

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

5.1 PRODUCTION

No information is available in the TRI database on facilities that manufacture or process uranium, because this chemical is not required to be reported under Section 313 of the Emergency Planning and Community Right-to-Know Act (Title III of the Superfund Amendments and Reauthorization Act of 1986) (EPA 1998c).

Uranium is present in the earth's crust at approximately 3 ppm (2 pCi/g) (Clark et al. 2006; du Preez 1989; WNA 2011). Of the more than 100 uranium ores, the primary (brannerite, carnotite, coffinite, davidite, pitchblende, thucholite, uraninite) and secondary (tobernite, autunite, tyuyamunite) are the main ores of commercial interest. The main ores are described in Table 5-1. The most economically attractive uranium ores have uranium concentrations >1,000 ppm (700 pCi/g) (Clayton and Clayton 1981; Weigel 1983; WNA 2011). In the United States, the major ore deposits are located in Colorado, Utah, Arizona, New Mexico, Wyoming, Nebraska, and Texas (EPA 1985a). The steps necessary to produce uranium for its various uses include mining, milling, conversion to uranium hexafluoride (UF₆), enrichment, reduction to metal or oxidation to uranium oxide, and fabrication into the desired shape. The steps for preparing commercial reactor grade, submarine reactor grade, or weapons-grade uranium are the same, except the last two require a more aggressive enrichment process. Depleted uranium metal is produced by reducing the depleted uranium hexafluoride byproduct. Conventional fabrication methods are used to configure the uranium for specific uses, such as rectangular solid blocks for helicopter rotor counterbalances and parabolic or cylindrical solids for military depleted uranium projectiles.

Mining. Open-pit mining, *in situ* leaching, and underground mining are three techniques that have been used for mining uranium-containing ores (EPA 1985a; WNA 2011). Uranium is found in all soil and rock, but the higher concentrations found in phosphate rock, lignite, and monazite sands are sufficient in some areas for commercial extraction (Lide and Frederikse 1994). The choice of mining method is influenced by factors such as the size, shape, grade, depth, thickness, disaggregation, and permeability of the ore deposits and the proximity to groundwater (Grey 1993; WNA 2011). Historically, open-pit and underground mining have been most commonly used mining methods. However, most uranium in the United States is currently mined through *in situ* leaching, which results in little disturbance to the surface and generates no tailings or waste rock (Grey 1993; EIA 2010b; WNA 2011). *In situ* leaching involves leaching (or dissolving) uranium from the host rock with liquids without removing the rock from the

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Table 5-1. Uranium Ores

Ore	Composition	Description
Primary ores		
Uraninite	$UO_2 + UO_3$	A steel-, velvet-, to brownish-black in color; major ore of uranium and radium
Pitchblende	$UO_2 + UO_3$	Essentially the same as uraninite
Brannerite	$U(TiFe)_2O_2$	A black, brownish, olive greenish ore; primary mineral in granite, associated with uraninite
Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$	A black or pale-to-dark brown mineral in sandstone, associated with uraninite
Davidite	$(CeLa)U(TiFe^{3+})_{20}(O,OH)_{38}$	A black-brownish mineral in granite, associated with ilmenite and others
Thucholite	Mixture of petroleum hydrocarbons, uraninite, and sulfides	Black mixture, acronym stands for thorium, uranium, carbon, and hydrogen
Carnotite	$K_2O \cdot 2U_2O_3 \cdot V_2O_5 \cdot 3 H_2O$ (uranium potassium vanadate)	Bright-, lemon-, or greenish-yellow mineral in sandstone associated with tyuyamunite and U-V oxides
Secondary ores		
Autunite	$Ca (UO_2)_2 (PO_4)_2 \cdot 10 H_2O$	Yellow-to-greenish mineral produced under oxidizing conditions and associated with tormernite
Torbernite	$Cu (UO_2)_2 (PO_4)_2 \cdot 10 H_2O$	An emerald-, grassy-, to apple-green mineral formed in an oxidized zone and associated with uraninite and autunite
Tyuyamunite	$Ca(UO_2)_2 (VO_4)_2 \cdot 5-8 H_2O$ (uranium calcium vanadate)	A canary-, lemon-, to greenish-yellow mineral associated with carnotite

Sources: Amethyst Galleries 1995; Mindat 2011; MSA 2011; Stockinger 1981; Uranium Institute 1996

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

ground and can only be carried out on unconsolidated sandstone uranium deposits located below the water table in a confined aquifer. A leaching solution is introduced into or below the deposit and pumped to the surface, where the uranium-pregnant liquor is processed in a conventional mill to precipitate the uranium as yellowcake (U_3O_8 and other oxides) (DOE 1995b; Grey 1993; WNA 2011).

