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Process Criticality Accident Likelihoods, Magnitudes and Emergency Planning – A Focus on Solution Accidents

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ABSTRACT

This paper presents analyses and applications of data from reactor and critical experiment research on the dynamics of nuclear excursions in solution media. Available criticality accident information is also discussed and shown to provide strong evidence of the overwhelming likelihood of accidents in liquid media over other forms and to support the measured data. These analyses are shown to provide valuable insights into key parameters important to understanding solution excursion dynamics in general and in evaluating practical upper bounds on criticality accident magnitudes. This understanding and these upper bounds are directly applicable to the evaluation of the consequences of postulated criticality accidents. These bounds are also essential in order to comply with national and international consensus standards and regulatory requirements for emergency planning.

1. Introduction

Evaluation of criticality accident risks in the processing of significant quantities of fissile materials is both complex and subjective. It can only be properly accomplished by criticality specialists working closely with operations staff to thoroughly understand and then evaluate both the normal and the spectrum of credible off-normal or upset conditions. With the recent publishing of previously unreported process criticality accidents,[1] evidence is becoming overwhelming that process criticality accidents are much more likely in solutions and other liquid media (such as slurries) than in any dry forms.

A previously reported article on the general theme of this paper discussed a broad range of fissile materials and media.[2] This prior article argued that criticality accidents in process operations with non-solution media were relatively easily preventable and that monies would generally be better spent in accident prevention rather than on criticality accident alarms (CAS) and on emergency plans and procedures. The recently released accident information supports this contention. Thus this paper focuses on solution media, providing greater depth of coverage in this regime than the previous article.

Much excursion data from past and on-going reactor and critical experiment research with solution media is available, and still being reported. This information is valuable for the criticality safety specialist, safety analysts, facility management, and regulatory personnel as they attempt to understand the realistic bounds on the magnitudes and time durations, i.e., power histories, of potential criticality accidents.

Past experimental series, KEWB and CRAC,[3,4] and ongoing excursion studies, SILENE, TRACY, and SHEBA[5,6,7] provide a wealth of information directly applicable to estimating accident power histories (i.e., source terms) and consequences from site-specific liquid process operations. The data cover broad ranges of key parameters such as solution volume, reactivity insertion rate, and solution concentration. Together these data also provide insights into physical phenomena that bound the practical upper limits of the specific fission yield in the first spike.

Emergency planning considerations may also be founded on these data, as required or recommended by both national and international consensus standards.[8,9,10,11,12] Estimation of a lower limit of the expected first spike yield is essential to the judicious placement of criticality alarm dosimetry as part of a CAS. In this regard, several of the Russian process criticality accidents did not reach prompt critical and had very slow time responses and thus very low peak fission rates. In spite of these characteristics, CAS detector heads were activated at large distances with typical threshold settings.[1]

Conversely, an estimation of the upper bound on the magnitude of possible continuing fission generation is valuable for selecting evacuation routes and initial muster locations as well as for estimating possible doses to the public and environment from airborne radioactivity. This latter excursion characteristic may be directly estimated based on the available data from these experimental series.

2. Likelihoods of Solution Criticality Accidents

Risk is a combination of likelihood and consequence, with the former being much more difficult to estimate and bound than the latter for solution media, as will be shown. It is noted that of the 22 reported process criticality accidents, 21 were in solution environments. References 1 and 2 provide discussions and insights as to the reasons for this disparity. A historical look at the time evolution of these accidents shows that there was roughly one accident per year, for several years, in each of the two countries with very large-scale fissile material production and handling operations. This accident frequency began in the 1950s and lasted about a decade.

At his time, the mid-1960s, the accident frequency dropped precipitously to about one accident per decade or less and has remained there or possibly decreased even further. This drop is attributed to the recognition that large capacity, i.e., unfavorable geometry, process vessels should be avoided in areas where significant quantities of rich fissile materials in liquid form are processed. Further refining the current accident rate is impossible due to the lack of data. Clearly these meager accident statistics only highlight the obvious – criticality accident likelihoods with fissile solutions have been reduced to an extremely low level and ones involving non-solution forms such as dry powders and metals are even much less likely.

