MODULE 1.0: OVERVIEW OF THE NUCLEAR FUEL CYCLE

Introduction

Welcome to Module 1.0 of the Fuel Cycle Processes Directed Self-Study Course! This is the first of nine modules available in this self-study course. The purpose of this module is to provide a basic overview of the nuclear fuel cycle. This self-study module is designed to assist you in accomplishing the learning objectives listed at the beginning of the module. There are seven learning objectives in this module. The module has self-check questions and activities to help you assess your understanding of the concepts presented in the module.

Before you Begin

It is recommended that you have access to the following materials:

- Trainee Guide

Complete the following prerequisites:

- There are no prerequisites to this module.

How to Complete this Module

1. Review the learning objectives.
2. Read each section within the module in sequential order.
3. Complete the self-check questions and activities within this module.
4. Check off the tracking form as you complete the self-check questions and/or activity within the module.
5. Contact your administrator as prompted for a progress review meeting.
6. Contact your administrator as prompted for any additional materials and/or specific assignments.
7. Complete all assignments related to this module. If no other materials or assignments are given to you by your administrator, you have completed this module.
8. Ensure that you and your administrator have dated and initialed your progress on the tracking form.
9. Go to the next assigned module.

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MODULE 1.0: OVERVIEW OF THE NUCLEAR FUEL CYCLE

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LEARNING OBJECTIVES

1.1 Upon completion of this module, you will be able to understand nuclear energy and its role in nuclear power.

1.1.1 Identify the common processes of the nuclear fuel cycle.

1.1.2 Identify applicable NRC regulations.

1.1.3 Identify chemical and radiological properties of uranium.

1.1.4 Identify uranium compounds and their importance to the nuclear fuel cycle.

1.1.5 Identify physical and chemical properties of UF_6.

1.1.6 Identify costs and economic considerations.

MODULE 1.0: OVERVIEW OF THE NUCLEAR FUEL CYCLE

Learning Objective

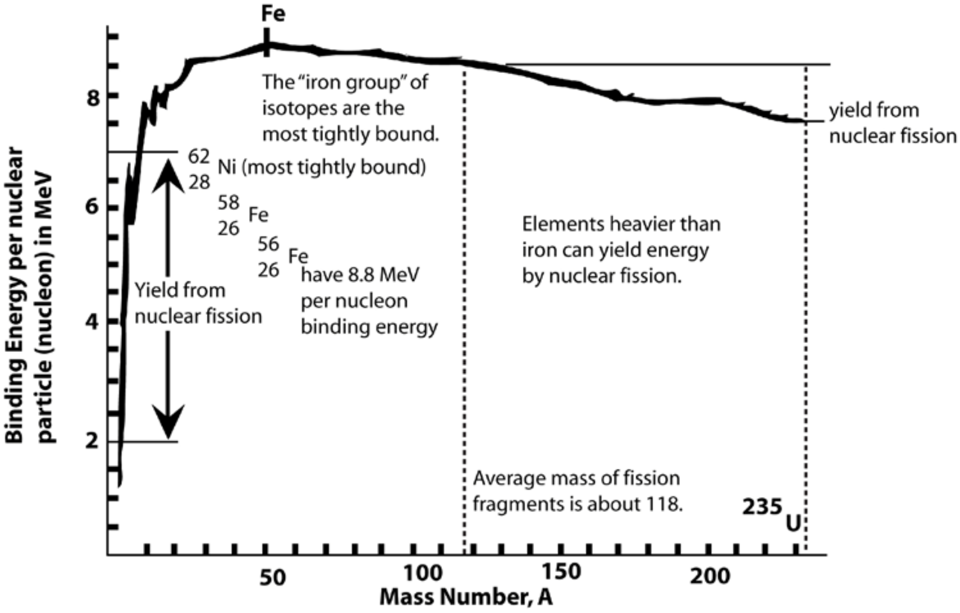
1.1 Understand nuclear energy and its role in nuclear power.

OVERVIEW OF ENERGY, NUCLEAR ENERGY AND NUCLEAR POWER

The world we live in relies upon energy. The energy is transmitted and utilized in two basic forms - as heat (e.g., internal combustion engines) and as electricity - both amounting to approximately 50% each of the total energy consumed. Much of the energy we experience in our everyday lives arises from combustion, a chemical reaction. Such reactions provide large quantities of energy from the rearrangement of electrons and atoms in molecules, often involving the splitting of larger molecules into smaller ones. Typical reactions produce about 4.8E4 joules for every gram of fuel consumed.

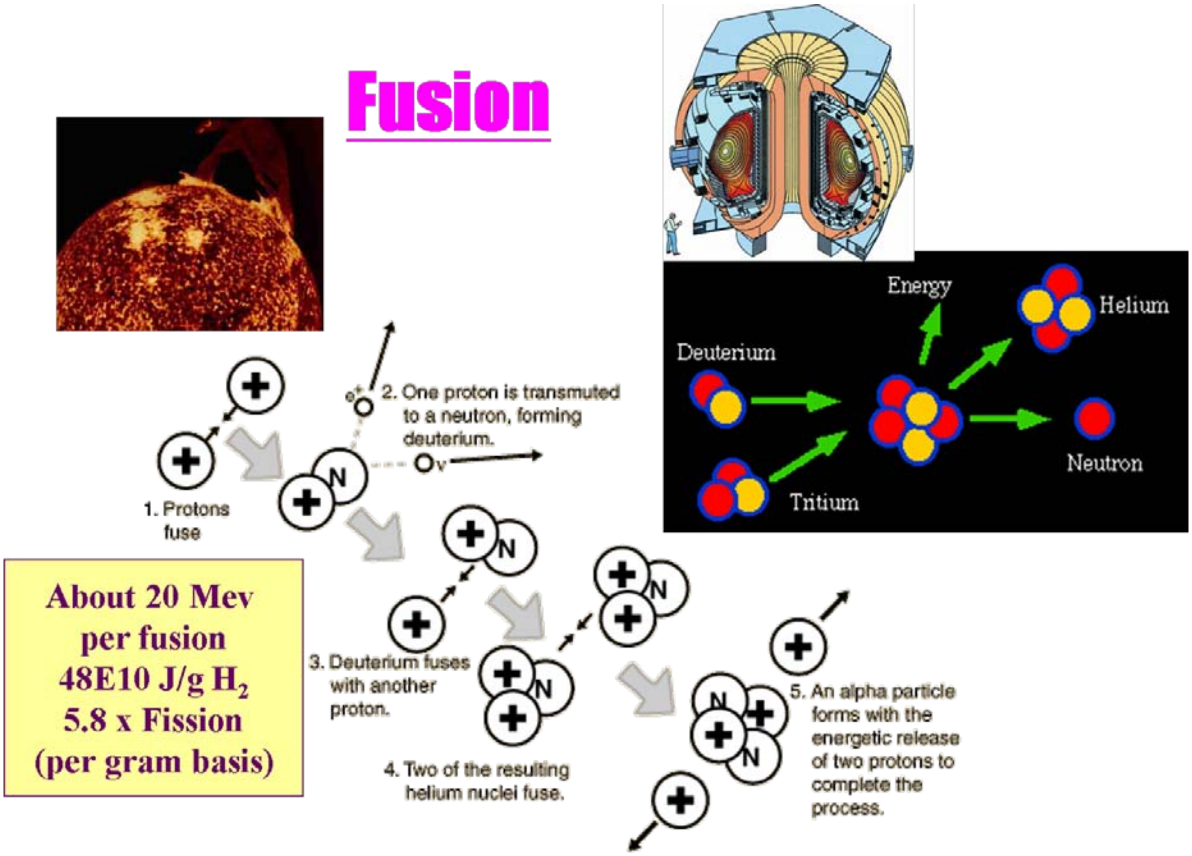
Nuclear reactions involve the rearrangement of the nuclei within the atoms, based upon the stability of the nucleus itself. The term “binding energy” measures the stability of the nucleus. As shown in Figure 1-1, the “iron group” of isotopes are the most tightly bound, and, therefore, the most stable.

Figure 1-1. The Binding Energy of Nuclei



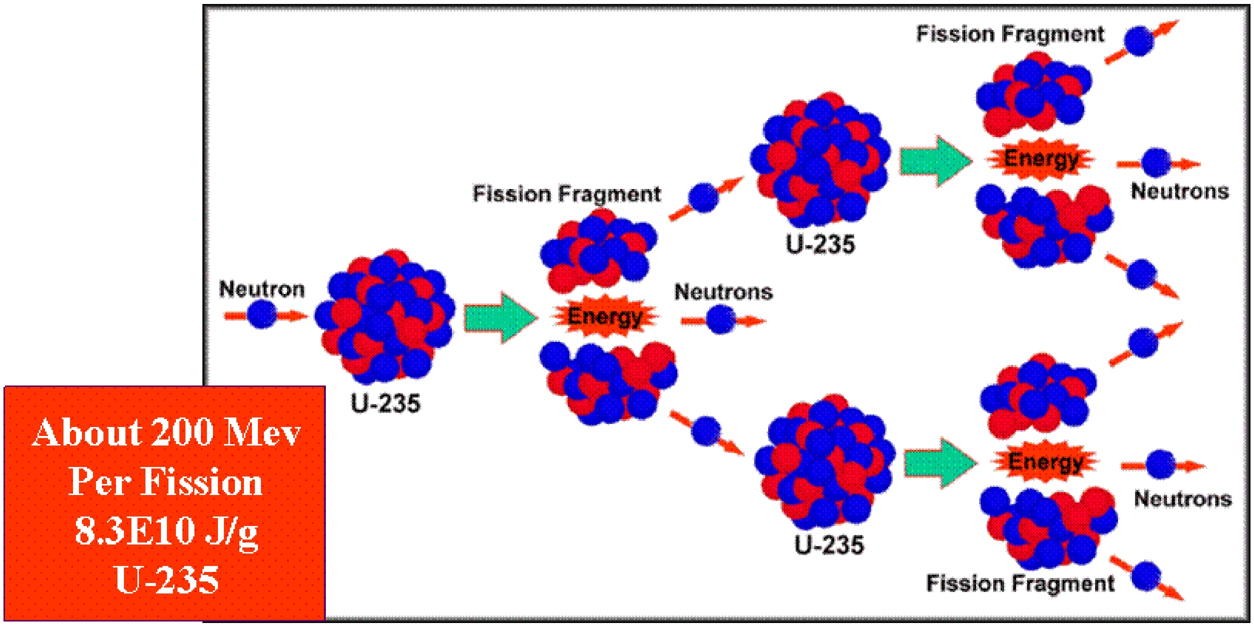
Elements with lower atomic masses can undergo fusion reactions, where two or more nuclei join together to form one new nucleus of a higher atomic mass. Fusion reactions liberate energy because the newly formed nucleus is more stable. Fusion generally requires high energies to overcome the electrostatic repulsion forces between separate nuclei and allow them to join; while some low temperature routes have been discovered, significant and potentially useful fusion usually requires very high temperatures and plasma conditions. As illustrated in Figure 1-2, the sun and most stars rely upon various reactions involving the fusion of four hydrogen nuclei to from helium, releasing about 20 MeV (primarily as heat) or about 48E10 J/g of hydrogen. Significant science and engineering are currently needed to make fusion a practical source of energy.

Figure 1-2. Fusion



Elements with atomic masses greater than iron can undergo fission reactions, where the nucleus reorganizes and splits into two or more fragments (Figure 1-3). Fission releases energy because the new nuclei formed are more stable than the parent nucleus. As with fusion, energy is needed to initiate fission reactions. Only two elements (four isotopes total) can initiate fission reactions under normal conditions by the absorption of a slow (sometimes called thermal) neutron - these isotopes are uranium-233, uranium-235, plutonium-239, and plutonium-241, and are termed fissile isotopes. Only uranium-235 is naturally occurring in significant quantities, where it is found isotopically diluted to around 0.71% (sometimes called the natural assay) with another uranium isotope, uranium-238. Fission forms two smaller nuclei and releases two or more neutrons, which can be absorbed by other fissile isotopes. This forms a continuing chain reaction that continuously releases energy. If more neutrons are produced than consumed by absorption reactions and leakage, then the reactions rapidly run away and an explosion can result. Nuclear fission releases about 0.9 MeV per nucleon, or about 200 MeV per fission (primarily as heat). This corresponds to about 8.3E10/g of uranium-235. Nuclear fission has been found to be a practical source of energy.

