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Revision 0

A RE-INTRODUCTION TO "ANOMALIES OF CRITICALITY"

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
Plateau Remediation Company

P.O. Box 1600
Richland, Washington 99352

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A RE-INTRODUCTION TO "ANOMALIES OF CRITICALITY"

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In 1974, a small innocuous document was submitted to the American Nuclear Society's Criticality Safety Division for publication that would have lasting impacts on this nuclear field. The author was Duane Clayton, manager of the Battelle Pacific Northwest National Laboratory's Critical Mass Lab, the world's preeminent reactor critical experimenter with plutonium solutions. The document was entitled, "Anomalies of Criticality" (1. "Anomalies... " was a compilation of more than thirty separate and distinct examples of departures from what might be commonly expected in the field of nuclear criticality. Mr. Clayton's publication was the derivative of more than ten thousand experiments and countless analytical studies conducted world-wide on every conceivable reactor system imaginable: from fissile bearing solutions to solids, blocks to arrays of fuel rods, low-enriched uranium oxide systems to pure plutonium and highly enriched uranium systems. After publication, the document was commonly used within the nuclear fuel cycle and reactor community to train potential criticality/reactor analysts, experimenters and fuel handlers on important things for consideration when designing systems with critically "safe" parameters in mind. The purpose of this paper is to re-introduce "Anomalies of Criticality" to the current Criticality Safety community and to add new "anomalies" to the existing compendium. By so doing, it is the authors' hope that a new generation of nuclear workers and criticality engineers will benefit from its content and might continue to build upon this work in support of the nuclear renaissance that is about to occur.

I. INTRODUCTION

From 1943 to nearly 2000, several-thousand articles and publications were issued, detailing nuclear criticality analytical and experimental studies for a variety of reactor systems. Much of this data was centered in areas associated with either fuel reprocessing/fabrication capability or around Department of Energy (and other international) weapons complex sites. To those of us who were aspiring criticality analysts or experimenters at the time, this work created an industry that supported the security of our nation(s) and offered promise for the world as a nearly cost-free form of energy. Experimenters at the various locations became closely aligned with the missions of their respective facilities, and as a consequence became expert in the criticality of certain "types" of reactor systems. For example, experimenters at Los Alamos and Livermore critical mass labs became experts in fast systems that supported nuclear weapons research. Experimenters at Hanford became experts in plutonium and uranium solutions that supported fuel reprocessing and separations activities, while experimenters at Rocky

Flats and Oak Ridge became experts in both types of systems. It was not uncommon to work with first-of-a-kind systems and materials or to design and operate these critical reactor systems under a variety of experimental conditions. Nor, was it uncommon to perform dozens of experiments with totally different configurations of fuel the very next day.

As these data became more visible to the nuclear community, it became apparent that computer codes could predict and extrapolate from systems of known critical systems. Consequently, critical experiments of well-documented systems were performed to adjust the calculation methods and cross-sections of materials used in such calculations. Although the physics of how things could be taken "critical" or "super-critical" was well-known, it was always a given that exceptions could be found to any rule. Consequently, it was paramount to nuclear safety workers that special precautions be taken to protect the welfare of nuclear workers. Along the way in the establishment of these procedures or methods for worker safety and protection, certain anomalous conditions were uncovered and noted that were highlighted so as to prevent nuclear accidents from occurring. "Anomalies of Criticality" thus was born out of a need for the nuclear community to share its joint knowledge of special considerations and anomalous conditions in nuclear criticality where systems might behave differently than expected.

The first revision of "Anomalies of Criticality was published by E. D. Clayton – then manager of the Battelle Critical Mass Lab in 1974[(1)]. At the time, Duane was the world's eminent expert on the criticality of plutonium solution systems and his lab had published more than half of the world's data on solution critical systems. It consisted of more than eighty examples of anomalies, covering a wide-range of fuel types, enrichments, neutron absorbers and fuel forms. As more experiments and analytical calculations were performed, "Anomalies" continued to grow to its point that it exists today. It covers a period from 1945 to 2000.

II. WHAT IS NEW

The current revision of "Anomalies of Criticality" (revision 6) builds upon Revision 5 [(3)] and adds several new anomalies. These can be captured under the following headings:

Physical characteristics of the actinides
Safety Implications of Anomalous effects of neutron absorbers on criticality
Interstitial moderation and its importance to criticality
Geometry effects
Universally safe containers
Super-heavy elements and an island of stability beyond Californium

The purpose of this paper is to highlight changes in Rev. 6 of "Anomalies of Criticality." It is hopeful that the reader will see the wisdom in utilizing this material collectively as a training tool for new criticality engineering personnel.

III. SAFETY IMPLICATIONS OF ANOMALOUS EFFECTS OF NEUTRON ABSORBERS ON CRITICALITY

A number of apparent "anomalies" have been disclosed in recent years, [(1, 3)] and as new data have become available, additional anomalies have come to light. An anomaly, once disclosed, is amenable to explanation since there is a valid reason for the occurrence of any happening and a scientific way to understand any phenomena. Application of existing data, without knowledge of the "anomalies" could lead to undesirable events, or diminished criticality control. Neutron absorbers are frequently used for criticality control in nuclear fuel cycle operations. In the following, several anomalies have been selected that have principle application in nuclear fuel processing.

Common neutron absorbers include: boron, cadmium, and gadolinium. Other materials are frequently present in the constituents that may act in the capacity of neutron absorbers such as NO_3, ^{238}U and ^{240}Pu. ^{240}Pu is a "fissible" nuclide that may serve either as a strong neutron absorber to inhibit a chain reaction or contribute neutrons to a chain reaction through fast fission, depending on the condition encountered.

III.A. Use of Soluble Absorbers for Criticality Control of Power Reactor Fuels in Water

The presence of large quantities of neutron absorbing nuclei can alter the neutronics of a system. High concentrations of thermal neutron absorbers such as boron, cadmium or gadolinium cause a shift in the neutron energy. For example, calculations by C. R. Marotta on the re-criticality potential of the TMI-2 core show that the peak value of k_∞ is shifted toward lower values of water-to-fuel volume ratios as the boron concentration is increased in the water moderator.[4] (See Figure 1)

If the concentration of boron in the water moderator of two different lattices is the same, then the lattice with the larger spacing (and water-to-uranium ratio) will have a higher ratio of boron to uranium. In addition, the neutron energy spectrum will be faster in the lattice of least water. In this case the boron can be expected to have a smaller effect on the criticality of that lattice.

Compacting a lattice of fuel rods from optimum spacing in water (i.e., reducing the separation between fuel rods in the assembly from that configuration, which gives the maximum buckling), can result in a larger critical size and number of fuel rods for criticality and lead to a safer condition. In the case of heavily borated lattices, however, it is possible for the reverse to occur, i.e., with the absorber present, compacting or consolidating, the lattice spacing from optimum spacing in water can result in a smaller critical size or volume and number of fuel rods for criticality.

This should not be confused with the fact that adding a "neutron absorber" to any given lattice (providing this absorber does not of itself substantially moderate neutrons or displace the moderator that does) will always render that lattice assembly further subcritical.