Probabilistic methods have been recognized as a possible avenue to estimate accident likelihoods. They have recognized drawbacks, notably in "hands-on" and one-of-a-kind operations where failure rate data are very uncertain. Additionally, it is argued that the large sums that would be spent (an estimate for the Los Alamos Plutonium Facility several years back was a few million dollars) could be better used on prevention measures such as more criticality safety staff presence on the process floor13). The author finds it noteworthy in this regard that: 1) criticality specialists worldwide are in general agreement that results of probabilistic analyses are likely to be misleading as to actual accident frequencies and 2) in one of the reported accidents (Windscale) experts were unable to ascertain the accident mechanism (prior to physical inspection and chemical analysis) even after it was determined in which vessel the accident had occurred.

3. Magnitudes of Solution Criticality Accidents

It has been common in the US to resort to regulatory handbooks and guides for obtaining the magnitudes of postulated process criticality accidents for emergency planning purposes.14,15) The fission yields in these reports largely stemmed from the original work of Woodcock and are discussed in some detail in Reference 2.

An exception in both of these two regulatory documents is a description of a solution accident power history involving an initial spike of $1.0x10^{18}$ fissions followed by 47 bursts of $1.9x10^{17}$ at 10-minute intervals for a total fission yield of $1.0x10^{19}$. This accident sequence was described in early Nuclear Regulatory Commission Guides (that are no longer officially endorsed by the NRC), but appears to not have a reported technical basis.16,17) Indeed, this scenario is inconsistent with all reported accidents and all data from the reported excursion studies discussed and referenced herein. However, this anomalous power history is still recommended in the regulatory handbook and guide.

A recent US National Consensus Standard, ANSI/ANS-8.23, speaks to the issue of accident magnitudes and provides guidance for emergency plans and procedures.10) In particular it states:

> *4.2 "Technical Staff Responsibilities*
>
> ***4.2.1 Planning.** The technical staff shall:*
> *(1) Identify potential criticality accident locations.*
> *(2) Evaluate and characterize potential criticality accidents, with this work to include prediction of radiological dose."*

Following these two requirements, an estimate of a reasonable upper limit of the excursion power history must be determined. This determination is readily facilitated by the reported excursion data, as discussed below.

There is a relatively large volume of available excursion data relevant to understanding the magnitudes of potential or hypothetical process criticality accidents. In particular, the CRAC experimental series covered a wide range of the most important parameters that influence the dynamics of a solution criticality accident. The two most important are the solution volume and the reactivity insertion rate, with even the latter being relatively unimportant for estimating the first spike yield of excursions that exceed prompt critical. The KEWB data support the CRAC data for first-spike specific fission yields in spite of the fissile solution being a different chemistry.

The parameter ranges in the CRAC experiments included: solution volumes from 20 to over 200 liters; uranium concentrations from 20 to 360 grams per liter; reactivity insertions up to several dollars above prompt critical. In contrast to these experiments where the fissile material was in nitric acid and in unreflected cylindrical geometries, the KEWB series involved uranyl sulfate solution in a reflected, 11.5-liter spherical geometry.

Figure 1 shows the variation in the specific yield of the first spike for prompt critical excursions in both CRAC and KEWB experiments. Clearly for all but very rapid excursions the specific fission yield is about 1.0x10^{15} fissions per liter even for relatively slow excursions. The very short period excursions result from very fast insertion rates that may be unattainable accidentally.

The basis for stating that excursions so rapid that the specific yield exceeds a nominal 1.0x10^{15} "may be unattainable accidentally" is simply that upon analyzing a postulated, process-specific, accident sequence, the rate at which actual events happen, e.g., gravity fall; movement of hands; rate of flow of solution through pipes; will generally result in neutronic periods in the horizontal part of the curve in Figure 1, or even less.

In addition, the specific yields of the reported solution criticality accidents, when available, support the information in Figure 1. The reported estimate of the first spike yield of the most recent accident, that in Japan in 1999, was not a measured value. It was generated from strong circumstantial evidence pointing to a prompt critical excursion (Reference 1) combined with the information in Figure 1 and the solution volume involved in the accident.

