Uranium to Electricity: The Chemistry of the Nuclear Fuel Cycle

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# Uranium to Electricity: The Chemistry of the Nuclear Fuel Cycle

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Expanded use of nuclear power is currently being considered as a no-carbon-emission energy source to reduce the harmful effects of climate change *(1)*. Currently nuclear power supplies 19.4% of U.S. electricity *(2)* and 14% globally *(3)*. Many nations, including the United States, are considering the construction of new nuclear facilities to both expand and maintain generating capacity. Some environmentalists who previously opposed the nuclear option have now embraced it, but opposition remains. Any substantive discussion of the pros and cons of nuclear power as a source of electricity requires some knowledge of the nuclear fuel cycle (Figure 1).

While many general chemistry texts have material on nuclear energy, this topic often receives a low priority relative to others owing to constraints of time and its usual position near the end of those texts. Given the current interest and importance of nuclear power, it is appropriate to have an up-to-date treatment of this subject centered on the nuclear fuel cycle. The goal of this article is to provide an introduction to the current fuel cycle with suggestions for case studies and problems as well as material with references for teachers and students wishing to pursue the subject in greater depth.

Figure 1. The nuclear fuel cycle (with permission from Informationskreis KernEnergie, Berlin) *(4)*.
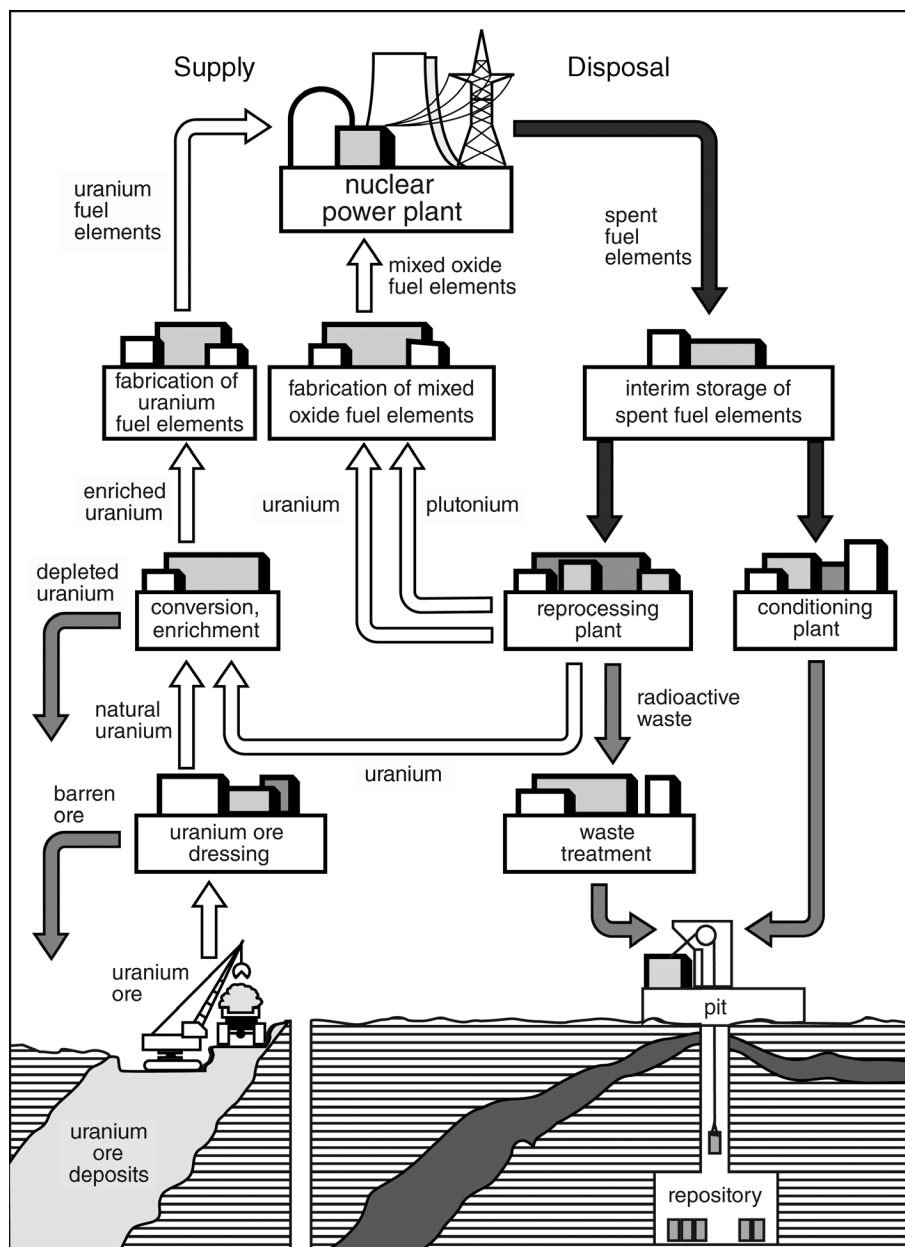
The fuel cycle consists of a series of industrial processes that produce fuel for the production of electricity in nuclear reactors, use the fuel to generate electricity, and subsequently manage the spent reactor fuel. Because the majority of the world's commercial reactors and all commercial U.S. reactors are light-water reactors, this article will address light-water nuclear reactors, which require enriched uranium fuel. In contrast, heavy-water reactors do not require enriched uranium; instead, natural uranium can be used as fuel. Electricity is created by using the heat from controlled fission in the reactor to produce steam, which drives a turbine connected to a generator. Spent fuel is removed from the reactor and either reprocessed to make new fuel or stored for future disposal. Each process in the cycle has safety, environmental, and economic issues. Proliferation of nuclear weapons is also an important consideration, as weapons-grade fissile materials can be prepared and diverted from either the enrichment or spent-fuel processes.

