APPROXIMATE METHODS FOR PILE DESIGN CALCULATIONS**Harvey Brooks**

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Approximate Methods for Pile Design Calculations

Introduction

At a certain stage in the design of a pile there comes a time when it is urgent to obtain day to day answers on the effects of various changes in the design parameters. The multi-group methods being used in the theory group are necessary for accurate values of critical mass and detailed study of power distribution and neutron spectrum. Nevertheless, a complete calculation by this method for one particular geometry and composition takes at least two weeks, whereas answers for design questions are needed in a matter of hours. It is hoped that the procedures described in the present memo will serve as a bridge between the crudest diffusion theory calculations and the more elaborate multi-group methods. As more and more of the elaborate calculations become available, these can be used to check the cruder approach and to dictate a better choice of parameters in the simple solution. In this way the approximate method eventually will become an interpolation procedure for joining the precise computations.

Starting Point of the Method

The starting point of the method is the Age Theory, the application of which has been described in detail in report GE-HB-7. This theory is practically rigorous when applied to bare spherical piles of uniform composition. It has been extensively applied by Dan Miller to assemblies of pure U^{235} and Be with various atomic ratios α of Be to U. The method

may be summarized as follows:

The basic criticality equation may be written

$$\frac{1}{\nu} = \int_0^{\infty} \frac{\sigma_f}{m_f \sigma_s} e^{-\theta_f} e^{-\theta_i} e^{-k^2 \tau} du \quad (1)$$

where

σ_f = effective fission cross-section as a function of energy.

σ_s = scattering cross-section of Be.

$u = \ln E_0/E$ where E_0 is the source energy.

θ_f , θ_i , and τ are functions of energy defined by the integrals:

$$\begin{aligned} \theta_f &= \int_0^u \frac{\sigma_f}{m_f \sigma_s} du \\ \theta_i &= \int_0^u \frac{\lambda \sigma_f + \sigma_i}{m_f \sigma_s} du \\ \tau &= \int_0^u \frac{1}{3 N^2 m^2 \sigma_s \sigma_t} du \end{aligned} \quad (2)$$

where

λ is the capture to fission ratio.

σ_i represents the absorption cross-section of impurities.

N number of U^{235} atoms per unit volume of mixture.

m number of Be atoms per U^{235} atom

ξ av. logarithmic energy loss for Be.

Equations (1) and (2) are written on the assumption that fission neutrons originate at a single energy E_0 . For each choice of E_0 there will be a different value of $\frac{1}{\nu}$, and the weighted average of $\frac{1}{\nu}$ over

the actual source spectrum will be the true value of $\frac{1}{\nu}$. The parameter k is adjusted until the mean value of $\frac{1}{\nu}$ agrees with the actual number of neutrons per fission, namely $\frac{1}{\nu} = 0.40$ in the case of U^{235} or 0.34 in the case of Pu. What is thus obtained from equations (1) and (2) is a value of k as a function of m . This has been done by Miller and the results are shown for k^{-1} in table I and figure I. These numbers will have to be revised somewhat in the future because of the following inadequacies in the calculation:

1. The source spectrum was taken too high, the peak in the distribution being at 1.5 mev. This is the distribution given in the wallpaper book but, according to Bethe, the original Bloch-Staub spectrum with its peak at 0.8 mev. would have been a better choice. The correction will reduce the values of k^{-1} .

2. Neglect of forward asymmetry and inelastic scattering in Be. It is now believed that these effects, if present at all, occur only in the high energy tail and are not significant for the criticality of the pile. Inelastic scattering would reduce the value of k^{-1} , forward asymmetry would increase it.

3. Failure to treat adequately self-absorption effects in the fission foils at energies below about 400 e.v. This will affect chiefly the neutron spectrum, but may also raise k^{-1} if improved.

4. Neglect of inelastic scattering in uranium. This is believed to be not too important, but will tend to lower the effective source spectrum.

