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An Early History of Criticality Safety



los alamos
scientific laboratory
of the University of California
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An Early History of Criticality Safety*

by

Roy Reider

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AN EARLY HISTORY OF CRITICALITY SAFETY

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ABSTRACT

Four of the earliest critical assemblies involving enriched ^{235}U are described. The safety procedures employed for them are discussed in detail.

The Water Boiler. A uranyl sulphate solution was remotely air-pumped from an ever-safe vessel into the reactor sphere above.

The Dragon Experiment. The reactor was constructed so that a slug dropped through an assembly (both of active material) gave a divergent chain reaction lasting for 1/100 sec and supported by prompt neutrons alone. An ingenious mechanical structure with multiple safety devices and interlocks gave a high degree of safety to the experiment.

The "Drop-Leaf" Assembly. A hydrogenous reflector in the form of paraffin slabs was stacked around an enriched uranium assembly; part of the reflector was built upon a hinged leaf supported by a prop that could be displaced electrically or by hand, using a long cord.

The Movable-Table Assembly. A critical assembly was divided between a stationary table and a movable table that could be remotely manipulated to achieve criticality. Several independent safety devices could disassemble the active material in case of high radiation or utility failure.

Conclusions are drawn from comparison of these well-planned experiments with the early hand-assembly accidents.

Introduction

The earliest safety considerations for critical assemblies actually predated by several years the availability of enriched fissionable material. In 1940, Peierls¹ examined the physiological action of the radiations resulting from a nuclear chain reaction in uranium both during continuous reaction and during an explosion involving either slow or fast neutrons. He estimated that 200 kW emitted in the form of gamma rays would give a person a dangerous dose in 10 min at 100 m and in 1 hr at 250 m. Peierls suggested that the reaction vessel could be destroyed by shelling well before fatal consequences ensued.

Water Boiler

The "water boiler," in early 1944, was the first critical assembly of enriched (14.7% ^{235}U) fuel. It was a homogenous chain-reacting pile using a water solution of uranyl sulphate (UO_2SO_4) in a 12-in.-diam stainless steel vessel surrounded by a fitted reflector of BeO blocks.²

The uranyl sulphate solution was stored in a flat vessel with a conical bottom (ever-safe geometry) into the center of which extended a pipe from the 12-in. sphere above. Forcing air into the conical reservoir pushed the solution up into the sphere. See Figs. 1 and 2. The conical pan had a large port in its lid through which active solution could be added and stirred.

