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Nuclear Criticality Safety Guide

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Nuclear Criticality Safety Guide

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ABSTRACT

This technical reference document cites information related to nuclear criticality safety principles, experience, and practice. The document also provides general guidance for criticality safety personnel and regulators.

PREFACE

This document is, in spirit, Revision 3 of *TID-7016, Nuclear Safety Guide.*[1] Due to changes in the US regulatory climate since the appearance of *TID-7016, Nuclear Safety Guide - Revision 2*,[2] we have concluded that a formal Revision 3 is not possible and have elected to change the title to "Nuclear Criticality Safety Guide" to better reflect the scope of the document. This document corrects all known errors in the previous *TID-7016* series and incorporates many changes that have been suggested by the criticality safety community.

TID-7016, Nuclear Safety Guide, published in 1957, allowed nuclear criticality data to be made available outside the family of Atomic Energy Commission installations as a result of declassification. *Revision 1 of TID-7016*,[3] four years later, was primarily a refinement based upon experience with the document. An accumulated wealth of experimental data and computational results led to *Revision 2* in 1978.

During the past two decades, little new experimental information has been reported, but abundant computational effort has been made. Stimulated by the American Nuclear Society Nuclear Criticality Safety Division, criticality-control problems and their resolution have been frequent topics of discussion. Consequently, this document incorporates little new experimental data, but incorporates modifications intended to extend the document's usefulness. It remains directed toward beginning criticality safety specialists who do not have the traditional background.

In August 1995, this document was reviewed in depth by the editors, four individuals with intimate technical knowledge of the history of the *TID-7016* document series, and two individuals from the two funding organizations, the Department of Energy and the Nuclear Regulatory Commission. These eight individuals are listed below.

- Dixon Callihan, Oak Ridge National Laboratory, retired
- Charles Harmon, Nuclear Regulatory Commission
- Calvin Hopper, Oak Ridge National Laboratory
- Elizabeth Johnson, Oak Ridge National Laboratory, retired
- Hugh Paxton, Los Alamos National Laboratory, retired
- Norman Pruvost, Los Alamos National Laboratory, retired
- Burton Rothleder, Department of Energy
- Joseph Thomas, Oak Ridge National Laboratory, retired

Special thanks is given to Thomas P. McLaughlin, leader of the Nuclear Criticality Safety Group at Los Alamos National Laboratory, to Charles Rombough of CTR Technical Services for his contributions in performing the MCNP calculations and formatting the document, and to Barbara D. Henderson, Los Alamos National Laboratory, for her efforts in editing, proofing, and cataloguing the reference material. We also wish to acknowledge Charles Nilsen of the Nuclear Regulatory Commission for his patient support during the preparation of this document.

Chapter I

BACKGROUND

A. The Nuclear Criticality Safety Problem

1. Introduction

The specific subject of this document is nuclear criticality safety. Nuclear criticality safety is defined as "protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention of the reaction."[4] This document treats the fissile nuclides ^{233}U, ^{235}U, and ^{239}Pu. These are the prevalent materials capable of criticality, i.e., capable of sustaining a nuclear chain reaction.* Potential criticality of other, less available nuclides, is discussed in *American National Standard Criticality Control of Special Actinide Elements, ANSI/ANS-8.15-1981*,[5] for consideration if a significant separated quantity should become available.

An excursion, the consequence of a nuclear chain reaction, can result if a sufficient quantity of fissile material is arranged into a critical configuration. An excursion resulting from such an accidental configuration is referred to as a criticality accident. The most adverse and potentially dangerous aspect of a criticality accident is the release of nuclear radiation. The radiation released from a criticality accident can be lethal to personnel in the vicinity of the accident. The potential for the accident and associated radiation to damage inanimate objects† or the environment is of some, but relatively minor, concern. Regardless of consequences, the objective of criticality safety remains the prevention of a criticality accident.‡

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*In this document, "nuclear chain reaction" will be understood to mean "neutron-fission chain reaction."

†Some equipment in which a criticality accident has occurred has been returned to service.

‡Criticality excursions have occurred in nature.[6] The practice of nuclear criticality safety, however, is restricted to those situations where man-made processes have the potential for an excursion that is not intended.

Chapter I presents the principles on which this document is based. For the most part, these principles arise from operational experience instead of abstract reasoning. A statement noted at a Russian conference, *Nuclear Energy and Human Safety (NE-93)*,[7] goes further: "Safety is based only on experience." Experience has led to the development of criticality safety technology as addressed in this document.

Criticality safety is practiced under well-established limitations which are sometimes overlooked or forgotten. Some of these limitations are imposed by nature. For example, no environment is entirely free of ionizing radiation, even if fissile material is not present. Therefore, exposures to radiation cannot be entirely eliminated. Other limitations result because neither physical nor administrative controls can achieve perfection. For example, safety budget limitations impose the condition that unlimited time and effort cannot be expended in an attempt to establish quantitatively the margin of safety for a particular process. Limitations such as these reduce concepts of perfect safety and a radiation-free environment to simplistic and unachievable idealizations. Recognition of these limitations avoids a diversion from practical criticality safety control.

