# Tracking the journey of a URANIUM CUBE

A mysterious object led two physicists to investigate the German quest and failure to build a working nuclear reactor during World War II.

Timothy Koeth and Miriam Hiebert

In the summer of 2013, a cube of uranium two inches on a side and weighing about five pounds found its way to us at the University of Maryland. If the sudden appearance of the unusual metal cube wasn't intriguing enough, it came with a note that read, "Taken from the reactor that Hitler tried to build. Gift of Ninninger."

The world entered the nuclear age when the Trinity bomb was detonated on 16 July 1945 near Alamogordo, New Mexico. The origin of the age can be traced back through a small uranium metal cube and 663 others like it. The Manhattan Project and the immense power unleashed by the weapons it produced were created in response to fears that scientists in Nazi Germany were working on their own weapon. The cube, a component of the "reactor that Hitler tried to build," represents the Germans' failed endeavor that catalyzed the nuclear age.

Some questions remain. How did a piece of uranium from Germany end up in Maryland 70 years later? How many like it are out there? What happened to the rest? Who is Ninninger? Years of research into the cube and its history has revealed a complex, intriguing, and incomplete story. From our research, we have uncovered some new information about the German nuclear program itself: The Germans could have built a nuclear reactor.

## The reactor that Hitler tried to build

Our investigation of the cube's origin began with the obvious. Had Timothy Koeth not recognized the cube immediately from old grainy photos in books on nuclear history, the first sentence of the accompanying note provided a starting point. "Taken from the reactor that Hitler tried to build" undoubtedly referred to the nuclear research program undertaken by German scientists during World War II in pursuit of nuclear

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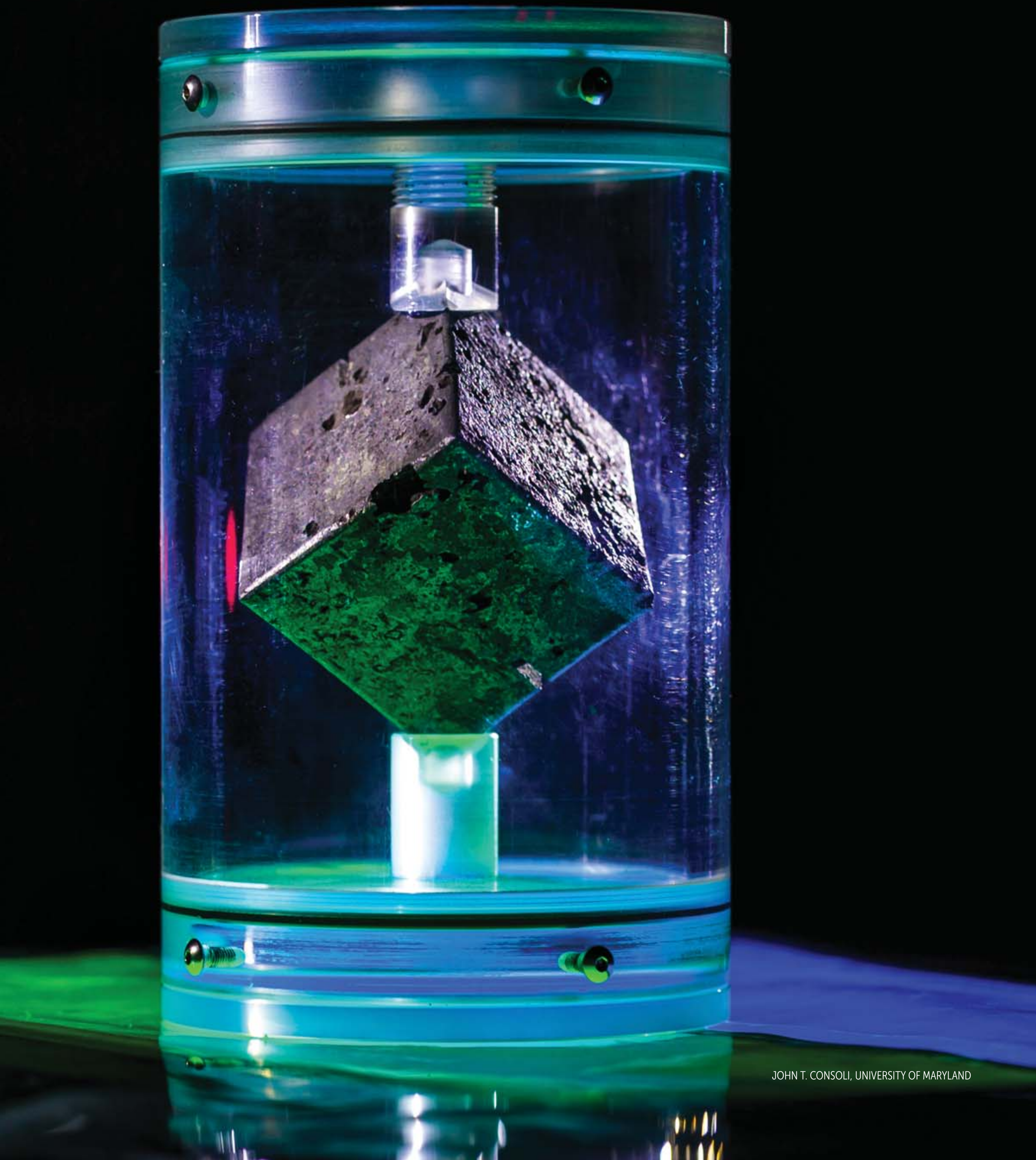

