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CRITERIA FOR CRITICALITY SAFETY LIMITS AND CONTROLS AT HANFORD ENGINEERING DEVELOPMENT LABORATORY

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1. INTRODUCTION

This report is a formal presentation of the philosophical and technical bases used to establish ex-reactor criticality limits and controls at the Hanford Engineering Development Laboratory. It is intended primarily as a guide for persons in the Nuclear Safety organization who are directly concerned with establishing criticality safety limits, but should be useful to others who are interested in the types of controls used. Applications of these criteria must be reviewed and approved by an experienced criticality safety specialist in the Nuclear Safety Organization prior to use.

Handling and storage of fissionable materials outside nuclear reactors must be performed in a manner which precludes a nuclear chain reaction. An accidental chain reaction could result in serious or fatal radiation exposure to nearby personnel, contaminate facilities, cause shutdown of needed facilities, and result in work delays.

The goal of the criticality safety program is to avoid accidental criticality through the use of proper facility design and administrative controls.

2. SCOPE

Criteria are presented which are used to establish criticality safety limits and controls for operations involving ^{235}U, ^{233}U, ^{239}Pu, and other fissionable materials outside of nuclear reactors and critical facilities. A discussion of administrative controls, design of processes or equipment, and criteria for transporting fissionable material can be found in the Criticality Safety Procedures Manual (WHAN-M-6) or in the literature and are not presented here. Although these criteria are intended to be complete, it is recognized that unforseen circumstances may arise requiring special controls.

3. DEFINITIONS

Definitions of important terms are presented to emphasize the precise nature of their meanings when used for criticality safety limits and controls.

3.1 Criticality Safety - The prevention of an inadvertent nuclear chain reaction in a non-reactor environment and the minimization of the consequences should such an incident occur.

3.2 Criticality Accident - The inadvertent occurrence of a self-sustaining or divergent neutron chain reaction.

3.3 Critical Mass - The smallest mass of a fissionable material capable of supporting a self-sustaining neutron chain reaction over the range of stated conditions (not necessarily including optimum conditions.)

3.4 Critical Mass, Minimum - The smallest mass of fissionable material capable of supporting a self-sustaining neutron chain reaction considering the entire range of all parameters which affect criticality. The conditions at which the Minimum Critical Mass occurs are called optimum conditions. Isotopic enrichment is usually considered fixed.

3.5 Critical Value - The value of a specified variable (mass, volume, dimension, etc.) at which a system is just critical (Critical Mass, Critical Volume, etc.)

3.6 Safe Limit - A stated fraction of a Critical Value for a specified variable (mass, volume, dimension, etc.) which allows for operating and design contingencies (e.g. double batching) as well as uncertainties in the Critical Value.

3.7 Areal Density - The mass of fissionable material per unit area projected onto a plane; for example, the product of the thickness of a uniform slab and the concentration of fissionable material.

3.8 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).

3.9 Primary Control - A method of control upon which principal dependence is placed to prevent a nuclear chain reaction.

4. GENERAL CRITERIA

Criteria used at the Hanford Engineering Development Laboratory to ensure maximum safety for the handling, processing, and storage of fissionable materials are listed in the following paragraphs:

4.1 At least two unlikely, independent, and concurrent events must occur before criticality is possible (two contingency policy). That is, no single occurrence can result in criticality. Judgment is required in determining whether two events are related and consequently whether they represent two contingencies or a single contingency. For example, exceeding storage limits and then flooding an area would constitute two independent events; however, fire and flooding from an automatic sprinkler system would be considered a single event.

4.2 Engineered safety features are preferred to administrative controls and should be used whenever practical. For example, geometrically favorable equipment should be used whenever practical. Physical barriers should be used to minimize the possibility or consequence of personnel errors.

4.3 Critical Values upon which criticality safety limits are based shall be established by: (1) accepted nuclear safety guides; or (2) data derived from experiment; or (3) in the absence of directly applicable experimental measurements, calculations made by a method shown to be valid and conservative in comparison with experimental data after sufficient allowances have been made for uncertainties in the data and the calculations.

4.4 An assessment of both normal and abnormal conditions to which the fissionable material might be exposed shall be considered in establishing Safe Limits.

