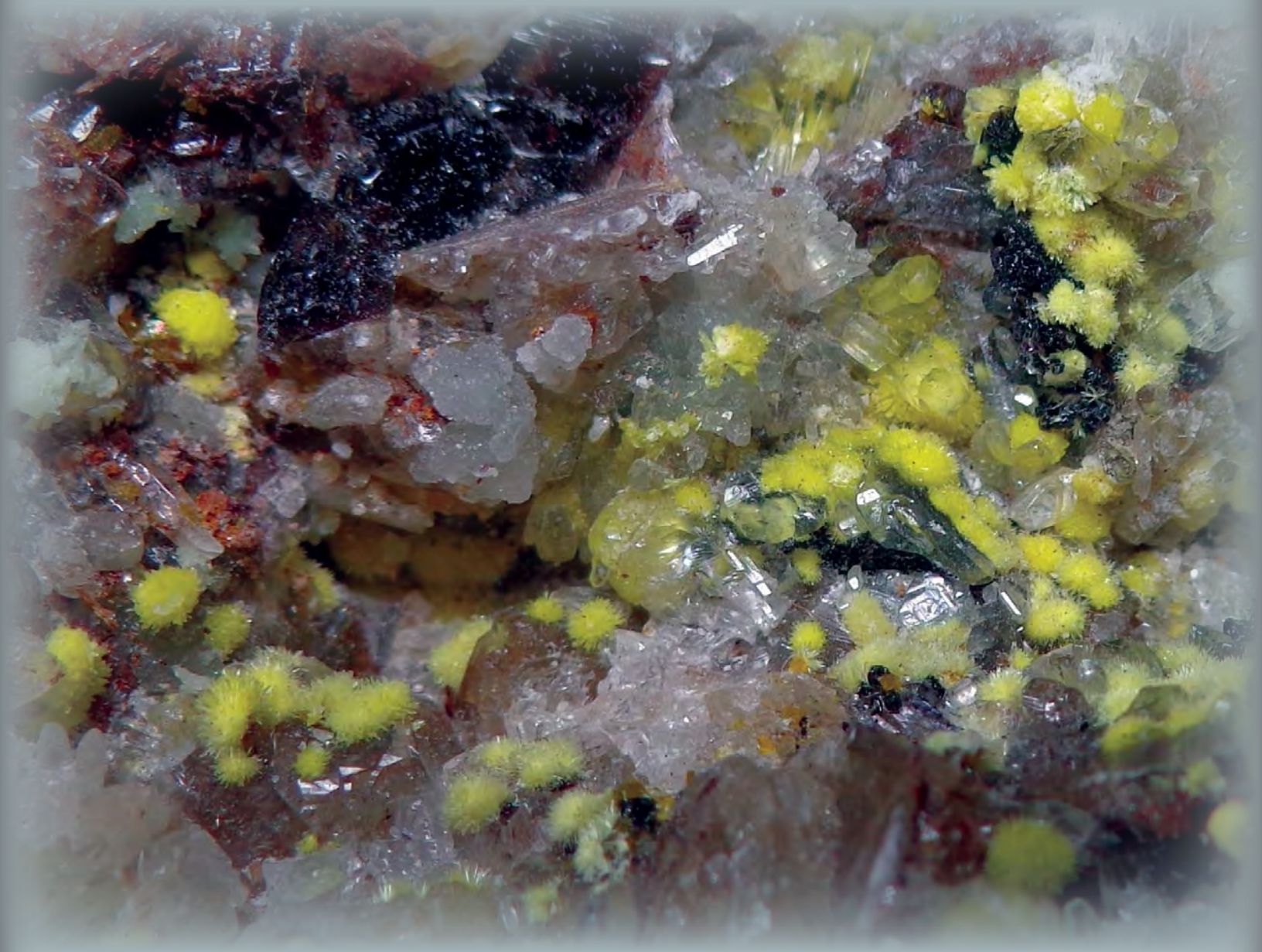
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean, Director and State Geologist

Uranium: Geology and Applications

Robert W. Gregory



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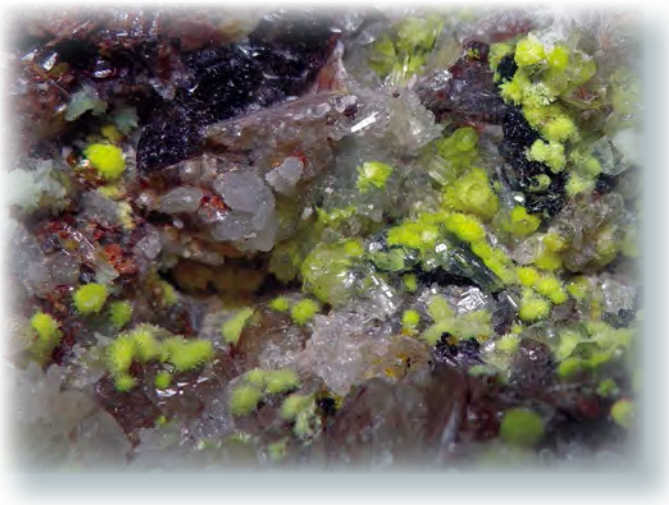

Cover photo: The Haiweeite mineral of Uranium. *Photo courtesy of John Veevaert, Trinity mineral Co.*

Uranium: Geology and Applications

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Uranium: Geology and Applications

Robert W. Gregory

Wyoming State Geological Survey

Public Information Circular No. 46 • 2016

Wyoming State Geological Survey, Laramie, Wyoming 82071

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WHAT IS URANIUM?

Introduction

Uranium has been a valued natural resource for centuries and a strategic commodity since the 1940s. It occurs nearly everywhere on the planet. Its unique radioactive properties were utilized in the medical field as well as in making the world's first nuclear weapons, bringing about the end of World War II. An entire industry has been built around its mining, processing, and utilization. With the largest economic reserves in the United States, Wyoming has benefited greatly from the uranium industry by way of jobs, tax revenues, and economic diversification. Among a wide variety of uses, uranium first and foremost provides energy for the generation of electricity worldwide and should continue to do so well into the future.

Uranium is a naturally occurring chemical element. It is a heavy metal usually found in nature as a mineral oxide. In the laboratory, uranium can be isolated as a ductile and malleable silvery white metal in its pure state. Uranium metal is about 60 percent denser than lead and almost as dense as gold (see Uranium Facts below). Uranium is a radioactive element and spontaneously decays into daughter elements at a unique and constant decay rate. The decay rate (half-life) is the length of time it takes for one half of any given amount to decay.

Uranium occurs as several different isotopes (elements with the same number of protons but different numbers of neutrons). More than 99 percent of all uranium is ^{238}U (atomic weight 238, or about 238 times the weight of one hydrogen atom), and less than 1 percent is in the form ^{235}U; other uranium isotopes are very rare. The atomic number of uranium is 92, as it contains 92 protons in its nucleus. The rest of the particles in the nucleus are neutrons; 146 in ^{238}U and 143 in ^{235}U. The ^{235}U isotope is less stable than ^{238}U and decays more rapidly. ^{235}U is the isotope that is used as fuel in nuclear reactors. In nature, uranium is found as ^{238}U (99.284 percent of all naturally occurring uranium), ^{235}U (0.711 percent), and a very small amount of ^{234}U (0.0058 percent). Several other isotopes of uranium are known but are very rare and usually very short-lived. Uranium decays slowly by emitting alpha particles. An alpha particle emitted from the uranium nucleus is positively charged and made up of two protons and two neutrons, which is physically and chemically identical to a helium nucleus. The half-life of ^{238}U is about 4.47 billion years and that of ^{235}U is 704 million years, making them useful in dating rocks and even the age of the Earth.

URANIUM FACTS

Symbol:	U
Atomic Number:	92 (number of protons in a uranium atom's nucleus)
Atomic Weight:	238.03 atomic mass units (average of isotopes)
Density:	19.05 grams per cubic centimeter (g/cm3)
Group name:	Actinide (in the actinium series on the periodic table)
Hardness (U metal):	~ 6 on the Mohs scale (slightly harder than steel)
Melting point:	2,070°F (1,133°C, 1,405°Kelvin)

Global abundances (estimated)

Crustal rocks:	~ 1.8 ppm* by weight
Sea water:	~ 3.3 ppm
Human body:	~ 1 ppm (average)

(*1 ppm = 0.0001%; 10,000 ppm = 1%)

WHERE IS IT?

Major Uranium Discoveries in Wyoming

The first uranium discovery in Wyoming was at the Silver Cliff Mine near Lusk. This mine was first developed in 1879 for silver and copper but failed to produce much ore (fig. 1). In 1918, prospectors discovered radium at Silver Cliff, which was the first reported uranium discovery in Wyoming (Galloway, 1961). Radium, a radiogenic daughter product of uranium, was in demand for scientific research purposes, particularly by Marie Curie. Ore samples were shipped to Curie in France from Wyoming and Colorado. She named the ore mineral Carnotite after the French Inspector General of Mines, Marie-Adolphe Carnot.

The most famous and significant uranium discovery in Wyoming was on October 15, 1951, by J.D. Love of the U.S. Geological Survey (USGS). Love, along with geologists Dick Hose and F.B. Van Houten, was investigating radioactivity anomalies identified by airborne surveys. The team discovered a uranium deposit in the Pumpkin Buttes area of southwest Campbell County (fig. 1). Love and his associates were excited about the discovery because it supported the idea of Denson, Bachman, and Zeller (1950) that uranium deposits could be derived from Tertiary volcanic ash beds (Love, 1952). The Pumpkin Buttes find led to the discovery of even larger deposits in similar geologic settings across the state, particularly the Gas Hills, Crooks Gap, and Shirley Basin.

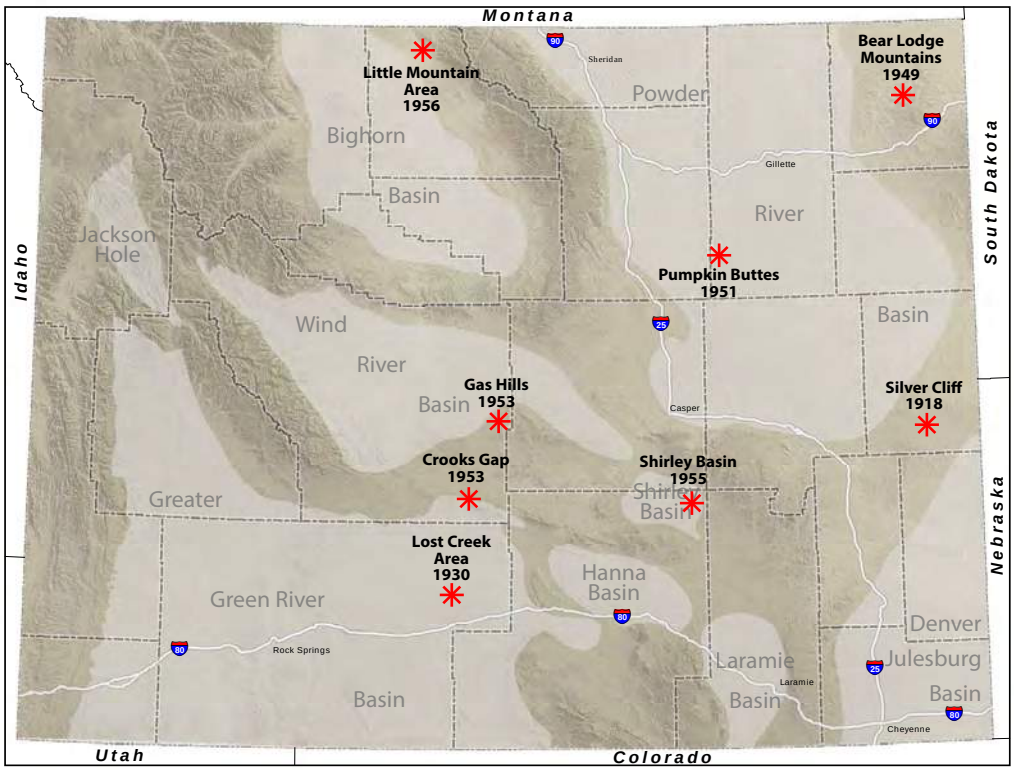

Figure 1. Some historic uranium discovery sites in Wyoming (Graphic by Robert W. Gregory and James R. Rodgers, 2016).

