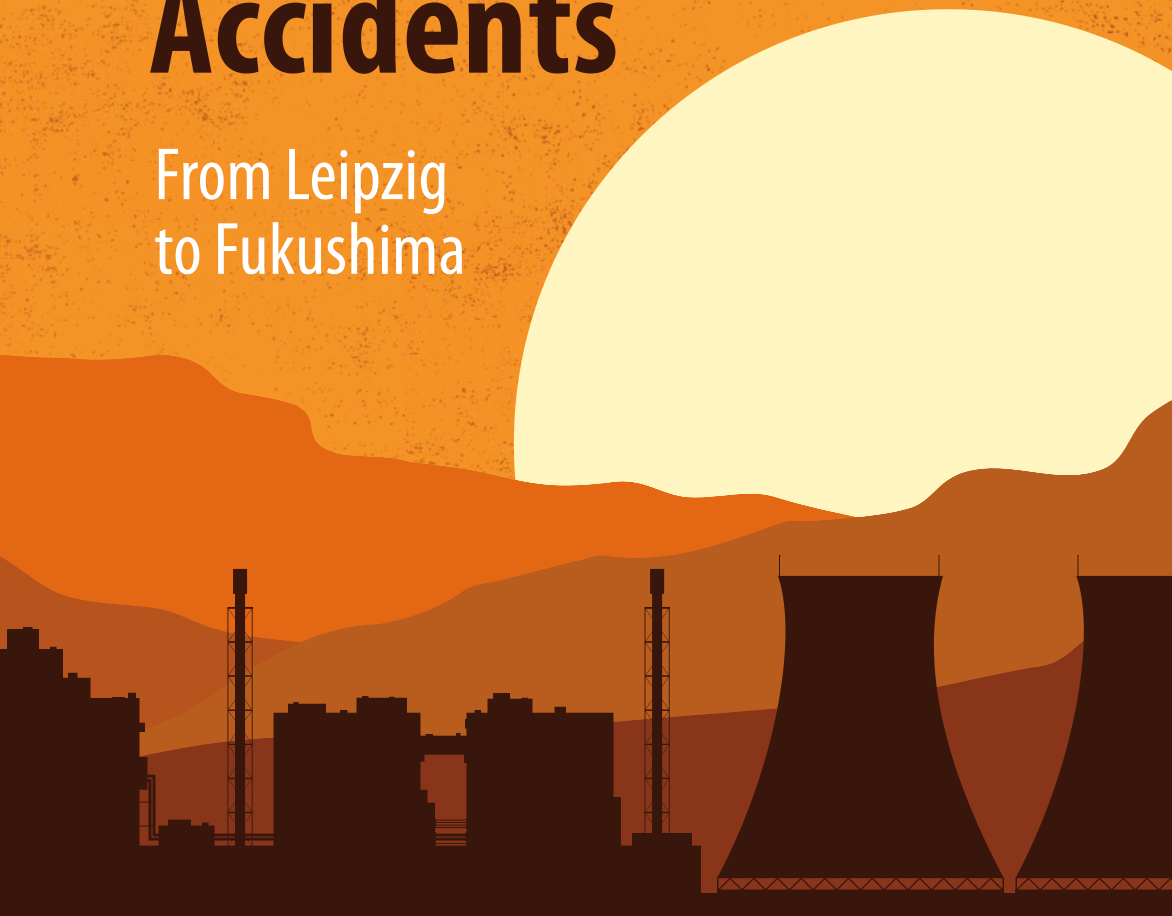
Serge Marguet

# A Brief History of Nuclear Reactor Accidents

## From Leipzig to Fukushima



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Cover figure: Silhouette of a nuclear power plant with lights at sunset in mountains. Vector illustration. Credit: Makhnach_S/Shutterstock.com

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# Preface

It is undeniable that if nuclear energy fascinates, it also frightens and even scares. It is difficult to find reliable information on the subject because of the technical nature of the nuclear field where self-proclaimed experts assert without demonstrating, explain without showing, and conclude without arguing. The anti-nuclear debate is often bogged down by simplistic shortcuts often based on the terror that nuclear accidents inspire. Pro-nuclear people hide by saying: "*It's too complicated, I can't explain!*" The purpose of this book is to inform, explain, and conclude based on proven facts and my long experience with the subject. On reflection, my own expertise could be questioned by the reader. If my expertise is proven by my participation and appointment in numerous committees and expert bodies throughout my 35 years of career in the nuclear field, my impartiality is undoubtedly more difficult to assert. Indeed, how could an expert be totally impartial. How could a surgical expert be totally foreign to the hospital environment. It is the case with nuclear energy as with any other human action; the expert is necessarily a stakeholder, since it is obvious that one must be familiar with the subject to provide an expert opinion.

Nuclear accidents are unfortunately a vast subject. In this book, I have concentrated on reactors in which nuclear fissions are voluntarily produced while avoiding the important issue of irradiation accidents in hospitals or accelerators, contamination in waste storage sites, or criticality accidents in radioactive liquid solutions. I have reviewed not only the emblematic accidents such as Three-Mile-Island, Chernobyl, and Fukushima, but also accidents that are much less well known but just as rich in lessons. "*Those who cannot remember the past are condemned to repeat it*," this quote from the philosopher George Santayana (1863–1952) in 1905 perfectly sums up the philosophy of this book. Whatever your initial point of view on nuclear energy, I hope that this book, which I wanted to be reader-friendly - judge by yourself!, will allow you to feel really informed, if not convinced!

Palaiseau, France Serge Marguet

# Introduction

**Abstract** Since the discovery of nuclear fission in 1939, physicists have postulated the possibility of using it for civilian energy production, but also for military applications. The German wartime tests to produce an atomic weapon caused the first nuclear reactor accident in Leipzig on June 23, 1942, destroying the experimental heavy water pile by fire. Other criticality accidents occurred in the USA during the Manhattan program and in the first reactors producing plutonium.

## The First Ever Nuclear Reactor Accident

Few fields fascinate the public as much as the atomic adventure. This fascination has a double meaning: interest but also fear. According to some exegetes, this fascination stems from the original flaw of nuclear energy: the atomic bomb, the absolute weapon that was supposed to put an end to all wars because of its atrocious efficiency. Nuclear power was born in secrecy, and Enrico Fermi's first uranium atomic pile (Photo 1) began to generate heat in a sustained manner, hidden under the bleachers of a Chicago stadium on December 2, 1942.

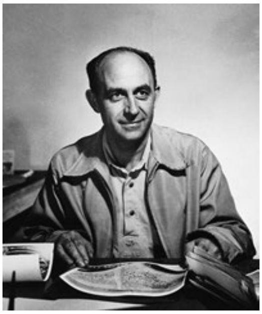

**Photo 1** Enrico Fermi. Designer of the first operational nuclear reactor in history. Fermi is considered by his peers as a giant of modern physics

Fermi[1] is the first to succeed, but not the first to try! As early as 1940, the Canadian physicist George Laurence[2] (Photo 2) tried in Ottawa

[1] Enrico Fermi (1901–1954). Italian physicist. After brilliant studies in mathematics, he studied physics at the University of Pisa. He published his first article in 1922 on general relativity, of which he was one of the main advocates in Italy. In 1926, he became professor of physics at the University of Rome. In 1934, he proposed a revolutionary theory of $\beta^-$ decay by introducing a new particle: the neutrino. He then devoted himself to the creation of new radioactive isotopes and was awarded the Nobel Prize in 1938. Faced with the rise of totalitarianism in Italy and his wife being of Jewish origin, he immigrated in 1939 to the USA, where he built in Chicago the first operational reactor of Humanity, known as Chicago Pile-1 or CP-1, which diverged on December 2, 1942. He participated intensively in the Manhattan Project to build the American atomic bomb and became an American citizen in 1945. He died of stomach cancer, possibly due to his exposure to radiation from the reactors and the testing of the first aerial atomic bombs.


Fermi"s certificate of entry into the USA and the Italian stamp in honor of the first critical reaction in the CP-1 pile in Chicago. On the right Fermi (wearing glasses) visits the Italian motorcycle firm Guzzi in 1954 shortly before his death.

