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**Critical Experiments on an
Enriched Uranium Solution
System Containing Periodically
Distributed Strong Thermal
Neutron Absorbers**

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**Critical Experiments on an Enriched Uranium
Solution System Containing Periodically Distributed
Strong Thermal Neutron Absorbers**

by

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September 30, 1996

This paper is written under contract C96-175866
with the United States Department of Energy,
administered by the Idaho National Engineering Laboratory,
although the work was performed at Rocky Flats, Colorado

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ABSTRACT

A series of 62 critical and critical approach experiments were performed to evaluate a possible novel means of storing large volumes of fissile solution in a critically safe configuration. This study is intended to increase safety and economy through use of such a system in commercial plants which handle fissionable materials in liquid form. The fissile solution's concentration may equal or slightly exceed the minimum-critical-volume concentration; and experiments were performed for high-enriched uranium solution. Results should be generally applicable in a wide variety of plant situations.

The method is called the "Poisoned Tube Tank" because strong neutron absorbers (neutron poisons) are placed inside periodically spaced stainless steel tubes which separate absorber material from solution, keeping the former free of contamination. Eight absorbers are investigated and, for most, the variation in critical height with lattice spacing is reported. Both square and triangular pitched lattice patterns are studied. Ancillary topics which closely model typical plant situations are also reported. They include the effect of removing small bundles of absorbers as might occur during inspections in a production plant. Not taking the tank out of service for these inspections would be an economic advantage. Another ancillary topic studies the effect of the presence of a significant volume of unpoisoned solution close to the Poisoned Tube Tank on the critical height.

Experiments were performed in the 1980s but are just reported in 1996 because publication was not permitted just after the experimental study was completed. Publication at this date is possible through a DOE contract to evaluate benchmark critical experiments of recent decades and from all over the world.

"A summary of the experimental findings is that boron compounds were excellent absorbers, as expected. This was true for granular materials such as Gerstley Borate and Borax; but it was also true for the flexible solid composed of boron carbide and rubber, even though only thin sheets were used. Pyrex glass was less effective than expected. In defense of the material, only hollow tubes were studied; solid rods might have compared better. Polyvinylchloride was a big disappointment. The minuscule influence of that material might be attributed to the very wide lattice spacing expected to be poisoned by such a weak absorber (35 barns). As an extreme example, a system with absorber rods so far apart that each and every solution region between is

individually critical can not be affected by any absorber regardless of its thermal neutron absorption cross section. This argument may apply to the 256-tube case; but it weakens when considering the 492-tube configuration for which the lattice spacing was quite small. Experiments with small bundles of absorbers intentionally removed reveal that quite reasonable tanks could be constructed that would allow a few tubes at a time to be removed from the tank for inspection without removing the tank from production service. This would effect a significant monetary savings over all other methods.

Experimental results were compared against calculational methods. This was done by two persons. Good agreement was found in both cases.

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INTRODUCTION

Criticality accidents can have quite severe consequences. Historically, 41 such accidents have been reported¹ in the free world since the birth of the industry. Three characteristics of such an accident, called a "prompt criticality excursion", include:

- 1) The creation of megajoules of energy in microseconds.
- 2) An instantaneous very large dose of neutron and gamma radiation, possibly lethal to persons nearby.
- 3) A very large inventory of extremely radioactive isotopes with half-lives ranging from microseconds to millennia.

These consequences are so significant - both in lives lost and expense - that accidents should be avoided almost independent of cost.

This concern applies to any chemical form, including fissile solutions. All forms are commonly found in production plants; but fissile solutions are especially dangerous because liquid can flow under gravity into unfavorable configurations unless safety features are engineered into their handling. The subject of this paper is the criticality safety of fissile solutions by one specific method. Many other methods have been proposed; and each may have areas of reasonable application. These methods have been surveyed in the literature²; but they are also briefly summarized below.

1) Small containers safely spaced from one another - The generally acknowledged "safe volume" is 4 liters or less. Still, large arrays of these are only safe when the spacing between each is greater than about 0.6 m. Storage of large volumes of fissile liquid requires a great deal of space; so the method is not economical there. Only about 1.5% of a storage room's capacity could contain fissile solution. Another potential problem is that engineered constraints to meet spacing requirements are not fool proof, especially if containers are mobile.

¹ William R. Stratton (revised by David R. Smith), "A Review of Criticality Accidents", Nuclear Criticality Information System, Livermore, California. March 1989.

² "A Survey of Fissile Solution Storage Methods: Champion the Poisoned Tube Tank", by **Robert E. Rothe**, Proceedings of a Topical Meeting of the American Nuclear Society (Idaho Section), Jackson, Wyoming (1985).

2) **Pencil tanks safely spaced from one another** - The generally accepted "safe diameter" is about 120 mm; but the pencil tank may be of any length. Spacing between tanks should also be at least 0.6 m. Such storage also requires a lot of space; so, it is not economical for large volumes. Only about 3.5 % of a room's capacity could contain solution. A pencil tank farm has a large number of welds and fittings which might be susceptible to leaks.

3) **Slab tanks safely spaced from one another** - The generally recognized "safe slab thickness" is only about 50 mm; but the slab may be arbitrarily large in the other two dimensions. Parallel slabs separated by air would also need to be about 0.6 m because of neutronic coupling. Only about 8% of a room is available for solution storage in this case.

Other media could be placed between slabs to isolate one from the other. The Critical Mass Laboratory at Battelle's Pacific Northwest Laboratories stored its plutonium solution in slab tanks with neutron-moderating plastic and neutron-absorbing cadmium metal sheets between them. This engineered safe system yielded a 35% efficiency in the use of floor space.

4) **Annular Tanks safely spaced from one another** - An annular tank may be viewed as simply a slab tank wound into a circle. At Rocky Flats, the few annular tanks in use have an allowed annular thickness of only 38 mm; and, still, they must be spaced from one another because of neutronic coupling between adjacent tanks. The resulting space utilization efficiency is less than 5% for a 1-m-diameter tank. A number of critical experiments were performed during the 1980s at Rocky Flats on annular tanks.

5) **Shielded annular tanks** - The problem of spacing one tank from another can be eliminated by isolating tanks to prevent neutronic coupling between them. This isolation can be accomplished by surrounding an unshielded annular tanks with a "shield" composed of neutron-moderating and neutron-absorbing materials. If this same shield also exists inside the annulus, neutronic coupling across its own chords is minimized. Such tanks may be almost twice as thick as unshielded annular tanks; so they allow almost 20% of a room's capacity to house solution. An extensive series of critical experiments on *shielded* annular tanks was also performed at Rocky Flats along with those mentioned above. Results of both studies were published³ under the same contract as the present paper.

³ "Experimental Critical Parameters of Enriched Uranium Solution in Annular Tank Geometries" by **Robert E. Rothe** under DOE contract #C96-175866. Submitted April 30, 1996.

6) **Raschig ring filled tanks** - All methods above relied on geometry considerations to prevent criticality. All proved to be relatively inefficient in the use of expensive floor space. Another approach ignores geometry altogether. Here, tanks are filled with a fixed neutron absorber (nuclear "poison") which occupies only a fraction of the tank's capacity. Then, the remainder may safely house fissile solution. The fissile solution and poison are in intimate contact with one another; so they compete for neutrons to absorb. One causes additional fissions; the other removes neutrons so they can not. Such tanks do not require spacing from one another.

The most common such absorber is a commercial borosilicate glass formed into cylindrical annular rings, called Raschig rings. Typically, these rings occupy about one-third of a tank's capacity when randomly deposited; but the remainder (about 65%) may safely be filled with fissile solution. Raschig rings have been used at Rocky Flats since 1952. Rings are about 38 mm in outside diameter, 6.4 mm thick, and 44 mm long. The glass contains about 12.6% boron oxide; and the ^{10}B isotope effectively absorbs neutrons preventing criticality. The sole negative feature of Raschig rings is that they *are* in intimate contact with the fissile solution. Since these solutions can be corrosive, some periodic inspection seems prudent. This inspection is made difficult because the rings are heavily contaminated. Raschig rings are the subject of and must conform to a national standard⁴.

7) **Soluble Poisons** - Another approach would be to form true chemical solutions containing both fissile material and strong neutron absorbers. The fear that the absorber compound could precipitate, leaving unpoisoned solution in an unsafe geometry, has never endeared this method to Rocky Flats. It is not in common use at other nuclear facilities throughout the United States either. The method could theoretically yield a considerably high efficiency - approaching 90% - in the use of floor space.

8) **Poison Tube Tank** - This methodology is the subject of this report. Poison Tube Tanks are similar in physics considerations to Raschig-ring-filled tanks except that the absorber material is physically isolated from direct contact with the fissile liquid. It is contained within stainless steel sleeves; and the solution is allowed to occupy the space between. Another difference is that the distribution of absorber is much more uniform than randomly oriented Raschig rings. The current experimental study reveals that Poison Tube Tanks can easily be constructed which have as good a

⁴ "Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Materials", ANSI/ANS 8.5-1996.

storage efficiency (about 65%) as Raschig ring tanks. They could even be considerably more efficient depending on the level of risk acceptable due to accidents and mishandling. One calculation suggests a subcritical tank for the storage of an arbitrarily large volume of unpoisoned fissile solution system would be possible with a floor space efficiency in excess of 90%. The removal of even one absorber rod, however, (as for inspection) would cause a criticality accident.

Rocky Flats has over 200 Raschig-ring-filled tanks which provide criticality safety for the many facets of a nuclear production facility. The plant has never had a criticality accident - or even a close call - since its inception in 1952. This admirable safety record includes daily use for a wide variety of purposes involving a wide variety of fissile solutions of differing description. Still, the cost of inspection and maintenance and the potential for contamination release associated with frequent inspections led Rocky Flats production management to seek other methods. The Poison Tube Tank study, reported here, was one response to that search.

A Poison Tube Tank visually resembles a commercial plate-and-tube heat exchanger, similar to that found years ago on steam locomotives. The difference is, however, that water for a locomotive flowed *inside* the flues (tubes). In a Poisoned Tube Tank, on the other hand, fissile solution occupies the space *outside* these tubes; and the nuclear poison is inside.

The greatest advantage of a Poison Tube Tank is that the absorber material never contacts fissile material. As a result, inspections, if necessary, can be done quickly, safely, and inexpensively. If the lattice spacing of absorber rods were prudently designed, criticality would **not** occur even if a small *bundle* of absorbers were removed simultaneously. That tank could remain "in service" while one rod at a time was withdrawn for inspection and reinserted before removing the next.

The uniform spacing of absorber tubes contributes to smooth laminar flow. This decreases both "holdup" (liquid remaining in a presumed empty tank) and the tendency to accumulate sludge or precipitated solids. One possible disadvantage to smooth laminar flow might be the increased time required to homogenize solution.

Recognizing these advantages, Rocky Flats set out in the early 1980s to establish the merit and quantify safety parameters of a Poison Tube Tank. This experimental program was the result of that effort. The plant hoped to phase out Raschig rings and replace them with Poisoned Tube Tanks based on this study.

A total of 62 experiments were conducted between September of 1983 and November of 1984. Of these, 48 achieved criticality. Seven different neutron absorbers were used, some in combinations. Five grid spacings in both square- and triangular-pitched arrays were studied. A few ancillary experiments were also performed which simulated transient, abnormal, or accident conditions which might reasonably occur in a production plant. (1) The effect of fairly large unpoisoned containers of fissile solution in close proximity to the tank were examined. This is a situation likely to occur in a production setting as an employee carries a critically-safe bottle past a storage tank. (2) The effect on system's reactivity due to the removal of a small group of absorber rods was also measured. This could occur in a production facility during periodic inspections. Finally, (3) this program gave the opportunity to measure the critical thickness of a fissile solution slab between loadings of different tube configurations.

Two calculational studies were undertaken to validate current computational methods by comparison with measured critical solution heights. One study was done at Rocky Flats; but a more comprehensive evaluation was done elsewhere. The results of both were in good agreement with experiments. Based on this confidence, Rocky Flats designed, built, and installed their first Poison Tube Tank for production use at Rocky Flats. Although its value was noted by many, the concept died in its infancy at Rocky Flats for reasons given later.

CHRONOLOGY

The 62 critical approach experiments described by this paper were actually performed between April of 1983 and November of 1984. Their publication at this time, more than a decade later, is an unfortunate circumstance with some real negative consequence on quality.

At the time experiments were performed, results were to be published within months. Unfortunately, this did not happen. Two consequences stem from this fact. First, preparation of this document is unnecessarily complicated by the delay. Details are difficult to recall, take much longer to locate, or may be less certain. Second, even Rocky Flats can no longer claim that they "have the data" because unpublished data are not an acceptable reference for safety-related decisions.

PROCEDURE

Construction

Each experiment began with setting up non-fissile components for the configuration later to be taken to criticality. Reactivity was added by the remotely controlled addition of fissile solution. Construction began by connecting the open-topped tank to its fill line and two SCRAM-line connections and surrounding that tank with a 4-sided concrete reflector. The reflector had no top nor bottom horizontal panels; it consisted only of four vertical wall panels.

This was the starting point for construction of each array of poison tubes. The periodic array of spaced, open-topped stainless steel tubes was built within the tank. Tubes were sealed at the bottom to prevent fissile solution from entering. Next, each was filled with the selected neutron absorber material. Some were solid; but some were powders. Powders were contained in paper tubes, forming rigid rods. The array of tubes was clamped in place to prevent flotation as the fissile solution was later added. This clamping was accomplished with a clear plastic circular cover sheet whose diameter equaled that of the tank. This rested on top of the array of absorber tubes and was bolted to the top rim of the experimental tank.

The solution fill line connection at the bottom of the experimental tank led back to the uranium solution storage tank farm, located in another room. This line contained appropriate valving to control solution movement into the tank via three different flow rates. It also served as a solution return line back to storage under normal (non-accident) conditions.

The two SCRAM-line connections, also at the bottom of the experimental tank, led to a pair of critically-safe SCRAM tanks nearby. These could hold almost the entire contents of the tank in the unlikely event of a nuclear criticality accident during one of the experiments. The solution would be highly radioactive if an accident had occurred. If solution entered otherwise (not involving an accident), it could be recovered through the SCRAM isolation valve back to storage. A schematic drawing of the fissile solution handling system is shown in Fig. 1.

No fissile solution was ever present in the experimental tank during any of these initial construction operations.

Figure 1. Uranium solution was pumped from storage tanks (one shown) into the Experimental Tank via one of three pumps. Vertical elevations are approximately correct in this schematic drawing.

The neutron source

A small neutron source was positioned along the central axis of the tank and a short distance above its bottom during reactivity additions. The source was not present when criticality was achieved. The purpose of this source was to bathe the experimental configuration in a steady flux of neutrons such that any reactivity addition would manifest itself immediately through an increased neutron population. If a source were not used, the physical addition of solution may have occurred with no *indicated* change in population. This is not a safe procedure. The source was removed remotely just before attaining criticality to keep the fission density as low as possible. With this procedure, the solution never accumulated any significant inventory of radioactive fission byproducts.

The source consisted of a few micrograms of Californium, mostly ^{252}Cf . This was doubly encapsulated within a cold-welded stainless steel cylinder small enough to move freely up or down a source guide tube. The guide tube was also open at the top and seal-welded at the bottom. Its purpose was to keep the neutron source free of contamination even though it needed to reside deep in the heart of a fissile solution system. The presence of this hollow tube in this important central region was a perturbing complication to an already complicated reactor geometry; but this compromise was accepted to keep the source cylinder uncontaminated.

The source fostered safety during the approach to criticality; but once the reactivity of a still-subcritical system was very close to unity, the neutron population was both very high and would die away relatively slowly if the source were not present. At this point, then, the movable neutron source was no longer necessary. In fact, its continued presence at criticality complicated radiation measurements needed to infer when that condition had been reached. Therefore, the source was withdrawn and small quantities of fissile solution were added in alternating incremental steps until the experimental configuration eased into a *very slightly supercritical* condition **and** the source had been removed to a considerable distance. At that moment, the neutron population would either grow or decay quite slowly depending on whether the system was either slightly supercritical or slightly subcritical.

Radiation detection

The radiation levels extant throughout an experiment were monitored by a set of detectors pre-positioned in close proximity to the apparatus. None were located within the fissile solution region so no solution was displaced by detectors. Most, however, were close to the side or bottom of the experimental tank or the reflector walls. Seven neutron-sensitive detectors were employed. Four were proportional counters used from the beginning of the experiment until dead-time losses rendered their indications questionable. The other three were ionization chambers which became responsive long before the proportional counters were ignored. They were followed throughout the remainder of the experiment. One of the three was electronically configured to indicate the natural logarithm of the instantaneous neutron flux **and** the instantaneous value of the indicated reactor period (time rate of change of the instantaneous neutron flux). Finally, one gamma-sensitive detector was mounted many meters away but within the room. It, too, showed the natural logarithm of the instantaneous gamma flux.

Reciprocal Multiplication

The reciprocal multiplication technique was used for a safe approach to criticality. Prior to the introduction on any fissile solution, the neutron count rate at each detector due to the neutrons from the pre-positioned source was noted. This initial count rate for each proportional counter was called C_0 . Subsequent additions of solution increased the neutron flux within the assembly corresponding to increased reactivity. At any height, H , a new neutron count rate existed, called $C(H)$. The ratio $C(H)/C_0$ is called the *multiplication* of the system at height H ; but this parameter approaches infinity as criticality is achieved. The inverse of that, $C_0/C(H)$, is called the *reciprocal multiplication*. It was the parameter used to monitor safe approaches to criticality because it approaches zero at criticality and is, therefore, more amenable to graphical representation.

In practice, experimenters generated graphs of this reciprocal multiplication as a function of the fissile solution height. They paused as often as necessary to observe and record the reciprocal multiplication. Monitoring this curve produced a safe approach to criticality because, at each pause, the critical height was predicted and a safe reactivity increment for the next addition selected. Each pause always occurred before the count rate had e-folded the previous one.

During each pause, a smooth curve was drawn through the last few data points to extrapolate an estimate of the critical height. This prediction, of course, assumed that the curve would continue with little change in curvature. That might **not**, in fact, be the case; and experimenters had to be watchful. This would occur if some aspect of equipment design caused a physical change in the reactivity addition rate. Potentially, this would not be safe if the reactivity increased more rapidly than expected. The procedure of always taking a new data point before e-folding the previous one - regardless of whether that might occur sooner than predicted - obviated that danger.

As the neutron count rate became very large quite close to criticality, proportional counters could no longer process the large count rates without suffering dead time losses. Dead time losses would be non-conservative, giving false indication that the experiment was still further from criticality than it actually was. This safety dilemma was resolved by transitioning safety dependence from proportional counters to ionization chambers. Three had been pre-positioned close to the experimental apparatus; and these generated an electric current proportional to the neutron flux. Readouts from two were linearly proportional to that flux. The current was not subject to dead time effects at the radiation levels encountered. Ionization chambers, alone, would not have sufficed because their currents were too small and statistically difficult to interpret near the start of an experiment.

Both kinds of neutron detection were necessary for safety. Midway through an experiment both were fully operational, statistically significant, and reliably pointed to the same critical condition. Thus, safety was ensured throughout an entire experiment even though a gradual transition from one instrument to another occurred.

One of these three ionization chambers was electronically configured to record the *natural logarithm* of the instantaneous neutron flux. The logarithmic device helped experimenters determine the precise nature of a slightly supercritical system because of its mathematical properties. The neutron population grows exponentially; and the natural logarithm of an exponential function is a straight line. A straight line is easy to identify on the strip-chart recorder associated with that detector.

Solution Handling

Fissile solution was pumped to the bottom of the experimental tank through a single stainless steel pipe from the storage tank farm, located in another room. Solution remained in the tank because both fast-acting, large-diameter SCRAM valves were closed. These "safety shutdown valves" would open automatically in response to any system emergency. They could also be opened manually. SCRAM valves were "normally open" such that external force was required to close and keep them closed throughout the experiment. They were "fail safe" devices.

The rate of solution addition during an experiment had to be varied over a wide range because of safety. Early, solution could be added quickly because the reactivity addition rate was small. That pump delivered one liter per second. Its rate was variable from that down to about 20% of that rate. The pump was a centrifugal pump; and throttling to slower rates was accomplished by a valve with a remotely adjustable orifice. Typically, this pump could be used safely up to between 80% and 95% of the eventual critical height. Eventually, this rate would have added reactivity too fast for safety. Then, the fast pump was shut off and physically disabled to prevent accidental subsequent additions.

The experiment continued with solution added via a pump capable of delivering only about 3 liters per minute. This pump was a diaphragm pump with a pulsed delivery; but waves did not form on the surface of the solution. One could barely discern the pulsed nature of solution movement. This medium-rate pump, too, was somewhat variable but not effectively so. The rate proved adequately slow to allow criticality to be achieved safely for cases where dr/dH was fairly low.

When necessary, a third pump, with a still-slower flow rate, was used. It moved about 3.6 liters per *hour*! It was also a diaphragm pump with a pulsed delivery and not effectively variable. This slow addition rate has proven adequate to permit a safe approach to criticality for even the most reactivity sensitive system ever studied at Rocky Flats.

Each experiment began by flooding the bottom of the tank with fissile solution. This was done to measure the pumping rates as a daily safety check of equipment. It also marked the start of an experiment because that solution was allowed to drain back to storage leaving a small quantity of solution in the low areas of the uneven tank bottom. Details of the fill line schematic close to the tank are shown in Fig. 2. The tank bottom problem is discussed in a later section.

Figure 2. This detail of solution piping close to the experimental tank shows the Sight Gauge connection for determining solution heights. The Mass Flow Meter would be just to the left; and the uneven bottom of the tank is suggested in this drawing.

Next, fissile solution was reintroduced to the line leading to the tank until it was seen passing through a length of clear plastic tubing, located close to the experimental tank itself. At this point, the reintroduction was stopped. This condition was decreed to be the start of an experiment. The volume of solution present in the storage tank(s) feeding that day's experiment was recorded; and the Mass Flow Meters, described later, were set to zero. Assumptions made at this initial condition were:

- 1) The solution fill line was very close to full such that the next incremental addition would flow solution into the tank. The error in this assumption was probably much less than one-half liter.
- 2) About 2 kg (1.3 liters) of solution flooded the low valleys of the uneven-bottomed tank. Any stainless steel tubes reduced this hold-up because they displaced solution.
- 3) "Empty tank" parameters, needed later, were recorded. This included recording storage tank volumes and setting the two Mass Flow Meters to zero.

Achieving criticality

Solution additions continued in this manner until the system's reactivity was such that the experimental system was still very slightly subcritical. Then, the procedure to remove the source and add solution in alternating incremental steps was begun. By this time, only the ionization chambers yielded useable data. The first step was to withdraw the source only a few millimeters. This caused a significant decrease, by a factor of five or more, in the neutron flux. This loss would be recovered by a slow addition of reactivity (fissile solution) using either of the two slower pumps. When the count rate had recovered to about the same value as before the first source movement, the source would be withdrawn another increment - a little larger than the first. Then, the resulting decrease would be recovered as before. The process was repeated until movement of the source many meters made no significant change in the flux. Finally, a very small incremental addition of fissile solution established an exponential growth in the neutron flux level. Generally, experimenters aimed at generating quite long e-folding times or "positive reactor periods" as these straight lines on the logarithmic flux readout device were called. The goal was 3 to 10 minutes. At this point the system was declared to be slightly *supercritical*. The solution height was noted carefully, often by three different methods as described in another section. This positive period was allowed to continue for several minutes. The purpose of this wait was to ensure growth was

truly exponential (linear on a logarithmic scale). This close to criticality, the evolution of all delayed neutrons required a long time to reach equilibrium.

Next, a small (but measured) amount of fissile solution was drained from the critical assembly through the incremental return (spring-loaded) valve shown in Fig. 1. This caused the system to become slightly subcritical, generating an exponential *decay* - rather than growth - of the neutron population. The logarithmic readout again drew a straight line but with a negative slope proportional to the subcritical condition. The slope of that line measured the "negative reactor period". The shallower this slope, the closer a subcritical system was to the critical state⁵. Again, the goal was a negative reactor period of between 3 and 10 minutes. This period was allowed to continue for several minutes for the same reasons as the positive period. After data for both had been collected, the experiment was terminated by allowing the uranium solution to flow freely back to its storage tank farm through the normal return valve.

The experimental assembly under study had been both above and below criticality over the previous several moments; but it had never been *precisely critical*. This is a practical observation because a very long time would be required to demonstrate that the observed reactor period was precisely constant - neither slightly positive (supercritical) nor slightly negative (subcritical). If a very long wait did reveal either case, then a small adjustment in reactivity would be required, followed by another very long waiting period. This was impractical and would have produced an unnecessary inventory of radioactive fission fragments.

Experience reveals that the **two** uranium solution heights corresponding to the few-minute-long positive and negative reactor periods differed by different amounts depending on specific conditions of each experiment. For example, one could hardly distinguish between the two heights for cases with a very large dr/dH ; they often differed by less than ± 0.1 mm! On other experiments, however, the two heights differed by several mm. Generally, the former existed at low critical heights while the latter was associated with greater heights.

Critical heights reported in this paper are always the mathematical interpolation between the two heights just described. This interpolation was accomplished using the following procedure.

1) Draw a straight line between the two points with coordinates:

⁵ A little reflection reveals that a precisely critical system would exhibit an infinite reactor period, consistent with the definition of criticality that such a system maintains a constant neutron population: $dn/dt = 0$. An infinite period would be neither positive nor negative.

(supercritical height, **reciprocal** of the positive reactor period)

and

(subcritical height, **reciprocal** of the negative reactor period)

2) The height, between the two, corresponding to a **reciprocal** reactor period of zero is the quoted critical height.

Figure 3, copied from another source, illustrates⁶ this procedure which may seem arbitrary; but on July 20, 1967, its validity was demonstrated by a rather simple study⁷. Specifically, a large-diameter uranium solution slab was taken to criticality. Then, a small amount of solution was drained away leaving a subcritical system with a negative reactor period of 2.66 minutes. An external sight gauge was noted (133.5 mm); but this reading never changed during the following operations. Timed incremental additions of solution for a few seconds each were added *back* to the slab via a pump which moved only 3.6 liters per hour. After each increment, the reactor period was measured. Five timed increments created a positive reactor period of 4.38 min. The incremental change in height vs the *reciprocal* of the reactor period is almost perfectly linear. That 1967 data is presented in Table I.

The critical height could have been derived from the above procedure or from an extrapolation of the reciprocal multiplication data described earlier. The former yielded much more precise data, a valuable asset to computer validation. The latter would have avoided actually achieving criticality (a little less risk) but sacrificed precision. Figure 4 shows three examples of reciprocal multiplication curves⁸ which illustrate the advantage of the interpolation procedure.

