T. C.
BAŞBAKANLIK
ATOM ENERJİSİ KOMİSYONU

ÇEKMECE NÜKLEER ARAŞTIRMA VE EĞİTİM MERKEZİ

RAPOR No: 85

LINEAR EXTRAPOLATION DISTANCES FOR CENTRALLY AND ECCENTRICALLY LOCATED CONTROL RODS

FAHİR BORAK

1972

LINEAR EXTRAPOLATION DISTANCES FOR CENTRALLY AND ECCENTRICALLY LOCATED CONTROL RODS

REACTORS

KEYWORDS: *neutron flux, extrapolation length, pulsed neutron techniques, neutron diffusion equation, control elements, moderators, configuration, distribution*

FAHIR BORAK* *Nuclear Engineering Department, New York University*
New York, New York 10453

Received July 2, 1971
Revised August 23, 1971

Using one-group diffusion theory, linear extrapolation distances for centrally and eccentrically located black control rods in cylindrical geometries have been determined by the pulsed neutron method. It is found that for a given radius control rod, the extrapolation distance increases with increasing moderator radius. Linear extrapolation distance is also found to increase with eccentrical location of control rods. In general, the values of the extrapolation distances determined for central rods in diffusion theory, in the range of moderator radii studied, are higher in value by 10 to 100% than the classical values based on the theoretical calculations of Davison and Zaretsky. The values of the linear extrapolation distances for eccentric control rods, in the range of the moderator radii studied, are also higher than the central control rod extrapolation distances up to a factor of 6, the increase depending on the location of the control rods.

INTRODUCTION

The worth of a control rod is a meaningful concept for multiplying systems. However, the theory used to determine the worth of a control rod and the linear extrapolation distance is also valid for nonmultiplying systems. An investigation using a moderator assembly, without the presence of fuel, void channels, etc., isolates the specific problem from the complications otherwise present.

*Present address: Çekmece Nuclear Research and Training Center, P.O. Box 1, Airport, Istanbul, Turkey.

Thus, in the following study linear extrapolation distance is studied under the above conditions. Specifically, since an infinite medium is assumed in the analytical treatment of the problem, the study is directed to the determination of the linear extrapolation distances in systems with increasing dimensions. In addition, the effect of eccentrically located control rods in finite systems is investigated. In practice, extrapolation distances for eccentric control rods are assumed to be the same as those of central control rods, and thus their worths depend only on the neutron flux distribution.

In this study one-group diffusion theory is used in conjunction with the experiment. The results thus obtained for linear extrapolation distances show variations from the theoretical values obtained in transport theory. Therefore, it is suggested that experimental results should be used with diffusion theory applications, as the use of transport theory values in diffusion theory may lead to significant errors.

THEORY

Solution of Diffusion Equation for a Purely Moderating Medium

In pulsed neutron experiments, the fundamental mode of decay of the neutron flux ϕ is given by

$$\phi \sim \exp(-\lambda t) \quad , \tag{1}$$

where

$$\lambda = \bar{\Sigma}_a \bar{v} + \bar{D}_0 B^2 + CB^4 \quad , \tag{2}$$

where

λ = fundamental mode decay constant

$\bar{\Sigma}_a$ = average macroscopic absorption cross section of the system

$\bar{v}$ = effective speed of thermal neutrons

$\bar{D}_0$ = average diffusion coefficient of the system

B^2 = buckling of the system

C = diffusion cooling coefficient of the system.

The buckling of the system can be found by solving the reactor equation, i.e.,

$$\nabla^2\phi + B^2\phi = 0 \qquad (3)$$

for a particular geometry and for a particular set of boundary conditions. For a purely moderating medium, due to the central location of the source if radial symmetry of the flux is assumed, the solution to the reactor equation together with the boundary conditions,

$$\phi(R + \epsilon, z) = \phi\left(r, \frac{H}{2} + \epsilon\right) = 0 \quad , \qquad (4)$$

where ϵ is vacuum extrapolation distance, gives

$$B_0^2 = \left(\frac{\gamma}{R + \epsilon}\right)^2 + \left(\frac{\pi}{H + 2\epsilon}\right)^2 \quad , \qquad (5)$$

where $\gamma = 2.405$ is the first zero of $J_0(\gamma)$.