[2] George Craig Laurence (1905–1987). Canadian physicist. After a doctorate in physics at Cambridge under the direction of Ernest Rutherford, he worked from 1930 for the National Research Council of Canada. In 1940, he attempted to build a fission reactor, succeeding in inducing fissions in a subcritical device, but not in maintaining the reaction. After the war, he worked at the Chalk River nuclear center on the piles ZEEP, NRX, and NRU.

(Canada) to build a small critical reactor made of uranium oxide bags surrounded by coke that can sustain a fission chain reaction. The coke is a relatively pure form of coal to slow down the neutrons that become more able to produce fissions[3] (Fig. 1). The experiment failed because of the lack of purity (limited by short funds) of the materials used (the insufficiently purified coke containing traces of neutron absorbers). These materials turn out to be too absorbent for neutrons. Moreover, the choice of a rather homogeneous geometry hinders the establishment of fissions (the neutrons are captured by uranium 238 to the detriment of fissions) and especially the absence of enrichment in uranium 235, because of the use of natural uranium that contains only 0.711% uranium 235, prevented the establishment of a regime of self-sustaining fissions.

**Photo 2** Georges Craig Laurence (1905–1987) was a Canadian pioneer in reactor physics who tried unsuccessfully in 1941 to build a small critical reactor

[3] This may seem counterintuitive, but the lower the velocity of neutrons, the greater their probability of producing fission in uranium 235. Even if the analogy is false, we can remember the idea of a soccer goalkeeper ($^{235}U$), who catches slow balls (slow or thermal neutrons) more easily than fast shots (fast neutrons).

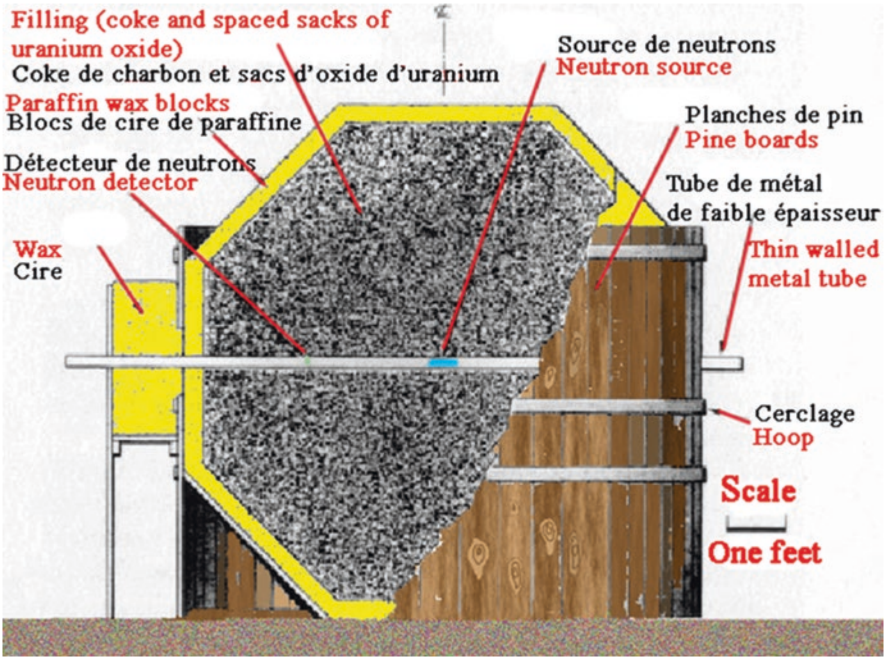


**Fig. 1** The Ottawa experiment (1941–1942). The device proved to be subcritical even though a neutron source was placed in the center of a tube embedded in the filling of coke (a usual form of coal) and uranium oxide multiplied by fissions, which was revealed by the neutron detector placed in the same tube. Carbon is a good slowing down agent for neutrons, which have a greater chance of causing fission if they have a slow speed. Actually, the probability of fission increases greatly when the neutrons are slow. Physicists therefore tried to slow them down efficiently without the moderator (retarder), the coke, capturing them too much. The experiment is therefore a half-failure because the device turns out to be subcritical and therefore incapable of sustaining a chain reaction, but fortunately, for the observers placed around the device! The paraffin wax is a hydrogenated material, which acts as a neutron reflector by reflecting neutrons toward the nuclear fuel and by limiting the neutron leakage of the device. The homogeneous mixture of coke and uranium oxide is not necessarily a good idea because it is better to separate the uranium and the carbon moderator in a heterogeneous geometry to favor reactivity (measure of the capacity of the device to establish a chain reaction). This technic limits the capture of neutrons by uranium 238, which is not fissile in the presence of slow neutrons ($^{238}U$ can fission only with fast neutrons). The idea of uranium bags is already better than fully homogeneous mixture of uranium and graphite, but the whole thing remained too homogeneous

More worryingly, in June 1942, Werner Heisenberg[4], Nobel Prize in Physics in 1932, answered the question posed by the German general Erhard Milch[5] that a bomb the size of a pineapple would be enough to destroy a city like London, which is close to reality.

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[4] Werner Heisenberg (1901–1976). Werner Heisenberg was a German physicist who won the Nobel Prize in Physics in 1932 for his work in quantum mechanics. After studying physics at the University of Munich, where he defended a thesis on fluid turbulence under the direction of Arnold Sommerfeld, he worked with the great physicists of his time: Max Born, Arnold Sommerfeld, and Niels Bohr. He introduced the use of matrices in quantum physics. At the age of 26, he was appointed professor of physics at the University of Leipzig, where he later launched the heavy water reactor experiments under the Nazi regime. In 1927, he formulated the uncertainty formalism that bears his name. Initially attacked by the Nazis who considered quantum physics to be ""Jewish,"" he was ""rehabilitated"" in 1939, mainly because his mother was a close friend of the mother of Heinrich Himmler, the supreme leader of the SS! Heisenberg directed the German nuclear program from 1942 to 1945, especially the experiments in Leipzig and Haigerloch. After the war, Heisenberg denied having wanted to develop an atomic bomb by voluntarily delaying the progress of the program (?). His ambiguous position toward the Third Reich earned him criticism, although he was not worried after the war.

From left to right: Enrico Fermi, Werner Heisenberg, and Wolfgang Pauli sitting on the shores of Lake Como (Italy). The first two worked on the atomic bomb in opposite camps.

[5] Erhard Milch (1892–1972). German air force general. *Generalfeldmarschall* Milch was charged by Hitler with the supervision of German aeronautical production, and specifically the special weapons (V1, V2, super-bombers). He was sentenced to life imprisonment for war crimes at Nuremberg but was released in 1954.

Milch still enjoys a certain popularity linked to the prestige of the Luftwaffe and special weapons.


As part of the German war effort, Heisenberg was part of the team attempting to develop a Nazi atomic bomb. As soon as fission was discovered by the German chemists Otto Hahn[6] and Fritz Strassmann[7] in 1938 (Photo 3), and that the chain reaction had been

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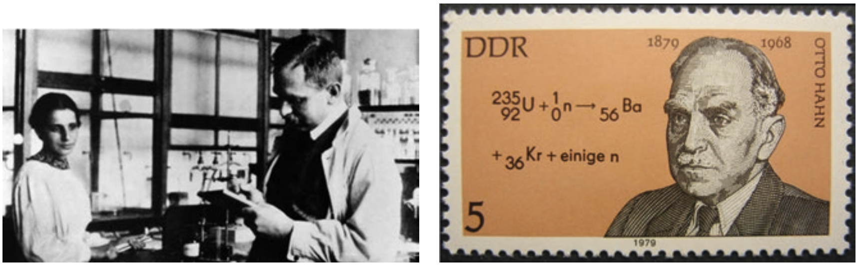
[6] Otto Hahn (1879–1968) was a German chemist. After studying chemistry in Munich and Marburg, he was introduced to radioactivity in 1904 in the English laboratory of Sir William Ramsay. Back in Germany, he worked at the Berlin Institute of Chemistry where he met Lise Meitner. In 1907, he discovered radium 228, thorium 230, and protactinium, a new chemical element in 1917. He studied heavy transuranic nuclei with his assistant Fritz Strassmann from 1935. This work led him to discover uranium fission at the end of 1938 by detecting the presence of radioactive barium in a liquid solution of uranium irradiated by neutrons. Hahn remained in Germany throughout the Second World War, keeping his distance from the Nazi dictatorship, and trying to protect his Jewish collaborators such as Lise Meitner. He learned of the use of the atomic bomb on Japan while being held prisoner with other German scientists at Farm Hall (photo below) in England. He was so horrified that it was feared that his life would be at risk by committing suicide. He was awarded the Nobel Prize in Chemistry in 1944 for his discovery of fission. A chemical body bearing his name, hahnium, was proposed for element 105, but it was finally the name dubnium that was officially retained. The same misfortune happened to him for element 108, which was finally named hassium, and again for element 110, which became darmstadtium. It is reasonable to think that his name will be definitively retained for a super-heavy nucleus in the future.




