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ANOMALOUS EFFECTS OF MODERATION IN
TRANSPORTATION AND STORAGE ARRAYS—REVISITED

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ABSTRACT

A number of anomalies have been observed for fissile material arrays This paper will review anomalous behavior associated with interstitial array moderation and correct one previously misidentified anomaly. Most arrays show a maximum k_{eff} with low-density water moderation. An earlier study, however, did not show this maximum for *unreflected* 5×5×5 and 10×10×10 arrays of 15-kg ^{235}U spheres. Our present calculations with MCNP and KENO V.a, however, show low-density maximums for both unreflected and reflected arrays of these units. We conclude that the earlier calculations for unreflected arrays were in error perhaps due to problem setup or code errors. The reactivity enhancement due to fissile material density reductions, however, still exits and is now seen to occur for both unreflected and water-reflected arrays.

The anomalous effects of moderation in transportation and storage arrays of nuclear materials present challenging calculational problems. The nuclear criticality safety of fuel storage arrays requires that the potential of low density moderation within the array be considered. Over the years, several anomalies have been described that pertain to, 1) the effect of internal low-density interstitial moderation on the criticality of storage arrays,[1] and 2) the reactivity enhancement that can be caused by a density reduction in the units composing an array with interstitial moderation.[2,3]

An interesting problem concerns the effect on criticality for an array of interacting units if water is present in the intervening interstitial air spaces. This could be brought about by the use of water for fire control or possibly through the use of automatic sprinkler systems in buildings so equipped. In the case of the storage of low-enriched fuels wherein the ^{235}U content is <5 wt% (typical power reactor fuels) moderation is a principal condition for criticality. Then, depending on the fuel composition of the fuel assemblies and the storage arrangement used, it is possible by means of Monte Carlo calculations to show that an initially subcritical dry array can be made to achieve criticality at three different densities as the water content is increased within the fuel assembly and within the interstitial spaces of the array. See Figure 1.[1]

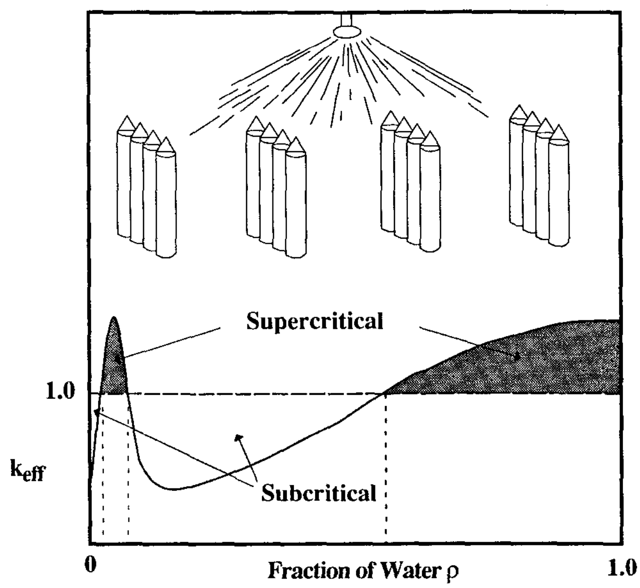

Figure 1. Effect of Internal Moderation on the Criticality of Storage Arrays.

The addition of water affects the criticality in several ways: 1) internal moderation is added to the fuel elements within each fuel assembly, 2) reflection is added to the array as a whole and also about each individual fuel assembly, and 3) neutron interaction is enhanced between fuel assemblies as a result of interstitial moderation. The degee to which each of the above plays a role on criticality depends on the density of the water.

It has also been pointed out that some interstially-moderated storage and transportation arrays will become more reactive if the density of the dry fissile material is reduced. In particular, a subcritical array of solid metal units inside shipping containers which contain moderator in the container materials or in the interstitial spaces between containers, can become supercritical when the density of fissile material in the container is reduced.[2] In this case a simple reduction in density of the nuclear material composing the individual units of an array, keeping the mass of each unit fixed, and spacing between units unchanged, with low-density moderation between, can cause a significant increase in the reactivity of the array.

