# Nuclear Element

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## 1. Introduction

There is no element as critical (as in criticality) to the development of nuclear power and nuclear weapons as uranium, and without uranium, neither would exist in their present forms. Also, the world would be a different place. Although it is not widely known, uranium has had many uses outside of nuclear applications, but the nuclear applications are (by far) the most important.

This paper is a review of all of the above, and also a book-review of reference 1 below.[1]

## 2. Early Uranium

Uranium was discovered well before scientists discovered radioactivity. Once they discovered radioactivity, it was still many decades before they understood the science behind it. Between its discovery and a thorough understanding of radiation, uranium compounds were just another chemical with some useful properties, thus it was used various products, mostly colored glass or ceramic glazes.

Your author's spouse was an antiques dealer for many years, and thus I was familiar with some of the products that used uranium, and yes, they are all slightly radioactive, but so are other chemicals in our environment.[2]

Uranium was first isolated and identified as a unique metal in 1789 by Martin Heinrich Klaproth in what is now Joachimsthal, Brandenburg, Germany. Uranium was named by Klaproth after the then recently discovered planet of Uranus.

The initial use for uranium oxide was in colored glass, and it had been identified in trace amounts in green glass dated to 79 CE in a Roman glass mosaic near Naples. Whether a uranium compound was intentionally added or was an accompanying-part of another ingredient is unknown.

However, in somewhat more modern times, we know that the UK glass manufacturer Whitefriars was using a uranium-based coloring agent in the 1830s. Many other glass-makers followed their lead and started using uranium coloring agents shortly thereafter. In the US, the La Belle Glass Company in Bridgeport, Ohio used a uranium coloring-agent in their widely distributed Custard glass, which made this glass more-opaque (see top image on next page).

[1] Lucy Jane Santos, "Chain Reactions," Copyright, 2024, Icon Books, Ltd.

[2] Naturally occurring radioactive materials (NORM) are both common and, in many cases, beneficial. The most important NORMs are uranium, thorium and potassium, which have been present since the formation of the earth approximately 4.5 billion years ago. NORMs are found everywhere in the environment including soil, rocks, water, air and vegetation. Potassium compounds are vital for the functioning of all living cells. Agricultural fertilizers contain potassium, accounting for 95% of global potassium chemical production, as potassium compounds are necessary nutrients for plants.

Uranium is also used in many ceramics. Most notably it was used in vintage Fiesta dinnerware glazes from the Homer Laughlin China Works in Steubenville, Ohio. Several colors of glazes contain the uranium (see image below of the vintage Fiesta ware colors). Note that the “red” (orange shade) was considered to be the most radioactive.

# 3. Foundational Discoveries

The true structure of the atom wasn't discovered until 1932. This discovery led to the discovery of the neutron. Atoms have a nucleus composed of tightly packed positively-charged protons and neutrally-charged neutrons. The rest of the atom is mostly space with one or more orbitals of negatively-charged electrons. An individual atom has the same number of electrons as protons (unless it's ionized) with the same charges, making its charge neutral. An atom can have multiple variants, each with different number of neutrons, which creates different isotopes of the same element.

With uranium there are two notable (relatively stable) isotopes: U-235 (with a nucleus containing 92 protons and 143 neutrons, 92+143=235) and U-238, which has 146 neutrons in its nucleus.

*Uranium-235 constitutes about 0.72 percent of all naturally occurring uranium. (Most naturally occurring uranium is uranium-238.) It has a half-life of 704 million years, decaying to thorium-231, with the radioactive decay chain eventually ending in the stable isotope lead-207.*[3]

*Uranium-235 must be separated from the more plentiful isotope uranium-238 for its various uses. Any of several methods—gaseous diffusion, gas centrifugation, liquid thermal diffusion—can be employed to separate and concentrate the fissile uranium-235 isotope into several grades, from low-enrichment (2 to 3 percent uranium-235) to fully enriched (97 to 99 percent uranium-235). Low-enrichment uranium is typically used as fuel for light-water nuclear reactors; fully enriched uranium is typically used for nuclear weapons.*

# 4. Nuclear Weapons and Reactors

## 4.1. Bombs

The original nuclear bomb development was spurred by the Japanese attack on Pearl Harbor. It was started in 1942. The project was originally code-named "Development of Substitute Materials," but this was changed to the "Manhattan Engineer District" shortly thereafter. The more common "Manhattan Project" was a shortened version of this.

