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THE NUCLEAR SAFETY GUIDE TID-7016 REVISION 2

J. T. Thomas

Computer Sciences Division
at Oak Ridge National Laboratory*
Union Carbide Corporation, Nuclear Division

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I welcome the opportunity to share with you some of the experiences and motivation which influenced the second revision of the Nuclear Safety Guide. The most striking and perhaps controversial feature is its changed format. The Guide no longer provides recommendations with applicable safety factors. There is now a mixture of critical, potentially critical and subcritical data. An analysis of an operation is essential and a safety factor judged to be adequate for the system must be supplied by the safety specialist. There are sound reasons for this departure from previous versions of the Guide.

- The limits for simple geometries were dominated by the factor 2.3, principally to protect against double batching. Time and technical advances have erroded this once deserved emphasis.

- Information was presented in a manner that encouraged relaxation of limits toward the critical state rather than in the direction of subcriticality.

- Arbitrary conservatism was necessary in providing general guidance for situations beyond the experimental base of the information available.

- Generalizations were restricted to observable effects in limited experimental data. This restraint is severly weakened by our present computational capabilities.

Calculations were used extensively in the second revision. The expanding use of calculated criticality data as a substitute for experimental data has its benefits and its detriments. The principle benefits of validated calculational results are in providing improved understanding of factors influencing criticality, establishing the magnitude of reactivity changes to associate with those factors, and producing parametric dependence of results which aid in interpolation, extension and application of the information.

The major detriment focuses on the adequacy of the validation. Although guidance is available in the American National Standard Validation of Calculational Methods for Nuclear Criticality Safety, N16.9-1975 (ANS-8.11), published documentation is sparce and an acceptable format can be said to be in the process of evolution. As such, acceptance of results remains subject to judgement by individuals and the regulatory agencies. A corollary, which is, perhaps, as important, is the increased significance being given to calculated neutron multiplication factors associated with subcriticality. There are strong advocates of the premis that needed safety information can be calculated.

We agree if the related economics or cost/risk benefits are suppressed. In either case, calculational data are predicated on what is known and understood. Unfortunately, this practice imposes a requirement of vigilance against results having no predicate in reality. It follows that each individual or organization utilizing a computational method to establish safety has an interest in experimental data. Experience is the link between what is understood and the realities of nature. Critical experiments establish the measure of reliability to associate with calculated results. As long as there is an expanding use of calculational methods in nuclear criticality safety, there is a concurrent continuing need for critical experiments data and, hence, a national critical experiments capability.

The Guide can be placed into perspective by considering the elements of a Nuclear Criticality Safety Program as summarized in the following:

NUCLEAR CRITICALITY SAFETY

- Program with defined administrative and technical practices
- Clear definition of responsibility and authority
- Written procedures and documented safety analyses for operations
- Criticality data and guides

It cannot be too strongly emphasized that criticality data and information from Guides are only elements of an effective safety program. Chapter I of the Guide addresses each of the first three listed areas and contains an excellent discussion of accident experience in process operations. Additional encounters with these listed topics can be had from the products of the American Nuclear Society Standards Subcommittee 8 on fissionable materials outside of reactors. Evidence is ample of the consistency between recommendations in standards and information in the Guide. The last item on the list, the information source, is the thrust of the remainder of the document. Before commenting on these data it is worthwhile to address criteria appropriate to prescriptions that might be considered on "how to establish a limit" for operations.

Succintly expressed in terms of the neutron multiplication factor, the principal elements may be ordered as in the following schematic:

CRITERIA FOR OPERATIONAL LIMITS

$k_{eff} = 1 \pm n\sigma$

k_1 — Potential criticality

$\Delta k_{eff} \equiv$ Minimum margin of subcriticality for operation

k_2 — Maximum limit

$\Delta k_{eff} \equiv$ Normal and credible abnormal contingencies

k_3 — Allowable limit

I regard the definition of criticality for the fissile material as essential whether experimental or calculational. The associated standard deviation, σ, embodies the uncertainty in the definition of criticality with some multiple, n, of these establishing k_1, a value at which a system must be regarded as critical. It may or may not result in actual criticality, but a judgement is made that its potential for critical is sufficient to regard the state characterized by k_1 as critical. The maximum limit for the operation, k_2, is to be a subcritical state. The associated first Δk_{eff} is also expressible as some multiple of the uncertainty in establishing the k_2, either experimental or calculational. The allowable limit, k_3, is sufficiently below k_2 to protect against reactivity changes which may occur in the operation because of contingencies symbolized by the second Δk_{eff}. It may be that administrative controls or limits on other controlled parameters would be adequate to permit k_2 and k_3 to be equal.