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power and, potentially, a nuclear weapon. Several German physicists were involved in that research program; perhaps the most widely recognized was Werner Heisenberg.

Rather than working together under central leadership the way the Manhattan Project scientists eventually would, the German nuclear researchers were divided into three groups that each ran a separate series of experiments. Each was code-named after the city in which the experiments took place: Berlin (B), Gottow (G), and Leipzig (L). Although the Germans began their work nearly two years before serious US efforts began, their progress toward creating a sustained nuclear reactor was extremely slow.[1] The reasons for the delay were varied and complex and included fierce competition over finite resources, bitter interpersonal rivalries, and ineffectual scientific management.

In the winter of 1944, as the Allies began their invasion of Germany, the German nuclear researchers were trying desperately to build a reactor that could achieve criticality (see the box on page 41 for a description of the physics of nuclear reactors). Unaware of the immense progress the Manhattan Project had made, the Germans hoped that though they were almost certainly going to lose the war, they would be able to salvage the reputation of their physics community by being the first to achieve a self-sustaining nuclear reactor.[2]

In holding out that hope, officials moved the Berlin reactor experiments headed by Heisenberg south ahead of the Allied invasion. They eventually landed in a cave underneath a castle, shown in figure 1, in the small town of Haigerloch in southwest Germany.[3]

In that cave laboratory Heisenberg's team built their last experiment: B-VIII, the eighth experiment of the Berlin-based group. Heisenberg described the setup of the reactor in his 1953 book *Nuclear Physics*.[4] The experimental nuclear reactor comprised 664 uranium cubes, each weighing about five pounds. Aircraft cable was used to string the cubes together in long chains hanging from a lid, as shown in figure 2. The ominous uranium chandelier was submerged in a tank of heavy water surrounded by an annular wall of graphite. That configuration was the best design the German program had achieved thus far, but it was not sufficient to achieve a self-sustaining, critical reactor (see the article by Hans Bethe, PHYSICS TODAY, July 2000, page 34).

## The cube

Our cube, shown in figure 3, was part of Heisenberg's B-VIII experiment. The faces of the cube contain large voids from bubbles that formed during a rough casting process. Those features are consistent with early uranium-processing methods where the metal components were cast individually.[5]

Two of the cube's edges have notches that were painstakingly hand filed. They would have served as tracks to hold in place the aircraft cable that was used to suspend the cubes in the long chains of the B-VIII setup.

We used nondestructive analytical techniques and nuclear forensics on the B-VIII reactor cube to confirm its identity in greater detail. High-resolution gamma-ray spectroscopy of the cube showed that its composition is that of natural uranium, not depleted or enriched, as shown in figure 4. Spectroscopy also confirmed that the cube of uranium was never part of a reactor that achieved criticality; it contained no telltale fission products, such as cesium-137. Both findings are consistent with what has been documented about the uranium used in the B-VIII reactor operation, which leads us to conclude that the cube is indeed an authentic one from Heisenberg's experiment.

