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ABSTRACT

Reasonable agreement between calculated and measured differential shim rod worths in the Oak Ridge Research Reactor (ORR) has been achieved by taking into account the combined effects of negative reactivity contributions from changing fuel-moderator temperatures and of delayed photoneutrons. A method has been developed for extracting the asymptotic period from the shape of the initial portion of the measured time-dependent neutron flux profile following a positive reactivity insertion. In this region of the curve temperature-related reactivity feedback effects are negligibly small. Results obtained by applying this technique to differential shim rod worth measurements made in a wide variety of ORR cores are presented.

INTRODUCTION

At the last International Meeting on Reduced Enrichment for Research and Test Reactors I presented a paper[1] dealing with analytical methods used to support the Oak Ridge Research Reactor (ORR) Whole-Core LEU U_3Si_2-Al Fuel Demonstration. In that paper it was noted that a large discrepancy existed between measured and calculated differential shim rod worths in partially burned cores. New data, based on measurements of the time-dependent flux following shim rod displacements, has shown that the presence of photoneutrons in the ORR complicates the interpretation of reactivity measurements obtained by the positive period method. To overcome the photoneutron source effect, it was necessary to operate the ORR at a steady state power of about 3 kW prior to the positive reactivity insertion. As a result, negative reactivity feedback effects, associated with increasing temperatures during the transient, contaminate the measurement of asymptotic periods. This paper presents a method for interpreting data measured under these conditions and shows that contributions to differential worth measurements from delayed photoneutrons are also important. Finally, comparisons between calculated and measured differential rod worths are presented.

METHOD

Normally one measures reactivities by the positive period method by waiting a sufficient length of time after a reactivity insertion for transient terms to die out so that the time-dependent flux approaches a pure exponential from which the asymptotic period is determined. The

inhour equation then relates the asymptotic period to the reactivity. If the temperature of the moderator and fuel changes during the transient, however, the time-dependent flux never approaches the shape of a pure exponential. This is the situation one encounters for reactivity measurements made in the ORR.

Based on the point kinetics model, a method has been developed for extracting the asymptotic period from the initial part of the time-dependent flux profile where transient terms are present but where fuel-moderator temperature changes are still negligible. The one-energy group, space-independent, kinetic equations are

$$\frac{dn}{dt} = [k_{eff}(1-\beta)-1]\frac{n}{\ell} + \sum_{i=1}^{m} \lambda_i C_i + S$$

$$\frac{dC_i}{dt} = \frac{k_{eff}\,\beta_i\,n}{\ell} - \lambda_i C_i$$

where the symbols have their usual meaning and are defined in Ref. (2). The total effective delayed neutron fraction for m groups is $\beta = \sum_{i=1}^{m} \beta_i$ and S is the extraneous neutron source strength in neutrons/cm^3-sec. It is to be understood that in these equations β_i is the effective delayed neutron fraction $(\beta_{eff})_i$ for the ith group.

If the reactor operates at a steady state level n_o long enough to obtain saturated concentrations C_i of the delayed neutron precursors, the time-dependent flux following a step change in reactivity is given by

$$\frac{n(t)}{n_o} = \sum_{j=1}^{m+1} (A_j + B_j)e^{w_j t} + C$$

where the w_j's are the (m+1) roots of the inhour equation,

$$\rho = \frac{\ell w + w\sum_{i=1}^{m} \beta_i/(w+\lambda_i)}{1+\ell w} = \frac{k_{eff}-1}{k_{eff}},$$

and where

$$A_j = \frac{(1-\rho)\,[\ell + k_o \sum_{i=1}^{m} \beta_i/(w_j+\lambda_i)]}{\ell(1-\rho) + \sum_{i=1}^{m} \beta_i\,\lambda_i/(w_j+\lambda_i)^2}$$

$$B_j = \frac{(1-\rho)\,(1-k_o)}{w_j\,[\ell(1-\rho) + \sum_{i=1}^{m} \beta_i\,\lambda_i/(w_j+\lambda_i)^2]}$$

$$C = (1-1/\rho)\,(1-k_o).$$

Note that k_o is the initial value of k_{eff} prior to the step change in reactivity. Since at this time the reactor is in a steady state condition, $k_o < 1$ if $S > 0$. From the original kinetic equations it follows that

$$1 - k_o = \ell S/n_o .$$

The photoneutron source S builds up in a reactor due to long-lived fission product gamma activity associated with partially burned fuel elements. For measurements made in the ORR the steady state power level was large enough to have essentially infinite multiplication and thus be truly critical. Under these conditions $k_o = 1$ and so the coefficients B_j and C vanish in the above equations. The flux amplitudes A_j are normalized so that $\sum_{j=1}^{m+1} A_j = 1.0$. For positive reactivities ($\rho > 0$) all the roots of the inhour equation are negative except one whose reciprocal is the asymptotic period.

