ORNL

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

ORNL-TM-605

73

EXPERIENCE WITH THE USE OF THE ROD-DROP METHOD OF ROD CALIBRATION AT THE ORR AND LITR

Frederick B. Buoni

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report. The information is not to be abstracted, reprinted or otherwise given public dissemination without the approval of the ORNL patent branch, Legal and Information Control Department.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ORNL TM- 605

Copy No.

CONTRACT NO. W-7405-ENG-26

EXPERIENCE WITH THE USE OF THE ROD-DROP METHOD OF ROD CALIBRATION AT THE ORR AND LITR

Frederick B. Buoni

DATE ISSUED

AUG 6 1963

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

CONTENTS

Page

Abstract 1

Introduction 1

Rod-Drop Method. 2

Description. 2

Equipment. 5

Experimental Data and Results. 5

Analysis of Errors 11

Conclusions. 12

Appendix A (Derivation of Rod-Drop Equations). 12

Appendix B (Delayed Neutron Tables). 15

Appendix C (Delayed Photoneutron Tables) 16

Appendix D (Detailed Calculations) 17

Appendix E (Rod-Drop Calibration Procedure). 20

References 22

EXPERIENCE WITH THE USE OF THE ROD-DROP METHOD OF ROD CALIBRATION AT THE ORR AND LITR

Frederick B. Buoni*

ABSTRACT

The rod-drop method is examined as a means of determining the shutdown worth of the LITR and ORR shim rods. The results obtained for the LITR are in close agreement with integral rod worths obtained previously by period methods. A procedure for calibration of rods which is applicable to both the LITR and ORR is given, and tables to permit rapid calculation of the shutdown Δk are presented. The method gives results reproducible to within 12% in comparing rod worths over a series of tests.

INTRODUCTION

The rod-drop method of determining shim rod reactivity worth is mentioned in several references (1, 2, 3, 4, 5, and 6). While it is known that there are severe limitations to the accuracy of this method, it was decided to investigate the possibility of using rod drops to obtain useful information about the LITR and ORR shim rods.

The rod-drop method does have several advantages over the period or distributed-poison methods of rod calibration. Firstly, it measures integral worth; and it can measure the worth of the entire rod. Secondly, it is faster. Finally, it may be done with no additional equipment or change in the instrumentation.

In spite of limitation in accuracy to be discussed later, the rod-drop method has been used to report rod worths for the Ford Nuclear Reactor, Yankee Power Reactor, and intermediate spectrum reactors and critical assemblies of the Naval Reactors program.[3,5,6] Furthermore, papers by Henry[7] and McMurry and Metcalf[4] indicate that sound theoretical basis for the method is available.

---

*On loan from Wright-Patterson Air Force Base

ROD-DROP METHOD

Description

If, when a reactor is operating at constant power, the reactor is scrammed, the power will decrease rapidly about two decades within one second and will then decrease with the characteristic delayed-neutron periods. As indicated in Appendix A, we may derive a relation between the shutdown reactivity worth of the rod scrammed and the time behavior of the power during the first minute after scramming. For reactors with fuel-follower shim rods, this relation is

$$1 - k = \frac{R\ (o)}{R\ (t)}\ f \left[\beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t} + C\beta_\gamma \sum_{j=1}^{9} \alpha_j e^{-\lambda_j t} \right] \qquad (1)$$

where: $R(o)$ = detector response at steady power.
$R(t)$ = detector response at a time, t, after dropping rod
f = fraction of total power generated in the core minus power generated in the dropped rod. This represents the fraction of delayed-neutron precursors which remains in the core.
β_{eff} = effective delayed neutron fraction
α_i = fraction of the delayed neutrons that are of the ith kind
C = effective beryllium photoneutron contribution factor
β_γ = effective delayed beryllium photoneutron fraction
α_j = fraction of the delayed beryllium photoneutrons that are of the jth kind.

The transient readings should be made after the higher modes of flux distribution have decayed and the fundamental mode persists, and before the intermediate delayed neutron groups are decayed. Times from 10 to 60 seconds are acceptable.

This method depends on the following assumptions:

1. Prior to the drop, the delayed neutron precursors are at equilibrium.
2. The space independent, one-energy group model kinetics equation for the delayed neutron precursors is applicable.
3. Source multiplication is given by

$$M = \frac{1}{1 - k} \qquad (2)$$

4. After the rod drop, the generation of delayed neutron precursors may be neglected.
5. The detector samples the same fraction of the neutron population before the drop and at a time, t, after the drop.

Assumption (1), that the delayed-neutron precursors are at equilibrium, may be assured by remaining at a steady-state condition for ten minutes before dropping a rod. This assures that the longest lived precursor is within 99.99% of its equilibrium value.

The second assumption, of using the space-independent, one-energy group kinetic equations for the delayed-neutron precursors, is sufficiently accurate for the purposes of rod-drop reactivity checks. Only the equation for the delayed-neutron precursors is used; and in this case, since the source has the spatial distribution of the delayed-neutron precursors and therefore of the power distribution, the equation is applicable.

