

Enriching Uranium

Two centuries ago this year, Martin Heinrich Klaproth discovered the element uranium while investigating the bluish-black mineral pitchblende (uraninite) found in Saxony.

Mineralogists in the late 1700s tended to classify pitchblende as an ore of zinc, but when Klaproth processed the pitchblende he discovered specks of a black substance, a new metal that he called "uranit." The following year he renamed his new element "uranium," in honor of the new planet Uranus, discovered by Sir William Herschel eight years before in 1781.

For the next 50 years Klaproth and other chemists assumed that the black specks derived from pitchblende were pure uranium metal. Klaproth later managed to create uranium nitrate, sulfate, formate, and acetate compounds. Klaproth, a Berlin apothecary, was also an outstanding analytical chemist. His other claims to fame include the discovery of three additional elements—cerium, titanium, and zirconium.

In 1841, however, Eugene Melchior Peligot showed that the "pure metal" was actually uranium oxide, UO_2 . Peligot passed chlorine over the heated substance and studied the products of the reaction, realizing that his original material was an oxide. He then prepared the actual metal by reducing uranium tetrachloride with potassium in a heated platinum crucible; the potassium chloride dissolved, leaving a black powder, which was uranium metal.

This metal was given an atomic weight of 120, but when Dmitri Ivanovich Mendeleev formulated the periodic table in 1869, he realized that uranium did not have the properties expected for such an atomic weight. Instead, he suggested 240 as the atomic weight. Uranium remained the heaviest of the elements until the first transuranic element was artificially created in 1940.

Not until 1896 did Henri Becquerel discover radioactivity in uranium, which stimulated renewed interest in what had been considered a relatively uninteresting element. Becquerel wrapped a photographic plate in black paper and exposed it to the fluorescent salt, potassium uranyl sulfate. He found that distinct parts of the photographic plate had been exposed. Later tests proved that all uranium salts, as well as metallic uranium and the mineral pitchblende, also had the same effect.

Uranium, however, found only limited use in practical applications. It became an occasional substitute for tungsten (very

scarce then) or molybdenum, and was also used in some ceramics. In its natural compounds, uranium had been used for nearly 2000 years as a coloring agent in the manufacture of glasses and glazes—glass dating from 79 A.D. contains uranium oxide. Uranium compounds were also used as a dye or stain in the leather and wood industries, yielding colors from a pale yellow to a bright green. The main interest in processing pitchblende ore then was to extract the accompanying radium, which was considered much more valuable. The uranium itself was seen as a relatively undesirable byproduct.

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In 1934 Enrico Fermi and his team found that neutrons striking uranium led to beta activity, but it wasn't until four years later in Germany that Otto Hahn and Fritz Strassman realized that the bombardment of neutrons actually caused the uranium nucleus to break down into radioactive isotopes of lighter elements, with the subsequent release of energy.

The following year, 1939, Fermi suggested that a split uranium nucleus might also release neutrons that could then sustain the fission reaction in other uranium nuclei. In such a sustained fission reaction, one pound of uranium (one cubic inch) could yield the same amount of energy as three million pounds of coal. This year also marks the 50th anniversary of the discovery of nuclear fission.

Uranium is a dense, hard metal, concentrated at about four parts per million in the Earth's crust, an abundance similar to tungsten and tantalum and considerably more common than gold, silver, mercury, or iodine. Since it is highly reactive, uranium forms many naturally occurring compounds, some water soluble. It is very malleable and ductile, a poor conductor, and strongly electropositive. Uranium has 14 known unstable isotopes and no stable ones.

Subsequent studies showed that the ^{235}U isotope—discovered in 1935 by the

Canadian-born physicist Arthur J. Dempster—is the best candidate for fission work. Unfortunately, ^{235}U is only 0.7% of natural uranium; so, if the process of fission in uranium was to be put to any practical use, some way had to be found to enrich the concentration of ^{235}U .

