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A Tool for Criticality Accident Emergency Planning, Training and Response

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ABSTRACT

Under past contract with the United States Nuclear Regulatory Commission (U.S. NRC) and using current computational capabilities, the Oak Ridge National Laboratory revised and extended a basic and easy-to-use tool for use in emergency response to nuclear criticality accidents. Though the tool, comprised of sliding nomographs, was intended for use in an emergency response environment, the tool is suited for estimating first pulse, subsequent fission yields of certain types of fissile solution criticality accidents and shielding effects of various materials. This paper describes the features of the tool, referenced as a “slide rule,” and discusses the application of the tool for emergency planning, training and response. These features include readily usable information for estimating nuclear criticality accident information from sliding graphs, thereby permitting (1) the rapid estimation of pertinent criticality accident information without laborious or sophisticated calculations in a nuclear criticality emergency situation, (2) the appraisal of potential fission yields and external personnel radiation exposures for facility safety analyses, and (3) a technical basis for emergency preparedness and training programs at nonreactor nuclear facilities. The slide rule permits the estimation of neutron and gamma dose rates and integrated doses based upon estimated fission yields, distance from the fission source, and time-after criticality accidents for five different critical systems. Another sliding graph permits the estimation of critical solution first-pulse fission yields based upon fissile material concentration, critical vessel geometry, and solution addition rate. Another graph provides neutron and gamma dose-reduction factors for water, steel, and concrete shields. The focus of the paper will be on the use and value of such a tool for emergency planning, training and response for nuclear criticality accidents.

INTRODUCTION

To develop and maintain a program of emergency preparedness and response for nonreactor nuclear facilities that process fissile materials, it is necessary to estimate credible fissile material types and magnitudes of nuclear criticality accidents, potential personnel hazards, and safe corrective actions in the event of a nuclear criticality accident. To provide general technical information that relates to these requirements, a rapid, “in-hand” method has been developed for estimating pertinent information needed to guide response team actions and to help characterize some types of criticality accidents. The concept uses a series of sliding graphs that function similar to that of a slide rule. This hand-held functional tool was developed with the premise that the visual demonstration of trends (e.g., dose versus time or distance) is helpful to response personnel and that the use of a nonelectronic estimator is prudent in the moments immediately following a criticality event. The characterization of and potential dose from a criticality event depends on numerous parameters: type and form of the fissile material in the system, plausible system conditions, time and distance from the critical event, and available shielding between the dose point and the criticality source. Using these parameters and a suitable range of parameter values, the slide rule is designed to provide estimates of the following

1. magnitude of the fission yield based on knowledge of the particular system parameters and/or personnel or field radiation measurements,
2. neutron- and gamma-dose at variable unshielded distances from the accident,
3. the skyshine component of the dose for use in situations where shielding around the event causes the skyshine component to be the dominant dose component,
4. time-integrated radiation dose estimates at variable distances from and time after the accident,
5. 1-min gamma radiation dose integrals at variable distances from and time after the accident,
6. dose-reduction factors for variable thicknesses of steel, concrete, and water.

The slide rule enables rapid estimation of unknown data based upon data that is available to the emergency response personnel from field measurements or conjecture for in training simulations. This capability permits continued updating of information during the evolution of an emergency response, including exposure information about “accident victims,” estimates of potential exposures to emergency response reentry personnel, estimation of future radiation field magnitudes, and fission yield estimates.

Originally conceived and developed for use at the U.S. Department of Energy’s Oak Ridge Y-12 Plant in 1974 [1], the slide rule concept has recently been expanded and updated to support the U.S. Nuclear Regulatory Commission (NRC) Response Technical Manual [2,3]. Five critical systems of unreflected spheres that provide general characteristics of the solution, powder, and metal operations likely encountered in facilities licensed by the NRC were considered:

1. low-enriched (4.95 wt % ^{235}U) aqueous uranyl fluoride solution with an H/X of 410 (solution density = 2.16 g/cm^3);
2. damp, low-enriched (5 wt % ^{235}U) uranium dioxide with an H/X of 200;
3. high-enriched (93.2 wt % ^{235}U) uranyl nitrate solution with an H/X of 500 (solution density = 1.075 g/cm^3);
4. high-enriched (93.2 wt % ^{235}U) uranium metal with density = 18.85 g/cm^3; and
5. damp, high-enriched (93.2 wt % ^{235}U) uranium oxide (U_3O_8) plus water with an H/X of 10 and a U_3O_8 density = 4.15 g/cm^3.