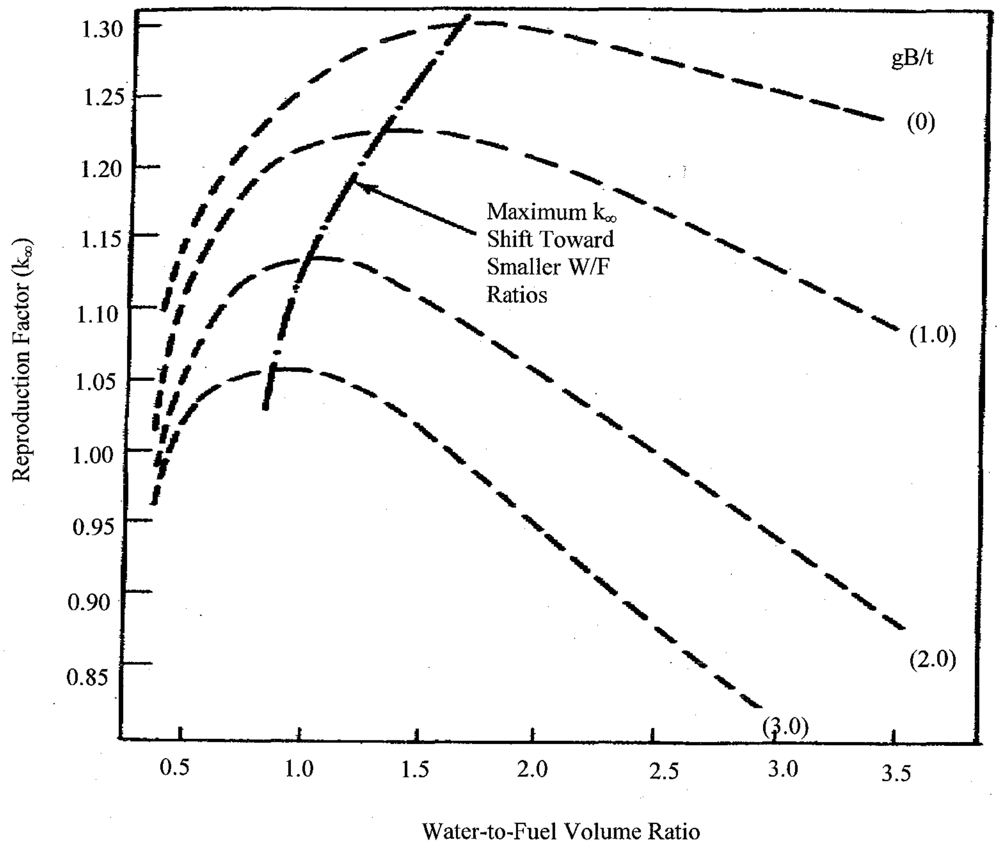


Fig. 1. Variation in Reproduction Factor (k_∞) of Water Moderated Lattices as Function of Water-to-Fuel Volume Ratio and Boron Content [Bottom Three Curves from Marotta [(4)]]

III.B. Use of Borated Glass Raschig Rings for Criticality Control in Vessels Containing Fissile Solutions

An American National Standard (ANSI/ANS-8.5) [(5)] provides guidance for the use of borosilicate glass Raschig rings as a neutron absorber for criticality control. In connection, with the preparation of this standard values of k_∞, they were calculated for various glass volume fractions versus the volume fraction outside the glass (glass tube OD = 38.10 mm). The volume fraction outside of the glass is the fraction of the cylindrical cell that is outside of the glass tube, and is a measure of the open space between the rings. One of the curves from these calculations is reproduced in Figure 2. [(6)] It is especially noted that although the volume of solution occupied by the glass is the same in each case, the rings are less effective when in contact or spread out.

Although the volume of the solution occupied by borated glass Raschig rings of different thickness can be the same, the rings may be less effective when in contact or spread out. Thus, in using Raschig rings for criticality control, not only must the glass volume fraction be specified, but also the outside diameter of the rings. It should be understood that for a Raschig ring of given dimensions, an increase in glass volume fraction (or stacking density) will always cause k_∞ to decrease.

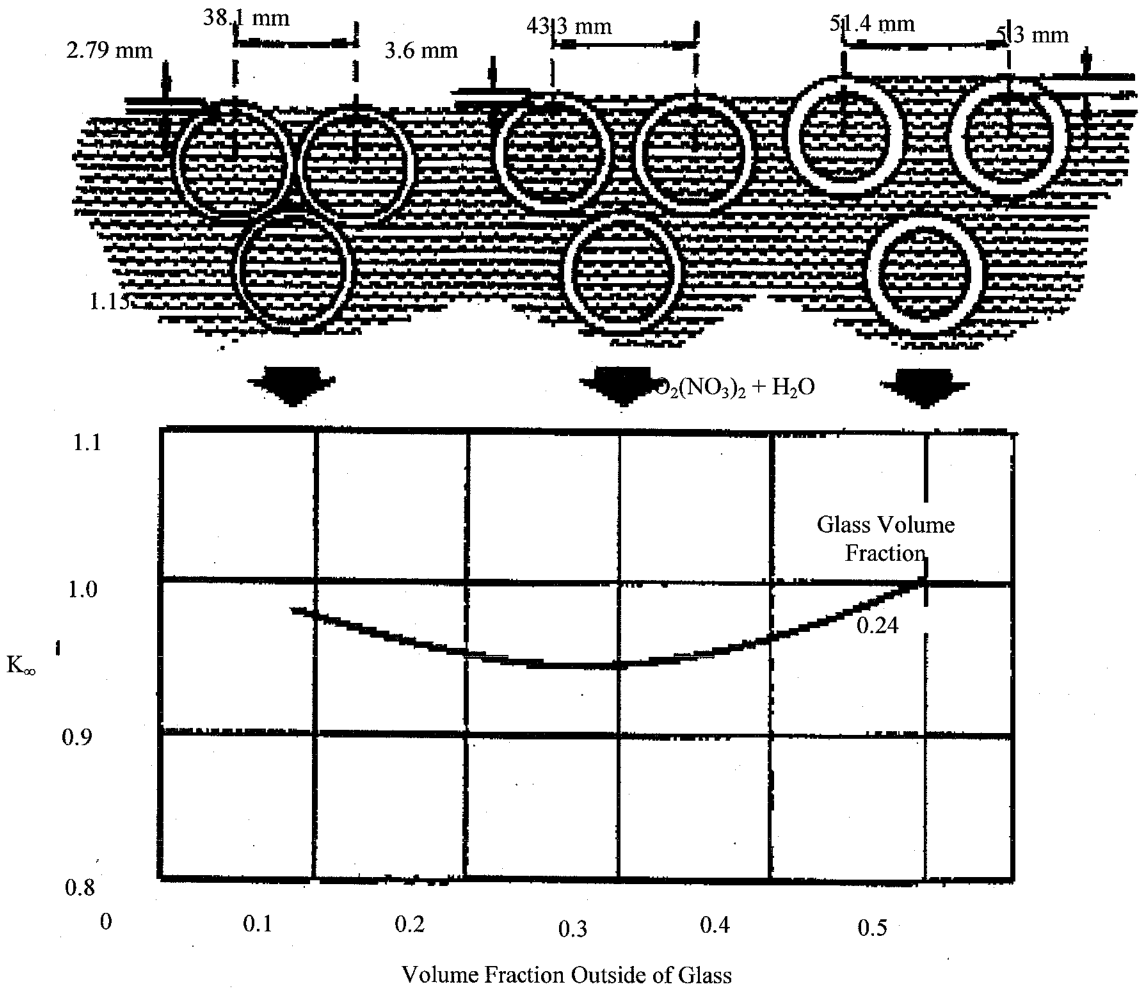


Fig. 2. Calculated k_∞ Versus Volume Fraction

III.C. Effect on Criticality of Mixtures of Soluble Absorbers in Plutonium Solutions

