Criticality
The Fine Line of Control

by Hugh C. Paxton

In the early days of the Manhattan Project, no one had experience in handling the large quantity of fissionable material needed to build a weapon because, quite simply, it hadn't been made yet. That was soon to change as Oak Ridge began to separate small amounts of uranium-235 and to prepare for processing kilogram amounts. This large a quantity posed the danger of accidental criticality—setting off a fission chain reaction—as scientists on Project Y well knew. But, as Feynman relates,* the demands for secrecy meant that this information was not widespread:

> . . . The higher people [at Oak Ridge] knew they were separating uranium, but they didn't know how powerful the bomb was, or exactly how it worked or anything. The people underneath didn't know at *all* what they were doing. . . . Segrè insisted they'd never get the assays right, and the whole thing would go up in smoke. So he finally went down [from Los Alamos] to see what they were doing, and as he was walking through he saw them wheeling a tank carboy of water, green water—which is uranium nitrate solution.
>
> He says, "Uh, you're going to handle it like that when it's purified too? Is that what you're going to do?"
>
> They said, "Sure—why not?"
>
> "Won't it explode?" he says.
>
> . . . The Army had realized how much stuff we needed to make a bomb—20 kilograms or whatever it was—and they realized that this much material, purified, would never be in the plant, so there was no danger. But they did *not* know that the neutrons were enormously more effective when they are slowed down in water. And so in water it takes less than a tenth—no, a hundredth—as much material to make a reaction that makes radioactivity. It kills people around and so on. So, it was *very* dangerous, and they had not paid any attention to the safety at all.

Thereafter, criticality safety became an important focus at Oak Ridge and Los Alamos, but when I arrived in Los Alamos, late in 1948, the state of the art was still fairly primitive. I was asked to head the critical assemblies group in Pajarito Canyon. With this assignment I became the Laboratory's immediate expert on nuclear criticality safety, although I had no pertinent background. Now, from the vantage point of today's abundant criticality information, I realize I should have been dismayed. But then there existed only a few-page summary of experimental data from Los Alamos, a couple of reports giving Oak Ridge measurements, and no reliable calculations (excellent methods were being developed but remained unconfirmed). This amount of information was certainly not overwhelming.

I had to learn rapidly the techniques for avoiding accidental criticality in processing, fabricating, storing, and transporting fissile materials. (At that time we had plutonium and uranium enriched in uranium-235; uranium-233 was added later.) These techniques were meant to control any variable that affects criticality, such as mass, dimensions, density, and concentration in solution. Criticality also is influenced by nearby objects that act as neutron reflectors, returning neutrons that otherwise would be lost to the fissile material. As mentioned in Feynman's tale, neutron moderation, especially by intermixing the fissile material with hydrogenous material, such as water, is particularly important to criticality. Hydrogen is very effective at moderating (decreasing the energy of) fission neutrons by scattering, and these less energetic neutrons are much more effective at initiating further fissions.

In the late 1940s it usually was necessary to compensate for insufficient data by introducing large factors of safety. This situation was acceptable for operations in processing plants because production rates of fissile material were still low. Weapons, however, were another matter. Design subtlety had not yet reduced their content of fissile

**From Richard P. Feynman, "Los Alamos From Below," in* Reminiscences of Los Alamos 1943-1945, *Lawrence Badash, Joseph O. Hirschfelder, and Herbert P. Broida, Eds. (D. Reidel Publishing Co., Dordrecht, Holland, 1980), pp. 120-132.*

