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Foreword

(This Foreword is not a part of American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, ANSI/ANS-8.1-1983.)

This standard provides guidance for the prevention of criticality accidents in the handling, storing, processing, and transporting of fissionable material. It was first approved as American Standard N6.1-1964. A substantial revision that included the specification of subcritical limits applicable to process variables was approved as American National Standard N16.1-1969 and was reaffirmed, with minor revisions, as American National Standard N16.1-1975/ANS-8.1, under the prescribed five-year review. It was subsequently supplemented by American National Standard for Validation of Calculational Methods for Nuclear Criticality Safety, ANSI N16.9-1975/ANS-8.11. To lessen the proliferation of nuclear criticality safety standards, the two standards have been consolidated in the present prescribed five-year review.

An important part of the present review was the examination of subcritical limits in the standard. In a few cases limits have been increased where the margin of subcriticality seemed unnecessarily large. In other cases, where subcriticality appeared doubtful, the limits have been reduced. Additional limits have been provided where they seemed likely to be useful. The limits make no allowance for operating contingencies (e.g., double batching) or for inaccurate knowledge of process variables (e.g., concentrations, masses, dimensions) and are "maximum subcritical limits." That is, under the stated conditions, the limits are close enough to critical to provide little incentive for attempting to justify slightly larger values, but, concomitantly, they are confidently expected actually to be subcritical. The stated conditions (infinitely long cylinders, absence of neutron-absorbing vessel walls, plutonium solutions without free nitric acid, etc.) are unlikely to be approached in practice; hence if a limit is reached, there will ordinarily be a larger margin of subcriticality than the minimal value used in its derivation. However, no account was taken of this unlikelihood in setting the limits. It is legitimate for the user of the standard, if he so chooses, (conservatively) to make adjustments in the limits to take advantage of the extent to which credible potential conditions may deviate from stated conditions, e.g., to increase a cylinder diameter limit to take advantage of a finite height and of neutron absorption in steel walls.

The prescribed five-year review of American National Standards N16.1-1975/ANS-8.1 and N16.9-1975/ANS-8.11 was performed by Subcommittee 8 of the Standards Committee of the American Nuclear Society, with Dr. H. K. Clark assuming principal responsibility for the revision. Limits were derived in accordance with the standard. The derivations have been reviewed by the subcommittee and have been published, largely in the open literature.

This revised standard was prepared under the guidance of ANS Subcommittee 8, Fissionable Materials Outside Reactors, which had the following membership at the time of its approval of this revision:

J. D. McLendon, Chairman, *Union Carbide Corporation, Nuclear Division*
Elizabeth B. Johnson, Secretary, *Oak Ridge National Laboratory*
F. M. Alcorn, *Babcock & Wilcox Company*
H. K. Clark, *Savannah River Laboratory*
E. D. Clayton, *Battelle Pacific Northwest Laboratories*
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D. R. Smith, *Los Alamos National Laboratory*
J. T. Thomas, *Oak Ridge National Laboratory*
G. E. Whitesides, *Oak Ridge National Laboratory*
F. E. Woltz, *Goodyear Atomic Corporation*

American National Standards Committee N16, Nuclear Criticality Safety, which reviewed and approved this revision in 1982, had the following membership:

Dixon Callihan, Chairman
Elizabeth B. Johnson, Secretary

Organization Represented	*Representative*
Allied-General Nuclear Services	William R. Waltz
American Institute of Chemical Engineers	Alex F. Perge
American Nuclear Society	Dixon Callihan
American Society for Testing and Materials (Liaison only)	Ricardo Artigas
Atomic Industrial Forum, Inc.	D. Frank Cronin
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Health Physics Society	Fred W. Sanders
	Norman C. Dyer (Alt.)
Institute of Nuclear Materials Management	Leo E. Hansen
U. S. Department of Energy	Lorin C. Brinkerhoff
U. S. Nuclear Regulatory Commission	George H. Bidinger
Individual Members	C. Leslie Brown
	Elizabeth B. Johnson
	Hugh C. Paxton

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Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors

1. Introduction

Operations with some fissionable materials introduce risks of a criticality accident resulting in a release of radiation that may be lethal to nearby personnel. However, experience has shown that extensive operations can be performed safely and economically when proper precautions are exercised. The few criticality accidents that have occurred show frequency and severity rates far below those typical of nonnuclear accidents. This favorable record can be maintained only by continued adherence to good operating practices such as are embodied in this standard; however, the standard, by itself, cannot establish safe processes in an absolute sense. Good safety practices must recognize economic considerations, but the protection of operating personnel[1] and the public must be the dominant consideration.

2. Scope

This standard is applicable to operations with fissionable materials outside nuclear reactors, except the assembly of these materials under controlled conditions, such as in critical experiments. Generalized basic criteria are presented and limits are specified for some single fissionable units of simple shape containing ^{233}U, ^{235}U, or ^{239}Pu, but not for multiunit arrays.[2] Requirements are stated for establishing the validity and areas of applicability of any calculational method used in assessing nuclear criticality safety. This standard does not include the details of administrative controls, the design of processes or equipment, the description of instrumentation for process control, or detailed criteria to be met in transporting fissionable materials.

[1]Guidance for establishing an alarm system is contained in American National Standard Criticality Accident Alarm System, ANSI/ANS-8.3-1979.

[2]Limits for certain multiunit arrays are contained in American National Standard Guide for Nuclear Criticality Safety in the Storage of Fissile Materials, ANSI/ANS-8.7-1982.

3. Definitions

3.1 Limitations. The definitions given below are of a restricted nature for the purposes of this standard. Other specialized terms are defined in American National Standard Glossary of Terms in Nuclear Science and Technology, ANSI N1.1-1976/ANS-9 [1].[3]

3.2 Shall, Should, and May. The word "shall" is used to denote a requirement, the word "should" to denote a recommendation, and the word "may" to denote permission, neither a requirement nor a recommendation. In order to conform with this standard, all operations shall be performed in accordance with its requirements, but not necessarily with its recommendations.

