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SHUTDOWN REACTIVITY BY THE MODIFIED ROD DROP METHOD

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SUMMARY

A reasonable value of shutdown reactivity available from control rods can be measured by the "Rod Drop" method. The procedure outlined here is not as simple nor fast as the classic "prompt drop" experiment, but it is considerably more accurate. Corrections due to flux shape changes can be applied to the measurements and the use of pretimed scram equipment makes reproducibility excellent. A further refinement also takes into account finite rod drop times. Results are presented for ARMF-II and ETRC.

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SHUTDOWN REACTIVITY BY THE MODIFIED ROD DROP METHOD

I. INTRODUCTION

Safety considerations require a reasonable estimate of the shutdown reactivity available from control rods. This knowledge is as important in normal reactor operations as it is during an initial startup.

Accuracy in these measurements is usually obtained at the expense of speed. For instance a period or distributed poison calibration over the total length of the safety rods can consume several days of operating time. On the opposite extreme, a scram measurement of the "prompt drop" effect is very quick but lacks accuracy and reproducibility if the data is simply a trace on a log N recorder. All of the methods for measuring shutdown k are based upon one or more simplifying assumptions for which the most important is that the relative neutron flux shape remains constant throughout the experiment. In reality this is never obtained. Local shading by poisons, location of the detecting chamber, type and location of the safety rods are important. These effects account for a great deal of the disparity between different methods of measuring shutdown k .

A "Modified Rod Drop Experiment", developed by Milani⁽¹⁾, was used as the basis for the shutdown k measurement in the ARMF. The design of the experiment using accurately timed and fast response equipment greatly increases the reproducibility between rod drops.

Essentially, the experimental system consists of a fission chamber, scaler, printer and an automatic pre-set scrambling device. The "prompt drop" is not measured but rather the integral of the flux-time curve after the scram is recorded. The scaler operates with an ON-OFF cycle where the counts accumulated during the ON portion of the cycle are printed during the OFF period.

Typical cycle times are: 5 seconds on, 2 seconds off; 10 on, 1 off; or any reasonable and convenient combination (see Figure 1). All important data are recorded in the first 30 seconds following the scram. Therefore, to obtain at least two data points, the total cycle time should not exceed 15 seconds.

For good data reproducibility, the scram must be initiated automatically with respect to the scaler-printer cycle. To accomplish this, a scram relay was tied into the scaler-printer. When activated during a count cycle, the relay operated off the signal generated in the

Figure 1
Flux vs Time Sketch for Rod Drop Measurements

scaler-printer at the beginning of the next print cycle. Thus, at the beginning of a print cycle, the scram signal is developed and the rods drop. The rod drop time must, in all cases, be less than the print cycle time, otherwise data will be recorded while the rods are moving. If the rods are assumed to be inserted step-wise, the actual drop time must be much less than the print cycle.

Converting the recorded data to Δk values can be accomplished by using calculated tables of relative counts vs Δk . These theoretical tables are computed from the space independent reactor kinetics equations.

II. KINETIC THEORY

The standard space independent reactor kinetics equations are

$$\frac{dn}{dt} = \frac{k(1-\beta)-1}{l} n + \sum \lambda_i C_i \quad (1)$$

$$\frac{dC_i}{dt} + \lambda_i C_i = \frac{k\beta_i}{l} n, \quad i = 1, 2, 3, \dots, 6 \quad (2)$$

where n = neutron density (or power)
 k = effective neutron multiplication factor
 l = prompt neutron lifetime
 C_i = concentration of the i th delayed neutron precursor
 β_i = effective delayed neutron fraction
 λ_i = decay constant of the i th type.

If the neutron multiplication factor is assumed to change step-wise from an initial critical system ($k = 1$) then by Laplace transforms we have

$$\frac{n(s)}{n(0)} = \frac{1 + \frac{1}{l} \sum_{i=1}^6 \frac{\beta_i}{s + \lambda_i}}{s \left[1 + \frac{k}{l} \sum_{i=1}^6 \frac{\beta_i}{s + \lambda_i} \right] - \frac{k-1}{l}} \quad (3)$$

The time solution can be written as

$$\frac{n(t)}{n(0)} = \sum_{j=1}^7 A_j e^{\alpha_j t} \quad (4)$$

where α_j are the roots of

$$s \left[1 + \frac{k}{l} \sum_{i=1}^6 \frac{\beta_i}{s + \lambda_i} \right] - \frac{k-1}{l} = 0 \quad (5)$$

and the A_j are the residues,

$$A_j = \frac{\left[1 + \frac{1}{l} \sum_{i=1}^6 \frac{\beta_i}{s + \lambda_i} \right]}{\frac{d}{ds} \left\{ s \left[1 + \frac{k}{l} \sum_{i=1}^6 \frac{\beta_i}{s + \lambda_i} \right] - \frac{k-1}{l} \right\}} \bigg|_{s = \alpha_j} \quad (6)$$

Numerical values for α_j and A_j as a function of k , β , and l are easily computed on digital machines.