One experiment (#37) illustrates the problem of not achieving criticality. The reciprocal multiplication curve was still approaching zero and its curvature was changing when the solution height reached near the top of the tank. A smooth curve through the last three data points with similar shape and curvature to other experiments predicted a critical height of about 2.5 m. A linear

⁶ This figure was copied from another program; so solution heights are not typical of those encountered here. The procedure was just as useful in the present study.

⁷ ROBERT E. ROTHE, "Critical Measurements on an Enriched Uranium Solution System", **Nuclear Science and Engineering**, 35, (1969).

⁸ Data for two proportional counters ($\diamond$ and $\times$) are shown; when only one is visible, the two are indistinguishable from one another.

Figure 3. Critical heights were interpolated from one slightly super critical height and a slightly subcritical one. This example was copied from another program and only illustrates the method.

Table I. "Fine-Tuned" Reactor Periods Near Criticality

Integrated Timed Pump Additions (sec)	Calculated Corresponding Incremental Height Change (mm)	Nuclear Reactor Period (min)
Initial	0.000	- 2.66
30	0.012	- 5.84
45	0.018	+1500
55	0.022	+14.35
65	0.026	+ 6.66
70	0.028	+ 4.38

From an enriched uranium solution slab-thickness experiment performed on July 20, 1967. The "measured" critical height remained observably unchanged throughout. The tabled incremental height changes were obtained from timed deliveries via a very slow rate pump (1 milliliter per second).

Figure 4. Three selected reciprocal multiplication curves suggest the uncertainty possible if criticality were not, in fact, attained. Table II compares extrapolated results with achieved criticality.

extrapolation using only the last two data points, however, yielded 1.9 m for the critical height. This large disparity leads to the large uncertainty in the tabled critical height for this case: 2000 ± 500 mm!

Table II compares interpolated heights with extrapolated predictions based on subcritical data. Sometimes the two agree quite well; experiment #41 is one example. More often, the two differ by a few percent. The benefit from more accurate data far overshadows the perceived safety consideration of not achieving criticality.

Theoretical Consideration

One interesting feature of critical experiments concerns the statistical implications of *random* events. The nuclear fission process is purely statistical in nature; one can never predict when a fission will occur. A consequence of that truth is that the *instantaneous* reactivity of any precisely time-averaged critical system is, at any given instant, neither well-defined nor constant. Conversely, the *average* reactivity - averaged over a very long time such as several seconds - is both constant and defined. Expressed differently, even a precisely critical system would be slightly subcritical one instant and slightly supercritical the next. This phenomenon is often called "reactor noise". At low reactivities and far from criticality, reactor noise is relatively large because of fewer neutrons. As reactivity increases, statistics improve markedly; and the fluctuation decreases dramatically. This is manifested by a narrower trace drawn by the readout device as seen on Fig. 5.

Table II. A Comparison of Critical Heights Obtained from Extrapolated Reciprocal Multiplication Curves and Actually Achieved Critical Heights.

Exp. #	Data From Reciprocal Multiplication Curves			Difference ^b (%)	Actually Achieved Critical Heights	
	Last Measured Subcritical Height ^a (mm)	Length of Extrapolation (%)	Extrapolated Critical Height ^a (mm)		Obtained from Sight Gauge ^a (mm)	Average, of all 3 Methods (mm)
#6	142.5	3.1	147	+3.2	142.5	143
#9	204	6.4	218	+0.5	217.0	218
#11	165.5	3.2	171	-1.7	173.9	175
#14	228.5	4.6	237	+0.6	235.7	238
#19	296	5.1	312	+0.5	310.5	319
#23	560	3.1	572	-0.5	574.7	557
#27	1003	6.3	1070	+2.5	1043.8	1042
#28	1055	7.0	1135	-1.6	1154	1150
#41	1221	6.1	1300	+0.0	1299.5	1295
#51	775	4.5	803	-0.4	806.5	804.9

^a Observed Sight Gauge data has been reduced 3 mm to account for the Sight Gauge scale not reading zero at the tank's bottom.

^b The amount by which the extrapolated critical height exceeds the actually achieved critical height, both determined by the Sight Gauge.

Figure 5. These recorder traces, from another program and another year, illustrate the decrease in reactor noise as the neutron flux increases during an experiment. The width of the figure spans about 40 minutes.

EQUIPMENT

The geometry and elemental composition of materials in and around critical configurations are described below. Decreasing detail is given for smaller components further away from the center of the experiment. The uranium solution and several neutron absorber materials are described in separate sections; but regions described here include: 1) the reactivity core with its stainless steel tank, spacer plates, and tubes, 2) intentional reflectors such as the concrete walls close to the tank and the plastic disk above the tubes, 3) nearby experimental components associated with the program such as the table supporting the entire apparatus, 4) the thin-walled room surrounding the experiment, 5) larger components within the room unrelated to the experiment, and, 6) the thick-walled concrete room in which criticality occurred. Nothing outside this boundary is described.

Tank

The tank measured 1066 mm in diameter by 1.51 m tall (inside dimensions). It was an open-topped right circular cylinder composed of nominal type 304 stainless steel. Its 9.5-mm-thick bottom disk was welded to the 6.4-mm-thick rolled-sheet side. The vertical seam in the side was welded leak tight. The top of the tank was stiffened with a rolled type 304 stainless steel angle "flange". The radial width of the flange was 50 mm; and the vertical dimension, welded to the tank, was 38 mm. The flange was 6 mm thick. Its 50-mm-wide horizontal top surface had 32 holes (12.7 mm diameter) equally spaced on a 1137 mm diameter bolt circle. A drawing of this tank is shown in Fig. 6. This tank was used for two earlier experimental programs^{9,10} at Rocky Flats. It has never been modified in any way.

The side of the right circular cylinder is imperfect because of welding distortions. Welding the side seam, top stiffening flange, and bottom caused warpage. In particular, the tank had been drawn slightly inward (smaller inside diameter) near top and bottom by welding. Even this detail was measured for a more precise description of the tank. A common machinist's measuring tool (dial indicator) was used to define the precise "profile" of one arbitrary vertical element of the

⁹ ROBERT E. ROTHE, "Critical Measurements on an Enriched Uranium Solution System", **Nuclear Science and Engineering**, 35, (1969).

¹⁰ ROBERT E. ROTHE, DONALD L. ALVAREZ, and HAROLD E. CLARK, "The Criticality of Periodically Boron-Poisoned Enriched Uranium Solution Systems", **Nuclear Technology**, 25, (1975).

Figure 6. The experimental tank stood on the thick steel top of the solution base (shown hatched). The top was stiffened by a rolled stainless steel angle; and supported by three stainless steel legs. The section view to the right shows the 6.4-mm-thick side and the 9.5-mm-thick bottom. Couplings at the bottom connected to the fill/return line and to the two scram valves.

outside surface of this tank. Measurements were made every 150 mm from the bottom of the tank to its top; and these are shown in Fig. 6a. Then, without moving the dial indicator tool, the tank was rotated azimuthally through 45° to obtain another vertical profile. Two additional 45° azimuthal rotations produced the four vertical profiles shown in the figure. For each profile the light vertical line to its left is located at the nominal inside diameter (1066 mm) of the tank, using the much enlarged horizontal scale factor shown between two profiles."

The tank's bottom was also imperfectly flat because of welding. In addition to welding the bottom disk to the side, four penetrations were welded onto the bottom for experimental purposes. These included two 114-mm-diameter couplings for connection to the tank's safety (SCRAM) valves, one 64-mm-diameter coupling for connection to the normal solution fill/return line, and a small diameter short nipple extending down from the bottom for connection to a site gauge. The SCRAM valve couplings had centered 50-mm-diameter holes; and the fill line's centered hole was 26.6-mm in diameter. The pattern of these penetrations is shown in the upper portion of Fig. 7.

Assuring the tank's vertical axis was not tilted in any direction and measuring the flatness of the tank's bottom was the subject of considerable effort. The former was addressed using a commercial 1.8-m-long level. This was laid across the top flange in many different compass directions. The tank's threaded pipe legs were then adjusted until that top plane was as horizontal as possible. This does not automatically ensure that the tank's bottom is also perfectly horizontal nor that its vertical axis was not tilted some small amount. It is almost impossible to manufacture a "perfect" right circular cylinder. Still, any deviations were not perceptible; the tank *looked* vertical. Alignment was important because deviations certainly could impact the precise measure of solution needed to achieve criticality.

The tank bottom's flatness was evaluated in two ways. One used the same commercial level used to level the tank. This tool was used to "map" the distance from that level down to the tank's bottom. The level was moved as required to measure this depth at a variety of locations. Results are shown in the bottom portion of Fig. 7.

The second method to evaluate the tank's bottom warp and/or tilt employed the uranium solution itself. The empty tank was wiped clean of any residual solution. Fissile solution was then pumped through the usual fill line to a point just before it entered the tank. Next, a photographer was stationed directly above the tank with his camera aimed directly downward.

Figure 6a. The tank was slightly warped by welding. Inside diameters at top and bottom were slightly smaller than elsewhere. Four vertical profiles were measured from the bottom to the top of the tank at arbitrary azimuthal orientations 45° apart. The vertical straight line to the left of each profile corresponds to the nominal inside diameter of the tank. Orthogonal scale factors are greatly different on this figure: vertically, the figure spans 1.51 m; horizontally, the scale factor (10 mm) is shown between two profiles.

Figure 7. Two SCRAM valves are shown one below the other in the photograph. The fill and normal return line bisects these and is further to the right. The arrow marks the Sight Gauge connection. A contour mapping of the bottom is presented in millimeters below an arbitrary horizontal plane.

Yellow liquid could be seen in the fill line just about to enter the tank. Here, a precise instrument in the fill line that measured the mass of solution pumped through it was reset to zero. Next, small quantities of solution were slowly pumped incrementally into the tank and allowed to flow down contours to the low points of the tank. The photographer photographed the pattern of solution on the tank bottom at 18 increments while the experimenter recorded the mass admitted via that increment. Very small changes in the Sight Gauge indication resulted from these increments, too; and these were also recorded. This process was repeated until the bottom was just completely covered. The 18th increment had added a total of 7.765 kg of solution; and the Sight Gauge read about 3.5 mm.

The solution density was 1.511 mg/mm^3 ; so 5.14 liters of solution had passed into the empty tank before the bottom was covered. Figure 8 shows six of these stages. The tank is empty at the upper left; the teflon blade used to wipe the bottom can be seen. Intermediate stages reveal the bottom might be described as having two "mountains". The taller (last to be covered) would be above and to the right of center in the photograph; and a somewhat lower mountain existed just below center. The lower right photo shows the very last increment. The fraction of the tank bottom covered at each increment was measured by dividing the area covered with solution by the total area of the bottom from the same photo. A "planimeter" was used directly on the set of photographs for this analysis. Table III contains detailed data obtained from the 18 photographs. For this one tank bottom study only, the manual valve between the solution fill line and the Sight Gauge (see Fig. 2) was left OPEN. This enabled the solution to be observed in the Sight Gauge even before it reached the coupling welded into the tank.

The top drawing of Fig. 9 shows data from 13 of the 18 increments (n); the first few have been omitted. The broadness of the shaded curve suggests the uncertainty of the data. Since each experiment began with an initial flooding of the tank bottom followed by a normal return, the curve suggests that the start of each experiment actually had about 36.7% of the bottom already covered with 1.32 l of solution weighing 2 kg. Sight Gauge readings are shown on the same drawing ($\bar{Y}$); and the range of solution added between 1.8 kg and 3.5 kg with no perceptible change in height suggests that Sight Gauge readings may possess a bias of about 0.3 mm. That is, actual solution heights measured from "the start of an experiment" by the Sight Gauge method may be about 0.3 mm smaller than results stated. The bottom photograph in Fig. 9 shows the solution distribution about 20 minutes after a normal return of solution to storage. Interpretation of these small perturbations to height measurements is not at all obvious and is discussed again in a later section.

Empty Tank

1.021 kg

2.020 kg

4.024 kg

4.514 kg

7.765 kg

Figure 8. Fissile solution appears dark as it was pumped into the empty tank. Six of 18 increments are shown here with the last (7.765 kg) just flooding the bottom.

Table III. Topographic Mapping of the Tank Bottom from Photographs.

Photograph Number	Sight Gauge (mm)	Solution Delivered through Mass Flow Meter			Area of Tank Bottom Still Uncovered by Solution (%)
		Mass Flow Meter (kg)	Volume ^a (liters)	Height ^b (mm)	
1	-0.2	0.317	0.21	0.24	52
2	-0.1	0.511	0.34	0.38	
3	-0.05	0.745	0.50	0.56	
4	0.0	1.021	0.68	0.76	
5	0.1	1.299	0.86	0.96	
6	0.3	1.498	1.00	1.12	44
7	0.3	1.773	1.18	1.32	37
8	0.3	2.020	1.34	1.51	
9	0.3	2.282	1.52	1.70	32
10	0.3	2.520	1.68	1.88	30
11	0.3	2.768	1.84	2.06	28
12	0.3	3.033	2.02	2.26	26
13	0.3	3.278	2.18	2.44	25
	0.3	3.513	2.34	2.62	
	0.5	3.777	2.51	2.82	
14	0.5	4.024	2.68	3.00	17
15	1.0	4.287	2.85	3.20	12
	1.3	4.514	3.00	3.37	
	1.5	4.795	3.19	3.57	
16	1.5	5.016	3.34	3.74	8
	1.5	5.291	3.52	3.94	
	2.0	5.512	3.67	4.11	
	2.0	5.785	3.85	4.31	
	2.0	6.004	3.99	4.48	
17	2.5	6.277	4.18	4.68	3
	3.0	6.514	4.33	4.86	
	3.0	6.787	4.52	5.06	
	3.0	7.027	4.68	5.24	
	3.0	7.277	4.84	5.42	
18	3.0	7.543	5.02	5.62	0
	3.5	7.765	5.17	5.79	
Condition after manual return under gravity					36.7
Condition after a SCRAM					37.8

^a Density = 1.503 mg/mm³

^b Mass divided by the density and the cross sectional area of the empty tank.

Figure 9. The shaded curve shows the percentage of the tank's bottom left exposed after each increment. Two arrows at 36.7% and 37.8% correspond to solution remaining after a normal return and a SCRAM, respectively. Triangles give the height observed on the Sight Gauge. The bottom photograph shows the solution pattern 20 minutes after a normal return.

Spacer Plates

The tubes which later contained neutron absorbers were held in a fixed pattern by matching pairs of round, horizontal, stainless steel plates. The bottom plate was raised above the tank's bottom about 25 mm by 4 adjustable "feet" (actually, 6-mm-diameter flat head machine screws). The upper plate lay in a plane about 25 mm above the top of the tank, held there by a few, small, plastic spacer blocks between the plate and the rolled angle at the top of the tank. This upper spacer plate was elevated for safety. In the event of an accident, this space all around the perimeter of the tank would provide an escape route for solution ejected by the rapid generation of a great deal of energy.

Bottom plates were 1060 mm in diameter; so they would slip down inside the tank with little tolerance. The upper plate was 1118 mm in diameter, larger than the tank so it would not slip inside the tank. Both plates were nominally 16 gauge (1.52 mm thick) type 304 stainless steel with a smooth ("2B") finish.

The center of each plate was located and drilled through so a concentric pair could be fastened together temporarily. Then, a pattern of *square* holes was punched simultaneously into both plates to assure identical locations in both plates. These square holes were 29.0 mm on a side, large enough to receive the round tubes easily but not sloppily. Square holes were chosen to reduce contact between tubes and holes to only four points and to facilitate the flow of solution.

These square holes were punched in a square matrix of equally spaced holes in two orthogonal directions. One exception to this is described a few paragraphs later. The center of the plates did not possess a hole¹¹. Rather, the center was at the center of the central set of four square holes; and holes progressed out from there toward the circular boundary. Table IV gives the square center-to-center lattice spacings used in this program.

Fitting a square array of holes into a round plate for a round tank means that different rows will have different numbers of holes (always even) because of shorter chords as one moves radially out from center. No square hole was punched unless it was completely contained within the boundary of the bottom spacer plate, the smaller of the two. Figure 10 shows the hole patterns

¹¹ If any pattern had a centered hole, the orthogonal symmetry would dictate an *odd* total number of holes. All patterns contained an *even* number. In fact, the two-dimensional symmetry demanded the number of holes per plate be divisible by four.

Table IV. Tube Spacer Plates.

Lattice Spacing (mm)	Number of Tube Positions	Mass of Top Plate (kg)	Mass of Bottom Plate (kg)
Square Array			
57.15	256	11.440	10.145
50.80	332	10.565	9.205
47.63	376	10.035	8.570
44.45	432	9.005	7.775
41.28	492	8.050	6.830
Triangular Array			
50.80	374	9.805	8.485

256

332

374

376

432

492

Figure 10. Hole patterns in the tube spacer plates. Five are square pitched; one (374 tubes) has a triangular pitch. The top of each pattern is "north".

used in this program. The hole pattern in all four quadrants of any plate were always congruent with one another. Moreover, they were symmetric with respect to the 45° axis of a quadrant. The following list gives the number of holes per row, starting from the center of the plate, in *each* quadrant for each of the lattice spacings used:

256 holes: 9,9,9,8,8,7,6,5,3

332 holes: 10,10,10,10,9,9,8,7,6,4

376 holes: 11,11,11,10,10,9,9,8,7,5,3

432 holes: 12,12,11,11,11,10,10,9,8,7,5,2

492 holes: 13,12,12,12,12,11,11,10,9,8,7,5,1

Some interesting mathematical consequences stem from this design. Obviously, the sum of each string is one-quarter the total number of holes. The *number of entries* in each sequence equals the largest number in the sequence. The number of rows having the largest number of tubes equals the smallest number of tubes in one row. The sum of the number of rows having that number of tubes or the next smaller number of tubes equals the second smallest number of tubes per row.¹²

One configuration studied did not possess a square matrix of square holes. This was a pattern of square holes in an equilateral triangular matrix with a 50.4 mm center-to-center lattice spacing. This pattern, containing 374 holes, was used on only two experiments. This one case did have a hole at the center of the plate. All other physical features of the spacer plates were the same. Plates with the triangular matrix had six almost congruent patterns azimuthially distributed around the plate. The constraints of punching many square holes with edges parallel to one another on a triangular pitch with no hole breaking the outer perimeter of the smaller bottom plate does not permit a clean written description of the number of holes per 60° wedge even though the center did contain a hole. Figure 10 also shows this one triangular pattern.

In addition to the five square matrix patterns and the one triangular array studied, three others were manufactured but never used. One was a square array at a 54.0 mm pitch; the other two were triangular pitched arrays (47.6 mm and 54.0 mm).

¹² To illustrate, consider the 432-tube example. There are 12 entries and that is the largest number of tubes per row. There are 2 rows of 12 tubes; and the smallest number of tubes per row is also 2. Five rows have 11 or more tubes; and the second smallest number of tubes per row is 5. Seven rows have 10 or more tubes; and the 3rd smallest number of tubes per row is 7. The pattern continues.

Tubes

Hundreds of stainless steel tubes were manufactured for this program. They were open at the top but seal-welded at the bottom to exclude solution. Each tube slipped easily into the square holes of the spacer plates with very little clearance. They measured between 1.575 m and 1.576 m long. Two random selections of 10 finished tubes were weighed with averages of 1320 ± 18 g and 1324 ± 8 g. The average of these two sets is 1322 ± 20 g. The outside diameter of two other sets of 10 finished tubes was measured at 4 points each along their length; this yielded averages of 28.44 ± 0.06 mm and 28.45 ± 0.02 mm. Finally, the wall thickness was measured on two sets of tubes in several locations: 1.196 ± 0.010 mm and 1.165 ± 0.015 mm. The nominal wall thickness for these 18 gauge tubes is 1.24 mm, somewhat thicker than actually measured. The thickness of the flat stainless steel (304L) stock from which the bottom disks were made measured 1.6 mm.

Tubes were manufactured from commercial type 304L stainless steel tubing. The manufacturer's specification required tubing designated ASTM A213 or A269. Tubing, rather than a comparable-sized pipe, was selected because manufacturing tolerances of tubing are tighter.

Tubes projected above the top plane of the tank about 66 mm. Thus, they would project above the upper spacer plate about 39 mm. This short length was used to grasp tubes for removal or insertion. In use, tubes rested on the bottom of the tank. Possibly, some tube could have fallen into the slight depression (50 mm in diameter) in the tank's bottom created by either of the two safety SCRAM valves; but this was not the case for any configuration.

Hold Down Plate

In the absence of solution, tubes and their contents would remain in place by gravity. The introduction of fissile solution, however, would reduce that apparent weight by the buoyant force. Tubes could float; and that would not be safe. A clear plastic cover plate was laid upon the combined tops of the many tubes in any experiment and bolted to the top flange of the tank. This "hold down" plate can be seen in Fig. 11. It was 25 mm thick and 1.18 m in diameter. The material was probably either Lucite^R or Plexiglas^R; but this information was not recorded.

Figure 11 presents a bird's eye view of a 256-tube experiment. The figure shows the hold-down plate, the upper tube sheet, and stainless steel tubes presumably filled with one of the

Figure 11. A nearly top view of the 256-tube configuration. The top spacer plate can be seen just below the tops of the tubes. Some holes could not receive tubes because of the tank wall. The clear plastic plate to hold the tubes down is barely visible. The source guide tube has a white plastic funnel attached. Three sides of the concrete reflector are seen.

absorber materials. The white funnel atop a central guide tube received the neutron source and is described next. The reflector is described after that.

Source Guide Tube

The neutron source was present at the start of each experiment but was withdrawn as criticality was approached to keep the (small) power level as low as reasonable. A long, vertical, 13-mm-diameter stainless steel, thin-walled tube was seal welded at its bottom and positioned along the tank's central axis. The length is not recalled; but this source guide tube rested on the bottom and projected between 0.2 and 0.4 m above the hold down plate. The top of this tube was fitted with a commercial plastic funnel whose tail was machined to make a press fit over the tube. This served as a guide for easy remote insertion of the source. The weight of this guide tube was greater than the buoyant force; so it may not have been clamped to the hold-down plate. No record is found to answer that question.

Level Detector

The only other neutron reflecting components on top of some experiments (but not all) was a light-weight aluminum device designed to provide one measure of the fissile solution height. This electronically controlled device, developed at Rocky Flats and called a Level Detector, had a 6-mm-diameter stainless steel threaded rod projecting down into the tank. The rod remained above the solution; but a gold tip at its lower end would touch the solution's surface. In use, the threaded rod would withdraw several millimeters, pause, then screw back toward the solution level. It would stop the instant the gold point "found" the solution level. This information was transmitted to a linear scale above the tank. The support structure was about 2 m tall and mounted above the plastic hold down plate. About mid-way through the program, use of this device was abandoned altogether because of questionable operation.

Concrete Reflector

Experiments were surrounded on four sides by a thick-walled concrete reflector. This simulates a production setting because many tanks stand close to a wall, in a corner (2 sides), or in a tight bay (3 sides). The four vertical reflector panels stood quite close to the tank. Only sides were reflected, however; no concrete reflector existed under the tank nor above it. The absence of bottom reflection does not simulate a production setting.

This concrete reflector was cast as four identical, flat, walls assembled into a square "house" without floor or roof. The four walls stood vertically. Each outside face would expose the full length of one panel plus the width of another to the right of the first. Repeating this four times to form a square reflector, the inside dimension of the square would be the width of a panel minus the thickness; and the outside dimension would be the width plus the thickness. All four were the same height; and all faces had this same appearance.

The inside dimension of this house was nominally 1.22 m square; but detailed measurements are presented later. Heavy cast panels do not always assemble exactly as planned. Panels were cast 0.25 m thick; so the outside dimension of the reflector would be about 1.72 m square.

The height of the finished reflector was 1.524 m high; but this height was actually composed of *two* segments placed one on top of the other. The four bottom segments were concrete reflectors used in previous experiments at this laboratory¹³ These were the stated length and thickness but were only 1.22 m high, not tall enough to reflect the experimental tank completely. The additional top segments were cast especially for this program. They were the same length and thickness as the existing panels but only 0.304 m high. The bottom of the finished concrete reflector was *about* co-planar with the tank's bottom; and the top was *about* co-planar with the top flange of the tank. The difference between the reflector's combined height (1.524 m = 1.22 m + 0.304 m) and the combined height of the interior of the tank (1.51 m) and its bottom thickness (9.5 mm) was only 4.5 mm. Whether the reflector rose a little above the tank's top plane or extended below its bottom is not recorded.

The four lower panels (1.22 m tall) were cast in April of 1976. The fabrication of these concrete pieces was monitored very carefully to assure good knowledge of the elemental composition. Two methods were used to determine this composition; and then the results were averaged. First, the initial ingredients that went into the concrete were analyzed **before** mixing. This included the Portland type III cement, the ordinary sand whose water content was first measured, and the Dolomite limestone (a mixture of calcium carbonate and magnesium carbonate) which served as the aggregate. Limestone was chosen over more-common river rock for its high

¹³ ROBERT E. ROTHE and INKI OH, "Benchmark Critical Experiments on High-Enriched Uranyl Nitrate Solution Systems", **Nuclear Technology**, **41**, (1978).

carbon content because carbon is a good neutron moderator. Water was not analyzed but assumed to be simply H_2O .

This analysis of the individual ingredients was combined with knowledge of the weight-fraction of each ingredient in the mix to determine the elemental composition of the finished concrete. The total amount of any element was obtained by just summing contributions from each component.

The second method of measuring the elemental composition of the concrete was to destructively analyze a sample of the same concrete mix formed at the same time and treated in the same way as the wall panels. The two methods were in excellent agreement with one another. The result of both efforts appear in Table V, copied from Ref 4.

Once "green" concrete is cast and set, its weight continues to decrease for many months. This is associated with the gradual loss of water over the extended setting process of concrete. Sixteen months after being cast, the combined weight of the bottom four panels, used much later in the present program, plus a top and a bottom panel, required for the earlier study, was measured at 7790.8 kg. The six pieces formed a cube when fully assembled; so, geometrically, the four walls would constitute 54.92% of the total weight, or 4279 kg. Seven years later (June 1983) and just prior to the start of the present program, these four walls (only) were weighed again: 4280 kg. The 1 kg difference may be attributed to measurement errors or to the fact that the four panels were given a light coat of paint after the first program to retard further water loss and to contain any possible loose contamination. Twenty-one months later (February, 1985) and after completion of the study, the four were again weighed: 4264 kg.

The author suggests using the elemental compositions in Table V; but, if the 16 kg weight loss (4280 kg - 4264 kg) to February of 1985 were real and caused by water loss, the hydrogen content would decrease from 0.75% to 0.747%, a truly small change.

