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PROCESS DEVELOPMENT PILE MEASUREMENTS OF LATTICE PARAMETERS OF NATURAL URANIUM IN HEAVY WATER

by

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Experimental Physics Division

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ABSTRACT

Details and complete results are given of a series of lattice studies performed in the Process Development Pile (PDP). Some of the results were presented at the Second United Nations International Conference on the Peaceful Uses of Atomic Energy[1].

The lattices studied covered a large range of configurations of natural uranium fuel in heavy water moderator. Fuel assemblies consisted of single bare metal rods, clustered bare metal rods, clustered bare metal plates, metal tubes in aluminum housings, and clustered rods of aluminum-clad UO_2. After the 1958 Geneva Conference, additional measurements were made with assemblies of metal plates inside gas-filled tubes. Triangular or equivalent lattice spacings were varied from 7.00 to 10.69 inches by the use of 7, 6, 5, 4, or 3 assemblies in the PDP test region.

A detailed tabulation contains the measured bucklings and the moderator purity corrections for all lattices measured. The tabulation also includes calculated parameters, such as ϵ, p, f, L^2, and τ. Corrections required because of the irregular spacing of the test assemblies are discussed and listed for each lattice. The two-group, two-region method of analyzing critical water heights is described in detail.

A comparison is made of the PDP measurements with similar measurements that were made at Chalk River, A.B. Atomenergi, Saclay, and North American Aviation.

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PROCESS DEVELOPMENT PILE MEASUREMENTS OF LATTICE PARAMETERS OF NATURAL URANIUM IN HEAVY WATER

INTRODUCTION

The purpose of the present report is to supplement the paper, "Physics of Natural Uranium Lattices in Heavy Water", presented by the Savannah River Laboratory at the Second United Nations International Conference on the Peaceful Uses of Atomic Energy[1]. Further information given here includes the detailed lattice spacings, the individual buckling data measured for each lattice, and corrections for impurity of moderator and for irregular spacing of lattice components. Also included are calculated values of the parameters L^2, τ, f, ϵ, and of S_{eff}/M for resonance capture. The method used for the two-group reduction of critical water heights to test region bucklings is described, and the mathematical procedure is given in detail. A possible small but systematic source of error in the Savannah River Laboratory measurements is indicated. The error becomes discernible only at very high moderator-to-fuel volume ratios, where it tends to lead to high values of buckling.

More general topics are also considered. One such topic is our own experience in the comparison of critical and subcritical buckling measurements on identical lattices. Another such topic is the Savannah River Laboratory procedure for using the method of Critoph[2] to relate the resonance escape probability to the effective resonance integral. The computational procedure has been greatly simplified for spacings of 6 inches or greater. It is felt that the present procedure will be of value to other experimenters making similar analyses.

Additional buckling measurements on uniformly spaced metal rods of 0.50- and 0.69-inch diameters have been made since the initial report. The results of these measurements are compared with similar measurements elsewhere.

Lattice measurements by other experimenters on clusters of metal and oxide rods and plates similar to those at Savannah River Laboratory are compared by means of the same "recipe" that was used to correlate the Savannah River Laboratory measurements.

SUMMARY

Buckling measurements were made on a series of approximately 250 natural uranium-D_2O test lattices, which were studied in the central test region of the PDP. The bucklings were obtained from a two-group, two-region analysis of measured critical water heights. A code for this analysis was developed for the IBM 650 computer. The code requires the knowledge of certain measured lattice parameters for the outer region and certain calculated lattice parameters for the test region.

The code yields both the buckling and the resonance escape probability of the test lattice.

The outer region parameters were determined on the basis of full pile loadings. In determining the inner region parameters the thermal utilization, f, and the thermal diffusion area, L^2, were calculated for each lattice by the P_3 approximation to diffusion theory. For these calculations, homogeneous cylindrical models were used for the fuel assembly. The slowing down area, τ, was obtained from the measured τ for D_2O by the inclusion of the slowing down properties of the fuel and aluminum. Streaming corrections to τ and L^2 were made for the gas-cooled lattices. The actual measurements were made in moderator which had an isotopic purity ranging from 99.1 to 99.3 mol % D_2O. Calculated corrections to a reference purity of 99.75% were made for each lattice. Additional corrections were made for the irregularly spaced lattices used in the metal plate clusters.

The corrected bucklings were correlated by a semiempirical recipe. This recipe was obtained by calculating each of the parameters, η, ϵ, f, L^2, and τ according to a fixed procedure and thus obtaining values of the buckling, B^2, and the resonance escape probability, p, from the critical water height and the critical equation, $k_\infty = \eta\epsilon fp = (1 + L^2B^2)(1 + \tau B^2)$. The resulting values of p were used to obtain an expression for the effective resonance integral as a function of the effective surface-to-mass ratio of the assembly. A good fit to the data was obtained by assuming that the resonance capture took place at an effective energy of 30 ev. The resultant expression for the "resonance integral" is the essential part of the SRL recipe for calculating bucklings. The derived resonance integrals for all SRL lattices are listed in Tables I to V. These tables also give the parameters, measured and calculated, and the corrections for each of the lattices studied.

The SRL recipe was used to compare the PDP measurements with similar buckling measurements on clustered rods and plates made at Chalk River and Saclay. The agreement was found to be extremely good for clusters of UO_2 rods. The agreement in the region of maximum buckling is also satisfactory for clusters of metal rods and plates, but the PDP measurements are consistently higher at high moderator-to-fuel volume ratio than those of Chalk River and Saclay. The SRL recipe predicts consistently higher bucklings than those measured at Chalk River and Saclay for assemblies consisting of single rods. However, the recipe also predicts higher bucklings than those measured later for similar lattices in the PDP. This suggests a partial breakdown of the recipe which was derived for clustered assemblies in the extension to the case of solid rods. The PDP measurements on solid rods give lower bucklings than expected from extrapolations of measurements at North American Aviation and A. B. Atomenergi, despite the fact that the SRL recipe is found to be in good agreement with the measurements of these laboratories.

A revision has been made in the method of calculating the reactivity change of natural uranium lattices with exposure. The results indicate that in some cases the maximum cycle exposure may be 1.5 times that reported earlier.

DISCUSSION

EXPERIMENTAL RESULTS

MEASUREMENTS

The tables included in this report give the measured and calculated values of the nuclear parameters for the lattices studied in the PDP and reported in part at the Geneva Conference[1]. Measured and calculated parameters are given for the reference moderator purity of 99.75 mol % D_2O. Actual moderator purities were 99.3% for the D_2O and gas-cooled plate lattices and for the tubes, 99.2% for the oxide-fueled lattices, and 99.1% for the clustered metal rod lattices.

The experimental procedure for buckling measurements consisted of adjusting the water height of the pile for criticality with the test lattice inserted. In addition to this critical water height, calculated parameters for the actual moderator purity were used in a two-group analysis to give the radial buckling, μ^2, of the test region. This analysis procedure is discussed in detail in a separate section.

ASSEMBLY DETAILS

For the gas-cooled lattices the gas-containing housings were of 2S aluminum. The dimensions given in Figure 13 of the Geneva report are the outer dimensions of the housings. The aluminum wall thickness was 0.064 inch. The lacquer coating of the metal plates and rods was found to contain no significant amount of strong neutron absorbers. The thin lacquer coating (approximately 0.001 inch) was estimated not to affect the data within the stated accuracy of the experiment. The same holds for the polyester tape that was used to hold the clustered assemblies together.

The geometrical shape for each type of clustered rod lattice is given in Figure 1 of the Geneva report. However, only representative plate lattices are given. Each of the plate assemblies was rectangular in shape. Each assembly consisted of one, two, or three rows of plates with an equal number of plates in each row. The number of rows and the number of plates in each row for all lattices studied is summarized in Table VI.

LATTICE SPACING

A schematic of the central test region is shown in Figure 1. The actual placement of the elements is indicated for the effective spacings 7.00, 7.56, 9.27, and 10.69 inches. As outlined in the Geneva report, corrections were made for those lattices not actually having triangular spacing. No correction, however, was made in the case of the 9.27-inch spacing used for the metal and oxide rods because it was a regular square lattice.

BUCKLING CALIBRATION

The calibration of the test region was established by use of known lattices of natural uranium. The material buckling of these lattices was accurately known from previous measurements in large-scale loadings of the PDP. Buckling values for these known lattices ranged from -1 to +6 m^{-2} and L^2 values were in the range of 50 to 100 cm^2. The value of the material buckling in the outer region was obtained at regular intervals during the experiments by measuring critical water heights of a one-region pile obtained by extending the outer lattice through the test region. The calibration lattices were also inserted at intervals and the critical water heights measured. The boundary between the test region and the outer region was taken as the only adjustable parameter in matching the known buckling values to the values obtained by the two-group analysis of the water heights. The boundary thus obtained was at a radius of 25.6 cm compared to 24.7 cm obtained by cylindricizing the cell area associated with the test region.

MODERATOR PURITY CORRECTIONS

Calculated corrections to the reference moderator purity were made for each of the parameters except for B^2, which was determined from the remaining parameters of the reference purity by the two-group critical equation $\eta\epsilon fp = (1 + L^2B^2)(1 + \tau B^2)$. The fast fission factor and η were assumed to be independent of the light water contamination. The corrections to f and L^2 were obtained from the change in effective absorption and scattering cross sections under the assumptions that the flux profiles of the cells were the same as those given by the P_3 theory for the lower moderator purity. The correction to τ was made on the basis of our own measurements of τ over an extended range of H_2O-D_2O mixtures[3]. The correction to the resonance escape probability was made under the assumption that the quantity (1 - p) varies inversely with the slowing down power ($\xi\Sigma_s$) for the moderator.

TWO-GROUP ANALYSIS OF TWO-REGION BUCKLING MEASUREMENTS

The Process Development Pile (PDP) is a large, heavy-water-moderated reactor. It has a cylindrical tank with an inner radius of 247.0 cm and a usable height of 465 cm. The walls and bottom are of stainless

steel 1.27 cm thick. The outer lattice used in these experiments was loaded so that there was no radial reflector. The fuel pieces in both the inner and outer lattices were, however, positioned 20.3 cm above the bottom of the reactor tank so as to produce a D_2O bottom reflector of that thickness. Since most of the experiments were performed at low water heights, the fuel assemblies normally projected above the water surface and there was thus no upper D_2O reflector. The effective nuclear dimensions of the reactor were determined by measuring radial and vertical flux profiles with various configurations of the normal outer lattice loaded throughout the pile. The nuclear radius of the reactor and the top and bottom flux extrapolation distances were found to be insensitive to water heights over a range of 200 to 450 cm. The present measurements used the much smaller range of 280 to 320 cm. The nuclear radius was 255.7 cm, and the flux extrapolations ended 3.1 cm beneath the bottom of the lower reflector, and 8.7 cm above the top of the water.

Extensive use has been made of the PDP as a two-region reactor. As outlined in an earlier section, a lattice of precisely known properties is loaded into the outer region of the reactor and an unknown lattice is loaded into the smaller central region. The critical moderator height is then determined for the combined loading. From the measured water height and from the known properties of the outer lattice, it is possible to infer the buckling of the inner lattice. For lattices in which the fast and slow diffusion properties of the unknown lattice are similar to those of the outer region, bucklings may be obtained from a calibration curve based on one-group diffusion theory, which is drawn through the measured water heights and bucklings for a series of reference lattices in the inner region. This technique has been described by B. M. Carmichael and G. F. O'Neill.[4]

However, the calibration curve technique is valid only for lattices having properties very nearly the same as those of the reference lattices. For lattices whose characteristics - bucklings, migration areas, diffusion coefficients, etc. - diverge widely from the reference lattices, large errors may sometimes result from the use of the calibration curve. Another approach is to analyze the results directly by two-group diffusion theory without reference to any calibration curve. This technique may be expected to give more accurate results over a wide range of lattices, although it may give less accurate results for lattices that are nearly identical to the calibration lattices. In the two-group theory both the fast and slow neutron fluxes and currents are matched at the central region - outer region interface. Physically, this theory implies that the critical water height depends not only on the bucklings of the two regions, but also on the other lattice constants of the two regions - viz., p, L^2, τ, D_f, and D_s which are, respectively, the resonance escape probability, the thermal diffusion area, the neutron age, and the fast and slow diffusion coefficients.

TWO-GROUP EQUATIONS

The calculations for the two-group analysis simply apply the general two-group diffusion equation to a two-region, cylindrical reactor. The development, derived by P. L. Roggenkamp, follows.

The reactor is considered to consist of two regions: a central region (a) with radius r_1; and an outer annular region (b), starting at r_1, and ending at the extrapolated outer boundary of the pile r_2.