3.3 Glossary of Terms

area(s) of applicability. The ranges of material compositions and geometric arrangements within which the bias of a calculational method is established.

areal density. The total mass of fissionable material per unit area projected perpendicularly onto a plane. (For an infinite, uniform slab, it is the product of the slab thickness and the concentration of fissionable material within the slab.)

bias. A measure of the systematic disagreement between the results calculated by a method and experimental data. The uncertainty in the bias is a measure of both the precision of the calculations and the accuracy of the experimental data.

calculational method (method). The mathematical equations, approximations, assumptions, associated numerical parameters (e.g., cross sections), and calculational procedures which yield the calculated results.

controlled parameter. A parameter that is kept within specified limits.

criticality accident. The release of energy as a result of accidentally producing a self-sustaining or divergent neutron chain reaction.

[3]Numbers in brackets refer to corresponding numbers in Section 7, References.

effective multiplication factor (k_{eff}). The ratio of the total number of neutrons produced during a time interval (excluding neutrons produced by sources whose strengths are not a function of fission rate) to the total number of neutrons lost by absorption and leakage during the same interval.

nuclear criticality safety. Protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention of the reaction.

subcritical limit (limit). The limiting value assigned to a controlled parameter that results in a subcritical system under specified conditions. The subcritical limit allows for uncertainties in the calculations and experimental data used in its derivation but not for contingencies; e.g., double batching or failure of analytical techniques to yield accurate values.

4. Nuclear Criticality Safety Practices

4.1 Administrative Practices

4.1.1 Responsibilities. Management shall clearly establish responsibility for nuclear criticality safety. Supervision should be made as responsible for nuclear criticality safety as for production, development, research, or other functions. Each individual, regardless of position, shall be made aware that nuclear criticality safety in his work area is ultimately his responsibility. This may be accomplished through training and periodic retraining of all operating and maintenance personnel. Nuclear criticality safety differs in no intrinsic way from industrial safety, and good managerial practices apply to both.

Management shall provide personnel skilled in the interpretation of data pertinent to nuclear criticality safety and familiar with operations to serve as advisors to supervision. These specialists should be, to the extent practicable, administratively independent of process supervision.

Management shall establish the criteria to be satisfied by nuclear criticality safety controls. Distinction may be made between shielded and unshielded facilities, and the criteria may be less stringent when adequate shielding and confinement assure the protection of personnel.[4]

[4]Guidance is provided in American National Standard Criteria for Nuclear Criticality Safety Controls in Operations with Shielding and Confinement, ANSI/ANS-8.10-1983.

4.1.2 Process Analysis. Before a new operation with fissionable materials is begun or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions.[5] Care shall be exercised to determine those conditions which result in the maximum effective multiplication factor (k_{eff}).

4.1.3 Written Procedures. Operations to which nuclear criticality safety is pertinent shall be governed by written procedures. All persons participating in these operations shall understand and be familiar with the procedures. The procedures shall specify all parameters they are intended to control. They should be such that no single, inadvertent departure from a procedure can cause a criticality accident.

4.1.4 Materials Control. The movement of fissionable materials shall be controlled. Appropriate materials labeling and area posting shall be maintained specifying material identification and all limits on parameters that are subjected to procedural control.

4.1.5 Operational Control. Deviations from procedures and unforeseen alterations in process conditions that affect nuclear criticality safety shall be reported to management and shall be investigated promptly. Action shall be taken to prevent a recurrence.

4.1.6 Operational Reviews. Operations shall be reviewed frequently (at least annually) to ascertain that procedures are being followed and that process conditions have not been altered so as to affect the nuclear criticality safety evaluation. These reviews shall be conducted, in consultation with operating personnel, by individuals who are knowledgeable in nuclear criticality safety and who, to the extent practicable, are not immediately responsible for the operation.

4.1.7 Emergency Procedures. Emergency procedures shall be prepared and approved by management. Organizations, local and offsite, that are expected to respond to emergencies shall be made aware of conditions that might be encountered, and they should be assisted in preparing suitable procedures governing their responses.

[5]In some cases it may be necessary to resort to *in situ* neutron multiplication measurements to confirm the subcriticality of proposed configurations. Guidance for safety in performing such measurements is contained in American National Standard for Safety in Conducting Subcritical Neutron-Multiplication Measurements In Situ, ANSI/ANS-8.6-1983.

4.2 Technical Practices

4.2.1 Controlling Factors. The effective multiplication factor (k_{eff}) of a system containing fissionable material depends on:

(1) The mass and distribution of all fissionable materials and

(2) The mass, distribution, and nuclear properties of all other materials with which the fissionable materials are associated.

Nuclear criticality safety is achieved by controlling one or more parameters of the system within subcritical limits. Control may be exercised administratively through procedures (e.g., by requiring that a mass not exceed a posted limit), by physical restraints (e.g., by confining a solution to a cylindrical vessel with diameter no greater than the subcritical limit), through the use of instrumentation (e.g., by keeping a fissile concentration below a specific limit by devices that measure concentration and prevent its buildup through reflux in a chemical system), by chemical means (e.g., by prevention of conditions that allow precipitation, thereby maintaining concentration characteristic of an aqueous solution), by relying on the natural or credible course of events (e.g., by relying on the nature of a process to keep the density of uranium oxide less than a specified fraction of theoretical), or by other means. All controlled parameters and their limits shall be specified.

4.2.2 Double Contingency Principle. Process designs should, in general, incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible.

4.2.3 Geometry Control. Where practicable, reliance should be placed on equipment design in which dimensions are limited[6] rather than on administrative controls. Full advantage may be taken of any nuclear characteristics of the process materials and equipment. All dimensions and nuclear properties on which reliance is placed shall be verified prior to beginning operations, and control shall be exercised to maintain them.

4.2.4 Neutron Absorbers. Reliance may be placed on neutron-absorbing materials, such as cadmium and boron, that are incorporated in process materials or equipment, or both.[7] Control shall be exercised to maintain their continued presence with the intended distributions and concentrations. Extraordinary care should be taken with solutions of absorbers because of the difficulty of exercising such control.

4.2.5 Subcritical Limits. Where applicable data are available, subcritical limits shall be established on bases derived from experiments, with adequate allowance for uncertainties in the data. In the absence of directly applicable experimental measurements, the limits may be derived from calculations made by a method shown by comparison with experimental data to be valid in accordance with 4.3.

4.3 Validation of a Calculational Method. There are many calculational methods suitable for determining the effective multiplication factor (k_{eff}) of a system or for deriving subcritical limits. The methods vary widely in basis and form, and each has its place in the broad spectrum of problems encountered in the nuclear criticality safety field. However, the general procedure to be followed in establishing validity is common to all.

