Section 2
Uranium Production and Utilization

This section contains an overview of the uranium mining, milling, refining, and enrichment processes. It provides a historical perspective of the programs that produced and utilized HEU and lists the facilities involved.

Overview of Uranium

Uranium is a slightly radioactive material that occurs naturally throughout the earth's crust. Although considered rare, it is actually more plentiful than gold and silver. Uranium was discovered in 1789 by the German chemist Martin H. Klaproth. He named uranium after the planet Uranus, which had been discovered a few years earlier. Uranium is the heaviest naturally occurring element and is used chiefly as a fuel for nuclear power reactors. Uranium is also vital to the U.S. nuclear weapons program and the Naval Nuclear Propulsion Program.

Uranium has at least 17 isotopes[6], all radioactive, ranging from uranium-225 to uranium-242 and half-lives[7] from 0.08 seconds (uranium-225) to about 4.47 billion years (uranium-238) (DOE 1996c). All atoms of uranium have the same number of protons (92) in the nucleus. Different isotopes of uranium exist because of differing numbers of neutrons in the nucleus. Each isotope has its own unique atomic weight, which is the sum of the number of protons and neutrons. For example, uranium-235 has 92 protons and 143 neutrons and an atomic weight of 235. The higher the atomic weight, the heavier the isotope.

Of the 17 isotopes, only 3 are found in nature: uranium-238, uranium-235, and uranium-234. The most common isotope is uranium-238, which makes up about 99.28 percent by weight of all uranium found in nature. Uranium-238 cannot be readily split or fissioned under most conditions. The second most common isotope is uranium-235, which makes up about 0.711 percent by weight of all uranium found in nature. Uranium-235 is the only naturally occurring fissile[8] isotope of uranium. The remaining naturally occurring isotope of uranium is uranium-234.

[6] Isotopes are different forms of the same chemical element that differ only by the number of neutrons in the nucleus. Most elements have more than one naturally occurring isotope. Many isotopes have been produced in nuclear reactors and scientific laboratories.

[7] Half-life is the time it takes for one-half of any given number of unstable atoms to decay. Each isotope has a specific half-life.

[8] The capability of being split by a low-energy neutron. The most common fissile isotopes are uranium-235 and plutonium-239.

Uranium-233 is another fissile isotope of uranium and, because of its fissile properties, has been considered for use in research, space, and power reactors. It is not found in nature but must be produced by reactor irradiation of thorium-232, the radioactive but very long-lived, naturally occurring isotope of thorium. A major drawback to the use of uranium-233 lies in the coincidental production of uranium-232 during irradiation, which is undesirable because of the extremely high radioactivity of uranium-232. The U.S. inventory of uranium-233 is relatively small and is not included in this report.

Uranium easily combines with most substances to form chemical compounds. For example, it combines with oxygen to produce several oxides including uranium octaoxide (U_3O_8). Uranium also reacts with fluorine to create uranium hexafluoride (UF_6).

There are four terms commonly used to describe the percentage of fissile material in uranium: natural, depleted, LEU, and HEU.

Because uranium in nature is a mixture of the naturally occurring isotopes of uranium, industrial processes like the gaseous diffusion process must be employed to isolate and concentrate the fissile isotope uranium-235. Concentrations of uranium-235 greater than or equal to 20 percent are considered to be weapons-usable material and are defined as HEU.

Four Terms Commonly Used to Describe Uranium

- ✓ *Natural uranium* is found in nature and contains approximately 0.711 percent uranium-235.
- ✓ *Depleted uranium* is produced when some of the uranium-235 isotope is extracted from natural uranium. The remaining uranium is called depleted since it has been depleted in the uranium-235 isotope. It contains less than 0.711 percent uranium-235, typically 0.20 to 0.40 percent.
- ✓ *Low enriched uranium* has been enriched in the uranium-235 isotope and contains more than 0.711 percent but less than 20 percent uranium-235.
- ✓ *Highly enriched uranium* has been enriched in the uranium-235 isotope and contains 20 percent or more of uranium-235. All HEU is considered weapons-usable.

The focus of this report is on the HEU used in the U.S. nuclear weapons program, the Naval Nuclear Propulsion Program, and government and commercial reactors. Most of the HEU information in this report is presented in two assay ranges: (1) HEU with a concentration of 90 percent or more of uranium-235, and (2) HEU with a concentration of 20 to less than 90 percent uranium-235. For HEU production, information is presented in four assay ranges of uranium-235:

(1) 20 to less than 70 percent,

(2) 70 to less than 90 percent,

(3) 90 to less than 96 percent, and

(4) 96 percent or greater.

