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SUBCRITICAL LIMITS FOR SPECIAL FISSILE ACTINIDES

by

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SUBCRITICAL LIMITS FOR SPECIAL FISSILE ACTINIDES

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ABSTRACT

Critical masses and subcritical mass limits in oxide-water mixtures were calculated for actinide nuclides other than ^{233}U , ^{235}U and ^{239}Pu that have an odd number of neutrons in the nucleus. S_n transport theory was used together with cross sections, drawn from the GLASS multigroup library, which were developed to provide accurate forecasts of actinide production at Savannah River. Subcritical limits proposed in support of ANS Standards Committee efforts to draft a standard for safely subcritical operations are: 201g for ^{241}Pu , 13g for $^{242\text{m}}\text{Am}$, 90 g for ^{243}Cm , 30g for ^{245}Cm , 900g for ^{247}Cm , 10g for ^{249}Cf , and 5g for ^{251}Cf . Increases in limits for ^{241}Pu , $^{242\text{m}}\text{Am}$, and ^{245}Cm resulting from association with ^{240}Pu , ^{241}Am , and ^{244}Cm are also proposed. A limiting mass of 8.15 kg for plutonium containing at least 67% ^{238}Pu as oxide is given.

INTRODUCTION

The most important nuclides in nuclear criticality safety are ^{233}U , ^{235}U , and ^{239}Pu , but other actinide nuclides capable of being made critical may be encountered in sufficient quantities to require the nuclear criticality safety evaluation of operations involving them. Subcommittee 8 of the Standards Committee of the American Nuclear Society is drafting a standard for "Nuclear Criticality Control of Special Actinide Elements" that will contain subcritical limits for these nuclides. In most cases, the limits will merely serve to indicate to the user that his system is critically safe. In other cases, they may be a useful basis for operating limits, and perhaps in a few cases may indicate the need for a detailed analysis of an operation. Limits will be included both for nonfissile nuclides, having an even number of neutrons in the nucleus, and for fissile nuclides, having an odd number, that generally accompany the nonfissile nuclides and that, by themselves, can be made critical in aqueous systems with masses, in some cases, much less than 1 kg.^a

In support of the ANS work group, critical masses and subcritical limits were calculated for the fissile nuclides in water-reflected, uniform, homogeneous oxide-water mixtures. In important cases, allowance was included for the increase in critical mass of a fissile nuclide resulting from a nonfissile isotope generally associated with it. The calculations are

^aThe definition of fissile nuclide is being altered here from the Standard definition given in the American National Standard "Glossary of Terms in Nuclear Science and Technology" ANS-9/ANSI N1.1-1976 to denote those nuclides having an odd number of neutrons in the nucleus. Despite some special cases mentioned below, this definition appears to be more useful and is unequivocal. The Standard definition is a nuclide "capable of undergoing fission by interaction with slow neutrons." According to either definition ^{233}U , ^{235}U , ^{239}Pu and ^{241}Pu are fissile and ^{238}U is not. However, according to the Standard definition, ^{234}U , ^{237}Np , ^{238}Pu , ^{240}Pu , ^{241}Am , ^{244}Cm , and ^{246}Cm are fissile because they have thermal fission cross sections, although in some cases very small; according to the altered definition, they are nonfissile. For these nuclides, the relative thermal capture and fission cross sections are such that the nuclides cannot be made critical in moderated systems, which suggests that the definitions may be made to coincide by extending the Standard definition to include those nuclides capable of being made critical with slow neutrons. Such is not always the case: ^{232}U and ^{236}Pu , which have an even number of neutrons and approximately equal thermal capture and fission cross sections, can be made critical with slow neutrons, but ^{237}U , which has an odd number, has a very small thermal fission cross section and cannot be made critical.

largely a repetition of previous work¹ but with more sophisticated computational techniques and more up-to-date cross sections.

