MODULE 1.0: INTRODUCTION TO URANIUM ENRICHMENT

Introduction

Welcome to Module 1.0 of the Uranium Enrichment Processes Directed Self-Study Course! This is the first of seven modules available in this self-study course. The purpose of this module is to assist the trainee in describing the role of enrichment in the nuclear fuel cycle; to identify where uranium occurs in nature; to identify chemical, physical, and radiological properties of uranium and uranium hexafluoride; to introduce five enrichment technologies and enrichment activities of historical significance; to identify the NRC's responsibilities related to uranium enrichment, and to identify safety concerns related to the shipping and handling of uranium hexafluoride. This self-study module is designed to assist you in accomplishing the learning objectives listed at the beginning of the module. The module has self-check questions 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 prerequisite:

- ☐ None

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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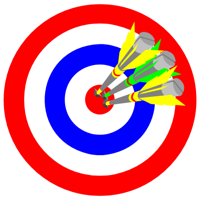


1.1 Upon completion of this module, you will be knowledgeable about the basics of uranium enrichment as it relates to the nuclear fuel cycle.

1.1.1 Describe the role of uranium enrichment in the nuclear fuel cycle.

1.1.2 Identify where uranium occurs in nature.

1.1.3 Identify chemical, physical, and radiological properties of uranium and uranium hexafluoride.

1.1.4 Identify five uranium enrichment processes.

1.1.5 Identify the NRC's responsibilities related to uranium enrichment.

1.1.6 Identify safety concerns related to uranium hexafluoride cylinders.

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 (J/g: about 20,000 BTUs/lb) 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.

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 form helium, releasing about 20 MeV (million electron volts) the energy is released (primarily as heat) or about 48E10 J/g of hydrogen. Significant science and engineering advances are currently needed to make fusion a practical source of energy.

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 (U-235) is naturally occurring in significant quantities, where it is found isotopically diluted to around 0.71% (sometimes called the natural assay) with another, more abundant uranium isotope, uranium-238 (about 99.274%). 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 J/g of U-235. Nuclear fission has been found to be a practical source of energy.

Figure 1-1. The Binding Energy of Nuclei

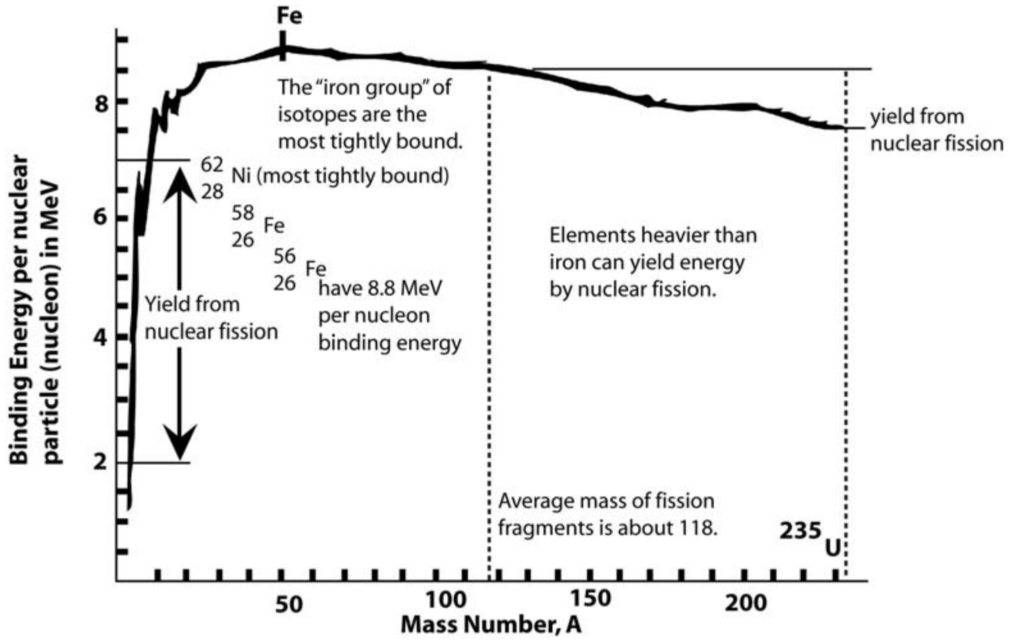
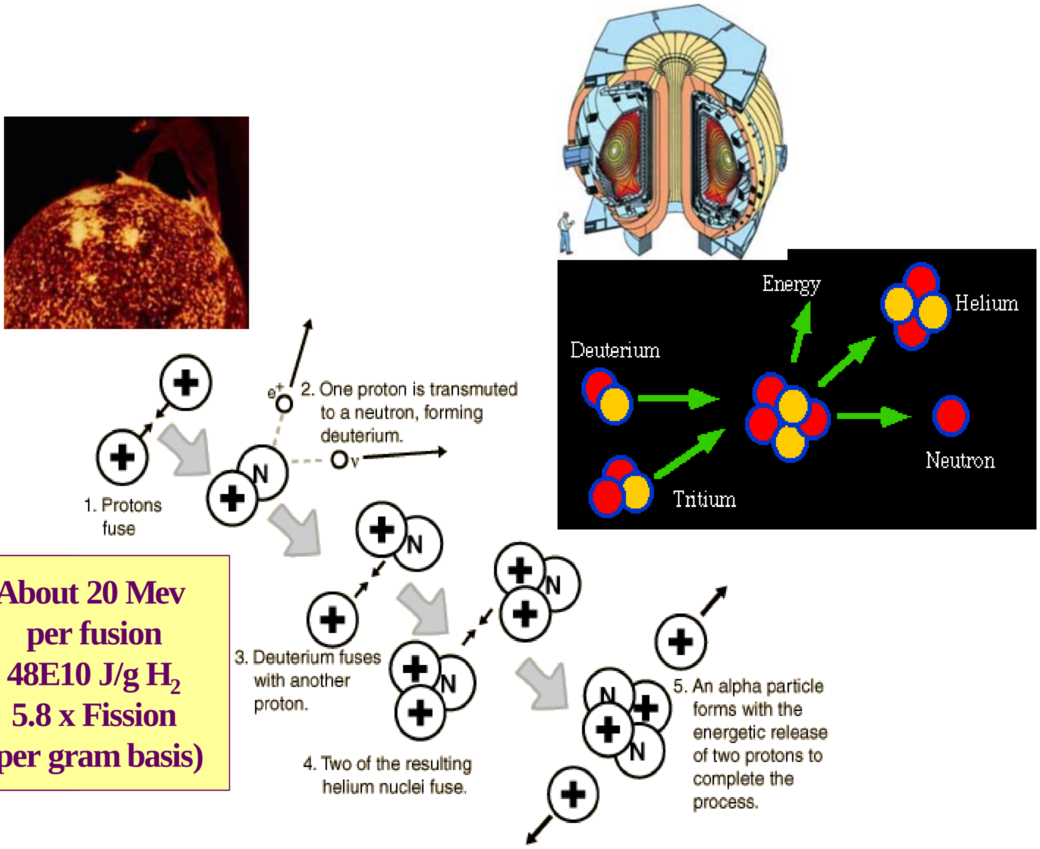
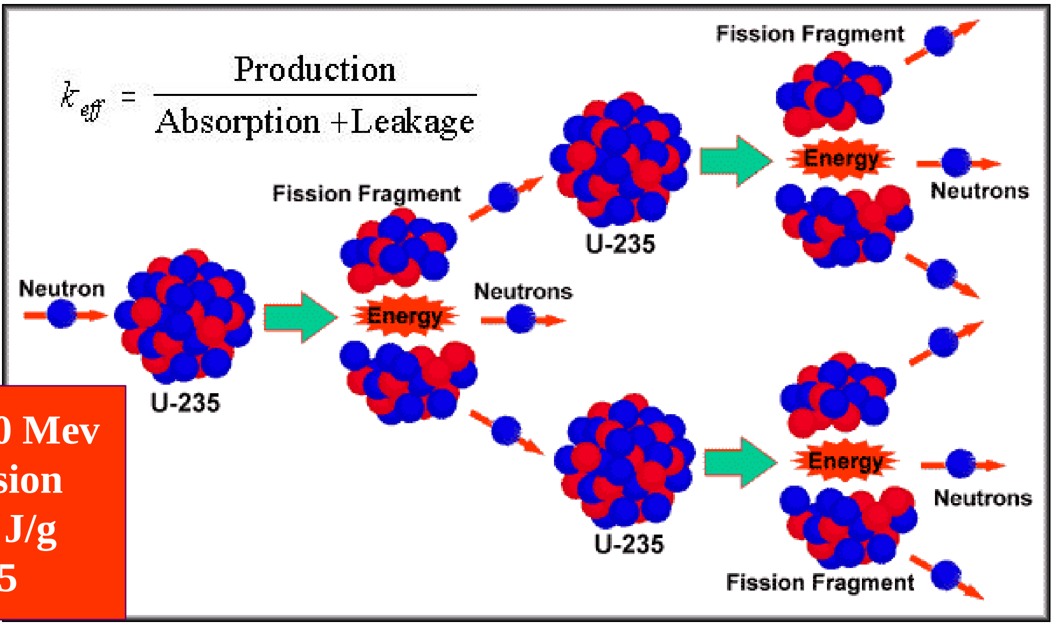


Figure 1-2. Fusion



About 20 Mev
per fusion
48E10 J/g H_2
5.8 x Fission
(per gram basis)

Figure 1-3. Nuclear Fission



$$k_{eff} = \frac{\text{Production}}{\text{Absorption} + \text{Leakage}}$$

About 200 Mev
Per Fission
8.3E10 J/g
U-235

Radioactive heavy elements like U-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 U-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% U-235) has an infinite critical mass under normal conditions (i.e., criticality cannot occur); criticality can only be obtained by increasing the concentration of U-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 U-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 likelihood 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 times more 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 (kilowatt-hours; 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. (megawatt electrical). 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

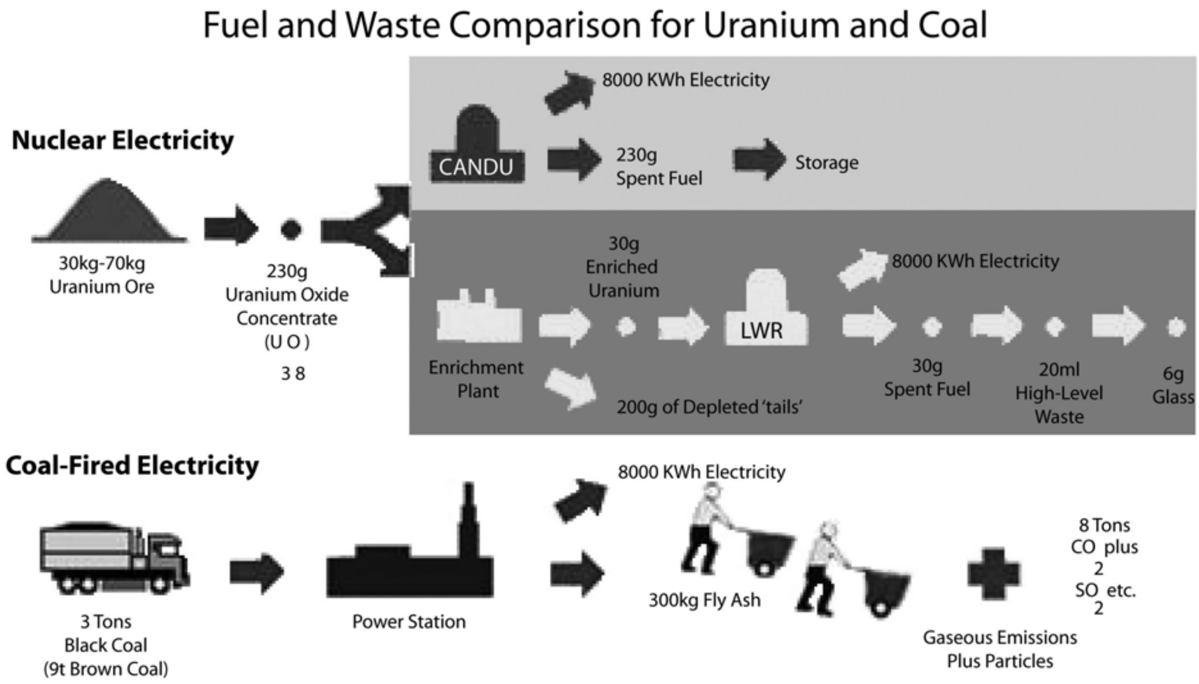
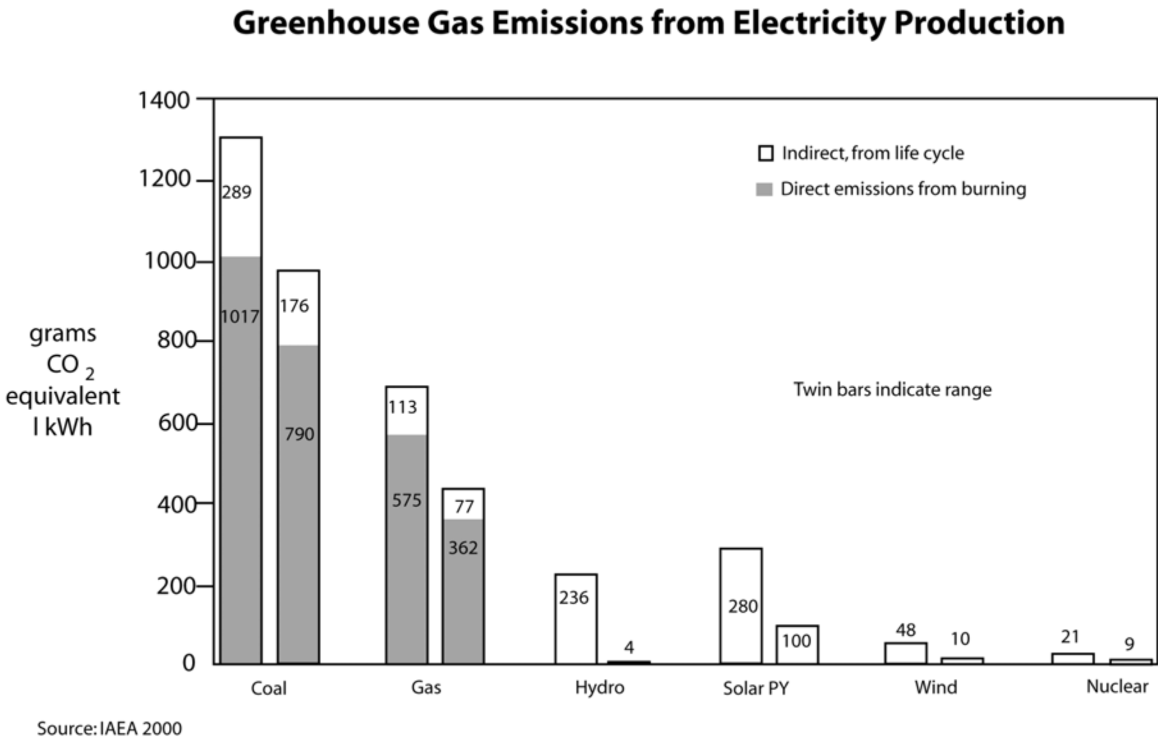


