W. R. STRATTON, "A REVIEW OF CRITICALITY ACCIDENTS," LOS ALAMOS
SCIENTIFIC LABORATORY REPORT LA-3611 (1967).

LA-3611

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

A Review of Criticality Accidents

This report expresses the opinions of the author or authors and does not necessarily reflect the opinions or views of the Los Alamos Scientific Laboratory.

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

A Review of Criticality Accidents

by

William R. Stratton

Abstract

A description of criticality accidents is presented along with a discussion of the characteristics of prompt power excursions. Thirty-four accidental power transients are described. In each case, enough detail is given to visualize the physical situation, the cause or causes of the accident, the history and characteristics of the transient, the energy release, and consequences, if any, to personnel and property. This review includes only those incidents which occurred before January 1967.

Table of Contents

I. INTRODUCTION[*]

Since the beginning of the atomic energy industry there have been no less than 34 occasions when the power level of fissile systems became uncontrollable because of unplanned or unexpected changes in the system reactivity. At least three of these power excursions were planned as such, but for various reasons the energy release was significantly larger than expected. Of these 34 cases, six caused eight deaths, two of which occurred in the early, rushed pace near the end of World War II.

It is hoped that this review will illuminate some of the causes of accidental excursions and aid to some extent our understanding of the physical phenomena that control their behavior. Such a study is of interest in itself, but of more importance is the possibility that in time we may be able to limit the magnitude of such excursions and minimize or eliminate radiation injuries and property damage.

---

[*]This chapter is the third edition of a review of criticality incidents. The earlier two are "A Review of Criticality Accidents," Progress in Nuclear Energy, Technology, Engineering, and Safety, Series IV, Vol. 3, Pergamon Press, New York, 1960 and "A Review of Criticality Incidents," Criticality Control, Karlsruhe Symposium, the European Nuclear Energy Agency, November 1961.

Of these 34 unexpected and often very complicated events, we may ask how many can be understood in a satisfactorily quantitative fashion. A brief answer is that it can be done in several cases. In others we can fix certain limits, and in a few we must restrict ourselves to qualitative statements of the events. A complete analytical description of all events would be interesting and satisfy our scientific curiosity; for some events, however, such a description probably never will be possible because of inadequate data.

This review attempts to include all those incidents in which, for some short time, the reactivity and fission power level were uncontrolled and increased independently of the efforts of the operators or experimenters. During many of these excursions the reactivity exceeded prompt critical, a most dangerous situation because of the possible very short periods for power generation, but, as will be seen, this criterion is neither necessary nor sufficent to guarantee personal injury or extensive property damage. Wherever possible, an estimate of the maximum reactivity will be made. It is realized that the list may not be complete, and, in particular, near misses--cases where a power excursion was narrowly averted--have not been discussed at all.

The causes and results of the several excursions will

be discussed qualitatively, arranged according to type, with some mention of their analyses (Section II), brief mention of the large amount of experimental and theoretical work in this field (Section III), and a summary of the contents of the review with an attempt at applications to production plant problems (Section IV).

II. THE ACCIDENTS[1-4]

Twenty-eight of the systems in which the excursions occurred can be classified according to three major types. These are (A) 10 water solutions of ^{235}U or ^{239}Pu, (B) nine metal assemblies in air, and (C) nine inhomogeneous light- or heavy-water-moderated metal systems. The remaining six assemblies are unique (in one case, unknown) and will be discussed under (D), Miscellaneous Assemblies

A summary of the data concerning these accidents is presented in Table I. For easy reference, the date, location, active material, geometry, number of fissions, cause, and resulting damage are listed.

II-A. Water Solutions of ^{235}U or ^{239}Pu

1. The Los Alamos Scientific Laboratory--December 1949[1,5-7]
   (Water boiler reactor, control rods removed by hand)

   This incident occurred while two new control rods (poisons) were being tested in the "water boiler" reactor.

The water boiler is a 12-in.-diameter stainless-steel
sphere containing 13.6 liters of a water solution of uranyl
nitrate. In 1949 it was reflected by a thick graphite
shield.

The rods had been installed, and the operator was
manually checking their dropping times. After several tests
of each rod individually, a safe procedure since one rod
was sufficient to maintain a subcritical reactivity, both
rods were pulled, held for about 5 sec and then dropped
simultaneously. A short time later the rods were pulled
again and dropped together a second time.

The removal of the two rods increased the reactivity
to about 3 cents* over prompt critical, corresponding to
a period of 0.16 sec. The power probably rose with this
period to a very broad peak of 2 or 3 x 10^{16} fissions per
sec and remained close to this value for about 1-1/2 sec.
The excursion was not detected immediately because all
equipment was turned off except for a a direct-reading
thermometer that showed a temperature rise of $25^{\circ}C$, equiv-
alent to a yield of 3 or 4 x 10^{16} fissions.

In this incident the operator received 2.5 R of gamma
radiation. No damage was done to the reactor.

---

*The dollar, or 100 cents, is defined as the reactivity in-
crement between delayed critical and prompt critical.

2.   The Hanford Works, Richland, Washington--November 16, 1951[8]

(Plutonium solution assembly, cadmium rod removed too rapidly, remote control)

The critical assembly in which the excursion occurred was a water solution of 1.15 kg of plutonium in the form of plutonium nitrate contained in an unreflected aluminum sphere 20 in. in diameter. The purpose of the experimental program was to determine the maximum safe mass of plutonium for various container geometries and solution densities. The excursion occurred during the approach to critical when the sphere was 93% full, as a result of withdrawing a remotely controlled hollow cadmium safety rod too rapidly in a series of steps with insufficient time between steps. The excursion yield was 8×10^{16} fissions, and a small amount of fuel was forced through gaskets at the top of the reactor assembly. As these gaskets sealed about 18 liters of air above the fuel level prior to the incident, pressures considerably in excess of atmospheric must have existed in the assembly during or immediately after the accident.

The published data suggest that the reactivity insertion rate resulting from the safety rod withdrawal must have been about 4.7 dollars/sec which would lead to a fission yield of about twice the observed value if known values of

temperature and void coefficients of reactivity are used.
In this case, however, the action of the scram circuit was
sufficiently fast that the cadmium rod most probably con-
tributed to the shutdown of the excursion. A slight reduc-
tion in the assumed reactivity insertion rate would lengthen
the time, making it even more certain that the excursion
was stopped by the falling poison rod.

In this excursion there was no personnel injury, but
plutonium nitrate solution contaminated the experimental
area. The rest of the building was successfully decon-
taminated in a few days, but before cleanup of the test
area was completed a fire occurred and the building was
abandoned.

3. The Oak Ridge National Laboratory--May 26, 1954[9]

(Uranium solution assembly, central poison cylinder

tilted from proper position, shielded and remote

operation)

The experiment in progress was one of a series in
which the critical properties of aqueous solutions in an-
nular cylindrical containers were being investigated. The
outer cylinder was 10 in. in diameter, and an inner cadmium-
clad cylinder was 2 in. in diameter. The system was unre-
flected and consisted of 55.4 liters of a water solution
of UO_2F_2 which contained 18.3 kg of enriched (93% ^{235}U)

12

uranium. The excursion occurred while the liquid level was at 40 in. and more solution was being added slowly to approach a delayed critical configuration. Figure 1 illustrates the experimental situation before and after the accident. The inner cylinder was essentially a poison rod, and when it became detached from its connection at the top and tipped to the side of the outer container, it fell to a less effective position, allowing the system reactivity to rise well over prompt critical, and causing a power excursion of 10^{17} fissions.

The reconstruction of this incident was most thorough. The tilting of the inner cylinder added reactivity to the system at a rate corresponding to 3.33 dollars/sec which continued well into the prompt critical region. Using known coefficients and generation times, an initial power spike[*] of 5.1 x 10^{16} fissions can be calculated. Since development of this power spike required only ~0.07 sec after the system reached prompt critical (0.43 sec after the cylinder began to tip), the cylinder was still falling, and it is characteristic of such incidents that after such an initial spike, the power adjusts to a value that cancels the reactivity insertion rate. For this solution, the required power was a

---

[*]The terms "power spike" and "plateau" are defined and discussed in Section III.

13

few megawatts and it must have been fairly constant until the inner cylinder reached its maximum displacement 0.91 sec after inception of the transient. At this time the power dropped sharply, and when the liquid began to drain the system became safely subcritical.

Because of thick shielding no one was irradiated in an amount greater than 0.9 rem, only a few tens of cubic centimeters of solution were displaced from the cylinder, and the area was returned to normal experimental use in 3 days.

4. The Oak Ridge National Laboratory--February 1, 1956[9]

(Uranium solution assembly, wave motion created by falling cadmium sheet, shielded and remote operation)

In this experiment certain reactor parameters were being investigated by measuring stable reactor periods. The system was a deep tank 30 in. in diameter, filled to a depth of 5 in. with 58.9 liters of water solution containing 27.7 kg of ^{235}U in the compound UO_2F_2. Transfer of solution from storage to the test cylinder was effected by the application of air pressure to the storage vessel, and flow was controlled by a remotely operated valve in a 1/2-in.-diameter line. With the control switch in the "feed" position, this valve was open and the air pressure was applied; with the switch in the "drain" position, the valve was also open, but the air supply was turned off and the

14

storage vessels were vented to the atmosphere. When the switch was in the intermediate "neutral" position, the valve was closed and the storage vessels were vented.

The situation was one in which the solution volume was about 100 ml less than the critical volume. An increment of solution was added, and the transient period decreased rapidly to approximately 30 sec at which it seemed to remain constant. Shortly thereafter the fuel control switch was placed in the "drain" position, and the period meter indicated a rapid decrease in period so that the safety devices were actuated almost simultaneously by both manual and instrument signal; the instrument trip point had been set at a 10-sec period. Immediately thereafter the excursion occurred. The burst yield was 1.6×10^{17} fissions, and in this case a "considerable volume" of solution was forcibly ejected from the cylinder.

Post-excursion tests showed that addition of solution to the reactor could have continued for several seconds after the control switch was placed in the drain position if insufficient time were allowed for venting the operation pressure. This addition of solution accounted for the decrease in period that precipitated the scram, but the increment of solution could not have added enough reactivity to account for the excursion.

It has been observed that the reactivity of such shallow, large-diameter assemblies is very sensitive to the solution depth but quite insensitive to changes in the diameter. For this system, the estimated difference between delayed critical and prompt critical is only 1 mm of depth. If the effective diameter were reduced to 20 in., the depth would have to be increased only 1/2 in. to maintain delayed critical. It is thought that the falling scram, a cadmium sheet slightly deformed at the bottom, set up a wave system which must have converged at least once and created a super-prompt critical geometry.

In this case the analysis was directed to finding what reactivity insertion rate would cause a power spike of the required yield. The analysis was then examined to see if it contradicted any known facts. It was found that a rate of 94 dollars/sec was adequate to cause a power spike of 8-msec duration over prompt critical, which would account for the observed yield. The maximum excess reactivity would be about 2 dollars over prompt critical, and the void volume could be 12 times that of case 3, thus easily accounting for the splashing of the solution.

A considerable volume of solution was ejected from the cylinder, requiring a laborious chemical decontamination of the assembly room. No damage was done except for distortion

of the bottom of the cylinder. No one was irradiated in an amount greater than 0.6 rem.

5. The Y-12 Chemical Processing Plant, Oak Ridge, Tennessee--June 16, 1958[10-12]

(Uranium process solution combined with wash water in 55-gal drum, unshielded operation)

The nuclear accident occurred in a processing area in which enriched uranium was recovered from various materials by chemical methods in a complex of equipment. This recovery process was being remodeled at the time, and the situation was further aggravated by an inventory then in progress. The inventory required disassembly, cleaning, reassembly, and leak testing of certain pieces of equipment, particularly several long, 5-in.-diameter pipes used for storage of aqueous solutions of ^{235}U. The shape and dimensions of these pipes were such that contained solutions could not become critical. The inventory procedures extended over several days, and operations had been reestablished in the step immediately ahead of the accident area. As a consequence of this close overlapping of operations and irregularities in the function and operation of some valves, a quantity of enriched uranium solution was inadvertently transferred from the area already in operation into the one still undergoing leak testing. It has been

established that the flow pattern from the storage pipes
into a drum intended to receive water that had been used for
leak testing was such that the accumulated solution preceded
the water. The dimensions of the 55-gal drum (about 22 in.
in diameter) permitted the solution to become critical.
Further flow of water first increased the uncompensated
reactivity[*] for about 11 min, then decreased it, and the
solution became subcritical after about 20 min.

When the system became critical the solution volume is
thought to have been 56 liters, a cylinder 23.45 cm high and
55.2 cm in diameter. The ^{235}U mass at this time was 2.1 kg;
0.4 kg was added later when water was diluting the system.
During the excursion a radiation detection instrument con-
sisting of a boron-lined ionization chamber, amplifier, and
recorder was operating about 1400 ft away and cross wind
from the area of the accident. The trace shows that the
radiation intensity first drove the pen off scale and about
15 sec later drove it off scale again. During the next 2.6
min, the trace oscillated an indeterminate number of times.
It is possible that these oscillations were decreasing in
amplitude, but this cannot be proved by examination of the
trace. This average high intensity field was followed by

---

[*]It is convenient occasionally to discuss the reactivity which
would pertain to a fissile system if the state of the system
were not altered by its power. This is referred to as the
"uncompensated" reactivity.

a slowly decreasing level, described as about five times background, for 18 min.

The power history can be reconstructed only qualitatively. The most likely source of initiation was neutrons from the reaction ^{16}O (α,n) ^{19}Ne between ^{234}U alpha particles and the oxygen in the water, so that it is possible that the system was over prompt critical before the first excursion started. The reactivity insertion rate was about 17 cents/sec at this time, a relatively low value, and the first spike must have been determined by the reactivity attained when the chain reaction started. Though there is no way to estimate this, a reasonable guess is that the first spike contributed about 10^{16} of the total yield of 1.3×10^{18} fissions. The second oscillation or spike (which also drove the recording pen off scale) occurred in 15 sec, a quite reasonable time for existing bubbles to have left the system. The oscillations for the next 2.6 min appeared to be no greater than about 1.7 times the average power.

The power trace suggests that most of the fissions occurred in the first 2.8 min, in which case the average power required to account for the observed yield is about 220 kW. After this, the system probably started to boil, causing a sharp decrease in density and reactivity and reducing the power to a low level for the final 18 min.

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

6. The Los Alamos Scientific Laboratory--December 30, 1958[13,14]

(Separated phases in plutonium process tank, unshielded operation)

The operations underway at the time of this incident were those chemical steps used to purify and concentrate plutonium from slag, crucible, and other lean residues resulting from recovery processes. Typical and expected solutions contained less than 0.1 g/liter plutonium and traces of americium.

At the time of the accident, a physical inventory was in progress so that the normal flow into the area was interrupted, and residual materials in all process vessels were to be evaluated for plutonium content. Reconstruction of significant events indicates that plutonium-rich solids, which normally would have been handled separately, were washed from two other vessels into a single large vessel that contained dilute aqueous and organic solutions. After removal of most of the aqueous solution from this vessel,

the remaining ~52 gal of material, including nitric acid wash, were transferred to the 225-gal, 38-in.-diameter stainless steel tank in which the accident occurred. This tank already contained ~78 gal of a caustic-stabilized aqueous-organic emulsion, and the added acid is believed to have separated the liquid phases.

The bottom layer (87.4 gal) is thought to have contained 60 g of plutonium; the top layer (42.2 gal) contained 3.27 kg of plutonium. Estimates indicate that the 8-in.-thick layer was perhaps 5 dollars below delayed critical and that the critical thickness was 8-1/4 in. When the motor drive of a stirrer was started to mix the solutions, the initial action was to force solution up along the tank wall, displacing the outer portion of the upper layer and thickening the central region. This motion changed the system reactivity from about 5 dollars subcritical to super-prompt critical, and a power excursion occurred. None of the gamma-sensitive recording meters within range of the accident showed an ideal trace; they suggest, however, that there was but a single burst. The excursion yield was 1.5 x 10^{17} fissions.

From post-excursion experiments[15] in a similar geometry it was observed that (1) there was no apparent delay between start and full speed of the stirrer at 60 revolutions/

min, (2) after 1 sec (i.e., one revolution) there was a visible movement or disturbance on the surface, and (3) in 2 or 3 sec the system was in violent agitation. From these observations it can be concluded that the system could have been made critical in about 1 sec, and in no more than 2 or 3 sec it must have been far subcritical and the burst terminated.

Since it was estimated that initially the system was 5 dollars subcritical, the reactivity insertion rate must have been about 5 dollars/sec. This, with coefficients consistent with the solution, leads to a burst yield of 2.2 x 10^{17} fissions with the burst completed in 1.65 sec, 0.45 sec after prompt critical was reached. To obtain the observed yield (1.5 x 10^{17} fissions) in a single spike, the reactivity insertion rate would have to be reduced to about 2 dollars/sec. As this is inconsistent with the time in-volved, i.e., complete mixing in 2 sec, the only alternative is to assume that the rate was somewhat less than 5 dollars/sec and that the excursion was terminated in about 2 sec by the stirring action. One can guess that the initial action was thickening of the upper layer, followed almost immediately by distortion into a less critical, vortex-like geometry by the action of the stirring blades.

This accident resulted in the death 36 h later of the

operator, who was looking into a sight glass when the motor was turned on. The radiation dosage was estimated to be 12,000 ± 50% rem. Two other persons were irradiated in the amounts of 134 and 53 rem and suffered no ill effects whatsoever. There was no contamination or damage to equipment even though the shock displaced the tank about 3/8 in. at its supports.

7. The Idaho Chemical Processing Plant, Idaho Reactor Testing Area--October 16, 1959[16]

(Enriched uranium solution siphoned from a safe to an unsafe geometry, shielded operation)

This incident occurred in a chemical processing plant which accepts, among other items, used fuel elements from various reactors. The active material involved (34 kg of enriched uranium, 93% ^{235}U) was stored in a bank of safe containers in the form of uranyl nitrate concentrated to about 170 g ^{235}U/liter. During an air-sparging operation, a siphoning action was initiated which transferred about 200 liters of this solution to a 5000-gal tank containing about 600 liters of water. The resulting power excursion created 4 x 10^{19} fissions, sufficient to boil away nearly half of the 800-liter solution volume.