The project was led by Corps of Engineer Colonel Leslie R. Groves, who was soon promoted to Brigadier General. *Groves was promoted to Temporary Lieutenant General in January 1948 and retired a month later on February 29.*[4]

The only isotope of Uranium that was usable for a nuclear weapon was U-235, but since this isotope was only found in trace amounts in natural uranium (see the last two paragraphs in Section 3), there was a concern that there was insufficient supply for a significant number of bombs.

However, in 1941 at the University of California Cyclotron, scientists bombarded U-238 with neutrons and created the first man-made element (element 93), neptunium, which quickly decayed to plutonium (element 94), which was relatively stable. Plutonium was analyzed and it was found not only was it fissionable (like U-235), but it was more so than U-235.

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[3] https://www.britannica.com/science/uranium-235
[4] https://ahf.nuclearmuseum.org/ahf/profile/leslie-r-groves/

Thus, the initial development of the atomic bomb would follow two tracks.

Track 1, would build a huge number of uranium isotope separation plants (most notably gaseous diffusion designs, but other designs were also used). These plants would produce relatively pure U-235, and this was be used in a conservative design for the first bomb to be employed in war.

Track 2 would build breeder reactors to produce plentiful supplies of plutonium used in a more advanced implosion bomb-design, which would be tested in the US, before being used in war.

It turned out that both tracks were successful.

*The manufacturing process at Hanford was developed from what Enrico Fermi and his team proved when they constructed the world's first, albeit small-scale, nuclear reactor in Chicago in 1942. If a reactor could be built sufficiently large, the intense flow of neutrons within it could, almost magically, change uranium into plutonium. This process of transmutation would not be creating gold from straw or lead but would be creating something much more valuable.*[5]

*To that end, the Army Corps of Engineers commandeered roughly 600 square miles of land, including the towns of Hanford, White Bluffs, and Richland, in Washington state. The vast, remote site was bordered by the Columbia River, a critical resource needed for cooling the nuclear reactors.*

*First, tons of uranium would be formed into 8.7-inch-long rods, about 1.5 inches in diameter. Each was then clad in aluminum in a process known as canning. The result was commonly referred to as a fuel slug, tens of thousands of which would be made for the next step of the process.*

*The next step was to irradiate the fuel slugs in a nuclear reactor. The B Reactor was the first of three plutonium-production nuclear reactors built at Hanford during World War II. At the core of each reactor was a huge matrix of graphite blocks, measuring 36 feet by 36 feet by 28 feet front to back, and enclosed in 5 feet of heavy shielding. From front to back ran 2004, 1.7-inch aluminum process tubes, into which were loaded more than 60,000 uranium fuel slugs. Cooling water from the Columbia River would flow in the narrow space between the fuel slugs and the process tubes. Enrico Fermi supervised the first loading of uranium slugs into the B Reactor on September 18, 1944. The B Reactor achieved criticality on September 26, 1944. A reactor achieves criticality when each fission event releases a sufficient number of neutrons to sustain an ongoing series of reactions.*

*The graphite blocks in the core of these nuclear reactors slow down the fast neutrons released during the fission of uranium 235 (U-235). The fission process generates neutrons that initiate fission in other U-235 atoms in a continual process of splitting U-235 atoms and releasing more neutrons. Soon, there are enough slowed neutrons to create a controlled sustained nuclear chain reaction. Some of the free neutrons are absorbed by uranium 238 (U-238) atoms becoming uranium 239 (U-239). The U-239 atoms then transmute (change into) into neptunium 239 (Np-239). Np-239 transmutes into plutonium 239 (Pu-239), the product of interest.*

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[5] National Park Service, "Manhattan Project Science at Hanford," https://www.nps.gov/articles/000/manhattan-project-science-at-hanford.htm

*Every four to six weeks of operation, workers pushed about 10-20 percent of the now highly radioactive fuel slugs out of the back of the reactor and into the water-filled fuel storage basin where they would thermally and radiologically cool off for approximately two to three months. After the cooling off period, the still highly radioactive fuel slugs were loaded into shielded, water-filled casks on train cars. They were then transported to the T Plant where multiple chemical processes would separate the plutonium from the uranium and other radioactive byproducts produced during irradiation. Dissolving the aluminum jacket around the fuel slugs and separating plutonium from the uranium and other radionuclides produced during irradiation required more than a dozen steps in the chemical separations process.*