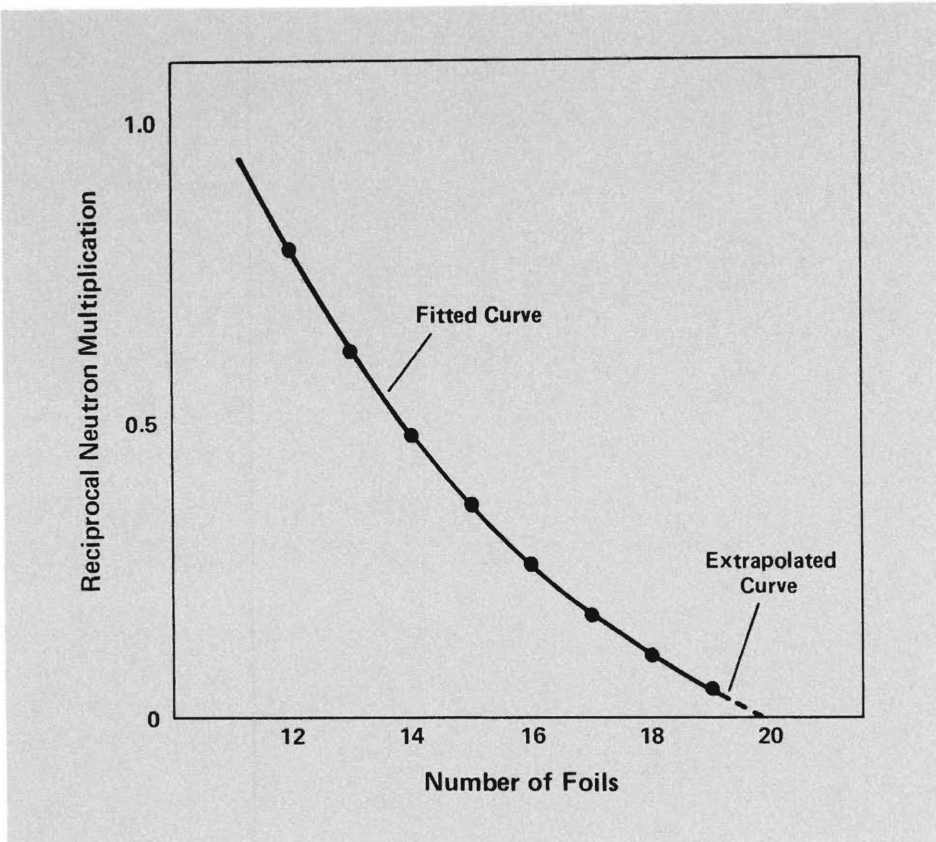


Fig. 1. The data points above were obtained from neutron count-rate measurements on a "sandwich" containing, alternately, slabs of Lucite (a neutron moderator) and foils of enriched uranium. As the sandwich is allowed to approach the critical state by adding uranium-Lucite layers one by one, the neutron count rate rises rapidly. Plotted above are reciprocal neutron multiplication values (ratios of count rate for the original sandwich to count rates as each layer is added) versus number of foils. Extrapolation of the fitted curve to zero establishes the critical number of foils.

material, and many weapons contained as much fissile material as could be introduced safely. Excessive safety factors could not be tolerated, and special measurements by the critical assemblies group were required for reasonably, but not excessively, safe designs.

Because the Pajarito group was capable and smoothly functioning when I arrived, it performed well while I learned from it about the conduct of critical experiments and their relation to weapon design. I learned about neutron-multiplication measurements with so-called long counters that responded uniformly to neutrons with a wide range of energy. I learned how multiplication, represented by neutron count rate, increases as the mass of plutonium or enriched uranium is increased and tends toward infinity as criticality is approached. The critical mass could be established, however, without actually reaching it. A plot of reciprocal neutron multiplication versus fissile mass (or other variable used to approach criticality) extrapolates to zero at criticality (Fig. 1) and thus establishes the critical mass by means of subcritical measurements.

To appreciate the significance of criticality, let us first note that a nuclear explosion is the result of a runaway fission chain reaction in which neutrons from fission produce an increased number of fissions, which in turn produce an increased number of neutrons, and so on. The term supercritical describes this state. In the critical state the fission rate and the number of neutrons remain steady. A sphere of the most dense phase of plutonium is just critical at a mass of 10.5 kilograms if bare, but the critical mass drops to about 6 kilograms if the plutonium is surrounded by a natural uranium reflector that returns neutrons to the plutonium. A more spectacular decrease, to a critical mass less than 0.6 kilogram, may occur in a uniform mixture of plutonium and water surrounded by a water reflector. This decrease is a result of neutron moderation by hydrogen.

Strictly, the steady-state fission chain reaction occurs at *delayed* criticality. That is, it depends upon the delayed neutrons emitted during decay of the fission products as well as the prompt neutrons emitted during fission. At steady state the delayed neutrons constitute less than 1 per cent of the total neutron population. The addition of a small amount of fissile material (1 per cent for plutonium and 2 per cent for uranium) to a critical mass produces *prompt* criticality. That is, delayed neutrons no longer influence the chain reaction, and fission power increases so rapidly that it is uncontrollable. If the increment between delayed and prompt criticality is termed 100 cents, prompt criticality may be exceeded a few cents without damaging a uranium metal system, but the intense radiation pulse would endanger a person nearby. At an excess of 10 cents, damage to the system would begin. The damage would become severe at a 15-cent excess, and the runaway chain reaction would lead to an explosion at an excess of 50 cents or less.

In weapon design it is important to know the delayed critical state because it must be exceeded during detonation but must not be attained during assembly, storage, and transportation. As plutonium and enriched uranium began to accumulate at Los Alamos, priority was attached to experiments that determined critical conditions by extrapolation from subcritical measurements. Before 1946 these urgent experiments had been conducted manually by persons who remained beside the experiment. Typically, the experiments involved the stepwise addition of reflector material to a fissile core with a multiplication measurement at each step.

