at high frequencies were observed for measure-

Fig. 16. Noise spectra for Core I, Experiment 6.

Fig. 17. Noise spectra for Core I, Experiment 8.

ments having a high counting loss (Figs. 18 and 19 in the Appendix, Sect. 8.1). However, these points appear to have no effect on the CPSD near the break-frequencies.

6.2.2 Inverse Kinetics Rod Drop (IKRD)

Thirty-one rod-drop experiments were performed at SEFOR (15 in Core I partially reflected, 12 in Core II fully reflected, and 4 in Core II partially reflected). As discussed in Sect. 3, the data were recorded on paper tape for off-line analysis. From the paper tape, the data, after being checked and corrected for obvious errors, were transferred to IBM-compatible magnetic tape. Also, the data were displayed graphically as observed counts vs time.

We knew that a significant counting loss occurred in some of the experiments. However, from theoretical analysis, we concluded that the counting loss would not cause an error in the inferred initial value of subcriticality (the subcriticality prior to the rod drop), but it would cause an error in the inferred final subcriticality unless the data were corrected for the counting loss. The observed data were corrected for counting loss, using the experimental data described in Sect. 5.3.

The $\$ _i$ and $\$ _f$ were both obtained by the IKRD technique. Results that illustrate the effect of counting loss are presented in Table 9. The $\$ _f$ for a given run corresponds to the $\$ _i$ for the next run listed in the table in that they are both estimates of reactivity for the reactor at the same state. There is poor agreement for the uncorrected results but excellent agreement for the corrected results. One can note especially that the $\$ _i$ values agree whether or not the data were corrected for counting loss. Failure to make the counting loss correction (columns 1 and 2 of Table 9) leads to large systematic errors in the final reactivity estimates. The inferred $\$ _i$ is not affected by counting loss. The results obtained (after correcting for counting loss) for each core configuration for all IKRD experiments are presented in Table 10. These values of subcriticality will be compared with the results from other measurement techniques in Sect. 6.3.

Table 8. Results of BFNA subcriticality measurements in SEFOR

Core I Partially Reflected		Core II Fully Reflected		Core II Partially Reflected	
Run No.	Reactivity (-\$)	Run No.	Reactivity (-\$)	Run No.	Reactivity (-\$)
N12	0.101 $\pm$ 0.031	N23	0.031 $\pm$ 0.023	N41	0.08 $\pm$ 0.04
				N42	0.08 $\pm$ 0.04
N6	0.163 $\pm$ 0.026	N25	0.03 $\pm$ 0.04	N43	0.27 $\pm$ 0.06
				N45	0.45 $\pm$ 0.06
N9	0.478 $\pm$ 0.025	N24 ^a	0.15 $\pm$ 11.5	N44	1.56 $\pm$ 0.21
		N28	0.42 $\pm$ 0.060	N46	--
N4	0.824 $\pm$ 0.04	N33	0.561 $\pm$ 0.048	--	--
N7	1.00 $\pm$ 0.05	N26	1.09 $\pm$ 0.13	--	--
N8	2.16 $\pm$ 0.20	N27	2.75 $\pm$ 0.57	--	--
N11	4.88 $\pm$ 1.25	--	--	--	--

^aRun 24 was a special case with PHS = 60 instead of the normal PHS = 24 (see Sect. 3.1).

Table 9. Effect of counting loss on subcriticality from IKRD runs

Run No.	Without Counting Loss Corrections		With Counting Loss Corrections	
	$\$ _i$	$\$ _f$	$\$ _i$	$\$ _f$
RD3	--	0.72	--	1.08
RD4	1.06	--	1.06	--
RD7	--	1.06	--	1.14
RD8	1.12	--	1.12	--
RD9	--	1.05	--	1.13
RD10	1.15	--	1.11	--
RD14	--	0.75	--	1.09
RD15	1.10	--	1.03	--