COMPUTATIONAL TECHNIQUES

The computer codes selected for the calculations were GLASS² and ANISN³ as executed by KOKO.⁴ The 84-group cross sections of GLASS were collapsed by a special subroutine that generates B_1 flux moments to a 16-group structure with P_1 scattering, approximating the Hansen-Roach⁵ structure. In the spherical fissile core, the weighting was by 84-group zero and first order B_1 flux moments developed in core material at critical buckling. Transport cross sections were determined from leakages so that the critical buckling and migration area of the 84-group calculation were preserved in the 16-group cross sections. This B_1 spectrum, however, was not deemed appropriate in all groups for the few cases where the core was metal or oxide without moderator and the reflector was water. In these cases, only in the first six groups (>150 eV) were the core cross sections weighted by flux moments developed in core material. Cross sections in the remaining ten groups were weighted by flux moments developed at zero buckling in a 50-50 (by volume) mixture of core material and water. Transport cross sections in these groups were weighted in a straightforward manner by first-order flux moments.

In the H₂O reflector, the cross sections were weighted by B_1 flux moments developed at zero buckling in H₂O from a ²³⁵U fission source. Again, transport cross sections were determined

to preserve migration area. Cross sections for thin aluminum shells enclosing the cores in correlated experiments were weighted by flux moments developed in H₂O. In all cases, up-scatter was removed from the 16-group cross sections in a manner that preserved 16-group B₁ flux moments.

Critical and subcritical sizes were computed from these 16-group cross sections by ANISN with S₄ quadrature. The H₂O reflector in all cases was taken to be 20 cm thick, an effectively infinite thickness.

CROSS SECTIONS

The 84-group cross sections were drawn, where available, from a special library of cross sections processed from ENDF/B-IV files and included cross sections for H, N, O, Al, ²³⁴U, ²³⁵U, ²³⁶U, ²³⁸U, ²³⁸Pu, ²³⁹Pu, ²⁴⁰Pu, ²⁴¹Pu, and ²⁴²Pu. The nitrogen, aluminum, and uranium cross sections were used only in testing the method of calculation against critical experiments with spheres of uranium solutions. Cross sections for the special actinides (²⁴¹Am, ^{242m}Am, ²⁴³Cm, ²⁴⁴Cm, ²⁴⁵Cm, ²⁴⁷Cm, ²⁴⁹Cf, and ²⁵¹Cf) were drawn from the Standard GLASS library of cross sections used routinely in calculations for Savannah River reactors. Except for ²⁴⁴Cm, ²⁴⁵Cm, and ²⁴⁷Cm inelastic scattering matrices are absent, and the cross sections are not appropriate for high concentrations of the nuclides. Scattering was limited

to P_0 for all nuclides except H, N, and O. The ordinary transport approximation was implemented for the heavier nuclides, the extended approximation for H, N, and O.

The development of consistent cross sections that will permit accurate forecasts of actinide production in Savannah River reactors in spectra of varying degrees of hardness has long been an important effort of the Savannah River Laboratory. Originally, the cross sections were merely thermal values and resonance integrals,⁶ but with the advent of HAMMER⁷ and later GLASS,² full 84-group cross section sets were developed based on evaluations of production data, published experimental data, calculations based on nuclear models, and empirical formulae.⁸⁻¹⁰ Some differential data were adjusted to improve agreement with production data; adjustments were within the error limits quoted by the data source. A few cross sections were measured where important data were required.¹¹ The cross sections are kept up-to-date, consistent with recent measurements.^{9,10,12,13} During the present work, a new evaluation of ^{245}Cm , sponsored by the Electric Power Research Institute for inclusion in a later release of ENDF/B-V, was made available for trial usage.¹⁴

VALIDATION OF METHOD

The only calculations made for cores not containing moderator were for cores of mixed $^{238}\text{PuO}_2$ and $^{239}\text{PuO}_2$. Pertinent experiments against which to validate the method of calculation (computational technique plus cross sections) are the Smith-Geer

determination of the critical mass of a water-reflected plutonium metal sphere¹⁵ and the ²³⁸Pu substitution experiment by Stubbins, et al.¹⁶ For the metal sphere experiment, k_{eff} was calculated by S_4 , S_8 , and S_{16} , respectively, to be 1.0265, 1.0120, and 1.0080. Extrapolation to S_{∞} gave 1.0066. (The result is not highly sensitive to the volume ratio of core material to water assumed in deriving cross sections for the bottom ten groups; with a 33-67 ratio, the S_4 result was 1.0251). Thus, the method is expected to underestimate the critical mass of ²³⁹PuO₂.

