TID-26286

nuclear criticality safety

Proceedings of a Short Course
held at the
D. H. Lawrence Ranch
near Taos, New Mexico
May 7-11, 1973

Sponsored by
University of New Mexico

Editor
R. Douglas O'Dell

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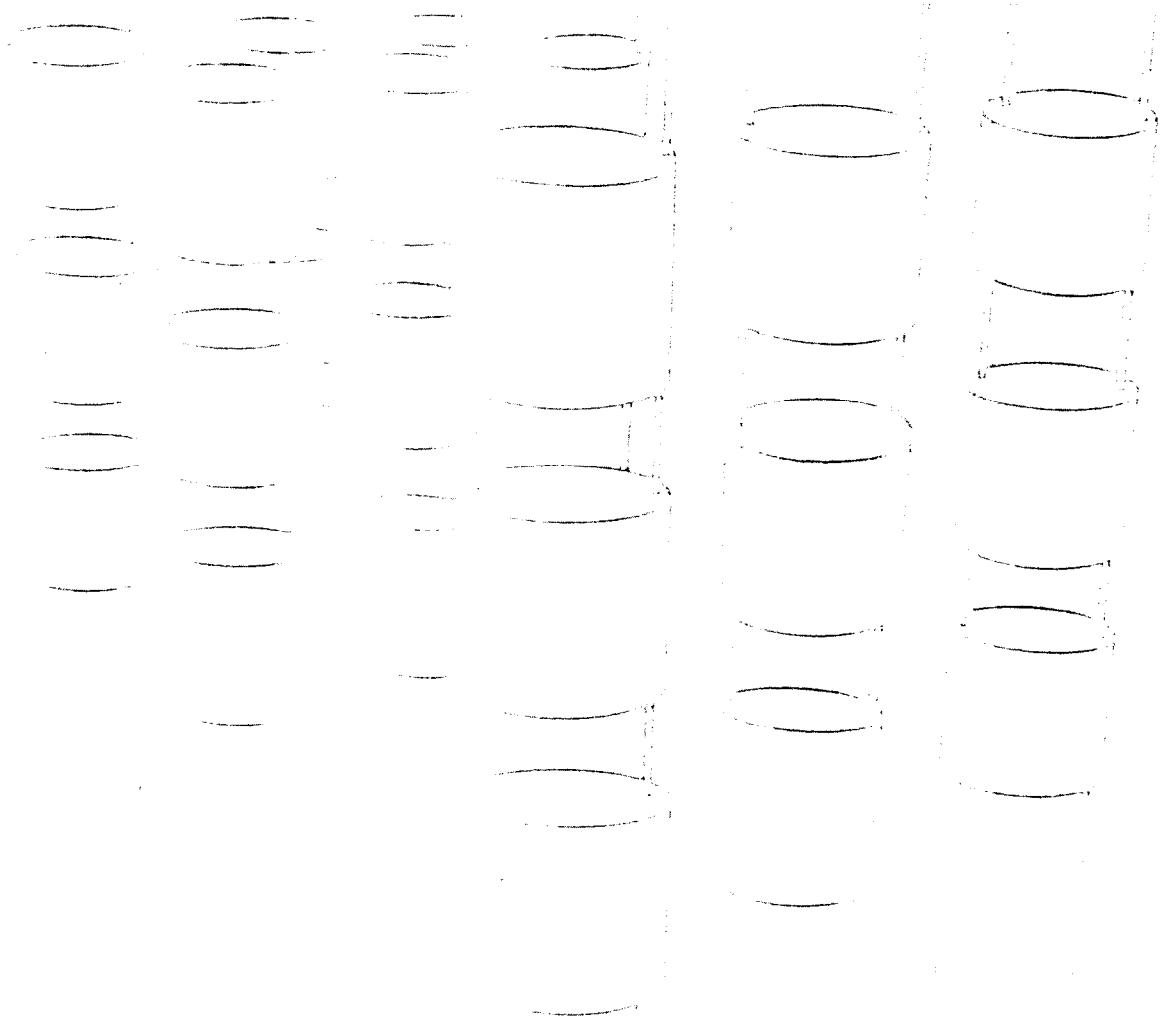

Technical Information Center Office of Information Services
UNITED STATES ATOMIC ENERGY COMMISSION

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3/CONSEQUENCES OF CRITICALITY ACCIDENTS

When we assess the consequences of accidental criticality in nuclear-fuel processing, the general reliance that we usually place on analytical evaluation of accidents can be tempered with reality by considering those industrial accidents which have already occurred and by using the results from a generally limited, but now growing, body of experimental information. These encounters with reality are summarized here. Those factors which are significant in controlling possible critical situations by appropriate design are identified.

The general conservatism used in the design of processing equipment to eliminate or reduce the possibility of criticality accidents, as well as the degree to which the lessons of the past have been taken to heart, is possibly best illustrated by the relatively slow rate at which criticality accidents seem to occur. Certainly no one would wish otherwise. Accordingly, much of the information that is available on criticality accidents is contained in the 1967 review by Stratton[1] and in the more recent compilation of criticality control data by Paxton.[2] In view of the general availability of these two summary reports, only a brief discussion of the accidents reported by Stratton and Paxton is given here. There is, in addition, one accident involving a plutonium processing operation which has been reported by Daniels et al.[3] and Hughes.[4] That incident is also briefly discussed.