Uranium Accountability

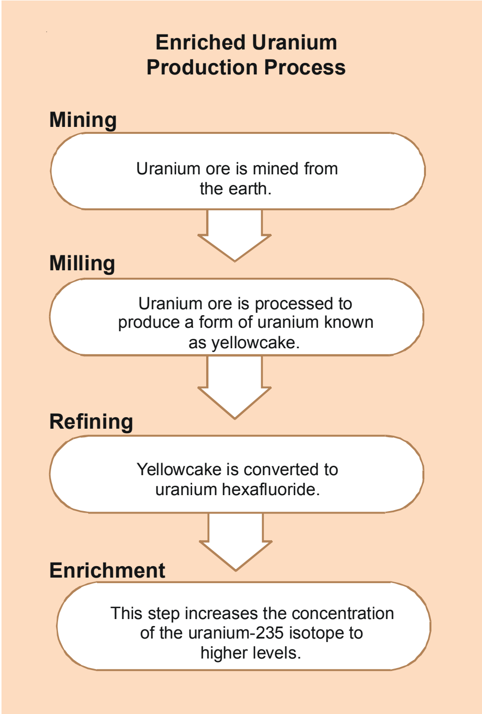
It is important to note that the nuclear material control and accountability (MC&A) program requires that all uranium transactions, inventories, and material balances be documented. In simple terms, the sites use one of three nuclear material ledgers to record uranium activities. There is a separate ledger for depleted uranium, natural uranium, and enriched uranium (includes all enrichments above 0.711 percent uranium-235).

Each of these nuclear material ledgers can, in simple terms, be thought of as a personal checkbook. With careful entries of checks written and deposits made, a current balance can be determined.

Because of the nature of the operation of a gaseous diffusion plant (GDP), uranium undergoing enrichment has a separate material ledger called "uranium in cascades." After being enriched, uranium is removed from the "uranium in cascades" ledger and added to the enriched uranium ledger. An examination of detailed plant records allows for the identification of material as either HEU or LEU based on the concentration of uranium-235. The HEU production numbers for this report were obtained by examining the GDP records for the uranium extracted from the cascades ledger with an isotopic concentration of equal to or greater than 20 percent uranium-235.

For security and accountability reasons, sites are usually subdivided into smaller more manageable accounts called Material Balance Areas (MBAs). An MBA could be a storage vault within the building or a well-defined physical area of a uranium processing plant. Each MBA has a set of uranium ledgers to record all MBA receipts and shipments. Inventories for each type of uranium are calculated by summing the many site MBA ledgers. To accomplish this, site accountability personnel submit MBA transaction information to the Nuclear Materials Management and Safeguards System (NMMSS) database maintained for that site. NMMSS is the national nuclear materials database that accounts for the overall uranium inventory. For more information on the safeguarding and accountability of nuclear materials, including NMMSS, see Section 4 of this report.

PRODUCTION OF ENRICHED URANIUM



The process of turning natural uranium into enriched uranium can be summarized as follows: (1) natural uranium ore is mined and milled, (2) processed ore is refined and combined with fluorine to form uranium hexafluoride (UF_6), and (3) UF_6 undergoes an enrichment process to segregate and thereby increase the percentage of uranium-235.

MINING AND MILLING

Mining and milling involves extracting uranium ore from the earth's crust and chemically processing it. While many rocks, including coal, contain small amounts of uranium, only certain mineral deposits such as pitchblende and carnotite contain large amounts of uranium. Underground, open pit, and solution mining techniques are used to recover uranium around the world.

A uranium mill is a chemical plant designed to extract uranium from the ore. The milling process produces a uranium concentrate called "yellowcake," which generally contains more than 60 percent uranium including some impurities. Uranium ore contains typically between 0.1 and less than 1.0 percent uranium.

About half of the uranium used in the U.S. nuclear weapons complex was imported from Canada, Africa, and other areas. The remainder came from the domestic uranium industry that grew rapidly in the 1950s. The first imported uranium, high-grade "pitchblende" ore containing up to 65 percent oxide by weight, was milled in Canada. After World War II, imported uranium was purchased in the form of already-milled concentrates and high-grade ores. Domestic uranium was purchased as either ore or concentrate.

REFINING

The product of a uranium mill is not directly usable as a fuel for a nuclear reactor. Refining involves the chemical conversion of uranium concentrates into purified forms suitable as feed material for enrichment processes. Refining, as discussed in this report, also involves the recycling of various production scraps, production residues, and uranium recovered from fuel reprocessing.

During World War II, uranium refining was performed by various contractors. After the war, the AEC built government-owned contractor-operated uranium refineries in Weldon Spring, Missouri, and Fernald, Ohio. These facilities operated until they were shut down in 1966 and 1989, respectively.