The substitution experiment was performed in "Dirty Jezebel," a bare sphere of plutonium containing about 20% ²⁴⁰Pu.¹⁷ With the present method (except with S_{16} rather than S_4 quadrature), the spectrum at the center of the core was calculated (the 1% Ga present in the plutonium was ignored). k_{eff} was calculated to be 1.0008. The average production cross sections ($\bar{\nu} \bar{\sigma}_f - \bar{\sigma}_a$) of ²³⁹Pu and ²³⁸Pu were obtained by weighting cross sections over the first six fast groups and were, respectively, 3.597 and 3.621 barns for a ratio of 1.007 compared with experimental values of the ²³⁹Pu production cross section of 3.76 ± 0.23 and of the ratio of 1.01 ± 0.06 . The good agreement indicates that good results may be expected from the ²³⁸Pu cross sections. A bare critical mass of ²³⁸Pu metal (with density relative to 19.84 g/cm³ for ²³⁹Pu with 5% ²⁴⁰Pu) of 7.45 kg was calculated, compared with a mass of 9.60 kg for ²³⁹Pu. Recent substitution experiments in other cores, however, give reactivity ratios less

than unity and indicate to the experimenters a bare critical mass of about 12 kg for ^{238}Pu .¹⁸ Extrapolation to S_∞ would increase the mass from 7.45 kg, but not this much. Certainly there is no indication that the present method will lead to non-conservative results for ^{238}Pu .

In a substitution experiment in Dirty Jezebel with ^{244}Cm ,¹⁹ agreement between calculations and experiment was much poorer than in the case of ^{238}Pu . The experimental value of the production cross section for ^{244}Cm was $3.41 \pm 0.24\text{b}$; the calculated value, 4.14b. Thus, calculations for ^{244}Cm as metal or oxide will, conservatively, underestimate the critical mass. For bare metal at 13.51 g/cm^3 , the calculations (S_4) give 8.73 kg, compared with $27.7 \pm 2.5 \text{ kg}$ estimated by Barton.¹⁹ Although this large discrepancy is not significant for this work, which deals principally with fissile nuclides, and in any case is in the conservative direction, reasons for it ought to be sought.

No critical experiments have been performed with fissile, transplutonium actinide nuclides in water against which to validate the method of calculation. The method was applied to several experiments^{20,22} in which bare and water-reflected spheres of solution of highly enriched uranium in water were made critical; k_{eff} calculated for critical conditions varied from 1.0411 at $H/^{235}\text{U} = 47.2$ to 0.9967 at 1837. Part of the conservatism at low $H/^{235}\text{U}$ is associated with S_4 quadrature; extrapolation to S_∞ reduced k_{eff} to 1.0318 at 47.2. At high ratio, the order of quadrature has little effect. Part of

the conservatism at low ratio is also caused by upscatter removal; with upscatter present, k_{eff} is 0.003 smaller at 47.2. Again the decrease is much less at high ratio. Finally, collapsing from 84 to 16 groups tends to introduce conservatism; k_{eff} increased by 0.0037 in the one case that was investigated at a ratio of 35.7, with upscatter removed. From these results, the computational technique would be expected to be conservative, but probably only slightly because critical masses for the special actinides have their minimum values at high ratios.