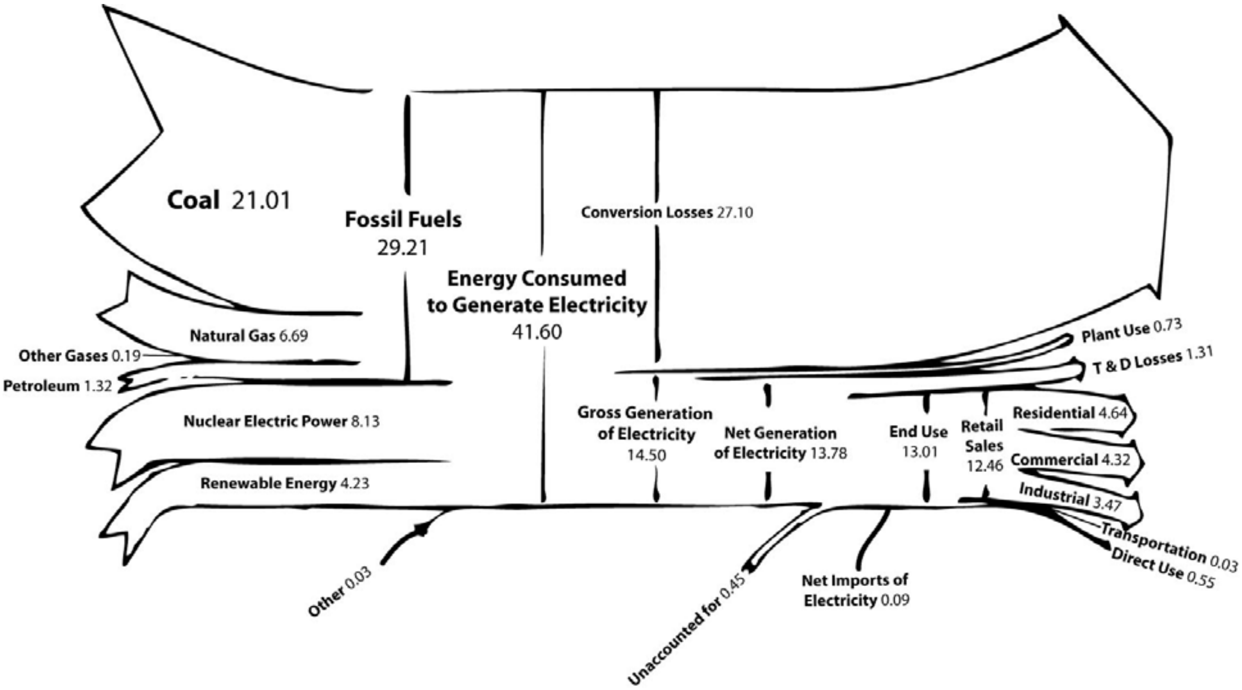
Figure 1-5. Greenhouse Gases



Source: IAEA 2000

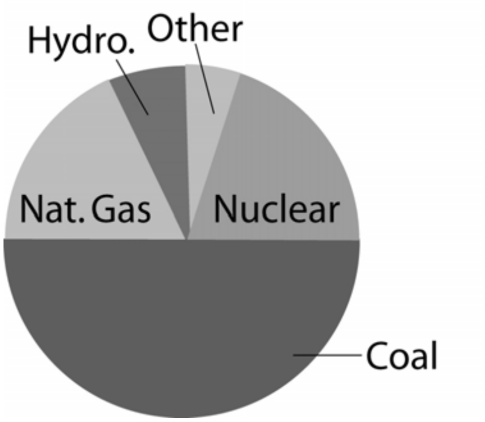
The United States uses about 101 Quads of energy (2005 data). Figure 1-6 shows the breakdown for generating electricity. Approximately 42% of the nation's total energy consumption is used to produce electricity; approximately 65% of this is lost in converting heat into electricity. This is about 25% of the world total energy. The U.S. also represents about 25% of the world's economy. This shows the linkage between energy and the economy. Figure 1-7 displays the principal generating methods for electricity. The 104 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 (gigawatt electrical), 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 total 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



(CY 2005 Values — note 65% conversion losses) (Values in Quads)

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 are 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 aerial views of 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.

Figure 1-8. Typical PWR Diagram

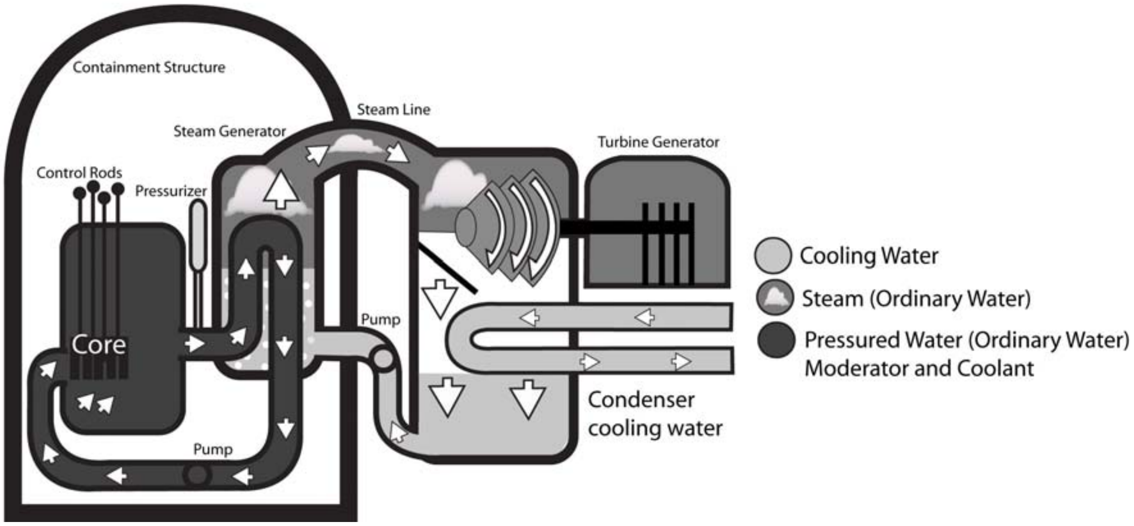


Figure 1-9. Typical BWR Diagram

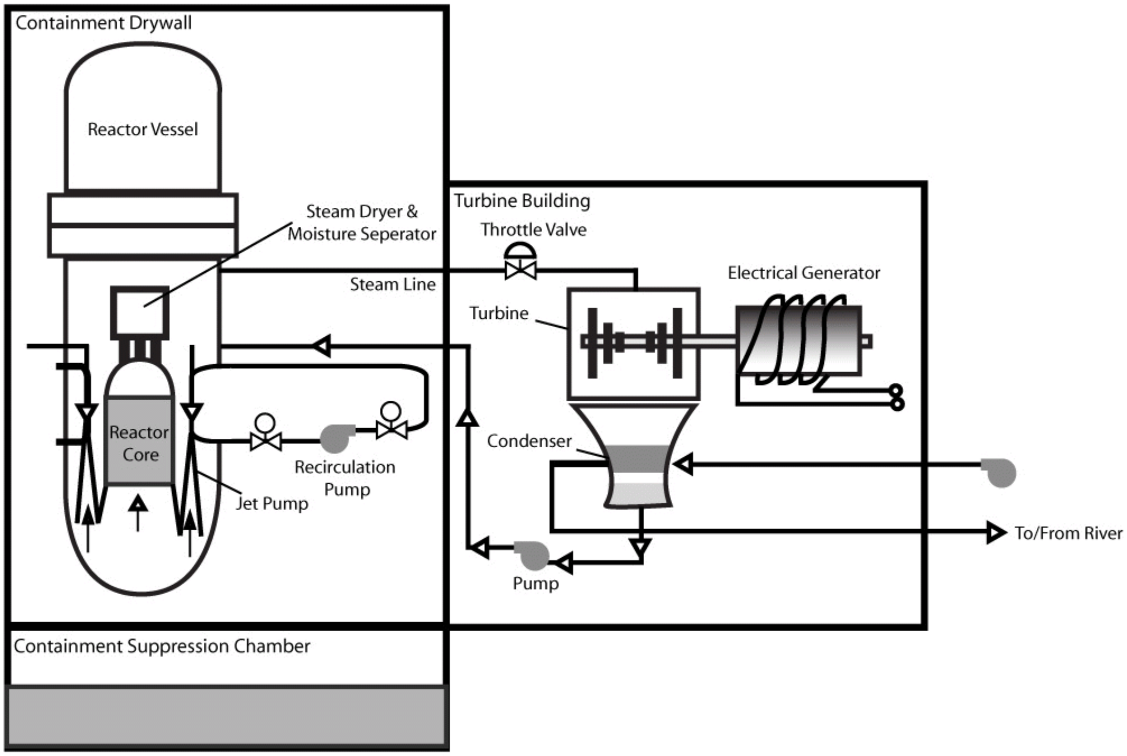
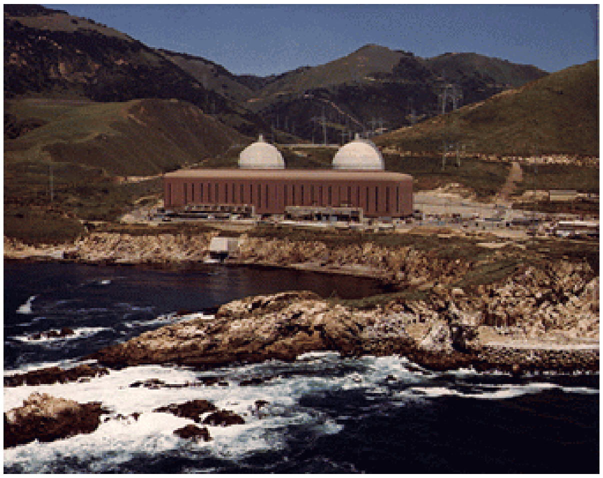


Figure 1-10. Typical Power Reactors



Self-Check Questions 1-1

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

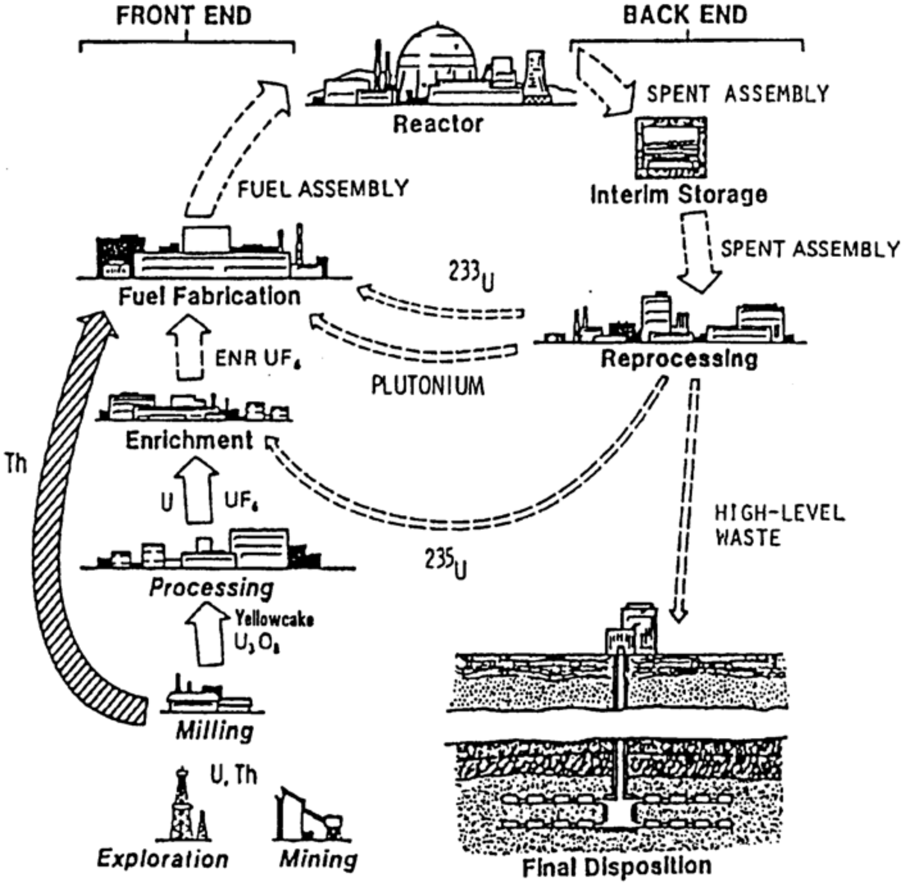
When you finish this section, you will be able to:

1.1.1 Describe the role of uranium enrichment in the nuclear fuel cycle.

THE NUCLEAR FUEL CYCLE

The nuclear fuel cycle includes a variety of processes utilizing uranium in different chemical and physical forms. Figure 1-11, Overview of the 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 Nuclear Fuel Cycle



Mining

Uranium ore is extracted from the earth through a variety of mining techniques. Traditionally, uranium was extracted from open pit and underground mines. In the past decade, alternative techniques such as in-situ leach (ISL) mining, in which solutions (called luxiviants) are injected into underground deposits to dissolve uranium, have become more widely used. There is renewed interest in mining uranium. However, at the present time imported uranium accounts for about 3/4 of the roughly 16,000 metric tons of refined uranium used domestically each year. The NRC regulates ISL mining but does not regulate other types of mining.

Recovery

A uranium recovery facility is a chemical plant designed to extract uranium from mined ore or uranium loaded, ISL luxiviants. The mined ore, brought to the recovery facility via truck, 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. For ISL, ion exchange resins recover uranium from the laded loaded luxiviants. Elution of the resins produces a concentrated uranium solution . Uranium is subsequent precipitated. The final product produced from the recovery, commonly referred to as "yellowcake" or "uranium ore concentrate" [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 recovery product is packaged and shipped in drums to a processing/conversion facility.

Processing/ Conversion

A uranium processing/conversion facility receives drummed yellowcake from a recovery facility and then converts it into uranium hexafluoride (UF_6). Honeywell International, Inc., located in Metropolis, Illinois, is the only processing/conversion facility presently operating in the United States. The final product of this facility is pure UF_6. It is produced as a liquid, then drained into 14-ton cylinders where it solidifies after cooling for approximately five days. (Note: 14-ton is the most commonly used cylinder, however, sometimes a 10-ton is used.) The UF_6 cylinder is then shipped off-site to the next step in the nuclear fuel cycle, which is enrichment.