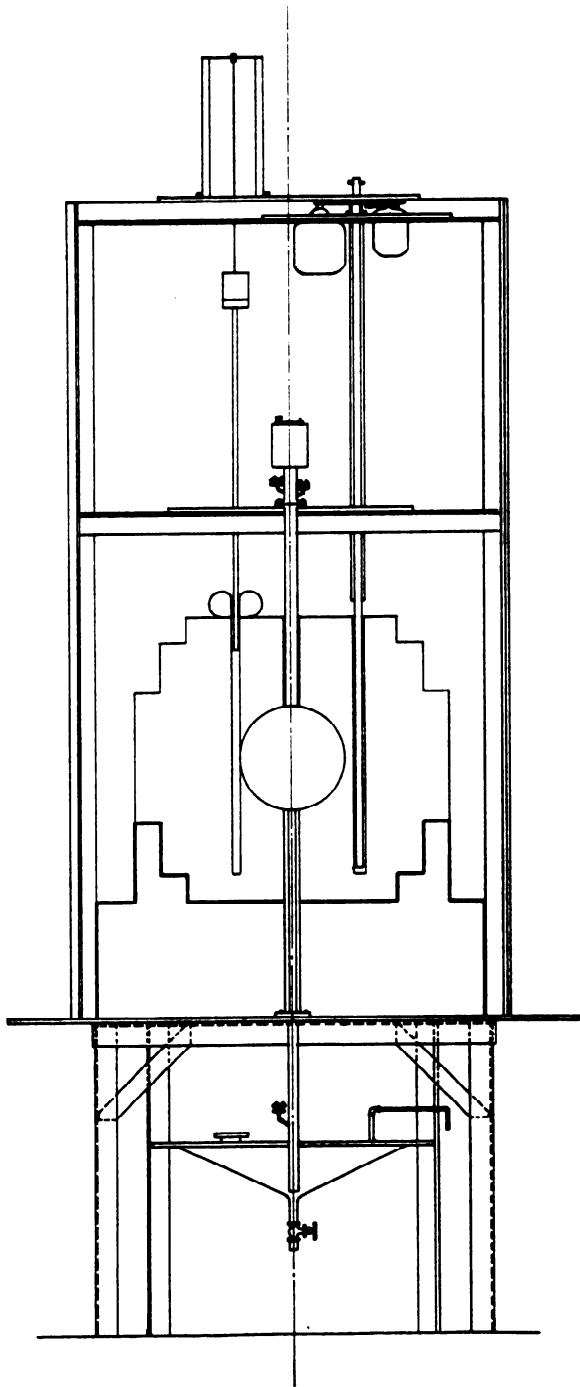


Fig. 1.
Schematic of Water Boiler.

The air pipe received air from thick-walled rubber balloons contained in a large tank. These balloons prevented water vapor from leaving the system and, thereby, changing the concentration. The air pipe was also connected to a water manometer in the control room to indicate the height to which the sphere was filled.

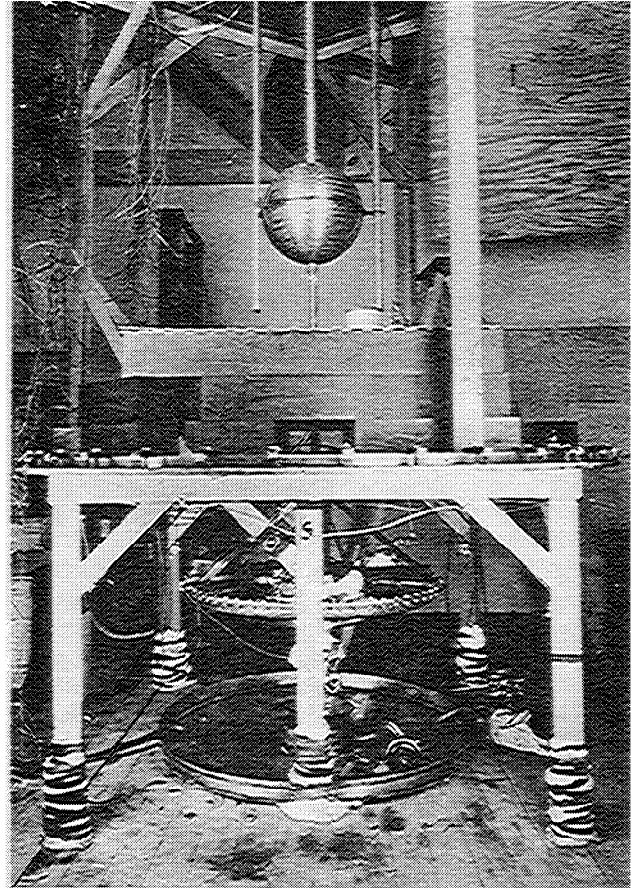


Fig. 2.
Water Boiler during initial stages of assembly.

Two electrodes, one above and one below the sphere, were connected to neon lights to indicate the solution level. There was an additional electrode to indicate overflow above the top of the standpipe that automatically released air pressure and dumped the solution back into the ever-safe reservoir. There was a solenoid-operated dump valve immediately over the conical pan to relieve the air pressure and rapidly dump the solution into the pan in case of emergency. The air-pressure filling system was controlled by a solenoid-actuated valve that prevented solution from being added in case of power loss, overflow, leakage, or high neutron levels.

As a final safety precaution, solution could be dumped from the flat conical pan through a stainless steel drain into a bucket located in a covered trench outside the laboratory. This could be done using a manual dump valve with a long extension handle, and it was to be a "last ditch" procedure to remove hot "soup."

Tickling the Dragon's Tail

Early in 1945, a chain reactor,³ known as the

“dragon,” was constructed so that dropping a slug through an assembly (both of active material) created a divergent chain reaction supported by prompt neutrons alone and lasting for about 1/100 sec. In this short time, neutron multiplications up to 10^{12} were obtained. UH_3 mixed into bricks with plastic binder to an effective ratio of about UH_{10} was used.