This document is not intended to substitute for the advice of an experienced criticality safety specialist. It is intended to be a useful reference for the specialist to provide starting points for criticality safety evaluations. Although the document does not address formal regulation, it is expected to provide information that regulators will find useful. The document may benefit people other than specialists or regulators. For example, it may allow managers to confirm criticality safety advice. It may help planners produce preliminary plant layouts that are favorable for criticality control. It can tell the plant superintendent whether a borderline situation may exist in which the advice of a criticality safety specialist is needed.

Terms in this document are used in accordance with definitions in report *LA-11627-MS*, *Glossary of Nuclear Criticality Terms*,[8] or the American Nuclear Society publication, *Glossary of Terms in Nuclear Science and Technology*.[9]

2. Criticality Safety Principles

The techniques employed in the practice of criticality safety have been developed since about 1945 and are still evolving. For example, the results of computer calculations are playing an ever larger role in providing guidance for criticality safety. Nevertheless, the safety fundamentals established when criticality safety was in its infancy stand unchallenged to date. These fundamentals are

- All processes with fissile material should be examined during the design phase in order to identify potentially critical configurations. Equipment and procedures should be tailored to preclude those configurations without unnecessarily sacrificing process efficiency. Review is usually iterative, calling for reexamination as the design progresses. This iterative review implies continuing cooperation among members of the design team, especially the criticality safety specialists, the designers, and the operators.

- Simple, convenient criticality safety controls are more effective than complex or awkward measures. Above all, criticality controls should be practical because poorly conceived controls that are difficult or impractical to follow invite violations. Stated differently, nuclear criticality safety is enhanced by arrangements of material and equipment that tend to make proper operations convenient and improper operations inconvenient. Unusual situations, however, may call for unusual controls.

- Safety regulations and practices should be based on professionally generated Standards. The *ANSI/ANS 8.xx* series are consensus Standards and are designed specifically for the practice of criticality safety.

- The criticality safety specialist must examine whether criticality safety restrictions place constraints on the process which might increase the risk in other types of safety.

- Accountability for safety should reside with personnel closest to the operation of the process. These personnel have the most complete knowledge of how all elements of the process come together. Good safety practices must address the specific elements of each process in the language of the operating personnel.

The above principles could be interpreted to suggest that the practice of criticality safety might be reduced to a routine handbook exercise or formulated as a comprehensive methodology. This is not the case for two reasons. First, the experimental data or computational results needed for direct applicability to a process do not always exist. In this case, the criticality safety specialist must be innovative in constructing the analysis which establishes an adequate margin of safety for the process, and must ensure compliance with regulations. Second, in almost all cases, the practicing criticality safety specialist finds that judgment is required to formulate criticality safety guidance. Such judgments are, of course, ultimately influenced by either personal or documented experience. Sound judgment is crucial. This exercise of judgment requires comprehensive understanding of the above principles. The criticality safety specialist must focus on the question, "Have all factors, existing and potential, been taken into account in evaluating the process?"

An advantage of reviews by personnel independent of operations is, for example, to detect deficiencies that may have escaped notice. These reviews may serve other purposes, such as comparing operations with criticality safety standards to uncover possible deviations. Reviews may include internal or external quality assurance audits.

3. Factors Affecting Criticality

A system containing fissile material is critical if it maintains a steady self-sustaining nuclear chain reaction. Strictly speaking, in the absence of a neutron source other than fission, this is "delayed criticality." In a critical configuration, then, of the several neutrons produced by a single fission, an average of one leads to a new fission, so that the neutron population remains statistically constant with time. The other neutrons are lost either by capture that does not produce fission or by escape from the system. The delicate balance required for criticality depends upon the composition, quantity, and shape of the material, and its environment. In many cases, however, critical specifications need not be complicated. For example, composition and critical mass or critical volume provide specifications adequate for evaluating criticality of a water-reflected sphere. In a subcritical configuration all neutron chains eventually die away to extinction. In a supercritical system, the neutron chains grow until the energy released in the fission process is sufficient to alter at least one of the controlling factors and cause the configuration to become subcritical. This episode, during which the fission rate increases, peaks, then decreases to a low value, is the nuclear excursion referred to in the introduction. In general, criticality can be affected by system mass, shape, volume, moderation, interaction, neutron absorption, reflection, and density.

If a given volume of fissile solution departs from spherical shape, there is an increase of surface area through which neutrons can escape. The neutron deficit resulting from this greater "leakage" makes the system less reactive. This fact underlies the important concept of criticality control by means of favorable geometry.[8] The most practical shape for criticality control is an elongated cylinder of sufficiently small diameter that the contents will remain subcritical. Another favorable shape is an extensive slab of restricted thickness. Subcritical limits for these shapes are provided in Chapter III. They are expressed as the diameter of a cylinder of unlimited length, and the thickness of a slab of unlimited extent. As with mass and volume limits for spheres, the assumed reflector is thick water.