Enrichment

Uranium enriched in U-235 is required in commercial light water reactors to produce a controlled nuclear reaction. All commercial enrichment facilities use UF_6 as the feed material. As previously mentioned, uranium hexafluoride is received at an enrichment facility from the processing/conversion facility in a 14-ton cylinder for enrichment. Enrichment allows the U-235 isotopes within the uranium hexafluoride to be increased from 0.711% (natural uranium) to a range between 2% to 5% (enriched uranium), depending on customer specifications. Currently, enriched uranium is produced in the United

States using the gaseous diffusion process. There are two gaseous diffusion plants in the United States, one at Piketon, Ohio, and the other at Paducah, Kentucky. The Paducah Gaseous Diffusion Plant (GDP) is currently operating, and the Portsmouth GDP in Piketon is in "cold standby" (since June 2001). Some sampling and transferring functions continue at the Portsmouth Plant. At these facilities, 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 converted later at a fuel fabrication facility to usable fuel for use in a light water reactor (LWR).

Two commercial plants utilizing gas centrifuge technology are planned for the U.S. Construction has started on one of these facilities.

Enrichments greater than 90% in U-235 are used in the U.S. Navy's nuclear propulsion reactors. For certain purposes, such as materials test reactors (e.g., the High Flux Isotope Reactor at Oak Ridge National Laboratory), enrichments of 93% to 97% have been used. It is now the policy of the U.S. government to encourage foreign research reactor operators to modify the reactor cores to utilize 19.75% ^{235}U.

Fuel Fabrication

Currently, there are seven fuel fabrication facilities operating in the United States:

- BWX Technologies (Naval) (Lynchburg, Virginia)
- Framatome ANP, Inc. (Richland, Washington)
- Framatome ANP, Inc. (Lynchburg, Virginia)
- Global Nuclear Fuel-Americas, LLC (Wilmington, North Carolina)
- Nuclear Fuel Services (Erwin, Tennessee)
- Westinghouse Electric (Columbia, South Carolina)
- ABB Combustion Engineering (Hematite, Missouri) (shutdown/D&D)

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

The enriched uranium hexafluoride product is sent to a fuel fabrication plant via a 2.5-ton cylinder, where it is introduced into a chemical process to convert the enriched uranium hexafluoride 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 that are shipped to nuclear reactor power plants via NRC- and Department of Transportation (DOT)-approved shipping containers.

Reactor

Fuel assemblies from a fuel fabrication facility are shipped to LWRs for use as fuel in power production. There are two types of LWRs: pressurized water reactor (PWR) and boiling water reactor (BWR). 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 a range of 225 to 289 fuel rods in an assembly and about 193 assemblies in its core. Typically in the United States up to one third of the assemblies are replaced each refueling because of the depletion of the U-235 and the buildup of fission products that absorb neutrons. Most commercial power reactors in the United States are refueled every 18 months, generally in either the spring or fall (the low peak power demand periods).

Spent Nuclear Fuel and Interim Storage

Spent nuclear fuel is irradiated reactor fuel that is no longer useful as fuel. Approximately 33% 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 from the reactor core 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 atom 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 assemblies under at least 20 feet of water, which provides adequate shielding from the radiation for anyone near the pool. The assemblies are moved into the water pools from the reactor along the bottom of water canals so that the spent fuel is always shielded.

If pool capacity is reached, licensees may move toward use of above-ground dry 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 metal container placed inside 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 stands vertically on a concrete pad. Dry storage is not suitable for fuel until the fuel has been out of the reactor for a few years and the amount of heat generated by radioactive decay has been reduced.

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 reprocessed 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 a gaseous diffusion 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.

High-Level Waste

Most (or nearly all) high-level waste (HLW) is generated either in a reactor, or if the fuel has been reprocessed, in the reprocessing facility. HLW 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, and solids into which such liquid wastes have been converted. HLW is primarily in the form of spent fuel from commercial nuclear power plants; it also includes some reprocessed HLW from defense activities and a small quantity of reprocessed commercial HLW. The current plan involves vitrification of HLW into a glass material, which is placed inside stainless steel containers. In general, reprocessing of SNF followed by HLW vitrification reduces repository waste volume significantly.

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 Yucca Mountain, Nevada, 100 miles northwest of Las Vegas.

On February 14, 2002, DOE recommended the Yucca Mountain site as a long-term repository for radioactive waste. On July 9, 2002, the U.S. Senate voted favorably on this site. As part of the license review, the NRC will review the scientific studies of Yucca Mountain and consider the site for a license. DOE plans to submit the license application for Yucca Mountain in 2008, and, if approved, will haul 77,000 tons of spent fuel and nuclear HLW to the repository.

Self-Check Questions 1-2 ✓

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 recovery designed to accomplish?

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

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 manufacturing?

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 the next section.

Learning Objectives

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

1.1.2 Identify where uranium occurs in nature.

1.1.3 Identify chemical, physical, and radiological properties of uranium and uranium hexafluoride.

CHEMICAL AND PHYSICAL 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. Naturally occurring 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 hence different atomic masses.

Although all isotopes of uranium have similar chemical properties, each of the isotopes has significantly different nuclear properties. The majority (99.2745%) of all atoms in natural uranium are U-238. Most of the remaining atoms (0.711%) are U-235, and a slight trace (0.0055%) are U-234.

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

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

Isotope	Natural	Typical Commercial Feed Enrichment	Depleted	Isotope Specific Activity Ci/g	Half-Life Years
U-238	99.2745	97.01	99.75	3.4 E-7	4.5 E9
U-235	0.711	2.96	0.25	2.2 E-6	7 E8
U-234	0.0055	4.5	0.0005	6.3 E-3	2.4 E5

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 from 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 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 ore bodies have been found that contain more than 10% U_3O_8, although ore bodies containing 0.3% have been worked commercially.

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 useful sources of uranium, which is concentrated in the 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 1-12), and the U-235 isotope is the first member of another series called the *actinium series* (Figure 1-13). Both of these series are present in the nuclear fuel cycle. Sometimes the actinium series is depicted as starting with plutonium-239, which alpha decays to U-235 The most abundant of all naturally occurring radioisotopes, thorium-232, is the first member of still another long chain of successive radioisotopes (Figure 1-14). 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 series is a different isotope of the element radon. A third common characteristic is that the end product in each series is a stable isotope of lead.

There is also a fourth decay chain based upon neptunium (Figure 1-15). 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 actinide series (U-235) is shown in Figure 1-16, Principal Actinium Series Decay Chain.

Figure 1-12. Uranium Series (U-238)