Lise Meitner on the left and Otto Hahn, and the stamp of the late East Germany in honor of Otto Hahn.

Farm Hall near Cambridge where the German scientists were kept as prisoners from July 3, 1945, to January 3, 1946.

[7] Fritz Strassmann (1902–1980) was a German chemist who co-discovered the nuclear fission of uranium-235 with Otto Hahn after studying chemistry and completing a thesis at the University of Hanover. From 1929, he worked at the prestigious Kaiser Wilhelm Institute in Berlin, where he specialized in analytical chemistry and became a very close collaborator of Otto Hahn, as well as Lise Meitner. After the war, he worked at the Max Planck Institute in Mainz. He received the Enrico Fermi Prize in 1966 as well as Hahn and Meitner.

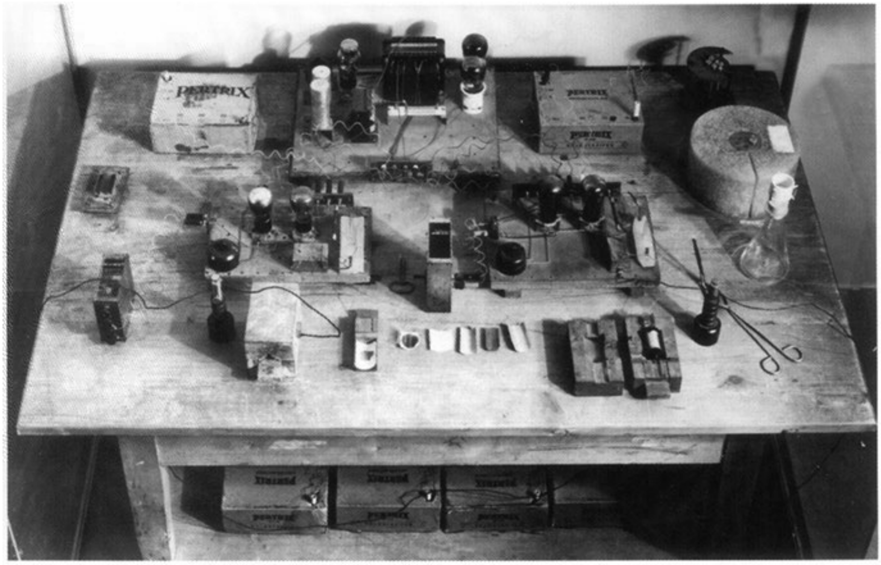



**Photo 3** The wood table on which fission was discovered. The uranium liquid solution was contained in the beaker seen on the right of the photo. The source of neutrons comes from a mixture of radium and beryllium placed in the center of a yellowish cylindrical block of paraffin wax located next to the beaker. The paraffin has the function of slowing down the neutrons, which makes them more likely to produce fissions on uranium 235. This wood table is piously preserved at the Karlsruhe nuclear research center

proven in 1939, some German physicists embarked on a train of research whose unavowed goal was the production of a nuclear weapon. The German army supported the informal military program *Uranverein*", "*the uranium club*", which brought together a few hundred scientists

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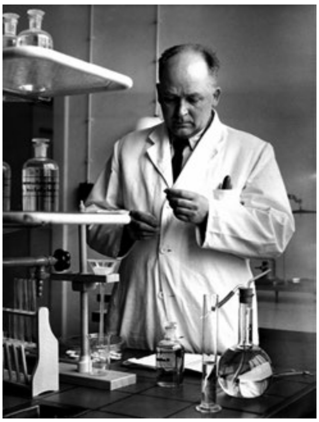
Fritz Strassman and the discovery report published in 1944.



concerned with the subject. First and foremost, Werner Heisenberg, technical leader of the German bomb research, Carl-Friedrich Von Weizsäcker who filed a patent in 1941 on the concept of an atomic weapon, son of the German diplomat and State Secretary for Foreign Affairs Ernst Von Weizsäcker from 1938 to 1943 under Hitler, but also Paul Hartek who worked on the enrichment of uranium and heavy water,[8] Walter Gerlach, Kurt Diebner[9] (member of the Nazi party and

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[8] Heavy water $D_2O$ has the same chemical properties as normal water $H_2O$, but the $^1H$ isotope of normal (light) water is replaced by the $^2H$ isotope in heavy water. To simplify the writing, the term deuterium D was invented to refer to $^2H$. Heavy water is a very expensive and difficult to produce product that is used as a neutron moderator in an atomic pile. A pile operating with heavy water can produce plutonium that can be used for a bomb. In 1934, Norsk Hydro built the world"s first commercial heavy water production plant in Vemork, Norway (see photo below), with a capacity of 12 tons per year. During the Second World War, the Germans invaded Norway in order to dispose of the Norwegian ports, but with an ulterior motive related to heavy water production. The British decided to destroy the plant by several military actions (commandos) in order to prevent Germany from developing its nuclear weapons program. On November 16, 1943, the Allies dropped more than four hundred bombs on the site, prompting the Germans to move all production to Germany. On February 20, 1944, Knut Haukelid, a Norwegian partisan, sank the ferry carrying heavy water on Lake Tinn. Contrary to what the Allies have long claimed, the Germans would have known about this raid and would have deceived the Allies, as most of the heavy water was actually evacuated by truck and used for the *Uranverein* program. The story of the heavy water sabotage was the basis for the French film ""*La bataille de l"eau lourde*"" in 1947 and the American film ""*The heroes of Telemark*"" in 1965 with Kirk Douglas in the main role.



[9] Kurt Diebner (1904–1965) was a German physicist and scientific advisor to the *Heereswaffenamt*, the Armaments Office of the German Army. He organized a conference on September 16, 1939, between the various German physicists concerned with nuclear energy, followed by a new conference on September 26, which led to the launch of a research program on the atomic bomb, the construction of a pile, and enrichment in U235. At the suggestion of Paul Harteck, the choice of pile was a natural uranium reactor moderated with heavy water. Erich Bagge, Diebner's assistant and a former student of Heisenberg's, took care of the isotopic separation. On October 5, 1939, Diebner took over the effective direction of the Kaiser Wilhelm *Institut für Physik* (KWIP) from the Dutchman Peter Debye, who did not want to take German nationality and participate in the war effort (he left for Cornell University in the USA). Fortunately for the rest of history, Heisenberg never accepted the tutelage of Diebner, whom he did not consider a physicist (despite his doctorate in physics), and he quickly "went it alone," fuelled by his poor relations with Diebner. This difference sums up the general atmosphere of the *UranVerein*, where several

manager of a nuclear research group), Erich Bagge (member of the Nazi party), Walther Bothe, Klaus Clusius who worked at the University of Zurich on heavy water production, Karl Wirtz who worked on reactor physics during the war and then at the Karlsruhe research center after the war, and Robert Döpel experimental physicist who worked on the heavy water reactor program in Leipzig and who was captured by the Russians to work on the Soviet atomic weapon.