This paper describes the features of the tool, referenced as a “slide rule” based upon the sources of the information, and discusses the application of the tool for emergency planning, training and response.

BACKGROUND AND GENERAL APPROACH

The original development of the slide rule of Ref. 1, was initiated by questions from administrative and emergency-planning and emergency-response personnel at the Oak Ridge Y-12 Plant. The three primary questions that initiated the development of the slide rule were

1) When can we send our emergency teams into the accident area to recover injured personnel or to intervene in continuing fissile material processes?
2) Where should we plan to muster evacuees and emergency response personnel?
3) What type of detectors and where should we expect to locate criticality accident alarm monitor detectors?

These questions prompted numerous subsequent questions, such as:

- What kind (i.e., fissile solution or metal) of an accident occurred?
- Is the accident recurring?
- How large (i.e., fission yield typical of historic accidents) was the accident?
- What time has elapsed since the accident occurred?
- What type (e.g., concrete, steel, water) of radiation shielding intervenes between the accident and the accident victim, or controls for intervening in continuing fissile material processes, or the necessary location of emergency response personnel?

None of the above questions are easily answered without some type of crude estimating tool. Reliable and rigorous computational methods typically are not readily available to perform instantaneous predictions of or responses to nuclear criticality accidents. For the original slide rule of Ref. 1, only high-enriched uranium metal and uranyl nitrate systems were considered and the mathematical models were limited (e.g., use of inverse distance square rule, neglect of air attenuation, neglect of "skyshine" radiation, and use of approximate analytic expressions for the time-dependent sources). However, these two limited models were carefully compared with available measurement data. The recent work that was performed for the U.S. NRC, reported in Refs. 2 and 3, expanded the systems of interest to the five types of accidents listed above. The work also sought to improve the technical information in the slide rules by utilizing more rigorous models for the fission yield, decay, and radiation transport. However, only three of the five systems selected for the current slide rule had relevant experimental data that could be used to verify the analytic results.

A flowchart that characterizes the basic steps in the generation of the original and current slide-rule tool is shown in Fig. 1. The interplay of the various analysis phases, prompt dose vs distance, fission-product gamma dose vs distance and time, total dose vs distance and time, and 1-m integral dose vs distance and time are noted. As a preliminary step in creating the current slide rule, initial scoping analyses were performed using one-dimensional (1-D) discrete-ordinates methods for static studies and point-depletion/decay methods combined with 1-D discrete-ordinates methods for time-dependent studies. These preliminary 1-D analyses enabled a ready comparison to the existing slide rule information and allowed efficient development of a production process for creating the slide rule data using two-dimensional (2-D) radiation transport models.

The influence of the air/ground interface, as well as the possible contributions due to radiation skyshine, are the major reasons for utilizing 2-D methods. The portion of the total dose due to skyshine is included in the current slide rule to allow the interpretation of radiation fields where substantial shielding is present between the criticality accident and the desired location of radiation hazard information.

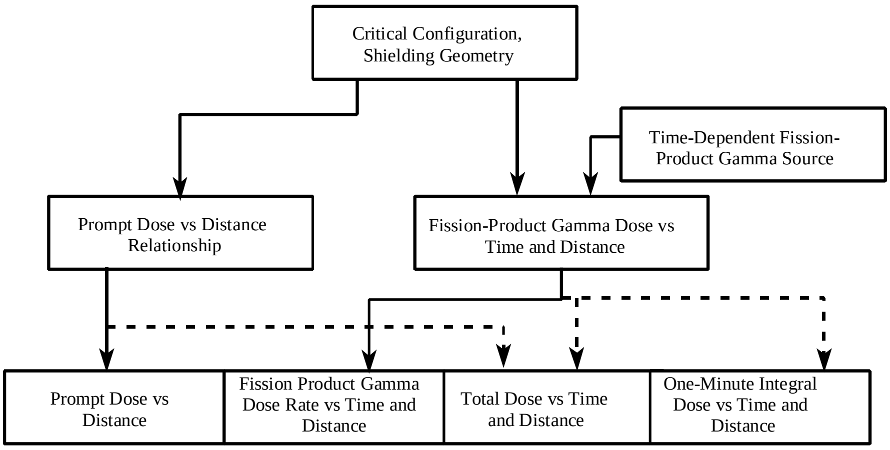

Figure 1. Slide-rule generation flowchart

In a similar format and fashion to the nuclear criticality slide rule radiation dose information, this work provided a simplified method of obtaining prompt and total fission yield information. The prompt fission yield estimation procedure is based on simplified relationships developed by Hansen [4]. The relationships correlate the reactivity insertion rate, system volume, neutron lifetime, intrinsic neutron source, and incremental reactivity worths with fission yields for a fairly large range of potential solution criticality scenarios. Also, a total fission yield estimation equation by Barbry [5] is provided for water-moderated criticality scenarios.