The addition of neutron absorbers in soluble or fixed form can be an effective means of criticality control. Calculations have indicated that mixtures of soluble absorbers may be more effective than single solutes in criticality control. (7)(8) Calculated amounts of boron and gadolinium to reduce k_∞ of Pu + U nitrate solutions (30% Pu in U) to unity are shown in Figure 3. A mixture of two soluble absorbers, of boron and gadolinium, can be more effective than either one separately, i.e., total quantity of B + Gd less, and the mixture ratio of the absorbers can be changed to shift the effectiveness toward either lower or higher concentrations of Pu or U to obtain the most worthwhile effect.

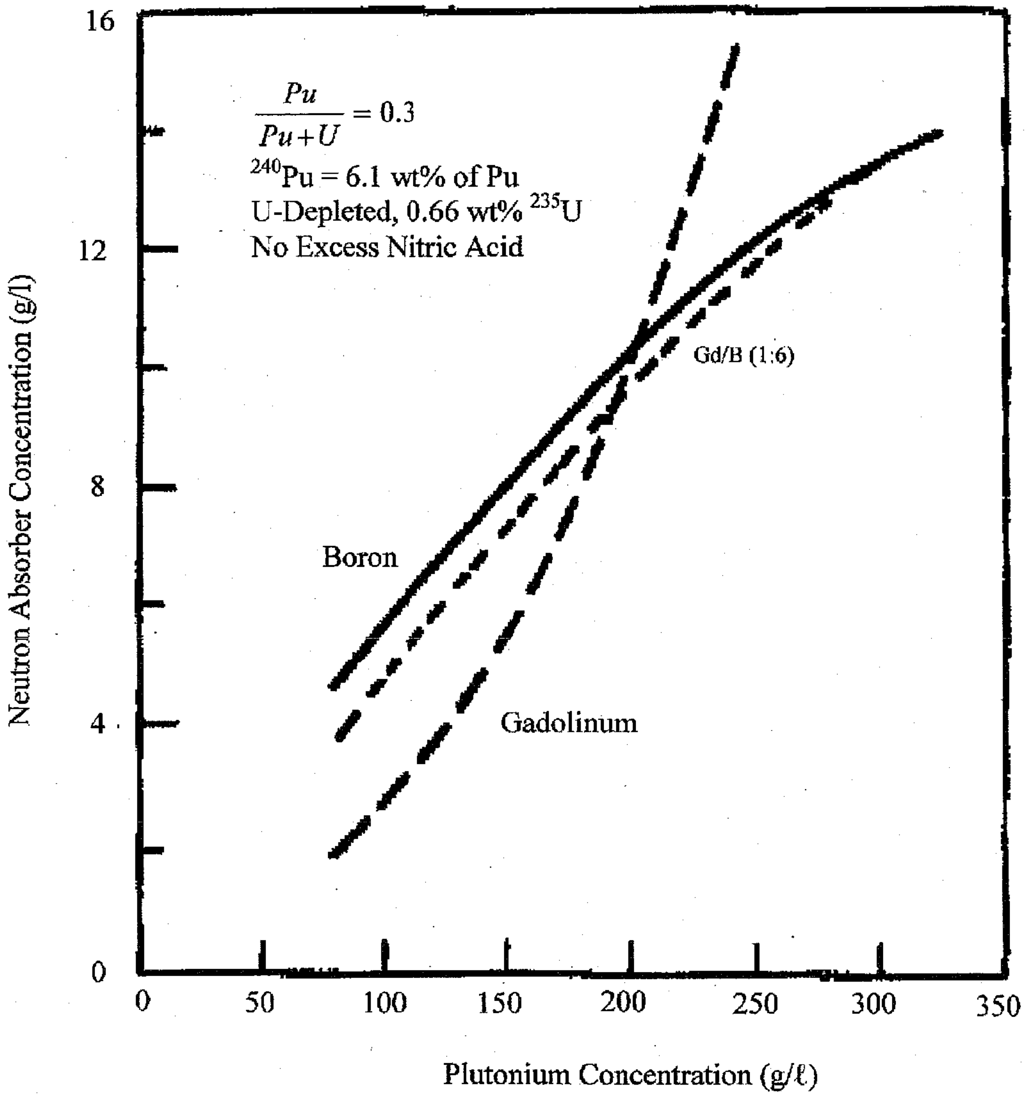


Fig. 3. Absorber Concentration Needed to Reduce k_∞ of Pu + U Solution to Unity

III.D. Effect of Boron on Criticality of Plutonium Nitrate Solutions

It has been suggested that a boron concentration required for safety of a homogeneous mixture of Pu atoms in water might not be conservative when applied to plutonium nitrate aqueous solutions. (10) At first glance this seems to be contrary to normal behavior.

If comparisons are made between an aqueous homogeneous plutonium nitrate solution [$Pu(NO_3)_4 + H_20$] and a homogeneous mixture of Pu atoms or PuO_2 in water at like Pu concentrations, the $Pu(NO_3)_4$ solution will have the larger critical dimension and mass, due to the presence of the nitrogen and neutron captured therein. It might be presumed, erroneously, that if a sufficient quantity of soluble neutron absorbers were added to render a mixture of Pu atoms in water subcritical, that a Pu nitrate solution with the same concentration of Pu in g/L would also be subcritical. At higher plutonium concentrations, however, more boron is required for the nitrate system.

The plutonium metal water mixture should always be more reactive than plutonium nitrate. However, the nonconservative behavior does occur. Figure 4 shows the boron concentration required to poison aqueous plutonium solution to $k_\infty = 1.0$. At lower plutonium concentrations the boron content required for the metal systems is sufficient for the nitrate. This is what one would normally expect since the nitrate is an additional neutron poison. At higher plutonium concentrations, more boron is required for the nitrate systems than the metal systems. This seeming anomaly is caused by the larger volume of the nitrate molecule. At the same plutonium concentration, the nitrate solution has a smaller volume of water than the metal solution. The reduction in hydrogen content reduces the effectiveness of the boron poison and more is required.

If the comparison is made at the same H/Pu atom ratios, not equal Pu concentration, then the quantity of boron will be sufficient, in every case, to cover the nitrate system as well.