*The plutonium was carefully and secretly shipped to the Manhattan Project site at Los Alamos, New Mexico in multiple shipments. There, scientists, engineers, and craft workers designed and built a device, known as the Gadget, to test an implosion-design plutonium-fueled atomic bomb. The Gadget used Hanford's plutonium and was successfully detonated during Trinity test in New Mexico on July 16, 1945. The Trinity test was the first human-caused nuclear explosion in history... A few weeks later on August 6, the Little Boy atomic bomb, fueled by enriched uranium from Oak Ridge, was detonated over Hiroshima, Japan, the first atomic weapon used in war. And then on August 9, 1945 the US dropped the Hanford plutonium-fueled Fat Man bomb over Nagasaki, Japan. This was the second atomic bomb used on a human population and, so far, the last.*

## 4.2. Nuclear Power Reactors

*After the war, the United States government encouraged the development of nuclear energy for peaceful civilian purposes. Congress created the Atomic Energy Commission (AEC) in 1946. The AEC authorized the construction of Experimental Breeder Reactor I at a site in Idaho. The reactor generated the first electricity from nuclear energy on December 20, 1951, albeit only a few watts.*[6]

*A major goal of nuclear research in the mid-1950s was to show that nuclear energy could produce electricity for commercial use. The first commercial electricity-generating plant powered by nuclear energy was located in Shippingport, Pennsylvania. It reached its full design power in 1957. Light-water reactors like Shippingport use ordinary water to cool the reactor core during the chain reaction. They were the best design then available for nuclear powerplants.*

*Private industry became more and more involved in developing light-water reactors after Shippingport became operational. Federal nuclear energy programs shifted their focus to developing other reactor technologies.*

*The nuclear power industry in the U.S. grew rapidly in the 1960s. Utility companies saw this new form of electricity production as economical, environmentally clean, and safe. In the 1970s and 1980s, however, growth slowed. Demand for electricity decreased and concern grew over nuclear issues, such as reactor safety, waste disposal, and other environmental considerations.*

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[6] U.S. Department of Energy, Office of Nuclear Energy, Science and Technology, "The History of Nuclear Energy" https://www.osti.gov/servlets/purl/1134452

*Still, the U.S. had twice as many operating nuclear powerplants as any other country in 1991. This was more than one-fourth of the world's operating plants. Nuclear energy supplied almost 22 percent of the electricity produced in the U.S.*

*The events at Three Mile Island (Pennsylvania) and Chernobyl (Ukraine) in 1979 and 1986, respectively, raised concerns about the safety of nuclear power and fueled anti-nuclear dissenters.*[7]

*The U.S. nuclear industry has since proved that nuclear energy is a safe and reliable power source. Nuclear reactors currently operate in 31 states, generating about 19 percent of electricity in the U.S., including more than 70 percent of the nation's carbon-free electricity. The total U.S. nuclear production amounts to more than 800 billion kilowatt-hours as the third-largest electrical energy source behind coal and gas.*

*Although the U.S. does not produce the greatest percentage of its own energy through nuclear power compared to other countries, it still boasts the highest percentage of worldwide nuclear power, as well as the most operating nuclear reactors. Accounting for about 30 percent of nuclear power generation worldwide, the U.S. is a solid leader in the industry.*

*As of August 1, 2023, the United States had 93 operating commercial nuclear reactors at 54 nuclear power plants in 28 states. The average age of these nuclear reactors is about 42 years old. The oldest operating reactor, Nine Mile Point Unit 1 in New York, began commercial operation in December 1969. The newest reactor to enter commercial service is Unit 3 at the Alvin W. Vogtle Electric Generating Plant in Georgia, which began commercial operation on July 31, 2023, and is the first reactor to come online since Watts Bar 2 was commissioned in 2016.*[8]

*The number of operating U.S. nuclear reactors peaked at 112, and their combined net summer electricity generation capacity was 99,624 megawatts. The number of operating reactors declined to 104 in 1998 and remained there through 2013. The number declined to 92 operating reactors in 2022. Total U.S. nuclear net summer electricity generation capacity peaked in 2012 at about 102,000 MW and declined to 94,765 MW in 2022. Although though the number of reactors has declined since 2012, power plant uprates—modifications to increase capacity—at individual nuclear power plants have made it possible for the entire operating nuclear reactor fleet to maintain high capacity-utilization rates (or capacity factors). These relatively high-capacity-factors helped nuclear power to provide 19%–20% of total annual U.S. electricity generation from 1990 through 2021. Some reactors also increased annual electricity generation by shortening the length of time reactors are offline for refueling.*

**Author's comment:** It became a real chore to put together enough information to thoroughly describe the history of power reactors to date, so I needed to use multiple references. The one thing I didn't cover was Small Modular Reactors, as none of these have been commissioned yet. I covered these designs in a 2021 paper linked below.

https://energycentral.com/c/pip/nukes-%E2%80%93-part-5

[7] https://nuclear.duke-energy.com/2012/07/31/a-brief-history-of-nuclear-power-in-the-u-s/

[8] https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php?os=..