Review of Industrial Accidents

The Y-12 Chemical Processing Plant, Oak Ridge, Tennessee, June 16, 1958. The accident occurred in a processing area where enriched uranium was being recovered from scrap. The recovery process was being remodeled at the time, and an inventory was in progress. The disassembly, cleaning, reassembly, and leak testing of equipment, including several long 5-in.-diameter pipes (a safe geometry) used for storage of aqueous solutions of ^{235}U, was necessary to meet inventory requirements. This effort extended over several days, and normal operations had been reestablished immediately ahead of the accident area. A quantity of enriched-uranium solution was inadvertently transferred from the area returned to operation into the one still undergoing leak testing. Flow from fuel-solution storage pipes was leaked into a 55-gal drum that was intended to receive water used for leak testing. The enriched solution, which was first leaked into the drum, was too shallow to allow criticality. As wash water was then added, the dimensions of the 55-gal drum (about 22 in. in diameter) permitted the mixed solution to become critical. Further flow of water first increased reactivity for about 11 min and then decreased it, and the solution became subcritical after about 20 min.

The drum was unshielded throughout the incident. A criticality volume was about 56 liters in a cylinder 23.45 cm high and 55.2 cm in diameter; the ^{235}U mass was 2.1 kg. Approximately 0.4 kg was added later when wash water was diluting the system. A radiation-detector trace shows that the radiation intensity first drove the pen off scale and about 15 sec later drove it off scale again. During the next 2.6 min, the trace oscillated an indeterminate number of times. This average high-intensity field was followed by a slowly decreasing level, described as about five times background, for 18 min.

The history can only be reconstructed qualitatively. The background neutron level was low; so it is quite likely that the system was over prompt critical before the first excursion started with magnitude of the first spike determined by the reactivity attained when the chain reaction started. It is estimated that the first spike contributed about 10^{16} of 1.3×10^{18} fissions. The second spike occurred 15 sec later, a quite reasonable time for bubbles generated by radiolysis to have left the system.

The power trace suggests that most of the fissions occurred in the first 2.8 min, in which case the average power required to account for the observed yield is about 220 kW. After this the system probably started

to boil, resulting in the decrease in density and reactivity and reducing the power to a low level for the final 18 min.

During this incident 1.3×10^{18} fissions occurred. There was no material damage or contamination of the area. Eight people were irradiated in the amounts 461, 428, 413, 341, 298, 86.5, 86.5, and 28.8 rems. At least one person owes his life to the fact that *prompt* and orderly evacuation plans were followed.

Los Alamos Scientific Laboratory, Dec. 30, 1958. At the time of this incident, chemical purification and concentration of plutonium from slag, crucible, and other lean residues resulting from recovery processes was under way. Less than 0.1 g of plutonium per liter and traces of americium were expected in the solutions.

A physical inventory was in progress; thus the normal flow into the area was halted, and residual materials in all process vessels were to be evaluated for plutonium content. Subsequent reconstruction of events indicates that plutonium-rich solids, which normally would have been handled separately, were washed from two other vessels into a single large vessel that contained dilute aqueous and organic solutions. Most of the aqueous solution was removed from this vessel, and the remaining ~52 gal of material, including nitric acid wash, was transferred to a 225-gal 38-in.-diameter stainless-steel tank, in which the accident subsequently occurred. This tank already contained ~78 gal of a caustic-stabilized aqueous–organic emulsion, and the added acid is believed to have separated the aqueous and organic liquid phases.

The bottom layer (87.4 gal) is thought to have contained 60 g of plutonium; the top layer (42.2 gal) contained 3.27 kg of plutonium. Estimates indicate that the 8-in.-thick upper layer was perhaps 5 dollars below delayed critical and that the critical thickness was $8\frac{1}{4}$ in. The excursion occurred when the motor drive of a stirrer was started to mix the solutions. The initial action was to force the lower layer of solution up along the tank wall, displacing the outer portion of the upper layer and thickening the central region. This thickening of the solution geometry changed the system reactivity from about 5 dollars subcritical to superprompt critical. A single burst having a yield 1.5×10^{17} fissions was experienced.

Later experiments indicate that:

1. There was no apparent delay between start and full speed of the stirrer at 60 rpm.
2. After 1 sec (i.e., about one revolution) there was a visible movement on the surface.
3. In 2 or 3 sec the system was in violent agitation.

Thus the system could have been made critical in about 1 sec, and in no more than 2 or 3 sec it must have been far subcritical and the burst terminated.

The operator was looking into a sight glass when the motor was turned on. The radiation dosage he received was estimated to be 12,000 rems ± 50%; death resulted 36 hr later. Two other persons received 134 and 53 rems, respectively, and suffered no ill effects whatsoever. There was no contamination or damage to equipment, even though the shock displaced the tank about $\frac{3}{8}$ in. at its supports.

Idaho Chemical Processing Plant, Idaho Reactor Testing Area, Oct. 16, 1959. This incident occurred in a chemical processing plant that processes spent fuel elements from various reactors. Thirty-four kilograms of enriched uranium, 93% ^{235}U, was stored in a bank of safe containers as uranyl nitrate concentrated to about 170 g of ^{235}U per liter. The excursion occurred as the result of an air-sparging operation, which initiated a siphoning action that transferred about 200 liters of this solution to a 5000-gal tank containing about 600 liters of water. The resulting power excursion created 4×10^{19} fissions, sufficient to boil away nearly half the 800-liter solution volume.