If subscripts f and s are used to denote quantities relating to the fast or slow flux, respectively, the radial distributions of the fast flux in region (a) is then given as

$$\Phi_{fa} = C_{1a}J_o(\mu_a r) + C_{2a}I_o(\nu_a r)^*$$

$$= C_{1a}F_a + C_{2a}G_a$$

where C_{1a} and C_{2a} are constants, one of which may be arbitrarily chosen,

$$F_a \equiv J_o(\mu_a r) \text{ and } G_a \equiv I_o(\nu_a r),\ \mu_a^2 = B_a^2 - \pi^2/H^2$$

and

$$-\nu_a^2 = -B_a^2 - \pi^2/H^2 - \frac{1}{\tau_a} - \frac{1}{L_a^2}$$

Also the radial distribution of the slow flux in region (a) is given as

$$\Phi_{sa} = S_{fa}C_{1a}F_a + S_{sa}C_{2a}G_a$$

where

$$S_{fa} = \frac{D_{fa}}{\tau_a D_{sa}} \times \frac{p_a}{\frac{1}{L_a^2} + B_a^2}$$

$$S_{sa} = -\frac{D_{fa}}{\tau_a D_{sa}} \times \frac{p_a}{\frac{1}{\tau_a} + B_a^2}$$

D_f and D_s are the fast and slow diffusion coefficients, respectively. L^2 and τ are the thermal and fast diffusion areas, respectively. H is the extrapolated critical water height. B^2 is the material buckling, and p is the resonance escape probability. In region (b) the radial equations for the fast and slow fluxes take the form

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* The precise functions J_o and I_o hold only for the normal case $\mu_a^2 > 0$ and $\mu_b^2 > 0$. For either $\mu_b^2 < 0$ or $\mu_a^2 < 0$, the corresponding Bessel functions must be used. The development does not require the argument to be real.

$$\phi_{fb} = C_{1b}\left[J_o(\mu_b r) - TY_o(\mu_b r)\right] + C_{2b}\left[I_o(\nu_b r) - UK_o(\nu_b r)\right]$$

$$= C_{1b}F_b + C_{2b}G_b$$

and $$\phi_{sb} = S_{fb}C_{1b}F_b + S_{sb}C_{2b}G_b$$

where $$F_b = J_o(\mu_b r) - TY_o(\mu_b r)$$

$$G_b = I_o(\nu_b R) - UK_o(\nu_b r)$$

$$T \equiv \frac{J_o(\mu_b r_2)}{Y_o(\mu_b r_2)}, \quad U \equiv \frac{I_o(\nu_b r_2)}{K_o(\nu_b r_2)}$$

and μ_b, ν_b, S_{fb}, and S_{sb} take the same form as for region a. Note that T and U are evaluated at the outer boundary by applying the condition $\phi_{fb}(r_2) = \phi_{sb}(r_2) = 0$. The equations for the fluxes and currents can be written in matrix form.

Let $$\psi = \begin{bmatrix} \phi_f \\ \phi_s \\ D_f\phi_f' \\ D_s\phi_s' \end{bmatrix}$$

where the symbol (') represents a differentiation with respect to r so that $D_i\phi_i'$ is the i^{th} current.

Then ψ_a and ψ_b can be written as $\psi_a = M_a\gamma_a$ and $\psi_b = M_b\gamma_b$

where $$\gamma_i = \begin{bmatrix} C_{1i} \\ C_{2i} \\ 0 \\ 0 \end{bmatrix} \text{ and } M_i = \begin{bmatrix} F_i & G_i & 0 & 0 \\ S_{fi}F_i & S_{si}G_i & 0 & 0 \\ D_{fi}F_i' & D_{fi}G_i' & 0 & 0 \\ D_{si}S_{fi}F_i' & D_{si}D_{si}'G_i' & 0 & 0 \end{bmatrix}$$

and i is either (a) or (b). Applying the boundary condition at r_1 that

$$\psi_a(r_1) = \psi_b(r_1)$$

it follows that $M_a(r_1)\gamma_a = M_b(r_1)\gamma_b$

It can be shown that there is a matrix Q(r) such that

$$Q_b(r_1)M_b(r_1)\gamma_b = 0$$

and by the preceding equation it must also be true that

$$Q_b(r_1)M_a(r_1)\gamma_a = 0$$

Since $\gamma_a \neq 0$, it must follow that the determinant of the product matrix $Q_b(r_1)M_a(r_1)$ is equal to zero.

This $Q_b(r_1)$ has the form

$$Q_b(r_1) = \begin{bmatrix} 1 & 0 & \dfrac{S_{fb}\dfrac{G_b}{G_b'} - S_{sb}\dfrac{F_b}{F_b'}}{-D_{fb}(S_{fb} - S_{sb})} & \dfrac{\dfrac{F_b}{F_b'} - \dfrac{G_b}{G_b'}}{-D_{sb}(S_{fb} - S_{sb})} \\ 0 & 1 & \dfrac{S_{fb}S_{sb}\dfrac{F_b}{F_b'} - \dfrac{G_b}{G_b'}}{D_{fb}(S_{fb} - S_{sb})} & \dfrac{S_{fb}\dfrac{F_b}{F_b'} - S_{sb}\dfrac{G_b}{G_b'}}{-D_{sb}(S_{fb} - S_{sb})} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The product $Q_b(r_1)M_a(r_1)$ reduces to a two-by-two matrix and its determinant can easily be evaluated. The advantage of using this method to solve the equations for B_a^2 is that, for a particular water height, Q_b is determined altogether by the properties of region b, whereas M_a depends only on properties of region a. The solution is then the B_a^2 for which the above determinant of the product matrix, $Q_b(r_1)M_a(r_1)$, is zero.

MACHINE COMPUTATIONS OF TWO-GROUP ANALYSIS

The two-group equations developed in the previous section were coded for computation on an IBM 650 computer. Input to the machine consists of the effective radii of the two reactor regions, the measured water heights, the constants, p, D_f, D_s, τ, L^2, and B^2 for the outer region, and the constants D_f, D_s, τ, L^2, and $\eta f\epsilon$ for the inner region.

Since both p_a and B_a^2 are unknown and hence are not specified, the solution which makes the determinant vanish is not unique. Each choice of p_a will, in general, result in a different value of B_a^2. To provide a unique solution, the machine code requires the simultaneous solution of the two-group critical equation

$$p_a(\eta f\epsilon)_a = (1 + L_a^2B_a^2)(1 + \tau_aB_a^2)$$

The resulting values of p_a and B_a^2 then satisfy both the criticality equation and the two-group flux and current continuity conditions at the boundary.

RELATION OF μ^2 to B^2 OF ONE-GROUP THEORY

The coefficients μ_a^2 and μ_b^2 which appear in the two-group development are taken as equivalent to the radial components of the buckling B^2 of one-group theory. The coefficients ν_a^2 and ν_b^2 have no such counterpart in one-group theory. The following considerations support this equivalence. First, for values of k_∞ close to unity the quadratic equation defining the μ^2 coefficients reduces to the familiar one-group equation $(\mu^2 + \pi^2/H^2) = (k_\infty - 1)/(L^2 + \tau)$. Second, the flux shape far from the boundary of the two regions, where one-group theory holds, is given closely by the functions of μ^2. The functions of ν^2 are large only near the interface. Finally, if for any given problem all parameters other than μ^2 and ν^2 are made equal in the two regions, the value μ_a^2 obtained is equal to the radial value of B_a^2 obtained by simple one-group diffusion theory.

COMPARISON WITH OTHER EXPERIMENTS

Comparison of the PDP measurements with those made at other sites with similar lattices is complicated by differences in cladding, differences in rod and plate sizes, differences in moderator purity, differences in fuel density, etc. A comparison can be made by calculating the buckling expected for the lattices of other experimenters on the basis of the "recipe" that was used at SRL to correlate the SRL measurements. This has been done for representative lattices measured at NAA[5], at Chalk River[6], and at Saclay in the "Aquilon" reactor[7]. The results of these calculations are shown in Figures 2 to 5. For each case the nuclear parameters given by these authors were calculated on a basis consistent with that used for the SRL lattices. Only values of the parameters L^2 and f given for the Saclay and Chalk River lattices agreed well enough with the SRL calculations to be used with only small moderator purity corrections. This agreement was determined by spot checks of typical lattices. These were, however, the only nuclear parameters, other than bucklings, derived from the separate reports.

The agreement among Chalk River, Saclay, and the PDP is very good for the oxide-fueled lattices. The metal lattices, however, do not compare quite so well. The Saclay lattices of uniformly spaced metal rods (BΦ26 to BΦ44) show consistently lower bucklings than those predicted by the SRL recipe except for the closest spacings. The Aquilon clusters of seven metal rods (G-0, G-2, and G-5) give lower bucklings at large spacings and show less spread with rod spacing at small spacings than predicted by the SRL recipe. The Aquilon plate lattices (4P4, 6P4, and 6P7) give reasonable agreement for the six-plate lattices, but the SRL recipe again gives higher values for the wide spacings than those measured.

The agreement of the SRL recipe with other measurements is least good for the Saclay measurements on uniformly spaced solid rods shown in

Figure 3. However Figure 4 shows the SRL recipe to be in good agreement with measurements made by Cohen of NAA[5] on similar lattices. As shown in Figure 7, the NAA measurements agree with early reports of measurements by A. B. Atomenergi[8]. Both are, however, higher by approximately 0.5 m^{-2} than measurements at ANL, Saclay, Chalk River, and subcritical measurements at SRL. The lower measurements are now believed to be the more accurate. A. B. Atomenergi now believe their early reported measurements to be high by 0.3 m^{-2} because of the use of too small a radial extrapolation distance.[9]

The disagreement of the SRL recipe with the greater number of uniform rod lattices may be less a disagreement in measurement techniques than a breakdown in the extrapolation to such lattices. No PDP measurements on uniformly spaced rods were included in the SRL recipe. However, following completion of the SRL report[1], lattices of uniformly spaced small-diameter rods were measured which displayed a similar disagreement with the recipe. These rods were 0.50 and 0.69 inch in diameter, smaller than those measured elsewhere at uniform spacings. These results are given numerically in Table II. Figure 6 shows the bucklings plotted against the moderator-to-fuel volume ratio. In this case the curves are drawn through the experimental points rather than being calculated from the recipe. To obtain curve from the small number of PDP measurements, the parameters ϵ, f, L^2, and τ were calculated by the procedure of the recipe. However, the resonance escape probability, p, was calculated by use of resonance integrals interpolated to those derived for the lattices plotted in Figure 6. At the buckling maxima these curves are approximately 0.3 m^{-2} lower than predicted by the recipe.

The measurements at NAA and at A. B. Atomenergi lend themselves to a direct comparison of bucklings for the uniformly spaced rods. Both laboratories covered a range of rod diameters with the smallest only slightly greater than those measured in the PDP. Figure 6 shows part of these measurements corrected to the case of no cladding. This correction included only the aluminum effect on thermal utilization. The NAA and unrevised Swedish bucklings at the buckling maxima suggest higher bucklings than those measured at SRL by approximately 0.4 m^{-2} for the PDP lattices of 0.50- and 0.69-inch-diameter rods. These SRL-measured bucklings at the maxima are also lower by approximately 0.3 m^{-2} than those predicted by the SRL recipe.

The PDP measurements on uniformly spaced rods agree better with the low values obtained for rod lattices at ANL, Chalk River, and Saclay than with the measurements of A. B. Atomenergi and NAA. The disagreement of the SRL recipe with these later PDP measurements appears to be largely a breakdown of the method when extrapolated to solid rods since the SRL recipe does agree reasonably well with the buckling maxima for SRL, Saclay, and Chalk River lattices of clustered assemblies. The PDP measurements at high moderator-to-fuel volume ratios are consistently higher than those at Saclay and Chalk River.

A reason for this disagreement is discussed in the section on Possible Errors in the PDP Measurements.

COMPARISON OF BUCKLING MEASUREMENTS IN CRITICAL AND EXPONENTIAL FACILITIES

Some observers share the opinion that there is a single systematic difference between buckling measurements made in critical and in subcritical experiments. Our own experience does not support this opinion. More than ten lattices of either natural or fully enriched uranium have been measured in both the critical facility, (PDP), and the subcritical facility, (SE), of the Savannah River Laboratory. The agreement in most cases has been within $\pm 0.10\ m^{-2}$. In those cases in which there appeared to be a major discrepancy, rechecks under more stringent conditions of materials quality and experimental method have failed to support the discrepancy. PDP critical loadings involving these test assemblies varied in size from the test cell of the present report to full pile loadings.