The critical configuration of fissile material is sensitive to the presence of neutron-moderating nuclides[9] that reduce the energy of neutrons, for example, hydrogen in water mixed with the fissile nuclide. The subcritical specifications for individual units presented in this document apply primarily to solutions* or mixtures with water, in which hydrogen is the moderating material. The relative amount of hydrogen may be expressed as the atomic ratio of hydrogen to fissile species. This ratio ranges from zero for metal to several thousand for a dilute solution. For a specific solution or uniform mixture, a value of mass of fissile species per unit volume implies a specific hydrogen content. As hydrogen content increases, the critical mass may vary from a few tens of kilograms, through a minimum of a few hundred grams, to unlimited quantities for very dilute solutions. In the latter case, neutron absorption by hydrogen predominates, making criticality impossible provided the hydrogen content is maintained.

With the exception of uranium enriched to less than about 6 weight percent (wt%) ^{235}U, subcritical masses for solutions apply conservatively to other distributions in water at the same hydrogen-to-fissile atomic ratio. The exception for low-enriched uranium is discussed in Chapter III, Section C-2, **Low-Enriched Uranium.**

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*Unless specified otherwise, "solution" means "uniform aqueous solution" throughout this document.

The critical mass of a fissile material also depends upon its density and distribution in intimate mixtures with materials other than water. Under most practical circumstances, the critical mass increases as the fissile density decreases, other parameters being constant. The critical mass of a sphere of ^{239}Pu metal, for example, is much less than that of a sphere containing unmoderated ^{239}Pu filings or chips. Exceptions are discussed in Reference 10.

The use of neutron-absorbing materials, such as cadmium and boron, distributed within the fissile material can render an otherwise critical system subcritical. Vigilance must be exercised to avoid unexpected loss of the absorber or change of its prescribed distribution, e.g., by corrosion or physical displacement. Solid absorbers may be included in the construction and assembly of equipment, or solutions of a neutron absorber may be added to process streams. Administrative controls, however, are required to ensure the continued presence and intended distribution of the neutron absorber. Intended neutron absorbers may not be effective if inappropriately located. For example, in the absence of external water, cadmium surrounding a process vessel will serve as a neutron reflector instead of an absorber. This topic is discussed further in Chapter III.

The nitrogen in nitrate solutions often used in chemical processing and the ^{240}Pu present in plutonium solutions are examples of naturally present absorbers. It should be noted, however, that ^{240}Pu is not an effective neutron absorber if little or no hydrogen or other moderator is present.*

The preceding comments have referred to individual units. The effects, however, of the mutual exchange of neutrons between subcritical units in a process or storage area must be considered in order to assess the nuclear safety of the system as a whole (see Chapter IV). Adequate criteria must be established for the separation of units in such arrays. Precautions taken to ensure the integrity of the spacing should receive careful attention, both in the design of plant facilities and in the storage and transport of units. The desire for compactness of storage and shipping arrays, customary in industrial practice, must be tempered where criticality is a possibility.

Neutron interaction in an array of fissile units is dependent upon such geometric factors as the size, shape, and separation of the units, as well as on the over-all size and shape of the array. Materials that may be intermingled among the units or that may surround the array are also important. A close-packed subcritical array may become critical if flooded. Conversely, a flooded subcritical array of large, less closely packed units may become critical if the water is removed, since the water, as a neutron absorber, may diminish neutron coupling of the units. (See Fig. 30 of Ref. 10.) An array that is subcritical when reflected by water may become critical when reflected by closely fitting concrete. These are some of the factors that must be recognized in establishing safe-separation criteria for handling fissile material.

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*A system of metallic ^{240}Pu can become critical.

4. Criticality Information

Data from experiments provide the basis for criticality safety, either by direct application or by validation of computations (discussed below). Only rarely, however, do experimental conditions match those of the desired application. Sometimes a close match is unnecessary; that is, measured critical specifications known to be more restrictive than necessary may be adequate. For example, the critical volume of a sphere is a conservative representation* of the critical volume of an elongated cylinder of the same composition. Frequently, however, a validated calculation is required for interpolation or extrapolation of experimental data. In general, experimental data and calculational results are complementary in that each may implement the interpretation of the other.

Experimental Data

A convenient source of criticality data from experiments through 1985 is the 1986 revision of *Critical Dimensions of Systems Containing* ^{235}U, ^{239}Pu, *and* ^{233}U.[11] More recent results must be obtained from journals or Transactions of the American Nuclear Society.

Even when criticality is determined experimentally, uncertainties reside in the description of the system. These uncertainties can be expressed as standard deviations of composition and dimensions. In an application of the experimental data, these indexes of uncertainty may be translated into an increment of the effective neutron multiplication factor, k_{eff}, discussed below. This increment must be included to establish the desired margin of safety.