OTHER DISCOVERY DATES

- 1930 – Sweetwater County; Minnie McCormick found a yellow mineral later identified as schroeckingerite
- 1949 – Crook County, Bear Lodge Mountains
- 1953 – Fremont County; Neil McNeice found uranium in Tertiary sandstones in the Gas Hills
- 1953 – Fremont County; Crooks Gap
- 1955 – Carbon County; Shirley Basin
- 1956 – Big Horn County; uranium in carbonate rock in the Little Mountain area

Geology of Uranium Deposits

Uranium occurs in trace amounts nearly everywhere on the planet, even in seawater, but only rarely is it concentrated into ore deposits. There are more than 200 different uranium-bearing minerals known and many other minerals that contain minor or trace amounts of uranium, such as zircon and feldspar. Uranium ore deposits can contain a number of different ore minerals such as uraninite, carnotite, tyuyamunite, coffinite, and several others although usually only a few dominate a given deposit.

COMMON URANIUM ORE MINERALS

Autunite	$Ca(UO_2)_2(PO_4)_2 \bullet 10H_2O$
Carnotite	$K(UO_2)_2(VO_4)_2 \bullet nH2O$
Coffinite	$USiO_4$
Pitchblende	~75% - 90% Uranium, mostly as UO_2
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \bullet 5\text{-}8H_2O$
Uraninite	UO_2
Uranophane	$Ca(UO_2)_2(Si_2O_7) \bullet 6H_2O$

There are three main types of uranium ore deposits: 1) conglomerate paleoplacer deposits, 2) unconformity deposits, and 3) sandstone-hosted deposits. A paleoplacer is a sedimentary accumulation of sand, gravel, and cobbles deposited by ancient stream and river systems. Most uranium deposits of this type were formed nearly 2 billion years ago when Earth's atmosphere contained no appreciable oxygen, and uranium could exist at the surface without becoming oxidized as it would today. These conglomerate hosts are usually very well lithified and resistant rock units. They can be quite rich deposits and are found in numerous locations around the world, including some of the mountain ranges in Wyoming, although such deposits in Wyoming have to date not been economical. There are several economic deposits of this type in Ontario, Canada and South Africa.

Of the three types, unconformity deposits are often the richest in uranium concentration. One good example is the Athabasca Basin in central Canada. Igneous and metamorphic basement rocks are overlain by much younger sedimentary rocks in a basin carved into the basement rocks. When conditions are favorable, rich concentrations of uranium can form where the two rock types meet in the depths of the basin. Most deposits of this type are Proterozoic (approx. 2,500 - 570 million years ago) in age, with the main depositional events taking place

between 1.35 billion and 820 million years ago and another around 380 million years ago. Australia also hosts very rich unconformity deposits.

Host Rock Formations

Sandstones and arkoses are the most common host rocks for mineable uranium deposits in Wyoming. Arkose is physically similar to sandstone, but it differs mineralogically in that it contains less quartz and more feldspar as sand grains. As long as a rock formation is permeable and porous it is a potential host to uranium deposits. While conglomerate and unconformity deposits tend to be higher grade (higher uranium to rock ratio) sandstone-hosted deposits tend to occupy a far greater volume of rock and are easier to mine. They are often much closer to the surface of the earth and most can be mined using in-situ recovery (ISR) methods rather than more expensive conventional methods such as open pits or underground mines.

Most of Wyoming's uranium deposits are found in medium- to coarse-grained sandstone/arkose formations of Paleocene and Eocene age within or along the margins of sedimentary basins. These host rocks are about 40-55 million years old, but the uranium ore deposits within them are much younger, even as young as 2 million or 3 million years. The most productive are the Fort Union and Wasatch Formations in the Powder River Basin, the Wind River Formation in the Shirley and Wind River Basins (Puddle Springs Member), and the Battle Spring Formation in the Great Divide Basin (Harris and King, 1993). In the Black Hills vicinity of northeastern Wyoming, most uranium host rocks are slightly older and include the lower Cretaceous Lakota and Fall River Formations (also known as the Inyan Kara Group). These rock formations are approximately 100-138 million years old. Host rocks there include sandstone, arkose, and conglomerate (conglomerate contains much coarser rock fragments, which are compositionally quite variable). Additionally, there are uranium deposits in the Little Mountain area of the northern Bighorn Mountains and the southeastern Greater Green River Basin. The approximate locations of these districts are shown in figure 2.

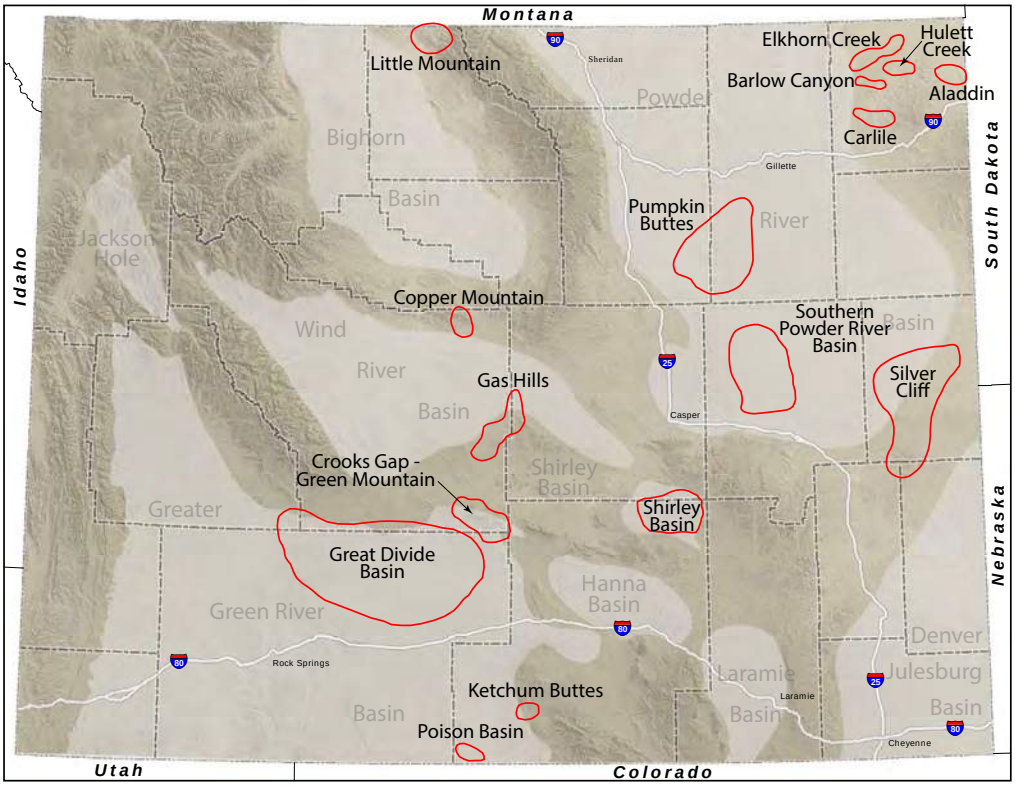

Figure 2. Wyoming uranium districts, both current and historic. Outlines are generalized (Graphic by James R. Rodgers, 2016).

If you could take away the surrounding (non-mineralized) rock from a uranium deposit and look at just the ore body, most would look like highly irregularly shaped blobs of black material with a few common features among most uranium ore deposits. The majority of Wyoming's uranium deposits take the form of roll fronts, which are arcuate, crescent-shaped bodies in cross sectional view (figs. 3, 4) and follow a sinuous (wavy) trend in plan view (fig. 5). The configuration of the ore body was initially called a "roll" by Colorado and Utah miners in the early 1950s. It was a name to distinguish them from tabular uranium deposits that were also found in sandstones. Tabular orebodies are uncommon but do occur in Wyoming, mostly in the lower Cretaceous sandstones in the Cretaceous units in northeastern Wyoming. Impermeable rock layers, typically shales referred to as aquitards, lie above and below the uranium host rocks (in roll front and tabular orebodies) and play a key role not only in the formation of the ore deposit but also during mining operations.

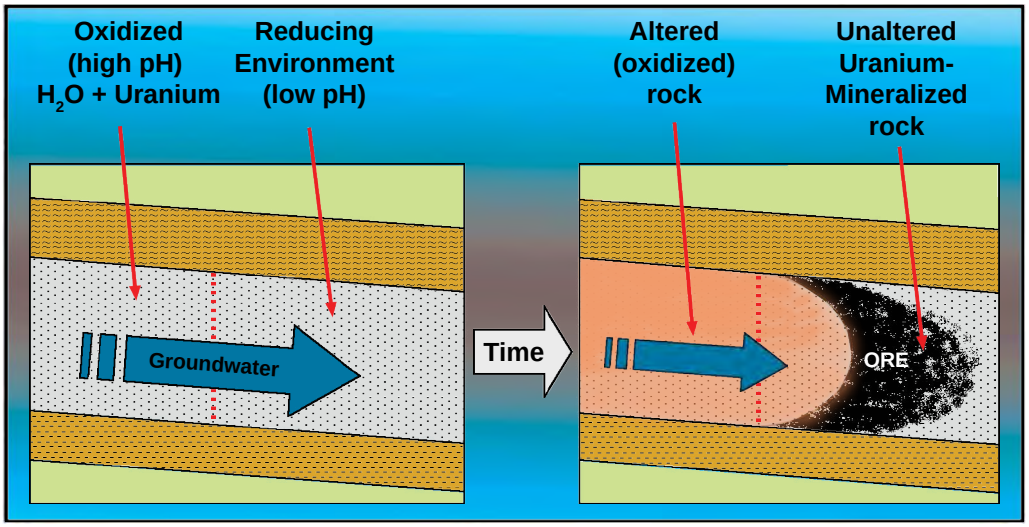

Figure 3. Simplified cross-sectional diagram of the development of a roll front uranium orebody. Oxidized water carries uranium in solution and precipitates uranium minerals in a reducing (acidic) environment (Graphic by Robert W. Gregory and James R. Rodgers, 2016).