The scope of the comparison is, however, limited. All of the lattices for which intercomparisons have been made were heavy lattices, that is, lattices having L^2 values less than 100 cm^2. Only indirect measurements are available for comparing higher L^2 values, especially at spacings of the test lattice greater than 10 inches. These suggest that higher values are obtained from two-region critical measurements than from the subcritical measurements. The discrepancy is believed to arise from systematic errors in the two-region critical measurements. These errors are discussed in a later section.

An apparent disagreement giving the opposite effect, that is, a critical facility giving lower bucklings than that of a subcritical is found by comparing the NAA measurements by Cohen[5] on 1-inch-diameter metal rods to those at the Chalk River critical facility on the same rods[6]. The Chalk River values are however in reasonably good agreement with subcritical measurements made at ANL[10] and with unreported subcritical measurements at SRL[11]. These comparisons are made graphically in Figure 7.

In any event, the spread in values reported for similar lattices by the various critical facilities and the various exponential facilities show far larger variation between similar facilities than any average difference between the two types.

RESONANCE INTEGRAL ANALYSES

The method of Critoph[2] has been used to reduce the PDP buckling measurements to the form of resonance integrals. For spacings wider than 6 inches it can readily be shown that the theory gives the following relation between the resonance integral, RI, and the resonance escape probability, p,

$$RI = (1 - p)(V_{cell}/V_{fuel}) \frac{(\xi\Sigma_s)_{mod}}{N_o(\bar{\Phi}_S/\bar{\Phi}_M)}$$

The terms are defined in the Appendix. The function $(\bar{\Phi}_S/\bar{\Phi}_M)$ is the resonance flux disadvantage factor and is given by Critoph's method as a function only of the assumed effective resonance energy, E_R, and of the effective spacing, $(\tau_{moderator}/\tau_{lattice})^{1/2}$ x spacing. A plot of this function is shown in Figure 8.

The above expression corresponds to the more familiar expression given by Glasstone[12] with only minor differences. One difference is the linear dependence of the resonance escape probability to the resonance integral in place of the usual exponential. This arises from Critoph's use of a single resonance capture energy. The second difference is the use of the volume ratio (V_{cell}/V_{fuel}) instead of the usual ratio (V_{mod}/V_{fuel}). This arises from Critoph's assumption of line sources as models of the fuel. The function $(\bar{\Phi}_S/\bar{\Phi}_M)$ is actually the ratio of the resonance flux at the fuel surface to that in the cell. However, because of the line source assumption the cell average is identical to the moderator average. These differences are considered weaknesses of the Critoph treatment. A possible improvement is the use of the normal form with Critoph's method used only to calculate $(\bar{\Phi}_S/\bar{\Phi}_M)$. It is the provision of a simple model for calculating this term that appears to be the chief strength of the Critoph method. This combination of the two methods has not yet been used, however, for any large-scale data reduction.

The term (V_{cell}/V_{fuel}) must be treated very consistently in comparing various measurements. As an example, Table II shows the difference in resonance integrals for a range of lattices depending on the choice of V_{cell} or V_{mod} in the volume ratio. On the resonance integral plots, Figures 16 and 18, of the SRL Geneva Report, the metal rod lattices and the gas tube lattices were analyzed using V_{mod}. The use of V_{mod} is felt to be physically more appropriate. However, the best fit to the largest number of lattices was obtained for the plate lattices in which V_{cell} was used. In order to apply this procedure using V_{cell} to metal lattices in which there was considerable aluminum or air the quantity $(V_{fuel} + V_{mod})$ was used in place of V_{cell} in the relation above. This substituted quantity is more appropriate for more general lattices, and for uranium-D_2O alone the two volumes are identical.

The SRL calculations of the effective interior surfaces for resonance capture in general agree with those of the other experimenters using a similar method of analysis. The one exception is in the calculation for the interior surfaces for the clustered rods. The method of numerical integration used at SRL agrees well with the Chalk River method, but gives decidedly lower effective interior surface areas than does the Saclay method. This difference is important only in comparing different lattices since the effective surface is used only

in the reduction of the buckling data to resonance integrals and does not affect the basic measured quantities.

POSSIBLE ERRORS IN PDP MEASUREMENTS

The major sources of error have been discussed in the Geneva report. They include the insufficiency of the two-group analysis, mechanical positioning, and the rather large moderator purity corrections. These errors are believed to be random. More recently, however, evidence has been uncovered which indicates a systematic error in the PDP measurements that becomes appreciable for lattices with high values of L^2. The effect arises because of the use of separated fuel and poison rods in the lattice of the outer region. These poison rods are necessary to lower the buckling of the outside lattice to a value suitable to the large PDP tank. A schematic of the combined fuel and poison rod lattice has been given by Carmichael[4]. When the absorption of the test cell differs markedly from that of the outer region, the sharp thermal neutron gradients at the cell boundary change the thermal absorption in the fuel relative to that in the poison rods. This effect depends primarily on L^2, or more properly on $(\Sigma_a)_{eff}$, of the test region. Estimates of this effect give PDP buckling measurements 0.30 m^{-2} high for L^2 values of 400 cm^2, 0.15 m^{-2} for 180 cm^2, 0.00 m^{-2} for 80 cm^2, and 0.10 m^{-2} low for 45 cm^2. This effect is believed to be responsible for the consistently high SRL bucklings at high L^2 values as compared to the values of most other experimenters.

REACTIVITY TRANSIENTS

The curves of reactivity transients of Figure 23 of the SRL Geneva report require additional explanation. First of all, the curves are for the case of fuel and moderator alone. If aluminum or other absorbing materials are used, the absorption of the aluminum relative to the fuel will decrease as the effective cross section of the fuel material increases with plutonium buildup. This reduces the reactivity loss with exposure for actual elements with absorbing housings. Also, the latest values of heavy element and fission product cross sections[13] differ slightly from those used in the paper. Further, there is reason to believe that the effective cross section calculated for Pu^{240} and used for the curves of Figure 23 is too high. This is because the self-shielding effect is likely to be greater than was estimated earlier. All of these effects go in the direction of giving longer exposures than shown in Figure 23. Preliminary calculations suggest that in at least one case the maximum exposure time may be 1.5 times as great. Calculations are continuing to investigate these effects in greater detail.

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APPENDIX

EQUATIONS FOR EVALUATION OF RESONANCE INTEGRALS

$$RI = (1 - p)\left(\frac{V_1}{V_o}\right) \frac{(\xi\Sigma_s)_1}{N_o} \left(\bar{\Phi}_M/\bar{\Phi}_S\right) \qquad (a)$$

$$\left(\bar{\Phi}_M/\bar{\Phi}_S\right) = \frac{\int_o^\infty 2\pi r q_M(r, E_R)_{dr}}{V_{cell} \sum_{i=o}^{\infty} n_i \, q_L(r_i, E_R)} \qquad (b)$$

$$\text{Effective Spacing} = \left(\tau_M/\tau_L\right)^{\frac{1}{2}} \times \text{Spacing}$$

RI = resonance integral for cell

p = resonance escape probability

τ_M = neutron age in moderator

τ_L = neutron age in lattice

r_i = distance from a given assembly

n_i = number of assemblies of distance r_i from a given assembly

E_R = neutron energy at which resonance absorptions are assumed to take place

$q_L(r_i, E_R)$ = slowing down density, in lattice, of neutrons of energy E_R at $r = 0$ due to neutron source (fuel assembly) at $r = r_i$

$q_M(r, E_R)$ = slowing down density, in moderator, of neutrons of energy E_R at r due to neutron source at $r = 0$

$(\xi\Sigma_s)_1$ = slowing down power of moderator

N_o = number of uranium atoms/cm^3 in fuel

V_o = volume of fuel in one assembly

V_1 = volume of one lattice cell

$\bar{\Phi}_M/\bar{\Phi}_S$ = ratio of average resonant neutron flux in moderator to average neutron flux at surface of assembly