**FIGURE 1. THE ENTRANCE TO THE LABORATORY** of the B-VIII reactor experiment was underneath a castle in Haigerloch, Germany. The site is now home to the Atomkeller Museum. (Courtesy of the AIP Emilio Segrè Visual Archives, Goudsmit Collection.)

## The Manhattan Project and the Alsos mission

The next question to consider was how a component of the German nuclear reactor experiment ended up on the western side of the Atlantic Ocean. The answer lies in a well-studied and extensively documented aspect of World War II history: the Alsos mission.

In 1944, as Allied forces began moving into German-occupied territory, Leslie Groves, commander of the Manhattan Project, ordered a covert mission code-named Alsos (Greek word for "groves") to take a small number of military personnel and scientists to the front lines in Europe to gather information on the state of the German scientific program. The mission broadly aimed to gather information and potentially capture data and instrumentation from all scientific disciplines from microscopy to aeronautics. The most pressing task was to learn how far

German physicists had gotten in their study of nuclear reactions. The initial leg of the Alsos mission began in Italy and moved to Germany as the Allied military forces swept south.[6] Among the men involved in the mission was Samuel Goudsmit. After the war, he went on to be the American Physical Society's first editor-in-chief and the founder of *Physical Review Letters*.

As the Allies closed in on southern Germany, Heisenberg's scientists quickly disassembled B-VIII. The uranium cubes were buried in a nearby field, the heavy water was hidden in barrels, and some of the more significant documentation was hidden in a latrine. (Goudsmit had the dubious honor of retrieving those documents.) When the Alsos team arrived in Haigerloch in late April 1945, the scientists working on the experiment were arrested and interrogated to reveal the location of the reactor materials. Heisenberg had escaped earlier by absconding east on a bicycle under cover of night with uranium cubes in his backpack.[7]

On 27 April 1945, the remaining 659 uranium cubes were dug up from the field (see figure 5) and shipped, along with the heavy water, to Paris and later to the US under the control of the Combined Development Trust.[8] The CDT was a collaborative organization established earlier by Groves between the US and the UK to prevent adversarial countries such as the Soviet Union from obtaining enough nuclear material to develop a nuclear program of their own.[9]

If those cubes were shipped to the US, what happened to them after they arrived, and how did one end up in Koeth's hands? The most obvious use for large amounts of natural uranium metal at that time was weapons enrichment at Oak Ridge National Laboratory. However, given the pristine condition of our cube, something else must have happened. Perhaps after arriving in New York, some cubes found their way into the hands of one or more Manhattan Project officials as paperweight spoils of war. Trying to determine who might have distributed our cube and others like it led us to the National Archives at College Park, Maryland, where we unearthed another facet of the story.