In the previous description of the experiment it was stated that the scaler-printer effectively integrates the signal which is proportional to neutron concentration. Consider the count-time as τ_c and the off-time (print cycle) as τ_p . Then the value printed at time t is

$$C_t = B \int_{t-\tau_c}^t n(t) dt \quad (7)$$

and the next value is

$$C_{t+\tau_c+\tau_p} = B \int_{t+\tau_p}^{t+\tau_p+\tau_c} n(t) dt \quad (8)$$

If prior to time t_0 , the reactor is in the steady state critical condition, the average value of C is

$$C_0 = B n_0 \tau_c \quad (9)$$

After the scram the subsequent values of C are

$$C_1 = B \int_{\tau_p}^{\tau_p+\tau_c} n(t) dt$$

or

$$\frac{C_1}{C_0} = \frac{1}{\tau_c} \int_{\tau_p}^{\tau_p+\tau_c} \sum_{j=1}^7 A_j e^{\alpha_j t} dt$$

$$\frac{C_1}{C_0} = \frac{1}{\tau_c} \sum_{j=1}^7 \frac{A_j}{\alpha_j} e^{\alpha_j \tau_p} (e^{\alpha_j \tau_c} - 1) \quad (10)$$

and

$$C_2 = B \int_{2\tau_p+\tau_c}^{2\tau_p+2\tau_c} n(t) dt$$

$$\frac{C_2}{C_0} = \frac{1}{\tau_c} \sum_{j=1}^7 \frac{A_j}{\alpha_j} e^{\alpha_j(2\tau_p + \tau_c)} (e^{\alpha_j \tau_c} - 1) \quad (11)$$

In general

$$\frac{C_n}{C_0} = \frac{1}{\tau_c} \sum_{j=1}^7 \frac{A_j}{\alpha_j} e^{\alpha_j[n\tau_p + (n-1)\tau_c]} (e^{\alpha_j \tau_c} - 1) \quad (12)$$

Therefore using a calculated graph of C_n/C_0 vs Δk , the actual shutdown Δk can be determined from the experimental data.

III. FLUX SHAPE CORRECTIONS

The most important correction to be applied to the original data is due to the change in the flux shape after the scram. Supposedly, the measured signal is proportional to the average neutron density, but if the space shape of the neutron flux changes then, in general, the output of the fission chamber will represent different fractions of the average neutron density before and after scram. This shape change can be calculated by two dimensional reactor flux codes as shown by Milani (Ref. 1). A crude correction factor can be calculated by estimating the geometry (buckling) changes relative to the chamber location.

Corrections to the calculated C_n/C_0 due to a non-step insertion of the rods can be computed, but usually this is a small error that can be neglected. As can be seen in Table 4, the first data point after the scram is slightly low with respect to the following points. This effect is due to the finite rod drop time.

IV. ARMF ROD DROP EXAMPLE

The ARMF reactor was initially taken critical on October 1960. As a part of the startup program the following data were taken to determine the shutdown worth of the control rods.

Geometrically, the ARMF is a symmetric square array of fuel elements with a cruciform control rod in each corner. To keep the relative importance of each rod approximately equal, the chamber was located in the center of the reactor. The control rods are numbered as follows: #1 is in the NW corner; #2 - SE corner; #3 - SW corner; and #4 - NE corner.

Although several drop measurements were performed for the various combinations of two or more rods, it is sufficient for this example to report only one set of data. Table 1 gives the basic experimental data along with the physical constants for the ARMF.