TABLE I

NUCLEAR PARAMETERS FOR D_2O-MODERATED CLUSTERS OF NATURAL URANIUM PLATES

Lattice Description			Lattice Parameters, 99.75% D_2O							Corrections Applied to B^2, m^{-2}			Resonance Integral Parameters	
Plate Spacing, inch	Triangular Lattice Pitch, inches	Plates Per Assembly	V_M/V_F	f	ϵ	p	L^2, cm^2	τ, cm^2	B^2, m^{-2}	k_∞*	D_2O Purity**	Small Sample	Nonuniform Spacing	I_o, Barns	(S_{eff}/M) cm^2/gm
0.025	10.69	46	9.1	0.9893	1.0761	0.8134	112	133.2	5.87	1.1491	0.06	-0.25	1.07	7.14	0.0392
		36	11.9	0.9872	1.0715	0.8450	135	130.1	6.72	1.1861	0.17		0.82	7.33	0.0406
		28	15.5	0.9852	1.0656	0.8684	155	127.7	7.07	1.2098	0.26		0.65	7.71	0.0456
		24	18.3	0.9840	1.0620	0.8822	167	126.6	7.23	1.2233	0.29		0.53	7.93	0.0485
		20	22.1	0.9814	1.0588	0.8973	195	125.4	7.03	1.2373	0.38		0.44	8.12	0.0520
		16	27.9	0.9786	1.0540	0.9162	224	124.3	6.91	1.2540	0.46		0.32	8.17	0.0579
		12	37.6	0.9744	1.0499	0.9348	268	123.2	6.52	1.2691	0.55		0.21	8.34	0.0642
		10	45.2	0.9715	1.0464	0.9358	298	122.7	5.93	1.2623	0.69		0.18	9.74	0.0683
	9.26	34	9.2	0.9910	1.0710	0.8052	95	133.0	5.70	1.1341	0.04	-0.35	0.97	7.76	0.0414
		26	12.4	0.9891	1.0645	0.8434	115	129.7	6.99	1.1783	0.17		0.71	7.98	0.0464
		20	16.4	0.9869	1.0588	0.8730	138	127.3	7.56	1.2106	0.29		0.52	8.24	0.0520
		16	20.7	0.9848	1.0540	0.8921	160	125.8	7.60	1.2288	0.36		0.40	8.60	0.0579
		14	23.8	0.9838	1.0511	0.9019	169	125.0	7.66	1.2376	0.41		0.35	8.85	0.0631
		12	28.0	0.9815	1.0499	0.9147	193	124.3	7.48	1.2508	0.47		0.27	8.93	0.0642
		10	33.7	0.9793	1.0464	0.9257	217	123.6	7.19	1.2588	0.52		0.21	9.26	0.0683
		8	42.4	0.9761	1.0421	0.9361	250	122.8	6.70	1.2636	0.59		0.16	9.85	0.0745
	7.56	20	10.6	0.9922	1.0588	0.8243	83	131.3	6.73	1.1492	0.00	---	0.42	7.99	0.0520
		16	13.5	0.9907	1.0540	0.8496	98	128.9	7.50	1.1773	0.10	---	0.33	8.33	0.0579
		12	18.3	0.9885	1.0499	0.8780	121	126.6	8.05	1.2092	0.22	---	0.25	8.95	0.0642
		10	22.2	0.9870	1.0464	0.8955	137	125.4	8.22	1.2273	0.30	---	0.20	9.14	0.0683
		8	27.9	0.9848	1.0421	0.9088	160	124.3	7.92	1.2376	0.37	---	0.16	9.85	0.0745
		7	32.1	0.9833	1.0400	0.9251	176	123.7	8.05	1.2554	0.43	---	0.12	9.25	0.0777
		6	37.6	0.9813	1.0375	0.9314	196	123.2	7.65	1.2583	0.48	---	0.10	9.81	0.0834
		4	56.9	0.9749	1.0313	0.9505	263	122.1	6.60	1.2682	0.61	---	0.06	10.46	0.1042
	7.00	20	8.9	0.9936	1.0588	0.7939	68	133.5	5.24	1.1081	-0.11	---	---	8.06	0.0520
		16	11.3	0.9925	1.0540	0.8272	80	130.6	6.81	1.1483	0.00	---	---	8.29	0.0579
		12	15.5	0.9906	1.0499	0.8600	99	127.7	7.90	1.1870	0.11	---	---	8.87	0.0642
		10	18.7	0.9893	1.0464	0.8795	112	126.4	8.32	1.2081	0.20	---	---	9.04	0.0683
		8	23.7	0.9874	1.0421	0.8993	132	125.1	8.41	1.2279	0.29	---	---	9.05	0.0745
		7	27.2	0.9861	1.0400	0.9131	145	124.4	8.52	1.2486	0.34	---	---	9.22	0.0777
		6	31.9	0.9844	1.0375	0.9228	163	123.8	8.26	1.2507	0.40	---	---	9.52	0.0834
		4	48.5	0.9789	1.0313	0.9472	220	122.5	7.42	1.2690	0.55	---	---	9.67	0.1042
0.075	10.69	45	9.3	0.9908	1.0634	0.7944	97	132.9	4.69	1.1107	0.04	-0.25	1.23	7.90	0.0536
		33	13.0	0.9882	1.0583	0.8387	124	129.2	6.23	1.1640	0.19		0.87	8.10	0.0594
		24	18.3	0.9852	1.0521	0.8758	156	126.6	6.91	1.2047	0.34		0.60	8.31	0.0683
		20	22.1	0.9832	1.0482	0.8892	176	125.4	6.83	1.2162	0.40		0.49	8.64	0.0687
		16	27.9	0.9804	1.0461	0.9034	205	124.3	6.63	1.2295	0.49		0.39	9.38	0.0739
		12	37.6	0.9763	1.0415	0.9160	247	123.2	6.07	1.2359	0.58		0.28	10.70	0.0836
		10	45.2	0.9734	1.0394	0.9235	278	122.7	5.71	1.2399	0.64		0.24	11.58	0.0898
		8	56.9	0.9690	1.0366	0.9363	324	122.1	5.31	1.2480	0.72		0.17	11.95	0.0921
	9.26	33	9.5	0.9920	1.0583	0.7928	85	132.6	4.69	1.1045	0.00	-0.35	1.05	8.39	0.0593
		24	13.5	0.9898	1.0521	0.8386	108	128.9	6.46	1.1588	0.15		0.75	8.79	0.0683
		20	16.4	0.9883	1.0482	0.8624	124	127.3	7.07	1.1856	0.22		0.60	8.88	0.0687
		16	20.7	0.9861	1.0461	0.8842	146	125.8	7.37	1.2103	0.34		0.41	9.19	0.0739
		12	28.0	0.9830	1.0415	0.9105	179	124.3	7.41	1.2370	0.45		0.30	9.37	0.0836
		10	33.7	0.9808	1.0394	0.9167	202	123.6	7.00	1.2402	0.51		0.25	10.32	0.0898
		8	42.4	0.9774	1.0366	0.9310	237	122.8	6.64	1.2517	0.59		0.18	10.63	0.0921
		7	48.7	0.9755	1.0350	0.9367	257	122.5	6.38	1.2549	0.63		0.16	11.10	0.0951
	7.56	20	10.6	0.9931	1.0482	0.8104	74	131.3	5.67	1.1195	-0.05	--	0.46	8.58	0.0686
		16	13.5	0.9917	1.0461	0.8392	89	128.9	6.88	1.1553	0.07	--	0.36	8.96	0.0739
		12	18.3	0.9896	1.0415	0.8713	110	126.6	7.75	1.1917	0.19	--	0.27	9.43	0.0836
		10	22.2	0.9881	1.0394	0.8833	126	125.4	7.73	1.2038	0.25	--	0.22	10.18	0.0898
		8	27.9	0.9858	1.0366	0.8985	149	124.3	7.60	1.2184	0.36	--	0.18	10.96	0.0921
		7	32.1	0.9844	1.0350	0.9093	164	123.7	7.57	1.2294	0.40	--	0.15	11.18	0.0951
		6	37.6	0.9825	1.0328	0.9268	184	123.2	7.64	1.2479	0.47	--	0.12	10.46	0.1013
		4	56.9	0.9763	1.0286	0.9491	249	122.1	6.76	1.2648	0.61	--	0.07	10.74	0.1147
	7.00	20	8.9	0.9945	1.0482	0.7769	60	133.5	3.80	1.0747	-0.14	--	--	8.67	0.0686
		16	11.3	0.9933	1.0461	0.8132	72	130.6	5.83	1.1213	0.04	--	--	8.92	0.0739
		12	15.5	0.9915	1.0415	0.8498	91	127.7	7.24	1.1644	0.09	--	--	9.51	0.0836
		10	18.7	0.9902	1.0395	0.8692	104	126.4	7.78	1.1872	0.17	--	--	9.80	0.0898
		8	23.7	0.9884	1.0366	0.8896	124	125.1	8.01	1.2095	0.26	--	--	9.89	0.0921
		7	27.2	0.9871	1.0350	0.9014	136	124.4	8.10	1.2220	0.32	--	--	10.46	0.0951
		6	31.9	0.9855	1.0328	0.9158	154	123.8	8.08	1.2369	0.39	--	--	10.38	0.1013
		4	48.5	0.9802	1.0286	0.9428	208	122.5	7.48	1.2615	0.54	--	--	10.49	0.1147
0.380	10.69	33	13.0	0.9931	1.0276	0.7907	78	129.2	3.36	1.0708	-0.04	-0.25	1.31	10.29	0.1344
		24	18.3	0.9901	1.0270	0.8352	109	126.6	5.23	1.1270	0.15		0.91	10.87	0.1406
		18	24.7	0.9869	1.0261	0.8674	142	124.9	5.97	1.1657	0.31		0.64	11.46	0.1459
		15	29.9	0.9846	1.0255	0.8874	166	124.0	6.24	1.1890	0.41		0.51	11.55	0.1473
		12	37.6	0.9815	1.0236	0.9065	198	123.2	6.20	1.2085	0.51		0.37	11.87	0.1553
		10	45.2	0.9785	1.0226	0.9174	228	122.7	5.94	1.2182	0.60		0.30	12.50	0.1593
		8	56.9	0.9742	1.0215	0.9312	274	122.1	5.54	1.2297	0.69		0.21	12.86	0.1665
	9.26	33	9.5	0.9958	1.0276	0.7276	52	132.6	-0.65	0.9880	-0.25	-0.35	1.52	10.80	0.1344
		24	12.5	0.9935	1.0270	0.7900	74	129.6	3.37	1.0697	-0.07		1.09	10.53	0.1406
		18	18.3	0.9911	1.0261	0.8351	98	126.6	5.49	1.1270	0.10		0.78	11.36	0.1459
		15	22.2	0.9894	1.0255	0.8601	116	125.4	6.31	1.1581	0.21		0.61	11.74	0.1473
		12	28.0	0.9870	1.0236	0.8817	140	124.3	6.60	1.1820	0.33		0.46	12.29	0.1553
		10	33.7	0.9848	1.0226	0.9031	164	123.6	6.86	1.2068	0.43		0.35	11.99	0.1593
		8	42.4	0.9814	1.0215	0.9212	198	122.8	6.69	1.2255	0.54		0.24	12.10	0.1665
		6	57.0	0.9762	1.0206	0.9432	252	122.1	6.28	1.2471	0.69		0.14	11.57	0.1763
	7.56	18	11.9	0.9952	1.0261	0.7725	57	130.1	2.48	1.0469	-0.17	--	0.58	11.24	0.1459
		15	14.4	0.9940	1.0255	0.8046	69	128.3	4.39	1.0883	-0.07	--	0.47	11.44	0.1473
		12	18.3	0.9924	1.0236	0.8384	85	126.6	5.97	1.1302	0.05	--	0.36	11.76	0.1553
		10	22.2	0.9909	1.0226	0.8604	101	125.4	6.68	1.1569	0.15	--	0.29	12.14	0.1593
		8	27.9	0.9886	1.0215	0.8860	124	124.3	7.22	1.1873	0.27	--	0.22	12.28	0.1665
		6	37.6	0.9850	1.0206	0.9147	161	123.2	7.37	1.2202	0.43	--	0.14	12.18	0.1763
		5	45.3	0.9829	1.0175	0.9250	183	122.6	7.08	1.2276	0.50	--	0.12	12.76	0.1971
		4	56.9	0.9792	1.0174	0.9395	220	122.1	6.72	1.2420	0.60	--	0.09	12.80	0.1972
	7.00	18	10.0	0.9963	1.0261	0.7315	46	132.0	-0.43	0.9924	-0.27	--	--	11.37	0.1459
		15	12.2	0.9953	1.0255	0.7729	56	129.8	2.50	1.0469	-0.18	--	--	11.48	0.1473
		12	15.5	0.9940	1.0236	0.8130	69	127.7	4.86	1.0977	-0.06	--	--	11.75	0.1553
		10	18.7	0.9927	1.0226	0.8417	83	126.4	6.20	1.1339	0.04	--	--	11.81	0.1593
		8	23.7	0.9908	1.0215	0.8700	102	125.1	7.13	1.1684	0.17	--	--	11.62	0.1665
		6	31.9	0.9877	1.0206	0.9020	133	123.8	7.67	1.2067	0.33	--	--	12.06	0.1763
		5	38.6	0.9859	1.0175	0.9159	152	123.1	7.58	1.2193	0.40	--	--	12.37	0.1971
		4	48.5	0.9827	1.0174	0.9316	183	122.5	7.33	1.2360	0.52	--	--	12.55	0.1972