SILENE data show that for excursions much slower than 1-second periods that the specific fission yield will drop below 1.0x10^{15} fissions per liter in the first power rise and fall, but it would be inappropriate to call such a power history a spike. The available Russian accident experience also indicates this effect. These very slow excursions are ones that do not even approach prompt critical.

4. Emergency Planning for Solution Criticality Accidents

It would be rare that the specific yield of the first spike of a postulated, bounding solution accident would be significantly less than the 1.0x10^{15} value. Thus, this value, multiplied by the

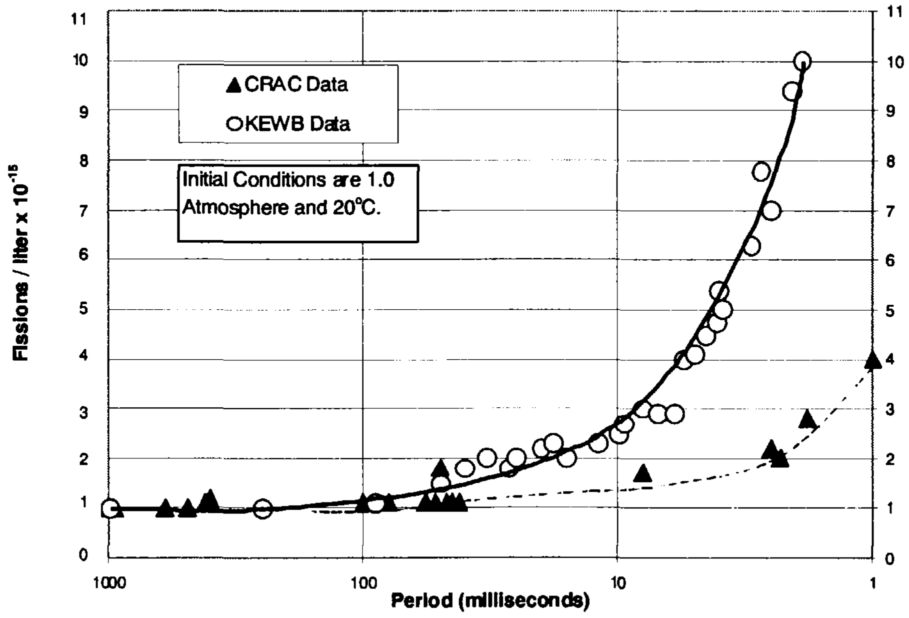

Fig. 1. Specific fissions in first spike as a function of reactor period.

involved volume, would be the source term for estimating doses to workers from direct neutrons and gamma rays, assuming that there is only one spike, or that the alarm triggers the usual prompt evacuation and significant doses are limited largely to a single spike.

The characterization of a postulated, process-specific accident, as required by the ANSI/ANS-8.23 standard, may lead to the conclusion that the accident is most likely to be terminated after the first spike. If this is not the case, then the fission rate subsequent to the first spike may be estimated from the CRAC data. Figure 2 shows both total fission and fission rate histories for one of the CRAC experiments, number 19.

For this prompt critical excursion, several important points are observed. First, the oscillations extend only a few minutes; at that time steady-state boiling sets in. This time delay is obviously dependent on the initial conditions at the time of the accident. That is, the CRAC experiments were initiated at about 20°C. Second, the time between the first and second spike is several seconds, sufficient time for those who were near the accident location at the time of the accident to remove themselves from significant additional doses. This is the benefit of a CAS. Third, subsequent spikes diminish in magnitude. Thus those evacuating, who happen to be at a lesser distance from the accident at the time of a subsequent spike, are very unlikely to receive a life-threatening dose. This conclusion is based not only of the lesser magnitude spike but also on the fact that most evacuations lead first to a hallway and not circuitously through laboratories and among equipment.

Fourth, the dose rate at the muster location would be reasonably constant, and, with conservative analysis and muster location placement, likely a low value, but still easily measurable. This would enable decisions about possible relocation of workers to proceed in an orderly manner. Fifth, airborne radioactivity could be determined and decisions made as to possible actions involving the public. Sixth, and related to the fifth point, decisions could be made as to actions to terminate the excursion. Generally it would seem that expeditiously draining the accident vessel or poisoning the solution, but in a manner that did not put workers at any undue risk, would be the desired courses of action. Expeditiously is stated due to the political sensitivity of airborne radiation, even if levels are deemed negligible from a health and environment viewpoint.