Figure 1-3. Nuclear Fission



Radioactive heavy elements like uranium-235 undergo radioactive decay. Some radioactive decay processes release neutrons. These neutrons may interact and result in some fission reactions. The presence of low atomic mass materials moderates (slows down) neutrons allowing for easier capture - and fission - of fissile materials like uranium-235. Moderating materials include normal (light) water and carbon. As the total quantity of fissile material increases, a situation may arise where the production of neutrons from fission equals the loss by absorption and leakage. This mass quantity is called a critical mass, and depends upon the isotopes, chemical forms, moderators, and any materials that inhibit neutron leakage (commonly called reflectors - water is also a reflector) or increase neutron loss (usually termed absorber or poison - boron and hafnium are examples) present in the system. Natural uranium (0.71% uranium-235) has an infinite critical mass under normal conditions (i.e., criticality cannot occur); criticality can only be obtained by increasing the concentration of uranium-235 (this is called enrichment) to levels of about 2% or more, or by improving the moderation (typically by using deuterated - heavy - water or dense carbon [graphite]). Usually, uranium enrichment is used for most reactors. Uranium containing below about 7% of the uranium-235 isotope requires the presence of a moderator for criticality; light water is the usual moderator used and also functions as a coolant. Higher densities and geometries with lower surface to volume ratios (e.g., spheres) increase the likelihoods of a chain-reaction and, thus, decrease the required critical mass for that combination of parameters.

Higher energy conditions can be used to initiate fission in some isotopes. For many heavy isotopes, such as uranium-238, neutrons with energies of 1 MeV or more can produce fission. The term “fissionable” applies to such isotopes. These “fast” neutrons form in the absence of a moderator.

Nuclear fission liberates about one million more times energy than conventional fossil fuels, and nuclear fusion liberates about six times more energy per gram than fusion. Matter and antimatter reactions, such as electron-positron anihilation, produce the highest energy per gram of material, about 9,000E10 J/g, or about 1,000 times more than nuclear fission. Obviously, the significant use of such matter-antimatter reactions remains in the realm of science fiction for now.

The world used about 421 Quads (1 Quad = 1E15 BTUs) of energy in 2003, the latest year for complete data. Energy usage is increasing at about 2.0% per year. Some 85% of this comes from fossil fuels - oil, coal, and natural gas. Nuclear power plants supply about 8% of the world’s total energy. Electricity consumes about 37% of the world’s energy (about 156 Quads) and delivers about 14,781 billion KW-hrs (equivalent to about 50 Quads of electricity) - conversion losses make up the difference. Electricity from nuclear power plants corresponds to about 18% of the total electricity produced (nuclear power plants currently only produce electricity). There are approximately 442 commercial operating reactors producing electricity, with an installed capacity of 370,000 MWe. In the last two decades, nuclear power has shown it is a compact power source that produces low emissions and wastes as compared to other generation methods, and the existing plants have become economically competitive and efficient. Figure 1-4 shows a simple comparison to coal and Figure 1-5 displays emission comparisons.

Figure 1-4. Nuclear and Coal Balances

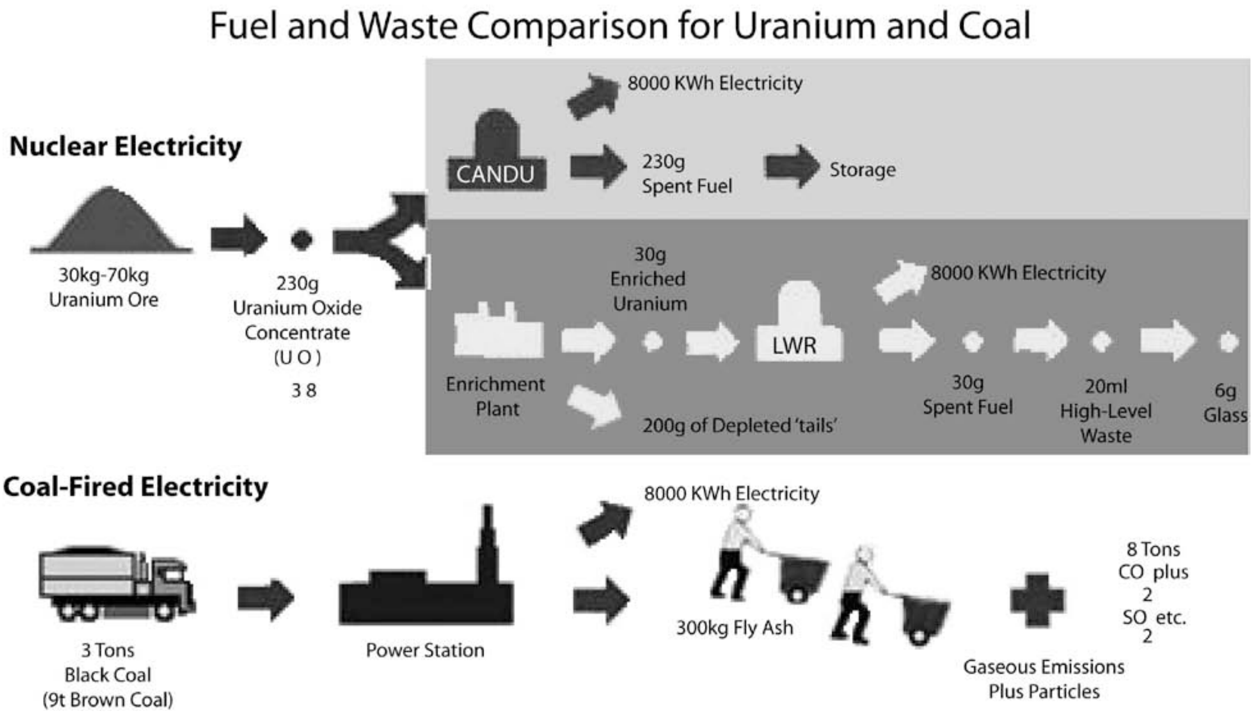
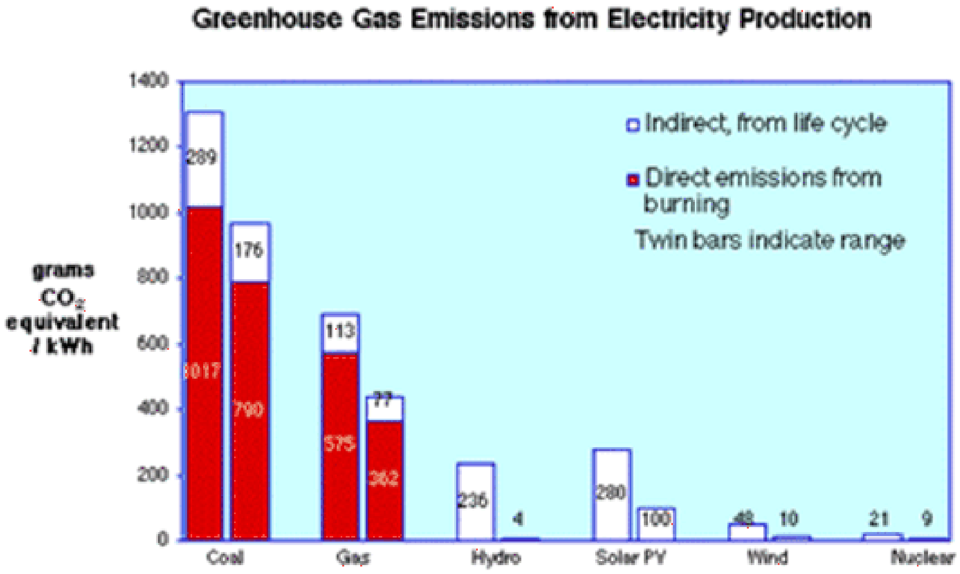


Figure 1-5. Greenhouse Gases



Source: IAEA 2000

The United States uses about 101 Quads of energy (2002 data). Figure 1-6 shows the breakdown. Approximately 42% of the nation's total energy consumption is used for electricity; approximately 65% of this is lost as heat at the power plant (a conversion loss). U.S. energy consumption is about 25% of the world total. The U.S also represents about 25% of the world's economy, thus showing the linkage with energy. Figure 1-7 displays the principal generating methods for electricity. The 103 operating nuclear power plants produce about 20% of the nation's electricity. The U.S. generated about 3,800 billion KW-hr (2002 data). Total generating capacity is around 950 GWe, and average production is around 500 GWe. The summer peak consumption (2006) was 573.3 GWe. Nuclear energy generally produces more than 30 times the energy used in the creation of the fuel and the manufacture of the plant (the so-called energy ratio). Plants that have undergone license renewal may exceed 50 for the energy ratio. In contrast, most fossil and renewable energy technologies have ratios of 9-10.

Figure 1-6. Energy and Electricity Flow

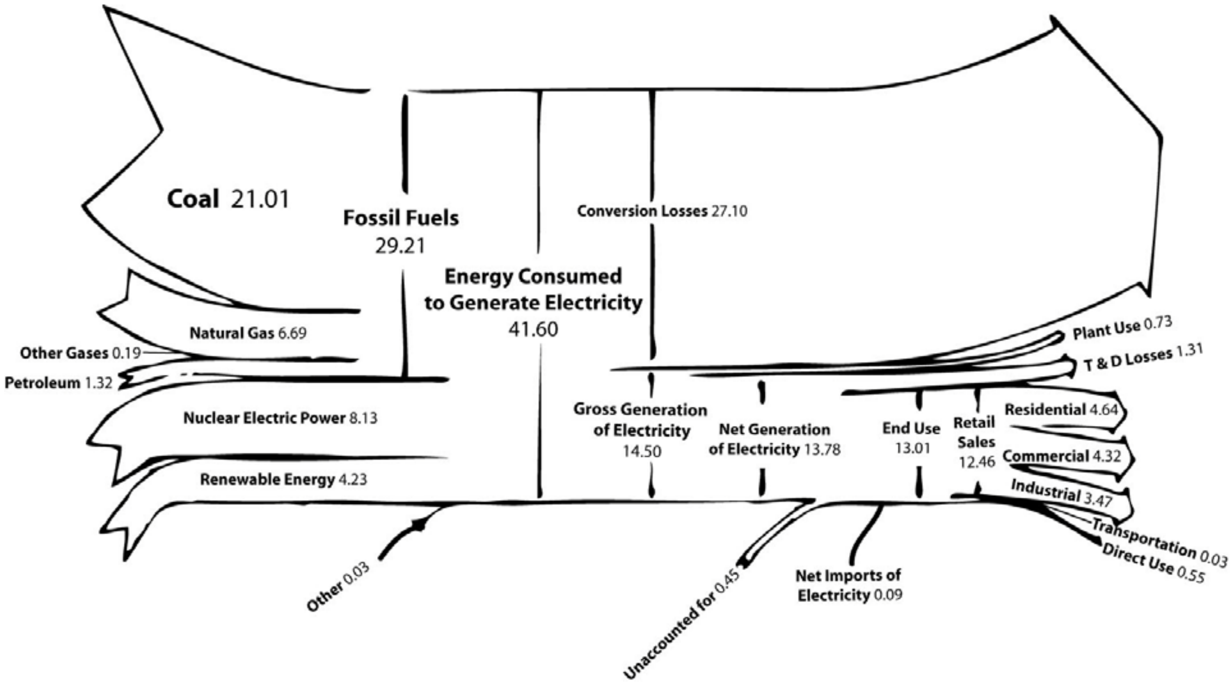
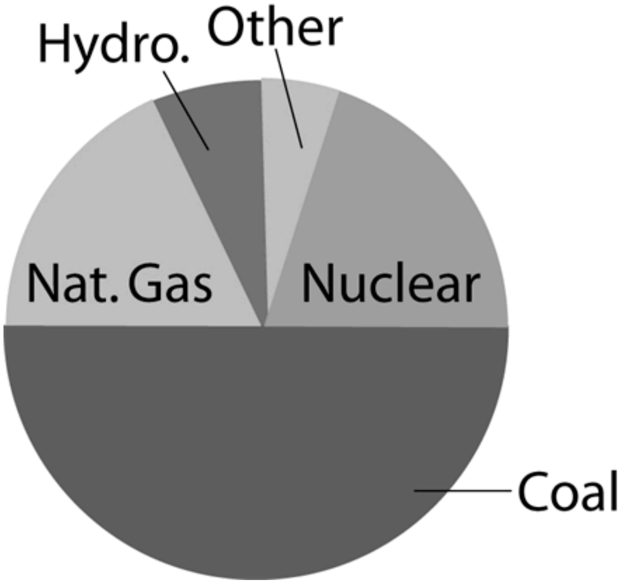


Figure 1-7. Pie Chart on U.S. Electricity



About 950 GWe capacity **2002 Data — Total = 3.8 Trillion KW-hrs**

500 GWe average **Percentages essentially same as 1998**

There is an interrelationship between the nuclear fuel cycle and the reactor type. There are several different nuclear reactor designs in use that have been practical for generating electricity. Reactors that use light water as the moderator and coolant dominate the power reactors. Hence, low-enriched uranium (LEU) is the basis for the fuel. Figure 1-8 represents a schematic of a pressurized water reactor (PWR), which accounts for about 75% of the reactors worldwide. A PWR generates steam for the turbine in a dedicated steam generator within the containment structure. High pressure in the primary loop prevents steam generation within the reactor itself. The separate secondary loop is at a lower pressure and boils, producing steam for a turbine outside of containment. The secondary loop is essentially nonradioactive. Most of the remaining light water reactors are boiling water reactors (BWR) (Figure 1-9). A BWR generates steam within the reactor vessel, which travels outside of containment to drive a turbine. Thus, in a BWR, the steam loop and turbine are more radioactive. Figure 1-10 shows modern nuclear power plants.