Computational Results

Insufficient experimental data may be augmented by calculational results of computer criticality codes. The most versatile are Monte Carlo codes, such as KENO,[12] MCNP,[13] and MONK,[14] which are capable of detailed geometric modeling.

Wide use of criticality codes has been made possible by modern, high-performance computers. As with experimental results, computed critical conditions must be evaluated for reliability before they can be applied. The best means of judging the reliability of a computational method is to validate it by comparing its results with appropriate experimental data.

Requirements for code validation are set forth in Paragraph 4.3 of Reference 4. This Standard emphasizes establishment of a bias by correlating experimental and computational results, and by adjusting the computational results to allow for both the bias and the uncertainty in the bias. Tests are required to confirm that the mathematical operations are performed as intended and to reconfirm whenever there is a change in the computer

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*A conservative representation is one that provides a greater margin of safety than does an accurate representation of the system.

program. Misapplication of codes is not addressed in the Standard because a knowledgeable user would be expected to detect resulting errors.

The provider of requested information concerning validation should not simply extract the desired number from a computer printout and pass it on to the requester. Beforehand, the provider should carefully verify the input file to be free of errors. More generally, as required by the Standard, the provider has the obligation to document the validation of the results.

5. Criticality Indices

Simplified methods* for calculating criticality that are found in reactor physics texts[15–24] do not usually substitute for detailed calculations using computer codes. However, comparison of simple calculational results with results from detailed computer calculations can expose the presence of error. In addition, simplified methods can sharpen the picture of neutron processes that influence criticality, can introduce useful criticality indices, and may even suggest forms for empirical correlations of criticality data.

Two common indices of criticality are the effective neutron multiplication factor and the buckling. The neutron multiplication factor, k_{eff}, is the ratio of the average rate of neutron production by fission to the average rate of loss by absorption and leakage. It follows that a system is critical if $k_{eff} = 1$, subcritical if $k_{eff} < 1$, and supercritical if $k_{eff} > 1$. The multiplication factor is a calculable parameter and is a standard result of criticality computer codes.

A 1% change in k_{eff} at critical corresponds to about a 3% change in critical mass or critical volume for solids, and solutions of ^{233}U, ^{239}Pu, or uranium highly enriched in ^{235}U, over most of the density range. The value is greater for very dilute solutions. For solutions of uranium enriched to 10 wt% in ^{235}U, the increment of critical mass or volume corresponding to $\Delta k_{eff} = 0.01$ is about 6% and becomes still larger at lower enrichment. Additional relationships between Δk_{eff} and increments of criticality parameters are shown in Chapter III, **Limits for Individual Units.**

The other index, called "buckling" and symbolized by B^2, depends only upon the composition of the fissile system and can be used to estimate the critical dimensions of various geometrical configurations. If the buckling is negative, the material is subcritical regardless of the quantity;† if zero, the composition is critical only if the size be infinite; if positive, the material can be critical in finite quantities. The buckling is then simply related by elementary theory to the critical dimensions of spheres, cylinders, and slabs. The

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*These methods include the four-factor formula, age theory, and one- or two-group diffusion theory.

†Some units composed of a material having a negative buckling may achieve criticality with an appropriate reflector.

equations giving these relationships provide the form of empirical expressions for converting from one critical shape to another.[23]

B. Nuclear Criticality Safety Practices

1. The General Criticality Safety Standards

This section expands upon *American National Standard Administrative Practices for Nuclear Criticality Safety, ANSI/ANS-8.19*,[25] and *American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, ANSI/ANS-8.1*.[4] The latter Standard presents generalized basic criteria and specifies numerical subcritical limits for certain simple single fissile units but not for multiunit arrays. The other Standard is also general. It was inappropriate to include in these Standards 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 fissile material because these are items related to specific conditions. The intent here is to provide some of this supplementary guidance.

The predecessor of *ANSI/ANS-8.1* was prepared in 1958 and adopted in 1964 as American National Standard N6.1-1964. An expanded version was approved as N16.1-1969 and was revised with minor changes in 1975, revised again in 1983 when it was designated *ANSI/ANS-8.1*, and reaffirmed in 1988. Thus, this Standard benefits from more than three decades of experience following the original version.

Both Standards, *ANSI/ANS-8.1* and *8.19*, treat **Administrative Practices** in somewhat different but consistent terms. **Technical Practices** are considered in *ANSI/ANS-8.1*.

2. Administrative Practices

Responsibilities

The two Standards require that management establish responsibility for criticality safety and the Standards recommend that supervision be made as responsible for criticality safety as it is for production, development, research, and other functions. Training is called for in accordance with *American National Standard Nuclear Criticality Safety Training, ANSI/ANS-8.20*.[26]

The Standards require that management provide personnel skilled in the interpretation of data pertinent to criticality safety and familiar with operations, to serve as advisers to supervision. They advise that these specialists, to the extent practicable, be independent of process supervision. This recommendation is not made binding in order to avoid penalizing small operations in which the skill exists in the line organization and a separate adviser would be of questionable value. The intent is also to recognize that successful criticality control depends more upon the competence of personnel than on the form of organization.