To analyze the data one begins by calculating the flux ratio $n(t_2)/n(t_1)$ from the measured flux profile where t_2 and t_1 are times after the reactivity step change. From an initial guess for the value of the asymptotic period a preliminary value for the reactivity is obtained from the inhour equation. After writing this equation in polynomial form, the subroutine ZRPOLY from the International Mathematical and Statistical Libraries, Inc. (IMSL) calculates the zeros (w_j) using the Jenkins-Traub three-stage algorithm described in Ref. 3. These values are then used in the above equations to calculate the flux ratio $n(t_2)/n(t_1)$. An iterative technique is followed whereby the value of the reactivity is adjusted until the calculated flux ratio agrees with the measured one. The asymptotic period is then just the reciprocal of the positive root corresponding to this reactivity. Using this procedure a program was developed to determine the reactivity, asymptotic period, and differential rod worth from the measured flux profile data. In principal, this method works equally well in the initial region of the flux profile where transient terms are present as well as in the asymptotic range where, if temperature changes are negligible, the time-dependent flux is a pure exponential. In practice, however, temperature changes are not negligible so that the $n(t_2)/n(t_1)$ flux ratio should be evaluated near the beginning of the profile where perturbations from changing temperatures are still very small.

In the application of this technique to the measurement of differential shim rod worths, it is important to consider factors which limit the accuracy of the method. The more important of these are discussed below.

The accuracy of the reactivity determination is limited by the statistical uncertainty with which the $n(t_2)/n(t_1)$ flux ratio is measured. The greater the period the more sensitive are the results to this error. For example, for periods in the range from 40-45 seconds, a 1% error in the flux ratio leads to about a 1.25% error in the differential worth. However, for periods in the 80-90 second range, a 1% error in the flux ratio results in about a 3% error in the differential worth. Thus, periods longer than 60 seconds should be avoided if possible. Because of the sensitivity of the results to the measured flux ratio, corrections should be applied for count losses associated with the detection equipment needed to record the time-dependent flux profile.

The analytical solution to the point kinetic equations, upon which this technique is based, assumes that the reactivity insertion is instantaneous. In practice, however, the shim rod cannot be moved instantaneously from its initial position R_i to its final position R_f. The effect of the finite time for the rod movement on the kinetic response has been addressed by C. E. Cohn (Ref. 4) who assumed that ρ varies linearly in time as the rod moves from R_i to R_f. The equivalent instantaneous step change occurs at a time $T' < 0.5\ T$, where T is the time for the rod movement. As $\rho \to 0$, $T' \to 0.5\ T$. However, the flux predicted by the equivalent instantaneous step change is always somewhat less than the actual case. For the purpose of data analysis it is usually sufficient to set $T' = 0.5\ T$. The error introduced by this assumption becomes vanishingly small for large t_1 and t_2 sampling times. However, to minimize errors from temperature-related negative feedback effects, small sampling times are needed. For $t_1 = 20.0$ sec and $t_2 = 40.0$ sec, as measured with respect to the end of the shim rod movement, the error in the differential shim rod worth due to the uncertainty in T' is about 0.6%.

Differential shim rod worths depend on the actual displacement, $R_f - R_i = \Delta R$, of the rod in question. In the ORR a digital readout system measures the rod positions to 0.01 inch. The accuracy relative to a fixed reference position is about 0.005 in. For differential worth measurements rod displacements may be as small as 0.25 inch so that these measurement errors can result in about a 3% error in the measured reactivity.

The accuracy of the reactivity obtained from the shape of the measured flux profile ultimately depends on the accuracy with which the kinetic parameters (i.e. the λ_i, β_i set) are known. These matters are discussed in the next section. Some errors in reactivity measurements due to photoneutron effects are examined in Ref. 5.

KINETIC PARAMETERS

The prompt neutron lifetime ℓ_p was calculated for several ORR core configurations using the 1/v insertion method with ^{10}B chosen as the 1/v absorber. According to this technique the reactor is uniformly poisoned with a weak concentration of ^{10}B and the corresponding eigenvalue calculated. It follows that

$$\ell_p = \frac{\delta k}{k}/N\ \sigma_{ao}\ v_o$$

where N is the ^{10}B concentration (atoms/b-cm) and σ_{ao} its neutron absorption cross section at the velocity v_o. For $v_o = 2200$m/sec, $\sigma_{ao}(^{10}B) = 3837$ barns. Strictly speaking, this equation is valid only in the limit as $N \to 0$.

Beginning with burnup-dependent cross sections, flux and adjoint distributions were calculated using the three-dimensional code, DIF3D.[6] With these distributions as input, VARI3D[7] calculations determined the effective delayed neutron fractions and corresponding decay constants for the delayed fission neutrons. The evaluated 6-family coalesced set of the kinetic parameters (λ_i, β_i) is based on ENDF/B Version V delayed neutron data. Values for the kinetic parameters determined in this manner are given in Table 1. The core configurations are described in Fig. 1.