4.3.1 Bias shall be established by correlating the results of criticality experiments with results obtained for these same systems by the method being validated. Commonly the correlation is expressed in terms of the values of k_{eff} calculated for the experimental systems, in which case the bias is the deviation of the calculated values of k_{eff} from unity. However, other parameters may be used. The bias serves to normalize a method over its area(s) of applicability so that it will predict critical conditions within the limits of the uncertainty in the bias. Generally neither the bias nor its uncertainty is constant; both should be expected to be functions of composition and other variables.

4.3.2 The area(s) of applicability of a calculational method may be extended beyond the range of experimental conditions over which the bias is established by making use of the trends in the bias. Where the extension is large, the method should be supplemented by other calculational methods to provide a better estimate of the bias in the extended area(s).

[6]Guidance for assessing the safety of piping systems for uranyl nitrate solutions is contained in American National Standard Nuclear Criticality Safety Guide for Pipe Intersections Containing Aqueous Solutions of Enriched Uranyl Nitrate, ANSI/ANS-8.9-1978.

[7]Guidance for the use of a particular absorber is contained in American National Standard Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Material, ANSI/ANS-8.5-1979.

4.3.3 A margin in the correlating parameter, which margin may be a function of composition and other variables, shall be prescribed that is sufficient to ensure subcriticality. This margin of subcriticality shall include allowances for the uncertainty in the bias and for uncertainties due to any extensions of the area(s) of applicability.

4.3.4 If the method involves a computer program, checks shall be performed to confirm that the mathematical operations are performed as intended. Any changes in the computer program shall be followed by reconfirmation that the mathematical operations are performed as intended.

4.3.5 Nuclear properties such as cross sections should be consistent with experimental measurements of these properties.

4.3.6 A written report of the validation shall be prepared.[8] This report shall:

(1) Describe the method with sufficient detail, clarity, and lack of ambiguity to allow independent duplication of results.

(2) State computer programs used, the options, recipes for choosing mesh points where applicable, the cross section sets, and any numerical parameters necessary to describe the input.

(3) Identify experimental data and list parameters derived therefrom for use in the validation of the method.

(4) State the area(s) of applicability.

(5) State the bias and the prescribed margin of subcriticality over the area(s) of applicability. State the basis for the margin.

5. Single-Parameter Limits for Fissile Nuclides

Operations with fissile materials may be performed safely by complying with any one of the limits given in 5.1, 5.2, 5.3, and 5.4 for single units provided the conditions under which the limit applies are maintained; these limits were calculated by methods satisfying the requirements of 4.3. A limit shall be applied only when surrounding materials, including other nearby fissionable materials, can be shown to increase the effective multiplication factor (k_{eff}) no more than does enclosing the unit by a contiguous layer of water of unlimited thickness. A limit may be applied to a mixture of fissile nuclides by considering all components of the mixture to be the one with the most restrictive limit.

Process specifications shall incorporate margins to protect against uncertainties in process variables and against a limit being accidentally exceeded.

5.1 Uniform Aqueous Solutions. Any one of the limits of Table 1 is applicable provided a uniform aqueous solution is maintained. It is therefore implied that the concentrations of the saturated solutions are not exceeded. The ^{239}Pu limits apply to mixtures of plutonium isotopes provided the concentration of ^{240}Pu exceeds that of ^{241}Pu and provided ^{241}Pu is considered to be ^{239}Pu in computing mass or concentration. (Less restrictive limits are provided in 6.3 for plutonium isotopic compositions containing appreciable concentrations of ^{240}Pu.) The limit on atomic ratio is equivalent to the limit on solution concentration, but the ratio limit may also be applied to non-aqueous solutions regardless of the chemical form of the fissile nuclide.

5.2 Aqueous Mixtures. The areal densities of Table 1 are independent of chemical compound and are valid for mixtures which may have density gradients provided the areal densities are uniform. The subcritical mass limits for ^{233}U, ^{235}U, and ^{239}Pu in mixtures that may not be uniform are 0.50, 0.70, and 0.45 kg, respectively, and are likewise independent of compound [2-4].

5.2.1 Enrichment Limits. Table 2 contains ^{235}U enrichment limits for uranium compounds mixed homogeneously[9] with water with no limitations on mass or concentration.

[8]Management may limit the distribution of the report to protect proprietary information.

[9]In the "homogeneous" mixtures to which calculations of these limits were normalized the average particle size of dry UO_3 was 60 microns [V. I. NEELEY and H. E. HANDLER, "Measurement of Multiplication Constant for Slightly Enriched Homogeneous UO_3-Water Mixtures and Minimum Enrichment for Criticality," HW-70310, Hanford Atomic Products Operations (August 1961)]. It seems likely that the average particle size of the dihydrate of $UO_2(NO_3)_2$ was approximately 100 microns [V. I. NEELEY, J. A. BERBERET and R. H. MASTERSON, "k_∞ of Three Weight Per Cent ^{235}U Enriched UO_3 and $UO_2(NO_3)_2$ Hydrogeneous Systems," HW-66882, Hanford Atomic Products Operations (September 1961)]. Various H/U ratios in the nitrate mixtures were achieved with 1/8-inch spheres of polyethylene [S. R. BIERMAN and G. M. HESS, "Minimum Critical ^{235}U Enrichment of Homogeneous Uranyl Nitrate," ORNL-CDC-5, Oak Ridge Criticality Data Center (June 1968)].

5.3 Metallic Units. The enrichment limit for uranium and the mass limits given in Table 3 apply to a single piece having no concave surfaces. They may be extended to an assembly of pieces provided there is no interspersed moderation.

The ^{233}U and ^{235}U limits apply to mixtures of either isotope with ^{234}U, ^{236}U, or ^{238}U provided ^{234}U is considered to be ^{233}U or ^{235}U, respectively, in computing mass [3]. The ^{239}Pu limits apply to isotopic mixtures of plutonium provided the concentration of ^{240}Pu exceeds that of ^{241}Pu and all isotopes are considered to be ^{239}Pu in computing mass [4]. Density limits may be adjusted for isotopic composition.

5.4 Oxides. The limits in Tables 4 and 5 apply only if the oxide contains no more than 1.5% water by weight. The mass limits apply to a single piece having no concave surfaces. They may be extended to an assembly of pieces provided there is no additional interspersed moderation.