Since the 9-ft-diameter 5000-gal tank was lying on its side, the solution configuration was a near-infinite slab, and waves in the solution could have caused large fluctuations of the system reactivity.

The power history likely had an initial spike of about 10^{17} fissions, followed by power oscillations and finally by boiling for 15 to 20 min. A large portion of the uranyl nitrate was found to be crystallized on the inner walls of the tank, and most of the water had left the tank. The very large yield is a result of the large volume of the system and the long duration of the excursion.

Because of thick shielding, no significant gamma or neutron doses were received, but airborne beta dosages were 50 R (1 person), 32 R (1 person), and small amounts for 17 persons, all received while the building was being evacuated. The physical equipment involved in the excursion was not damaged.

Idaho Chemical Processing Plant, Idaho Reactor Testing Area, Jan. 25, 1961. This plant incident is thought to have been caused by the transfer of solution from a "safe-geometry" storage pipe into a vapor-disengagement vessel where the excursion occurred. Apparently, a bubble of high-pressure air from an earlier line-unplugging operation forced about 40 liters of 200 g ^{235}U/liter uranyl nitrate solution up the 5-in.-diameter storage pipe into the vapor-disengagement vessel whose dimensions were 2 ft in diameter and 4 ft high. The excursion probably occurred as a single power spike since the 40 liters are only marginally sufficient to create a critical system in a 2-ft-diameter tank. The yield was 6×10^{17} fissions.

Prior to this run the portion of the plant involved had been idle for about 12 months. Two pumps were, at best, working poorly, and a line may have been plugged. Apparently the bubble of air resulted from efforts to cure these difficulties.

Irradiations were trivial because the process cell provided extensive shielding. The solution was contained, and plant operations were resumed within an hour.

Hanford Works, Richland, Washington, Apr. 7, 1962. This accident involved the cleanup of the floor of a solvent-extraction hood, a product receiver tank that

could overflow into this hood, a *temporary line* running from the hood floor to a transfer tank, and the apparent misoperation of valves. The most plausible course of events could have been as follows:

1. The receiver tank overflowed into the hood, leaving solution containing about 45 g of plutonium per liter on the floor and in the sump.
2. The operator (contrary to orders) opened the valve that allowed this solution to be transferred to the transfer tank.
3. The later addition of aqueous solution (10 to 30 liters at 0.118 g of plutonium per liter) precipitated the burst through additional moderation following mixing and/or deaeration of the contents of the transfer tank. Other mechanisms cannot be ruled out.

The total excursion yield was 8×10^{17} fissions with the initial power spike estimated to be no more than 10^{18} fissions. Following this spike the solution remained somewhat supercritical for 37½ hr with the power level steadily decreasing. Of the 22 people in the building at the time (a Saturday morning), only 3 received significant exposures to radiation. These were 110, 43, and 19 rems. The incident itself caused no damage or contamination but did precipitate final shutdown of the plant.

Wood River Junction, Rhode Island, Scrap Recovery Plant, July 24, 1964. This processing accident occurred in the United Nuclear Corporation's ^{235}U scrap recovery facility. The plant was designed to recover enriched uranium from unirradiated scrap resulting from the fabrication of reactor fuel elements. Because of start-up difficulties, an unusually large amount of uranium-contaminated trichloroethane (TCE) solution had accumulated. The low-concentration uranium in this solution was laboriously recovered by mixing and hand-agitating the TCE with sodium carbonate solution. Prior to July 17 this operation was performed by hand in small bottles (5-in. diameter, 11-liter volume) of safe dimensions. On that date, because of the large amount of solution that had accumulated, the operation was shifted to a sodium carbonate makeup tank approximately 18 in. in diameter and 25 in. deep. This tank is an unsafe geometry for concentrated solutions; however, only dilute solutions were expected in this particular area.

The day before the accident a plant evaporator malfunctioned. Upon investigation, a plug of uranium nitrate crystals was found in a connecting line. These crystals were dissolved with steam, and the resulting concentrated solution (240 g of ^{235}U per cubic centimeter) was drained into polyethylene bottles identical to those used to store the very low concentration TCE. A bottle of this concentrated solution was mistaken for TCE solution, and the operator poured it into the makeup tank. The tank contained 41 liters of sodium carbonate solution and was being agitated by an electric stirrer. The critical state was reached, and a burst occurred when nearly all the uranium had been transferred. This burst of $\sim 1 \times 10^{17}$ fissions created a flash of light, splashed about 1/5 of the solution out of the makeup tank, and knocked the operator to the floor. He was able to regain his feet and to run from the area to an emergency building some 200 yards distant, but his radiation dose, estimated to be 10,000 rads, was fatal; he died 49 hr later.

One and one-half hours after the excursion, two men entered the area to drain the solution into safe containers. In the process they turned off the stirrer, and, apparently, the change in geometry created as the stirrer-induced vortex relaxed added enough reactivity to create a second excursion (or possibly a series of small excursions). The estimated yield of this burst was $2 \text{ to } 3 \times 10^{16}$ fissions. The occurrence of this second excursion was not established until much later, for the alarm was still sounding because of the first burst.