Twice, criticality was attained accidentally during these experiments. The first incident, in 1945, resulted in fatal radiation injury to Harry Daghlian. It occurred when a heavy uranium block slipped from Daghlian's hand onto a near-critical assembly consisting of a plutonium ball and a natural uranium reflector. The damaging radiation consisted of neutrons and gamma rays from the intense fission chain reaction. Manipulation by hand continued until Louis Slotin suffered a similar fate about a year later. Again something slipped—in this case a screwdriver being used to lower a beryllium reflector shell toward the same plutonium ball involved in the earlier accident. The shell dropped instead of being held short of criticality. In neither accident was equipment damaged. Manual control was outlawed after the second accident, and the facility in Pajarito Canyon was rushed to completion.

At the Pajarito facility experiments are carried out by remote control from a control room one-quarter mile away. (Other critical assembly facilities of the time used massive shielding, rather than distance, for personnel protection.) The building in which the experiments were carried out (Fig. 2) was called the kiva, a term borrowed from the Pueblo Indians and referring to their ceremonial chambers. The facility became available for subcritical measurements in 1947 and for critical operation a year later. In subsequent years two other kivas were added. Separate control rooms for the three kivas are located in a central building.

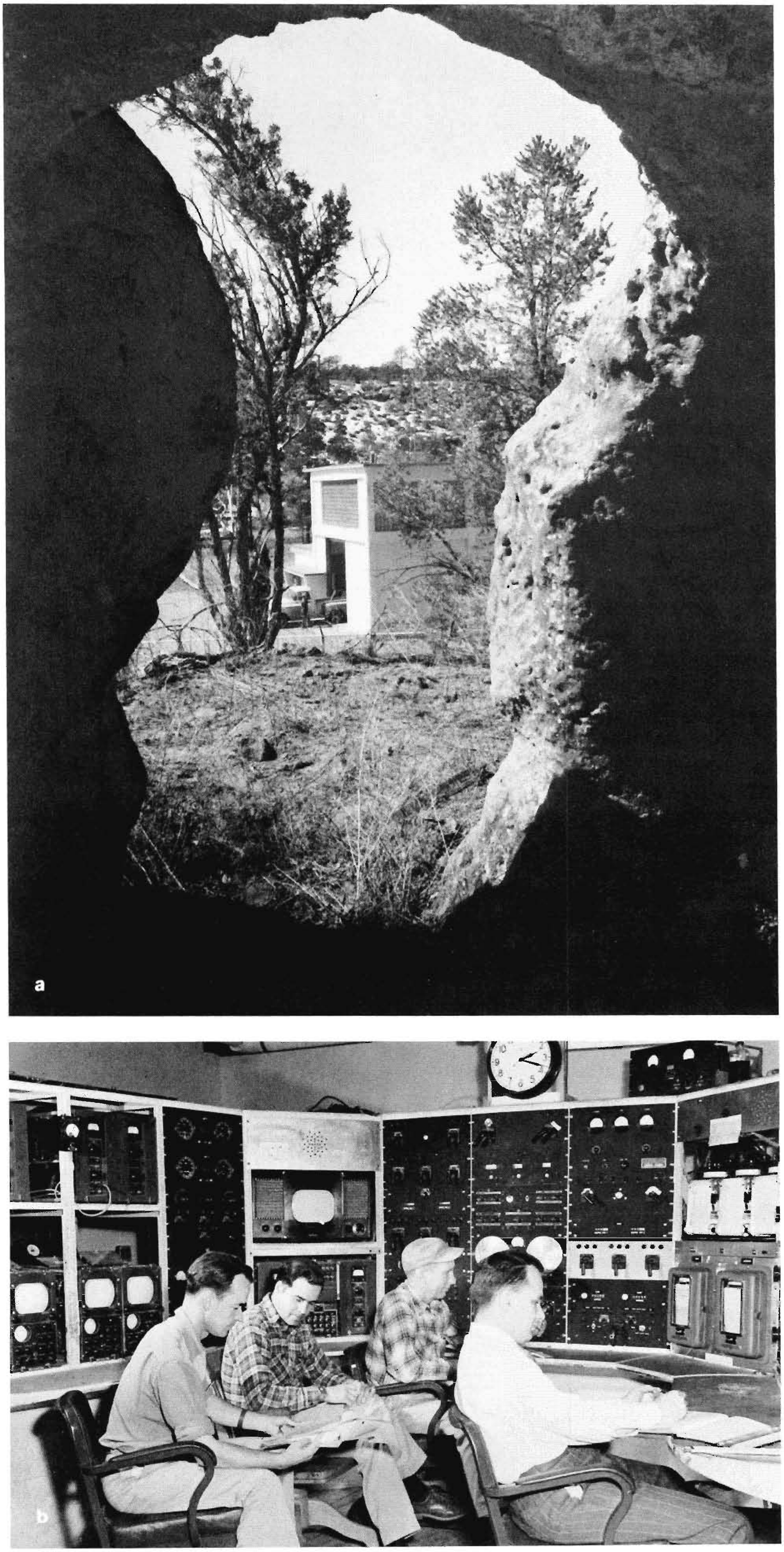
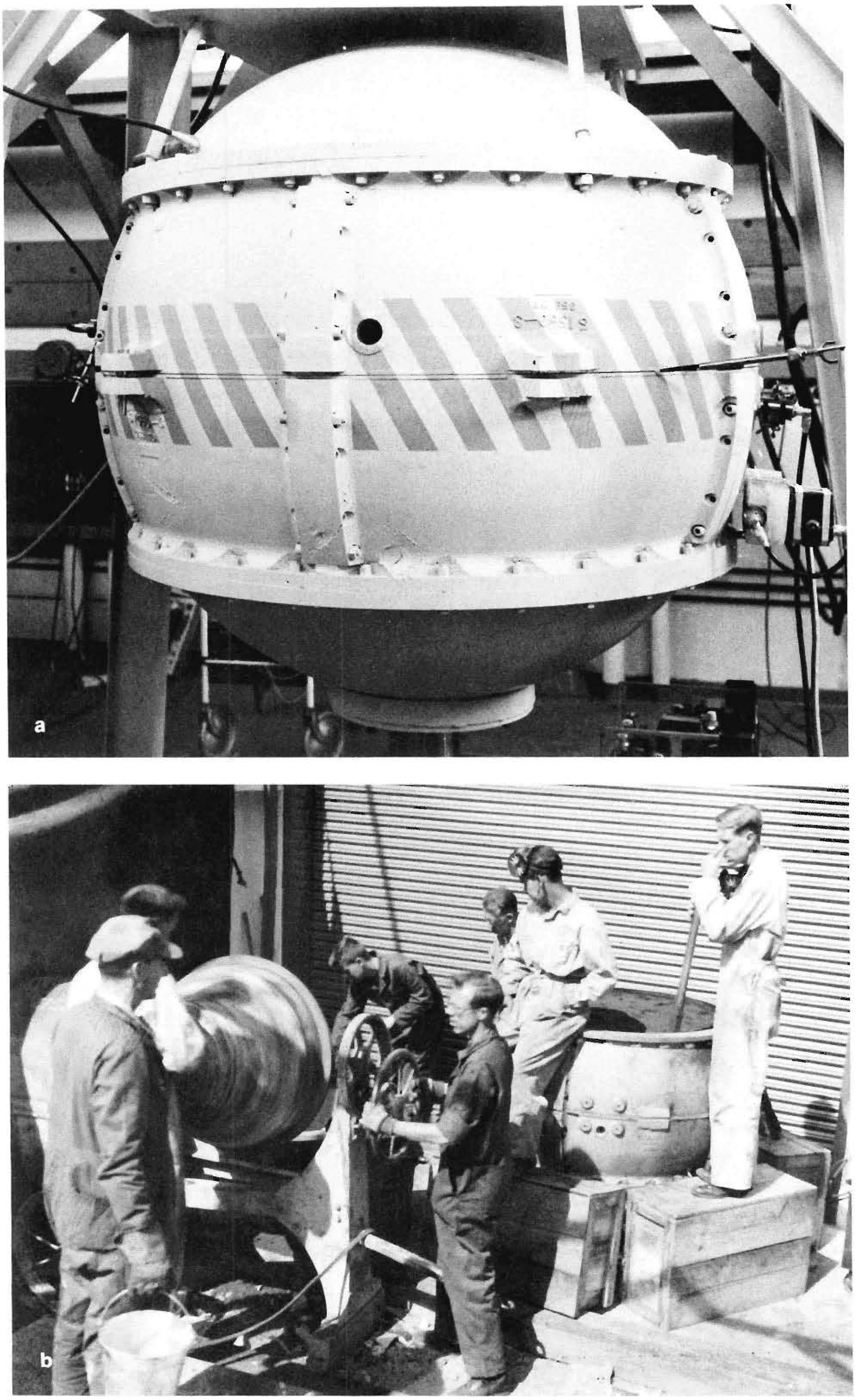


Fig. 2. (a) The original kiva, photographed from an Indian cave in the nearby wall of Pajarito Canyon, and (b) its control room, which was first housed in an existing shack. The racks contain controls for gradually separating and bringing together the parts of a critical assembly, displays of the long-counter responses that indicate neutron multiplication, radiation monitors that trigger a scram (automatic disassembly) if the level should become higher than intended, and a television screen for viewing the assembly. From left to right, Vernal Josephson, Roger Paine, Lester Woodward, and Hugh Karr. Paine and Woodward were military personnel who contributed invaluably to our critical experiments.