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TABLE I

<u>m</u>	<u>k⁻¹</u>	<u>2k^{3/2}</u>
19.3	7.75	0.182
28.9	8.05	0.171
48.3	8.49	0.167
89.5	9.02	0.159
151.0	9.50	0.147

5. Neglect of the so-called first-collision correction to age theory. In pure Be this increases the average age to a given energy by about 5 cm^2 , and therefore raises k^{-1} .

It is intended to start revised age calculations as soon as better data on the cross-sections has been prepared. In the meantime, it is probable that the present values of k^{-1} are not too unreliable, and are on the pessimistic side from the standpoint of critical mass and size.

Returning to equation (1), if the assembly is bare, the critical radius a is determined by the condition

$$\begin{aligned} ka &= \pi \\ a &= \pi k^{-1} \end{aligned} \quad (3)$$

Strictly speaking, a is not the physical radius but the extrapolated radius:

$$a = a_0 + 0.71 \lambda$$

where λ is the mean free path for the assembly at the low end of the energy range, a_0 is the physical radius.

The following generalization of bare pile theory is very useful. Consider an assembly surrounded by a reflector which does not moderate the neutrons but whose cross-sections vary slowly with energy. Then in equation (1) let us replace $k^2 \tau$ by:

$$k^2 \tau \rightarrow \int_0^u \frac{[K(u)]^2}{\partial N_m^2 \xi \sigma_s \sigma_t} du \quad (4)$$

where k satisfies a boundary condition for each energy of the form:

$$-\frac{\tan ka}{ka} = \frac{p(u)}{p(u) - 1} \quad (5)$$

p is a kind of admittance function for the reflector and in the particular case of an infinite reflector of mean free path λ' and diffusion length L , takes the form:

$$p = \frac{\lambda}{\lambda'} \frac{1}{1 + \frac{a}{L}} \quad (6)$$

where λ , λ' , and L may all be functions of u . What to do in the case of inelastic scattering is not clear, but the formula is probably applicable if one takes L as equal to the diffusion length for "equilibrium" neutrons above the inelastic scattering threshold. For pure natural U this diffusion length is 9.6 cm. The choice of a in equation (5) which leads to the correct value of $\frac{1}{k}$ when the corresponding values of k are used in equations (4) and (1), gives the critical radius for the assembly.

It is possible to define an average admittance in terms of the following procedure. Choose a value of a and solve (5) for each energy.

Next define:

$$\overline{k^2} = \frac{\int_0^{u_0} \frac{k^2}{3\xi^2 \sigma_s \sigma_t} du}{\int_0^{u_0} \frac{1}{3\xi^2 \sigma_s \sigma_t} du} \quad (7)$$

where u_0 is some value of the energy beyond which the survival of neutrons

becomes small. The definition is not very critical to the choice of u_0 . The value of p in equation (5) which leads to $k = (\bar{k}^2)^{1/2}$ may be called the average admittance, and the diffusion length corresponding to this may be used in the calculations to be described below. This will be called the effective diffusion length of the blanket.

The principles described above enable us to compute an equivalent critical k^{-1} for uniform cores of moderator and fuel inside a U^{238} blanket. If the pure Be reflector of the pile is not too thick, it is possible to replace the core + reflector by a uniform core having a different dilution ratio m , so far as the effective spectrum of the mixture goes. Using the principles of perturbation theory it is possible to show that this effective value of m is given by:

$$\frac{m}{m_0} = \frac{a}{b} \frac{1 - \frac{\sin 2 ka}{2 ka}}{1 - \frac{\sin 2 kb}{2 kb}} \quad (8)$$

where b and a are respectively the core and reflector radii. This relation can be further generalized to cover cores where the moderator has different density in reflector and core. Cf. equation (11) in the next section.