One man received a fatal radiation dose from the first excursion; the two men who were involved in the second excursion received doses estimated at between 60 and 100 rads. Other persons in the plant received only trivial irradiations, and no physical damage was done to the system, although cleanup of the splashed solution was necessary. The total energy release was equivalent to $1.30 \pm 0.25 \times 10^{17}$ fissions.

Windscale Works, United Kingdom Atomic Energy Authority, Aug. 24, 1970. Following the activation of the criticality alarms in the plutonium recovery facilities at the Windscale Works, the two buildings involved were promptly evacuated, and personnel assembled in the criticality control center. A review of operations disclosed that Building B.203 was the likely location of the incident, if one occurred, since it contained the only fissile material in the area at that time. Initial monitoring of the two men evacuated from the building showed no detectable personal contamination and no indication of significant irradiation.

When the building was reentered, abnormal levels of gamma rays were detected, both in the control room and in the ventilation filters. Subsequent measurements of decay rates indicated the presence of short-lived fission products, a clear indication that a criticality incident had occurred, albeit without significant radiation exposure.

At the time of the incident, the plant was engaged in the recovery of plutonium by solvent extraction from both liquid and solid residues. These residues included oxides, fluorides, nitrates, slag, etc. In addition, various off-specification products had been recycled from time to time. The line in which this program was being performed was housed in a cell with walls 12 in. thick. All solutions were converted to nitrate with extraction then being carried out in geometrically safe columns. Dissolver units, conditioners, and constant-volume feeders, which preceded the extraction columns, were all maintained in a criticality-safe condition by mass or concentration limits. The transfer of solutions between containers was made via closed transfer vessels with a vacuum-lift system. The outlet from the transfer vessel (which was 2 ft in diam-

eter by 2 ft 3 in. high) was a ½-in. bottom drain line that connected to a constant-volume feeder by way of a 25-ft-deep lute.

A program designed to recover and process oxide material had been under way for 10 days at the time of the incident. The incident occurred at the completion of the removal of solution from a conditioner to one of the closed transfer vessels. Since the transfer vessel does not begin to drain until the vacuum is broken, i.e., until the conditioning vessel has emptied, the maximum volume of solution was in the transfer vessel at the time of the incident.

Although the evidence of the excursion was clear, it was also obvious that the yield was quite small. Measurements of decay rates and analysis of fission products indicated a total yield of $\sim 10^{15}$ fissions. There were fission products in the aqueous solution siphoned from the constant-volume feeder, but its low plutonium concentration (6 g/liter) ruled it out as the main source of reactivity. In addition, the small yield could not have had significant influence in providing any inherent shutdown mechanism. Thus it was deemed likely that the bulk of the material responsible for the excursion was still in the transfer vessel and very likely only just subcritical. There thus existed a still-present danger that any disturbance or increase in reflection could result in another and even larger excursion. One other point was that it appeared likely criticality had been achieved by the addition of a small increment of reactivity during a transfer to an already near-critical solution.

Subsequently, measurements established that the closed transfer vessel contained an 8½-in.-deep layer of solution containing kilogram quantities of plutonium. Following remote removal in 2½-liter increments, about 40 liters of solvent containing a plutonium concentration of 55 g per liter was found. This, together with the aqueous solution removed via the lute, indicated a total transfer-vessel content at criticality of 40 liters of solvent at 55 g of plutonium per liter, together with 50 liters of 7*M* nitric acid solution with approximately 7 g of plutonium per liter. The solvent and aqueous phases were separated with densities of 0.96 g/ml and 1.3 g/ml, respectively. The observed solvent degradation products in the solution indicated that it could very well have accumulated in the transfer vessel over a period of 1 to 2 years.

Subsequent trials were conducted with the aqueous solutions in a transparent plastic model of the system. These trials indicate that solvent present in an aqueous solution as it is lifted into the transfer vessel tends to separate, with the heavier aqueous layer forming a layer on the bottom of the vessel. At the end of the lift into the transfer vessel, the vacuum breaks, allowing the aqueous layer to drain through the lute to the constant-volume feeder. The less dense solvent layer remains behind, trapped in the transfer vessel. Once solvent is trapped, the sequential processing of plutonium nitrate solution through the vessel, with attendant extraction into the solvent, would result in the steady buildup of plutonium in the vessel. On the basis of concentrations and acidities at the time of criticality, the last cycle is estimated to have involved the transfer from the 7 g/liter aqueous solution of as little as 30 g of plutonium to the solvent, resulting in a small increase in reactivity. The low energy release rules out boiling, expulsion, or bubble formation as a credible shutdown mechanism. Thus it was highly likely that a transient geometric configuration existed which produced the criticality increment necessary to cause the incident and that, as soon as the geometry relaxed from that transient configuration, shutdown was automatic. Observation in the model showed that the aqueous solution flowed into the vessel as a streamlined jet, impinging on the solvent layer and generating a bank of emulsion as a transition layer between the solvent and aqueous layers. On the basis of subsequent analysis, it appears that the impinging jet created a "hole" in the solvent layer with consequent decrease in reactivity as long as the flow continued. As the incoming flow ceased, the emulsion layer produced a more reactive system that persisted until the phases separated, some 5 or 10 sec after the cessation of flow. Thus it appears that the system became prompt critical as soon as flow stopped and, subsequently, was shut down as the interface emulsion layer collapsed.