The mass limit is given equivalently as mass of nuclide and as mass of oxide (including moisture). It is emphasized that the limits in Tables 4 and 5 are valid only under the specified bulk density restrictions.[10] With water content limited to 1.5% the enrichment limit of Table 2 for uranium oxides is increased to 3.2% ^{235}U [3].

[10]The user is cautioned that, particularly for UO_3, material densities in excess of the full densities of Table 4 may be possible and hence that the limits of Table 4 may not be valid for highly compacted oxides. However, it is expected that oxides will generally be in the form of loose powders or, in the case of UO_2, of accumulations of pellets and that the limits of Table 4 and perhaps Table 5 will be valid. Where other density limits are desired, where it is inconvenient to maintain the water content below 1.5% (H/U $\cong$ 0.47), or where oxides are non-stoichiometric, the limits may be useful as points of departure in deriving more appropriate values.

The maximum bulk densities were derived from CRC Handbook values of 10.96, 8.3, 7.29, and 11.46 g/cm^3 for UO_2, U_3O_8, UO_3, and PuO_2 together with the assumption of additive volumes of oxide and water. However, x-ray densities of UO_3 as high as 8.46 g/cm^3 have been reported. Moreover, the assumption of additive volumes may be incorrect; with H_2O assigned a density of unity, an effective UO_3 density of 10.47 g/cm^3 is required to produce a reported x-ray density of 6.71 g/cm^3 for α-$UO_2(OH)_2$.

6. Multiparameter Control

Although the single-parameter limits are adequate for many purposes, they are inconveniently and uneconomically small for many others. Simultaneous limitation of two or more parameters results in a less restrictive limit for the one of interest. A few particularly useful examples are given in 6.1 through 6.4. All were calculated by methods satisfying 4.3. These limits shall be applied only when surrounding materials can be shown to increase the effective multiplication factor (k_{eff}) no more than does enclosing the system by a contiguous layer of water of unlimited thickness. General guidance for multiparameter control may be found in the technical literature.[11-14]

Process specifications shall incorporate margins to protect against uncertainties in process variables and against a limit being accidentally exceeded.

6.1 Uranium Metal- and Uranium Oxide-Water Mixtures at Low ^{235}U Enrichment. An application of multiparameter control is control of both the ^{235}U enrichment of uranium and one of the parameters of Section 5. Subcritical limits [5] applicable to aqueous systems containing uranium metal or uranium oxide (UO_2), regardless of the size and shape of metal or oxide pieces, are specified as functions of enrichment in Figs. 1 through 5 which give, respectively, the mass of ^{235}U, the cylinder diameter, the slab thickness, the volume, and the areal density.[15]

[11]H. C. PAXTON, J. T. THOMAS, D. CALLIHAN, and E. B. JOHNSON, "Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U," TID-7028, U.S. Atomic Energy Commission (1964).

[12]J. T. THOMAS, "Nuclear Safety Guide, TID-7016, Rev. 2," NUREG/CR-0095 (ORNL/NUREG/CSD-6), Oak Ridge National Laboratory (1978).

[13]H. K. CLARK, "Handbook of Nuclear Safety," DP-532, Savannah River Laboratory (1961).

[14]R. D. CARTER, G. R. KEIL, K. R. RIDGWAY, "Criticality Handbook," ARH-600, Atlantic Richfield Hanford Company (1973).

[15]The data points through which the curves in Figs. 1-5 were drawn are the subcritical values listed in Tables VI-VIII of Ref. [5].

6.2 Aqueous Uranium Solutions at Low ^{235}U Enrichment. A similar application of multiparameter control is control of both ^{235}U enrichment and one of the parameters of Table 1, together with the maintenance of a uniform aqueous solution. Table 6 lists subcritical limits for uniform aqueous solutions of uranium where the enrichment is controlled within the stated limit. Concentrations of saturated solutions, which are here taken to be 5 molar for UO_2F_2 solutions and 2.5 molar for $UO_2(NO_3)_2$ solutions, shall not be exceeded.

6.3 Uniform Aqueous Solutions of $Pu(NO_3)_4$ Containing ^{240}Pu. Reliance on, and hence control of, the isotopic concentration of ^{240}Pu in plutonium permits greater limits for $Pu(NO_3)_4$ solutions than are listed in Table 1.[16] However, the amount of the increase is dependent on ^{241}Pu concentration. Table 7 contains limits for uniform aqueous solutions of $Pu(NO_3)_4$ as a function of isotopic composition. Any ^{238}Pu or ^{242}Pu present shall be omitted in computing the isotopic composition.

6.4 Aqueous Mixtures of Plutonium Containing ^{240}Pu. Subcritical mass limits for plutonium as PuO_2 in aqueous mixtures, which may be nonuniform, where ^{240}Pu and ^{241}Pu are subject to the three pairs of restrictions on isotopic composition of Table 7, are, in increasing order of ^{240}Pu concentration, 0.53, 0.74, and 0.99 kg, respectively [4].

[16]Where plutonium, in addition, is intimately mixed with natural uranium, limits are even greater. Limits for this case are included in American National Standard for Nuclear Criticality Control and Safety of Homogeneous Plutonium-Uranium Fuel Mixtures Outside Reactors, ANSI/ANS-8.12-1978.

7. References

[1] American National Standard Glossary of Terms in Nuclear Science and Technology, ANSI/N1.1-1976/ANS-9. American Nuclear Society, La Grange Park, Ill.

[2] H. K. CLARK, "Subcritical Limits for ^{233}U Systems," *Nucl. Sci. Eng.* **81**, 379-395 (1982). American Nuclear Society, La Grange Park, Ill.

[3] H. K. CLARK, "Subcritical Limits for ^{235}U Systems," *Nucl. Sci. Eng.* **81**, 351-378 (1982). American Nuclear Society, La Grange Park, Ill.

[4] H. K. CLARK, "Subcritical Limits for Pu Systems," *Nucl. Sci. Eng.* **79**, 65-84 (1981). American Nuclear Society, La Grange Park, Ill.

[5] H. K. CLARK, "Critical and Safe Masses and Dimensions of Lattices of U and UO_2 Rods in Water," DP-1014, Savannah River Laboratory, Aiken, S. C., (1966).

When the preceding American National Standard referred to in this document is superseded by a revision approved by the American National Standards Institute, Inc., the revision shall apply.