Theoretical work by Heisenberg, the tests (one cites the test named "L-IV", L for Leipzig), were carried out in the first half of 1942, and extrapolations (erroneous) by Heisenberg indicated that the spherical geometry, with five tons of heavy water and 10 tons of metallic uranium, could be critical. The calculations are simpler in spherical geometry because of the symmetry of revolution (a problem that can be reduced to a geometry with a single radial dimension of successive layers). The tests conducted by Robert Döpel showed indeed a production of neutrons, but still subcritical. An article by Klara Döpel, Robert Döpel's wife, and Werner Heisenberg was first published in the *Kernphysikalische Forschungsberichte* (Research Reports in Nuclear Physics), a classified journal of the *Uranverein*. The first L-I and L-II tests used uranium oxide and 164 kg of heavy water. The replacement in 1942 of uranium oxide by uranium metal plates increased the production of neutrons more than expected. The L-III reactor at Leipzig used 108 kg of metallic uranium (and still 164 kg of heavy water); then L-IV reached 750 kg of uranium (with still the same 164 kg of heavy water) in the spring of 1942. L-IV showed in April 1942 an increase of 13% in the neutron flux, "*the experimental proof of the effective multiplication of neutrons in a concentric sphere of $D_2O$ and uranium*," as the Döpels wrote in July 1942. These results indicated that a self-sustaining reaction was within the realm of possibility, provided allegedly that 5 tons of

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competing teams were working separately, the probable cause, along with the lack of means, of the German failure in the field. Kurt Diebner.

heavy water and about ten tons of uranium were available. Increasing the size of the pile reduces neutron leakage.

The Leipzig research group was led by Heisenberg until 1942. Heisenberg then withdrew from practical experiments and left the execution of the L-III and L-IV experiments (Fig. 2) mainly to his colleagues under the direction of

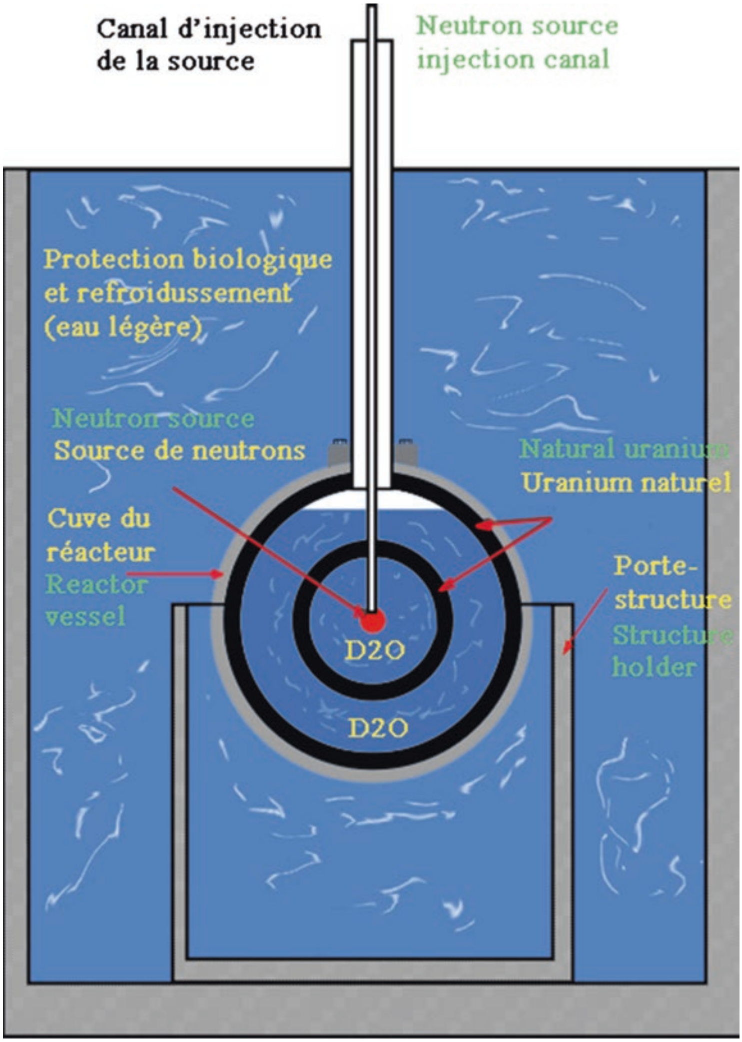


**Fig. 2** Leipzig reactor of 1942 (L-IV with metallic uranium). It was necessary to leave a little vacuum in the vessel to take into account the thermal expansion of the heavy water during the heat-up. One of the realistic causes of the explosion of June 23, 1942, is that this void would have been filled with air at dismantling, reacting explosively with the uranium at high temperature, especially in the form of powder, and especially if the uranium had been hydrated during the 20 days of operation. It is known that uranium hydrides are particularly pyrophoric. It should be noted that no system for

Döpel. The theoretical calculation of a pile made of laminated materials would be the work of two young physicists because Heisenberg was rather uninterested in the practical aspects: Karl-Heinz Höcker (1915–1998), a former student of von Weizsäcker, and Paul O. Müller (1915–1942), a former student of Erwin Shrödinger (both were mobilized, Müller was killed on the Russian front, and Höcker was able to be reinstated at the KWIP in 1942 after strong and motivated pressure on the Army). The team, at the suggestion of Paul Harteck, quickly understood that it was better to separate (heterogeneous geometry) the fissile material from the moderator than to achieve an intimate mixture. In a homogeneous mixture, the neutrons do not have time to slow down because they are captured without fission by uranium 238, without being slowed down enough to induce fissions in uranium 235. However, the probability of fission is much greater with slowed neutrons than with fast neutrons. In a heterogeneous geometry, neutrons arriving in heavy water can slow down without risk of capture (heavy water is not very absorbent) and can return to the fuel to induce fissions by geometrically avoiding capture in $^{238}$U, hence the need for technological ingenuity in the respective distribution of uranium and heavy water. This idea of heterogeneity is still used in present

controlling the chain reaction existed on all the types of piles built by the Germans, which highlights a flagrant incompetence in the kinetic aspects of the reactor. The consequences of uncontrolled over-criticality seemed to escape them (radiation protection of operators). A form of modern fantasy tends to say that the Germans would have developed a low-power atomic bomb, but their inability to enrich uranium in the isotope 235, let alone plutonium 239, which is an artificial isotope produced in a reactor (which they did not possess), makes this hypothesis totally unrealistic. Any scientific evidence other than conspiracy rumors or vague testimonies of unusual explosions (the Italian journalist Luigi Romersa or the airplane pilot Rudolf Zinsser in October 1944) that could have used conventional explosives does not support even the testing of a "dirty" bomb, i.e., a conventional bomb loaded with radioactive waste. Other testimonies relate to a very bright explosion at the Ohrdruf concentration camp on March 3, 1945. Even after so many years, residual radioactivity would be easily detected in case of success, as well as fission products such as technetium or promethium that do not exist in nature and a large quantity of unfissioned uranium, even if the atmospheric nuclear tests after 1945 tend to create background noise. Another argument is that the Germans never had uranium enriched to more than 0.8% U235, and even then, in ridiculous quantities, not to mention plutonium 239, the extraction technique for which was totally unknown to them, and which their experimental subcritical piles could not produce continuously. At most, one can imagine a test of compression of natural uranium by a conventional explosive, but the result could not be anything other than a dispersion of nuclear fuel without precise control of the compression zone. How could such a test have been unknown to the specialists at the head of the *Uranverein*? The astonishment of the most famous German physicists, held at Farm Hill, at the announcement of the explosion of the first American atomic bomb was not feigned: Heisenberg even thought that an entire atomic pile had been launched on Hiroshima! The German atomic bomb remains an anticipation-book uchrony that excites people who like to be scared.

reactors. Reactor physics calculations aim at calculating the pitch between the plates or the fuel cubes, since if the plates or the cubes are too close, the neutrons do not have time to thermalize (i.e., to slow down) before returning to the fuel, and if on the contrary the plates or the cubes are too far apart, the neutrons will be absorbed before returning to the fuel. There is therefore an optimum of moderation where the effective multiplication factor $k_{eff}$ is maximum: we speak of the optimum moderation ratio, that is to say the ratio between the volume of moderator (heavy water) and the volume of fuel. To hope to be critical, the $k_{eff}$ must be at least greater than 1 at the optimal moderation ratio; otherwise the pile can never hope to be critical whatever the arrangement of fissile materials. It should be noted that the Germans did not choose the simplest geometry. The principle of these experiments was to have the powder of metallic natural uranium and the moderator in the form of heavy water loaded in a device designed to slow down the neutrons produced by a radium-beryllium source. In the case of L-IV, the uranium was plated against the inner face of the spherical container and in a spherical inner shell (Fig. 2). The whole assembly swims in heavy water. The pile is submerged in light water that serves as a neutron reflector and biological protection outside the spherical shell.