Table 10. Results of IKRD subcriticality measurements in SEFOR

Run No.	β_i	β_f
A. For Partially Reflected Core I (Assembly I-P)		
RD1	0.179	1.03
RD2	0.179	1.08
RD3	0.180	1.08
RD4	1.06	2.26
RD5	0.58	5.90
RD6	^a	
RD7	0.59	1.14
RD8	1.12	2.31
RD9	0.58	1.13
RD10	1.11	2.30
RD11	1.90	2.58
RD12	2.81	3.41
RD13	3.70	4.40
RD14	0.18	1.09
RD15	1.03	2.19
B. For Fully Reflected Core II (Assembly II-A)		
RD16	0.06	1.14
RD17	0.06	1.15
RD18	1.16	2.56
RD19	^a	
RD20	^a	
RD21	0.46	1.08
RD22	1.06	2.39
RD23	1.88	2.80
RD24	^a	
RD25	^a	
RD26	0.561	1.10
RD27	1.11	2.46
RD28	2.40	3.61
C. For Partially Reflected Core II (Assembly II-C)		
RD29	0.181	1.46
RD30	0.444	1.46
RD31	1.21	2.09

^aNot processed.

6.2.3 Modified Source Multiplication

From Eq. (15), counting rates and subcriticality can be related for a known reactor state (subscript o) to a reactor state in question by using the form

$$\$ = R_W R_S \left(\frac{CR_o}{CR} \$ _o \right) . \quad (31)$$

The enclosed terms were measured. The ratio R_S was determined from experimental evidence (Sect. 5.4) or from knowledge of the sources inherent in any fuel movements that may have occurred between the determination of $[CR]_o$ and $[CR]_i$. The ratio R_W was determined using standard reaction physics codes (Sect. 5.1).

As indicated in Sect. 5.1, changes in W were small (< 1.04) for the entire range of experiments because the detectors had been installed at the center of the core and reflectors were controlled. However, in an LMFBR, W changes of a factor of 2 or more may be encountered.²

The results of applying this MSM algorithm to the data for Cores I and II are shown in Table 11, using both BFNA and IKRD calibrations. The subscripts on MSM indicate the number of the run to which the results were calibrated. For comparison, results are also listed for Assemblies I-P and II-C using BFNA results obtained with the reactor nearer critical; however, in general, the calibration point $\$ _o$ will be 1 to 2 dollars subcritical.

The detailed data used to generate these results are given in the Appendix, Sect. 8.1.

6.3 Comparison of Techniques

The relation between IKRD and BFNA measurements is shown in Table 12. A limited number of comparisons of IKRD and BFNA (Table 13) shows agreement within one standard deviation for all measurements. A comparison is shown for the full shutdown subcriticality, using both IKRD and BFNA to calibrate all three core configurations.

Table 11. Summary of subcriticality experimental results for SEFOR cores

Run No.	IKRD		BFNA		
	-\$	MSM ₇	-\$	MSM ₆	MSM ₇
A. For Partially Reflected Core I (Assembly I-P)					
N12		0.112	0.101	0.111	0.108
N6	--	0.164	0.163	0.163	0.158
N9	--	0.550	0.478	0.546	0.529
N4	--	0.829	0.824	0.823	0.798
N7	1.06	1.06	1.00	1.03	1.00
N8	2.27	2.20	2.16	2.19	2.12
N11	--	4.40	4.88	4.20	4.23
N1	--	5.34	--	5.29	5.13
B. For Fully Reflected Core II (Assembly II-A)					
Run No.	-\$	MSM ₂₆	-\$	MSM ₂₆	
N23	--	0.01	0.03	0.01	--
N25	--	0.054	0.03	0.05	--
N28	--	0.46	0.42	0.45	--
N33	--	0.57	0.56	0.56	--
N26	1.12	1.11	1.09	1.09	--
N27	2.47	2.40	2.75	2.36	--
N29	--	5.87	--	5.55	--
N21	--	8.77	--	8.62	--
C. For Partially Reflected Core II (Assembly II-C)					
Run No.	-\$	MSM ₄₄	-\$	MSM ₄₄	MSM ₄₅
N42	--	0.03	0.08	0.03	0.03
N41	--	0.05	0.08	0.05	0.05
N43	--	0.18	0.27	0.19	0.18
N45	--	0.45	0.45	0.48	0.45
N44	1.46	1.46	1.56	1.56	1.46
N46	--	6.93	--	7.35	6.89

^a $\Lambda/\beta = 130.5 \pm 0.6 \mu\text{sec}$, and BF = 1220 $\pm$ 5.2 Hz.