Since these "anomalies" were pointed out, a number of papers have been written to assess the criticality safety of proposed and existing storage arrays, and to examine the effects of low-density moderation in further detail.[2,4,5,6,7] Two papers also were presented on the subject at the International Seminar on Nuclear Criticality Safety, October 1987, Tokyo, Japan.[8,9] A paper also was presented at the International Conference on Nuclear Criticality Safety, Oxford, England, September 1991.[10]

The availability of appropriate benchmark experiments for low-density moderation is quite limited. The French, however, performed experiments at Valduc in which four PWR-type assemblies were made critical in water with various hydrogenous compounds interposed between the assemblies.[11] The interposed materials were water, polystyrene balls, polystyrene powder, expanded polystyrene and air. Expanded polystyrene $(C_8H_8)n$ was reported to have a hydrogen concentration equivalent to about 2% full-density water whereas polyethylene powder $(CH_2)n$ was equivalent to about 38% full-density water. Attempts to validate calculations against the one set of suitable experiments at low density moderation were reported as disappointing.[8] It has been pointed out[12] that there is a need for critical experiments to accurately appraise the effect of introducing low-density water (such as spray from a water sprinkler or loosely packed snow) into an array of unmoderated units of fissile material.

It has been reported that the maximum k_{eff} for a typical PWR fuel storage array will occur for interstitial moderation equivalent to 5% of full density water or 0.05 to ~0.1 g H_20/cm^3 depending on the array.[5,8] These densities although relatively small, are still quite large compared with the density of water provided by an overhead sprinkler system.

Experiments to measure the water density from sprinklers and fire hoses have recently been reported in detail.[9] Since the maximum water density was only 0.004 g/cm^3, achieving a density in the range of 0.05 to 0.1 g/cm^3 was considered unachievable or incredible. Most of the papers pertaining to the effect of density reduction and/or low density interstitial moderation on storage arrays show the proposed or existing arrays to be "OK," but this is principally due to the fact that the maximum achievable water density from the overhead sprinkler system is not high enough to increase the k_{eff} of the proposed finite array above unity. If the array were large enough, however, and the enrichment of the uranium near 5% or greater, this would not necessarily be the case. Thus, interacting arrays of storage materials require detailed examination for the effect of possible interstitial moderation and density reduction on the criticality of the units composing the array. It is often required to show that the fuel array is subcritical for the aqueous atmosphere of all water densities from 0.0 to
1.0 g/cm^3

Although the effect of most sprinkler systems may be unimportant due to the very low density of the moderator—it has been observed[13] that a quantity of mist moderation judged to be safe might still be unacceptable due to water film formation on the fuel material. The film thickness is due to the viscosity of water and possibly an updraft during a fire. The effective film thickness should increase also if the fuel rods are stored horizontally. KENO V.a displayed this effect for fuel assemblies containing 256 rods, composed of UO_2 at 4.1 wt % enrichment, in a 16 × 16 array. The assemblies were in 19 × 34 storage array. The KENO results are plotted in Fig. 2.

In reviewing anomalous effects of moderation in arrays we observed that one previously-misidentified anomaly does not exist. Most arrays show an maximum k_{eff} with low-density water moderation. An earlier study,[2] however, did not show this maximum for *unreflected* 5^3 and 10^3 arrays of 15-kg ^{235}U spheres. In our current study we repeated some calculations for these arrays, and obtained some interesting results. Figure 3 shows the results of calculations for the 10^3 arrays with the MCNP neutron Monte Carlo code with the pointwise X6XS.0 cross section library.[14] The present results for unreflected arrays are in marked contrast to the results shown in Fig. 4 of the earlier study, i.e., low-density water-moderation is now seen to produce maximum reactivity at water densities near 0. 1 g/cm^3. We also calculated the unreflected 10^3 arrays with KENO V.a-CSAS4 in SCALE4. 1, with the 27-group cross section library, and matched the MCNP results.

We observe another interesting effect (anomaly?) by comparing results plotted at the left end (no interstitial moderation) of Figs. 3 (a) and (b). We see considerably higher k_{eff} for the low-density units in unmoderated reflected arrays than for unmoderated bare arrays, but for arrays with interstitial moderation the difference is quite small. This can be explained by the action of the interstitial moderation in keeping neutrons from leaking from the array by acting as a internal reflector as well as providing some degee of reflection at the array edges of "unreflected arrays," due to the unit cell setup which includes water in the region external to the edge units of the array.