There is the further requirement that management establish criteria to be satisfied by criticality safety controls. Of course, criteria existing in regulations, Standards, or guides may be either adopted or adapted to special conditions that may exist. In the complementary *American National Standard Criteria for Nuclear Criticality Safety Controls in Operations with Shielding and Confinement, ANSI/ANS-8.10*,[27] there is allowance for distinction between shielded and unshielded facilities, so it is recognized that the criteria may be less stringent when adequate shielding protects personnel.

The distinction between "management" and "supervision" is clarified by the following definition that is borrowed from another Standard:[28] "Management: the administrative body to which the supervision of a facility reports."

Other Administrative Practices

Standards *ANSI/ANS-8.1* and *8.19* call for the following additional administrative practices:

> "Before a new operation with fissile material 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." *(ANS-8.19, Section 8.1)*

This requirement interplays with the technical practices discussed below, especially the double contingency principle and geometry control. In some cases it may be desirable to resort to *in situ* neutron multiplication measurements to confirm the subcriticality of proposed configurations. Guidance for safety in performing such measurements appears in the *American National Standard for Safety in Conducting Subcritical Neutron-Multiplication Measurements in Situ, ANSI/ANS-8.6.*[29]

> "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." *(ANS-8.1, Section 4.1.3)*

> "The movement of fissile material 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." *(ANS-8.19, Sections 9.1-9.2)*

Of course, movement of fissile material is included in the operations to be governed by written procedures.

> "Deviations from procedures and unforeseen alterations in process conditions that affect nuclear criticality safety shall be documented, reported to management and investigated promptly. Action shall be taken to prevent a recurrence." *(ANS-8.19, Sections 7.6-7.7)*

It is expected that the preventive action, which might include modification of procedures, will be implemented before routine process operations are resumed.

> "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." *(ANS-8.1, Section 4.1.6)*

Again, this recommendation is tempered to avoid penalizing small, inflexible operations or forcing a change in a demonstrably successful organization.

> "Emergency procedures shall be prepared and approved by management. Organizations, local and off-site, 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." *(ANS-8.1, Section 4.1.7)*

3. Technical Practices

Obviously, criticality safety depends upon control of the factors affecting criticality which were discussed in Section A of this chapter. An equivalent statement is that criticality safety is achieved by exercising control over the quantity and distribution of fissile material and associated material. Standard *ANSI/ANS-8.1*, which addresses technical aspects of such control, leads to the following.

Double Contingency Principle

The double contingency principle is expressed in this Standard as follows.

> **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.

The principle implies good judgment that is difficult to specify in detail and to confirm. Nevertheless, consideration of this time-honored principle is a part of sound criticality safety practice.

Geometry Control

The Standard also recommends that reliance for criticality control be placed, where practicable, on equipment in which dimensions are fixed and limited rather than on administrative controls. There is the requirement, however, that all dimensions and fissile material properties on which the reliance is placed be controlled. It is pointed out that full advantage may be taken of fissile material characteristics and of equipment. Of course, controls must be effective during inventory procedures and while equipment is being loaded or unloaded with fissile material.

Control by Neutron Absorbers

Because of accidents that have occurred during inventory,[30] the trend is to "poison" large vessels for which geometry control is impractical. The Standard permits reliance upon neutron-absorbing materials, such as cadmium, boron, or gadolinium, in process streams or equipment, provided there is assurance that the absorber continues to be effective. Particular care is required when the absorbers are in solution.

A proven and often effective means of preventing criticality in a large vessel is to pack it with borosilicate glass Raschig rings. Guidance for permissible usage, degree of protection, and appropriate surveillance is given by *American National Standard Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Material, ANSI/ANS-8.5.*[31]

Subcritical Limits

The Standard *ANSI/ANS-8.1* emphasizes subcritical limits, discussed earlier, and defines them as follows.

> **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.

The above definition, however, does not explicitly clarify that, in practice, subcritical limits are adjusted criticality data. The adjustments to the data allow for uncertainties in the data. It should be understood that subcritical limits do not apply directly to the conditions encountered in operations with fissile material. Criticality safety analysis incorporates subcritical limits and contingencies that could be encountered in the operation. Where applicable data are available, the Standard requires that subcritical limits be established on bases derived from experiments with adequate allowance for uncertainties in the data. In the absence of directly applicable experimental measurements, it is permissible to derive the limits from calculations validated in accordance with Paragraph 4.3 of the Standard. It

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*Examples of such analytical techniques are radiological, chemical, and isotopic analyses.

should be reiterated that allowances must be sufficient to cover uncertainties in the data and in the calculations.