The siphoning rate was 13 liters/min, but the reactivity insertion rate depended on the degree of mixing; it could

have been as high as 25 cents/sec. Since the 9-ft-diameter

tank was lying on its side, the solution configuration was

a near-infinite slab, and waves in the solution could have

caused violent fluctuations of the system reactivity.

The power history is a matter of conjecture - one can

guess that it was similar to that of the Y-12 incident. It

is not unreasonable to assume an initial spike of about 10^{17}

fissions, followed by power oscillations and finally by

boiling for 15 to 20 min as much of the uranyl nitrate was

found to be crystallized on the inner walls of the tank and

most of the water had left the tank. The very large yield

is a result of the large volume of the system and the long

time rather than of the violence of the excursion.

Personnel received no significant gamma or neutron

doses because of thick shielding, but beta dosages were 50 R

(one person), 32 R (one person), and small amounts for 17

persons, all obtained while the building was being evacuated.

The physical equipment involved in the excursion was not

damaged.

8. The Idaho Chemical Processing Plant, Idaho Reactor

   Testing Area--January 25, 1961[17]

   (Uranium process solution transferred from a safe to an

   unsafe geometry, shielded operation)

   This plant incident is thought to have been caused by

a bubble of high pressure air (residuum from an earlier line unplugging operation) forcing about 40 liters of 0.20 g $^{235}U/cm^3$ uranyl nitrate solution up a pipe 5 in. in diameter into a vapor-disengagement cylinder 2 ft in diameter and 4 ft high. The excursion occurred in the cylinder, probably as a single power spike since the 40 liters are only marginally sufficient to create a critical system in a tank of this diameter. The yield was 6 x 10^{17} fissions, but no estimates are available for the reactivity and power history.

Previous to the run with this solution, the portion of the plant involved had been idle for about 12 months. Two pumps pertinent to the operation were, at best, working poorly, and a line may have been plugged. Apparently the bubble of air was caused by efforts to cure these difficulties.

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

9. The Hanford Works, Richland, Washington—April 7, 1962[18, 19]

(Plutonium solution incorrectly siphoned)

This process plant (Recuplex system) accident involved the clean-up of the floor of a solvent extraction hood, a

product receiver tank which could overflow into this hood, a temporary line running from the hood floor to a transfer tank, and the apparent misoperation of valves. The testimony of witnesses and operators and the technical findings of the investigating committee are not in full agreement, and the final triggering mechanism cannot be determined. The most plausible (and simplified) course of events could have been as follows. (1) The receiver tank overflowed into the hood, leaving solution containing about 45 g Pu/liter on the floor and in the sump, (2) the operator (contrary to orders) opened the valve that allowed this solution to be transferred to the transfer tank, and (3) the later addition of aqueous solution (10 to 30 liters at 0.118 g Pu/liter) precipitated the burst through additional moderation following mixing and/or de-aeration of the contents of the transfer tank. Other mechanisms cannot be ruled out.

The total excursion yield in the transfer tank was 8×10^{17} fissions with the initial power spike estimated to be no more than 10^{16} fissions. Following this spike the tank was supercritical for 37-1/2 hr with the power level steadily decreasing. Of the 22 people in the building at the time (a Saturday morning) only three received significant exposures to radiation. These were 110, 43, and 19 rem. The incident itself caused no damage or contamination

but did precipitate final shutdown of the plant. The Recuplex operation was designed originally as a pilot plant and only later converted to production. Prior to the accident a new plant had been authorized.

Study of this incident is unique in the use of a small, remotely controlled, television-equipped robot. This device was used to reconnoiter the building interior, fix precisely the point of the incident (through use of an attached, highly directional gamma probe), read meters, deposit instrumentation at specified locations, and operate valves upon demand.

10. The Wood River Junction, Rhode Island, Scrap Recovery
Plant--July 24, 1964[20]

(Concentrated uranyl nitrate solution hand-poured into a geometrically unsafe container, two power excursions.)

This chemical processing plant accident occurred in the United Nuclear Corporation's ^{235}U scrap recovery facility. The plant was designed to recover highly enriched uranium from unirradiated scrap material resulting from the fabrication of reactor fuel elements. Because of startup difficulties, an unusually large amount of uranium-contaminated trichloroethane (TCE) solution had accumulated. The uranium in this solution (very low concentration) was recovered by mixing the TCE with sodium carbonate solution.

27

Prior to July 17, this operation was performed by hand in small bottles (5-in.-diameter, 11-liter-volume) of safe dimensions, but on that date, because of the large amount of solution, the operation was shifted to a sodium carbonate makeup tank approximately 18 in. in diameter and 25-in. deep--an unsafe geometry for concentrated solutions, which, however, were not expected in this particular area.

On the day before the accident, a plant evaporator failed to operate properly, and a plug of uranium nitrate crystals was found in a connecting line. These crystals were dissolved with steam, and the resulting concentrated solution (240 g ^{235}U/cm^3) was drained into polyethylene bottles identical to those that normally held the very low concentration TCE. A bottle of this concentrated solution was mistaken for TCE solution, and the operator poured it into the makeup tank. As the tank contained 41 liters of sodium carbonate solution and was being agitated by an electric stirrer, the critical state was reached, and a burst occurred when nearly all of the uranium had been trans-ferred. This burst of 1.0 to 1.1 x 10^{17} fissions created a flash of light, splashed about 1/5 of the solution out of the makeup tank, and knocked the operator to the floor. He was able to regain his feet and to run from the area to an emergency building some 200 yards distant, but his radiation

dose, estimated to be 10,000 rad, was fatal and he died 49 h later.

One and a half hours after the excursion, two men entered the area in order to drain the solution into safe containers. In the process, they turned off the stirrer, and, apparently, the change in geometry created as the stirrer-induced vortex relaxed added enough reactivity to create a second excursion (or possibly a series of small excursions). The estimated yield of this burst was 2 to 3 x 10^{16} fissions, and in this case no solution was splashed from the tank. The occurrence of this second excursion was not established until much later, as the alarm was still sounding because of the first burst.

During this solution accident involving two distinct periods of supercriticality, one man received a fatal radiation dose, while the two men who were involved in the second excursion received doses estimated at between 60 and 100 rads. Other persons in the plant received only trivial irradiations, and no physical damage was done to the system, although cleanup of the splashed solution was necessary. The total energy release was equivalent to 1.30 ± 0.25 x 10^{17} fissions.

II-B. Metal Assemblies in Air

1. Los Alamos, New Mexico--August 21, 1945[1,5,21]

    (Plutonium core reflected with tungsten carbide,

    hand assembly)

2. Los Alamos, New Mexico - May 21, 1946[1,5,21]

    (Plutonium core reflected with beryllium, hand

    assembly)

These two accidental excursions occurred in the same core and were, in several respects, quite similar. The core consisted of two hemispheres of delta-phase plutonium coated with 5 mils of nickel. The total core mass was 6.2 kg, and the density was about 15.7 g/cm^3.

In the first incident a critical assembly was being created by hand stacking 4.4 kg tungsten-carbide bricks around the plutonium core. The lone experimenter was moving the final brick over the assembly for a total of 236 kg when he noticed from the nearby neutron counters that the addition of this brick would make the assembly supercritical. As he withdrew his hand, the brick slipped and fell onto the center of the assembly, adding sufficient reflection to make the system superprompt critical, and a power excursion occurred. As quickly as possible, he pushed off the final brick and proceeded to unstack the assembly. He died 28 days later as a result of radiation injuries. The exposure

was about 800 rep.

The yield of this incident was 10^{16} fissions.* An Army guard assigned to the building, but not helping with the experiment, was irradiated in the amount of 20 rep. The nickel canning on the plutonium core did not rupture.

In the second incident, the techniques involved in creating a metal critical assembly were being demonstrated to several people. The system consisted of the same plutonium sphere, reflected in this case by beryllium. The top and final hemispherical beryllium shell was being lowered slowly into place; one edge was touching the lower beryllium hemisphere while the edge 180° away was resting on the tip of a screwdriver. The person conducting the demonstration was holding the shell with his left hand with his thumb placed in an opening at the polar point, while slowly working the screwdriver out with his right hand. At this time the screwdriver slipped from under the shell and the shell fell completely on to the lower hemisphere. A burst occurred at once, the shell was thrown to the floor, and all personnel left the room.

---

*The Los Alamos archives include some data and comments about a "rerun"[5,22] on October 2, 1945, performed to determine the radiation dose received in the incident of August 21, 1945. The yield of this "rerun" was about 6×10^{15} fissions, but the prompt critical state was not reached. The maximum reactivity of the system during this experiment was about 60 cents above delayed critical.

The yield of this excursion was 3×10^{15} fissions, and again there was no plutonium contamination. The eight people in the room were irradiated in the amounts ~ 900, 185, 116, 93, 41, 26, 18, and 18 rep respectively. The man who performed the experiment died 9 days later as a result of radiation injury.

Semiquantitative analyses of these two incidents can be made. By analogy to similar near-solid metal critical assemblies,[23] a rough prompt-negative temperature coefficient of reactivity can be estimated ($\sim 3.6 \times 10^{-3}$ dollars/ $^\circ$C), and by comparison with the behavior of the Los Alamos Godiva reactor (to be discussed), the fact that the nickel coating did not rupture indicates that the excess reactivity over prompt critical was not more than 10 or 12 cents.

In the earlier incident, if the excess reactivity were 10 cents, the yield in the power spike would be 1.8×10^{15} fissions and the remaining fissions could have been created in the plateau, in which region the power would be close to 10^{16} fissions/sec. The time for this power to produce the remaining fissions would be 0.8 sec, a not unreasonable value for the reaction time required to remove a brick. Clearly, the observed yield can be satisfied with slightly different assumptions.

The latter accident can be examined in the same manner.

If the excess reactivity over prompt critical were, for example, 1 cent, the spike yield would be 1.8×10^{14} fissions and the remaining 2.9×10^{15} fissions could have occurred in the 0.28 sec before the shell was removed. Again the assumptions are not unique.

3. The Los Alamos Scientific Laboratory--April 18, 1952[3,24]

(Jemima, a cylindrical, unreflected ^{235}U metal assembly, control 1/4 mile away)

The system in which this excursion took place was a cylindrical, unreflected, enriched (93% ^{235}U) uranium metal assembly made up of a number of plates each 26.7 cm in diameter and 0.8-cm thick. Figure 2 shows the assembly, commonly called Jemima, in the scrammed condition.

Complete assembly of the two components had been made previously with six plates in the lower component, but with first three and then four plates in the upper component.

A plot of the reciprocal multiplication* versus number of plates, or total uranium, shows clearly that the system should not have been assembled with 11 plates. Nevertheless, such an assembly was attempted following a computational

---

*The multiplication is the ratio of the leakage neutron flux from the enriched assembly to the leakage flux from an identical normal uranium assembly each containing the same neutron source. Clearly, the reciprocal multiplication goes to zero at delayed critical.

error made independently by two people. Contrary to operating regulations, a graph of the data had not been plotted. The burst yield was 1.5×10^{16} fissions.

There is no way of determining uniquely the power history experienced by the 92.4-kg mass without reproducing the experiment. At the time the system was near prompt critical, the lower component was coasting upward and probably inserting no more than 2 or 3 dollars/sec, a rate which could cause a power spike of about 10^{15} fissions. The power would then stabilize at about 10^{17} fissions/sec, just enough to compensate for the reactivity insertion rate, so that most of the 1.5×10^{16} fissions must have occurred in this plateau. The power dropped to zero when the automatic scram system separated the two masses of metal.

During this remotely controlled operation no damage was done to the system, even to the fissile material, no one was irradiated, and the experimental area was not contaminated. The apparent self-terminating property of this excursion stimulated study of Godiva-I,[25-27] which became a facility for generating large bursts of fission spectrum neutrons in less than 100 μsec.

4. **The Los Alamos Scientific Laboratory--February 3, 1954**[4,26]

(Godiva, a bare ^{235}U sphere, control rod misoperation, control 1/4 mile away)

5. **The Los Alamos Scientific Laboratory--February 12, 1957**[28-30]

(Godiva, a bare ^{235}U sphere, added reflection, control 1/4 mile away)

These two excursions occurred in the Lady Godiva[25-27] assembly, an unreflected metal reactor fabricated in three principal sections which when assembled formed a sphere. Figure 3 shows Godiva in the disassembled state. The central section was fixed in position by small tubular steel supports, while the upper and lower sections were retractable by means of pneumatic cylinders, thus providing two independent scram mechanisms. The critical mass was about 54 kg of uranium enriched to 93.7% ^{235}U. It was operated remotely at a distance of 1/4 mile.

The first accidental excursion occurred during preparations for a scheduled prompt burst, part of a program to measure the parameters associated with excursions. Normally, a burst was initiated by (1) establishing delayed critical by adjusting control rods, (2) lifting the top section to reduce reactivity and allow decay of the neutron

population, and (3) lowering the top section into position and rapidly inserting a burst rod worth slightly more than 1 dollar. A power excursion usually creating about 10^{16} fissions in 100 μsec followed, and in 40 msec the system was scrammed safely. As the only source of neutrons was spontaneous fission, it was customary to assemble to an excess reactivity of about 70 cents to accelerate the rise to sufficient power for establishing the settings for delayed critical in a reasonable time. This accidental excursion was caused, apparently, because additional reactivity was inserted by error after assembly to 70 cents but before a fission chain started.

The excursion yield was 5.6 x 10^{16} fissions, about six times the yield of the average burst. There was no radiation hazard, spreading of contamination, personnel irradiation, or significant damage to the major uranium parts. One piece was slightly warped and required remachining, and several light steel supporting members were bent or broken.

The second accidental excursion occurred during preparations for an experiment in which Godiva was to provide a pulse of fast neutrons. Again the burst occurred during assembly to establish, in this case, a fiducial point at about 80 cents excess reactivity. Control rods were to be adjusted on the basis of this period. The extra reactivity is thought

to have been contributed by a large mass of graphite and polyethylene that was to be irradiated. This mass had just been moved close to Godiva, and either the change in reflection was underestimated or the material slumped further toward Godiva.

The burst yield was 1.2×10^{17} fissions, about 12 times the standard excursion. The metal was severely oxidized, had warped, and apparently had been plastic near the center. The central burst rod was nearly ruptured, and at its center must have been within $100^\circ C$ of the uranium melting temperature. Figure 4 shows several of the pieces. External damage was limited to the supporting structure; radioactive contamination consisted of oxide scale, and cleanup proceeded rapidly. Repair of Godiva was not practicable, and construction of Godiva-II,[29] specifically designed for burst operation was accelerated. Despite the severity of the excursion, operating personnel were not irradiated.

The behavior of the Godiva system during superpromnt critical power excursions is well understood both experimentally and theoretically. Godiva-I experienced well over 1000 safe, controlled bursts, and a coupled hydrodynamics-neutronics code describes the behavior of the system quite adequately.

The first excursion (5.6×10^{16} fissions) must have had

a period of 6.4 μsec, equivalent to a reactivity excess over prompt critical of 15 cents. The excess reactivity of the larger excursion (1.2 x 10^{17} fissions) was 21 cents above prompt critical, corresponding to a period of 4.7 μsec.

The fission yield of 1.2 x 10^{17} in the second incident is equivalent to the energy contained in 1.7 lb of high explosive, but the damage (Fig. 4) was much less than would have been caused by this quantity of H.E. The above-mentioned code can predict the fraction of fission energy converted to kinetic energy, and, in this case, only about 1.4% of the energy, equivalent to 0.024 lb H.E., was available as kinetic energy to do damage. The damage was consistent with this figure, and it is evident that most of the fission energy was deposited as heat.

6. The Los Alamos Scientific Laboratory--June 17, 1960[5]
   (Graphite reflected, cylindrical ^{235}U metal system)

The critical parameters of highly enriched (93% ^{235}U) uranium metal cylinders were being investigated in thick-graphite (~ 9 in.) and near-infinite water reflectors. In the experiment of interest, an annular system of ~48 kg was built up on a cylinder of graphite which, in turn, rested on a hydraulic lift device. This system was raised, by remote control, into a volume of graphite resting on a stationary steel platform. The system became critical before complete

assembly and was scrammed manually and automatically at about 1 in. from closure. Following the scram signal, the lift dropped rapidly and the system became subcritical, but about 1/3 of the metal mass stuck in the graphite reflector for a few seconds before falling to the floor. The burst yield was 6×10^{16} fissions; there was no damage to the fissile metal or any contamination. Personnel irradiations were immeasurably small.

This incident was, in many respects, similar to the case for Jemima. The reactivity sensitivity of this particular experiment was not measured after the power transient but, from examination of similar systems, the reactivity insertion rate probably did not exceed a few dollars per second and the first spike could have included 10^{15} fissions.

The fission yield was very close to that of the first Godiva accident (February 3, 1954), and the two masses are quite comparable. In the earlier case, all the energy release took place during the power spike and some warping of pieces and damage to supports was seen. In this more recent transient, the metal was quite undamaged, thus supporting the assertion that the initial power spike was small compared to the total yield.

7. The Oak Ridge National Laboratory--November 10, 1961[31] (^{235}U metal, paraffin-reflected)

This power transient in about 75 kg of highly enriched (~ 93% ^{235}U) uranium metal reflected with paraffin took place while one portion on a vertical lift machine was approaching the other, stationary, portion. The experiment was the last of a series during which uranium or paraffin had been added by increments to change the reactivity of the complete system; all previous experiments had been sub-critical when fully assembled. In this case the system became supercritical while the lift was in motion, leading to a burst yield of between 10^{15} and 10^{16} fissions.

The closure speed of the lifting device was 16 in./min; delayed critical was later determined to be at a separation distance of 2.7 in., and the sensitivity of the system at this point was 8.6 dollars/in. Thus, the reactivity inser-tion rate was 2.3 dollars/sec and the lift slowdown, which became effective at 1.94 in.,did not affect the course of the transient.

The reactivity and power histories must have been similar to those of the Jemima accident except that the per-tinent scram-delay time was only 50 msec in this case. The first spike could not have exceeded 10^{15} fissions, and the remaining energy must have been created during the subsequent plateau.