4.5 Appropriate factors of safety shall be included in all limits. The magnitude of the safety factor shall be commensurate with the uncertainty in the Critical Value, the probability of violating the limit and the maximum probable consequences of an incident.

4.6 Criticality safety margins shall as a minimum meet the Safe Limit criteria specified in this report. Where feasible, larger safety factors should be considered.

4.7 Design of processes and equipment should make proper operation convenient and maloperation either inconvenient or impossible.

4.8 All criticality safety limits shall be based on optimum interspersed moderation and full reflection, except when other than optimum moderation or less than full reflection can be positively assured. It should be noted that in some cases "optimum moderation" may be no moderation.

4.9 Fissionable material operations are normally assessed on the basis of water being the neutron reflector and moderator. When other more effective reflectors or moderators are present, such as concrete, beryllium, deuterium, carbon, heavy oil, organic plastics, and certain heavy metals, their effects must be considered.

4.10 Criticality safety shall not be compromised for the sake of expediency, production, or economic pressure.

5. CRITICALITY SAFETY CONTROLS

Accidental criticality can be prevented by exercising control over parameters to ensure against their achieving a Critical Value. A brief description of controls having significance to nuclear safety are listed below.

5.1 Mass Control - Safe Limits shall restrict fissionable material accumulations to a specified fraction of a Critical Mass.

5.2 Piece Count Control - Safe Limits shall restrict fissionable material accumulation to a specified fraction of a Critical Number of pieces. Limits must account for credible variations and changes in piece geometry.

5.3 Moderation Control - Safe Limits shall be based on optimum water moderation, unless other than optimum moderation can be assured. If moderation control is a Primary Control, exclusion of moderation is subject to the two contingency policy. Situations in which nonoptimum moderation may be assumed are listed in Appendix A.

5.4 Reflection Control - Safe Limits shall be based on full water reflection except when less than full water reflection can be assured. Situations in which less than optimum reflection may be assumed are listed in Appendix B. Reflecting materials which are better than water must be considered when they are present.

5.5 Geometry Control - Safe Limits shall be based on spherical geometry, unless a less favorable geometry can be assured. Cylindrical and slab geometries are often desirable from an operational standpoint because a greater volume of material can be safely handled. Geometry can be a Primary Control only if adequate spacing from other fissionable materials is assured.

5.6 Density Control - Safe Limits shall be based on the mass of fissionable isotope per unit volume which results in greatest reactivity, unless a lower density is assured.

5.7 Areal Density Control - Safe Limits shall be based upon optimum water moderation and full reflection. Internal moderation of individual units need not be considered if internal moderation is not possible. All units in an array shall be assumed uniformly spaced at the smallest edge-to-edge spacing permitted between units.

5.8 Concentration Control - Safe Limits shall restrict the permitted concentration of fissile materials dissolved or dispersed in another medium to a specified fraction of the Minimum Critical Concentration in that vessel. In addition, if the possibility exists of inadvertent increase in concentration as by precipitation or evaporation, either a mass limit shall be specified or the concentration limit reduced to ensure that k_{eff} does not exceed a specified limit under the worst conditions [see Section 6.1(g)].

5.9 Interaction Control - Safe Limits shall be based on the maximum attainable interaction with other fissile material. Interaction may be controlled by unit spacing, arrangement and/or by neutron shielding. Situations in which systems can be considered isolated are listed in Appendix C. Criticality safety criteria and design considerations for fissionable material storage arrays are given in Appendix D.

5.10 Neutron Absorber Control - Safe Limits shall be based on the presence of neutron absorbers only if their continued presence, with the intended distributions and concentrations under both normal and abnormal conditions can be assured. Soluble poisons shall not be used as a Primary Control in unshielded facilities.

5.11 Enrichment Control - Safe Limits may be based on less than full enrichment provided it can be assured that the enrichment limit will not be exceeded or that an enrichment error would not result in criticality.

5.12 A combination of the controls 5.1 - 5.11 may be used.

6. SAFE LIMITS

When criticality safety is dependent upon the control of a given parameter, that parameter is restricted to values less than a specified value, called the Safe Limit, chosen such that no violation of a single contingency can result in criticality. Safe Limits presented in this section are to be used in conjunction with definitions and cautions given in section 5.