Solution of Diffusion Equation for a Central Control Rod

When a control rod is inserted into the moderating assembly, the diffusion equation applies only to the moderator region. In this case, in addition to the above boundary conditions, it is necessary to have another boundary condition at the surface of the control rod and the moderator. This boundary condition is given as

$$\frac{1}{\phi}\frac{d\phi}{dn}\bigg|_{r=a} = \frac{1}{d} \quad , \qquad (6)$$

where a is the radius of the control rod, d is the linear extrapolation distance into the control rod, and thus the left-hand side of Eq. (6) is the normal derivative of the flux divided by the flux evaluated on the surface of the control rod. Application of all the boundary conditions gives

$$\frac{1}{d} = -\frac{\alpha[J_1(\alpha a) - J_0(\alpha\tilde{R})\,Y_1(\alpha a)/Y_0(\alpha\tilde{R})]}{J_0(\alpha a) - J_1(\alpha\tilde{R})\,Y_0(\alpha a)/Y_0(\alpha\tilde{R})} \quad , \qquad (7)$$

where

$$\alpha^2 = B^2 - \left(\frac{\pi}{\tilde{H}}\right)^2 \qquad (8)$$

and

$$\tilde{R} = R + \epsilon \quad , \quad \tilde{H} = H + 2\epsilon \quad . \qquad (9)$$

Thus, if the linear extrapolation distance, d, is known, then the perturbed radial buckling, α^2, can be calculated and the worth of the control rod can be determined. The worth ρ of a control rod, as given by modified one-group diffusion theory is

$$\rho = \frac{(B^2 - B_0^2)M^2}{1 + B_0^2M^2} \quad , \qquad (10)$$

where M^2 is the migration area.

Conversely, if the perturbed buckling is known, then the linear extrapolation distance can be calculated.

Solution of Diffusion Equation for an Eccentrically Located Control Rod

In this case the details of the solution can be followed from Lamarsh.[1] The diffusion equation is applied throughout the system excluding the region occupied by the control rod. As in the previous case the boundary condition at the system-rod interface is

$$\frac{1}{\phi}\frac{d\phi}{dn} = \frac{1}{d} \quad . \qquad (11)$$

With the assumption that the linear extrapolation distance is independent of the angle about the rod, the final expression obtained for d is

$$\frac{1}{d} = \frac{-\alpha\,Y_1(\alpha a)}{Y_0(\alpha a) - \sum_{m=0}^{\infty} \partial_m\,Y_m(\alpha\tilde{R})J_m^2(\alpha r_0)/J_m(\alpha\tilde{R})} \quad , \qquad (12)$$

where

$$\partial_m = \begin{cases} 1 & m = 0 \\ 2 & m \geq 1 \end{cases}$$

and r_0 is the center-to-center distance between the moderating system and the control rod. Again, as in the preceding section, if the linear extrapolation distance is known, the perturbed buckling α^2 can be calculated and the rod worth can be determined through Eq. (10).

EXPERIMENTAL EQUIPMENT

The source of neutrons was a Philips neutron generator tube, in which neutrons are produced by $T(d, n)^4$He reaction. Pulsing is achieved by imposing square voltage pulses, from an external square wave generator, into the ion grid.

The neutron detector used in this study was a ^{6}LiI (europium activated) scintillation crystal 2 in. in diameter and 2 mm in thickness. The crystal had been enriched[2] in ^{6}Li to 95.62% ^{6}Li. The efficiency of the crystal, though it is only 2 mm thick, is more than 95% as computed from the macroscopic absorption cross section of 16.7 cm^{-1}.[2] The crystal was coupled to a photomultiplier tube

through a 1-in. Lucite light-pipe. The remainder of the electronic circuitry which basically consisted of a preamplifier, an amplifier, a single-channel analyzer, and a multichannel analyzer is shown in Fig. 1.

In this study, distilled water was used as moderator material. For moderator geometry, a right circular cylindrical shape was used. The moderator containers were constructed of 0.125-in.-thick Plexiglas cylinders. For the control rod experiments, holes of appropriate size were drilled through the covers and a second bottom was provided with corresponding holes; thus the control rod locations were fixed precisely. The covers and containers were covered with cadmium. This arrangement eliminates "container effects."