Extrapolating k_{eff} at high ratio to even higher ratio leads to $k_{\text{eff}} = 0.98$ at a ratio of 4000 (6.5 g $^{235}\text{U}/\ell$). This is not significant if caused by slightly erroneous uranium cross sections, but could be important if caused by slightly too large a hydrogen absorption cross section. The 2200-m/sec value in the special 84-group library derived from ENDF/B-IV is 332 mb; rough calculations indicate that it would have to be decreased to 322 mb to increase k by 2% at a ratio of 4000, which is outside the limits of experimental error for the cross section.

The accuracy of critical mass calculations for the special actinides is expected to depend principally on the accuracy of the actinide cross sections. Agreement of calculations, with reactor production experiments is a good indication of cross section accuracy, but critical masses may not be sensitive to cross section errors in the same way that production data are. Estimates have been provided, however, of cross section errors in terms of

uncertainties in $\bar{\nu}$, in resonance integrals, and in thermal cross sections.^{12,13} The effect on critical mass of these errors, chosen to increase reactivity, was investigated in this work. The variations assumed are given in Table I.

CRITICAL MASSES AND MASS LIMITS

Critical masses were calculated with 84-group library cross sections both unmodified and modified as in Table I. Masses were also calculated with unmodified cross sections corresponding to $k_{\text{eff}} = 0.90$ (0.95 for ^{241}Pu for which cross sections are stated to be very good¹³). This value was arbitrarily chosen with the assumption that it should be sufficiently far below unity to ensure subcriticality and that masses corresponding to this choice would be suitable subcritical limits, even with nonuniform distribution of fissile material. (Rough calculations show that minimum critical masses at optimum distribution²³ are subcritical by about 0.01 at uniform distribution: 0.007 for ^{239}Pu , 0.009 for ^{233}U , 0.012 for ^{235}U .) Generally, the critical masses calculated with cross sections modified in accordance with Table I were appreciably greater than masses calculated to correspond to the subcritical value of k_{eff} . Where they were not, proposed limits were reduced to correspond to a lower k_{eff} .

The fissile actinides are likely to be encountered only as small concentrations in mixtures with nonfissile (but fissionable)

isotopes. Because of their large fission cross sections, however, concentrations in some cases need not be large before they dominate the mixture. As a first step, in assuring the safety of an operation, one determines whether mass limits for pure fissile nuclides are met. If limits are met, one need not be concerned with isotopic concentrations; the nonfissile isotopes may be regarded as providing additional margins of subcriticality. (Mass limits for nonfissile isotopes must of course be satisfied.) Critical masses and subcritical limits were accordingly calculated for pure fissile nuclides in oxide-water mixtures. Oxide was selected as being the form most likely to be encountered; but at the low concentrations at which critical masses occur, the chemical form has little effect, and the limits are valid for metal-water mixtures or for solutions.

In some cases, these limits may not be satisfied. To increase the mass limit for the fissile nuclide, it may be desirable to rely on (and hence control) the concentration of fissile nuclide in a mixture with nonfissile isotope that accompanies it. The limit increases as the concentration decreases, but attention must not be focused solely on the fissile mass because eventually the total mass reaches the limit for the nonfissile isotope.

Plutonium

To illustrate the behavior of the critical mass of mixtures of fissile and nonfissile isotopes, critical masses of water-reflected $\text{PuO}_2\text{-H}_2\text{O}$ mixtures were calculated for various isotopic mixtures of ^{238}Pu and ^{239}Pu . The density of the oxide was relative

to 11.46 g/cm^3 for plutonium containing 95% ^{239}Pu , 5% ^{240}Pu . Masses at high and low concentrations are expected to be underestimated. Underestimations at lower concentrations are expected because the minimum critical mass calculated for ^{239}Pu is 445 g. This is lower than the generally accepted value, based on critical experiments, which is in excess of 500 g (see Reference 23).