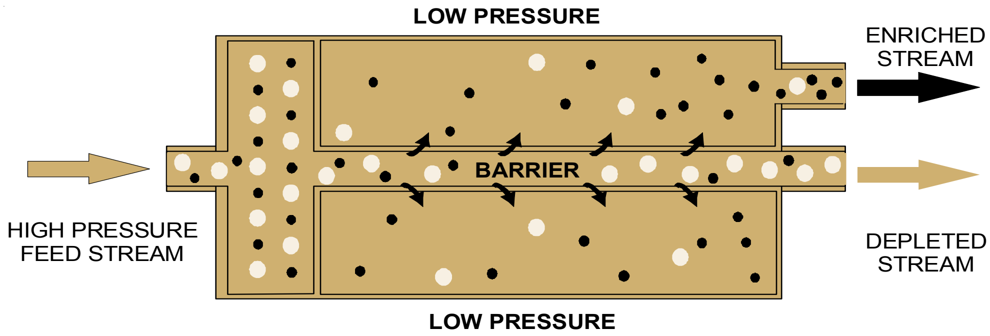
ENRICHMENT

The final step, which is the most difficult and costly, is the enrichment process. Several different methods (gaseous diffusion, electromagnetic separation, and thermal diffusion) have been developed to increase the concentration of the uranium-235 isotope. Most of the uranium enriched in the U.S. was produced using the gaseous diffusion method.

The enrichment process begins after refining, when UF_6 is received in solid form at a GDP and heated to form a gas. This UF_6 gas contains both uranium-235 and uranium-238 isotopes. In the gaseous diffusion enrichment process, UF_6 gas is pumped through miles of piping and barrier-like structures that have millions of uniformly sized, tiny holes. The weight differential between molecules containing uranium-235 and molecules containing uranium-238 determines the rate at which the isotopes pass through the holes. The gas molecules containing the lighter uranium-235 move slightly faster than those containing the heavier uranium-238 and diffuse through the barrier at a faster rate than do the molecules containing uranium-238. As a result, a partial separation of the uranium isotopes is accomplished, resulting in uranium-235 having a higher concentration on the downstream side of the barrier than on the feed side of the barrier.

About one-half of the feed stream diffuses through the barrier, and it is then fed to the next higher stage, where the process is repeated. The remaining gas, which is slightly depleted in the uranium-235 isotope, is recycled back to a previous stage (**Figure 2-1**). Because of the very small amount of separation occurring in a single stage, the process must be repeated thousands of times by coupling the stages in a series arrangement called a "cascade." When the uranium-235 concentration in the enriched stream meets requirements, the UF_6 is withdrawn from the process, cooled to a solid, and shipped to the customer or converted to an oxide or metal depending on the application.

Figure 2-1 Single Stage of the Gaseous Diffusion Process



In summary, the gaseous diffusion process consists of pumping gaseous UF_6 through diffusion barriers that separate the uranium-235 from uranium-238. Uranium-238 is removed from the system as depleted uranium. The maximum enrichment achieved using the gaseous diffusion process is between 97 and 98 percent. When uranium is enriched to a uranium-235 concentration of 20 percent or more, it is considered HEU.

Uranium Enrichment Production Sites

Gaseous diffusion plants were constructed at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. The DOE produced HEU at the Oak Ridge and Portsmouth Gaseous Diffusion Plants for nuclear weapons, naval reactors, and other reactor fuels beginning in the mid-1940s and ending in 1992. The Paducah Gaseous Diffusion Plant never produced HEU but instead produced large quantities of LEU enriched to about 1.0 percent uranium-235. This LEU was then shipped to the Portsmouth and Oak Ridge sites for further enrichment. **Table 2-1** summarizes general information for these sites. More specific information about the Oak Ridge and Portsmouth Gaseous Diffusion Plant operations, including detailed production information, is provided in Section 5 of this report.