The control rod material used in this experiment was elemental boron in the so-called amorphous form. A Plexiglas cylindrical tube of known inside dimension was filled with this amorphous boron to produce highest density. This density may effect the measured extrapolation distance. A parameter which can be used to determine this effect is the blackness, β, of the rod to the thermal neutrons.[3] Blackness is defined as

$$\beta = \frac{J^{in} - J^{out}}{J^{in}} , \qquad (13)$$

where J^{in} is the thermal-neutron current into the rod, and J^{out} is the thermal-neutron current out of the rod. Values of blackness have been calculated[3] in terms of the properties of the control rod elements, these properties being radius of the absorber, absorption, and transport mean-free-path in the absorber. The control rod used in this experiment had a radius of 0.8377 ± 0.0071 cm, a density of 0.6583 g/cm^3, and blackness of 0.9984.

EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

Experimental Arrangement

In pulsed neutron experiments two of the major problems are room-return background neutrons and harmonic contamination of the fundamental mode of decay. These factors can be minimized, if not eliminated, by the proper arrangement of the pulsing experimental setup.

To reduce room-return neutrons, the moderating assemblies were surrounded by heavily borated paraffin blocks at least 10-in. thick (Fig. 2). This shielding was lined with cadmium on the inside. In addition to this, moderator assemblies were covered with another layer of cadmium. This second layer of cadmium had a circular

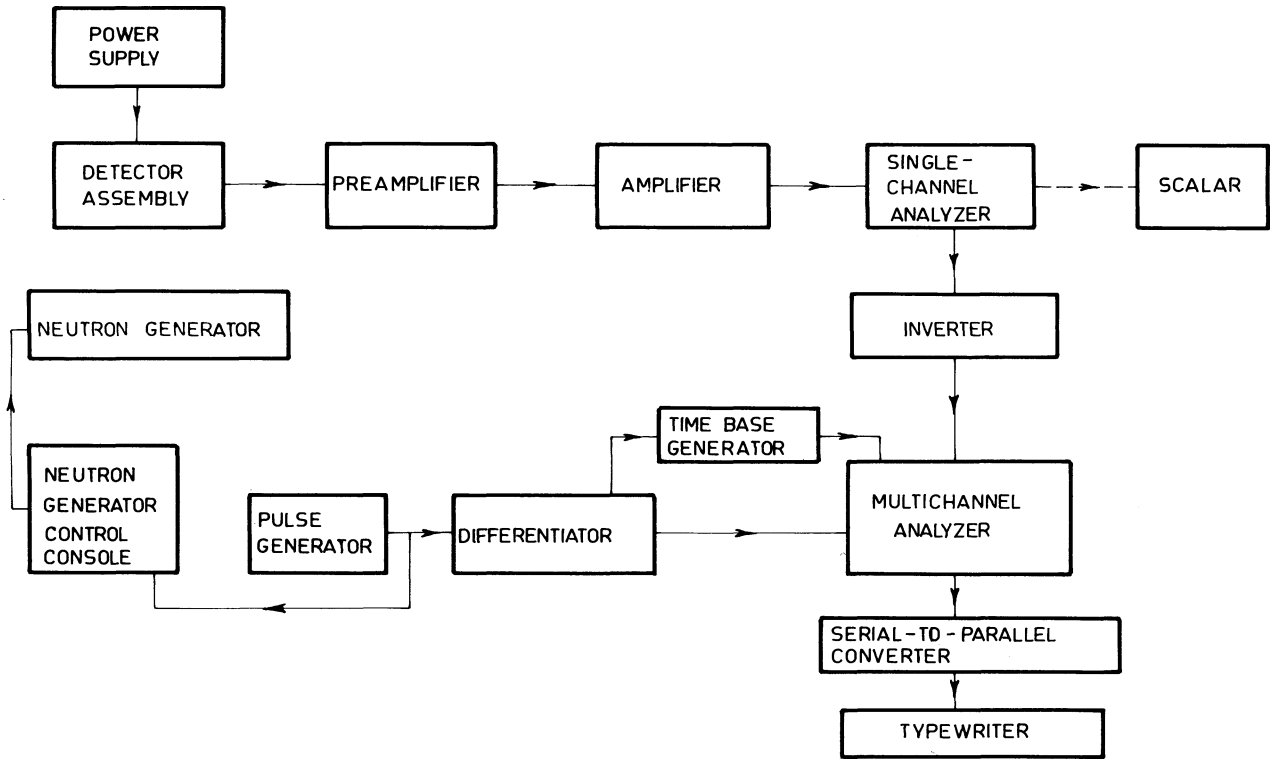


Fig. 1. Block diagram of electrical circuitry.