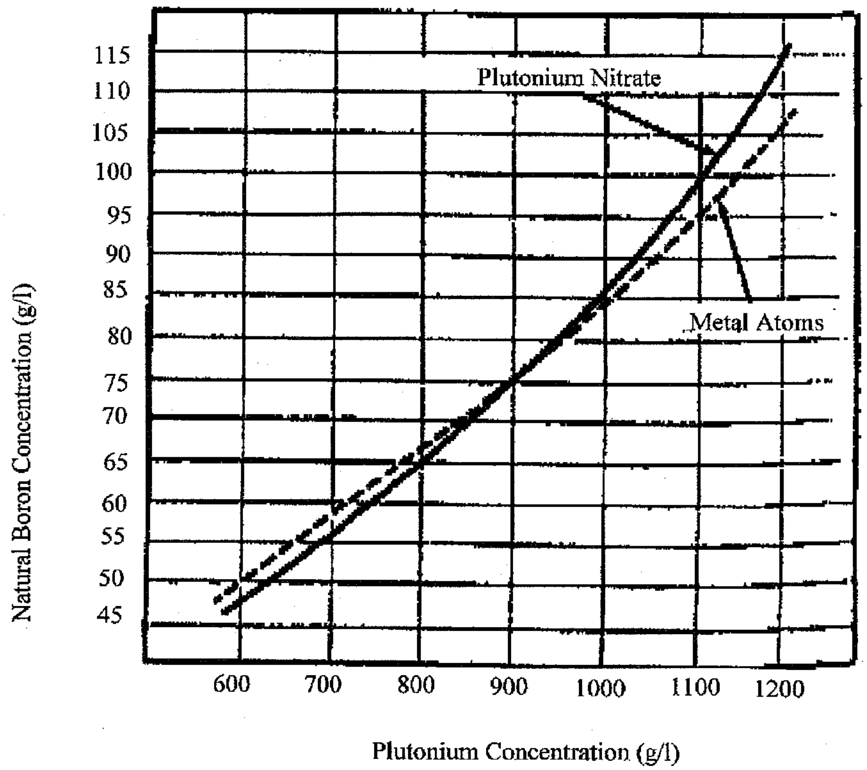


Fig. 4. Quantity of Boron Required to Reduce k_∞ of Homogeneous Aqueous Pu Solutions to Unity

III.E. Enhanced Effect of a Gadolinium Absorber on the Criticality of Plutonium-Uranium Nitrate Solutions with ^{240}Pu Content in the Plutonium

An interesting anomaly was reported wherein the effectiveness of a soluble gadolinium absorber was significantly enhanced by the presence of ^{240}Pu and ^{238}U in a Pu + U (30% Pu) nitrate solution. (7) When the Pu contained 19 percent ^{240}Pu, the Gd appeared to be up to some three-four times more effective in increasing the minimum critical mass than for the case with no ^{240}Pu (8). A qualitative explanation for the high efficiency of two or three coexistent nuclides in the solute is the various resonance peaks that occur in the neutron cross sections of the capturing nuclei over a broad energy range. Data from the French report are shown in Figure 5 (8).

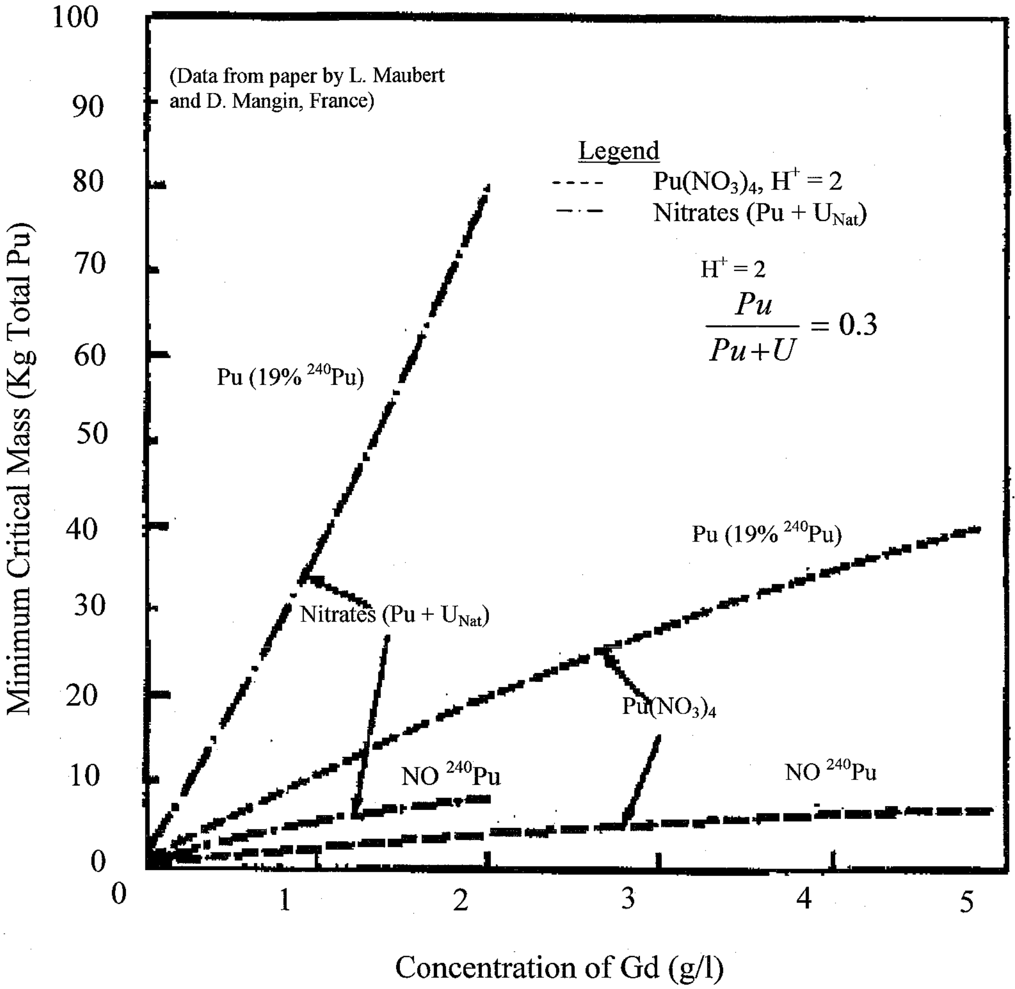


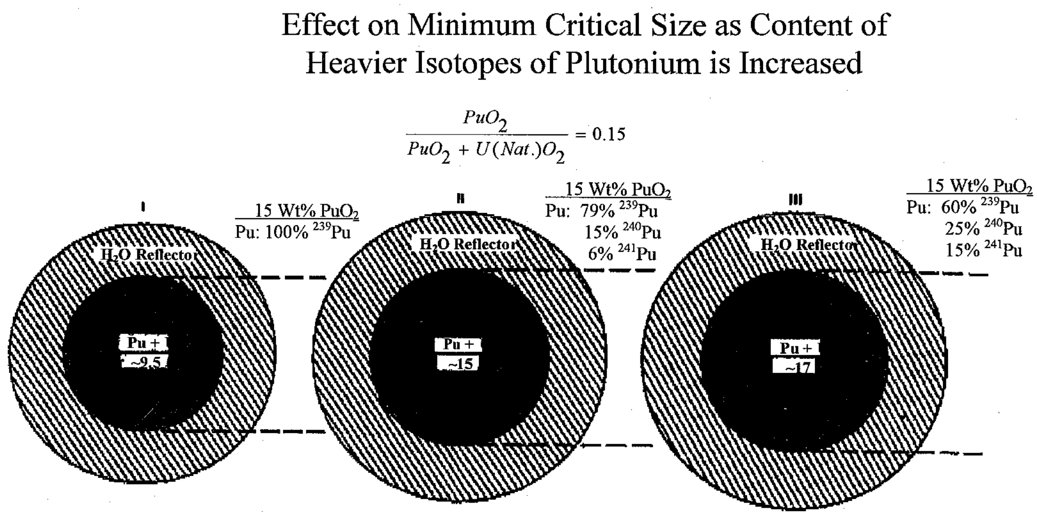
Fig. 5. Calculated Minimum Critical Masses for Aqueous Solutions of Pu and U Containing Gd