The third assumption, that the subcritical reactor multiplies the delayed-neutron source by source multiplication $M = \frac{1}{1 - k}$, is not followed in actuality. The flux that results from $\phi = MS$, where M is given above and S is flux due to the source alone, is an asymptotic steady-state value. In this application, however, the decaying delayed neutrons and photo-neutrons are the sources; so the asyptotic value is never reached. However, in the period of time after shutdown, which we are considering, the transient behavior of the delayed neutron source should be sufficiently slow that this assumption may be accepted.

Assumption (4) is valid since within one second after the drop the flux has dropped by two decades. Thus any contribution to the delayed-neutron precursors from this time would be less than 1%.

Assumption (5) reflects the major limitation of the method. It assumes that one has identical reactors before and after the drop such that the flux the reactor sees is proportional only to the time behavior, or

$$\phi(t,\underline{r}) = \psi(t)\ \Phi(\underline{r}) \tag{3}$$

However, the insertion of the rod into the reactor does change the reactor and alters the spatial distribution of the flux.

This may be illustrated by considering that the reactor is uniformly poisoned so that it has the same flux distribution as before the reactivity change. This is illustrated in Figure 1. Now consider the case where the same power is generated by the reactor with the rod inserted. Since the power is the same, the area under the curve should be the same. This is shown in Figure 2.