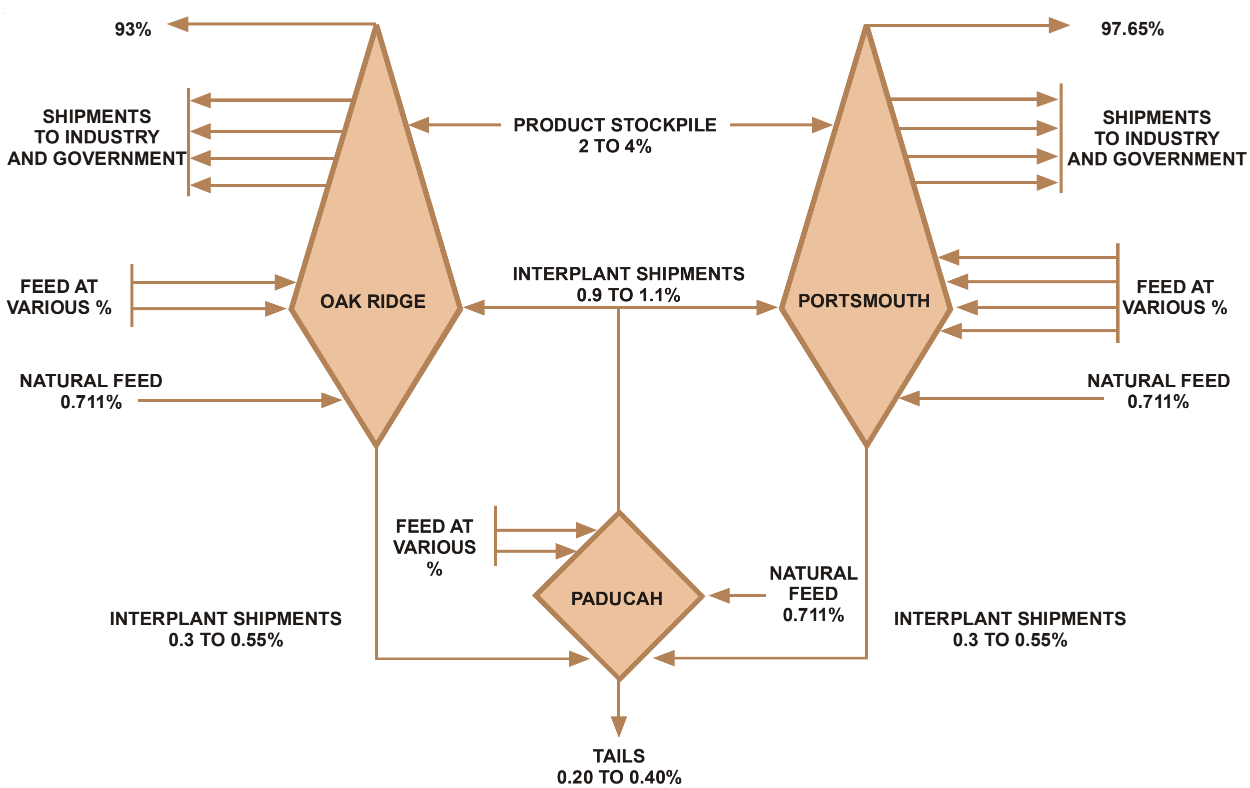
Before enriched uranium can be used for nuclear reactor fuel or weapons production, it must be chemically converted from uranium hexafluoride to an oxide or metal. This conversion is fairly straightforward, and several government-licensed chemical companies furnish conversion services to the civilian atomic industry routinely. As discussed earlier, the HEU was produced primarily for defense requirements while the principal use of LEU is for the civilian atomic power industry.

Table 2-1 Site Information of the Gaseous Diffusion Plants

Site Information	Oak Ridge	Paducah	Portsmouth
City/State	Oak Ridge, TN	Paducah, KY	Portsmouth, OH
Construction Began (year)	1943	1951	1953
Operation Began (year)	1945	1952	1954
Site Area (acres)	640	750	640
Process Building Floor Area (acres)	210	150	200
Enrichment Stages	5,104	1,760	4,020
Full Power (megawatts)	2,105	3,040	2,260
Shutdown	1987	--	--

Although the three GDPs could be operated individually, they were operated as an integrated production complex during full production. The uranium feed to all three plants consisted primarily of natural uranium UF_6 supplemented by varying amounts of feed materials of higher concentrations of uranium-235. From Paducah, a product enriched to approximately 1.0 percent uranium-235 was shipped to the Oak Ridge and Portsmouth sites for further enrichment. **Figure 2-2** illustrates the integrated operation of the three GDPs.[9]

Figure 2-2 Integrated Operation of the Gaseous Diffusion Plants



[9] In June 1999, the Secretary of Energy initiated an investigation into allegations that trace elements in feed material for the GDPs may have endangered the health of employees.

HEU UTILIZATION AND FACILITIES

For over 50 years, HEU has been used in nuclear weapons, naval reactors, and research and development (R&D) programs. These programs covered a wide spectrum of nuclear energy activities—from research on exotic elements to the production of nuclear components for weapons, power generation, medical purposes, and industrial uses.

Figure 2-3 provides the location of sites discussed in this report. It is important to note that this listing does not include waste sites. A brief narrative of the sites listed in Figure 2-3 is provided in Appendix B. Some of the sites were established by commercial entities when privatization was encouraged by legislation that precluded the Government from competing with industry.

U.S. programs involved in HEU utilization can be grouped into four general categories:

- U.S. Nuclear Weapons Program
- Military Reactors
- Space Propulsion
- Other Government and Commercial Reactors

A brief description of each of these categories is provided below.

U.S. NUCLEAR WEAPONS PROGRAM

From the beginning, the U.S. nuclear weapons program consisted of developing, designing, fabricating, and testing nuclear weapons as requested by the DoD and approved by the President. The design, development, and production of weapons systems requires a large number of manufacturing techniques and capabilities. Research and development in the program provides for the basic research necessary for advances in weapons technologies and the specific weapons development activities for meeting DoD-approved requirements.