The fuel cycle is divided into three components: the front end, which encompasses all activities prior to placement of the fuel into the nuclear reactor; the service period, which includes the conversion of fuel to energy in the reactor; and the back end, which incorporates all processes involving spent fuel. The fate of the spent fuel determines whether the fuel cycle is *closed* or *open.* In the closed cycle, the spent fuel is reprocessed, whereas in the open cycle, it is sent to storage. To date, the United States has opted for the open cycle, while France, the United Kingdom, Russia, China, and Japan reprocess spent fuel.

While the physics and engineering of the service period are central to reactor processes, chemistry dominates the other processes of the nuclear fuel cycle. Chemical reactions transform uranium ore into reactor fuel and then convert the spent fuel from the reactor into disposable waste and recyclable fuel. This article provides the chemical background essential to understanding the important role of the fuel cycle in any expanded use of nuclear power. It also provides perspectives on the economics of nuclear fuel and a comparison of the relative costs associated with producing electricity from other sources of energy.

The Front End of the Fuel Cycle

Uranium occurs in rocks, soil, and bodies of water. While it is 500 times more prevalent than gold and about as abundant as tin, it is usually found dispersed in trace quantities. Most of the radioactivity associated with uranium comes from its daughters[1] such as radon. Pitchblende is the common mineral form of uranium, composed largely of UO_2 with smaller concentrations of UO_3. If its concentration is large enough to be extracted economically, the material is known as an ore. The cost of recovering uranium is determined by the concentration of ore: the lower the concentration the higher the cost. Deposits containing 0.1–20% pitchblende are economically viable. Ores in Canada, Australia, and Kazakhstan accounted for more than half the world's uranium production in 2007 *(5).*

### Uranium Ore Dressing: Mining and Initial Concentration

Traditionally, uranium ore is extracted by either open pit or underground mining, depending on the location of the ore. Recovery of uranium from the ore is often difficult, and the procedures vary with the geological environment. The ore is first milled (crushed and ground) to liberate mineral particles and then exposed to a leaching solution whose composition is determined by the geochemistry of the deposit. Ores containing high concentrations of silicates are leached with sulfuric acid to produce the water soluble UO_2^{2+} ion. Those with high concentrations of carbonates are converted by a similar process using $(NH_4)_2CO_3$ to form the water soluble $UO_2(CO_3)_3^{4-}$ ion.

Two methods are used to extract the uranium from the leach solutions: solvent extraction and ion exchange. Solvent extraction, the more common method, employs tertiary amines dissolved in kerosene in a continuous extraction process. First, the amines, R_3N, react with sulfuric acid:

$$2\,R_3N(org) + H_2SO_4(aq) \rightarrow (R_3NH)_2SO_4(org) \tag{1}$$
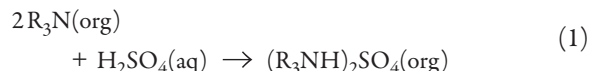
The resulting amine sulfate extracts the uranyl ions into the organic phase, while the impurities remain in the aqueous phase. In the case of UO_2^{2+}, the following reaction occurs:

$$2\,(R_3NH)_2SO_4(org) + UO_2^{2+} \rightarrow (R_3NH)_4UO_2(SO_4)_2^{2+}(org) \tag{2}$$
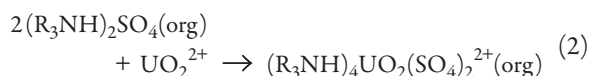
The solvents are removed by evaporation, and ammonium diuranate, $(NH_4)_2U_2O_7$, is precipitated by adding ammonia to neutralize the solution. Finally, the diuranate is heated to yield a concentrated solid, U_3O_8, known as yellowcake.

Ion exchange extraction involves passing the uranium in solution through a resin bed, which exchanges the uranium–carbonate ion with a negative ion such as chloride. The uranium complex concentrated on the resin is then removed with a salt solution and precipitated as diuranate, which when heated yields yellowcake.

Recently, another technique for extraction and concentration of uranium ore has gained popularity, in situ leaching *(6)*. This technique involves circulating oxygenated groundwater through a porous ore body to dissolve the uranium and bring it to the surface. The composition of the leaching solution is determined by the geology and groundwater of the ore deposit. If the deposit contains significant quantities of calcium, an alkaline solution is employed. Otherwise, a slightly acidic leach is used. The solution also contains a complexing agent to hold the extracted uranium in solution. At the surface, the uranium is recovered using ion exchange columns and then oxidized to U_3O_8.

The global 2007 figures for extraction methods are underground mining and open pit mining combined, 62%, in situ leaching, 29% and by product,[2] 10% *(7)*. The solutions and materials (tailings) remaining after uranium extraction contain both chemically toxic and radioactive substances that require secure containment.