CRITICAL SYSTEM PARAMETER DETERMINATIONS

Details of the critical system radiation sources are reported in Ref. 6 for the five systems and are shown in Table 1.

The methods used for the determination of the;

- neutron and gamma radiation leakage spectra,
- time-dependent radiation sources,
- 2-D radiation transport for determining skyshine
- shielding effects for single and multiple thickness of concrete, steel, and water, and
- fission yield prediction models

are also provided in Ref. 6 and is provided in greater detail and depth in Ref. 2. These references also cite the sources of information for verifying or validating the methods.

Table 1 Critical system parameters[a]

Parameter	Uranyl fluoride (4.95%)	Damp UO_2 (5%)	Uranyl nitrate solution (93.2%)	U metal[b] (93.2%)	Damp U_3O_8 (93.2%)
Number density[c]					
U-235	1.3173E-4	2.6060E-4	1.3154E-4	4.5012E-2	6.4361E-3
U-238	2.5342E-3	4.9592E-3	9.6010E-6	2.6704E-3	4.6956E-4
N	–	–	2.8205E-4	–	–
O	3.1989E-2	3.6544E-2	3.4012E-2	–	5.0641E-2
F	5.3345E-3	–	–	–	–
H	5.3314E-2	5.2203E-2	6.5769E-2	–	6.4460E-2
Sphere radius (cm)	25.5476	23.2133	18.9435	8.6518	11.8841
H/X	405	200	500	0	10

[a] Air number densities are N (4.00-5), O (1.11-5).

[b] For the metal system, the following material number densities were also used: U-234 (4.8503-4) and U-236 (9.6182-5).

[c] Units of atom/barn-cm.

SHIELDING EFFECTS

Fig. 2 provides the graphic results for prompt radiation dose-reduction factors for multiple thin shields, that is, 3 in. (7.62 cm)-thick layers of concrete or 3 in. (7.62 cm)-thick layers of water or 1 in. (2.54)-thick layers of steel that are located at multiple 24-ft (7.32-m) intervals. The use of Fig. 2 for a series of composite shielding materials (i.e., water then steel) may yield erroneous results and should be considered as only a first order estimate of the combined shielding effectiveness.

FIRST ORDER DOSE AND DOSE RATE INFORMATION

An example of the slide rule plots (at a fixed fission yield of 10^{17} fissions) is shown in Fig. 3 for the low-enriched uranyl fluoride system. It was a straightforward process to utilize the neutron and gamma-ray results from the 2-D analysis models to generate the prompt dose-versus-distance relationships shown in the lower-left slide rule plots of Fig 3. Similarly, the time-dependent fission product gamma-ray doses shown in the lower-right slide rule plot were obtained from the assumed number of fissions and time after fission. The remaining two slide-rule plots merely require the processing of the above-described prompt and time-dependent dose information. The total dose vs time and distance shown in the upper-left slide rule plot consists of the prompt dose as a function of distance plus the fission-product gamma-ray dose rate information integrated from time zero until the tabulated time of 1 s to 1000 min. The upper-right slide-rule plot is the 1-min time-integrated dose due to fission-product gamma rays at each of the same time points from 1 s to 1000 min.