For two of these cores the ratio of the effective delayed neutron fraction to the prompt neutron lifetime, β_{eff}/ℓ_p, was measured by J. T. Mihalczo and G. C. Regan from the Oak Ridge National Laboratory (ORNL) using a cross correlation method[8] to obtain the prompt neutron decay constant. The β_{eff}/ℓ_p C/E ratio for the water-reflected core with fresh fuel was found to be 0.9943 ± 0.0041. Since the ^{10}B 1/v insertion method provides an accurate way for calculating the prompt neutron lifetime in thermal reactors, this result suggests that delayed photoneutrons make negligible contributions for ORR cores containing only fresh fuel. However, the β_{eff}/ℓ_p C/E ratio for the 179A core, most of whose fuel had been previously irradiated for a number of weeks at 30 MW, was found to be 0.9297 ± 0.0060. Therefore, it appears that β_{eff} is undercalculated because delayed photoneutrons associated with long-lived fission product activities have not been taken into account.

Delayed photoneutrons arise from the $^9Be(\gamma,n)$ reaction in the beryllium reflector and from the $^2H(\gamma,n)$ reaction in the water moderator. Because of the years of operation of the 30 MW ORR reactor, the deuterium content in the water (from the $^1H(n,\gamma)^2H$ reaction) is considerably higher than what one might expect based only on natural abundance considerations.

The effective delayed neutron fraction, β_{eff}, may be written as

$$\beta_{eff} = \sum_{i=1}^{m} \gamma_i \beta_i (1-e^{-\lambda_i t_e}) + \sum_{j=1}^{n} \gamma_j \beta_j (1-e^{-\lambda_j t_e})$$

where the indices i and j refer to delayed fission neutrons and delayed photoneutrons, respectively. The factor $(1-e^{-\lambda t_e})$ corrects for undersaturation precursor concentrations where t_e is the time during which the reactor is maintained at a steady state power level prior to the reactivity transient. In so far as promoting fission is concerned, the effectiveness of delayed neutrons (γ_i,γ_j) is different from that of prompt neutrons. This is because the delayed neutrons have a lower average energy than prompt neutrons and so fewer of them leak out of the reactor. However, gamma energy degradation, absorption and leakage reduce the values of γ_j. For $t_e > 7$ min, the above equation may be written in the form

$$\beta_{eff} = \sum_i \beta_{eff_i} + \bar{\gamma}_p(Be) \sum_j \beta_j (1-e^{-\lambda_j t_e}) + \bar{\gamma}_p(^2H) \sum_k \beta_k (1-e^{-\lambda_k t_e})$$

Photoneutron parameters for beryllium and deuterium are taken from Ref. 9 and are shown in Table 2. Plans to measure the average effectiveness of delayed photoneutrons in beryllium, $\bar{\gamma}_p(Be)$, and in deuterium, $\bar{\gamma}_p(^2H)$, by a careful analysis of the flux dieaway curve following a rod drop measurement had to be abandoned when the ORR was permanently shut down. In the absence of experimental data, estimates for $\bar{\gamma}_p(Be)$ and $\bar{\gamma}_p(^2H)$ were obtained by requiring the average value of the C/E ratios for differential shim rod worths to be approximately unity for cores 179AX3 and 179AX4 (see Fig. 1). These two cores are nearly identical and contain previously irradiated fuel. However, 179AX3 is beryllium-reflected whereas 179AX4 is water-reflected. This analysis yielded the values $\bar{\gamma}_p(Be) \approx 0.90$ and $\bar{\gamma}_p(^2H) \approx 0.54$. Using these values for the average photoneutron effectiveness, the calculated value of β_{eff} for

the 179A core increases from 0.725% (see Table 1) to 0.792%. Consequently, the β_{eff}/ℓ_p C/E ratio for this core increases from 0.9297 ± 0.0060 to 1.014 ± 0.007.

Determinations of Differential Shim Rod Worths in the Oak Ridge Research Reactor

The detection channel used to record the time-dependent flux profiles consisted of a fission chamber (operating in the pulsed mode), a high voltage supply, a preamplifier, a delay line amplifier (for high-counting rate applications), a single-channel analyzer (for alpha count rejection), and a 1024-channel analyzer used as a multiscaler. Nearly all the data was taken with a 400 millisecond channel width. Using a double pulser, the resolving time of the detection channel was found to be about 1.5 μsec. This value was used to correct the data for counting losses.

To illustrate the effect of changing temperatures on the measured flux profiles, segments of the curve were fit by the least squares process to a pure exponential function. These segments were chosen at times well removed from the end of the rod motion so that contributions from transient terms should be negligibly small. Thus, the fit determines an asymptotic period which should be independent of time if temperature-related feedback effects are negligible. Some typical results are shown in Table 3. In all cases the asymptotic period increases with time due to negative reactivity feedback effects associated with rising temperatures. However, the rate of increase is substantially less for the high flow rate case (18000 gpm) than for the low flow rate case (1200 gpm) in core 179AX7.