Figure 4. Underground mine photo of a well formed roll front with associated high grade uranium ore on the right side of the front (Photo courtesy of R.V. Bailey, circa 1960).

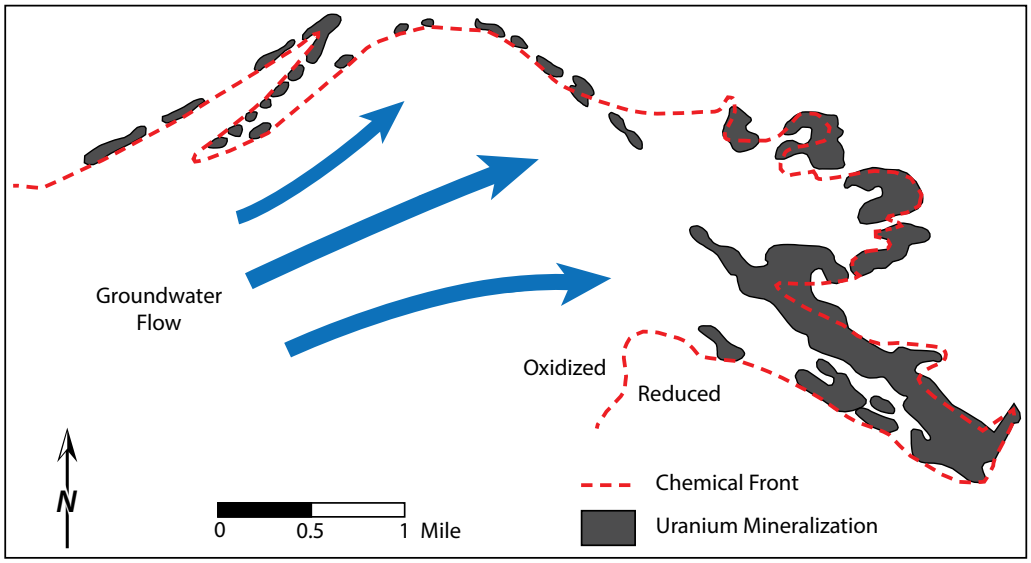

Figure 5. Diagram of uranium roll front mineralization in plan view, southern Powder River Basin. (Graphic by James R. Rodgers, 2016, modified from Dahl and Hagmaier, 1976).

Roll Front Geology

Roll front uranium deposits are found at the boundary between unaltered (reduced) and altered (oxidized) sandstone. The terms altered and unaltered refer to mineralogical changes (or lack thereof) brought about by ground water migrating through the permeable sandstones during ore deposition. Unaltered rock typically contains organic carbon and minerals such as pyrite, magnetite, amphibole, pyroxene, biotite mica, and calcite. Altered (oxidized) sandstone typically contains limonite, hematite, and other oxidized minerals. Sometimes, as in the southern Powder River Basin in northeast Wyoming, this alteration is distinctly visible as a gradual gray to red color change in the rock. In other Wyoming basins, such as the Shirley Basin, the alteration is more subtle, appearing as a color change from gray- to yellowish-gray rock, although the mineralogical changes are largely the same (Harris and King, 1993).

Uranium is irregularly distributed and may not be present everywhere on the roll front (Harris, 1984). An ideal roll front cross-section (figs. 3 and 4) has several unique characteristics: (1) uranium is concentrated along the concave side of the C-shape; (2) concentrations decrease abruptly into barren oxidized rock near the concave boundary; and (3) uranium concentrations gradually decrease toward the convex boundary in reduced rock. In addition to uranium, elements concentrated in a roll front can include vanadium, selenium, molybdenum, copper, silver, lead, and zinc (Harris, 1984).

There are two other deposit types in Wyoming that have produced significant amounts of uranium ore in the past, Tertiary unconformity deposits and paleokarst. Tertiary unconformity deposits occur where Precambrian rocks are overlain by younger Tertiary rocks. In the Copper Mountain district (fig. 2), small mines of this type were operated between 1954 and 1958 and produced less than 50 tons of ore. Most of the uranium mineralization in these mines occurred as fracture fillings in Precambrian rocks and grain coatings on Tertiary arkosic sediments derived from the igneous rocks.

The other deposit type is paleokarst. This term refers to a geologic setting in which the rocks, mostly carbonates such as limestone and dolomite, have developed caves, sinkholes, and other erosional features at some point in their burial history and have since become overlain by other sediments. Uranium generally occurs within layers of secondary deposits in caves, fractures, and other voids in the original rocks. The Little Mountain district in north central Wyoming (fig. 2) is this type of deposit and produced approximately 23,000 tons of uranium between 1955 and 1970.

HOW MUCH IS THERE?

Uranium in the U.S. and globally

In addition to Wyoming, many other states hold significant uranium resources. Figure 6 shows the states with mineable resources. Currently, uranium is mined in Wyoming, Texas, and Nebraska (EIA, 2015).

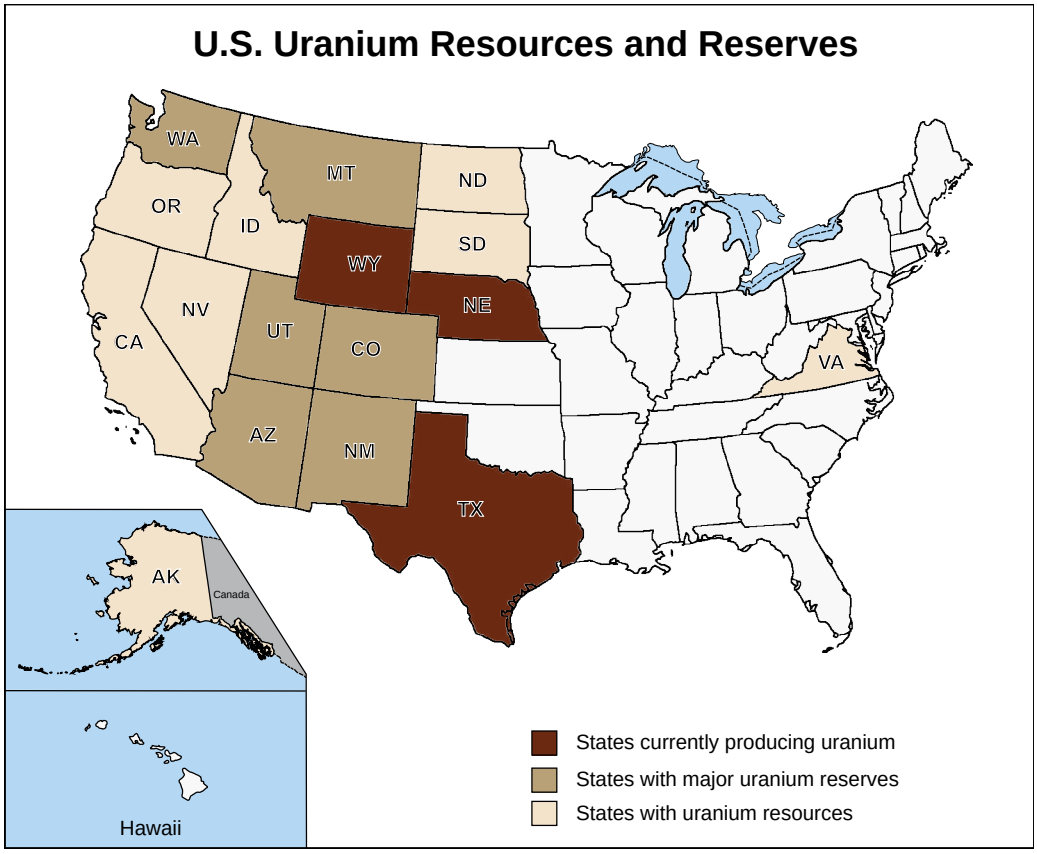

Figure 6. States with known mineable uranium resources, reserves, and those that currently produce uranium (Graphic by James R. Rodgers, 2016).

Several dozen countries around the world also contain mineable uranium resources, the top 16 of which are listed in table 1 and shown in figure 7. Australia holds the world's largest resources, with the United States ranking ninth on that list. Kazakhstan has led the world in production since 2009, and in 2015, produced 23,800 tonnes (metric tons). The United States ranked ninth in worldwide production in 2015, according to the World Nuclear Association's 2015 data. Uranium production from Wyoming totaled just over 2.6 million pounds of yellowcake in 2015, nearly 78 percent of the United States' total (U.S. Energy Information Administration).

Resources vs Reserves

When considering this distinction, it is important to clarify the meaning of the terms 'deposits,' 'resources,' 'reserves,' and 'ore.'

Deposits are accumulations of any type of earth material (rocks, sediments, minerals, etc.) by way of natural geologic processes such as flowing water, wind, glacial ice, volcanism, chemical precipitation. A resource is simply that material in a deposit that may eventually become economically recoverable. Since much of the Earth's crust contains uranium, there are many potential resources. Ore is the economically recoverable material containing the mineral or minerals of value such as uranium, gold, or copper. Ore deposits, or orebodies, are mostly continuous, well-defined accumulations of material containing enough ore to make extraction economically feasible; they are the mineable portions of the resource. Reserves are that part

of a deposit or resource that is proven to be economically recoverable at a profit under current economic conditions using existing technology.

Table 1. World uranium resources.

KNOWN RECOVERABLE RESOURCES OF URANIUM (2013)		
COUNTRY	TONNES U	% OF WORLD
AUSTRALIA	1,706,100	29%
KAZAKHSTAN	679,300	12%
RUSSIA	505,900	9%
CANADA	493,900	8%
NIGER	404,900	7%
NAMIBIA	382,800	6%
SOUTH AFRICA	338,100	6%
BRAZIL	276,100	5%
USA	207,400	4%
CHINA	199,100	4%
MONGOLIA	141,500	2%
UKRAINE	117,700	2%
UZBEKISTAN	91,300	2%
BOTSWANA	68,800	1%
TANZANIA	58,500	1%
JORDAN	33,800	1%

SOURCE: WORLD NUCLEAR ASSOCIATION

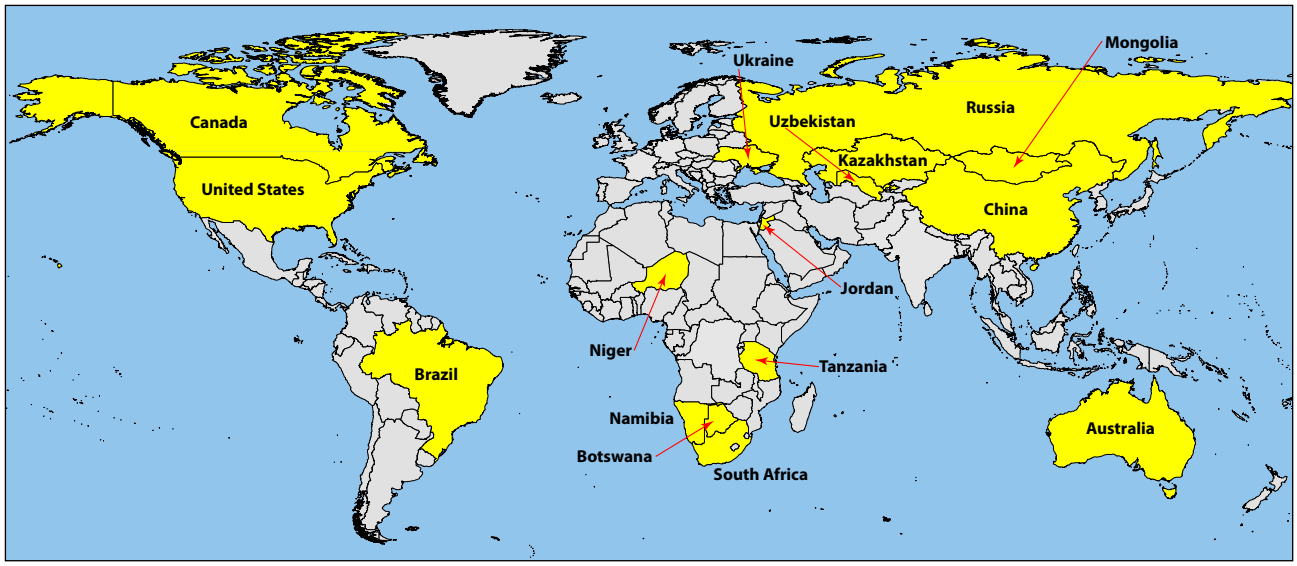

Figure 7. Uranium resources worldwide, 2015 figures (Graphic by Robert W. Gregory and James R. Rodgers, 2016).