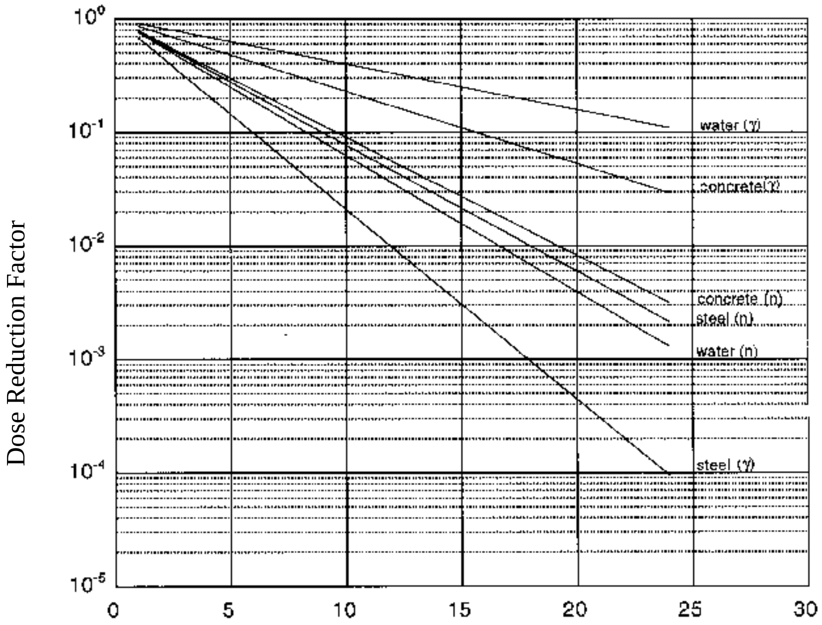

Figure 2. Total thickness of multiple "thin" shields (3" water, 3" concrete, and 1" steel) at 24-ft intervals

FIRST PULSE FISSION YIELDS FOR FISSILE SOLUTIONS

First-pulse fission yields for water reflected supercritical systems were estimated using Hansen's [4] theory as typically implemented by Hankins [7] and Mee et al. [8] for a series of parametric variations in LEU nitrate solutions and oxides and HEU nitrate solutions that are representative of a large number of potential applications. Presentation of the results in a graphic format allows for easy interpolations within the individual parameter space and limited extrapolations outside the parameter ranges when the trends appear to be smooth. Graphic presentations of the computed fission yield estimates are provided in Fig. 4 for LEU and HEU systems. One of two characteristic cylindrical-tank types (i.e., vertical-axis tank diameter or horizontal-axis tank length) is provided in each figure. This manner of presentation allows for quick fission-yield estimates (maximum or minimum) for different assumed values of water reflected and water-moderated oxide or solution uranium densities, and critical volumes for variable material addition rates. The estimated fission yields, as influenced by solution or damp oxide addition rates between 0.01 gal (0.038 L) and 200 gal (757 L)/min, are scaled for each of the four graphs to permit interpolation of the estimates.