Table 1
ARMF Rod Drop Data

Case #	Rods Dropped	C ₀ Counts	C ₁ Counts	C ₂ Counts	C ₃ Counts	$\frac{C_1}{C_0}$	$\frac{C_2}{C_0}$	$\frac{C_3}{C_0}$
1	1,2,3,4	236913	9109	4221	2859	0.03845	0.01782	0.01207
2	1,2,3,4	235579	8974	4287	2788	0.03809	0.01820	0.01183
3	1,2,3,4	223861	8504	3879	2697	0.03799	0.01733	0.01205

$\ell = 8 \times 10^{-5}$ seconds
 $\beta = 0.00755(2)$
 Count time, $\tau_c = 9$ seconds
 Off time, $\tau_p = 1$ second

From the roots and residues listed in Table 3, values for C_n/C_0 can be computed. Using the specific ON-OFF cycle times of 9 seconds on and 1 second off, C_n/C_0 values for this experiment were computed and are listed in Table 2. Therefore, by using the measured values of C_n/C_0 from Table 1 in comparison to the computed values in Table 2, the following values of Δk (uncorrected) are tabulated in Table 4.

Table 2
Computed Values of C_n/C_0

$\tau_o = 9$ seconds, $\tau_p = 1$ second

k	C_n/C_0			
	n = 1	n = 2	n = 3	n = 4
0.995	0.412476	0.276005	0.210339	0.167597
0.99	0.255567	0.150870	0.108223	0.082554
0.98	0.144120	0.077487	0.053601	0.039880
0.97	0.100147	0.051851	0.035424	0.026133
0.96	0.076692	0.038910	0.026419	0.019409
0.95	0.062124	0.031123	0.021055	0.015429
0.94	0.052202	0.025927	0.017498	0.012801
0.93	0.045011	0.022216	0.014968	0.010937
0.92	0.039559	0.019433	0.013076	0.0095459
0.91	0.035285	0.017268	0.011608	0.0084688
0.90	0.031845	0.015538	0.010437	0.0076102
0.88	0.026646	0.012943	0.0086831	0.0063260
0.86	0.022907	0.011090	0.0074343	0.0054130
0.84	0.020087	0.0097011	0.0064990	0.0047299
0.82	0.017887	0.0086224	0.0057737	0.0042007
0.80	0.016120	0.0077587	0.0051935	0.0037775
0.75	0.012927	0.0062043	0.0041500	0.0030170
0.70	0.010791	0.0051693	0.0034561	0.0025118

Table 3
Roots and Residues for $\beta = 0.00755(3)$, $\ell^* = 8 \times 10^{-5}$ Seconds

k	9950000050+	*	*	*	*	*	*
A _j	8349640749+	2399286350+	1342715550+	1117800250+	2586063149+	9327873148+	3953346750+
C _j	1165296749-	2285367149-	9055857049-	2310186650-	1062251451-	2941498051-	1566490753-
k	9900000050+	*	*	*	*	*	*
A _j	3252625949+	1466249050+	1021893250+	1145534850+	2724992349+	9832958648+	5670227350+
C _j	1209256249-	2611985449-	9843016049-	2503514350-	1082388451-	2961487351-	2186060453-
k	9800000050+	*	*	*	*	*	*
A _j	1424958149+	7878939349+	6259756849+	3957476149+	2262344249+	8196555148+	7239691650+
C _j	1227823349-	2818684549-	1041762150-	2689917550-	1101566951-	2980349651-	3425977653-
k	9700000050+	*	*	*	*	*	*
A _j	9085867148+	5351765449+	4440193049+	7042531849+	1843388849+	6699439648+	7974353450+
C _j	1233541249-	2894425949-	1064439250-	2778607650-	1110789951-	2989380351-	4666236453-
k	9600000050+	*	*	*	*	*	*
A _j	6664925648+	4046967849+	3429216149+	5754043149+	1540132649+	5609733248+	8400224750+
C _j	1236314549-	2933575749-	1076498650-	2830147350-	1116206551-	2994674451-	5906625053-
k	9500000050+	*	*	*	*	*	*
A _j	5261087448+	3252323549+	2790211849+	4850790749+	1318170349+	4808616248+	8678155650+
C _j	1237952649-	2957472049-	1083970950-	2863781750-	1119768151-	2998154651-	7147074053-
k	9400000050+	*	*	*	*	*	*
A _j	4344808048+	2718088049+	2350894249+	4187790349+	1150441049+	4201484948+	8873818950+
C _j	1239034349-	2973569349-	1089051450-	2887444050-	1122288451-	3000616551-	8387552553-
k	9300000050+	*	*	*	*	*	*
A _j	3701051048+	2334354649+	2030603949+	3682030149+	1019827549+	3727660548+	9019028950+
C _j	1239800549-	2985150449-	1092729550-	2904994350-	1124165651-	3002449951-	9628057553-
k	9200000050+	*	*	*	*	*	*
A _j	3222561048+	2045478449+	1786921649+	3284274549+	9154179548+	3348803948+	9131072150+
C _j	1240373349-	2993880249-	1095514550-	2918524150-	1125618651-	3003867051-	1086857354-