III.F. Possible Anomalous Effect of ^{240}Pu on the Minimum Critical Dimension of mixed Oxide (Pu –Natural U) Fuel Pins in Water

The American National Standard for *Nuclear Criticality and Safety of Homogeneous Plutonium-Uranium Fuel Mixtures Outside Reactors* (ANSI/ANS-8.12) is being revised to include subcritical limits on heterogeneous systems. In connection with this effort a number of calculations were completed for heterogeneous systems of mixed fuel pins in water. [(9)(11)]

Some of the calculations, however, have disclosed what may be an anomaly, and if not, then perhaps the failure of existing codes to perform certain types of calculations. The problem concerns the effect of ^{240}Pu on the dimensional limits for heterogeneous systems of mixed oxides when the PuO_2 concentration in the mixed oxides (PuO_2 + UO_2) is at 30 wt%. The latter represents the high-end of the Pu concentration for Pu in U for which subcritical limits were provided in the revised standard. Figure 6 shows the minimum critical size for 15 wt% PuO_2 in mixed oxide to increase as higher isotopes of Pu displace ^{239}Pu, as expected. The results in Figure 7 for 30 wt% PuO_2, however, show the minimum critical dimension initially increases with ^{240}Pu content and then, contrary to expectation, may decrease as higher isotopes of Pu displace the ^{239}Pu.

Although this problem has not been studied in detail, a possible explanation for the phenomena is as follows. In the absence of ^{240}Pu, the minimum critical dimensions occur for the heterogeneous systems under well moderated conditions, a thermal reactor system. If the Pu content in the natural U is substantial, for example, at 30 wt% and the ^{240}Pu content of the Pu is as high as ~25 wt%, the minimum critical dimension is obtained under low or essentially unmoderated conditions. Under the latter circumstances of high Pu content and a relatively fast neutron spectrum, the ^{240}Pu begins to fission in substantial quantity and contributes neutrons to the chain reaction, whereas under moderated conditions the ^{240}Pu serves principally as a neutron absorber with little or no fission. The latter is understandable when it is considered that ^{240}Pu metal (a fissible nuclide) can be made critical by itself with a finite calculated critical mass of 33 kg for a bare sphere, a value that is less incidentally than that for ^{235}U metal. (12, 13)



For 15 Wt% PuO_2 in mixed oxide, minimum critical size continues to increase as higher isotopes of Pu displace ^{239}Pu; smallest size occurs for case 1 and largest for case III.

Fig. 6. Effect on Minimum Critical Size as Content of Heavier Isotopes of Plutonium is Increased

Calculated Variation in Minimum Critical Volume for
Heterogeneous Systems of Mixed Oxides as Function of ^{240}Pu Content in Pu

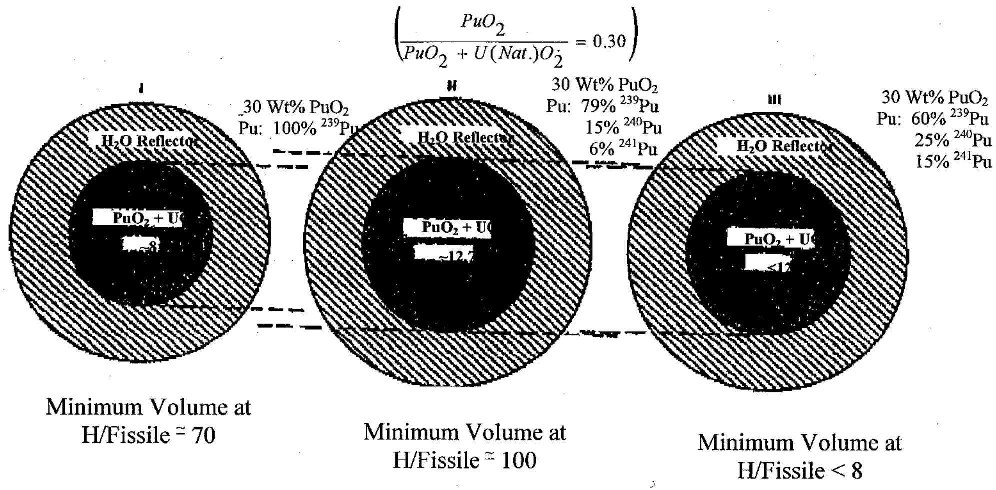


Fig. 7. Calculated Variation in Minimum Critical Volume for Heterogeneous Systems of Mixed Oxides as Function of ^{240}Pu Content in Pu

III.G. A Condition when a Smaller Critical Mass of Pu can be Obtained with More Cadmium Neutron Absorber and Less Pu

An example is also given in a paper by R .D. Carter pertaining to criticality considerations in reprocessing wastes and contaminated soils wherein a smaller critical mass could be found for a mixture which had more cadmium and less plutonium than another because of differences in the H/Pu ratios of the mixtures. [14]

For example, at six grams of plutonium per liter in soil, a mixture containing 0.2 grams of cadmium per liter and 20 percent water had a calculated critical mass of 7.6 kilograms while a mixture of 15 grams of plutonium per liter with no cadmium had a critical mass of 10.6 kilograms at 10 percent water.

Therefore, it is not the concentration of Pu per se, but the hydrogen content that is the controlling factor in determining the effectiveness of soluble absorbers in aqueous solutions.

III.H. General Comments On Soluble Absorbers

This section could have been entitled, "Some Precautions on the Use of Neutron Absorbers." It has been the intent to summarize and briefly discuss several anomalies that pertain to the effect of neutron absorbers on criticality. Some of these deserve further study, which may be the result of inadequate cross section data and raise questions concerning the validity of computer codes. The presence of large quantities of neutron absorbing nuclei can alter the neutronics of the system causing unexpected results. In particular, mixtures of neutron absorbers in combination with ^{240}Pu and ^{238}U can have surprising results. The nuclide, ^{240}Pu, may serve in the capacity of a resonance absorber or as a fissible nuclide, depending on the energy spectrum or degree of neutron moderation.