The U.S. Energy Information Administration (EIA) estimated in 2008 that Wyoming held about 220 million pounds of recoverable U_3O_8 if the price were $50 per pound of yellowcake. That estimate was 446 million pounds of U_3O_8 at a price of $100 per pound because the additional cost of producing lower grade ore would be surpassed by the profit a company could earn selling at the higher price. Although there are no current estimates of reserves at today's prices (around $26.00 per pound in August 2016), the current reserve number is probably lower than 220 million pounds of U_3O_8.

WHERE DID IT COME FROM?

Mineable uranium ore deposits are secondary in nature; that is they formed subsequent to their host rocks and by different geological processes. In the case of roll fronts the uranium was transported in by ground waters; unconformity deposits accumulated uranium ore by a combination of water transport and favorable geochemical conditions; conglomerate deposits are simply stream systems into which particles of uranium-rich sediments were added. But where did that uranium originate?

Uranium is more or less ubiquitous on the planet, occurring primarily in igneous and metamorphic minerals, but can also occur in solutions such as seawater. Its decay is responsible for much of the heat in the subsurface and is a part of the reason there is a geothermal gradient (an increase in ground temperature with increasing depth below the surface). It is present in volcanic systems and is found in most magma bodies. Uranium is one of the last elements to be incorporated into minerals as they crystallize out of the magma during cooling and solidification. As a result, the last pockets of molten rock to crystallize are often enriched with respect to uranium. When these crystalline rocks weather and erode, the derived sediments can form concentrated uranium deposits. These processes can take dozens (or even hundreds) of millions of years to form an ore deposit. Additionally, if uranium is present in the magma beneath a volcano, ash and other ejecta erupted from that volcano should contain uranium as well.

With respect to the uranium deposits in Wyoming, there are two main schools of thought as to their source of origin. One school maintains that the weathering and erosion of Precambrian igneous and metamorphic rocks in mountain ranges such as the Granite Mountains, seen in figure 8, and the Laramie Range have released uranium as they eroded over millions of years. Both mountain ranges have shed massive amounts of material since their tectonic origins between 40 and 80 million years ago.

Figure 8. View of the Granite Mountains, Fremont and Natrona Counties, Wyoming, looking north from Green Mountain (Photo by Robert W. Gregory, 2010).

A second proposed source for uranium is Middle Eocene and younger tuffs (volcanic ash-rich material). The tuffaceous beds were laid down beginning about 50 million years ago, creating such rock bodies as the Wagon Bed, Washakie, White River (fig. 9), Split Rock, and the Moonstone Formations. Volcanism, in what is now the western United States as well as north-

western Wyoming, occurred off and on for some 40 million years and was the most likely source for Wyoming's numerous tuffaceous rock units.

Weathering and erosion extensively reworked the ash beds (along with other surface deposits) shortly after deposition, during which time uranium would have been leached from the ash. What's left of the White River Formation is exposed in several Wyoming basins and forms broad, near-horizontal surfaces; as it erodes, it typically forms prominent flat-topped ridges and badland topography. Neutral waters (pH = 7), or those with slightly higher pH, can mobilize uranium and carry it in solution until the oxidized water encounters a reducing (acidic, lower pH) environment, usually deeper in the basin. During the course of weathering and erosion, uranium was leached from its original source rock, transported in solution by surface and groundwaters to the basins, and finally precipitated back out of solution in the host rock, creating an ore deposit.

Figure 9. The Eocene White River Formation in the western Shirley Basin, Carbon County, Wyoming (Photo by Robert W. Gregory, WSGS, 2010).

The Ultimate Source of Uranium

The above-mentioned are the two most likely sources of Wyoming's uranium ore deposits, and it's quite possible that a combination thereof has resulted in the deposits we know today. But how did the uranium get into the magma in the first place, and how did it become part of the Earth? Ultimately uranium – as well as many other elements – actually has a very dramatic origin tied to the formation of our entire solar system.

Uranium is a very heavy element (18.9 grams per cubic centimeter, nearly that of gold) and is thought to have originally formed during the supernova explosion of stars several times more massive than the sun. When stars at least eight times as massive as our sun self-destruct in a supernova explosion, heavy elements such as uranium are created amidst the extreme energy and abundance of neutrons and other particles.

Such massive stars have extremely strong gravitational fields. The tendency of the star to compress due to that gravity (gravitational collapse) is counterbalanced by the tremendous energy of heat (thermal expansion) created in such a star as it burns fuels such as hydrogen, helium, and carbon by the fusion process. Uranium decays by fission, the spontaneous 'splitting' of

the nucleus of one element into two or more different elements and an accompanying release of energy. Fusion occurs when, in the presence of sufficient heat and energy, two atoms are joined together to form a different element, i.e., two hydrogen atoms forming one helium atom, again with an accompanying release of energy.

As that elemental fuel becomes depleted and fusion begins to cease, gravity overcomes the ability of the thermal expansion of fusion to maintain the balance that holds the star together. The eventual result is gravitational collapse and the corresponding release of a tremendous shockwave of energy directed outward from the star.

As the shockwave travels away from the core of the star, excess heat from compression of the core breaks down atoms in the interior of the star by a process known as photodisintegration. During this time, some of the matter is converted to energy along with a chaotic array of particles such as neutrinos and neutrons. The matter remaining in the aftermath of that explosion is very abundant in neutrons, which are captured relatively quickly by available elements that survived the explosion. The newly-formed elements are neutron-rich and thus denser; these, including uranium, are the heavier elements of the periodic table.

Scientists believe gases and debris ejected during the supernova explosion form a giant expanding cloud around the remnants of the star, called a nebula. The nebula would contain primarily hydrogen and helium, plus other elements formed inside the star during its life, as well as elements heavier than iron that formed during the supernova explosion. The nebula eventually begins to differentiate due to cooling and gravitational perturbations, which cause parts of it to collapse under the forces of gravity. When enough of this matter coalesces it forms a protoplanetary disc (a broad, relatively flat mass) with a new, young star at its center. The new star begins fusing hydrogen into helium, releasing energy and solar winds, much like most stars. These solar winds largely prevent additional accumulation of matter into the star in addition to creating a gravitational field around itself. The remainder of the protoplanetary disc is then affected by the new star's solar winds as well as the star's gravity as the matter in the disc revolves around the star. Eventually, the temperature and chemical composition of the protoplanetary disc becomes differentiated with increasing distance from the new star, and the planets form as the matter in various zones of the disc continue to coalesce due to gravity. The geochemistry of Earth is derived from the material that existed in our region of the early solar system (protoplanetary disc) approximately 4.5 billion years ago.

The chemistry of that material is thought to be well represented in a type of meteorite known as chondrite. Chondrites are thought to be remnants of the protoplanetary material that eventually came together to form the Earth, and they do contain uranium. Thus, the chemical composition of chondrites is thought to be the same as the matter that formed the Earth. Since the time Earth began cooling from this material more than 4 billion years ago, the original matter has differentiated into the inner and outer cores, the mantle, and eventually oceanic and continental crust. But those processes are unique to Earth itself, and have been ongoing since its formation, including magmatic processes such as regional igneous intrusions and volcanism.

WHERE DOES IT GO, HOW DO WE USE IT?

Historical Uses

The first known use for uranium was to add a greenish-yellow color to glass as early as 100 BC. Oxidized forms of uranium, such as carnotite, have a bright yellow color and were added in small amounts to glass mixtures prior to heating and blowing. However, scientific discoveries and advancements in the last few hundred years has revolutionized the use of uranium.

Early Research

In the 18th and 19th centuries, scientists were expanding their knowledge of elements and their properties, and eventually discovered uranium associated with an ore named pitchblende, so named because its color (black) and that it appeared to be a blend of metal-bearing

minerals. Heinrich Klaproth studied pitchblende ore, and in 1791, he discovered and proposed to call the element uran after the planet Uranus. Eventually, the name uranium was adopted. In 1841, French chemist Eugene-Melchior Peligot (1811-1890) successfully isolated the first sample of metallic uranium using potassium to reduce uranous chloride (UCl_4), thus proving that Klaproth's sample was not the pure metal, but rather an oxide.

In 1895, the German physicist Wilhelm Roentgen was doing research with a variety of vacuum tubes, and eventually discovered X-rays, so named because there was so little known about them, and used "X" after the mathematical designation for the unknown. The following year, a French scientist named (Antoine) Henri Becquerel was conducting experiments on the effects of X-rays on photographic plates. After storing the plates in a drawer in his lab – taking care to avoid their exposure to any sources of light – he discovered that the plates had indeed been exposed to some source of energy. Also in that drawer, however, were some mineral crystals that contained uranium. Becquerel then concluded there was something within the crystals that emitted its own energy, rather than having to be charged or energized by some other source.

Following up on Becquerel's work, Marie Curie and her husband Pierre (fig. 10) conducted a series of experiments on uranium and other elements leading to the discovery of new elements polonium, (named for her birthplace, Poland) and radium. They also coined the term radioactivity, and in 1903, were awarded the Nobel Prize in physics along with Henri Becquerel for their work on radiation.

Figure 10. Pierre and Marie Curie in their laboratory, circa 1905. Some of the ore mined at the Silver Cliff Mine in Niobrara County, Wyoming, was shipped to the Curies.

Fission

During the course of experimentation on radioactive materials, scientists made a significant discovery. They were able to show that these atoms emitted radiation without an external input of energy, resulting over time in an increasing amount of lighter elements and a decreas-

ing amount of the original radioactive material. This was the result of atoms spontaneously fissioning (splitting) and leaving two or more lighter elements, releasing energy and subatomic particles in the process (fig. 11).

