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TITLE **PROCESS CRITICALITY ACCIDENT LIKELIHOODS, CONSEQUENCES, AND EMERGENCY PLANNING**

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ABSTRACT

Evaluation of criticality accident risks in the processing of significant quantities of fissile materials is both complex and subjective, largely due to the lack of accident statistics. Thus, complying with standards such as ISO 7753 which mandates that the need for an alarm system be evaluated, is also subjective. A review of guidance found in the literature on potential accident magnitudes is presented for different material forms and arrangements. Reasoned arguments are also presented concerning accident prevention and accident likelihoods for these material forms and arrangements.

INTRODUCTION

General guidance for emergency planning for facilities and operations involving significant quantities of fissile materials is contained in various regulations and consensus standards. In particular, American National Standard ANSI/ANS-8.3, Criticality Accident Alarm Systems, and its international counterpart, ISO 7753 "Nuclear Energy - Performance and Testing Requirements for Criticality Detection and Alarm Systems", mandate that the need for an alarm system be evaluated and that one be made operational when it is deemed that it will reduce overall risk. This mandate considers only a risk/risk evaluation, with no guidance provided as to cost/risk or cost/benefit considerations.

Since risk is a combination of likelihood and consequence, both aspects must be considered, yet each is extremely difficult to quantify in most process situations. Concerning likelihoods, it is noted that only eight process accidents have been reported in the forty-five years that minimum critical quantities of fissile material have been available.[1] All eight of these have involved solutions and only one occurred in a volume greater than 200 liters. Clearly these meager accident statistics only highlight the obvious - criticality accidents with fissile solutions are very unlikely and ones involving nonsolution forms are much less likely still.

Probalistic risk assessment (PRA) has been recognized as a possible avenue to determine likelihoods, but it has recognized drawbacks, notably in "hands on" operations where failure rate data is very uncertain. Additionally, it is argued that the large sums that would be spent (an estimate for the Los Alamos Plutonium Facility is a few million dollars) could be better used on control measures such as more criticality staff presence on the process floor. A recent "test" PRA on only one of hundreds of operations in the Los Alamos facility cost about $20,000, exclusive of the value of the time operating personnel and criticality staff spent working with the PRA contractor.[2]

The author finds it noteworthy, in regards to the application of PRA, that in one of the eight accidents (Windcsale), after it was determined in which vessel the accident had occurred, experts were still unable to ascertain the accident mechanism.

The consequences of criticality accidents are a function of several factors: whether or not the operation is "hands on" or in a shielded facility; the magnitude of the .excursion; emergency actions. These latter two will be discussed in detail in the remainder of this paper where it is also argued that with reasonable controls on operations, accidents with metals and dry compounds should be able to be made so unlikely as to be considered incredible.

Magnitudes of criticality accidents are the subject of much controversy and misunderstanding. For example, the 1986 Los Alamos report, "A Guide to Radiological Accident Considerations for Siting and Design of DOE nonreactor Nuclear Facilities" contains a brief section entitled Criticality Accidents.[3] In this section a table is presented of fission yields from accidents with different material forms. This table was reproduced from Woodcock and is included here as Table 1.[4] The Nuclear Regulatory Commission also issues guidance on the magnitude of criticality accidents.[5],[6] It is noted in these NRC documents that predicting fission yields in some heterogeneous and non-solution systems such as described in Table 1 "results in a broad range of possible yields" and "methods for estimating possible fission yields are less reliable". The NRC also recommends that credible accidents be assessed for potential magnitude on an individual case basis.

TABLE 1 - Criticality Accident Fission Yields

System	Initial Burst Yield (fissions)	Total Yield (fissions)
Solutions under 100 gal (0.46 m^3)	1×10^{17}	3×10^{18}
Solutions over 100 gal (0.46 m^3)	1×10^{18}	3×10^{19}
Liquid/powder[b]	3×10^{20}	3×10^{20}
Liquid/metal pieces[c]	3×10^{18}	1×10^{19}
Solid uranium	3×10^{19}	3×10^{19}
Solid plutonium	1×10^{18}	1×10^{18}
Large storage arrays[d] (below prompt critical)	None	1×10^{19}
Large storage arrays[d] (above prompt critical)	3×10^{22}	3×10^{22}

[a] Based on a similar table by Woodcock (1966).