There are small numbers of reactors that use natural uranium as the fuel, and, thus, use enhanced moderation. Pressurized heavy water reactors, such as CANDUs, use heavy water as the moderator and (usually) the coolant. MAGNOX reactors use graphite as the moderator and carbon dioxide as the coolant. The fuel has to be tailored to its use in the reactor. For more on fuel, see Module 5.0, Fuel Fabrication.

Figure 1-8. Typical PWR Diagram

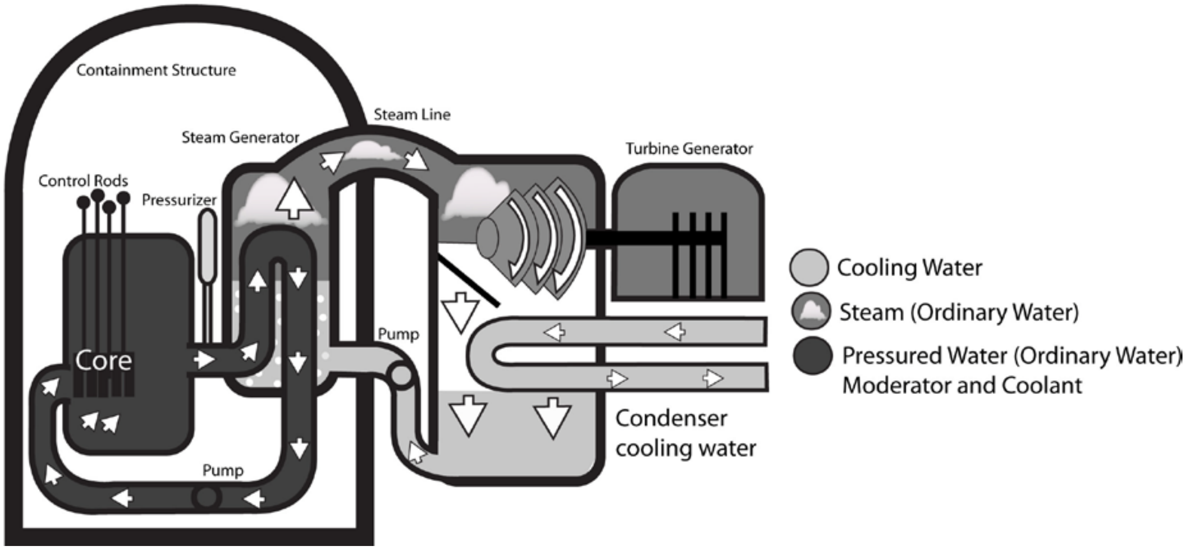


Figure 1-9. Typical BWR Diagram

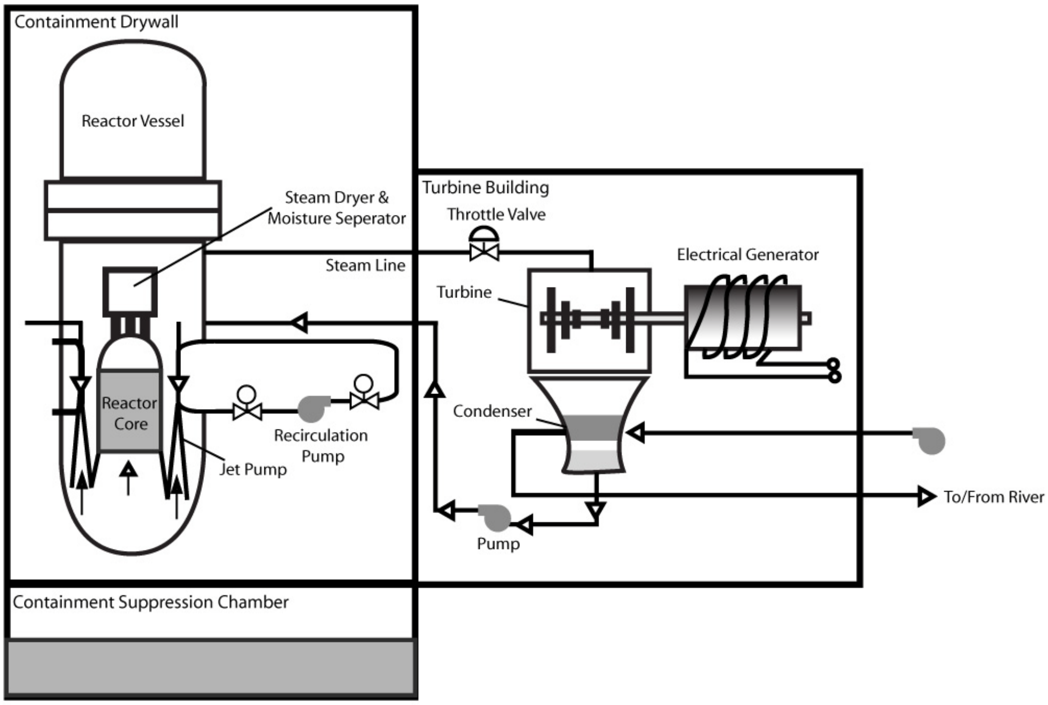
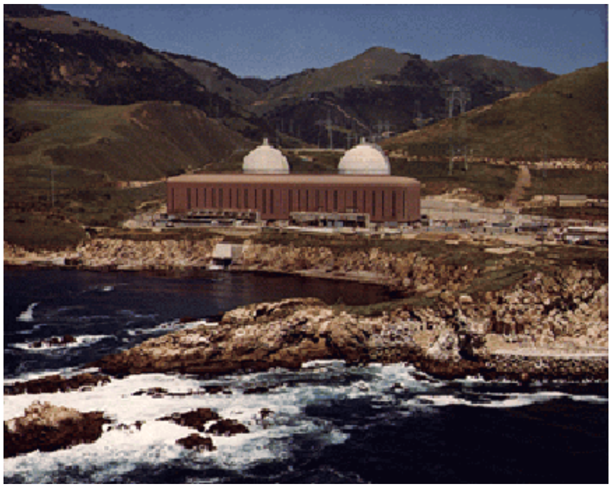


Figure 1-10. Typical Power Reactors



Self-Check Questions 1-1

INSTRUCTIONS: Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. The United States accounts for approximately _________ % of the world's energy consumption, and represents about _________ % of the world's economy?

2. Energy used to produce electricity corresponds to about ________ % of total energy consumed.

3. The principal energy source for electricity in the United States is _______ and supplies about ________ % of the electricity.

4. Nuclear power supplies about ________ % of electricity generated in the United States.

5. Coal produces ________kg of CO^2 per KW-hr of electricity, while nuclear power produces _________ kg of CO^2 per KW-hr of electricity.

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

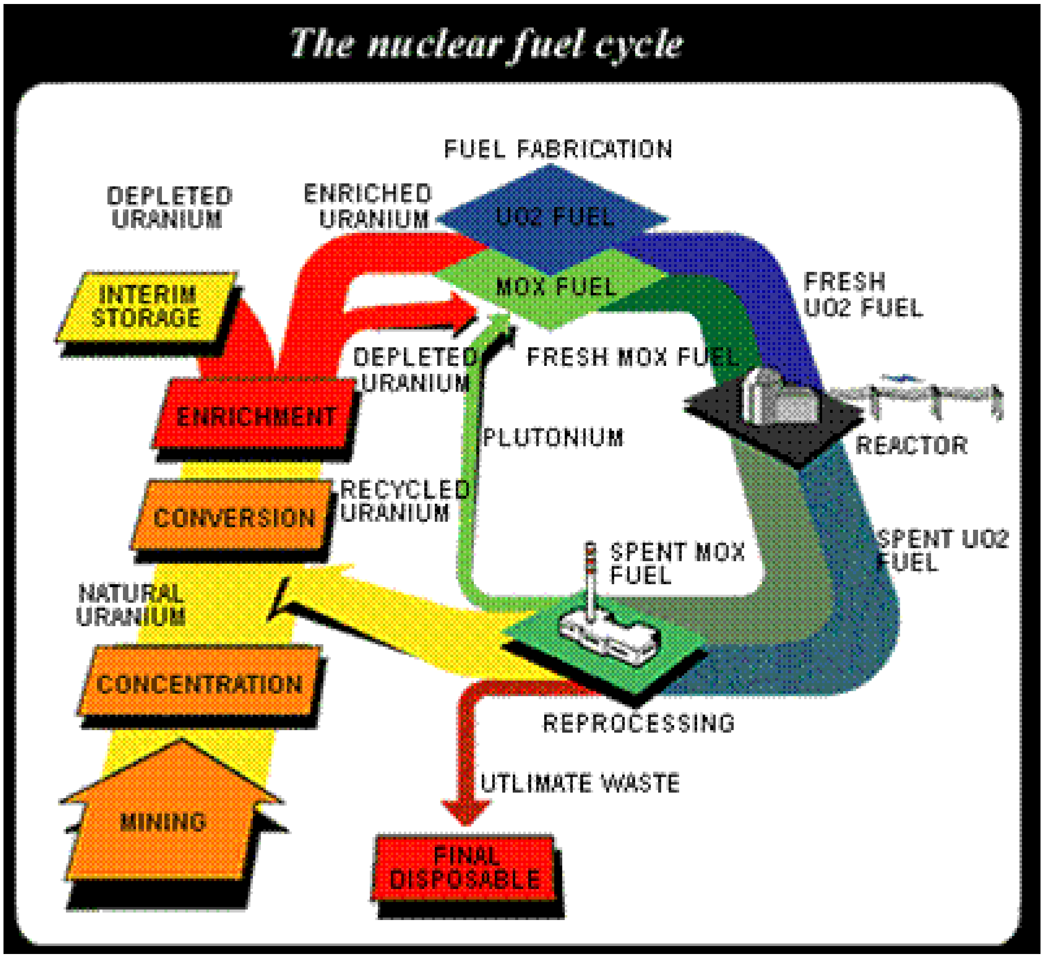
Learning Objective

1.1 Identify the common processes of the nuclear fuel cycle.

NUCLEAR FUEL CYCLE

The nuclear fuel cycle includes a variety of processes that use uranium in different chemical and physical forms. Figure 1-11, Overview of the Closed Nuclear Fuel Cycle, represents a flow diagram of chemical and metallurgical operations that make up the nuclear fuel cycle.

Figure 1-11. Overview of the Closed Nuclear Fuel Cycle



MODULE 1.0: OVERVIEW OF THE NUCLEAR FUEL CYCLE

Natural uranium that has been mined/extracted from the earth undergoes several processes before it can be used as fuel in a nuclear reactor. Along with mining, the processes of recovery (refining), conversion, enrichment, and fabrication, make up the “front end” of the nuclear fuel cycle. After the uranium has been used in a reactor, it becomes “spent fuel” and may undergo further steps that include temporary storage, reprocessing, and recycling before eventual disposal as waste. These steps are the “back end” of the fuel cycle. See Module 6.0, Back-end of the Fuel Cycle: Spent Nuclear Fuel and Irradiated Materials.

Spent fuel may be sent to a reprocessing plant where the residual uranium and newly produced plutonium are recovered for re-use as fuel. Such reprocessing takes place at a facility where the plutonium oxide is mixed with uranium oxide to produce a mixed oxide or MOX nuclear fuel (discussed in Module 5.0, section 5.1.10). MOX fuel can then be irradiated just like fresh fuel in a commercial nuclear power plant. The processes that make up the nuclear fuel cycle are described below.

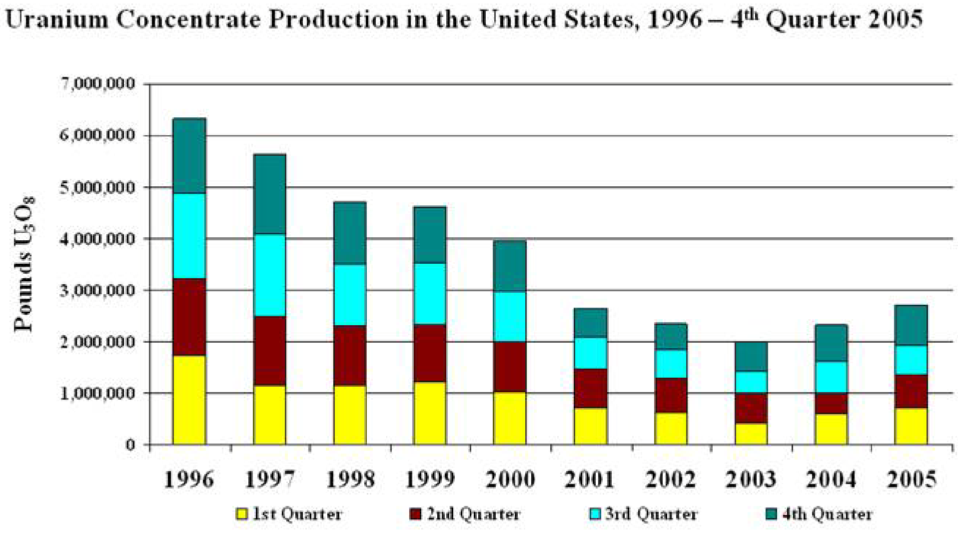
Mining

Traditionally, uranium ore was mined from open-pit and underground mines (deep mining); however, in the past decade, most mines in the United States have shut down. Alternative techniques such as in-situ leach (ISL) mining have become more widely used. ISL makes use of solutions that are injected into underground deposits to dissolve uranium. An example of this extraction process is heap leach. Although ISL is a mining technique, the ISL recovery is defined as milling under 10 CFR 40, Appendix A, and is therefore regulated by the NRC. The NRC does not regulate mining. See ISL Process in Module 2.0, Uranium Recovery. Imported uranium accounts for about three-quarters of the refined uranium used domestically each year. Radiation hazards associated with mining involve radon and its decay products.