There was no damage to the plant as such, although procedures have now been modified to ensure positive drainage and washout. Subsequent whole-body monitoring of the two men exposed indicate that one man received a dose less than 1 rad and the other less than 2 rads.

Factors Influencing the Magnitude of Criticality Accidents

A comprehensive understanding of the parameters of importance in criticality accidents has, until recently, been necessarily based on reasonably simple analytical models with the few accidents briefly sketched here as valuable "bench marks" that generally confirm those models. This situation existed since experimental efforts were restricted to the verification of criticality parameters with no investigation of the deliberate accumulation of supercritical amounts of material.

This state of affairs was changed when, in November 1968, the Service d'Etudes de Criticité of the French Commissariat à l'Energie Atomique initiated a program designed to provide data on the consequences of exceeding delayed criticality with various solutions of uranyl nitrate. In this program, designated "Consequences Radiologiques d'un Accident de Criticité" (CRAC), experiments were performed in which aqueous uranyl nitrate solutions at various concentrations were injected into a large-diameter pipe to heights in excess of the critical height. The uranium was 93% enriched in ^{235}U.

The results of these experiments give valuable insight into the behavior expected in accidental supercritical

accumulations of fissile materials which may occur in chemical processing.

Experiments with the uranyl nitrate solution in a 300-mm-diameter pipe (CRAC 01 to 29) and in an 800-mm-diameter pipe (CRAC 37 to 44) have been completed. The results are summarized in USAEC Report Y-CDC-12 (Ref. 5). In the experiments conducted in the 300-mm-diameter pipe, critical heights varied from 193.9 cm to 27.47 cm at corresponding ^{235}U concentrations of 48.2 g/liter and 298 g/liter, respectively. The pipe is placed inside a large airtight enclosure to contain any gas or liquid ejected from the reacting volume. Figure 1 is a plan view of the experimental area showing the location of various radiation detectors. The experimental vessel is shown in Fig. 2.

The normal experimental procedure was to inject solution into the pipe at a constant rate. Rates ranged from 104 liters/hr to 1864 liters/hr. The addition of solution at a constant rate resulted initially in a uniform ramp-rate increase in reactivity. In most experiments the ramp was initiated with a subcritical volume of solution in the pipe. In four experiments, however, the volume in the pipe was initially critical at a low steady power when the ramp was initiated. In some experiments in which the solution in the pipe was initially subcritical, an external neutron source was present during the reactivity ramp. The remaining experiments were performed by adding solution to initially subcritical volumes without an external neutron source being present.

After a supercitical volume of solution was accumulated in the pipe, power increased to a peak corresponding to overriding the excess reactivity by thermal expansion and gas formation. This initial pulse died out and was followed by a series of peaks of generally decreasing size. In all these cases solution was added through the duration of the first peak and, in many instances, was continued until after several peaks were observed. Several flux traces are shown in Figs. 3 to 5 as representative of the experiments. Eventually, fissions generated in the solution caused heating, material ejection, and gas formation such that the excess reactivity made available by the excess fuel was balanced and a steady power was achieved. The range of some parameters for the experiments is given in Table 1. For a detailed tabulation of the CRAC results, see the report by Lécorché and Seale.[5]

The results of the CRAC experiments demonstrate several points of interest. The peak fission rate per unit volume for the 300-mm-diameter cylinder is plotted versus the ramp rate of reactivity addition in Fig. 6 for a large number of experiments. Experiments CRAC 15, 16, 17, and 18 were started from delayed criticality. Notice that the pulse size achieved from their initial ramp rate is smaller than for the other experiments. Experiments CRAC 14, 20.1, 20.2, and 20.3 were started from below delayed criticality in the presence of an external neutron source. According to the standard neutron-kinetics analysis of an assembly in the presence of a source, the peak fission rate in the first pulse should vary as the ramp rate. In Fig. 6 a line of slope unity is drawn through the CRAC 14 data and passes fairly close to the CRAC 20.1, 20.2, and 20.3 cluster. Since CRAC 20.5 was performed within 30 min after CRAC