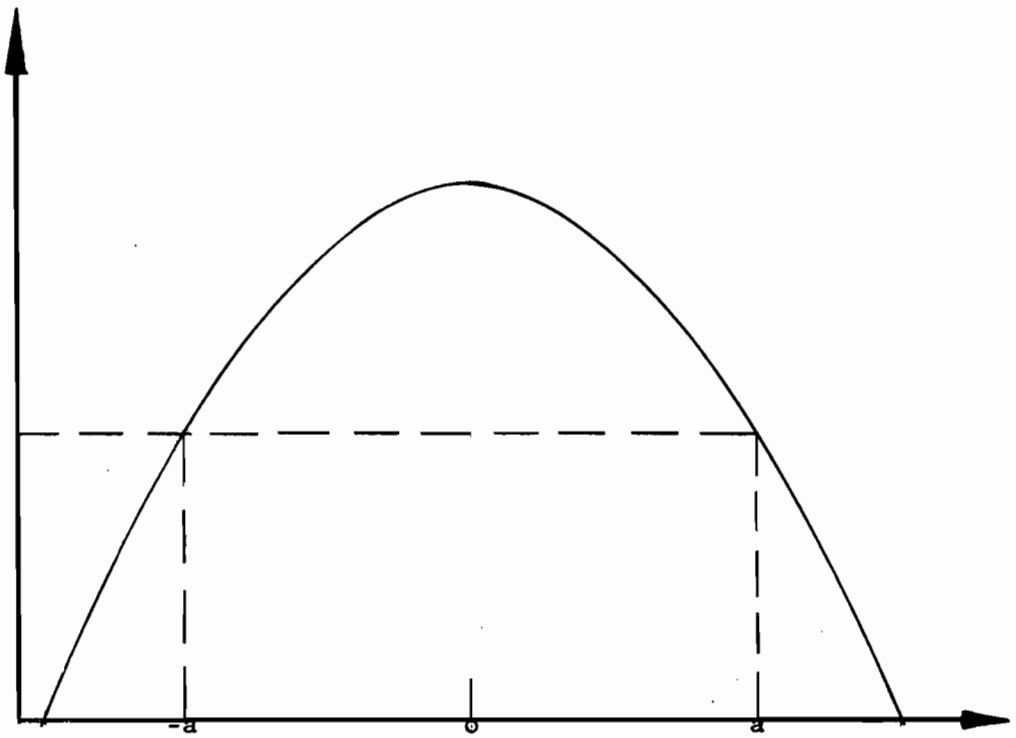


Figure 1. Flux Distribution in Uniformly Shutdown Reactor

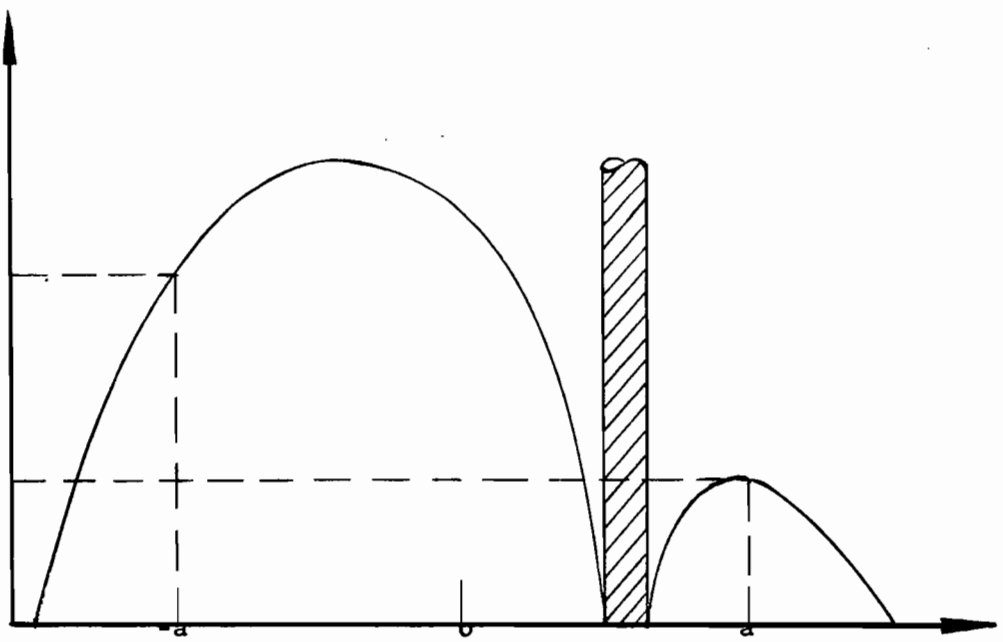


Figure 2. Flux Distribution in a Shutdown Reactor with Rod Inserted

Thus we see that a detector at (a), near the rod, sees a much smaller proportion of the neutron population than before; while the detector at (-a), far from the rod, sees a larger proportion than before. The magnitude of the error in the absolute value of the reactivity resulting from this effect cannot be determined without extensive computation of the flux distributions. From results presented later and from the literature it appears that the magnitude of this error may approach 50%. However, provided the core geometry remains the same, the results should be reporducible and thus give an indication of changes in worth between similar cores.

Equipment

Many combinations of detector, amplifier, and counting or indicating equipment may be used. For an operating reactor, it is most convenient to use the log-N channel with its compensated ionization chamber as the data source. The data at the specific times after shutdown may be obtained by either using a recorder chart speed of about 48 inches per hour or by marking the indicator position on the recorder chart at the required times. While the former is capable of greater accuracy, with care the latter will give satisfactory results.

In the tests reported below, the log-N channel with a 48-inch-per-hour recorder was used at the LITR. At the ORR, the No. 1 log-N channel with a 216-inch-per-hour recorder and the No. 2 log N marked by hand on a 2-inch-per-hour recorder were used. A discussion of the accuracies possible is given later.

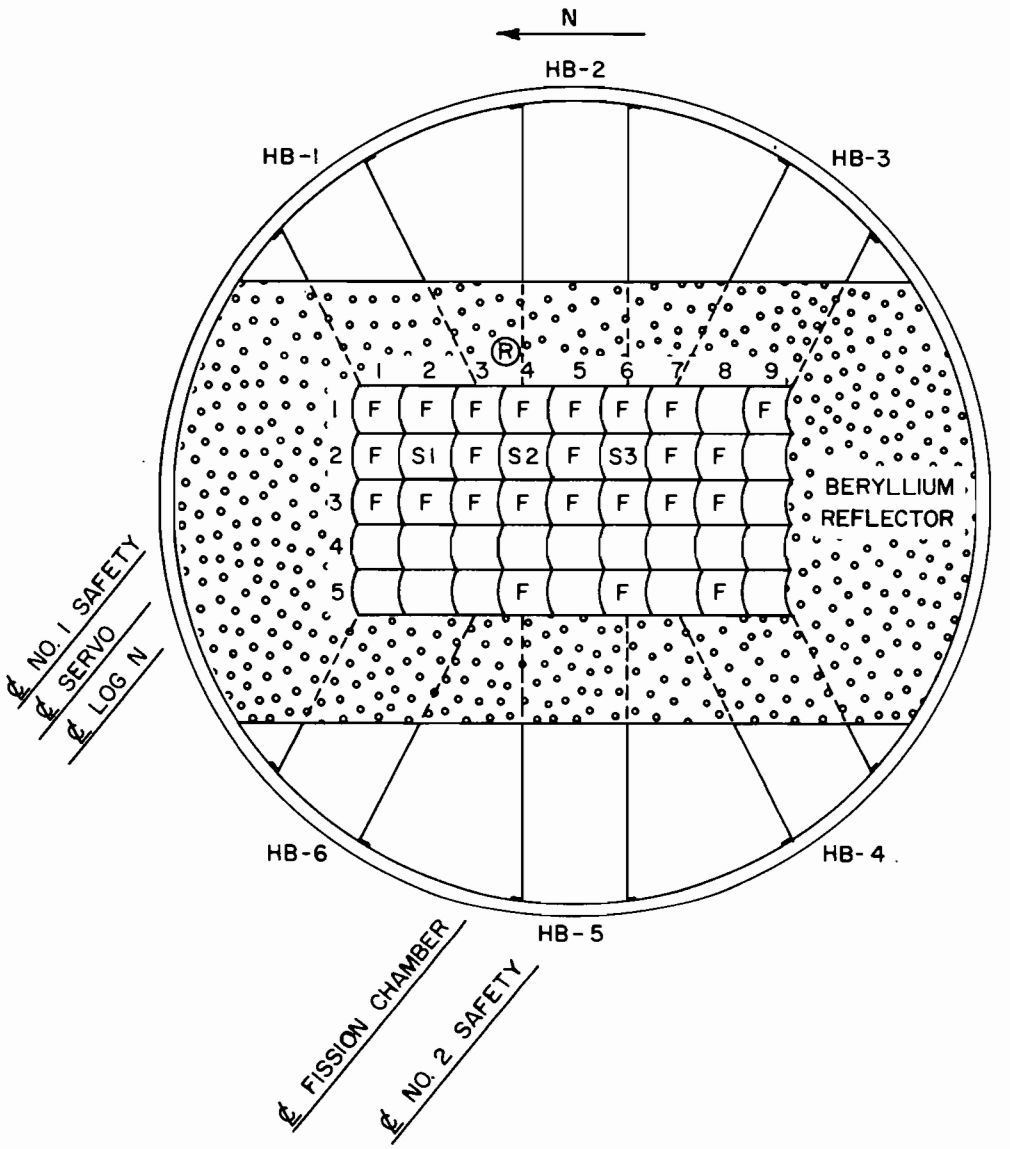
The core configurations and approximate locations of ion chambers for the LITR and ORR are shown in Figures 3 and 4, respectively.