One senses the desire to keep a spherical geometry, no doubt because the calculations were made in this geometry. However, plans show one of the geometries made up of a laminate of uranium (551 kg) and paraffin wax, an alkane derived from solid petroleum residues (Fig. 3, Photo 4). The paraffin $C_nH_{2n+2}$ therefore contains carbon and hydrogen, which are excellent neutron moderators, although less effective than heavy water, which captures fewer neutrons, as the Germans must have realized. Such a geometry is simpler to realize and preserves the heterogeneous character of the pile. The Germans knew the neutrophageous character of uranium 238 (especially when the temperature increases because of the Doppler Effect), which makes homogeneous geometries particularly inefficient. Heisenberg even considered that the temperature increase was a stabilizing character of the pile to avoid a power excursion. However, he did not seem to differentiate between thermal and fast neutrons, being content to use rough estimates of cross-sections averaged over the entire energy spectrum, hence the confusion between a thermal spectrum pile and a fast spectrum bomb. On June 23, 1942, after 20 days of operation, Robert Döpel[10] noted the appearance of blisters at the level of the vessel seal, probably caused by a heat-up and a rise in pressure (dilatation of the heavy

[10] Georg Robert Döpel (1895–1982) was a German physicist who studied in Leipzig and Munich. He obtained his doctorate in 1924. He was a member of the *Uranverein* and worked with Werner Heisenberg at the University of Leipzig, where he directed the L heavy water reactor experiments. Captured by the Russians in 1945, he had to work on the atomic bomb project in the USSR. He married a Russian

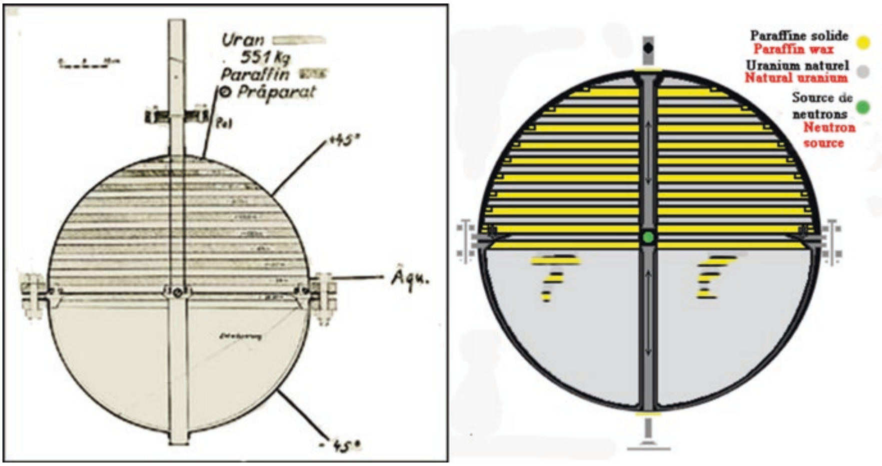


**Fig. 3** L-I reactor with uranium oxide and paraffin layers (1940). Beginning in October 1940, Heisenberg and Karl Wirtz carried out a series of chain reaction experiments at the KWIP in Berlin using an arrangement of successive layers of natural uranium oxide and paraffin (used as a moderator), the whole immersed in light water (used as a neutron reflector, heat sink, and biological protection)

water, steam production?). It must be understood that the source of neutrons imposed by *S neutrons per second* can multiply by fission even in a subcritical environment and that the neutron level will stabilize at a level of $S/(1-k_{eff})$ neutrons per second, therefore higher than the neutron source as soon as the $k_{eff}$ is non-zero. With a $k_{eff}$[11] of the order of 0.8, this is equivalent to multiplying the source by 5 and by 10 if the $k_{eff}$ is worth 0.9. Note that the formula is not valid if $k_{eff} = 1$ since one would find an infinite result. This is because a much more complex calculation has to be performed when the reactor is

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woman in 1954 and was not allowed to return to East Germany until 1957 in Thuringia to teach at the University.

Robert Döpel in 1935

[11] We will return in more detail to the concept of $k_{eff}$. For now, it is enough to understand that the $k_{eff}$ is a multiplication coefficient of neutrons in the considered geometry and materials. Starting from *n* given neutrons, the next generation will count *n* times $k_{eff}$ neutrons. This is the neutron equivalent of the famous $R_0$ coefficient used in pandemic epidemiology studies such as COVID-19.

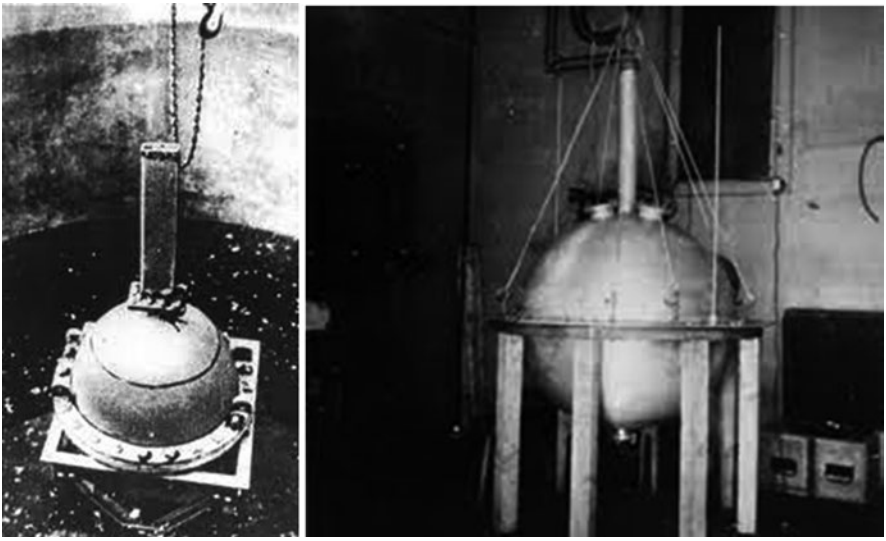

**Photo 4** Two pictures of L reactors from Leipzig. Vents can be seen on the pile on the right. The pile on the left should be L-II with a spherical geometry. L-II allowed an increase in neutron flux to be measured on October 28, 1941, but it contained only 142 kg of uranium oxide and 164 kg of heavy water, far from the critical mass necessary to reach sustainable criticality. The pile on the right is L-IV, the one that exploded on June 23, 1942

critical. Nevertheless, even in subcritical conditions, enough fissions can be produced to heat up the pile. The opening of the vessel by the operator lets in air, and uranium and especially uranium hydrides (which were created by direct contact with heavy water) are particularly pyrophoric, i.e., they ignite in air. This property is used in weapons with depleted uranium cores, such as certain tank shells: the uranium of the shell in contact with the steel armor of an enemy tank creates a low-melting point eutectic, resulting in a "*butter-like*" penetration, and then the depleted uranium core explodes mechanically inside, setting the tank ablaze (it is not a nuclear explosion at all!). The greater density of the uranium makes the projectile heavier at constant volume and increases the kinetic energy at constant speed. In the case of the L-IV pile, the ignited uranium caused the water to boil, generating enough steam pressure to dismantle the reactor. As it burned, the uranium powder dispersed throughout the laboratory, causing a larger fire in the facility. It was reported that glowing uranium powder had reached the ceiling of 6 meters high, spreading a severe fire, and that the device had heated up to 1000 °C. Leipzig L-IV can be considered as the first severe accident in history. This will not shut down the German research on the subject.