A nuclear weapon is a complex device consisting of many parts. A number of these parts require special materials in their manufacture; all of them have rigorous specifications for assembly.

Primary HEU Utilization Sites in the U.S. Nuclear Weapons Program

✓ Materials Production: Savannah River Site[10]

✓ Weapons Component Fabrication: Y-12 Plant and the Rocky Flats Plant[11]

✓ Weapons Operations (assembly and dismantlement): Pantex Plant and Iowa Army Ordnance Plant[11]

✓ Research, Development, and Testing: Los Alamos, Lawrence Livermore, and Sandia National Laboratories, and the Nevada Test Site

[10] The Savannah River Site used HEU to produce plutonium and tritium for the weapons program.
[11] A former nuclear weapons site.

All nuclear weapons require fissile materieals, i.e., materials capable of being split or "fissioned" by low-energy neutrons. Fission releases energy and additional neutrons, leading to a self sustaining chain reaction. HEU is one of the fissile materials the U.S. uses to make nuclear weapons.

MILITARY REACTORS

HEU utilization in military reactors includes the Naval Nuclear Propulsion Program and the Army Nuclear Power Program. The Naval Nuclear Propulsion Program is a joint Department of the Navy and DOE program. The principal objective of the program is the continued development and improvement of naval nuclear propulsion plants and reactor cores for use in ships ranging in size from small submarines to large combatant surface ships. In conjunction with the basic research and development work on advanced reactor plants and long-life cores, DOE constructed and operated nine training platforms. As of September 30, 1996, the Navy had built over 200 nuclear-powered ships. Of these, 96 submarines, 8 aircraft carriers, and 4 guided missile cruisers were still in operation. Construction was underway on three additional nuclear-powered submarines and aircraft carriers.

The Army Nuclear Power Program developed specialized nuclear power reactors that were operated by military services in some of the most remote areas of the world. These reactors largely eliminated the need for supplying large amounts of fossil fuel for power production. The first pressurized water reactor for Army use began operation at Fort Belvoir, Virginia, in 1957. During the life of the program (1954-1977), the Army designed, constructed, and deactivated nine nuclear power program facilities. A description of the reactors in the Army Nuclear Power Program and the Naval Nuclear Propulsion Program is provided in Appendix D.