The four smaller (top) concrete pieces were cast May 12, 1983. The same formulation of ingredients was used in an effort to make the two castings as similar as possible. Table VI gives the combined weight of the four panels as a function of time. The decrease in weight is a clear illustration of the water loss during setting. The present experimental program took place between October, 1983, and September, 1984. Most critical heights occurred low in the tank and would be

Table V. Composition of Concrete Reflector (wt-%) as of December, 1978.

Element	Analysis of Ingredients	Analysis of Cured Concrete	Average	Method ^a	Number Density ^b (atom/b-cm)
Hydrogen	0.75	0.75	0.75	CH	0.0104 008
Carbon	5.57	5.52	5.55	CH	0.0064 590
Nitrogen	0.00	0.02	0.01	K	0.000 100
Oxygen	50.09	48.49	49.29	Difference	0.0430 634
Sodium	0.21	0.63	0.42	AA	0.0002 554
Magnesium	1.71	1.25	1.48	AA	0.0008 509
Aluminum	1.94	2.17	2.06	AA,C	0.0010 672
Silicon	15.91	15.50	15.70	AA,C	0.0078 138
Sulfur	0.15	0.19	0.17	Eschka	0.000 741
Potassium	0.13	1.37	0.75	AA	0.0.002 681
Calcium	22.91	23.00	22.95	AA	0.0080 040
Titanium	0.00	0.10	0.05	AA	0.0000 146
Iron	0.63	1.01	0.82	AA	0.0002 052
Total	100.0	100.0	100.0		

^a AA= atomic absorption

CH = carbon/hydrogen analyzer

K = Kjeldahl

C = calorimetric.

^b Based on a density of 2.321 g/cm³.

Table VI. Combined Weight of Four Upper Concrete Reflector Components as a Function of Time After Casting.

Date	Weight (kg)	Age
May 16, 1983	1070	4 days
June 1, 1983	1066	20 days
February, 1984	1042	21 months
February, 1985	1032	33 months

more affected by the bottom concrete reflector walls. Only a few experiments achieved critical near the top of the tank where the fresher concrete would have a sizable reflector impact.

Both sets of four wall segments were tied together at their tops for seismic stability. Two square "picture frames" of mild steel bar stock were used. One was bolted to the top horizontal surface of each set of wall segments. The center of the bar stock about bisected the thickness of the walls. Both frames were made from 50 mm wide stock; but the one for the lower walls was 13 mm thick while the upper one was 6.3 mm thick. The picture frame for the upper reflector can be seen in Fig. 11. A groove, cast into the bottom surface of the new reflector components, accommodated the picture frame for the older set.

The actual assembly of the reflector yielded a configuration *slightly* different than that expected. This is so because cast concrete blocks are not precision components and do not assemble perfectly. The actual dimensions inside the reflector are presented in Table VII. These may lack accuracy because they were made in cramped quarters. The *expected* inside dimension of the concrete reflector was 1219 mm; but the worst departure from that was only 15 mm at two locations.

A telescoping T-gauge was used to measure the distance from the outside of the tank to the inside surface of the reflector. This, too, was difficult to measure and may lack accuracy. Irregularities in the tank caused its top to be less well centered within the reflector than the bottom. The arithmetic sum of the inside diameter of the tank (1.066 m) plus twice its wall thickness (6.4 mm) plus the measured distances to the reflector's interior (right-hand column of Table VI) do not exactly add up to either the nominal dimension (1219 mm) or any of the measured values. Bottom measurements are in better agreement (2 mm) than top (4 to 21 mm). Fortunately, most critical conditions occurred at lower heights.

All eight wall segments contained some steel for strength. The older four contained only 0.2% (by weight) steel. The newer, upper ones contained about 1%.

Reflector Support

The concrete reflector was supported about 213 mm above a sturdy table, described below. A frame of mild steel channel stock was welded into a square 1.42 m on a side. The channel's 102-mm web was vertical and the 41-mm-wide flanges faced inward. Eight sections of mild steel

Table VII. Interior Dimensions of Assembled Reflector
and Tank Location Within It.

Along Which Wall	Distance Between Walls (m)	Closest Distance from Tank to Wall Face (mm)
Near Top		
North	1.217	53
East	1.204	53
South	1.221	68
West	1.208	68
Near Bottom		
North	1.215	71
East	1.217	72
South	1.213	71
West	1.204	71

pipe were welded to the outside of this frame, one at each corner and one in the center of each side. The 165-mm-long pipes were threaded on both ends and extended above and below the channel. Stainless steel end caps were screwed onto both ends to make slight adjustments possible. The length of the pipes plus two end caps made the overall height of this reflector support about 241 mm. The eight pipes were 60 mm diameter with a 3.9 mm wall. A portion of each equal to the channel's web was machined away to provide more surface for welding. The finished support had the bottom screw caps about co-planar and slightly adjustable. The plane of the top screw caps was about 213 mm above the bottom plane and also adjustable.

A steel plate rested on top of the eight pipes to distribute the weight of the concrete. This plate was fabricated of four flat panels, 311 mm wide by 13 mm thick, of mild steel welded into a flat square with an open center. With this plate in place, the bottom of the concrete was *about* co-planar with the bottom of the tank. The outside dimension of this square was 1.78 m on a side; the inside dimension was 1.16 m. Each corner had short lengths of 25-mm x 25-mm x 3-mm-thick angle iron welded to it. These were located both inside and outside. They kept the reflector from shifting, even in a seismic event.

Solution Base Table

All components were supported by a sturdy heavy-weight steel table resting on the floor. The mild steel top of this table was 1.5 m square and 25 mm thick. The bottom of the tank was elevated about 250 mm above this surface by three stainless steel pipe legs threaded into couplings welded to the tank, while the reflector was elevated by eight pipe supports described above¹⁴.

The top frame was constructed of 152-mm x 152-mm x 11-mm-thick steel angle iron welded into another square 1.5 m on a side. The table top merely rested directly on this frame. The final height of the top surface of the table top above the floor was 1.38 m. The four corners had legs of the same angle iron stock welded to the top frame. Steel pads (203 mm square by 9 mm thick) had been welded to the bottom of these legs initially; but the present loading called for

¹⁴ Comparing sums of vertical measurements of individual components tends to answer an earlier question: was the tank's top surface a little above or below the top surface of the reflector? Using the Solution Base surface as reference, the tank's rim rose 1.7695 m summed from the 1.51 m interior height, the 9.5-mm-thick tank bottom, and the 250 mm legs. In comparison, the top of the reflector stood 1.750 m high, summed from the 1.524 m height of two concrete pieces, a 13-mm-thick load bearing plate, and the 213-mm-tall pipe leg supports. This analysis suggests the tank's surface stood 19.5 mm above the reflector.

larger pads to distribute weight better. Larger pads (300 mm square by 13 mm thick) were added under the existing ones to prevent digging into the concrete floor. Triangular gussets welded to leg and table frame strengthened the structure. Eight gussets (two per corner) added about 0.25 m² of 9-mm-thick mild steel. The only other steel associated with the table was about 6 m of 50-mm x 50-mm x 6-mm-thick angle iron stock near the bottom.

The spacious underside of this sturdy table supported a few components associated with fissile solution handling. (1) A single stainless steel solution fill pipe (commercial 1-inch schedule 40 pipe) passed solution into the tank during an experiment. This line would contain fissile solution throughout the experiment. It extended about 0.5 m below the tank before a 90° bend led to a long horizontal run away from the table. (2) Two safety SCRAM valves were suspended from the bottom of the tank. The valve's seat closed close to the bottom plane of the tank; but a 50 mm diameter by *approximately* 20 mm deep pocket of solution remained above each SCRAM valve even when the solution was nominally drained away. The valves, themselves, were complex geometry but each could be approximated by about 0.5 m length of commercial 3" schedule 40 pipe extending below the tank with a heavy electric solenoid hung about 0.6 m below the tank's bottom. These SCRAM lines contained no solution during the experiment. (3) Both valves connected to a nearly horizontal, critically-safe-diameter "dump tank". This, also, was empty of solution during the experiment. The dump tank was constructed of nominal 5 inch diameter schedule 10 stainless steel pipe. It was 1.8 m long and an average of about 0.9 m below the tank's bottom. (4) A vent line rose vertically from the higher end of the dump tank to a height about 1.5 m above the top of the tank. This was nominally 2 inch schedule 10 stainless steel pipe; and it was fully outside of the concrete reflector.

Hood

The entire experimental apparatus was about centered horizontally in the south half of a stainless steel hood. This hood was intended (in 1964) to control contamination in fissile solution experiments. This hood was situated within the west half of the Assembly Room. The hood, itself, was 3 m wide by 4.9 m long and stood 5.7 m tall. It was constructed of 11 gauge stainless steel (3 mm thick); but about 19% of the four walls contained 13-mm-thick plastic windows for viewing. In addition, four small windows (0.5% of the wall area) were composed of safety glass. The hood had a stainless steel floor and ceiling (3 mm thick). Walls and roof were stiffened on the outside by stainless steel structural members; but these are considered unimportant and not described.

The long dimension of the hood stood parallel to the west wall of the Assembly Room, described below. The southwest corner of this hood was 1.57 m east of this west wall and 3.30 m north of the south wall.

The other half of the hood was occupied by an uninvolved piece of experimental equipment, called a Vertical Split Table. Its light-weight and open, "airy", construction used very little tubular stainless steel stock. The mechanism is described no further because of its low mass and its distance outside the thick-walled reflector.

Environment

Outside the hood, only two sizeable components are described, and only approximately at that. One of these, called a Horizontal Split Table, is a fairly massive steel structure. The Split Table was situated within the east portion of the Assembly Room. Its overall dimensions were about 5.4 m long by 2.2 m wide; and it rose about 0.7 m above the floor. Although the table had a complicated geometry of honeycombed steel webbing and structural steel channel, a conservative approximation to its steel content would be a 25-mm-thick vertical rectangular cylinder measuring 5.4 m by 2.2 m on the outside supporting two horizontal and co-planar table tops. Each top would be 1.9-m-long by 2.2-m-wide and 50 mm thick. One would be located at each end of the rectangle. The long dimension of this table was parallel to the long dimension of the hood and about 1.9 m east of it. The northeast corner of the Split Table was 2.44 m west of the east wall and 1.09 m south of the north wall.

The other sizeable object, sufficiently large to constitute some environmental reflection, was an elevated concrete platform built into the southeast corner of the Assembly Room. It measured 4.9 m (east/west) by 3 m (north/south) and was 0.2 m thick. Its underside was elevated 3.4 m above the floor. This elevated platform was built for earlier experimental programs and used again for the first Annular Tank program¹⁵ reported under the present contract. The elevated platform did contain some equipment at the time of the program here reported; but no further description is offered because of the small size and mass of the items present.

¹⁵ ROBERT E. ROTHE, "Experimental Critical Parameters of Enriched Uranium Solution in Annular Tank Geometries", DOE Contract C96-175866, (1996).

Assembly Room

The last feature which could reasonably affect the neutronics of this experimental system was the thick-walled concrete room called the Assembly Room. This room was designed to contain completely the physical consequences of an accidental prompt nuclear criticality excursion, should one occur during a planned experimental approach to criticality. Locations of other major components contained within that room are described above, often referenced to its four walls. The interior of this room measured 10.7 m (north/south) by 11.3 m (east/west). The ceiling stood 9.8 m above the floor. The north wall was the thickest (1.52 m) to provide additional radiation shielding for experimenters during a critical approach. The other three walls were only 1.22 m thick. The ceiling was 0.61 m thick; and the 0.2-m-thick floor rested directly on the earth.

Two access doorways penetrated the enclosure. An equipment access existed in the south wall at the east side and began at floor level. This opening was 2.4 m wide and the same height. During experiments, the opening was always closed with a 0.15-m-thick, honeycombed, steel door to guard against possible blast effects should an unplanned nuclear excursion occur. In addition, a 1.32-m-thick sliding door cast of concrete provided radiation shielding to the outside in the event of that same accident. This "Shield Door" measured 3.05 m wide by 2.78 m high. The concrete has never been analyzed for elemental composition. The specifications document¹⁶ for the facility, however, defines the intended concrete to be "Type A, Class I". Walls and ceiling contain rebar for reinforcement as shown in the July, 1964, photograph at the top of Fig. 12. The bottom of the same figure shows the exterior of the completed Assembly Room, August 20, 1964, just after concrete had been poured.

¹⁶ *Specifications for Nuclear Safety Facility Building 86 USAEC Rocky Flats Plant, Denver, CO*, U.S. Atomic Energy Commission, Stearns-Roger Corporation, Denver, CO, (1963).

Figure 12. Rebar was in place for the pouring of the Rocky Flats Critical Mass Laboratory on July 8, 1964; and the pour was finished by August 20, 1964. The wall to the right faces south.

URANIUM SOLUTION

The fissile liquid was uranyl nitrate solution with only enough excess nitric acid to keep the uranium salt well dissolved. The chemical formula for the dry salt is:

The solution was prepared by dissolving this salt in dilute nitric acid and then evaporating to the desired concentration. It was prepared at Rocky Flats in 1964 specifically for their newly-opened Critical Mass Laboratory; and the entire holding has remained there ever since. The initial concentration averaged about 450 gU/liter. The uranium is highly enriched in ^{235}U .

This solution has been used in about one thousand critical approach and low-power critical experiments between 1967 and 1988. In spite of this history, the solution contains no measurable inventory of radioactive fission byproducts because of the low power level. The solution is quite free of other, more common, impurities as well. There are essentially no fluorides to attack glass, chlorides which could attack stainless steel, phosphates, organic contaminants, or other corrosive radicals in the solution.

Over the 20 months of the experimental program, the solution was sampled on three occasions. Each time, three samples were drawn; and each of these was analyzed for concentration twice. The average of these 18 determinations was 362.5 ± 3.4 gU/liter. Other properties of the solution, not measured twice for each of the nine samples, are shown in the top portion of Table VIII.

Solution samples were converted to uranium oxide (U_3O_8) as described below. Both impurities and enrichment were obtained from these oxides. Impurities were measured on some mixture of these oxides; but the particular mixture chosen cannot be recalled a decade after the fact. The analytical method for impurity analysis was uncertain by about a factor of two. Either Spark Source or Emission Spectroscopy was used. The impurity distribution is presented in the middle of Table VIII expressed in parts per million by weight. Important neutron absorbers are shown in bold face font. Fortunately, beryllium is also very low because it would contribute additional neutrons through the (n,2n) reaction.

Table VIII. Average Uranium Solution Properties.

major	concentration $362.5 \pm 3.4 \text{ g U/liter}$ density $1.503 \pm 0.047 \text{ mg/mm}^3$ free nitric acid normality 0.502 ± 0.024 total impurities $653 \pm 533 \text{ ppm}$		
isotopic enrichment	^{234}U	1.001 wt-%	
	^{235}U	93.172 wt-%	
	^{236}U	0.433 wt-%	
	^{238}U	5.394 wt-%	
impurities (ppm)	Al	525	B 2.3
	Be	<0.5	Bi 46
	Ca	100	Cd <0.7
	Cr	42	Cu 51
	Fe	515	K 2700
	Mg	340	Mn 20
	Mo	<1	Ni 75.9
	P	<23	Pb 50
	Si	50	Sn 150
	V	<5	Zn <11

Impurities found are very consistent with the long-term characterization of this captive solution at Rocky Flats. Impurity data collected from dozens of measurements between 1965 and 1972 reveal that the above results - measured in 1985 - lie between the ranges of values found in those early days in all cases.

Isotopic composition was also measured on the same oxides. Average isotopic values are given in the bottom portion of Table VIII. No ^{233}U has ever been found in the Rocky Flats solution.

Analytical Procedure

The sampling and analysis procedure began with a thorough mixing of the tanks to be sampled. These were the tanks that had been used in experiments over the preceding several weeks. While the solution was circulating, the sample port was purged of possibly non-representative solution by passing a small quantity of solution through the port with no intention to analyze it. Next, a 125 ml polyethylene sample bottle was filled almost full. This minimized evaporation between the date of sampling and its eventual analysis. After the cap was tightly sealed, the procedure was repeated for other samples.

Samples may not have been analyzed immediately, although this detail cannot be recalled years later. That possibility is inferred from the fact that all sample analyses were reported on the same document dated May, 1985, six months after the program ended.

The solution sample was first drawn into a clean temperature-calibrated 25 ml pipette. Weighing this gave the solution density quite precisely ($\pm 0.2\%$). The uranium concentration is obtained from the mass of the sample placed into the dish, this precision density, and the eventually determined uranium weight. The nominal precision of concentration measurements is about $\pm 1\%$. The isotopic distribution of the uranium was measured by Isotopic Mass Spectrometry to better than 1%.

Uranium concentration was measured by a procedure called Gravimetric Titration. Here, a precisely weighed volume of solution is evaporated to uranyl nitrate salt in a passive metal (platinum) dish and then calcined to the black oxide (U_3O_8) and weighed. The uranium oxide weight is corrected for the weight of metallic impurities, all assumed to be in their oxide state, by

subtracting the weights of impurity oxides. Finally, the uranium weight is calculated from the stoichiometric composition of the uranium oxide.

Solution History

The Rocky Flats Critical Mass Laboratory began operations in January, 1964. A little more than 560 kg of nominally 93% ^{235}U uranium solution was prepared in another building and shipped during the summer of 1965 in approximately 1170 liters with concentrations ranging from 404 gU/liter to 574(!) gU/liter. The average was about 450 gU/liter; and this remained unchanged until 1971. At that time, the high concentration was lowered intentionally to about 380 gU/l solution. Both concentrations may still be regarded as falling within the broad definition of "the minimum critical volume concentration".

This captive solution has been analyzed many, many times since the mid-1960s. Samples have ranged from the highest concentration all the way down to nearly water. Figure 13 shows data collected over about a quarter century and demonstrates the tight linearity between density and concentration. Dots show only a fraction of the data used to determine the least-squares parameters; and the x's demonstrate that subsequent measurements continue to fit the curve. The equation which best represents the linear regression fit is:

$$\text{solution density} = 0.001365(\text{uranium concentration}) + 1.001409$$

where the density is measured in mg/ml and the concentration is expressed in gU/liter.

Figure 13. The uranium concentration and solution density are linearly related. The line represents a linear regression fit to several year's data (o); and the x's show subsequent data.

SOLUTION HEIGHT

Fissile solution height was the sole independent variable in each experiment. Good control was important for safety. The rate at which liquid was added close to criticality had to be slow enough to limit reactivity addition to a safe rate. Earlier, it could safely be added much faster. Accurate measurements were imperative for quality data. The **critical** solution height was the principal parameter of this entire paper.

Height Measurement

Generally, three methods were employed to measure critical heights. The Sight Gauge was the simplest. Solution in a vertical small-diameter transparent tube, at equilibrium with the tank itself and a distance from it, was read via closed-circuit-television and recorded. Subtracting the observed height at criticality from that for the "empty tank" yielded the critical height. A second method employed two Mass Flow Meters. The mass delivered into an "empty tank" up to criticality is related to the critical height and other known parameters of the program. The last method used the volume of solution transferred from the storage tanks into a critical system. This volume yields the critical height when divided by the cross sectional area available to solution.

These three were compared with one another; and critical heights reported in this paper represent a subjective judgement as to the "best" value. This point is discussed further after the three methods are described.

Sight Gauge - A length of 25-mm-diameter clear plastic tubing was clamped to the stainless steel nipple welded into the bottom of the tank. It passed under the tank and reflector before it rose vertically to a height above the top of the tank. This vertical "Sight Gauge" was about 2 m from the center of the tank. It was viewed remotely via closed-circuit television. A calibrated linear scale, adjacent to the tubing, was used to measure these heights.

Three procedures improved accuracy of Sight Gauge data greatly. (1) The television camera was mounted horizontally on a fixture free to move up and down along a vertical shaft. This eliminated parallax. (2) Parallax was reduced further by reading heights at about the same region of the television monitor. This minimized distortions there. (3) The television camera was rotated 90° to lay on its side. The image rotated also; but optical interference between the monitor's raster retrace lines and fiducial marks on the scale was eliminated.

Several factors reduce the value of a Sight Gauge. (1) The calibrated scale existed alongside the clear tube. Any height had to be determined by visually aligning the meniscus bottom with marks on the scale, about 15 mm to one side. This yielded readabilities of about ± 0.5 mm. (2) The meniscus, itself, is curved requiring the flat solution surface be viewed through it. (3) The round tubing acts like a cylindrical lens making viewing difficult. (4) Air bubbles trapped in the tubing give false readings. These displace solution or, equivalently, approximate a reduced-density solution in the measurement leg. (5) The Sight Gauge may contain a different density solution. The first solution to an experiment floods the bottom and fills the Sight Gauge line. This solution remains in the Sight Gauge throughout the experiment. If subsequent additions have a slightly different density, the Sight Gauge will indicate wrongly. (6) Density variations could result from residual solution from the previous experiment through evaporation. Day-old solution might have a slightly different density than fresh.

The Sight Gauge did not read zero at the bottom of the tank. Another section describes a + 0.3 mm bias in Sight Gauge readings. That is, the Sight Gauge read 0.3 mm when the tank was claimed to be empty. This applies to all experiments after experiment #5. Before that, a larger bias (+ 17 mm) existed. Only two experiments included in the Results Section (#3 and #5) would have been affected by this larger bias; and both are reported in the same table (Table XI). These corrections have been subtracted from the data taken directly from the calibrated meter sticks alongside the plastic tube. The calibrated scale adjacent to the Sight Gauge consisted of two commercial meter-long scales fastened end to end. The upper one was attached with about a 1 mm gap between the two. This correction has also been made to later results. That is, any critical height greater than 1 m in the results tables includes that 1 mm bias correction. To illustrate, the critical height of 1195 mm in one of the Results tables was actually a reading of 1194 mm to which the 1 mm bias was added.

Storage tank volume - Storage tanks from which solution was drawn are "volume calibrated" to aid nuclear material accountability. Each tank has a vertical scale adjacent to its Sight Gauge that displays the volume contained. Even though filled with randomly placed borosilicate glass Raschig rings, the relationship between height and volume is remarkable linear. Any volume between calibrated increments may reliably be interpolated.

These calibration data were used to provide an absolutely independent *second* measure of the critical solution height. The contents of relevant storage tanks were recorded at the precise start of an experiment. Similar data were recorded again when the slightly super critical solution height

had been attained¹⁷. The volume delivered to the experiment equalled the slightly super critical height times the cross sectional area of the experiment. This area was well known. The interior diameter of the empty tank had been measured many times; and the total area of an integer number of tubes could be calculated. As one final adjustment, this height was increased because of the very small volume of the bottom spacer plate.

In summary, the formula used for this slightly super critical height, H_{c+} , calculation was:

$$\frac{\text{volume of solution added} + \text{volume of bottom tube plate}}{\text{cross sectional area of tank} - \text{area of all tubes.}}$$

Intrinsic errors in this technique reduce its precision. Sight Gauge limitations discussed above apply here, too. Raschig rings in the storage tanks introduced two new problems. (1) Solution held up on the combined surface area of thousands of rings slowly drip back to the solution level changing it. This effect can be significant. (2) Experience reveals that a storage tank's printed scale does not yield the best measure of the actual volume. It is a linear regression fit to *all* calibration data and does not characterize small, local, variations near the volume to be read. The raw data, from which the regression curve was derived, provided a better measure of the volume. Interpolation between adjacent pieces of this raw data which bounded the desired volume provided that better measure.

Mass Flow Meter - Two devices had been installed in the solution feed line leading to the experimental tank. These were commercial "Mass Flow Meters"¹⁸ which measured the mass of solution delivered past some arbitrary starting point. These meters are independent of flow rate and several other parameters over reasonably large ranges. Still, two were used because solution was delivered to the experiment at widely different flow rates at different times during an experiment. Both were reset to zero just before fissile solution entered the tank.

¹⁷ Operational procedures required two certified experimenters remain fully attentive at the reactor control console at all times during an experiment. A third person, uninvolved in the experiment, obtained these data from the well-shielded storage room a distance from the critical assembly. That same person had read tank volumes at the start of the experiment. Using the same person minimized observer bias.

¹⁸ This device measured both the density of solution contained in it and the mass of solution passing through it. A U-shaped rigid tube containing solution was set into vibration. The frequency of this vibration was a sensitive measure of the mass of solution; and, since the volume is precisely known, the data yields the density of the liquid contained. The mass delivered through it was determined using the Coriolis effect. As solution passed through the vibrating U-shaped tube, a twist was produced proportional to the mass delivered.

Early in an experiment, solution was delivered at about 1 liter per second; and the mass delivered was integrated by the larger Mass Flow Meter to the nearest 10 grams. The smaller unit continued to read zero. When the experiment was no longer safe to add solution that fast, that pump was decommissioned and the mass delivered through the larger meter recorded. As more solution was added via a smaller pump, it passed through the smaller Mass Flow Meter. This device also integrated the total mass delivered through it, but to the nearest gram. The mass corresponding to the slightly super critical situation was, then, just the sum of the two readouts.

This mass is a *third* independent measure of the solution height for that slightly super critical condition. The delivered mass equals the density of the solution times the volume delivered. The density was needed for other reasons and was quite well known. The volume of the solution, again, equals the cross sectional area of the solution-filled region of the tank times the height. The formula used to calculate this height measure, H_{c+} , from mass delivery data is:

$$\frac{(\text{total mass delivered/solution density}) + \text{volume of bottom spacer plate}}{\text{cross sectional area of tank} - \text{area of all tubes}}$$

Experience reveals that Mass Flow Meter measurements are both accurate and precise. This is also claimed by the manufacturer. Many experiments contained over 1000 kg of solution; and critical masses were recorded to about ± 10 g - or one part in 10^5 ! Conservatively, critical masses obtained by this method are claimed to have a precision¹⁹ of about $\pm 0.01\%$!

Mass Flow Meters had the capability to measure mass drained from an experiment, too. A simple switch reversed its direction sensitivity. After the slightly super critical data had been recorded, the smaller unit was again set to zero; and incremental returns were integrated until the slightly subcritical reactor period was obtained. This usually amounted to between a few hundred grams and a couple of kilograms.

¹⁹ One illustration of the precision of these instruments as a density measuring device comes from a 1989 inventory measurement of the uranium contained in the solution stored. A solution density standard was prepared and poured into the device. An unbiased observer, ignorant of the standard value, read the density on the Mass Flow Meter. The two agreed to five significant figures! That is a precision of 1 part in 10,000.

Mass Flow Meter results, tabled later, are those corresponding to the meter having been set to zero at the conditions following a normal return of solution to storage at the beginning of an experiment. They do not include the ≈ 2 kg (1.3 l) believed to reside in the low valleys of the warped tank. This adjustment would be less if a few hundred tubes were present because the tubes would occupy some of the volume of those low valleys.