*$k_\infty = \eta\epsilon fp = (1 + L^2B^2)(1 + \tau B^2)$

**Actual moderator purity, 99.3 mol % D_2O

TABLE II

NUCLEAR PARAMETERS FOR D_2O-MODERATED CLUSTERS OF NATURAL URANIUM RODS

Lattice Description					Lattice Parameters, 99.75% D_2O							Lattice Parameters, 99.12% D_2O				Resonance Integral Parameters		
Rod Diameter, inch	Rod Spacing, inch	Rods Per Cluster	Triangular Lattice Pitch, inches	V_M/V_F	f	ϵ	p	L^2, cm^2	τ, cm^2	B^2, m^{-2}	k_∞	f	L^2, cm^2	τ, cm^2	B^2, m^{-2}	I_o, barns, using (V_M/V_F)	I_o, barns, using (V_{cell}/V_F)	(S_{eff}/M) cm^2/gm
0.500	0.151	7	7.00	29.8	0.9867	1.0277	0.9087	143.68	123.9	7.92	1.2230	0.9674	137.27	121.3	7.52	10.18	10.52	0.1089
		7	7.56	35.1	0.9839	1.0277	0.9168	172.92	123.3	7.38	1.2302	0.9607	164.53	120.7	6.87	11.17	11.49	0.1089
		7	9.26	53.0	0.9747	1.0277	0.9469	270.96	122.2	6.25	1.2586	0.9387	254.29	119.6	5.50	9.90	10.09	0.1089
		7	10.69	71.1	0.9653	1.0277	0.9590	365.97	121.7	5.14	1.2624	0.9171	312.16	119.1	4.42	9.34	9.47	0.1089
		13	7.00	15.6	0.9921	1.0340	0.8461	86.87	127.2	6.85	1.1518	0.9806	83.67	124.5	6.79	9.38	9.98	0.0945
		13	7.56	19.4	0.9903	1.0340	0.8625	106.11	125.9	7.12	1.1720	0.9761	101.92	123.3	6.93	9.92	10.43	0.0945
		13	9.26	28.0	0.9840	1.0340	0.9083	172.05	124.2	7.26	1.2263	0.9609	163.72	121.6	6.77	9.28	9.61	0.0945
		13	10.69	37.7	0.9777	1.0340	0.9275	240.12	123.1	6.39	1.2442	0.9456	226.31	120.5	5.71	9.26	9.51	0.0945
		19	7.00	10.4	0.9945	1.0380	0.7915	62.55	130.5	4.29	1.0843	0.9863	60.54	127.8	4.46	8.79	9.63	0.0827
		19	7.56	12.2	0.9930	1.0380	0.8211	77.49	129.1	5.79	1.1230	0.9828	74.74	126.4	5.83	8.86	9.59	0.0827
		19	8.28	14.91	0.9912	1.0380	0.8390	96.59	127.5	6.28	1.1456	0.9783	92.88	124.8	6.16	9.58	10.22	0.0827
		19	9.26	18.9	0.9881	1.0380	0.8729	129.26	126.0	7.05	1.1880	0.9708	123.75	123.4	6.75	9.20	9.69	0.0827
		19	10.69	25.5	0.9830	1.0380	0.8979	183.68	124.0	6.68	1.2157	0.9583	174.49	121.4	6.17	9.13	9.49	0.0827
	0.500	7	7.00	29.8	0.9891	1.0179	0.8989	122.58	123.9	7.78	1.2009	0.9732	117.54	121.3	7.50	11.33	11.71	0.1484
		7	7.56	35.1	0.9867	1.0179	0.9043	148.09	123.3	7.21	1.2052	0.9673	141.48	120.7	6.95	12.14	12.49	0.1484
		7	9.26	53.0	0.9785	1.0179	0.9416	234.21	122.2	6.52	1.2445	0.9477	221.05	119.6	5.86	10.78	10.98	0.1484
		7	10.69	71.1	0.9693	1.0179	0.9536	321.22	121.7	5.36	1.2486	0.9284	299.81	119.1	4.56	10.59	10.74	0.1380
		13	7.00	15.6	0.9944	1.0208	0.8250	67.35	127.2	5.58	1.1112	0.9862	65.10	124.5	5.69	10.60	11.28	0.1380
		13	7.56	19.4	0.9930	1.0208	0.8465	82.93	125.9	6.43	1.1386	0.9862	79.96	123.3	6.40	10.84	11.40	0.1380
		13	9.26	28.0	0.9878	1.0208	0.8928	137.17	124.2	7.12	1.1947	0.9700	131.16	121.6	6.68	10.93	11.32	0.1380
		13	10.69	37.7	0.9824	1.0208	0.9146	193.96	123.1	6.53	1.2172	0.9570	183.97	120.5	5.95	10.88	11.17	0.1380
		19	7.00	10.4	0.9967	1.0216	0.7573	44.16	130.5	1.33	1.0233	0.9918	42.83	127.8	1.73	10.06	11.03	0.1272
		19	7.56	12.2	0.9956	1.0216	0.7915	55.29	129.1	3.66	1.0684	0.9892	53.54	126.4	3.92	10.16	10.99	0.1272
		19	8.28	14.9	0.9943	1.0216	0.8133	69.81	127.5	4.78	1.0963	0.9858	67.45	124.8	4.83	10.97	11.71	0.1272
		19	9.26	18.9	0.9919	1.0216	0.8499	95.06	126.0	6.25	1.1428	0.9799	91.54	123.4	6.14	10.68	11.24	0.1272
		19	10.69	25.5	0.9877	1.0216	0.8803	138.07	124.0	6.54	1.1787	0.9699	132.00	121.4	6.20	10.65	11.07	0.1272
0.687	0.165	7	7.00	15.2	0.9918	1.0377	0.8511	89.97	127.4	7.20	1.1624	0.9797	86.64	124.7	7.10	9.47	10.09	0.0778
		7	7.56	17.9	0.9899	1.0377	0.8685	109.81	126.3	7.46	1.1838	0.9751	105.39	123.6	7.24	9.79	10.34	0.0778
		7	9.26	27.4	0.9835	1.0377	0.9110	177.51	124.2	7.35	1.2337	0.9596	168.75	121.6	6.85	9.55	9.90	0.0778
		7	10.69	36.8	0.9769	1.0377	0.9280	247.25	123.2	6.37	1.2483	0.9438	232.78	120.6	5.68	9.61	9.87	0.0778
		10	7.00	10.4	0.9942	1.0420	0.8001	66.54	130.5	4.95	1.0999	0.9856	64.33	127.8	5.09	8.52	9.34	0.0710
		10	7.56	12.3	0.9928	1.0420	0.8207	82.13	129.0	5.83	1.1267	0.9821	79.20	126.3	6.23	8.68	9.39	0.0710
		10	9.26	19.0	0.9877	1.0420	0.8779	136.36	126.0	7.24	1.1989	0.9699	130.39	123.4	6.93	8.79	9.25	0.0710
		10	10.69	25.7	0.9825	1.0420	0.9009	193.14	124.5	6.71	1.2239	0.9573	183.21	121.7	6.20	8.93	9.28	0.0710
		13	7.00	7.74	0.9953	1.0450	0.7472	52.51	134.0	1.67	1.0313	0.9885	50.89	131.2	1.98	8.33	9.51	0.0664
		13	7.56	9.58	0.9941	1.0450	0.7876	65.51	131.2	4.28	1.0857	0.9855	63.34	128.4	4.41	8.27	9.14	0.0664
		13	9.26	14.2	0.9898	1.0450	0.8477	111.31	127.8	6.58	1.1635	0.9448	106.82	125.1	6.37	8.68	9.29	0.0664
		13	10.69	19.4	0.9851	1.0450	0.8782	157.88	125.9	6.72	1.1996	0.9636	152.37	123.3	6.25	8.63	9.08	0.0664
	0.500	7	7.00	15.2	0.9926	1.0258	0.8394	74.91	127.4	6.44	1.1342	0.9817	72.31	124.7	6.46	10.31	10.99	0.1028
		7	7.56	17.9	0.9908	1.0258	0.8589	88.84	126.3	7.10	1.1584	0.9773	85.56	123.6	7.00	10.65	11.24	0.1028
		7	9.26	27.4	0.9847	1.0258	0.8996	151.00	124.2	7.32	1.2058	0.9625	144.09	121.6	6.91	10.52	10.92	0.1028
		7	10.69	36.8	0.9784	1.0258	0.9235	212.32	123.2	6.52	1.2299	0.9475	200.92	120.6	5.91	10.45	10.73	0.1028
		10	7.00	10.4	0.9957	1.0276	0.7768	52.08	130.5	2.96	1.0546	0.9893	50.46	127.8	3.31	9.39	10.29	0.0975
		10	7.56	12.3	0.9945	1.0276	0.8037	64.90	129.0	4.55	1.0899	0.9863	62.76	126.3	5.12	9.46	10.23	0.0975
		10	9.26	19.0	0.9901	1.0276	0.8650	110.25	126.0	6.83	1.1678	0.9757	105.82	123.4	6.62	9.68	10.19	0.0975
		10	10.69	25.7	0.9855	1.0276	0.8922	158.43	124.5	6.72	1.1990	0.9646	151.01	121.7	6.29	9.65	10.03	0.0975
		13	7.00	7.74	0.9970	1.0290	0.7154	38.92	134.0	-1.51	0.9740	0.9925	37.76	131.2	-1.04	9.24	10.43	0.0962
		13	7.56	9.58	0.9960	1.0290	0.7615	49.20	131.2	1.96	1.0356	0.9900	47.65	128.4	2.29	9.16	10.12	0.0962
		13	9.26	14.2	0.9925	1.0290	0.8290	86.19	127.8	5.61	1.1235	0.9813	83.04	125.1	5.57	9.65	10.33	0.0962
		13	10.69	19.4	0.9886	1.0290	0.8637	126.29	125.9	6.33	1.1660	0.9720	121.00	123.3	6.04	9.57	10.06	0.0962
0.687	---	1	4.00*	42.1	0.9853	1.0197	0.9234	156.22	122.8	7.86	1.2311	0.9641	148.95	120.2	7.39	11.99	12.27	0.1225
0.687	---	1	3.00*	23.3	0.9920	1.0197	0.8752	85.95	124.9	7.97	1.1748	0.9803	82.83	122.3	7.85	10.80	11.26	0.1225
0.687	---	1	2.00*	9.8	0.9966	1.0197	0.7536	37.23	131.1	0.96	1.0163	0.9917	36.10	128.4	1.29	9.12	10.05	0.1225
0.500	---	1	3.00*	44.8	0.9861	1.0145	0.9219	148.26	122.6	7.85	1.2238	0.9659	141.53	120.0	7.46	12.63	12.91	0.1681
0.500	---	1	2.00*	19.4	0.9940	1.0145	0.8430	65.10	125.9	6.52	1.1280	0.9852	62.96	123.3	6.57	11.36	11.95	0.1681
0.500	---	1	1.50*	10.4	0.9967	1.0145	0.7417	36.61	131.5	-0.29	0.9951	0.9919	35.50	128.7	0.15	10.01	10.98	0.1681

*Square lattice

TABLE III

NUCLEAR PARAMETERS FOR D_2O-MODERATED CLUSTERS OF NATURAL URANIUM PLATES IN GAS-FILLED TUBES

Lattice Description					Lattice Parameters, 99.75% D_2O						Corrections Applied to B^2, m^{-2}			Resonance Integral Parameters	
Gas Tube, inches	Triangular Lattice Pitch, inches	Plates Per Assembly	V_M/V_F	V_{Void}/V_{Cell}	f	ϵ	p	L^2, cm^2	τ, cm^2	B^2, m^{-2}	k_∞	D_2O Purity	Nonuniform Spacing	Housing Tube	I_o, Barns	(S_{eff}/M), cm^2/gm
4.0 x 5.0	9.26	14	17.9	0.228	0.9920	1.034	0.8519	161	259	3.65	1.159	0.05	0.25	0.53	10.13	0.0825
		12	20.9	0.235	0.9911	1.032	0.8743	190	270	3.88	1.186	0.08	0.18	0.56	9.99	0.0870
		10	25.1	0.241	0.9900	1.030	0.8812	222	278	3.68	1.192	0.11	0.15	0.59	11.27	0.0938
		8	31.4	0.246	0.9879	1.028	0.9065	278	291	3.70	1.222	0.15	0.10	0.64	11.07	0.1039
		6	41.9	0.252	0.9846	1.025	0.9271	363	302	3.44	1.242	0.19	0.06	0.69	11.45	0.1204
	10.69	14	26.2	0.172	0.9871	1.034	0.8898	212	218	4.56	1.206	0.21	0.35	0.51	10.62	0.0825
		12	30.6	0.176	0.9855	1.032	0.9110	246	226	4.62	1.230	0.24	0.25	0.53	10.04	0.870
		10	36.7	0.180	0.9843	1.030	0.9170	273	232	4.39	1.234	0.25	0.20	0.59	11.19	0.0938
		8	45.9	0.185	0.9813	1.028	0.9337	339	240	4.08	1.250	0.29	0.14	0.62	11.19	0.1039
		6	61.2	0.189	0.9767	1.025	0.9493	432	247	3.64	1.261	0.32	0.09	0.67	11.39	0.1204
3.5 x 3.5	7.00	12	11.6	0.228	0.9952	1.032	0.7934	93	238	2.40	1.081	-0.08	0.00	0.58	9.20	0.0870
		10	13.9	0.238	0.9945	1.030	0.8180	113	251	3.00	1.112	-0.03	0.00	0.63	9.78	0.0938
		8	17.4	0.249	0.9935	1.028	0.8415	144	266	3.29	1.139	0.01	0.00	0.69	10.90	0.1039
		6	23.2	0.254	0.9916	1.025	0.8747	190	279	3.69	1.180	0.08	0.00	0.79	12.41	0.1204
	9.26	12	24.0	0.131	0.9890	1.032	0.8899	152	187	5.81	1.207	0.20	0.36	0.58	9.86	0.0870
		10	28.8	0.136	0.9877	1.030	0.9050	177	191	5.75	1.223	0.25	0.28	0.62	10.19	0.0938
		8	36.0	0.142	0.9853	1.028	0.9265	217	197	5.60	1.245	0.30	0.18	0.68	9.88	0.1039
		6	48.0	0.148	0.9816	1.025	0.9337	279	203	4.84	1.247	0.33	0.13	0.75	11.83	0.1204
	10.69	12	33.7	0.098	0.9830	1.032	0.9185	212	170	5.89	1.237	0.38	0.36	0.51	9.65	0.0870
		10	40.4	0.102	0.9809	1.030	0.9294	244	174	5.53	1.244	0.43	0.27	0.48	10.03	0.0938
		8	50.5	0.106	0.9776	1.028	0.9444	295	181	5.17	1.260	0.48	0.18	0.64	9.91	0.1039