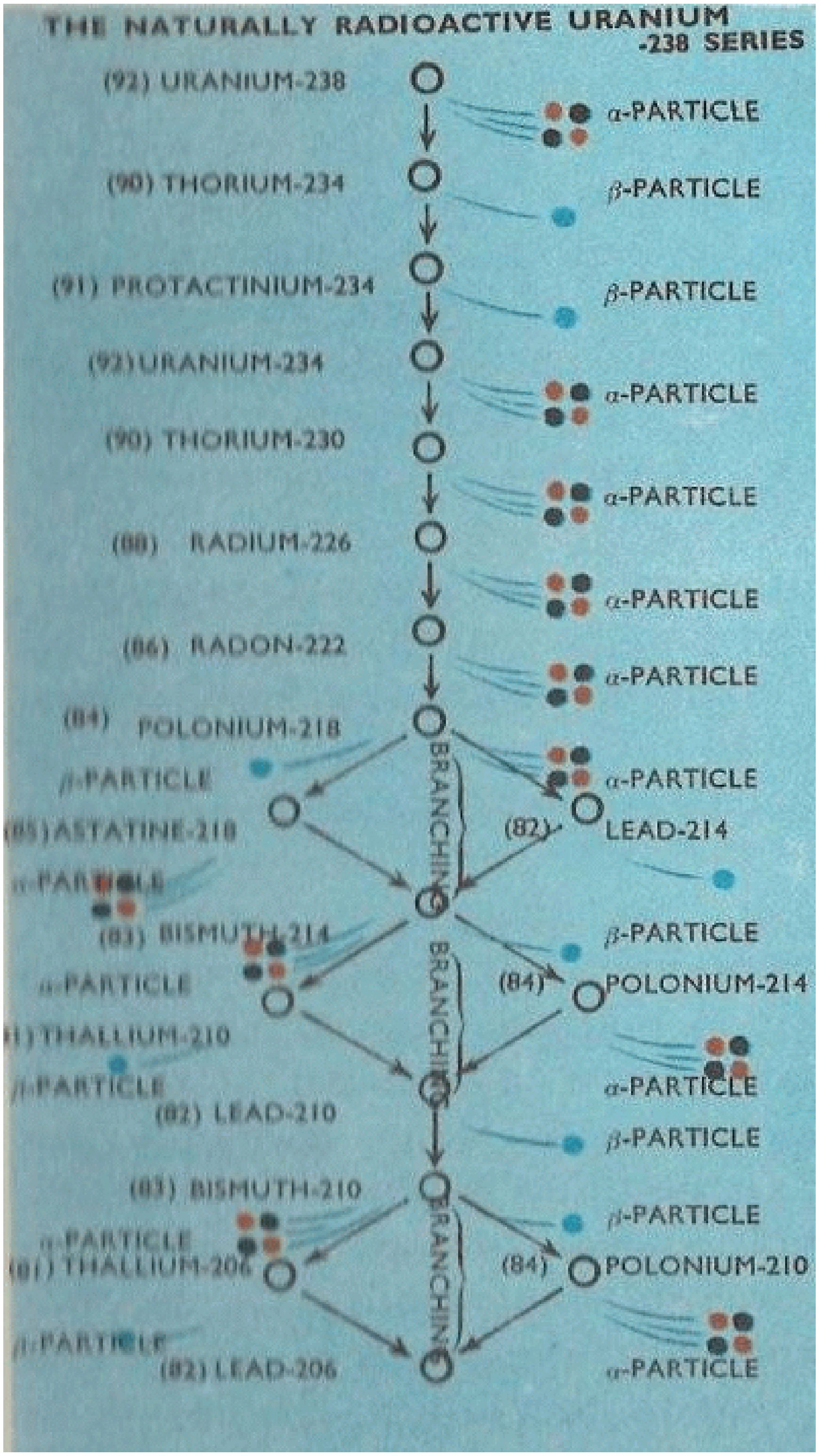


Figure 1-13. Actinium Series (U-239) Decay Chain

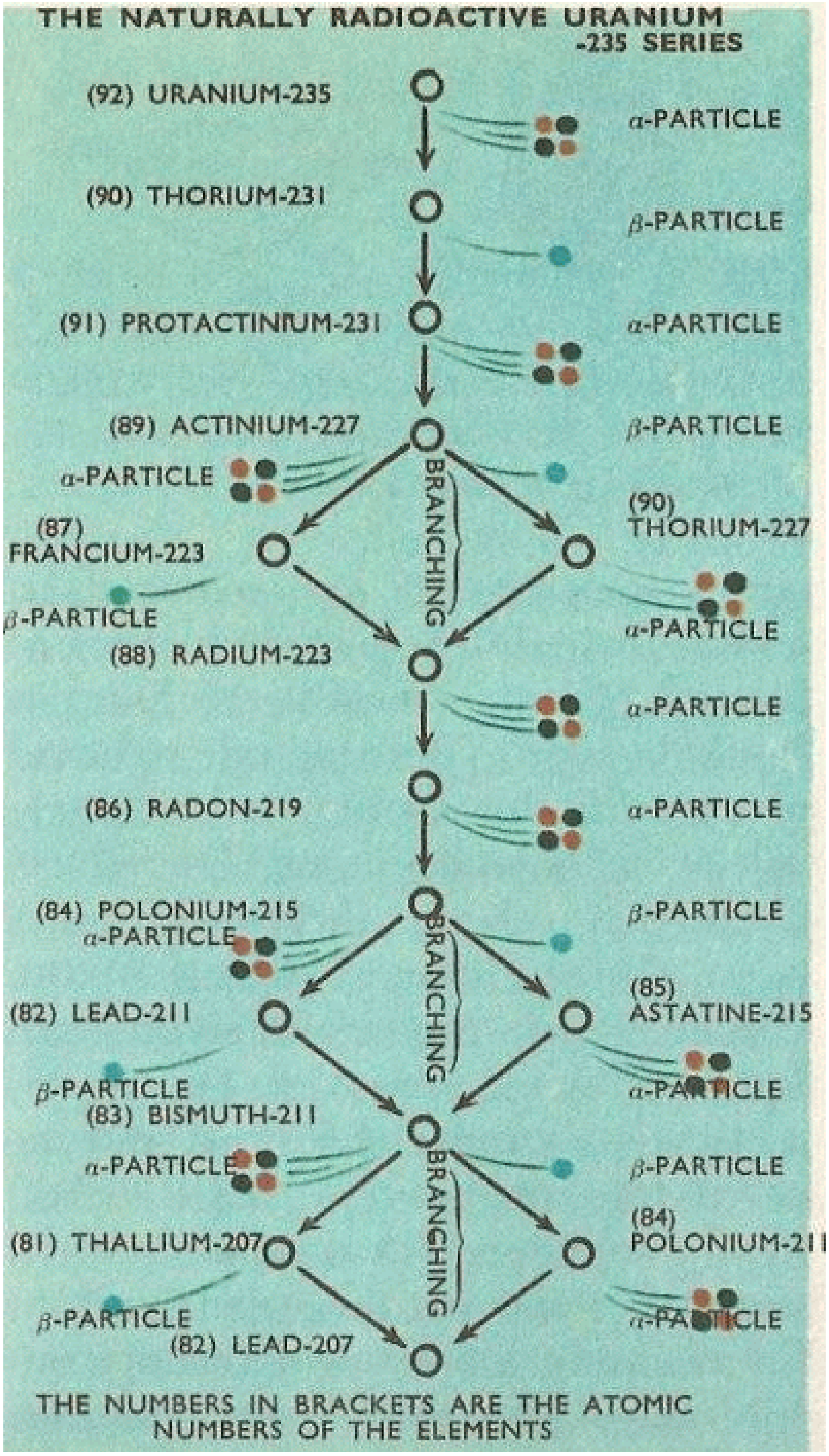


Figure 1-14. Thorium Series (Th-232) Decay Chain

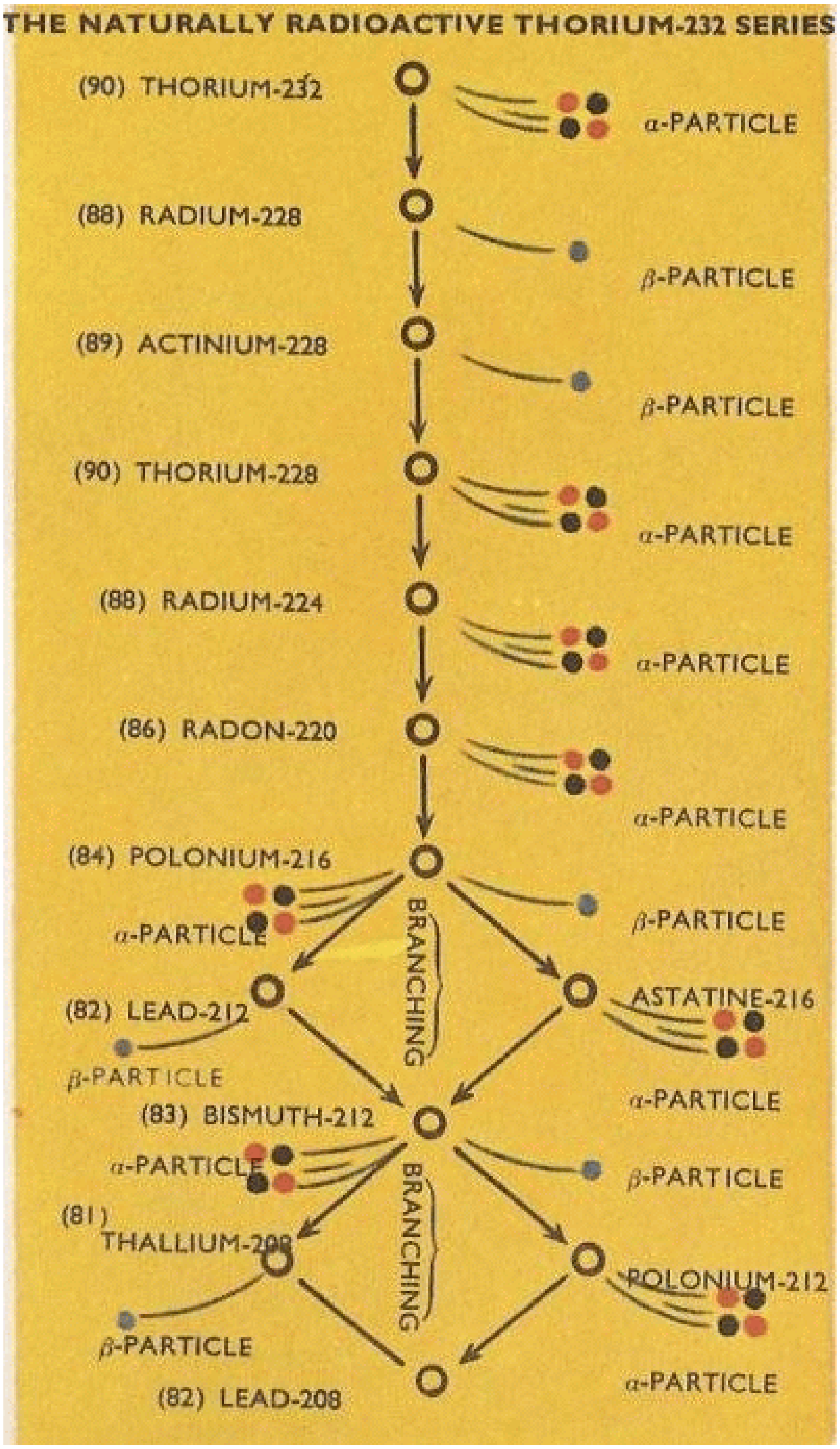


Figure 1-15. Neptunium Series (Np-237) Decay Chain

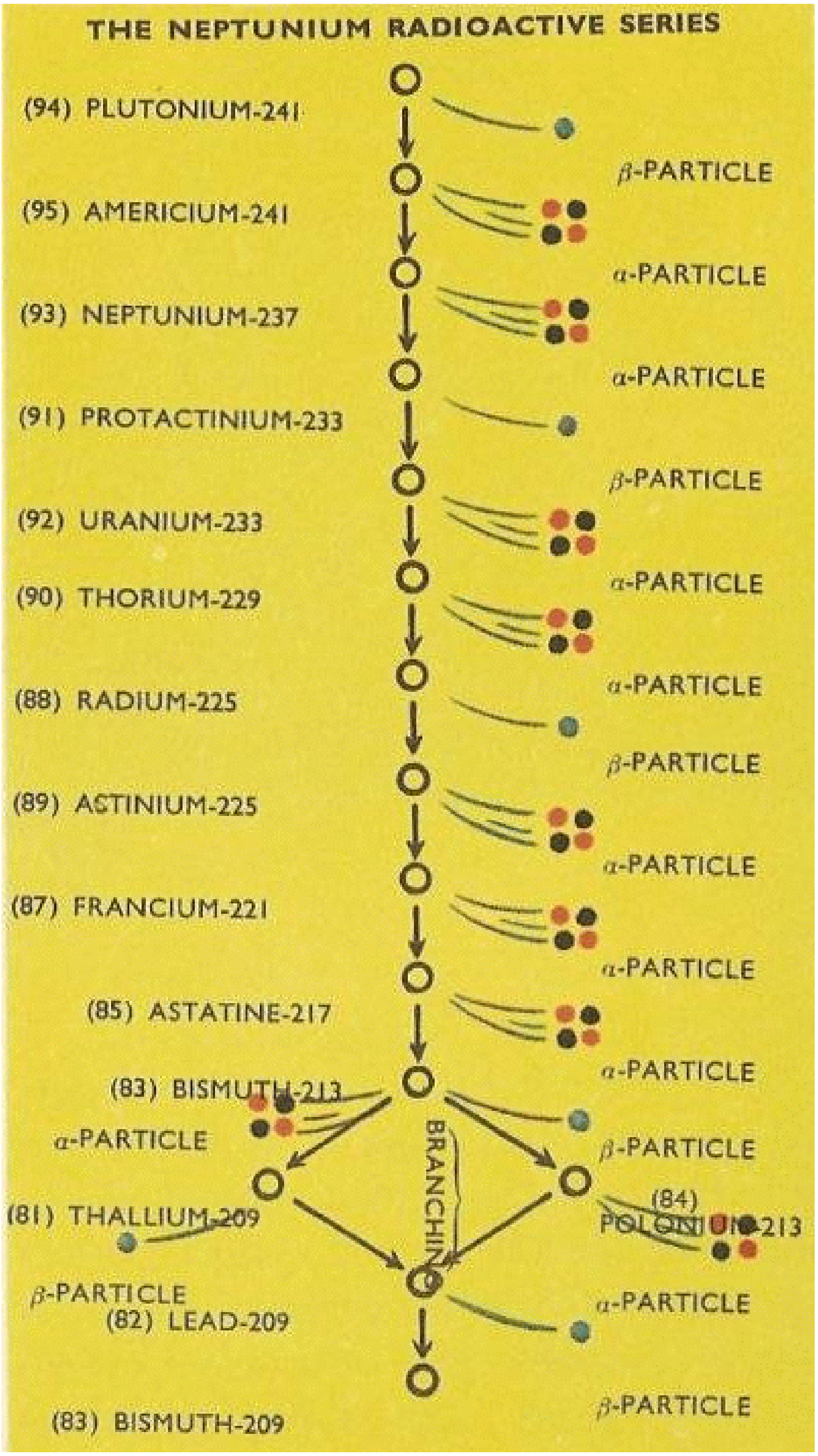
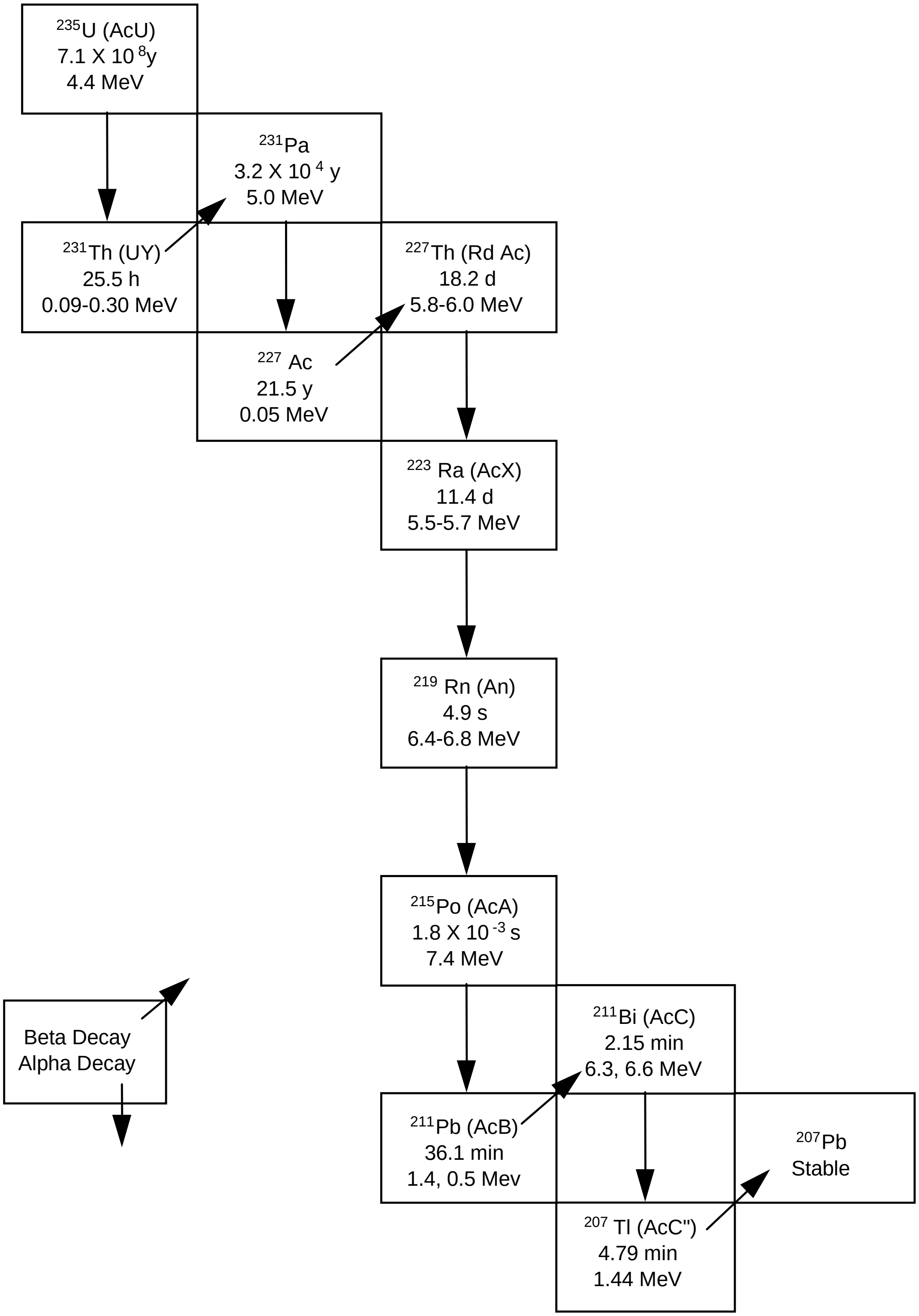


Figure 1-16. Principal Actinium Series Decay Chain



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 build up 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 Figure 1-17.

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 recovery stages of the fuel cycle.

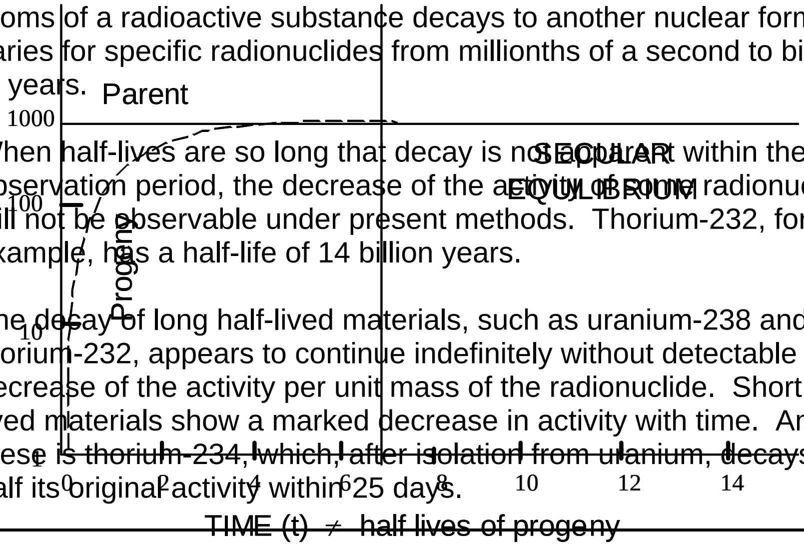


Figure 1-17. Secular Equilibrium

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 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 proportionately 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 five-fold 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 chain reaction 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 chain reaction accidentally occurs 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

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 currently conducted in the United States, uranium from the Hanford Site and nuclear Navy program have been recycled. This is also sometimes referred to as reprocessed uranium.

Recycled uranium also contains small amounts of uranium isotopes not found in nature, such as U-236, which reduces the reactivity of the fuel by absorbing neutrons. The chemical processes by which recycled uranium is purified may leave trace amounts of transuranic (TRU) material (neptunium and plutonium) and fission products (Technetium-99 [Tc-99]). A test program that re-enriched recycled uranium is responsible for the TRU and technetium contamination found at the gaseous diffusion plants. 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.

URANIUM HEXAFLUORIDE

General Information

Uranium hexafluoride (UF_6) is a compound of uranium and fluorine. Figure 1-18 represents the phase diagram and Figure 1-19 shows the crystals at room temperature. It is the process gas used by the gaseous diffusion plants in the United States and gas centrifuge facilities in other countries to increase the concentration of U-235. There are two reasons for using UF_6. First, these two enrichment processes are gas phase processes and UF_6 can be easily changed to a liquid for feeding and withdrawing, and to a solid for storage and transportation. Each of these states is achievable at relatively low temperatures and pressures. Second, because fluorine has only one natural isotope, all the isotopic separative capacity of the enrichment plant is used to enrich the concentration of the lighter uranium isotopes. UF_6 is processed in leakproof piping, equipment, and containers. It is transported as a solid in large, protective cylinders. UF_6 handling and transportation are subject to strict standards designed to protect the health and safety of workers, the public, and the environment.

Figure 1-18. UF_6 Phase Diagram

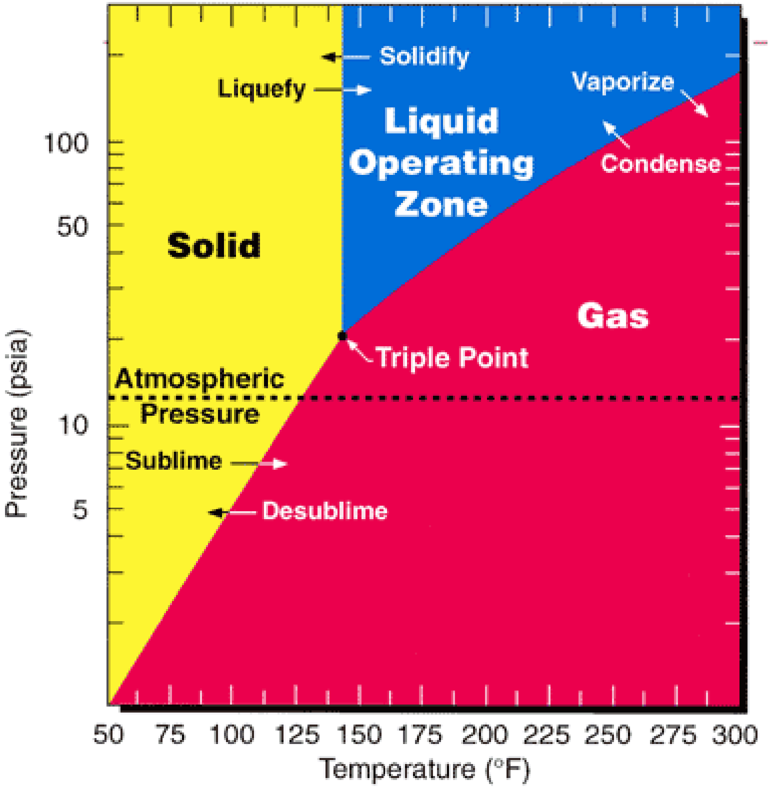


Figure 1-19. UF_6 Crystals (in a glass vial)

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 1-3

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:

actinium
chain
compounds
different
enrichment
equilibrium
exposures
feeding
fluorinated
gaseous
half-life
hazard
higher
isotopes
lead
liquid
long-lived
materials
prevention
radium
safety
smaller
specific
transuranic
transportation
uranium
U-234
U-235
U-236
uranyl

1. Naturally occurring uranium consists of three ______________________: uranium-238, uranium-235, and uranium-234.

2. The isotope ____________________ is usually the desired material for use in 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 recovery 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 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, a release of energy will occur. 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 a stable isotope of ______________________

12. In newly purified uranium, the immediate decay products of Th-234, Pa-234m, and Th-231 will have grown to their ______________________ levels within a few weeks.