Net Height

Critical heights determined by these three methods did not always agree with one another perfectly. As stated above, critical heights reported here are subjectively chosen from data obtained from the three methods. Generally, this subjective selection adopted the following principals. Data from the Mass Flow Meter method was considered the most precise and, therefore, "best". These heights were given strong weight. If this did not disagree with other methods, that height was quoted. The Sight Gauge was second in this arbitrary scheme. Tank Volume Calibration data was considered the least trustworthy.

An Alternate Viewpoint

One person (Dr. John E. Tanner) validating these results against computational methods suggests a slightly different approach to publishing critical heights from this study. His opinion is, again, related to the problem of the warped tank bottom. His interpretation of the experimental critical heights are contained in a later table (Table XXI). This issue is discussed again in the section on calculational validations.

His contention is that residual solution (≈ 1.3 l) remaining in low valleys of the tank's bottom between successive experiments *where the tank was not emptied of stainless steel tubes* should have been added to the published critical heights.

Specifically, he argues that whenever the lattice spacing was changed after a given experiment, the tank would have been emptied of all tubes and the tube spacer plates. At this moment, residual solution in these low valleys *could* have been wiped away back to storage. Then, the *next* experiment (at some new loading of stainless steel tubes) would have required the first 1.3 l of solution to create the same initial condition as subsequent experiments where it was not physically possible to wipe the bottom beforehand.

Four considerations shroud this proposal with uncertainty. First, record books do not indicate whether or not the tank's bottom was, in fact, wiped clean whenever the opportunity presented itself. I do not recall any cleaning being performed. I also recognize my own penchant for "clean" experiments; thus, I can not imagine that I did not do so. Adding confusion, I can not recall the existence of a tool for this purpose. Figure 8 shows such a tool used in the tank bottom mapping study; but the tool is not recalled to have been kept. It would have been heavily contaminated; and no storage location is visualized. Such cleaning probably was not done. In fact, I do recall a great deal of yellow cake and "slaking" present on the bottom of the tanks.

A second reason for not including these adjustments in the published critical heights is that the tank bottom possessed *both* valleys *and* mountains. Figure 8 shows this well. Dr. Tanner's proposal would quote the **maximum** height of the critical cylinder because it extended from the lowest point of the deepest valley. An opposite approach would have been to start the critical cylinder at the point where the *highest* mountain was completely filled. Both starting points, it is argued, are wrong. The "best" initial condition would have been some arbitrary situation near the beginning of an experiment where half the tank bottom was covered and half yet exposed. This was not used either. Referring, again, to Fig 9, about 37% of the tank bottom contained that 1.3 l of solution but the mountains of the other 63% still needed to be filled before volume increments would be linearly related to height increments.

A third reason is that those tubes which stood in the low valleys would have displaced some of that 1.3 l to some lesser volume. This reduction would have been equal to the volume occupied by the tubes out of the volume of solution in the valleys. Dr. Tanner's height adjustments did not include this factor. He increased all critical heights for experiments which did not have an empty tank just prior to it by 1.5 mm: $1.3 \text{ l} \div \text{the cross sectional area of the empty tank}$.

Finally, the fourth reason reflects this author's preference to present data with the least possible numbers of modifications. Rather than publish data derived from numerous and possibly questionable corrections, he prefers to publish data as close as possible to direct readings. Then, he describes possible corrections to be considered.

Philosophy of Height Measurements

The critical height of any vertical solution cylinder equals the elevation of the top surface, guaranteed by gravity to be both flat and horizontal, minus the elevation of the inside surface of the tank's bottom. That surface is more difficult to guarantee either flat or horizontal.

Two factors enter into measuring each surface:

- (1) determining *when* either condition exists, and
- (2) reading the measuring devices at that condition.

For example, when criticality existed, that condition was precisely known. Positive and negative reactor periods on either side bracketed that state within a small fraction of a millimeter. Reading height-related parameters there was as accurate and precise as the measuring tools themselves. The tank bottom, however, was a greater problem. Determining the best start of an experiment was not easy, even though reading its height-related parameters had the same accuracy and precision as the later critical height. In summary, the critical state was precisely identified and quite well measured. The tank's bottom, however, was not accurately identified even though whatever height was decreed to be the tank's bottom could be measured equally as well. Consequently, almost all uncertainty in reporting critical solution heights is attributed to the problem with the tank bottom.

NEUTRON ABSORBERS

A total of eight different neutron absorbers occupied various numbers of stainless steel tubes throughout the entire experimental program. The purpose of the program was to evaluate materials for potential application to production tanks at Rocky Flats. Such tanks would house possibly very high concentrations of fissile solution using the neutron absorption characteristic to render large storage configuration well subcritical. Absorbers would be individually contained in such a way that they, themselves, would not be contaminated; and use of one would not preclude another.

Poison Tube Tanks were never adopted at Rocky Flats. Consequently, the value in these data now lie in their use as a benchmark-quality experiment against which calculational methods may be compared.

Many absorbers could have been selected for this study. The basis for selecting them were:

- (1) an abundant isotope should have a high thermal neutron absorption cross section,
- (2) the material should be readily available as a commercial product,
- (3) it should be inexpensive,
- (4) the material should be suitable for fabrication into rods for easy insertion into tubes,
- (5) the material should be amenable to different forms of manufacture such that criticality could be achieved when *less* absorber was present, as in these experiments, and *more* material could be used to yield critically safe tanks. [Tanks would be constructed for plant applications by using *more* absorber.], and
- (6) the product should be non-toxic and easy for humans to handle.

Three rigid solid materials, one flexible solid product glued to a rigid tube, and four powdered materials were the eight selected which met all or most of these requirements. The three rigid solids were polyvinyl chloride (PVC) rods, borosilicate glass tubing, and cadmium metal sheet rolled into a tube-like geometry. The flexible product was a commercial rubber sheet composed of about 50% boron carbide and 50% silicone rubber. This product was called Boroflex™. To make rigid rods, thin sheets were wrapped around and glued to a mild steel tube. These were later slipped down inside the stainless steel tubes. The four powdered materials included: a) borax, a granular product often made into a commercial laundry whitener; b) an inexpensive boron-rich mineral mined in Death Valley called Gerstley Borate; c) a fairly common

commercial chemical compound: cadmium oxide; and d) a more uncommon and expensive chemical compound: gadolinium oxide. A fifth powdered material, boron oxide, was prepared but never used. The reason is somewhat humorous and is explained later.

Loose powders were funneled into paper tubes just enough smaller than the stainless steel tubes to slide down them easily. Each paper tube had a plastic cap glued inside the bottom to hold the powder in place. Another cap was merely press-fit into the top. Tubes were gently tapped against the floor during filling to maximize powder density.

Figure 14 shows short sections of the four solid absorbers, prepared especially for these photographs. Materials used were much longer rods. Figure 15 shows small quantities of three of the four powdered materials. These powders have been cast onto a dark surface for the photograph. Two granules exhibited a wide range of particle sizes from true powders to small chunks. To estimate granular sizes, each material is contained in a 30 to 40 mm diameter circle. A short section of paper tubing and the end cap is also shown in Fig. 15.

Glass Tubing

This product was purchased from a commercial scientific supply house as ordinary Pyrex²⁰ glass tubing sold for chemical laboratory use. Rods were $1219 \text{ mm} \pm 2.5 \text{ mm}$ long, significantly shorter than the length of the stainless steel tubes; but no experimental critical system using this absorber came close to the height of the glass. Rods were added and removed from tubes using a special tool created for the purpose. The handle, when squeezed, would expand a small rubber stopper attached to the bottom of the tool. The unexpanded stopper fit inside the glass rod near its top.

A dozen rods were measured at various points along their length to determine the diameter. The average outside diameter was $25.57 \pm 0.14 \text{ mm}$. The inside diameter averaged $17.88 \pm 0.14 \text{ mm}$; but these measurements were confined to ends. The commercial tube was advertized as having 3.97-mm-thick walls, slightly thicker than measured (3.845 mm). Six tubes were selected at random from each of 14 boxes and weighed; the average weight was $702.6 \pm 1.1 \text{ g}$. The boron content was measured by first intentionally breaking four rods. Shards from each rod were mixed such that a sample from this pile of broken glass would represent the entire rod. These four

²⁰ PYREX is a registered trademark of Corning, Incorporated, of Corning, New York.

Figure 14 Four rigid absorber rods include borosilicate glass tubing (upper left), solid PVC bar stock, boron-loaded rubber glued to steel pipe and overlaid with a vinyl wrap, and rolled tubes of cadmium metal (lower right).

Figure 15. Three of four granular absorbers include Borax (upper left), Gerstley Borate, and cadmium oxide (lower left). Gadolinium oxide is not pictured but resembled borax in texture. The paper tube and plastic end cap contain these loose materials.

samples were sent to a private, off-site laboratory to be analyzed for their boron oxide (B_2O_3) content expressed in weight percent. This was done by two methods with the following result:

Inductively Coupled Plasma method	12.45 ± 0.13
Manitol Titration method	12.66 ± 0.04

The latter, a wet chemistry procedure, is recognized as the most precise; but the former is much faster and less expensive.

Pyrex glass is very common. Its commercial composition is presented in the top portion of Table IX. This is the composition claimed by Corning Glass since 1938. Corning consistently tries to attain the nominal goal of 12.9 % boron oxide; but all analyses of finished glass made at Rocky Flats and elsewhere and by a variety of methods indicate the final product contains about 12.6 ± 0.2 % of this oxide.

Boroflex²¹

Boron-loaded flexible rubber sheet from which these neutron absorber rods were made was a commercial product called Boroflex, manufactured by Bisco Products in Illinois. It was composed of about 47% boron carbide (B_4C) and 53% silicone rubber. The particular elastomer used was a commercial product called Sylgard which was prepared from two components: Sylgard 170A and Sylgard 170B. The manufacturer claims the final elemental composition given at the bottom of Table IX. Restrictions on the release of proprietary information did not allow further elaboration of the composition.

Boron carbide, being so important in this product, was analyzed before being mixed with the elastomer. The composition, measured for two batches, proved to be 79.0 ± 0.1 % boron and 19.6 ± 0.1 % carbon for one batch and 79.1 ± 0.1 boron and 20.1 ± 0.1 % carbon for the other. Both showed small impurities of iron and calcium. The isotopic analysis of the boron was also measured for the same two lots:

²¹ Boroflex is a registered trademark of Bisco Products in Park Ridge, Illinois, now owned by Dow Corning of Midland, Michigan.

Table IX. Composition of Two Neutron Absorbers.

Pyrex Glass				
SiO ₂ 80.5%	Na ₂ O 3.8%	K ₂ O 0.4%	B ₂ O ₃ 12.9%	Al ₂ O ₃ 2.2%
Boroflex				
Boron			35.7%	
Hydrogen			2.4%	
Oxygen			19.6%	
Carbon			20.6%	
Silicon			21.6%	

^{10}B : 18.49 ± 0.06 and 18.50 ± 0.06 %

^{11}B : 81.51 and 81.50 %

These isotopic analyses were done per procedure ASTM C-791-80.

Sheet rubber was manufactured 1.024 ± 0.020 mm thick. One batch had a specific gravity of 1.7600 ± 0.0037 , another, 1.7581 ± 0.0014 . The areal density for the primary neutron absorbing isotope, ^{10}B , was 0.1 mg/mm^2 as determined by the manufacturer. The manufacturer also asserts that the boron carbide had a density of 2.52 mg/mm^3 while the density of the elastomer was 1.3761 mg/mm^3 .

This rubber was wrapped onto mild steel tubes by the same manufacturer, providing Rocky Flats with a finished product ready for use. The rubber was glued to the tubes before being encased in a very thin overlay of heat-shrinkable PVC plastic tubing. The mild steel tubes were 1574 mm long based on only one measurement; but all of the tubes were about the same length.

The average weight of one finished absorber, based on a set of ten, was 956 ± 5 g; and the average outside diameter from the same set was 22.26 ± 0.04 mm. The tubing was nominally 18 gauge (1.24 mm thick). The thickness of this PVC overlay is very difficult to measure; and the manufacturer of the heat shrink tubing, Insulation Plastic of Cary, Illinois, can not locate in their records - 10 years later - the thickness of the product supplied to Bisco Products. They best help they could provide was to note that this kind of tubing is currently available in 0.10, 0.15, and 0.20 mm thick. He suggests that the 0.15-mm-thick stock was the most likely to have been supplied but has no strong basis for this opinion. The composition of the glue used by Bisco Products to attach the sheet rubber to the mild steel tubing, likewise, is not known.

The rubber wrap was not perfect; a small gap existed along an element of the tube as a flat width of rubber was rolled onto the tube. This azimuthal gap was important to minimize because it formed a "slit window" through which neutrons could pass without interacting with absorber material. This gap was measured for three finished tubes selected at random as being visually representative of all tubes. The measured gaps were 2.5, 2.8, and 3.0 mm; thus the average gap exposed about 3.5% of a tube's circumference. This gap can be seen in the lower left portion of Fig. 14.

The finished diameter of these same three sample rods were measured at three heights and at three azimuths. The reason for this detailed concern over a constant diameter was because a flexible product such as rubber could result in some variation in actual diameters. This was not the case, however. The average of these nine measurements for these three tubes were: 24.86 ± 0.06 , 24.86 ± 0.11 , and 24.86 ± 0.18 , respectively, showing good constancy over the nine locations of a single tube and surprising agreement between tubes.

PVC Rod

Polyvinyl chloride (PVC) is a common industrial product; and rods of it were selected for this program because the material is so inexpensive and chlorine has a reasonably high thermal neutron absorption cross section. The compound can be manufactured in two slightly different forms differing in the amount of chlorine. Ordinary polyvinyl chloride, called PVC, is $\text{CH}_2\text{:CHCl}$. The other is "chlorinated polyvinyl chloride", or CPVC; and is thought to be $\text{C}_2\text{H}_2\text{Cl}_2$. The latter (CPVC) was purchased because chlorine was the important neutron absorbing nucleus; and it contains about 52% chlorine, stoichiometrically.

"Samples of these same rods were analyzed in a Rocky Flats Analytical Laboratory in the fall of 1996. This was associated with a plant application of the results contained in this paper. These tests yielded 69 ± 4 weight-percent chlorine in the CPVC rods. This was the result of 11 measurements on a single pellet prepared from 1.5 g of ground rod stock added to 1.5 g of plasticizer pressed into that pellet. Each measurement entailed flipping and turning the pellet to arrive at a more representative chlorine concentration. The analysis was by X-ray Fluorescence Spectroscopy using KCl as the standard. The calibration curve ranged from 7% to 40% chloride; so a dilution of 2:1 was prepared as described above."

Commercial bar stock in the "one inch" size was purchased in standard lengths (3.048 m). When cut in two, each long rod yielded two absorbers 1.524 m long. Assuming nominal diameter, these PVC rods should have slipped into the stainless steel tubes with about 0.35 mm radial clearance; but they didn't. Many did fit; but some did not. The fit problem was solved by having each of the 520 rods turned to 25.4 ± 0.08 mm in diameter. After that, all rods fit easily into any tube.

The weight was determined from a sample set of only 35 rods and was remarkably constant: 1072.4 ± 0.88 g. One final detail results from the fact that half a standard length was just a little shorter than the length of the stainless steel tubes. This would have made rod removal difficult. Each PVC rod was fitted with a concentric commercial metal screw eye such as is used on a screen door. This provided a grip to withdraw the rod easily.

Cadmium Metal

Absorbers of this metal were fabricated by cutting flat cadmium metal stock into long narrow strips. These were rolled into tubes suitable to slide over smaller-diameter stainless steel tubing as a "sleeve". The two annularly nested tubes were later slipped inside the larger stainless steel tubes which had housed all other absorbers. A small disk, slightly larger than the inner tube, kept the sleeve from slipping past the bottom. Cadmium metal sheet stock was not analyzed for other elements or impurities but was considered pure cadmium.

The specific material used had been part of other programs²². It had been glued to cardboard tubes years earlier. The recycled metal was cleaned of residual glue as well as possible; but, almost certainly, some impurities were introduced by this economy measure.

Cadmium is expensive and experimental plans did not call for an exhaustive study using this metal; so only 64 tubes were rolled. Each was about half the height of the experimental tank; so two lengths formed one absorber. Thus, only 32 such absorber rods could be made from the number rolled. The neutronic influence of this material was studied by "substitution" experiments. Here, the critical height with some absorber would be measured first; and then, a new critical height would be obtained after some portion of that first absorber had been replaced by cadmium.

These cadmium tubes were rolled from nominally 1.59-mm-thick stock. Each was 762 mm long. Only a very narrow gap existed where the rolled edges came close to meeting. This gap was not measured; but Fig. 14 (lower right) shows it to be small. The average weight of 24 pairs of cadmium sleeves was 1648 ± 12 g. The average combined weight of two cadmium sleeves and one stainless steel tube was 2734 ± 27 g. Subtracting the two, the weight of each stainless steel

²² "Experimental Critical Parameters of Enriched Uranium Solutions in Annular Tank Geometries" by **Robert E. Rothe** under DOE contract #C96-175866. Submitted April 30, 1996.

tube alone calculates to 1086 ± 30 g. The length of each stainless steel tube was 1575 mm; and the outside and inside diameters were 20.2 mm and 15.7 mm, respectively.

Paper Tubes

The four powdered absorber materials were contained in paper tubes to form rigid rods. Powders were held in place by a plastic end cap glued into the bottom. Both tube and cap are shown in the lower right photo of Fig. 15. Later, after being filled, another plastic cap would be press fit into the top.

The commercial tubes were wrapped around a 23.1-mm-diameter mandrel; so that defined the inside diameter. Paper tubes were formed from three spiral-wound wraps of 0.406-mm-thick paper covered with a thin overlay of another paper forming a total wall thickness of 1.22 mm. Three thousand such tubes were purchased to accommodate all the powdered materials planned. Neither the composition of the paper nor the glue is known this long after manufacture. The best recollection by the manufacturer many years after the fact is that the paper used was "a recycled paper board stock" and that the glue was "a cornstarch derivative much like paste". The assumption is that neither material was neutronically significant. Any composition of like products could be used in a computer simulation of these experiments.

Tubes were cut to length by the manufacturer; but two distinct lengths emerged from this process. Both were used in the program²³. "Longer" tubes were 1.572 ± 0.003 m long, the "shorter" averaged 1.521 ± 0.003 m. Both were used because no critical heights were expected to occur anywhere near the top of these absorber tubes; so any small variation in height would not matter significantly.

Empty tubes exhibited a large variation in weight. This is partly attributed to their different lengths. Tubes were delivered from the manufacturer in four batches, each of which differed in average weight. For over 100 samples each, the average weights were:

115.6 ± 2.1 , 111.6 ± 0.4 , 97.5 ± 1.1 , and 119.5 ± 0.7 g.

²³ All tubes containing the mineral mined in Death Valley were "short" tubes. All of the borax-loaded tubes were "long". About 70% of the tubes containing cadmium oxide were "long", the rest were "short".

These data suggest that three of the batches were "long" tubes while one was "short". Still, even the three batches of the same length differed significantly. The average of these four average values is 111 ± 10 g. Another entry in the record book states that the grand average for all 3070 paper tubes was 103.2 ± 8.5 g. Considering the large standard deviation of both average weights, the two are not in disagreement.

Good knowledge of this weight is also not terribly important. The procedure followed during the filling process was to weigh each empty paper tube plus its two, small, plastic, end caps before filling. Next the tube was filled with one of the several neutron absorber powders. Finally, it was weighed again immediately upon filling. The difference yields the weight of absorber powders and is independent of the weight of the specific paper tube. Throughout this document, that powder weight - averaged over tubes containing the same powder - is the one quoted.

Each plastic cap was nominally 22 mm in diameter, 24 mm high, and 0.76 mm thick; and each weighed 1.39 g. Bottom caps were glued in place with either of two adhesives: Permatex²⁴ or Duratite²⁵. Neither the detailed composition of the plastic or the glues is known; but both are assumed neutronically insignificant.

The packaging procedure began by lightly pressing a plastic funnel - machined to fit over a paper tube at the top - into place. Scoops of powder were poured into the funnel and allowed to flow into the paper tube under gravity. From time to time, settling was aided by lightly tamping the rod onto the floor and by tapping the side during filling. Some (it's not known which) were in contact at the bottom with a drug store vibrator during filling. All these tamping techniques were intended to increase the final density of the powder. When full to within a few millimeters of the top, the funnel was removed and the top plastic end cap inserted. Dust was wiped from the outside of the finished absorber rod before its final weighing.

The goal was to fill each tube such that the end cap would be flush with the end of the paper tube when pushed in as far as possible. This was seldom the case because usually the push would compact the last powder added just a little bit more. The depression of this cap inside the tube varied widely and is discussed specifically for each material.

²⁴ Registered trademark of Loctite Corporation, Kansas City, Kansas.

²⁵ Registered trademark DAP, Incorporated, Dayton, Ohio.

Gerstley Borate

This boron-rich mineral, mined in Death Valley, California, is called Gerstley Borate²⁶ by its supplier. It is a mixture of two minerals: Colmanite, a calcium borate, and Ulexite, a sodium/calcium borate. Colmanite's formula is $2\text{CaO} + 3\text{B}_2\text{O}_3 + 5\text{H}_2\text{O}$; and that of Ulexite²⁷ is $\text{Na}_2\text{O} + 2\text{CaO} + 5\text{B}_2\text{O}_3 + 16\text{H}_2\text{O}$. Gerstley Borate is thought of, by its distributor, as having a "crude composition". That is, the specific distribution between the two minerals and the inclusion of other, perhaps boron-free, minerals such as ordinary sand and dirt is not specified from batch to batch.

Figure 15 reveals that Gerstley Borate exhibited a wide range of particle sizes. The size distribution was determined as part of the elemental composition analysis. Four different bags from the original shipment were selected at random. Samples of between 700 and 1000 g were taken and sifted through a set of six USA Standard Testing Sieves having ASTM E-11 specifications. The weight percent of material **not** passing through (retained by) each of the six sieves is given in the top portion of Table X. The final entry is, of course, that which passed through the smallest sieve.

No obvious pattern of preferred particle sizes emerges from this table. All material fell through the coarse sieve; so all material had to ultimately reside in one of the six remaining possible states. The average of the last column is 16.67%; but this is no surprise at all because $1/6$ of 100% = 16.67%. The only interesting result is the standard deviation of the six percentages in the last column. It is $\pm 8.3\%$, half that average. Stated another way, a nearly uniform (within about 50%) distribution of particle sizes existed for this material from about the size of kernel corn down to that of face powder.

One bag (#4) was analyzed for boron content in each of the six particle size groups. A portion was ground into a fine powder and analyzed for boron in weight percent by D.C. argon plasma emission spectrometry. Because the boron content did not vary greatly as a function of

²⁶ Gerstley Borate is a commercial product sold by U. S. Borax, Incorporated, of Valencia, California.

²⁷ Another document, Rocky Flats Analytical Laboratory report # M80-774 dated November 17, 1981, suggests that the oxygen content of Ulexite contains 2 fewer oxygen atoms than that shown. It claims a total of 16 oxygen atoms in the mineral and 16 more associated with water of hydration instead of the 18 and 16, respectively, shown by the above formula. The truth is not known.

Table X. Properties of Gerstley Borate.

Particle Sizes						
Sieve No.	Opening (mm)	Material Remaining at Each Mesh				
		Bag 1	Bag 2	Bag 3	Bag 4	Average
3	6.680	0	0	0	0	0
8	2.36	39.9	17.6	29.9	17.1	26.1
12	1.70	11.2	6.74	7.67	6.75	8.1
20	0.850	16.4	15.5	14.9	17.0	16.0
40	0.425	9.50	16.3	12.6	16.4	13.7
100	0.147	10.3	23.5	17.6	23.4	18.7
passed through smallest		12.7	20.3	17.3	19.1	17.4
Totals		100	99.94	99.97	99.75	100
Boron Content in wt-%						
Bag #	Size	Boron Content		Weighted Average		
1	3 - 12	7.7		7.8		
	12 - 40	7.7				
	>40	8.0				
2	3 - 12	6.5		7.3		
	12 - 40	7.1				
	>40	7.8				
3	3 - 12	9.0		7.0		
	12 - 40	7.4				
	>40	6.7				
4	3 - 8	7.8		7.5		
	8 - 12	6.6				
	12 - 20	7.5				
	40 - 100	7.4				
	>100	8.0				
Impurities						
Impurity	Size					
	3 - 12	12 - 40	>40			
Absorbed Moisture	0.9	6.4	5.4			
Al	0.28	0.41	0.51			
Ca	17	16	12			
Mg	2.0	2.7	3.2			
Na	4.3	3.2	4.0			
Si	1.9	3.2	4.0			
Sr	0.31	0.40	0.38			
C	0.280	0.255	0.161			
S	0.0004	0.0002	0.0002			

particle size, the six sizes were combined into three according to sieve sizes (#3 to #12, #12 to #40, and less than #40) for the remaining determinations on the other three bags. Results are presented in the middle section of Table X. The weighted average was calculated by considering the weight fraction of the Gerstley Borate having the tabled boron concentration.

The grand average boron content for material from the four bags was $7.4 \pm 0.3\%$. The relative error of the boron-determination by the analytical procedure used is expected to be about five percent.

Calculating from the chemical formulae presented earlier in this section, Colmanite should contain about 16% boron and Ulexite about 13.6%. Neither agrees with the observed boron content (7.4%) suggesting that the two minerals were "diluted" with other fines - perhaps ordinary sand. Fifty percent mineral and an equal portion of sand would about explain the observed boron content of Gerstley Borate.

Bag #1 was also analyzed for absorbed water (not including water of hydration in the borate) and for metallic impurities including carbon and sulfur. Water content was determined by thermogravimetric analysis; and metallic impurities were estimated ($\pm 50\%$) by semiquantitative emission spectroscopy. Elements present in amounts greater than 0.1% by emission spectroscopy were then determined more accurately ($\pm 5\%$) by atomic absorption spectrophotometry. Carbon and sulfur were determined by furnace methods. These impurities are reported in the bottom portion of Table X.

A total of 464 tubes were filled with Gerstley Borate. The average weight of powder was 997 ± 13 g. This result was obtained from a complete set of measurements on all rods, not just a sample set. Consequently, the denominator of the standard deviation calculation used the full number of rods measured, not one smaller. About 80% of the rods ended up with their top cap flush with the end of the tube; but depressions for the others ranged from a couple of millimeters to about 29 mm. The average depression of the end cap was 9 ± 7 mm below the tube's top. Thus, the average effective length of the Gerstley Borate absorber within their "short" paper tubes was 1.512 ± 0.008 m.