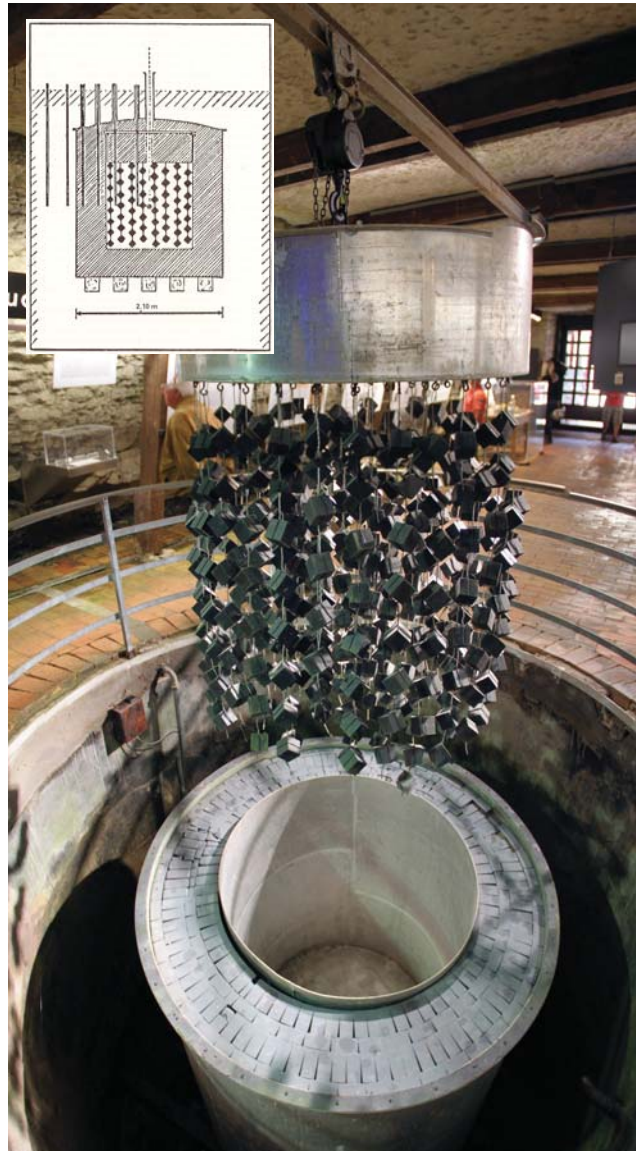


**FIGURE 2. A DIAGRAM AND PHOTO** showing the construction of the B-VIII reactor. The 664 uranium cubes were strung in chains using aircraft cable. The distances between the cubes in each chain and the chains themselves were precisely calculated, and in the final reactor design the entire apparatus was lowered into a pit filled with heavy water. (Diagram from ref. 4; photo from LepoRello, CC BY-SA 3.0.)

## There were more cubes

Many scholars have long thought that the German scientists could not have possibly created a working nuclear reactor because they did not have enough uranium to make the B-VIII reactor work. In Heisenberg's own words, "The apparatus was still a little too small to sustain a fission reaction independently, but a slight increase in its size would have been sufficient to start off the process of energy production."[10] That statement was recently confirmed using Monte Carlo N-particle modeling of the B-VIII reactor core.[11] The model showed that the rough analyses completed by the Germans in 1945 were correct: The reactor core as designed would not have been able to achieve a self-sustaining nuclear chain reaction given the amount of uranium and its configuration. But the design might have worked if the Germans had put 50% more uranium cubes in the core.

In looking for information on where the 659 Haigerloch cubes went, Koeth came across a box at the National Archives labeled "German Uranium." Rather than containing information on the whereabouts of the cubes in the US, the box had hundreds of recently declassified documents discussing other uranium cubes in Germany. Approximately 400 additional cubes of the exact size and shape of the Haigerloch ones were in Germany as part of another, later abandoned reactor experiment led by Kurt Diebner of the Gottow experiment group.[12] The combined inventory would have been more than enough to have achieved criticality in the B-VIII reactor.

Many contributing factors were likely involved in the resulting sequence of events, yet the revelation of the existence of the additional cubes makes it clear that if the Germans had pooled rather than divided their resources, they would have been significantly closer to creating a working reactor before the end of the war.