Uranium Ore Dressing: Refining Yellowcake to UO₃

In the second component of ore dressing, yellowcake, containing 70–90% by mass U_3O_8, is dissolved in nitric acid at a refinery. The resulting solution of uranyl nitrate is fed into a continuous solvent extraction process. The uranium is extracted into an organic phase (kerosene) with tri-*n*-butyl phosphate, and the impurities remain in the aqueous phase. After this purification, the uranium is washed out of the kerosene with dilute nitric acid and concentrated by evaporation to pure $UO_2(NO_3)_2 \cdot 6H_2O$, which upon heating yields pure UO_3. The processes involved in dressing the ore generate large volumes of acidic and organic waste.

Conversion to Uranium Hexafluoride, UF$_6$

It is necessary to increase the isotopic concentration of the ^{235}U isotope from its natural composition in uranium (0.7% ^{235}U, 99.3% ^{238}U) for use as fuel in light-water reactors. Typically, reactor fuel contains 3.0 to 5.0% ^{235}U and is known as low-enriched uranium (LEU).[3] Because the uranium isotopes have identical chemical properties, the processes employed for enrichment must use physical techniques that take advantage of the slight differences in their masses. The two enrichment methods currently used, centrifugation and diffusion, require the uranium to be in a gaseous form, uranium hexafluoride, UF$_6$(g). Although the enrichment involves physical processes, chemistry plays an important role in synthesizing UF$_6$ and returning the UF$_6$ enriched in ^{235}U to the solid, UO$_2$.

Preparation of UF$_6$ from UO$_3$ involves a multistep chemical process. The concentrated UO$_3$ extracted from the yellowcake is reduced with hydrogen in a kiln:

$$UO_3(s) + H_2(g) \rightarrow UO_2(s) + H_2O(g) \tag{3}$$
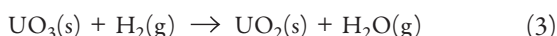
The uranium dioxide is then reacted with hydrogen fluoride to form uranium tetrafluoride:

$$UO_2(s) + 4HF(g) \rightarrow UF_4(s) + 2H_2O(g) \tag{4}$$
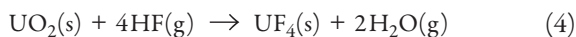
Finally, the uranium tetrafluoride is fed into a fluidized bed reactor and reacted with gaseous fluorine to obtain the uranium hexafluoride:

$$UF_4(s) + F_2(g) \rightarrow UF_6(g) \tag{5}$$
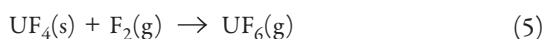
In an alternative process, yellowcake is fluoridated and the resulting UF$_6$ is separated by fractional distillation. The uranium hexafluoride from either process is now suitable feedstock for enrichment by either gaseous diffusion or centrifugation.

Uranium Enrichment with Gaseous Diffusion

The United States has relied on the gaseous diffusion process to enrich uranium for both nuclear weapons and fuel for its fleet of light-water reactors. The U.S. government built a large gaseous diffusion plant at Oak Ridge, Tennessee during World War II and added other plants in the post-war period. The gaseous diffusion process is based on molecular effusion, a phenomenon that occurs whenever a gas is separated from a vacuum by a porous barrier that contains microscopic holes. A gas flows from the high-pressure side to the low-pressure side; it passes through the holes because there are more "collisions" with holes on the high-pressure side than on the low-pressure side. Thomas Graham, a Scottish chemist, observed that the rate of effusion of a gas through a porous barrier was inversely proportional to the square root of its molecular mass. Thus, lighter molecules pass through the barrier faster than heavier ones (Figure 2).

The ratio of times it takes the equal quantities of two gases, A and B, to effuse through a barrier is

$$\frac{\text{rate}_{\text{eff}}(A)}{\text{rate}_{\text{eff}}(B)} = \frac{\sqrt{M_B}}{\sqrt{M_A}} \tag{6}$$

Applying this equation to uranium hexafluoride where there is only one common isotope of fluorine, ^{19}F, the ratio of rates for the uranium hexafluoride from the two isotopes is

$$\frac{\text{rate}_{\text{eff}}\left(^{235}UF_6\right)}{\text{rate}_{\text{eff}}\left(^{238}UF_6\right)} = \frac{\sqrt{352}}{\sqrt{349}} = 1.004 \tag{7}$$
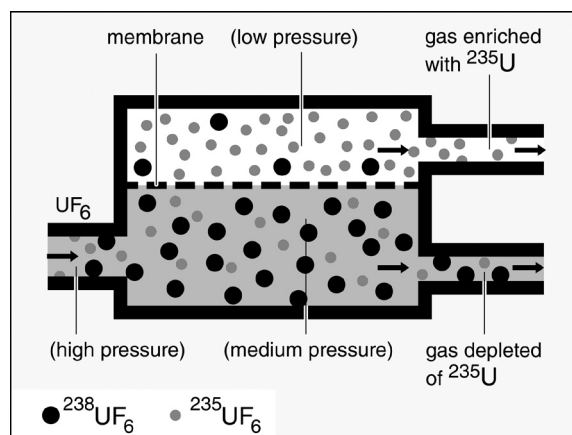