In parallel to Heisenberg's work, Kurt Diebner developed his own concepts in Berlin. After having returned the control of the KWIP to the *Reichsforschungsrat*, the Army had nevertheless retained a research center, directed by Diebner and located in Gottow, about 50 km from Berlin. Diebner's work followed more or less the same steps as Heisenberg's. The two scientists hated each other cordially, and it is doubtful that they would work together. His first spherical reactor, G-I—G for Gottow, used cubes of uranium oxide inserted in paraffin in the fall of 1942. Since he had no metallic uranium, neither in plates nor in powder, Diebner used the unused uranium oxide of the *UranVerein*. He first considered alternating layers of paraffin and uranium oxide, but finally opted for cubes. The size of the cube was chosen to be smaller than the mean free path of a neutron so that it would have a good chance of being slowed down in the paraffin before fissioning another uranium-235 nucleus or being captured by a uranium-238. The G-II reactor (Fig. 4) used heavy water[12] (in the form of ice) instead of paraffin. The idea of heavy water ice is rather curious in a device intended to heat up, hence the variations in internal density when the ice melts. Here again, the geometry of fuel cylinders, much simpler to realize and more efficient, escaped Diebner. The cubic distribution was nevertheless more interesting than the layered one advocated by Heisenberg for L-I, as the theoretician Karl-Heinz Höcker had calculated. Höcker, a former doctoral student of von Weizsäcker and his collaborator at the KWIP and then in occupied Strasbourg, collaborated with Diebner's team in 1943 after his brief incorporation into the army. The cubes were more favorable to a chain reaction than the alternating or concentric layers of the Heisenberg device because the risk of resonant capture of neutrons by uranium 238 was much lower. Moreover, the cubes were much easier to fabricate than the large plates required by Heisenberg. On the other hand, the orderly structuring of the lattice of cubes in a sphere remains technically difficult to achieve (positioning to respect the regular lattice).

From March 1945, Heisenberg and his team at Berlin-Dahlem attempted to create a heterogeneous critical device consisting of a lattice of uranium cubes attached to chains that were immersed in heavy water enriched in deuterium contained in a vessel (Pile B for Berlin? Fig. 5). Curiously, he did not think of the much simpler and more efficient solution of a vertical lattice of

[12] The natural hydrogen contained in water has two isotopes. The nucleus of the first, the most abundant, has a single proton; the second, 7000 times less abundant, is sometimes called deuterium and has a neutron and a proton. Deuterium is therefore heavier than the single-proton hydrogen. Because of its nuclear properties, deuterium is much less neutron absorbing than natural hydrogen, hence the idea of using water enriched in deuterium, so-called ""heavy water,"" to slow down without absorbing neutrons, which become more efficient for the chain reaction. Heavy water is 10% heavier than light water (its density compared to water is 1.1), hence its name.

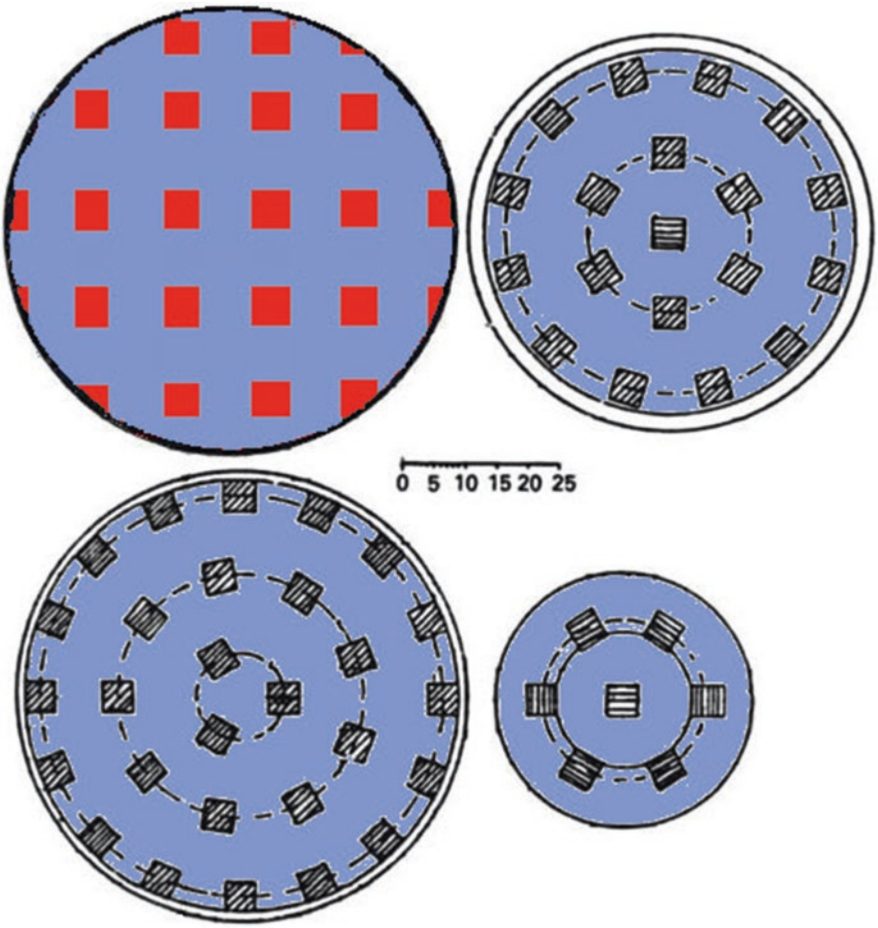


**Fig. 4** The G-II pile (Gottow) designed by Diebner and his team

tubes containing uranium, a solution that would be adopted 20 years later in the pressurized water reactors (PWRs). This cube device, which in any case could not have been critical, was found by the American army in April 1945 in an underground brewery in Haigerloch[13] and dismantled for transfer to the USA by the ALSOS mission[14] organized to recover technology and German

[13] 60 km South of Stuttgart.

[14] The ALSOS mission was a secret mission created on April 4, 1944, by the Americans in order to gather information on the progress of the German nuclear program. It was composed of about 100 military personnel and scientists commanded by American Colonel Boris Pash, a former athletics professor at Hollywood College who was later charged with investigating the alleged anti-American activities of Robert Oppenheimer, and under the scientific direction of the Dutch-born physicist Samuel Goudsmit, nicknamed ""*Uncle Sam.*" This mission first operated in Italy on the immediate rear of the advancing

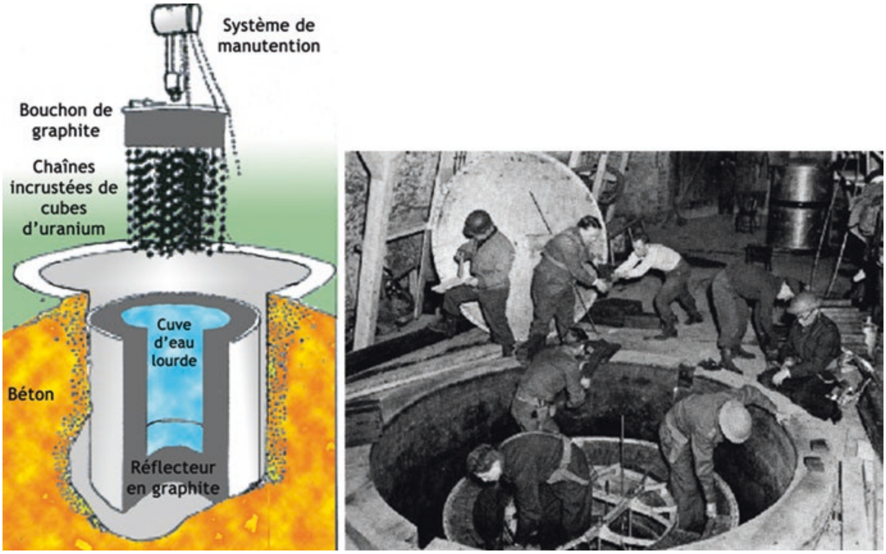


**Fig. 5** The US Army dismantles the German "reactor" known as "B VIII" at Haigerloch (US Army photo, 1945). A military column including General Harrison's 1279th Engineer Battalion and led by Colonel Pash of ALSOS took the small town of Hechingen next to Haigerloch (operation "Humbug") with the objective of reaching it before the French. The French had the political intention of creating a vast zone of occupation east of the Rhine and were unaware of the scientific potential of Haigerloch. By trickery, the Americans succeeded in saying that the Heichingen area would be heavily bombed to frighten the French, and were the first to capture Carl Friedrich von Weizsäcker, Karl Wirtz, and Erich Bagge, the elite of reactor physics. Otto Hahn and Max von Laue were captured in Tailfingen. Werner Heisenberg, target number one, was caught at his chalet in Urfeld in the Bavarian Alps, where he had taken refuge. As for the pile, the very number of the name suggests preparatory tests in Berlin. The pile in Haigerloch had been moved from Berlin-Dahlem to avoid the bombing and to escape the dangerously approaching Russians. A posteriori, analysis showed that the reactor could not have reached criticality because of a lack of critical mass. The value of the $k_{\text{eff}}$ multiplication coefficient is only 0.89, whereas it should be 1 to reach criticality. This value could have been reached with a much larger size (to reduce neutron leakage) or a slight enrichment in uranium 235 (1 to 2% instead of the 0.711% of natural uranium). The "pile" contained about 1500 kg of heavy water, 1500 kg of uranium metal, the refining process of which the Germans had mastered, in the form of cubes, 10,000 kg of graphite serving as a neutron reflector around the magnesium vessel (a metal that is a weak neutron absorber, unlike steel), and a source of initiating neutrons made up of a mixture of 500 mg of radium (radioactive $\alpha$) and beryllium that produced neutrons by reaction ($\alpha$, $n$). The cubes of natural uranium were fixed in a spaced-apart manner on chains and form a fuel lattice embedded in heavy water