Subcritical limits for mass, volume, and other parameters, which appear in Chapter III, assume the equivalent of a contiguous water reflector of unlimited thickness (thick water reflector), and allow for experimental and computational uncertainties. They do not, however, cover contingencies such as errors in quantitative measurements or sample analyses, misinterpretation of procedures, and human fallibility. Allowance for these depends upon process specifics, and, for evaluation, calls for the judgment of plant personnel and the advice of a criticality safety specialist.

The assumed thick water reflector is seldom encountered in practice. Nevertheless, the thick water reflector is a useful reference condition. As discussed later, some materials, when thick and closely fitting, can be more effective as reflectors than ordinary water. If such materials are present, special evaluation is needed, probably requiring the use of experimental data. In the absence of such materials, the equivalent of a thick water reflector (15 cm or more) is a reasonably conservative representation of other common reflector materials.

A nearby interacting fissile unit may also be more effective than a water reflector, so would require special consideration. In evaluating interaction of a few units, comparison with a larger, somewhat more reactive, array from Chapter IV may be a useful conservative extreme. Sometimes, however, a more appropriate experimental system may be found in other references, for example, in Reference 11, *Critical Dimensions of Systems Containing* ^{235}U, ^{239}Pu, *and* ^{233}U. Where interaction of several vessels, such as those in a processing plant must be judged, one of the semi-empirical methods of Chapter IV may be adequate.

4. The Role of Calculational Validation

The need for calculational validation arises when the system of interest has not been built as an experimental configuration. In practice, this is almost always the situation. The purpose of calculational validation is to establish a credible calculational model relating experimental data and the system of interest. In this context, *calculational model* means both the mathematical model for neutron transport and the evaluated cross section data used in the model. The experimental data must be derived from an experimental critical configuration that is similar in geometry and material composition to the system of interest. Similarity is a matter of judgment. The spirit of validation is to recognize that uncertainties are inherent in both the calculational model and experimental data. The usefulness of validation is that credible information can be gained about the system of interest even though these uncertainties exist.

Reported experiments do not always include the details needed to reduce the experiment to an ideal macroscopic description of the system geometry and material. Different evaluators may derive different macroscopic descriptions from the same experimental results. There is no assurance, therefore, that reported experimental results, when evaluated by different evaluators, will lead to a unique macroscopic description of the system. Also, very few reported experimental critical configurations include any analysis of the uncertainty. References 32 and 33 are unusual in that examples of the experimental uncertainties in the experimental results were given. The uncertainties were estimated from calculational corrections in both geometry and the material composition. In each case, these corrections were used to simplify the description of the system. Such calculational corrections are imperfect and are incapable of eliminating the experimental error. In practice, it must be understood that experimental results can never be made free of error and that the estimation of experimental error unavoidably involves judgment. Such judgment is involved whether adjustments to experimental results are based on calculations or on experimental measurements.

Calculational validation requires that k_{eff} be calculated for at least one experimental critical system similar to the system of interest. Comparison of the calculated k_{eff} with unity establishes a numerical difference. Standard *ANSI/ANS-8.1* appears to make a working assumption when determining the bias between calculational results and experimental data. This apparent assumption is that experimental and calculational uncertainties are negligible or zero compared to the bias. Such an assumption leads to assigning the bias as equal to the numerical difference. At this stage of the validation process, however, the practitioner should review the definition of bias provided in the Standard's glossary of terms. Simply assigning the bias to be equal to the numerical difference may not be sufficient to be in compliance with the Standard. In the Standard, bias is defined as "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." Clearly, this definition requires the practitioner to establish the bias on the basis of the numerical difference *and* assessment of the potential experimental uncertainties.

The Standard leaves several matters of judgment to the practitioner. For example, if only a single experimental system is available to establish a numerical difference, this single difference would *not* constitute a "*systematic* disagreement between the results calculated by a method and experimental data." With regard to the uncertainty in the bias, the bias becomes undefined when the uncertainty of the experimental data is large compared to the numerical difference. As mentioned above, reported experimental results do not always include the experimental uncertainty. The Standard points out "generally neither the bias nor its uncertainty is constant; both should be expected to be functions of composition and other variables." Judgmental matters such as these play a crucial role when extrapolating the applicability of a calculational method beyond the range of experimental conditions over which the bias was established.

5. Interaction of Safeguards Procedures and Criticality Control

Safeguards procedures may have either a favorable or detrimental effect on criticality control, so interaction of these procedures with criticality safety should be examined before they are instituted. Periodic surveys of chemical processing lines for material accountability can actually contribute to criticality safety by detecting unanticipated deposits of fissile material.[34–36]

On the other hand, the implementation of safeguards procedures may favor arrangements of fissionable objects that detract from criticality safety. For example, it may be convenient to cluster the objects in an easily protected location instead of spreading them out for better criticality control. When recognized, such conflicts should be readily resolved.