^b $\Lambda/\beta = 139.8 \pm 2.2 \mu\text{sec}$, and BF = 1140 $\pm$ 18 Hz.

^c $\Lambda/\beta = 131.1 \pm 4.3 \mu\text{sec}$, and BF = 1215 $\pm$ 37 Hz.

Table 12. Relation of IKRD to BFNA measurements

BFNA		IKRD	
Run No.	\$	Run No.	\$
A. For Partially Reflected Core I (Assembly I-P)			
N7	1.00 ± 0.05	RD1	1.03
		RD2	1.08
		RD3	1.08
		RD14	1.09
N8	2.16 ± 0.20	RD4	2.26
		RD8	2.31
		RD10	2.30
		RD15	2.19
B. For Fully Reflected Core II (Assembly II-A)			
N26	1.09 ± 0.13	RD16	1.14
		RD17	1.15
C. For Partially Reflected Core II (Assembly II-C)			
N44	1.56 ± 0.22	RD29	1.46

Table 13. Summary of experimental subcriticality results for SEFOR cores

Reactor Configuration	Measured Λ/β (μsec)	Subcriticality (\$)			
		Techniques		Full Shutdown	
		By BFNA ^a	By IKRD ^b	MSM _N ^c	MSM _{IK} ^d
Core I Partially Reflected (soft spectrum)	130.5 $\pm$ 0.6	1.00 $\pm$ 0.05 2.16 $\pm$ 0.20	1.07 $\pm$ 0.03 2.26 $\pm$ 0.05	5.13 $\pm$ 0.26	5.34 $\pm$ 0.05
Core II Fully Reflected (hard spectrum)	139.2 $\pm$ 2.2	1.09 $\pm$ 0.13 2.75 $\pm$ 0.57	1.11 $\pm$ 0.02 2.47 $\pm$ 0.04	8.62 $\pm$ 1.02	8.77 $\pm$ 0.16
Core II Partially Reflected	131.1 $\pm$ 4.3	1.56 $\pm$ 0.22	1.46 ^e	7.72 $\pm$ 1.04	6.96 ^e

^a Breakfrequency noise analysis.

^b Inverse kinetics rod drop.

^c Modified source multiplication calibrated using BFNA at $-\$1$ nominal.

^d Modified source multiplication calibrated using IK at $-\$1$ nominal.

^e A precise estimate is not available.

7. CONCLUSIONS

The major conclusions from the subcriticality measurements in SEFOR are:

1. The subcriticality monitoring system prototype performed successfully in an LMFBR-like environment. This demonstration established the engineering feasibility of such a system for application to future LMFBR's as they are presently envisioned.
2. Precise values of Λ/β were obtained for SEFOR Core I and two configurations of Core II.
3. No systematic differences were observed in a limited comparison of reactivity values inferred from IKRD and BFNA measurements.

Other conclusions from this evaluation are as follows. Detection efficiencies could be precalculated that agreed with measured results. The prompt die-away time constants for all three core configurations were nearly identical--an unexpected result because, based on intuition, we had expected greater effects from reflector and neutron energy spectrum changes. The unexpected counting loss effects on the CPSD at high and low frequencies caused no difficulty in interpreting the data. Finally, counting loss appeared to have no effect on the initial subcriticality predicted by IKRD measurements but did have a significant effect on the prediction of the final subcriticality when the data were left uncorrected.

8. APPENDIX

8.1 Tabulation of Experimental Data

Much of the experimental data used in producing the final results for this report are listed in Table 14 for Cores I and II.

The effects of high counting loss in the low-frequency and high-frequency regions of the experimental CPSD can be seen by comparing Figs. 18 and 19. In Fig. 18 where the counting loss was 15%, the frequency effects are markedly present; whereas in Fig. 19 where the counting loss is 4%, the frequency effects are not discernible.