The appearance of the metal (smooth, no oxide) and the
fact that the paraffin did not melt qualitatively confirmed
the yield estimate of 10^{15} to 10^{16} fissions. Personnel
irradiations were trivial, and the laboratory was ready for
normal use within 1-1/2 h.

8. The E. O. Lawrence Radiation Laboratory--March 26,
   1963[32, 33]

   (Beryllium-reflected, cylindrical metal system)

   The critical assembly consisted of concentric cylinders
of enriched uranium metal surrounded by a beryllium reflec-
tor. The total enriched uranium mass of 47 kg was divided
into two parts with the central core on a lift device and
the larger diameter rings with the reflector on a fixed
platform. The approach to criticality was to be achieved
by lifting the core upward in a series of steps into the
hollow cylinder. The experiments were performed in a
heavily shielded vault, previously used as the area in
which the Kukla reactor produced prompt bursts of neutrons.

   This stepwise procedure was successfully followed for
seven multiplication measurements, but after the eighth
apparently normal assembly, the system suddenly became
highly supercritical. An explosive sound was heard, scrams
and alarms were actuated, and after a few seconds the uranium
could be seen melting and burning. The yield was later

41

measured to be 3.76×10^{17} fissions, but little or no
explosive energy was generated. About 15 kg of uranium
burned, and about 10 kg melted and spread over the floor.
Exposure to personnel in or near the building was low and
in no case exceeded 120 mrem. The vault was highly contam-
inated.

The incident is believed to have been caused by the
central cylinder of metal on the lift being very slightly
off center. When this was lifted into the fixed half, one
or more of the metal rings was carried upward. Following
the eighth assembly the system adjusted itself and the
rings settled properly around the central core, abruptly
increasing the reactivity. The rate is not known, nor is
the maximum reactivity. The first spike was probably small
(order of 10^{15} fissions) with most of the energy being
generated during a high plateau. Quenching came through
thermal expansion and melting.

9. The White Sands Missile Range--May 28, 1965[34]

(Unreflected uranium-molybdenum metal fast burst reactor)

The success of the Godiva reactor in creating very
quick, intense bursts of near fission spectrum neutrons has
caused several similar reactors to be created for production
of pulsed irradiations. One of these is the White Sands
Missile Range Fast Burst reactor, which is composed of 96 kg

42

of an alloy of highly enriched uranium and 10 wt/% molyb-
denum. This reactor design is somewhat similar to the
Godiva II reactors[29]--seven rings and a top plate all
of which partially enclose a large central volume which, at
critical, is filled with a safety block. Two control rods
and a burst rod penetrate the rings, and the assembly is
held together by three metal bolts. Initially, these bolts
were of stainless steel, but just prior to the incident,
they had been replaced by three composed of the uranium-
molybdenum alloy, and recalibration of the reactivity worth
of various components was under way. The new worth of the
control rods, burst rod, minor components, and the first
1/2 in. withdrawal of the safety block had been measured.
Further calibration of the safety block seemed to require
higher neutron flux than that given by a polonium-beryllium
neutron source, and to obtain a power of about 1W an inter-
lock was bypassed and the safety block was set into motion
inward, approaching a state thought to be known. The
excursion took place as the safety block neared the 1/2 in.
position.

All scrams functioned as designed, but the short period
allowed a very high power level to be created, and the
excursion was actually terminated by thermal expansion of
the metal. Failure (snapping of the heads) of the new

uranium-molybdenum assembly bolts and the tossing of the
two top rings and minor parts some 5 to 15 ft away followed.

This incident was well instrumented. The minimum period
was 9.2 μsec, the maximum reactivity 1.15 dollars above
delayed critical, the reactivity insertion rate 2.2 dollars/
sec, and the burst width 28 μsec. The internal temperature
rise of 290°C suggested a fission yield of 1.5 x 10^{17}, which
is only 1.4 times the maximum expected from normal operations.

During this unexpected burst, damage was limited to the
failure of the assembly bolts and very slight chipping of
the nickel coating of the rings. Personnel irradiations
were immeasurably small. One hour after the excursion,
entry into the cell was accomplished, and radiation levels
were determined to be higher than normal background but not
appreciably higher than those measured after a normal burst.

II-C. Water-Moderated Metal Systems

1. Los Alamos, New Mexico--June 6, 1945[1, 5]

   (Pseudosphere of uranium cubes, water-reflected, local
   control)

The experiment was designed before the days of remote
control and was intended to establish the critical mass of
enriched uranium metal when it was surrounded by hydrogenous
material. The uranium mass of 35.4 kg was stacked in the
form of a pseudosphere constructed of 1/2-in. cubes and

blocks 1/2 in. x 1/2 in. x 1 in. The core was in a 6-in. cubical polyethylene box, with the void space filled with polyethylene blocks. The whole assembly was placed in a large tank which was then partially filled with water.

The assembly became critical (unexpectedly) before water had completely covered the polyethylene box. The situation was aggravated because no scram device was built into the system and the inlet and drain valves were 15 ft apart. Before the system was reduced to a safe subcritical state 5 or 10 sec later, a total of 3 to 4 x 10^{16} fissions were created, an energy release sufficient to raise the average temperature of the metal more than 200°C. As subsequent examination of the polyethylene box showed that it was not watertight, it is probable that water seeped slowly into the assembly as the level was being raised above the bottom of the box. The additional moderation then caused the prompt-critical situation which was quenched by boiling of the water within the box and next to the metal cubes.

The characteristics of excursions of large masses of fissile metal in water are, at best, poorly known. A calculation by Hansen[71] has shown that for a 6.85-cm-radius, ^{235}U sphere in water, 15% of the fission occur in the outer 0.05 cm, and the fission density in this region is six times

that at the center. A burst of 3 x 10^{15} fissions would then raise the surface temperature $130^{O}C$ while the central regions would remain relatively cool with a temperature rise of only $19^{O}C$. Apparently the first spike must have been of this order of magnitude with the majority of the fissions occurring at a much lower average power.

In this excursion three people received radiation exposures in the amounts of 66, 66, and 7.4 rep respectively. There was no contamination, and the active material was used again in 3 days.

2. The Los Alamos Scientific Laboratory--February 1, 1951[3,4,35]

(Critical separation experiment, two large ^{235}U metal masses in water, control 1/4 mile away)

A water-reflected system was set up in 1949 to obtain the neutron multiplication of a single piece or arrangement of fissile metal in water. The system had two scram devices. The first, with a quick response, consisted of a pneumatic cylinder which raised the unit out of the water, while the second and slower action drained the tank. A traveling support was added later so that critical separation distances between two units could be determined; a dropping cadmium screen provided an additional scram.

The experiment which precipitated the excursion

consisted of measuring the critical separation distance of
two enriched uranium masses in water, one a solid cylinder
of 24.4 kg and the other a hollow cylinder of mass 38.5 kg,
each of 93.5% ^{235}U content. Sheet cadmium 10-mils thick
was fastened to the outer surface of the solid cylinder and
to the inside surface of the hollow cylinder, and a paraffin
slug filled the cavity in the hollow cylinder. The general
geometry of this experiment is shown in Fig. 5.

At the completion of the critical separation experi-
ment (at a multiplication of 65.5), the assembly was
scrammed as a final flourish. Simultaneously, the water
started draining, the cadmium screen dropped, the solid
cylinder (left-hand body in Fig. 5) was lifting, and an
excursion (later determined to be 10^{17} fissions) was
observed as jamming of counters and evidence on television
of a vapor cloud above the water.

Later reconstruction of the accident showed that the
pneumatic tangential scram was first to be effective and
led directly to two types of difficulty. First, the center
of reactivity of the left-hand cylinder (Fig. 5) proved
to be below that of the stationary cylinder, and, second
the rapid lift through the water created Bernoulli forces
which swung the cylinders closer together. The combination
of the two effects was enough to drive the assembly prompt

critical and to have maintained this or a greater reactivity

for 0.2 sec if the power excursion had not occurred. In a

manner analogous to the earlier metal-water system, the

first power spike is estimated to have contained 6×10^{15}

fissions. It is possible that one or more excursions into

the prompt region followed because boiling was the primary

quenching mechanism.

In this excursion of 10^{17} fissions, no one was irra-

diated, and no contamination was found in the experimental

area. Damage to the uranium consisted of a very small

amount of oxide flaking and blistering. The experimental

area was in use 2 days later.

3. The Argonne National Laboratory--July 6, 1952[36]

   (Reactor mockup, UO_2 particles in plastic, water-

   moderated)

   This accident occurred in a light-water-moderated core

in which 6.8 kg of ^{235}U oxide were embedded in strips of

polystyrene plastic. The oxide particles were mostly (all

but 0.5%) 10-μ in diameter or less, the remainder, up to

40-μ in diameter. Seven strips of the plastic fastened to

six zirconium strips 0.91 in. x 0.110 in. x 43 in., formed

one standard fuel element. The core was roughly cylindrical

and contained 324 fuel elements. The zirconium fuel strips

and water occupied 60, 7.71, and 32.2%, respectively, of

the core volume.

The experiment in progress at the time of the accident consisted of making comparisons of the worth of central control rods of different design. The system became super-prompt critical following an attempt (contrary to operating regulations) to replace the central control rod when the normal amount of water was in the core. Peripheral poison rods were in position but were inadequate to maintain a subcritical reactivity.

The quenching mechanism for this excursion of 1.22 x 10^{17} fissions was the near-uniform expansion of the plastic as the 10-μ particles became hot, and bubble formation in the neighborhood of the 40-μ particles. This plastic expansion forced most of the water out of the core, and the entire excursion was over about 0.6 sec after the operator started raising the control rod. The maximum α(reciprocal period) was nearly 100/sec, the maximum power was 1.7 x 10^8 W, and the half-width of the power spike was 18.5 msec.

In this excursion, the core fuel elements were ruined, but no significant amount of fissile material was lost. The activity in the reactor room was above tolerance for about a day. The core elements were removed after 5 days, and decontamination was completed by a single application of detergent and warm water. Four persons were irradiated

in the amounts 136, 127, 60, and 9 rep respectively.

4. Atomic Energy of Canada, Limited, Chalk River, Ontario-
December 12, 1952[37-39]

(NRX reactor, normal uranium rods, heavy-water-
moderated, graphite reflected)

The NRX reactor is a natural-uranium, heavy-water-
moderated system with the uranium rods cooled by a thin
sheath of light water flowing between the aluminum clad
rod and a slightly larger concentric aluminum cylinder.
Space for 198 fuel or control rods is available in a graph-
ite shielded "calandria" 8-3/4 ft in diameter and 10-1/2-ft
high.

Through a very complicated series of operator errors
and electrical and mechanical safety circuit failures, the
reactor was forced to be supercritical by about 60 cents.
Initially the power diverged rapidly, but because of a
slowly moving control rod the reactor gave every indication
of leveling off at a power of about 20 MW. Normally this
would have been a high but tolerable power, and very likely
the situation would have been controllable if the planned
experiments had not required reduced light-water cooling
flow for several of the fuel rods. At a power of ~17 MW,
the cooling water commenced to boil in those channels with
reduced flow. This autocatalytic action (the light water

was effectively a poison) increased the reactivity by about 20 cents, and the power rose again with a period estimated to be between 10 and 15 sec. When the power reached 60 to 90 MW, the heavy-water moderator was dumped and the reaction stopped.

The reactor power was greater than 1 MW for no more than 70 sec, and the total energy release has been estimated at 4000 MW-sec or about 1.2×10^{20} fissions. The core and calandria were damaged beyond repair, and some 10^4 curies of long-lived fission products were carried to the basement by a flood of 10^6 gallons of cooling water. Personnel irradiations were apparently low, and the reactor was restored to operation in slightly more than 1 year.

5. The Argonne National Laboratory, Idaho Reactor Testing Area - July 22, 1954[40-42]

(Borax reactor, aluminum-uranium alloy, water-moderated, remote control)

This excursion was an accident only in the sense that it was larger than expected. The Borax-I reactor[43] had been built as a temporary affair, steady-state and transient studies were regarded as complete, and it was decided that the reactor should be forced onto a short period transient to obtain the maximum amount of experimental information before it was dismantled. The excess reactivity was chosen

to produce a fission yield such that about 4% of the fuel plates would melt.

The Borax-I reactor consisted of 30 MTR-type fuel elements moderated by light water. Each element contained 18 fuel plates 2.845 in. x 0.060 in. x 24.6 in., consisting of aluminum-uranium alloy, clad with about 0.020 in. of aluminum. The whole core was in a semiburied tank 4 ft in diameter and 13-ft high.

It had been estimated from earlier controlled prompt excursions that about 4% excess k would put the reactor on a period between 2.0 and 2.5 msec and that the resulting excursion would release about 80 MW-sec of fission energy. To perform this experiment a larger than usual fuel loading was needed and a stronger central control rod was required.

The excursion, following rapid ejection of the control rod, completely disassembled the reactor core and ruptured the reactor tank. Very extensive melting of the fuel plates occurred; some elements remained in the tank while small pieces were found up to 200 ft away. "An example of the force of the explosion was the carrying away of the control rod mechanism. This mechanism, which weighed 2,200 lbs, sat on a base plate, about 8 ft above the top of the reactor tank. Except for the base plate, about 4 ft square, the top of the 10-ft shield tank was essentially

unobstructed. The force of the explosion, plus the impinge-
ment of water and debris on the base plate tore the plate
loose from its coverage, and, as revealed by high speed
movies, tossed the mechanism about 30 feet into the air."[39]

The total energy release was 135 MW-sec or, assuming
180 MeV deposited per fission, 4.68 x 10^{18} fissions. This
energy is equivalent to that contained in about 70 lb of
high explosive, but it has been estimated that between 6
and 17 lb of H.E. would produce comparable damage. The
minimum period was 2.6 msec, and the maximum power was about
1.9 x 10^{10} W. It is apparent that the nuclear excursion was
completed before the steam explosion destroyed the system.

In this excursion the reactor was destroyed, but
because of the remote site physical damage was limited to
the reactor, and personnel were not irradiated.

6. Vinca, Yugoslavia - October 15, 1958[44]*

(Unreflected, D_2O-moderated, natural uranium assembly,
unshielded)

The critical facility at the Boris Kidrich Institute
in Vinca, Yugoslavia, is composed of an unreflected matrix
of natural uranium rods moderated by heavy water. The

---

*I am indebted to Dr. T. J. Thompson for first reporting the
correct sequence of events. Some of the details of this
incident are taken verbatim from his discussion.[44]

aluminum clad rods are 2.5 cm in diameter and 210-cm long; the total core uranium mass is 3,995 kg in a volume of 6.36×10^6 cm^3. Two cadmium safety rods were installed but were not interlocked with the flux recorder, and normally the liquid level was used to control the system reactivity (the critical level was 178 cm).

At the time of the accident, a subcritical foil counting experiment was in progress. To obtain as much activation of the foils as possible it was desired to raise the multiplication to some high, but still subcritical, level. This was done by raising the heavy water in the tank in a series of steps. On the last step, two of the BF$_3$-lined chambers performed as before - leveling off at a higher signal level, but the third behaved erratically and was disconnected.

After the assembly had been at this D$_2$O level about 5 to 8 min, one of the experimenters smelled ozone, and they realized that the system was supercritical at some unknown power level. The cadmium safety rods were used to stop the reaction.

Later investigation showed that both of the detecting chambers which were believed to be working properly had reached saturation and were reading a constant maximum value even though the power level was rising steadily.

Irradiations were very intense, being estimated at 400, 700, 850, 850, 850, and 1100 rem. Of the six persons present, one died while the other five recovered after severe cases of radiation disease. The critical assembly absorbed the energy release of 80 MW-sec ($\sim$ 2.6 x 10^{18} fissions) with no reported damage.

7. Centre d'Etudes Nucleaires de Saclay, France - March 15, 1960 [45]

(UO$_2$ rods, uranium enriched to 1.5%)

The "Alize" critical assembly is a water-reflected and water-moderated system utilizing, in this case, UO$_2$ rods as fuel in which the uranium was enriched to 1.5%. The rods were 1-meter long and 1 cm in diameter with the total UO$_2$ mass equal to 2.2 tons.

The experiment in progress at the time of the incident required a stable positive period at a very low power level. To accomplish this the critical rod configuration was found experimentally and the rod position required for the necessary period was calculated. After allowing for the decay of delayed neutron precursors the rods were withdrawn to the predetermined position. However, for reasons unknown, the operator then completely withdrew a rod which previously was not fully out. This placed the system on a period of about 1/4 sec.

The subsequent power excursion created 3×10^{18} fissions, but the peak temperatures in the UO_2 were less than $550^{\circ}C$. The core was undamaged, and personnel irradiations were trivial.

It was deduced that the quenching action must have been due to the ^{238}U Doppler effect. This judgment has been substantiated by the recent SPERT experiments using a similar core in which the uranium is enriched to 4%.

8. Stationary Low Power Reactor No. 1, Idaho Reactor Testing Area - January 3, 1961[44, 46, 47]

   (SL-1 reactor, aluminum-uranium alloy, water-moderated)

   The SL-1 reactor (originally known as the Argonne Low Power reactor) is a direct-cycle, boiling-water reactor of 3 MW gross heat capacity, using enriched uranium fuel plates clad in aluminum, moderated and cooled by water. Because the reactor was designed to operate for 3 years with little attention, the core was loaded with excess ^{235}U. To counterbalance this excess of ^{235}U, a burnable poison (^{10}B) was added to some core elements as aluminum-boron-10-nickel alloy. Because these boron plates had a tendency to bow (and, apparently, to corrode, increasing reactivity), some of them were replaced in November 1960 with cadmium strips welded between thin aluminum plates. At this time the shutdown margin was estimated to be 3%, or about 4 dollars,

compared to the initial value of 3-1/2 to 4%. The control rods, which tended to stick, were large cruciform cadmium sheets sandwiched between aluminum plates. The nuclear incident was independent of the poor condition of the core.

After having been in operation for about 2 years, the SL-1 was shut down on December 23, 1960, for routine maintenance; on January 4, 1961, it was again to be brought to power. The three-man crew on duty the night of January 3 were assigned the task of reassembling the control rod drives and preparing the reactor for startup. Apparently they were engaged in this task when the excursion occurred.