The quasi-steady-state fission rate is needed to estimate direct dose rates as well as airborne dose rates at potential muster locations. In addition, these data permit the estimation of dose rates to the offsite public from airborne radionuclides. All of these dose rates would, in fact, be experimentally determined were an actual criticality accident to occur. As stated previously, the CRAC series of experiments investigated broad parameter ranges, which are of great value in this regard.

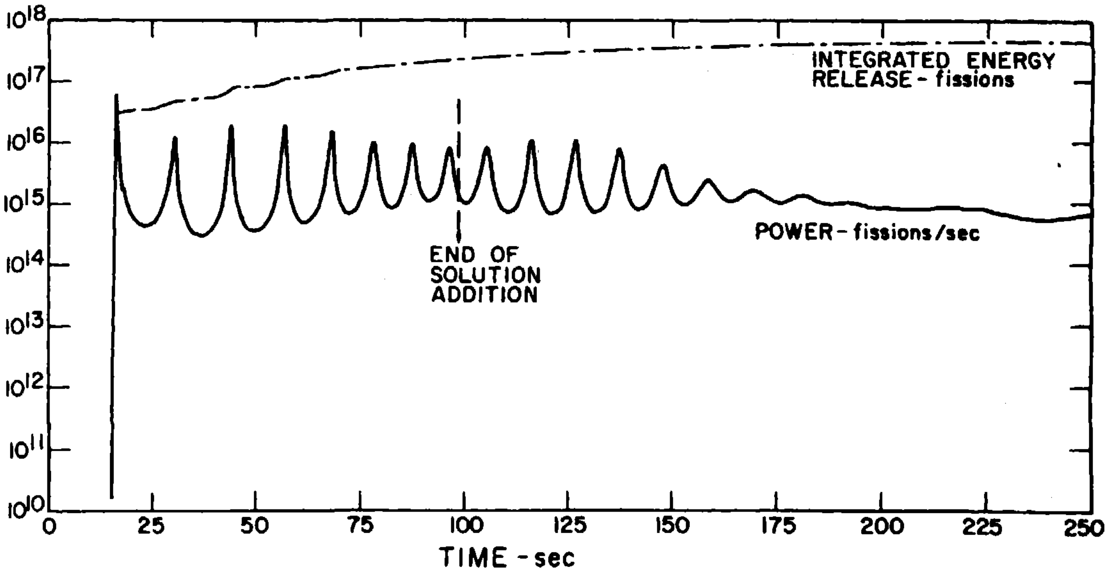

Fig. 2. Power and energy histories for experiment CRAC 19.

Figure 3 shows the bounding, integrated, specific fission yield for the first ten minutes of a solution excursion based on all the CRAC and SILENE experiments.[18] This is valuable information for estimating practical upper bounds on doses and dose rates for emergency planning purposes. Note that the first spike value is shown as $1.1\mathrm{x}10^{15}$. It is acknowledged that for very fast transients that this value can be exceeded, as shown in Figure 1. The authors of the paper from which Figure 3 is extracted are the same researchers who performed the CRAC and SILENE experiments. They are indicating that, in general, the practical "maximum specific fission yield....." (Figure 3 caption) will not exceed this value; they are not making an absolute statement.

For emergency planning purposes, there is little practical significance to a specific first spike yield that might be larger than the nominal $1.0\mathrm{x}10^{15}$ value, even were it exceeded by as much as an order of magnitude. The CAS coverage is improved by a larger first spike yield. Also, while the life-threatening radius of the prompt radiation to the worker would be increased, the dose to the public would not be measurably impacted as this is expected to be negligible for the first spike. For on-going criticality accidents such as in Japan in 1999, the time-integrated fissions always dominate the first spike fissions.