Determination of Effective Diffusion Length

Application of the procedure indicated in connection with equation (7) shows that the effective diffusion length L should be taken as the equilibrium value of 9.6 cm, and that the appropriate transport cross-section for U is in the ratio of 0.65 to Be. Corrections can be made for reduced blanket density by means of the following correction factor:

TABLE 2

Illustrating Determination of Effective Diffusion Length
 Pure Be in Contact with Pure U-238

<u>n</u>	<u>λ/k</u>	<u>L</u>	<u>$p(u)$</u>	<u>ka</u>	<u>$(ka)^2$</u>
1	.814	9.6	.2046	2.557	6.538
2	.618	9.6	.1571	2.677	7.166
3	.597	9.6	.1447	2.709	7.339
4	.723	9.6	.1753	2.630	6.917
5	.692	7.0	.1309	2.746	7.540
6	.638	5.6	.1191	2.778	7.717
7	.566	4.8	.0781	2.898	8.398
8	.530	4.8	.0731	2.914	8.491
9	.530	4.8	.0731	2.914	8.491
10	.530	4.8	.0731	2.914	8.491

$$(ka)^2 = 7.254$$

$$L = \left\{ \frac{\sigma_t \text{ for pure U}}{\text{actual } \sigma_t \text{ of blanket}} \cdot \frac{1}{\% \text{ by vol. of U in blanket}} \right\}^{1/2} 9.6 \text{ cm. (9)}$$

Procedure for Calculations

First, it is necessary to determine transport and slowing down cross-sections for all portions of the assembly. The energy at which these cross-sections are taken is chosen somewhat arbitrarily as 100 KV. This is the energy above and below which roughly 50% of the neutron flux is distributed in the types of assemblies in which we are interested. The actual median energies as obtained by D. R. Miller are shown in Table 3. The exact choice of energy is

<u>n</u>	<u>u = 0 → 10⁷ ev.</u>	
	<u>u</u>	<u>E</u>
19.3	2.9	5.6 × 10 ⁵ e.v.
28.9	3.2	3.1
48.3	3.7	2.6
89.5	4.2	1.5
151.0	4.7	0.9

TABLE 3

not very important since transport and scattering cross-sections are relatively insensitive to energy, and furthermore, the results depend only on ratios of cross-sections which are even more independent of energy.

The transport cross-sections are shown in Table 4, for materials which appear in the pile.

Table 4 - Transport Cross-Sections

Substance	Nuclear	Atomic Volume	Bulk
Be	$4.23 \times 10^{-24} \text{ cm}^2$	$8.1 \times 10^{-24} \text{ cm}^3$	0.522 cm^{-1}
Fe	3.6	11.9	.305
Na	4.0	39.4	.101
U	8.5	21.3	.400
UO ₂	16.5	74.1	.223
O ₂	4.12	9.87	

The actual transport cross-section is computed by multiplying each bulk cross-section by the volume fraction of the given material, adding, and thence obtaining a weighted average.

The bulk slowing down cross-sections are similarly shown in

Table 5.

Table 5 - Slowing Down Cross Sections Σ^s

Substance	Nuclear Cross Section	At. Vol. Bulk Cross Section
Be	$0.952 \times 10^{-24} \text{ cm}^2$	0.1175 cm^{-1}
Fe	0.129	0.0108
Na	0.348	0.0088
O	.593	.0668 X 2
O ₂	.593	

Weighted averages are obtained from this table in the same manner as described for the transport cross-sections.

To determine an effective value of m we proceed as follows:

The effective slowing down cross-section for the reactor as a whole may be taken as:

$$\frac{b}{a} \left(\frac{1 - \frac{\sin 2kb}{2kb}}{1 - \frac{\sin 2ka}{2ka}} \right) \left(\xi \Sigma_{\text{core}}^s - \xi \Sigma_{\text{refl.}}^s \right) + \xi \Sigma_{\text{refl.}}^s \quad (10)$$

where $\xi \sigma_s^{\text{core}}$ and $\xi \sigma_s^{\text{refl.}}$ are the bulk slowing down cross-sections for core and reflector, respectively. The effective number of uranium 235 atoms in the reactor as a whole is given by:

$$\frac{U^{235} \text{ volume fraction}}{21.3 \times 10^{-24}} = \frac{b}{a} \frac{1 - \frac{\sin 2kb}{2kb}}{1 - \frac{\sin 2ka}{2ka}} \quad (10')$$