It does not require much of a temperature change to noticeably alter the shape of the flux profile. The isothermal temperature coefficient was measured in core 179AX7 (see Fig. 1) by observing the change in the critical position of the B4 shim rod as the temperature of the coolant was slowly increased from 77°F to 111°F. At the beginning and end of these measurements the differential worth of the B4 shim rod was determined over this same rod displacement interval. From these measurements the isothermal temperature coefficient was found to be

$$\alpha_T = \frac{d\rho}{dT} = -(1.341 \pm 0.075)10^{-4}/°C.$$

Using this value combined with reactivities calculated from the average periods given in Table 3 for the 179A core, the temperature change between the last two time intervals is estimated to be

$$\Delta T = \frac{\rho(\tau_2) - \rho(\tau_1)}{\alpha_T} = 0.77°C.$$

This example illustrates why it is important to evaluate the $n(t_2)/n(t_1)$ flux ratio near the beginning of the flux profile in order to minimize the effects of temperature changes.

For a typical ORR core with burned fuel the initial steady state power before a differential rod worth measurement is ~3 kW. During the course of the measurement fluxes increase by factors as large as 50-75. Thus, at the end of the transient the reactor power may be as large as 200 kW so that temperatures changes in the fuel, clad and coolant are not negligible even under high flow rate (18,000 gpm) conditions.

ORR shim rids consist of a lower fuel follower section and an upper poison section. The poison section is a square water-filled cadmium annulus 0.040" thick, 2.30" on a side, and 30.5" long. Differential shim rod worths are calculated by determining the eigenvalues corresponding to the measured R_i and R_f rod positions. Thus,

$$\% \frac{\delta k}{k}/\text{in. (calc.)} = 100 \left(\frac{1}{k_i} - \frac{1}{k_f}\right)/(R_f - R_i).$$

It was shown in Ref. 10 that the cadmium control elements may be represented in diffusion calculations by blackness-modified diffusion parameters in which the cadmium absorber is black to all neutrons with energies below 0.625 eV.

It was pointed out earlier that errors associated with the determination of the $n(t_2)/n(t_1)$ flux ratio limit the accuracy of the reactivity determination. In an effort to minimize these errors, the measured flux profile, corrected for counting losses and obvious noise spikes, was fit by the least squares process to a high degree polynomial in the range over which flux ratios are to be determined. Three sets of flux ratios were evaluated at different times along this fitted curve. The three corresponding differential shim rod worths were then calculated by the methods described earlier and averaged to obtain the final result.

A typical set of data used to evaluate the differential shim rod worth is shown in Table 4. Note that delayed photoneutrons are needed to give a reasonable comparison between the measured and calculated differential worths.

Semilog plots of calculated and measured flux profiles are compared in Fig. 2 for the B4 shim rod measured under low (1200 gpm) and high (18,000 gpm) flow rate conditions in core 179AX7. The calculated curves show the influence of transient terms at the beginning and the pure exponential shape in the asymptotic region near the end of the curves. Because of the finite time required to move the shim rod from the initial to the final position, the experimental curves fall above the calculated ones. Rod movement times for the low and high flow rate cases are 11.2 and 18.8 seconds, respectively. Therefore, the measured curve is closer to the calculated one for the low flow rate case. A careful examination of the experimental curves shows that because of increasing temperatures neither curve approaches a pure exponential. These temperature effects are smallest for the high flow rate case, as would be expected. For this particular set of data the $\% \frac{\delta k}{k}$/in. C/E ratios are 0.990 ± 0.052 (1200 gpm) and 0.990 ± 0.050 (18,000 gpm). Even with very different temperature-related feedback effects, the methods described earlier give equally good differential shim rod worths.

Flux profile curves for small shim rod displacements were measured for each of the cores shown in Fig. 1. Using the methods just described, differential shim rod worths were obtained for each of these cores from a careful analysis of the shape of these curves. The results are summarized in Table 5. Generally speaking, measured and calculated differential worths are in reasonable agreement. However, the errors (1 σ) are quite large. Most of these errors result from the statistical uncertainty with which the $n(t_2)/n((t_1)$ flux ratios were measured. In most cases these flux ratio errors were in the 3-4% range. At the time of the measurements it was thought that the asymptotic periods could be obtained directly from the final portions of the flux profiles. Therefore, the detector locations were chosen so as to give good counting statistics in the asymptotic region. Because of temperature effects, however, the

initial shape of the curve becomes very important and this shape, unfortunately, was not measured as precisely as it might have been. Nevertheless, results from core 179AX6, where flux ratios were determined to a precision of about 1.5%, suggest that the method is potentially capable of measuring differential worths to an accuracy of one or two percent. For the 179AX4 core small shim rod displacements resulted in unusually large asymptotic periods (in the 70-85 sec range). Therefore, the total errors are very large (~10%) because for long periods the results are extremely sensitive to uncertainties in the flux ratios. Similar comments apply to core 179AX7 for the B6 and F4 shim rods.