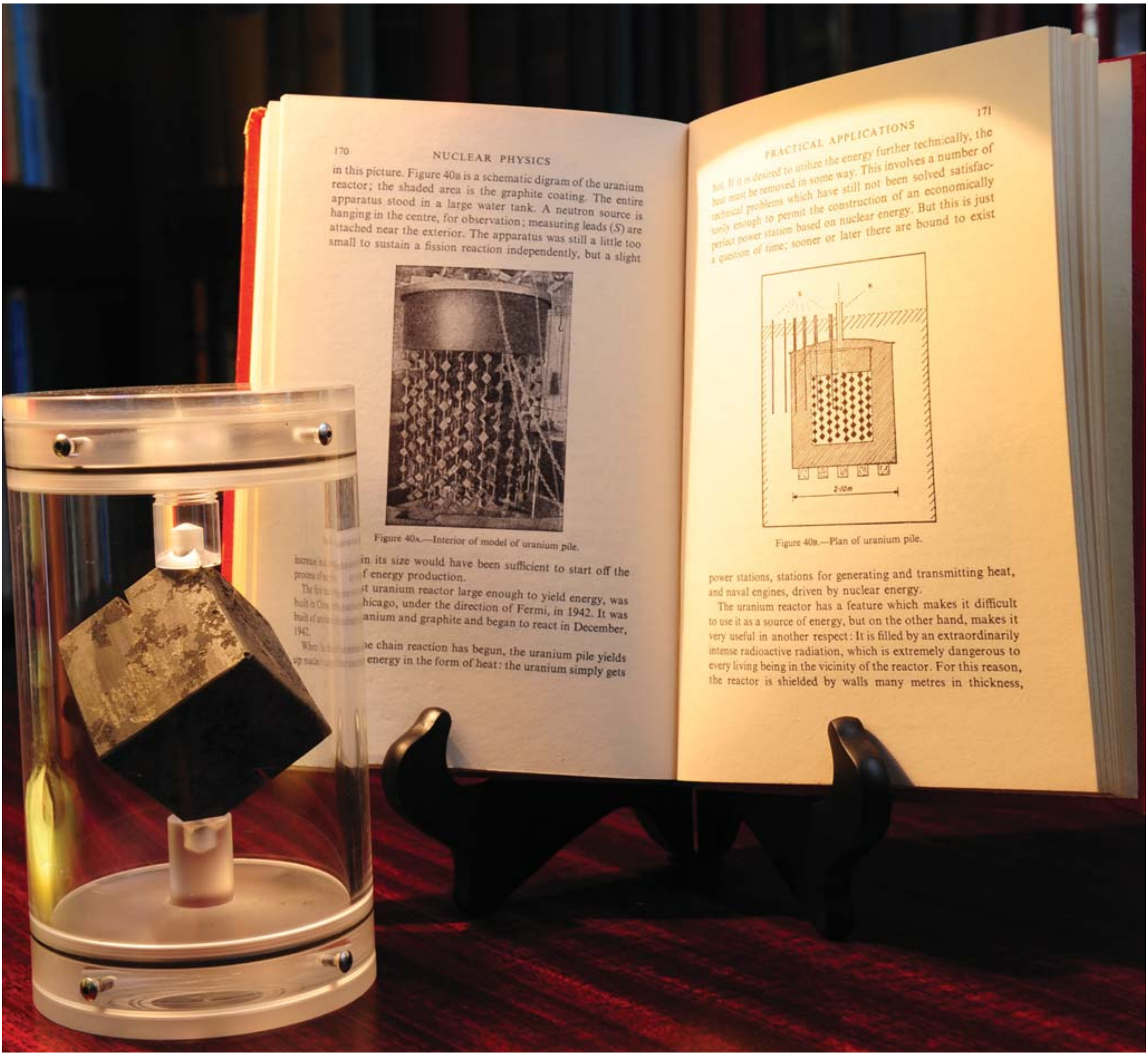



**FIGURE 3. OUR URANIUM CUBE** shown here weighs five pounds and measures two inches on a side. None of its faces are perfectly parallel. The large voids likely formed from bubbles made during the rough casting characteristic of early uranium-metal-processing methods. (Courtesy of Timothy Koeth, University of Maryland.)

The cubes fueled a black market in uranium throughout Eastern Europe after the war, peddled by what intelligence officer Joseph Chase described in a 16 March 1951 communiqué as a "ghostly gang" of profit seekers.[13] Since the Allied Control Commission prohibited German citizens from possessing any amount of uranium, the black-market dealers assumed the cubes were a rare commodity and took considerable personal risk in attempting to sell them.[14] Documents show that every few months, US officials received sinister letters, like one to the head of the Atomic Energy Commission, David Lilienthal, presenting opportunities to purchase a quantity of cubes for hundreds of thousands of dollars each, lest they be sold to entities "not considered over-friendly to the United States."[15] As the US was in no short supply of uranium ore by that time because of the work of the CDT, the US countered those offers with the going price of raw uranium metal, which was about six dollars per pound. The communications in the National Archives are replete with fantastic stories of con artists and smugglers trying to make a windfall profit and of scientists desperate to get their hands on small amounts of materials with which to continue their research.

In one such story, German citizens Helmut Goltzer and Gisela Nitzke were arrested and sentenced to life in prison in 1952 for the possession of a cube of uranium.[14] In the photographs accompanying the newspaper article about the arrest, the uranium taken from their apartment looks nearly identical to the cube in our possession. Upon hearing of the confiscated uranium during the trial, none other than Max von Laue wrote a letter to a Mr. Bierman imploring that he be given pos-