Table 3
(Continued)

k	9100000050+	*	*	*	*	*	*
A _j	2853678648+	1820221749+	1595346649+	2963479649+	8302305548+	3038656048+	9220145650+
α _j	1240816949-	3000694949-	1097696450-	2929274450-	1126775651-	3004997451-	1210910054-
k	9000000050+	*	*	*	*	*	*
A _j	2561341848+	1639580749+	1440757449+	2699413949+	7594051348+	2781033348+	9292655750+
α _j	1241169849-	3005164649-	1099452450-	2938021750-	1127719351-	3005917751-	1334963554-
k	8800000050+	*	*	*	*	*	*
A _j	2124090948+	1363003249+	1206839749+	2290730749+	6485845048+	2376802948+	9403568150+
α _j	1241699549-	3014396449-	1102102250-	2951389250-	1129165051-	3007329451-	1583071054-
k	8600000050+	*	*	*	*	*	*
A _j	1815090448+	1173607049+	1038188849+	1989157749+	5658371548+	2074844848+	9484414150+
α _j	1242075549-	3020295549-	1104007450-	2961127350-	1130221351-	3008360051-	1831181254-
k	8400000050+	*	*	*	*	*	*
A _j	1584129248+	1027545749+	9108740848+	1757591149+	5017803648+	1840969948+	9545958450+
α _j	1242357349-	3024731449-	1105442950-	2968536150-	1131026351-	3009145151-	2079290454-
k	8200000050+	*	*	*	*	*	*
A _j	1406385248+	9133650148+	8113669248+	1574311149+	4507549148+	1654021648+	9594378450+
α _j	1242574949-	3023186749-	1106563350-	2974359850-	1131660051-	3009764551-	2327401354-
k	8000000050+	*	*	*	*	*	*
A _j	1263903348+	8227975448+	7313997548+	1425526449+	4091213648+	1501540948+	9633465750+
α _j	1242749549-	3030955949-	1107462650-	2979061350-	1132172251-	3010264751-	2575512054-
k	7500000050+	*	*	*	*	*	*
A _j	1007731448+	6586834748+	5868401448+	1153055349+	3322645048+	1220184848+	9704624850+
α _j	1243063949-	3035945749-	1109086350-	2987614050-	1133106551-	3011176251-	3195791754-
k	7000000050+	*	*	*	*	*	*
A _j	8385239747+	5491462948+	4900370248+	9679944848+	2797709248+	1027502048+	9752646450+
α _j	1243272349-	3039285349-	1110172350-	2993381950-	1133737051-	3011792151-	3816068454-

Note: Numbers are machine floating point where + 1.0 = 10 0000 0051 + and + 0.10 = 10 0000 0050 +.

Table 4
 Δk Values for ARMF Data

<u>Case Number</u>	<u>$\Delta k_1\%$ (C_1/C_0)</u>	<u>$\Delta k_2\%$ (C_2/C_0)</u>	<u>$\Delta k_3\%$ (C_3/C_0)</u>
1	-8.2	-8.71	-8.65
2	-8.3	-8.55	-8.80
3	-8.3	-9.1	-8.66

Average -8.59%

To compute an approximate correction factor for the flux shape change, the system is considered homogeneous over the critical volume, V_1 . When the rods are dropped, symmetry is retained but the effective volume of the system is reduced. Therefore, the chamber, located in the center, measures a larger fraction of the average flux after the scram.

For a homogeneous critical rectangular system

$$\phi = \phi_c \cos \frac{\pi x}{2\tilde{x}} \cos \frac{\pi y}{2\tilde{y}} \cos \frac{\pi z}{2\tilde{z}} \quad (13)$$

where ϕ_c is the center flux and the coordinate system origin is at the center of the reactor and $\tilde{x}$, $\tilde{y}$, and $\tilde{z}$ are extrapolated dimensions of volume V_1 .

The average flux is

$$\bar{\phi} = \frac{\int_{V_1} \phi dV}{\int_{V_1} dV} = \frac{8\phi_c}{\pi^3} \quad (14)$$

Thus, before the scram the chamber measures a signal that is a factor of $\frac{\pi^3}{8}$ times the average flux. After the scram, the system is considered homogeneous throughout the volume V_2 , although this volume is slightly smaller than V_1 .