The falling slug of active material was contained in a 14 by 2-1/8 by 2-1/8 in. steel box. Its path was defined by four guides, with a clearance of about 1/8-in. so that warping of the guides would not interfere with its drop. The guides, attached to a steel derrick, about 12 ft high, passed through a hole in a 3/8-in.-thick steel table on which the active material and tamper could be assembled around them, and led into a catcher box below, into which the slug fitted with a few mils clearance. This close-fitting catcher box served as a pneumatic brake.

Part of the reacting assembly was contained in a pivoted steel box that could be raised into position by compressed air acting on a piston. This “safety box” could be raised and lowered by throwing a switch that operated an electromagnetic air valve. During static calibration, this valve was connected to a neutron monitor so that the box would drop automatically whenever the neutron level exceeded a preset value. When the safety box was down, the reactivity of the system was decreased so that even with the slug at the center position no reaction could occur.

To control the multiplication, a flat brass box (a control vane) filled with a suitable absorber could be inserted between the safety box and the rest of the system. The position of this box could be adjusted by a screw drive. Figure 3 shows the whole Dragon setup, without active material.

Before each drop, the slug was picked up by an electromagnet hanging on a rope and was hoisted to a suitable point near the top of the guides. To do this safely, one had to lower the safety box first, and, lest one should forget to do so, the magnet was wired in series with a microswitch that was closed only when the safety box was down. On arrival at the top of the guides, the slug was secured by a latch to prevent it from being dropped unintentionally, as by a power failure. Pushing in this latch closed another microswitch that provided an alternative path for the magnet current so that the safety box could be lifted without dropping the slug on the latch. When the operator was sure that everything was ready for a drop (controls properly adjusted, no people near the system, etc.), he pressed the “Here We Go” (HWG) button, establishing a third path for the magnet current and enabling him to remove the latch and subsequently, by releasing the HWG button, drop the slug.

This whole, somewhat complicated, arrangement was designed to prevent operator error until the HWG button was pressed. If, for instance, the operator tried to raise the safety box before the slug was at the top and secured by the latch, the magnet would immediately release the slug, which would fall into the catch box well

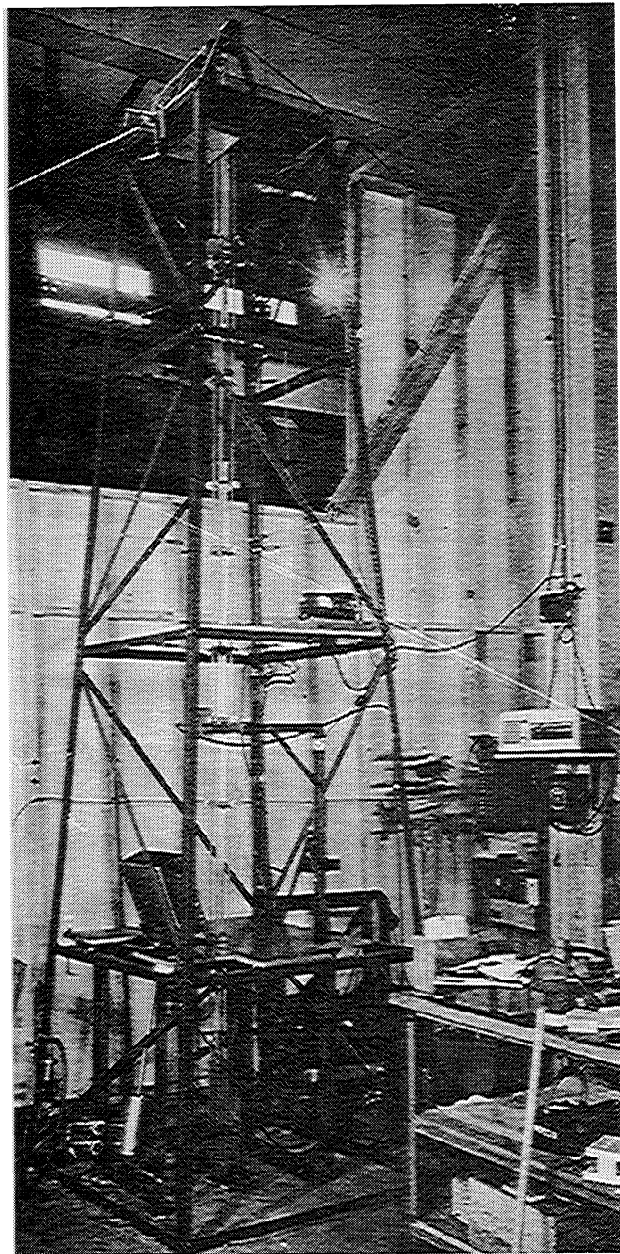


Fig. 3.
Derrick framework for Dragon experiment, without active material.