TABLE IV

NUCLEAR PARAMETERS FOR D_2O-MODERATED CLUSTERS OF ALUMINUM-CLAD UO_2 RODS

Lattice Description				Lattice Parameters, 99.75% D_2O						Lattice Parameters, 99.2% D_2O				Resonance Integral Parameters	
Rod Spacing, inch	Triangular Lattice Pitch, inches	Rods Per Assembly	V_M/V_F*	f	ϵ	p	L^2, cm^2	τ, cm^2	B^2, m^{-2}	k_∞	f	L^2, cm^2	τ, cm^2	B^2, m^{-2}	I_o, Barns	(S_{eff}/M) cm^2/gm
0.132	10.69	61	27.6	0.9352	1.016	0.8645	125.5	149.9	3.20	1.0900	0.9229	121.2	147.7	2.98	16.07	0.1899
		55	31.0	0.9340	1.016	0.8769	138.7	147.0	3.56	1.1042	0.9203	133.4	144.8	3.29	15.96	0.1936
		43	40.7	0.9308	1.015	0.9034	173.4	141.2	4.09	1.1326	0.9132	166.4	139.0	3.89	15.60	0.2096
		33	47.9	0.9285	1.015	0.9158	198.0	138.4	4.18	1.1453	0.9082	189.5	136.2	3.70	15.56	0.2125
		31	57.9	0.9353	1.014	0.9302	230.8	135.7	4.17	1.1582	0.9014	220.0	133.5	3.61	15.18	0.2217
	9.26	43	29.6	0.9355	1.015	0.8746	122.9	148.1	3.67	1.1020	0.9235	118.7	145.9	3.46	16.30	0.2096
		37	35.0	0.9339	1.015	0.8904	141.4	144.2	4.08	1.1200	0.9157	136.2	142.0	3.78	16.35	0.2125
		31	42.5	0.9315	1.014	0.9071	165.9	140.4	4.33	1.1370	0.9148	159.4	138.2	3.95	16.32	0.2217
		19	71.7	0.9231	1.013	0.9452	255.4	133.1	4.29	1.1729	0.8966	242.7	130.9	3.68	15.30	0.2461
	7.00	37	18.4	0.9401	1.015	0.8030	73.5	163.0	0.71	1.0168	0.9338	71.4	160.8	0.79	17.43	0.2125
		31	22.7	0.9389	1.014	0.8346	87.4	155.6	2.21	1.0544	0.9310	84.8	153.4	2.18	17.32	0.2217
		19	39.4	0.9340	1.013	0.9005	138.6	141.8	4.52	1.1306	0.9204	133.6	139.6	4.22	16.70	0.2461
		13	59.3	0.9287	1.011	0.9311	195.9	135.3	4.66	1.1601	0.9085	187.5	133.1	4.17	16.72	0.2806
0.395	10.69	37	47.9	0.9294	1.008	0.9072	175.5	138.4	3.95	1.1278	0.9128	168.6	136.2	3.58	17.06	0.2978
		31	57.9	0.9264	1.008	0.9222	207.5	135.7	4.03	1.1428	0.9063	198.6	133.5	3.56	16.83	0.3060
	9.26	37	35.0	0.9341	1.008	0.8788	124.7	144.2	3.56	1.0980	0.9232	120.6	142.0	3.37	17.98	0.2978
		31	42.5	0.9319	1.008	0.8982	148.8	140.4	4.02	1.1196	0.9183	143.4	138.2	3.73	17.81	0.3060
		19	71.7	0.9237	1.007	0.9382	236.3	133.1	4.13	1.1580	0.9005	225.4	130.9	3.60	17.19	0.3264
	7.00	37	18.4	0.9396	1.008	0.7787	65.3	163.0	-0.94	0.9787	0.9356	63.6	160.8	-0.75	19.46	0.2978
		31	22.7	0.9385	1.008	0.8183	78.3	155.6	1.16	1.0273	0.9327	76.2	153.4	1.22	18.94	0.3060
		19	39.4	0.9338	1.007	0.8922	128.1	141.8	4.09	1.1133	0.9225	123.8	139.6	3.88	18.06	0.3264
		13	59.3	0.9285	1.007	0.9244	184.4	135.3	4.44	1.1469	0.9109	177.0	133.1	4.03	18.32	0.3532

*The fuel volume, V_F, is that for natural uranium metal having the same total number of uranium atoms per assembly.

TABLE V

NUCLEAR PARAMETERS FOR D_2O-MODERATED TUBES OF NATURAL URANIUM

Lattice Description			Lattice Parameters, 99.75% D_2O*						Corrections Applied to B^2, m^{-2}				Resonance Integral Parameters	
No of Tubes Per Assembly	Triangular Lattice Pitch, inches	V_M/V_F	f	ϵ	p	L^2, cm^2	τ, cm^2	B^2, m^{-2}	k_∞	D_2O Purity	Small Sample	Nonuniform Spacing	Cladding	I_o, Barns	(S_{eff}/M), cm^2/gm
1	10.69	59.8	0.935	1.014	0.932	231	122.0	4.72	1.1729	0.84	-0.25	0.22	1.27	12.92	0.2088
1	9.26	43.8	0.943	1.014	0.919	167	122.7	5.51	1.1658	0.64	-0.35	0.27	1.52	12.58	0.2088
1	7.56	28.9	0.952	1.014	0.874	103	124.0	5.12	1.1196	0.31	0.00	0.26	1.82	13.74	0.2088
1	7.00	24.6	0.954	1.014	0.859	85	124.7	4.77	1.1024	0.17	0.00	0.00	1.96	13.36	0.2088
2	10.69	31.2	0.956	1.029	0.901	207	123.7	5.13	1.1764	0.41	-0.25	0.39	0.94	10.95	0.1212
2	9.26	23.1	0.962	1.029	0.871	123	125.0	5.62	1.1442	0.23	-0.35	0.53	1.21	11.14	0.1212
2	7.00	12.8	0.970	1.029	0.791	59	128.7	2.51	1.0476	-0.21	0.00	0.00	1.49	10.52	0.1212

*The parameters include corrections for D_2O purity, small samples, and nonuniform spacing. They do not, however, include corrections to the case of no aluminum housing. The cladding corrections of this table must be added to the lattice bucklings of this table to obtain the bucklings of Figure 9 of the Geneva report.

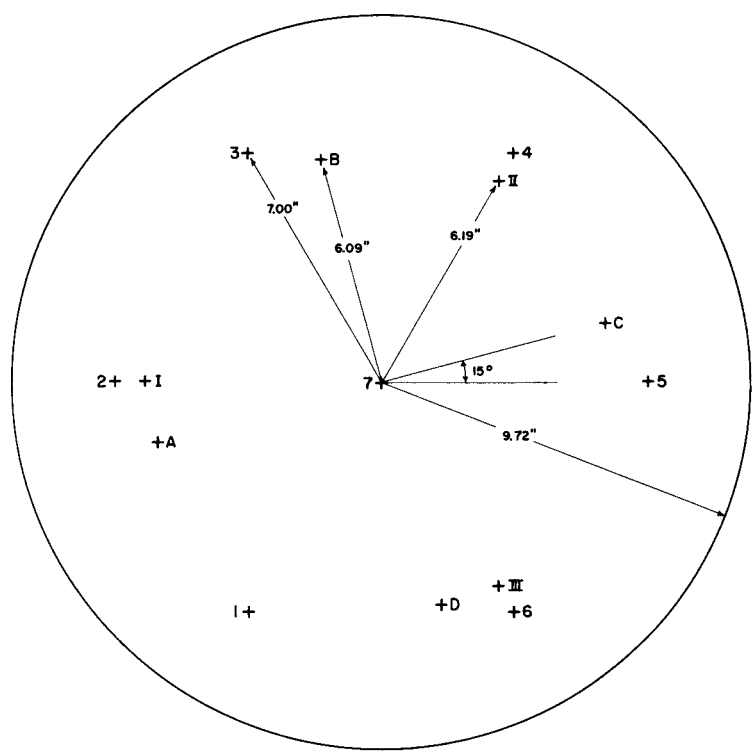
TABLE VI

GEOMETRICAL CONSTRUCTION OF SRL PLATE LATTICES

Total No. of Plates Per Assembly	Plate Spacing, inch					
	0.025		0.075		0.380	
	Rows	Plates Per Row	Rows	Plates Per Row	Rows	Plates Per Row
46	2	23	--	--	--	--
45	--	--	3	15	--	--
36	2	18	3	12	--	--
34	2	17	--	--	--	--
33	--	--	3	11	3	11
26	2	13	--	--	--	--
24	2	12	2	12	3	8
20	2	10	2	10	--	--
18	--	--	--	--	3	6
16	2	8	2	8	--	--
15	--	--	--	--	3	5
14	2	7	--	--	--	--
12	2	6	2	6	2	6
10	2	5	2	5	2	5
8	1	8	1	8	2	4
7	1	7	1	7	--	--
6	1	6	1	6	2	3
5	--	--	--	--	1	5
4	1	4	1	4	1	4

The circle defines the cylindricized boundary of the central test region of the PDP. A hexagonal 7-inch spacing is given by the points numbered 1 to 7. For the plates, tubes, and gas-filled plates different combinations of these seven positions were used. An "Equivalent Triangular Spacing" is defined as the spacing of an infinite triangular lattice having the same fuel to cell volume as the test assemblies in the test zone. The actual spacing coincided with the "Equivalent Triangular Spacing" only for the 7.00-inch spacing. For the remaining cases the buckling values for the actual lattice measured were corrected to apply to an idealized triangular lattice having the indicated spacing.

A different test lattice positioning was used for the measurements on the metal and oxide rods. The "Equivalent Triangular Spacing" 7.00 and 10.69 inches for the rods coincided with the actual spacing. The positions for the 9.27-inch spacing were on a square lattice having the same moderator-to-fuel ratio as the "Equivalent Triangular Spacing". Only the 7.56-inch spacing was irregular for the rods and the only one for which corrections were made for irregular spacing.



EQUIV. TRIANGULAR SPACING	LATTICES	
	PLATES, TUBES, GAS-COOLED PLATES	METAL RODS, OXIDE RODS
7.00"	1,2,3,4,5,6,7	1,2,3,4,5,6,7
7.56"	1,2,3,4,5,6	1,2,3,4,5,6
9.27"	1,3,5,7	A,B,C,D
10.69"	1,3,5	I,II,III

FIGURE 1 - ELEMENT POSITIONS IN TEST ZONE

The points are the Saclay measurements corrected by Saclay to a set of consistent outer region bucklings. The curves are the calculations by the SRL recipe. The metal rods were in bundles of 7 rods with the rods having a diameter of 16.5 mm in their aluminum jackets and being separated, between jackets, by 0, 2, and 5 mm (G-0, G-2, and G-5, respectively). The plates were rectangular in cross section, 4.5 x 55.5 mm in aluminum jackets. The first number of the lattice designations on the figure gives the number of plates per assembly, the second gives, in millimeters, the water space between jackets.

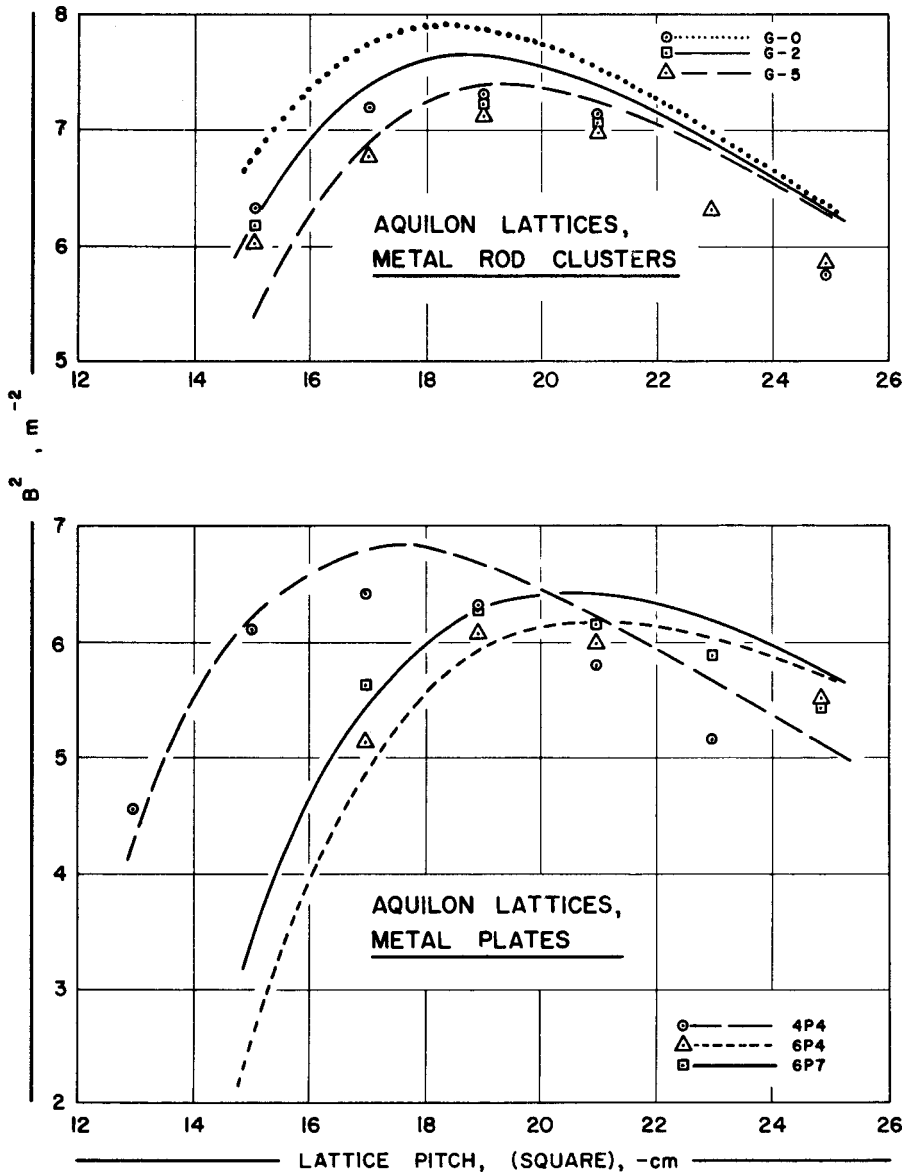


FIGURE 2 - COMPARISON OF SRL RECIPE TO SACLAY MEASUREMENTS IN AQUILON (METAL ROD CLUSTERS AND METAL PLATES)

The points are the measurements corrected by Saclay to a set of consistent outer region bucklings. The curves are the calculations by the SRL recipe. The lattice (OS 19/1) consisted of bundles of 19 oxide rods having diameters of 15.6 mm in aluminum jackets, separated between jackets by 1 mm. The lattices (OS 19/2) and (OC 19/4) consisted of bundles of 19 oxide rods having diameters of 13.2 mm in aluminum jackets with, respectively, 2- and 4- mm spacing between jackets. The metal rod lattices used bare metal rods with diameters of 26, 29.2, 35.6, and 44 mm. Measurements include those from the substitution and from the flux profile method.