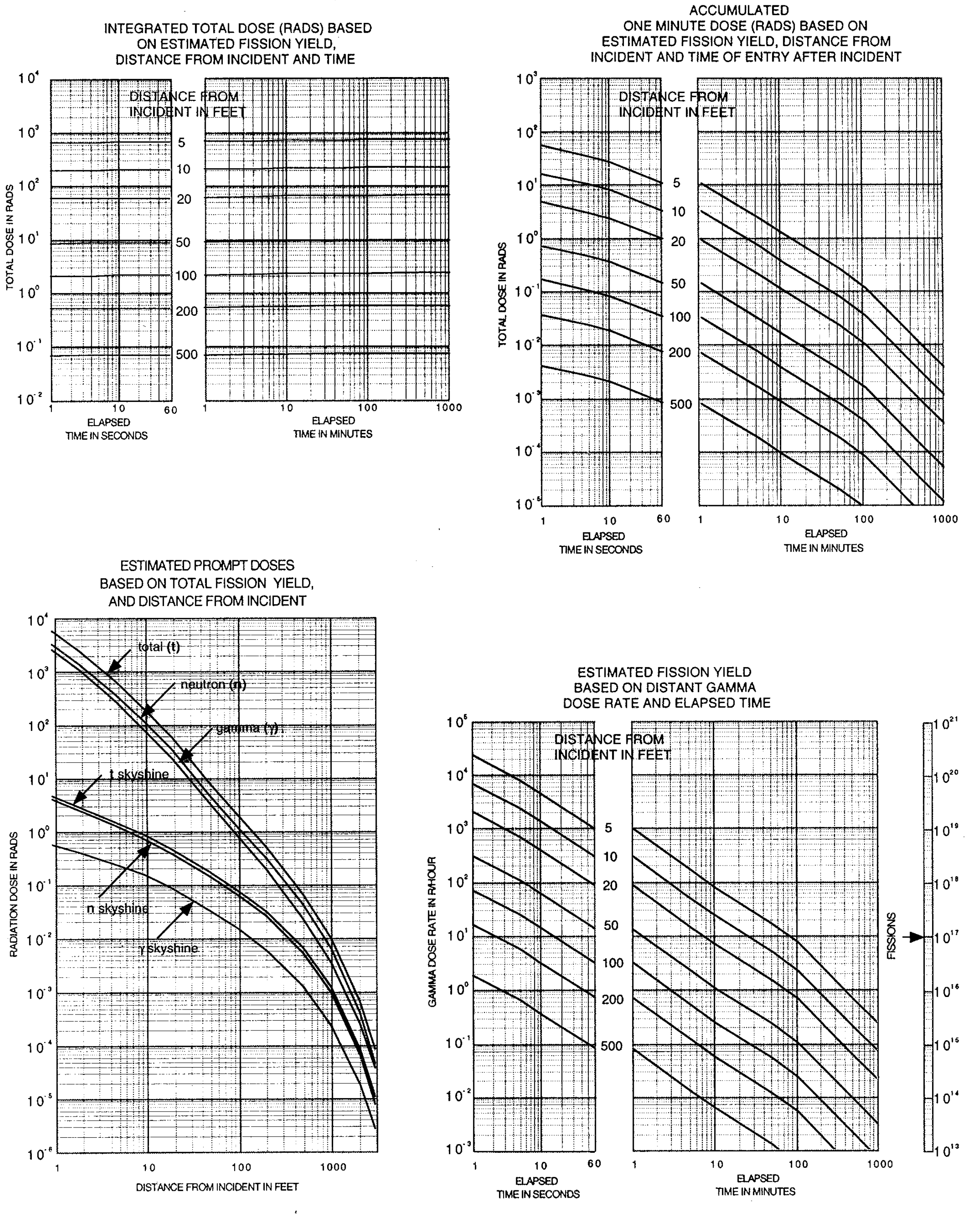

Figure 3. Damp U(4.95)O_2F_2 @ H/^{235}U = 410

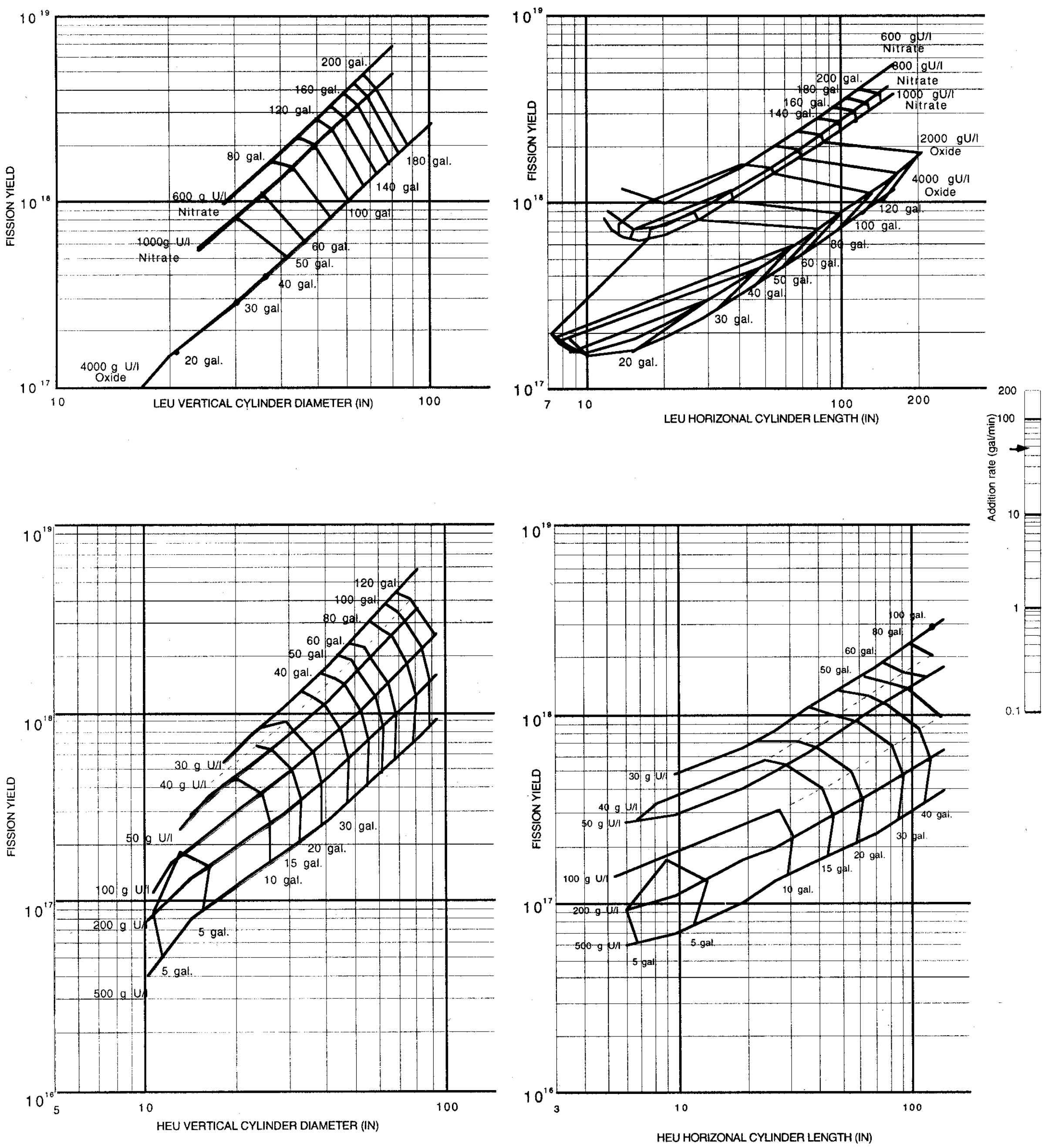

Figure 4. First pulse fission yield estimate for LEU and HEU in cylindrical geometries.

Each graph provides four parameters: (1) cylindrical tank dimension in inches, either a vertical cylinder diameter or a horizontal cylinder length, (2) uranium density in grams of uranium per liter (ounces/gallon), (3) critical fissile material volume in gallons, and (4) first-pulse fission yields that are representative of a fissile material addition rate of 45 gal (170.33 L)/min. Each fission yield graph may be scaled with a common fifth parameter, fissile material addition rate, that is provided on the functional slide rule. In Fig. 4 the user may estimate the critical volume of 5 wt % LEU solution at 600 g U/L in a 60-in. (152.4-cm)-diam vertical tank to be about 160 gal (605.6 L). If fissile material were to be introduced into such an empty tank at 45 gal (170.33 L)/min (the assumed rate for the graph), it would take about 3.5 min to attain criticality, and the estimated first-pulse fission yield for such a criticality would be 4×10^{18} fissions. Because the first-pulse fission yield is not directly proportional to the fissile material addition rate, it is necessary to use the addition rate (gal/min) scaling graph to make first-pulse fission yield estimates for addition rates other than 45 gal (170.33 L)/min.

The results clearly show the trends toward larger fission yields for larger systems (resulting in greater volumes of material with smaller quenching constants), lesser densities (resulting in smaller intrinsic neutron source values per unit volume), and higher reactivity insertion rates (as influenced by solution reactivity worth and geometric-change reactivity worth). It can be observed that the graphs predict very large first-pulse fission yields for large system volumes and