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troops, but with very inconclusive results, because the Italians, whether in Naples, Brindisi or Taranto, knew nothing of the secret German projects. ALSOS was redeployed to France at the German border and then to Germany itself, where it finally collected scientific reports, equipment, and fissile materials and recovered many scientists and specialized technicians. The insignia of the mission was a white alpha

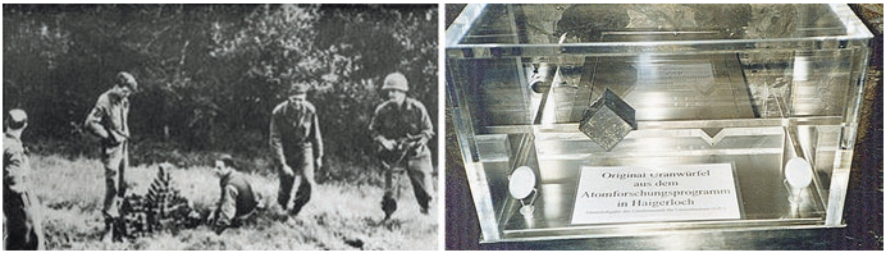



**Photo 5** Recovery of the Haigerloch uranium cubes by the ALSOS team of the American army led by Samuel Goudsmit, a scientist from MIT with knowledge of nuclear energy, who oversaw the task of scouring Germany behind the troops in order to recover researchers and expertise, especially in the nuclear field. The Russians, the British, and the French (in France alone, more than 1000 engineers and researchers between 1945 and 1950 in the field of submarines, missiles, aeronautics...!) did the same. One of the uranium cubes is shown in the Haigerloch museum. The total lack of precaution in the handling of the cubes by the soldiers suggests that it is not believed that the Germans could have operated the pile, Goudsmit having the knowledge to detect radioactive materials and probably a Geiger counter to make sure. A professional advice: never pile up cubes of fissile material as these soldiers do at the risk of a bad surprise! It should be remembered that even subcritical operation will produce fission products in quantities depending on the operating time and the level of neutron flux reached

scientists (Photo 5). This same ALSOS mission was able to establish, as soon as Strasbourg was taken at the end of November 1944, that the Germans had only just begun to build a pile in August 1944, when Samuel Goudsmit[15] and

struck by a red lightning bolt, rather indiscreet for such a secret mission. The mission was disbanded on October 15, 1945, after having scoured the western part of Germany, the rest being scoured by the Russians in a more aggressive way. An identical mission of smaller size was ordered to examine the state of Japanese science after Japan"s surrender.

[15] Samuel Abraham Goudsmit (1902–1978). Born in La Hague (Netherlands). While studying theoretical physics at the University of Leiden in 1925, Goudsmit discovered the phenomenon of electron spin with George E. Uhlenbeck. He was a student of Paul Ehrenfest at the University of Leiden (Netherlands), from which he received a doctorate in 1927. He was then a professor at the University of Michigan (USA) from 1927 to 1946. In 1941, Goudsmit joined the Radiation Lab at the Massachusetts Institute of Technology (MIT), where he conducted radar research and headed the laboratory"s document room, which contained invaluable information about German technical capacities. In May 1944, Goudsmit became scientific director of the Manhattan Project"s Alsos Mission, a top-secret operation responsible for gathering intelligence on Germany"s atomic program. He worked there with captain Reginald C. Augustine and Fred Wardenburg to build an efficient hunting team. The mission investigated German scientists" progress toward nuclear weapons as the Allies liberated the European continent. While in Europe, he traveled to his childhood home in The Hague, where he found that his parents had been killed in a concentration camp. Concerning the German bomb, Goudsmit concluded that the failure of the German project was attributable to a number of factors, including dictature bureaucracy, Allied bombing campaigns, the persecution of Jewish scientists, and Werner Heisenberg"s failed leadership. After the war, Goudsmit briefly taught at Northwestern University and then was chairman of the physics department at Brookhaven National Laboratory. He also edited the American Physical Society"s *Physical Review* for 25 years.

Fred Wardenburg analyzed Von Weisäcker's papers that had been left at the University of Strasbourg where he was working (Bar-Zohar, 1965, p. 64). The German nuclear program collapsed in 1945 at the same time as the Third Reich, Adolf Hitler having never shown a particular interest in these subjects, as he was more interested in super-tank programs, Messerschmitt 262 jet fighters, and long-range launchers such as the V2 (the famous "retaliation weapons"). However, it has been reported that Hitler himself wondered about an uncontrollable chain reaction leading to the extinction of all life on Earth! The Nazi nuclear program never monopolized more than a hundred people, compared to the 120,000 people affiliated with the American Manhattan Project. It was therefore an arms race won by the Allies that contributed to the beginnings of nuclear power, and the founding fathers of reactor physics were soon faced with difficult moral choices.

From 1942 onward, the American war effort was considerable, and the Manhattan Project produced most significant results: a highly enriched uranium bomb totally destroyed Hiroshima on August 6, 1945 (the Americans were so sure of its success that it was not even tested!); then a plutonium bomb (this bomb will be tested in the desert of Alamogordo) destroyed Nagasaki on August 9, 1945, with the human consequences that we know. The Americans preferred to sacrifice two Japanese cities rather than consider a terribly deadly landing on Japanese soil, widely predicted by the fierce resistance of the Japanese army on every island in the Pacific. A controversy about the real need to launch the second bomb erupted after the war, accusing some scientists of wanting to "experiment" with this new type of bomb. Accidents had already occurred during the preparation of the bomb. It was at Los Alamos (USA) on February 11, 1945, the first criticality incident in human history took place. An uncontrolled start of criticality took place on the Dragon reactor using a uranium compound, $UH_3$, compressed in Styrex.[16] As a notable effect, it is noted that one operator

Samuel "*Uncle Sam*" Goudsmit

[16] An extruded polystyrene insulation.

had a significant loss of hair, but without lethal effect. On August 21, 1945, the first criticality accident occurred at the Los Alamos research center, resulting in one identified victim, independently of the many victims of the two atomic bombs over Japan, which could not be called an accident. The accident occurred when a block of tungsten carbide used as a reflector slipped from the hands of an experienced operator, Harry K. Daghlian Jr. who positioned these blocks by stacking them around a fissile core (Photos 6 and 7). The block in question felt

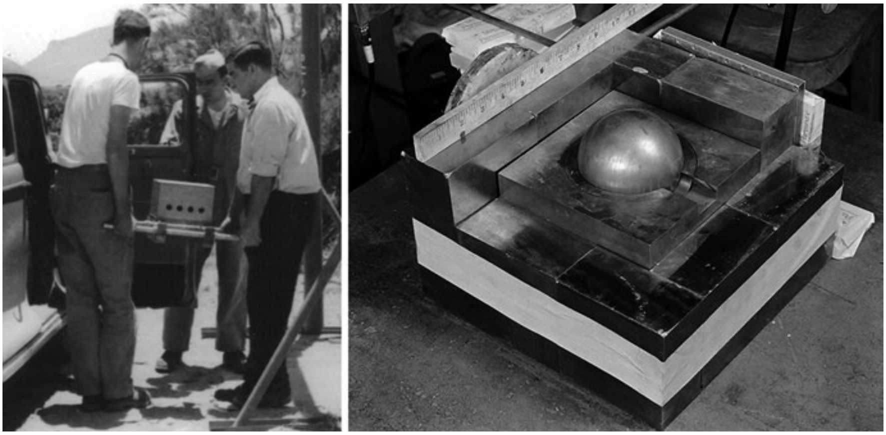


**Photo 6** Herbert Lehr (left) and Harry Daghlian, Jr. (right), loading the assembled tamper cap containing the plutonium "compartment" and initiator into a sedan for transport from McDonald Ranch to the firing tower on July 13, 1945. The photo on the right shows a reconstruction made in 1946 with an object of the same size