Borax

This commercial product is a mineral found naturally as sodium tetraborate decahydrate; but the refined product sold as laundry whitener and for other purposes is sodium tetraborate pentahydrate. Its chemical formula is $\text{Na}_2\text{B}_4\text{O}_7 + 5\text{H}_2\text{O}$. The latter was the powder used in this program. Commercial borax is believed to be free of other mineral impurities; so the above chemical was all that was assumed present; however no chemical analysis was performed to confirm this assumption. With this assumption, the boron component of the total powder weight would have been about 15.2%. The material can also be seen from Fig. 15 (upper left) to be quite uniform in particle size.

A total of 454 tubes were filled with borax. The average weight, measured for all rods, was 751 ± 7 g. Only about 13% of the rods ended up with their top cap flush with the end of the tube. For the rest, the end cap was depressed from several millimeters to 48 mm below the end of the tube. The average depression was about 22 ± 13 mm. Thus, the average effective length of the borax absorber within their "long" paper tubes was 1.550 ± 0.022 m.

Cadmium Oxide

This commercial compound is assumed to be 100% cadmium oxide: CdO . It was assumed free of impurities, although no laboratory analysis was performed. The important neutron absorber is, of course, cadmium. Stoichiometrically, the oxide contains 87.5% cadmium. The material can also be seen by Fig. 15 (lower left) to be only fairly uniform in particle size. No analysis of particle sizes was done for cadmium oxide similar to that for Gerstley Borate.

A total of 317 tubes were filled with cadmium oxide. Of these, 230 were "long" tubes while the other 87 were "short". The average weight of the cadmium oxide powder, measured for all rods was 717 ± 27 g for the "long" rods and 701 ± 35 g for the shorter ones. Few tubes ended up with their top cap flush with the top of the paper tube. Most were depressed from a few to about 50 mm below the top of the paper tube. The average depressions for the two sets were 10 ± 8 mm and 29 ± 32 mm for the "long" and "short" tubes, respectively. Thus, the average effective length of the 230 "long" tubes was 1.545 ± 0.027 m and 1.492 ± 0.032 m for the few shorter ones.

Gadolinium Oxide

A small quantity of gadolinium oxide sand was on hand and was used in one critical experiment as a "replacement experiment". Here, a few rods of Boroflex absorber from one critical experiment were replaced by rods filled with this material. Then, a new critical height was measured. The change in critical height provided some comparison of the two absorbers. The important isotope in this case was ^{157}Gd with its quarter-million-barn cross section in the resonance region of neutron energies. Eleven tubes were prepared containing 1032 ± 22 g of gadolinium oxide each. The oxide is stoichiometrically calculated to contain 91% gadolinium.

Boron Oxide

A fifth powered absorber was *intended* but, ultimately, not used. Another 472 paper tubes were filled with commercial boron oxide about the same time other powders were loaded. This common and quite inexpensive chemical contains about 31% boron and seemed a likely candidate.

Boron oxide, however, is very hygroscopic. Between the time these rods were prepared (August, 1983) and three months later when they would have been used, this property came into full evidence. Figure 16 shows the surprising scene discovered one humid day.

Fig. 16

Figure 16. The hygroscopic nature of boron oxide prevented use of this material as a neutron absorber. In the short time between filling and first use, the powder absorbed enough water to cause the results shown.

RESULTS

The principal objective of this entire program was to evaluate a number of likely materials for use in a Poison Tube Tank design. This concept was thought to be a viable candidate to replace Raschig ring filled tanks at Rocky Flats. A second equally important goal was to document precisely the functional relationship between lattice spacing and critical height. These data could then be used to validate computational computer codes over a wide range of parameters.

The entire set of experimental results are expressed in Tables XI through XVIII. Eight tables (rather than just one long table) are used for clarity. Experiments with a given absorber are grouped together, one table for each material. Two other special groupings exist in the last two tables. All tables have many columns each; and, in an effort to enhance clarity, precise definitions of each are given later.

Each table is divided into sections by vertical heavy lines. Columns within each section are all related to one specific aspect of the experiment. Table XI serves as an example. The second section (second through sixth columns) pertains to that moment when the experimental system was slightly super critical and a long positive reactor period existed. Data for all three methods of obtaining heights are included to allow the reader to note the sometimes large disagreements. The next set of four columns pertain to the slightly subcritical phase. This reflects the *change* in height measured for a subcritical system. The single (11th) column contains the interpolated critical height claimed by this author. Its importance is emphasized by the use of bold face type. "Best" columns are the subjective judgement of the author; and critical heights are interpolated between them.

The last section blocked by heavy vertical lines, to the right of column 11, describes lattice characteristics. Many combinations of tubes and absorber rods were used. While spacer plates defined lattice spacing and the maximum number of tubes possible, some experiments had some tubes absent and, in some cases, absorber was *not* present even though stainless steel tubes were. Absorber rods were never used without stainless steel tubes.

Some tables are also divided by horizontal lines. For Tables XV and XVI, all tubes contained absorber for the upper set. The next lower block in Table XV presents the impact of removing bundles of absorbers, leaving stainless steel tubes in place. The lowest block of both

Tables attempt to compare square- and triangular-pitched arrays, suggested by the symbols in the 14th column

Heavy horizontal line of Tables XVII and XVIII divide data differently. The upper block of Table XVII shows data just for combinations of cadmium materials. The lower block presents two "substitution experiments" involving other materials. Table XVIII pertains to situations where regions of unpoisoned solution impact critical heights of an otherwise uniformly poisoned Poisoned Tube Tank. The upper block refers to single-unit containers alongside such a tank; the lower block considers a simulated rolling cart.

Column Definitions

The precise meaning of each column is described below beginning with the left hand side of each table:

Exp. # - The chronological sequence number of the experiment. Not all experiments achieved criticality; but even subcritical systems earned an experiment number because their subcriticality was not known *a priori*. A few even produced useful data. Useless experiments are never referenced in the text.

The next five columns pertain to that moment in an experiment when the system is slightly super critical and has a Positive Reactor Period.

Sight Gauge - This is not the height actually read on the Sight Gauge at criticality. Small adjustments to this have already been described and were applied to obtain the number shown. The Sight Gauge scale was significantly displaced (17 mm) from the tank bottom for the first five experiments. It was adjusted for the rest and this correction was reduced to only 0.3 mm. To be clear, tabled heights (believed accurate) are 0.3 mm smaller than those actually observed for Experiments #6 and beyond. Finally, any heights in excess of one meter received an additional 1.0 mm because the upper one-meter-long scale was not perfectly butted against the lower one.

Mass Flow Meter - This equipment was employed on all experiments from #16 through the end except for experiments #53, #54, #55, #57, & #58 when the device was not working properly. The mass of solution delivered is divided by the density of the solution (1.503 mg/mm³) and by the "effective area of the tank" to calculate the height. The "effective area" was the cross

sectional area of the tank less the number of stainless steel tubes in place times the cross sectional area of one tube²⁸. Finally, the height thus calculated was increased a small amount for the presence of the bottom tube spacer plate. This equaled the mass of that plate divided by a density of stainless steel (7.8 mg/mm₃) and that divided by the same "effective area".

Tank Volume Calib. Data - Storage tank volume calibration data was employed on all experiments from #5 through the end of the program. The volume delivered to the tank divided by the "effective area" described above gave the height. Again, this result was increased a small amount for the bottom plate as just described. Experiments #5 through #35 plus experiments #41 and #61 used the linear regression fit to the entire tank's calibration data to obtain the volume of solution in a tank at the start and finish of an experiment. All the rest of the experiments used a more accurate method of determining the volume in a tank. The better method used the raw tank calibration data as described elsewhere in the text.

"Best" Height - A subjective selection by the author of some height within the range of the three methods that best represents the true super critical height corresponding to a given reactor period. The number of significant figures entered in tables is an estimate of confidence in the value.

Positive Reactor Period - The e-folding time in minutes for the growth of the neutron flux at the slightly super critical condition. The exponential growth of this flux would be hard to verify without elaborate curve fitting techniques except that one recorder read out the natural logarithm of the instrument's input signal. The logarithm of an exponential growth function is, of course, a straight line. The linearity of this growth is easy to establish with any straight edge; and the slope of this line directly yields the reactor period.

The next four columns pertain to that moment when the system is slightly sub critical and has a Negative Reactor Period.

Sight Gauge - The observed *change* in the Sight Gauge as the experiment moved from slightly super critical to slightly subcritical. No corrections were made since this is a relative measurement. Fortunately, no critical height occurred precisely at one meter; so that correction did not come into play.

²⁸ $(\pi/4) \times (1066 \text{ mm})^2 - [\text{number of tubes}] (\pi/4) \times (28.45 \text{ mm})^2$.

Mass Flow Meter - A toggle switch allowed this device to measure reverse solution flow. It was reset to zero at the slightly super critical state. Then, a small amount of solution was allowed to leak away from the system back to storage through a small-diameter line. That returned mass divided by the density of the solution and the "effective area" gave another measure of the *change* in solution height.

"Best" Height - A subjectively determined average of the two measured decreases in height was subtracted from the "best" height for the positive reactor period. Generally this decrease favored the result obtained from the Mass Flow Meter; but the result from Sight Gauge data was considered.

Negative Reactor Period - The exponentially decreasing neutron flux was displayed on the same logarithmic recorder used for the positive period. The negative period was merely a straight line of opposite slope whose steepness inversely measured the negative reactor period.

The eleventh column reports Critical Height data. This is the ultimate parameter of this report - thus, bold face type.

Interpolated critical height - A linear interpolation between the two "best" heights, each at the *reciprocal* of the reactor periods. This procedure is discussed in the text.

Remaining columns which vary in number from table to table describe the Lattice Configuration.

Number of Stainless Steel Tubes Present - The actual number of vertical, parallel, and uniformly-spaced stainless steel tubes present regardless of the number which would have been allowed by the hole pattern of the spacer plates. When some eligible tubes were absent or present, but empty, this fact is noted via various symbols in Fig. 17. The figure serves many tables.

Percent (%) - The percent of the cross sectional area available to receive solution. This is the "effective area", defined above, divided by the area of the empty tank (expressed as a percentage).

Square Lattice Spacing - The center-to-center spacing between holes in spacer plates. When the pattern is fully loaded, this parameter also equals the spacing between tubes. Two experiments only (#61 & #62) had a triangular pitch; but this is documented by triangle symbols (D) for the two

Figure 17. Anomalous tube distribution patterns for several experiments throughout the entire field of tube positions are presented. Full patterns appear almost round; but square patterns (shaded) portray only the central region with the tank's center at the intersection of dashed lines. Various symbols represent different absorbers and vacant positions. Table references near the top correspond to the materials shown above.

tables involved. For square arrays, the center-to-center lattice spacing also equalled the edge-to-edge spacing between holes. Only the center-to-center concept really has meaning for square holes in triangular arrays.

Tubes Containing Absorber - The number of eligible stainless steel tubes that actually contained absorber rods. Figure 17 shows which tubes were empty (o) and which tubes were missing (blank or faint x). That figure is associated with several tables. It also shows which tubes contained cadmium metal sleeves (§), cadmium oxide (f) or gadolinium oxide (≈). Table XVII pertains to mixtures of two different absorbers on a single experiment; so an additional column there explains those combinations. Table XVIII always had a full compliment of absorber; so that column is headed differently for that table.

Unpoisoned Solution in Corner . Table XVIII pertains to large regions of unpoisoned solution intentionally placed alongside a Poisoned Tube Tank. Two studies involving unpoisoned regions are separated by a horizontal heavy line.

- (1) The upper six experiments studied the neutronic interaction between a fully poisoned tank and a bottle or pipe of unpoisoned solution. The tank had a full compliment of Boroflex absorber rods.
- (2) The last two experiments studied the influence of a simulated rolling cart containing four 4-liter bottles of fissile solution in close proximity to a heavily poisoned tank.

Table XI. Experimental Critical Heights: No Absorber.

Exp. #	Positive Reactor Period					Negative Reactor Period				Interpolated Critical Height (mm)	Stainless Steel Tubes Present	
	Height (mm) measured by...			“Best” Height (mm) positive period	Positive Reactor Period (min)	Change in Height (mm) as measured by...		“Best” Height (mm) negative period	Negative Reactor Period (min)			
	Sight Gauge	Mass Flow Meter	Tank Volume Calib. Data			Sight Gauge	Mass Flow Meter					
3	117.9			117.9	7.4				23.9	118 ^a	0	100
5	121.0		121.4	121.2	3.7	0.2		121.2	5.5	121.2	0	100
20	119.0	120.0	119.6	120	3.0	0	0.1	120	6.6	120	0	100
21	117.0	119.8	121.3	120	3.19	0	0.1	120	9.46	120	0	100
62	117.65	120.4	120.6	120.4	13.9	0	00.1	120.3	7.6	120.4	0	100
6	145.2		147.0	143	7.4	0		143	13.1	143	256	81.8
50	191	191.7	194.4	192	5.6	0	00.1	192	25.0	192	492	65.0

^a The correction to the height observed on the sight gauge scale may have been more uncertain than thought due to the bottom of the scale not coinciding with the bottom of the tank.

Table XII. Experimental Critical Heights: PVC

Exp. #	Positive Reactor Period					Negative Reactor Period				Interpolated Critical Height (mm)	Stainless Steel Tubes Present		Square Lattice Spacing (mm)	Tubes Containing Absorber No.
	Height (mm) as measured by...			“Best” Height (mm) positive period	Positive Reactor Period (min)	Change in Height (mm) as measured by...		“Best” Height (mm) negative period	Negative Reactor Period (min)					
	Sight Gauge	Mass Flow Meter	Tank Volume Calib. Data			Sight Gauge	Mass Flow Meter							
6	145.2		147.0	143	7.4	143.9		143	131	143	256	81.8	57.15	0
7	153.2		152.3	151	5.9	150.5	0.2	151	66	151	256	81.8	57.15	256
49	230.2	230.1	231.5	230	5.0	229	00.6	229	33	230	492	65.0	41.28	492
50	191	191.7	194.4	192	5.6	190	00.1	192	250	192	492	65.0	41.28	0

Table XIII. Experimental Critical Heights: Pyrex Glass.

Exp. #	Positive Reactor Period					Negative Reactor Period				Interpolated Critical Height (mm)	Stainless Steel Tubes Present		Square Lattice Spacing (mm)	Tubes Containing Absorber No.
	Height (mm) as measured by...			“Best” Height (mm) positive period	Positive Reactor Period (min)	Change in Height (mm) as measured by...		“Best” Height (mm) negative period	Negative Reactor Period (min)					
	Sight Gauge	Mass Flow Meter	Tank Volume Calib. Data			Sight Gauge	Mass Flow Meter							
6	145.2		147.0	143	7.4	0		143	13.1	143	256	81.8	57.15	0
8	193.2		199.8	194	3.7	0	02	194	10.6	194	256	81.8	57.15	256
17	242.1	245.2	245.9	245	12.0	1.2	0.1	244	14.9	244	332	76.4	50.80	332
44	400.2	402.4	408	402	14.6	0	00.4	402	13.9	402	432	69.3	44.45	432
51	809.2	806.4	812.2	806.5	6.7	02.5	02.9	803.8	9.7	804.9	492	65.0	41.28	492
50	191	191.7	194.4	192	5.6	0	00.1	192	25.0	192	492	65.0	41.28	0

Table XIV. Experimental Critical Heights:
Gerstley Borate.

Exp. #	Positive Reactor Period					Negative Reactor Period				Interpolated Critical Height (mm)	Stainless Steel Tubes Present		Square Lattice Spacing (mm)	Tubes Containing Absorber No.
	Height (mm) as measured by...			“Best” Height (mm) positive period	Positive Reactor Period (min)	Change in Height (mm) as measured by...		“Best” Height (mm) negative period	Negative Reactor Period (min)					
	Sight Gauge	Mass Flow Meter	Tank Volume Calib. Data			Sight Gauge	Mass Flow Meter				No.	%		
6	145.2		147.0	143	7.4	0		143	13.1	143	256	81.8	57.15	0
9	153.2		152.3	218	16.8	0	0.2	218	9.7	218	256	81.8	57.15	256
18	230.2	230.1	231.5	321	6.93	0.4	0.4	321	16.6	321	332	76.4	50.80	332
47	Subcritical near top of tank; but might extrapolate to criticality ^a										432	69.3	44.45	432
48	759.9	760.9	764.4	760	5.3	03.7	04.2	756	7.0	758	432	69.3	44.45	423 ^b

^a See Fig. 18

^b A central pattern of 9 tubes did not contain absorber. See Fig. 17.

Table XV. Experimental Critical Heights: Boroflex Rubber.

Exp. #	Positive Reactor Period					Negative Reactor Period				Interpolated Critical Height (mm)	Stainless Steel Tubes Present		Square Lattice Spacing (mm)	Tubes Containing Absorber No.
	Height (mm) as measured by...			“Best” Height (mm) positive period	Positive Reactor Period (min)	Change in Height (mm) as measured by...		“Best” Height (mm) negative period	Negative Reactor Period (min)					
	Sight Gauge	Mass Flow Meter	Tank Volume Calib. Data			Sight Gauge	Mass Flow Meter							
											No.	%		
19	313.2	320.6	319.3	320	4.8	05	06	319	9.05	319	332	76.4	50.80	332
57	444.4		453.0	446	9.9	01.2	0.3	445	5.77	446	376	73.2	47.63	376
22	1193.2	1201.1		1200	9	4.5	5.4	1195	42	1195	432	69.3	44.45	432
53	1080.2		1085.1	1081	10.3					1081	432	69.3	41.28 ^a	432 ^a
52	Subcritical near the top of the tank. Multiplication about 3										492	65.0	41.28	440 ^b
22	1193.2	1201.1		1200	9	4.5	5.4	1195	42	1195				432
27	1046.5	1045.4	1054.0	1045	9.2	02.3	03.2	1042	68	1042	↑	↑	↑	430 ^c
26	907.2	909.7	920.1	910	11.1	01.5	01.9	910	61	910	432	69.3	44.45	428 ^c
25	666	666.0	677.1	666	7.1	02	0.2	664	12.7	665	↓	↓	↓	423 ^c
23	577.4	578.3	584.0	578	6.3	1.5	1.5	576	8.6	577				420 ^c
57	444.4		453.0	446	9.9	01.2	01.3	445	5.77	446	376	73.2	□47.63□	376
61	471.7	474.3	481.5	474	5.5	01	01.2	473	11.6	473	374	73.4	Δ50.80Δ	374

^a The lattice spacing for the 492-tube uniform spacing with 60 SS tubes removed according to the pattern shown in Fig. 17.

^b Absorber-free SS tubes for experiments with 2,4,9, and 12 missing absorbers were located close to the center of the tank as shown in Fig 17.

^c The lattice spacing for which 52 absorber rods were removed leaving the empty SS tubes as show in Fig. 17.

Table XVI. Experimental Critical Heights: Borax

Exp. #	Positive Reactor Period					Negative Reactor Period				Interpolated Critical Height (mm)	Stainless Steel Tubes Present		Square Lattice Spacing (mm)	Tubes Containing Absorber No.
	Height (mm) as measured by...			“Best” Height (mm) positive period	Positive Reactor Period (min)	Change in Height (mm) as measured by...		“Best” Height (mm) negative period	Negative Reactor Period (min)					
	Sight Gauge	Mass Flow Meter	Tank Volume Calib. Data			Sight Gauge	Mass Flow Meter							
6	145.2	320.6	147.0	144	7.4	0	0.6	143	13.1	143	256	81.8	57.15	0
13	240.2		241.9	239	2.7	0.3	0.4	239	14.9	239	256	81.8	57.15	256
14	238.4		243.2	238	4.3	0.2	0.3	238	15.9	238	256	81.8	57.15	256 ^a
16	383.2	388.5	382.1	387	7.4	0.5	0.6	386	98	386	332	76.4	50.80	332
59	724.2	723.9	729.1	724	5.7	02	02.6	722	44.6	722	376	73.2	47.63	376
32	Subcritical near the top of the tank. Multiplication about 3										432	69.3	41.28	432
38	456.2	467.1	478.2	467	5.6	01.5	01.4	466	209	466	423 ^b	69.9	41.28 ^b	423 ^b
35	Subcritical near the top of the tank. Multiplication about 17										432	69.3	41.28	423 ^c
37	Subcritical near the top of the tank. Multiplication about 27										432	69.3	41.28	422 ^d
36	1444	1439	1449	1440	1.3	41.5		1398	22.7	1400	432	69.3	41.28	421 ^e
33	1087.2	1081.6	10.3	1082	17.4	07.0	07	1075	10.0	1079	432	69.3	41.28	420 ^f
34	658	658.6	658.6	658.6	24	03.2	03.3	655		657	432	69.3	41.28	416 ^g
59	724.2	723.9	729.1	729.1	5.7	02	02.6	722	44.6	722	376	73.2	□47.63□	376
60	855	853.1	859.7	859.7	30.8	02	02.3	851	12.6	852	374	73.4	Δ50.80Δ	374

^a Absorber tubes chosen at random rearranged by being exchanged one for another.

^b This is the lattice spacing for a full 432-tube pattern; but nine tubes and absorbers were absent. See Fig. 17

^{c-g} The central 16 eligible absorber positions had absorber rods removed as specified in Fig 17.

Table XVII. Experimental Critical Heights: Cadmium and Gadolinium

Exp. #	Positive Reactor Period					Negative Reactor Period				Interpolated Critical Height (mm)	Stainless Steel Tubes Present		Square Lattice Spacing (mm)	Tubes Containing Absorber No.	
	Height (mm) as measured by...			“Best” Height (mm) positive period	Positive Reactor Period (min)	Change in Height (mm) as measured by...		“Best” Height (mm) negative period	Negative Reactor Period (min)						
	Sight Gauge	Mass Flow Meter	Tank Volume Calib. Data			Sight Gauge	Mass Flow Meter				No.	%		No.	Kind
6	145.2		147.0	143	7.4	0		143	13.1	143	256	81.8	57.15	0	
10	175.7		175.4	174	3.0	0.5	0.2	174	4.9	174	256	81.8	57.15	256	CdO
11	176.6		180.6	175	3.6	0.4	0.2	175	8.8	175	256	81.8	57.15	232	CdO ^a
														24	Cd (metal)
12	176.2		179.2	175	5.77	0.1	0.2	175	11	175	256	81.8	57.15	232	CdO ^b
														24	Cd (metal)
53	1080.2		1085.1	1081	10.3					1081	432	69.3	41.28°	432°	Boroflex
55	794.2		801.2	796	17.7	01.3	01.3	795	18.5	795	432	69.3	41.28°	408	Boroflex
														24	Cd (metal) ^d
54	1014.2		1018.5	1015	10.2	03.5	03.7	1011	21.9	1012	432	69.3	41.28°	421	Boroflex
														11	GdO ^e

^a A central pattern of 24 SS tubes with their cadmium oxide absorber replaced by cadmium metal shown in Fig. 17.

^b The 24 cadmium metal absorbers were distributed among the cadmium oxide absorbers. See Fig. 17.

^c The lattice spacing for the 492-tube uniform spacing even though 60 SS tubes were removed for this experiment. See tube pattern in Fig. 17.

^d See Fig. 17.

^e See Fig. 17.

Table XVIII. Experimental Critical Heights:
Unpoisoned Regions Alongside Tank

Exp. #	Positive Reactor Period										Negative Reactor Period																		
	Height (mm) as measured by...					Tank Volume Data	Mass Flow Meter	Height positive (mm)	Positive Reactor Period (min)	Change in Height (mm) as measured by...	Mass Flow Meter	Sight Gauge	Height negative (mm)	Negative Reactor Period (min)	Interpolated Critical Height (mm)	Stainless Steel Tubes Present	Square Lattice Spacing (mm)	Absorb. In Each Tube	Unpoisoned Solution in Corner of Reflector Between Tank and Concrete or Unpoisoned solution on "Cart"	None	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart		
22	1193.2	1201.1	1155.1	1164.0	1155	1170	1138	1033	13.9	9	4.5	5.4	1195	42	1153	1166	1136	1031	432	69.3	41.28	None	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart
28	1157	1155.1	1169.6	1181	1170	1138	1138	1033	13.9	25.9	01	02.4	1153	70	1153	1166	1135	1031	432	69.3	41.28	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart	
31	1157.0	1155.1	1169.6	1181	1170	1138	1138	1033	13.9	10.9	03.5	03.9	1166	103	1166	1135	1136	1031	432	69.3	41.28	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart	
30	1118.7	1138.3	1138.3	1150.3	1170	1138	1138	1033	13.9	18.9	03	03.4	1135	22.6	1166	1135	1136	1031	432	69.3	41.28	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart	
29	1004	1033.2	1138.3	1045.1	1170	1138	1138	1033	13.9	9.2	02.5	02.0	1031	125	1166	1135	1136	1031	432	69.3	41.28	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart	
41	1302.2	1304.9	1303.2	1309.0	1305	1303	1303	1033	13.9	9.2	10.5	10.5	1294	56.0	1153	1166	1135	1031	1295	396	71.8	44.45 ^a	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart
42	1268	1266.0	1266.0	1272.5	1266	1266	1266	1033	13.9	18	05.5	05.4	1260	27.3	1262	1295	1295	1031	1262	396	71.8	44.45 ^a	One 4-liter bottle	108.3 mm dia. cylinder	135.3 mm dia. cylinder	162.8 mm dia. cylinder	Borax	Simulated "cart" but no solution	Four 4-liter bottles on the stimulated cart

^a Positions containing no symbol on Fig. 17 contained neither absorber nor stainless steel tubes. The 396 solid circles contained borox absorber rods.

Discussion

Table XI presents seven experimental critical heights for which *no* absorber was present. In the first five, no stainless steel tubes were even present; so the full cross sectional area (0.89283 m^2) of the tank would have been flooded with uranium solution. The geometry of these experiments ($D \approx 9H$) approximates that of a nearly-infinite slab of unpoisoned fissile solution. The last three of these five appear to be quite consistent with one another at about 120 mm. The first seems low; but a greater uncertainty is noted, possibly due to the 17 mm Sight Gauge bias. The second result (121.2 mm) is inexplicably greater than the consistent three, although the difference is only 1%. Still, this is considered large because the reactivity addition rate (Dr/DH) for such geometries is extremely sensitive. For example, the incremental height necessary to drive a delayed critical system into prompt criticality is about 1 mm.