Recovery

Uranium recovery is designed to extract uranium from mined ore. The mined ore is brought to the recovery facility via truck where the ore is crushed and leached. In most cases, sulfuric acid is used as the leaching agent, but alkaline leaching can also be used. The leaching agent not only extracts uranium from the ore, but also several other constituents like molybdenum, vanadium, selenium, iron, lead, and arsenic. The final product produced from the recovery, commonly referred to as “yellowcake” [Triuranium Octoxide (U_3O_8) with impurities], is not directly usable as a fuel for a nuclear reactor. Additional processing at a conversion facility is required. Therefore, the product is packaged and shipped in drums to a processing or conversion facility. Most domestic mills are now closed and there was a steady decline in U_3O_8 production from 1996 to 2005. However, since 2004, domestic production has been increasing. See Figure 1-12. See also Module 2.0, Uranium Recovery.

Figure 1-12. Uranium Concentrate Production in the U.S.



4th Quarter 2002 through 2nd Quarter 2004 and 4th Quarter 2004 production are estimated by rounding to avoid disclosure of individual company data.
Source: Energy Information Administration, Form EIA-851Q "Domestic Uranium Production Report"

Conversion

A uranium conversion facility receives drummed ore from a mill and then converts it into uranium hexafluoride (UF_6). Honeywell, Inc., located in Metropolis, Illinois, is the only processing/conversion facility presently operating in the United States. The final product of this facility is UF_6. It is produced as a liquid, then drained into 14-ton cylinders where it solidifies after cooling for approximately five days (Dry Conversion Process). The UF_6 cylinder is then shipped offsite for the next step in the nuclear fuel cycle, which is enrichment. See Module 3.0, Uranium Conversion.

Enrichment

Uranium enriched in uranium-235 (U-235) is required in commercial light water reactors to produce a controlled nuclear reaction. Uranium hexafluoride is received at an enrichment facility from the processing/conversion facility in a 14-ton cylinder. Enrichment allows the U-235 isotopes within the UF_6 to be increased from .711% (natural uranium) to a range between 2% to 5% (enriched uranium) depending on customer specifications. Enriched uranium is produced in the United States using the gaseous diffusion process. One gaseous diffusion plant (GDP) is currently operating at Paducah, Kentucky. The Portsmouth GDP at Piketon, Ohio, is being held in “cold stand-by”; however, some sampling and transferring operations are continuing. The gaseous diffusion process uses the separation effect of molecular effusion (i.e., the flow of gas through small orifices) to produce enriched uranium. This enrichment enables the uranium to be used in a light water reactor. See Module 4.0, section 4.1.3.

The gas centrifuge enrichment process uses a large number of rotating cylinders in series and parallel formations. Centrifuge machines are interconnected to form trains and cascades. In this process, UF_6 gas is placed in a cylinder and rotated at a high speed. This rotation creates a strong centrifugal force so that the heavier gas molecules (containing U-238) move toward the outside of the cylinder and the lighter gas molecules (containing U-235) collect closer to the center. The stream that is slightly enriched in U-235 is withdrawn and fed into the next higher stage, while the slightly depleted stream is recycled back onto the next lower stage. Significantly more U-235 enrichment can be obtained from a single unit gas centrifuge than from a single unit gaseous diffusion stage. It requires less energy to achieve the same separation than the older gaseous diffusion process, which has been largely replaced. Two gas centrifuge facilities are under construction in the U.S., New Mexico, and Ohio. See Module 4.0, section 4.1.4.

Enrichments greater than 90% of U-235 are used in the U.S. Navy's nuclear propulsion reactors. Certain nonpower research and test reactors, e.g., the High Flux Isotope Reactor at Oak Ridge National Laboratory (ORNL) and Advance Test Reactor at Idaho National Laboratory (INL), use U-235 enrichments of 93% to 97%. Such high enriched uranium is not currently produced in the U.S. today.

LEU for nuclear power plants is also being produced by the downblending of excess high-enriched uranium (HEU) from naval and defense programs. This has supplied between 30% and 50% of the enrichment requirements for U.S. power plants. LEU from downblending is distinguished from LEU created by normal enrichment by its higher uranium-234 to uranium-235 ratio. This ratio increase occurs because the uranium-234 is slightly preferentially increased in enrichment due to its (slightly) lower molecular weight; the effect is greater for HEU materials.

Uranium and LEU recovered from reprocessing can be re-enriched back to useful assay levels. Reprocessed Uranium, or REPU, contains uranium-236 (a neutron poison) and has to be enriched to a lightly higher final level for the same reactivity, even though it usually is still slightly enriched prior to re-enrichment. REPU also can contain traces of other isotopes, e.g., transuranics (TRUs), such as neptunium and plutonium, and fission products (technetium-99). The Paducah GDP feed included REPU prior to about 1975, with a total of approximately 130,000 te of REPU feed. This is responsible for the technetium-99 and low levels of TRU found at the facility. REPU has been re-enriched in campaigns overseas as well. However, REPU is not currently re-enriched and, if it is in the future, it would likely be in a facility dedicated to REPU enrichment.

Fuel Fabrication

Fuel fabrication facilities convert enriched UF_6 into fuel for nuclear reactors. The enriched UF_6 product is sent to a fuel fabrication plant via a 2.5 ton (30-B) cylinder, where it is introduced into a chemical process to convert the enriched UF_6 to uranium dioxide (UO_2) powder. The UO_2 powder is converted into ceramic fuel pellets. The fuel pellets are then mechanically loaded into corrosion-resistant fuel rods. The fuel rods are configured into fuel assemblies which are shipped to reactor power plants via NRC and Department of Transportation (DOT)-approved shipping containers.

Six fuel fabrication facilities are licensed to operate in the United States:

- AREVA-L (Lynchburg, Virginia)
- AREVA-R (Richland, Washington)
- BWX Technologies, Inc. (Lynchburg, Virginia)
- Global Nuclear Fuels-Americas (Wilmington, North Carolina)
- Nuclear Fuel Services (Erwin, Tennessee)
- Westinghouse (BNFL, Toshiba) (Columbia, South Carolina)

BWX and Nuclear Fuel Services are licensed to process highly enriched uranium (>20% 235U) and have the capability to blend it down to low-enriched uranium; however, they do not fabricate power reactor fuel.

Fabrication also can involve mixed oxide (MOX) fuel, which is a combination of uranium and plutonium components. A facility mixes plutonium oxide from the pit disassembly and conversion process with uranium oxide to form mixed oxide fuel pellets. The pellets are used to fabricate mixed oxide fuel assemblies for use in commercial reactors. See Module 5.0, section 5.1.10.

Reactor

Fuel assemblies from a fuel fabrication facility are shipped to light water reactors (LWR) for use as fuel in power production. As noted previously, there are two types of LWRs: pressurized water reactor and boiling water reactor. Both are thermal reactors in which circulating light water is used to cool the reactor core and to moderate (reduce the energy of) the neutrons created in the core by the fission reactions. All commercially operating reactors in the United States and most commercial reactors worldwide are LWRs. A typical 1000-Mw pressurized water reactor has about 200 fuel rods in an assembly. A typical 1,000 MWe LWR contains approximately 100 te of uranium in its core, enriched to 4-5%. Such a reactor operates on a nominal 18 month cycle and replaces one-third of its core with fresh fuel every eighteen months or so because of the depletion of the uranium-235 content and the accumulation of neutron-absorbing fission products. A typical PWR fuel assembly contains about 500 kg of LEU in 150-200 fuel rods. A typical BWR assembly has around 200 kg of LEU in 60-100 fuel rods. Both assemblies are square. See Module 5.0, section 5.1.5.

Spent Nuclear Fuel and Interim Storage

Spent nuclear fuel is irradiated reactor fuel that is no longer useful as fuel. Approximately one-third of the nuclear fuel in a reactor is replaced during each refueling. Fuel assemblies (pellets stacked in metal rods and bundled into assemblies) are removed and are replaced periodically. As it is removed from the reactor core, spent nuclear fuel is highly radioactive and, thermally speaking, also very hot since decay of radioactive fission products is accompanied by the release of energetic atomic fragments and particles. Currently, most spent nuclear fuel is safely stored in specially designed water pools at individual reactor sites around the country. The water-pool option involves storing spent fuel in rods under at least 20 feet of water, which provides adequate shielding from the radiation for anyone near the pool and adequate cooling of the spent fuel. The rods are moved into the water pools from the reactor along the bottom of water canals so that the spent fuel is always shielded.

Licensees are increasingly using above-ground storage casks. The first dry storage installation was licensed by the NRC in 1986. In this method, spent fuel is surrounded by inert gas inside a container called a cask. The cask can be made of metal or concrete, and can be used for both storage and transportation. It is either placed horizontally or vertically on a concrete pad. Dry storage is not suitable until the fuel has been out of the reactor for a few years and the amount of heat generated by radioactive decay has been sufficiently reduced. See Module 6.0, section, section 6.1.2.

Reprocessing

Reprocessing of uranium involves the chemical treatment of spent fuel from a nuclear reactor to separate unused uranium and plutonium from radioactive fission product wastes. Briefly, reprocessing consists of fuel bundle disassembly, chopping of the fuel pins, leaching out fuel and fission products from chopped fuel pins, solvent extraction of the leachate to separate uranium, plutonium and fission products, chemical recovery of the various fractions, and waste stabilization. While the products of the LWR fuel cycle are slightly enriched uranium and plutonium, cycles that contain thorium produce U-233.

This uranium can be recycled through an enrichment plant for further enrichment. Plutonium-239 recovered in reprocessing may be used in place of some U-235 in new fuel assemblies. This combination of plutonium and uranium is referred to as mixed oxide or MOX fuel. Presently, the United States does not have commercial reprocessing facilities. See Module 6.0, section 6.1.3.

High-Level Waste

Most high-level waste (HLW) is generated either in a reactor, or if the fuel has been reprocessed, in the reprocessing facility. It includes: irradiated (spent) reactor fuel; liquid wastes resulting from the operation of the first cycle solvent extraction system; the concentrated wastes from subsequent extraction cycles in a facility for reprocessing irradiated reactor fuel; and solids into which such liquid wastes have been converted. In the U.S., HLW is primarily in the form of spent fuel from commercial nuclear power plants. The waste also includes some reprocessed HLW from defense activities and a small quantity of reprocessed commercial HLW. See Module 6.0, section 6.1.4.

Final Disposition

Congress gave the Department of Energy (DOE) responsibility for developing permanent disposal capacity for spent fuel and other high-level nuclear waste. DOE, as directed by Congress, investigated a disposal facility site in Nevada: Yucca Mountain, located 100 mi. NE of Las Vegas. The site would serve as a repository to hold the nation's nuclear waste.

On February 14, 2002, the Secretary of Energy recommended the Yucca Mountain site for storage of radioactive waste and the U.S. Senate has since voted favorably on this site. DOE submitted the license application for Yucca Mountain to the NRC in 2008. The NRC is reviewing the license application and related scientific studies. The license review will take several years. NRC will review the scientific studies of Yucca Mountain and consider the site for a license. DOE plans to haul about 77,000 tons of spent fuel and nuclear waste to the repository, if approved for storage. See Module 6.0, section 6.1.5.

Self-Check Questions 1-2

INSTRUCTIONS: Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. List the first five steps of the nuclear fuel cycle.

2. Identify three uranium mining techniques.

3. What is a uranium mill designed to accomplish?

4. What is the final product produced from uranium recovery?

5. What is the final product of a conversion/processing plant?

6. What isotope of uranium is preferred for enrichment and why?

7. During fuel fabrication, enriched UF_6 is converted to what uranium compound for fuel pellets?

8. What are the final products at a fuel fabrication facility and where are they shipped?

9. Describe the three basic steps for the fabrication of light water reactor fuel.

10. What is spent nuclear fuel?

11. How is spent fuel stored?

12. What is high-level waste?

13. Where is the proposed site for the permanent disposal of high-level waste?

You have completed this section.
Please check off your progress on the tracking form.
Go to Activity 1

Activity 1 – Nuclear Fuel Cycle Puzzle

PURPOSE: The purpose of this activity is to identify processes, activities, and terminology related to the nuclear fuel cycle.