[b] A system where agitation of a powder layer could result in progressively higher reactivity insertion.

[c] A system of small pieces of fissile metal.

[d] Large storage arrays in which many pieces of fissile material are present and could conceivably come together.

In the body of this paper we discuss each of the material forms indicated in Table 1, the appropriateness of the fission yield values, and, particularly for non-solution systems, reasons why effort might be better spent in controlling the accident likelihood at a vanishingly low level than attempting to quantify its likelihood and consequences.

SOLUTIONS

Significantly, although not surprisingly, all eight of the reported process criticality accidents have involved material in solution as opposed to dry materials or mixtures of metal/powders and water. Reasons are numerous: (1) solutions have much smaller critical masses than dry materials and, indeed, all eight of the process accidents, while not in optimum geometries or concentrations, occurred with much less than minimum critical masses for unmoderated materials; (2) dry powders and accumulations of small metal pieces such as cutting chips from a machining operation, which (if immersed) may have small critical masses similar to solution values, have additional lines of defense which should be formidable - they are usually processed in moderation-controlled environments and/or in small vessels of favorable geometry; (3) loss of configuration control, that is, the controls which prevent fissile material from accidentally achieving a more reactive state than operating procedures provide, has lead to all eight accidents. Simply put, material moved or was moved from favorable geometry vessels to unfavorable geometry vessels due to combinations of design oversight, operator error, and equipment failures. Clearly, similar inadvertent movement of dry materials is much less likely as should be the inadvertent loss of moderation control if it had been identified as a major line of defense in accident prevention.

A recent analysis for a design basis solution criticality accident at the Oak Ridge Y-12 Plant[7] exemplifies the benefits of a situation specific review: 1) one has a reasonably firm basis for emergency planning; 2) other simplified methods, such as offered by Tuck,[8] may not be appropriate for potential upset conditions considered credible; 3) single values such as offered by the NRC guides or by Woodcock (Table 1), provide no insight into what may actually lead to an accident situation and may be either significantly under or over conservative for emergency planning purposes.

The Y-12 analysis used CRAC solution excursion data to provide confidence in the upper limit of the first spike fission yield of a solution criticality accident.[9] This approach may be applied even more readily to plutonium solution systems where one is confident that there is not significant wait-time associated with the initiation of the first persistent fission chain after the prompt critical state is reached.

The potential for subsequent fission bursts and for eventual quasi-steady state solution boiling near the delayed critical point is also recognized. While it may be difficult to assess the likelihood of permanent shutdown after the first fission spike when performing analyses for safety documentation, more importantly, the case may be made that subsequent fission bursts and even significant additional fissions beyond the first burst are not a serious threat.

The CRAC data demonstrate that even with the continual introduction of fissile solution into a system which has just undergone a fission burst, subsequent spikes are delayed several seconds or more. Secondly, any additional bursts will likely be reduced in intensity by a factor of 5 or 10 from that of the initial burst. Power and energy histories for one of the (typical) CRAC excursions is shown in Figure 1. This illustrates both the time delay and lower magnitude associated with subsequent bursts. These two observations have important implications on emergency planning:

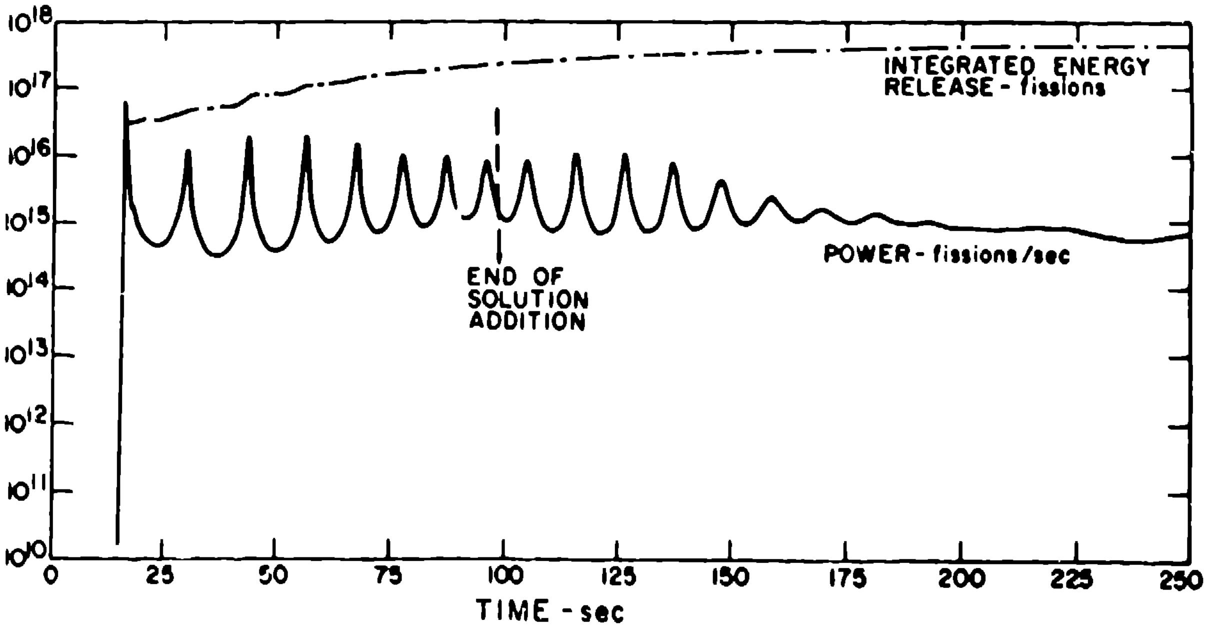

Figure 1 - Fission Rate and Integrated Fission Energy Release in CRAC 19 as a Function of Time

(1) The time delay of several seconds between bursts provides anyone in the immediate vicinity of the initial burst ample time to remove themselves significantly further by the time of the second burst. This is a major justification for a criticality accident alarm system.

(2) For those not immediately threatened by exposure to direct radiation from the first burst, a combination of evacuation routes and (expected) reduced yields of subsequent spikes should assure that no life threatening dose is received during facility evacuation. Once personnel are sufficiently distant such that direct doses are not a concern (and this should be verified at any muster location) then one can monitor for fission product radiation levels and move personnel as appropriate to prevent further exposures. It is noteworthy that fission product doses have not led to life threatening exposures even though yields in some of the eight accidents exceeded the initial burst yield by more than two orders of magnitude.

In summary, one can conclude with reasonable confidence that if prompt evacuation proceeds via appropriate routes then significant, direct doses should be limited largely to those resulting from the initial burst. Finally, if the reaction is not shut down after the first burst then area monitoring should enable the prevention of significant exposures from persistent, low level direct doses or from fission product radiation.

Liquid/Powder

The scenario which led to the 3×10^{20} value in Woodcock's report (table 1) is one whereby autocatalytic phenomena are acting. In particular he describes a situation in which dry powder becomes flooded, goes prompt critical as an equivalent very rich solution, and then the mixing and dilution which accompany the excursion introduces additional reactivity since one is sliding down the critical mass versus concentration curve. Woodcock acknowledges that there are competing feedback effects, the positive one already postulated and the known negative effects of thermal expansion and microbubble formation. Finally he states, "This estimate is rather a shot in the dark."

Stratton also alludes to the possibility of positive feedback as rich solution becomes diluted. However, he states, "it is difficult to imagine an explosive reaction." Clearly, then, he does not give credence to the 3×10^{20} value since in a few hundred liters or less this would lead to an extraordinary explosion.