In 1942, at the height of World War II, Dr. Vannevar Bush, head of the Carnegie Institution in Washington, DC, advised U.S. President Franklin Roosevelt about the possibilities of enormous energy to be released from a mass of fissioning uranium, and how it could be used to create a weapon. Bush also suggested the possibility of producing enriched uranium or the also fissionable new element, plutonium (its existence was a closely kept secret, known only to American and British scientists).

President Roosevelt then turned the project over to the U.S. Army and ordered that the idea be converted to full-scale production of fissionable uranium. By May 1942, the Manhattan Project scientists proposed five feasible methods: two involved production of plutonium; the other three focused on enriching uranium. These latter three were the electromagnetic, the centrifuge, and the gaseous-diffusion methods.

Much discussion and debate ensued as to which of the five proposed methods should be chosen. Each seemed to have the same likelihood of success (or failure) as the others, and each would entail enormous hours of work and resources to develop. But in the urgency of war and the rush to develop the bomb, they could not risk choosing the wrong method. In exasperation, they chose an unorthodox course, which was okayed by President Roosevelt—all five methods would be developed simultaneously.

After beginning work, the researchers discarded the centrifuge method as unfeasible, and they selected only one of the two plutonium production methods, leaving the Manhattan Project to concentrate on three of the original five proposals: creating plutonium in a graphite-moderated pile, and using the gaseous-diffusion and electromagnetic methods for enriching uranium.

The gaseous-diffusion method, led by Dr. Manson Benedict, was implemented at Oak Ridge, Tennessee, in a plant called K-25. Benedict and his team had to develop a workable cascade of thousands of diffusion stages through which gaseous uranium hexafluoride would pass, each stage separating out the heavier and more abun-

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dant isotope ^{238}U and enriching the 0.7% of the desirable ^{235}U . The principle of gaseous diffusion had been known for over a century; in the 1920s German chemist Gustav Hertz had separated isotopes of neon by cycling the gas through many different filtering stages. Unfortunately, the UF_6 gas was so corrosive that it destroyed the pipes and pumps used in the process! And, because of the scarcity of the ^{235}U isotope, enormous quantities of the gas were needed to produce even minute amounts of pure ^{235}U .

Ernest O. Lawrence and his team at Berkeley concentrated on the electromagnetic method, which used a cyclotron-style device to separate the slightly lighter isotope from the abundant ^{238}U in a vacuum chamber with large magnetic fields. Some of the Manhattan Project engineers became exasperated at the theoretical work Lawrence did with his "calutron" device and at the minuscule amounts of ^{235}U he was able to separate. Lawrence's giant magnets and round-the-clock work were able to separate three samples of 75 micrograms each, and the samples contained

only 30% ^{235}U . To create the pounds of enriched uranium needed for weapons would require an enormous industrial complex with magnets larger than any previously imagined. But Lawrence was persuasive and had faith in his ideas; he ultimately convinced the project engineers to undertake the task.

The electromagnetic production plants, known as Y-12 and also located at Oak Ridge, encountered great technical problems, dealing with magnets, vacuums, electric power supplies, and control devices of totally new, never-before-used designs and magnitudes. The magnets were each 250 feet long and composed of thousands of tons of steel, with magnetic fields great enough to require that all movable equipment in the vicinity be created of nonferrous metals or nonmagnetic steel—and these materials were already badly needed for other war efforts. An entire series of beryllium copper tools was designed and fabricated for use with the project. Also, because of the reactivity of the uranium feed material, innovative glass-piping systems were developed,

which led to new techniques for cutting and welding glass tubing.

Ultimately, the Manhattan Project focused the resources of the United States to an extent that has never been matched, not even with the Apollo program. Sufficient quantities of fissionable uranium were created to make the atomic bombs tested at Alamogordo, New Mexico on July 15, 1945, and the "Little Boy" bomb dropped on Hiroshima, Japan on August 6, 1945. The bomb dropped on Nagasaki three days later used plutonium instead of uranium for the fissionable material. Both bombs abruptly changed the course of the war and forever changed the context of global politics and survival.

The manufacturing, enrichment, and separation techniques developed by the Manhattan Project continue to be used to produce uranium for nuclear power plants as well as weapons. These uses have taken uranium from its rather mundane early history to its present status as one of the most important elements worldwide.

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