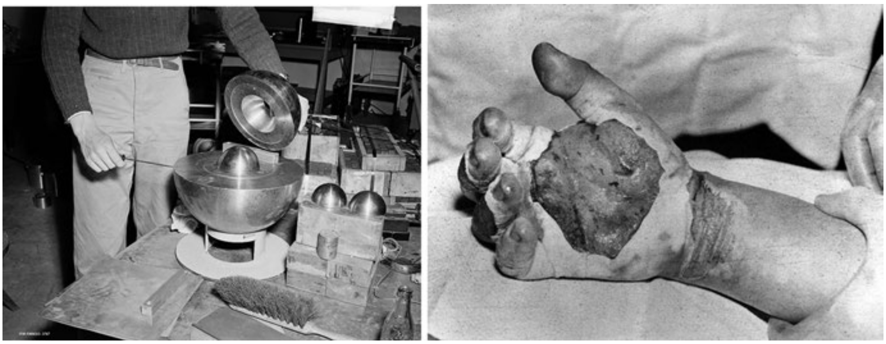


**Photo 7** Reconstruction made in 1946 of the fit-up of the upper reflector of the "demon core" and photo of Daghlian's hand after this deadly irradiation

close to a subcritical sphere[17] of 6.2 kg of plutonium 239, making it over-critical by the reflector effect, the carbide blocks sending the neutrons back to the fissile core. The operator then suffered a lethal dose estimated (although he was not wearing a dosimeter) to 200 *rads*[18] on his body with peaks of 40,000 rads on his hands, and he died 26 days after his fatal exposure from radiation sickness[19] (destruction of the spinal marrow with the impossibility of producing red blood cells along decay of all the organs).

It is reported that Enrico Fermi had written a memorandum before this case to Robert Oppenheimer,[20] responsible for the Manhattan Project, to

[17] A reactor is said to be ““critical”“ when the fission chain reaction is stabilized and continuous. A subcritical reactor sees a progressive smothering of the chain reaction when it has taken place, or the impossibility of the establishment of the critical reaction at start-up, whereas a super-critical reactor sees an exponential progression of the chain reaction. An atomic bomb is a particular highly over-critical core whose geometry and constitution (materials) are designed to voluntarily maintain the over-criticality as long as possible. A nuclear reactor has a core whose geometry and constitution are calculated to be just critical. We will return to this crucial concept later. It should be noted that the uranium 238 present in a civil pile prevents a total nuclear explosion as in the case of a bomb (because of the Doppler effect of uranium 238). A mechanical explosion by expansion of the components, thermochemical interaction, or hydrogen explosion is always possible.

[18] Remember that a rad is the old unit of dose absorbed by a gram of biological tissue subjected to 100 erg, a unit of energy that is no longer used today: 1 erg = $10^{-7}$ Joule. The official unit today is the Gray, which is one Joule deposited in 1 kg of material. The damage suffered by the tissues is proportional to the dose received.

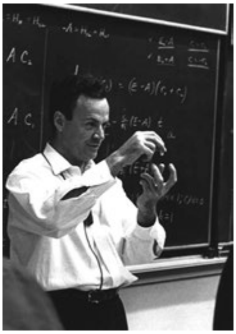
[19] This event is particularly well portrayed in Roland Joffé"s 1989 film "*Masters of the Dark*" with Paul Newman and John Cusack as the operator. The events described in the film relate rather to the death of Louis Slotin (1910–1946), fatally irradiated on May 21, 1946, while demonstrating reflector assembly around the same plutonium sphere that killed Daghlian. One can easily find photos of the reconstruction that took place afterward.

[20] Robert Oppenheimer (1904–1967). American physicist. After a degree in chemistry, he became an outstanding theorist (he was responsible for major theoretical advances on black holes) and obtained a doctorate at the age of 22 under the direction of Max Born in Göttingen. He then became a professor of physics at Berkeley. Despite his possibly sympathetic views toward communism, he was appointed to head the Manhattan Project to build the first atomic bomb. In 1947, he replaced Albert Einstein at Princeton.


Oppenheimer was the scientific director of the Manhattan project point out the danger of performing these manipulations by hand rather than by remote control, but that Oppenheimer believed that such operations would delay the schedule for making the first atomic bomb, "*Little Boy.*" The same core, later nicknamed "*The demon core*," was the cause of another fatal accident on May 21, 1946, under somewhat similar conditions, when Louis Slotin caused a screwdriver to shatter during a dangerous fit-up of the two half-spheres of the core, the half-spheres then closing by engaging the over-criticality. Richard Feynman,[21] future Nobel Prize winner in physics and a young scientist on the Manhattan team, used the term "*tickling the dragon's tail*" when referring to these risky experiments.

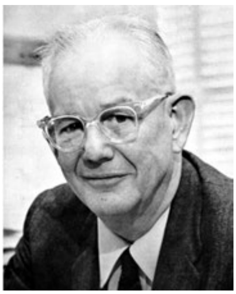
From the first Fermi pile in 1942 (Photo 8), there was concern about the safety of the reactor and a redundancy of reactor shutdown resources was planned. First of all, a scientist, Norman Hilberry, nicknamed afterward "*the Axe man*",[22] armed with an axe, stands over the pile, ready to cut the rope holding a cadmium-coated shutdown control rod, a powerful neutron

[21] Richard Feynman (1918–1988). American physicist. After brilliant studies at MIT, he introduced the concept of path integral in quantum physics and published many books on physics and popularization. He then taught at the Californian Institute of Technology (Caltech). He was awarded the Nobel Prize in Physics in 1965 for his work on quantum electrodynamics.



Richard Feynman

[22] I personally find it hard to see this great physicist holding an axe in the role he is given! This is perhaps an urban legend that is repeated over and over again. I understand that he has always denied this anecdote.



Norman Hilberry (1899–1986), director of *Argonne National Laboratory* from 1957 to 1961.

**Photo 8** The famous CP-1 pile of Fermi (*pile* in English means stack. The word is also used in French, although the usual meaning is *battery*). As there are practically no photos of the pile itself and of this historical event, only this painting allows us to understand the excitement preceding the divergence of December 2, 1942. At the top of the pile is the wooden frame under which the shutdown control rod is suspended (Painting by Gary Sheahan (Joseph "Gary" Sheahan (1893–1978) was born in Winnetka, Illinois. He studied at the University of Notre Dame and the Chicago School of Art before joining the *Chicago Tribune* as an illustrator in 1922. He is best known for his World War II paintings, having participated in the D-Day landings.))

absorber, which will then fall by gravity into the core. The image is so striking that at the end, the word SCRAM, widely used in the nuclear industry to signify the shutdown, has been associated a posteriori[23] with the significance *Safety Cute Rope Axe Man* or *Safety Control Rod Axe Man*. A second operator, the physicist Wallace Koehler, is always standing over the pile, armed with a tub full of a cadmium sulfate solution, ready to spray it in the reactor. Cadmium is indeed one of the most powerful absorbers of slow neutrons. We find here the current principles of redundancy in safety systems. The pile is controlled by a horizontal cadmium control rod handled by hand by the operator George Weil, and Enrico Fermi supervises the neutron flux measuring devices.

In the 1950s, it was civil nuclear power that gave the atom its moral support. If nuclear energy can kill, it can also produce heat. Numerous more or less realistic projects flourished: the use of small atomic bombs to pierce

[23] Volney Wilson, head of instrumentation, is also credited with answering the electrician who was wiring the red shutdown button and asking what would happen if that button were to be pressed, so that he could title it correctly on the control panel: Wilson answered "*You scram out of here as fast as you can*!"