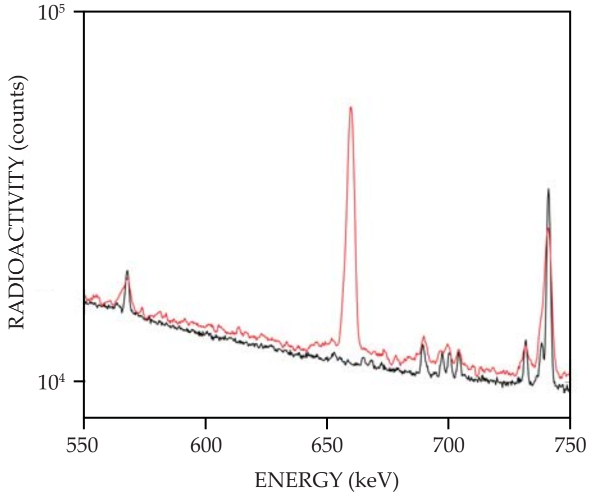



**FIGURE 4. IN GAMMA-RAY SPECTROSCOPY**, a peak at 662 keV indicates the presence of cesium-137, a ubiquitous fission product of uranium-235. The peak is present in the red spectrum obtained from a piece of the Chicago Pile-1 reactor, which achieved criticality; the piece is part of a collection of the Smithsonian National Museum of American History. However, the peak's noticeable absence in the spectrum obtained from our cube (black) confirms that it was never part of a critical chain reactor.

session of the cube for his research as it represented "irretrievable value since uranium, as you know, [could] not be bought in Germany."[16]

The documents at the National Archives also suggest that the majority of the cubes eventually ended up in the Soviet Union. Gordon Arneson, special assistant to the secretary of state, explained in a 1953 communication that every so often as "an offer is made to us of a kilogram or two of U-235 for a million dollars or so, a threat is delivered that the materials will be sold to the USSR unless the US purchases it. It seems that at last such a threat has materialized."[17] What happened to the cubes on their arrival in the Soviet Union is unknown.

## Cubes in the US

Questions remained about our cube. If it wasn't processed at Oak Ridge, where was it for the intervening 70 years, and are there more out there? The second sentence on the note that was

## THE PHYSICS OF A NUCLEAR REACTOR

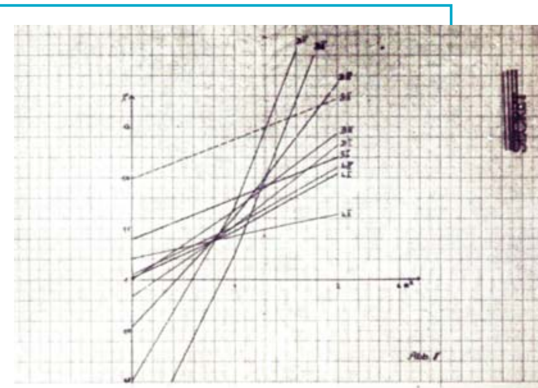
A nuclear reactor is at once both simple and complex. Once it is assembled, the only moving parts required are control rods that are moved in and out of the core to modulate its power output. However, choosing the appropriate number and orientation of a reactor's various components requires a detailed understanding of nuclear fission physics.

Fission readily occurs in a few isotopes of certain elements–for instance, uranium-235 and plutonium-239–when a neutron is absorbed into the nucleus. Because the nuclei of those fissile isotopes lie close to the edge of stability, the addition of a single neutron splits the nucleus into two smaller pieces called fission fragments, which are lighter elements such as barium and cesium. Along with those fission fragments, two or three neutrons are also ejected, and a large amount of energy is released that can be used for power generation. Since a single neutron leads to fission that produces more neutrons, the newly generated neutrons generate subsequent fission reactions, producing the famous nuclear chain reaction. The self-sustaining cycle perpetuates until all the fissile material is consumed. The process is the fundamental operating principal of a critical nuclear reactor.

A minimum quantity, the so-called critical mass, of fissile material is required to create a self-sustaining chain reaction. In a simplified model of the assembled pile of fissile uranium, two competing effects determine the neutron's outcome: The neutrons released from fission can lead to new fission or can escape the surface of the uranium pile and not participate in further fission. In practice, there are many other opportunities for neutrons to go unused, but with careful design, the neutron losses are surmountable, and self-sustaining reactors are possible. To quantify that condition, physicists talk in terms of an overall neutron multiplication factor, $k_{eff}$, which equals the number of neutrons in generation $n+1$ divided by the number of neutrons in generation $n$.