The result of an assessment is the k_3 which is usually translated into a limit on mass, dimension, concentration, or some other quantity recognizable by the operators. It is considered poor practice for an authority remote from the operation or outside the defined safety program to specify the Δk_{eff}'s to be used. These should be the product of detailed analyses and overall evaluation of the operation.

As an illustration of the effort to produce data in the Guide, let us examine single unit limits for simple geometries such as those which appear in Chapter II. Figure 1 is typical and shows the variation of mass as a function of the Uranium concentration. The masses corresponding to a particular concentration are applicable to any ^{235}U content of the uranium. These curves represent the formerly defined 'nominal' and 'full' reflector conditions. The 'minimal' reflector condition is absent and we will return to this later. The computer codes and cross sections were validated against representative experiments performed over the density range and, with interpolative calculations, the curves defined. They describe uranium systems that are expected to attain a k_{eff} of about 0.95 for the respective reflector conditions. The densities associated with the metal-water mixtures were defined by a simple volume displacement from theoretical density. At an H:U of 100 these are not distinguishable from calculations of solution systems. While these data represent a near uniform margin of subcriticality in terms of the neutron multiplication factor, they represent different practical margins of safety dependent on the contingencies that may occur. For example, a factor of 2 in mass could be tolerated only at the very low uranium concentration. At higher concentrations the mass must be adjusted downward.

A point on the curve is the result of more than a single calculation. The k_{eff} response to changes in the dimension of a unit with a 300-mm thick reflector for selected concentrations were calculated and are shown in Figure 2. These data are typical. The abscissa variable is the fraction of the critical dimension. The top figure displays the spherical geometry; the center, infinite cylinders; and, the bottom, infinite slabs. The solution concentrations are given by their corresponding H:U ratios described in the upper left corner of the figure. There is no significant difference in the results shown for the H:U range from 20 to 500 for spheres, a range encompassing the concentrations for minimum critical volume and mass. As the concentration decreases, a larger fractional reduction of the critical radius is required to result in a constant k_{eff} of 0.90, for example. The arrow drawn at the abscissa value of 0.8 corresponds to a reduction in the critical mass by a factor of 2. At any point on the abscissa, except unity, k_{eff} would increase as the concentration decreases. The cylinder and slab geometries evidence a decrease in the k_{eff} response to changes in the fraction of the critical dimension. This effect is completely reversed for the unreflected condition, but the 25 mm reflector thickness data are more closely represented by the data shown. There is a broadening of the results for the concentration range from an H:U of 20 to 500 for the infinite geometries. The H:U of 20 is the open circle to the left at the constant k_{eff} value and moves to the right as the concentration decreases, to an open circle defining a maximum value for the abscissa, and reverses on further dilution of the solution. These data typify and display a small portion of the calculational effort and consideration given to the production of the finished work presented in the Guide.

One of the difficulties faced by the group participating in the revision was striking some sane balance between, on the one hand, representing current practices and the interests of specialists and, on the other, satisfying the needs of the neophyte for generalized nuclear criticality safety information. An example of this point was the decision not to present information on the minimal reflector condition.