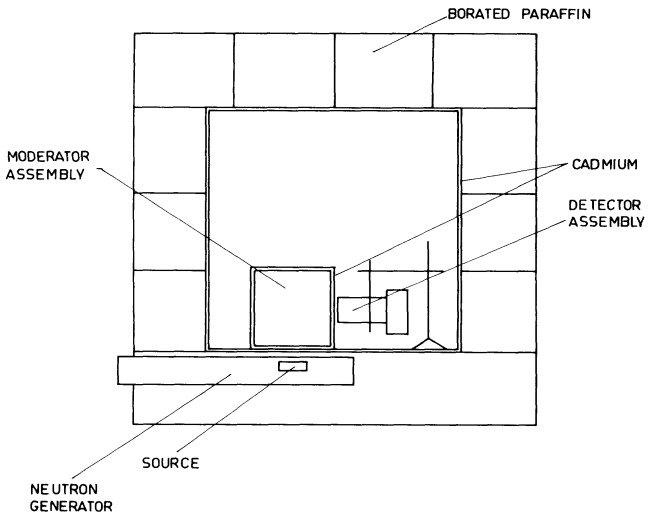


Fig. 2. Sectional view through center of experimental apparatus.

opening so that the detector could be placed on the outside of the moderator assembly, being in physical contact with it. Thus, time-of-flight effects would not interfere with the decay constant measurements.[4]

The effectiveness of the shielding system was tested by determining the decay constant of the system with no moderator assembly being present in the system. The result showed that the shielding decay time was satisfactorily short ($\tau \sim 18$ μsec) and that it was of low intensity.

To reduce the harmonics problem, the source was located at the radial center, underneath the assembly and the detector was located at the axial center, outside the moderator.

Experimental Procedure

Before the main experimental study, the resolution of the crystal and of the photomultiplier assembly for best operating conditions was determined and found to be 8%. The discriminator was adjusted to accept signals around the thermal-neutron peak, and in this energy interval virtually no gamma radiation was recorded.

For eccentrically placed control rod measurements, no dependence of the decay constant to the relative positions of the control rod and the detector was observed.

The multichannel analyzer was operated at 25-μsec channel width with 12.5-μsec dead time between each successive channel. For each measurement, data were accumulated for 40 to 60 min until the maximum channel count was 4.5×10^5 to 1×10^6 counts. At each decay constant measurement the temperature of the moderator was determined in order to correct the decay constants for changes in the temperature.

Data Analysis

Determination of the Fundamental Mode of Decay. If sufficient time elapses after the introduction of the neutron pulse, the neutron flux consists of only the fundamental mode and is described by a single exponential term.

The problem then arises of determining the channel in which the decay of the fundamental mode begins, that is, the channel in which the higher harmonics have effectively died away.

It was found that the background was constant and could be calculated by taking the average of the counts recorded by the channels 50 to 79, as the flux for any system died away well before channel 40.

The decay rate of the fundamental mode after correcting for background is given by

$$\phi(t) = \phi_0 \exp(-\lambda t) \quad . \qquad (14)$$

To determine the fundamental mode decay constant λ, least-squares fitting was applied to the data with a weight factor of $1/\phi_i(t)$. In this way the "best" straight line for the given data points can be determined. However, the isolation of the portion of the decay curve at which only the fundamental mode of decay exists requires further analysis; for this the "block analysis" method was used. In this method, after an estimate of the starting channel is made, the first n channels are used to evaluate the decay constant. Then the first channel that has been used in the evaluation of the decay constant is dropped, and the $(n + 1)$'th channel is included in the calculation of the new decay constant. This process is repeated until the last channel used contains counts approximately five times the background. For the analysis of the results of this investigation, five-, seven-, and nine-channel block analysis was used. This mode of analysis allows one to determine the initial channel where the higher harmonic contamination is negligible and also the last channel at which statistical variation of the data is acceptable. This analysis was performed with the use of a computer program.

RESULTS

Determination of Perturbed Bucklings

To determine the extrapolation distance d, it is first necessary to determine the perturbed radial

buckling. If λ_c is the decay constant of the system with the control rod, centrally or eccentrically located, then

$$\lambda_c - \lambda_0 = D_0(B'^2 - B_0^2) + C(B'^4 - B_0^4) \quad , \quad (15)$$

where B_0^2 is the buckling without the control rod and B'^2 is the buckling with the control rod. If the perturbed radial buckling is denoted by α^2,

$$B'^2 = B_H^2 + \alpha^2 \quad . \quad (16)$$

Substituting Eq. (16) into Eq. (15) and solving for α^2, one obtains

$$\alpha^2 = -\frac{D_0^2}{2C} - \left(\frac{D_0^2}{4C^2} - \frac{D_0 B_0^2 + C B_0^4 + \lambda_c - \lambda_0}{C}\right)^{1/2} - B_H^2 \quad . \quad (17)$$