IV. INTERSTITIAL MODERATION AND ITS IMPORTANCE TO CRITICALITY

There have been a number of papers written to assess the criticality safety of proposed and existing storage arrays and to examine the effects of low-density moderation.[15, 16, 17, 18, 19, 20, 21] The most recent paper was presented at the International Conference on Nuclear Criticality Safety, Oxford, England, September 1991.[22]

The availability of appropriate benchmark experiments for low-density moderation is quite limited. The French, however, have performed experiments at Valduc in which four pressurized water reactor (PWR)-type assemblies were made critical in water with various hydrogenous compounds interposed between the assemblies.[23] 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 two percent full-density water whereas polyethylene powder $(CH_2)n$ was equivalent to about 38 percent full-density water. Attempts to validate calculations against the one set of suitable experiments at low density moderation were reported as disappointing.[20]

It has been reported that the maximum k_{eff} for a typical PWR fuel storage array will occur for interstitial moderation equivalent to 5 percent of full density water or 0.05 to ~0.1 g H_2O/cm^3 depending on the array. [17, 20] 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.[21] 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 percent 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/cc.

Although the effect of most sprinkler systems may be unimportant due to the very low density of the moderator – it has been observed [24] 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 x 16 array. The assemblies were in 19 x 34 storage array. The KENO results are plotted in Figure 9.

Most arrays show a maximum k_{eff} with low-density water moderation. The study by Koponen in 1977, [2] did not show this maximum for unreflected 5^3 and 10^3 arrays of 15-kg ^{235}U spheres. Repeat calculations were made in 1993 for some of the unreflected arrays reported by Koponen in 1977 [2] with some interesting results. [28] Figure 10 shows the results of calculations for the 10^3 arrays with the MCNP neutron Monte Carlo code with the point-wise X6XS.0 cross section library.[25] Low density water moderation is now seen to produce maximum reactivity at water densities near 0.1 g/cc. Calculations on unreflected 10^3 arrays with KENO V.a – CSAS4 in SCALE 4.1, with the 27-group cross section library, matched the MCNP results. [28]

Another interesting effect becomes apparent by comparing results plotted at the left end (no interstitial moderation) of Figure 10. A considerably higher k_{eff} is obtained 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 degree 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.

The reactivity enhancement due to fissile material density reductions exists for both unreflected and water-reflected arrays.

As pointed out by Koponen, [2] it may be worth considering that some shipping containers that have been approved for shipping compact fissile units may not be in compliance with criticality safety requirements if the fissile units are very low in density.

Previous calculations in two earlier papers, one by W. R. Stratton [26] and also by C. B. Mills [27] show that by surrounding a single reactor unit of fissile material with a thick weakly absorbing reflector such as graphite, heavy water or beryllium, it is possible to affect a reduction in the critical mass by a decrease in core density, but no such effect has been clearly demonstrated to date in the case of a single fissile unit with a thick light water reflector.

There also may be a condition whereby a reflected array of fissile units, that is subcritical initially, could become supercritical from either an increase or decrease in density of the individual units of the array-even though the mass of each unit were conserved and the separation between units remained unchanged. (In a theoretical sense, at least, this would be quite possible).