6. Instrumentation

An important contribution of instrumentation to criticality safety is demonstration of adequate subcriticality of a fissile system. For example, this demonstration can be the quantitative measurement of k_{eff} by means of the ^{252}Cf-source-driven neutron noise analysis method.[37] This method has been used to measure the subcriticality of a multiplying system to a k_{eff} as low as 0.3 with data accumulation in as little as six seconds for a uranyl nitrate solution tank. Before this technique was developed, measurements of characteristic radiation* could indicate changes in quantity of fissile material, but required calibration to give quantitative results.[38–40] Special instrumentation for measuring the ^{235}U content of uranium involves the so-called random-source technique.[41–42]

Another contribution of instrumentation to criticality safety is the identification of unplanned deposits of fissile material by means of changes of characteristic radiation. Periodic surveys of deposits are desirable where fissile material may accumulate in locations such as filters, tank walls, or solution residues.† In gaseous diffusion plants, for example, accumulations of ^{235}U have been detected by periodic measurement of characteristic gamma radiation from ^{235}U. Such measurements allow removal of the accumulations before they became dangerous.[36]

Another method makes use of the high spontaneous fission rate of the ^{240}Pu isotope which accompanies ^{239}Pu in a proportion characteristic of the material history. The neutron background in a plutonium process is therefore a measure of the plutonium density, and a change in an established background can signal an abnormal condition in a process stream. Because of this effect, surveys with neutron detectors can establish the location of

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*Characteristic radiations include 1) gamma rays from ^{235}U and plutonium, 2) neutrons from spontaneous fission of ^{240}Pu and ^{238}U, 3) neutrons from (α,n) reactions of fissile oxides, carbides, and fluorides, and 4) high energy gamma radiation from ^{208}Tl, a decay product of ^{232}U that usually accompanies ^{233}U.

†In some cases, inventory discrepancies can indicate the possibility of such deposits. See Ref. 35.

unplanned plutonium deposits.[43] These indirect methods of criticality control are empirical and must be based on the calibration of appropriate instruments.

It might seem that warning of an accidental approach to criticality could be given by a neutron detector. Such a warning would require an appropriately placed neutron source such as those used for subcritical *in situ* multiplication measurements.[29] It is rare, however, that plant process conditions are sufficiently favorable and stable for a meaningful indication of increased neutron multiplication before criticality would be attained. The warning probably would be too late except to signal personnel evacuation. However, absorption by the fissionable material of gamma rays or neutrons directed through a process stream depends upon the fissile density of the solution and can be used for fissile density control if there is a suitable source and detector.[44–45]

Instruments for the detection of radiation are also useful in criticality accident alarm systems that provide a signal for evacuation. The value of these systems has been clearly demonstrated as will be seen in Chapter II. Gamma-ray detectors rather than neutron detectors are usually selected. Reliable instrumentation and freedom from false alarms are more important than sensitivity. The requirements on such instrumentation are addressed in *American National Standard Criticality Accident Alarm System, ANSI/ANS-8.3.*[46]

7. Quality Assurance for Criticality Safety

Quality assurance is defined as follows in the *Quality Control Handbook.*[47] "Quality assurance is the activity of providing, to all concerned, the evidence needed to establish confidence that the quality function is being performed adequately." "The quality function is the entire collection of activities through which we achieve fitness for use, no matter where these activities are performed."

The relevant quality assurance Standards are *American National Standard Quality Assurance Program Requirements for Nuclear Facilities, ASME NQA-1-1989,*[48] issued by the American Society of Mechanical Engineers and supplementary *American National Standard Quality Assurance Requirements for Nuclear Facility Applications, ASME NQA-2-1989.*[49] Between them they contain the essence of 15 quality assurance standards of the *ANSI/ASME N45.2* series. The 18 Basic Requirements of *NQA-1* with Supplements have been applied in full to power reactors but are intended to be selective for other applications. As stated in the foreword, "The extent to which this document should be applied, either wholly or in part, will depend upon the nature and scope of the work to be performed and the relative importance of the items or services being produced. The extent of application is to be determined by the organization imposing this document. For example, it may only involve the Basic Requirements; Basic Requirements in combination with selected Supplements; Basic Requirements in combination with Supplements with appropriate changes; or the entire document."

The complexity and sensitivity of power reactors led to adoption of all Supplements as well as Basic Requirements. The Basic Requirements are generally adequate for nonreactor operations with fissile material, which are much simpler and avoid the critical condition that is maintained so sensitively in reactors.

The 18 Basic Requirements of *NQA-1* are summarized as follows. Titles from the Standard are in boldface.