Figure 2. Gaseous diffusion (with permission from Informationskreis KernEnergie, Berlin) *(8)*.
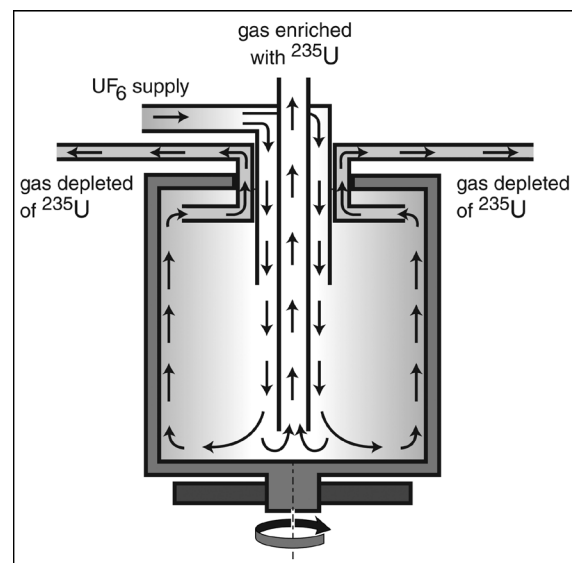

Figure 3. Centrifugation (with permission from Informationskreis KernEnergie, Berlin) *(10)*.

This small difference in rates means that many effusion barriers (stages) are necessary for enrichment by passage of the enriched stream through successive stages. The gaseous diffusion plant at Oak Ridge, called K-25, required 4000 stages to assist in the production of the highly enriched uranium (HEU), approximately 90% ^{235}U, for the weapon used on Hiroshima.[4] The size of this plant, one-half mile long and six stories high, indicates the magnitude of this industrial-scale process. The production of a suitable barrier was the key to successful separation. The microscopic holes were approximately one-millionth of an inch in diameter and uniform in size. In addition the material had to be porous enough to maintain gas flow and remain chemically resistant to the corrosive uranium hexafluoride. It was found that nickel and aluminum oxide are best suited for barrier materials.

Diffusion equipment is large and consumes significant quantities of energy. Furthermore, the entire system must be leak free; no air can be allowed in and no uranium hexafluoride allowed out. Most of the world's gaseous diffusion plants have been shut down with the advent of the more efficient, less expensive centrifugation process. Today, China, France, and the United States still have operating diffusion facilities *(9)*.

Uranium Enrichment with Centrifugation

The United States explored centrifugation of UF_6 as a means of enriching ^{235}U in the Manhattan Project during World War II, but found that the technology required was not robust enough for large-scale production. Since that time, new technology has allowed industrial-scale production of both LEU and HEU. Today, lower energy consumption (5% of that required for gaseous diffusion), short equilibrium (separation) time, and modular design make centrifugation the preferred method of uranium enrichment.

In centrifugation, gaseous UF_6 is fed into a centrifuge unit consisting of a cylindrical rotor spinning at a high speed inside an evacuated casing (Figure 3). The centrifugal force in the rapidly spinning rotor causes a partial separation of the UF_6, with the heavier ^{238}U molecules becoming slightly more concentrated around the outside walls, while the concentration of the lighter ^{235}U molecules increases around the middle of the tube. The separation is facilitated by a relatively slow axial countercurrent flow in the rotor that moves the molecules enriched in ^{235}U to one end and the depleted molecules containing increased concentration of ^{238}U to the other. The separation can be enhanced further by heating the lower end of the casing, creating convection currents that move the ^{238}U down and the ^{235}U up *(11)*. Although it is possible to obtain significantly more enrichment from a single centrifuge than from a single gaseous diffusion stage, this process must be repeated in a series of connected centrifuges known as a cascade to obtain the desired concentration of enriched uranium. The slightly enriched stream is fed to the next higher stage, while the depleted stream is recycled back to the preceding stage. Cascades containing several hundred or even thousands of units are the basic component of a centrifuge-enrichment facility. Cascades of centrifuges operating in parallel to produce LEU for reactors can be easily reconfigured to form a single unit to produce HEU, or the LEU can be returned to the parallel cascade to increase the concentration of ^{235}U. Thus, any centrifuge-enrichment facility has the potential to produce HEU for weapons, a major concern with respect to nuclear weapon proliferation.

Equipment for centrifuge enrichment requires complex metallurgy and precise engineering. Materials used for tubes must be able to withstand mechanical stress and contact with corrosive UF_6 gas. Current materials include high-strength alloys of steel or aluminum or fiber-resin composites. These materials must be precisely machined to maintain balance at the high speeds necessary for separation of the isotopes. The ability of a single centrifuge tube to separate uranium isotopes depends on the outside speed of the rotor raised to the 4th power. Thus, doubling the speed increases the efficiency of separation by a factor of 16. The degree of enrichment also depends on the length of the tube, with the latest 10–12 meter tubes obtaining an enrichment factor 100 times greater than a single gaseous diffusion stage.

The production of 1.0 kg LEU requires approximately 11 kg uranium for the enrichment process while 1.0 kg HEU requires about 176 kg of uranium. The production of this quantity of HEU requires 33 times the energy required for the corresponding quantity of LEU. Gaseous diffusion consumes about 40 times as much energy to produce equivalent quantities of enriched uranium as does centrifugation *(12)*.