We conclude that the earlier calculations for unreflected arrays were in error. At this time it is difficult to determine exactly why the earlier MORSE-C calculations for unreflected arrays were in error. Our guess is that the version of MORSE-C in use at that time accepted unreflected array input but did not replicate the units as intended. The evidence for this is supported by the MCNP calculations we show in Fig. 4 for single 15-kg

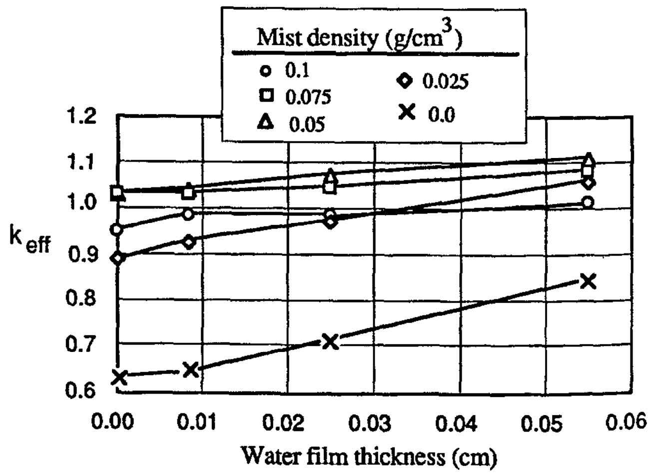

Figure 2. Film effects of water sprinklers on storage array of 4.1%-enriched-UO2 rods. Assemblies consist of 256-rod-assemblies in 19 × 34 storage array. Calculations are with KENO V.a. with 27-group SCALE cross section library.[13]

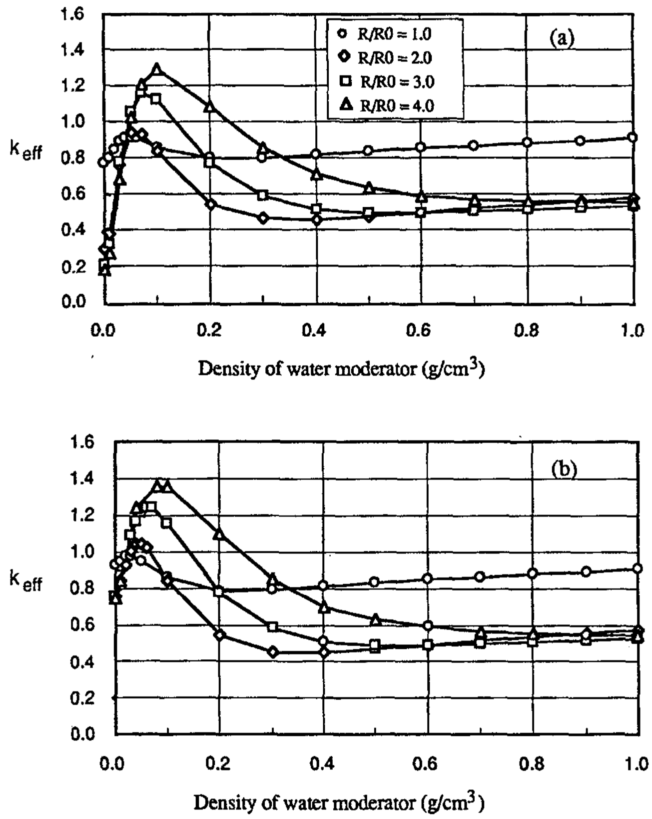

Figure 3. Effect of unit density variations and interstitial water-moderator density variations in 10^3 array of dry 15-kg ^{235}U units at 60.96-cm CTC separations calculated by the MCNP neutron Monte-Carlo code with the pointwise X6XS.0 cross section library: (a) calculations for an unreflected array, and (b) calculations for an array surrounded by a full-density water reflector.

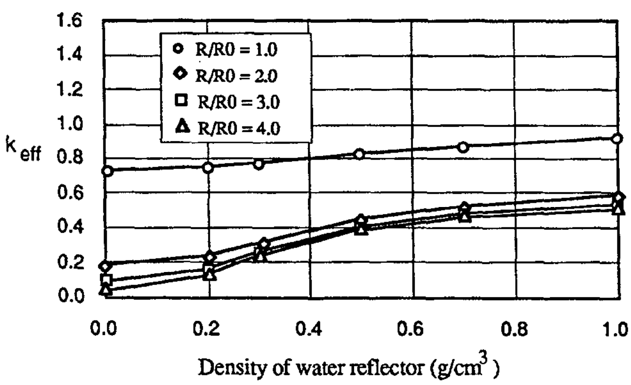

Figure 4. Effect of unit density variations for single, dry 15-kg ^{235}U units surrounded by 15.24 cm thick, varying-density water reflectors.

^{235}U units with varying density water reflection. These results are essentially identical to the "unreflected array" results shown in Fig. 4 (a) of the 1977 study.

The reactivity enhancement due to fissile material density reductions, however, still exits and is now seen to occur for both unreflected and water-reflected arrays.

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