within the time required for the compressed air to raise the safety box (about 10 sec). Again, if the operator tried to pull out the latch without pressing the HWG button, the slug would fall on the latch which then could no longer be moved. (The latch was moved through a slow gear so that one could not pull it out in less than about 5 sec.) Colored lights were arranged to keep the operator informed about the position of the safety box, latch, and magnet.

At the beginning of each series of drops, several dummy drops (with the safety box down) were made to ensure that the slug was falling freely and with the correct velocity. All the operating and recording equipment was placed in a room about 40 ft from the assembly and behind a 5-ft-thick wall of concrete and earth. If (to assume the worst) the slug had stuck in the center of the assembly, there would have been an inefficient explosion, probably equivalent to a few ounces of high explosive. In this case, the control room would have afforded sufficient protection against the prompt radiation.

The "Drop-Leaf" Assembly

Snell⁴ and others have described experiments conducted shortly after World War II on the critical sizes of assemblies of fluorinated hydrogenous mixtures containing 24% enriched uranium. A hydrogenous reflector in the form of 6-in.-thick slabs of paraffin was used.

For such assemblies as actually became critical, the final step to add the last blocks of paraffin to the side of the reflector. As a safety precaution, this side of the paraffin reflector was built upon a hinged leaf attached to the assembly table. This leaf was supported by a prop that could be jerked out either by a solenoid or by hand, using a long cord. The solenoid was actuated by a radiation-level monitoring device. See Fig. 4.

The Movable-Table Assembly

Using uranium enriched to approximately 30% in the 235 isotope and fabricated into 1-in. cubes having a density of 4.8 g/cm³ with the nuclear properties of UF₆, Beck and others,⁵ in 1946, studied several conditions affecting the assembled mass at criticality. To determine the critical amount of ²³⁵U for these experiments, it was necessary to build an assembly to criticality or nearly so. As the danger to the experimenters was realized, it was

decided to actually assemble all near-critical accumulations by remote control and behind suitable shields.

Remote assembly was accomplished by building the desired accumulation in two parts separated by a suitable distance and, then, from a remote point, bringing them slowly together. One part was built along the edge of a stationary platform; the other was built along the facing edge of a movable platform of the same height, which could move on ball bearings along grooved steel tracks toward or away from the stationary platform.

Figure 5 shows the stationary platform on the right and the movable one on the left. A typical experimental array is also shown. Figure 6 shows the movable platform on the right. The operating position from which assembly was effected is behind the concrete-block wall at the left. Note the viewing ports which were two aquariums filled with water, but no fish.

The platform motion was controlled by pneumatic pressure on a double-acting piston in a cylinder mounted under the stationary platform. The piston rod extended from the cylinder through a packing gland and was connected to the movable table through an electromagnetic coupling. Electric switches at the operating position controlled the solenoid-operated air valves that admitted air to the front and back faces of the piston. At any time during assembly, the movable table was free to move away from the stationary platform to the end of its track if control or automatic safety devices were actuated. However, the forward motion of the table during an assembly was limited to the rate at which an operator unscrewed a vernier on the end of a rod extending from the movable platform, through the shielding wall, to the operator's position.

Several automatic safety devices were provided to disassemble the material in case of high radiation or of power or air-pressure failure. A counterweight was attached to the movable platform by a cable over a pulley so that the two platforms would separate automatically if the magnetic coupling connecting the movable platform to the control piston became disengaged. (See lower left-hand corner of Fig. 5.) Switches and relays were so adjusted that electrical power failure would (a) automatically operate the proper air valves to separate the platforms and (b) de-energize the magnetic coupling, thus allowing the counterweight to separate the platforms. These operations also took place if the air-supply pressure dropped below a predetermined value well above the normal operating pressure in the cylinder. Two of the neutron detectors were connected independently to this safety mechanism so that the platforms were automatically separated by either detector if the neutron density exceeded a predetermined value. All automatic safety devices were tested before each experiment.