5. Conclusions

Accident experience, supported by common sense reasoning, supports the contention that non-solution process criticality accidents are inherently much less likely than those that might occur in solution operations. Reference 1 examines this issue in some detail. Given this seemingly negligible accident rate in non-solution media, it would seem to be difficult to justify emergency plans and procedures, including a CAS, for operations with fissile material only in dry forms. This conclusion is based on both risk and cost issues, which themselves are always intertwined. The four inadvertent CAS activations in the 25-year history of the current Los Alamos Plutonium Facility have each had at least a minor injury associated with the building evacuation. The monies otherwise spent on the CAS,

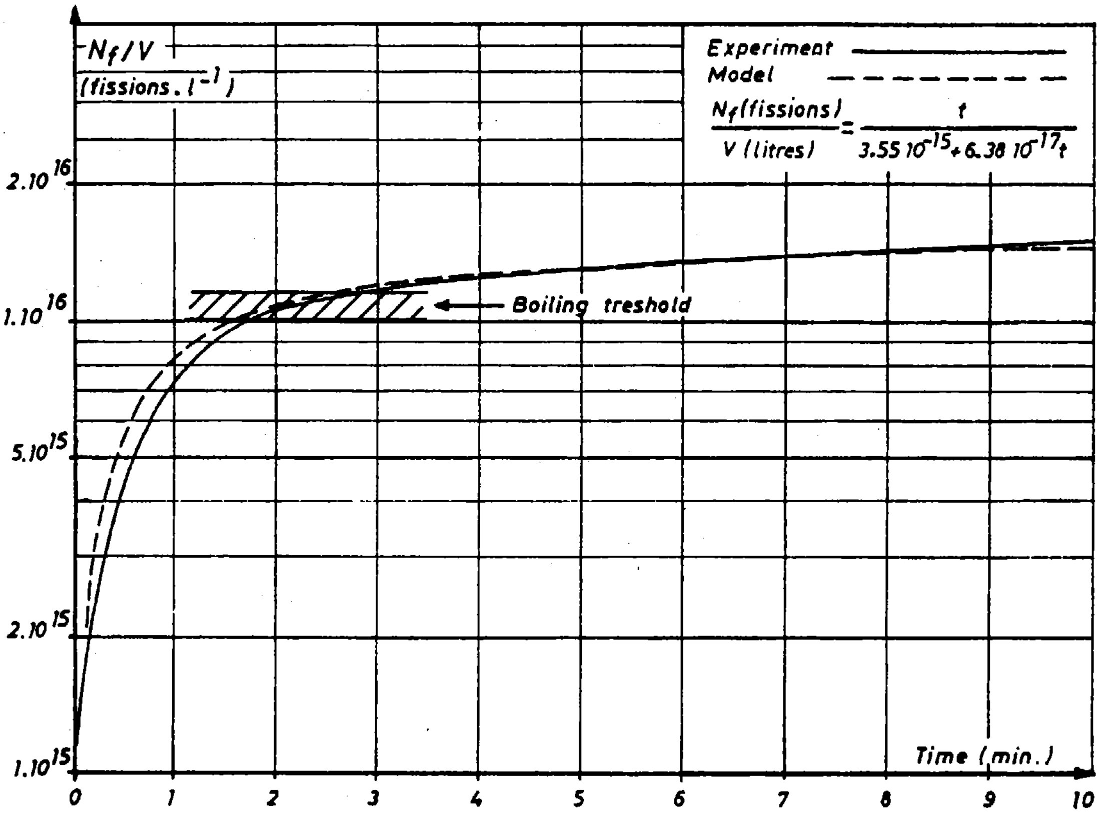

Fig. 3. Maximum specific fission yields resulting from solution excursion experiments in CRAC and SILENE.[18]

its maintenance, and other emergency plans and preparations might well be better spent on additional accident prevention measures.

For operations with significant quantities of fissile materials in solution form, there are significant reported experimental data, and more being generated. Practically all site- and process-specific criticality accident characterizations and evaluations should be able to be performed by the direct use of these data. The absence of computer codes and software models of physical processes such as bubble generation does not appear to be an impediment to the implementation of well-founded emergency plans and procedures. On the contrary, it is always preferable to solve issues with directly applicable experimental data, and such data appear to be largely available for solution criticality accidents.

In summary, the criticality safety practitioner is in the desirable position of having directly applicable data, supported further by 21 reported solution accidents, that collectively enable a very wide range of postulated, site- and facility- specific accident scenarios to be analyzed for the fission source term over time periods of interest.

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