Table 14. Data for SEFOR cores

ORNL Expt. No.	Reference in ORNL SEFOR Log	Nominal Shut- down Condition (\$)	CRM Scale Setting	Average Counting Rates (counts/sec)		Counting Loss Factor CR_L/CR_O	Corrected Counting Rates (counts/sec)		Time Dependent Source		Noise Results (Hz)		
				Channel A	Channel B		Channel A	Channel B	Time (hr)	Correction Factor	Break Frequency	σ	
A. For Partially Reflected Core I (Assembly I-P)													
1	10	Shutdown	--	1,239 + 5	1,280 + 5	1.020	1,264 + 5	1,306 + 5	9.33	0.9590	--	--	
2	11	Shutdown	--	1.23 + 5	1.28 + 5	1.020	1,255 + 5	1,306 + 5	11.08	0.9515	--	--	
3	11	-0.80	10^6	7,189 + 5	7,201 + 5	1.127	8,102 + 5	8,116 + 5	15.33	0.9336	2225	26	
4	12	-0.80	10^6	7,201 + 5	7,218 + 5	1.127	8,116 + 5	8,135 + 5	18.25	0.9215	--	--	
5 ^a	14	Critical	--	--	--	--	--	--	--	--	--	--	
6	14	-0.15	10^6	2,323 + 6	2,133 + 6	1.170	3,972 + 6	3,647 + 6	25.25	0.8930	1418	27	
7	17	-1.35	10^5	5,582 + 5	5,206 + 5	1.094/1.086	6,107 + 5	5,654 + 5	31.42	0.8686	2445	32	
8	19	-2.40	10^5	2,680 + 5	2,732 + 5	1.043/1.044	2,795 + 5	2,852 + 5	38.25	0.8424	3859	78	
9	21	-0.50	10^5	9,334 + 5	9,495 + 5	1.175/1.180	1,097 + 6	1,120 + 6	42.75	0.8256	1802	20	
10 ^b	23	-4	--	--	--	--	--	--	--	--	--	--	
11	24	--	10^5	1,290 + 5	1,324 + 5	1.020	1,316 + 5	1,350 + 5	52.0	0.7920	7175	260	
12	25	-0.10	10^6	2,607 + 6	2,506 + 6	1.955/1.860	5,097 + 6	4,661 + 6	55.25	0.7806	1343	35	
13 ^c	26	--	--	--	--	--	--	--	--	--	--	--	
B. For Fully Reflected Core II (Assembly II-A)													
21	30	Shutdown	--	White Noise	--	1.0	4,071 + 3	--	0	1.0	--	--	
22 ^d	32	Critical	10^6	2,356 + 6	2,254 + 6	--	--	--	--	--	--	--	
23	33	Critical	10^6	2,300 + 6	2,212 + 6	1.70/1.635	3,91 + 6	3,617 + 6	17.5	0.9657	1175.4	18.3	
24 ^e	35	Critical	10^6	6,435 + 5	5,084 + 5	--	--	--	20.5	0.9598	1311.0	113.6	
25	36	Critical	10^6	5,964 + 5	5,920 + 5	1.10	6,560 + 5	6,512 + 5	24.0	0.9529	1173.7	41.6	
26	38	-1.35	10^5	3,145 + 4	3,328 + 4	1.005	3,161 + 4	3,254 + 4	28.0	0.9451	2384.3	70.6	
27	39	-2.40	10^4	1,451 + 4	1,474 + 4	1.0	1,451 + 4	1,474 + 4	32.0	0.9373	4270.3	173.2	
28	39	-0.50	10^5	7,446 + 4	7,510 + 4	1.011	7,528 + 4	7,593 + 4	34.0	0.9324	1613.4	46.2	
29	43	-4	10^3	5,797 + 3	6,143 + 3	1.0	5,797 + 3	6,143 + 3	42.5	0.9167	1368.4	129.3	
30 ^f	44	--	--	--	--	--	--	--	--	--	--	--	
31 ^g	44	--	--	--	--	--	--	--	--	--	--	--	
32 ^h	44	--	--	--	--	--	--	--	--	--	--	--	
33	45	-0.50	10^5	5,796 + 4	5,899 + 4	1.009	5,851 + 4	5,955 + 4	48.5	0.9049	1779.5	33.0	
C. For Partially Reflected Core II (Assembly II-C)													
41	53	Critical	10^6	6,803 + 5	--	1.12	7,619 + 5	--	0	1.000	1310	39.6	
42	53	Critical	10^6	1,024 + 6	1,026 + 6	1.196	1,225 + 6	1,227 + 6	2.75	0.9963	1313	42.8	
43	54	Critical	10^6	1,946 + 5	1,992 + 5	1.046/1.047	2,036 + 5	2,086 + 5	7.0	0.9905	1544	50.4	
44	55	-1.40	10^5	2,478 + 4	2,533 + 4	1.004	2,488 + 4	2,543 + 4	10.0	0.9865	3108	97.5	
45	55	-0.50	10^5	7,992 + 4	8,173 + 4	1.006	8,040 + 4	8,222 + 4	13.0	0.9824	1767	42.9	
46	56	Shutdown	--	5,057 + 3	--	1.00	5,057 + 3	--	--	--	--	--	