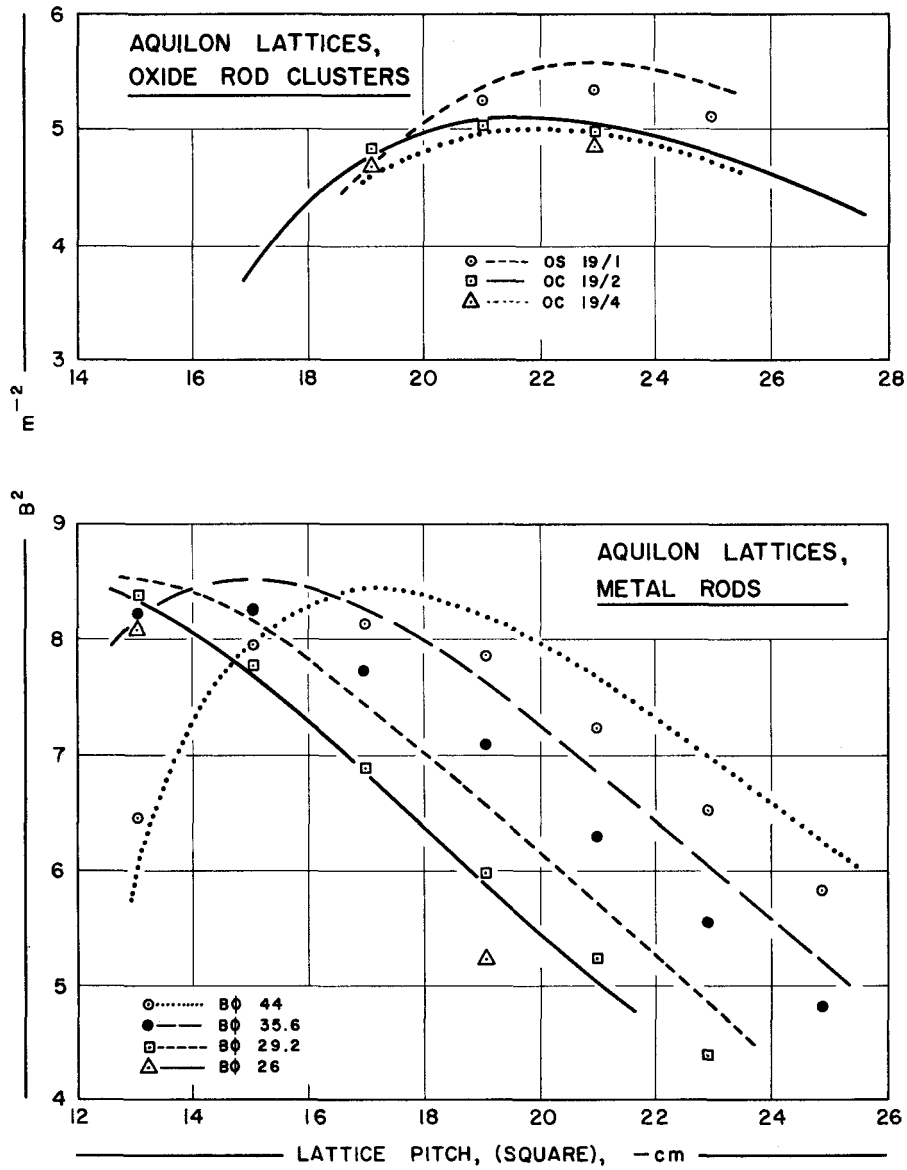


FIGURE 3 - COMPARISON OF SRL RECIPE TO SACLAY MEASUREMENTS IN AQUILON (OXIDE ROD CLUSTERS AND METAL RODS)

The data points are the measurements. The curves are the calculations by the SRL recipe. The NAA exponential measurements were on solid metal rods of the indicated diameters in inches. All buckling measurements and calculations include aluminum jackets. The Chalk River NPD lattices were clusters of 19 rods in a hexagonal bundle. The metal and oxide rods had diameters of 13.1 and 13.23 mm, respectively. The rods were in aluminum jackets and had spacings between jackets of 2.04 mm for the (1) lattices and 4.06 mm for (2) lattices.

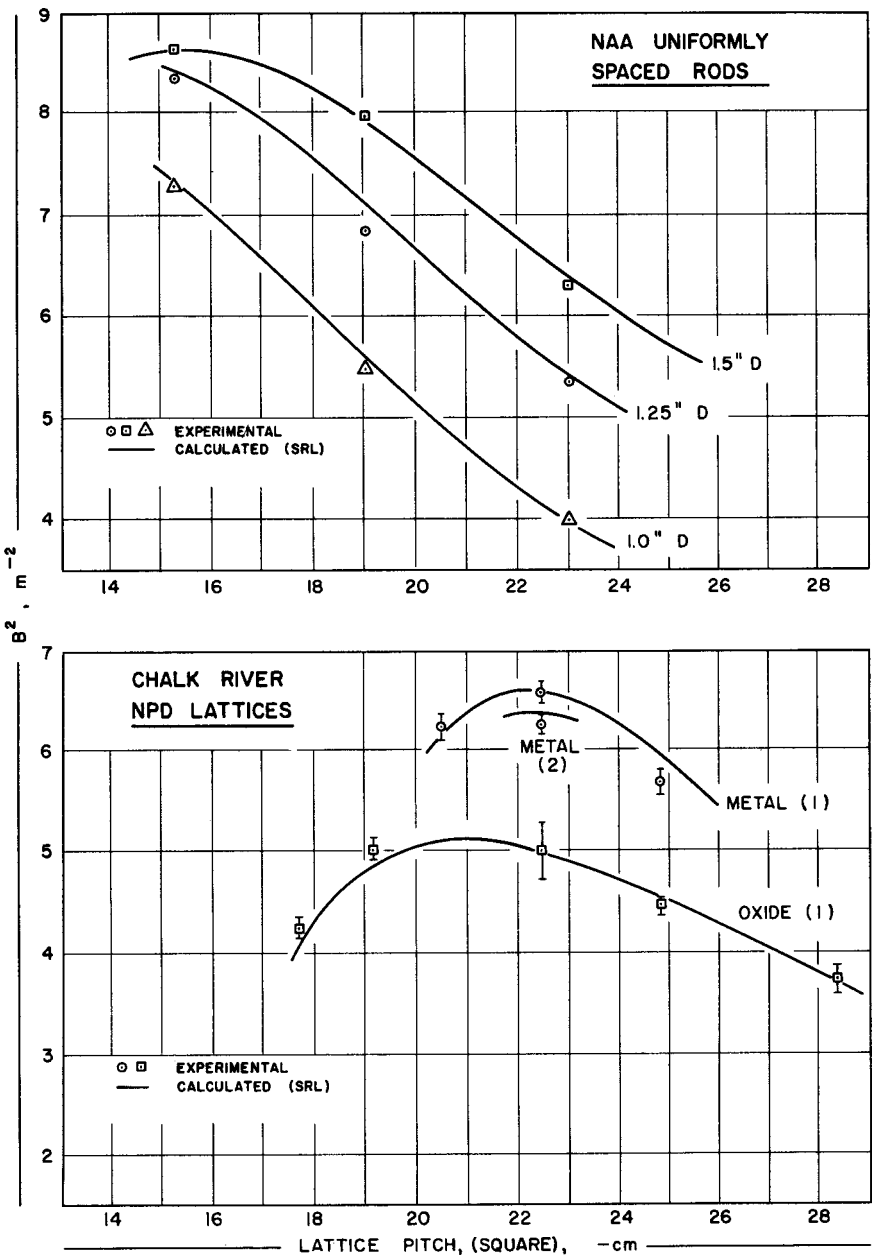


FIGURE 4 - COMPARISON OF SRL RECIPE TO NAA AND CHALK RIVER MEASUREMENTS (METAL RODS AND NPD LATTICES)

The points are experimental measurements. The curves are the calculations by the SRL recipe. The ZEEP lattices used metal rods 32.57 mm in diameter in aluminum jackets. The NRU lattices used metal plates in aluminum jackets inside a cylindrical aluminum housing tube. The five plates included one 3.96 x 57.78 mm, two 3.96 x 53.08, and two 4.50 x 34.04 mm. The spacing between jackets was 2.96 mm. The actual lattices were triangular. The curve gives the square lattice equivalent with the same moderator-to-fuel ratio for both sets of measurements.

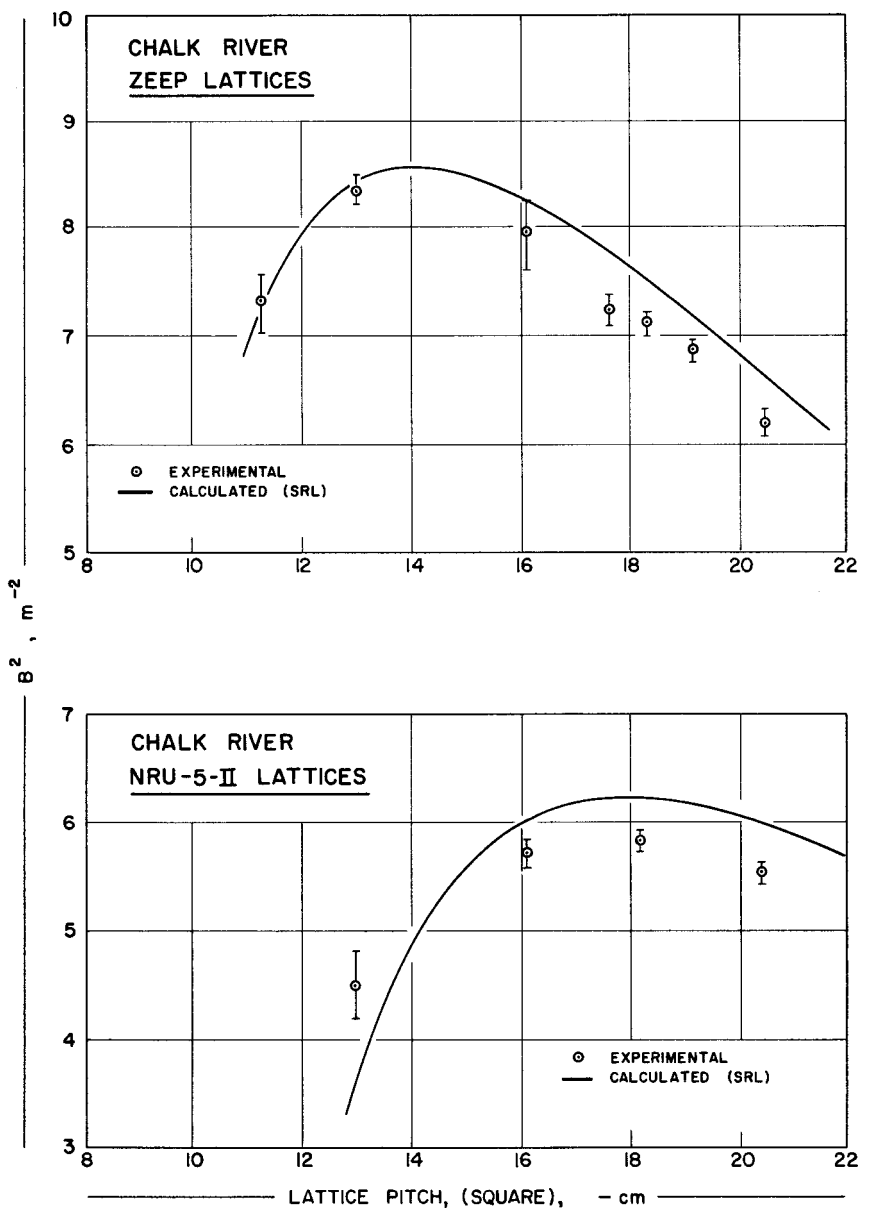


FIGURE 5 - COMPARISON OF SRL RECIPE TO CHALK RIVER MEASUREMENTS (ZEEP AND NRU-5-II LATTICES)

The curves give a direct comparison of the Swedish measurements on bare uranium rods to the measurements made in the PDP. Similar measurements at NAA are indicated by data points above. The Swedish and NAA measurements have been corrected to the case of no aluminum cladding to make them consistent with the PDP measurements. The text discusses this correction as well as the procedure for determining the shape of the PDP curves.