For each set of control rod decay constant measurement with a given system, a decay constant measurement of moderator alone was also performed. The diffusion parameters of water determined previously had the following values:

$$\overline{\Sigma_a \upsilon} = 4778.4 \pm 66.8 \text{ sec}^{-1}$$

$$D_0 = 38181.2 \pm 866.6 \text{ sec}^{-1} \text{ cm}^{-2}$$

$$C = -5529.3 \pm 1857.8 \text{ sec}^{-1} \text{ cm}^{-4} \quad .$$

These values correspond to a temperature of 25.5°C.

Determination of the Linear Extrapolation Distance for Central Control Rods

The linear extrapolation distance into a central control rod was determined by the use of Eq.(7). For this, a computer program was used. Then the value of d was corrected for blackness. The form of the correction is[3]

$$\left.\frac{d}{\lambda_{tr}}\right|_{\text{black}} = \left.\frac{d}{\lambda_{tr}}\right|_{\text{grey}} - \frac{4(1-\beta)}{3\beta} \quad . \quad (18)$$

Table I gives the results of the central control rod measurements. Figure 3 is the graph of d/λ_{tr} vs extrapolated system radius. From this graph it can be seen that in diffusion theory the experimentally determined linear extrapolation distance increases with the increasing moderator dimensions and can be extrapolated to an infinite system value which is considerably higher than that predicted from the theoretical calculations of Davison and Kushneriuk[5] and Zaretsky.[6]

Determination of Linear Extrapolation Distance for Eccentrically Located Control Rods

The linear extrapolation distance into an eccentrically located control rod was determined by

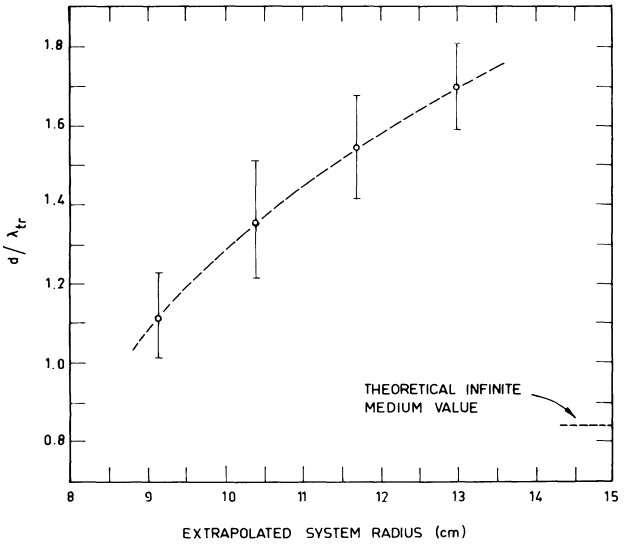


Fig. 3. Variation of extrapolation distance with radius of assembly for a control rod of radius 0.8377 cm.

TABLE I

Linear Extrapolation Distance for a Central Control Rod of Radius 0.8377 cm

Moderating System		Decay Constant (sec^{-1})		Pert. Radial Buckling (cm^{-2})	d/λ_{tr}	$\overline{d/\lambda_{tr}}$[a]
Radius (cm)	Height (cm)	Rod in	Rod out			
8.802	12.318	10 996.9	9416.2	0.11278	1.022	
	18.579	9 834.9	8315.3	0.11070	1.205	1.112
10.045	12.529	9 915.3	8781.3	0.08466	1.125	
	14.084	9 423.0	8385.0	0.08194	1.505	1.313
11.371	9.863	10 581.8	9834.2	0.06274	1.662	
	14.214	8 806.7	8010.4	0.06378	1.425	1.542
12.654	15.843	8 040.3	7459.5	0.04993	1.774	
	17.789	7 814.4	7215.5	0.05039	1.630	1.700

[a]Average linear extrapolation distance corrected for blackness.

the use of Eq. (12). A computer program was used to compute the linear extrapolation distance. This program calculated the summation term in the denominator until the last term added to it was less than 0.01% of the sum already computed. As a previous calculation, using the criterion of 0.1% gave essentially the same results; the accuracy of the summation term is considered satisfactory. The linear extrapolation distances calculated using Eq. (12) were corrected for blackness using Eq. (18).