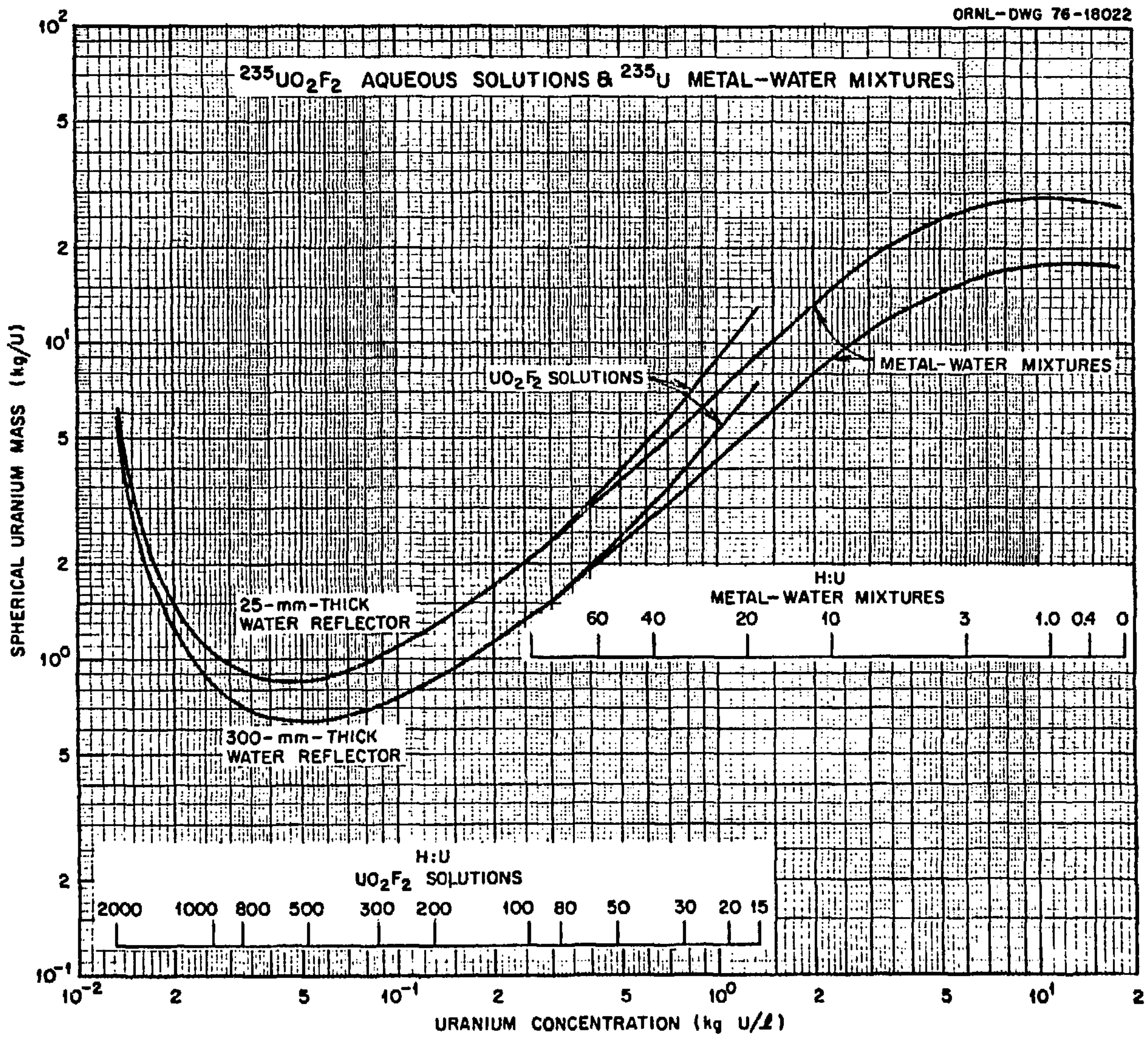
The rationale for this action begins with the problem presented by the establishment of k_2 (maximum limit) for an operation which requires the effects of neutron reflectors and other nearby fissile materials be no greater than the effects of the reflector condition of a stated limit. A minimal reflector was defined in Revision 1 as one no more effective than a 3.2-mm thickness of stainless steel or other common metal. Solutions in cylindrical geometries will experience a positive Δk_{eff} of between 2 and 3% upon the addition of a small thickness of container materials. A single unreflected vessel placed in an operational area can be expected to gain an additional Δk_{eff} of as much as 3% depending upon its location in the area, but maintaining a 300 mm distance from the walls; so we are concerned with 4 to 6% as a Δk_{eff}. This is about the worth of a 25-mm-thick water reflector, a value we can estimate in the following manner.

Consider an unreflected critical sphere and the smaller dimensioned reflected critical sphere of fissile material. Removal of the reflector from the smaller sphere will result in a $k'_{eff} < 1$ and $\Delta k_{eff} = 1 - k'_{eff}$, or its equal expression as reactivity, is the reactivity that must be removed from the unreflected sphere to accommodate the reflector. Define this Δk_{eff} as the total reactivity worth of a thick water reflector. Intermediate reflector thicknesses can be evaluated similarly and expressed as a fraction of the total worth. The result can be displayed as in Figure 3 where the fractional reactivity worth of the reflector is given as a function of the reflector thickness. The experimental arrays are from work performed at Oak Ridge; the metal sphere data are from Los Alamos results; and, the solution data were calculated. The extreme geometries and fission energy spectra represented in these data suggest this expression of reactivity worth is generic.

Now, the total reactivity worth of a thick water reflector on a concentrated solution system is somewhere between 15 and 20%. It follows that the fractional worth of the minimal reflector condition is between 0.25 and 0.30, which corresponds to an equivalent water thickness between 2 and 3 cm. We conclude that the 25-mm-thick water reflector condition would be a good point of departure for the neophyte to establish a limit, and, perhaps, the specialist as well.