^aDiscontinued owing to a high counting loss.^bWhite noise measurement only.^cWhite noise correction factors.^dRun discontinued owing to temperature drift.^eSpecial case where PHS = 60 instead of 24.^fWhite noise for CRM of 10^3 .^gWhite noise for CRM of 10^4 .^hWhite noise for CRM of 10^5 .

Fig. 18. Noise spectra for Core I, Experiment N8 (counting loss is 15%).

Fig. 19. Noise spectra for Core I, Experiment N9 (counting loss is 4%).

8.2 Tabulation of Computational Data

Data pertaining to number densities for SEFOR and to delayed-neutron data generation are listed in Tables 15 to 20.

Table 15. SEFOR full-size core compositions at 350°F (634 fuel rods and 14 B₄C rods)

Region	Nuclide Concentration in Regions [(Atoms/cc × 10 ²⁴)]										235 U	238 U	239 Pu	240 Pu	10 B	11 B
	Be	O	Na	Cr	Fe	Ni	Mo	Al	Mg	C						
1	3.7768-3	2.2146-2	6.8099-3	3.7929-3	1.3368-2	2.2297-3	1.1915-4	--	--	--	1.6154-5	7.3328-3	1.7260-3	1.5504-4	--	--
2	3.7768-3	2.1041-2	6.8099-3	3.7929-3	1.3368-2	2.2297-3	1.1915-4	--	--	--	1.5032-5	6.8236-3	1.6061-3	1.4429-4	--	--
2 ^a	--	--	--	3.0580-4	1.0710-3	1.7436-4	--	--	--	2.8465-4	--	--	--	--	2.2326-4	8.9661-4
3	3.7768-3	2.1170-2	6.8099-3	3.7929-3	1.3368-2	2.2297-3	1.1915-4	--	--	--	1.5144-5	6.8745-3	1.6181-3	1.4537-4	--	--
3 ^a	--	--	--	2.7522-4	9.3692-4	1.5692-4	--	--	--	2.5619-4	--	--	--	--	2.0094-4	8.0875-4
4	2.6840-3	2.1052-2	6.8099-3	3.9587-3	1.3952-2	2.3272-3	1.2436-4	--	--	--	1.6154-5	7.3328-3	1.7260-3	1.5506-4	--	--
5	2.6840-3	1.9948-2	6.8099-3	3.9587-3	1.3952-2	2.3272-3	1.2436-4	--	--	--	1.5032-5	6.8236-3	1.6061-3	1.4429-4	--	--
5 ^a	--	--	--	3.0580-4	1.0710-3	1.7436-4	--	--	--	2.8465-4	--	--	--	--	2.2326-4	8.9661-4
6	2.6840-3	2.0077-2	6.8099-3	3.9587-3	1.3592-2	2.3272-3	1.2436-4	--	--	--	1.5144-5	6.8745-3	1.6181-3	1.4537-4	--	--
6 ^a	--	--	--	2.7522-4	9.3692-4	1.5692-4	--	--	--	2.5619-4	--	--	--	--	2.0094-4	8.0875-4
7	3.7768-3	1.0742-2	6.8099-3	5.1126-3	1.7323-2	3.6254-3	1.1924-4	--	--	--	7.6230-6	3.4578-3	--	--	--	--
8	3.7768-3	1.0194-2	6.8099-3	4.9310-3	1.6719-2	3.4650-3	1.1924-4	--	--	--	7.0936-6	3.2177-3	--	--	--	--