In Table II the results of eccentric control rod measurements are given. Figure 4 is the graph of d/λ_{tr} vs $r_0/\tilde{R}$. From this graph it can be seen that the experimentally determined extrapolation distances for eccentric control rods are considerably higher than those of the central rod. The linear extrapolation distance is observed to increase with eccentricity and approach a limiting value.

DISCUSSION

Discussion of the Results

The results show that in one-group diffusion theory the extrapolation distance for central control rods increases with the increasing moderator radius. In cylindrical geometry no analytical solutions are available which can be used to predict this variation. However, an analogy can be made with slab geometry (Fig. 5). Since the absorber at the center is black, either half of the

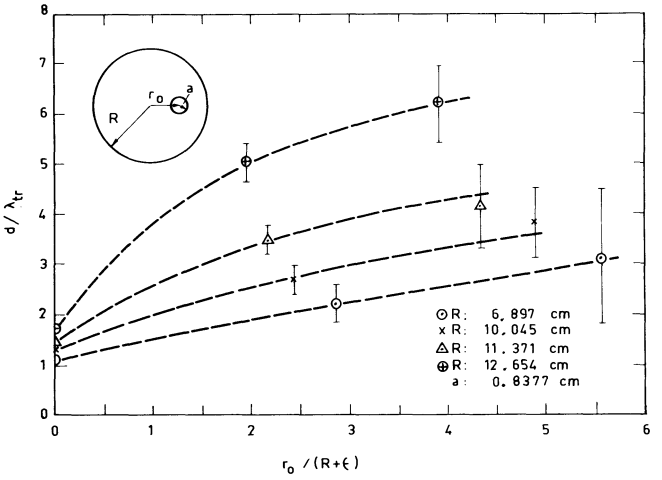


Fig. 4. Variation of extrapolation distance with eccentricity for a control rod of radius 0.8377 cm.

TABLE II

Linear Extrapolation Distance For an Eccentric Control Rod of Radius 0.8377 cm

Moderating System		Decay Constant (sec^{-1})					
Radius (cm)	Height (cm)	Rod in	Rod out	r_0/R	Pert. Radial Buckling (cm^{-2})	d/λ_{tr}	$\overline{d/\lambda_{tr}}$[a]
8.802	12.318	10 224.7	9416.2	0.288	0.09157	2.150	
	18.579	9 092.9	8315.3		0.09152	2.407	2.277
	12.318	9 764.4	9416.2	0.557	0.07913	1.815	
	18.579	8 552.4	8315.3		0.07590	4.483	3.147
10.045	12.529	9 417.3	8781.3	0.245	0.07109	2.324	
	14.084	8 946.1	8395.0		0.06900	3.085	2.703
	12.529	9 064.4	8781.3	0.490	0.06150	3.014	
	14.084	8 611.7	8395.0		0.05995	4.723	3.867
11.371	9.863	10 248.0	9834.2	0.218	0.05360	3.638	
	14.214	8 445.1	8010.4		0.05402	3.373	3.504
	9.863	9 925.8	9834.2	0.435	0.04481	5.715	
	14.214	8 190.9	8010.4		0.04717	2.601	4.156
12.654	15.843	7 755.6	7455.5	0.196	0.04229	4.814	
	17.789	7 493.7	7215.0		0.04181	5.328	5.069
	15.843	7 625.4	7455.5	0.382	0.03880	6.138	
	17.789	7 376.1	7215.0		0.03866	6.450	6.292

[a]Average linear extrapolation distance corrected for blackness.

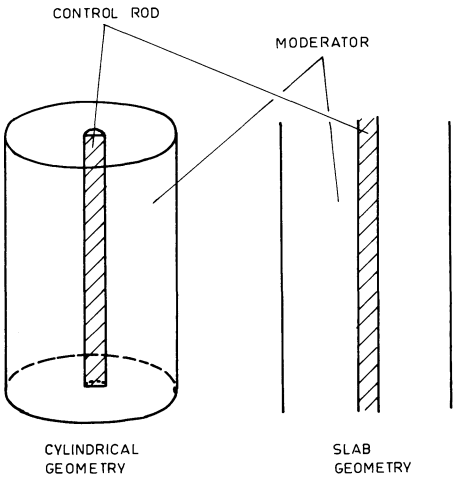


Fig. 5. Cylindrical and slab geometries for central control rod measurements.

slab can be considered separately; the boundary conditions between the half slabs and the absorber can be replaced by a vacuum boundary condition. In this case one can use the results of Gelbard and Davis[7] who, using the Radkowsky kernel, calculated the vacuum extrapolation distance for pulsed water experiments. These results show that, as the thickness of the system increases, the extrapolation distance into the vacuum increases. Therefore, in slab geometry one rigorously obtains the behavior that is obtained experimentally for cylindrical geometry.