To get the effective number of Be atoms per U^{235} atom, we divide (9) by (10'), obtaining the slowing down cross-section per U^{235} atom, and divide the result by the slowing down cross-section for a single Be atom, i.e. $0.952 \times 10^{-24} \text{ cm}^2$. The resulting expression for n_{eff} is:

$$n_{\text{eff}} = \frac{22.4}{\text{Volume fraction } U^{235}} \left\{ \xi \sigma_s^{\text{core}} - \xi \sigma_s^{\text{refl.}} + \frac{\xi \sigma_s^{\text{refl.}}}{W} \right\} \quad (11)$$

where

$$W = \frac{b}{a} \frac{\left(1 - \frac{\sin 2kb}{2kb}\right)}{\left(1 - \frac{\sin 2ka}{2ka}\right)}$$

W is known as the statistical weight of the core. This factor is plotted in Figure 2 as a function of b/a for several different values of ka . The result (11) may be regarded as a generalization of the basic relation equation (8).

Having determined n_{eff} , we find the corresponding value of k^{-1} from Table 1 or Figure 1. This number must then be multiplied by the following factor:

Correction factor =

$$\left\{ \frac{(\xi \sigma_s)_{\text{core}} (\sigma_{\text{tr}})_{\text{core}}}{[(\xi \sigma_s)_{\text{Be}} (\sigma_{\text{tr}})_{\text{Be}}] \left[\frac{8.1 m_{\text{eff}}}{21.3 \cdot 8.1 m_{\text{eff}}} \right]^2} \right\}^{-1/2} \left(\frac{m_{\text{eff}}}{m} \right)^{-1/2} \quad (11')$$

Here m is effective ratio of Be to U in core, taking into account moderation by Na and Fe but not the influence of the reflector. The reason for the last factor in (11') is that the reflector increases the effective moderation ratio but does not add volume to the core.

Correction factor =

$$\frac{.2475}{1 + \frac{2.63}{m}} \cdot \frac{1}{\sqrt{(\xi \sigma_s \sigma_{\text{tr}})_{\text{core}}} \sqrt{1 + \frac{\xi \sigma_s R}{\xi \sigma_s C} \left(\frac{1}{W} - 1 \right)}} \quad (12)$$

Thus the more dilute the core, the larger the value of k^{-1} .

Once the true k^{-1} for the core is determined, the criticality condition is determined by:

$$-\frac{\tan kb}{kb} = \frac{p}{1-p} \quad (13)$$

where now p is fixed by conditions in the reflector, and blanket. The solutions of equation (13) are tabulated in Table 6, together with first and second differences for interpolation. The results are also presented in graphical form in Figure 3. Equation (13) may usually be regarded as an equation for determining b , a fixed value of b/a and of k^{-1} being assumed. Since p depends also on a alone, as shown below, there is a

Solutions of $-- \frac{\tan kb}{kb} = \frac{p}{1-p}$

TABLE 6

<u>p</u>	<u>kb</u>	<u>Δ</u>	<u>Δ^2</u>
0.0	3.1416	.3053	
0.1	2.8363	.2559	.0394
0.2	2.5704	.2172	.0477
0.3	2.3522	.1776	.0406
0.4	2.1746	.1458	.0318
0.5	2.0288	.1217	.0242
0.6	1.9071	.1031	.0186
0.7	1.8041	.0885	.0145
0.8	1.7155	.0770	.0116
0.9	1.6385	.0677	.0093
1.0	1.5708		

condition of self-consistency involved. That is, one must assume a value of a to determine p , thence determine b from (13), and from the known value of b/a deduce a corrected value of a and hence of p , until the results are self-consistent. This can be done by interpolation with respect to the quantity $a_{\text{assumed}} - a_{\text{calculated}}$ plotted as a function of a_{assumed} .

The geometry of the proposed pile may be represented schematically by the spherical assembly of Figure 4.

FIGURE 4

We have:

$$p = \frac{\sigma_{tB} b}{\sigma_{tC} a} \frac{1}{1 + \frac{a}{L}} + \frac{\sigma_{tR}}{\sigma_{tC}} \left(1 - \frac{b}{a}\right) \quad (14)$$

for this problem, where the blanket is assumed to be infinite in extent.