Experimental Data and Results

A series of rod drops was carried out at the LITR and ORR. The worth of a rod was calculated using equation (1) and the data and procedures of Appendices B through E.

The results of the first series of drops at the LITR are shown in Table 1. In this table, the shutdown Δk, or 1 - k, is given. This calculation did not include any contribution from beryllium photoneutrons.

UNCLASSIFIED
O.R.N.L. DWG. 63-1967



LEGEND

F - FUEL ELEMENT (INCLUDING PARTIAL ELEMENTS)
S1, S2, & S3 - SHIM RODS
R - REGULATING ROD

Figure 3. LITR Lattice Pattern, Experiment Locations, and Approximate Ionization-Chamber Locations

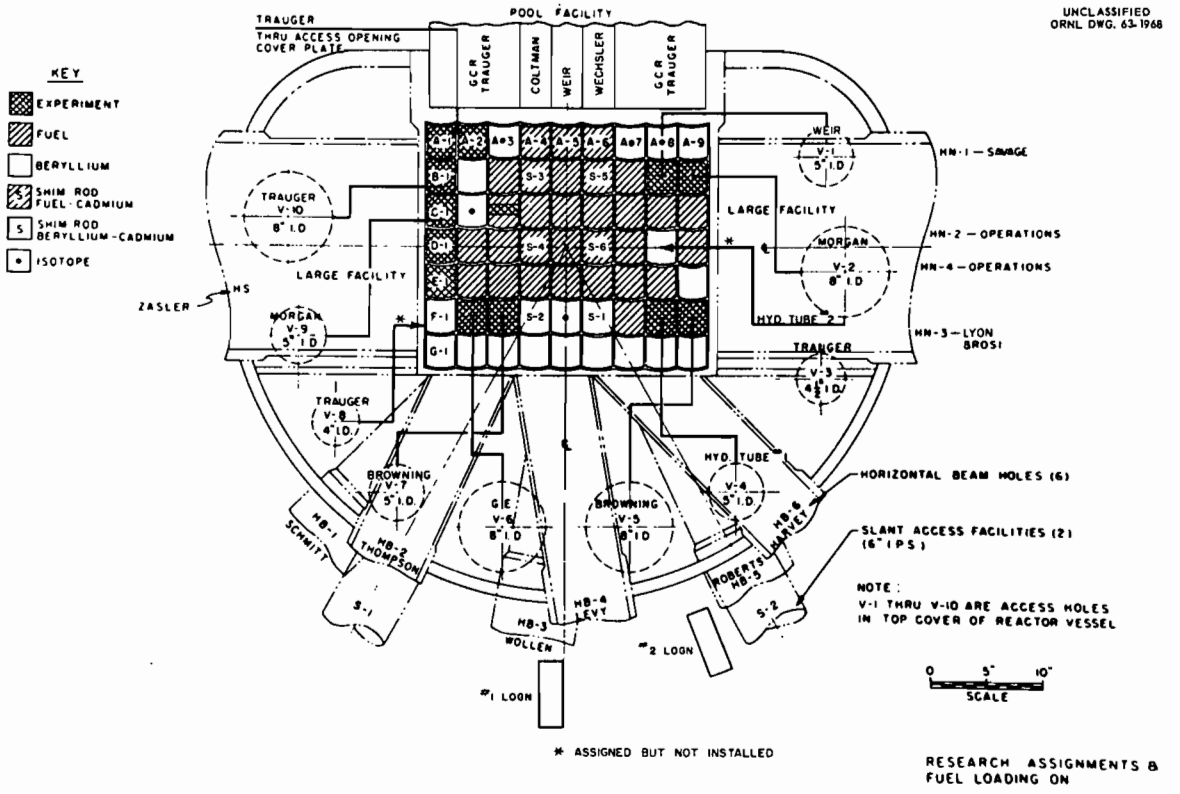


Figure 4. Research Reactor Lattice Pattern, Experiment Locations, and Approximate Log-N Chamber Positions

Table 1. LITR Shutdown Δk Calculated Without Be γ-n Correction

Rod Dropped	1 - k				
	15 sec	30 sec	45 sec	60 sec	Average
1	.0716*	.0648	.0631	.0582	.064
2**	.0611	.0558	.0544	.0510	.056
3	.0304	.0294	.0257	.0269	.028
All	.1696	.1437	.1256	.1112	.137
All	.1847	.1626	.1389	.1209	.152

* This point was taken at 20 seconds instead of 15. It is included here to show the trend.