The last two entries in Table XI illustrate the increase in critical height as the slab of fissile solution is interrupted by arrays of stainless steel tubes - even though *no absorber materials* are present. These cases approximate, by one model, a homogeneous slab of reduced-density fissile solution. An 18.2% "reduction" in solution density for Experiment #6 increased the critical height 19%. The last case, however, for which the density was "reduced" only 35% produced a 60% increase in critical height. That model does not work very well. A different model might expect that tubes merely *displace* volume and that the total *volume* of solution with and without empty tubes might be about the same. Experiments #6 and #60 test this hypothesis: (1) The critical height uninterrupted by tubes was about 120 mm; but 256 tubes of Experiment #6 would have displaced that same volume to a height of 147 mm. Yet, criticality occurred with only 143 mm of solution in the tank. (2) Beginning with the same initial condition, 492 tubes of Experiment #50 would have displaced that same volume to 184 mm. This time, criticality occurred at 192 mm of solution. The volume displacement model doesn't fit either case very well either. An interesting observation is that one case over estimates criticality while the other underestimates it.

Tables XII to XIV and the upper portions of Tables XV and XVI present the functional relationship between critical height and lattice spacing for five absorber materials: polyvinyl chloride (PVC), borosilicate glass (Pyrex), a boron-rich mineral called Gerstley Borate, a rubber sheet half loaded with boron carbide, and a common commercial powder containing boron (Borax), respectively. In several cases, an identical configuration including the stainless steel tubes but excluding the absorber is included for comparison.

Table XIV contains the first departure from an orderly progression to more absorber rods within a perfectly uniform periodic array of stainless steel tubes corresponding to increased critical heights. Experiment #47 (432 Gerstley Borate absorber rods) proved to be greater than the tank's limited height. Because of this, nine absorber rods subcritical even with the tank nearly full of solution. The critical-approach curve showed multiplications of 17.86, 13.85, and 10.00 at solution heights of 1.40, 1.15 and 0.90m, respectively. A graph of this non-linear data is inconclusive as to whether or not such a configuration would have been critical or only slightly subcritical if the tank had been taller. Because of this, nine absorber rods were removed according to the pattern shown for Experiment #48 in one column of Fig. 17. The stainless steel tubes remained; only the Gerstley Borate was absent from this 3x3 pattern. A critical height of 758 mm resulted.

The questionable nature of Experiment #47 is illustrated in Fig. 18. Its reciprocal multiplication curve is nearly linear and would extrapolate to a critical height of about 2.2 m. The uncertainty exists because experience suggests that the curve *may* have flattened out such that an infinitely tall tank might prove to be subcritical. The actual tank, itself, was not tall enough to resolve the issue.

Experimental results using Boroflex rubber absorber rods are displayed in Table XV. The first three entries follow that same progression where the number of stainless steel tubes present completely filled different lattice spacings and all tubes contained an absorber rod. Beyond there, departures from an orderly progression occurred. Experiment #52, which had 492 tube positions filled with 440 absorber rods leaving 52 empty positions, proved to be well subcritical with solution near the top of the tank. The pattern for these empty positions is also identified in the second section of Fig. 17. The multiplication was only about three. The next experiment had 60 absorber tubes **and** the corresponding stainless steel tubes removed according to the pattern illustrated to the right in the same section of Fig. 17. This arrangement, again, proved to be critical.

Two experiments had the same number of absorber rods (432). The one with a perfectly uniform lattice spacing (44.45 mm) yielded a critical height significantly greater (9.5%) than the case with regions of unpoisoned solution (Experiment #53). Evidently, reactivity could build up in these unpoisoned regions such that the uniform poisoning elsewhere was not effective at controlling reactivity. One theorem suggested by this observation is that *a uniform periodic*

Figure 18. The reciprocal multiplication curve for Experiment #47 could not determine whether or not criticality would have occurred had a taller tank been used.

distribution of any absorber material is more effective than an irregular distribution of the same absorber.

The next block of five experiments in Table XV contained the same pattern of 432 stainless steel tubes in a uniform lattice spacing of 44.45 mm. The first is a repeat of the third entry in the table; but the subsequent four report the consequence of removing 2, 4, 9, and 12 absorber rods, respectively. The locations of these absent Boroflex rods is displayed in the second section of Fig. 17. In the figure, only the central 16 tube locations are specified; all others (not shown) contained Boroflex rods. The critical height was about cut in half when a nearly circular cylindrical pattern of 12 absorbers were removed.

The final two entries of Table XV compared almost the same number of filled absorber positions (374 and 376) but for two different matrix geometries. One was triangular; the other, the more normal square-pitched array. Two fewer tubes at a greater triangular spacing yielded a more efficient poisoning since the critical height was higher than for the square array. A theorem resulting from this observation is that *a triangular pattern of the same absorber at the same lattice spacing is better than a square configuration.*

Experimental results for tubes of Borax powder are presented in Table XVI. The widest configuration (256 rods) was repeated with 20 absorber rods, selected at random, interchanged with one another. Both experiments yielded essentially the same critical height; so the conclusion is that these experiments were not terribly sensitive to the particular placement of specific absorber rods. The critical height increased steadily as the square lattice spacing reduced from 57.15 mm down to 47.63 mm. After the 47.63 mm grid, the next smaller (432 tubes) proved to be very unreactive; the full-tank multiplication was only about 3. In an effort to achieve criticality, absorber rods were pulled out, leaving stainless steel tubes behind, in five patterns shown in the third section of Fig. 17. These 16-tube segments represent only the very central 4x4 array of possible positions. The dashed lines intersect at the center of the tank. The remaining 416 positions all contained Borax. The faint x's (Experiment #38) correspond to the one case for this material for which both absorber and tube were absent. When nine were removed, the tank was much more reactive but remained subcritical. A tenth rod added some reactivity but not enough. One more removal (Experiment #36) yielded a very high critical height (1400 mm). Removing a 12th rod reduced the critical height significantly; but removing a total of 16 absorbers in a 4x4 pattern (Experiment #34) produced a quite low critical height. Evidently, this square column of

"reduced-density solution" (the stainless steel tubes were still present) was so reactive when "reflected" by heavily poisoned fissile solution that criticality occurred at a low height.

These experiments (removing bundles of absorber rods) yielded additional data of interest to a production plant. In such a plant, a Poison Tube Tank would need to be inspected periodically to assure continued serviceability. Ideally, this inspection would be less of a problem if the tank did not need to be taken out of service to perform it. A Poison Tube Tank, designed such that at least one rod at a time could be removed from the pattern without causing criticality, would satisfy that objective.

Experiments #35 and #38 make an interesting comparison. The former was a 432-tube pattern with nine absent absorbers but the tubes remained. It proved to be subcritical, although somewhat reactive. The former was identical except that the tubes were also removed. A very low critical height resulted. Evidently, the square column of completely unpoisoned full-density solution was very close to the dimensions of an infinitely long square column; but the same column was too small for the unpoisoned "reduced-density" solution. Both cases were "reflected" on all sides by uniformly-poisoned uranium solution.

The last two entries of Table XVI provide another comparison between square- and triangular-pitched arrays. As before, fewer absorbers at a wider spacing yielded a less reactive system. This agrees with one of the theorems suggested above.

Table XVII presents a potpourri of critical experiments. None represent a systematic evaluation of the relationship between lattice spacing and critical height. Instead, various combinations of absorber materials were used. The first four experiments compare cadmium oxide and cadmium metal. Experiment #10 contained 256 rods of oxide. The next had a central bundle of oxide rods replaced by cadmium metal according to the pattern described in the fourth section of Fig. 17. Experiment #12 had the same set of 24 cadmium metal rods about uniformly distributed throughout the field of cadmium oxide absorbers; Fig. 17 shows this pattern also. All these cadmium-only experiments had a wide lattice spacing; and critical heights were understandably low. They are so low, in fact, that observed differences in critical height may not reflect differences in materials very accurately.

The last three experiments of Table XVII present substitution experiments on one experiment (#53) listed in Table XV. This was the 432-tube study that involved Boroflex rubber;

and results are repeated here for comparison. When 24 rubber rods were replaced by cadmium metal according to the pattern given in Fig. 17 for Experiment #55, the critical height decreased sharply. Evidently, these cadmium metal absorbers were no where near as effective as these Boroflex rubber absorbers. On the contrary, replacing 11 rubber absorbers by tubes of gadolinium oxide reduced the critical height only a few percent. Evidently, these rods of gadolinium oxide bundled near the center as shown in Fig. 17 were only slightly less effective than the Boroflex rubber they replaced.

Another practical study was designed to approximate conditions found in a production plant. This considered the interaction between a highly poisoned tank containing fissile solution and a region of unpoisoned fissile solution. The concern was that a person carrying containers of fissile solution might approach a Poison Tube Tank; and the neutronic interaction between the two could cause an accident. Three common situations were studied: 1) a single 4-liter bottle of the solution carried by an employee close to a poisoned tank, 2) a solution transfer line or pipe of possibly large diameter which happened to pass reasonably close to the tank, and 3) a rolling transfer cart loaded with as many as four 4-liter bottles of fissile solution.

Approximations to these conditions were studied experimentally and are reported in Table XVIII. These experiments were conducted as "replacement" experiments. The initial condition for the first two situations was the 432-tube loading of Boroflex rubber rods of Experiment #22. For the first study, one 4-liter bottle filled with fissile solution was nestled close to the initially empty tank. Then the poisoned tank was filled. For the second, an empty long thin cylinder (three small diameters were studied) was nestled close to the tank. This was filled with solution along with the tank itself.

The bottle study began with filling a wide-mouth, commercial, 4-liter, polyethylene bottle with the same uranium solution later used in the tank itself. The full bottle contained 5940 g of uranium solution. The empty bottle weighed 262 g; so the total was 6202 g. Its outside diameter was about 152 mm which extended over about 200 mm of height. The overall height of the bottle, including its curvature at the neck and at the bottom, was 283 mm. The full bottle rested on a low-mass steel framework weighing only 2392 g and supporting the bottle 0.62 m above the top surface of the support table for the tank itself. The full bottle was pressed against the tank in one corner of the square concrete reflector by crushing a second (empty) bottle against it. This held the full bottle against the tank. This perturbation to experiment #22 lowered the critical height from 1195 mm to 1153 mm.

Figure 19 shows the author inspecting one of the long, thin, unpoisoned cylinders before installation alongside the tank. Three were fabricated, having inside diameters of 108.3, 135.3, and 162.8 mm. Each was placed, in turn, in the same space vacated by the removed 4-liter bottle apparatus. Cylinders were the same height as the tank itself. Contrary to the bottle study, these tanks were filled with solution at the same time the tank, itself, was. They were not filled first.

The smallest cylinder weighed 14.80 kg. Its wall thickness was 2.98 mm; and the outside diameter was 114.3 mm. The middle one weighed 17.85 kg, had a wall thickness of 2.98 mm, and had an outside diameter of 141.3 mm. The largest weighed 19.35 kg and had a wall thickness of 2.72 mm and an outside diameter of 168.3 mm. All were fabricated from commercial stainless steel pipe, type 304L (ASTM A-312). Each was open at the top but had a bottom disk welded to the cylinder. Each was supported by three mild steel legs to raise the bottom equal to the bottom of the tank.

The largest cylinder was located 3.7 mm from the west wall of the reflector and 7.5 mm from the south wall. This found the cylinder 4.8 mm from the tank itself. This cylinder reduced the critical height from 1195 mm (base case) to 1031 mm as solution was simultaneously admitted to both. The middle-sized cylinder was located 69, 91, and 46 mm from the same surfaces; and its presence only reduced the critical height to 1136 mm. The smallest cylinder had very little effect - even less than the one 4-liter bottle. It was 63, 136, and 48 mm from the same three surfaces; and the critical height was lowered only 29 mm from the base case.

Interestingly, the shorter-but-fatter 4-liter bottle at one point along the side of the tank possessed more reactivity than a much longer (but thinner) cylinder stretched the entire vertical length of the tank even though the less-reactive cylinder contained 2.6 times more volume than the bottle.

Another observation of qualitative interest emerges from these results. The three cylinders and their impact on critical height permit a speculation on the concept of "reactivity distribution". The smallest cylinder reduced the critical height only 2.4%. Increasing the diameter 25% doubled the reduction. The next increase (to only 51%), however, caused a nearly *6-fold decrease in critical height* over the first case. This may be viewed in terms of a mythical notion the author calls "the center of reactivity". This center would be at the precise center of the Poison Tube Tank for the base case. As unpoisoned cylinder diameters get larger and larger, this "center of reactivity" gets drawn closer and closer to the unpoisoned cylinder. At some diameter, this mythical "center"

Figure 19. The author examines one of the unpoisoned cylinders used to obtain results reported in Table XVIII.

gets sucked right into the unpoisoned cylinder itself. This shift continues with increasing cylinder diameters until the "center of reactivity" is just about at the center of the unpoisoned cylinder. Then, the cylinder alone is critical; and the poisoned tube tank appended to it contributes very little reactivity.

Figure 20 shows two views of the "simulated rolling cart" apparatus. One views the "cart" from above; the other, from below. Space for this "cart" was made by removing the entire east wall of the square reflector. This wall was absent only for the two experiments (#41 and #42) of this study. The "cart" was simulated by lengths of slotted steel angle stock and aluminum plates. Commercial, narrow-mouthed, polyethylene, 4-liter bottles were filled with the same fissile solution used throughout this program.

The four bottles contained 5921, 5936, 6090, and 6020 g of fissile solution; and these occupied the top right, top left, bottom right, and bottom left positions on the simulated "cart", respectively. The empty bottles weighted 449 g each for the upper pair and 425 g each for the lower. Empty narrow-mouth bottles were heavier than the wide-mouth one used in the bottle study; perhaps the wall thickness was greater.

The "cart" was composed of 7.8 m of slotted steel angle stock to represent the frame of the cart and a piece of 13-mm-thick aluminum (203 x 711 mm) representing each of two "shelves". Brackets holding the bottles weighed 133 g each. The calculated weight of all these pieces was 9.3 kg.

The four 4-liter bottles of the "simulated cart" experiment produced unexpectedly little change in critical height. The base case (Experiment #41) had one concrete reflector wall removed and a simulated "cart" but no fissile solution. The next (Experiment #42) had exactly the same configuration except that the four 4-liter bottles full of solution. The presence of the "cart" only decreased the critical height 2.5%.

Figure 20. Slotted steel angle stock was used to construct a "simulated cart". Four bottles of uranium solution were spaced from one another as they would be on a cart; but, unlike a cart, they were in contact with the tank. Two photographs show the apparatus from two angles.

UNCERTAINTIES

Solution Height

Certainly, the most significant uncertainty associated with this entire program is the critical height of the fissile solution cylinder. This is not the largest uncertainty, only the most important. The problem stems from defining the bottom of the tank. This is discussed in great detail in the SOLUTION HEIGHT Section. The top surface of the critical solution cylinder was guaranteed by gravity to be both flat and horizontal. For that reason, it could be very precisely defined. The bottom, however, was irregular; and it was difficult to determine a starting point accurately. The bottom also had an independent readability uncertainty. The vertical measuring scale was not aligned such that its bottom and the presumed bottom of the tank were co-planar. Thus, cylinder heights were necessarily the result of subtracting two readings. This second problem was also complicated by the imperfectly flat bottom of the tank. Finally, the possibility exists that the bottom may not have been perfectly horizontal nor the tank's axis perfectly vertical. They appeared correctly aligned; but small deviations could escape notice.

In contrast to these many sources of uncertainty, the height measurement scale was an engraved linear standard instrument certified against a secondary standard of the National Bureau of Standards. It was not likely to contribute much to any height uncertainty. In summary, any critical height quoted in this paper should have an uncertainty associated with it of ± 2 to 3 mm.

In spite of this relatively large uncertainty in *accuracy*, critical heights quoted in this paper are expressed at a *precision* associated with measurements at the top of the critical solution cylinder. This uncertainty is about ± 0.25 mm, a factor of ten better than the overall uncertainty! This policy recognizes that any one critical height may possess the larger uncertainty; but *relative* measurements (comparing changes in critical height between any two experiments) are free of the common bias associated with the uneven bottom. That is, both experiments would have the same systematic bias which would subtract away in any such comparison.

The precision of height determinations in the immediate vicinity of criticality is even better. The difference in height between a slightly super critical and a slightly subcritical configuration is so certain because it is obtained by measuring the mass of solution removed. Typical values of mass drained were about 2500 g with a precision of about ± 5 g. This translates into a height change of about 2 mm; but the uncertainty in that is an amazing ± 0.004 mm!

Elemental Composition

Accurate knowledge of elemental compositions of materials is most important in reporting experimental measurements. The closer an item is to the center of reactivity, the more important both accuracy and precision are. Improvements in calculational methods have exposed a subtle flaw in early experimental reporting into the 1980s. Experimentalists used to report compositions of materials only out to a distance felt, at the time, important. Often, walls of the experimental room would not be described because "they were too far away". As computational methods improved, however, experimenters were being contacted directly by those performing calculations for more details.

Another important issue with impact on both the *precision* and *accuracy* of an elemental analysis involves the question:

Is it better to sample a common material (type 304L stainless steel provides a good example) in one location and analyze that single sample; or is it better to quote the nominal manufactured composition of that well-defined and well-controlled material?

The question persists even if the number of samples is increased. Sampling is subject to manufacturing inhomogeneities resulting in a possibly non-representative sample. A related problem involves the uncertainty of that **one** analysis. Generally, most of these are accurate to only about $\pm 1\%$. Better confidence requires considerable additional effort and expense. Ideally, a large number of samples of each material would be obtained from a variety of locations and analyzed each a number of times to obtain an average and a standard deviation. Unfortunately, this elaborate study can seldom be afforded in actual practice²⁹.

On the other hand, assuming nominal values may define the actual situation more accurately because these common materials are bound by rigid manufacturing standards and are well-controlled during manufacture. Their composition would benefit from many years of closely controlled manufacture coupled with many, many analytical measurements over years. That,

²⁹ A second choice would be to quote the nominal composition and confirm that through an analysis of a single sample. The least certain option is to assume nominal composition and only confirm that through visual observation.

certainly, is much better than a single analysis of a single sample. If nominal compositions are used, certainly the mid-point of allowed (usually tight) composition ranges should be assumed.

This author asserts that most common structural materials are so well controlled in their manufacture that elemental composition for bench-marking purposes would be best approximated by quoting the nominal standard composition. Less common materials or those prepared specifically for a program do not fit this generalization. Examples would be the fissile solution, concrete, and earthen neutron absorber materials such as Gerstley Borate.

Statistics

Throughout this paper, the number of figures given in any parameter is an implied indication of its precision. A small uncertainty may exist in the last place of the number quoted; but no uncertainty should exist in the preceding place. This rule-of-thumb applies unless a measured average and standard deviation is given. In those cases, multiple measurements were obtained such that the average and standard deviation are deemed statistically reliable. The uranium solution concentration is one example. When given, standard deviations are expressed at the one-sigma confidence level unless stated otherwise.

CONCLUSIONS

The Poison Tube Tank is a feasible method of storing large volumes of fissile solution safely. It is at least as efficient as the Raschig ring filled tank³⁰. A Raschig-ring-filled tank houses solution in two-thirds of its capacity and can contain fissile solution of any reasonable concentration. It is possibly the most efficient storage method in common use today. A Poison Tube Tank, on the other hand, could even be designed to contain almost 90% of its capacity with solution! This marginal design, however, is not recommended; it would push limits of the safety envelope too much. Operators would have little leeway in handling absorbers or their spacing without causing an accident. Still, a very safe tank can be designed with little loss in efficiency. For example, a slightly closer lattice spacing with a wise selection of absorber could easily yield a Poison Tube Tank with 70% efficiency - even better than the best of today's options. It would be so safe that one or two absorber rods could be removed from the tank for inspection while the tank *remained in continuous service*. This would greatly enhance productivity because the tank would not need to be taken out of service for periodic inspection. Whatever inspections might be required could be accomplished by withdrawing one tube at a time while solution remained in the tank.

Inspections would be further simplified if absorber never contacted fissile solution. For the Poison Tube tank, the tubing separates the two. This mitigates the long-standing problem at Rocky Flats. There, contamination of Raschig rings with plutonium or uranium solutions has been a continuing problem since the 1950s.

The design would likely prove to have good liquid flow characteristics. Precipitates would not tend to collect within the tank as they do in the Raschig ring environment. Smooth, laminar flow into and out of a tank could be expected. This characteristic could lengthen the time required for homogenization - a possible shortcoming; but thorough mixing should take no longer in a Poison Tube Tank than in an unpoisoned vessel. Liquid flow properties expressed here are

³⁰ Here, the notion of "efficiency" is measured by the overall volume of fissile solution safely stored in a very large room. Efficiency is not just the volume fraction of a single container; a requirement to space containers from one another also reduces efficiency. For example, a single 4-liter bottle is critically safe at 100% capacity; but bottles must be well-spaced from one another. Such a method is not efficient. Raschig ring tanks only contain about two-thirds solution; but they do not need to be spaced. This is much more efficient.

conjecture; the author has done no experiments to establish these opinions. Another group³¹ within Rocky Flats did some experimental studies along this line in the mid-1980s.

Several readily available and inexpensive materials appear to be good candidates for fixed neutron absorbers in Poisoned Tube Tanks. Such tanks may be of arbitrarily large size containing solutions of almost arbitrarily concentrations of fissile material. Two of the better powdered materials were ordinary borax and the calcium borate mineral. Powders face a possible problem of settling. Gerstley Borate and other similar products are raw and unrefined minerals. Their elemental composition might vary from time to time and from location to location. A standard for defining minimum boron content would be indicated. No upper limit would be required.

Two other good materials were borosilicate glass and the boron-loaded silicone rubber. Both are solid and avoid the settling issue. The rubber rods have the added benefit that they bend easily as withdrawn. This reduces head height requirements above a tank. A tall tank poisoned with rigid glass rods would have to reside in a room more than twice as tall as the tank. One innovation would be to orient absorber rods horizontally so they could be withdrawn into aisle space adjacent to a tank.

Tables and figures published here do not immediately reveal the superiority of these two solid materials over the still-excellent granular ones. These experiments sought to *achieve* criticality, not prevent it as in a production setting. The purpose was to obtain the necessary safety data to validate criticality safety calculational methods. To permit criticality, the amount of material used was tailored to allow criticality. Often, space was wasted. The boron-loaded rubber, for example, was a relatively thin sheet wrapped upon a hollow tube. The glass tubing, likewise, was both hollow and thinner than Raschig rings, made of the same borosilicate glass. Critical heights were quite high even with this intentionally wasted space.

Production applications would not waste this space. They must necessarily remain sub-critical under all conditions. Solid Pyrex rods or solid rods of boron-loaded rubber would be much more effective. The two powders mentioned were effective poisons; but they were also present at about their maximum density.

³¹ Richard M. Saiki, Materials & Surface Technology, Building 881, Rocky Flats Plant, private communication.

Polyvinyl chloride proved to be a disappointing absorber. Even at the closest spacing studied, criticality occurred at a surprisingly low height. Chlorine does not have a huge thermal neutron absorption cross section. Although the use of boron oxide as an absorber was planned, the hygroscopic nature of the powder precluded its use. If selected, the material would have to be encapsulated. No experimental data is available for this material. The hygroscopic nature of boron oxide brings to light an important caution. Any granular material used must be analyzed for the consequences of possible water absorption.

Cadmium oxide was not adequately studied to determine its worth as a candidate material. At the widest lattice spacing, it was the second least effective material. Only PVC was less effective; but no material was much better at those wide spacings for reasons discussed below. Cadmium oxide was studied at closer lattice spacings only via one "substitution experiment". That is, only a few absorbers of one material (Boroflex) were replaced by rods of cadmium oxide. Then, the critical height for the first absorber was compared with that for the mixed loading of the first absorber and a few cadmium oxide rods. The study showed that cadmium oxide was much less effective than the boron-loaded rubber; but this may have been an unfair comparison. Boroflex proved to be one of the best absorbers. For this reason, the worth of cadmium oxide is not deemed to have been adequately investigated. Although worse than the best, it may still be good enough for some applications. Finally, one consideration may inadvertently justify this lack of further study, both cadmium oxide and cadmium metal, are hazardous materials. Handling them would be both expensive and complicated.

No material proved adequate at the widest spacing (57.15 mm). Even as the absorber lattice spacing decreased to 50.80 mm, critical heights grew only a little. Evidently, these wider spacings allow too much reactivity to accumulate in the cylinder of unpoisoned solution surrounded by even a number of widely-spaced absorber rods. The critical cylinder height almost equals the thickness of an infinite slab. This phenomenon may be understood by a neutron physics notion the author refers to as *piece-wise contributions of reactivity*.

To understand this, consider a very large homogeneous system that is just precisely critical - $k_{\infty} = 1.0000$. Any smaller - but still large - sub-region would also be critical. A smaller *piece* of the larger system is no less reactive than the infinite one provided it still is very large. In this analogy, the smaller piece may be viewed as "piece-wise critical". Another example further clarifies the point. If a truly large volume of fissile solution were just precisely critical, a few absorber rods widely spaced would not change the condition. The solution would be still be

"piece-wise critical" in the region between rods. This example more closely relates to slab-like critical heights for wide absorber spacings.

Mechanical designs for Poisoned Tube Tanks seem practical and well within current technology. Most designs would have absorber rods accessible from the top of a tank. Sealed-at-the-bottom tubes could rest on an unbroken tank bottom; or tubes open at both ends could pass through the bottom plane. Both designs are quite satisfactory. Tubes passing through the bottom could be welded in place; or they could be "roller expanded" in place to provide a leak tight joint. Roller expanding technology is well-developed in the United States. Using the former design (seal-welded tubes), they could be screwed into or flanged onto the tank's top surface to facilitate eventual replacement if that were ever desired.

Many designs are possible and practical. The Poison Tube Tank is very efficient in the use of floor space. It is inexpensive to build and easy to monitor. The concept has a viable future in the nuclear industry. Failure to adopt this design at Rocky Flats can be traced directly to an unresolved issue concerning a hypothetical situation. Welds are not flawless; they can leak. If the design featured tubes which penetrated the bottom, that leak could spread contamination to the floor of the room. This is undesirable to Radiation and Contamination Protection personnel. If the other design were selected (seal-welded tubes), that leak would contaminate the absorber rod itself. This concerned criticality safety personnel.

Certainly, compromise is possible. A valuable methodology should not be discarded because engineered solutions to simple problems are ignored. Both hypothetical situations can be dealt with easily. A bottom tray sealed onto the bottom of a tank with penetrations would contain contamination due to that hypothetical leak. A simple liquid sensor could detect the presence of unwanted solution inside a tube in the other case. Then, a flanged or screwed connection to the top of a tank could facilitate repair from that hypothetical leak by simply replacing the defective tube.

CALCULATIONS

These experimental results were compared against Monte Carlo calculations by two persons on two widely separated occasions in the years following the study. Both intended to validate computational methods then in current use against these results. Dr. Jerry N. McKamy was the first. He began in late 1983 and completed his effort early the following year. He was employed at Rocky Flats at the time and deeply involved in criticality safety there. His prompt calculations of still-unpublished data was intended to facilitate a planned plant-wide shift toward Poison Tube Tanks. These were to replace Raschig ring filled tanks in most applications at Rocky Flats.