CONCLUSION

In the past discrepancies between measured and calculated differential shim rod worths in the ORR were observed to be as large as 20-40% (see Ref. 1). It has now been found that these discrepancies resulted from the failure to take into account the combined effects of negative reactivity feedbacks associated with changing temperatures during positive period measurements and of contributions from delayed photoneutrons. A method, based on the point kinetic model, has been developed for extracting the reactivity from the shape of the initial portion of the measured flux profile following a positive reactivity insertion. In this region of the curve temperature-related feedback effects are negligibly small. The accuracy of the method depends mostly on the statistical precision with which the initial portion of the flux profile is measured. For long period measurements the errors are significantly amplified and, therefore, reactivity insertions should be chosen, if possible, so as to produce periods of 60 seconds or less. The measurements reported here have appreciably larger errors than might have been the case if more attention had been paid to obtaining good statistics for the early regions of the flux profile curves. For example, a very accurate flux profile could be measured with a detection channel consisting of a current chamber, an electrometer, a voltage-to-frequency converter, and a multichannel scaler.

Plans to measure an effective set of kinetic parameters, including delayed photoneutrons, by the flux dieaway method[11] following a rod drop had to be abandoned because of the early shutdown of the Oak Ridge Research Reactor. In the absence of this data, a rough estimate of delayed photoneutron effects was obtained by comparing the kinetic response of two nearly identical cores one of which was reflected with water and the other with beryllium.

By using the methods described in this paper, calculated and measured differential shim rod worths have been shown to be in reasonable agreement for 7 different ORR cores.

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Table 1. Delayed Fission Neutron Parameters

Core	ℓ_p μ-sec	Quantity	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	β_{eff}
179AX5	41.552	$\lambda_i(sec^{-1})$:	1.2722E-2	3.1743E-1	1.1619E-1	3.1146E-1	1.4002E+0	3.8751E+0	
		$(\beta_{eff})_i$:	3.0436E-4	1.6940E-3	1.4926E-3	3.2461E-3	1.0305E-3	2.1204E-4	7.9795E-3
179AX6	76.520	$\lambda_i(sec^{-1})$:	1.2722E-2	3.1743E-2	1.1617E-1	3.1142E-1	1.4002E+0	3.8746E+0	
		$(\beta_{eff})_i$:	3.0073E-4	1.6746E-3	1.4756E-3	3.2080E-3	1.0176E-4	2.0914E-4	7.8857E-3
179A	55.542	$\lambda_i(sec^{-1})$:	1.2726E-2	3.1718E-2	1.1658E-1	3.1196E-1	1.3990E+0	3.8547E+0	
		$(\beta_{eff})_i$:	2.7436E-4	1.5488E-3	1.3620E-3	2.9396E-3	9.3599E-4	1.9410E-4	7.2546E-3

Table 2. Group Constants for Delayed Photoneutrons from ^{235}U Fission Gammas on Be and D_2O*

Group Index, i	Beryllium $\lambda_i(sec^{-1})$	Beryllium $\beta_i(10^{-5})$	Deuterium $\lambda_i(sec^{-1})$	Deuterium $\beta_i(10^{-5})$
1	6.24E-7	0.057	6.26E-7	0.05
2	2.48E-6	0.038	3.63E-6	0.103
3	1.59E-5	0.260	4.37E-5	0.323
4	6.20E-5	3.20	1.17E-4	2.34
5	2.67E-4	0.36	4.38E-4	2.07
6	7.42E-4	3.68	1.50E-3	3.36
7	3.60E-3	1.85	4.81E-3	7.00
8	8.85E-3	3.66	1.69E-2	20.4
9	2.26E-2	2.07	2.77E-1	65.1
Total		15.175		100.75
Ave. Photoneutron Lifetime $= \Sigma(\beta_i/\lambda_i)/\Sigma\beta_i$:		3.33 hr.		24.1 min.

*Data taken from G. Robert Keepin, Physics of Nuclear Kinetics, Addison-Wesley (1965)

Table 3. Influence of Temperature Changes on the Asymptotic Period Calculated from Measured Flux Profiles

Core	Rod	Flow Rate, gpm	Time Interval After Rod Movement, sec Start	Stop	Period - sec
179AX5	F4	1200	60.0	120.0	70.76 ± 0.39
			120.0	180.0	75.56 ± 0.32
			180.0	213.2	82.52 ± 0.69
179AX7	B6	1200	60.0	120.0	60.70 ± 0.25
			120.0	170.0	66.34 ± 0.27
			170.0	201.6	75.86 ± 0.53
179AX7	B6	18000	60.0	120.0	85.34 ± 0.66
			120.0	180.0	88.45 ± 0.52
			180.0	246.8	91.75 ± 0.31
179A	F4	1200	60.0	120.0	63.93 ± 0.41
			120.0	180.0	68.01 ± 0.27
			180.0	230.4	78.51 ± 0.31