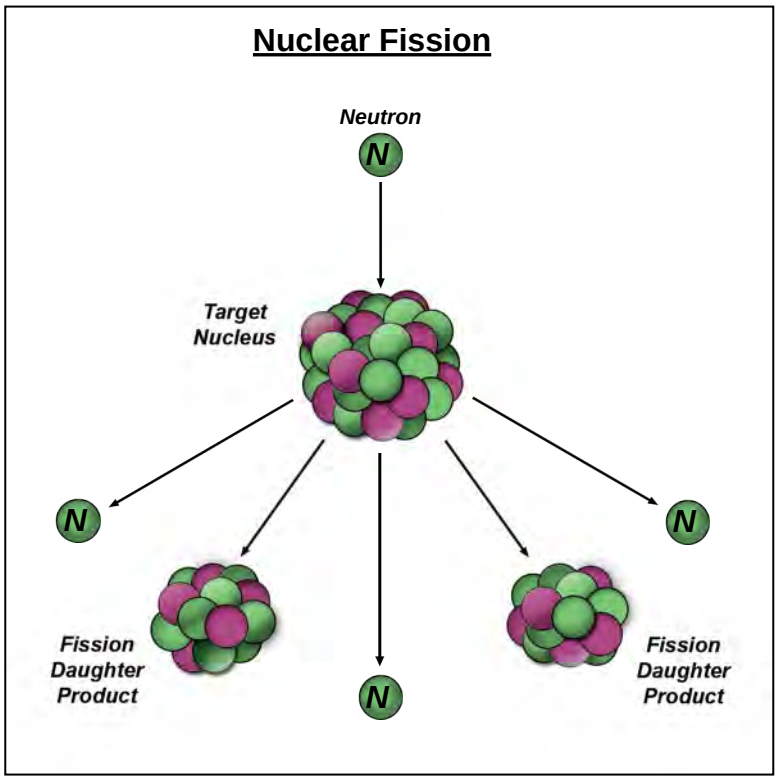

Figure 11. Conceptual illustration of nuclear fission (neutrons in green, protons in red, electrons omitted for simplicity). The sum of the masses of these fragments (daughter products plus emitted neutrons) is less than the original mass of the target nucleus. This missing mass (about 0.1 percent of the original mass) has been converted to energy, according to Einstein's equation, E = mc2. Fission can occur when the nucleus of a heavy atom captures a neutron or it can happen spontaneously (Graphic by Robert W. Gregory and James R. Rodgers, 2015).

Eventually, scientists became more and more aware of the energy stored within the nucleus of the atom. Despite their knowledge of the significance of fission, researchers such as New Zealand physicist-chemist and Nobel laureate Ernest Rutherford, dismissed the phenomenon as a poor and inefficient way of producing energy. However, other scientists continued researching the potential energy stored within individual atoms and the amount of energy released during fission. They postulated that given the right amount of fissionable uranium (^{235}U) under the right conditions, a chain reaction should occur wherein the decay of one uranium atom would release both energy in the form of heat, and subatomic particles that could trigger the subsequent decay of other ^{235}U atoms, furthering the reaction until the nuclear fuel is exhausted.

Hungarian-born physicist Leo Szilard in the 1930s filed for a patent in Great Britain on his idea of a nuclear chain reaction. Shortly thereafter, he and Enrico Fermi filed for a U.S. patent based on uranium decay. Szilard and Fermi were instrumental in the development of the world's first nuclear reactors and successfully achieved a sustained, controlled chain reaction in December 1942 as part of the Manhattan Project. Their success in making a nuclear reactor work helped advance the technology required to not only help Manhattan Project scientists make the first atomic weapons, but also to usher in the nuclear age of electricity generation.

Harnessing energy from uranium

In August 1939, prior to the United States entering World War II, Szilard wrote a confidential letter to President Roosevelt, which he convinced his friend and collaborator Albert Einstein to sign as well. President Roosevelt recognized the urgency of the situation and authorized implementation of the extensive research and development efforts that would become the Manhattan Project. Einstein informed the president that (1) a chain reaction of fissionable ^{235}U was theoretically possible, (2) a chain reaction could generate "vast amounts of power" and "large quantities of new radium-like elements, 3) Germany was at that time conducting similar research on uranium, and (4) the United States had "only very poor ores of uranium in moderate quantities."

The Manhattan Project was a widespread massive effort in the early 1940s geared to make America the first nation in the world to harness the immense energy within the ^{235}U atom for the purpose of making atomic bombs. At the time, Germany was believed to be conducting similar research. The Manhattan Project was conducted at dozens of sites across the United States, most notably Chicago, Illinois; Oak Ridge, Tennessee; Hanford, Washington; and Los Alamos, New Mexico; as well as at a few sites in Canada and Great Britain. In the process, it was necessary to not only develop the technology of the atomic bomb, but to also build the massive infrastructure needed to process and enrich uranium to weapons grade concentrations required to assemble the first bombs.

By July 1945, the scientists and engineers at Los Alamos, New Mexico, led by J. Robert Oppenheimer, had assembled three nuclear weapons. Two were plutonium implosion bombs and one was a uranium gun-type bomb, nicknamed "Little Boy." The first detonation of an atomic bomb was on July 16, 1945. This was a plutonium implosion bomb similar to the one detonated over Nagasaki on August 9, 1945, nicknamed "Fat Man."

The "Little Boy" bomb, detonated over Hiroshima on August 6, 1945, used several kilograms of the fissionable ^{235}U. Furthermore, for the critical mass required to create a nuclear blast, the explosive material needed to be enriched to about 90 percent ^{235}U, up from less than 1 percent in naturally occurring uranium. Several different enrichment techniques were researched and tested, some of which are still used in today's nuclear power industry. In all, more than 130,000 people were involved in the Manhattan Project at all levels from clerical duties to hands-on research and development.

The Manhattan Project played a key role in bringing about the end of World War II. Afterward, it provided the basic infrastructure for continuing the build-up of the nation's nuclear arsenal. The federal government actively pursued domestic uranium supplies, giving rise to the first exploration rush in uranium mining history in the late 1940s. Eventually, the U.S. nuclear arsenal would become very large, as would our supply of uranium resources and reserves, as the Cold War progressed.

With such a surplus in uranium supply, the nation's focus turned to the use of uranium for nuclear-powered electricity generation. Nuclear reactors were developed to power much of the American naval fleet, and that technology was applied to develop those used in the nuclear power industry we know today. There are still other military uses for uranium as well. Uranium's two most unique qualities – its high density and its radioactivity – are the basis for its modern uses in both military and civilian life.

Aside from atomic weapons, the primary military use for uranium is for specialized nuclear reactors to power naval vessels. Other uses include high-density penetrators used to attack armored vehicles such as tanks. High-density uranium is also used to fortify tanks and other armored vehicles. The uranium used for this purpose is depleted uranium metal (^{238}U left over from the enrichment process for making fuel and weapons). Depleted uranium is actually less radioactive than naturally occurring uranium since most of the ^{235}U has been removed by the enrichment process. Depleted uranium is alloyed with small amounts of other metals for the

above-mentioned applications. Additional uses include shielding materials, chemical catalysts, trim weights for aircraft (military and civilian), counterweights and ballasts for space vessels re-entering the atmosphere, and other applications requiring a high-density material for stability (Kirk, 1980; World Nuclear Association, 2010).

The major civilian use for uranium is as a fuel for nuclear-powered electrical generating plants (see Nuclear Fuel Cycle discussion below). Other civilian uses include shielding for industrial radiography cameras and other radioactive materials, ballasts, and counterweights for a variety of applications, including sailboats, aircraft, oil wells, inertial guidance systems, and gyro compasses. As uranium decays, some of its daughter products have specific medicinal uses in the diagnosis or treatment of a number of human ailments.

The heat produced at nuclear reactors has great potential for uses other than electricity generation, primarily desalination to produce potable water from seawater and the mass production of hydrogen gas (World Nuclear Association, 2010).

URANIUM AND THE NUCLEAR FUEL CYCLE

Nuclear power plants supply approximately 20 percent of America's electricity. From mining to electricity generation, uranium goes through several stages of the process known as the nuclear fuel cycle. The main steps in the nuclear fuel cycle are depicted in figure 12 and described in the following sections.

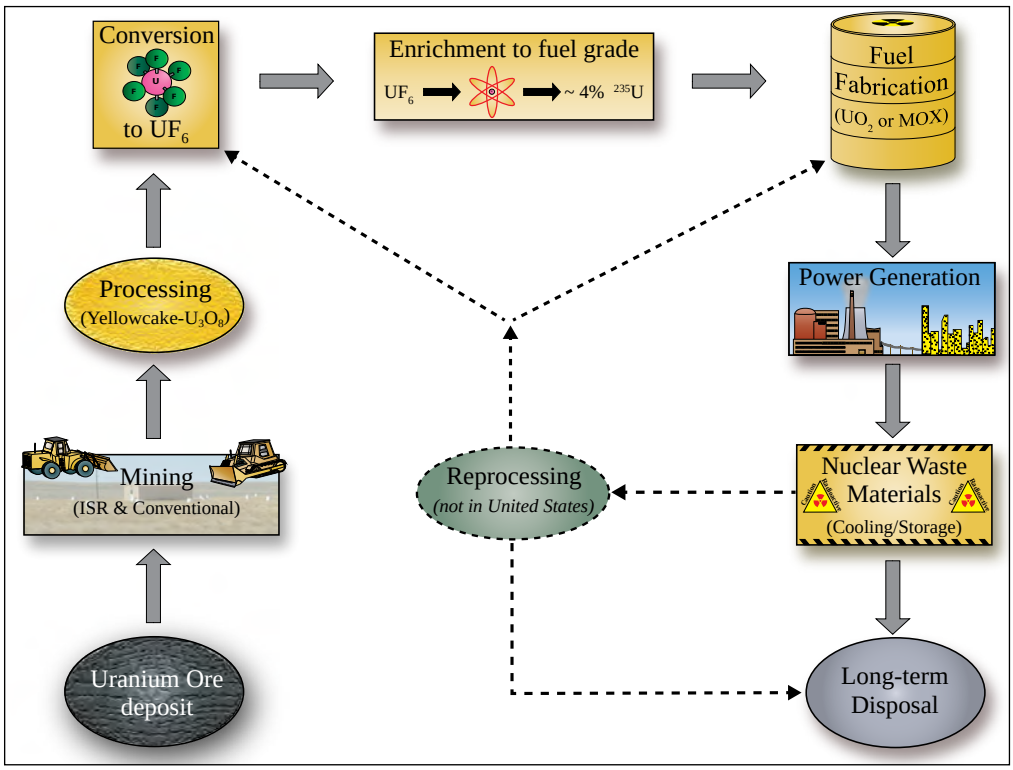

Figure 12. Generalized diagram of the various stages of the nuclear fuel cycle. Some countries reprocess spent fuel into material suitable for new fuel while discarding unusable material. The United States does not currently reprocess any spent fuel, nor are there any long-term disposal facilities, but one is proposed for Yucca Mountain, Nevada (Graphic by James R. Rodgers, 2016).

Once uranium ore deposits are located, the ore is mined to extract uranium and then processed into U_3O_8 (yellowcake), usually at or near the mine site. That yellowcake must then be converted into a form that allows it to be enriched, and ultimately processed into fuel for nuclear reactors. After the uranium has undergone fission reactions to produce heat, the spent fission products are stored and allowed to cool; the ultimate goal is to permanently store the material in an underground disposal site to protect the public from harmful radiation.