**The No. 2 rod dropped from 23.27 inches withdrawn.

It can be seen that in the case of each rod there is a decrease in the shutdown margin as the time after shutdown increases. This was assumed to result in part from neglecting the action of photoneutrons resulting from fission product γ-n reactions in the beryllium reflector. As described in Appendix D, the contribution from these γ-n reactions was estimated, and the resulting corrected shutdown worths are given in Table 2.

Table 2. LITR Shutdown Δk Calculated With Be γ-n Correction

Rod Dropped	1 - k				
	15 sec	30 sec	45 sec	60 sec	Average
1	.0791*	.0740	.0762	.0752	.076
2**	.0664	.0638	.0658	.0659	.065
3	.0331	.0336	.0310	.0348	.033
All	.1843	.1642	.1516	.1436	.161
All	.2008	.1859	.1677	.1562	.178

* This point taken at 20 seconds after the drop.

**The No. 2 rod dropped from 23.27 inches withdrawn.

It must be remembered that changes in the spatial distribution of the flux have not been considered; and since these will be greater for drops of larger reactivity worth, it is assumed that the variation in the case of the all-rod drops is caused by this effect.

An all-rod drop was repeated two weeks later after refueling. With the No. 2 rod at 19.74 inches and the No. 1 and No. 3 at the upper limit, a Δk of .161 was obtained as compared to the .161 and .178 obtained when the No. 2 rod was at 22.25 and 24.00 inches respectively and the No. 1 and No. 3 were at the upper limit. This indicates a good degree of reproducibility.

At the end of the March 10th long shutdown of the ORR, a series of rod-drop checks were made. Here the reactor was at N_L, 300 kw, for the individual rod drops, and at 5 Mw for the all-rod drop. An opportunity to obtain a drop from 30 Mw arose later in the cycle. The results are given in Table 3 and show a comparison of results obtained from the No. 1 and No. 2 log N channels. A correction for beryllium γ-n reactions is included.

Table 3. ORR Rod-Drop Rod Worths

	No Beryllium Correction % $\Delta k/k$			With Beryllium Correction % $\Delta k/k$		
Rod	No. 1 Log N	No. 2 log N	Average	No. 1 log N	No. 2 log N	Average
1&2		5.5	5.5		5.9	5.9
3	3.1	2.8	3.0	3.3	3.0	3.2
4	9.0	7.5	8.3	9.7	8.0	8.9
5	3.1	2.9	3.0	3.3	3.1	3.2
6	10.7	9.7	10.2	11.5	10.3	10.9
All*	27.9	22.4	25.2	30.4	24.3	27.3
All**	40.8	38.1	39.5	44.7	41.6	43.2

* Power at 5 Mw; No. 1 and 2 at upper limit; No. 3, 4, 5, and 6 at 14.84 inches withdrawn.

**Power at 30 Mw; No. 1 and 2 at upper limit; No. 3, 4, 5, and 6 at 20.13 inches withdrawn.

Here the spatial distribution effect is shown in two ways. First, the No. 2 log N results are consistently lower than the No. 1 log N values. Since these chambers see the core from different positions, the spatial variation of the flux after a drop would not be expected to be the same for both chamber locations. Secondly, the values of rods No. 3 and No. 5, on the side of the core away from the chambers, are much less than the estimated worth of the rods. The results for the other rods are close to that expected.

The only comparison between the rod-drop and period measurements was made at the LITR with rod No. 3. As shown in Table 4, the agreement is quite close.

Table 4. Comparison of LITR Shim Rod No. 3 Worth by Period and Rod-Drop Methods

	% $\Delta k/k$	
	Rod-Drop	Period
Al-Cd Rod in No. 3	3.4	3.4
U-Cd Rod in No. 3	3.5	4.0

In the case of rods of small worths the agreement should be better than with heavier rods, since there is likely to be less drastic disturbance of the spatial distribution.

At the ORR, the only previous calibration for rods 3, 4, 5, and 6 was made at the time of initial startup by the distributed poison method (Reference 8). A comparison of results is presented in Table 5 but should be considered qualitatively, since the original work was done with a clean cold core with only mock-ups of experiments installed.

Table 5. Comparison of Rod-Drop and Distributed-Poison Calibrations at the ORR

Rod	% $\Delta k/k$ Rod-Drop 1963	% $\Delta k/k$ Distributed-Poison 1958*
3	3.2	5.84
4	8.9	10.37
5	3.2	6.70
6	10.9	10.35

*C. D. Cagle and R. A. Costner, Jr., Initial Post-Neutron Measurements in the ORR, ORNL 2559, 1958.

Analysis of Errors

The four main sources of error in this method are: (1) errors in reading the charts and determining the time after the rod drop, (2) errors in the power factor used for cores with fuel-follower rods, (3) errors in the delayed-neutron and photoneutron constants, and (4) errors due to flux distribution changes caused by the inserted rod.

While all four of the above types of errors affect the value of rod worth obtained, only the first would affect a series of comparative readings. Thus the first would affect the reproducibility of the method.