Table 4. Differential Worth of the D6 Shim Rod in ORR Core 179AX7

Quantity	Case 1	Case 2	Case 3
R_i - in.	12.00	12.00	12.00
R_f - in.	12.36	12.36	12.36
Flow Rate, gpm	1200	1200	1200
Period Guess, sec[1]	42.0	42.0	42.0
t_1, sec[2]	10.0	20.0	30.0
t_2, sec[2]	30.0	40.0	50.0
$n(t_2)/n(t_1)$	1.62073	1.61574	1.59461
Stat. Err. in Ratio, %	2.92	2.56	2.27
T, sec[3]	16.8	16.8	16.8
% $\delta k/k/in.$:			
Calc.	0.4287	0.4287	0.4287
Meas. no (γ,n)	0.351 ± 0.015	0.356 ± 0.015	0.353 ± 0.014
Meas. with (γ,n)	0.411 ± 0.017	0.420 ± 0.016	0.418 ± 0.017
C/E	1.043 ± 0.042	1.021 ± 0.040	1.027 ± 0.040

[1]The initial asymptotic period guess is taken as the e-unfolding time recorded with a stop watch at the time of the measurement.

[2]These times are measured with respect to the end of the rod motion.

[3]T is the time for the rod displacement from R_i to R_f.

Table 5. Differential Shim Rod Worths in the Oak Ridge Research Reactor

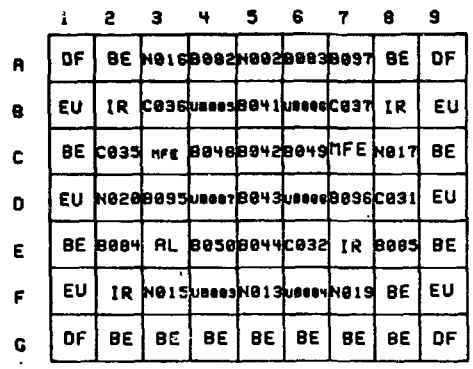
Core	Shim Rod	R_i in.	R_f in.	Flow gpm	$X \equiv \% \frac{\delta k}{k}$/in. Exp.	% Err. in X from Step	% Err. in X from $n(t_2)/n(t_1)$	Err. in ΔR	Total	C/E
179A	D4	12.00	12.38	1200	0.4002	0.59	4.80	1.86	5.18	1.089 ± 0.056
179A	D6	12.00	12.32	1200	0.4720	0.64	4.17	2.21	4.76	0.910 ± 0.043
179A	B4	12.01	12.64	1200	0.2330	0.67	6.38	1.12	6.51	1.082 ± 0.070
179A	B6	12.01	12.53	1200	0.2574	0.70	6.88	1.36	7.05	0.943 ± 0.066
179A	F4	12.01	12.80	1200	0.1500	0.85	9.10	0.90	9.18	1.084 ± 0.099
179A	F6	12.00	12.69	1200	0.1757	0.84	8.93	1.02	9.03	0.947 ± 0.085
179AX2	D4	12.00	12.37	1200	0.3856	0.58	4.34	1.91	4.77	1.063 ± 0.051
179AX2	D6	12.00	12.37	1200	0.4203	0.61	3.19	1.91	3.77	0.998 ± 0.038
179AX2	B4	12.00	12.54	1200	0.2853	0.58	3.50	1.31	3.78	0.931 ± 0.035
179AX2	B6	12.00	12.53	1200	0.2591	0.71	4.78	1.33	5.01	1.038 ± 0.052
179AX2	F4	12.00	12.86	1200	0.1392	0.80	6.05	0.82	6.16	1.077 ± 0.066
179AX2	F6	12.00	12.90	1200	0.1587	0.71	3.51	0.79	3.67	1.001 ± 0.037
179AX3	D4	12.00	12.34	1200	0.4718	0.56	3.70	2.08	4.28	0.894 ± 0.038
179AX3	D6	12.00	12.34	1200	0.4107	0.66	4.81	2.08	5.28	1.062 ± 0.056
179AX3	B4	12.00	12.56	1200	0.2671	0.67	4.71	1.26	4.92	1.050 ± 0.052
179AX3	B6	12.00	12.50	1200	0.2750	0.72	6.04	1.41	6.24	1.048 ± 0.065
179AX3	F4	12.00	12.74	1200	0.2118	0.62	3.94	0.96	4.10	1.071 ± 0.044
179AX3	F6	12.00	12.54	1200	0.2655	0.69	4.92	1.31	5.14	0.910 ± 0.047
179AX4	D4	12.00	12.27	1200	0.3717	0.71	8.42	2.62	8.85	1.033 ± 0.091
179AX4	D6	12.00	12.27	1200	0.3435	0.70	9.07	2.62	9.47	1.139 ± 0.108
179AX4	B4	12.01	12.33	1200	0.3197	0.64	8.99	2.21	9.28	0.960 ± 0.089
179AX4	B6	12.00	12.33	1200	0.3085	0.81	8.91	2.14	9.20	1.000 ± 0.092
179AX4	F4	12.01	12.75	1200	0.1310	0.42	9.61	0.96	9.67	1.070 ± 0.103
179AX4	F6	12.00	12.78	1200	0.1408	0.73	11.64	0.91	11.70	1.036 ± 0.121

Table 5. Differential Shim Rod Worths in the Oak Ridge Research Reactor (Cont.)