Uranium Mining

Wyoming benefits from uranium mining in many ways. Uranium mining has put thousands of people to work in the last few decades and generated millions of dollars in revenue to the state in severance taxes. Uranium mining has helped diversify the economy, as the state has experienced many boom and bust cycles over the years, which is common with commodity-related industries.

Wyoming in 2015 produced more than 2.6 million pounds of uranium yellowcake from its five ISR mining operations. Elsewhere in the United States, uranium is mined in southern Texas and western Nebraska (fig. 5). Additionally, the White Mesa mill in Utah has been processing stockpiled ore and alternate feedstock from mines in the southwestern United States. Wyoming has led the nation in uranium production for several years and should continue to do so well into the future.

Globally, uranium is mined on every continent except Antarctica. The top three uranium producing countries, Kazakhstan, Canada, and Australia, account for 60 percent of the world's total uranium production. According to the World Nuclear Association (2015), the rest of the top 10 producers, in order of decreasing rank, are Niger, Russia, Namibia, Uzbekistan, China, U.S.A. (9th), and Ukraine.

Types of uranium mining

There are two primary methods by which uranium is mined. The first (and older) method is conventional mining. The second method, the modern alternative is in-situ recovery (ISR, in-situ leach, or ISL). Historically, Wyoming has had both types of uranium mining.

Conventional mining involves the physical removal of ore from the ground. The ore is then milled and processed to extract and refine the uranium. Removing the ore from the ground is accomplished via underground mining (fig. 13) or surface pit mining (fig. 14). Where the ore does not crop out at the surface, conventional mining requires the removal of overburden (topsoil, sand, gravel, etc.) down to the orebody horizon. Underground mining typically involves sinking a vertical shaft from the surface and driving adits (horizontal tunnels) at depth to reach the ore body. Some underground mines are accessed from a horizontal entrance, such as on the side of a hill or a mountain, but usually lead to a vertical shaft elsewhere in the mine. The main factors that determine whether to mine by surface pit or underground methods are depth and cost of production. Orebodies lying less than about 500 feet down are typically surface-mined, as it is much less expensive than underground mining.

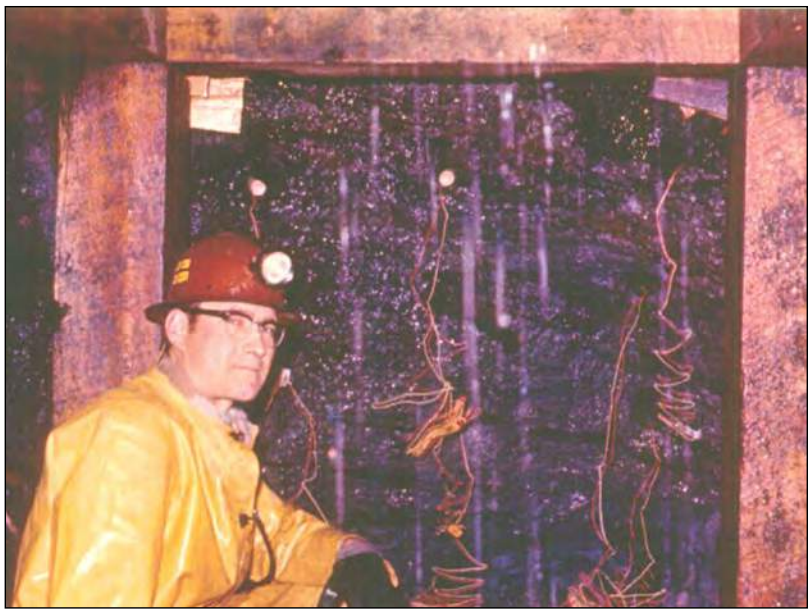

Figure 13. A miner prepares for blasting in the underground mine at Shirley Basin (circa 1960). Surface pits eventually succeeded underground operations at Shirley Basin and currently plans are in place for in-situ recovery operations sometime in the next few years. (Photo courtesy of R.V. Bailey).

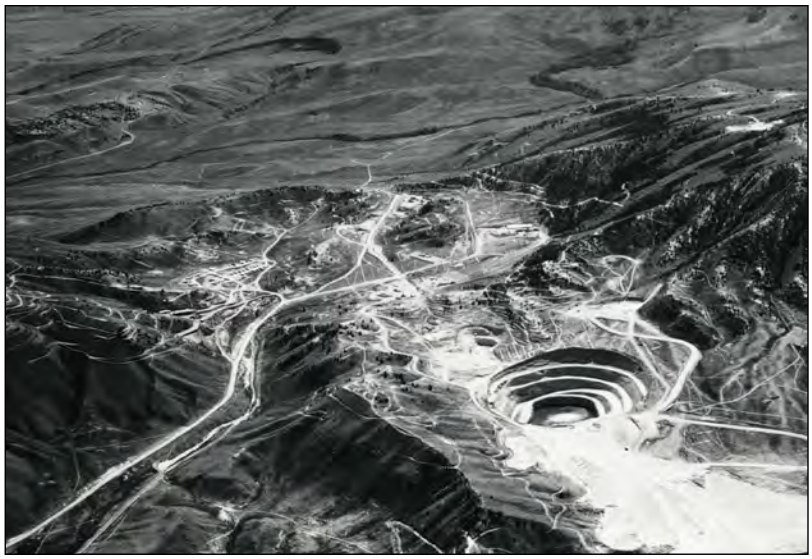

Figure 14. The Paydirt pit surface mine in the Crooks Gap area, southeastern Fremont County, Wyoming, circa 1970 (Photo courtesy of U.S. Department of Energy, Grand Junction, Colorado).

ISR is more economical and has a lower environmental impact than conventional mining. Today, it is the more common and preferred uranium mining method. Figure 15 is a conceptual diagram of ISR-type mining of a roll front, and figure 16 shows an example of what an ISR uranium mine looks like on the surface of the land.

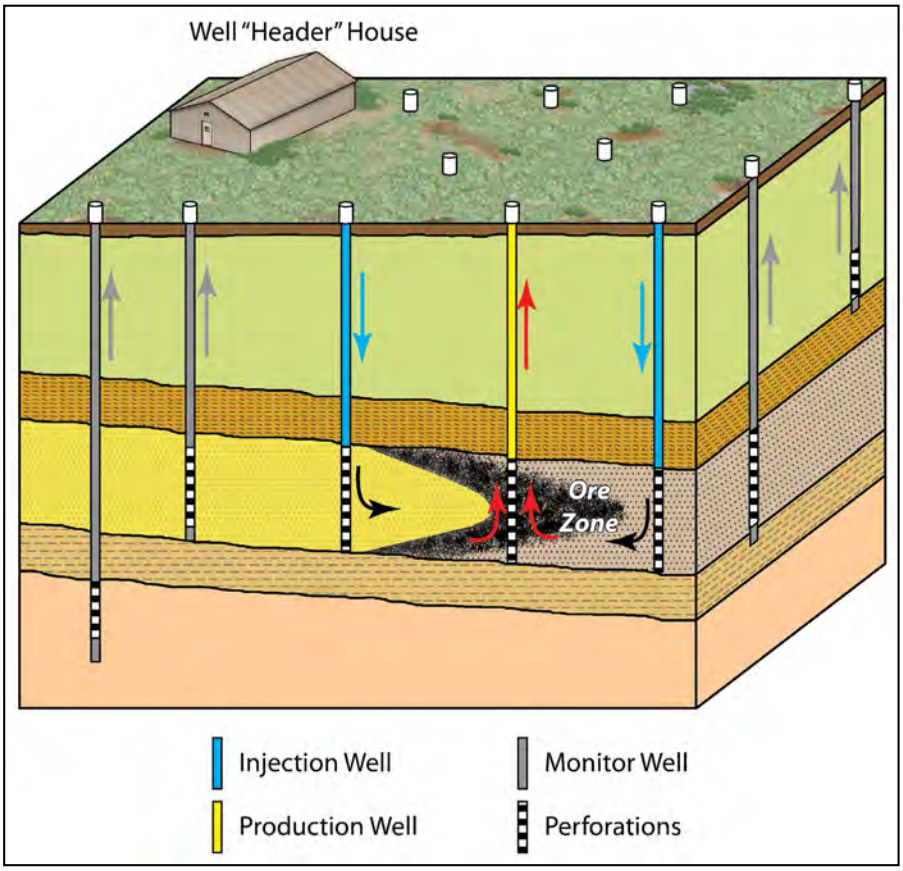

Figure 15. Conceptual diagram of an in-situ recovery (ISR) operation. Header house controls water flow to and from wells (not to scale). (Graphic by James R. Rodgers, 2015).

Figure 16. Header house and well heads in an ISR field at the Smith Ranch-Highland mine operation in Converse County, Wyoming. (Photo by Robert W. Gregory, 2006).

ISR is essentially the reverse of the natural geologic processes that originally concentrate uranium in an ore deposit (fig. 3). After natural processes oxidize and leach uranium from its source, surface and groundwaters transport the uranium to a reducing environment, typically in a porous host rock where the uranium is then deposited. In the ISR process, the uranium minerals are oxidized, remobilized, and pumped to the surface for processing. One of the advantages of this method is that there is very little surface disturbance other than the necessary infrastructure such as roads, well head covers, and widely scattered small buildings.

The ISR method was developed on an industrial scale in southern Texas in the 1970s, and since 1993 has been the only uranium extraction method used in Wyoming. The history of ISR dates back to the early 1960s in the Gas Hills and Shirley Basin uranium districts. Miners found that leaching solutions could be pumped through permeable tailings and also through host rocks underground. The ISR process leaves the host rock in place and removes uranium by pumping a mixture of water and oxidizing agents, including dissolved gases such as oxygen (O_2) or carbon dioxide (CO_2) through the rock.

The mixture, called lixiviant, consists of water pumped from the orebody aquifer plus the oxidizing agents added at the surface. In order to remove uranium from its location in the orebody, the lixiviant is pumped into the aquifer from injection wells, through the orebody, and back to the surface. The lixiviant liberates the uranium from the orebody and into solution so that it can be removed at the surface by an ion exchange process. In addition to injection and production/extraction wells, ISR operations utilize monitor wells, which continually sample the water at the margins of the orebody, laterally, as well as above and below, to ensure that the injected water does not migrate away from the targeted orebody and into adjacent aquifers, an occurrence called an excursion.

In Wyoming, uranium is currently mined at six different ISR operations, five of which are in the Powder River Basin (fig. 2). The other ISR operation in Wyoming is in the Great Divide Basin (in the northeastern part of the Greater Green River Basin) north of Wamsutter. Additional ISR operations are planned for other locations in the Powder River Basin as well as the Gas Hills (part of the Wind River Basin) and the Crooks Gap District situated between the Great Divide and Wind River Basins. Conventional mining operations are currently in

the permitting process at two districts in eastern Fremont County. Surface pits are planned for the Gas Hills, and at the Crooks Gap district, about 30 miles to the southwest, both surface pit and underground mining is forthcoming. Historically, uranium has been produced from all of the districts shown in figure 2.

Regardless of the mining technique used to get uranium out of the ground, a processing plant is necessary to get uranium out of the ore. A series of chemical treatments produces the first concentrated product, yellowcake (fig. 17), which is then marketed to utilities and moved further along in the nuclear fuel cycle.