The error in reading the charts to determine $\frac{R(o)}{R(t)}$ has been determined to be 6%, while the error due to an uncertainty of 2 seconds in the time after shutdown is 6%. Thus the error in reproducibility should be within 12%.

The error introduced by the uncertainty in the fraction of the power generated in the core minus the dropped rod is less than 1%.

In the calculation of the rod worth by use of this method, an error of 10% is due to uncertainty in the effective delayed-neutron fraction, 4% from the uncertainty in the fraction of delayed neutrons that are of the ith kind, and 2% from the uncertainty in the decay constants of the delayed-neutron precursors.

Thus a total estimated error of 29% is obtained, while reproducibility should be within 12%. As mentioned above, no reliable estimate can be made of the effect of the error due to changes in the spatial distribution of the neutron flux.

CONCLUSIONS

Since the rod-drop method quickly and with no additional equipment can determine a rod worth reproducible to within 12%, it follows that the method may be used as a tool to compare reactivity values of a rod over a period of time or under slightly varying core conditions.

If inaccuracy of greater than 30% can be tolerated, this method may be used to determine the rod worth. This may be of value if other means are not feasible or worth the time and effort necessary to obtain greater accuracy.

A procedure which may be used to calibrate rods by this method, and the numerical values needed for calculation of the rod worth, are provided in Appendix E.

The author wishes to acknowledge the invaluable assistance of Mr. A. L. Colomb for providing considerable guidance in conducting this investigation.

APPENDIX A

Derivation of Rod-Drop Equations

A reactor, immediately after the drop of a rod, is assumed to subcritical. Thus, consider that the neutron generation rate is equal to a source multiplied by a subcritical multiplication factor. Thus,

$$R(t) = M\,S(t) \tag{A.1}$$

where $M = \frac{1}{1 - k}$

If the reactor is shut down from power operation, the source will be the delayed neutrons from the decay of the delayed neutron precursors.

$$S(t) = \sum_i \lambda_i C_i(t) \tag{A.2}$$

where $C_i(t)$ = concentration of delayed neutron precursors of the ith kind,
λ_i = decay constant of the delayed-neutron precursor of the ith kind.

The kinetics equations of the neutron population are usually given as

$$\frac{dN(t)}{dt} = [k(1 - \beta_{eff}) - 1]\,\frac{N(t)}{} + \sum_i \lambda_i C_i(t) \tag{A.3}$$

$$\frac{dC_i(t)}{dt} = k\beta_i\,\frac{N(t)}{} - \lambda_i C_i(t) \tag{A.4}$$

Thus if the neutron generation is given by

$$R(t) = \frac{kN(t)}{}\,, \tag{A.5}$$

at steady state equation (A.4) becomes

$$\beta_i\,R(o) = \lambda_i C_i(o) \tag{A.6}$$

If we neglect the production of delayed-neutron precursors after shutdown, a contribution less than 1%, then

$$C_i(t) = C_i(o)e^{-\lambda_i t} \tag{A.7}$$

Using equations (A.2), (A.6), and (A.7) in equation (A.1) gives

$$R(t) = \frac{i}{1 - k}\sum_i R(o)\beta_i e^{-\lambda_i t}, \text{ or}$$

$$1 - k = \frac{R(o)}{R(t)}\,\beta_{eff}\sum_i \alpha_i e^{-\lambda_i t}, \text{ where} \tag{A.8}$$

$$\alpha_i = \frac{\beta_i}{\beta}$$

There is, however, an additional source in beryllium-reflected reactors such as the ORR and LITR. The gamma rays emitted from the fission products form photoneutrons by a γ-n reaction with beryllium. This effect can be considered to affect the reactor in the same manner as the delayed neutrons.

One additional effect introduced by the use of fuel-follower shim rods is that a portion of the delayed-neutron source is removed from the reactor when a rod is dropped. This effect is represented by including a factor, f, which represents the fraction of the total power of the reactor that is generated in the entire core minus the dropped rod.

With the inclusion of the latter two effects, equation (A.8) becomes

$$1 - k = \frac{R(o)}{R(t)} f \left[\beta_{eff} \sum_i \alpha_i e^{-\lambda_i t} + \beta_\gamma \sum_j \alpha_j e^{-\lambda_j t} \right] \qquad (A.9)$$

APPENDIX B

Delayed Neutron Tables

The delayed neutron data used in these calculations are given in Table B.1.

Table B.1. Delayed Neutron Data

Precursor Type	Decay Constant	Relative Abundance
i	λ_i (sec $^{-1}$)	α_i
1	0.0127 ± 0.0002	0.039 ± 0.003
2	0.0317 ± 0.0008	0.213 ± 0.005
3	0.115 ± 0.003	0.188 ± 0.016
4	0.311 ± 0.008	0.407 ± 0.007
5	1.40 ± 0.081	0.128 ± 0.008
6	3.87 ± 0.369	0.026 ± 0.003

The values of $\alpha_i e^{-\lambda_i t}$ were calculated, and the values of $\beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t}$ for time, t, of 15, 30, 45, and 60 seconds are given in Table 2 for β = .0080.