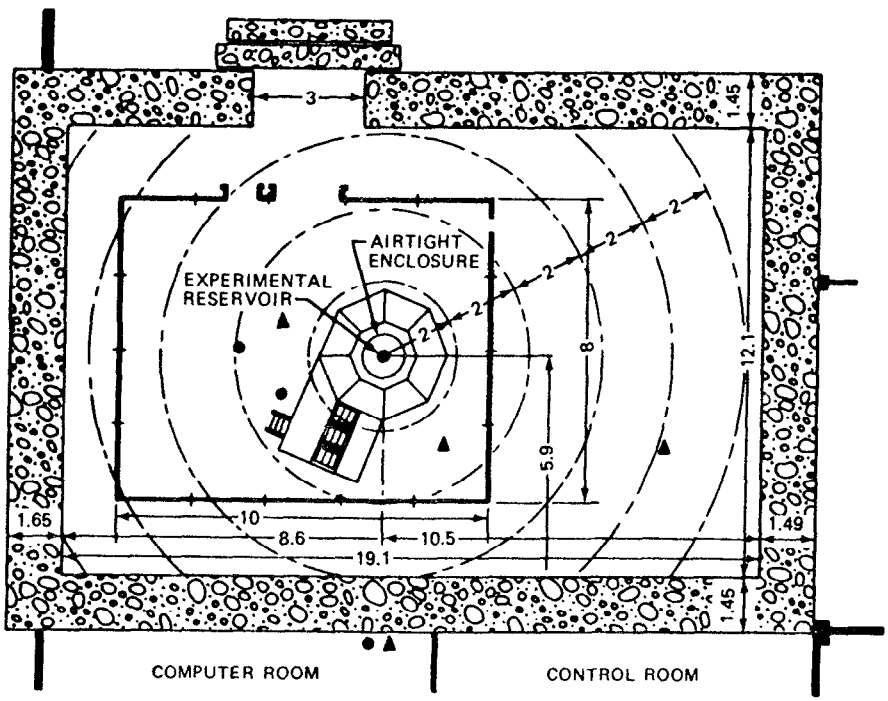

Fig. 1 Experimental arrangement of CRAC experiments in shielded cell. ▲, gamma-ray ionization chamber. ●, neutron ionization chamber. Dimensions are in meters.

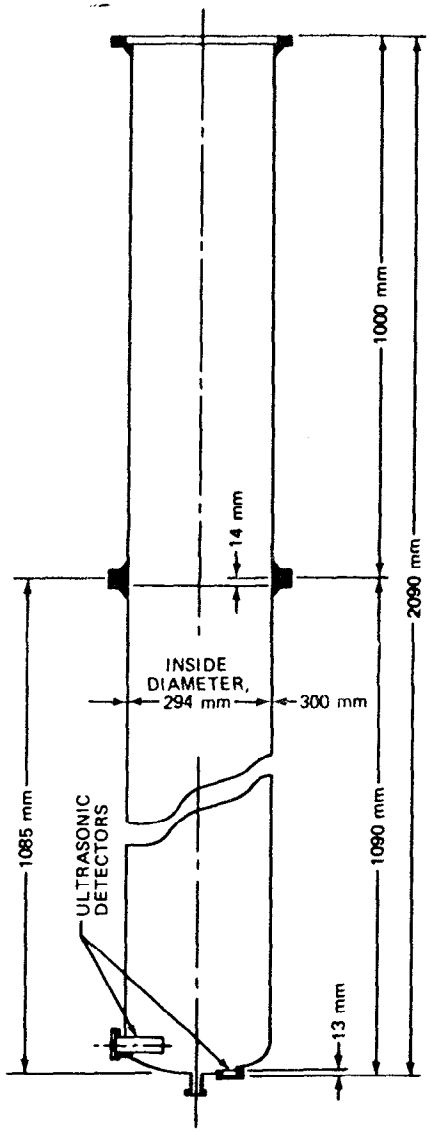

Fig. 2 Sketch of the 300-mm-diameter vessel used in early CRAC experiments.

20.4, photoneutron production in the solution from residual gamma-ray activity apparently acted as a start-up source.

The remaining CRAC experiments were conducted without an external source and demonstrate the quantitative behavior expected for assembly in the presence of a "weak source." At low ramp rates (<0.05 dollar/sec) all pulses have peak yields that fall near the standard kinetics family; however, as the ramp rate increases above 0.05 dollar/sec, solutions assembled without an external source show an increasing tendency for significant delays in the initiation of the pulse and result in larger pulse peaks. As ramp rates approach 1 dollar/sec, pulses having peak yields ~100 times that of "standard kinetics" are observed (CRAC 08). Number CRAC 20.4, which was the same as CRAC 20.1, 20.2, and 20.3 except that no source was present, had a peak yield ~20 times larger than the pulses produced with a source present.

The total fission yield during the train of pulses of an experiment is apparently dependent on the total reactivity available. In a typical experiment there was a chain of pulses of decreasing size until the fission rate damped to a more or less steady rate. The total number of fissions in the pulsing portion of an experiment, normalized to the total volume of the solution (and hence to its heat capacity), fit an expression of the form

$$\frac{\text{Yield}}{\text{Total volume}} \approx k\rho_{\text{total}}$$

where $k \approx 1$ or 2×10^{15}.

During the course of the CRAC experiments, gamma-ray dose rates were measured with dosimeters located 3 or 4 m from the solution container. The detected dose at 4 m was $1.8 \pm 0.4 \times 10^{-15}$ R/fission for the experiments performed in the 300-mm-diameter vessel. The integrated yield in a pulse is relatively insensitive to the peak fission rate since the pulse tends to broaden as the peak rate decreases. Thus the integrated dose during the first pulse at a point 4 m from the assembly