Figure 2-3 Sites Discussed in this Report

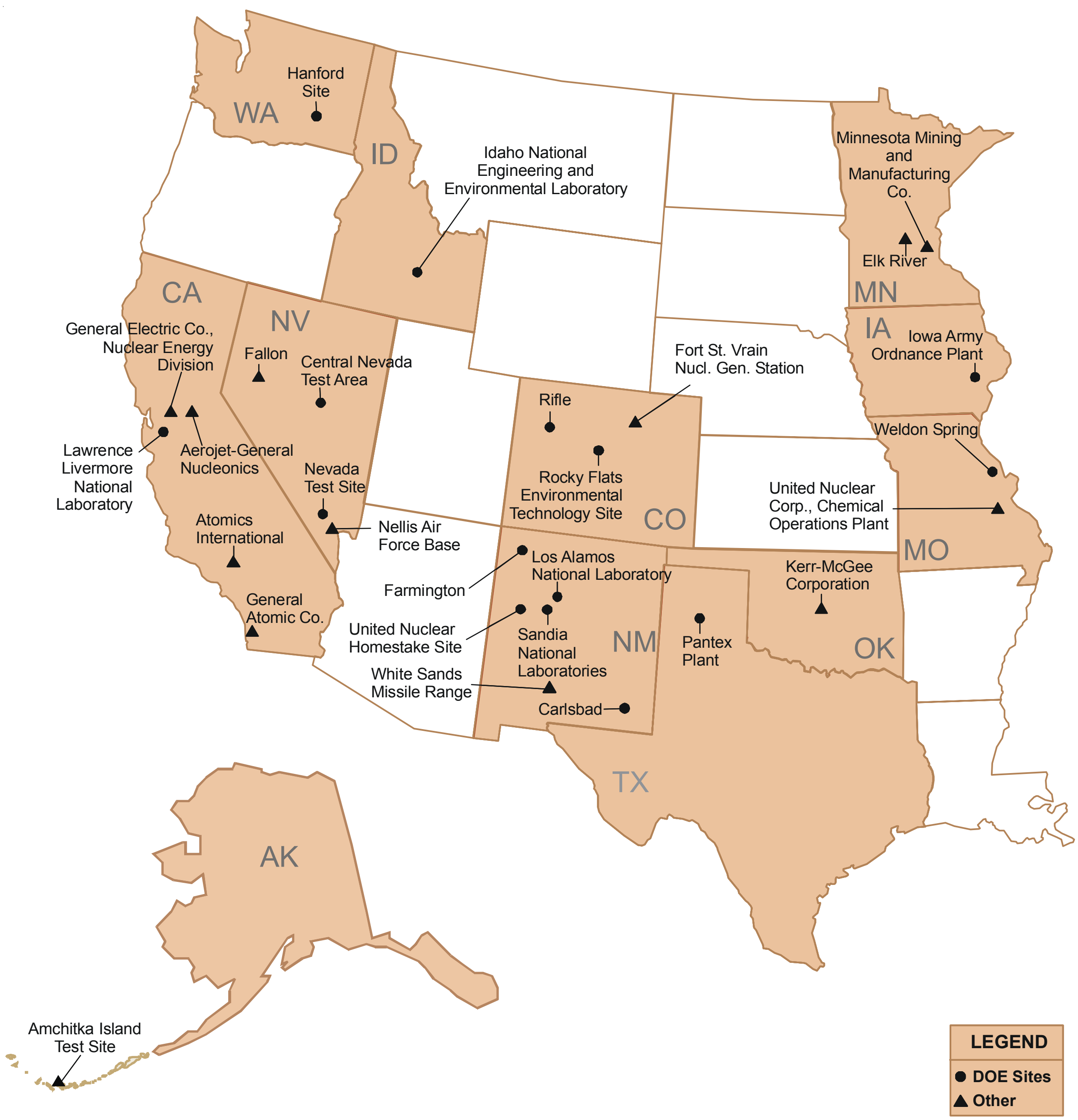