6.1 The Safe Limit (mass, volume, dimension, etc.) can be obtained by multiplying the proper parameter by a specified fraction. The parameters and maximum fractions corresponding to different types of control are as follows:

(a) mass control - multiply the Critical Mass by 0.45.

(b) piece count control - multiply the Critical Number of pieces by 0.45.

(c) moderation control - multiply by 0.45, the minimum amount of moderator that is necessary for criticality when added to a fixed quantity of fissile material. When moderation control is used, the mass of fuel shall not exceed 45% of an unmoderated Critical Mass.

(d) volume control - multiply the Minimum Critical Spherical Volume by 0.75.

(e) dimension control - when the dimension is assured by mechanical design, multiply the infinite cylinder Critical Diameter or the infinite slab Critical Thickness by 0.85. When the slab thickness is controlled procedurally:

(1) for unmoderated fissionable material in normally unmoderated operations (that is, moderator present only under accidental conditions), multiply the Critical Slab Thickness by 0.85 assuming interspersed moderation or by 0.45 assuming no interspersed moderation, whichever is more restrictive; or

(2) for moderated fissionable material, and for normally moderated operations, multiply the Critical Slab Thickness by 0.45 assuming interspersed moderation.

(f) areal density control - multiply the critical areal density by 0.75.

(g) concentration control - multiply the critical concentration in the vessel by 0.45. In addition, if the possibility exists of an inadvertent increase in concentration of the fissile material as by precipitation or evaporation, the quantity of fissile material shall be limited to 0.90 Critical Mass or k_{eff} shall be governed by rule 6.2 under the worst conditions.

6.2 When k_{eff} is used as a limit, it shall not exceed 0.95 on a 95% confidence level. The confidence level shall be established from experimentally measured values or by calculational methods which conservatively reproduce experimental values. In general, this method is used for arrays which include geometry control.

6.3 If k_{eff} is not used as a basis for an array, then the number of units in the array shall not exceed 0.45 of the Critical Number for the array.

7. ANALYTICAL METHODS

Methods found useful for obtaining critical parameters are listed as a guide. Each method has both strong and weak points. Consideration must be given to estimating the probable accuracy when using any of the methods.

7.1 Compiled Criticality Data - Many critical parameters can be obtained from handbooks and other sources of compiled data. The most useful sources include:

(a) Criticality Handbook (ARH-600), Volumes 1, 2, and 3. Revised September, 1971

(b) Handbook of Criticality Data, AHSB(S) Handbook 1, (Rev. 1) UKAEA 1967

(c) Critical and Safe Masses and Dimensions of Lattices of U and UO_2 Rods in Water (DP-1014), February, 1966

(d) Critical Dimensions of Systems Containing U^{235}, Pu^{239}, and U^{233} (TID-7028), June, 1964

(e) Nuclear Safety Guide (TID-7016, Rev. 1), 1961

7.2 Computer Codes - Acceptable computer codes for calculating critical parameters include, but are not necessarily restricted to, the following:

(a) GAMTEC-II - used to obtain cross sections for HFN and DTF

(b) THERMOS - used for thermal cross sections

(c) HFN - does multigroup diffusion calculations

(d) DTF - does multigroup transport calculations

(e) HAMMER - calculates infinite lattice parameters using multigroup transport theory

(f) GEM - does Monte Carlo calculations for complex geometries

(g) KENO - does Monte Carlo calculations

(h) O5R - does Monte Carlo calculations

7.3 Manual Computational Methods

(a) Solid Angle Method - Useful for simple interaction calculations. Use is restricted to systems for which $k_{eff} \leq .85$.

(b) Density Analog Method - Useful for simple interaction calculations.

(c) NB^2 Method - Useful for array calculations.

7.4 Consideration must be given to the accuracy of the critical parameters obtained by any method. Care should be exercised when looking up, plotting, and calculating data. Methods used to check accuracy include:

(a) Compare data from two sources, if possible.

(b) Use two methods to calculate parameters. Check computer calculations with hand calculations; and vice-versa.

(c) Calculate a similar known system to obtain check on accuracy of method.