8 ^a	--	--	--	3.0580-4	1.0710-3	1.7436-4	--	--	--	2.8465-4	--	--	--	--	2.2326-4	8.9661-4
9	3.7768-3	1.0242-2	6.8099-3	4.9492-3	1.6779-2	3.4811-3	1.1923-4	--	--	--	7.1466-6	3.2417-3	--	--	--	--
9 ^a	--	--	--	2.7522-4	9.3692-4	1.5692-4	--	--	--	2.5619-4	--	--	--	--	2.0094-4	8.0875-4
10	2.3175-4	1.8660-3	6.9576-3	3.6373-3	1.2837-2	2.1522-3	1.2014-4	--	--	--	1.7800-6	8.1126-4	--	--	--	--
10 ^b	--	--	--	--	--	3.7352-2	--	--	--	--	--	--	--	--	--	--
11	2.3175-4	1.7524-3	6.9576-3	3.6373-3	1.2837-2	2.1522-3	1.2014-4	--	--	--	1.6564-6	7.5492-4	--	--	--	--
11 ^b	--	--	--	--	--	3.7433-2	--	--	--	--	--	--	--	--	--	--
12	2.3175-4	1.7638-3	6.9576-3	3.6373-3	1.2837-2	2.1522-3	1.2014-4	--	--	--	1.6688-6	7.6059-4	--	--	--	--
12 ^b	--	--	--	--	--	3.7424-2	--	--	--	--	--	--	--	--	--	--
13	3.2470-4	1.9590-3	6.8702-3	3.9048-3	1.3748-2	2.2842-3	1.1797-4	--	--	--	1.7800-6	8.1126-4	--	--	--	--
13 ^b	--	--	--	--	--	3.6620-2	--	--	--	--	--	--	--	--	--	--
14	3.2470-4	1.8454-3	6.8702-3	3.9048-3	1.3748-2	2.2842-3	1.1797-4	--	--	--	1.6564-6	7.5492-4	--	--	--	--
14 ^b	--	--	--	--	--	3.6699-2	--	--	--	--	--	--	--	--	--	--
15	3.2470-4	1.8568-3	6.8702-3	3.9048-3	1.3748-2	2.2842-3	1.1797-4	--	--	--	1.6688-6	7.6059-4	--	--	--	--
15 ^b	--	--	--	--	--	3.6691-2	--	--	--	--	--	--	--	--	--	--
16	--	--	1.6616-2	5.3564-3	1.8373-2	2.7465-3	--	--	--	--	--	--	--	--	--	--
17	--	--	1.6616-2	2.0624-3	7.0745-3	1.0575-3	--	--	--	--	--	--	--	--	--	--
18	--	--	1.6616-2	3.1760-3	1.0894-2	1.6285-3	--	--	--	--	--	--	--	--	--	--
19	--	--	1.6900-2	4.4759-3	1.4172-2	2.3799-3	--	--	--	--	--	--	--	--	--	--
20	--	--	1.3526-2	5.9192-3	1.8825-2	3.1419-3	1.2872-4	--	--	--	--	--	--	--	--	--
21	--	--	1.4842-2	5.3140-3	1.7345-2	3.8328-3	--	--	--	--	--	--	--	--	--	--
22	--	--	--	2.7620-3	9.4740-3	1.4160-3	--	1.1270-2	5.2116-4	--	--	--	--	--	--	--
23	--	--	--	5.9730-4	2.0489-3	7.3986-2	--	2.0362-3	9.4100-5	--	--	--	--	--	--	--
24	--	--	--	2.2274-3	7.0523-3	1.1843-3	--	7.5555-3	--	6.8119-3	--	--	--	--	2.7248-2 ^c	--
25	--	--	--	2.6590-3	9.0930-3	1.3640-3	--	--	--	--	--	--	--	--	--	--

^aShielded B₄C cell.^bSelf-shielded.^cThis value is for boron, not just ¹⁰B.