The calculations are plotted in Figure 1. The behavior of other mixtures of fissile and nonfissile isotopes will depend on relative cross sections but is expected to be similar. Starting with water-reflected, dry theoretical density oxide, the critical mass of which is here only slightly dependent on isotopic composition, the critical mass increases as water is added and the concentration of plutonium decreases. Depending on isotopic composition, the critical mass continues to increase or falls off to a minimum before increasing to infinity when k_{∞} drops to unity. Again, depending on isotopic composition, the minimum may or may not lie below the mass for dry oxide. Thus, depending on isotopic composition a single mass limit may be that for oxide (or metal) without moderator or that for a mixture with water. The composition at which the two are equal is of some interest. The critical masses are equal for a mixture containing about 37% ^{239}Pu . Masses corresponding to $k_{\text{eff}} = 0.9$ are equal for a mixture containing about 33% ^{239}Pu . In this case the mass is 8.15 kg Pu (2.69 kg ^{239}Pu). The margin of subcriticality provided by $k_{\text{eff}} = 0.9$ is ample to compensate for ^{238}Pu cross section changes

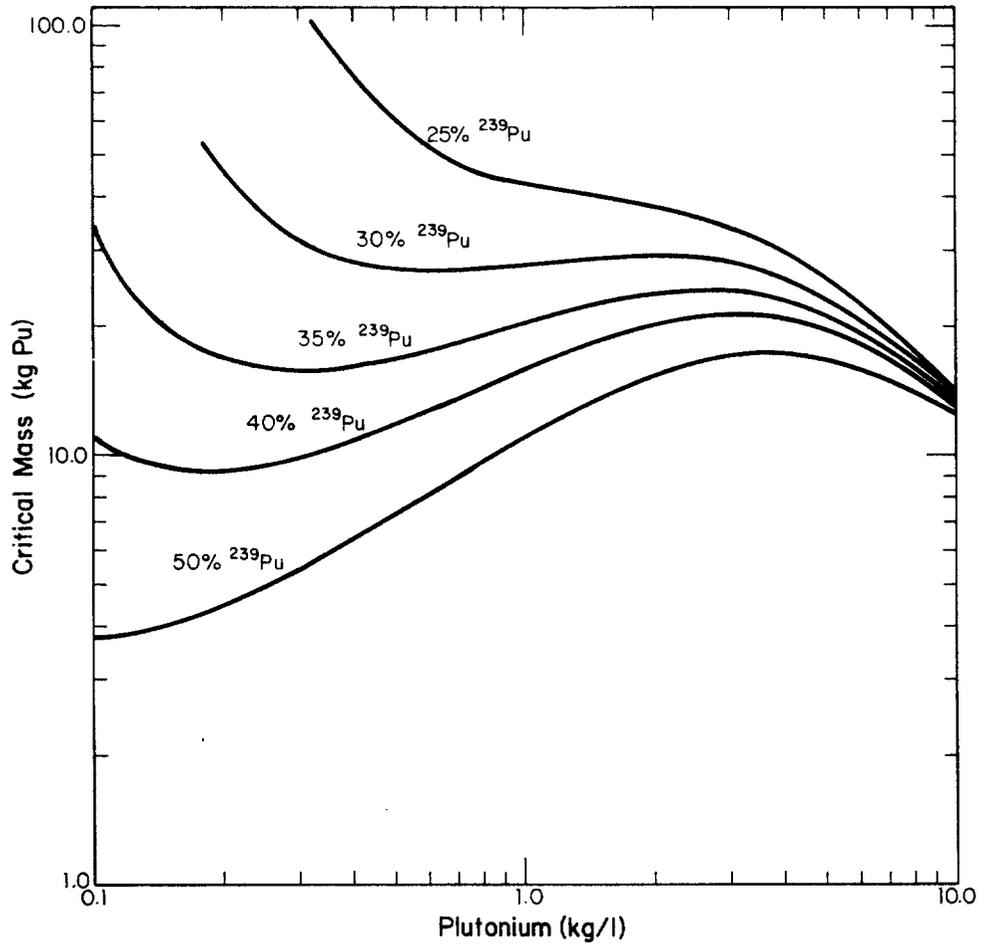


FIGURE 1. Critical Mass of Pu in $\text{PuO}_2\text{-H}_2\text{O}$ Mixtures as Function of Concentration of Pu in Mixture and of ^{239}Pu in Mixed ^{238}Pu and ^{239}Pu Isotopes

of Table I; for 30% ^{239}Pu at 500 g Pu/l the critical mass is 26.7 kg Pu, the critical mass with modified cross sections is 22.1 kg, and the mass at $k_{\text{eff}} = 0.9$ is 12.