Core	Shim Rod	R_i in.	R_f in.	Flow gpm	$X \equiv \% \frac{\delta k}{k}$/in. Exp.	Step	% Err. in X from Err. in $n(t_2)/n(t_1)$	ΔR	Total	C/E
179AX5	D4	12.00	12.23	1200	0.5836	0.36	3.90	3.07	4.98	1.045 ± 0.052
179AX5	D6	12.00	12.19	1200	0.5809	0.56	5.81	3.72	6.92	1.054 ± 0.073
179AX5	F4	12.00	12.39	1200	0.2517	0.63	8.05	1.81	8.12	1.425 ± 0.116*
179AX5	F6	12.00	12.36	1200	0.3364	0.55	5.62	1.96	5.98	1.066 ± 0.064
179AX6	D4	12.00	12.31	1200	0.5690	0.29	0.98	2.28	2.50	1.014 ± 0.025
179AX6	D6	12.00	12.19	1200	0.5810	0.53	1.03	3.72	3.90	0.986 ± 0.038
179AX6	F4	12.00	12.31	1200	0.5438	0.32	1.18	2.28	2.59	1.044 ± 0.027
179AX6	F6	12.00	12.28	1200	0.5564	0.37	1.68	2.52	3.05	1.027 ± 0.031
179AX7	D4	12.00	12.39	1200	0.3934	0.58	3.36	1.81	3.86	1.006 ± 0.039
179AX7	D4	12.00	12.38	18,000	0.3648	0.69	4.81	1.86	5.20	1.085 ± 0.056
179AX7	D6	12.00	12.36	1200	0.4160	0.62	3.31	1.96	3.90	1.030 ± 0.040
179AX7	D6	12.00	12.33	18,000	0.4509	0.60	3.40	2.14	4.06	0.951 ± 0.039
179AX7	B4	12.00	12.52	1200	0.2511	0.61	5.10	1.36	5.31	0.978 ± 0.052
179AX7	B4	12.00	12.53	18,000	0.2543	0.79	4.90	1.33	5.14	0.966 ± 0.050
179AX7	B6	12.00	12.47	1200	0.2659	0.82	5.77	1.50	6.02	1.022 ± 0.062
179AX7	B6	12.00	12.34	18,000	0.2836	0.89	11.54	2.08	11.76	0.958 ± 0.113
179AX7	F4	12.00	12.81	1200	0.1288	0.90	8.42	0.87	8.54	1.146 ± 0.098
179AX7	F4	12.00	13.06	18,000	0.1449	0.66	3.31	0.67	3.50	1.018 ± 0.036
179AX7	F6	12.00	12.92	1200	0.1573	0.69	3.74	0.77	3.88	1.053 ± 0.041
179AX7	F6	12.00	12.80	18,000	0.1670	0.78	4.81	0.88	4.95	0.992 ± 0.049

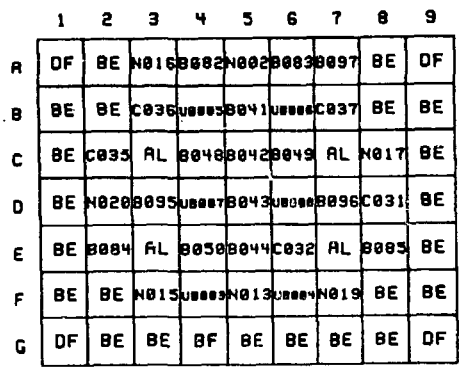
*This measurement is obviously in error. Symmetry considerations demand that the D4 and D6 and the F4 and F6 shim rods have equal differential worths in the 179AX5 core. If a recording error took place and R_f were actually 12.29 inches, the F4 and F6 shim rods would have equal C/E ratios.