Dr. McKamy documented his efforts in a preliminary report which is copied, almost *verbatim*, below. His words have essentially remained unaltered to preserve his opinions as closely as possible. Only units have been changed from centimeters to millimeters, figures re-numbered to fit the present document, and other minor editorial improvements incorporated. Some disagreement may be found between this author's numerical values and those used by him. Still, his are repeated whether or not they agree exactly with values reported elsewhere.

VALIDATION OF KENO-IV FOR POISON TUBE TANKS

J. N. McKamy

Preface:

The safe storage of high density fissile solutions in a cost efficient manner is a problem of continuing interest to the nuclear materials processing community. Criticality control has been achieved largely through the use of Raschig ring filled tanks; and this method has been extensively studied. In addition, many other methods have been studied including soluble poisons and poisoned annular tanks. Each of these methods presents its own set of compromises with respect to such concerns as cost and confidence in nuclear criticality safety calculations.

This paper reports benchmark calculations for Poison Tube Tanks using KENO-IV and Hansen-Roach sixteen-group cross sections. These calculations were performed in conjunction with the Poisoned Tube Tank experimental program conducted at Rockwell International's³² Rocky Flats Critical Mass Laboratory. The detailed results of the critical experiments are reported elsewhere in this journal.

Introduction

Little data exists in the literature directly addressing the criticality safety aspects of solution storage tanks containing fixed neutron absorbers in the form of rods. This paper reports benchmark calculations for a series of critical experiments performed in such a Poisoned Tube Tank. This study utilized 360 g/l highly enriched uranyl nitrate solution and a wide variety of neutron absorbing materials. This method appears to be quite promising with regard to maximizing useable solution volume and minimizing installation and maintenance costs while retaining a high level of confidence in the ability to use Monte Carlo codes to calculate criticality safety guidelines.

Monte Carlo codes such as KENO-IV have been used extensively to model systems containing highly enriched uranyl nitrate solution systems in the past. Handley, *et al.*, have reported a validation study for KENO-IV using Hansen-Roach sixteen-group cross sections for high-assay uranium systems. *A priori*, one would expect from their study that the code can be

³² Rockwell International operated Rocky Flats at the time of Dr. McKamy's report.

used reliably in calculations regarding the Poisoned Tube Tanks considered here. This is, in fact, the case; and data reported in this paper is consistent with and extends the range of the validation work of Handley, *et al.*

Calculational Method

The Poison Tube Tank consisted of a 1079.6-mm-outside diameter, 1520-mm-high cylindrical stainless steel tank containing rectangular (sic) lattices of poison tubes. The lattice pitches varied from 57.15 mm to 44.45 mm which contained 256 and 432 tubes, respectively. The tank was surrounded on four sides by 254-mm-thick concrete reflector. The tank rested on a 26-mm-thick mild steel table and was covered by a 24.4-mm-thick Plexiglas lid. This entire assembly was contained in a thin-walled stainless steel hood.

Because of the complexity of the system, Generalized Geometry was not used. Instead, the model was subdivided into an array of unit cells in the x-y plane of edge length equal to the lattice spacing. A top view of the model for the 44.45-mm lattice shows the 26 x 26 array of unit cells in Fig. 21. The task was then reduced to simply filling the unit cells with the appropriate materials and box types. The model was subdivided in the z-direction into six levels to accommodate divisions in the system caused by thin stainless steel spacer plates near the top and bottom of the tank that kept the tubes vertical at the correct spacing. In addition, box types were needed to partially fill the tank with solution. The (vertical) z-divisions of the model are shown in Fig. 22.

For the 44.45 mm lattice case, the model required an array of 26 x 26 x 6 box types. In a typical calculation, 48 different box types were required utilizing a total of 115 geometry cards. In all cases, 30,000 neutrons were tracked. The neutrons were started in a cosine distribution over the core or in a small cuboid in the center of the tank. The value of k-effective (k-eff) was insensitive to these changes in start type. Elemental number densities, expressed in atoms per barn-centimeter, for material compositions assumed in the calculations are shown in Table XIX.

The approximation used to model the tank was tested by running a calculation without the poison tubes in the tank. In this instance, the tank could be modeled exactly using routine geometrical shapes supplied by KENO. The values of k-eff for several solution heights were calculated and no differences were seen.

Figure 21. As an example, the horizontal description of the entire assembly for the 432-tube case was divided into 676 square unit cells in a 26 x 26 array. The size of each cell equalled the 44.45 mm lattice spacing for this tube array. The heavy circle shows the actual inside diameter of the tank; but the stair-step boundary of boxes shows the computer model which approximates it. The area of a 1066.8-mm-diameter (sic) tank would be 893 832 mm²; but the area of the model is 893 063 mm².

Figure 22. The vertical profile of the entire assembly was divided into six blocks named by numbers in heavy squares. The second box from the top was an afterthought; and its number is out of sequence. Materials are identified by various shadings and cross hatchings. Each is keyed to one definition somewhere on the drawing. All dimensions are in millimeters.

Table XIX. Isotopic Number Densities (atomic/barm-cm^b) Used in Calculations Performed at Rocky Flats

Non-Neutron Absorber Materials											
351.71 g/l Uranyl Nitrate Solution		Stainless Steel		Plastic		Concrete		Paper ^c		Combination of Uranium Solution and Metal ^d	
92400	9.400 (-6)	6100	2.623 (-4)	1102	5.688 (-2)	1102	1.040 (-2)	1102	5.431 (-2)	92400	2.900 (-9)
92508	3.133 (-4)	24100	1.699 (-2)	6100	3.555 (-2)	6100	6.459 (-3)	6100	3.233 (-2)	92508	9.399 (-8)
92509	5.407 (-4)	25100	1.121 (-3)	8100	1.422 (-2)	7100	1.000 (-5)	8100	2.694 (-2)	92509	1.622 (-7)
92600	4.000 (-6)	26100	5.986 (-2)			8100	4.306 (-2)			92600	1.200 (-9)
92852	2.750 (-5)	28100	7.538 (-3)			11100	2.554 (-4)			92852	8.250 (-9)
92853	2.110 (-5)	14100	1.377 (-3)			12100	8.509 (-4)			92853	6.330 (-9)
1102	5.820 (-2)	16100	2.830 (-5)			13100	1.067 (-3)			1102	1.746 (-5)
7100	2.163 (-3)	42100	9.000 (-6)			14100	7.814 (-3)			7100	6.488 (-7)
						16100	7.410 (-5)			8100	1.118 (-5)
						19100	2.681 (-4)			6100	5.882 (-5)
						20100	8.004 (-3)			26100	1.252 (-3)
						22100	1.460 (-5)				
						26100	2.052 (-4)				
Neutron Absorber Materials											
Gerstley Borate		Cadmium Oxide		Cadmium Metal		Borax		Boron Oxide ^e		PVC	
11100	1.532 (-3)	48100	5.176 (-3)	48100	4.651 (-2)	5100	8.929 (-3)	5100	1.840 (-2)	6100	2.816 (-2)
20100	3.388 (-3)	8100	5.176 (-3)			8100	2.680 (-2)	8100	2.951 (-2)	1102	4.390 (-2)
5100	6.077 (-3)					11100	4.467 (-3)			8100	8.251 (-4)
8100	3.480 (-2)					1102	2.231 (-2)			17100	1.139 (-2)
1102	2.277 (-2)										
13100	1.338 (-4)										
12100	9.787 (-4)										
14100	9.679 (-4)										
6100	2.266 (-3)										
26100	9.679 (-6)										
19100	1.390 (-5)										
3200	2.581 (-5)										
22100	1.882 (-6)										

a. The first number in each column is the isotope identification number used in the Hansen-Roach cross section set.

b. The number in parentheses is the multiplied exponent of ten. For example, 9.400 (-6) refers to a number density of 9.400×10^{-6} .

c. Cellulose, taken directly from the KENO manual.

d. A combination of uranium solution and metal with a density adjusted to account for extraneous material under the tank and uniformly distributed beneath the support table.

e. Boron oxide was not used in the experiments but was calculated

The real system was modeled as exactly as possible with no significant approximations. Extraneous steel and solution (in lines under the tank) were modeled as a uniform material under the tank between the table and the floor. The number of absorptions and fissions in this pseudo-void space were insignificant. The most significant environmental reflector neglected in the calculations was a vertical split table device located on the north side of the tank outside the 254-mm-thick concrete reflector. Calculations with varying reflector thickness indicate that all environmental reflectors outside the concrete have negligible impact on the calculated value of the multiplication.

Presentation and Discussion of Results

Thirty benchmark experiments have been modeled in this study. The average value of k -eff over all these is 1.00329 with an average statistical uncertainty of 0.00450. Values calculated by KENO for the experimental conditions are shown in Fig. 23 for each experiment performed. The full-width-at-half-maximum of the distribution is 0.01609. These results are consistent with those of Handley, *et al.* The worst case in terms of k -eff was for the empty tank which is essentially a reflected slab of solution. However, the experimental uncertainty of 3 mm (sic) is sufficiently large so that error bars overlap; and the calculated and experimental results are consistent. For this case, an error of 1 mm results in a change in k -eff of about one percent. The average neutron energy causing a fission was in all cases equal to the 14th energy group in the Hansen-Roach cross sections. This is indicative of a well-moderated solution system.

The critical heights calculated by KENO are less accurate³³ in general than the values calculated for k -eff. For critical heights in excess of a meter, the change in k -eff per millimeter change in solution height is, as expected, small.

Conclusion

The KENO-IV code with Hansen-Roach cross sections has been shown to be accurate for a wide range of Poison Tube Tank configurations. The results are consistent with other validation work previously reported. The average value of k -eff of 1.00329 indicates KENO results used in conjunction with nuclear criticality safety considerations can be applied without an unduly

³³ A k -eff of unity is achieved over a relatively broad range of solution heights in these cases because the neutron leakage does not change a large amount with a change in solution height near criticality [Ed].

Figure 23. The calculated k-eff for the experimental critical heights shows a small conservative bias for 16 cases and a non-conservative bias in 8. The largest non-conservative bias was for the empty tank of Experiments #20 and #21.

conservative bias. Indeed, the distribution of k-eff's shows a 99% confidence interval equal to 0.968. Hence, any calculation for a similar system yielding a value of k-eff plus 2s greater than or equal to 0.968 should be considered critical.

This ends Dr. McKamy's copied narrative but not his work. Table XX displays a comparison between experiments and calculations for 25 cases. Experiment numbers correspond to those in Tables XI to XVIII. Experimental critical heights are merely copied from those tables. The third column is the critical height calculated for the experiment as modeled by him; and the fourth is the value of k-eff calculated for the critical height reported.

Finally, one complete input deck for one experiment is attached as an example in the appendix. These computer-generated pages are merely copied to illustrate the calculational method. That example corresponds to a 256-tube array of Borax absorber rods. The tank model as described in Figs. 21 and 22 was modeled full of 357.71 gU/l (sic) uranyl nitrate solution to the height recorded in the experimental results tables. No explanation is offered as to why he used a concentration different than the 362.5 ± 3.4 gU/l quoted in an earlier section. The difference, however, is well within the analytical 1% uncertainty of either value.

The second calculational study was performed in the early 1990s by Dr. John E. Tanner. He was employed at the time at the Westinghouse Idaho Nuclear Company in Idaho Falls, Idaho. This effort was undertaken simply to broaden validations for three combinations of Monte Carlo codes and cross section sets used by his company.

Dr. Tanner and this author had many long conversations about precise implications of detailed procedures followed during experiments. These discussions were sometimes hampered by the decade which elapsed between experiments and his questions. The result of these conversations led him to question some published critical heights. He judged that certain experiments should have their height increased a very small amount. This adjustment came to 1.5 mm on some experiments.

His conjecture is that heights may have been determined differently depending on the condition of the apparatus just prior to the experiment in question. The uneven bottom of the tank precipitated his conjecture. He argued that the first time fissile solution was added to a *new* configuration of tubes, a different initial condition for determining the critical height existed than for subsequent experiments at that configuration. Those subsequent ones retained 1.3 l of solution

Table XX. Comparison Between Calculated and Experimental Results

Experiment Number	Experimental Critical Height (mm)	Calculated Critical Height (mm)	k-eff for Experimental Height (± 0.005)	Percent Error		Description
				in H_c	in k-eff	
05,20,21	~ 121	127.5 $\pm$ 0.8	0.95670	5.4	-4.3	empty tank
06	149.5	152.7 $\pm$ 1.1	0.98425	2.1	-1.6	256 empty tubes
07	154.1	156.8 $\pm$ 1.3	0.98939	1.8	-1.1	256 PVC
08	199.9	195.8 $\pm$ 2.1	1.00973	-2.1	1.0	256 pyrex
09	223.9	221.2 $\pm$ 3.2	1.00418	-1.2	0.4	256 Gerstly Borate
10	178.6	180.3 $\pm$ 1.6	0.99504	1.0	-.5	256 CdO
11	181.8	186.2 $\pm$ 5.9	0.98847	2.4	-1.2	cadmium, see Table
12	181.0	185.6 $\pm$ 2.1	0.988365	2.5	-1.2	cadmium, see Table
13	244.1	242.7 $\pm$ 3.2	1.00204	-0.6	0.2	256 Borax
16	385.2	362.2 $\pm$ 8.7	1.01178	-6.0	1.2	332 Borax
17	244.7	258.4 $\pm$ 3.9	0.98125	5.6	-1.9	332 Pyrex
18	319.4	297.9 $\pm$ 5.0	1.01960	-6.7	2.0	332 Gerstly Borate
19	318.7	317.8 $\pm$ 6.3	1.00067	-0.3	0.1	332 Boroflex
22	1194	1047.4 $\pm$ 66.1	1.00877	-12.3	0.9	432 Boroflex
23	581.2	558.0 $\pm$ 21.1	1.00460	-4.0	0.5	420 Boroflex
25	670	620.0 $\pm$ 23.1	1.00895	-7.5	0.9	423 Boroflex
26	913	862.9 $\pm$ 48.1	1.00448	-5.5	0.4	428 Boroflex
27	1048.5	872.7 $\pm$ 46.0	1.01342	-16.8	1.3	430 Boroflex
28	1159.4	1047.4 $\pm$ 66.1	1.00690	-9.7	0.7	Bottle of solution
29	1006.6	1047.4 $\pm$ 66.1	0.99710	4.1	-0.3	Large pencil tank
30	1120.4	1047.4 $\pm$ 66.1	1.00466	-6.5	0.5	Middle pencil tank
31	1155.7	1047.4 $\pm$ 66.1	1.00687	-9.6	0.7	Small pencil tank
32	subcritical	4296.5 $\pm$ 1372.8	0.97227	NA	NA	Small pencil tank
33	~ 1080	834.3 $\pm$ 48.8	1.01835	-22.8	1.8	420 Borax
34	~ 655	573.1 $\pm$ 20.1	1.01487	-12.5	1.5	416 Borax
35	subcritical	1132.2 $\pm$ 83.2	1.01447	NA	NA	423 Borax

on the uneven bottom surface of the tank unlike that first experiment. He assumed the tank would have been wiped dry of residual solution every time *all* tubes were removed leaving an empty tank. Whether or not this was done is neither recorded nor recalled.

The author contends that the point is moot in any case. Assuming the tank was otherwise perfect, the only deviation from a perfect right circular cylinder for the critical configuration would be the irregular bottom of the actual tank. It possessed a low valley and two high mountains due to welding warpage; but this problem is discussed several places throughout the text.

The *correct* place to define as the initial condition for this experiment would have been that unknown situation when

reactivity added by solution residing in the valley exactly equalled reactivity not yet added because of the high mountains³⁴.

That point is not known. Indeed, the fraction of the tank's valley to be covered to produce that best initial condition can never be known because the precise contour mapping of the bottom can never be determined. The best estimate comes from a set of 18 photographs, some of which are presented in Fig. 8.

If the "best" initial condition cannot be determined, then at least a *consistent* one would introduce no more than a systematic bias in critical heights. The initial condition assumed throughout this document is very close to that "best" initial condition. That is, critical heights published in Tables XI through XVIII began with about 37% of the tank's bottom containing 1.3 l of solution. The remaining 63% needed about 2 additional liters of solution before both mountains were flooded. That is a reasonable initial condition considering the above argument.

³⁴ An important observation which modifies this point is that a protruding "bump" on a critical geometry may add more reactivity than a precisely equal-sized depression would remove reactivity. This nuance becomes clear through the following illustration. An infinite critical slab with a slight protruding "bump" over a significant area is more reactive than a slab without the bump. That bump forms a thicker slab which determines reactivity. Conversely, an infinite critical slab with an equal-sized "depression" is still critical with absolutely no reduction in reactivity. The *rest* of the infinite slab is "piecewise critical" all by itself.

Increasing critical heights to account for the residual 1.3 l of solution, as Dr. Tanner did, is tantamount to quoting the *thickest* height of a right circular cylinder with one uneven surface. Dr. Tanner's heights are shown in Table XXI in bold face italics, ordinary font type reflects critical heights from this document. When no bold face italic value is given, his heights were the same as the current document. They should always predict higher values of k-eff because some solution presumed present was actually absent.

Table XXII reports his Monte Carlo calculations for his critical heights. Three combinations of computer codes and cross section sets are reported in the three columns. No details were provided as to the number of neutron histories followed and other details associated with the computational technique.

Table XXI. Suggested Corrections^a to Experimental Critical Heights of Tables XI to XVIII
as Proposed by Dr. John E. Tanner

No Absorber	PVC	Pyrex Glass	Gerstley Borate	Boroflex Rubber	Borax	Cadmium and Other Materials	Unpoisoned Regions Alongside Tank
Table XI	Table XII	Table XIII	Table XIV	Table XV	Table XVI	Table XVII	Table XVIII
118	143	143	143	319 320.9	143	143	1195
121.2	151 152.8	194 195.8	218 219.8	446	239 240.8	174 175.8	1153 1155.1
120	230	244 245.9	321 322.9	1195	238 239.8	175 176.8	1166 1168.1
120	192 194.3	402 404.1	758 760.1	1081 108.31	386	175 176.8	1136 1138.1
120 121.5		804.9 807.2		1195	722 724.0	1081 1083.1	1031 1033.1
120.4		192 194.3		1042 1044.1	466 468.1	795 797.1	1295 1297.0
143				910 912	1400 1402.1	1012 1024.1	1262 1264.0
192 194.3				665 667.1	1079 1081.1		
				577 579.1	657 659.1		
				446	722 724.0		
				473 475.0	852		

^a Results copied from the referenced tables are given to the left; and suggested better values are given in italics to the right. Where no second value is given, no correction was suggested. The basis for these correction are discussed in the text.

Table XXII. Calculated k_{eff} for Experimental Critical Heights as Adjusted in Table XXI.

Experiment Number	k_{eff}			Description
	KENO5.a, 16 gr	KENO5.a, SCALE, 27 gr	MCNP4A continuous	
3	$0.984 \pm .0028$	$1.007 \pm .0029$	$1.009 \pm .0028$	empty tank
6	$0.988 \pm .0026$	$1.011 \pm .0028$	$1.009 \pm .0033$	256 empty tubes
50	$1.000 \pm .0026$	$1.032 \pm .0026$	$1.036 \pm .0033$	492 empty tubes
19	$1.008 \pm .0021$	$1.018 \pm .0024$	$1.002 \pm .0029$	332 Boroflex
57	$1.001 \pm .0024$	$1.011 \pm .0023$	$1.007 \pm .0027$	376 Boroflex
23	$1.012 \pm .0024$	$1.019 \pm .0023$	$1.005 \pm .0029$	432 Boroflex
26	$1.015 \pm .0022$	$1.025 \pm .0022$	$1.004 \pm .0030$	432 Boroflex
27	$1.012 \pm .0021$	$1.018 \pm .0022$		432 Boroflex
22	$1.014 \pm .0021$	$1.016 \pm .0023$	$1.002 \pm .0028$	432 Boroflex
53	$1.004 \pm .0023$	$1.016 \pm .0023$	$0.988 \pm .0027$	432 Boroflex
49	$0.993 \pm .0024$	$0.991 \pm .0024$	$0.985 \pm .0030$	492 PVC
10	$0.978 \pm .0029$	$1.022 \pm .0028$	$1.007 \pm .0028$	256 CdO
11	$0.984 \pm .0028$	$0.996 \pm .0027$	$1.007 \pm .0031$	Cadmium, see Table
12	$0.984 \pm .0027$	$1.020 \pm .0029$	$1.014 \pm .0029$	Cadmium, see Table
8	$1.000 \pm .0026$	$1.022 \pm .0025$	$1.025 \pm .0024$	256 Pyrex
44	$1.007 \pm .0025$	$1.018 \pm .0022$	$1.017 \pm .0024$	432 Pyrex
51	$1.015 \pm .0022$	$1.022 \pm .0022$	$1.012 \pm .0021$	492 Pyrex

PROTOTYPE APPLICATION

The objective of this program was to establish the merit of the Poison Tube Tank design as a possibly viable means of safely storing large quantities of fissile solution of arbitrarily high concentration. The next goal was to establish a "best" lattice spacing to ensure criticality safety - that is, the periodic grid of parallel tubular regions containing a selected neutron absorbing material. Too large a spacing would compromise safety. Too small a spacing would decrease the fraction of the tank available for solution storage. The final task of this program was to evaluate several absorber materials in search of the "best" or, possibly, several "good", candidates.

The data suggested a Poison Tube Tank could be constructed that was at least as efficient as a Raschig ring filled tank. Ring-filled tanks are in abundant use at Rocky Flats. They safely contain fissile liquid to about two-thirds of the tank's capacity; but certain required inspection procedures prompted this search for an alternate procedure. Based on these favorable results, Rocky Flats set out to design and build its first Poison Tube Tank for use in a production application.

This first Poison Tube Tank was a 514 liter, stainless steel tank measuring 0.91 m in diameter by 1.28 m high. The tank's top and bottom surfaces were steeply sloped (15°) to aid drainage and minimize sludge collection. Though sloped, these two surfaces remained parallel. Figure 24 shows this tank shortly after its receipt at Rocky Flats. The top photo shows the tank lying on its side as delivered.

It had 300 uniformly spaced, parallel, vertical, stainless steel pipes which were designed to contain absorber rods. Each pipe had an outside diameter of 31.75 mm and 3-mm-thick walls. The square lattice configuration had a center-to-center spacing of 43.43 mm. The very symmetrical layout yielded four identical quadrants, each with 10, 10, 9, 9, 9, 8, 7, 6, 5, and 2 pipes, respectively, in rows. This pattern is obvious from the lower photograph of Fig. 24.

The pipes passed *through* both the tank's top *and* bottom surfaces. This was a design choice. It could have had an unbroken bottom plane with pipes, seal welded at the bottom, stopping at the inside top surface of this bottom plane. That design, however, was not chosen.

Figure 24. This first prototype Poison Tube Tank was delivered to Rocky Flats in the mid-1980's. It is shown here on its side. Unfortunately, the tank never saw service for reasons discussed in the text. The face view shows locations for 300 absorber rods.

The seal at the bottom had to be leak tight. This was accomplished by a procedure known as "roller expanding". Here, the pipe is positioned in a precisely machined hole. Then, a hardened steel ball, a little *larger* than the inside of the pipe, is forced into the pipe under great pressure. This squeeze causes the metal to cold-flow against the edge of the hole, forming the required seal. The quality of the seal was enhanced by first machining a double groove and a relief chamfer into each hole. This provided space for the steel to flow into forming "integral metal O-rings".

Roller expansion produces a leak-tight seal. Its use is even permitted in the nuclear industry for power plants for naval vessels. The decision was made at Rocky Flats, however, to back-weld each roller-expanded joint. This was thought to add safety by increasing confidence against leaks. This proved to be unnecessary and probably even unwise. Heat from welding warped a few pipes slightly out-of-round and compromised the integrity of roller-expanded joints. Even subsequent insertion of a few absorber rods became difficult; they could be forced in but could not easily be withdrawn.

The tank bottom design chosen followed many discussions related to safety. The safety group concerned contamination control wanted Poison Tube Tanks with seal-welded tubes resting on the bottom of an unpenetrated bottom. This would reduce the potential for contamination from a hypothetical leak. Criticality Safety specialists, on the other hand, required bottom penetrations to preclude fissile liquid ever contacting absorber rods. The hypothetical leak would pass harmlessly onto the floor causing no criticality concern. The conjecture was that leaks were inevitable; and leaks outside were preferred to those which would contaminate an absorber rod. This concept proved more persuasive; and the first tank followed that design.

Unfortunately, no engineered improvement to mitigate either hypothetical problem found favor; and interest in the Poisoned Tube Tank design eventually waned at Rocky Flats. This first prototype tank sat idle for several years. It never saw useful service. The unwanted vessel was latter given to another governmental facility in Idaho. Its service history there is unknown.

ACKNOWLEDGMENTS

This program was indeed fortunate to have several innovative scientists assisting in experiments and other phases of the program. Many have gone on to establish reputable careers in the nuclear safety industry over the following decade. These talented scientists included Dr. Richard E. Anderson, now the NIS-6 Group Leader at Los Alamos National Laboratory, Dr. Jerry N. McKamy, DOE HQ office of Engineering Assistance and Site Interface, EH-34. Dr. John S. Pearson, now a Deputy Division Leader at Lawrence Livermore National Laboratory, and Dr. Steven H. Manglos, no longer involved in the nuclear industry.

The author acknowledges the special efforts of two others. Howard C. Bachman (retired) kept electronic and mechanical equipment in good working order. His innovative abilities were used often to create unique measurement devices and to improve the quality of experiments. Gilbert J. Garcia served well as Radiation Protection Technologist to control radiation and fissile material contamination problems.

Two others deserve very special recognition. Each has performed an exhaustive calculational study of the experimental data, now contained in this document. Their task was not easy in the absence of a prompt formal publication of experimental results. A great deal of "personal communication" with the author was necessary. Portions of their work are included in one section of this paper. The first calculations were performed by Dr. Jerry N. McKamy, already mentioned above. His study was motivated by Rocky Flats' decision to obtain a prototype Poison Tube Tank for production use. Dr. John E. Tanner, now retired, performed the second set. At the time, he was a *Fellow Scientist* at Lockheed Idaho Technologies Company. He conducted his elaborate study in an effort to contribute to the ever-widening validation base of current computational methods used throughout the United States.

Peer reviews are essential to publishing quality data. The author thanks Dr. Jerry N. McKamy and Jerry E. Hicks for their careful review of the text.