The best available evidence (circumstantial, but convincing) suggests that the central rod was pulled out manually, as rapidly as the operator was able to do so. This rapid increase of reactivity placed the reactor on about a 4-msec period; the power continued to rise until thermal expansion and steam void formation quenched the excursion. The peak power was about 2×10^4 MW, while the total energy release was 133 ± 10 MW-sec. The subsequent steam explosion destroyed the reactor and killed two men instantly, while the third died in 2 h as a result of a head injury. The reactor building and, especially, the reactor room were most seriously contaminated by the reactor water carrying fission fragments with it. Initial

57

investigations were hindered by the high radiation field
(500 to 1000 R/h) in the reactor room. In spite of this
large radioactivity release from the core, very little
escaped from the building which was not designed to be air-
tight.

In many respects this reactor excursion resembled that
of the BORAX and SPERT destructive experiments. Each of
these, and especially SPERT, was instrumented to
follow just such an excursion. W. Nyer[47] notes that the
crucial quantity is the energy density in the core. This
is larger for the SL-1, but not grossly so, being 12% more
than BORAX and 60% more than SPERT. The prompt alpha for
SL-1 seems to have been slightly lower. The steam explosion
caused considerable damage in all three power transients
but especially in the BORAX and SL-1. In the SL-1 the core
was enclosed, and the water apparently was accelerated
upward more or less as a single slug. The energy acquired
by the water was sufficient to lift the entire reactor
vessel some 9 ft before it fell back to its normal position.

In the SPERT experiment, the steam explosion followed
the nuclear power spike by 15 msec. It is not known if
such a delay occurred following the SL-1 power transient.

9. Mol, Belgium--December 30, 1965

(VENUS critical facility, UO_2 rods in H_2O-D_2O, 7% enriched)

VENUS is a tank-type, water-moderated, critical assembly machine, currently used for experiments apropos of the "Vulcan" reactor. This is a "spectral shift" reactor, so-called because the initial moderator of D_2O will be diluted with H_2O to soften the spectrum and maintain reactivity as the fissile material disappears. For the experiments in progress, the composition of the moderator and reflector was 70% H_2O and 30% D_2O; this reflector extended 30 cm above the top of the core, the height and diameter of which were about 1.6 meters. The fuel was UO_2 in the form of pelleted rods, the total mass of UO_2 was 1.2×10^6 g, and the ^{235}U enrichment was 7%.

The primary reactivity control was by motion of poison rods (eight safety rods and two regulating rods); eight absorbing rods were available for manual positioning in the core.

Just before the accident, all safety rods were IN, a regulating rod was IN, seven manual rods were IN, and a regulating rod was being inserted; the reactor was subcritical by one safety rod and one regulating rod.

To perform an experiment with a new rod pattern, the

operator of the reactor decided, first, to decrease reactivity by inserting the last manual rod, waiting until the second regulating rod was fully inserted. Then, as the reactor should have been subcritical by one safety rod, two regulating rods, and one manual rod, a different manual rod located near the last one inserted could be pulled out of the core and the reactor made critical again by lifting two safety rods.

Such a program required a man to insert a manual rod and to extract another one. The operator did not take into account a rule written into the Safety Report of the reactor according to which no manipulation of a manual rod in the core should be performed without first emptying the vessel, and he gave a written order to a technician prescribing the loading of a manual rod followed by the unloading of another one. The technician did not wait until the moving regulating rod reached its bottom position and started the manipulation in the wrong order. He first extracted a manual rod instead of first inserting such a rod.

During the extraction of the manual rod the reactor became critical. The technician had his left foot projecting over the edge of the tank and resting on a grating which was about 5 cm above the reflector; his right foot and leg were somewhat behind him and partly shielded. He

noticed a glow in the bottom of the reactor, immediately dropped the control rod, and left the room.

The energy release was about 13 MW-sec (4.3×10^{17} fissions) and, apparently, the excursion was stopped by the falling manual rod, although the scram may have been speeded up by a combination of the emptying of the vessel, which was automatically "provoked", and of the Doppler effect. This is not yet precisely known.

No steam was created, no damage was done to the fuel, and there was no contamination, but the technician received a severe irradiation, primarily of gamma rays. Some 300 measurements were made in a phantom during an experiment 8 days later and, roughly, the dose to his head was 300 to 400 rem, to his chest 500 rem, and to his left ankle 1750 rem, and at the end of his foot the dose approached 4000 rem. Medical treatment of the patient has been successful except that the left foot had to be amputated.

II-D. Miscellaneous Assemblies

1. Los Alamos, New Mexico--February 11, 1945[48-52]

   (The Dragon reactor, UH_3 pressed in styrex, shielded operation)

   The Dragon reactor was the first fissile system designed to generate prompt power excursions, and, to my knowledge, it was the first reactor of any kind whose

reactivity exceeded prompt critical.* This was accomplished

(by intent) on January 18, 1945; the temperature rise is

quoted as $0.001^{\circ}C$,[48] and the yield (which is not quoted)

can be estimated to have been about 2×10^{11} fissions.

The Dragon was made of enriched UH_3 pressed with a

special plastic, styrex, into small cubes of average chem-

ical composition UC_4H_{10}. The stacking for the final exper-

iments contained only 5.4 kg of this material, was diluted

with polyethylene, and was reflected by graphite and poly-

ethylene.

The reactor was made prompt critical for about 1/100

sec by dropping a slug of the active material through a

vertical hole in the remaining portion, which was stacked

on a heavy (3/8-in.) steel table. The falling slug of

active material was contained in a steel box, and its path

was closely defined by four guides. Generally, the fission

energy did not contribute to the quench of the excursion;

the burst size was determined by the background fission

---

*Because of the similarity of the procedures used in these
experiments to tickling the tail of a dragon (pointed out
by R. Feynman), the experiment has been sometimes called the
"Dragon Experiment." The name has stuck and is often
applied to the class of prompt-burst experiments where reac-
tivity is added and subtracted mechanically, and where
quenching mechanisms dependent upon the fission energy re-
leased do not contribute significantly to the shutdown
process.

rate and the stacking configuration on the table. Thus,
the burst size could be controlled by (a) moving a reflector
nearer the assembly or (b) increasing the background fission
rate. Both techniques were often employed, and this may
have been the case in the final experiment because the
bursts were being made steadily larger. During the final
excursion of about 6 x 10^{15} fissions, the UH_{10} cubes became
so hot that blistering and swelling occurred. The whole
system had expanded about 1/8 in.

In the final excursion the core material was damaged,
but no active material was lost, there was no contamination,
and no one was irradiated.

2. The U.S.S.R.--1953 or 1954[53]

This incident apparently took place during 1953 or
early in 1954. The location, date, facility, burst yield,
and causes are not mentioned. Two persons described as
being "close to the reactor" and "in close proximity to
the reactor" were subjected to "a short, general external
gamma and neutron irradiation" equivalent to 300 and 450 R,
respectively. Their exposures could have been caused by
a power excursion of any one of a large number of possible
systems but one suspects a small critical assembly, pos-
sibly metallic, whose stacking was unintentionally increased
to a reactivity well above delayed critical and possibly

above prompt critical. It is unlikely that the burst yield exceeded 10^{16} to 10^{17} fissions. It may be noted that the radiation dose at 1 meter from a Godiva burst of 10^{16} fissions is 400 R (30 R gamma and 370 R neutron).

3. The Argonne National Laboratory, Idaho Reactor Testing Area--November 29, 1955[54, 55]

   (EBR-1, Enriched Uranium Fast Breeder reactor, shielded operation)

   Design of the EBR-1 fast neutron reactor was started in 1948 with the objectives of establishing possible breeding values and demonstrating the feasibility of cooling a metallic reactor with liquid metals. These objectives were met, and, indeed, in early 1952 the plant furnished more than enough electrical power for the reactor and the reactor building; excess steam was blown to the condenser.

   The reactor core consisted of cylindrical, highly enriched, uranium rods slightly less than 1/2 in. in diameter canned in stainless steel with a bonding of NaK between the rod and can. The total core mass of about 52 kg was bathed in a stream of NaK which served as a coolant.

   The final experiment was designed to investigate coefficients of reactivity and, in particular, to study a prompt positive power coefficient for the case of no coolant flow. To do this the system was placed on a period of 60 sec at

a power of 50 W. About 300 sec later the power was 1 MW, the period had decreased to 0.9 sec, and core temperatures were rising significantly. The signal to scram the system was given, but by error, the slow moving, motor-driven control rods were actuated instead of the fast acting scram - dropping under gravity of part of the natural uranium blanket - as had been done to conclude similar experiments. This change in reactivity caused a momentary drop in power, but was inadequate to overcome the natural processes (very slight bowing inward of the fuel elements) adding reactivity to the system. After a delay of not more than 2 sec, the fast scram was actuated both manually and by instruments and the experiment was completed.

It was not immediately evident that the core had been damaged, but later examination disclosed that nearly one-half the core had melted, and vaporized NaK had forced some of this molten alloy into the reflector. The theoretical analysis showed that the excursion was stopped by the falling reflector, after the power reached a maximum of 9 to 10 MW. The total energy release was close to 14 MW-sec, or about 4.6×10^{17} fissions. The theoretical analysis was carried further in an attempt to determine if the core would have shut itself off in a noncatastrophic manner. The conclusion was that the energy release could have been

nearly 2-1/2 times the observed yield and have been obtained
in a nonexplosive manner.

During this incident no one received more than trivial
irradiation from airborne fission products, and the direct
exposure was essentially zero.

4. The Los Alamos Scientific Laboratory—July 3
   1956[3, 4, 5]

   (The Honeycomb critical facility, ^{235}U foils moderated
   with graphite, control 1/4 mile away)

The machine in which this excursion occurred is typ-
ical of several in existence. The Los Alamos machine con-
sists of a large matrix of 576 square aluminum tubes, 3 in.
x 3 in. x 6 ft, that is split down the middle with one-half
moveable on tracks. The "Honeycomb" in the disassembled
state is shown in Fig. 6. Generally the facility has been
used to simulate design features of complicated reactors
as there is considerable versatility in arrangements of
uranium foil and various moderating materials. Inhomog-
eneous stackings in this and other machines of the same
type are potentially the most dangerous critical assemblies
in existence today. This conclusion stems from the apparent
lack of any quenching mechanism short of vaporization of
the uranium foils or a sufficiently fast acting scram
mechanism.

The stacking on July 3, 1956, consisted of 58 kg of enriched (93% ^{235}U) uranium in the form of 2- and 5-mil foils arranged between slabs of graphite, with some additional beryllium reflector surrounding the core. The total mass of graphite was 1139 kg. At the time, some changes had been made in the reflector and graphite moderator, and criticality was being approached for routine measurements. While the cart was moving at about 0.2 in./sec, the system became prompt critical, a burst occurred, and the scram system ejected beryllium control rods (reducing reactivity), and reversed the motion of the cart. The burst yield was 3.2 x 10^{16} fissions.

Apparently, this was a Dragon-type excursion in that the excess reactivity was added and subtracted mechanically. There was no damage and no contamination. Since it was a device remotely controlled from a distance of 1/4 mile, no one was irradiated.

5. The Reactor Testing Area, Idaho Falls, Idaho--
   November 18, 1958 [56]

   (Prototype aircraft engine, instrumentation failure)

   The HTRE No. 3 (High Temperature Reactor Experiment) power plant assembly was a large (core diameter 51 in., length 43.5 in.) reactor with nickel-chromium-UO$_2$ fuel elements, hydrided zirconium moderator, and beryllium

67

reflector. The experimental objective at the time of the accident was to raise the power level to about 120 kW, about twice that attained earlier in the day. This was done with manual control until about 10% of desired power was reached; at this point control was shifted to a servo-mechanism which was programmed to take the reactor power to 120 kW on a 20-sec period. When about 80% of full power was attained, the flux as shown on the power level recorder began to fall off rapidly, and the servosystem further withdrew the control rods; the power indication, however, did not increase but continued to drop. This situation existed for about 20 sec when the reactor scrammed automatically, and within 3 sec the operator took action and also scrammed the system manually. It is thought that the automatic scram was triggered by melting thermocouple wires.

The primary cause of the accident was a drop in the ion-collecting voltage across the detection chamber of the servosystem with increasing neutron flux. This behavior was, in turn, caused by the addition to the wiring of a filter circuit designed to reduce electronic noise coming from the high voltage supply or its connecting cable. Thus this accident seems to be unique in that it was due solely to instrumentation.

In this nonviolent power excursion of about 2.5×10^{19}

fissions, all core fuel elements experienced some melting, but only a few of the zirconium hydride moderator pieces were ruined. The melting of the fuel elements allowed a minor redistribution of fuel, decreasing the reactivity by about 2%. Some reactivity was released downwind, but personnel irradiations were apparently negligible.

6. The Los Alamos Scientific Laboratory - December 11, 1962 [5]

   (Zepo critical facility, ^{235}U foils moderated with graphite)

   This critical assembly consisted of a large cylindrical enriched uranium-graphite core on a lift device and a stationary platform holding a reflector of graphite and beryllium into which the core was raised. Most of the ^{235}U was placed in the graphite in the form of thin foils, and, in this respect, the excursion characteristics should be similar to those of the Honeycomb assembly. The experiment planned at the time was concerned with measurements of the axial fission distribution which was perturbed from its normal value by an end reflector made up of layers of graphite and polyethylene. For this reason, some fresh ^{235}U foils had been placed in the assembly, and these were used to obtain a reasonably precise value of the fission energy release.

It was assumed by the crew that the assembly had been run together and checked the previous day. This was not the case, however, and the system became critical with the ram in motion upward. The instrumentation scrammed the core when the power was about 200 W, but before the lift could coast to a stop and start down the system reactivity exceeded prompt critical (Δk prompt $\sim$ 12 cents). Peak power was about 1 MW, and the maximum alpha was 40/sec. The yield was 3×10^{16} fissions, but no damage was done and personnel irradiations were unmeasurable. The laboratory was entered within 30 min.

III. CHARACTERISTICS OF PROMPT EXCURSIONS
AND QUENCHING MECHANISMS

Power excursions are regarded as dangerous because, for extreme cases, the exponential rise of power is so rapid that safety devices cannot react in time to prevent damage to the system and irradiation of personnel. Indeed, this is often, but not necessarily, the case. Some excursions have been terminated by safety devices, while others have been terminated by natural quenching mechanisms that are roughly proportional to the fission energy that has been generated. This self-terminating characteristic has been demonstrated experimentally by the eight reactor

systems that have been used in this field: the Dragon,[48] the Borax systems,[40, 43] Godiva-I,[25, 26] the several Spert reactors,[57-59] the Kewb reactors,[60, 61] Godiva-II,[29] Triga,[62, 63] Treat,[64] and the Snaptran reactors. Of these, the first three and the last no longer exist, but the other five are working reactors. Several are no longer concerned with providing information about prompt excursions per se, but are used to provide quick pulses of neutrons for other experimental purposes.

The quenching actions utilized by the above experimental reactors which have terminated many of the accidental excursions are thermal expansion, rise in neutron temperature, boiling, ^{238}U Doppler effect, and bubble formation from fission fragments. The order here is of no importance, and not all are independent. In addition, in some reactors, more than one mechanism contributes to quench or shutdown of the excursion, and in many cases additional quenching actions set in when energy densities or temperatures reach some threshold value. The ramifications of this subject are varied and numerous, but the simplest and most generally applicable case is that of the energy model[65, 66] in which the change of reactivity is proportional to the release of fission energy.

For the special case of a step increase in reactivity,

ΔK_o, we can write

$$\Delta K(t) = \Delta K_o - bE(t), \qquad (1)$$

where $E(t)$ is the fission energy released to time t, and b is a constant characteristic of the system. With this assumption the reactor kinetic equations have been coded for numerical solution by use of digital computers. Such codes exist in many laboratories; the results quoted here are from the Los Alamos RTS Code.[67, 68] Figure 7 illustrates a series of computations for hypothetical systems in which the step increase of ΔK is 1.20 dollars, the value of b is constant, and the neutron lifetime, l, is varied from 10^{-8} to 10^{-4} sec. The power and reactivity traces for the short neutron lifetime cases (simulating a fast reactor) are characteristic of prompt excursions in such systems. The very sharp rise and fall in power is called the spike, and the relatively constant power following the spike is the plateau. During the spike, the reactivity changes by $2\Delta K_o$ - it reflects about prompt critical. The characteristics of these spikes are established almost entirely by the prompt neutrons. The traces for $l = 10^{-4}$ (simulating a moderated reactor) do not show the reflection about prompt critical, and there is no well-defined plateau following the spike. The time scale is of the order of the

72

decay times of the delayed neutron precursors, and the effects of these neutrons cannot be ignored in this case.

Figure 8 illustrates comparable data for a step increase in reactivity of 1.0 dollar. The time history of the reactivity and power in this case is quite different and, indeed, is typical of excursions in the delayed critical region. The time scale is much extended, allowing the possibility of mechanical devices shutting off the tranient; power peaks are broader; and the reactivity now attempts to reflect about delayed critical. It should be noted that the implicit assumption of no heat loss from the system cannot be realized in practice. Any such loss of energy could only hold the power to values greater than those plotted.

Some of the results illustrated in Figs. 7 and 8 can be obtained analytically. For sufficiently large step increases in reactivity above prompt critical, the delayed neutrons may be ignored and the kinetic equations integrated to give the total excursion yield.[*]

$$E = \frac{2\Delta K_p}{b}, \tag{2}$$

_____

[*]A similar result can be obtained for the delayed critical region, but the implicit adiabatic assumption vitiates the result.

where ΔK_p is the step increase relative to prompt critical.
The half-width of the spike is given by

$$\Delta t_{1/2} = \frac{3.52 \; \ell}{\Delta K_p}, \tag{3}$$

where ℓ = the neutron lifetime and the maximum power is

$$\frac{dE}{dt} \; max \; \sim \; \frac{2}{3.5} \; \frac{\Delta K_p^2}{b \; \ell}. \tag{4}$$

The experimental systems which have been most inten-
sively studied and which exemplify best the data in Figs.
7 and 8 and many of the possible hazards in the nuclear
energy industry are the Godiva, Kewb, and Spert reactors.
Each of these will be discussed briefly.