Fuel Fabrication

The enriched UF_6 gas is transported in tanks from the enrichment plant to the fabrication facility, where it is converted into uranium dioxide powder. The powder is then transformed into cylindrical, ceramic pellets that are ground to a uniform size. These pellets are sealed into tubes made of zircaloy, an alloy of zirconium containing small quantities of tin and other metals. In addition to its corrosion-resistant property, zirconium also has a low cross-section for thermal neutron absorption, making it an ideal cladding material for the tubes. These tubes, known as fuel rods, are bundled together into fuel assemblies for insertion into the reactor core. Depending upon the reactor type, a fuel assembly may contain up to 264 fuel rods in a 5–9 inch square that is about 12 feet in length.

In the closed fuel cycle, plutonium oxide reprocessed from spent reactor fuel or dismantled nuclear weapons *(13)* is combined with depleted uranium oxide to form mixed oxide, MOX,[5] with a composition of 3–7% PuO_2 and the rest depleted UO_2.[6] The MOX is then mixed with ordinary LEU in a ratio of ⅓ MOX and ⅔ LEU for fueling light-water reactors (see the reprocessing section below).

Consumption of Fuel in the Reactor

The reactor fuel burnup is an important parameter in the nuclear fuel cycle. It determines the fuel requirements and the quantity of waste produced. It is usually defined as the energy obtained from a given mass of fuel expressed in units of gigawatt·days[7] per tonne[8] of heavy metal.[9] A reactor producing electricity at a rate of 1000 megawatts (MW_e) and operating at a thermal efficiency[10] of 32% produces a total quantity of thermal energy at the rate of 3125 megawatts (MW_t). Thus, a typical 1000 MW_e reactor generating one gigawatt·year (GW_e·year) of electric power produces a thermal output of 1141 gigawatt thermal·days (GW_t·days).

$$1 \, GW_e \cdot year \; = \; 365 \, GW_e \cdot day$$

$$365 \, \frac{GW_e \cdot day}{GW_e \cdot year} \bigg/ \left(0.32 \, \frac{GW_e \cdot day}{GW_t \cdot day} \right) \; = \; 1141 \, \frac{GW_t \cdot day}{GW_e \cdot year} \quad (8)$$

Therefore, if the average burnup of fuel in a reactor is 40 GW_t·days/tonne, 28.5 tonnes of enriched uranium are required to produce one GW_e·year.

$$1141 \, \frac{GW_t \cdot day}{GW_e \cdot year} \bigg/ \left(40 \, \frac{GW_t \cdot day}{tonne} \right) \; = \; 28.5 \frac{tonne}{GW_e \cdot year} \quad (9)$$

The value of the burnup depends on the enrichment of the fuel, the power density in the reactor, and the length of time the fuel remains in the reactor *(14)*. High values for burnup reduce the quantity of waste.

The Back End of the Fuel Cycle

Current reactors are typically shut down for 1 month out of every 18 months for refueling and maintenance. Approximately one-third of the spent fuel is removed and replaced with fresh fuel assemblies. Typical fresh and spent fuels[11] removed after 3 years in a light-water reactor are compared in Table 1 *(15)*.

Initially, the level of radioactivity of spent fuel is extremely high owing to emission from short-lived fission products and transuranium elements formed by neutron capture. It is also thermally hot due to the thermal energy released with the radioactive emissions. Thus, the first step in processing the weapons-grade fuel is to allow the radiation from the short-lived isotopes to dissipate and to permit the fuel to cool thermally. This occurs in water-filled cooling pools at the reactor site.

The components of spent fuel determine the methods employed for reprocessing and storage. High-level waste is composed of the radioactive products resulting from the fission of ^{235}U in the reactor and some short-lived transuranic elements produced by absorption of neutrons by ^{238}U. Although the high levels of radiation from many of these relatively short-lived isotopes and their daughters decrease rapidly, radiation from the long-lived products will remain for thousands of years. In the initial decay period, most of the radiation is due to ^{137}Cs, ^{90}Sr, and their short-lived daughters. High-level waste comprises only 3% of the volume of radioactive waste worldwide, but it contains 95% of the radioactivity. Transuranic (TRU) waste contains alpha-emitting isotopes of transuranic elements with half-lives greater than twenty years and a combined activity of greater than 100 nanocuries per gram of waste, a relatively low level of radioactivity. However, many of the isotopes in TRU waste have long half-lives and remain radioactive for thousands of years.

Open Cycle Interim Storage

The ultimate form of the spent fuel depends on whether the fuel cycle is open or closed. In the open cycle, because no country has a fully functioning, permanent high-level nuclear waste repository, spent fuel remains untreated in the fuel assemblies, which are placed in pools or stored in dry casks at the reactor site. In the closed cycle, the waste is the material remaining after the fuel rods have been processed to remove the uranium and plutonium. In the open cycle, the spent-fuel assemblies are initially placed in pools under at least 20 feet of water at the reactor site to provide shielding from radiation and to aid in thermal cooling of the waste. Current regulations permit reconfiguration of the rods to increase the quantity of fuel that can be stored in a given pool. Dry-cask storage is also used to increase spent-fuel storage at reactor sites and for removal to other locations. In this method, spent fuel that has been cooled in the spent-fuel pool for at least one year is placed in a cylinder from which water and air are removed and replaced with an inert gas. The cylinder is sealed and then encased in steel and concrete to contain the radiation and to provide security for transportation or storage.