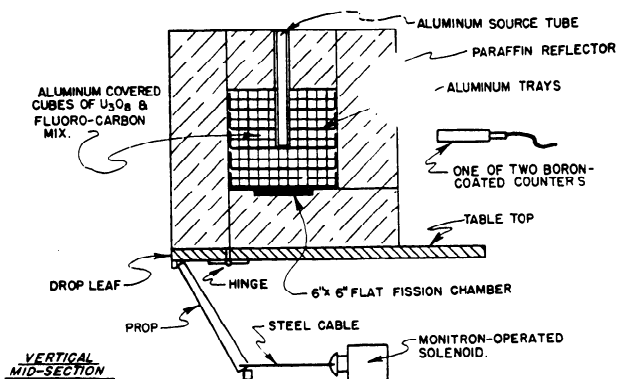


Fig. 4.
Cross section of "Drop-Leaf" assembly.

Conclusions

Any history of safety usually recognizes the enormous influence that accidents have on the safety

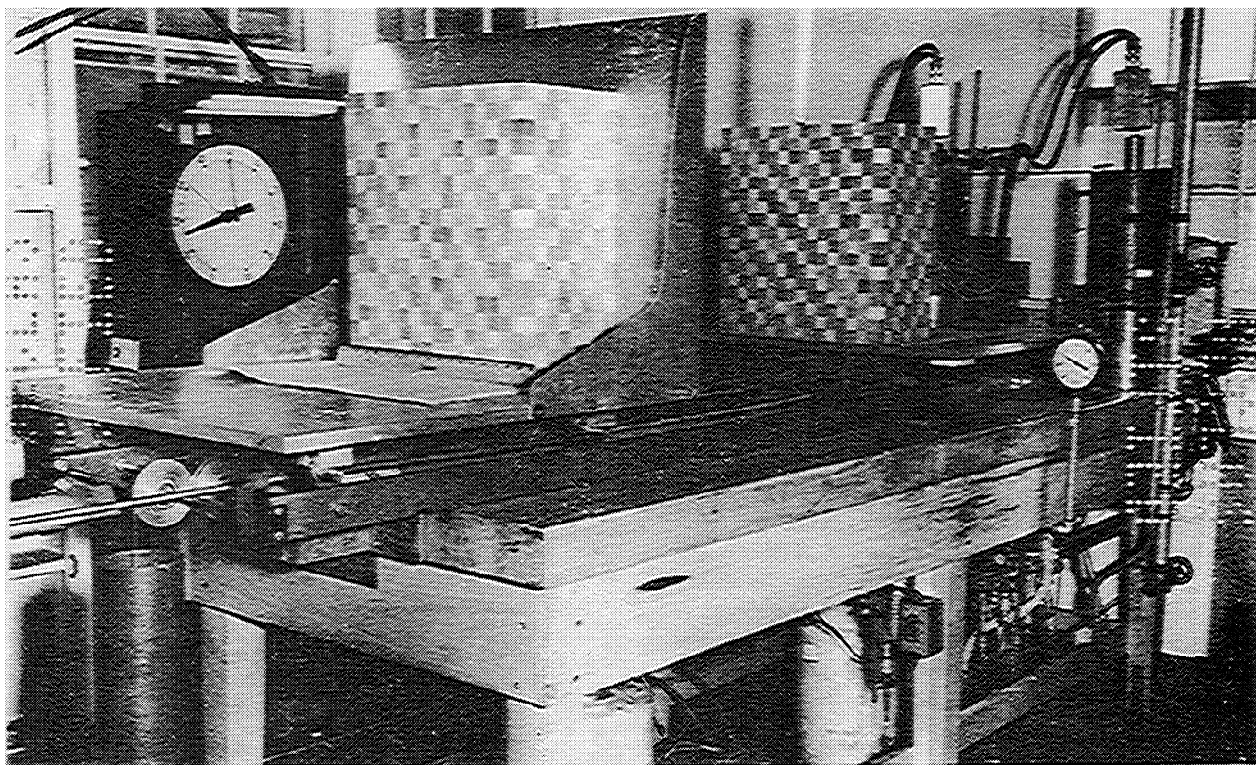


Fig. 5.