Briefly then, the undertaking of the second revision provided an opportunity to correct errors in the first revision that had surfaced during its 15 years of use. Guidance was improved and augmented by information on fissile materials as oxides and mixtures of oxides, the use of neutron absorbers, storage and transportation, neutron interaction, examples of applications in process operations, and an appendix on the criticality of special actinide elements. Any one of these could occupy us for hours. I believe it's a fair summary to say the present revision:

- strengthens nuclear criticality safety as a discipline,
- provides a data base more useful to those employing calculational methods,
- expands the guidance in a manner more consistent with current practices, and
- shifts the responsibility for definition of safe limits from authors of guides and reports to the specialist, who should provide a definite systematic evaluation.



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$^{235}UO_2F_2$ AQUEOUS SOLUTIONS & ^{235}U METAL-WATER MIXTURES
UO_2F_2 SOLUTIONS
METAL-WATER MIXTURES
25-mm-THICK WATER REFLECTOR
300-mm-THICK WATER REFLECTOR
H:U
METAL-WATER MIXTURES
60 40 20 10 3 1.0 0.4 0
H:U
UO_2F_2 SOLUTIONS
2000 1000 800 500 300 200 100 80 50 30 20 15
SPHERICAL URANIUM MASS (kg/U)
URANIUM CONCENTRATION (kg U/ℓ)
10^{-1} 2 5 10^0 2 5 10^1 2 5 10^2
10^{-2} 2 5 10^{-1} 2 5 10^0 2 5 10^1 2

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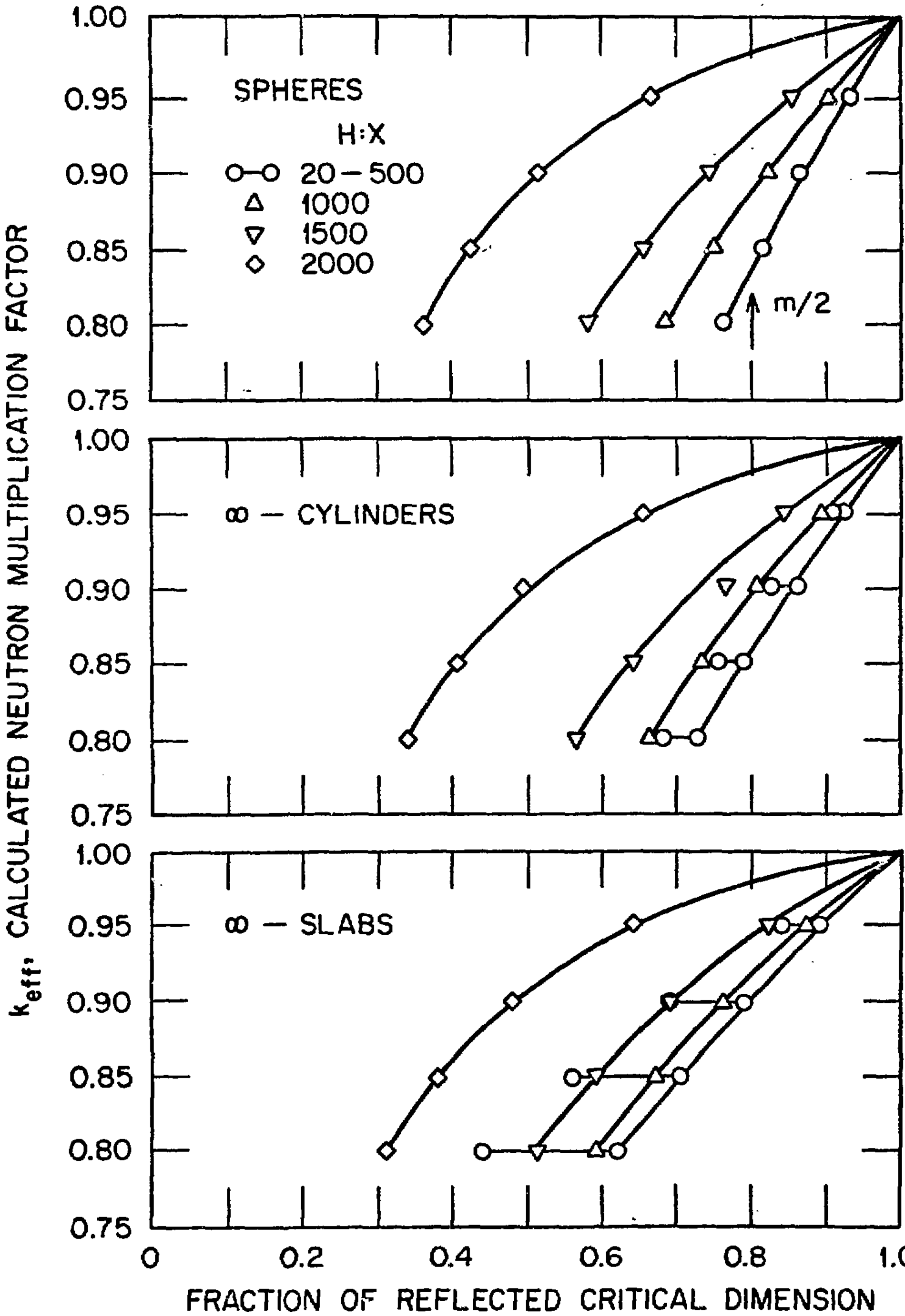