Table B.2. Delayed Neutron Contributions

Time t (sec)	$\sum_{i=1}^{6} \alpha_i e^{-\lambda_i t}$	$\beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t}$
		(x 10^{-3})
15	.2011	1.609
30	.1143	.9144
45	.0738	.5904
60	.0497	.3976

APPENDIX C

Delayed Photoneutron Tables

The photoneutron data used in these calculations are given in Table C.1.

Table C.1. Delayed Photoneutrons from Beryllium

Group Index	Decay Constant	Group Fraction	Relative Abundance
j	λ_j (sec^{-1})	β_j (x 10^{-5})	α_j
1	6.24×10^{-7}	0.057	.0038
2	2.48×10^{-6}	0.038	.0025
3	1.59×10^{-5}	0.260	.0171
4	6.20×10^{-5}	3.20	.211
5	2.67×10^{-4}	0.36	.0248
6	7.42×10^{-4}	3.68	.242
7	3.60×10^{-3}	1.85	.122
8	8.85×10^{-3}	3.66	.136
9	2.26×10^{-2}	2.07	.136
	Total	15.175×10^{-5}	

The values of $\alpha_j e^{-\lambda_j t}$ were calculated, and the values of $\beta\gamma \sum_{i=1}^{9} \alpha_j e^{-\lambda_j t}$ for times, t, of 15, 30, 45, and 60 seconds are given in Table C.2. where $\beta\gamma = 15.18 \times 10^{-5}$.

Table C.2. Delayed Photoneutron Contribution

Time t (sec)	$\sum_{j=1}^{9} \alpha_j e^{-\lambda_j t}$	$\beta\gamma \sum_{j=1}^{9} \alpha_j e^{-\lambda_j t}$
		(x 10^{-5})
15	.9220	14.00
30	.8598	13.05
45	.8080	12.27
60	.7654	11.62

APPENDIX D

Detailed Calculations

The calculation of 1 - k using equation (A.9) is quite straightforward. If one considers first only the delayed neutron effect,

$$1 - k = \frac{R(o)}{R(t)} f \beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t} , \qquad (D.1)$$

values for the drop of the LITR No. 2 shim rod are shown in Table D.1.

Table D.1. Computation of 1 - k for LITR No. 2 Shim Rod

Time After Drop (sec)	R(t)	$\frac{R(o)}{R(t)}$	$\frac{R(o)}{R(t)}f$	$\beta_{eff} \sum_i \alpha_i e^{-\lambda_i t}$	1 - k
				x 10^{-4}	x 10^{-2}
0	101				
15	2.6	38.8	37.9	16.088	6.11
30	1.62	62.4	61.0	9.144	5.58
45	1.08	94.3	92.2	5.904	5.44
60	.77	131	128	3.976	5.10

For this rod f is .978.

It can be seen from Table D.1. that the value of Δk decreases as the time after the drop increases. Also obvious is that $\frac{R(o)}{R(t)}$ is an increasing function of the time. It, therefore, seems apparent that another effect is operating--the beryllium photoneutrons. Since the magnitude of the effect of the photoneutrons is unknown, equation (A.9) can be rewritten

$$1 - k = \frac{R(o)}{R(t)} f \left[\beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t} + C \beta_\gamma \sum_{j=1}^{9} \alpha_j e^{-\lambda_j t} \right] \qquad (D.2)$$

where C is a constant denoting the effective importance of the photoneutrons. This may then be considered in the form

$$K = A_t + C B_t \qquad (D.3)$$

where $K = 1 - k$

$$A_t = \frac{R(o)}{R(t)} f \, \beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t}$$

$$B_t = \frac{R(o)}{R(t)} f \, \beta_\gamma \sum_{i=1}^{9} \alpha_j e^{-\lambda_j t}$$

Rearranging this gives

$$A_t = K - C \, B_t \tag{D.4}$$

Using computed values for A_t, B_t, and K, the least squares method may be applied to obtain C which would minimize the deviation in K. This is given by

$$C = \frac{(\Sigma A_t)(\Sigma B_t) - 4\Sigma A_t B_t}{4 \Sigma B_t^2 - (\Sigma B_t)^2} \tag{D.5}$$

Using this method to determine an effective photoneutron factor for each rod drop for the LITR gives the results

Rod	C
1	1.2
2	.97
3	.75
All	2.9

Since this is seen to vary with the magnitude of the Δk worth of the rod, it is apparent that the spatial distribution effect is also involved. However, since the average value of C for the small reactivity drops is about 1, this figure is adopted for use at the LITR.

At the ORR the value of C obtained did not appear to vary with the Δk of the rod, but varied about an average of .37 ± .03. These values of an effective photoneutron factor are used in all the calculations. A comparison of values for the LITR No. 2 shim rod and ORR No. 4 shim rod, using No. 1 log N data for computation with and without the photoneutron correction, are given in Tables D.2. and D.3.