The linear extrapolation distance for central control rods, again in one-group diffusion theory and using the pulsed neutron method, have also been determined by Starr[8] and by Fierberg.[9] In both the above studies, experimentally determined extrapolation distances are higher than the theoretical values.

Another similar study has been performed by Sjöstrand et al.[10] In this investigation, the effects of cadmium rods in a moderating system are studied, but rather than calculating the extrapolation distance, the theoretically predicted values of change in buckling and the experimentally observed values are compared. The experimental values are slightly less than the theoretical values. Due to the functional dependence of the perturbed buckling on linear extrapolation distance as given by Eq. (7), use of a higher extrapolation distance would lead to lower values of theoretically predicted change in buckling. Thus the results of these experiments are all in agreement.

The experimental extrapolation distances for central control rods are considerably higher than the theoretically predicted values. The theoretical values of extrapolation distances are obtained in a finite absorbing medium with no sources. The theoretical approach was to solve the one-velocity Milne problem, where the absorption around the rod is assumed to be zero and the sources are located at infinity. Theoretical calculations by Pellaud[11] without the above assumptions show that extrapolation distance increases. Multivelocity calculations performed by Williams[12] indicate that the linear extrapolation distance depends on the energy dependence of the mean-free-path and that one velocity approach underestimates the extrapolation distance. However, the above corrections are not sufficient to increase the theoretical values to the experimental results.

The linear extrapolation distance increases if the rods are located eccentrically. Other experimental results concerning the linear extrapolation distance for eccentric control rods are not available. However, a similar study for diagonal rods has been carried out by Sjöstrand[10] and Nilsson and Sjöstrand.[13] Sjöstrand investigated the change in buckling that is theoretically predicted by one-group diffusion theory. He calculated the theoretical values by assuming that the effect of a diagonal control rod relative to an axial one should be equal to the ratio of the integrals of the squares of the neutrons flux over the rod volumes, i.e.,

$$\text{ratio} = \frac{4}{\pi}\left(1 + \frac{4H^2}{H^2}\right)^{1/2} \int_0^{\pi/2} J_0^2\left(\frac{4.18}{\pi}\, x\right)\cos^2 x\,dx . \quad (19)$$

The theoretical values were found to be 20 to 30% higher than the experimental results.

Nilsson expanded the experiments for varying values of the height/radius ratio. The experimental values were again considerably lower than the theoretical values predicted by Eq. (19).

Diagonal rods can be considered to be "partially" eccentric. Thus, a higher value of linear extrapolation distance for eccentric parts would have led to lower theoretical values of perturbed buckling and to a better agreement with experimental results.

As a result of the experimental studies discussed above, and the present one, it can be stated that the theoretical values of the linear extrapolation distances used for control rod worth calculations by diffusion theory overestimate the rod worth. For central control rods, this error may be 0 to 12% and for eccentric control rods the error may be 0 to 40%. The value of the error depends on system size, rod radius, and the eccentrical location of the control rod.

Finally, in view of the above discussion, the linear extrapolation distances determined in this investigation should be considered as boundary conditions to be used in conjunction with one-group diffusion theory rather than being compared

to analytically determined values. With the use of experimental results, the application of diffusion theory for centered, and particularly for off-centered, rods will lead to correct reactivity worth determinations, and this is the significance that one attaches to linear extrapolation distances.

Discussion of Errors

In calculating the linear extrapolation distances into control rods, there are two distinct steps of calculation:

1. calculation of the perturbed buckling from the change in the decay constant with and without the control rod
2. determination of the linear extrapolation distance from the perturbed buckling.

Because of the complicated functional dependence of the linear extrapolation distance on the parameters used, it is best to study errors in each step separately.