Control Problems

In order to estimate the effectiveness of the controls it is sufficient in a first approximation to determine the change in reactivity

resulting from altering the average density of the reflector. To do this we start with an assumed geometry and composition. This determines p , and hence ultimately k^{-1} through the application of equation (13). Since ka and b/a are then known we can determine W and hence m_{eff} from equation (11). Also, we can determine the correction factor (12). If we apply this factor inverted to the value of k^{-1} determined from (13) we obtain the k^{-1} of the equivalent uniform mixture, appropriate to this value of m . Now, from equation (1), we have the relation:

$$-\nu \frac{d}{d(k^2)} \left(\frac{1}{\nu} \right) = \bar{\tau} \quad (14)$$

where $\bar{\tau}$ is the average age appropriate to this value of m . Equation (14) may be put in the form:

$$\nu d \left(\frac{1}{\nu} \right) = 2k^3 \bar{\tau} dk^{-1} \quad (15)$$

If the assembly is near to critical, we may use equation (15) to find the change in $\frac{1}{\nu}$ corresponding to the change in k^{-1} necessary to bring the k^{-1} of the equivalent mixture into agreement with the value given in Figure 1.

If the calculation described above is repeated for a different density reflector a new value of the equivalent k^{-1} will be determined, and the change in reactivity may be computed directly from equation (15). In this way we get an expression for the change in reactivity per fractional removal of the reflector. This result applies if the material is removed uniformly from all parts of the reflector. The effectiveness of

material removed at different radii is for a given fraction of the reflector volume proportional to the inverse 4th power of the distance from the center of the reactor, to quite a good approximation. Another useful relation is that the control effectiveness is proportional to the transport cross-section of the material removed. (Cf. report GE-HB-8, A-4269).

The quantity $2k^3\bar{v}$ involved in equation (15) is plotted as a function of m in Figure 1.

First Numerical Example

As a first illustration we choose a case which has already been treated by the multi-group method by Ehrlich and Hurwitz (Report GE-HB-1). Using their percentage compositions, we have the following constants:

$$b = 25 \quad a = 35 \quad \text{Volume fraction } U^{235} = .0329$$

$$\int \sigma_{sc} = .0735 \quad \int \sigma_{sR} = .1104$$

$$\sigma_{tc} = .3927 \quad \sigma_{tR} = .448$$

There is no blanket in this problem, hence we have:

$$p = \frac{.448}{.3927} \frac{10}{35} = .3265$$

from which we obtain $kb = 2.305$, or

$$k^{-1} = 10.85$$

Next we find $W = 0.87$, whence:

$$m_{eff} = \frac{22.4}{.0329} \left[-.0369 + \frac{.1104}{.87} \right] = 61.3$$

using equation (11). Next we obtain from (12),

Correction factor =

$$\frac{.236}{.170} \frac{1}{\sqrt{1.225}} = 1.254$$

Hence the k^{-1} for the equivalent mixture becomes

$$\frac{10.85}{1.254} = 8.65$$

whereas from Table 1 the true value of k^{-1} to give $\nu = 2.5$ is 8.66. ^{7/}

Thus the given assembly is almost exactly critical and we have:

$$\nu d\left(\frac{1}{\nu}\right) = (.165)(-.01) \cong .0016$$

which corresponds with:

$$\nu_c = 2.51$$

as compared with a value of 2.25 by the multi-group method. Some of the discrepancy is due to the fact that a lower spectrum was assumed in the multi-group calculations than in the age calculations. It can be estimated that the lower spectrum in the multi-group calculations increases the reactivity by 2.3%, which would reduce ν_c to 2.45, and make the agreement between exact and approximate theories somewhat better.

As a second example, we consider a reflector of 75% density. For this case $p = .245$, $kb = 2.472$, $k^{-1} = 10.11$. Since $W = 0.87$ we have:

$$n_{\text{eff}} = 58.5$$

Correction factor =

$$\frac{.237}{.170} \frac{1}{\sqrt{1.169}} = 1.289$$

Thus the equivalent k^{-1} is 7.85 as compared with a critical value of 8.62.