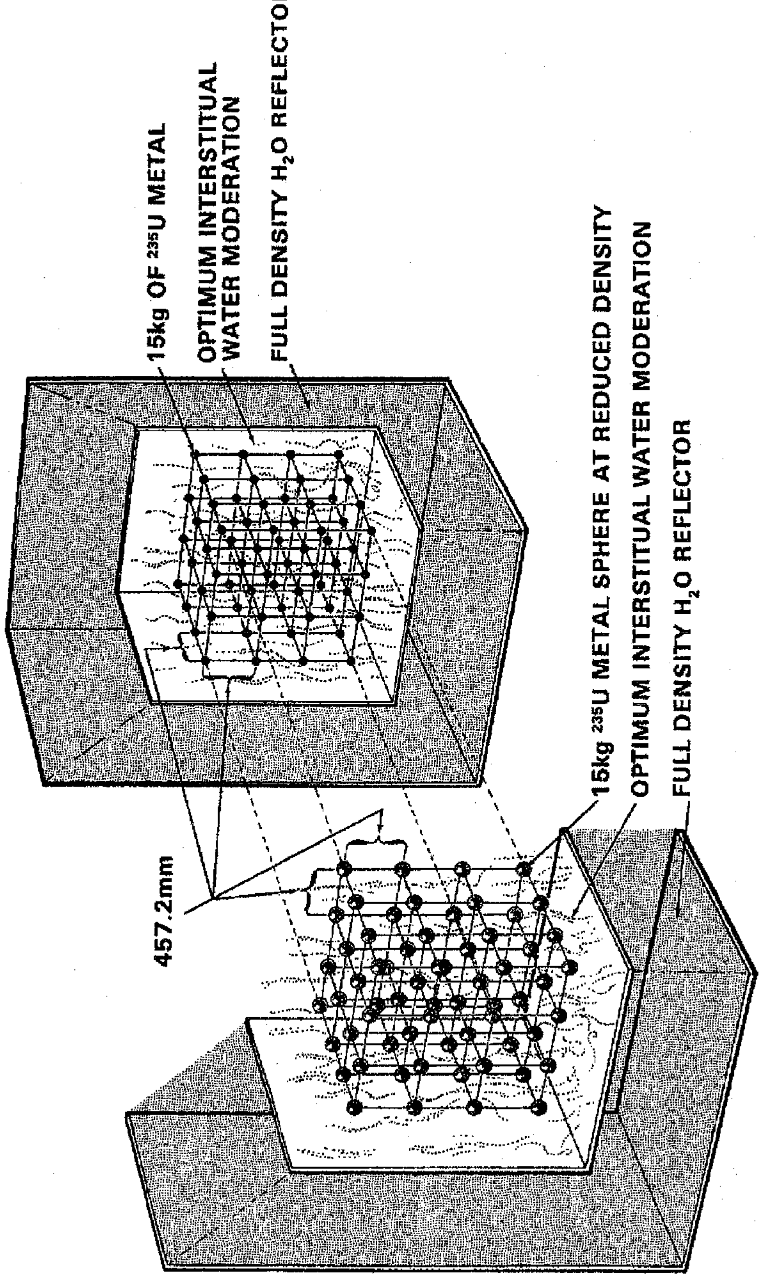


Fig. 8. Reactivity Enhancement Due to Density Reduction in Units

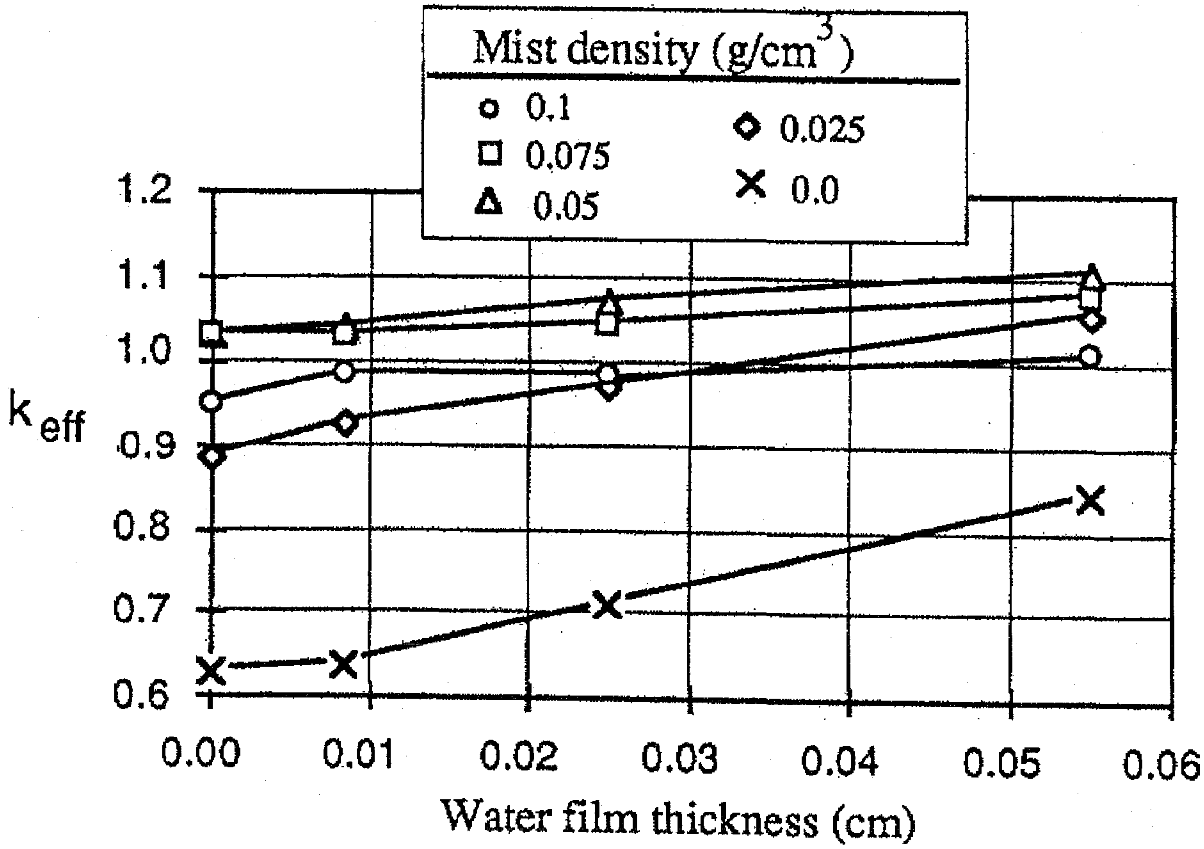


Fig. 9: Film Effects of Water Sprinklers on Storage array of 4.1%-enriched UO_2 rods.

(Assemblies consist of 256-rod-assemblies in 19 x 34 storage array. (Calculations are with KENO V.a. with 27-group SCALE cross section library [24])

IV.A. Fire (Fog, Mist or Flooding: A Potential for Triple Criticality)

An interesting problem concerns the effect on criticality for an array of interacting units if the water content of the intervening airspaces within the array was increased. 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 storing mixed oxide fuels of PuO_2 and $U_{NAT}O_2$, or slightly enriched uranium, three effects (shown schematically in Figure 11) will be paramount. For purposes of illustration, let us assume the Pu content, or ^{235}U content in the U, to be less than 5 percent, such that criticality would not be possible without the addition of a moderator, taken in this case to be water. The array is well subcritical initially. Depending on the fuel composition making up the fuel bundles and the storage arrangement used, it is possible by means of Monte Carlo calculations to generate the type of curve shown. The three effects involved: 1) internal moderation of the fuel elements within each fuel bundle, 2) reflection about the array as a whole and also about each individual unit, and 3) interaction between units. Initially, the value of k_{eff} increases rapidly with increased water density due to internal moderation, external reflection and enhanced interaction. Interaction is enhanced because a small amount of water (typically a few percent of full water density) in the space between units will slow down some of the neutrons in the interaction process. The number of neutrons actually arriving at a second unit will be less, but there will be a higher probability for fission if the neutron energy is reduced. However, with too much moderation or intervening water, too many neutrons will be absorbed between the units and the effect of interaction will be reduced. The value of k_{eff} is rapidly increased at first, and then falls due to the decrease in neutron interaction. If the surface-to-surface distance between fuel bundles is some 8 – 12 inches or more, then on full flooding the reactivity of the array would become merely that for a single bundle of fuel immersed in water. With full flooding, the neutron interaction would be reduced to zero.

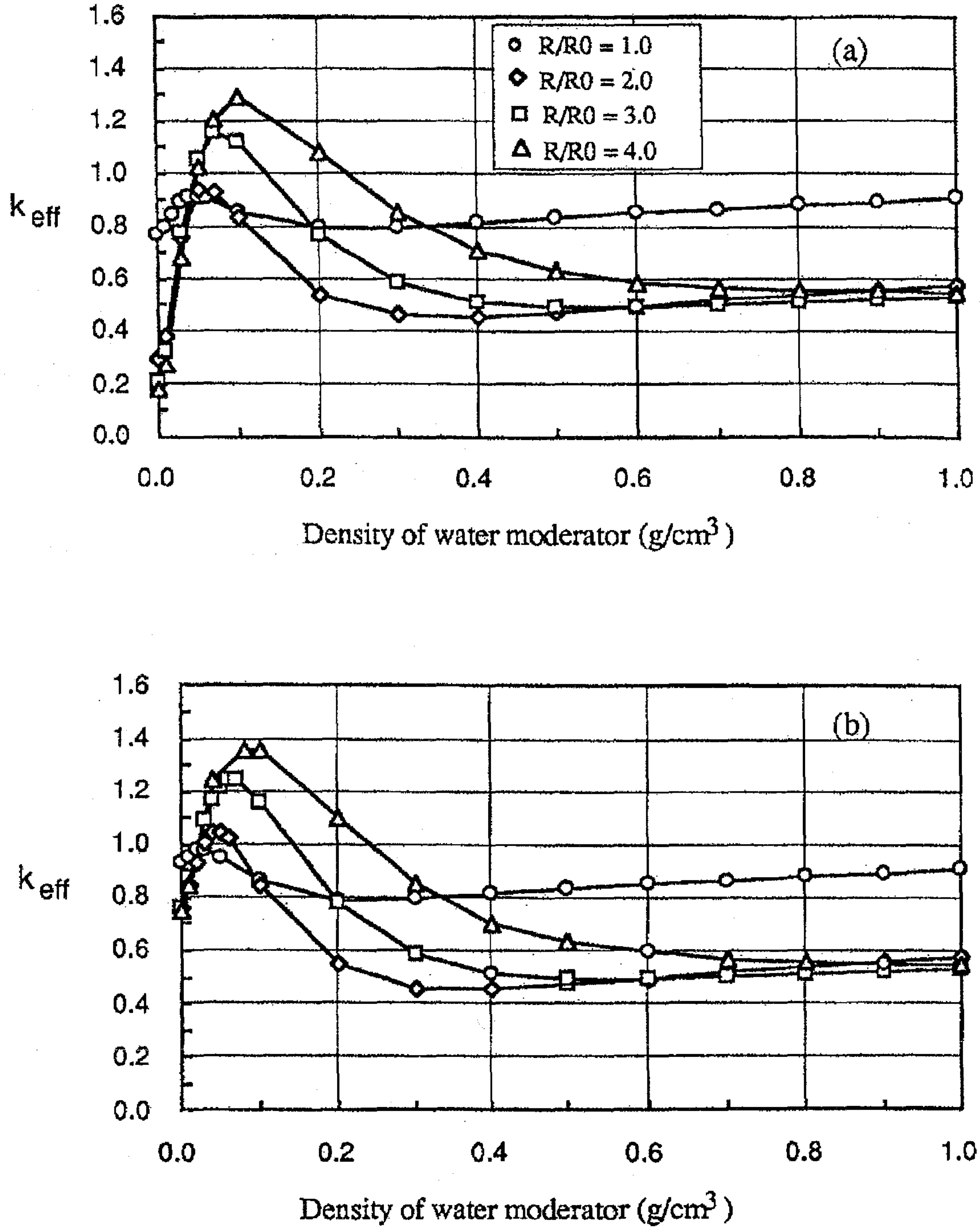


Fig. 10. Effect of unit density variations and interstitial water-moderator density variations in 10^3 arrays of dry 15-kg ^{235}U units at 60.96-cm CTC separations calculated by the MCNP neutron Monte-Carlo code with the pointwise X6XS.0 cross section library: (a) calculations for an unreflected array,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