The self-sustaining status of a pile can then be placed into three categories. For a subcritical pile, $k_{eff}$ is less than 1, the number of neutrons lost is greater than the number produced by fission, and the neutron population decreases with time. In a critical pile, where $k_{eff} = 1$, the population of neutrons remains constant from generation to generation. Finally, in a supercritical status, where $k_{eff}$ is greater than 1, an increasing number of neutrons is produced each cycle. Steady-state operation of a nuclear reactor at $k_{eff} = 1$ requires continuous fine-tuning of the pile's geometry, typically by inserting or withdrawing one or more of the neutron-absorbing control rods, analogous to pressing on a car's accelerator or brake to maintain a constant speed.

In their experiments, the German scientists were empirically searching for the optimal geometry and minimum quantity of uranium needed. Placing a neutron-generating radium–beryllium mixture at the center of their pile as the initial source of neutrons, the German scientists measured the neutron population near the periphery as they added increasing amounts of natural uranium, which contains approximately 0.7% fissile $^{235}U$.



The graph shown here was obtained by an Allied reconnaissance mission during World War II and shows the criticality calculations for each of the reactor experiments. (Image courtesy of the AIP Niels Bohr Library and Archives.) Each line plots the subcritical multiplication factor for an experiment. As the amount of uranium was increased with each experiment, the slope of the line will approach infinity. With each successive experiment, the slope of the line increases, showing that the German scientists were approaching, but never achieved, criticality.

**FIGURE 5. THE CUBES FROM THE B-VIII REACTOR** experiment during World War II were buried in a field near the underground laboratory. Members of the US Alsos mission to Germany found them and dug them up. Michael Perrin (far left), Samuel Goudsmit (third from left), and others are shown here retrieving the cubes from the ground. (Photograph by Samuel Goudsmit, courtesy of the AIP Emilio Segrè Visual Archives, Goudsmit Collection.)

included with our cube, "Gift of Ninninger," provided some hints but few substantial answers. In a bizarre stroke of luck almost too good for scientific minds to believe, Koeth was poking around a used-book store days after receiving the cube when he came across *Minerals for Atomic Energy* by Robert D. Nininger, published in 1954.

Despite the apparent misspelling of the name, Koeth decided the author had to be the man referenced in the note. Although Robert Nininger died in Rockville, Maryland, in 2004, a brief phone call with his widow confirmed our suspicions that he was likely the correct man. Nininger had apparently given the cube to a friend, and it changed hands once again before it got to Koeth. In March 1945, just a month before the Alsos seizure of materials at Haigerloch, Nininger was appointed interim properties manager for the Manhattan Project's Murray Hill Area in New York City.[18] The Murray Hill Area oversaw the uranium procurement efforts of the CDT. So Murray Hill was likely where the cubes were shipped to from Europe.

Ten other cubes, in private and public collections, have been identified around the country. Each has a different story for how it arrived at its current location, though most of the stories are incomplete at best. We hope to eventually trace all the cubes and their stories back to a common source. The Smithsonian Institution has one in its collection alongside a slug of uranium from the Chicago Pile-1 reactor. (Both are stored in the Washington, DC, area in a massive facility that calls to mind an Indiana Jones movie.) The cube was donated to its collection by Merril Eisenbud of New York University

Medical Center. In the letter he wrote to the curator of the physics collection at the time, he mentioned that he believed the cube was the only such one in existence. Harvard University also has a cube in its possession, donated by professor and Alsos mission participant Edwin Kemble. That cube is apparently passed among students in introductory physics courses: Its density makes it surprisingly heavy. There is no telling how many more cubes might be in university museums, private collections, and basements across the country. If interested readers have any information pertaining to one, the authors want to hear about it.

## Lessons learned

The cubes represent a bygone era in science when researchers were just beginning to discover the subatomic world. We hope that by finding the cubes and piecing together what happened to them we will return a small amount of context to forgotten objects that have played a monumental role in human history. The cubes and the science they represent still shape modern life decades later.

Perhaps most importantly, the story of the cubes is a lesson in scientific failure, albeit a failure worth celebrating. The experiment they were part of, designed by some of the greatest scientific minds of the time, did not work. Thankfully for us all, the competitive approach and limited scientific resources of the German nuclear research program may have been what foiled Heisenberg and his colleagues in their pursuit of nuclear power. In science, as in other fundamentally human pursuits, we would do well to remember that we are only truly at our best and most equipped to tackle grand challenges when we put our differences aside and work together.

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