The value of the perturbed buckling depends on the measured decay constants and on diffusion parameters of water. The error in decay constants arises from an uncertainty in defining a fundamental mode caused by harmonic contamination, the background, and statistics. The mode of analysis minimizes the harmonic contamination and the background effect, but as observed from block analysis, statistical variation may effect the results up to 0.5%. The value of the decay constant, although $1/y$ weight is used, is more sensitive to the first channel used than to the last channels. An error of 1% in decay constant gives a 2 to 3% error in perturbed buckling. The value of the perturbed buckling is also sensitive to errors in the diffusion coefficient and to errors in the radial buckling. However, the physical dimensions of the moderator assembly were measured to better than 0.1% which would give an error of $<0.2\%$ in radial buckling. This is also the same order of magnitude of error caused by using the same vacuum extrapolation distance for all systems.

The linear extrapolation distances calculated by Eqs. (7) and (12) depend on the extrapolated system radius, the control rod radius, the location of the control rod, and the perturbed buckling. The error contributed by each of the above parameters was investigated by calculating the extrapolation distance for a given parameter and recalculating the extrapolation distance. The results of this parameter study show that the extrapolation distance is most sensitive to perturbed buckling. Extrapolation distance for a central rod varies by 8 to 10% if perturbed buckling varies by 1%, the error depending on other parameters and on whether the error is positive or negative. However, for an eccentric rod placed 5.04 cm from the center, the error increased to about 20% for the same percentage of error in the perturbed buckling. For this reason the error associated with eccentric control rod extrapolation distances is considerably higher than those of the central rod.

The uncertainty caused by an error of 1% in control rod radius is about 1.5 to 2% in extrapolation distance for central rods, the error being greater for small systems. This error reduces to 1% or less for eccentrically placed rods. Since the control rod radius is measured to better than 1%, the contribution of the error to the extrapolation distance from this parameter is relatively small.

The location of the control rod was determined with an accuracy of 1 mm. This uncertainty in the location gives an error of 0.5% in extrapolation distance for central rods but increases to 2% for a 2.5-cm off-centered rod and to about 7% for a 5.04-cm off-centered rod.

The central rod extrapolation distance can be calculated by using the equation for eccentric control rod extrapolation distance by decreasing the value of the eccentricity, r_0, to zero. The value thus obtained for the central rod extrapolation distance is about 2 to 2.5% lower than the value calculated by using the equation for central rod extrapolation distance. The difference is due to the approximations made in the derivation of the eccentric control rod extrapolation distance.

In view of these errors, it is estimated that the results given for extrapolation distances have an error of 10% for central rods and 30% for eccentrically located rods.

ACKNOWLEDGMENTS

Appreciation is due to J. Herbst for his valuable guidance and discussions throughout the experiment and analysis of the results.

The scholarship by Turkish Ministry of Education which made this work possible is gratefully acknowledged. This paper is based on the work submitted as a PhD thesis at New York University.

REFERENCES

1. J. LAMARSH, *Nuclear Reactor Theory*, Addison-Wesley Publishing Company Inc., Reading, Massachusetts (1966).

2. "Europium Activated Lithium Iodide Phosphors," The Harshaw Chemical Company, Cleveland (1966).

3. N. SPINKS, *Nucl. Sci. Eng.*, **22**, 87 (1965).

4. G. A. PRICE and H. H. WINDSOR, *Nucl. Sci. Eng.*, **31**, 547 (1968).

5. B. DAVISON and S. A. KUSHNERIUK, *Proc. Phys. Soc.*, **A64**, 881 (1951).

6. D. F. ZARETSKY, "Effective Boundary Conditions for Grey Bodies," *Proc. U.N. Intern. Conf. Peaceful Uses At. Energy*, 1st, Geneva, **5**, 525 (1955). Available from the Clearinghouse for Federal Scientific and Technical Information.

7. E. M. GELBARD and J. A. DAVIS, *Nucl. Sci. Eng.*, **13**, 237 (1962).

8. E. STARR, "An Experimental Determination of the Thermal Neutron Extrapolation Distance at the Surface of a Black Control Element," PhD thesis, New York University, unpublished (1965).

9. S. FIERBERG, "The Variation of the Linear Extrapolation Distance at the Surface of a Highly Absorbing Body as a Function of the Buckling," PhD thesis, New York University, unpublished (1965).

10. N. G. SJÖSTRAND et al., *Arkiv Fysik*, **15**, 471 (1959).

11. B. PELLAUD, *Nucl. Sci. Eng.*, **33**, 169 (1968).

12. M. M. R. WILLIAMS, *Nucl. Sci. Eng.*, **18**, 260 (1964).

13. T. NILSSON and N. G. SJÖSTRAND *Nucl. Sci. Eng.*, **8**, 12 (1960).