Movable-table experimental array; stationary platform at right, movable platform at left. (Figure reproduced from Ref. 5.)

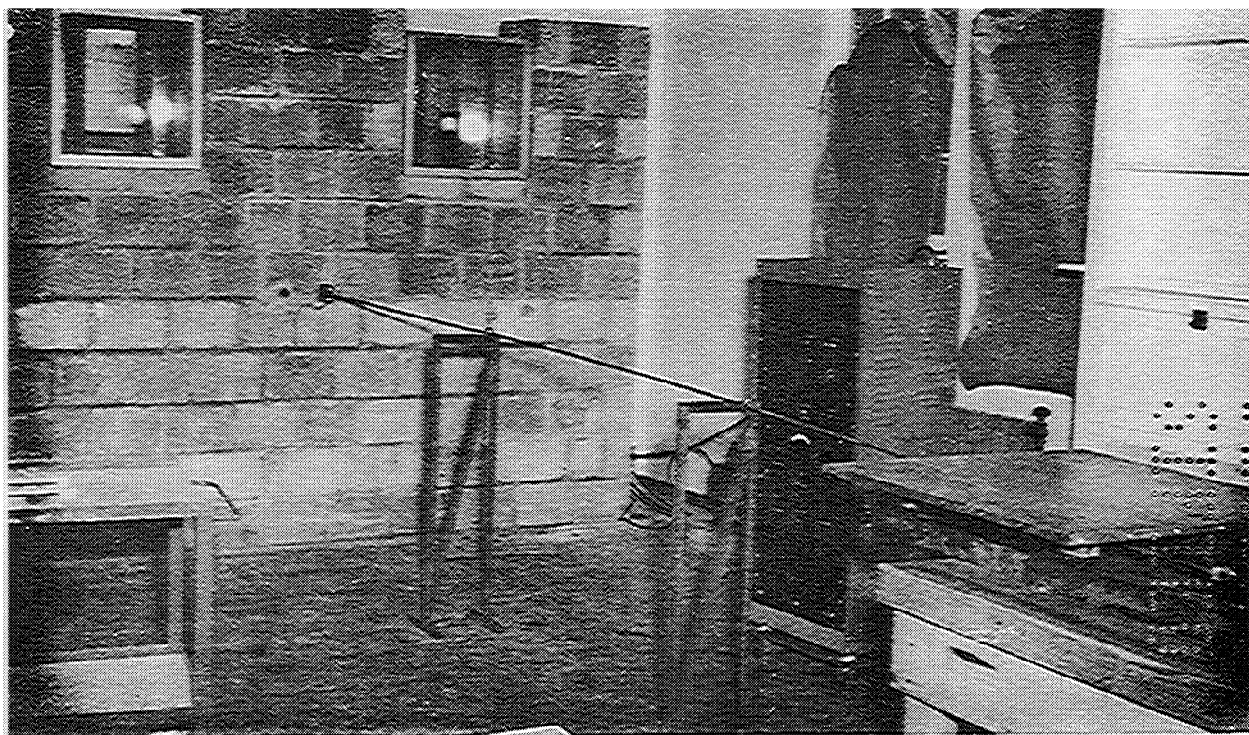


Fig. 6.

Shield wall and viewing ports for movable-table experiment; movable platform at right. (Figure reproduced from Ref. 5.)

standards and procedures employed thereafter. Actually, the Water Boiler critical assembly and the Dragon experiment were carried out before the early hand-assembly fatalities, and the Snell hinged-table experiment was conceived before the first hand-assembly accident. The Oak Ridge experiment by Beck and his coworkers followed the first hand-assembly fatality and may have been influenced by that accident.

The two fatalities from direct-observation accidents have been described in the literature.^{6,7} These incidents should be of only historic interest now because the techniques employed then would not even be considered today. However, there are powerful lessons to be learned from the early history of criticality safety as well as the early history of criticality accidents. Experiments thought out ahead of time and subject to discussion between the experimenters and their principals, a procedure to be prepared by the person doing the work and reviewed by higher authority competent in the nature of the work, and a test of equipment and procedures under "inert dry run" or "dummy" circumstances: these are the elements of safety. On the other hand, actions of individuals without sufficient training or practice, supervision or direction, procedural control or review, give much less assurance of safety.

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