rapid material addition rates. It is appropriate to consider restraint in predicting first-pulse solution fission yields much in excess of a 5×10^{18} fission yield. Such a fission yield was observed, but from an intentionally designed, extremely large and rapid reactivity insertion in the destructive BORAX-I experiment accident [9]. Though this experiment was performed with plate-type material test reactor (MTR) aluminum clad fuel elements, the neutronics and radiation heating of the water moderator is much like a somewhat undermoderated uranium solution.

The complete functional slide rule is provided in Ref. 3 and will be demonstrated at the paper presentation. As readily noticed within this paper there is an abundance of mixed English and metric units used throughout the slide rule to accommodate historic and typical use in the U.S. industry. Historically, nonreactor nuclear facilities were built to English unit specifications (e.g., 50,000-gal tank, 16-in.-diam pipes/tubes, 2-gal/min pump capacity, etc.), whereas operating process specifications have evolved to metric units (e.g., grams of U or grams ^{235}U per liter of solution, kg U, grams of U per cubic centimeter, etc.). The intent of providing mixed units is to ease data conversion and manipulation during a potentially stressful period of emergency response when data exchange is provided in mixed units.

CONCLUSION

An effective and efficient tool has been prepared for ;

- developing emergency preparedness training of personnel,
- designing of nuclear criticality accident drills, and
- assisting in the evaluations necessary during the emergency responses to criticality accidents in nonreactor facilities.

The slide rule has been designed to be applicable to five generic types of systems involving ^{235}U. Expansion of the slide rule to other generic systems involving MOX or plutonium is possible.

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