Godiva I (discussed in Section I) and Godiva-II are
near-solid uranium (93% ^{235}U) metal critical assemblies,
which were pressed into service as irradiation facilities.
At a few cents above prompt critical, controlled prompt
excursions provide an excellent experimental picture to
complement the curves of Fig. 7. The prompt negative
temperature coefficient of reactivity of about 4.3 x 10^{-3}
dollar/$^{\circ}$C (depending on the model) arises from thermal
expansion and is directly related to the disposition of
fission energy. The transient proceeds so rapidly that no
heat is lost from the system. When the step change of
reactivity is increased to 4 or 5 cents above prompt

critical, a new effect sets in. The power level rises to
such high values that the thermal expansion lags the energy
deposition, and the simple ratio of E and ΔK_p in Eq. 2 is
no longer true. At still higher step changes, the energy
release becomes proportional to the square and eventually
to the cube of the initial excess reactivity. Structural
damage from shocks commences at 10 or 11 cents, thus
providing a limit for repetitive bursts.

The transient behavior of solution systems has been
studied with the two Kewb reactors. The Kewb-A core was a
13.6-liter stainless steel sphere containing 11.5 liters of
enriched UO_2SO_4 solution. The reflector was thick graphite.
This reactor provided a means of studying transients in
solution systems during which the period was as short as
2 msec. The Kewb-B core was designed specifically to
extend these measurements to a period of 1 msec. It was
cylindrical, and during the transient experiments (up to
about 5.2 dollars over prompt critical) contained 18 liters
of UO_2SO_4 solution.

In the Kewb system two quenching mechanisms seem to be
dominant over a wide range of excursions. The first of
these is the rise in neutron temperature and thermal expan-
sion as the core temperature rises, which results in a
prompt temperature coefficient equal to -2 cents/$^\circ$C at

75

$30^{\circ}C$. This effect is sufficient to account for the observed yield of excursions starting near prompt critical, but is inadequate for more violent transient experiments. The second quenching mechanism is bubble formation.[69] The available evidence supports the contention that during the spike void space consisting of many very small bubbles (microbubbles) with internal pressures of from 10 to 1000 atm are created by the fission process. These small bubbles later coalesce and leave the system, giving the observed gas production coefficient of about 4.4 liters/MW-sec.

The growth of these microbubbles seems to involve the repeated interaction between fission fragments and existing microbubbles from earlier fissions. Thus a quenching mechanism proportional to the square of the energy release can be invoked. This model is successful in describing the solution transients, notwithstanding imprecise knowledge of the manner in which the bubbles form and grow.

The family of Spert-I reactor cores[47] have been of two general types, both heterogeneous, water-moderated and reflected. The first had fuel in the form of the MTR-type aluminum uranium-plates, and the cores have been designed to include the range from undermoderation to the hazardous region of overmoderation. The second Spert-I core was composed of canned UO_2 rods of about 1-cm diameter. The

uranium enrichment in these rods was 4%.

Transients on the plate-type reactors have been intensively studied since 1957 to solve core design problems and find the limitations of such reactors. In particular, the period and energy release which can cause damage has been carefully determined. The shutdown of a power transient in the Spert systems is more complicated than in the simpler reactors. The model developed includes (a) heating and density change of the water, (b) heating of the core structure including its own geometry changes and moderator expulsion from such changes, and finally (c) the boiling of water next to the plates and loss of moderator when water is expelled from the core.

This program was climaxed by a series of experiments in 1962 during which the reactor period was forced to successively smaller values. Damage in the form of blisters, cracking, and warping to the central fuel elements commenced during transients in which the period was 4.5 to 5 msec. When the period was reduced to 3.2 msec, the core was destroyed. However, for this last experiment, the reactivity, period, peak power, and energy release were closely predicted. The core was destroyed by a steam pressure pulse starting some 15 msec after completion of the nuclear phase. This effect was not predictable and is thought to

have been caused by the successive collapse of near-molten fuel elements.

The second type of Spert-I core[47] (4% enriched UO_2 rods in water) was tested during 1963 and 1964. Transient experiments with this core have demonstrated the effectiveness of the Doppler mode of self-shutdown and provide a basis for analysis of accidents in similar power reactor systems. Two attempts to destroy this core by placing the reactor on very short periods (2.2 and 1.55 msec) have failed. In each case the Doppler effect was operative, and additional quenching developed because one or two fuel pins (out of several hundred) cracked and caused local boiling. These pins were thought to have been water-logged before the test.

IV. SUMMARY

Some of the conclusions of Section II are summarized in Table II. Where possible and appropriate, the excursion fission energy is divided into that created in the spike and that in the plateau. Some time intervals of interest are also listed: the spike width at half maximum, the time from prompt critical to peak power, and the duration of the plateau. Also given are the maximum alpha (reciprocal period), the peak power during the spike, the initial

78

plateau power, and the probable quenching mechanism. Many
of these numbers are at best approximate so that no estimate
of probable error is attempted. As can be seen, the time
scales vary from microseconds to seconds, and for some ex-
cursions practically all fissions were in the plateau while
others consisted of a single spike.

Though the accidental excursions are too few to permit
reliable statistical conclusions, there are some observa-
tions that may be of general interest and importance. Of
the 34 excursions studied, six occurred in production plants
(and therefore were a complete surprise), five in what must
be called working reactors (the water boiler, the second
Godiva accident, the Dragon, the SL-1, and the NRX), and
the remainder in critical facilities where the properties
of the assemblies themselves were being investigated. One
suspects that the frequency of accidents may be related to
the frequency of producing an unfamiliar critical configur-
ation although the statistics to prove this hypothesis are
not available.

The causes of excursions can be generalized to some
extent. Four resulted from failure of some part of the
experimental equipment during operation near critical, two
were induced by scram devices, the production plant acci-
dents must be related to inadequate control over large and

complex systems, and two are unknown. The responsibility for the others invariably returns to the personnel operating the facility, and these incidents must be attributed to impatience, lack of planning or understanding of the experiment, or to simple carelessness.

The thought often has been expressed that, for reasons unknown, prompt critical accidents are limited in yield to a range roughly between 10^{16} and a few times 10^{17} fissions. Recent excursions have demolished this myth rather effectively, for now the ratio of yields of the largest to the smallest excursions is over 10^4. The ratio of fission densities, though less, is still a rather large number. It is quite true that as the fission density increases there appear more effective (and destructive) quenching mechanisms, such as boiling of water and melting and vaporization of metals. For the special case of slow insertion of reactivity, the fission densities corresponding to such phase changes can be regarded as order of magnitude upper limits for excursions of some systems, but these limits do not apply in general.

A potentially most dangerous manufacturing plant accident is possible (but may not be credible) in the handling and storage of large masses of fissile metal. The model to which one goes for information in this area is the Godiva

reactor, for which experiment and theory are well enough established to permit extrapolations to catastrophic conditions. One can imagine, for example, the consequences of inserting 3 dollars excess reactivity (relative to delayed critical) into Godiva; the resulting excursion would produce 10^{19} fissions, vaporize the entire mass, and possibly destroy (but certainly damage) the building in which the experiment was being performed. Under some circumstances the consequences of this type of accident can be estimated with reasonable accuracy. If the reactivity insertion rate is known and if a source of neutrons is present and sufficiently strong to guarantee that a continuing fission chain starts at or above prompt critical, the burst yield can be calculated. A most extraordinary rate is then required to produce a catastrophic explosion. The case for a quick step increase of reactivity can also be calculated quite exactly. If a neutron source is not present an explosion could be created.

This situation in which no external source is present and a high reactivity insertion rate is imposed on the system has been a matter of experimental and theoretical investigation at the Los Alamos Scientific Laboratory[70] using the Godiva-II reactor and at the Idaho Reactor Testing Area using the Spert-I reactor. The background fission rate

of Godiva-II is only 40/sec, primarily from the spontaneous
fission of the 6.5% ^{238}U, and quick (about 50 msec) changes
of reactivity to a few cents above prompt critical can be
made before a continuing fission chain is born. Generally
after such a step increase of reactivity there is a "wait
time" of the order of seconds before a continuing fission
chain develops. The statistics associated with these exper-
iments are illustrated in Fig. 9 where the fraction of the
bursts occurring in 1-sec intervals is plotted against the
wait time in seconds. The most probable delay is about 2
sec, and observed wait times have been as long as 11 sec.
These experiments are continuing for various steps and ramp
increases of reactivity.

The application of these results to some ^{235}U metal
safety problems is a two-edged sword. The very low neutron
background associated with ^{235}U could allow (for example)
sizable masses to fall together before a fission chain
started. An external neutron source to guarantee initiation
then would very substantially reduce the yield of such an
accidental power excursion. On the other hand, in some
cases the very real and possible wait times could allow
mechanical dispersion of the active material before a chain
started. An external neutron source would then be the
trigger for a power transient which otherwise might not have

occurred. This dilemma does not exist for plutonium metal for which the spontaneous fission rate guarantees a strong and reliable source.

A possible application of these results can be found in the conflicting economic and safety requirements associated with complicated or multiple-fuel-element castings. Some such operations now forbidden for safety reasons might be reconsidered if heavy shielding were available to protect operators and if strong neutron sources were present to guarantee initiation. Under these conditions, the risk of a nonexplosive power excursion might be acceptable.

The chemical plant incidents along with the Kewb reactor (Section III) experiments bring to focus the possibility that less stringent criticality rules may be applicable also to some ^{235}U solution operations where the operators are protected by heavy shielding. It is possible that significant economic savings could be realized with no increased radiation hazard if certain plants were designed with the expectation that such incidents might occasionally occur. The Kewb experiments provide much information on transient pressures, temperatures, fission yields, and neutron and gamma-ray fluxes associated with solution excursions. The results also suggest that only with difficulty can a solution system be forced to explode violently if it fills only a

small fraction of the available volume. As was discussed, enriched ^{235}U systems probably require an external neutron source.

These possibilities must be viewed with more caution when plutonium solutions are considered. It is well known that plutonium-rich, silica-like sludges tend to accumulate in significant quantities in chemical plants that have been in operation over a period of years. The second plant accident was caused by such an accumulation; furthermore, these deposits have been discovered in several plants, sometimes in more than modest amounts. Fortunately, dissolution of the sediments has generally been accomplished without incident. These deposits can be created with a relatively low H/Pu atomic ratio (of the order of 20) thus raising the possibility of an autocatalytic nuclear excursion. One can imagine a mass of this material forced to the critical state or above by immersion in water and, when boiling commences, mixing caused by bubble action could raise the H/Pu ratio. As mixing with water will (in this case) reduce the critical mass, the net effect is to increase the reactivity of the solution and cause the power to diverge even more. However, even for such an apparently dangerous situation it is difficult to imagine an explosive reaction. Again, it is quite possible that thick shielding

could nullify radiation hazards.