13. 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 _____________________ present.

14. Nuclear criticality safety is the prevention or termination of an inadvertent nuclear ______________________ reaction in nonreactor environments.

15. The chemical processes by which recycled uranium is purified leave trace amounts of _____________________ material (neptunium and plutonium) and fission products (Technetium-99 [Tc-99]). Recycled uranium also contains small amounts of uranium isotopes not found in nature, such as _____________________ .

16. There are two reasons for using UF_6. First, it can conveniently be used as a gas for ______________________ , as a liquid for _____________________ and withdrawing, and as a solid for storage and ______________________ . Each of these states is achievable at relatively low temperatures and pressures. Second, because fluorine has only one natural isotope, all the isotopic separative capacity of the enrichment plant is used to enrich the concentration of the lighter uranium isotopes.

17. Uranium hexafluoride will increase in volume by more than 30% as it changes from a solid to a ________________________ .

18. Uranium hexafluoride is reactive with water or moisture in the air to form ________________________ fluoride and hydrogen fluoride.

19. Protective measures required for an enrichment plant are similar to those taken by other chemical industries concerned with the production of ____________________ chemicals.

20. Exposure of the UF_6 gas to the atmosphere can lead to the formation of other ______________________ , but any effects remain essentially chemical.

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

OVERVIEW OF URANIUM ENRICHMENT

Enrichment of U-235 is an essential stage of the fuel cycle process that "concentrates" the uranium isotopes for delivery to fuel fabrication facilities for production of uranium fuel for use in commercial nuclear power plants in the United States and abroad. No reactor can operate without a fuel cycle. Enriched uranium is a critical component for both civil nuclear power generation and military nuclear weapons. The International Atomic Energy Agency attempts to monitor and control enriched uranium supplies and processes in its efforts to ensure nuclear power generation safety and curb nuclear weapons proliferation.

Enrichment Process

Uranium has three naturally occurring isotopes: U-234, U-235 and U-238. Enriched uranium is uranium whose U-235 content has been increased through the process of isotope separation. Enrichment is the percentage of increase of the U-235 isotope in the fuel above the natural assay of 0.711% (the balance is primarily U-238). Because U-235 can fission (split) to produce heat, it is the most efficient isotope of uranium to fuel power plants. U-235 makes up less than 1% of natural uranium, but most current nuclear power plants require 3% to 5% concentrations of U-235 for a usable fuel.

Isotope separation is based on slight physical property differences. A few methods rely on chemical kinetic effects and exchange. Separation methods include: “Physical” (barrier diffusion, ion exchange, thermal, centrifugation, etc.) and “Chemical” (ionization, laser/light, etc.) The methods are sometimes combined for greater efficacy; for example, gas centrifuge (GC) involves centrifugation plus thermal. See Figure 1-20, Isotope Separation Methods (U-235). The enrichment process dictates the chemical form, the most common form being uranium hexafluoride (UF_6) which combines uranium with fluorine. UF_6 exhibits ideal gas behavior with a moderate triple point - solid, liquid, and a gas - at 22 pounds-force per square inch absolute (psia) and 147.3°F that allows processing as a gas/feed, withdrawal as a liquid, and storage as a solid. Several phases are required for desired enrichment.

The following are levels or grades of enrichment:

LEU - Low Enriched Uranium: assay less than 10%
“IEU” - Intermediate Enriched Uranium: assay greater than 10%; less than 20%
HEU - High Enriched Uranium: assay greater than 20% (usually focuses on an assay greater than 90%)

The U-238 remaining after enrichment is known as depleted uranium (DU) and is considerably less radioactive than even natural uranium. It is useful for armor, armor penetrating weapons and other material density applications such as radiation shielding.

Figure 1-20. Isotope Separation Methods (U-235)

BASED ON	EXAMPLES
DIFFUSION PRINCIPLES	GASEOUS DIFFUSION* MASS DIFFUSION THERMAL DIFFUSION
DIFFUSION IN A PRESSURE GRADIENT	GAS CENTRIFUGE* SEPARATION NOZZLE VORTEX TUBE
PHASE EQUILIBRIUM PRINCIPLES	DISTILLATION
CHEMICAL EQUILIBRIUM PRINCIPLES	CHEMICAL EXCHANGE ION EXCHANGE
PHOTOEXCITATION PRINCIPLES	ATOMIC VAPOR LASER ISOTOPE SEPARATION MOLECULAR LASER ISOTOPE SEPARATION*
ELECTROMAGNETIC PRINCIPLES	PLASMA SEPARATION ELECTROMAGNETIC ISOTOPE SEPARATION PLASMA CENTRIFUGE

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*PROCESS OF CURRENT INTEREST

Enrichment Technology

Several enrichment methods have been in use in the past or have the potential for future processing. These are primarily thermal diffusion, electromagnetic separation, gaseous diffusion, gas centrifuge, and laser-based processes. Today, only gaseous diffusion and gas centrifuge are operating on a commercial scale at enrichment facilities; each accounts for about 50% of world capacity. Both processes require large facilities and buildings for production; however, some differences between the two are:

Gaseous Diffusion	Gas Centrifuge
Requires large equipment - (circa1,000 main stages)	• Uses small equipment in - large numbers - (circa 100,000 stages)
• Historical facilities that are amortized	• Financed by sales
• High energy consumption/cost	• Low energy consumption/costs

The capacity of enrichment plants is measured in terms of “separative work units” or SWU. The SWU is a complex unit which is a function of the amount of uranium processed and the degree to which it is enriched. It measures the quantity of separative work, indicative of energy used in enrichment when feed, tails, and product quantities are expressed in kilograms.

* SWU = Separative Work Unit
  - measure of isotopic separation capacity/physical effort in separation for enrichment plants
  - SF = SXU factor, SWU/kg

* <u>Mathematical definition</u>:

SWU = [P*V(xp) + W*V(xw) - F]*V(xf)] * T
where:
T = time (usually 1 year)
P, W, F are product, waste, and feed flow in kg

V(xi) = “separation potentials”

The separation potentials are defined by the following logarithmic relationship:

V(xi) = (2 * xi - 1) * LN(xi / (1 - xi))

where xi = xf, xp, or xw; the feed, product, or waste (tails) assay concentration.

Flow rates are calculated from the total and U-235 material balances; for example:

(F / P) = (xp - xw) / (xf - xw)

About 100-120,000 SWU is required to enrich the annual fuel loading for a typical 1000 MWe light water reactor. Enrichment costs are substantially related to electrical energy used. The gaseous diffusion process consumes about 2500 KWh per SWU, while modern gas centrifuge plants require only about 50 KWh per SWU.

Essentially all expansions and new plants are gas centrifuge. See Table 1-2 that shows uranium enrichment plants and locations. See Table 1-3 for a comparison of enrichment processes. Figure 1-21 shows worldwide supply from GDP and GC processes.

Nuclear power plants contain approximately 100 tonnes (i.e. metric tons) of uranium in their reactor cores (i.e., for a nominal 1,000 MWe size). Approximately one-third is removed and replaced with fresh fuel every refueling outage, or cycle. Typical LWRs use uranium fuels with enrichments of 3-5% U-235. Enrichment levels around 3% approximately correspond to 12 month cycles (i.e., refuel every 12 months), while enrichment levels close to 5% approximately correspond to 24 month cycles. Thus, as an example, these equations indicate 1 kg of 3% LEU (a 12 month cycle fuel) requires 5.479 kg of natural uranium fed to the enrichment facility, producing a depleted uranium (tails) stream of 4.479 kg at 0.2% assay. Approximately 4.3 SWUs would be required (per kg of 3% product). Therefore, a reactor reload of around 30,000 kg 3% assay would require 164,000 natural uranium feed and 129,000 SWUs.

A higher tails assay of, say, 0.3%, reduces the SWU requirement but increases the feed requirements and generates greater quantities of tails. Commercial enrichment plants modify operations slightly to balance the power and feed costs for the most economical results.

Most power reactors today operate on 18-24 month cycles which require higher product fuel assays. Using 4.5% as an approximation, the 18 month cycle requires about 10 kg of natural uranium per kg of product fuel and about 6.2 SWU per kg of product. Total feed and SWU requirements per cycle are 300,000 kg and 190,000 SWU, respectively.

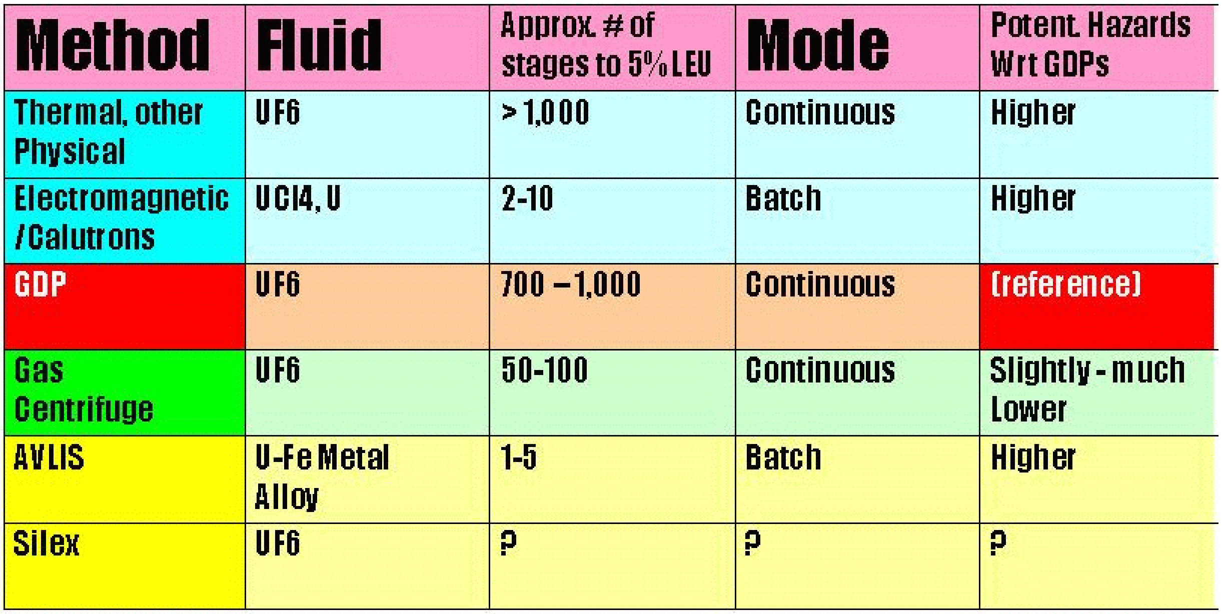
Sometimes the SWU calculations are displayed graphically. Figure 1-22 provides an example based upon a 0.2% tails assay.

Hence, regardless of the refueling cycle, current power reactors require about 100,000 to 120,000 SWU/yr for a typical, 1,000 MWe LWR. The 104 power reactors in the U.S. need about 10 million SWUs annually.

Table 1-2. Uranium Enrichment Plants Worldwide

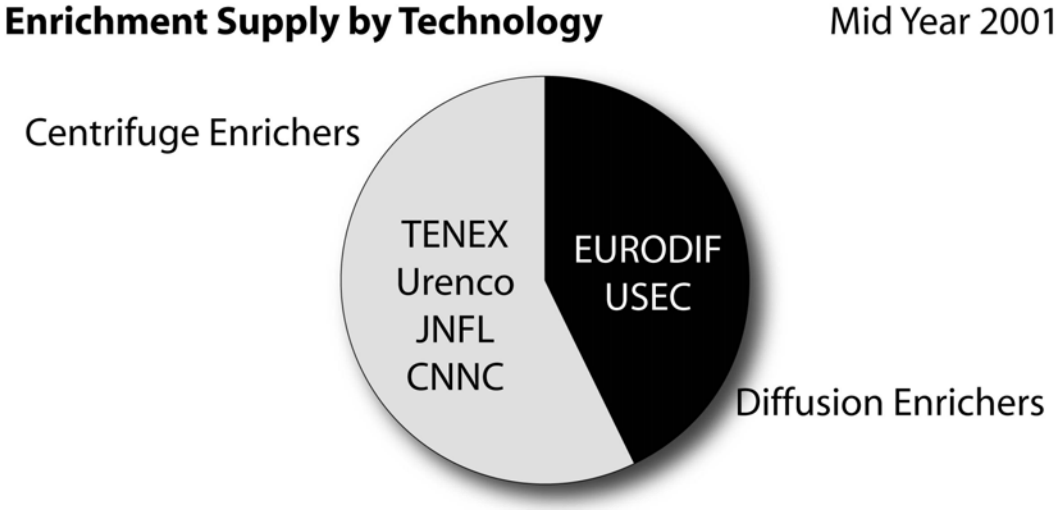
Nation	Location	Process	Dates	M SWUs
China	Lanzhou Chengdu	GDP GDP	1960s 1970s	0.2 0.2
France	Tricastin	GDP	1982	10.8
Japan	Ningyo Toge Rokkasho-Mura	GC GC	1988 1992	0.2 0.6 (to 1.5)
Russia	Several	GC	1960s	20
Urenco	Almelo Capenhurst Gronau	GC GC GC	1970s 1970s 1980s	1.6 2.3 1.4
US	Paducah Portsmouth	GDP GDP	1950s 1950s-2001	18 (11.2 to 3) 11 (7.7, now 0)

Table 1-3. Comparison of Enrichment Processes



Method	Fluid	Approx. # of stages to 5% LEU	Mode	Potent. Hazards Wrt GDPs
Thermal, other Physical	UF6	> 1,000	Continuous	Higher
Electromagnetic /Calutrons	UCl4, U	2-10	Batch	Higher
GDP	UF6	700 – 1,000	Continuous	(reference)
Gas Centrifuge	UF6	50-100	Continuous	Slightly - much Lower
AVLIS	U-Fe Metal Alloy	1-5	Batch	Higher
Silex	UF6	?	?	?