Figure 17. Yellowcake (U_3O_8), the end product of uranium mining. (Photo courtesy of Strathmore Minerals, Riverton, Wyoming, 2010).

Conversion

After mining and processing uranium into yellowcake (U_3O_8), the next step in the uranium fuel cycle is conversion. Conversion facilities produce uranium hexafluoride (UF_6) from yellowcake by chemical processes. After heating to remove impurities, yellowcake is reduced with hydrogen in the presence of heat to form uranium dioxide (UO_2). Following that reduction, UO_2 is reacted with gaseous hydrogen fluoride (also in the presence of heat) to form uranium tetrafluoride (UF_4), followed by further processing into uranium hexafluoride (UF_6). The UF_6 gas is then pressurized and cooled, forming a liquid that is stored in special cylindrical containers. After several days of further cooling, the UF_6 becomes a solid white crystalline mass that is shipped to an enrichment facility (see enrichment section). There is currently only one conversion facility operating in the United States. It is located in southern Illinois in the town of Metropolis and is owned and operated by Honeywell International, with conversion and related services exclusively marketed by ConverDyn Corporation (fig. 18).

Enrichment

In order to sustain a controlled chain reaction sufficient to fuel a nuclear power plant, the concentration of fissionable uranium (^{235}U) must be between 3 percent and 5 percent, depending on the reactor design. Since naturally occurring uranium contains only 0.72 percent ^{235}U (and >99% ^{238}U), the uranium in uranium hexafluoride (UF_6) must be enriched with respect to ^{235}U. There are two main types of uranium enrichment processes in use today, gaseous diffusion and gas centrifugation. Both processes take advantage of the very slight difference in mass between ^{235}U and ^{238}U. Since a ^{235}U atom has three fewer neutrons in its nucleus, it is about 1 percent lighter than ^{238}U.

The gaseous diffusion enrichment method was developed in the 1940s during the Manhattan Project and is still in use today. It involves moving pressurized UF_6 gas through diffusion chambers, each containing a special membrane (also called a diaphragm). UF_6 molecules containing the lighter ^{235}U isotopes move slightly faster and are more likely to pass through the membrane than UF_6 molecules containing the heavier ^{238}U isotopes. As this molecular separation takes place through the series of diffusion chambers, the UF_6 gas is eventually enriched to requisite fuel grade. There are two gaseous diffusion plants in the United States (fig. 18) but only one is currently operational in Paducah, Kentucky. The other plant is in Piketon, Ohio, and ceased operations in March 2001. Both plants are leased by the U.S. Enrichment Corporation (USEC).

Enrichment by gas centrifugation also separates ^{235}U from ^{238}U utilizing the difference in mass between the two isotopes. Whereas gaseous diffusion uses pressure, centrifugation uses motion and angular momentum to separate the heavier molecules from the lighter ones. UF_6 gas is passed through a succession of cylindrical centrifuges. The high rotation speed of the centrifuge's rotor (up to 70,000 rpm) gradually concentrates the UF_6 molecules containing the lighter ^{235}U toward the center of the centrifuge.

The gas from the center of the centrifuge is collected and processed through subsequent centrifuges until a fuel-grade concentration of ^{235}U is achieved. According to the NRC, there are currently two gas centrifuge plants in operating in the United States. Louisiana Energy Services operates one plant in Eunice, New Mexico, and USEC operates a plant in Piketon, Ohio. Construction of two other gas centrifuge plants, one near Idaho Falls, Idaho, and another in Piketon, Ohio, has started but is currently on hold at both locations.

Laser enrichment is a process that has been researched for a number of years. It is not currently in use on a commercial scale, but rather in the research and development stages. Laser enrichment is promising in that it offers significant economic advantages over diffusion and centrifugation, requiring less energy input and lower capital costs. The process uses finely tuned laser beams to drive off fluorine atoms from UF_6 molecules, creating a positively charged UF_5 molecule. UF_6 molecules containing ^{235}U (rather than ^{238}U) are more likely to give up a fluorine atom in this process. The positively charged UF_5^+ ions can then be collected on a negatively charged collecting plate. The process is continued until a fuel-grade concentration of ^{235}U is attained.

Fuel Fabrication

Once concentrated to the appropriate level of ^{235}U, the UF_6 is converted back into the reduced form of uranium oxide (UO_2) or to a mixed oxide (MOX), depending on the type of reactor in which it will be used. The fuel is usually formed into ceramic pellets and encased in special metal alloy tubes, bundles of which comprise a fuel assembly. The assembly is placed into the reactor to heat water.

Another technology, known as the pebble bed modular reactor (PBMR), is being developed and shows great promise for future reactor designs. PBMRs use a different type of fuel configuration than most reactors in operation today. Instead of fuel rods, spheres about the size of billiard balls are the source of heat and are continuously fed through the reactor. According to

the NRC, a demonstration plant of this type is planned in South Africa. Figure 18 shows the locations of fuel fabrication plants in the United States.

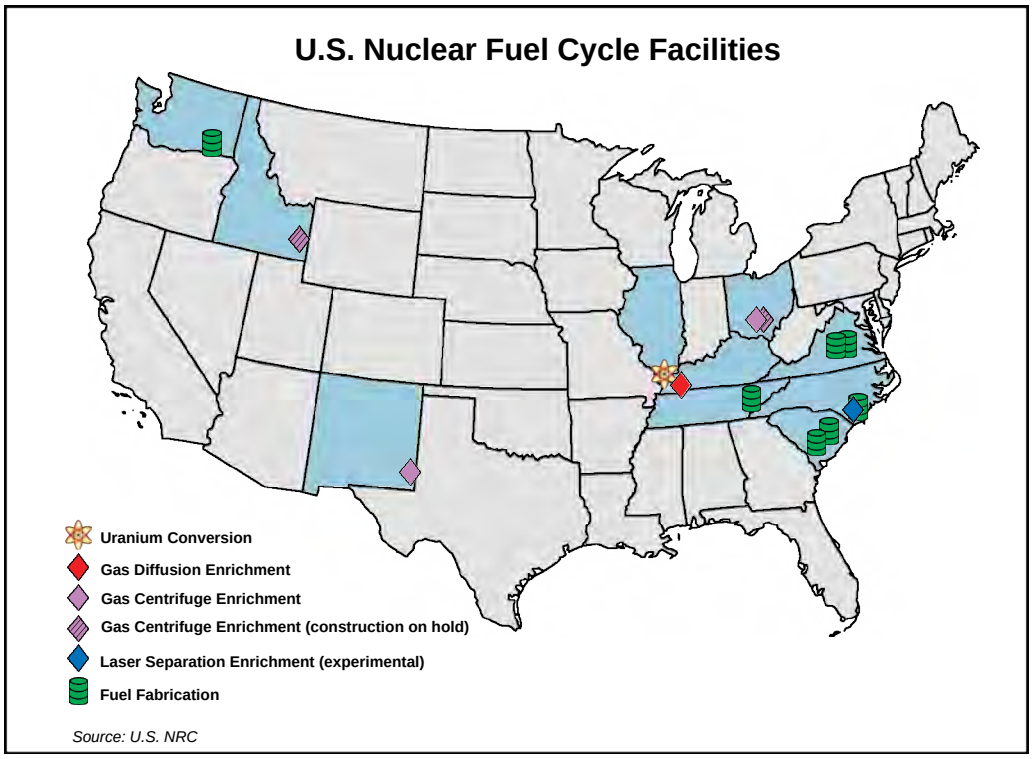

Figure 18. Locations and types of nuclear fuel cycle facilities in the United States (Graphic by James R. Rodgers, 2015; modified after U.S. Nuclear Regulatory Commission).

Power Generation

According to the World Nuclear Association, there were 99 operational nuclear power generating stations in the United States in 2015 (fig. 19) and another five reactors under construction. Of these, 65 are pressurized water reactors (PWRs) and 34 are Boiling Water Reactors (BWRs). The technology for these reactor designs was developed in the 1950s for the first nuclear submarines and other ships for the U.S. Navy. These designs were later adapted for electrical power generation. In both reactor types, water surrounds the core and is heated by a controlled chain reaction. In a BWR, water from the reactor vessel is heated and converted to steam, which turns turbine generators (fig. 20). In a PWR, heat is transferred from water surrounding the reactor core to a secondary water system to generate steam (fig. 21). The superheated steam is piped to turbines that turn electrical generators. The steam is then cooled, condensed back into water, and cycled back through the system.

Technologically advanced reactor designs such as Generation III, Generation III+, and Generation IV, offer promise for future nuclear power plants with improved efficiency, safety, longer operating life, and easier operation with fewer possibilities for human error. As long as such advancements continue to be made, the expense and time required to build new reactors may continue to decrease.

Some spent fuel can be reprocessed to remove fissile material and reused in nuclear power generation, although this is not done in the United States. Several countries in Europe and Asia reprocess used fuel, as it reduces the amount of material that requires long-term disposal. Reprocessing contributes up to 25 percent more energy from the original uranium. The material that is not reprocessed, or that remains after reprocessing, is then ready for storage and disposal.

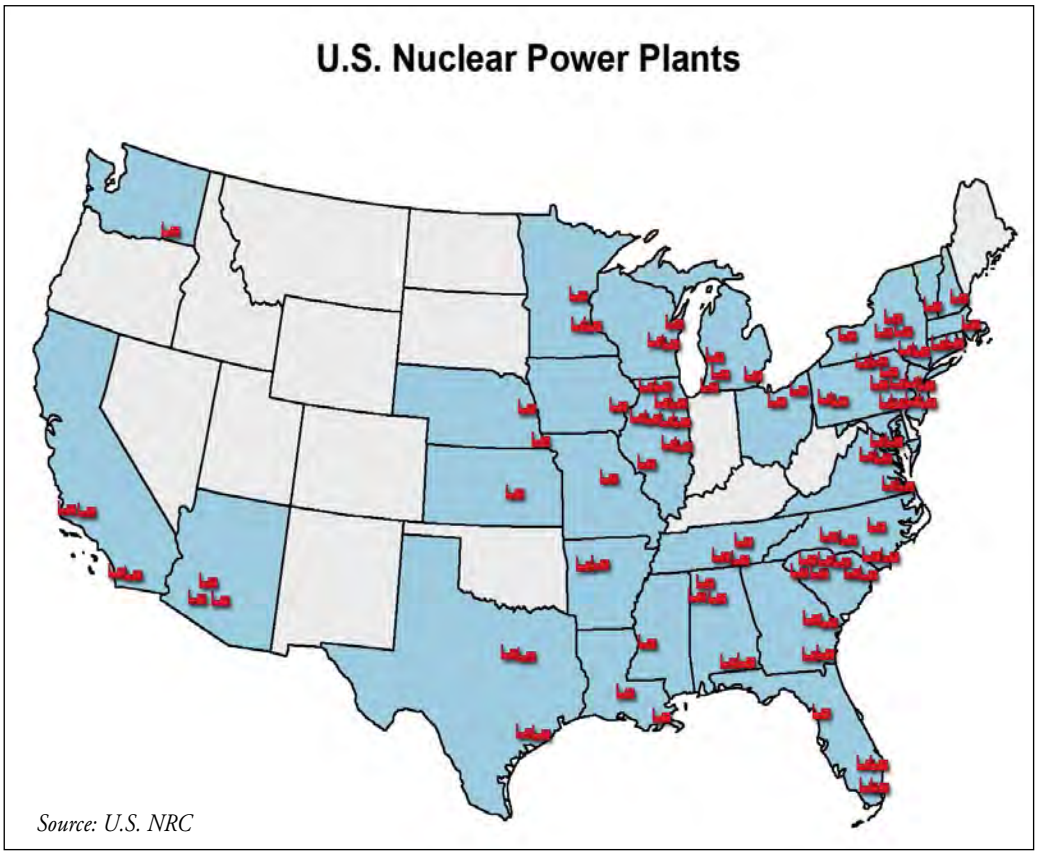

Figure 19. Locations of nuclear power plants in the United States (Graphic by James R. Rodgers, 2015; modified after U.S. Nuclear Regulatory Commission).