Closed Cycle Reprocessing

Reprocessing employs chemical reactions (redox, precipitation, and extraction) to separate the uranium and plutonium from the other components of spent fuel. The extracted uranium can be converted into UF_6 to produce enriched uranium for additional reactor fuel, while recovered plutonium can be mixed with enriched uranium to produce MOX fuel. The relatively small volume of remaining high-level radioactive waste can be stored in liquid form and then solidified.

Fuel assemblies are placed in storage pools and allowed to cool and decrease in radioactivity for 5 to 25 years after removal from the reactor. They are then put into secure containers and transported to the reprocessing plant. Here the assemblies are removed and the fuel rods chopped to expose the spent fuel for leaching with nitric acid. The cladding is insoluble in the acid and is removed as waste. The leaching occurs in containers designed to resist the corrosive nitric acid and to ensure that no critical mass of fissile ^{235}U or ^{239}Pu can accumulate.
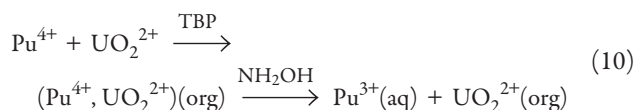
The PUREX Process

The plutonium recovery by extraction (PUREX) process used by all commercial reprocessing plants separates the uranium and plutonium from the fission products and other transuranic elements using redox and nonaqueous chemistry. The recovery of relatively small quantities of plutonium in the presence of large quantities of uranium depends upon the relative ease of the redox reactions involving plutonium. The spent fuel is then taken from the pool for reprocessing, the outer cladding is removed either chemically or mechanically and the fuel dissolved in nitric acid. The pH of the resulting aqueous solution is raised, and then this solution is equilibrated with an immiscible solution of tri-*n*-butyl phosphate (TBP) in refined kerosene. The TBP solution extracts the UO_2^{2+} and Pu^{4+}, leaving the other components of the spent fuel in the aqueous phase. The plutonium is then reduced to the 3+ state by a solution containing hydroxylamine (NH_2OH), extracted into a fresh aqueous phase, and sent to the plutonium purification section. The uranium in the 6+ state remains in the organic phase. It is then extracted into an aqueous solution of nitric acid and removed for further

Table 1. Composition of Fresh and Spent Fuel

Material	Fresh Fuel (%)	Spent Fuel (%)	Product
Transuranic Elements[a]	0.000	0.065	Transuranic waste
^{236}U	0.02	0.56	Uraniumisotope produced
Pu Isotopes	0.000	0.89	Transuranic waste
Fission Products	0.000	5.11	High-Level waste
^{235}U	4.0	0.81	Unreacted ^{235}U[b]
^{238}U	95.95	92.3	Unconverted ^{238}U[c]

[a] Excluding plutonium. [b] ^{235}U that did not undergo fission prior to removal of fuel rods. [c] ^{238}U that did not convert to Pu via neutron absorption.

purification.

$$Pu^{4+} + UO_2^{2+} \xrightarrow{\text{TBP}} \quad\quad\quad\quad (10)$$
$$(Pu^{4+}, UO_2^{2+})(org) \xrightarrow{\text{NH}_2\text{OH}} Pu^{3+}(aq) + UO_2^{2+}(org)$$

Final purification removes lingering fission products, other impurities, as well as trace quantities of plutonium from the purified uranium and trace quantities of uranium from the plutonium. All plutonium is treated with ascorbic acid to ensure that it is in the 3+ state and then precipitated as PuF_3. Uranium is converted to the oxide for storage. The solid metal form of both elements can be produced by reacting their fluorides with calcium or magnesium at elevated temperature in a sealed container. The availability of plutonium from reprocessing is a major concern in the proliferation of nuclear weapons (16).

Reprocessing must occur in isolated environments with robots or humans using remote devices to manipulate the highly radioactive materials and toxic chemicals. Nitric acid and TBP/kerosene solvents are recycled, gaseous effluents filtered and scrubbed before discharge, and liquid waste concentrated or solidified for storage. All materials are monitored to protect workers and to prevent the accidental discharge of harmful agents into the environment.

The UREX Process

The uranium extraction (UREX) process, currently under development, uses acetohydroxamic acid to suppress the extraction of plutonium and promote the separation of uranium along with technetium. The highly radioactive technetium is then separated from the uranium, which can be disposed of as low-level waste or stored in an unshielded facility for re-enrichment. This process produces five output streams: uranium at a purity of 99.999%; plutonium with other transuranic elements, which is suited for MOX reactor fuel but not for weapons; long-lived fission products, mostly ^{129}I and ^{99}Tc, which can be stored or destroyed in a reactor; and the short-lived fission products, predominately ^{137}Cs and ^{90}Sr, which can be kept on site in pools for rapid radioactive decay. In addition to producing fuel to burn in reactors and reducing the threat of proliferation, this process also reduces the quantity of waste sent to storage. If the UREX process proves feasible, it could replace the PUREX process (17).