Figure 1-21. Enrichment Supply by Technology



Enrichment Economics

In the U.S., enrichment accounts for almost 25% of the cost of nuclear fuel and about 5% of the total cost of the electricity generated. It can also account for the main greenhouse gas impact from the nuclear fuel cycle if the electricity used for enrichment is generated from coal.

The total U. S. market is about $1.2 billion; world market about $4 billion. Currently, the main supplier/broker for enrichment in the U.S. is the United States Enrichment Corporation (USEC); however, the Louisiana Energy Services (LES) in a consortium with Urenco, has plans to operate a gas centrifuge plant (see below).

Future for Uranium Enrichment

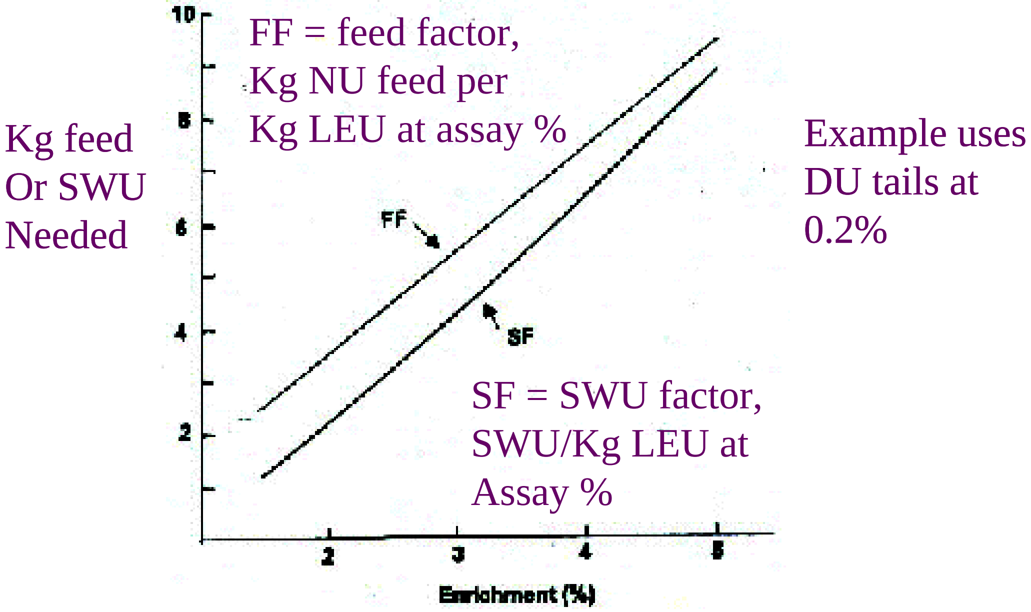
It is likely there will be significant activities with the GDPs in the near future, some of which will be GDP shutdowns. Over the next few years, the NRC staff are expected to be involved with advanced enrichment technologies.

GC enrichment facilities planned in the U.S. are The American Centrifuge Plant (ACP) at Piketon, OH, operated by USEC, and the National Enrichment Facility (NEF) in New Mexico, operated by the European consortium, LES - Urenco.

USEC submitted an application to the NRC in 2004 for the ACP. The NRC has conducted safety and security reviews and issued a safety evaluation report in mid-2001. Earlier, the NRC signed an MOU with DOE for a Lead Cascade, part of the ACP.

In June 2006, the NRC issued a license to LES - Urenco, to operate the National Enrichment Facility to be built by Louisiana Energy Services. The new plant will use gas centrifuge technology and will be nearly identical to the Urenco plant in the Netherlands.

Figure 1-22. Feed Factor and SWU Curves



FF = feed factor,
Kg NU feed per
Kg LEU at assay %

Example uses
DU tails at
0.2%

SF = SWU factor,
SWU/Kg LEU at
Assay %

Learning Objective

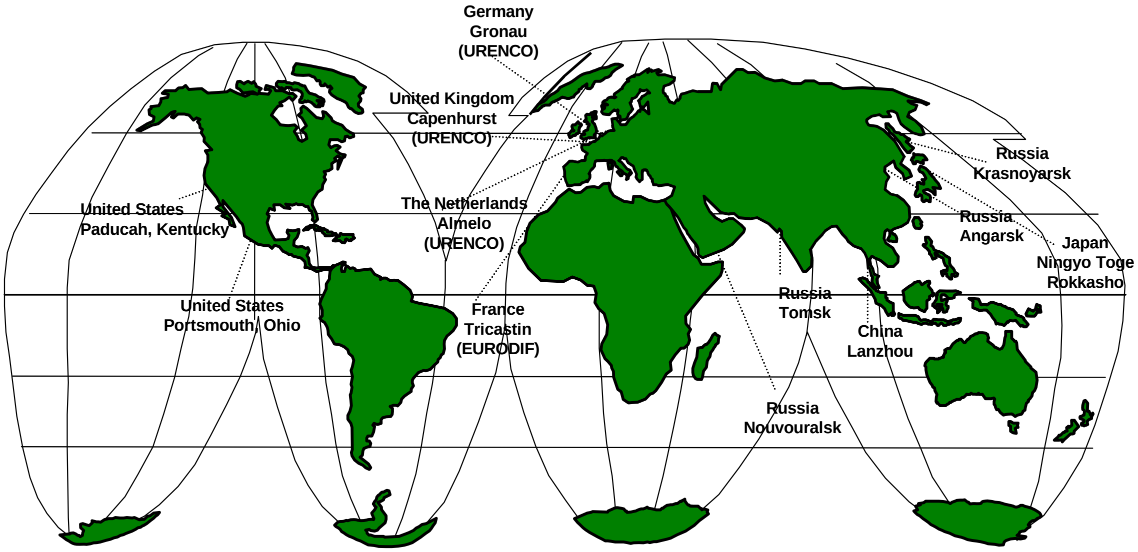
When you finish this section, you will be able to:

1.1.4 Identify five uranium enrichment processes.

BRIEF DESCRIPTION OF FIVE ENRICHMENT PROCESSES

Figure 1-23 indicates enrichment locations around the world. Table 1-4 provides a brief introduction of the five uranium enrichment technology processes addressed in this directed self-study course. Each of these processes is discussed in more detail in subsequent modules.

Figure 1-23. Commercial Uranium Enrichment Facilities



Gaseous Diffusion Facilities:

United States-Paducah, Kentucky (United States Enrichment Corporation)
United States- Portsmouth (Piketon), Ohio (United States Enrichment Corporation) (operational status: cold standby)

France-Tricastin (EURODIF)

Gas Centrifuge Facilities:
China-Lanzhou
Germany-Gronau (URENCO)
The Netherlands-Almelo (URENCO)
United Kingdom-Capenhurst (URENCO)
Japan-Ningyo Toge Rokkasho-mura
(Japan Nuclear Fuel Limited)

Russia-Angarsk
Russia-Krasnoyarsk

Russia-Nouvouralsk
(also referred to as Ekaterihburg and Verkh Nervinskiy)
Russia-Tomsk

Table 1-4. Five Uranium Enrichment Processes

Enrichment Process	Enriches uranium based on . . .	Status
Gaseous Diffusion	. . . the difference in rates at which uranium isotopes in the form of gaseous uranium hexafluoride diffuse through a porous barrier.	This is the main enrichment process used today in the United States. A full scale gaseous diffusion plant was completed and operated at Oak Ridge, Tennessee, from August 1945 until 1985. Two current gaseous diffusion plants are located at Paducah, Kentucky, and Piketon, Ohio. France also operates a large gaseous diffusion plant at Tricastin.
Atomic Vapor Laser Isotope Separation (AVLIS)	. . . using process lasers to emit precise frequencies of light that differentiate between uranium-238 and U-235 isotopes to selectively ionize U-235 atoms. It entails processing uranium metal alloy feedstock through the use of laser systems and separator systems. An electron beam vaporizes a uranium metal alloy by heating it to more than 5,000 degrees Fahrenheit. The U-235 atoms are withdrawn from uranium vapor by a charged extractor plate, solidified and collected.	The AVLIS intellectual property, developed by the U.S. government over 20 years, was transferred to the USEC as part of privatization. Plans for an AVLIS plant in the United States were suspended by USEC in June 1999.

Table 1-4. Five Uranium Enrichment Processes

Enrichment Process	Enriches uranium based on . . .	Status
Gas Centrifuge	. . . a centrifugal force separating lighter U-235 atoms from uranium-238 atoms. This process is conducted in a large number of rotating cylinders in a series and parallel. The lighter uranium-235 isotope concentrates at the center of a spinning centrifuge of gaseous uranium hexafluoride.	This method produced the first gram quantities of enriched uranium in 1944 in Oak Ridge, Tennessee. There are no operating gas centrifuge plants in the United States today. However plants are planned and have received licenses. There are commercial plants operating in western Europe, Russia and Japan. The technology was terminated by the DOE in 1985.
Electromagnetic Separation (Calutron)	. . . the tendency of ions of the uranium-238 to deflect at a lower rate than ions of U-235 as they travel through a magnetic field.	This process was used in a device called a "Calutron" and was in production at the Y-12 Plant in Oak Ridge, Tennessee, from late 1943 through 1946.
Thermal Diffusion	. . . the faster diffusion rate of uranium-235 than uranium-238 in the presence of a temperature difference.	Thermal diffusion was employed on a production scale at the S-50 plant in Oak Ridge, Tennessee in 1945. It was shut down within a month of the bombing of Hiroshima, Japan.

Historical Perspective

Table 1-5 provides a chronological listing of significant historical activities that have occurred for enrichment along with some other selected nuclear highlights.

Table 1-5. Historical Perspective of Enrichment Process Activities and Other Selected Nuclear Highlights

Date	Activity
1912	Cloud chamber for tracking charged particles is invented.
1913	Word "isotope" coined by Soddy (England). Radiation detector is invented.
1919	Aston and Lindemann (England) identified four distinct principles on which separation of isotopes could be based: distillation, diffusion, density (gravitational or centrifugal fields), and electromagnetic methods.
1920	Aston separated neon isotopes in a single stage.
1925	First cloud-chamber photographs of nuclear reactions.
1930	First crude particle accelerator is built: Cyclotron invented to accelerate atomic particles.
1932	Atom split with particle accelerator. James Chadwick (England) discovered the neutron. Hertz (Germany) used a 24-stage cascade to separate neon isotopes and soon thereafter separated isotopes of hydrogen, nitrogen, and carbon.
1934	Proposal to use neutrons to split atoms. Hertz used gaseous diffusion to separate neon isotopes. Beams (United States) developed the first convection-free vacuum gas centrifuge and soon thereafter used it to separate chlorine isotopes.
1938	Clausius and Dickel (Germany) built the first thermal diffusion column. Uranium fission achieved.
Late 1930s	Lawrence (United States) developed the forerunner of the calutron, the cyclotron, a device used for accelerating charged particles to high energy for physics research.
1940	Beams first separated uranium isotopes using experimental centrifuge machines. Betatron is built accelerating electrons on circular path.
1941	German attention centered on enrichment by the gas centrifuge process. Subsequently, progress was made on centrifuge machine design, but the effort was greatly hampered by Allied bombing, and the process was not taken beyond a very small pilot scale.

Table 1-5. Historical Perspective of Enrichment Process Activities and Other Selected Nuclear Highlights

Date	Activity
1942	First controlled self-sustaining nuclear reaction occurred at University of Chicago.
1943	By the end of 1943, U.S. and British scientists and engineers were freely sharing information on the gaseous diffusion process, and the decision to build a large-scale plant in the United States had already been made.
1944	Electromagnetic method of "enrichment" separation of uranium isotopes U-235 and U-238 is achieved in Tennessee (United States) with calutrons. Construction of gaseous diffusion enrichment plant at Oak Ridge, Tennessee begins. It replaces calutrons in early 1947.
1945	On July 16, the first atomic bomb exploded in United States.
1947	Y-12 electromagnetic plant (calutrons) ceased operation in early 1947 after the K-25 plant was able to produce weapon grade uranium (93% ^{235}U).
Early 1950s	Novel bearing design replaced the conventional oil bearings with pivot and magnetic bearings (Russian centrifuge work). Paducah and Portsmouth Gaseous Diffusion (United States) Plants were built.
1951	First nuclear reactor built by U.S. Atomic Energy Commission.
1952	First H-bomb tested. First breeder reactor, the Experimental Breeder Reactor (United States) commences operation.
1954	First nuclear powered submarine launched.
1955	Electricity first generated by nuclear power in the United States.
1957	First Russian gas centrifuge pilot plant goes into operation.
1958	U.S. government support of gas centrifuge research and development was resumed (United States).
1959	Dresden, the first commercial boiling-water nuclear reactor commences operation (United States).
1960	First nuclear powered surface ship, the USS Enterprise, starts operation (United States).

Table 1-5. Historical Perspective of Enrichment Process Activities and Other Selected Nuclear Highlights

Date	Activity
Early 1960's	Full scale gas centrifuge plant project commences operation (Russia).
1964	K-25, Paducah and Portsmouth Gaseous Diffusion Plants (United States) ceased producing highly enriched uranium (HEU) for weapons purposes, dramatically decreasing their output, while production of low enriched uranium (LEU) for production reactor fuel continued.
Late 1960s	K-25, Paducah and Portsmouth Gaseous Diffusion Plants (United States) increased their output in response to growing demand for enriched uranium for the U.S. Naval Nuclear Propulsion Program and the nuclear power industry. Portsmouth produced the HEU for the Navy propulsion reactors.
1970s	Gas centrifuge enrichment process begins to challenge the worldwide dominance of gaseous diffusion.
1972	By 1972, pilot plants at Capenhurst (United Kingdom) and Almelo (the Netherlands) were well under construction and, in fact, partially operational, having been already started under the national programs even before the formation of Urenco. Construction began at the centrifuge plant at Almelo.
1974	Using a refractory metal oven to produce vaporized uranium, the Morehouse experiment produced milligram quantities of enriched uranium, verifying the physics of the AVLIS process for the first time at Lawrence Livermore National Laboratory (LLNL) (United States). A combination of lasers, resonance optical radiation, and electrostatic ion collection were used.
1976	Almelo has the first delivery of enriched UF_6. E21(D) began operation at Capenhurst (United Kingdom) and was shut down in 1991.
1978	The United States committed itself to the construction of a Gas Centrifuge Enrichment Plant on the site of its Portsmouth, Ohio, Gaseous Diffusion Plant. A pilot plant comprised of 120 plant prototype centrifuges arranged in a single process unit was constructed and successfully operated at Oak Ridge (United States). (This facility was shut down in 1985.)
1979	Construction of current commercial centrifuge cascade (E22) began at Capenhurst (United Kingdom).