Basic Requirements of Standard *NQA-1*:

1. Description of **organization**, assignments of responsibility and authority.
2. Description of **quality assurance program** and its implementation including training.
3. **Design control** and verification, design change control.
4. **Procurement document control**, applicable design bases.
5. **Instructions, procedures, and drawings** governing activities.
6. **Document control**, including distribution, changes, and reviews for adequacy.
7. **Control of purchased items and services**, suppliers' evidence of quality.
8. **Identification and control of items**, maintenance thereof.
9. **Control of processes**, qualification of personnel such as welding personnel, and procedures.
10. **Inspection** by persons not directly involved in operations.
11. **Test control**, including plans, documentation, and evaluation.
12. **Control of measuring and test equipment**, including periodic calibration.
13. **Handling, storage, and shipping**, cleaning and packaging.
14. **Inspection, test, and operating status**, prevention of inadvertent operation.
15. Identification and **control of nonconforming items** to prevent inadvertent use.
16. **Corrective action** of conditions adverse to quality.
17. **Quality assurance records**, retrievability and protection.
18. **Audits** by persons independent of operations, written procedures or checklists.

The Standard *ANSI/ANS-8.19, Administrative Practices for Nuclear Criticality Safety,* addresses Basic Requirements 1, 3, 5, 6, 8, 10, 13, 14, 16, and 18. Guidance is given in *ANSI/ANS-8.20* for the training portion of 2, 9, and 11. Thus, observing these standards takes a major step toward satisfying quality assurance requirements. Application of the remaining Basic Requirements depends upon the nature of the operation, for example, the degree to which there is dependence on procured items, or reliance on tests.

It follows that provisions of Standards *ANSI/ANS-8.19* and *8.20*, and several selected Basic Requirements of *NQA-1*, can constitute an appropriate checklist for monitoring quality assurance conformance of nonreactor operations that require criticality control. With this checklist, quality assurance auditing can become more than a formality.

Adequate documentation is necessary even when good practices are observed. Without adequate documentation, surveys and audits become unnecessarily burdensome.

8. Probabilistic Methods

It is not obvious that power-reactor safety practices such as Probabilistic Risk Assessment (PRA) should be applied to other operations such as operations with fissile material in which consequences of potential accidents may be orders of magnitude less than those for power reactors. Guidance for deciding in a given situation whether PRA is appropiate as opposed to qualitative evaluation is given in a JBF Associates report, *Evaluating Process Safety in the Chemical Industry, A Manager's Guide to Quantitative Risk Analysis.*[50]

Residual fission products in a fuel reprocessing plant increase the presumed consequences of a criticality accident. This presumption can lead to interpreting Reference 50 guidance as recommending PRA. Wilson[51] of the Idaho Chemical Processing Plant concludes the following about the application of PRA.

> "PRAs can be a very useful tool in setting criticality safety margins as long as careful planning goes into deciding when and how to use PRAs, particularly:
>
> 1. Don't allow the mystique of PRA to cause you to take actions which are inappropiate or not cost effective.
> 2. Recognize the power of PRA and exert your full efforts to bring it to bear on your problems.
> 3. Structure your PRA program from the ground up (be involved in setting safety goals and training).
> 4. Until the remaining subjectivity and predictive uncertainty can be removed from PRAs, a companion qualitative goal, such as the contingency approach, should also be employed."

Regarding item 4 above, it should be recognized that the "remaining subjectivity and predictive uncertainty" may never be removed from PRAs. Experts in the application of PRA emphasize its usefulness early in the life of a project.[52] The need for updating, as appropriate, is implied.

In addition to its part in criticality control, PRA can be a useful regulatory adjunct when combined with *Nuclear Regulatory Commission Regulatory Guide 3.33.*[53] An illustration by Thomas and Gmal[54] is the application of PRA to satisfy a licensing requirement for accident dose restriction outside a German fuel reprocessing plant.

For a situation different from a fuel reprocessing plant, PRA has been tested for one operation at the Plutonium Facility at Los Alamos. This exercise was conducted by an independent organization, and is mentioned in a paper by McLaughlin.[55] McLaughlin argues in his paper that the estimated few million dollars cost of PRA for the entire Plutonium Facility "could be better used on control measures such as more criticality staff presence on the process floor." This observation is not surprising if the guidance of Reference 50 is considered. In the absence of fission products, foreseeable consequences of a criticality accident with plutonium are so limited that this guidance calls for qualitative analysis instead of PRA.

Many applications of criticality safety involve systems where hands-on operations take place with a few fissile-bearing components. In addition, only two or three persons may be authorized to carry out the work. The elements which need be considered to carry out a criticality safety analysis in such a situation appear relatively simple when compared with the complexity inherent in power-reactor safety analysis. In the exercise described by McLaughlin, the application of PRA did not reveal any elements that were not incorporated by prior qualitative criticality safety analysis. Experience, however, indicates that this may not always be the case for complex systems. System complexity and the potential consequences of an accident can both play a role in the decision to apply PRA.

The use of PRA in criticality safety was the subject of several papers presented at the Fifth International Conference on Nuclear Criticality Safety (ICNC '95).[56] The conclusion of the ICNC '95 reviewers was, "It is evident that more experience is needed before these methods will be generally accepted."*

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*C. V. Parks and G. E. Whitesides, "Summary of ICNC '95," distributed to conference attendees after the meeting.