A practical mass limit for $^{238}\text{Pu} - ^{239}\text{Pu}$ mixtures, then, is 8.15 kg Pu provided the plutonium is compacted no more densely than in theoretical density oxide (unlikely or impossible due to heat generation), provided any surrounding reflector is no more effective than water, and provided the plutonium mixture contains at least 67% ^{238}Pu . At higher concentrations of ^{239}Pu , the fissile isotope dominates, but ^{238}Pu may be relied upon to increase the ^{239}Pu limit above the standard subcritical limit of 450 g.²⁴

The only fissile plutonium isotope besides ^{239}Pu important to nuclear criticality safety is ^{241}Pu . Although ^{237}Pu has a large (2200-barn) thermal fission cross section, it has a fairly short (45.63 d) half life and is unlikely to be encountered in significant concentrations. ^{243}Pu has a much shorter half life (4.955 h), and its thermal fission cross section is only 180 b. The minimum critical mass of ^{241}Pu , which occurs at a concentration of about 30 g $^{241}\text{Pu}/\ell$ was calculated to be 244 g, 232 g with the changes of Table I. At $k_{\text{eff}} = 0.95$, the minimum mass was calculated to be 201 g. An appropriate subcritical limit for pure ^{241}Pu is thus 201 g. However, special effort (e.g., by laser isotope separation) is required to obtain pure ^{241}Pu ; normally it will be accompanied by other plutonium isotopes,

TABLE I
Cross Section Modifications

Nuclide	$\bar{\nu}^a$	% Change in			
		Resonance Integral ^b		Thermal Cross Section ^c	
		Fission	Absorption	σ_f	σ_c
²³⁸ Pu	6 ^d	20	-10	3	-4
²⁴⁰ Pu	3	20	-12	50	-1
²⁴¹ Pu	0.4	3	2.2	1	-3
²⁴¹ Am	2 ^e	10	-9	4	-3.5
^{242m} Am	0.7	7	7	4	-10
²⁴³ Cm	1.4	9	6.7	5	-7
²⁴⁴ Cm	10 ^f	10	-9.1	100 ^g	-20
²⁴⁵ Cm	1	5	3.6	5	-10
²⁴⁷ Cm	10 ^e	6	-1.3	6	-10
²⁴⁹ Cf	11 ^e	10	4.4	3	-6
²⁵¹ Cf	10 ^h	15	10.7	10	-10

^aApplied in all 84 groups. No allowance for effect of change on Maxwellian fission spectrum.

^bApplied to resonance reaction rate in all groups containing resonances

^cApplied in each of 30 thermal groups below 0.785 eV.

^dUncertainty quoted in Ref. 12 is 1%, but value quoted is 5% greater than ENDF/B-IV value.

^eContains an allowance for discrepancy between library value⁸ and experimental value.¹²

^fNo experimental value of $\bar{\nu}$ listed in Reference 12. Value in cross section library was 3.46 as calculated in Reference 10 rather than 3.23 from Reference 8.

^gCross section in library is 0.6b. Evaluation¹⁰ could not match experimental value of 1.1b without an excessively large fission width.

^hNo experimental value for $\bar{\nu}$. Library value⁸ is 4.14. Based on analogy with spontaneous fission yields 4.48 was previously assumed.¹

notably ^{240}Pu . In plutonium produced in a reactor, the ^{241}Pu concentration will never exceed the ^{240}Pu concentration. Minimum critical masses were accordingly calculated for a 50-50 mixture of ^{240}Pu and ^{241}Pu . With no cross section modifications, the mass of ^{241}Pu was 1060 g; with the modifications of Table I, 854 g. At $k_{\text{eff}} = 0.95$, the minimum mass was 780 g, well above the standard limit for ^{239}Pu . Hence, as regards mass, it is conservative to treat ^{241}Pu as ^{239}Pu provided the ^{240}Pu concentration is at least equal to the ^{241}Pu concentration.