The Bomb Mockup (Fig. 3), the first remotely controlled machine for bringing together two parts of a near-critical assembly, was similar in size to Fat Man, the Nagasaki weapon. The two hemispheres of the Bomb Mockup were separated, and a core of fissile material was placed in a recess in the lower hemisphere. After personnel retreated to the control room, remotely actuated controls brought the two hemispheres together and instruments recorded the neutron count rate. The process was repeated with increasing masses of fissile material until extrapolation to criticality was acceptable.

These subcritical neutron-multiplication measurements with the Bomb Mockup demonstrated safe loading of implosion-weapon components, confirmed the intended reactivity (deviation from the critical state) of production cores, and provided safety guidance for new implosion-weapon designs. To

Fig. 3. (a) The Bomb Mockup, a simulation of an implosion weapon in Kiva 1. After a fissile core was placed in a cavity in the lower hemisphere, neutron count rates were measured as the two hemispheres were gradually brought together by remote control. Before personnel could re-enter the kiva, the two halves of the mockup had to be separated. Neutron-multiplication measurements in this mockup established subcritical limits for weapons of more advanced design than the Nagasaki weapon. (b) An adult version of mud pies was an essential preliminary to experiments with the Bomb Mockup. Surrounding the fissile core in the mockup was a material that simulated the neutron reflection and moderation properties of high explosives. The photograph shows the material being mixed and tamped into parts of the mockup. Identifiable are William Wenner holding the bucket, Gustave Linenberger in the center foreground, and James Roberts standing above.

supplement experiments with the Bomb Mockup, flooding tests confirmed subcriticality should a core fall accidentally into a body of water. The flooding tests were carried out in a temporary setup consisting of a tank that was filled by remote control and had a large dump valve as a safety device. Other safety tests involved cores surrounded by paraffin, concrete, and natural uranium.

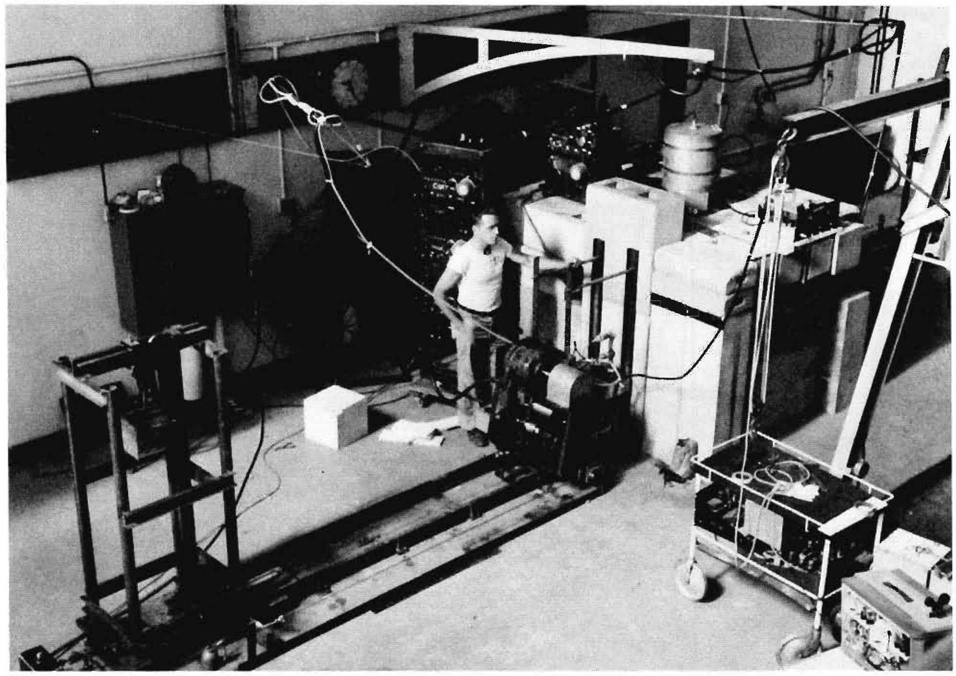


Fig. 4. A concrete vault in Kiva 1 for criticality tests on weapon cores arranged as they might be during storage. As many as 27 cores (the country's entire stockpile) were supported on two lightweight frames similar to jungle gyms (within the vault in this photograph and shown schematically in Fig. 5). Each frame was mounted on a track and could be moved in and out of the vault by remote control. A portion of the vault wall—a "door"—moved with each frame. Raemer Schreiber is shown beside the one visible drive mechanism and track (the other drive mechanism and track are hidden behind the vault). The number of cores on the frames was increased a few at a time, and neutron multiplication was measured as the frames were moved into the vault and the doors closed. Stringent security measures were maintained during these experiments, including a special contingent of military guards, machine gun emplacements on the walls of Pajarito Canyon, and a requirement that all personnel wear distinctive jackets while moving between buildings. Operations were conducted around the clock to minimize the time the stockpile was removed from its usual location.