Table 16. Description of delayed-neutron calculations performed

Calculation	
I.	Basic core, Be-centered clusters, stainless steel reflected, P_0S_2 calculation.
II.	Same as for I, except P_3S_6 calculation.
III.	Stainless-steel-centered clusters, stainless steel reflected, P_0S_2 calculation.
IV.	Be-centered clusters, Na filling reflector volume, P_3S_6 calculation.

Table 17. Fission fractions

Fission Fractions (f_n , fission per fission neutron)					
	<u>U-235</u>	<u>U-238</u>	<u>Pu-239</u>	<u>Pu-240</u>	<u>Total</u>
I	0.00332	0.03243	0.30124	0.00559	0.34258
II	0.00331	0.03269	0.30098	0.00560	0.34258
III	0.00320	0.03230	0.30101	0.00586	0.34237
IV	0.00313	0.03370	0.29966	0.00608	0.34257

Table 18. Delayed-neutron energy spectra

Energy Group	Delay Group				
	1	2	3	4	5 and 6
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0.0014407	0
4	0.00012228	0.0012361	0.00065058	0.023778	0.0087084
5	0.0021151	0.024959	0.015114	0.057070	0.031429
6	0.0038525	0.058473	0.053026	0.0916950	0.047851
7	0.0054487	0.066204	0.050221	0.0789340	0.039731
8	0.0067997	0.033685	0.030635	0.0681120	0.022069
9	0.0071738	0.17213	0.020937	0.0417630	0.0054477
10	0.0047280	0.010741	0.016714	0.0197660	0.0013438
11	0.0021168	0.0064887	0.0085386	0.0124400	0.0003528
12	0.00056264	0	0.00016347	0	0.000065911
13	0.000080463	0	0	0	0.0000011222
14	0	0	0	0	0
15 thru 30	0	0	0	0	0

Table 19. Delayed-neutron yields

Delayed Group	Yields ($Y_{d,n}$) ^a			
	n=1 U-235	n=2 U-238	n=3 Pu-239	n=4 Pu-240
1	0.063	0.057	0.024	0.025
2	0.354	0.603	0.176	0.240
3	0.312	0.713	0.136	0.169
4	0.676	1.707	0.207	0.308
5	0.212	0.990	0.065	0.113
6	0.043	0.330	0.022	0.025
Total	1.66	4.4	0.63	0.88

^aDelayed neutrons in nth delay group from 100 fissions of dth nuclide.

Table 20. Delayed-neutron yields for SEFOR Core I (Assembly I-P) $P_3 S_6$

Delay Group	U-235	U-238	Pu-239	Pu-240	$\frac{\sum_n \beta_{d,n}^*}{\sum_n \beta_{d,n}}$
1	0.000209 ^a 0.000182 ^b	0.001863 0.001623	0.007224 0.006293	0.000140 0.000122	0.87113
2	0.001172 0.001049	0.019712 0.017637	0.052972 0.047396	0.001344 0.001203	0.89473
3	0.001033 0.000917	0.023308 0.020700	0.040933 0.036353	0.000946 0.000840	0.88810
4	0.002238 0.002016	0.055802 0.050259	0.062303 0.056114	0.001725 0.001554	0.90067
5	0.000702 0.000640	0.032363 0.029516	0.019564 0.017843	0.000633 0.000577	0.91202
6	0.000142 0.000130	0.010788 0.009839	0.006622 0.006039	0.000140 0.000128	0.91202
Total	0.00549 0.004934	0.14384 0.12957	0.18962 0.17004	0.004928 0.004423	0.34388 0.30900

^a $\beta_{d,n}$ = neutrons in dth delayed group from nth nuclide per 100 fission neutrons.

^b $\beta_{d,n}^*$ = effective $\beta_{d,n}$.

8.3 Detector Cable Testing

The neutron detection channels in the SEFOR experiment were tested extensively in laboratory simulated LMFBR conditions. Electromagnetic noise pickup, temperature effects, and gamma effects were investigated individually.

The two detection channels were tested in the laboratory for electromagnetic noise pickup, using actuation of switches and relays as noise sources. The dual noise-shield system on the cables adequately eliminated noise pickup.