## 4.3. GE's Vallecitos Nuclear Center

In the late 1970s your author was employed for a few years as the Facilities Electrical Engineer at the title facility. This is located in the eastern SF Bay Area just south of Livermore (where I lived then and live now).

*The Vallecitos boiling water reactor (VBWR) was the first privately owned and operated nuclear power plant to deliver significant quantities of electricity to a public utility grid. During the period October 1957 to December 1963, it delivered approximately 40,000 megawatt-hours of electricity. This reactor—a light-water moderated and cooled, enriched uranium reactor using stainless steel-clad, plate-type fuel—was a pilot plant and test bed for fuel, core components, controls, and personnel training for the Dresden Nuclear Power Plant, a Commonwealth Edison station built in Illinois five years later.*[9]

*The plant was originally a collaborative effort of General Electric and Pacific Gas and Electric Company, with Bechtel Corporation serving as engineering contractor. Samuel Untermyer II, was the General Electric engineer responsible for the initial design of the VBWR. Vallecitos Power Plant held the US Atomic Energy Commission's "Power Reactor License No. 1". The main power generating facilities closed in 1963. The discovery of an active fault running beneath the facility led to the closure of its most productive reactors in 1977.*

*Nearly 60 years after shutting down for the last time, the reactor vessel of the prototype boiling water reactor in California has been removed from its containment and shipped for final disposal in 2023.*[10]

**Author's comment:** There is much additional information about Vallecitos Nuclear Center through the link in Reference 10 below, including the full decommissioning of the other reactors at the site (see below), and the future full decommissioning of this site. There is also a short video from when VBWR was initially commissioned in 1957.

There were three other reactors when your author worked there. The most important was the General Electric Test Reactor (GETR, pronounced Jeeter). GETR produced a large percentage of the medical and industrial radioisotopes used in the world at the time I started, but was closed in 1977 (see above). The other reactors were ESADA Vallecitos Experimental Superheat Reactor (EVESR, pron. Eeveeser) it was shut down and mothballed when I started there (ESADA was Empire State Atomic Development Associates), and a small 100-kilowatt research reactor called the Nuclear Test Reactor (NTR), which was the last operational reactor at the site after GETR was shut down.

[9] https://en.wikipedia.org/wiki/Vallecitos_Nuclear_Center
[10] https://www.world-nuclear-news.org/Articles/Vallecitos-reactor-removal-complete

## 4.4. Power Reactor Types

There are basically two types of light-water power reactors from US Manufacturers – Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). The main difference between a BWR and PWR is that, in a BWR the reactor core heats water, which boils in the reactor vessel and produces steam, which then drives a steam turbine/ generator. In a PWR, the reactor core heats water, which does not boil. This hot water then exchanges heat with a lower pressure system, which boils its water, which produces steam that drives the turbine. Most reactors in the world are PWRs, since this design allows the turbine/generator to be separated from the potentially radioactive "nuclear island."

Canada uses a CANDU heavy water design (Canada Deuterium Uranium). The water in a CANDU Reactor is not light-water ($H_2O$) like US designs, but heavy water $D_2O$) where "D" is for Deuterium, the second isotope of hydrogen. Heavy water is a much better moderator than light water, enabling CANDU to use natural (rather than enriched) uranium.

# 5. Chain Reactions, The Book

If this book (reference 1) had focused on nuclear technology development, I would have been happy. Although it had decent coverage of the technology development, it mostly focused on the human-side of this story (society, personalities, interactions, back-stories, etc.). This made for a more interesting read. I believe that this book is well worth the price (in the $20 to $30 range for a hardback, $24 on Amazon, go through link below), and also a reasonable reference for the history of uranium, and the US nuclear industries. It's almost 300 pages long.

https://www.amazon.com/s?k=Lucy+Jane+Santos%2C+%E2%80%9CChain+Reactions%E2%80%9D&crid=19K7OY5KV7RGN&sprefix=lucy+jane+santos%2C+chain+reactions+%2Caps%2C157&ref=nb_sb_noss_2