Information to guide the safe storage of weapon components was obtained in 1947 with another temporary setup (Fig. 4). It consisted of a concrete vault of adjustable size that was closed by remote control and opened automatically when the radiation near the vault exceeded a safe level. Multiplication measurements on arrays of implosion-weapon cores or capsules as they were built up stepwise within the vault (Fig. 5) provided the required guidance. Some years later these measurements were supplemented by neutron-multiplication tests on arrays of cores in storage arrangements simulated at Rocky Flats and, finally, by other measurements at an actual storage site.

Only once did we use a live weapon for measurements at Pajarito Site. The purpose was to determine how well our high-explosive mockup material simulated the neutron reflection and moderation properties of real high explosive. The tests were performed on Sunday so that few people would be at risk if something should go wrong. There was one scary moment when the capsule assembly stuck as it was being inserted by remote control into the high explosive. (Neutron multiplication was so low that this difficulty was corrected easily by hand.) On comparing notes with those who brought the high-explosive assembly, we learned that they breathed a sigh of relief when they left our dangerous fissile material behind, just as we did when they departed with their dangerous high explosive.

At no other time was explosive permitted at our facility. Over the years mockup material was improved to simulate precisely the elemental composition of high explosive. Thus it became prudent to test the material to be sure that the simulation was not so good that it, too, might be explosive.

Criticality considerations for gun-type weapons differed from those for implosion weapons because of the requirement that the total mass of fissile material become supercritical as soon as its subcritical components were engaged. Experiments on a new design first established the total fissile mass needed for the weapon. Then, the measured separation of components at criticality provided a basis for choosing a safe initial separation. Other tests demonstrated safety of assembly operations, including reaching down into the cavity to perform manual adjustment with components in place. As gun devices became smaller than the Hiroshima weapon, experimental safety guidance had to include the effects of surrounding materials in, for example, the breech of a naval gun.

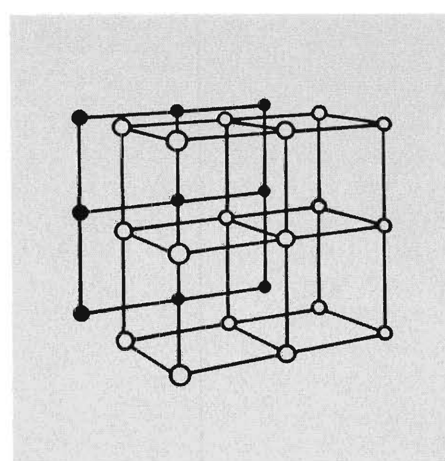


Fig. 5. Schematic arrangement of weapon cores during the criticality tests with the vault shown in Fig. 4. Two separate frames supported the cores at the positions represented by the solid and open circles.