The detectors, connectors, and cables were temperature tested in an oven at 400°F for 30 days and also repeatedly thermally cycled between room temperature and 400°F. Neither pulse noise nor degradation in the neutron integral bias curves or neutron pulses (width and amplitude) that would indicate failure due to temperature effects was observed throughout the tests.

The detection channels were also tested for gamma discrimination in a neutron and gamma flux from a spent fuel element from the High Flux Isotope Reactor (HFIR). The discrimination was demonstrated to be more than adequate at 10^6 R/hr and marginal at 10^7 R/hr.

8.4 Description of Detector Assembly

An assembly for containing the two fission counters to be inserted into the SEFOR center channel was designed and built at ORNL. The assembly drawings are shown in Figs. 20-23. The following items are particularly noteworthy about the assembly:

1. All components to be in contact with the sodium were made from 300-series stainless steel.
2. A 0.275-in. -thick sleeve of lead was included to reduce the gamma flux.
3. The detectors were spring loaded within the housing to accommodate differential thermal expansion among the various materials (lead, stainless steel, aluminum, and alumina).
4. Lead shot was loaded into the rear extension pipe which housed the cables to eliminate radiation streaming effects in the pipe (the shot was partially loaded and the cables were rotated sequentially several times).

P.C. NO.	NO. REQ'D	DWG. NO.	DESCRIPTION	MATERIAL
1	1	SEFOR-101 SK	Endpiece	S. ST. 302 SS
2	1	SEFOR-101 SK	Housing	S. ST. 302 SS
3	1	SEFOR-101 SK	Rear Endpiece	S. ST. 302 SS
4	1	SEFOR-101 SK	Rear Extension	S. ST. 302 SS
5	1	—	Screw, #10-32 Round Hd. Hex. Scr. 1/2" Lg.	S. ST.
6	1	SEFOR-101 SK	Rear Cap	S. ST. 302 SS
7	1	SEFOR-101 SK	Grappling Mechanism	S. ST. 302 SS
8	1	—	Bolt, #16 NC Hex. Hd. MS. 2 1/2" Lg.	S. ST.
9	1	SEFOR-102 SK	Chamber Housing, Endcap	Alum. 6061
10	2	SEFOR-102 SK	End Shield	Alum. 6061
11	1	SEFOR-102 SK	Chamber Housing 2 Shield	S. ST. 302 SS
12	1	SEFOR-102 SK	Front Position Sleeve	Alum. 6061
13	1	SEFOR-102 SK	Rear Position Sleeve	Alum. 6061
14	1	SEFOR-102 SK	Spring	S. ST.
15	1	SEFOR-103 SK	Chamber Housing Rear Endcap	Alum. 6061
16	1	SEFOR-103 SK	Front Shot Plug	Alum. 6061
17	1	SEFOR-103 SK	Rear Shot Plug	Alum. 6061
18	3	—	Screw, #6-32 NC Round Hd. MS. 1/2" Lg.	S. ST.
19	3	—	Screw, #6-32 NC Flat Hd. MS. 1/2" Lg.	S. ST.
20	As Needed	—	Tape, Fiber Glass, Scotch-2" wide	Glass
21	As Needed	—	Shot, 1/16" dia.	Lead
22	1	—	Wire, #24 (.020" dia) 6 inches long	Nickel
23	2	—	Detectors, Reuter Stores #RSN10A-10	Alum. Can.
24	2	—	Connector, Reuter Stores #J-3127K-00	Al. M. Al ₂ O ₃
25	2	—	Cable, Santa Fe Textiles #SF38B, 15 ft.	Qs. 4. Co.
26	2	—	Braid, 1/2 inch tinned copper	Copper

NOTES:

1. Helium leak test welds using a leak detector having a minimum sensitivity of 10^{-10} standard cubic centimeter per second. There shall be no indication of leakage.
2. Rotate cables (i.e. #25) 180° while filling tube (R.#4) with shot (R.#21).

Fig. 20. SEFOR noise detector housing assembly.

Fig. 22. SEFOR noise detector housing detail sheet 2.

Fig. 23. SEFOR noise detector housing detail sheet 3.

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