INSTRUCTIONS: Complete the following activity using terminology used in the first section of the module. Answers are located in the answer key section of the Trainee Guide.

Note: Blank space is included between words where appropriate

Across

1. Used as a leaching agent (skip space between words – two words).
8. Abbreviation of place where fuel assemblies are shipped to.
9. Can be made of metal or concrete, and can be used for both storage and transportation.
11. Abbreviation of agency responsible for licensing a disposal facility.
13. A chemical plant designed to extract uranium from mined ore.
14. Irradiated reactor fuel that is no longer useful as fuel.
15. Type of light water reactor - last space blank.
18. Mill product is packaged and shipped in these containers.
19. Abbreviation for the second name of #20 down.
20. A mill product.
21. Abbreviation for a facility that recovers uranium.
22. These are mechanically loaded into fuel rods.
23. Level of irradiated reactor fuel waste.
24. Process for increasing U235 isotopes.

Down

2. Name of fuel used to form pellets (skip space between words – three words).
3. Name of fuel shipped to reactor power plants (skip space between words – two words).
4. Involves the chemical treatment of spent fuel from a nuclear reactor.
5. This facility receives ore from a mill and then converts it into uranium hexafluoride (UF_6).
6. In this process, solutions are injected into underground deposits to dissolve uranium (skip space between words – two words).
7. Process by which uranium is enriched in the U.S. (skip space between words – two words).
9. A process used to convert UO_2 powder to pellets.
10. Also known as yellowcake (skip space between words – two words).
12. UF_6 is transported to an enrichment facility in this container.
16. Needed for power production.

17. This powers a reactor.
20. First name of a possible disposal facility site in Nevada.
22. Abbreviation for a type of light water reactor.

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	■		■	■	24									

Learning Objective

When you finish this section, you will be able to:

1.1.2 Identify applicable NRC regulations.

NRC REGULATION OF FUEL CYCLE FACILITIES

The NRC licenses and inspects all commercial nuclear fuel facilities involved in the processing of uranium ore, the enrichment of uranium, and the fabrication of enriched uranium into nuclear reactor fuel. The agency also certifies and inspects the gaseous diffusion plants. These facilities may also be subject to the applicable requirements of the Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and State regulatory agencies.

NRC regulations are issued under the United States Code of Federal Regulations (CFR) Title 10, Chapter I. Principal statutory authorities that govern NRC's work include:

- Atomic Energy Act of 1954, as amended
- Energy Reorganization Act of 1974, as amended
- Uranium Mill Tailings Radiation Control Act of 1978, as amended
- Nuclear Non-Proliferation Act of 1978
- Low-Level Radioactive Waste Policy Act of 1980
- West Valley Demonstration Project Act of 1980
- Nuclear Waste Policy Act of 1982
- Low-Level Radioactive Waste Policy Amendments Act of 1985
- Diplomatic Security and Anti-Terrorism Act of 1986
- Nuclear Waste Policy Amendments Act of 1987
- Solar, Wind, Waste and Geothermal Power Production Incentives Act of 1990
- Energy Policy Act of 1992

The NRC fulfills its responsibilities through a system of licensing and regulatory activities that include:

- Licensing the construction and operation of nuclear reactors and other nuclear facilities, such as nuclear fuel cycle facilities and nonpower test and research reactors, and overseeing their decommissioning.
- Licensing the possession, use, processing, handling, and export of nuclear material.
- Licensing the siting, design, construction, operation, and closure of low-level radioactive waste disposal sites under NRC jurisdiction and the construction, operation, and closure of the geologic repository for high-level radioactive waste.
- Licensing the operators of nuclear power and nonpower test and research reactors.
- Inspecting licensed facilities and activities.
- Conducting research to provide independent expertise and information for making timely regulatory judgments and for anticipating problems of potential safety significance.
- Developing and implementing rules and regulations that govern licensed nuclear activities.
- Investigating nuclear incidents and allegations concerning any matter regulated by the NRC.
- Enforcing NRC regulations and the conditions of NRC licenses.
- Conducting public hearings on matters of nuclear and radiological safety, environmental concern, common defense and security, and antitrust matters.
- Developing effective working relationships with the States regarding reactor operations and the regulation of nuclear material.
- Maintaining the NRC Incident Response Program, including the NRC Operations Center.
- Collecting, analyzing, and disseminating information about the operational safety of commercial nuclear power reactors and certain nonreactor activities.

The objectives of the NRC regulations are to protect the health and safety of the public and plant workers and the environment from radiological and certain chemical hazards present at fuel cycle facilities. See Tables 1-1 and 1-2 for a list of the common regulatory requirements for the various fuel cycle facilities. Exceptions may occur from the list given in each of these tables. The tables show some common regulation, but not all regulations for each type of facility.

Table 1-1. NRC Regulatory Requirements

Regulation		Milling (U Recovery)	Processing/Conversion	Enrichment	Fuel Fabrication	Spent Fuel	Waste
10 CFR 19	Notices, Instructions and Reports to Workers: Inspection and Investigations	x	x	x	x	x	x
10 CFR 20	Standards for Protection Against Radiation	x	x	x	x	x	x
10 CFR 21	Reporting of Defects and Noncompliance	x	x	x	x	x	
10 CFR 26	Fitness for Duty Programs				x		
10 CFR 40	Domestic Licensing of Source Material	x	x				
10 CFR 51	Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions	x	x	x	x	x	x
10 CFR 61	Licensing Requirements for Land Disposal of Radioactive Waste						x
10 CFR 63	Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca					x	x
10 CFR 70	Domestic Licensing of Special Nuclear Material			x	x	x	x
10 CFR 71	Packaging and Transportation of Radioactive Material		x	x	x	x	x
10 CFR 72	Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste					x	
10 CFR 73	Physical Protection of Plants and Materials			x	x	x	x
10 CFR 74	Material Control and Accounting of Special Nuclear Material			x	x	x	x
10 CFR 75	Safeguards on Nuclear Material—Implementation of US/IAEA Agreement			x	x	x	x
10 CFR 76	Certification of Gaseous Diffusion Plants			x			
10 CFR 95	Security Facility Approval and Safeguarding of National Security Information and Restricted Data			x	x	x	x

Table 1-2. Related Protection of Environment Regulatory Requirements

Regulation		Mining	Milling (U Recovery)	Processing/Conversion	Enrichment	Fuel Fabrication	Spent Fuel	Waste
40 CFR 61*	National Emission Standards for Hazardous Air Pollutants	x	x	x	x	x		x
40 CFR 190	Environmental Radiation Protection Standards for Nuclear Power Operations	x	x	x	x	x	x	
40 CFR 192	Health and Environmental Protection Standards for Uranium and Thorium Mills Tailings	x	x	x	x			x

*Subpart B	National Emission Standards for Radon Emissions From Underground Uranium Mines
Subpart H	National Emission Standards for Emissions of Radionuclides Other Than Radon From Department of Energy Facilities
Subpart I	National Emission Standards for Radionuclide Emissions From Facilities Licensed by the Nuclear Regulatory Commission and Federal Facilities Not Covered by Subpart H
Subpart T	National Emission Standards for Radon Emissions From the Disposal of Uranium Mill Tailings
Subpart W	National Emission Standards for Radon Emissions From Operating Mill Tailings

The following are recently issued regulations, guides, and notices applicable to the fuel cycle process:

NUREGs

“Integrated Safety Analysis Guidance Document,” (NUREG-1513) U.S. Nuclear Regulatory Commission, Washington, DC (May 2001).

“Standard Review Plan for In-Situ Leach Uranium Extraction License Application,” (NUREG-1569) U.S. Nuclear Regulatory Commission, Washington, DC (June 2003).

“Standard Review Plan for the Review of a License Application for a Mixed Oxide (MOX) Fuel Fabrication Facility,” (NUREG-1718) U.S. Nuclear Regulatory Commission, Washington, DC (October 2002).

“Standard Review Plan for the Review of a License Application for the Atomic Vapor Laser Isotope (AVLIS) Facility,” (NUREG-1701) U.S. Nuclear Regulatory Commission, Washington, DC (March 1999). (Draft)

“Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility,” (NUREG-1520) U.S. Nuclear Regulatory Commission, Washington, DC (June 2003).

“Standard Review Plan for the Review of a Reclamation Plan for Mill Tailings Sites,” (NUREG-1620, Rev. 1) U.S. Nuclear Regulatory Commission, Washington, DC (June 2003).

Regulatory Guides

U.S. Nuclear Regulatory Commission, Regulatory Guide 3.72, “Guidance for Implementation of 10 CFR 72.48, Changes, Tests, and Experiments,” U.S. Nuclear Regulatory Commission, Washington, DC (March 2001).

U.S. Nuclear Regulatory Commission, Regulatory Guide 8.30, “Health Physics Surveys in Uranium Mills,” U.S. Nuclear Regulatory Commission, Washington, DC (May 2002).

U.S. Nuclear Regulatory Commission, Regulatory Guide 8.31, “Information Relevant to Ensuring that Occupational Radiation Exposures at Uranium Recovery Facilities will be As Low As Reasonably Achievable,” U.S. Nuclear Regulatory Commission, Washington, DC (May 2002).

NRC Notices

NRC Information Notice 2003-31, Supplement 1: “Potentially Defective UF_6 Cylinder Valves (1-inch)” (March 24, 2003).

NRC Regulatory Issue Summary 05-22: “Requirements for the Physical Protection During Transportation of Special Nuclear Material of Moderate and Low Strategic Significance: 10 CFR Part 72 vs. Regulatory Guide 5.59 (1983" (October 28, 2005).

NRC Information Notice 05-28: “Inadequate Test Procedure Fails to Detect Inoperable Criticality Accident Alarm Horns” (October 31, 2005).

NRC Regulatory Issue Summary 05-25: “Clarification of NRC Guidelines for Control of Heavy Loads” (October 31, 2005).

NRC Information Notice 2006-07: “Inappropriate Use of a Single-Parameter Limit as a Nuclear Criticality Safety Limit” (March 31, 2006).

NRC Information Notice 2006-10: “Use of Concentration Control for Criticality for Criticality Safety“ (April 23, 2006).

Applicable NRC regulations are discussed in specific fuel cycle modules and in Module 9.0.

Regulations on Conversion

Natural uranium used in a conversion facility poses little radiation danger to humans; however, it is toxic and must be closely regulated. The production of uranium hexafluoride at the Honeywell facility is licensed by the NRC pursuant to the provisions of 10 CFR Part 40, Domestic Licensing of Source Material.

Regulations on Enrichment

The Energy Policy Act of 1992 established the United States Enrichment Corporation (USEC), a government-owned corporation, to take over the DOE’s low uranium enrichment activities. The corporation must comply with relevant federal and state environmental statutes. In lieu of a license, the corporation obtained a certificate of compliance from the NRC pursuant to Title 10 CFR 76. On April 26, 1996, the President signed the USEC Privatization Act, H.R. 3019, which provided for USEC to become a private corporation. The law also changed certain regulatory provisions, including authorization for NRC to impose civil penalties on USEC, extension of the certification period to up to five years as determined by the NRC; and a requirement for NRC and OSHA to develop a memorandum of understanding (MOU). The MOU between NRC and OSHA was signed in August 1996.

Additional information on NRC Regulations can be found in Module 9 of this course.

MODULE 1.0: OVERVIEW OF THE NUCLEAR FUEL CYCLE

Self-Check Questions 1-3

INSTRUCTIONS: Fill in the missing words in each statement. Answers are located in the answer key section of the Trainee Guide. Choose from the following words.

10
allegations
Chemical
enforcing
Enriched
Enrichment
fuel
health
high
inspecting
licensed
nuclear
public
radiological safety
regulation
uranium
waste

1. The Nuclear Regulatory Commission (NRC) licenses and inspects all commercial nuclear fuel facilities involved in the processing of ________________ ore, the ________________of uranium, and the fabrication of ___________________ uranium into nuclear reactor_____________________.

2. NRC regulations are issued under the United States Code of Federal Regulations (CFR) Title _______________________, Chapter I.

3. The NRC fulfills its responsibilities through a system of licensing and regulatory activities that include:

   Licensing the siting, design, construction, operation, and closure of low-level radioactive
   _____________________ disposal sites under NRC jurisdiction and the construction, operation, and closure of the geologic repository for _______________-level radioactive waste
   ___________________ licensed facilities and activities
   Developing and implementing rules and ___________________ that govern
   ___________________ nuclear activities
   Investigating ___________________ incidents and ___________________ concerning any matter regulated by the NRC
   ________________ NRC regulations and the conditions of NRC licenses
   Conducting ___________________ hearings on matters of nuclear and
   ________________, environmental concern, common defense and security, and antitrust matters

4. The objectives of the NRC regulations are to protect the ___________________ and safety of the public and plant workers from radiological and certain____________________hazards present at fuel cycle facilities.