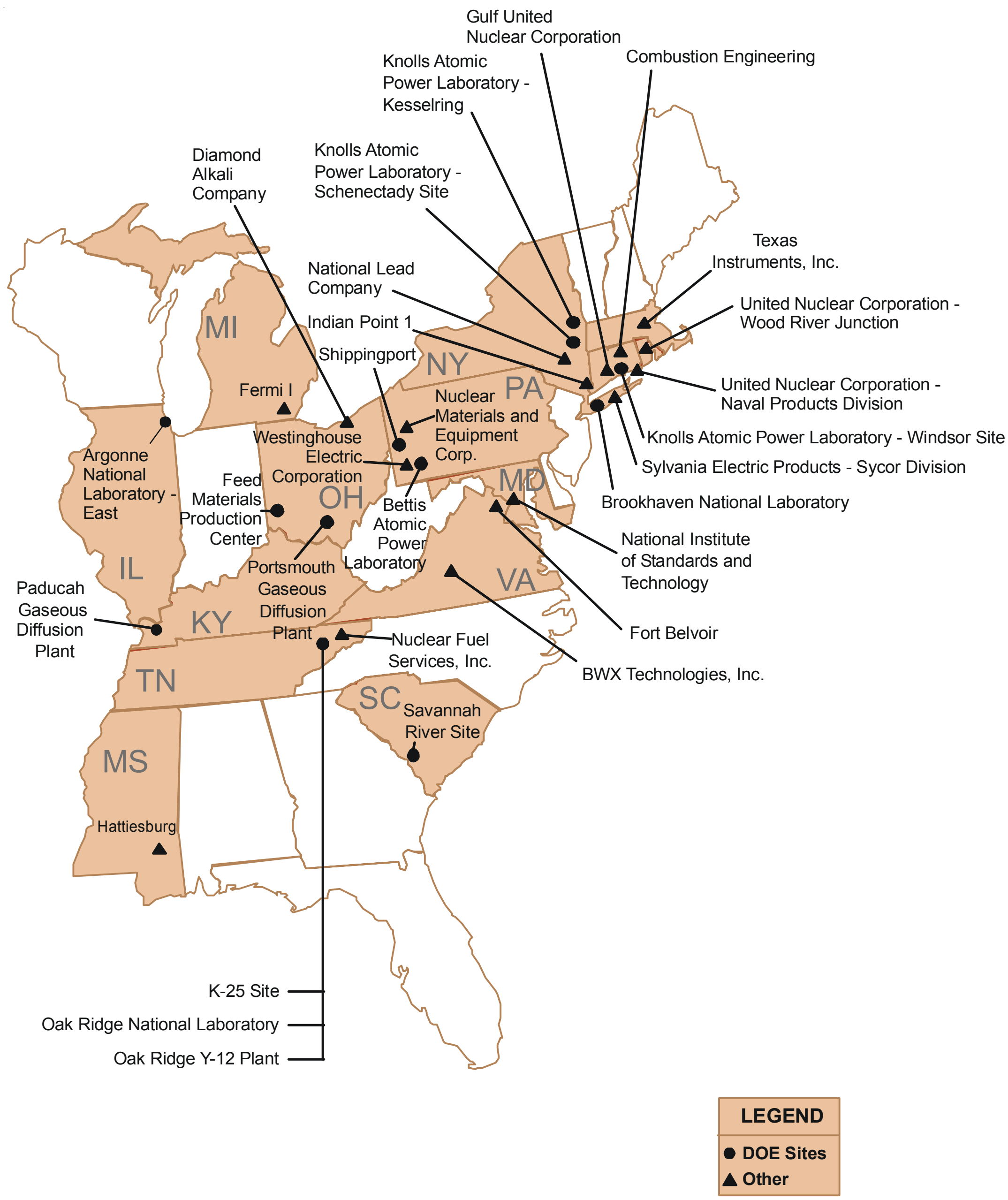
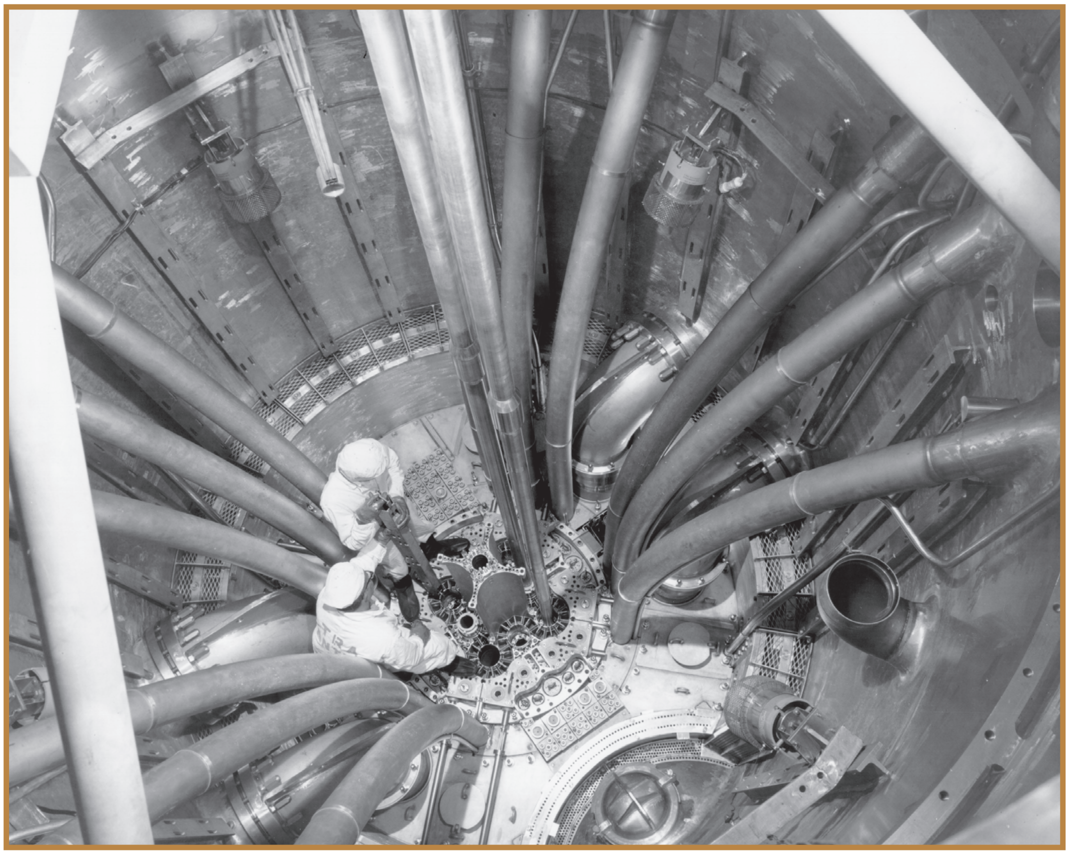