APPENDIX A

SITUATIONS IN WHICH NONOPTIMUM MODERATION MAY BE ASSUMED

All criticality safety limits shall be based on optimum moderation, except when the addition of moderator alone will not cause criticality or when the addition of more than a limit quantity of moderator to the fissionable material is excluded by the two contingency policy. The following list contains examples of situations in which nonoptimum moderation may be assumed. Limits must take into account the worst credible accident conditions.

1. Normally dry operations in which the fissionable material is in water tight containers of high integrity. Water inleakage into any single container must not result in criticality.
2. Fissionable material in water tight gloveboxes in which the amount of moderating material is limited and its introduction is controlled.
3. Fuel rods securely bundled as in an autoclave, fuel element, or suitable metal shipping container such that optimum moderation is impossible even under flooding conditions.
4. Systems in which the moderator is solid, thus fixing the H/X ratio to a certain value or range of values, as in the case of metallographic samples.
5. Fissile units for which internal moderation is not possible. Optimum interspersed moderation between such units must be assumed, unless other than optimum interspersed moderation can be assured.

APPENDIX B

SITUATIONS IN WHICH LESS THAN FULL REFLECTION MAY BE ASSUMED

Full reflection shall be assumed except when less than full reflection can be assured by the two contingency policy. Limits must take into account the worst credible accident conditions. Examples of situations in which less than full reflection might be assumed include:

1. Fixed, unreflected process vessels in an enclosure to which access is controlled and which either has no entry for water or is positively drained.
2. Unreflected process vessels wrapped with cadmium sheeting of sufficient thickness (at least 20 mil) to assure neutron absorption, with the sheeting so protected that its presence can be assured intact.
3. Individual units in a storage array. Full reflection of an interior unit may tend to isolate it from other units thereby reducing the reactivity of the array.

APPENDIX C

NUCLEAR ISOLATION

Examples of situations where the neutron interaction is negligible are:

1. Fissionable units separated by at least one foot of water or of a material possessing an equivalent hydrogen density.
2. Units separated by at least one foot of concrete of a density not less than 140 lbs. per cubic foot.
3. The unit(s) of interest subtend a solid angle of less than 0.005 steradian at the point under consideration.
4. All units combined constitute less than a Safe Mass Limit.
5. All units consist of homogeneous mixtures with a fissile isotope concentration less than 6 grams per liter.

APPENDIX D

CRITICALITY SAFETY CRITERIA AND DESIGN CONSIDERATIONS FOR FISSIONABLE MATERIAL STORAGE ARRAYS

Considerations to be given when designing or using fissionable material storage arrays include the following:

1. At least two unlikely, independent, and concurrent events must occur before criticality is possible.

2. For arrays that have been experimentally measured, or for which calculational methods accurately or conservatively reproduce experimental values, k_{eff} shall not exceed 0.95 at a 95% confidence level for the worst credible conditions. If k_{eff} is not used as a basis, the number of units in the array shall not exceed 0.45 of the Critical Number for the array.

3. A 12-inch edge-to-edge spacing provides isolation between units when the array is completely submerged in water.

4. Caution should be exercised in permitting moderated and unmoderated material storage in the same array (due to the increased effectiveness of moderated neutrons).

5. Fuel storage devices shall be designed with an adequate strength factor to assure against failure under forseeable loads or accident conditions such as fire, melting, impact, wind, earthquake, corrosion, and leakage. The adequacy of the structural integrity of fuel storage devices shall be evaluated during the design phase.

6. Arrays which use off-floor storage shall be fastened to the floor or wall, or be sufficiently stable to prevent tipping over under normal or anticipated accident conditions.

7. Fuel storage containers and structures shall be constructed of non-combustible material unless it can be shown that a fire would not result in criticality.

8. Engineered safety features are preferred to administrative controls and shall be used whenever feasible. For example:
   (a) Spacing between units should be limited by mechanical means.
   (b) Mechanical barriers should be used to prevent placing material between ports or shelves or designated storage positions.
   (c) A mechanical barrier should be used to prevent stacking of material on top of an array.
9. Criticality alarm coverage should be provided for the entire storage area and personnel entrances.

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