Table 1

Single-Parameter Limits for Uniform Aqueous Solutions of Fissile Nuclides

Parameter	Subcritical Limit for Fissile Solute				
	$^{233}UO_2F_2$ [2]	$^{233}UO_2(NO_3)_2$ [2]	$^{235}UO_2F_2$ [3]	$^{235}UO_2(NO_3)_2$ [3]	$^{239}Pu(NO_3)_4$ [4]
Mass of fissile nuclide, kg	0.54	0.55	0.76	0.78	0.48
Diameter of cylinder of solution, cm	10.5	11.7	13.7	14.4	15.4
Thickness of slab of solution, cm	2.5	3.1	4.4	4.9	5.5
Volume of solution, ℓ	2.8	3.6	5.5	6.2	7.3
Concentration of fissile nuclide, g/ℓ	10.8	10.8	11.6	11.6	7.3
Atomic ratio of hydrogen to fissile nuclide[a]	2390	2390	2250	2250	3630
Areal density of fissile nuclide, g/cm^2	0.35	0.35	0.40	0.40	0.25

[a] Lower limit

Table 2

^{235}U Enrichment Limits for Uranium Mixed Homogeneously with Water [3]

Compound	Subcritical Limit, wt% ^{235}U
Uranium metal	0.93
UO_2, U_3O_8, or UO_3	0.96
$UO_2(NO_3)_2$	1.96

Table 3

Single-Parameter Limits for Metal Units

Parameter	Subcritical Limit for		
	^{233}U [2]	^{235}U [3]	^{239}Pu [4]
Mass of fissile nuclide, kg	6.0	20.1	5.0
Cylinder diameter, cm	4.5	7.3	4.4
Slab thickness, cm	0.38	1.3	0.65
Uranium enrichment, wt% ^{235}U	—	5.0	—
Maximum density for which mass and dimension limits are valid, g/cm^3	18.65	18.81	19.82

Table 4

Single-Parameter Limits for Oxides Containing No More Than 1.5% Water By Weight at Full Density

Parameter	$^{233}UO_2$ [2]	$^{233}U_3O_8$ [2]	$^{233}UO_3$ [2]	$^{235}UO_2$ [3]	$^{235}U_3O_8$ [3]	$^{235}UO_3$ [3]	$^{239}PuO_2$ [4]
Mass of fissile nuclide, kg	10.1	13.4	15.2	32.3	44.0	51.2	10.2
Mass of oxide,[a] kg	11.7	16.0	18.7	37.2	52.8	62.6	11.5
Cylinder diameter, cm	7.2	9.0	9.9	11.6	14.6	16.2	7.2
Slab thickness, cm	0.8	1.1	1.3	2.9	4.0	4.6	1.4
Maximum bulk density[b] for which limits are valid, g/cm^3	$\frac{9.38}{1-0.085(1.5-w)}$	$\frac{7.36}{1-0.065(1.5-w)}$	$\frac{6.56}{1-0.056(1.5-w)}$	$\frac{9.44}{1-0.086(1.5-w)}$	$\frac{7.41}{1-0.065(1.5-w)}$	$\frac{6.60}{1-0.057(1.5-w)}$	$\frac{9.92}{1-0.091(1.5-w)}$

[a] These values include the mass of any associated moisture up to the limiting value of 1.5% by weight.

[b] w represents the quantity of water, in wt %, in the oxide.

Table 5

Single-Parameter Limits for Oxides Containing No More Than 1.5% Water By Weight at No More Than Half Density[a]

Parameter	$^{233}UO_2$ [2]	$^{233}U_3O_8$ [2]	$^{233}UO_3$ [2]	$^{235}UO_2$ [3]	$^{235}U_3O_8$ [3]	$^{235}UO_3$ [3]	$^{239}PuO_2$ [4]
Mass of fissile nuclide, kg	23.4	30.5	34.7	88	122	142	27
Mass of oxide,[b] kg	27.0	36.6	42.4	102	146	174	30
Cylinder diameter, cm	11.9	14.8	16.3	20.4	26.0	28.8	12.6
Slab thickness, cm	1.6	2.2	2.6	5.8	8.0	9.3	2.8

[a] These are half the maximum bulk densities of Table 4.

[b] These values include the mass of any associated moisture up to the limiting value of 1.5% by weight.

Table 6

Subcritical Limits for Uniform Aqueous Solutions of Low-Enriched Uranium [3]

Parameter	Enrichment, wt% ^{235}U	Subcritical Limit	
		UO_2F_2	$UO_2(NO_3)_2$
Mass, kg ^{235}U	10.0	1.07	1.47
	5.0	1.64	3.30
	4.0	1.98	6.50
	3.0	2.75	—
	2.0	8.00	—
Cylinder diameter, cm	10.0	20.1	25.2
	5.0	26.6	42.7
	4.0	30.2	58.6
	3.0	37.4	—
	2.0	63.0	—
Slab thickness, cm	10.0	8.3	11.9
	5.0	12.6	23.4
	4.0	15.1	33.7
	3.0	20.0	—
	2.0	36.5	—
Volume, *l*	10.0	14.8	26.7
	5.0	30.6	111.0
	4.0	42.7	273.0
	3.0	77.0	—
	2.0	340.0	—
Concentration, g U/*l*	10.0	123.0	128.0
	5.0	261.0	283.0
	4.0	335.0	375.0
	3.0	470.0	—
	2.88	—	594.9[a]
	2.0	770.0	—
	1.45	1190.0[a]	—

[a] Saturated solution.