Table D.2. Comparison of Δk Worth of LITR No. 2 Shim Rod With and Without Photoneutron Correction

Time After Drop (sec)	1 - k (x 10^{-2}) No Be γ-n Correction	1 - k (x 10^{-2}) With C = 1.0 Be γ-n Correction
15	6.11	6.64
30	5.58	6.38
45	5.44	6.58
60	5.10	6.59
Average	5.56	6.55

Table D.3. Comparison of Δk Worth of ORR No. 4 Shim Rod With and Without Photoneutron Correction

Time After Drop (sec)	1 - k (x 10^{-2}) No Be γ-n Correction	1 - k (x 10^{-2}) With C = .37 Be γ-n Correction
15	8.58	8.86
30	8.42	8.87
45	8.11	8.74
60	8.06	8.93
Average	8.29	8.85

APPENDIX E

Rod-Drop Calibration Procedure

1. Preparation
   a. Either connect a fast speed (48 to 72 inch per hour) recorder to the log-N channel or prepare to mark the log-N chart to obtain the readings at the specified times after the rod drop.
   b. Operate at a steady power and with as little rod movement as possible for more than 15 minutes.
2. Rod Drop
   a. At the specified time, drop the rod either by reducing magnet current or by opening the lead from the Sigma Bus to the magnet amplifier. All rods may be dropped by any normal scramming action.
   b. At 15, 30, 45, and 60 seconds after the drop, mark the power level on the log-N recorder.
3. Calculation
   a. For each of the periods after the drop, form the ratio $\frac{R(o)}{R(t)}$.
   b. Obtain the factor, f, for the rod dropped. This is equal to one minus the burnup factor of the rod or rods dropped.
   c. Determine the factor

$$T(t) \equiv \beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t} + C\, \beta_\gamma \sum_{j=1}^{9} \alpha_j e^{-\lambda_j t}$$

   for each time after drop for the reactor concerned. These values are given in Table E.1., where C = .37 is applicable for the ORR and C = 1.0 is applicable for the LITR. The use of C = 0 gives conservative results by not including any additional contribution due to beryllium photoneutrons.

Table E.1. Values of $T(t) \equiv \beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t} + C\, \beta_\gamma \sum_{j=1}^{9} \alpha_j e^{-\lambda_j t}$

Time After Rod Drop (sec)	$T(t) = \beta_{eff} \sum_{i=1}^{6} \alpha_i e^{-\lambda_i t} + C\, \beta_\gamma \sum_{j=1}^{9} \alpha_j e^{-\lambda_j t}$		
	C = 0	C = .37	C = 1.0
	(x 10^{-4})	(x 10^{-4})	(x 10^{-4})
15	16.088	16.605	17.487
30	9.144	9.627	10.449
45	5.904	6.358	7.130
60	3.976	4.406	5.137

d. To obtain 1 - k for each time interval, multiply the three numbers determined above.

$$1 - k = \left[\frac{R(o)}{R(t)} \right] \left[f \right] \left[T(t) \right]$$

e. Average the values of 1 - k obtained for the various times.

f. Determine the reactivity worth of the rod in % $\Delta k/k$ as follows:

$$\% \frac{\Delta k}{k} = \frac{(1 - k)}{1 - (1 - k)} \times 10^2$$

REFERENCES

1. W. C. Ballowe et al., Intercomparison Measurements, GEAP-3639, January 18, 1961.

2. W. A. Clark, Measurement of Rod Strengths by Analysis of Scram Transients, HW-23353, 1952.

3. J. M. Gallaher, Jr., et al., The Startup Experiment Program for the Yankee Reactor, YAEC-184, June, 1961.

4. H. L. McMurry and D. R. Metcalf, Measurement of Reactivity in Thermal Reactors, IDO-16709, 1960.

5. J. L. Shapiro et al., Initial Calibration of the Ford Nuclear Reactor, MMPP-110-1, June, 1958.

6. J. R. Stehn (ed.), Naval Reactors Physics Handbook III, USAEC (1958).

7. A. F. Henry, Nuclear Science and Engineering 3, pp 52-70 (1958).

8. C. D. Cagle and R. A. Costner, Jr., Initial Post-Neutron Measurements in the ORR, ORNL-2559, 1958.

9. G. R. Keepin, Nucleonics 20 (8), August, 1962.

DISTRIBUTION

1. F. T. Binford
2. H. Blauer
3-12. F. B. Buoni, Wright-Patterson Air Force Base
13. C. D. Cagle
14. W. R. Casto
15. A. L. Colomb
16. B. L. Corbett
17. R. A. Costner, Jr.
18-37. J. A. Cox
38. E. N. Cramer
39. W. H. Culbert
40. C. B. Gaither
41. L. A. Haack
42-46. T. P. Hamrick
47. W. A. Hartman
48. S. S. Hurt, III
49-53. H. V. Klaus
54. R. V. McCord
55. K. H. Poteet
56. E. F. Roy
57. R. L. Scott, Jr.
58. T. M. Sims
59. L. E. Stanford
60. R. S. Stone
61. C. A. Sweet
62. W. H. Tabor
63. C. C. Webster
64. R. C. Weir
65. K. W. West
66-67. Central Research Library
68-69. Document Reference Section
70-72. Laboratory Records Department
73. Laboratory Records Department (ORNL-RC)
74. ORNL Patent Office
75-89. Division of Technical Information Extension
90. Research and Development Division (ORO)