(8.72)

Thus:

$$\rho_d\left(\frac{1}{f}\right) = (.165)\left(-.77\right) = -.127$$

which represents a reactivity decrease of 12.5% due to reduction in reflector density. This is to be compared with a value of 16% obtained by the multi-group calculation. Here the discrepancy is believed due to the fact that the multi-group calculation gives a more rigorous treatment of the slowing down. The extra effectiveness of the Be arises from the slowing down effect at low energies. The point is that the neutron spectrum in the reflector is lower than that in the core, and therefore the transport cross-section of the reflector Be is higher than that of the core Be. Indeed, if the result is estimated with a transport cross-section of 5.6 barns for Be, the reactivity change becomes 16.5% instead of 12.5%, in better agreement with the multi-group calculation. This is probably a consequence of the unusually large amount of Be in the reflector, and the same change in cross-section is not recommended for the case of a U^{238} blanket.

Second Numerical Example

As a second example, let us consider the Schenectady Pile with specifications as contained in Lockhart's compilation of April 4, 1947 (Memo-GM-1, before Figure 5), but having a natural U instead of a U-Be breeding blanket. The volume percentage compositions are, then, to be taken as follows:

	<u>Core</u>	<u>Reflector</u>	<u>Blanket</u>
U^{235}	.030		
U^{238}	.004		.869
Be	.508	.854	
Fe	.075	.108	.029
Na	.383	.038	.102
	$b = 25.54$	$a = 30.54$	

The radius b is calculated from the radius of the sphere of volume equal to that of the actual core. The reflector thickness is taken as 5 cm. Using the bulk cross-sections of Tables 4 and 5 we have:

	<u>Core</u>	<u>Reflector</u>	<u>Blanket</u>
σ_{tr}	.340	.483	.368
$\rho\sigma_a$	.0638	.1016	—
L			10.4

Thus we have:

$$p = \frac{.483}{.340} \cdot \frac{5}{30.54} + \frac{.368}{.340} \cdot \frac{1}{1 + \frac{30.54}{10.4}} \cdot \frac{25.54}{30.54} = .4384 \text{ or } \underline{\underline{.438}}$$

$$kb = 2.119, k^{-1} = 12.06$$

$$b = 25.5 \text{ cm}$$

Also, we have for the calculation of W that $ka = 2.53, kb = 2.12$

Then:

$$W = \frac{25.54}{30.54} \cdot \frac{1 + .210}{1 + .186} = .853$$

Thus:

$$M_{\text{eff}} = \frac{22.4}{.030} \left\{ - .0378 + \frac{.1016}{.853} \right\} = 60.8$$

Thus the correction factor becomes:

$$\frac{.236}{.1474} \cdot \frac{1}{\sqrt{1 + .276}} = 1.417$$

Equivalent k^{-1} is 8.51 as compared with true value of 8.66. Hence, this assembly is under critical by an amount:

$$\rho_d\left(\frac{1}{\beta}\right) = (.165) (.15) = .0297 \text{ so that}$$

$$\rho_c = 2.562$$

The assembly could thus be made critical with a slightly thicker reflector.

To investigate control, we consider a reflector with 75% density.

For this case we have: $p = .3804$, $k_b = 2.210$, or $k^{-1} = 11.56$. Also:

$$M_{\text{eff}} = \frac{22.4}{.030} .0769 = 57.4$$

$$\text{Correction factor } \frac{.2365}{.1474} \cdot \frac{1}{\sqrt{1 + .207}} = 1.460$$

Equivalent k^{-1} is $\frac{11.56}{1.460} = 7.92$, so that

$$\rho_d\left(\frac{1}{\beta}\right) = (.165) (8.62 - 7.92) = .115$$

Thus the change in reactivity is 9%. Comparing this result with the first example we observe that 9% is probably somewhat of an underestimate,

and the result may be closer to 11%, for 25% removal of the reflector. In the structure proposed by Lockhart the Be control rods comprised 42% of the total Be. This would suggest a value of something like 15% for the total reactivity held in the control rods if the same volume ratio could be maintained in the thinner reflector.

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