Table 7

Subcritical Limits for Uniform Aqueous Solutions of $Pu(NO_3)_4$ Containing ^{240}Pu [4]

Parameter	Subcritical Limit		
	≥5 wt% ^{240}Pu ≤1 wt% ^{241}Pu	≥15 wt% ^{240}Pu ≤ 6 wt% ^{241}Pu	≥25 wt% ^{240}Pu ≤15 wt% ^{241}Pu
Mass, kg Pu	0.57	0.78	1.02
Cylinder diameter, cm	17.4	19.5	21.3
Slab thickness, cm	6.7	8.0	9.2
Volume, *l*	10.0	13.6	17.2
Concentration, g Pu/*l*	7.8	8.9	10.2
H/Pu	3400	2980	2600
Areal density, g Pu/cm^2	0.28	0.34	0.4

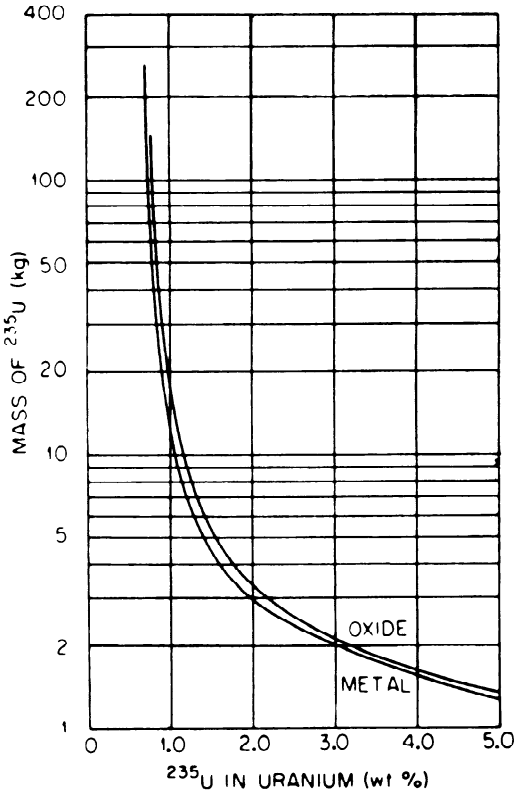

Fig. 1 Mass limit for uranium-water lattices.

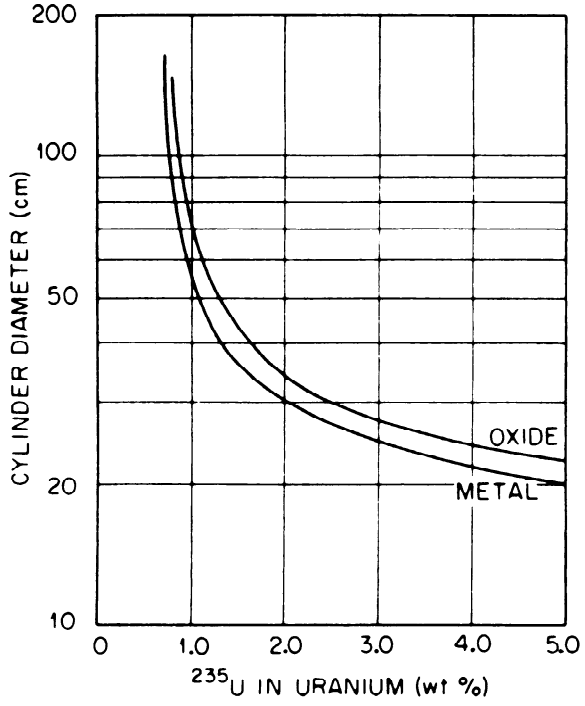

Fig. 2 Cylinder diameter limit for uranium-water lattices.

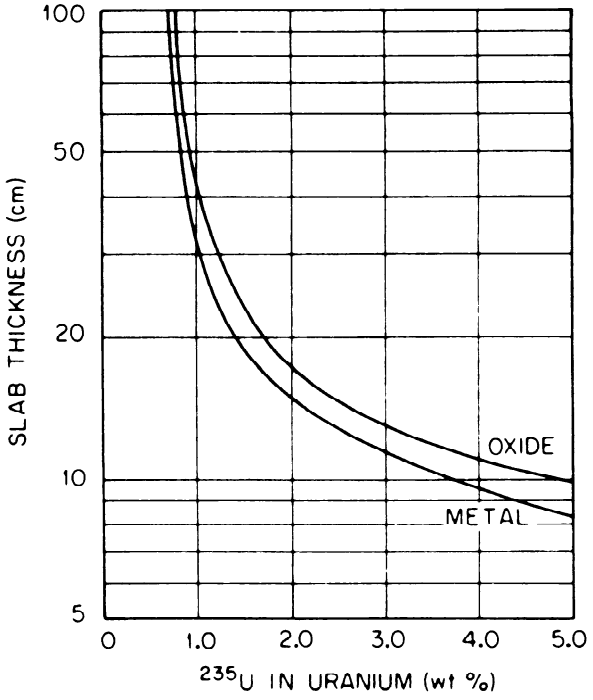

Fig. 3 Slab thickness limit for uranium-water lattices.

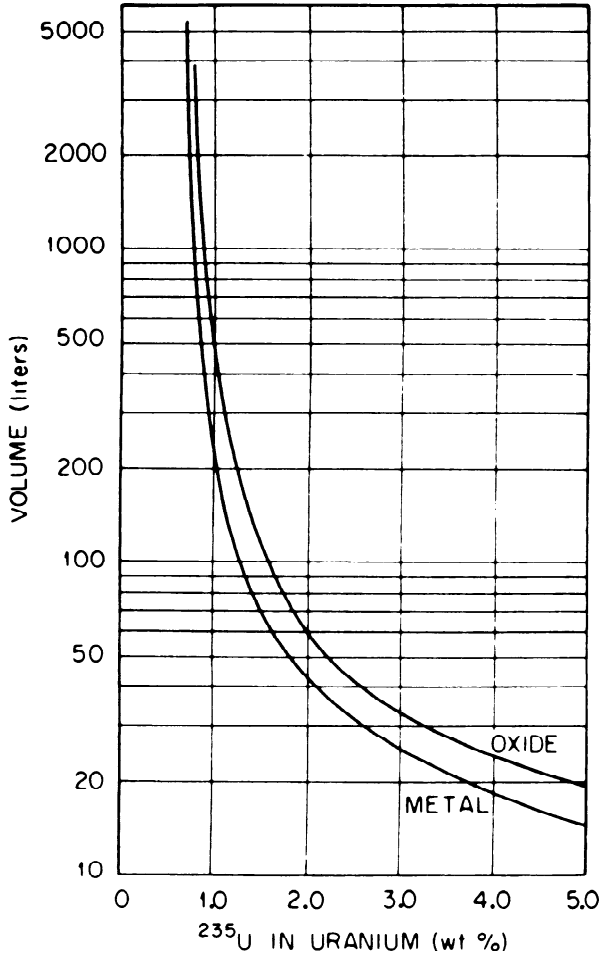

Fig. 4 Volume limit for uranium-water lattices.