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

MODULE 1.0: OVERVIEW OF THE NUCLEAR FUEL CYCLE

Learning Objective

When you finish this section, you will be able to:

1.1.3 Identify chemical and radiological properties of uranium.

CHARACTERISTICS OF URANIUM

Uranium was first discovered in the 18th century and is a naturally occurring element found everywhere on earth. It is present in nearly all rocks and soils. Natural uranium (U) consists of three isotopes: uranium-238, uranium-235, and uranium-234.

An isotope is an atom of an element with a specific atomic number and atomic mass. Isotopes of the same element have the same number of protons (atomic number) but different numbers of neutrons and different atomic masses.

Although all isotopes of uranium have similar chemical properties, each of the isotopes has significantly different nuclear properties. The majority (99.276%) of all atoms in natural uranium are U-238. Most of the remaining atoms (0.711%) are U-235, and a slight trace (0.0057%) are U-234.

The natural abundances of these isotopes are given in Table 1-3, Uranium Isotopic Percent (%) Abundances. The isotope U-235 is usually the desired material for use in light-water reactors.

Table 1-3. Uranium Isotopic Percent (%) Abundances [Grams (gm) of Isotope per 100 gm of Natural Uranium]

Isotope	Half-Life	% Natural Abundance	% Specific Activity per 100g of Natural Uranium	Typical Commercial Feed Enrichment	Depleted
U-238	4.5×10^9y	99.27	.89	97.01	99.75
U-235	7.1×10^8y	0.711	4.14	2.96	0.25
U-234	2.5×10^5y	0.0057	94.8	0.03	0.0005

The world average concentration of uranium in soil is about 1 part per 1 million (ppm) and ranges from about 0.3 ppm to 3 ppm. It is estimated that uranium in the earth's crust varies to 2 ppm to 4 ppm. The average uranium concentration in United States soils is about 1.5 ppm.

Higher levels of uranium are found in the surface soils of such areas as the Colorado Plateau, lands affected by the phosphate tailings in Florida and elsewhere, such as the Reading Prong in northeastern Pennsylvania, northern New Jersey, and southeastern New York.

Uranium never occurs naturally in the free state but is found as an oxide or complex salt in minerals such as pitchblende and carnotite. It has an average concentration in the crust of the earth of about 2 parts per 1 million, and, among the elements, ranks about 48th in natural abundance in crustal rocks.

Uranium is economically recoverable from a large number of relatively low-grade ores because it is associated with precious metals. For example, South African gold ores contain approximately six times as much uranium as gold. Similarly, ores mined for their copper, vanadium, chromium, etc. are profitable sources of uranium, which is concentrated in the milling and recovery operations for the primary materials of interest.

Radiological Properties of Uranium

The U-234 and U-238 isotopes belong to one family, the uranium series Figure 1-13 and the U-235 isotope is the first member of another series called the actinium series. Both of these series are present in the nuclear fuel cycle. The most abundant of all naturally occurring radionuclides, thorium-232, is the first member of a long chain of successive radionuclides in yet another series called the thorium series. All of these radioactive series have several common characteristics. First is the fact that the first member of each series is very long-lived. A second characteristic common to all three naturally occurring series is that each has a gaseous member and, furthermore, that the radioactive gas in each case is a different isotope of the element radon. A third common characteristic is that the end product in each case is lead. There is also a fourth decay chain based upon neptunium. This no longer occurs naturally.

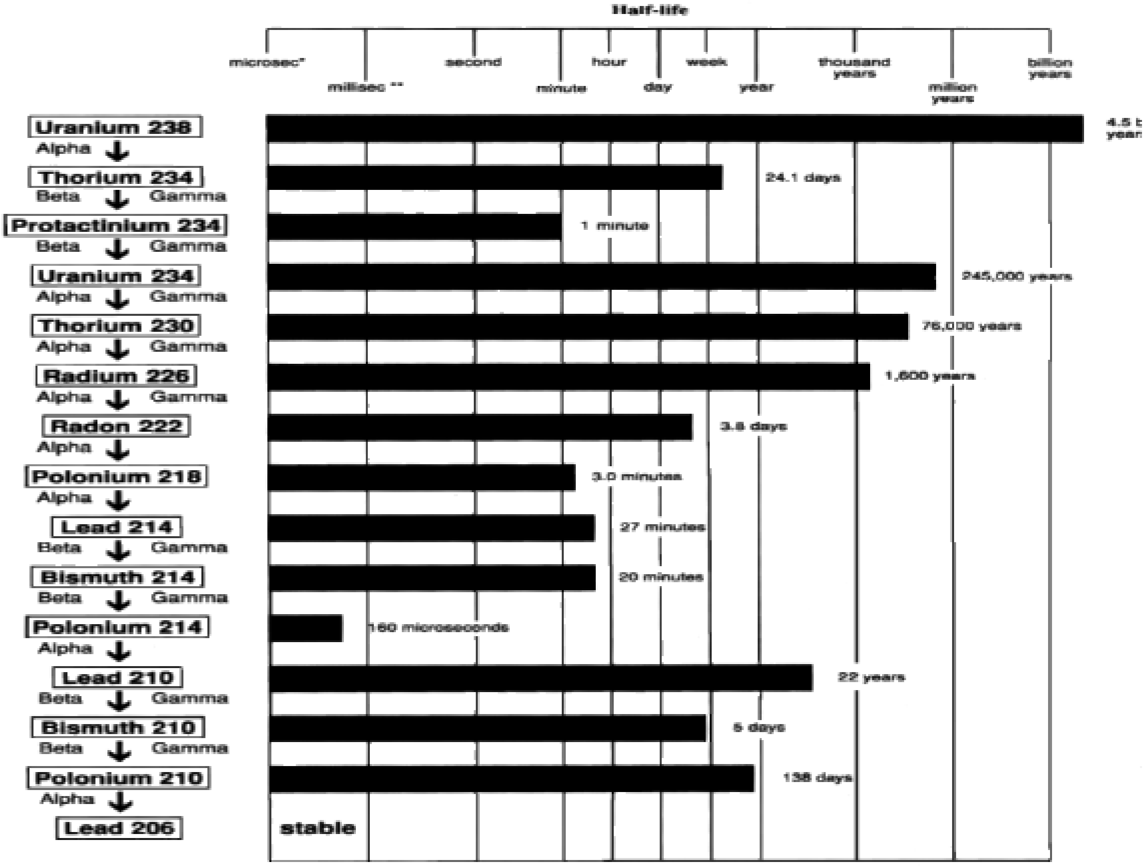
Radioactive Decay

Radioactive decay is the decrease in the amount of any radioactive material with the passage of time, due to the spontaneous transformation of an unstable nuclide into a different nuclide or into a different energy state of the same nuclide; the emission of nuclear radiation (alpha, beta, or gamma radiation) is part of the process.

When uranium-238 decays by alpha emission, thorium-234 is formed. Thorium-234 is a beta emitter and decays to form protactinium-234. Protactinium-234 in turn is a beta emitter, forming a new isotope of uranium, uranium-234. Uranium-234 decays in turn by alpha emission to yield the predominant isotope, radium-226. This radioactive decay series, called the uranium-radium series, continues similarly through five more alpha emissions and four more beta emissions until the end product, a nonradioactive (stable) isotope of lead (element 82) of mass 206 is reached. Every element in the periodic table between uranium and lead is represented in this series, and each isotope is distinguishable by its characteristic half-life.

The principal decay schemes for the uranium series (U-238) are shown in Figure 1-13, Uranium Decay Chain. Its starts with a long-lived radionuclide, includes a gaseous decay product (Rn), and ends with stable lead (Pb) as final member.

Figure 1-13. Uranium Decay Chain



*Microsec: 1/1,000,000 of a second

**Millisec: 1/1,000 of a second

Half-Life

Each individual radioactive substance has a characteristic decay period or half-life. A radiological half-life is the time in which half the atoms of a radioactive substance decays to another nuclear form; this varies for specific radionuclides from millionths of a second to billions of years.

When half-lives are so long that decay is not apparent within the observation period, the decrease of the activity of some radionuclides will not be observable under present methods. Thorium-232, for example, has a half-life of 14 billion years.

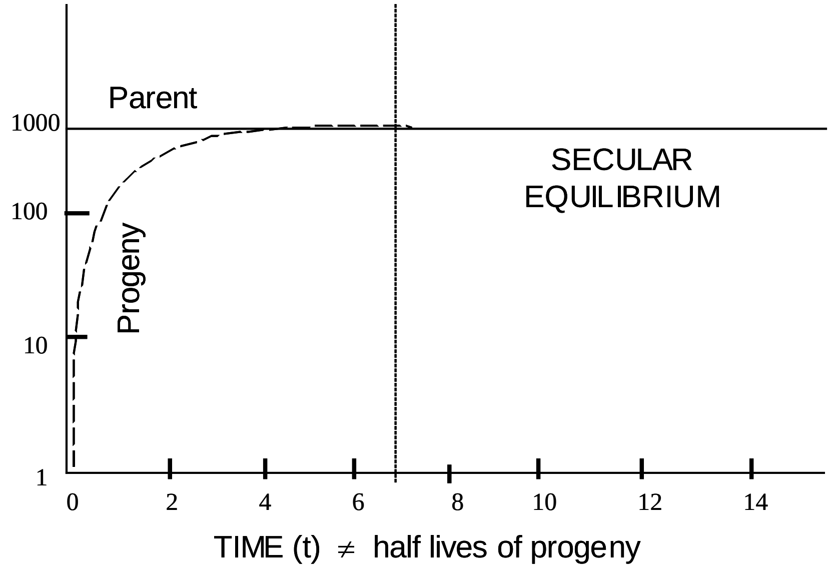
The decay of long half-lived materials, such as uranium-238 and thorium-232, appears to continue indefinitely without detectable decrease of the activity per unit mass of the radionuclide. Short half-lived materials show a marked decrease in activity with time. Among these is thorium-234, which, after isolation from uranium, decays to half its original activity within 25 days.

Decay Products

In the case where a very long-lived parent radionuclide decays into a relatively short half-life decay product, a situation known as secular equilibrium can be established. Secular equilibrium is the buildup of a very short-lived progeny from a long-lived parent. The activity of the parent remains constant. Given an initially pure sample of the parent (no progeny activity present), after 7-10 half-lives of the decay product, the decay product activity will increase and become equal to that of the parent activity. Thus, the total activity of the sample will be a constant at secular equilibrium, and the activities of parent and decay product will be the same.

For example, Ra-226 (1,600 year half-life) decays into Rn-222 (3 day half-life). After about 7-10 half-lives of Rn-222, or about 30 days, the activity of Rn in the sample will be equal to that of its parent Ra-226. This is shown in the Figure 1-17.

Figure 1-14. Secular Equilibrium



As a result of weathering and the various chemical properties of the members of the decay chains, the decay products may not all be present in their maximum equilibrium amounts. These decay products can represent the most significant hazard from uranium ore in the milling stages of the fuel cycle.

Typically, the most radiologically significant isotopes in natural uranium are radium and their decay products (radon and polonium). Following the purification of the uranium from the ore, these decay products will be removed. Therefore, in milling facilities, radium and its decay products would be expected to be a significant hazard, but would not be considered a hazard in other parts of the fuel cycle.

On the other hand, in newly purified uranium (U-234, U-235, and U-238), the immediate decay products of Th-234, Pa-234m, and Th-231 will have grown to their equilibrium levels within a few weeks. Because of the relatively short time for ingrowth of these products, they exist at all nuclear fuel cycle facilities. In addition, trace amounts of the other decay products may exist, so it is prudent to conduct analysis for them when appropriate.

Enrichment Effect

Enriched uranium has more than the normal or natural amount of the fissionable isotope U-235. The higher the enrichment, the smaller the mass generally required to sustain a chain reaction. The specific activity of uranium depends upon its degree of "enrichment," and normally describes only alpha activity. Specific activity increases with enrichment, not because of the replacement of U-238 with U-235, but primarily because of the increase in the amount of U-234 present. Gaseous diffusion enrichment technology causes a greater increase in U-234 than in

U-235. For example, when U-235 content is increased from 0.711% (natural) to 2.96% (a factor of approximately four), U-234 content increases from 0.006% to 0.03%, a fivefold increase.

Nuclear Criticality Safety

Nuclear criticality safety has been defined as the prevention or termination of an inadvertent nuclear chain reaction in nonreactor environments. Nuclear criticality control for uranium facilities involves measures to maintain conditions for processing, handling, storing, or transporting uranium such that a critical mass is prevented.

Nuclear energy is attractive because a relatively small mass of fissionable material can create a large amount of energy, which in turn can be used to heat water to drive turbines, etc. However, when a critical mass is accidentally assembled in an unprotected area, the relatively small mass and large release of energy can result in high radiation exposures to personnel, the release of radioactive materials to the environment, and the contamination of facilities.

Reclaimed or Recycled Uranium (REPU)

Some uranium feed material currently being handled has been reclaimed, or recycled, from reprocessed/spent reactor fuel. While recycling of commercial reactor fuel is not conducted in the United States, uranium has been recycled as part of the nuclear Navy program, and recycling is an option in other countries.