Fig. 1. ORR Core Configurations



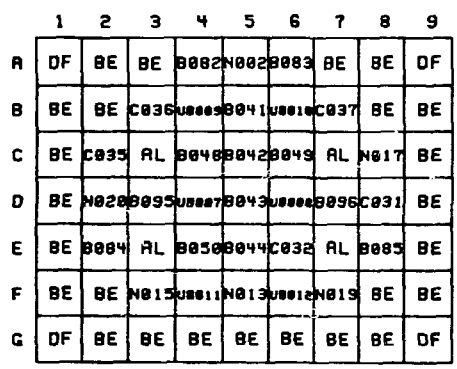
	1	2	3	4	5	6	7	8	9
A	DF	BE	N016	B082	N002	B083	B097	BE	DF
B	EU	IR	C036	UB005	B041	UB006	C037	IR	EU
C	BE	C035	MFE	B048	B042	B049	MFE	N017	BE
D	EU	N020	B095	UB007	B043	UB008	B096	C031	EU
E	BE	B084	AL	B050	B044	C032	IR	B085	BE
F	EU	IR	N015	UB009	N013	UB004	N019	BE	EU
G	DF	BE	BE	BE	BE	BE	BE	BE	DF

Core 179A. Fuel elements C035 and N017 and shim rod followers UB007 and UB008 are fresh.



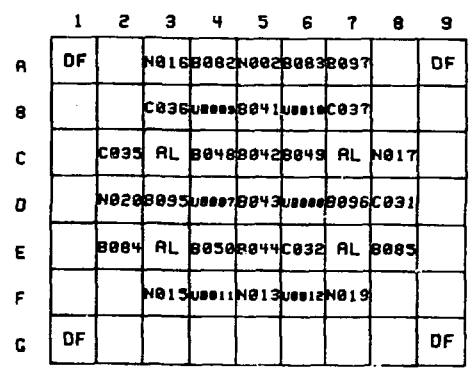
	1	2	3	4	5	6	7	8	9
A	DF	BE	N016	B082	N002	B083	B097	BE	DF
B	BE	BE	C036	UB005	B041	UB006	C037	BE	BE
C	BE	C035	AL	B048	B042	B049	AL	N017	BE
D	BE	N020	B095	UB007	B043	UB008	B096	C031	BE
E	BE	B084	AL	B050	B044	C032	AL	B085	BE
F	BE	BE	N015	UB009	N013	UB004	N019	BE	BE
G	DF	BE	BE	BF	BE	BE	BE	BE	DF

Core 179AX2. Like core 179A, but without experiments.



	1	2	3	4	5	6	7	8	9
A	DF	BE	BE	B082	N002	B083	BE	BE	DF
B	BE	BE	C036	UB005	B041	UB010	C037	BE	BE
C	BE	C035	AL	B048	B042	B049	AL	N017	BE
D	BE	N020	B095	UB007	B043	UB008	B096	C031	BE
E	BE	B084	AL	B050	B044	C032	AL	B085	BE
F	BE	BE	N015	UB011	N013	UB012	N019	BE	BE
G	DF	BE	BE	BE	BE	BE	BE	BE	DF

Core 179AX3. Beryllium-reflected core with all fresh shim rod followers.



	1	2	3	4	5	6	7	8	9
A	DF		N016	B082	N002	B083	B097		DF
B			C036	UB005	B041	UB010	C037		
C		C035	AL	B048	B042	B049	AL	N017	
D		N020	B095	UB007	B043	UB008	B096	C031	
E		B084	AL	B050	B044	C032	AL	B085	
F			N015	UB011	N013	UB012	N019		
G	DF								DF

Core 179AX4. Water-reflected core with all fresh shim rod followers.

Fig. 1. ORR Core Configurations (Cont.)

	1	2	3	4	5	6	7	8	9
A									
B									MICRO MICRO AMP
C				F	F	F			
D			F	SR	F	SR	F		
E			F	F	F	F	F		
F	FC		F	SR	F	SR	F		FC
G									

Core 179AX5. Water-reflected critical with all fresh LEU fuel.

	1	2	3	4	5	6	7	8	9
A									
B									MICRO MICRO AMP
C		BE	BE	BE	BE	BE	BE	BE	
D		BE	BE	SR	F	SR	BE	BE	
E		BE	BE	F	F	F	BE	BE	
F	FC	BE	BE	SR	F	SR	BE	BE	FC
G		BE	BE	BE	BE	BE	BE	BE	

Core 179AX6. Beryllium-reflected critical with all fresh LEU fuel.

	1	2	3	4	5	6	7	8	9
A	DF	BE	N016	B082	N002	B083	B097	BE	DF
B	BE	BE	C036	[illegible]	B041	[illegible]	C037	BE	BE
C	BE	C035	[illegible]	B048	B042	B049	AL	N017	BE
D	BE	N020	B095	[illegible]	B043	[illegible]	B096	C031	BE
E	BE	B084	AL	B050	B044	C032	AL	B085	BE
F	BE	BE	N015	[illegible]	N013	[illegible]	N019	BE	BE
G	DF	BE	BE	BE	BE	BE	BE	BE	DF

Core 179AX7. Core used for measurements under high (18,000 gpm) and low (1200 gpm) flow rate conditions.

Fig. 2

RELATIVE FLUX FOLLOWING B4 SHIM ROD MOVEMENT

ORR CORE 179-AX7