Figure 2-3 Sites Discussed in this Report - continued



Pictured is an elevated port beam view of the nuclear-powered aircraft carrier U.S.S. Dwight D. Eisenhower (CVN 69) underway off the Virginia Capes.



Pictured is the core of the Advanced Test Reactor located at the Idaho National Engineering and Environmental Laboratory. Since 1968, this reactor has contributed substantially to reactor technology and development.

Space Propulsion-Project Rover/NERVA

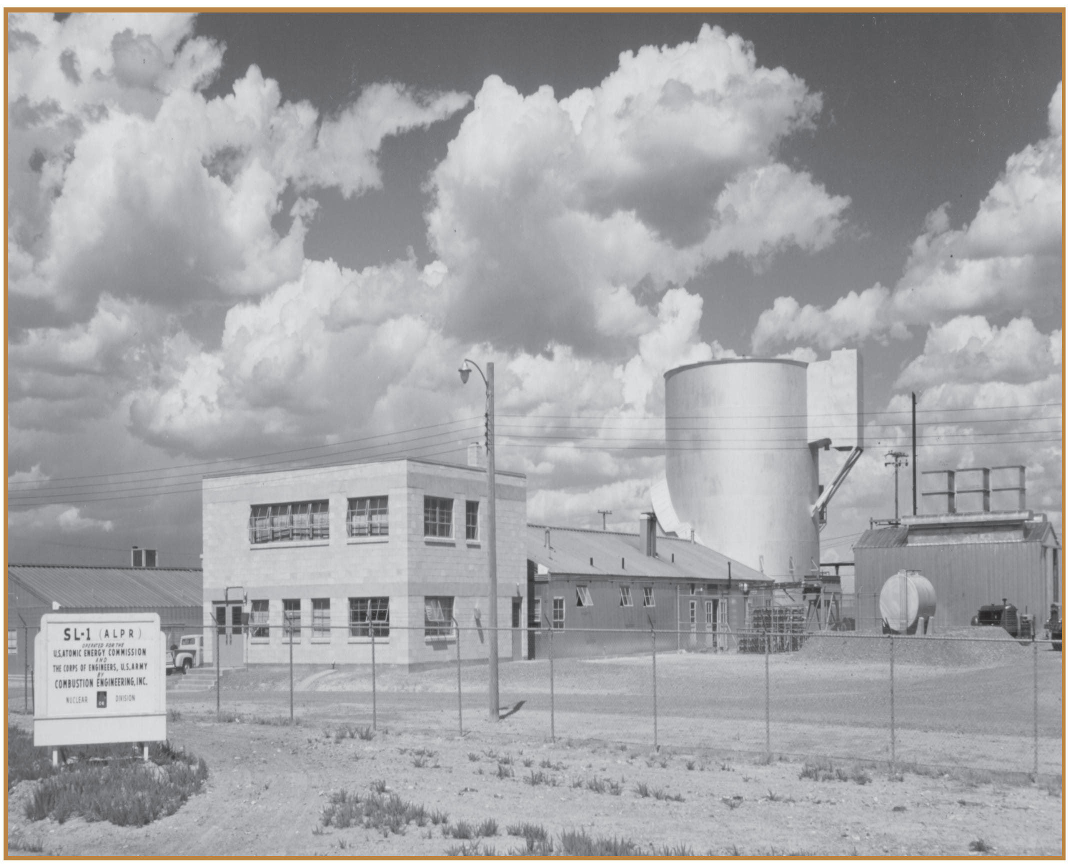
In 1956, the U.S. Government initiated "Project Rover," a program at the Los Alamos National Laboratory, Westinghouse Astronuclear Laboratory, Aerojet-General Corporation, and other industrial partners, to determine the feasibility of utilizing nuclear energy for rocket vehicle propulsion. The goal of this joint AEC-National Aeronautics and Space Administration (NASA) program was to develop nuclear rocket propulsion systems for transporting heavy payloads and conducting missions in space, including manned missions to other planets.

In 1967, after 11 years of extensive research and development, the performance of the nuclear rocket had been demonstrated, and the technological basis had been established for the development of a flight engine called NERVA (Nuclear Engine for Rocket Vehicle Application). The NERVA used HEU fuel in a graphite matrix. The first experimental space propulsion reactor (Kiwi-A) was tested in Nevada in July 1959. In all, 23 nuclear reactor rocket engine tests were conducted at the Nuclear Rocket Development Station (NRDS) located at the Nevada Test Site. While many rocket engines were designed, built, and tested, they were never used in the space program. In 1971, the program to develop space propulsion systems was terminated.

Other Government and Commercial Reactors

Other government reactors also used HEU as fuel for research, training, and test purposes, and for the production of radioisotopes for medical and industrial uses. These reactors include: the Experimental Breeder Reactor-II; the High Flux Isotope Reactor; the Advanced Test Reactor; the High Flux Beam Reactor; some university reactors; and the National Institute of Standards and Technology research reactor. Commercial reactors that used HEU as fuel to produce electric power include: the Fort St. Vrain Nuclear Power Generating Station in Colorado; the Enrico Fermi Atomic Power Plant, Unit 1 in Michigan; and the Elk River Reactor in Minnesota.

Pictured is the Phoebus 1B reactor mounted on a test cart en route to the Nuclear Rocket Development Station at the Nevada Test Site. The Phoebus 1B was one of 23 nuclear reactor rocket engines tested in the 1960s as part of the space propulsion program.



Pictured is the Stationary Low Power Plant (SL-1) at the Idaho National Engineering and Environmental Laboratory. The SL-1 was part of the Army Nuclear Power Program constructed to gain experience in boiling water reactor operations, develop performance characteristics, train military crews, and test components. The SL-1 operated from August 11, 1958, through January 3, 1961, when it was destroyed in an accident.

HEU is contained in tens of thousands of individual items and in hundreds of unique chemical and physical forms. Some examples of forms include metals, oxides, other compounds, combustibles, residues, solutions, and irradiated materials. Pictured to the left is HEU in storage containers at the Oak Ridge Y-12 Plant.

This page intentionally left blank