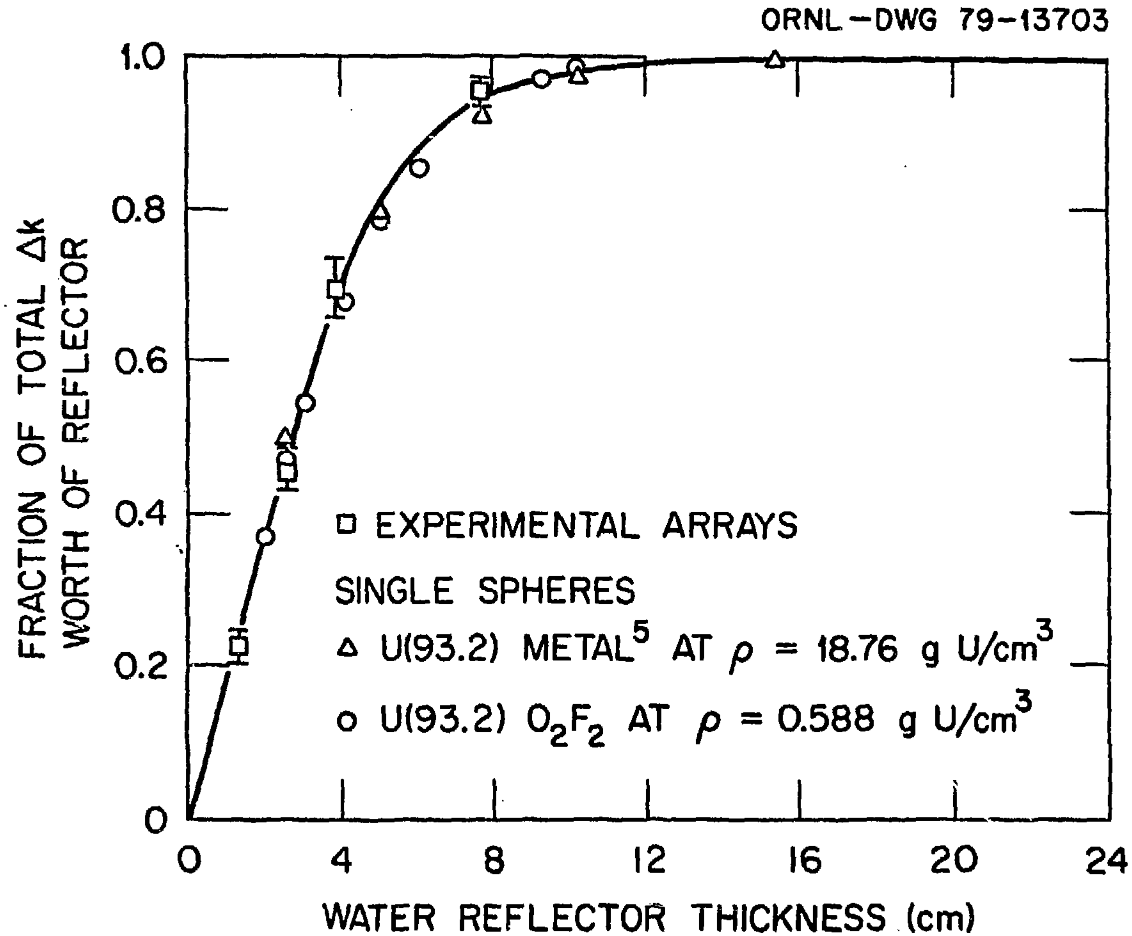
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FRACTION OF TOTAL Δk WORTH OF REFLECTOR
1.0
0.8
0.6
0.4
0.2
0
0
4
8
12
16
20
24
WATER REFLECTOR THICKNESS (cm)
EXPERIMENTAL ARRAYS
SINGLE SPHERES
U(93.2) METAL5 AT ρ = 18.76 g U/cm3
U(93.2) O2F2 AT ρ = 0.588 g U/cm3