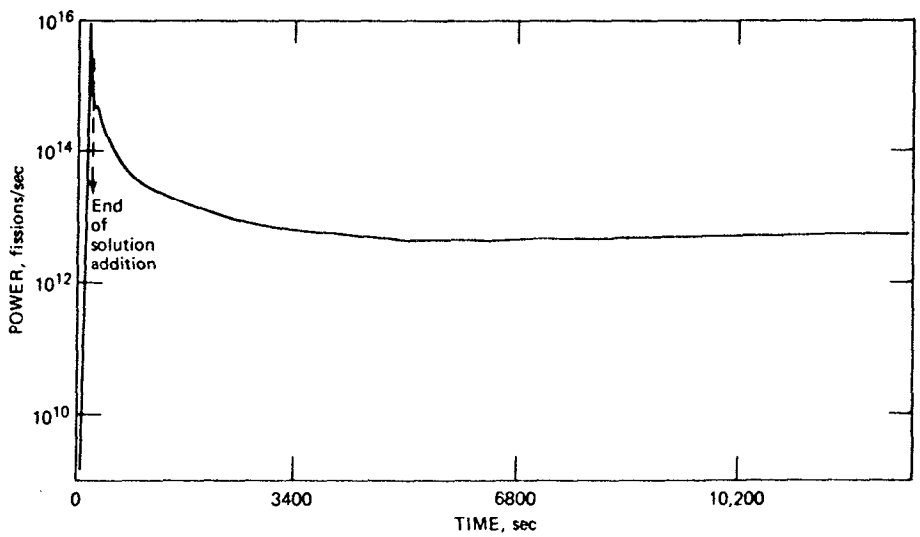

Fig. 3 Power trace for the CRAC 04 experiment. This experiment involved low reactivity-addition rates and was dominated by a single large pulse.

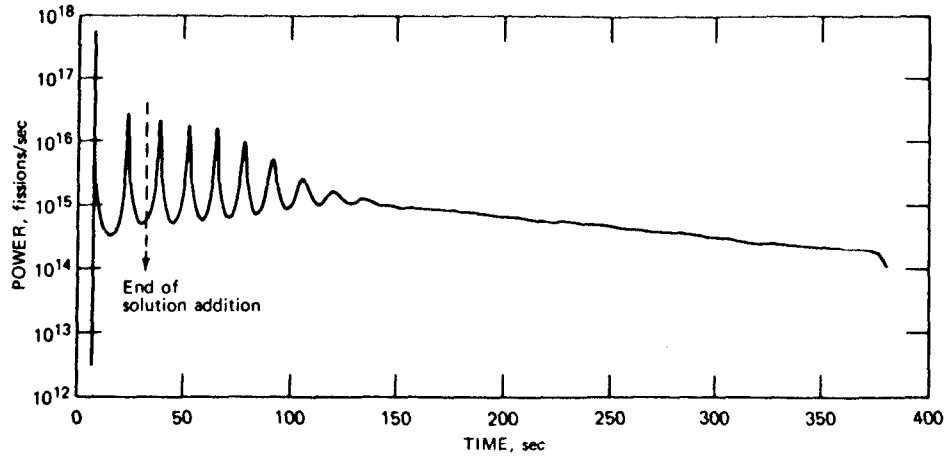

Fig. 4 Power trace for the CRAC 13 experiment. Solution was added through the completion of the second power pulse with eventual quiescence due to heating of the volume.

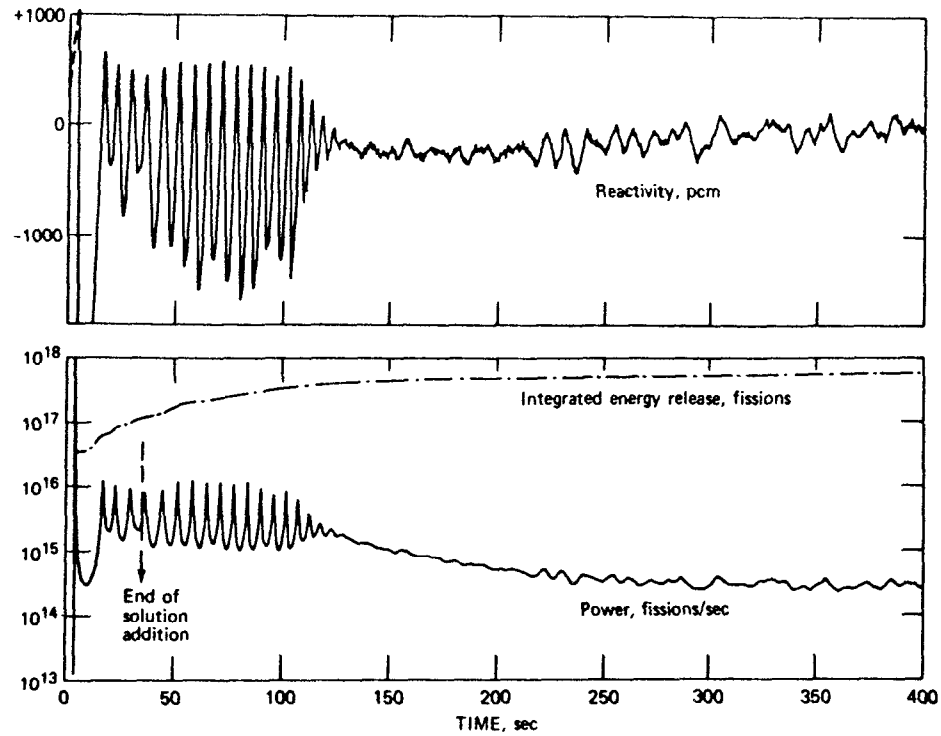

Fig. 5 Power and reactivity trace for CRAC 23. Reactivity was determined by on-line solution of the kinetics equations.

generally ranged between 40 and 550 R, i.e., by a factor of ~14. Greater integrated dose occurred for the relatively broad low peak pulses rather than the high narrow pulses.

