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SAFE FISSILE MATERIAL
SPACING IN WATER

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SAFE FISSILE MATERIAL SPACING IN WATER

One of the common fissile systems in the nuclear industry is that of an array of uniformly-spaced, sub-critical fissile units stored either in water or in air. Irradiated reactor fuels are, because of cooling and radiation shielding requirements, normally stored in water. Hanford's Purex plant has probably processed these fuels in as great, or greater variety than any other reprocessing plant. For example, large buckets of closely packed fuel elements with up to 0.95 percent enrichment, two-barrel cannisters of NPR fuels with up to 2.1 percent enrichment, PRTR PuO_2 in UO_2 fuels with up to 4.0 weight percent PuO_2 in UO_2 , and various other fuels with up to at least 6.6 percent enrichment have been stored and processed. Design or process studies where fuel parameters are not fixed can result in a number of computer calculations. The safe storage of such fuel requires that storage density limitations be established for each type of fuel stored. A method for determining a near-maximum, safe fuel-storage density with few computer calculations might save both time and money during preliminary studies.

Storage of fuels in water reduces the energy of the neutrons and therefore increases the probability of nuclear fission and the possibility of a nuclear criticality incident. At the same time, the probability that neutrons can pass from one unit of the array to another is generally reduced by the presence of water between the units. These units can be effectively isolated from each other by 10 to 12 inches of water between units; sophisticated calculations are not normally required for this arrangement. However, for large arrays this spacing is generally neither necessary nor economical. It is only necessary that the effective

multiplication constant of the array, k_a , be kept less than 1.0 to prevent criticality. (It might be necessary to calculate k_a to a maximum value which is significantly less than 1.0, say 0.95 or lower, to allow for uncertainties in calculational methods and for errors in fuel handling.)

The multiplication constant for an array can change with the composition of the fuel, the cladding material, the fuel dimensions (including all the various permutations and combinations that can occur within the fertile imagination of the various reactor fuel designers) and the spacing between the subcritical units as stored. Stored units can consist of one or more complete fuel elements or containers of loose rods. Each arrangement, therefore, would appear to be an isolated case. A request for an analysis of fuel storage which does not involve complete isolation and where the exact fuel to be stored is not certain would appear to require a separate calculation for each type of subcritical unit considered.

For an array, k_a varies from that at large water gaps which is equal to k_u , the multiplication constant of an isolated (or single) unit, to the k_a value representative of zero water spacing which we can define as k'_∞ . In this case, k'_∞ is equal to the k_∞ of the material of which the unit is composed if the array is large, there is no water between units at zero spacing (cylindrical units of course would have some water between units), no interface effect from whatever supports each unit and the units are all long enough to be considered infinite in length. For short units k'_∞ as defined here could be equal to the k -effective of an array in the form of an infinite slab. However, in all calculations all array dimensions are assumed infinite and therefore k'_∞ does not differ from k_∞ . If the subcritical

units are well moderated, no value of k_a will be greater than k'_∞ . Poorly moderated systems, however, can have k_a values somewhat greater than k'_∞ at small between-unit spacings.

The k'_∞ will be the same for all arrays where the unit composition is the same, even though the unit horizontal dimensions in one array may be different than those in another array. If a family of curves could be generated for such a material, for k_a versus the water gap, each curve would represent a different value of k_u and all would meet at k'_∞ . Two such families are shown in Figure 1, which is a graph of idealized curves illustrating variations in the shapes of curves of k_a versus unit separation. The solid lines represent arrays of units composed of well moderated material and the dashed lines arrays of units of undermoderated material. Two sizes of units are represented for each material, one having a k_u value of 0.7 and the other 0.9. On the right side of the graph, curves of different materials but identical k_u values approach each other as the units become isolated by the increasing water gap between units. On the left side of the graph, at zero water gap, the curves for different unit sizes but the same unit composition meet at the same k_a value (which we defined above as k'_∞).

As can be seen in Figure 1, k_a can be quite variable with a different value of k_a for each value of k_u and k'_∞ at a given water spacing (or vice versa). The k_a value is higher for higher k_u values, but the Δk_a is less (ignoring the effects of thermalization between units) since the difference between k'_∞ and k_u is smaller the higher the value of k_u . This complex relationship must be simplified if the need for computer usage is to be reduced.

Since the curves have somewhat similar shapes it appears as though the effect of the water gap can be simplified if the end points can be made identical, or nearly so, for any set of values of k_a and k'_∞ . This can be done if the "reactivity ratio" $(k_a - k_u)/(k'_\infty - k_u)$ is used; this ratio is zero at infinite separation since k_a is equal to k_u , and equal to 1.0 at zero separation since k_a is then equal to k'_∞ . It only remains necessary to show that for various subcritical units the relationship is similar between these points.

It is obvious from Figure 1 that the curves cannot be identical unless the neutron energy spectra at the fuel boundary of different types of units are identical. A higher value for the ratio should be obtained for the more poorly moderated systems. However, for any reasonable set of fuel geometries a curve can be drawn that, for many different fuels, will permit the determination of a safe unit separation which is much less than the isolation thickness.

To determine such a limiting curve, a number of different subcritical units were investigated. All units were assumed to be infinitely long. It was also assumed that there were no interfaces such as steel or aluminum carriers surrounding the material in the units. A summary of the type of systems for which calculations were made is shown in Table 1.