Americium

$^{242\text{m}}\text{Am}$ has the largest known thermal fission cross section, approximately 7000 barns. However, as with ^{241}Pu , a special effort is required to obtain the pure nuclide. Normally, it is associated with nonfissile ^{241}Am , which has a large absorption cross section (831.8b equivalent $1/v$ at 2200 m/sec). Am-243 may also be present, but its thermal cross section is less than one-tenth that of ^{241}Am . In Table II, minimum critical and sub-critical masses of Am in AmO_2 (11.7 g/cm^3)- H_2O mixtures are given as a function of isotopic concentration of ^{241}Am . The minimum critical masses occur at a concentration of about 4 g $^{242\text{m}}\text{Am}$ per liter for 100% $^{242\text{m}}\text{Am}$, dropping to 2.5 g/l for 6.25% $^{242\text{m}}\text{Am}$. The minimum masses at $k_{\text{eff}} = 0.9$ occur at slightly lower concentration. Masses at $k_{\text{eff}} = 0.9$ are suitable sub-critical limits. Americium containing no more than 5% $^{242\text{m}}\text{Am}$ ($^{241}\text{Am}/^{242\text{m}}\text{Am} > 19$) cannot be made critical in water until the

TABLE II

Effect of Concentration of ^{242m}Am in Am ($^{241}\text{Am} + ^{242m}\text{Am}$) on Minimum Critical and Subcritical Masses of Water-Reflected $\text{AmO}_2\text{-H}_2\text{O}$ Mixtures

^{242m}Am (wt %)	Mass Basis	Mass (g)		
		Critical	Critical ^a	$k_{\text{eff}} = 0.9$
100	-	19	17	13
20	^{242m}Am	49	40	28
20	Am	245	200	140
10	^{242m}Am	250	160	105
10	Am	2500	1600	1050
8	^{242m}Am	980	420	240
8	Am	12,250	5250	3000
6.25	^{242m}Am	b		1830
6.25	Am	b		29,280

^aCalculated with cross sections modified in accordance with Table I.

^bMaximum value of k in concentration range 32-80 g Am/l was 0.966.

concentration gets quite high. A maximum value of $k = 0.842$ occurs at a concentration of about 55 g Am/l. As concentration increases, k drops to 0.660 at 600 g Am/l before rising through 0.9 at a concentration of about 2500 g Am/l to values greater than unity as dry oxide is approached. The lack of an inelastic scattering matrix for Am, however, casts some doubts on the validity of the calculations at high concentration, but should lead to an overestimate of reactivity.

Curium

Of the fissile curium isotopes ^{243}Cm , ^{245}Cm , and ^{247}Cm , ^{245}Cm is most likely to be encountered in significant concentrations and has the largest fission cross section. Minimum critical and subcritical masses for these pure isotopes in $\text{CmO}_2(11.9 \text{ g/cm}^3)\text{-H}_2\text{O}$ mixtures are given in Table III. For ^{243}Cm and ^{245}Cm , the minimum masses at $k_{\text{eff}} = 0.9$ are appropriate as subcritical limits, but not for ^{247}Cm . Mainly because of the uncertainty in $\bar{\nu}$, the minimum critical mass with cross sections altered according to Table I corresponds to a k_{eff} less than 0.9. A suitable subcritical limit is 900 g. On the basis of the subcritical limits, 3 g ^{243}Cm or 30 g ^{247}Cm may be considered equivalent to 1 g ^{245}Cm .