Note that in going from the completely dry case to the fully flooded condition, criticality could occur at three different water densities being separated by two subcritical regions of water density. It is important for determining the safety of a given storage array that the effect of sprinkler systems and the use of water for fire control be fully examined over the full range of water densities that may be encountered[29].

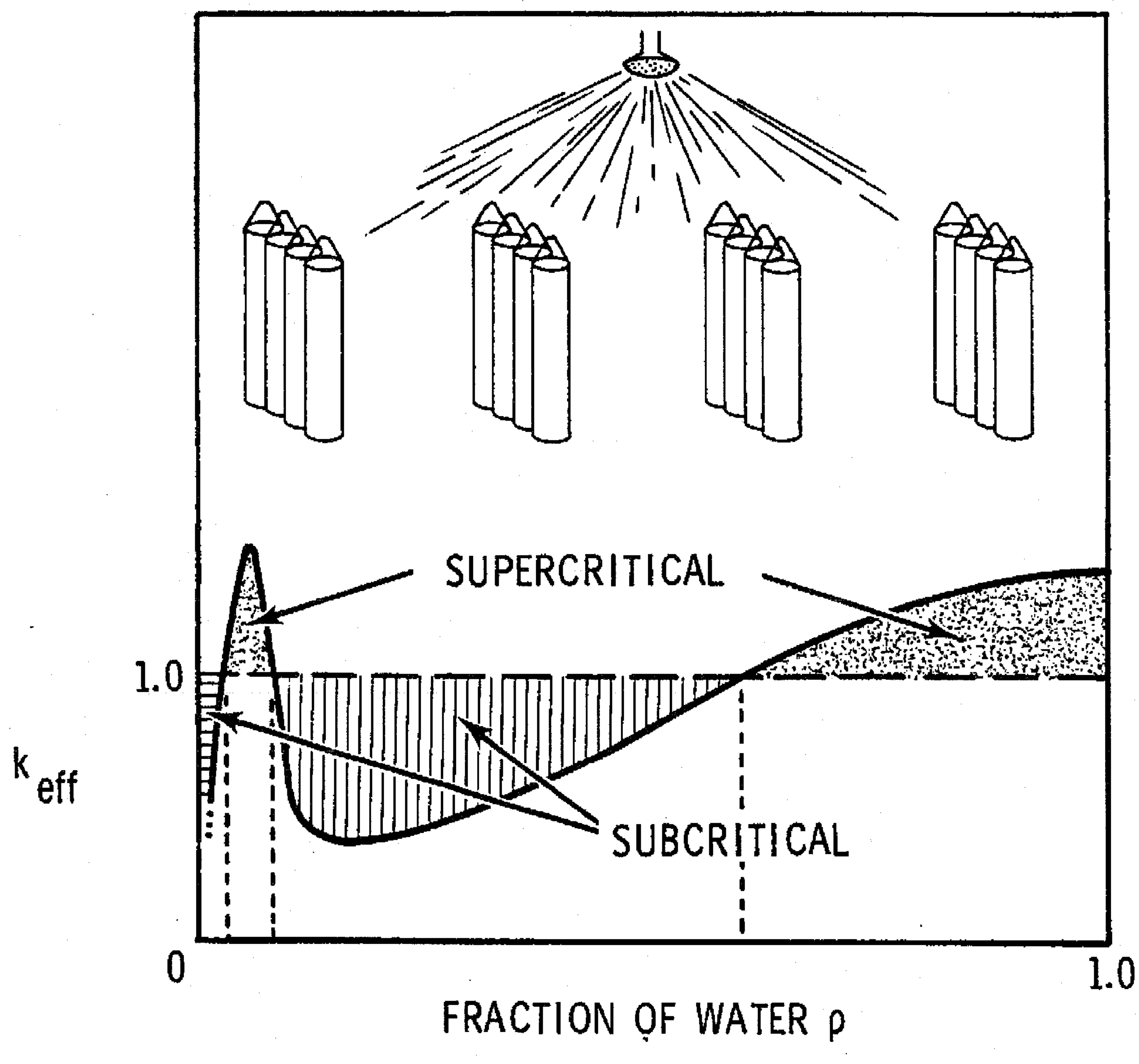


Fig. 11. Fire (Fog, Mist, or Flooding: The Potential of Triple Criticality in a Storage Array)

V. CONCLUSIONS

The authors have attempted to illustrate the value of "Anomalies of Criticality" as a tool that can enhance the training of nuclear criticality professionals, experimenters and analysts. If used in conjunction with improved worker safety methods and modern calculation techniques it will improve the workers' understanding and appreciation for the complexity of nuclear criticality. The derivative will be a safer work environment for everyone in the nuclear industry.

It is appropriate that we conclude this paper with the words of its principal author – Duane Clayton – as recorded at the end of rev. 6 of "Anomalies of Criticality." It reflects well the feelings and intent of those of us who were fortunate to work with Duane on the publication of this latest revision:

"*The experiments or calculations, which form the bases of nuclear criticality safety and control, were performed by a special breed of person, criticality experimenters, many of whom have vanished, or are now rapidly vanishing from the scene. This is a natural consequence as the critical experiment work is brought to its logical conclusion, and as new critical experiment data requirements have been reduced. The benefits of the contributions of the criticality experimenters to nuclear energy will accrue in the course of time largely to their offspring, or the progeny thereof, and will contribute to a higher quality of life for those surviving in the future.*

It has been a privilege for the author to have known and worked with some of these fine individuals over the course of some years. As has been stated, there are those individuals who live out their lives in a state of quiet desperation, but for those of us fortunate enough to be involved in the field of nuclear energy during its early stages of development, there have also been some interesting and highly gratifying moments along the way. But, as in the mythical story about the ten little Indians, one day there were none.

> *"I had a dream, which was not all a dream. The bright sun was extinguished, and the stars did wander darkling in the eternal space. Rayless, and pathless, and the icy earth swung blind and blackening in the moonless air."*[30]

Perhaps in the end all that any of us can say is that it has been a great privilege for each of us to have lived briefly during a unique cycle of the total history of the cosmos in which nature has been kind enough to have made at least a portion of the cycle knowable to man.

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