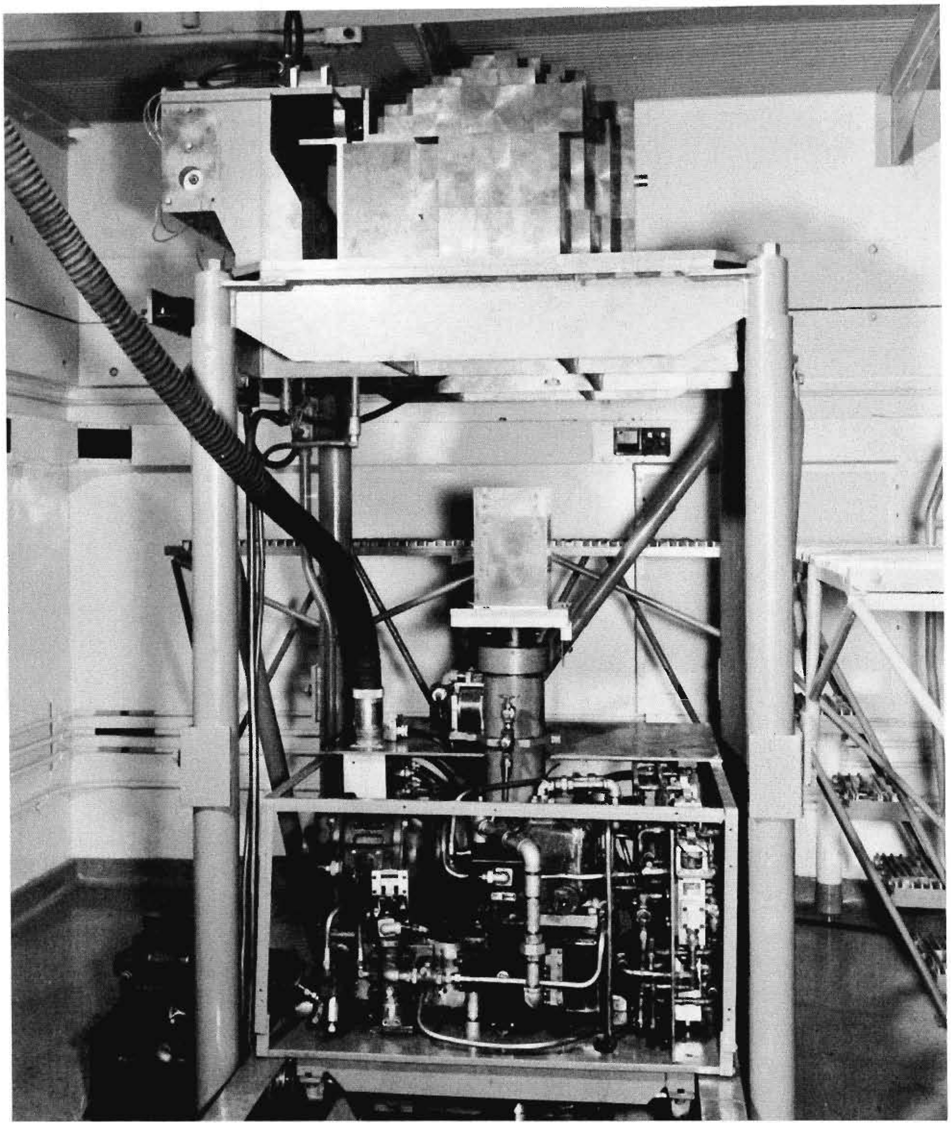


Fig. 6. The Topsy critical assembly. The central box-like structure contains an enriched-uranium core embedded in some natural uranium reflector. This structure is raised by remote control into a cavity in the main reflector body, the pile of large uranium blocks above. Spherical or cylindrical cores were approximated by arrays of half-inch cubes of enriched uranium.

Interaction among most simple implosion weapons of modern design is not a consideration except, perhaps, for clustered configurations. For some fission-fusion devices, however, interaction of weapons may be sufficiently important to require measurement. In one instance we tested an array of fission-fusion weapons that simulated a shipboard storage proposal. The tests were carried out at an assembly site because transportation of the weapons to a critical assembly facility was undesirable.

In the 1950s the critical assemblies group became involved in reactor-related activities culminating in the Rover rocket-propulsion reactor program. Although these activities eventually occupied most of our effort, weapon tests retained the highest priority. We had to be prepared for short-notice safety checks on each device destined for testing in the Pacific or Nevada. Typically, about one day was available for the safety check between completion of the device and shipment to the test site. Obtaining meaningful data on short notice was challenging but exhilarating.

Measured criticality data for easily calculated systems have also been of value for improving or confirming the detailed neutronic calculations that enter weapon design. The first critical assembly for this purpose (Fig. 6) began operating in late 1948. Named Topsy—she just grew—the assembly consisted of a nearly spherical core of highly enriched uranium embedded in thick natural uranium. Topsy was followed in 1951 by a bare sphere of highly enriched uranium, named Lady Godiva by Raemer Schreiber because, like the lady of Coventry, she was unclad. Ultimately we also obtained data on plutonium and uranium-233 assemblies as bare spheres and spheres reflected by thick natural uranium. Other simple assemblies consisted of combinations of fissile materials of interest to weapon designers, some in thin reflectors of various materials. Over the years hundreds of critical specifications have accumulated, which, when used for validation, have greatly expanded the range and reliability of detailed neutronic calculations.

Criticality control is necessary in aspects of the weapons program other than weapon safety. Accidental criticality must be avoided in the purification of fissile material, the production of metal, the fabrication of components, and the recovery of scrap. Other nuclear programs, such as the production of reactor fuel, involve similar operations and therefore require similar criticality information for safety measures. Criticality data from Los Alamos have been incorporated in compilations and safety guides and standards. Thus the scope of Los Alamos criticality safety activities has been national and even international. For example, Los Alamos has hosted two international meetings on criticality, and our short courses on criticality safety, conducted in cooperation with the University of New Mexico, have been attended by interested persons from other countries. ■