Perhaps the Woodriver Junction criticality accident came as close to matching Woodcock's scenario as any experimental evidence existing. Here eleven liters of 240g ^{235}U/l solution was poured into a large vessel containing about 40 liters of sodium carbonate reagent. A fission burst occurred near the end of the pouring process which had about 10^{17} fissions, a specific yield of about 5×10^{15} fissions/liter. This specific yield is within the range of the CRAC data specific yields and thus does not show a discernable autocatalytic yield augmentation as the fissile solution diluted in the sodium carbonate solution.

If process specific reviews by criticality specialists ever reveal any scenarios leading to unacceptable consequences then controls must be exercised that reduce the likelihood to a vanishingly small value, that is, an acceptable risk level.

Liquid/Metal Pieces

Woodcock does not include any discussion of the bases for the fission yields of 3×10^{18} and 1×10^{19} in his report. It should be noted, however, that he is not referring to the "system of small pieces of fissile metal" which footnote c of Table 1 indicates, but instead, "the yields for metals or solids in water refer to one or a small number of pieces." This situation should be easily controllable and indeed may be incredible in most operations. It would be extremely rare that a water flooded and/or reflected critical mass would be assembled as a single, dry unit. Were this necessary, certainly additional precautions to preclude the possibility of flooding/reflection would be taken. For a few large pieces one would certainly provide spacing controls to assure generous safety margins. Solid material in storage would generally be in containers such that the container volume provides approximately one/liter per kilogram of stored material. This assures that no accumulation of a small number of pieces, dry or in any admixture of water will pose any credible criticality concerns.

Solid Uranium and Solid Plutonium

Criticality accidents with solid metal systems (including alloys) should be readily controlled at a likelihood of occurrence that is vanishingly small. It is almost inconceivable that masses approaching the bare critical sphere values would be handled in any compact form, either as a single unit or an accumulation of pieces such as in a burst reactor configuration. Only rarely are there operational requirements which necessitate working with more than the water reflected spherical critical mass which was addressed in the previous section.

However, the criticality safety specialist has long recognized the potential for extreme consequences were an unmoderated, metal criticality accident to occur.[10] As Table 1 illustrates, the possible magnitudes are greater for uranium than plutonium (all else being the same) due to the statistical nature of fission chain initiation in the presence of a weak source.

A manifestation of this recognition of potentially large fission yields with uranium metal is the large casting facility at the Y-12 plant.[11] This is a shielded facility with a built in neutron source to minimize both yields and consequences of extremely unlikely accidents.

It should be emphasized that in spite of the shielding, it is the effort put into accident prevention and yield mitigation that is most important. If the consequences are unacceptable then the accident likelihood must not be credible.

Large Storage Arrays

Normal operations involving storage of fissile materials should be in compliance with appropriate federal requirements and concensus standards such as DOE Order 5480.5 and ANS-8.7. The storage arrays may be expected to have sufficient margins of subcriticality to compensate for credible normal and abnormal contingencies. A typical arrangement should be expected to result in a maximum neutron multiplication factor not exceeding about 0.9 for all evaluated credible contingencies. Further, it is required that no single mishap, misoperation, or violation of procedure will lead to nuclear criticality.

The additional mass necessary to achieve prompt criticality with a single unit is between 1 and 3% of its critical mass, depending on whether the material is plutonium or uranium. The same can be said of an array at critical. However, the relation between the reactivity change to a unit in the array and the array reactivity is such that the 1 to 3% change in mass must be uniform throughout the array, i.e., to increase the array reactivity by an amount Δk, each unit in the array must be increased by this same Δk.

An equivalent reactivity addition to the array may be also effected by increasing the number of storage units or by reducing the volume of the storage container or of the storage cell volume in the array. In either of these cases, there is a dependence on the neutronic coupling between the units of the array. At critical, low-mass units will be strongly coupled, while large-mass units will be weakly coupled, a condition that also subsists in the subcritical state.