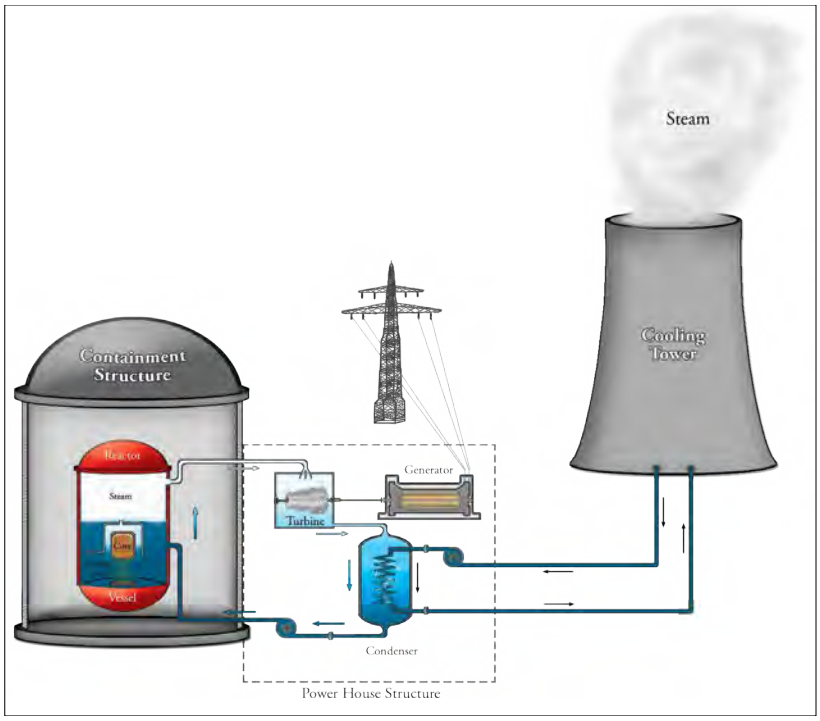

Figure 20. Simplified diagram of power generation from a boiling water reactor, or BWR (Graphic by James R. Rodgers, 2015; modified after U.S. Nuclear Regulatory Commission).

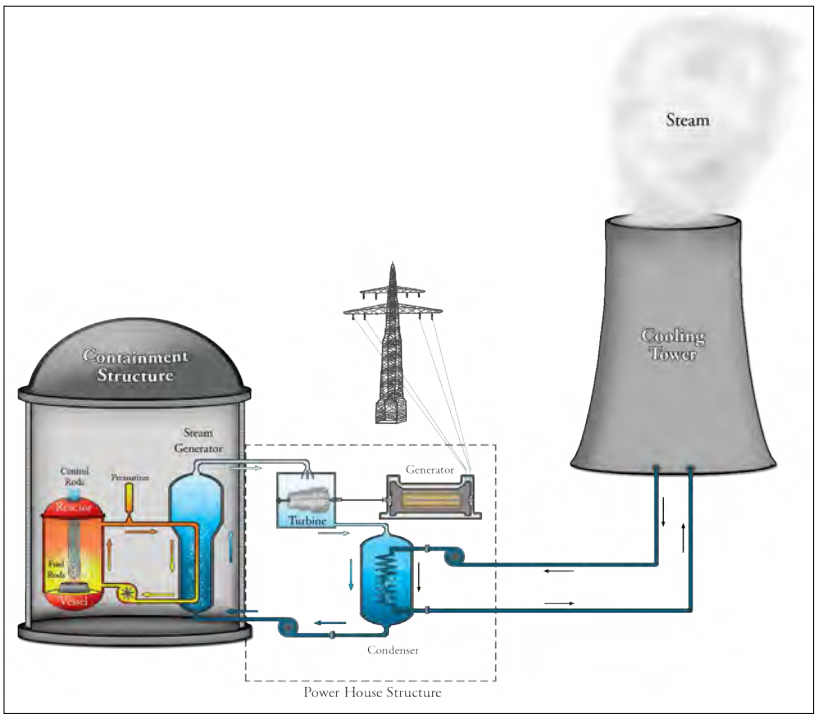

Figure 21. Simplified diagram of power generation from a pressurized water reactor, or PWR (Graphic by James R. Rodgers, 2015; modified after U.S. Nuclear Regulatory Commission).

The World Nuclear Association estimates that there is enough energy in currently stored used fuel to run the entire fleet of American reactors for 30 years. Radioactive wastes are divided into three classes: low, intermediate, and high-level waste on the basis of their level of radioactivity.

Nuclear Waste Materials

Mining Waste

In-situ recovery: Small amounts of solid waste and liquid effluents (acids and other chemicals used in the extraction process) are produced and usually re-injected into disposal wells drilled into deep geologic formations, which isolates the waste from the biosphere.

Conventional mines: There is considerably more waste produced at conventional mines and mills. After the ore is transported to the mill, it is leached to remove the uranium. The leftover material (tailings) consists primarily of sands and sludge and is usually placed in a special impoundment at the mill site. The hazardous part of tailings is its content of radioactive particles (radionuclides) such as radium, thorium, and radon gas. Some liquid forms of waste from ore processing are injected into deep disposal wells.

Other Nuclear Waste

Waste from conversion, enrichment, and nuclear reactors is handled differently: the handling of such materials is strictly regulated by the NRC. Additional information can be found on the NRC or World Nuclear Association websites.

Low-level waste (LLW) includes materials such as paper, rags, tools, clothing, that contain small amounts of short-lived radioactive material. All stages of the nuclear fuel cycle produce LLW. This type of waste accounts for about 90 percent of the total volume of all radioactive waste and only about 1 percent of the radioactivity in all waste. Most of this type of waste can be compacted or incinerated prior to being discarded safely in specially certified shallow landfills.

Intermediate-level waste (ILW) contains higher levels of radioactivity and requires shielding when handled. The half-life of most of this material is relatively short, so it can be discarded along with the LLW. Some ILW, however, remains radioactive for longer periods of time and requires special treatment and conditioning prior to disposal. Typically, this material is incorporated into cement or bitumen (fusible solid and semi-solid hydrocarbons) and placed into shielded containers. It is then specially packaged for transport to storage repositories, ultimately underground although some of this material is stored at interim facilities. By volume, ILW makes up about 7 percent of all radioactive waste and about 4 percent of radioactivity. Some ILW may ultimately end up in deep disposal sites.

High-level waste (HLW) is essentially spent reactor fuel and its decay products. It is both highly radioactive and remains very hot, and thus requires cooling and shielding. HLW accounts for the remaining 95 percent of radioactivity and 3 percent of the volume of all radioactive waste. Fission products are removed from the spent fuel and converted to a solid, making it easier and safer to transport and store. In this process, vitrification, the hazardous material is mixed with a type of glass that incorporates the radioactive material into its structure. HLW requires a significant amount of time to cool and thus is stored on-site at the reactor for about 50 years. After about 40 years, the material has approximately 0.01 percent (one one-thousandth) of its original level of radioactivity and heat.

The final step is the actual permanent disposal of the hazardous material. There are currently no disposal facilities for HLW in the world, although some countries are working toward that objective. Intensive research in several countries has shown that select sites in granite (Switzerland, Sweden, Canada, Japan), salt (Germany, United States), and claystone rock formations (Switzerland, France) to be viable settings for deep disposal of HLW. The first such repositories are expected to be operational within 10 years (International Atomic Energy Agency, 2015). The total amount of spent nuclear fuel from U.S. reactors is about 62,500 metric tons. In terms of volume, that material would cover a football field to a depth of about 21 feet (Nuclear Energy Institute, 2010).

LOOKING FORWARD

The future of uranium remains strong, as there is a growing international and existing domestic demand. This stems from the growing demand for electric power from burgeoning economies as well as from smaller nations trying to modernize and elevate their standard of living. In pursuit of meeting these electricity demands, nuclear energy has received growing favorable opinion in light of concerns over CO_2 emissions from fossil fuel-based electricity generation. Nuclear power plants do not emit CO_2; the vapors seen coming from their large towers is steam from cooling the process water. Advanced reactor and fuel technology have made nuclear power plants far more efficient than plants that burn fossil fuels. For example, one small nuclear fuel pellet (about the size of the tip of your little finger) can provide as much energy as 149 gallons of oil, 1,780 pounds of coal, or 17,000 cubic feet of natural gas. Five of those pellets can provide electricity to the average household for one year. Additionally, a wind farm that could produce 1,000 megawatts (1 gigawatt) of electricity would need more than 235 square miles of land. A one-gigawatt nuclear plant occupies a little over 2 square miles of land and can meet the electrical needs of a city the size of Boston or Seattle for one year (Nuclear Energy Institute, 2014).

Rising prices of harder-to-find petroleum energy sources have also led countries to choose nuclear over fossil fuels. Given the abundant supply of uranium that exists around the world and its advantages over fossil fuels, use of uranium could increase and keep the industry strong for the foreseeable future.

The Wyoming State Geological Survey sells a number of publications on the geology of uranium and its occurrences in the state. We also keep an extensive set of historic files and documents covering a wide variety of uranium-related topics. For information visit our website, (www.wsgs.wyo.gov) or contact our sales desk at (307) 766-2286.

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The following are resources for information on uranium and the nuclear power industry:

U.S. Department of Energy, Energy Information Administration, at www.eia.doe.gov/

International Atomic Energy Agency, at www.iaea.org

National Atomic Museum, at www.atomicmuseum.com

National Mining Association, at www.nma.org

Nuclear Energy Institute, at www.nei.org

Rocky Mountain Mineral Law Foundation, at www.rmmlf.org

Stock-Interview.com, at www.stockinterview.com/index.html

U.S. Bureau of Land Management, at www.blm.gov/wo/st/en.html

U.S. Environmental Protection Agency, at www.epa.gov

U.S. Geological Survey, at www.usgs.gov

U.S. Nuclear Regulatory Commission, at www.nrc.gov

World Nuclear Association, at www.world-nuclear.org

Wyoming Department of Employment, Office of the State Inspector of Mines, at http://wydoe.state.wy.us/doe.asp?ID=6

Wyoming Department of Environmental Quality, at http://deq.state.wy.us/

Wyoming Mining Association, at www.wma-minelife.com/

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