Conclusions. The CRAC experiments provide a wealth of information on the behavior of critical solutions and an insight into the characteristics of those solutions over a wide range of geometrical shapes. The critical heights in the experiments with the 300-mm-diameter vessel ranged from ~260 to 2000 mm, thus covering the range from a near-circular cylinder to a rather long, slender reacting volume. The 800-mm-diameter vessel experiments provided rather squat cylindrical shapes with critical heights ranging from ~140 to ~450 mm. This range of configurations should be readily extrapolated to virtually any situation encountered in fuel-processing operations.

The observed wide variation in peak fission yield in those instances for which no external neutron source was present suggests the use of neutron sources to provide "background neutrons" in various processing

TABLE 1

Range of CRAC Experiment Parameters and Results

Parameter	*Experiment No.*				
	04	*08*	*13*	*20.4*	*23*
Concentration, g of ^{235}U/liter	56.9	188	72.5	203	85.5
Critical height, cm	193.9	27.25	48.90	27.10	37.00
Solution-addition rate, liters/hr	1699	1622	1429	1489	1377
Rate of reactivity addition, dollars/sec	0.0039	0.746	0.157	0.685	0.310
Minimum doubling time, sec	3.2	0.00069	0.012	0.00118	0.0058
Total yield, 10^{17} fissions	4.0	2.7	5.8	0.61	5.3
Peak power, 10^{17} fissions/sec	0.087	300	5.3	100	12

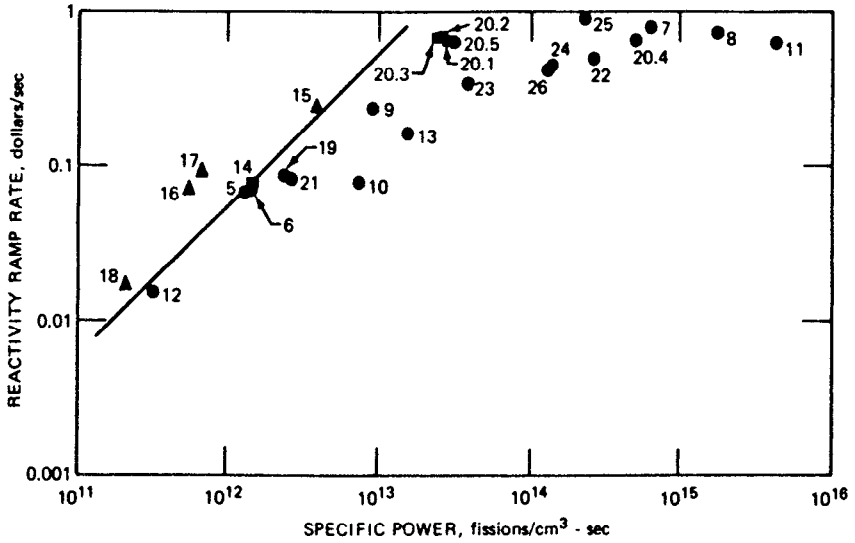

Fig. 6 Specific power for the first pulse and the entire group of CRAC experiments performed with the 300-mm pipe geometry. ●, experiments without source of neutrons. ■, experiments with external source. ▲, experiments started from delayed critical.

operations as a device to limit the magnitude of inadvertent criticality. This procedure would not limit the gamma-ray dose received by personnel in the vicinity of the excursion since analysis indicates that integrated yield is relatively insensitive to the first-peak burst size. An external source would, however, limit the first peak size with a consequent decrease in the resulting pressure pulses to a size below the level that would result in significant equipment damage with consequent dispersal of solution.

Process Design for Criticality Control

The specific controls used in the design of process equipment to attain the desired criticality control are:

1. Safe geometry (limiting radius or height of containers).
2. Concentration control.
3. Use of distributed poison (Raschig rings, boron–stainless steel rings, etc.).

These controls are used with appropriate assumptions regarding reflection, batching errors, etc., to ensure that the desired safety limits for the facility are satisfied. Ingenuity, rather than the ability to make "extreme" assumptions, in testing the suitability of a design is a requirement that implies detailed knowledge of the process and of the safety criteria by the designer. An example of an "extreme" assumption is accepting infinite water reflection of piping in systems where such water volumes are not credibly available. On the other hand, recognition of the mechanism by which "waves" could be generated in a large-diameter vessel where solution height is generally used as a control parameter could take some imagination. These specific comments are made to suggest the kinds of questions we can expect to address in the sessions that follow.

Based on the results of experiences to date in criticality safety, some general observations can be made that characterize a design philosophy that should lead to safe processing system design and operational procedures. Possibly there is no better example of the intimate connection between system design and safety of operation than in the criticality safety field. Indeed, the unfortunate accidents that have occurred to date

have been directly due either to the adaptation of equipment designed for one use to the performance of processing of different solutions or to "cleanup" operations; or they have been the result of the ad hoc use of available hardware without due consideration of criticality safety. It would appear that criticality-accident prevention depends on careful consideration of criticality during system design and continued vigilance on the part of management during operations to ensure that responsible, trained people are aware of all modifications in the processes involved and that a continuing review of the use of such processing equipment is made to guard against casual or ad hoc design modifications.

In such design general safety criteria should be based on well developed and understood standards and procedures. These standards should preserve the option of alternative methods of achieving the safety objective, and under those circumstances an integrated process design can be achieved which makes a given operation natural and safe and to that extent discourages improvisation. Finally, it might be regarded as a truism that one should make it simple and convenient to carry out a given process in a safe manner. The safe thing should be the natural thing.

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