The chemical processes by which recycled uranium is purified leave trace amounts of transuranic material (neptunium and plutonium) and fission products (Technetium-99 [Tc-99]). Recycled uranium also contains trace amounts of uranium isotopes not found in nature, such as U-236. Due to the low concentrations of these impurities and the fact that most uranium is not recycled, the radiological impact of these impurities is negligible in most cases. However, there are many routine chemical processes that tend to concentrate these impurities either in uranium products or in by-product materials. In these cases, appropriate radiological controls and effluent/environmental monitoring programs need to be instituted.

Self-Check Questions 1-4

INSTRUCTIONS: Fill in the missing words in each statement. Answers are located in the answer key section of the Trainee Guide. Choose from the following words.

Fill in the missing words or numbers in each statement. Answers are located in the answer key section of the Trainee Guide. Choose from the following words or numbers:

234 actinium different exposures half-life hazard
higher gaseous lead long-lived materials prevention
radium safety smaller specific uranium U-235

1. Naturally occurring uranium consists of three isotopes: uranium-238, uranium-235, and uranium- ___________________ .
2. The isotope ___________________ is usually the desired material for use in lightwater reactors.
3. The U-234 and U-238 isotopes belong to one family, the ___________________ series, and the U-235 isotope is the first member of another series called the__________________series.
4. Each individual radioactive substance has a characteristic decay period or _______________.
5. Decay products can represent the most significant ___________________ from uranium ore in the mining and milling stages of the fuel cycle.
6. Typically, the most radiologically significant isotopes in natural uranium are isotopes of ______________________ and its decay products (radon and polonium).
7. The ___________________ the enrichment, the ___________________ the mass generally required to sustain a chain reaction.
8. Nuclear criticality ___________________ has been defined as the ___________________or termination of an inadvertent nuclear chain reaction in nonreactor environments.

9. If a critical mass is accidentally assembled in an unprotected area and a release of energy occurs, the following may happen:

   - ◙ high radiation __________________ to personnel
   - ◙ release of radioactive __________________ to the environment
   - ◙ contamination of facilities

10. The concentration of uranium products or by-product materials can result in higher activity.

11. The common characteristics of the three naturally occurring uranium isotopes include:

   - ◙ The first member of each series is very __________________.
   - ◙ Each has a __________________ member and the radioactive gas in each case is a __________________ isotope of the element radon.
   - ◙ The end product in each case is __________________.

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

MODULE 1.0: OVERVIEW OF THE NUCLEAR FUEL CYCLE

Learning Objective

When you finish this section, you will be able to:

1.1.4 Identify uranium compounds and their importance to the nuclear fuel cycle.

URANIUM COMPOUNDS

Table 1-4 lists some of the common compounds that are encountered in the nuclear fuel cycle. Their importance and some of the compounds' physical/chemical characteristics are also listed.

Uranium hexafluoride (UF_6) is a key compound in the U.S. fuel cycle. See following section for a discussion of UF_6. See also Module 4.0, Uranium Enrichment, section 4.1.3.

Table 1-4. Uranium Compounds

COMPOUND	IMPORTANCE	PHYSICAL/CHEMICAL CHARACTERISTICS
OXIDES		
Uranium Dioxide UO_3 (Brown Oxide, or Uraninite)	◙ Widely used to form pellets ◙ Reaction of UO_3 with hydrogen fluoride to produce uranium tetrafluoride is of great importance as an intermediate step in the production of uranium hexafluoride	◙ When pressed and sintered, UO_3 is stable when exposed to air or water below 570° F ◙ Inert to heated steam ◙ Melts at about 4500° F ◙ Can be dissolved in nitric acid or concentrated sulfuric acid ◙ Finely powdered form ignites spontaneously
Uranium Trioxide UO_3 (Orange Oxide)	◙ Intermediary in the conversion of uranium oxides to Uranium Hexafluoride	◙ Readily formed by thermal decomposition of such uranyl compounds as Peroxides, Carbonates, Oxalates, Ammonium urinate, uranyl nitrate ◙ Can be dissolved in nitric or sulfuric acid ◙ Decomposes when heated
Triuranium Octoxide U_3O_8 (Yellowcake)	◙ Product from uranium milling operations	◙ Can be dissolved in nitric or sulfuric acid ◙ Decomposes when heated
Uranium Peroxide $UO_4 – xH_2O$	◙ Important in uranium purification ◙ Dehydration of UO_4 yields UO_3	◙ Slightly soluble in water and dissolves in HCI ◙ Prepared b y added hydrogen peroxide to uranyl nitrate solution to cause its precipitation
FLUORIDES		
Uranium Tetrafluoride UF_6 (Green Salt)	◙ Key compound in uranium conversion plants for use as a fuel for uranium enrichment by gaseous diffusion or gas centrifugation	◙ Prepared by hydrofluorinaton of UF_2 with excess gaseous HF ◙ Volatile ◙ Dissolves in concentrated nitric acid, hot sulfuric acid, or perchloric acid ◙ Melts at 1832° F ◙ Highly corrosive
Uranium Hexafluoride UF_6	Produced on large scale at conversion plants for use as fuel for uranium enrichment by gaseous diffusion or gas centrifugation	◙ Prepared by direct fluorination of UF_4 with fluorine ◙ Forms volatile crystals ◙ Sublimes at room temperature and atmospheric pressure ◙ Melts under elevated pressure ◙ Highly corrosive ◙ Reacts vigorously with water, alcohol, either, an most metals

Table 1-4. Uranium Compounds

COMPOUND	IMPORTANCE	PHYSICAL/CHEMICAL CHARACTERISTICS
	NITRATES	
Uranyl Nitrate Hexahydrate $UO_2(NO_3)$ – $6H_2O$) or UNH (Yellow Nitrate Hexahydrate)	◙ Important in the recovery of uranium from process waste ◙ Important in the reprocessing of irradiated fuels ◙ Its solubility in organic solvents allows the use of solvent extraction to remove uranium from aqueous nitrate solutions	◙ Prepared by evaporating a neutral solution to a temperature of 244° F and allowing to cool to room temperature ◙ Insoluble in dilute alkaline solutions, but is very soluble in acids and organic solvents, such as diethyl ether

Self-Check Questions 1-5

INSTRUCTIONS: Match the uranium compounds listed in column A with the characteristic/comment listed in column B. Answers are located in the answer key section of the Trainee Guide.

Column A Uranium Compounds	Column B Characteristic/Comment
A. Uranium Trioxide (UO_3)	1._____Produced at conversion plants
B. Uranium Dioxide (UO_2)	2._____Important in uranium purification
C. Uranium Hexafluoride (UF_6)	3._____Decomposes when heated
D. Uranium Tetrafluoride (UF_4)	4._____Widely used to form pellets
E. Uranyl Fluoride (UO_2F_2)	5._____Key compound in uranium conversion
F. Triuranium Octoxide (U_3O_8)	6._____Hazardous in liquid and gaseous form
G. Uranium Peroxide (UO_4 x H_2O)	7._____Also known as yellowcake

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objective

When you finish this section, you will be able to:

1.1.5 Identify physical and chemical properties of UF_6

URANIUM HEXAFLUORIDE

Uranium hexafluoride (UF_6) is a compound of uranium and fluorine. It is used by the gaseous diffusion plants in the enrichment process because it can conveniently be used as a gas for processing, as a liquid for feeding and withdrawing, and as a solid for storage. Each of these states is achievable at relatively low temperatures and pressures. UF_6 exhibits ideal gas behavior. UF_6 is also used because fluorine exists as one isotope, so separation by means of the uranium hexafluoride is effective in enriching U-235.

In the solid state, UF_6 is a nearly white, dense crystalline solid. The appearance of the solid is a function of whether it was formed by freezing from the liquid phase or desubliming from the vapor phase. In the first case, the solid particles will be irregularly shaped grains somewhat like rock salt (see Figure 1-18), and in the second case, the solid will be an amorphous mass. The liquid is colorless and, even though it is very heavy, has a low viscosity so it flows freely and completely wets the surface of its container. The liquid phase is not stable at atmospheric pressure. The pure gas is colorless.

Uranium hexafluoride does not react with oxygen, nitrogen, carbon dioxide, or dry air; however, each of these gases is soluble in the UF_6 liquid phase, and very much less soluble in the solid phase. Gaseous UF_6 does react rapidly with water vapor as does the exposed surface of solid UF_6. This reaction can cause corrosive and toxic hydrofluoric acid to be formed which can be lethal to operators. Because of this, UF_6 is always handled in leak-tight containers and processing equipment to prevent it from reacting with water vapor in the air. The operator must follow the presence of UF_6 by observing changes in pressure or weights. Such changes are illustrated by means of a phase diagram that shows the physical state, i.e., solid, liquid, or gas, of UF_6 as a function of its pressure and temperature. It should be noted that these data are for UF_6 alone, as a single-component system. If air, nitrogen, hydrogen fluoride or other gases are present, the total pressure condition for a given temperature will be higher, i.e., the sum of the partial pressures of the system components.

Figure 1-19 shows the phase diagram covering the range of conditions usually encountered in working with UF_6. It shows the correlation of pressure and temperature with the physical state of the UF_6. The triple point occurs at 22 psia (pounds per square inch absolute) and 147.3°F. These are the only conditions at which all three states: solid, liquid, and gas can exist together in equilibrium. If the temperature is greater than at the triple point, there will be only gas or liquid. If the temperature or pressure is lower, there will be only solid or gas. For instance, at atmospheric pressure, 14.7 psia, there can only be gas or solid regardless of the temperature. At 100°F, for example, the pressure of gas over solid is 5 psia. This is a typical condition in a UF_6 cylinder in storage.

Figure 1-16 also shows the terms used to describe the changes of phase that occur as temperature and/or pressure are altered. Below the triple point, solid UF_6 sublimes to gas, and gaseous UF_6 desublimes to solid. Above the triple point, liquid UF_6 vaporizes to gas, and gaseous UF_6 condenses to liquid. At 147.3°F and pressures above 22 psia, liquid UF_6 and solid UF_6 exist in equilibrium with no driving force for phase alteration.

As heat is added to solid UF_6 in a closed system, the solid mass absorbs heat and some of it sublimes to gas. Sublimation continues until the pressure of 22 psia and the temperature of 147.3°F are reached, at which point solid, gas, and liquid coexist. Additional heat incrementally melts the remaining solid, and when all of the solid UF_6 has melted, further addition of heat increases the temperature of the liquid and causes a portion of the liquid to vaporize to gas.

Figure 1-15. UF_6 Crystals

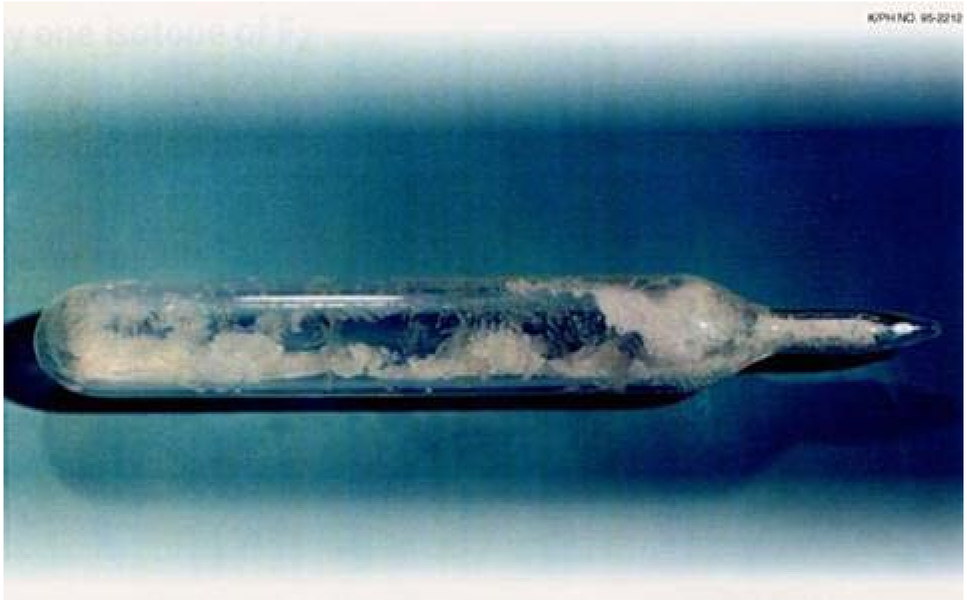
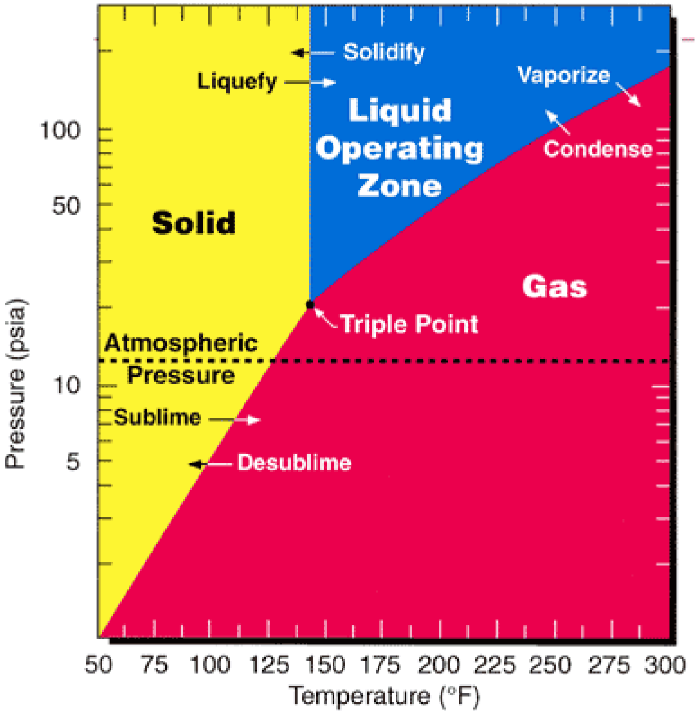


Figure 1-16. UF_6 Phase Diagram



Chemical and Physical Characteristics of UF_6

The following are chemical and physical characteristics of UF_6:

- A nearly white, dense, crystalline solid at room temperature and atmospheric pressure; colorless in a gaseous state.
- Increases in volume by more than 30% as it changes from a solid to a liquid.
- Highly reactive with water, oil, and organics (skin and membranes).
- Highly reactive with glass, rubber, and most metals.
- Not reactive with oxygen, nitrogen, hydrogen, and dry air at room temperature.
- Not reactive with aluminum, copper, nickel, Monel, and Teflon.
- Severely corrosive and toxic when concentrated; shipped in special steel cylinders as a crystalline solid.
- Reactive with water or moisture in the air to form uranyl fluoride (UO_2F_2), and hydrogen fluoride (hydrofluoric acid).
- Not flammable.