Because of the relative ease of obtaining the data, the initial calculations to determine $(k_a - k_u)/(k'_\infty - k_u)$ were performed with the DTF-IV code⁽¹⁾ using cylinders of plutonium solution with varying plutonium concentration and ^{240}Pu content. To illustrate the effect of using the

TABLE 1

<u>UNIT COMPOSITION</u>	<u>OUTER SHAPE OF UNIT</u>	<u>k_u</u>	<u>COMPUTER CODE</u>
30 g/l Pu Nitrate 0 and 20 wt% ²⁴⁰ Pu	Cylinder	0.70,0.90	DTF-IV
150 g/l Pu Nitrate 0 and 20 wt% ²⁴⁰ Pu	Cylinder	0.70,0.90	DTF-IV
600 g/l Pu Nitrate 0 and 20 wt% ²⁴⁰ Pu	Cylinder	0.70,0.90	DTF-IV
150 g/l Pu Nitrate 0 wt% ²⁴⁰ Pu	Square	0.859	KENO
U(4)O ₂ , 0.5-inch Rods in Square Array, W/UO ₂ = 1.0	Square	0.57,0.82	KENO
U(4)O ₂ , 0.5-inch Rods in Square Array, W/UO ₂ = 2.0	Square	0.62	KENO
U(2)O ₂ , 0.5-inch Rods in Square Array, W/UO ₂ = 1.0	Square	0.73	KENO
BWR - Type Design* U(3)O ₂	Square	*	KENO, GEM4
PWR - Type Design** U(3)O ₂	Square	**	KENO, GEM4

* BWR geometry was 0.494-inch diameter rods with 0.034-inch Zircalloy cladding, 0.7467-inch lattice spacing and 7 x 7 rod lattice. The k_u was 0.6859 ± 0.0204 for GEM4 and 0.6000 ± 0.0084 for KENO.

** PWR geometry was 0.373-inch diameter rods with 0.0243-inch Zircalloy cladding, 0.5617 lattice spacing and 15 x 15 rod lattice. The k_u was 0.8796 ± 0.0172 by GEM4 and 0.9173 ± 0.0180 for KENO.

the reactivity ratio, the data is plotted as a function of k_a in Figure 2 and the reactivity ratio in Figure 3. As can be seen, the greater the plutonium concentration, (and the poorer the neutron moderation) the higher the reactivity ratios.

More appropriate calculations were made with GEM4⁽²⁾ and KENO⁽³⁾ Monte Carlo codes using fuel elements composed of square rod lattices, since square units should be more limiting than cylindrical units for the same edge-to-edge spacing. The k_a values are graphed in Figure 4. This graph shows that undermoderated lattice systems (those with lower water-to-fissile volume ratios) can have a k_a higher than k_∞ , the maximum value occurring around a 0.5-inch separation.

Figure 5 shows the data from Figure 4 as a function of the reactivity ratio and includes the plutonium solution data. As before, some of the data is connected by a continuous curve so that the relationship can be more easily seen. It was not considered necessary to calculate a large number of data points for each type of fuel.

As discussed before, the lower the water-to-fissile material volume ratio the greater the water gap required to reduce k_a to a safe value. A water-to-UO₂ ratio of 1.0 was selected as being the least moderated of any fuel system which was likely to be encountered. (The only exception to this might be for baskets of loose rods which could conceivably become tightly packed). Figure 5 demonstrates that this is the most limiting case.

Based on the data in Figure 5, a curve can be drawn which gives a slightly greater water gap than the largest gap shown by the data for a given reactivity ratio. This curve can be used as a basis for determining a safe water

gap between subcritical units for any material for which k_{∞} and k_u is known (or for which limiting values can be selected) and where a k_a value is selected based on "safe" array requirements. Conversely, for a selected water gap a maximum k_u value or unit size can be determined if k_{∞} is known. Such a limiting relationship can be modified depending on the fissile material to be stored. A less restrictive limiting curve might be used if it were known that the water-to-uranium ratio was great enough. On the other hand, there might possibly be a somewhat more exotic fuel or one with a higher moderator-to-fuel ratio which would require a more restrictive limit. The limiting curve shown, however, should be satisfactory for all normal fuels.

One implication of the data is that various types of fissile material may be safely mixed together, the minimum spacing being determined by the unit with the highest value of $(k_a - k_u)/(k_{\infty} - k_u)$.

Once the "safe" curve has been determined, it can be used in various ways to show the relationship of k_a , k_u , k_{∞} and spacing. Figure 6 shows such a relationship where a constant safe value for k_a of 0.95 was assumed. Here the safe spacing can be determined directly from the graph. This figure also shows that for small changes in unit separation, the allowable k -effective of a unit must change rapidly to maintain a constant k_a . It indicates how accurately k_u must be calculated at a given spacing, or conversely, how the accuracy of positioning the stored units affects the allowable unit reactivity.

For survey studies, the use of the "limiting" curve (Figure 5) can be used to reduce the demand for computer calculation, reserving definitive calculations for final

planning when the fuel type and spacing requirements may be better known. It might eliminate the need for computer calculations entirely for arrays where it is not necessary to reduce spacing to the minimum.

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