Fuel from Reprocessing

The uranium oxide from reprocessing is reintroduced into the fuel cycle for conversion into UF_6. The conversion of plutonium into reactor fuel is more complicated. The plutonium is converted into PuO_2 and mixed with the UO_2 extracted from the spent fuel to form a mixed oxide (MOX) fuel. In the dry process, the oxides are mixed to yield a composition of 3–7% PuO_2 and the remainder UO_2. An alternative wet process uses a base such as ammonia to convert a mixture of uranyl nitrate and plutonium nitrate into ammonium diuranate and plutonium hydroxide, which, when heated, becomes a mixture of uranium dioxide and plutonium dioxide. The difference in nuclear properties of ^{239}Pu and ^{235}U dictates a ratio of ⅓ MOX, ⅔ LEU as fuel for most light-water reactors. MOX fuel is also used to dispose of plutonium from dismantled nuclear weapons.

Immobilizing High-Level Waste

High-level waste can be transformed into solid, glassy materials for safer storage. These materials can be mixed with wastes of different compositions and cast into usable forms that conduct heat well and are chemically stable in storage environments. The liquid high-level waste from reprocessing is converted into solids by evaporation, mixed with a sodium borosilicate composite, and heated to produce a molten mixture containing approximately 25% waste. The molten mixture is poured into a stainless-steel container and welded shut. These containers can then be moved to temporary or permanent storage sites.

The Economics of the Nuclear Fuel Cycle

While chemistry plays a critical role in the nuclear fuel cycle, no discussion would be complete without presenting the economics of each component of the cycle, the costs of producing and disposing of fuel relative to the other costs associated with nuclear power, and a comparison of nuclear power with other sources of electricity. In the final analysis, these economics will be critical factors in determining the role of nuclear power in the global energy portfolio. The data presented here relate to estimated U.S. costs. Current costs associated with the front end and the back end of the nuclear fuel cycle are provided in Tables 2 and 3 (18).

These data indicate the cost associated with the production and disposition of fuel to be $2000/(kg ^{235}U) for LEU fuel and $5.0/(megawatt·hour) of electricity. These costs are compared with other costs associated with nuclear power and the other sources of electricity in Table 4. It indicates that the cost of producing fuel and handling spent fuel is only 7% of the total cost of producing nuclear electricity. The data also show that a $100/ton carbon emission tax on coal and natural gas could make nuclear energy competitive with the alternatives.

Table 2. Front-End Costs

Process	Cost/[$/(kg ^{235}U)]	Cost/[$/(MW h)]
Mining and Milling	500	1.3
Conversion	50	0.1
Enrichment	600	1.5
Fabrication	250	0.6
Total	1400	3.5

NOTE: Assumes fuel enriched to 4.4% ^{235}U by centrifugation, a burnup of 50 MW$_t$·day/kg, a tails assay (concentration of ^{235}U in depleted material) of 0.3%, and an efficiency of 33%.

Table 3. Back-End Costs

Process[a]	Cost/[$/(kg ^{235}U)]	Cost/[$/(MW h)]
Dry Storage	200	0.5
Geological Disposal[b]	400	1.0
Total	600	1.5

[a]Cost of wet storage on the reactor site is included in the capital, operational, and maintenance costs. [b]These values are estimated.

Table 4. Costs of Nuclear vsersus Alternative Sources of Energy

Area[a]	Nuclear/[$/(MW h)]	Coal/[$/(MW h)]	Gas/[$/(MW h)]	Wind/[$/(MW h)]	Solar/[$/(MW h)]
Capital	50	30	12	60	250
Operation and Maintenance	15	5	3	10	5
Fuel	5	10	25–50	0	0
Total	70	45	40–65	70	255
Carbon Tax at $100/ton[b]	0	25	12	0	0
New Total	70	70	52–77	70	255

[a]Data are from ref *19*. According to the U.S. Energy Information Agency, in 2006, only 2% of U.S. electricity was produced from petroleum *(2)*. [b]Ton (also called the short ton) can be converted to metric tons (or tonne) by multiplying by 0.907184.

The energy requirements and carbon emissions associated with production, transport, and waste associated with nuclear fuel compared with those for coal and natural gas must also be considered in the role of nuclear power in reducing greenhouse emissions. Typical data on the energy requirements for the entire fuel cycle from mining to storage and decommissioning indicate 5.7% of thermal energy output (MW_t) of a reactor if gaseous diffusion is used for enrichment and 1.7% if the fuel is enriched by centrifugation *(20)*. The cost associated of obtaining hydrocarbon fuels are 2 to 10 times greater than those for nuclear fuel *(19)*. Carbon dioxide emission data in g CO_2 per kilowatt·hour indicate nuclear at 10–26 compared with 894–975 for coal and 450–608 for natural gas *(20)*. These data favor production of electricity from uranium over production from hydrocarbon fuels.

However, even with the low cost of nuclear fuel, lower greenhouse emissions, and the possibility of a carbon emissions tax increasing the economic competitiveness of nuclear power, the environmental, safety and nuclear proliferation issues associated with the fuel cycle remain. Furthermore, repositories for the long-term storage of waste must be developed and placed in service. If nuclear power is to be a significant contributor to the global energy portfolio, these issues must be addressed with strict regulations, vigilant monitoring, and strong enforcement of all aspects of the fuel cycle. It will also require educating citizens, policy makers, and financial analysts about the benefits and risks of the nuclear fuel cycle to provide a realistic assessment of this energy source.