These chemical plant accidents also point up the problem of the large and complicated interconnected network of piping and tanks required for dissolution of fuel elements and separation of uranium, plutonium, fission fragments, and alloying materials. All of the six plant accidents have been caused by solutions flowing from safe to unsafe geometries, and these transfers were caused by failures in the network or were in some way associated with peripheral operations. The possibility of nuclearly safing large auxiliary containers and the insertion of positive blocks in certain lines has been considered, but it would be presumptuous to suggest detailed design features in this review.
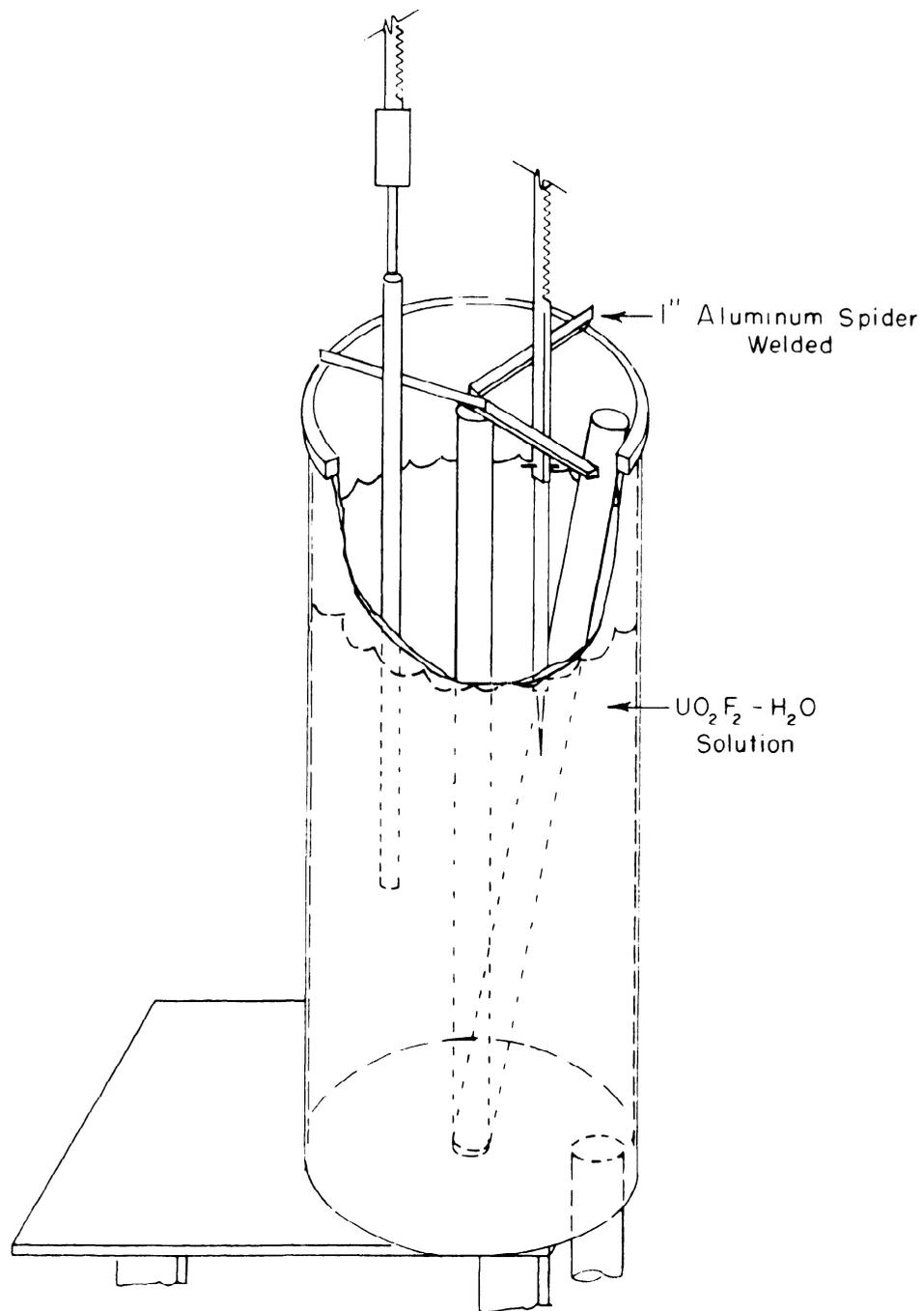
Fig. 1. The ORNL uranium solution assembly showing the
normal and detached positions of the central poison
rod.
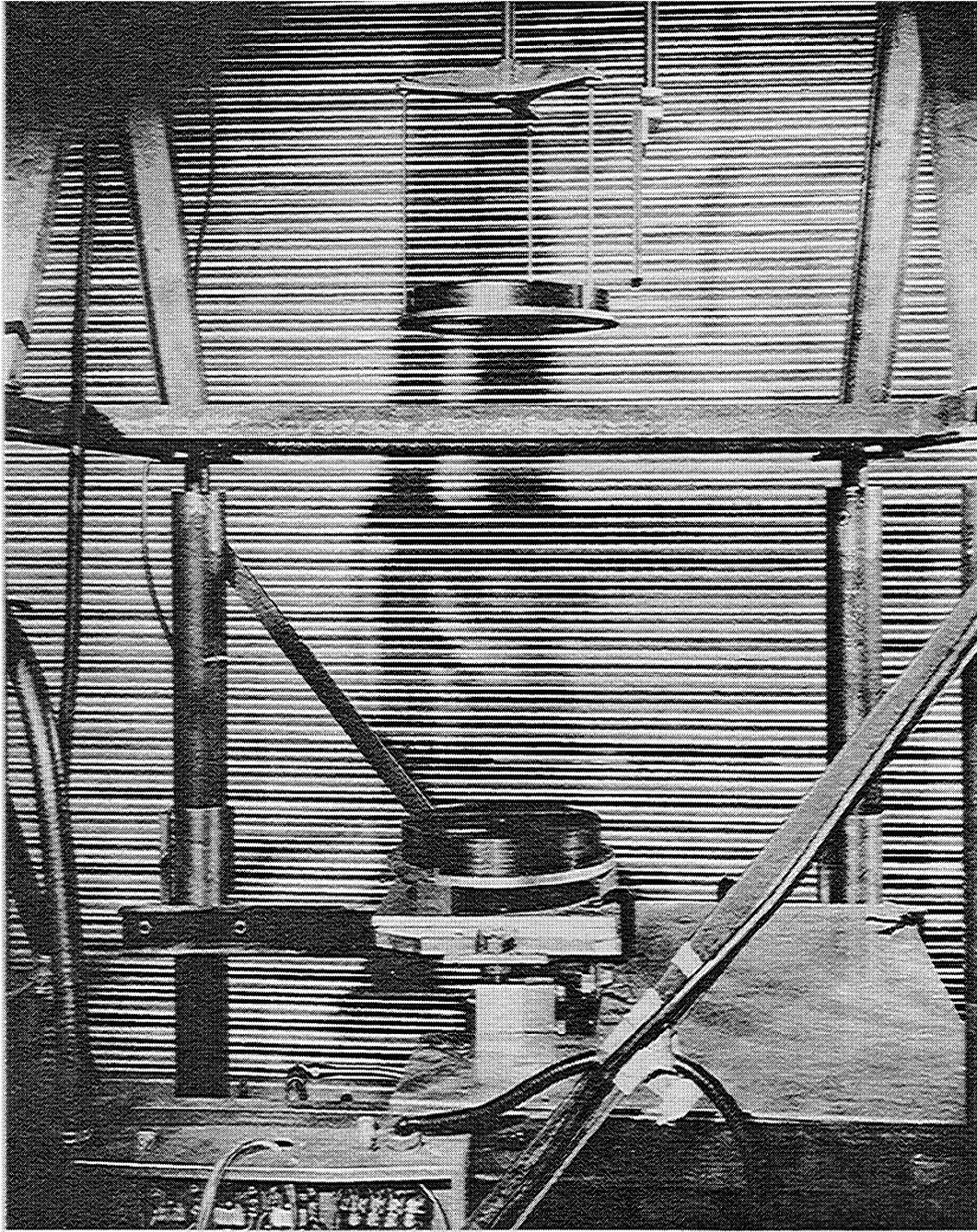
Fig. 2. The LASL Jemima enriched-uranium metal assembly in the scrammed configuration.
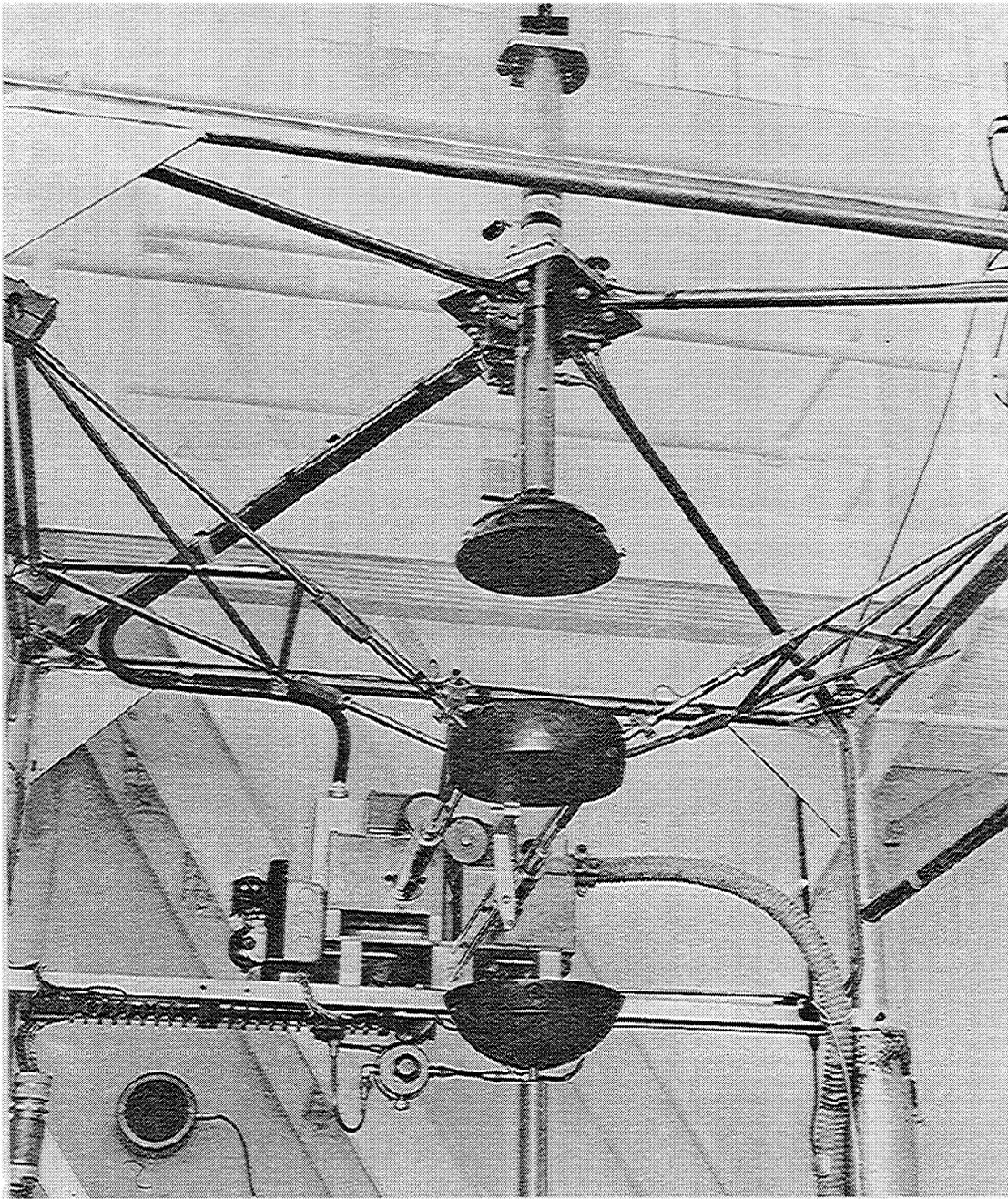
Fig. 3. The LASL Lady Godiva assembly (unreflected enriched-
uranium sphere) in the scrammed configuration.
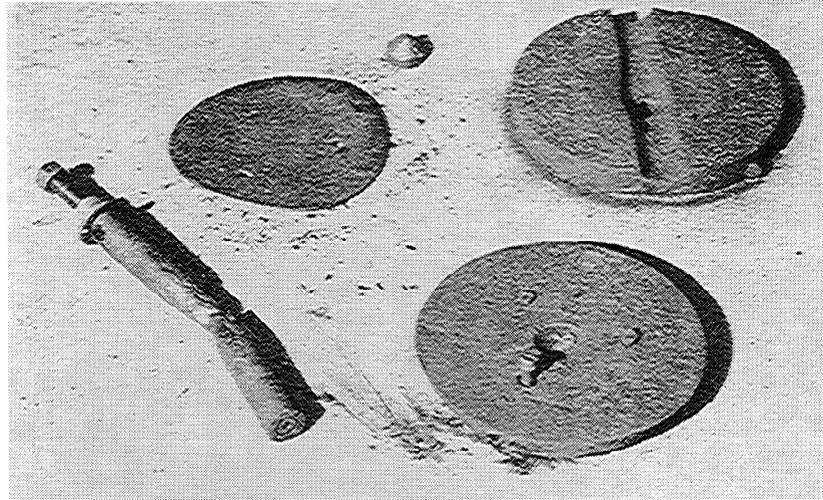
Fig. 4. The burst rod and several sections of Lady Godiva showing the oxidation and warpage which accompanied the second accidental excursion.
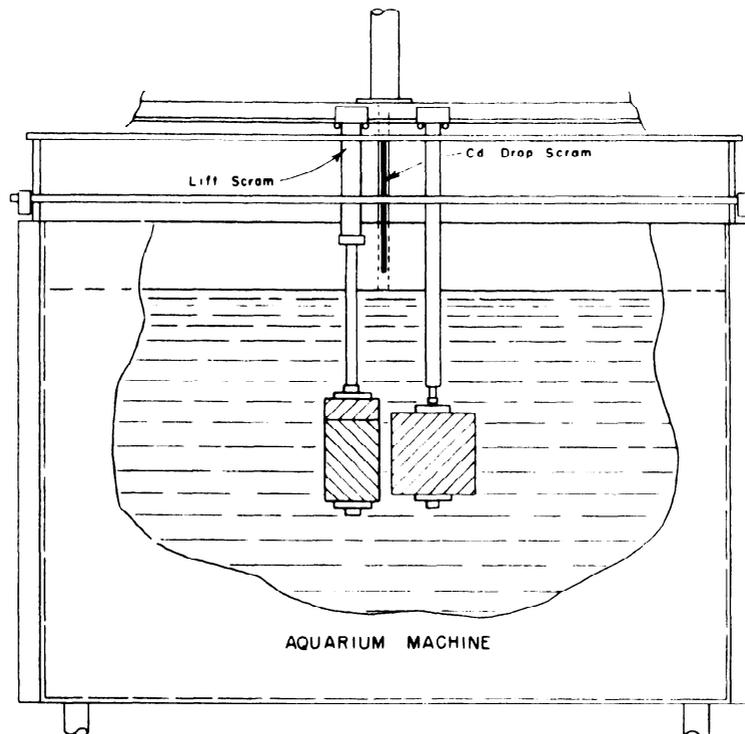
Fig. 5. The LASL Aquarium assembly machine which was employed for measurements of critical separation distances.
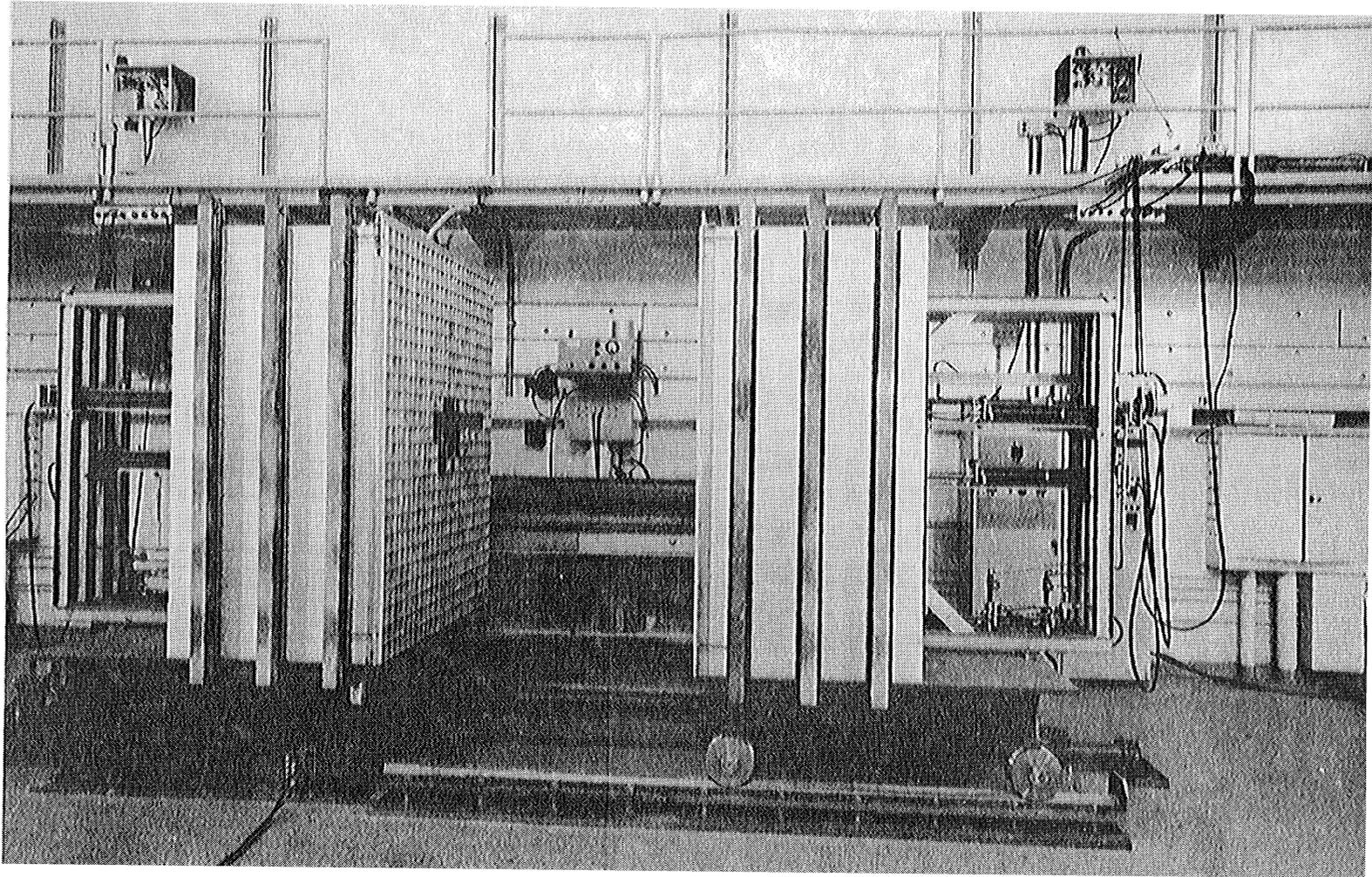
Fig. 6. The LASL Honeycomb assembly machine. The movable section (right) is
in the withdrawn position, and the aluminum matrix is only partially
loaded.
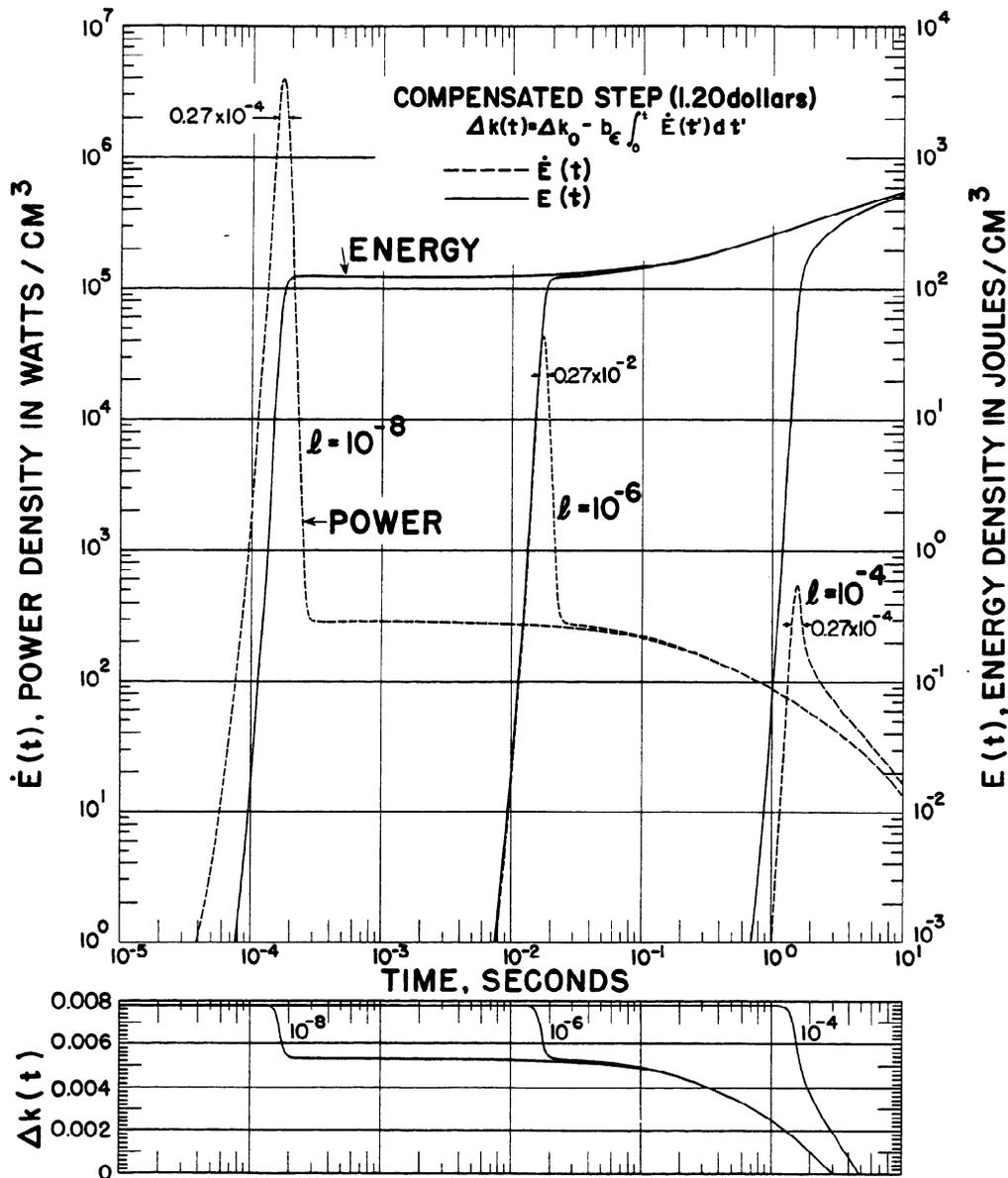
Fig. 7. Energy model computation of power versus time and energy release versus time, for an initial reactivity of 1.2 dollars above delayed critical for three different neutron lifetime values, $l = 10^{-8}$, 10^{-6}, and 10^{-4} sec. Below are the corresponding curves of reactivity versus time.
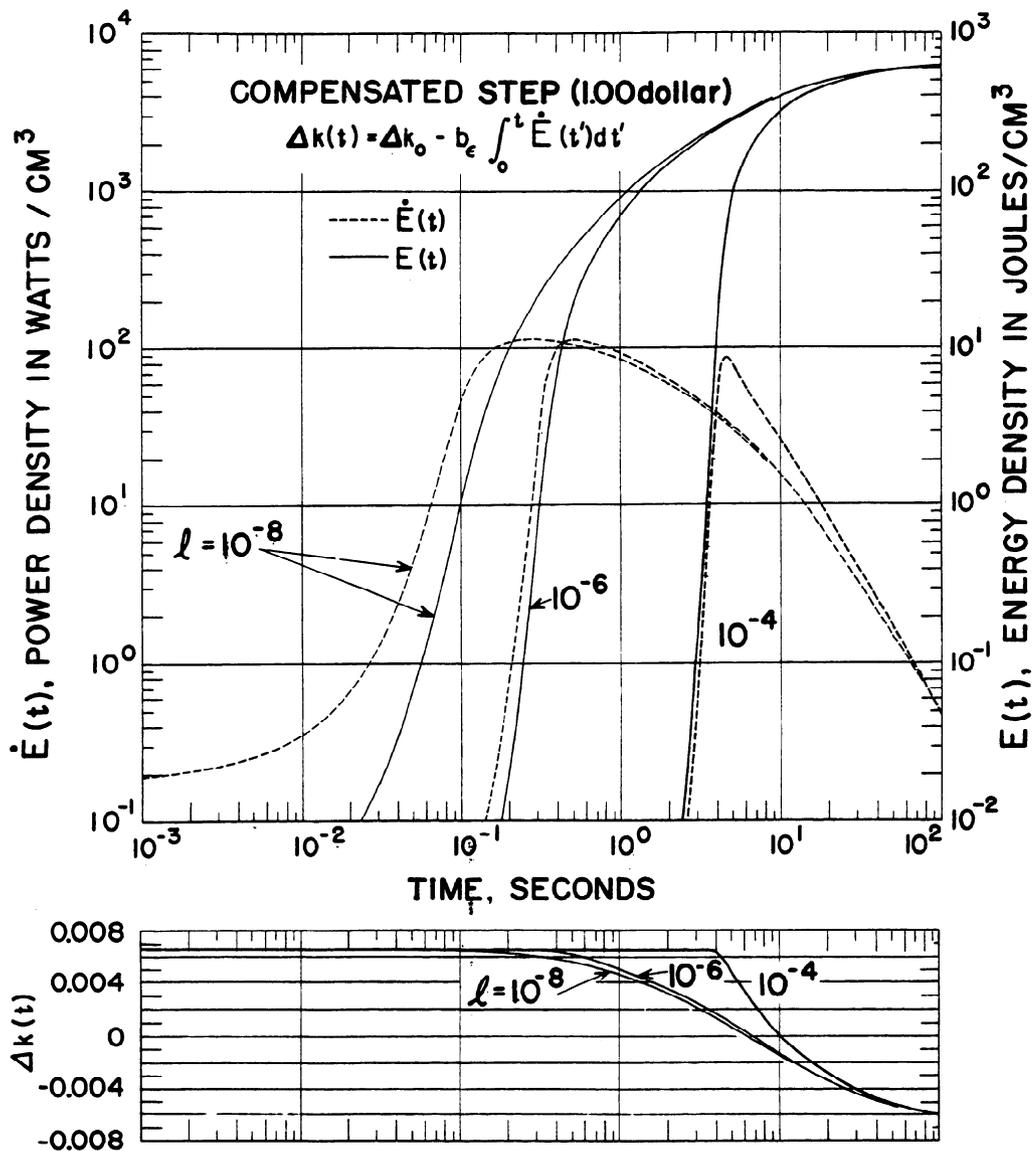
Fig. 8. Energy model computation of power versus time for
an initial reactivity of 1.0 dollar above delayed
critical for three different neutron lifetime
values, $l = 10^{-8}$, 10^{-6}, and 10^{-4} sec. Below are
the corresponding curves of reactivity versus
time.
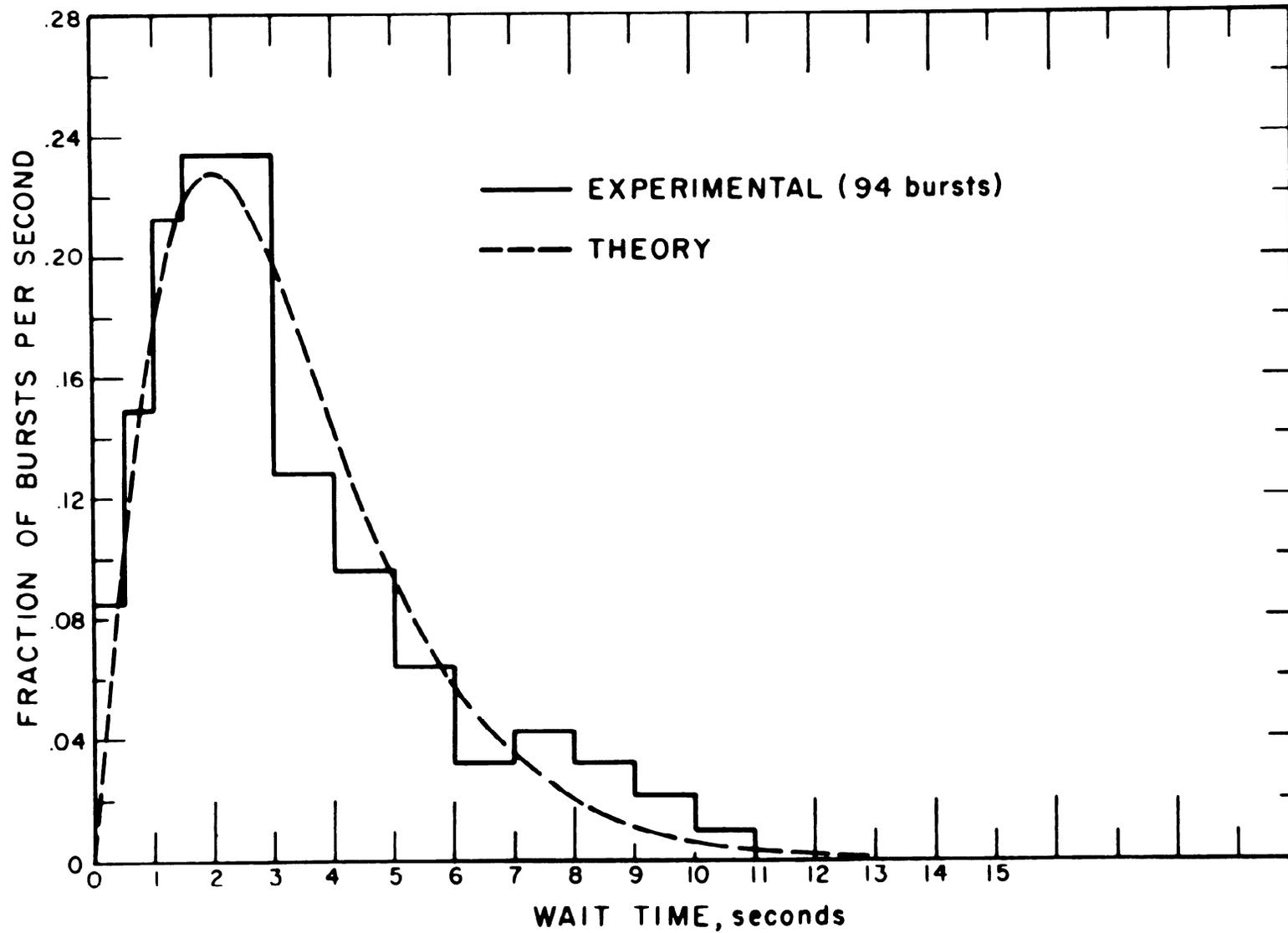
Fig. 9.   Distribution in burst wait times after quick (~50-msec) insertion of
1.05 dollars in Godiva-II.   Plotted is the fraction of the bursts in
each second versus the wait time in seconds.