Finally, the author acknowledges the patience of two persons at Lockheed Martin Idaho Technologies Company. Christine White composed the many figures found in the text, making them both clear and attractive. Peggy Shiffer prepared the tables. She, too, contributed clarity and accuracy to an attractive display. Confusing aspects of either are solely the author's responsibility.

Their task was further complicated by the necessity to collaborate by mail and telephone only since they and the author were separated by several hundred miles.

APPENDIX

The calculational study performed by Dr. Jerry N. McKamy is illustrated by one example calculation presented in Table XXIII. This is a copy of the computer-generated input deck for one of his calculations. Other calculations would have had quite similar input decks. This example happens to be for the 256-tube array filled with the Borax absorber. He used 357.71 gU/liter uranyl nitrate solution in his calculational model rather than the concentration quoted in the paper. The reason for this small difference is unknown.

The calculational study performed by Dr. John E. Tanner is much more complete. All 380 pages of Monte Carlo input and output data have been transmitted to the International Criticality Safety Benchmark Evaluation Project leader (J. Blair Briggs) at Lockheed Idaho Technologies Company; but they are not included in this paper.

Table XXIII. Selected Computer Input Data for One Calculation Performed at Rocky Flats.

POTTE - 256 TUBE ARRAY - 357.71 G/L U SOL. - BENCHMARK RUN - BORAX																				
20	110	300	10	16	6	XS	M	XS	115	48	20	20	6	XS	0	0	2010	00	1	82
1	92400	9.4	-6.	1	92508	3.133	-4	1	-92509	5.407	-4	1	92600	4.0	-6					
1	92852	2.75	-5	1	92853	2.11	-5	1	1102	5.8199	-2	1	7100	2.1626	-3					
1	8100	3.7254	-2																	
2	6100	3.169	-4	2	24100	1.6471	-2	2	25100	1.7321	-3	2	26100	6.036	-2					
2	28100	6.4834	-3	2	14100	1.694	-3													
3	1102	5.6884	-2	3	6100	3.5552	-2	3	8100	1.4221	-2									
4	1102	1.0401	-2	4	6100	6.459	-3	4	7100	1.00	-5	4	8100	4.3063	-2					
4	11100	2.554	-4	4	12100	8.509	-4	4	13100	1.0672	-3	4	14100	7.8138	-3					
4	16100	7.41	-5	4	19100	2.681	-4	4	20100	8.004	-3	4	22100	1.46	-5					
4	26100	2.052	-4																	
5	1102	5.431	-2	5	6100	3.233	-2	5	8100	2.694	-2									
***** THE MATERIAL BELOW IS A COMBINATION OF U SOL AND STEEL																				
***** WITH A DENSITY ADJUSTED TO ACCOUNT FOR THE EXTRANEOUS																				
***** MATERIAL UNDER THE TANK. IT IS UNIFORMLY DISTRIBUTED																				
***** BENEATH THE STEEL TABLE. THE NUMBER OF XS IS 49 WO POISON.																				
6	92400	2.9	-9	6	92508	9.399	-8	6	-92509	1.622	-7	6	92600	1.2	-9					
6	92852	8.25	-9	6	92853	6.33	-9	6	1102	1.7459	-5	6	7100	6.4878	-7					
6	8100	1.1176	-5																	
6	6100	4.754	-6	6	24100	2.4707	-4	6	25100	2.5982	-5	6	26100	9.054	-4					
6	28100	9.7251	-5	6	14100	2.541	-5													
7	5100	1.4323	-2	7	8100	2.5024	-2	7	11100	7.1642	-3									
BOX TYPE 1																				
CYLINDER	7	1.16	3.81	1.40	16Z															
CYLINDER	5	1.30	3.81	1.40	16Z															
CYLINDER	2	1.43	3.81	1.27	16Z															
CUBOID	1	2.8575	-2.8575	2.8575	-2.8575	3.81	1.27	16Z												
CUBOID	2	2.8575	-2.8575	2.8575	-2.8575	3.81	0.00	16Z												
BOX TYPE 2																				
CYLINDER	7	1.16	0.32	0.00	16Z															
CYLINDER	5	1.30	0.32	0.00	16Z															
CYLINDER	2	1.43	0.32	0.00	16Z															
CUBOID	1	1.43	-1.43	1.43	-1.43	0.32	0.00	16Z												
CUBOID	2	2.8575	-2.8575	2.8575	-2.8575	0.32	0.00	16Z												
BOX TYPE 3																				
CYLINDER	7	1.16	10.00	0.00	16Z															

BOX TYPE	9								
CUBOID	0	2.8575	-2.8575	2.8575	-2.8575	141.12	0.00	16Z	
BOX TYPE	10								
CUBOID	0	2.8575	-2.8575	2.8575	-2.8575	5.98	0.00	16Z	
BOX TYPE	11								
CUBOID	2	2.8575	-2.8575	0.525	0.00	3.81	0.00	16Z	
CUBOID	0	2.8575	-2.8575	5.715	0.00	3.81	0.00	16Z	
BOX TYPE	12								
CUBOID	2	2.8575	-2.8575	0.525	0.00	0.32	0.00	16Z	
CUBOID	0	2.8575	-2.8575	5.715	0.00	0.32	0.00	16Z	
BOX TYPE	13								
CUBOID	2	2.8575	-2.8575	0.525	0.00	10.00	0.00	16Z	
CUBOID	0	2.8575	-2.8575	5.715	0.00	10.00	0.00	16Z	
BOX TYPE	14								
CUBOID	2	2.8575	-2.8575	0.525	0.00	138.50	0.00	16Z	
CUBOID	0	2.8575	-2.8575	5.715	0.00	141.12	0.00	16Z	
BOX TYPE	15								
CUBOID	2	0.525	0.00	2.8575	-2.8575	3.81	0.00	16Z	
CUBOID	0	5.715	0.00	2.8575	-2.8575	3.81	0.00	16Z	
BOX TYPE	16								
CUBOID	2	0.525	0.00	2.8575	-2.8575	0.32	0.00	16Z	
CUBOID	0	5.715	0.00	2.8575	-2.8575	0.32	0.00	16Z	
BOX TYPE	17								
CUBOID	2	0.525	0.00	2.8575	-2.8575	10.00	0.00	16Z	
CUBOID	0	5.715	0.00	2.8575	-2.8575	10.00	0.00	16Z	
BOX TYPE	18								
CUBOID	2	0.525	0.00	2.8575	-2.8575	138.50	0.00	16Z	
CUBOID	0	5.715	0.00	2.8575	-2.8575	141.12	0.00	16Z	
BOX TYPE	19								
CUBOID	2	2.8575	-2.8575	0.00	-0.525	3.81	0.00	16Z	
CUBOID	0	2.8575	-2.8575	0.00	-5.715	3.81	0.00	16Z	
BOX TYPE	20								
CUBOID	2	2.8575	-2.8575	0.00	-0.525	0.32	0.00	16Z	
CUBOID	0	2.8575	-2.8575	0.00	-5.715	0.32	0.00	16Z	
BOX TYPE	21								
CUBOID	2	2.8575	-2.8575	0.00	-0.525	10.00	0.00	16Z	
CUBOID	0	2.8575	-2.8575	0.00	-5.715	10.00	0.00	16Z	
BOX TYPE	22								
CUBOID	2	2.8575	-2.8575	0.00	-0.525	138.50	0.00	16Z	
CUBOID	0	2.8575	-2.8575	0.00	-5.715	141.12	0.00	16Z	
BOX TYPE	23								
CUBOID	2	0.00	-0.525	2.8575	-2.8575	3.81	0.00	16Z	
CUBOID	0	0.00	-5.715	2.8575	-2.8575	3.81	0.00	16Z	
BOX TYPE	24								
CUBOID	2	0.00	-0.525	2.8575	-2.8575	0.32	0.00	16Z	
CUBOID	0	0.00	-5.715	2.8575	-2.8575	0.32	0.00	16Z	
BOX TYPE	25								
CUBOID	2	0.00	-0.525	2.8575	-2.8575	10.00	0.00	16Z	
CUBOID	0	0.00	-5.715	2.8575	-2.8575	10.00	0.00	16Z	
BOX TYPE	26								
CUBOID	2	0.00	-0.525	2.8575	-2.8575	138.50	0.00	16Z	
CUBOID	0	0.00	-5.715	2.8575	-2.8575	141.12	0.00	16Z	
BOX TYPE	27								
CUBOID	0	0.00	-5.19	0.00	-5.19	3.81			

CUBOID	0	0.00	-5.19	0.00	-5.19	138.50	0.00	16Z
CUBOID	2	0.00	-5.715	0.00	-5.715	141.12	0.00	16Z
BOX TYPE	31							
CUBOID	0	0.00	-5.19	5.19	0.00	3.81	0.00	16Z
CUBOID	2	0.00	-5.715	5.715	0.00	3.81	0.00	16Z
BOX TYPE	32							
CUBOID	0	0.00	-5.19	5.19	0.00	0.32	0.00	16Z
CUBOID	2	0.00	-5.715	5.715	0.00	0.32	0.00	16Z
BOX TYPE	33							
CUBOID	0	0.00	-5.19	5.19	0.00	10.00	0.00	16Z
CUBOID	2	0.00	-5.715	5.715	0.00	10.00	0.00	16Z
BOX TYPE	34							
CUBOID	0	0.00	-5.19	5.19	0.00	138.50	0.00	16Z
CUBOID	2	0.00	-5.715	5.715	0.00	141.12	0.00	16Z
BOX TYPE	35							
CUBOID	0	5.19	0.00	5.19	0.00	3.81	0.00	16Z
CUBOID	2	5.715	0.00	5.715	0.00	3.81	0.00	16Z
BOX TYPE	36							
CUBOID	0	5.19	0.00	5.19	0.00	0.32	0.00	16Z
CUBOID	2	5.715	0.00	5.715	0.00	0.32	0.00	16Z
BOX TYPE	37							
CUBOID	0	5.19	0.00	5.19	0.00	10.00	0.00	16Z
CUBOID	2	5.715	0.00	5.715	0.00	10.00	0.00	16Z
BOX TYPE	38							
CUBOID	0	5.19	0.00	5.19	0.00	138.50	0.00	16Z
CUBOID	2	5.715	0.00	5.715	0.00	141.12	0.00	16Z
BOX TYPE	39							
CUBOID	0	5.19	0.00	0.00	-5.19	3.81	0.00	16Z
CUBOID	2	5.715	0.00	0.00	-5.715	3.81	0.00	16Z
BOX TYPE	40							
CUBOID	0	5.19	0.00	0.00	-5.19	0.32	0.00	16Z
CUBOID	2	5.715	0.00	0.00	-5.715	0.32	0.00	16Z
BOX TYPE	41							
CUBOID	0	5.19	0.00	0.00	-5.19	10.00	0.00	16Z
CUBOID	2	5.715	0.00	0.00	-5.715	10.00	0.00	16Z
BOX TYPE	42							
CUBOID	0	5.19	0.00	0.00	-5.19	138.50	0.00	16Z
CUBOID	2	5.715	0.00	0.00	-5.715	141.12	0.00	16Z
BOX TYPE	43							
CUBOID	2	2.8575	-2.8575	2.8575	-2.8575	1.27	0.00	16Z
CUBOID	1	2.8575	-2.8575	2.8575	-2.8575	3.81	0.00	16Z
BOX TYPE	44							
CUBOID	2	2.8575	-2.8575	2.8575	-2.8575	0.32	0.00	16Z
BOX TYPE	45							
CUBOID	1	2.8575	-2.8575	2.8575	-2.8575	10.00	0.00	16Z
BOX TYPE	46							
CUBOID	0	2.8575	-2.8575	2.8575	-2.8575	3.58	0.00	16Z
CUBOID	3	2.8575	-2.8575	2.8575	-2.8575	5.98	0.00	16Z
BOX TYPE	47							
CUBOID	1	2.8575	-2.8575	2.8575	-2.8575	0.32	0.00	16Z
BOX TYPE	48							
CYLINDER	7	1.16	0.32	0.00				16Z
CYLINDER	5	1.30	0.32	0.00				16Z
CYLINDER	2	1.43	0.32	0.00				16Z
CUBOID	0	1.43	-1.43	1.43	-1.43	0.32	0.00	16Z
CUBOID	2	2.8575	-2.8575	2.8575	-2.8575	0.32	0.00	16Z
CORE BOY	0	57.15	-57.15	57.15	-57.15	161.55	0.00	16Z
CUBOID	0	58.34	-58.04	57.84	-58.14	161.55	0.00	16Z
CUBOID	4	83.74	-83.44	83.54	-83.64	161.55	0.00	16Z
CUBOID	0	83.74	-83.44	83.54	-83.64	161.55	-24.30	16Z
CUBOID	2	83.74	-83.44	83.54	-83.64	161.55	-26.90	16Z

***** INSERT THE EXTRANEIOUS MATERIAL REFLECTOR

CUBOID. 6 83.74 -83.44 83.54 -83.54 161.55 -161.3 162
 ***** BUILD THE HOOD AND FLOOR IN
 CUBOID 0 150.00 -150.00 340.00 -150.00 408.70 -161.30 162
 CUBOID 2 150.16 -150.16 340.16 -150.16 408.70 -161.46 162
 CUBOID 4 150.16 -150.16 340.16 -150.16 408.70 -191.46 162
 ***** FILL TANK WITH SOLUTION - NO TUBES

43 1 20 1 1 20 1 1 1 0
 47 1 20 1 1 20 1 2 2 1 0
 45 1 20 1 1 20 1 3 3 1 0
 9 1 20 1 1 20 1 4 4 1 0
 7 1 20 1 1 20 1 5 5 1 0
 46 1 20 1 1 20 1 6 6 1 0
 46 1 20 1 1 20 1 6 6 1 0

***** FILL THE VOID SPACES ON THE LEFT SIDE

6 1 7 1 1 20 19 1 1 1 0
 6 1 5 1 2 19 17 1 1 1 0
 6 1 4 1 3 18 15 1 1 1 0
 6 1 3 1 4 17 13 1 1 1 0
 6 1 2 1 5 16 11 1 1 1 0
 6 1 1 1 6 15 9 1 1 1 0
 6 1 1 1 7 14 7 1 1 1 0

 7 1 7 1 1 20 19 2 5 3 0
 7 1 5 1 2 19 17 2 5 3 0
 7 1 4 1 3 18 15 2 5 3 0
 7 1 3 1 4 17 13 2 5 3 0
 7 1 2 1 5 16 11 2 5 3 0
 7 1 1 1 6 15 9 2 5 3 0
 7 1 1 1 7 14 7 2 5 3 0

 8 1 7 1 1 20 19 3 3 1 0
 8 1 5 1 2 19 17 3 3 1 0
 8 1 4 1 3 18 15 3 3 1 0
 8 1 3 1 4 17 13 3 3 1 0
 8 1 2 1 5 16 11 3 3 1 0
 8 1 1 1 6 15 9 3 3 1 0
 8 1 1 1 7 14 7 3 3 1 0

 9 1 7 1 1 20 19 4 4 1 0
 9 1 5 1 2 19 17 4 4 1 0
 9 1 4 1 3 18 15 4 4 1 0
 9 1 3 1 4 17 13 4 4 1 0
 9 1 2 1 5 16 11 4 4 1 0
 9 1 1 1 6 15 9 4 4 1 0
 9 1 1 1 7 14 7 4 4 1 0

 10 1 7 1 1 20 19 6 6 1 0
 10 1 5 1 2 19 17 6 6 1 0
 10 1 4 1 3 18 15 6 6 1 0
 10 1 3 1 4 17 13 6 6 1 0
 10 1 2 1 5 16 11 6 6 1 0
 10 1 1 1 6 15 9 6 6 1 0
 10 1 1 1 7 14 7 6 6 1 0

***** FILL IN VOID SPACES ON THE RIGHT SIDE.

6 14 20 1 1 20 19 1 1 1 0
 6 16 20 1 2 19 17 1 1 1 0
 6 17 20 1 3 18 15 1 1 1 0
 6 18 20 1 4 17 13 1 1 1 0
 6 19 20 1 5 16 11 1 1 1 0
 6 20 20 1 6 15 9 1 1 1 0
 6 20 20 1 7 14 7 1 1 1 0

7	14	20	1	1	20	19	2	5	3	0
7	16	20	1	2	19	17	2	5	3	0
7	17	20	1	3	18	15	2	5	3	0
7	18	20	1	4	17	13	2	5	3	0
7	19	20	1	5	16	11	2	5	3	0
7	20	20	1	6	15	9	2	5	3	0
7	20	20	1	7	14	7	2	5	3	0

8	14	20	1	1	20	19	3	3	1	0
8	16	20	1	2	19	17	3	3	1	0
8	17	20	1	3	18	15	3	3	1	0
8	18	20	1	4	17	13	3	3	1	0
8	19	20	1	5	16	11	3	3	1	0
8	20	20	1	6	15	9	3	3	1	0
8	20	20	1	7	14	7	3	3	1	0

9	14	20	1	1	20	19	4	4	1	0
9	16	20	1	2	19	17	4	4	1	0
9	17	20	1	3	18	15	4	4	1	0
9	18	20	1	4	17	13	4	4	1	0
9	19	20	1	5	16	11	4	4	1	0
9	20	20	1	6	15	9	4	4	1	0
9	20	20	1	7	14	7	4	4	1	0

10	14	20	1	1	20	19	6	6	1	0
10	16	20	1	2	19	17	6	6	1	0
10	17	20	1	3	18	15	6	6	1	0
10	18	20	1	4	17	13	6	6	1	0
10	19	20	1	5	16	11	6	6	1	0
10	20	20	1	6	15	9	6	6	1	0
10	20	20	1	7	14	7	6	6	1	0

***** BUILD THE TANK WALL

19	7	14	1	1	1	1	1	1	1	0
20	7	14	1	1	1	1	2	2	1	0
21	7	14	1	1	1	1	3	3	1	0
22	7	14	1	1	1	1	4	4	1	0

35	6	6	1	2	2	1	1	1	1	0
36	6	6	1	2	2	1	2	2	1	0
37	6	6	1	2	2	1	3	3	1	0
38	6	6	1	2	2	1	4	4	1	0
19	5	5	1	2	2	1	1	1	1	0
20	5	5	1	2	2	1	2	2	1	0

21	5	5	1	2	2	1	3	3	1	0
22	5	5	1	2	2	1	4	4	1	0
35	4	4	1	3	3	1	1	1	1	0
36	4	4	1	3	3	1	2	2	1	0
37	4	4	1	3	3	1	3	3	1	0
38	4	4	1	3	3	1	4	4	1	0

35	3	3	1	4	4	1	1	1	1	0
36	3	3	1	4	4	1	2	2	1	0
37	3	3	1	4	4	1	3	3	1	0
38	3	3	1	4	4	1	4	4	1	0
23	2	2	1	5	5	1	1	1	1	0
24	2	2	1	5	5	1	2	2	1	0

25	2	2	1	5	5	1	3	3	1	0
26	2	2	1	5	5	1	4	4	1	0
35	2	2	1	6	6	1	1	1	1	0
36	2	2	1	6	6	1	2	2	1	0
37	2	2	1	6	6	1	3	3	1	0
38	2	2	1	6	6	1	4	4	1	0

23	1	1	1	7	14	1	1	1	1	0
24	1	1	1	7	14	1	2	2	1	0

25	1	1	1	7	14	1	3	3	1	0
26	1	1	1	7	14	1	4	4	1	0
39	2	2	1	15	15	1	1	1	1	0
40	2	2	1	15	15	1	2	2	1	0
41	2	2	1	15	15	1	3	3	1	0
42	2	2	1	15	15	1	4	4	1	0
23	2	2	1	16	16	1	1	1	1	0
24	2	2	1	16	16	1	2	2	1	0
25	2	2	1	16	16	1	3	3	1	0
26	2	2	1	16	16	1	4	4	1	0
39	3	3	1	17	17	1	1	1	1	0
40	3	3	1	17	17	1	2	2	1	0
41	3	3	1	17	17	1	3	3	1	0
42	3	3	1	17	17	1	4	4	1	0
39	4	4	1	18	18	1	1	1	1	0
40	4	4	1	18	18	1	2	2	1	0
41	4	4	1	18	18	1	3	3	1	0
42	4	4	1	18	18	1	4	4	1	0
11	5	5	1	19	19	1	1	1	1	0
12	5	5	1	19	19	1	2	2	1	0
13	5	5	1	19	19	1	3	3	1	0
14	5	5	1	19	19	1	4	4	1	0
39	6	6	1	19	19	1	1	1	1	0
40	6	6	1	19	19	1	2	2	1	0
41	6	6	1	19	19	1	3	3	1	0
42	6	6	1	19	19	1	4	4	1	0
11	7	14	1	20	20	1	1	1	1	0
12	7	14	1	20	20	1	2	2	1	0
13	7	14	1	20	20	1	3	3	1	0
14	7	14	1	20	20	1	4	4	1	0
27	15	15	1	19	19	1	1	1	1	0
28	15	15	1	19	19	1	2	2	1	0
29	15	15	1	19	19	1	3	3	1	0
30	15	15	1	19	19	1	4	4	1	0
11	16	16	1	19	19	1	1	1	1	0
12	16	16	1	19	19	1	2	2	1	0
13	16	16	1	19	19	1	3	3	1	0
14	16	16	1	19	19	1	4	4	1	0
27	17	17	1	18	18	1	1	1	1	0
28	17	17	1	18	18	1	2	2	1	0
29	17	17	1	18	18	1	3	3	1	0
30	17	17	1	18	18	1	4	4	1	0
27	18	18	1	17	17	1	1	1	1	0
28	18	18	1	17	17	1	2	2	1	0
29	18	18	1	17	17	1	3	3	1	0
30	18	18	1	17	17	1	4	4	1	0
15	19	19	1	16	16	1	1	1	1	0
16	19	19	1	16	16	1	2	2	1	0
17	19	19	1	16	16	1	3	3	1	0
18	19	19	1	16	16	1	4	4	1	0
27	19	19	1	15	15	1	1	1	1	0
28	19	19	1	15	15	1	2	2	1	0
29	19	19	1	15	15	1	3	3	1	0
30	19	19	1	15	15	1	4	4	1	0
15	20	20	1	7	14	1	1	1	1	0
16	20	20	1	7	14	1	2	2	1	0
17	20	20	1	7	14	1	3	3	1	0
18	20	20	1	7	14	1	4	4	1	0
31	19	19	1	6	6	1	1	1	1	0
32	19	19	1	6	6	1	2	2	1	0
33	19	19	1	6	6	1	3	3	1	0
34	19	19	1	6	6	1	4	4	1	0

15	19	19	1	5	5	1	1	1	1	0
16	19	19	1	5	5	1	2	2	1	0
17	19	19	1	5	5	1	3	3	1	0
18	19	19	1	5	5	1	4	4	1	0
31	18	18	1	4	4	1	1	1	1	0
32	18	18	1	4	4	1	2	2	1	0
33	18	18	1	4	4	1	3	3	1	0
34	18	18	1	4	4	1	4	4	1	0
31	17	17	1	3	3	1	1	1	1	0
32	17	17	1	3	3	1	2	2	1	0
33	17	17	1	3	3	1	3	3	1	0
34	17	17	1	3	3	1	4	4	1	0
19	16	16	1	2	2	1	1	1	1	0
20	16	16	1	2	2	1	2	2	1	0
21	16	16	1	2	2	1	3	3	1	0
22	16	16	1	2	2	1	4	4	1	0
31	15	15	1	2	2	1	1	1	1	0
32	15	15	1	2	2	1	2	2	1	0
33	15	15	1	2	2	1	3	3	1	0
34	15	15	1	2	2	1	4	4	1	0

***** FILL IN THE TUBES

1	4	17	1	5	16	1	1	1	1	0
2	4	17	1	5	16	1	2	2	1	0
3	4	17	1	5	16	1	3	3	1	0
4	4	17	1	5	16	1	4	4	1	0
48	4	17	1	5	16	1	5	5	1	0
5	4	17	1	5	16	1	6	6	1	0

1	8	13	1	2	19	17	1	1	1	0
2	8	13	1	2	19	17	2	2	1	0
3	8	13	1	2	19	17	3	3	1	0
4	8	13	1	2	19	17	4	4	1	0
48	8	13	1	2	19	17	5	5	1	0
5	8	13	1	2	19	17	6	6	1	0

1	6	15	1	3	18	15	1	1	1	0
2	6	15	1	3	18	15	2	2	1	0
3	6	15	1	3	18	15	3	3	1	0
4	6	15	1	3	18	15	4	4	1	0
48	6	15	1	3	18	15	5	5	1	0
5	6	15	1	3	18	15	6	6	1	0

1	5	16	1	4	17	13	1	1	1	0
2	5	16	1	4	17	13	2	2	1	0
3	5	16	1	4	17	13	3	3	1	0
4	5	16	1	4	17	13	4	4	1	0
48	5	16	1	4	17	13	5	5	1	0
5	5	16	1	4	17	13	6	6	1	0

1	3	18	15	6	15	1	1	1	1	0
2	3	18	15	6	15	1	2	2	1	0
3	3	18	15	6	15	1	3	3	1	0
4	3	18	15	6	15	1	4	4	1	0
48	3	18	15	6	15	1	5	5	1	0
5	3	18	15	6	15	1	6	6	1	0

1	2	19	17	8	13	1	1	1	1	0
2	2	19	17	8	13	1	2	2	1	0
3	2	19	17	8	13	1	3	3	1	0
4	2	19	17	8	13	1	4	4	1	0
48	2	19	17	8	13	1	5	5	1	0
5	2	19	17	8	13	1	6	6	1	0

***** FILL IN THE STEEL PLATE WHERE THE TUBES DONT FIT
***** THAT IS, IN THE "BLUE" SQUARES.

44	7	7	1	2	2	1	2	2	1	0
44	5	5	1	3	3	1	2	2	1	0
44	4	4	1	4	4	1	2	2	1	0
44	3	3	1	5	5	1	2	2	1	0
44	2	2	1	7	7	1	2	2	1	0
44	2	2	1	14	14	1	2	2	1	0
44	3	3	1	16	16	1	2	2	1	0
44	4	4	1	17	17	1	2	2	1	0
44	5	5	1	18	18	1	2	2	1	0
44	7	7	1	19	19	1	2	2	1	0
44	14	14	1	19	19	1	2	2	1	0
44	16	16	1	18	18	1	2	2	1	0
44	17	17	1	17	17	1	2	2	1	0
44	18	18	1	16	16	1	2	2	1	0
44	19	19	1	14	14	1	2	2	1	0
44	19	19	1	7	7	1	2	2	1	0
44	18	18	1	5	5	1	2	2	1	0
40	17	17	1	4	4	1	2	2	1	0
44	16	16	1	3	3	1	2	2	1	0
44	14	14	1	2	2	1	2	2	1	1

END KENO