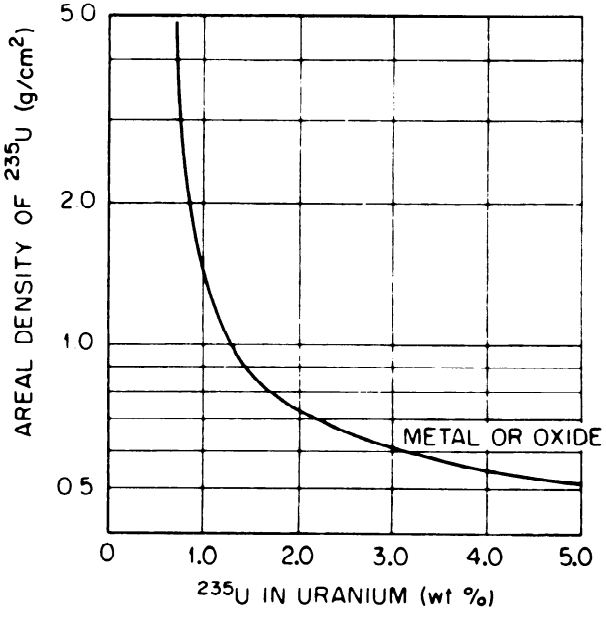

Fig. 5 Areal density limit for uranium-water lattices.

Appendix A

(This Appendix is not a part of American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, ANSI/ANS-8.1-1983, but is included for information purposes only.)

The determination, required by 4.2.1, that a process will be subcritical under normal and credible abnormal conditions and the determination of those conditions resulting in the maximum effective multiplication factor (k_{eff}) require careful study. The few criticality accidents that have occurred in industrial operations have resulted from failure to anticipate conditions that might arise; none has resulted from a faulty calculation[17] of k_{eff}. The following are typical examples of variations in process conditions that should be considered:

(1) A change in intended shape or dimensions resulting from bulging, corrosion, or bursting of a container, or failure to meet specifications in fabrication;

(2) An increase in the mass of fissionable material in a location as the result of operational error, improper labeling, equipment failure, or failure of analytical techniques;

(3) A change in the ratio of moderator to fissionable material resulting from:
  (a) Inaccuracies in instruments or chemical analyses,
  (b) Flooding, spraying, or otherwise supplying units or groups of units with water, oil, snow (i.e., low-density water), cardboard, wood, or other moderating material,
  (c) Evaporating or displacing moderator,
  (d) Precipitating fissionable material from solutions,
  (e) Diluting concentrated solutions with additional moderator,
  (f) Introducing air bubbles between rows of fuel assemblies in a storage basin;

(4) A change in the fraction of the neutron population lost by absorption resulting from:
  (a) Loss of solid absorber by corrosion or by leaching,
  (b) Loss of moderator,
  (c) Redistribution of absorber and fissionable material by precipitation of one but not the other from a solution,
  (d) Redistribution of solid absorber within a matrix of moderator or solution by clumping,
  (e) Failure to add the intended amount of absorber to a solution or failure to add it with the intended distribution,
  (f) Failure of analytical techniques to yield correct amounts of concentrations;

(5) A change in the amount of neutron reflection resulting from:
  (a) An increase in reflector thickness by adding additional material (e.g., water or personnel),
  (b) A change in reflector composition such as loss of absorber (e.g., by corrosion of an outer casing of absorber);

(6) A change in the interaction between units and reflectors resulting from:
  (a) The introduction of additional units or reflectors (e.g., personnel),
  (b) Improper placing of units,
  (c) Loss of moderator and absorber between units,
  (d) Collapse of a framework used to space units;

(7) An increase in the density of fissionable material.

[17]See H. C. PAXTON, "Criticality Control in Operations with Fissile Material," LA-3366 (Rev.), Los Alamos National Laboratory (1972).

Appendix B

(This Appendix is not a part of American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, ANSI/ANS-8.1-1983, but is included for information purposes only.)

The following fictitious example is presented to illustrate the application of the requirements of 4.3 for validating a calculational method.[18]

B1. Problem. Validate a method for calculating subcritical mass limits for water-reflected solutions of fictitium (Fi) ranging in concentration from 2 to 32 g ^{292}Fi/ℓ with no restriction on shape.

B2. Method. The method selected consists of the XYZ computer code for spherical systems using Smith's approximations as described in NIL-3638 and Jones' 3-group cross sections (NIL-5000).

Available Data from Criticality Experiments - (NIL-2867)

Concentration, ρ (g ^{292}Fi/ℓ)	Critical Radius (cm)
2	19.9
8	10.7
16	10.2

The solution was contained in thin water-reflected spherical shells having nuclear properties differing insignificantly from those of water.

B3. Validation.

B3.1 The XYZ code was operational on the local computer. Sample problems distributed with the code were run. A comparison with results obtained from the code author for the sample problems indicated the code was operating correctly for multi-region spherical systems.

B3.2 Computations were made for the three experimental points and produced the following results:

Concentration, ρ (g ^{292}Fi/ℓ)	k_{eff}
2	1.0046 ± 0.0057
8	0.9864 ± 0.0041
16	0.9696 ± 0.0041

The quoted errors represent those introduced by the quoted experimental data errors. The calculations were converged to a computational error in k_{eff} of ±0.0001, which is small compared with the experimental error. Within the area of applicability covered by experimental data (2 to 16 g/ℓ), the computed value of k_{eff} is a nearly linear function of concentration and there appears to be no reason to expect deviations from smooth behavior. The area of applicability, however, must be extended to include concentrations as great as 32 g/ℓ. Between 2 and 16 g/ℓ, k_{eff} as a function of concentration is slightly concave upward (see Fig. B1); hence linear extrapolation of the values at 8 and 16 might be expected to give an estimate of k_{eff} which is too low at 32 g/ℓ. The linearly extrapolated result, which is shown in Fig. B1, is k_{eff} = 0.936. The large extrapolation, however, should receive further support.