Other Considerations

- Some considerations to think about:
- Types of hazards associated with enrichment are quite different from those associated with nuclear reactors, fuel reprocessing, or radioactive waste disposal.
- Enrichment process involves only natural, long-lived radioactive materials; there is no formation of fission products or irradiation of materials, as in a reactor.
- Enrichment plant feed, product, and depleted material are all in the form of UF_6, the sole difference being their respective U-235 concentrations.
- Protective measures required for an enrichment plant are similar to those taken by other chemical industries concerned with the production of fluorinated chemicals.
- Exposure of the UF_6 gas to the atmosphere can lead to the formation of other compounds, but any effects remain essentially chemical.

Self-Check Questions 1-6

INSTRUCTIONS: Complete the following questions. Answers are located in the answer key section of the Trainee Guide.

1. Why is uranium hexafluoride used in gaseous diffusion plants?

2. Describe the appearance of UF_6 when it is a solid.

3. List some chemical characteristics of liquid UF_6.

4. List some chemical characteristics of gaseous UF_6.

5. Why should precautions be taken to avoid introducing hydrocarbon oil into processing equipment or cylinders?

6. What does a UF_6 phase diagram show?

7. Where is the triple point on the UF_6 phase diagram and what is its significance?

8. What phase(s) will UF_6 be in if the temperature or pressure is greater than at the triple point?

9. What phase(s) will UF_6 be in if the temperature or pressure is less than at the triple point?

10. What happens if heat is added to solid UF_6 in a closed system?

You have completed this section.
Please check off your progress on the tracking form.
Go to Activity 2.

Activity 2 – UF_6

PURPOSE: The purpose of this activity is to provide a basic understanding of the phases of UF_6.

INSTRUCTIONS: Complete the following activity. Answers are located in the answer key section of the Trainee Guide.

1. What atoms make up the uranium hexafluoride compound?

2. What is the triple point?

3. What are three ways UF_6 reacts with heat?

4. What two phases of UF_6 are present at atmospheric pressure?

5. How is UF_6 usually removed from a cylinder?

6. What would happen if a cylinder containing UF_6 was punctured?

7. What is the white smoke that is released when UF_6 is exposed to the atmosphere?

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objective

When you finish this section, you will be able to:

1.1.6 Identify costs and economic considerations.

URANIUM QUANTITY AND ECONOMIC ESTIMATES

The quantities of materials involved in the nuclear fuel cycle are small compared to other energy industries because of the concentrated nature of nuclear energy. Rough estimates of uranium quantities and economics (assumptions noted generally 2008 basis) for a 1,000 MWe nominal light water reactor (LWR) are as follows:

Front End

Mining and Recovery

Uranium ores vary significantly in terms of concentrations; some are below as 0.1% while others are as high as 30% uranium. Using 1% as a basis, 20,000 te of ore (either mined or in-situ leached) produces about 200 te uranium (as U3O8). The uranium price is about $40/lb (late 2008) and increasing; at $40/lb, this becomes around $18 M.

Conversion

This requires conversion to UF_6 at an assured cost of $10/kgU, which becomes about $2 M.

Enrichment

LWRs require low enriched uranium (LEU). Enrichment to the 4.5-5% range requires about 5 SWU/kg LEU for a total of 150,000 SWU; at around $100/SWU, this becomes $15 M. This generates about 30 te of LEU and 170 kg of depleted uranium (DU).

Fuel Fabrication

For approximately 30 te uranium and assuring $200/kg for the fabrication cost, it becomes about $6 M.

The total front end costs of the fuel cycle are about $40 M per reload, corresponding to $1,400/kg. This equates to around $700,000 for a pressurized water reactor assembly.

Back End

Mining and Recovery

There are no significant hidden or back-end costs associated with in-situ leach. Costs associated with conventional mills are larger but still remain a small percentage.

Conversion

There are no significant hidden or back-end costs; expected decommissioning and waste management costs are included in the conversion price.

Enrichment

Depleted uranium is the only back-end cost.

Depleted Uranium

The 170 te of DU is assured to cost $10/kg for disposition, for a total of around $2 M.

Fuel Fabrication

There are no significant hidden or back-end costs; decommissioning and waste management costs are included in the price.

Spent Nuclear Fuel (SNF) Storage

Storage casks hold about 12 te of SNF and cost $400,000 to $500,000 a piece. Two or three cask equivalents would be needed for SNF from a reload for a total of around $2 M.

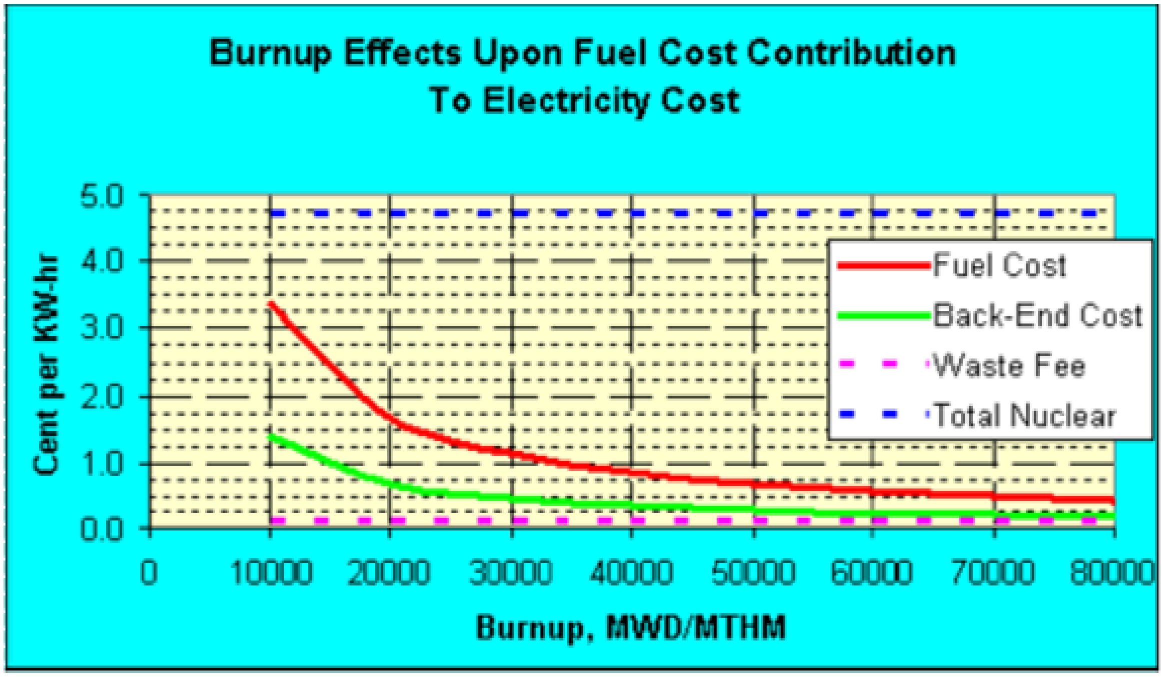
Direct Disposal or Reprocessing

Direct disposal costs are only estimated because no SNF disposal has occurred yet; current (2008) estimates correspond to around $1,000/kg. Reprocessing has been performed under contracts at the European facilities for a price around $1,000. Either approach produces a charge of around $30 M. No benefit is assigned to recovered uranium (REPU) either for its resource saving or residual enrichment value.

Total Cost

The total fuel cycle cost is around $74 M per reload. The front end costs represent about 60% of the total fuel cycle cost. The total back-end costs accrue to around $34 M. Figure 1-20 shows that fuel cycle costs remain a small percentage of the total cost of electricity generated by nuclear power.

Figure 1-17. Contribution to Electrical Cost Estimate



Waste fee is 1 cent per KW-hr. Assumes 33% efficiency, 24 Te U reload.
Total new nuclear electricity cost from EPRI/Energy Daily, February 27, 2006

It's time to schedule a progress meeting with your administrator. Review the progress review meeting form on the next page. In Part III, as a Regulator, write your specific questions to discuss with the administrator.

PROGRESS REVIEW MEETING FORM

Date Scheduled: ________________________________**Location:**______________________

I. The following suggested items should be discussed with the administrator as to how they pertain to your current position:

- Nuclear fuel cycle flow diagram
- NRC regulations
- Chemical and radiological properties of uranium
- Uranium compounds
- Physical and chemical properties of UF_6
- Costs and economic considerations.

II. Use the space below to take notes during your meeting.

III. As a Regulator:

- Which area of the nuclear fuel cycle will I need to become most familiar with in my work?
- Which regulations should I review for my present duties?
- Tell me more about oxides, fluorides, and nitrates and their effect on problems that have occurred in a particular fuel cycle facility.
- What do you think is important for me to remember about UF_6 and its physical and chemical properties?

Use the space below to write your specific questions.

IV. Further assignments? If yes, please note and complete. If no, initial completion of progress meeting on tracking form.

Ensure that you and your administrator have dated and initialed your progress on your tracking form for this module.
Go to the Module Summary.

MODULE SUMMARY

Key Points:

- The NRC licenses and inspects all commercial nuclear fuel facilities involved in the processing of uranium ore, enrichment of uranium, and fabrication of enriched uranium into nuclear reactor fuel. The NRC does not regulate mining.
  - 10 CFR Part 40 – recovery and conversion
  - 10 CFR Part 70 – fuel fabrication, MOX and new enrichment facilities
  - 10 CFR Part 76 – gaseous diffusion facilities
- Chemical and metallurgical operations that make up the nuclear fuel cycle include
  - Uranium mining (open-pit/deep mines)
  - Milling/uranium recovery (including in-situ leach)
  - Conversion of uranium (dry conversion)
  - Enrichment of uranium (gaseous diffusion/preparing for gas - centrifuge)
  - Fabrication of uranium fuel
  - Generation of electricity by a light-water-cooled nuclear power plant using uranium fuel (input - fuel assemblies)
  - Spent fuel storage
  - Reprocessing
  - Waste disposal
- Natural uranium consists of three isotopes and associated (%) abundances:
  - U-238, 99.276%
  - U-235, 0.711%
  - U-234, 0.0057%

- Radioactive decay is the decrease in the amount of radioactive material with time. Nuclear radiation emission (alpha, beta, or gamma) is a spontaneous decay process. Decay products are a significant hazard from uranium ore. Radiologically significant isotopes are radium and the decay products, radon and polonium. Recovery strips away decay products.
- Uranium compounds can be categorized into: oxides, fluorides, nitrates
    - UF_6 is produced at conversion plants
    - U_3O_8 is yellowcake
    - UO_2 is dominant fuel type used to produce pellets
- Uranium hexafluoride, or UF_6, is a compound of uranium and fluorine and is used in gaseous diffusion and gas centrifuge plants to enrich U-235.
- UF_6 goes from solid state to liquid to gas in a series of phases. Change is a function of pressure and temperature.
    - Solid for storage
    - Liquid for feeding/withdrawing
    - Gas for processing
- The total fuel cycle cost is around $74 M per reload. Total front end costs of the fuel cycle are about $40 M per reload, corresponding to $1,400/kg. This equates to around $700,000 for a PWR assembly. The front end costs represent about 60% of the total fuel cycle cost. The total back-end costs accrue to around $34 M.

Congratulations! You are ready to go to the next assigned module.