Table 1-5. Historical Perspective of Enrichment Process Activities and Other Selected Nuclear Highlights

Date	Activity
1980	A larger, gram-scale experiment using electron beams to vaporize uranium and more powerful lasers successfully separated several grams of enriched uranium at an enrichment of a few percent. This was achieved with the REGULIS separator (United States).
1982	Construction began at the centrifuge plant at Gronau (Germany). First operation of E22 began at Capenhurst (United Kingdom). Ningyo Toge gas centrifuge pilot plant was built (Japan), shut down in 1990, and dismantled. (1982-1985) U.S. Department of Energy (DOE) decides in favor of uranium AVLIS over other enrichment technologies (including gaseous diffusion and the gas centrifuge) for continued development of an advanced commercial enrichment process to provide low-enriched uranium to power reactors (United States).
1985	The DOE terminated all of its centrifuge activities including centrifuge research and development and gas centrifuge enrichment plant construction (United States). Gronau produced first enriched uranium (Germany). Lead-iron phosphate glass invented creating more durable containment medium for storing nuclear wastes.
1986	(1986-1992) The Uranium Demonstration System (UDS) and the Laser Demonstration Facility (LDF) at LLNL were constructed to test the uranium-AVLIS process at plant scale and are the basis for developing a complete plant conceptual design (United States).
1987	K-25 enrichment plant in Oak Ridge, Tennessee shut down (United States).
1988	Ningyo Toge Works Demo plant (DOP-1) began operation (Japan).
1989	Ningyo Toge Works Demo plant (DOP-2) began operation (Japan).
1990	Ningyo Toge pilot plant was shut down and dismantled (Japan).
1991	The Capenhurst E21 Demonstration Facility was shut down (United Kingdom).
1992	Rokkasho-Mura enrichment plant became operational (Japan). Under the Energy Policy Act of 1992, the Portsmouth and Paducah Gaseous Diffusion Plants were leased by DOE to the newly created United States Enrichment Corporation USEC (United States).
1993	October 1, USEC assumed control and funding of the AVLIS program (United States).

Table 1-5. Historical Perspective of Enrichment Process Activities and Other Selected Nuclear Highlights

Date	Activity
1994	July, USEC's Board of Directors approved initial path for AVLIS commercialization (United States).
1995	April, DOE and USEC signed an AVLIS memorandum of agreement. (DOE responsible for eventual decontamination and decommissioning of facilities; USEC responsible for decontamination and decommissioning of USEC-installed equipment.) June/July, Lawrence Livermore National Laboratory (LLNL) begins staffing up for first quarter FY 1997 AVLIS Integrated Process Demonstration. December, USEC issues environmental assessment for the continuation of AVLIS Integrated Process Demonstration at LLNL (United States).
1998	October, USEC begins process of siting new AVLIS Uranium Enrichment facility (United States).
1999	Urenco - Qualifying sixth generation gas centrifuge machines expected to be brought into production (United Kingdom, The Netherlands). June, USEC suspends AVLIS technology (United States).
2001	June, Portsmouth GDP placed in “cold standby.”
2002	LES and USEC discussing new gas centrifuge enrichment facilities with the NRC.
2004	LES submits license application for National Enrichment Facility, New Mexico. USEC submits license application for American Centrifuge Enrichment Plant Facility, Piketon, Ohio.
2006	LES receives NRC license centrifuge plant National Enrichment Facility and initiates construction.
2007	USEC receives license for American Centrifuge Plant.

Self-Check Questions 1-4 ✓

Match the enrichment technology in column A with the process description in column B. Answers are located in the answer key section of the Trainee Guide.

Column A – Enrichment Technology

A. Gaseous Diffusion

B. AVLIS

C. Gas Centrifuge

D. Electromagnetic Separation

E. Thermal Diffusion

Column B – Process Description

This enrichment technology uses:

1. ___ a centrifugal force to separate lighter U-235 atoms from U-238 atoms

2. ___ process lasers to emit precise frequencies of light that differentiate between U-238 and U-235 isotopes to selectively ionize U-235 atoms

3. ___ a porous barrier to diffuse uranium hexafluoride

4. ___ a temperature difference

5. ___ a magnetic field

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 the NRC's responsibilities related to uranium enrichment.

NRC REGULATION

The regulation of commercial nuclear fuel facilities is primarily the responsibility of the NRC, although these facilities are also subject to applicable requirements of the Occupational Safety and Health Administration and the Environmental Protection Agency. The objectives of 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. In addition, for those facilities that store or process special nuclear material, the NRC requires that facilities safeguard such material from loss, theft or diversion.

Gaseous Diffusion

The President signed H.R. 776, the "Energy Policy Act of 1992" (the Act), into law on October 24, 1992. Among other things, the Act amended the Atomic Energy Act of 1954 to establish a new government corporation, the USEC, for the purpose of managing and operating the uranium enrichment enterprise owned and previously operated by the DOE. The Act required that, within two years after enactment of the legislation, the NRC was to develop standards for the USEC's two operating gaseous diffusion plants to protect public health and safety from radiological hazards and to provide for the common defense and security. The Act further directed the NRC to establish a process under which the two gaseous diffusion plants will be certified annually by the NRC for compliance with those standards. The Act also required the NRC to report annually to Congress on the status of the gaseous diffusion plants.

In 1994, the NRC issued requirements and procedures for the certification process (10 CFR Part 76). The DOE remains responsible for decommissioning the plant sites and retains ownership of the facilities. USEC began leasing the plants on July 1, 1993.

On April 26, 1996, the President signed into law H.R. 3019, "The USEC Privatization Act," which provides for USEC to become a private corporation. The law also changed certain regulatory provisions, including extending the certification period to five years as determined by the NRC.

On November 26, 1996, the NRC issued USEC initial certificates of compliance for the two plants and assumed regulatory oversight on March 3, 1997. The first annual report to Congress on the status of the gaseous diffusion plants was issued January 5, 1998.

The President signed into law the "Federal Reports Elimination Act of 1998," Public Law 105-362, on November 10, 1998, which modified the requirement for the NRC to issue an annual report to Congress on the gaseous diffusion plants. The law now states that the report to Congress does not have to be annual but is to be issued "not later than the date on which a certificate of compliance is issued."

NRC's regulations for handling special nuclear materials, such as enriched uranium, are codified in 10 CFR 70, "Domestic Licensing Of Special Nuclear Material." This applies to all new enrichment facilities, such as the two planned gas centrifuge plants and the proposed Silex facility, even if they are co-located at a GDP site. Part 70 is a risk-informed, performance based regulation and requires licensees to have an integrated safety analysis (70.62) to demonstrates compliance with performance requirements (70.61). The performance requirements bin potential accident scenarios based upon consequence level and likelihood, for different receptors.

Atomic Vapor Laser Isotope Separation

In addition to the operation of the gaseous diffusion plants, USEC had planned to submit an application to the NRC to construct and operate a plant using AVLIS technology in fiscal year 2000. NUREG-1701, Standard Review Plan for the Review of a License Application for the Atomic Vapor Laser Isotope (AVLIS) Facility, is a draft report that has been distributed for comment. It was to have provided guidance to the NRC staff reviewers in the Office of Nuclear Material Safety and Safeguards who perform safety and environmental reviews of the license application for AVLIS under 10 CFR Part 70, as revised. In June,1999, USEC announced it had suspended further development of its AVLIS enrichment technology.

Gas Centrifuge

USEC and the Louisiana Energy Services (LES) are in discussion with the NRC regarding new GC enrichment facilities. Each company has submitted a license application.

Past action: In January 1991, the NRC received an application to construct and operate the nation's first privately owned gas centrifuge uranium enrichment facility in Homer, Louisiana, from LES. The NRC's Safety Evaluation Report for the facility was published in January 1994, and the NRC's Final Environmental Impact Statement was published in August 1994. The hearings were completed in 1995. Decisions on all hearing issues from the NRC Atomic Safety and Licensing Board (ASLB) were issued in 1997, resulting in a denial of the applicant's requested authorization for a license. The ASLB rejected claims that the plant would be unsafe, but found that LES had not proven that they could afford the construction cost. These decisions were originally appealed to the Commission by LES; however, on April 30, 1998, LES petitioned the Commission asking to withdraw its license application, and this request was granted.

Electromagnetic and Thermal Diffusion

There are no operating electromagnetic and thermal diffusion enrichment facilities in the United States, therefore, there is no regulation by the NRC for these technologies.

The thermal diffusion facility (S-50 plant) discontinued operation shortly after the Oak Ridge K-25 Gaseous Diffusion Plant was able to produce significant quantities of enriched uranium. The S-50 plant was dismantled in its entirety. The Y-12 electromagnetic plant (calutrons) ceased operation in early 1947 after the K-25 plant was able to produce weapon grade uranium (93% ^{235}U).

Self-Check Questions 1-5

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

1. What three things did the Energy Policy Act of 1992 require the NRC to do?

2. What change occurred for the NRC when the President signed into law the "Federal Reports Elimination Act of 1992" ?

3. What document provides guidance to NRC staff reviewers for AVLIS license application?

4. What are the current plans for building a gas centrifuge facility in the United States?

5. What three enrichment technologies have been used in the past but are not operating in the United States today?

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 safety concerns related to uranium hexafluoride cylinders.

UF$_6$ CYLINDERS

Standards and Regulations

Design, fabrication and certification standards for uranium hexafluoride cylinders are addressed in ANSI N14.1, American National Standard for Nuclear Materials-Uranium Hexafluoride Packaging for Transport.

The packaging and transportation of radioactive materials are regulated by many organizations including the NRC, the Department of Transportation (DOT), the DOE, the U.S. Postal Service, and state and local governments. Radioactive materials are also regulated by the International Civil Aeronautics Organization (ICAO), the International Atomic Energy Agency (IAEA), and the International Air Transport Association (IATA).

Specific references to UF$_6$ transport regulations for the NRC are located in the following documents:

- Title 10 Code of Federal Regulations (CFR) Part 50, “Domestic Licensing of Production and Utilization Facilities,” which also includes Appendix B, Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants
- Title 10 CFR Part 71, “Packaging and Transportation of Radioactive Material”
- Title 10 CFR Part 76, “Certification of Gaseous Diffusion Plants”
- Title 10 CFR Part 830, “Nuclear Safety Management”

Specific references to UF$_6$ transport regulations for the DOT are located in the following documents:

- Title 49 CFR Part 171, “General Information, Regulations, and Definitions”
- Title 49 CFR Part 172, “Hazardous Materials Table Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements”

- Title 49 CFR Part 173, “Shippers – General Requirements for Shipments and Packaging (Subpart I – Radioactive Materials)”
- Title 49 CFR Part 174, “Carriage by Rail”
- Title 49 CFR Part 175, “Carriage by Aircraft”
- Title 49 CFR Part 176, “Carriage by Vessel”
- Title 49 CFR Part 177, “Carriage by Public Highway”
- Title 49 CFR Part 178, “Specifications for Packaging”

Types of Cylinders

There are various types of cylinders at an enrichment facility. A few selected examples:

- 14-ton feed cylinder (Model 48H). See Figure 1-24.
- 10-ton parent cylinder that fills four daughter cylinders as UF_6 is withdrawn from the cascade (Model 48X). See Figure 1-25.
- 14-ton feed or parent cylinder (Model 48Y). See Figure 1-26.
- 2½-ton daughter cylinder that can be used to ship enriched UF_6 to a fabricator (Model 30B). See Figure 1-27.
- 14-ton tails cylinder for depleted uranium storage (Model 48G). See Figure 1-28.

Figure 1-24. 14-Ton Feed Cylinder (Model 48H)

Nominal Diameter	48 in. (122 cm)
Nominal Length	146 in. (370 cm)
Nominal Wall Thickness	5/16 in. (0.8 cm)
Nominal Tare Weight	3,170 lb (1,438 kg)
Maximum Net Weight	27,030 lb (12,261 kg)
Nominal Gross Weight	30,200 lb (13,700 kg)
Minimum Volume	140 ft^3 (3.96 m^3)
Basic Material of Construction	A-516 Steel
Service Pressure	100 psig (690 kPa gage)
Hydrostatic Test Pressure	200 psig (1380 kPa gage)
Isotopic Content Limit	1% ^{235}U

Valve Used - 1-in. Valve

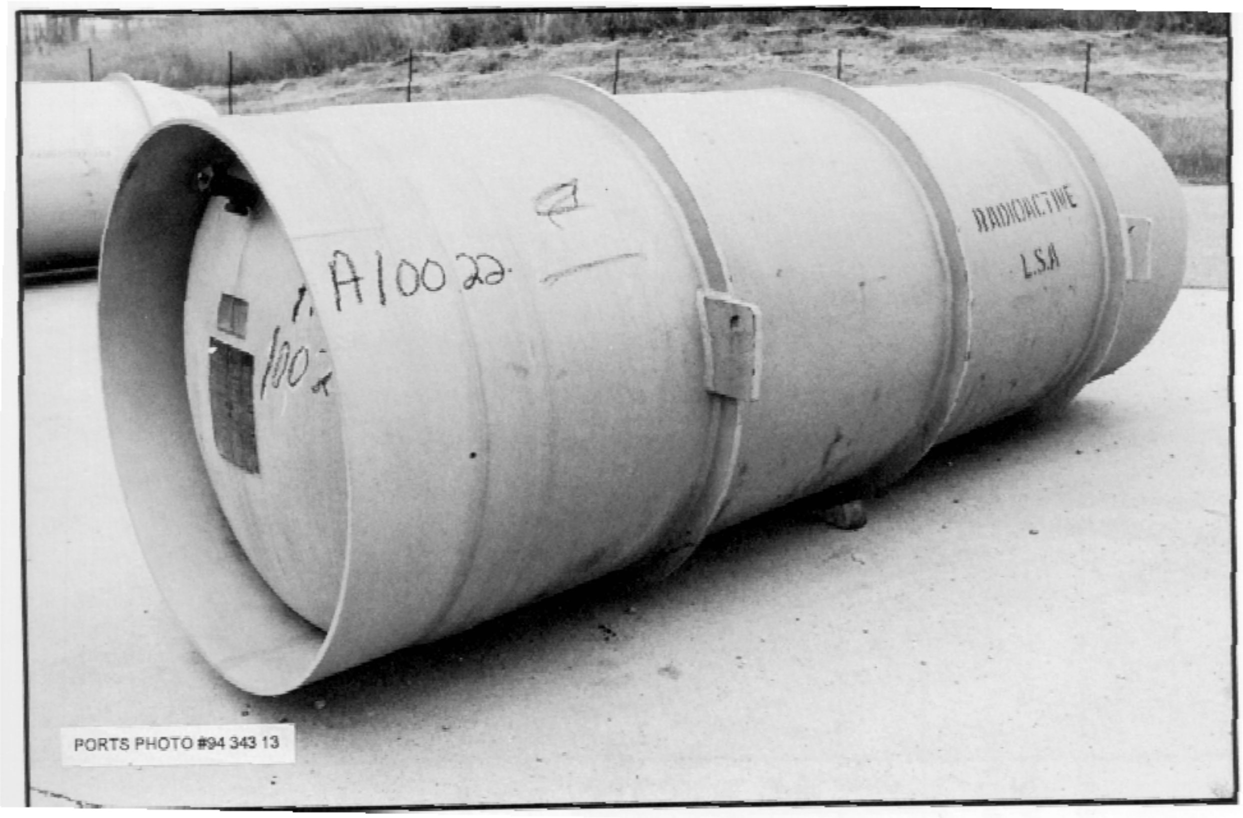
Figure 1-25. 10-Ton Parent Cylinder (Model 48X)

Nominal Diameter	48 in. (122 cm)
Nominal Length	119 in. (302 cm)
Wall Thickness	5/8 in. (1.6 cm)
Nominal Tare Weight	4,500 lb (2,041 kg)
Maximum Net Weight	21,030 lb (9,539 kg)
Nominal Gross Weight	25,530 lb (11,580 kg)
Minimum Volume	108.9 ft^3 (3.084m^3)
Basic Material of Construction	Steel (ASTM A-516)
Service Pressure	200 psig (1380 kPa gage)
Hydrostatic Test Pressure	400 psig (2760 kPa gage)
Isotopic Content Limit	4.5% ^{235}U (max. with moderation control for transport, 5.0% for in-plant use.)