For example, to change the k_{eff} (for uranium units) from the critical state to a value of 1.01 would require a uniform change in excess of 3% in the mass of the units in the array, or a 5 to 7% uniform reduction in the volume of the array, or a 7 to 13% increase in the number of units in the array. The mass increment required is independent of the neutronic coupling and the ranges given for the volume and number of units correspond to progressing from strong to weak neutron coupling. These values are about the minimum to produce the prompt critical state for enriched uranium.

An accident during operation in a facility, however, can be expected to be initiated from the subcritical state. If the sequence of events leading to delayed criticality in a storage array were to begin at a nominal k_{eff} of 0.9, then the above required changes become a uniform mass augmentation of 37%, a uniform array volume reduction ranging from 44 to 53%, and an increase ranging from 262 to 377% in the number of units.

The implications of these results are that the accidental achievement of the critical state throughout a storage array due to successive violations of administrative controls has a very low probability of occurrence and prompt criticality is impossible, given the time required to effect the necessary changes.

The achievement of the critical or prompt-critical state in a single storage location would have to be considered or interpreted as array criticality. However, the contribution to the fission yield of the event by the array reactivity contribution among the units of an array is a function of the margin of subcriticality of the units.[12] An increase in the reactivity of a single unit in an array by an amount Δk, leads to a reactivity increase of about Δk/N to the array, where N is the total number of units in the storage array. This is typically a value of magnitude about that of the uncertainty associated with the array k_{eff}.[13] The total yield may even be less than would occur were the overloading of mass accomplished outside a storage area. Since the neutron background is higher than normal in storage areas there is the likelihood of an earlier than usual initiation of the fission chain.

For extreme upset conditions such as vault flooding or material collecting on the floor during an earthquake, simple, common-sense storage practices and a case-specific analysis should lead to the conclusion that either the critical state cannot credibly be reached or, if the upset condition is so severe that criticality can not be precluded, then consequences of the criticality accident are minor compared to the total accident consequences. Under no circumstances can an accidental scenario be envisioned which would incorporate the simultaneity, speed, and neutron source requirements which would lead to anything approaching the "$3x10^{22}$ fissions" and "serious explosion" Woodcock proposes.

A fundamental storage practice for unmoderated fissile materials should be a maximum effective density, i.e., the fissile mass divided by the outer container volume, which does not exceed about 1.0 kg/liter. For such a simple storage practice it can be readily shown that even relatively large, compact accumulations of containers (such as are often postulated to be associated with earthquakes) remain subcritical.

SUMMARY

While most regulatory guidance and, indeed, common sense, dictates that criticality accident risks be evaluated, both the likelihood and the consequence components of this risk are very difficult to quantify. However, this risk evaluation is necessary input into decisions relating to criticality accident emergency planning, including alarm systems.

Several points relating to these likelihood and consequence issues are argued in this paper:

- A case-specific analysis should be performed rather than adopting simplistic fission yield values such as presented in Table 1.

- Fissile material processes and storage involving dry materials should, in general, be much more readily controlled than those involving solutions.

- Efforts expended on emergency planning for criticality accidents postulated to occur with dry materials might be better spent on reducing accident likelihoods by providing more effective design and oversight of process operations and improved operator and supervisor knowledge and awareness.

- For large-scale fissile solution processing, accident likelihoods, while not readily quantified, will generally not be able to be reduced to the "incredible" level. That is, it is generally agreed for that such operations emergency planning is cost and risk effective. However, the CRAC data coupled with site specific evaluations, provide sufficient information to enable emergency planning to be based on realistic fission yield estimates.

In summary, accident experience, CRAC data, and case specific evaluations, coupled with appropriate emergency planning should provide confidence that criticality accidents are local events with insignificant off-site consequence. Postulated accidents with large fission yields such as indicated in Table 1 must be controlled so that likelihoods are so remote as to be considered incredible and thus the risks are acceptable.

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