TABLE I. CRITICALITY INCIDENTS

SOLUTION SYSTEMS

| DATE	LOCATION	ACTIVE MATERIAL	GEOMETRY	TOTAL FISSIONS	CAUSE	PHYSICAL DAMAGE
December 1949	LASL, New Mexico	~1 kg ^{235}U $UO_2(NO_3)_2$ in 13.6 liters H_2O	Sphere, graphite reflected	$3-4 \times 10^{16}$	Manual withdrawal of two poison control rods	None
November 16, 1951	Hanford Works, Richland, Washington	1.15 kg Pu $PuO_2(NO_3)_2$ in 63.8 liters H_2O	Sphere, 93% full unreflected	8×10^{16}	Poison control rod run out too fast	None
May 26, 1954	ORNL, Tennessee	18.3 kg ^{235}U UO_2F_2 in 55.4 liters H_2O	Cylindrical annulus unreflected	1×10^{17}	Tilting of inner poison cylinder	None
February 1, 1956	ORNL, Tennessee	27.7 kg ^{235}U UO_2F_2 in 58.9 liters H_2O	Cylinder unreflected	1.6×10^{17}	Falling scram set up waves creating critical geometry	Warping of bottom of cylinder
June 16, 1958	Y-12 Processing Plant, Oak Ridge, Tennessee	2.5 kg ^{235}U $UO_2(NO_3)_2$ in 56 liters H_2O	Cylinder concrete reflected below	1.3×10^{18}	Wash water added to $UO_2(NO_3)_2$ solution	None
December 30, 1958	LASL, New Mexico Pu Processing Plant	3.27 kg Pu $PuO_2(NO_3)_2$ in ~168 liters H_2O	Cylinder water reflected below	1.5×10^{17}	Agitator created critical geometry	None
October 16, 1959	Chemical Processing Plant Idaho Reactor Testing Area	34.5 kg ^{235}U ~800 liters $H_2O-UO_2(NO_3)_2$	Cylinder concrete reflected below	$~4 \times 10^{19}$	Solution siphoned from safe to unsafe geometry	None
January 25, 1961	Chemical Processing Plant Idaho Reactor Testing Area	8 kg ^{235}U $UO_2(NO_3)_2$ in 40 liters H_2O	Cylinder	6×10^{17}	Solution pumped from safe to unsafe geometry	None
April 7, 1962	Hanford Works, Richland, Washington	1.55 kg Pu	Cylinder unreflected	8×10^{17}	Concentrated solution incorrectly siphoned	None
July 24, 1964	The Wood River Junction, R. I. scrap recovery facility	2.64 kg ^{235}U in $UO_2(NO_3)_2$	Cylinder unreflected	1.3×10^{17}	Concentrated solution poured into unsafe geometry. Additional moderation in tank	None

94

TABLE I (Continued)   METAL SYSTEMS IN AIR

DATE	LOCATION	ACTIVE MATERIAL	GEOMETRY	TOTAL FISSIONS	CAUSE	PHYSICAL DAMAGE
August 21, 1945	Los Alamos, New Mexico	6.2 kg δ-phase Pu	Spherical core WC reflected	$\sim 10^{16}$	Hand stacking reflector	None
May 21, 1946	Los Alamos, New Mexico	6.2 kg δ-phase Pu	Spherical core Be reflected	$\sim 3 \times 10^{15}$	Hand stacking reflector	None
April 18, 1952	LASL New Mexico	92.4 kg U metal 93% ^{235}U	Cylinder unreflected	1.5×10^{16}	Computation error	None
February 3, 1954	LASL New Mexico	53 kg U metal 93% ^{235}U	Sphere unreflected	5.6×10^{16}	Incorrect operation	Slight warping of pieces
February 12, 1957	LASL New Mexico	54 kg U metal 93% ^{235}U	Sphere unreflected except for experiment	1.2×10^{17}	Shift of experiment	Warping oxidation near melting close to center
June 17, 1960	LASL New Mexico	~ 48 kg ^{235}U	Cylinder 9-in. graphite reflected	6×10^{16}	Change of k from previous assembly too large	Trivial
November 10, 1961	ORNL Tennessee	~ 75 kg ^{235}U	Paraffin reflected	$\sim 10^{16}$	Change of k from previous assembly too large	None
March 26, 1963	LARL California	47 kg U	Cylinder Be reflected	3.76×10^{17}	Mechanical failure -- sudden assembly of metal core	Metal melted and some burned, contamination
May 28, 1965	WSMR New Mexico	96 kg enriched U-Mo alloy	Cylinder unreflected	1.5×10^{17}	Incorrect operation	Assembly bolts broken, minor damage to coating

TABLE I (Continued)   INHOMOGENEOUS WATER-MODERATED SYSTEMS

DATE	LOCATION	ACTIVE MATERIAL	GEOMETRY	TOTAL FISSIONS	CAUSE	PHYSICAL DAMAGE
June 4, 1945	Los Alamos, New Mexico	35.4 kg U ~83% ^{235}U 1/2" cubes	Pseudosphere water reflected	~3 x 10^{16}	Water seeping between blocks	None
February 1, 1951	LASL, New Mexico	2 cylinders U 24.4 and 38.5 kg 93% ^{235}U	2 cylinders water reflected	10^{17}	Scram increased reactivity	Slight oxidation
July 6, 1952	ANL Illinois	6.8 kg ^{235}U oxide particles in plastic	Inhomogeneous cylinder water reflected	1.22 x 10^{17}	Manual withdrawal of central safety rod	Plastic destroyed
December 12, 1952	Chalk River Canada	Normal U	Rods, D_2O moderated graphite reflected	1.2 x 10^{20}	Safety circuits failed control rod misoperation	Core ruined
July 22, 1954	Reactor Testing Area Idaho Falls, Idaho	U-Al plates Al clad	Inhomogeneous cylinder water moderated	4.68 x 10^{18}	Estimate of expected excursion too low	Reactor destroyed
October 15, 1958	Vinca, Yugoslavia	3996 kg Normal U	Rods D_2O moderated unreflected	2.5 x 10^{18}	Too much D_2O added in final step of experiment	None
March 15, 1960	Saclay, France	2.2 tons UO_2, 1.5% enriched	Canned UO_2 rods in water	3 x 10^{18}	Control rod withdrawn	None
January 3, 1961	Reactor Testing Area Idaho Falls, Idaho	U-Al plates Al clad	Inhomogeneous cylinder, water moderated	4.4 x 10^{18}	Quick manual withdrawal of control rod	Reactor destroyed, building contaminated
December 30, 1965	Mol, Belgium	1.2 x 10^6 g-UO_2 7% enriched	Canned UO_2 rods in H_2O-D_2O	4.3 x 10^{17}	Manual withdrawal of control rod	None

96

TABLE I (Continued) MISCELLANEOUS SYSTEMS

DATE	LOCATION	ACTIVE MATERIAL	GEOMETRY	TOTAL FISSIONS	CAUSE	PHYSICAL DAMAGE
February 11, 1945	Los Alamos, New Mexico	UH_3 pressed in styrex	Cylinder	$\sim 6 \times 10^{15}$	Reflector added and/or source too large	UH_3-styrex cubes swollen and blistered
1953	U.S.S.R.	Unknown	Unknown	Unknown	Unknown	Unknown
November	Idaho Reactor Testing Area	1/2" ^{235}U rods	Cylinder, rods NaK cooled	4.7×10^{17}	Incorrect scram used	Core molten
July 3, 1956	LASL, New Mexico	58 kg U 93% ^{235}U, 2- and 5-mil foils	Cylinder	3.2×10^{16}	Change of k from previous assembly too large	None
November 18, 1958	Reactor Testing Area, Idaho Falls, Idaho	^{235}U Ni-Cr elements ZrH moderated	Cylinder prototype aircraft engine	2.5×10^{19}	Incorrect wiring in ion chamber circuit	Every fuel cartridge melted
December 11, 1962	LASL New Mexico	^{235}U foils in graphite	Cylinder graphite and Be reflected	3×10^{16}	Inadequate communication between work crews	None

TABLE II. ANALYSIS OF CRITICALITY INCIDENTS

SOLUTION SYSTEMS

INCIDENT	OBSERVED FISSION YIELD	SPIKE YIELD (FISSIONS)	PLATEAU YIELD (FISSIONS)	MAXIMUM α (SEC^{-1})	TIME FROM PROMPT CRITICAL TO PEAK POWER (SEC.)	WIDTH OF SPIKE AT ONE-HALF MAXIMUM VALUE (SEC.)	DURATION OF PLATEAU (SEC.)	PEAK POWER DURING SPIKE (FISSIONS/SEC)	INITIAL PLATEAU POWER (FISSIONS/SEC)	PROBABLE QUENCHING MECHANISM
Water Boiler Reactor Control Rods Removed By Hand December, 1949	$3\text{-}4\times10^{16}$	$\sim3\times10^{15}$	$2.7\text{-}3.7\times10^{16}$	6.25	~3.5	-	~1.5	-	$2\text{-}3\times10^{16}$	Thermal expansion
Pu Solution Assembly Cd Rod Removed Too Rapidly November 16, 1951	8×10^{16}	8×10^{16}	0.0	No Estimate	No Estimate	No Estimate	0.0	No Estimate	0.0	Micro-bubbles, thermal expansion, and poison rod
U Solution Assembly, Central Poison Cylinder Tilted To Less Favorable Position May 26, 1954	10^{17}	5×10^{16}	5×10^{16}	4.8×10^{2}	7.8×10^{-2}	5.4×10^{-3}	~0.5	8.2×10^{18}	4.8×10^{16} to 1.4×10^{17}	Micro-bubbles, and thermal expansion
U Solution Assembly, Wave Motion Created By Falling Cd Sheet February 1, 1956	1.6×10^{17}	1.6×10^{17}	0.0	6.1×10^{3}	7.4×10^{-4}	3.7×10^{-4}	0.0	$\sim3.5\times10^{20}$	0.0	Micro-bubbles, and thermal expansion
U Process Solution Combined With Wash Water in 55-Gal Drum June 16, 1958	1.3×10^{18}	$\sim10^{16}$	1.29×10^{18}	No Estimate	No Estimate	No Estimate	170.0	No Estimate	No Estimate	Micro-bubbles, thermal expansion, and boiling
Separated Phases in Pu Process Tank December 30, 1958	1.5×10^{17}	1.5×10^{17}	0.0	No Estimate	No Estimate	No Estimate	0.0	No Estimate	0.0	Micro-bubbles, thermal expansion, and stirring action
U Process Solution Siphoned From Safe to Unsafe Geometry October 16, 1959	4×10^{19}	$\sim10^{17}$	$\sim4\times10^{19}$	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Micro-bubbles, and thermal expansion
U Process Solution Pumped From Safe to Unsafe Geometry January 25, 1961	6×10^{17}	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Micro-bubbles, and thermal expansion
Pu Solution Incorrectly Siphoned April 7, 1962	8×10^{17}	$\sim10^{16}$	7.9×10^{17}	~0.2	No Estimate	No Estimate	No Estimate	3×10^{14}	No Estimate	Micro-bubbles boiling
U Solution Hand-poured into Unsafe Tank, Two-Bursts, July 24, 1964	1.3×10^{17}	1.1×10^{17} 0.2×10^{17}	zero or very small	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Micro-bubbles, Expulsion of Liquid