Use of This Material with Classes

This material can be used with introductory and inorganic chemistry courses as well as courses in other disciplines that address environmental science and energy issues. This article supports the scientific and technical aspects of the following activities, which may be assigned as individual or group presentations.

- Compare the science, technology, economics, and environmental impacts of producing nuclear fuel with those for coal and natural gas.

- Compare the science, technology, economics, and environmental impacts of the waste from nuclear reactors with those for coal and natural gas power plants.

- Perform the same comparisons for nuclear power with renewable energy sources (wind, solar, hydro, and biomass).

- Compare the advantages and disadvantages of the open and closed nuclear fuel cycles.

- Given the percentage UO_2 in a given ore deposit, calculate how many tons (short ton) of ore would have to be processed to produce 100 pounds of nuclear fuel (uranium metal containing 3.5% ^{235}U).

- How many pounds of spent fuel from a light-water reactor would have to be processed to produce 4.2 pounds of ^{239}Pu required for a nuclear fission weapon?

- Calculate the mass of fuel required for a 1500 megawatt (MW_e) reactor to operate for 6 months if the average burnup of fuel is 40 gigawatts (GW_t)·days/tonne.

- A major component of the fission products in spent nuclear fuel is ^{137}Cs. If it has a half-life of 30 years, what percent of the original ^{137}Cs remains in the fuel after 90 years?

- Americium-241 with a half-life of 432 years is found in transuranic waste. What percent ^{241}Am remains after 864 years?

- What is the relationship between the half-life and the intensity of radiation emitted by radioactive isotopes? How does this apply to the fission products and transuranic elements in spent fuel?

- Explain how nuclear weapons-grade material can be obtained from the nuclear fuel cycle.

Useful Web Sites (all sites accessed Nov 2008)

Beckjord, E. S. The Future of Nuclear Power: An Interdisciplinary MIT Study. *http://web.mit.edu/nuclearpower/*

Cameco Corp. Uranium 101: Fact Sheets. *http://www.cameco.com/uranium_101/fact.php*

Gonyeau, J. The Virtual Nuclear Tourist. *http://www.virtualnucleartourist.com/*

The Keystone Center. Nuclear Power Joint Fact Finding. *http://www.keystone.org/spp/documents/FinalReport_NJFF6_12_2007(1).pdf*

Settle, F.; Blackmer, E.; Strang, J.; Whaley, T. Alsos Digital Library for Nuclear Issues, Nuclear Fuel Cycle. *http://alsos.wlu.edu/qsearch.aspx?browse=science/Nuclear+Fuel+Cycle*

Settle, F. Concept Map for Nuclear Power. *http://alsos.wlu.edu/conceptmaps/nuclearpower/main/index.html*

Acknowledgments

Notes

1. Daughters are radioactive elements produced by radioactive decay of uranium.

2. Uranium is often obtained as a by product from the processes involved in mining other metals.

3. Some research reactors use fuel around the 20% enrichment level, the upper limit for LEU.

4. The ^{235}U for the first atomic bomb was enriched to 7% at the gaseous diffusion plant and then used to feed the electromagnetic units (calutrons) for final enrichment to approximately 90%.

5. The United States and Russia are investigating the use of uranium and plutonium from dismantled nuclear weapons as a source of MOX and are planning to dispose of up to 68 metric tons of weapon-origin plutonium as MOX.

6. Depleted uranium contains less than 0.72% uranium-235. Thus, it is less reactive in the nuclear reaction sense than natural or enriched uranium, which have greater concentrations of the fissile isotope ^{235}U.

7. One gigawatt·day = 8.64×10^{13} joules.

8. One tonne or metric ton = 1000 kilograms.

9. There is a difference between the mass of heavy metal and the mass of fuel. In the case of uranium oxide fuel, uranium comprises 88% of the mass of the fuel.

10. The thermal efficiency is limited by the second law of thermodynamics. Thus 3200 megawatts total (thermal) is required to produce 1000 megawatts electrical.

11. The composition of spent fuel is determined by the ^{235}U concentration of the fresh fuel, the time fuel remains in the reactor, and the neutron flux within the reactor core.

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3. Nuclear's Great Expectations, International Atomic Energy Agency. *http://www.iaea.org/NewsCenter/News/2008/np2008.html* (accessed Nov 2008).

4. European Nuclear Society. Nuclear Fuel Cycle. *http://www.euronuclear.org/info/encyclopedia/n/nuclear-fuel-cycle.htm* (accessed Nov 2008).

5. Uranium Production Figures 1998–2007. *http://www.world-nuclear.org/info/uprod.html* (accessed Nov 2008).

6. In Situ Leach (ISL) Mining of Uranium. *http://www.uic.com.au/nip40.htm* (accessed Nov 2008).

7. World Uranium Mining. *http://www.uic.com.au/nip41.htm* (accessed Nov 2008).

8. Diffusion Separation Process. *http://www.euronuclear.org/info/encyclopedia/d/diffusionseparating.htm* (accessed Nov 2008).

9. Gaseous Diffusion Uranium Enrichment. *http://www.globalsecurity.org/wmd/intro/u-gaseous.htm* (accessed Nov 2008).

10. Gas Centrifuge Process. *http://www.euronuclear.org/info/encyclopedia/g/gascentrifuge.htm* (accessed Nov 2008).

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