Valve Used - 1-in. Valve

NOTE: Previously built 48A cylinders are similar in design, but do not have certified volumes.
Some model 48X cylinders have a tapered skirt on the plug end.

Figure 1-26. 14-Ton Feed or Parent Cylinder (Model 48Y)



4.5% ^{235}U (max. with moderation control)

NOTE: Previously built 48F cylinders are similar in design, but do not have certified volumes.

Figure 1-27. 2½-Ton Daughter Cylinder (Model 30B)

Nominal Diameter	30 in. (76 cm)
Nominal Length	81 in. (206 cm)
Wall Thickness	½ in. (1.25 cm)
Nominal Tare Weight	1,400 lb (635 kg)
Maximum Net Weight	5,020 lb (2,277 kg)
Nominal Gross Weight	6,420 lb (2,912 kg)
Minimum Volume	26 ft^3 (736 liters)
Basic Material of Construction	Steel (ASTM A-516)
Service Pressure	200 psig (1380 kPa gage)
Hydrostatic Test Pressure	400 psig (2760 kPa gage)
Isotopic Content Limit	5.0% ^{235}U (max. with moderation control)

Valve Used - 1-in. Valve

Figure 1-28. 14-Ton Tails Cylinder (Model 48G)

Nominal Diameter	48 in. (122cm)
Nominal Length	146 in. (370 cm)
Nominal Wall Thickness	5/16 in. (0.8 cm)
Nominal Tare Weight	2,600 lb (1,179 kg)
Maximum Net Weight	28,000 lb (12,701 kg)*
Nominal Gross Weight	30,600 lb (13,800 kg)
Minimum Volume	139 ft^3 (3.94 m^3)
Basic Material of Construction	Steel**
Service Pressure	100 psig (690 kPa gage)
Hydrostatic Test Pressure	200 psig (1380 kPa gage)
Isotopic Content Limit	1% ^{235}U
Valve Used - 1-in. Valve	

* Based on 235 ^{0} F (113 ^{0} C).

** Steel specification changed from A-285 to A-516 for cylinders ordered after 1978.

NOTE: For depleted uranium storage only. Cylinders with serial numbers below 111821 do not have certified volumes. An earlier design was designated Model OM.

Cylinder Inspection and Maintenance

Cylinders of various sizes are used at enrichment facilities depending on the total quantity of UF_6 and/or U-235 assay (weight percent of U-235) involved. Occasionally, UF_6 cylinders require cleaning to remove excessive buildup of impurities. It may also be desirable to remove the heel (the residual quantity of uranium material that remains in a cylinder after routine evacuation procedures) when UF_6 of a different isotopic assay is to be added to a cylinder.

Empty, clean cylinders received for filling with product or depleted uranium material should be inspected, weighed, and documented. All cylinders shall be periodically inspected and tested throughout their service lives at intervals not to exceed five years. Empty cylinders must be free of impurities, particularly hydrogenous materials, which could contaminate or react with UF_6 added to the cylinder. After valve installation, empty cylinders are pressurized with dry oil-free inert gas (such as air, nitrogen, or carbon dioxide) to a minimum of 100 pounds per square inch gage (psig) and soap tested. Acceptable cylinders are then evacuated to 5 psia or less. Cylinders failing to meet these criteria are rejected until proper repair and/or cleaning is completed.

A UF_6 cylinder shall be removed from service (for repair or replacement) when it is found to have leaks, excessive corrosion, cracks, bulges, dents, gouges, defective valves, damaged stiffening rings or skirts, or other conditions which, in the judgment of the qualified inspector, render it unsafe or unserviceable. Cylinders shall no longer be used in UF_6 service when their shell and/or head thicknesses have decreased below the values specified in ANSI N14.1. A UF_6 cylinder shall also be removed from service if inspections show that any unauthorized repair or modification has been made to the cylinder.

Safety Considerations

Some safety considerations regarding UF_6 cylinders:

- Gaseous UF_6 does react rapidly with water vapor as does the exposed surface of solid UF_6. Because of this, UF_6 is always handled in leak-tight containers and processing equipment to prevent its reacting with water vapor in the air.

- Uranium hexafluoride reacts rapidly with hydrocarbons. If the UF_6 is in the gas phase, the reaction forms a black residue of uranium-carbon compounds. In the liquid phase, the reaction proceeds at an accelerated rate and has been known to cause explosions in cylinders. Great care must be taken to avoid introducing hydrocarbon oil into processing equipment or cylinders.

- When UF_6 is transformed from a solid to a liquid, volume expansion increases and density decreases. The density of UF_6 decreases more than 30% when heated to a maximum temperature of 250° Fahrenheit. For example, a gallon of solid

> UF_6, when melted, would fill a 1.33-gallon container. This large increase in volume places restrictions on handling systems and procedures. If a cylinder were filled with solid UF_6 for instance, by desubliming in a cold trapping facility, it is possible to put more solid UF_6 in the cylinder than the cylinder can hold as liquid UF_6. If such a cylinder were heated, the melting of the solid and the expansion of the liquid UF_6 would completely fill it. Continued heating would cause the cylinder to rupture, resulting in a release of the UF_6.

The same rupture potential exists if UF_6 freezes and plugs a process line. Application of external heat to the middle portion of the plug can melt the solid and develop large hydraulic forces on the pipe and the ends of the plug, creating the potential for a UF_6 release due to pipe rupture. To remove a pipe plug, the best practice is to evacuate the pipe to a low enough pressure that the UF_6 will be removed by sublimation without entering the liquid phase.

Handling Cylinders of Liquid UF_6

Movement of large cylinders containing liquid UF_6 should be minimized, especially with respect to lift height, and performed only with the valve protector correctly installed. Liquid UF_6 under pressure is hot, very dense, and mobile. Movements of partially filled cylinders result in surges of the dense liquid that can upset handling equipment and cause loss of control. At ambient air temperatures, a three-day cool-down period should be observed for the Model 30B cylinder and a five-day period for Model 48 cylinders before transporting.

Leaks in a cylinder containing UF_6 are difficult to control. Caution should be exercised in handling cylinders until the contents have solidified. A cylinder shall not be shipped until its contents have completely solidified and the pressure in the cylinder is below atmospheric pressure.

On October 31, 2002, the NRC issued an Information Notice (2002-31) to address safety concerns related to UF_6 cylinder valves. The two safety concerns involve (1) cracked packing nuts, and (2) loss of material traceability and failure to conduct hardness testing of the valve stems.

Two types of UF_6 cylinder valves are currently in use: a ¾-inch valve designated as cylinder valve 51, which is not known to be affected by the defects addressed in the notice, and a one-inch valve designated as cylinder valve 50, which is affected. These valves form part of the pressure boundary for Model No. 30B (30-inch d.) cylinders that contain low enriched uranium, and various 48-inch diameter cylinders containing enriched, natural, and depleted (tails) uranium.

For details, read NRC Information Notice 2002-31.

Damaged Cylinder Valves

Valves that are damaged while handling full cylinders of UF_6 require immediate action. If the valve has been broken off, the release can usually be stopped by driving a tapered wood plug into the opening.

Manifold Connection Leaks

Leaking connections can result in significant UF_6 releases. All connections, especially flexible connectors, should be checked for tightness, kinking, abrasion, and other damage before use. After cylinder hookup, all connections should be pressure tested and vacuum leak rated before use.

Release of UF_6

The control of UF_6 releases requires pre-planning with respect to emergency procedures and equipment. Protective respiratory equipment, wooden plugs, patches, a release detection and alarm system, and some type of cooling mechanism should be readily available in areas where UF_6 is processed. Wooden plugs used for controlling releases should be designed to be inserted into holes that might occur as a result of broken or defective valves, line breakage, etc. Patches should be shaped to fit contours of the UF_6 cylinders.

A UF_6 release may be controlled by freezing the opening in the system with appropriate cooling. This cooling is usually provided by a water stream for cylinders not requiring moderation control. In no case should water be streamed directly into a cylinder opening. A wet towel or rag wrapped around the release area can be very effective in stopping leaks. Dry ice or pressurized CO_2 from large-capacity fire extinguishers may be used safely with any enrichment to stop leaks. If the cylinder content is liquid, extended cooling periods will be required.

Radiation

Alpha particles, resulting from the primary disintegration of uranium, present no external radiation problem, since they do not penetrate the dead layer of skin. The decay products of uranium, however, include isotopes that emit mildly penetrating beta rays and highly penetrating gamma rays. Beta radiation levels as high as 200 mrad/hr may be found at the surface of UF_6 cylinders. When UF_6 is vaporized from a cylinder, the decay products usually remain behind. Thus, the internal surfaces of an empty cylinder may have beta radiation levels up to several rad/hr. Similarly, the gamma radiation from an empty cylinder will be much higher than from a filled cylinder and may range up to 200 mrad/hr. Radiation exposures of employees working around UF_6 cylinders are easily controlled at very low levels through conventional distance-time limitations.

Mechanical Hazards

The mechanical hazards of handling UF_6 cylinders are not unique. The surging of liquid in partially filled cylinders and the eccentric center of gravity of cooled cylinders add to the normal hazards of handling heavy loads.

Criticality Control

A consideration of foremost importance in the handling and shipping of cylinders of UF_6 is the application of stringent controls to prevent an inadvertent criticality. This goal is accomplished by employing, individually or collectively, specific limits on U-235 enrichment, mass, volume, geometry, moderation, and spacing, and in some instances, utilizing the neutron absorption characteristics of the steel cylinder walls.

The amount of UF_6 that may be contained in an individual cylinder and the total number of cylinders that may be transported concurrently are determined by the nuclear properties of enriched UF_6. Spacing of cylinders of enriched UF_6 in transit is assured by use of DOT specification packages or DOE and/or NRC approved packages, which also provide protection against impact and fire.

Use of 30-inch and 48-inch cylinders at U-235 enrichments of 5.0% and 4.5%, respectively, is dependent upon moderation control, i.e., a hydrogen-to-uranium atomic ratio of less than 0.088, which is equivalent to the purity specification of 99.5% for UF_6. For shipment of UF_6 above 5.0% U-235 enrichment, geometry or mass limits are employed. Shipment of UF_6 in Models 48G and H cylinders without overpacks is limited to a maximum of one weight percent of U-235.

Self-Check Questions 1-6 ✓

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

1. What ANSI standard addresses design, fabrication, and certification standards for uranium hexafluoride cylinders?

2. What Title 10 CFR Parts address the transporting of UF_6 cylinders?

3. Why should empty cylinders remain free of impurities such as hydrogenous materials?

4. When should a UF_6 cylinder be removed from service?

5. Why is UF_6 always handled in leak-tight containers and processing equipment?

6. What happens when hydrocarbon oil is introduced into processing equipment or cylinders when uranium hexafluoride is in the liquid or gaseous phase?

7. What happens to volume and density when UF_6 transforms from a solid to a liquid?

8. What precautions should be administered when large cylinders containing liquid UF_6 are moved?

9. What type of action should be required if valves are damaged while handling full UF_6 cylinders?

10. What routine procedure should be administered after cylinder hookup?

11. Should water be streamed directly into a cylinder opening?

12. What could be used effectively to stop a UF_6 release?

13. When UF_6 is vaporized from a cylinder, what usually remains behind? What is emitted?

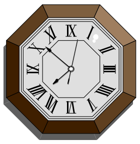
14. How can radiation exposures of employees working around UF_6 cylinders be controlled?

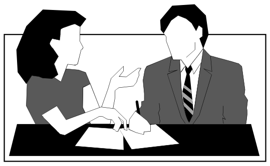
15. How is the goal of preventing an inadvertent criticality with one or more cylinders accomplished?

16. For shipment of UF_6 above 5.0% U-235 enrichment, what controls or limits are employed?

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

It's time to schedule a progress meeting with your administrator. Review the progress 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:

- Role of uranium enrichment in the nuclear fuel cycle
- Chemical and physical characteristics of uranium
- Radiological properties of uranium
- Chemical and physical characteristics of UF_6
- Historical perspective of enrichment processes
- NRC regulation of enrichment facilities
- UF_6 cylinders

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

III. As a Regulator:

- Which enrichment regulations should I review for my present duties?
- Tell me more about NRC regulation of enrichment processes.
- What do you think is important for me to remember about UF_6 and its physical and chemical properties within enrichment processes?

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

Enrichment is an important component of the nuclear fuel cycle. Uranium hexafluoride is received at an enrichment facility from the processing/conversion facility in a 14-ton or 10-ton cylinder for enrichment. Enrichment allows the U-235 isotopes within the uranium hexafluoride to be increased from 0.711% (natural uranium) to a range between 2% to 5% (enriched uranium) depending on customer specifications.

Currently, enriched uranium is produced in the United States using the gaseous diffusion process. There are two gaseous diffusion plants in the United States. One, the Portsmouth Gaseous Diffusion Plant is located in Piketon, Ohio, and the other is in Paducah, Kentucky. Both plants are operated by the USEC and are certified by the Nuclear Regulatory Commission. The Portsmouth Plant is currently in “cold standby.”

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 converted later at a fuel fabrication facility as usable fuel for use in a light water reactor.

Other enrichment technologies such as electromagnetic and thermal diffusion were previously used in the United States in the 1940s with very limited production capabilities. The AVLIS intellectual property, developed by the U.S. government over 20 years, was transferred to the USEC as part of privatization. Plans for a AVLIS plant were suspended by the USEC in June 1999. Gas centrifuge enrichment uses centrifugal sources inside rotating centrifuges to enrich uranium. It is the predominant enrichment technology overseas. Worldwide, gaseous diffusion and gas centrifuge technologies have dominated the enrichment industry. The trend is towards more enrichment using gas centrifuges due to lower energy consumption and costs. Three gas centrifuge enrichment facilities have been licensed by the NRC. Large, multi-million SWU/yr plants are planned in New Mexico and Ohio. Once these facilities are built, it is likely that the Paducah Gaseous Diffusion Plant will shut down.

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

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