TABLE II (Continued) METAL SYSTEMS IN AIR

INCIDENT	OBSERVED FISSION YIELD	SPIKE YIELD (FISSIONS)	PLATEAU YIELD (FISSIONS)	MAXIMUM α (SEC^{-1})	TIME INTERVAL FROM PROMPT CRITICAL TO PEAK POWER (SEC.)	WIDTH OF SPIKE AT ONE-HALF MAXIMUM VALUE (SEC.)	TIME DURATION OF PLATEAU (SEC.)	PEAK POWER DURING SPIKE (FISSIONS/SEC)	INITIAL PLATEAU POWER (FISSIONS/SEC)	PROBABLE QUENCHING MECHANISM
Pu Core Reflected With Tungsten Carbide August 21, 1945	10^{16}	~1.8×10^{15}	~8.2×10^{15}	~10^4	~2×10^{-3}	~3.5×10^{-4}	0.8	~5×10^{18}	~1.2×10^{16}	Thermal expansion
Pu Core Reflected With Be May 21, 1946	3×10^{15}	~1.8×10^{14}	~2.86×10^{15}	~10^3	1.5×10^{-2}	~3.5×10^{-3}	0.28	~5×10^{16}	~1.2×10^{16}	Thermal expansion
Jemima, Cylindrical Unreflected ^{235}U Assembly April 18, 1952	1.5×10^{16}	~10^{15}	~1.4×10^{16}	8×10^3	4.3×10^{-3}	4.4×10^{-4}	≤ 0.3	2.3×10^{18}	$\leq 10^{17}$	Thermal expansion
Godiva, Bare ^{235}U Sphere February 3, 1954	5.6×10^{16}	5.6×10^{16}	0.0	1.6×10^5	2.4×10^{-4}	1.8×10^{-5}	0.0	3.5×10^{21}	0.0	Thermal expansion
Godiva, Bare ^{235}U Sphere February 12, 1957	1.2×10^{17}	1.2×10^{17}	0.0	2.1×10^5	1.9×10^{-4}	1.2×10^{-5}	0.0	10^{22}	0.0	Thermal expansion
^{235}U Core, C Reflected June 17, 1960	6×10^{16}	~10^{15}	5.9×10^{16}	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Thermal expansion
^{235}U Core, Paraffin reflected November 10, 1961	~10^{16}	~10^{15}	~9×10^{15}	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Thermal expansion
^{235}U Core Be reflected	3.76×10^{17}	10^{17}	2.7×10^{17}	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Thermal expansion
^{235}U-10 wt/% Mo Bare Pulsed Reactor	1.5×10^{17}	1.5×10^{17}	0.0	1.08×10^5	5×10^{-4}	28×10^{-6}	0.0	5.3×10^{21}	0.0	Thermal expansion

TABLE II (Continued)   INHOMOGENEOUS WATER-MODERATED SYSTEMS

INCIDENT	OBSERVED FISSION YIELD	SPIKE YIELD (FISSIONS)	PLATEAU YIELD (FISSIONS)	MAXIMUM α (SEC^{-1})	TIME INTERVAL FROM PROMPT CRITICAL TO PEAK POWER (SEC.)	WIDTH OF SPIKE AT ONE-HALF MAXIMUM VALUE (SEC.)	TIME DURATION OF PLATEAU (SEC.)	PEAK POWER DURING SPIKE (FISSIONS/SEC)	INITIAL PLATEAU POWER (FISSIONS/SEC)	PROBABLE QUENCHING MECHANISM
Pseudosphere of U Cubes, H$_2$O Reflected June 6, 1945	$3\text{-}4\times10^{16}$	$\sim3\times10^{15}$	$2.7\text{-}3.7\times10^{16}$	No Estimate	No Estimate	No Estimate	~5.0	No Estimate	No Estimate	Boiling
Critical Separation Experiment, Two Large ^{235}U Masses in H$_2$O February 1, 1951	10^{17}	$\sim6\times10^{15}$	$\sim9.5\times10^{16}$	No Estimate	No Estimate	No Estimate	~0.1	No Estimate	$\sim10^{17}$	Boiling
UO$_2$ Particles in Plastic, H$_2$O Moderated July 6, 1952	1.22×10^{17}	1.22×10^{17}	0.0	100	~0.6	1.9×10^{-2}	0.0	5.4×10^{18}	0.0	Plastic Bubbles
NRX Reactor Normal in D$_2$O, Graphite Reflected December 12, 1952	1.2×10^{20}	Not Prompt Critical	Not Prompt Critical	~0.33	Not Prompt Critical	~30	0.0	$\sim3\times10^{18}$	0.0	D$_2$O Drained From Core
Borax Reactor Al-U Alloy, H$_2$O Moderated July 22, 1954	4.68×10^{18}	4.68×10^{18}	0.0	385	7.9×10^{-2}	6.5×10^{-3}	0.0	6.6×10^{20}	0.0	Boiling
Critical Assembly of normal U rods in D$_2$O October 15, 1958	2.5×10^{18}	Not Prompt Critical	Not Prompt Critical	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Cd rods inserted into core
1.5% ^{235}U UO$_2$ rods in H$_2$O March 15, 1960	3×10^{18}	No Estimate	No Estimate	~2.0	No Estimate	No Estimate	No Estimate	About 3×10^{17}	About 1 megawatt	Control rods inserted into core
SL-1 Reactor Al-U Alloy Plates, H$_2$O moderated January 3, 1961	4.4×10^{18}	4.4×10^{18}	0.0	280	No Estimate	About 11 msec	0.0	About 6×10^{20}	0.0	Boiling
7% ^{235}UO$_2$ rods in H$_2$O, December 30, 1965	4.3×10^{17}	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	No Estimate	Insertion of poison rod

TABLE II (Continued)   MISCELLANEOUS SYSTEMS

101

INCIDENT	OBSERVED FISSION YIELD	SPIKE YIELD (FISSIONS)	PLATEAU YIELD (FISSIONS)	MAXIMUM α (SEC^{-1})	TIME INTERVAL FROM PROMPT CRITICAL TO PEAK POWER (SEC.)	WIDTH OF SPIKE AT ONE-HALF MAXIMUM VALUE (SEC.)	TIME DURATION OF PLATEAU (SEC.)	PEAK POWER DURING SPIKE (FISSIONS/SEC)	INITIAL PLATEAU POWER (FISSIONS/SEC)	PROBABLE QUENCHING MECHANISM
The Dragon Reactor UH$_3$ Pressed in Styrex February 11, 1945	$\sim$6x10^{15}	$\sim$6.10^{15}	0.0	No Estimate	$\sim$10^{-2}	No Estimate	0.0	No Estimate	0.0	Thermal Expansion
Experimental Reactor, U.S.S.R. 1953	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
EBR-1 Fast Breeder Reactor, ^{235}U Rods in NaK, November 29, 1955	4.7x10^{17}	Not Prompt Critical	Not Prompt Critical	$\sim$3.6	Not Prompt Critical	$\sim$1.0	0.0	$\sim$3x10^{17}	0.0	Reflector Dropped from Core
The Honeycomb, ^{235}U Foils, C Moderated July 3, 1956	3.2x10^{16}	3.2x10^{16}	0.0	$\sim$40	$\sim$1.1	0.1	0.0	9.4x10^{17}	0.0	Motion of Safety Rods
HTRE Reactor Instrumentation failure November 18, 1958	2.5x10^{19}	Not Prompt Critical	Not Prompt Critical	About 0.12	Not Prompt Critical	Not Prompt Critical	Not Prompt Critical	No Estimate	Not Prompt Critical	Scram inserted control rod
Zepo ^{235}U foils in C December 11, 1962	3x10^{16}	3x10^{16}	0.0	38	No Estimate	No Estimate	0.0	3x10^{16}	0.0	Scram dropped core

Acknowledgments

It is a pleasure to thank H. C. Paxton and G. E. Hansen for their interest and considerable assistance in the preparation of this report. Thanks are given to G. R. Keepin and Mrs. Clarice Cox for permission to use unpublished results of the Los Alamos R.T.S. code. Finally, I thank the very large number of people who by letter or by personal contact contributed information without which this review would have been incomplete.

REFERENCES

1. D. F. Hayes, A Summary of Accidents and Incidents Involving Radiation in Atomic Energy Activities, June 1945 through December 1955, U. S. Atomic Energy Commission, Technical Information Service Report TID-5360, 1956.

2. D. F. Hayes, A Summary of Incidents Involving Radio-active Material in Atomic Energy Activities, January - December 1956, U. S. Atomic Energy Commission Technical Information Service Report TID-5360 (Supplement), 1957.

3. H. C. Paxton, Critical-Assembly Booby Traps, Nucleonics 16, 80 (March 1958).

4. H. C. Paxton, Booby Traps, Paper presented at the June 12, 1957 meeting of the American Nuclear Society, Pittsburgh, Penn.

5. The Los Alamos Scientific Laboratory archives, unpublished information.

6. L. D. P. King, The Los Alamos Scientific Laboratory, private communication.

7. L. D. P. King, Design and Description of Water Boiler Reactors, Proc. Intern. Conf. Peaceful Uses At. Energy, Geneva, 1955, 2, 372 (1955).

8. B. R. Leonard, Jr., A Study of the Radiation Burst in the Hanford Homogeneous Reactor, The General Electric

Company, Nucleonics Division report HW-24327, 1952.

9. J. T. Thomas and A. D. Callihan, <u>Radiation Excursions</u>
    <u>at the ORNL Critical Experiments Laboratory; I, May 26,</u>
    <u>1954; II, February 1, 1956,</u> The Oak Ridge National
    Laboratory report ORNL-2452, 1958.

10. F. S. Patton et al., <u>Accidental Radiation Excursion at</u>
    <u>the Y-12 Plant,</u> June 16, 1958, Union Carbide Nuclear
    Company report Y-1234, 1958.

11. A. D. Callihan and J. T. Thomas, <u>Accidental Radiation</u>
    <u>Excursion at the Oak Ridge Y-12 Plant, Description and</u>
    <u>Physics of the Accident,</u> Health Physics, Pergamon
    Press, London, 1958, <u>1</u>, 363.

12. <u>Oak Ridge Y-12 Accidental Excursion, June 16, 1958,</u>
    Nucleonics, <u>16</u>, 138 (November 1958).

13. H. C. Paxton et al., <u>Nuclear-Critical Accident at the</u>
    <u>Los Alamos Scientific Laboratory on December 30, 1958,</u>
    The Los Alamos Scientific Laboratory report LAMS-2293,
    1959.

14. H. C. Paxton et al., <u>Los Alamos Criticality Accident,</u>
    <u>December 30, 1958,</u> Nucleonics, <u>17</u>, 107 (April 1959).

15. Eldon Christensen, The Los Alamos Scientific Labora-
    tory, private communication.

16. W. L. Ginkel et al., <u>Nuclear Incident at the Idaho</u>
    <u>Chemical Processing Plant on October 16, 1959,</u> Phillips

Petroleum Co. report IDO-10035, 1960.

17. R. C. Paulus et al., Nuclear Incident at the Idaho Chemical Processing Plant on January 25, 1961, Phillips Petroleum Company report IDO-10036 (1961).

18. D. Callihan, Accidental Nuclear Excursion in Recuplex Operation at Hanford, April 1962, Nuclear Safety, 4, No. 4, 136 (1963).

19. Duane Clayton, Hanford Atomic Products Operation, private communication.

20. F. R. Nakuche and M. M. Shapiro, The Nuclear Aspects of the Accidental Criticality at Wood River Junction, Rhode Island, July 24, 1964, United Nuclear Corporation (1964).

21. J. G. Hoffman, Radiation Doses in the Pajarito Accident of May 21, 1946, The Los Alamos Scientific Laboratory report LA-687, 1948.

22. D. C. Aebersold, U. S. Atomic Energy Commission, private communication.

23. G. A. Jarvis et al., Two Plutonium-Metal Assemblies, Nucl. Sci. Eng. 8, 525 (1960).

24. G. A. Linenberger et al., Neutron Burst from a Cylindrical Untamped Oy Assembly, The Los Alamos Scientific Laboratory report LA-1477, 1952.

25. R. E. Peterson and G. A. Newby, An Unreflected ^{235}U

Critical Assembly, Nucl. Sci. Eng. 1, 112 (1956).

26. T. F. Wimett, Time Behavior of Godiva Through Prompt
    Critical, The Los Alamos Scientific Laboratory report
    LA-2029, 1956.

27. H. C. Paxton, Godiva, Topsy, Jezebel - Critical
    Assemblies at Los Alamos, Nucleonics 13, 48 (October
    1955).

28. H. C. Paxton, Godiva Wrecked at Los Alamos, Nucleonics
    15, 104 (April 1957).

29. T. F. Wimett and J. D. Orndoff, Applications of
    Godiva-II Neutron Pulses, Proc. UN Intern. Conf.
    Peaceful Uses At. Energy, 2nd, Geneva, 1958, 10, 449
    (1958).

30. W. R. Stratton et al., Analyses of Prompt Excursions in
    Simple Systems and Idealized Fast Reactors, Proc. UN
    Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva,
    1958, 12, 196 (1958).

31. Dixon Callihan, Criticality Excursion of November 10,
    1961, Oak Ridge National Laboratory Report ORNL-TM-
    139, February 1962.

32. Ronald L. Kathren et al., Health Physics Following a
    Nuclear Excursion: The LRL Incident of March 26, 1963,
    Lawrence Radiation Laboratory document UCRL-7345, 1963.

33. Oscar Kolar, Lawrence Radiation Laboratory, private
    communication.

34. White Sands Missile Range, New Mexico, Fast Burst Reactor Facility Operations report Number 2, July 1965.

35. E. W. Paine, Jr., A Study of an Accidental Radiation Burst, The Los Alamos Scientific Laboratory report LA-1289, 1951.

36. R. O. Brittan et al., Technical Review of ZPR-1 Accidental Transient - The Power Excursion, Exposures, and Clinical Data, The Argonne National Laboratory report ANL-4971, 1953.

37. W. B. Lewis, The Accident to the NRX Reactor on December 12, 1952, Atomic Energy of Canada, Limited, Chalk River Project report DR-32, 1953.

38. W. J. Henderson et al., An Investigation of some of the Circumstances Pertinent to the Accident to the NRX Reactor of December 12, 1952, Atomic Energy of Canada, Limited, Chalk River Project report NEI-26, 1953.

39. D. G. Hurst and A. G. Ward, Canadian Research Reactors, Progress in Nuclear Energy, Series II, Reactors, Vol. I. Pergamon Press, London, 1956.

40. J. R. Dietrich, Experimental Investigation of the Self-Limitation of Power Driving Reactivity Transients in a Subcooled, Water-Moderated Reactor, The Argonne National Laboratory report ANL-5323, 1954.

41. Reactors, Nucleonics 13, 40 (September 1955).

42. J. R. Dietrich, Experimental Determinations of the Self-Regulation and Safety of Operating Water-Moderated Reactors, Proc. Intern. Conf. Peaceful Uses At. Energy, Geneva, 1955, 13, 88 (1955).

43. W. H. Zinn et. al., Transient and Steady State Characteristics of a Boiling Reactor, The Borax Experiments, 1953, The Argonne National Laboratory report ANL-5211, 1954.

44. T. J. Thompson, The Technology of Nuclear Reactor Safety, Vol. 1, 1964, The M.I.T. Press, Cambridge, Mass.

45. D. Breton et al., Centre de E'tudes Nucleaires de Saclay, private communication.

46. A. N. Tardiff, Some Aspects of the WTR and SL-1 Accidents, Proc. Symp. Reactor Safety and Hazards Evaluation Techniques, IAEA, Vienna, Vol. 1, (1962).

47. W. E. Nyer et al., Reactor Excursion Behavior, Proc. UN Intern. Conf. Peaceful Uses At. Energy, 3rd, Geneva, 1964, 13, 13 (1965).

48. O. R. Frisch, Controlled Production of an Explosive Nuclear Chain, The Los Alamos Scientific Laboratory report LA-397, 1945.

49. F. de Hoffman et al., Delayed Neutrons from ^{235}U After Short Irradiation, Phys. Rev. 74, 1330 (1948).

50. F. de Hoffman, General Dynamics Corporation, private communication.

51. B. T. Feld, Massachusetts Institute of Technology, private communication.

52. O. R. Frisch, University of Cambridge, private communication.

53. A. K. Guskova and G. D. Baisogolov, Two Cases of Acute Radiation Disease in Man, Proc. Intern. Conf. Peaceful Uses At. Energy, Geneva, 1955, 11, 35 (1955).

54. R. O. Brittan, Analysis of the EBR-1 Core Meltdown, Proc. UN Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 12, 267 (1958).

55. J. H. Kittel et al., The EBR-1 Meltdown - Physical and Metallurgical Changes in the Core, The Argonne National Laboratory report ANL-5731, 1957.

56. Summary Report of HTRE No. 3 Nuclear Excursion, General Electric report APEX-509, 1959.

57. S. G. Forbes et al., Analysis of Self-Shutdown Behavior in the Spert-I Reactor, The Phillips Petroleum Company, Atomic Energy Division report IDO-16528, 1959.

58. W. E. Nyer and S. G. Forbes, Spert-I Reactor Safety Studies, Proc. UN Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 11, 470 (1958).

59. F. Schroeder et al., Experimental Study of Transient

Behavior in a Subcooled Water-Moderated Reactor, Nucl.
Sci. Eng. 2, 96 (1957).

60. M. E. Remley et al., Experimental Studies on the
Kinetic Behavior of Water Boiler Type Reactors, Proc.
UN Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva
1958, 11, 447 (1958).

61. R. E. Wemmer, A Summary of Experimental Results of the
Spherical Core Investigations in the Kewb Program,
Paper 25-2, Summer Meeting, American Nuclear Society,
Gatlinburg, Tenn., June 17, 1959.

62. R. S. Stone et al., Transient Behavior of TRIGA, a
Zirconium-Hydride, Water-Moderated Reactor, Nucl. Sci.
Eng. 6, 255 (1959).

63. S. L. Koutz et al., Design of a 10-KW Reactor for
Isotope Production Research and Training Purposes,
Proc. UN Intern. Conf. Peaceful Uses At. Energy, 2nd,
Geneva, 1958, 10, 282 (1958).

64. G. A. Freund et al., Treat, A Pulsed Graphite Moderated
Reactor for Kinetic Experiments, Proc. UN Intern. Conf.
Peaceful Uses At. Energy, 2nd, Geneva, 1958, 10, 461
(1958).

65. G. E. Hansen, Burst Characteristics Associated with the
Slow Assembly of Fissionable Materials, The Los Alamos
Scientific Laboratory report LA-1441, 1952.

66. K. Fuchs, _Efficiency for Very Slow Assembly_, The Los Alamos Scientific Laboratory report LA-596, 1946.

67. G. R. Keepin, _Physics of Nuclear Kinetics_, Addison Wesley Pub. Co., 1965, Reading, Mass., 1960.

68. G. R. Keepin, _General Solution of the Reactor Kinetics Equations_, Nucl. Sci. Eng., 8, 670 (1960).

69. D. P. Gamble, _A Proposed Model of Bubble Growth During Fast Transients in the Kewb Reactor_, Paper 25-3, Summer Meeting of the American Nuclear Society, Gatlinburg, Tenn., June 17, 1959.

70. G. E. Hansen, _Assembly of Fissionable Material in the Presence of a Weak Neutron Source_, Nucl. Sci. Eng., 8, 709 (1960).