B3.3 In view of the downward drift of k_{eff} with an increase in concentration, a study was made to determine the cause. The result of this study was that the epithermal capture cross section of ^{292}Fi

[18]The literature contains other, more complex examples of validations generally meeting the requirements of 4.3. In particular, the subcritical limits in the standard were calculated by methods meeting these requirements.

appeared to have the greatest uncertainty and was the likely cause of the discrepancy. A reduction of 20% in the epithermal capture cross section was made. Calculations made with the modified method (epithermal cross sections reduced 20%) yielded:

Concentration, ρ (g ^{292}Fi/ℓ)	k_{eff}
2	1.0109
8	1.0084
16	1.0106

This modification produced results which appear to minimize the drift with concentration variation and which may be expected to produce a k_{eff} of approximately 1.01 at 32 g/ℓ.

B3.4 The following calculations were made at a concentration of 32 g/ℓ:

Radius (cm)	k_{eff} (original ^{292}Fi cross sections)	k_{eff} (80% epithermal ^{292}Fi cross sections)
12.429	1.0000	1.0708
11.274	0.9343	1.0000

This shows that the reactivity difference or relative bias between the two calculations is $\delta k_{eff}/k_{eff} = -0.068 \pm 0.002$.

B3.5 Based on the assumption that the modified method would yield a $k_{eff} = 1.01$ for a critical system, it can be determined by linear interpolation of the data shown in the table of B3.4 that the unmodified method should give a $k_{eff} = 0.9443$ for a critical water-reflected solution containing 32 g ^{292}Fi/ℓ, when using the XYZ code with the unmodified Jones cross sections.

B3.6 The bias for the XYZ code using unmodified Jones cross sections, over the concentration range $2 \leq \rho \leq 32$, is thus estimated to be:

Concentration, ρ (g ^{292}Fi/ℓ)	Bias
2	+0.0046
8	−0.0136
16	−0.0304
32	−0.0557

B3.7 The uncertainty in the bias in the range of 2 to 16 g ^{292}Fi/ℓ is mainly due to experimental error. (Some uncertainty is associated with interpolation.) The uncertainty at 32 g ^{292}Fi/ℓ also must cover all errors introduced by extrapolation. A margin in k_{eff} ample to compensate for uncertainty in the bias and to assure subcriticality was judged to be 0.03 in the 2 to 16 g ^{292}Fi/ℓ range and 0.05 at 32 g ^{292}Fi/ℓ. Any system with k_{eff}, computed by this method, no greater than 0.9746, 0.9564, 0.9396, or 0.8943 for concentrations of 2, 8, 16, and 32 g ^{292}Fi/ℓ, respectively, is confidently expected to be subcritical.

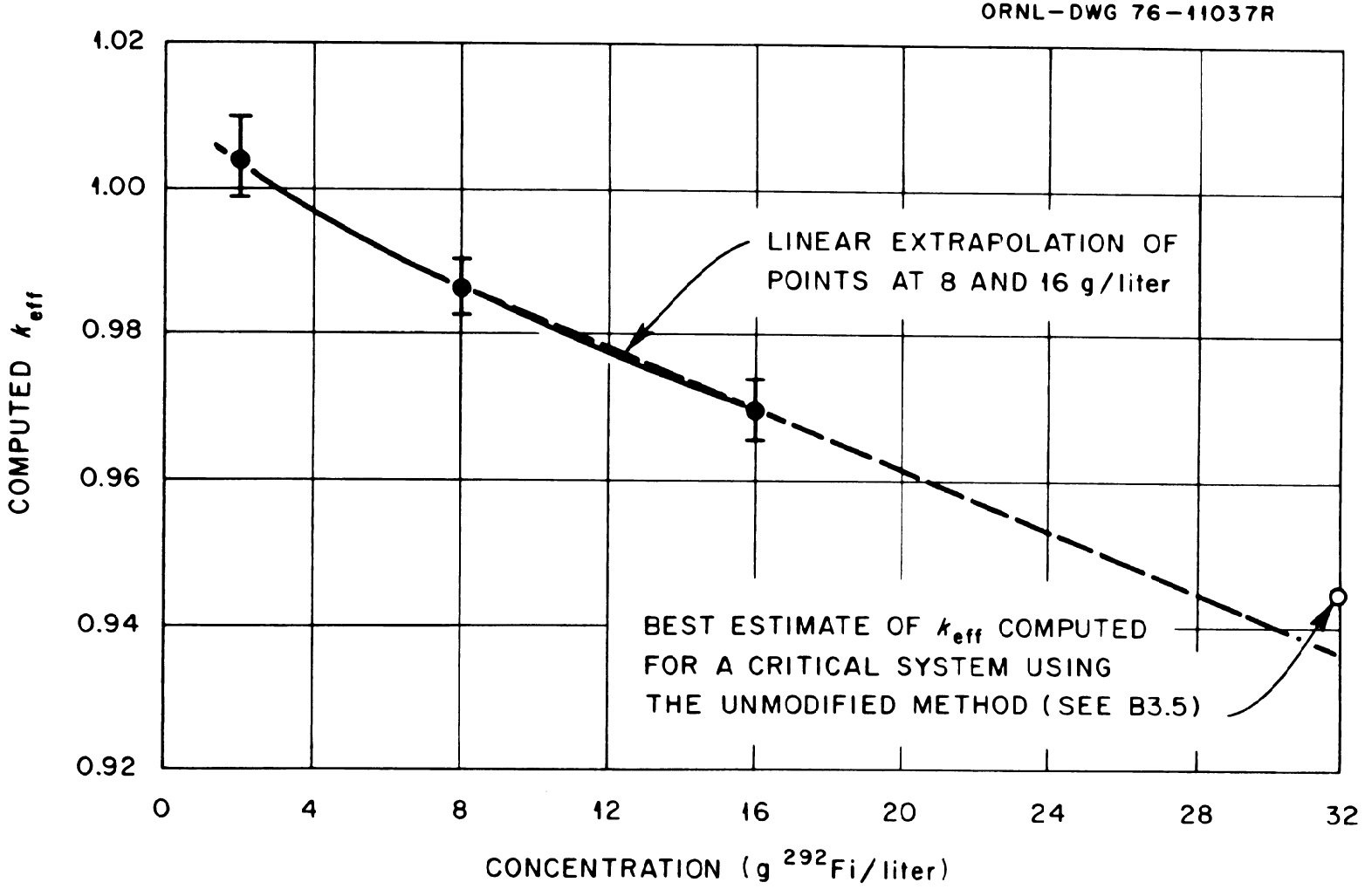

Fig. B1 Computed k_{eff} as a function of ^{292}Fi density for experimentally critical systems.