After the scram

$$\phi_A = \phi_{ca} \cos \frac{\pi x}{2\tilde{x}_a} \cos \frac{\pi y}{2\tilde{y}_a} \cos \frac{\pi z}{2\tilde{z}_a}, \text{ within } V_2 \quad (15)$$

and

$$\phi_A = 0, \text{ outside } V_2 \quad (16)$$

Therefore

$$\bar{\phi}_A = \frac{\int_{V_1} \phi_A dV}{\int_{V_1} dV} \quad (17)$$

with respect to the original volume, or

$$\bar{\phi}_A = \frac{\int_{V_2} \phi_A dV}{\int_{V_1} dV} = \frac{8\phi_{ca}}{\pi^3} \frac{\tilde{x}_a \tilde{y}_a \tilde{z}_a}{\tilde{x} \tilde{y} \tilde{z}} \quad (18)$$

where

$$\begin{aligned} \tilde{x}_a &\leq \tilde{x} \\ \tilde{y}_a &\leq \tilde{y} \\ \tilde{z}_a &\leq \tilde{z} \end{aligned}$$

After the scram the chamber measures a flux that is

$$\frac{\pi^3}{8} \frac{\tilde{x} \tilde{y} \tilde{z}}{\tilde{x}_a \tilde{y}_a \tilde{z}_a}$$

times the average.

In the ARMF the vertical dimension is not distorted, only the x-y plane is affected.

Therefore, guessing that the change in the extrapolated boundary distance is 10% then

$$\bar{\phi}_A = \frac{8}{\pi^3} (.9)(.9) \phi_{ca} \quad (19)$$

or

$$\frac{\bar{\phi}_A}{\phi} = (.81) \frac{\phi_{ca}}{\phi_c}$$

If the data in Table 1 is modified by this factor we have for case 1,

$$C_1/C_0 = (0.81) (0.03845) = 0.03114$$

From Table 2 this gives a value of

$$\Delta k = -10.4\%$$

The theoretical calculated value by reactor physics methods is $-11.1\% \Delta k$. Although this type of correction is very crude, it can be useful in at least estimating the true shutdown.

For non-symmetric geometry, this type of flux shape correction may not be valid. In any case, this type of crude correction must be viewed pessimistically and used only as a quick estimate when digital flux shape calculations are not available.

V. CONCLUSIONS

The rod drop method can be used to obtain reliable shutdown reactivities, although care and judgment must be exercised in choosing a chamber location and in the analysis of the data.

Included with this report are several tables of roots and residues and integrals of the relative flux for a specific count-print cycle times. The roots-residues are for

$$l = 8 \times 10^{-5} \text{ seconds}$$

and β effective = 0.00755. Equation (12) with the roots-residues can be used to develop C_n/C_0 values for any desired count-print cycle times.

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In the absence of the author, K. V. Moore, minor corrections and additions to the original internal report were made in this revision by S. R. Gossmann and E. Fast. K. R. Katsma recalculated the curves of Figures 2 and 3 using the most recent data from the ARMT and ETRC.

APPENDIX

A further refinement has been made to take into account finite rod drop time for specific application to ARMF-II and ETRC. These calculations were made by a digital solution of the differential equations:

$$\frac{dn}{dt} = \frac{(\rho(t) - \beta)_n}{\Lambda} + \sum_{i=1}^6 \lambda_i C_i \quad (20)$$

$$C_i + \lambda_i C_i = \frac{\beta_i}{\Lambda} n \quad i = 1, 2, \dots, 6 \quad (21)$$

$$\frac{\rho(t)}{\rho_m} = \frac{X(t)}{X_m} - \frac{1}{2\pi} \sin \frac{2\pi X(t)}{X_m} \quad (22)$$

$$\frac{d^2 X}{dt^2} = -\alpha g$$

where

n = flux level

ρ = reactivity $\equiv \frac{k_{\text{eff}} - 1}{k_{\text{eff}}}$

$\Lambda \equiv \frac{l}{k}$ = generation time

X = rod position

Subscript m = total or maximum

g = gravitation acceleration constant

α = a fraction which was measured to be 0.5 for the ARMF and ETRC.

The digital differential equation program IREKIN⁽⁴⁾ was used to calculate curves for the ARMF-II and ETRC. The curves of Figures 2 and 3 give the shutdown reactivity for these reactors as a function of the normalized integrated flux as practical examples of the proposed method.

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Figure 2
ARMF Normalized Integrated Flux vs Reactivity

Figure 3
ETRC Normalized Integrated Flux vs Reactivity

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