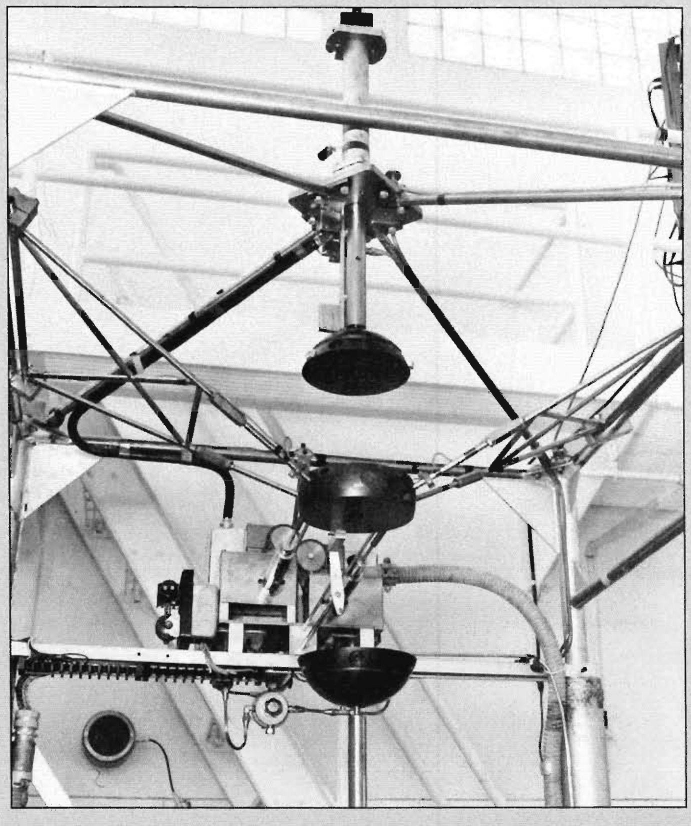
Further Reading

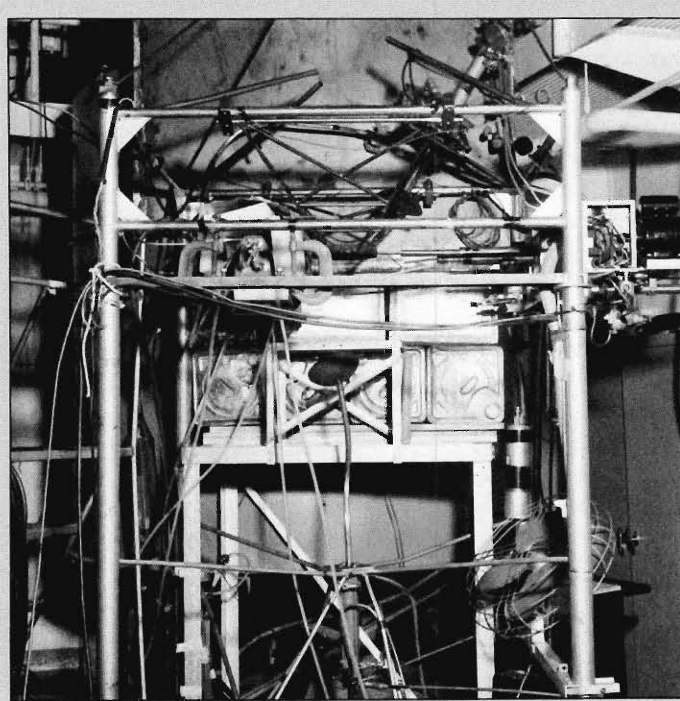
Hugh C. Paxton, "Thirty-Five Years at Pajarito Canyon Site," Los Alamos Scientific Laboratory report LA-7121-H, Rev. (1981).

Hugh C. Paxton, "A History of Critical Experiments at Pajarito Site," Los Alamos National Laboratory report LA-9685-H (to be published).

Sidebar

Prompt Criticality Under Control





Lady Godiva became the forerunner of the family of fast-pulse reactors at Los Alamos, Sandia National Laboratories, White Sands Missile Range, Aberdeen Proving Ground, and Oak Ridge National Laboratory. These reactors simulate the radiation from a weapon that occurs beyond the weapon's blast-damage range and therefore are used to test instruments, rocket guidance systems, and electronic equipment for proper functioning in the presence of a weapon burst.

In mid 1953 Lady Godiva, essentially an unreflected sphere of highly enriched uranium, was coaxed gingerly to prompt criticality (the usually forbidden region) and slightly beyond. The typical result was radiation from a sharp, intense fission pulse terminated by expansion of the uranium. Although the intent was simply to confirm predictions about the assembly's behavior at superprompt criticality, these pulses were immediately in demand as nearly instantaneous sources of radiation for experiments in areas ranging from biology to solid-state physics, and soon they were used to proof-test instrumentation and controls that were supposed to withstand the radiation from a nuclear explosion.

The total of about 1000 prompt pulses from Lady Godiva was not without incident, for twice the safe limit beyond prompt criticality was overstepped. The first incident did not cause irreparable damage, but in the second uranium parts became too badly warped and corroded for further use. The assembly was then replaced by Godiva II, designed specifically for burst production. This first of the fast-pulse reactors has been succeeded at Los Alamos by Godiva IV. ■

Top. The Lady Godiva critical assembly of highly enriched uranium. A nearly spherical, unreflected critical assembly was formed as the upper cap was dropped and the lower cap was slowly raised. Lady Godiva was portable and was even operated outdoors to eliminate the effects of neutron reflection from the kiva walls.

Bottom. Lady Godiva after the accident that led to her retirement. The enriched-uranium parts were severely warped and corroded, having approached the melting point at the center of the assembly. The support was damaged as a result of mechanical shock.