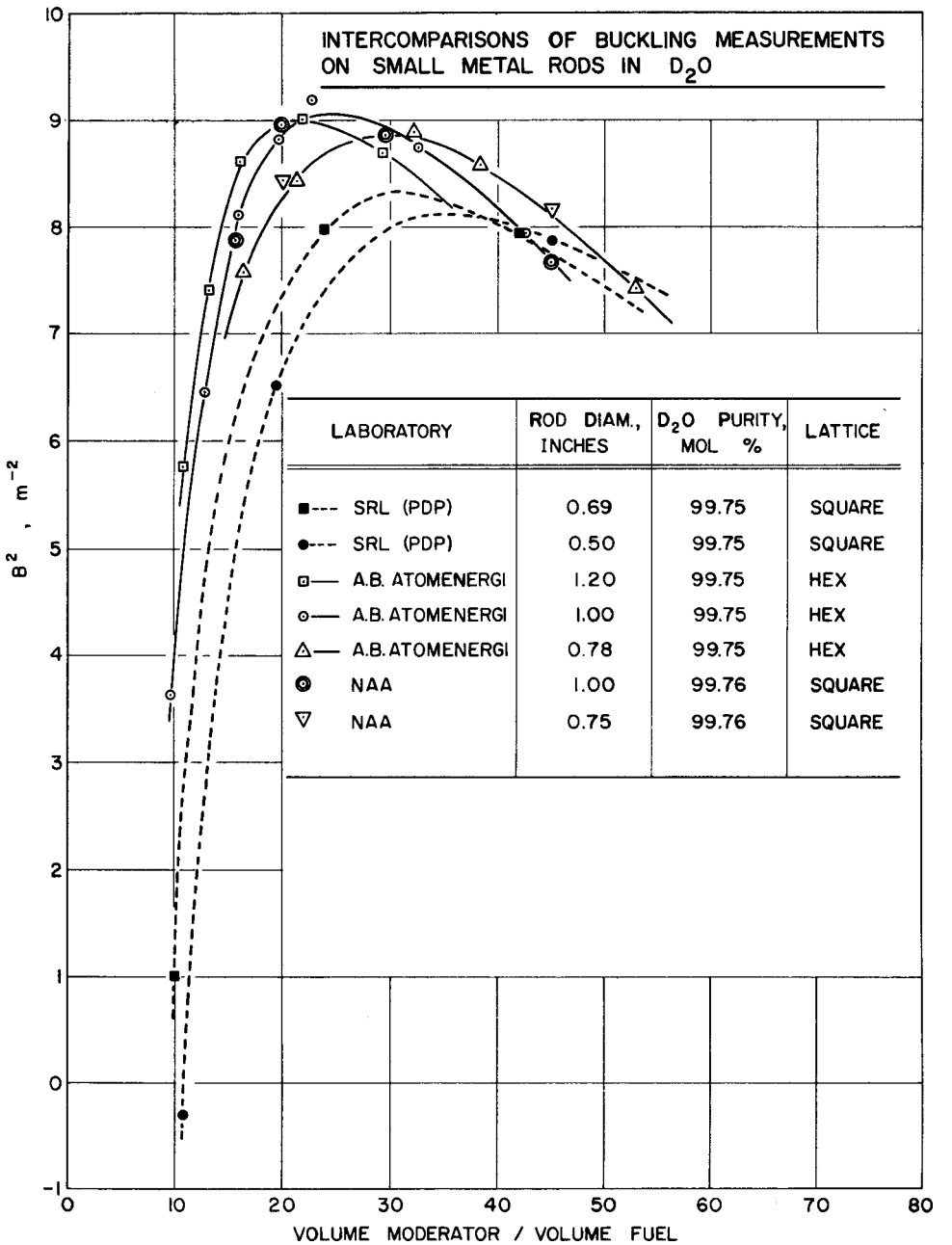


FIGURE 6 - BUCKLINGS OF LATTICES OF UNIFORMLY SPACED BARE URANIUM RODS IN D_2O OF 99.75 MOL % PURITY

The diameter of the natural uranium metal rods was 1.00 inch for all cases except for the rods used at Saclay in Aquilon, for which the diameter was 1.02 inches. The buckling values are for the moderator purities and the cladding thicknesses indicated. (These data were compiled by T. F. Parkinson of SRL and are to be published at a later date.)

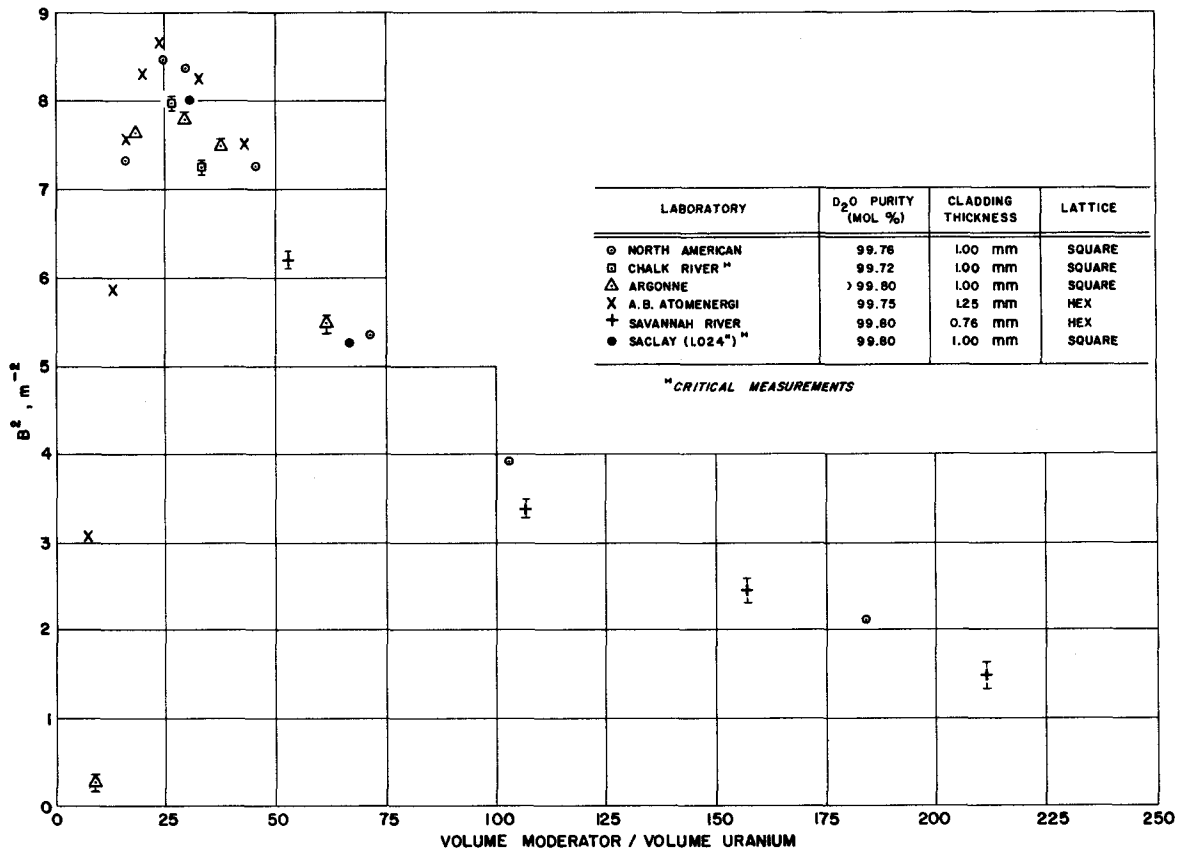


FIGURE 7 - INTERCOMPARISON OF BUCKLING MEASUREMENTS ON ONE-INCH-DIAMETER RODS IN D_2O

Curves are shown for resonance energies of 7, 30, and 100 ev. The terms are defined in the Appendix. The effective lattice pitch is the actual spacing times $(\tau_M/\tau_L)^{\frac{1}{2}}$. To obtain the effective pitch for gas-filled tubes the τ_L includes the volume of the gas tube but no streaming correction. The asymptotes give the degree of self-interaction on resonance capture. The difference between the curves and the asymptotes gives the mutual interaction.

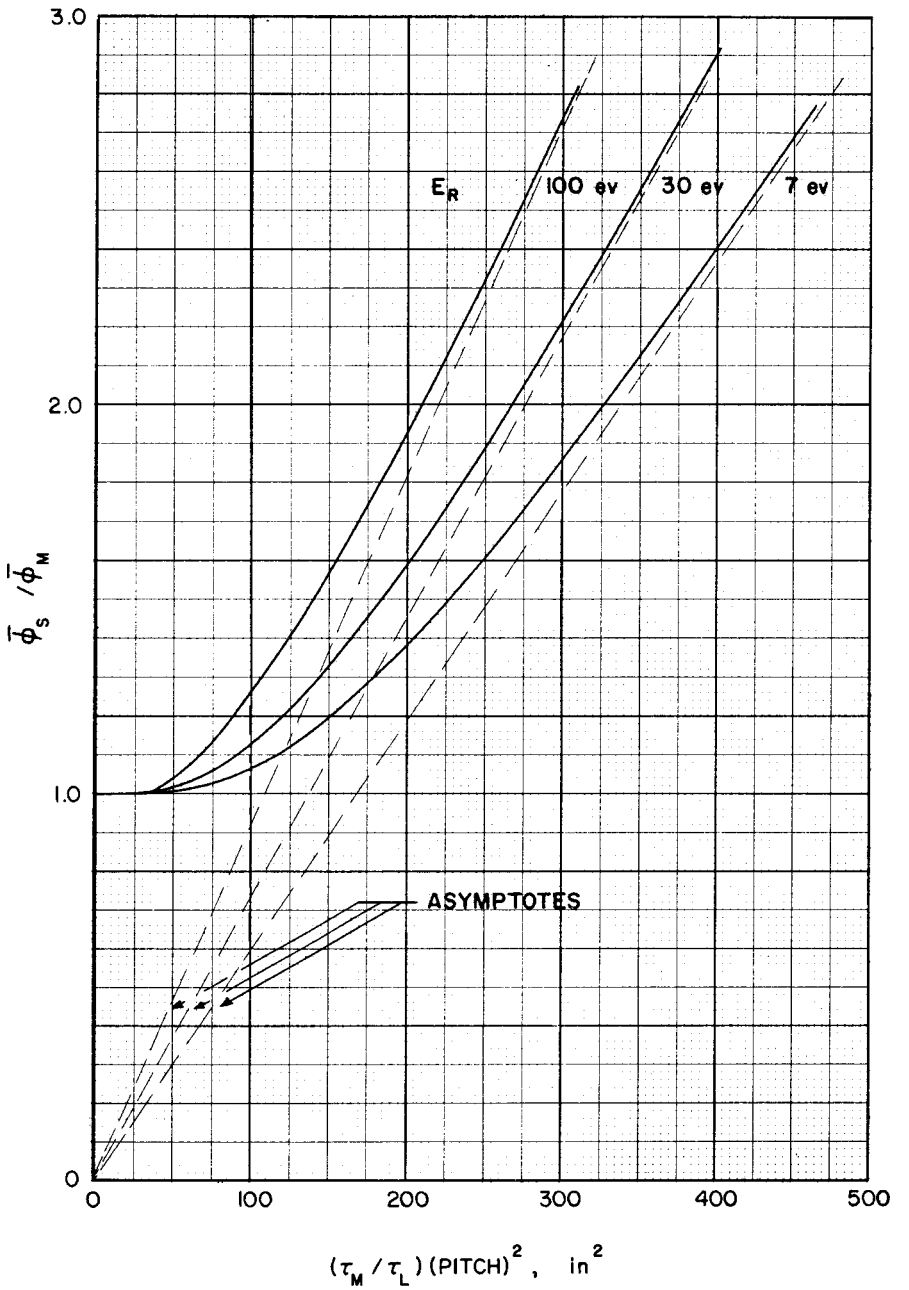


FIGURE 8 - RESONANCE FLUX DISADVANTAGE FACTOR AS A FUNCTION OF EFFECTIVE TRIANGULAR LATTICE PITCH