^{245}Cm is normally associated with ^{244}Cm . Some ^{246}Cm may also be present, but its thermal capture cross section is only about 1/8 that of ^{244}Cm , which in turn is quite small compared to the thermal fission cross section of ^{245}Cm . The effect of

TABLE III

Minimum Critical and Subcritical Masses of
Water-Reflected CmO₂-H₂O Mixtures

<u>Isotope</u>	<u>Approx. Conc (g Cm/ℓ)</u>	<u>Critical</u>	<u>Critical^a</u>	<u>k_{eff} = 0.9</u>
²⁴³ Cm	40	122	108	90
²⁴⁵ Cm	12	41	36	30
²⁴⁷ Cm	240	2050	1170	1360

^aCalculated with cross sections modified in accordance with
Table I.

^{244}Cm on the minimum masses of ^{245}Cm is shown in Table IV. The minimum occurs at a concentration that drops from about 12 g $^{245}\text{Cm}/\ell$ to 8 as the isotopic concentration of ^{245}Cm drops from 100% to 1.25%. The uncertainties in the ^{244}Cm cross sections become more important as the ^{244}Cm concentration increases until at 98.75% ^{244}Cm the mass with modified cross sections only slightly exceeds the mass at $k_{\text{eff}} = 0.9$. The increase in ^{245}Cm mass at $k_{\text{eff}} = 0.9$ is nearly linear with $^{244}\text{Cm}/^{245}\text{Cm}$ ratio, and a linear relation for the subcritical limit seems appropriate:

$$\text{Limiting mass} = 30 + 0.3 \text{ } ^{244}\text{Cm}/^{245}\text{Cm}$$

The masses in Table IV bend upward slightly with increasing ratio, and the formula gives a limiting mass of 54 g at a ratio of 79.32 (1.25% ^{245}Cm). The formula thus compensates for the increasing importance of uncertainties in the ^{244}Cm cross sections as the $^{244}\text{Cm}/^{245}\text{Cm}$ ratio increases. Care must of course be taken not to extend the formula beyond the point where the limit for ^{244}Cm is exceeded.

The evaluation of the cross section of ^{245}Cm for ENDF/B-V¹⁴ did not become available until after the calculations for Table IV had been completed. Critical mass calculations with the evaluated cross sections gave a minimum value of 40.3 g compared with 41.2 obtained with the older cross sections, an insignificant change in view of the large margin provided in the limit.

TABLE IV

Effect of ^{244}Cm on Minimum Critical
and Subcritical Mass of ^{245}Cm

$\% \text{ } ^{245}\text{Cm}$ (wt %)	Basis	Mass, g		
		Critical	Critical ^a	$k_{\text{eff}} = 0.9$
100	-	41	36	30
10	^{245}Cm	48	41	35
10	Cm	480	410	350
5	^{245}Cm	55	46	39
5	Cm	1100	920	780
2.5	^{245}Cm	70	54	48
2.5	Cm	2800	2160	1920
1.25	^{245}Cm	103.	68 (67)	66
1.25	Cm	8240	5440 (5360)	5280

^aCalculated with cross sections modified in accordance with Table I, but change in ^{244}Cm thermal fission cross section only 50% except for 1.25% ^{245}Cm where the effect of both a 50% and a 100% change () was calculated.

TABLE V

Minimum Critical and Subcritical Masses of
Water-Reflected CfO₂-H₂O Mixtures

Isotope	Approx. Conc. (g Cf/l)	Critical	Mass (g Cf)	
			Critical ^a	$k_{\text{eff}} = 0.9$
²⁴⁹ Cf	12	70	47	50
²⁵¹ Cf	4	22	13	16

^aCalculated with cross sections modified in accordance with Table I.

Californium

Critical and subcritical masses for ²⁴⁹Cf and ²⁵¹Cf are given in Table V. The large cross section uncertainties of Table I result in critical masses with modified cross sections being less than masses with unmodified cross sections at $k_{\text{eff}} = 0.9$. A 10 g limit for ²⁴⁹Cf and a 5 g limit for ²⁵¹Cf appear adequate, however, and are ones that for a number of reasons are likely never to be tested in practice.

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