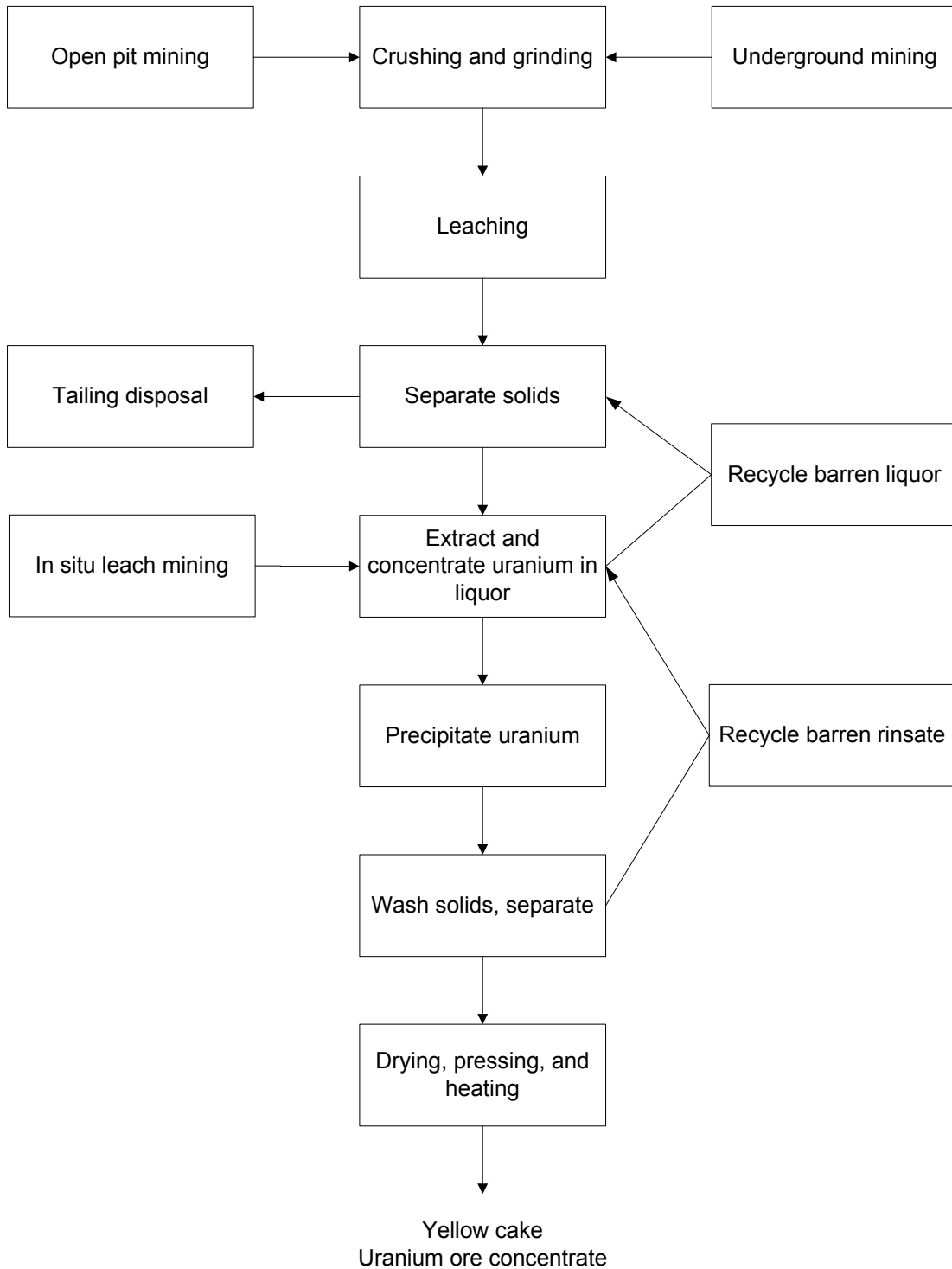
Milling. Ore mined in an open-pit or underground mine is crushed and leached in a uranium mill. The initial step in conventional milling involves crushing, grinding, and wet and/or dry classification of the crude ore to produce uniformly sized particles that are similar in size to beach sand (Clark et al. 2006; WNA 2011). A slurry generated in the grinding circuit is transferred to a series of tanks for leaching by either an alkaline or acid process (Clark et al. 2006; WNA 2011). Generally, leaching is a simple process whereby uranyl ions are extracted by a solvent. Uranyl ions are stripped from the extraction solvent and precipitated as yellowcake, predominantly U_3O_8 (Clark et al. 2006; EPA 1995d; WNA 2011).

Yellowcake is pressed, dried, banded, and shipped for refinement and enrichment. The byproduct of this process is the leftover sand, known as tailings (Clark et al. 2006; WNA 2011). Thus, tailings are the original sand minus much of the uranium plus residual process chemicals. Tailings are less radioactive than the original ore (Uranium metal production in a conversion facility is done postenrichment.) Generalized flow charts for the alkaline and acid leaching processes for ore concentration and uranium production are shown in Figure 5-1.

Enrichment. Next, the U_3O_8 is chemically converted to UF_6 . The enrichment process increases, or enriches, the percentage of the fissionable ^{235}U isotope, as well as ^{234}U . Until recently, the major process used for uranium enrichment in the United States has been gaseous diffusion. The mechanism for enrichment is based on the fact that a UF_6 molecule containing ^{235}U or ^{234}U is lighter and smaller, and has, therefore, a slightly higher thermal velocity than a UF_6 molecule containing ^{238}U (WNA 2011). As the UF_6 passes through the series of diffusion stages, the $^{234}UF_6$ and $^{235}UF_6$ molecules gradually become more concentrated downstream and less concentrated upstream, while the $^{238}UF_6$ concentrates conversely. The lead portion of the stream is collected and recycled to reach the desired enrichment. The tail portion containing a reduced $^{235}UF_6$ content, called depleted UF_6 , can be stored in the vicinity of the gaseous diffusion plant sites (DOE 1994b). There are an estimated 686,500 metric tons of depleted uranium currently in storage as UF_6 (ANL 2011). A second enrichment technology, gas centrifuge separation, is now replacing gas diffusion in the United States and is expected to be the dominant enrichment process in coming years (WNA 2011). During gas centrifuge enrichment, UF_6 gas is fed into centrifuge cylinders containing rotors that are spun at 50,000–70,000 rpm (WNA 2011). The heavier $^{238}UF_6$ molecules

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Figure 5-1. Uranium Ore Processing



Sources: Agency for Toxic Substances and Disease Registry 1997; Uranium Institute 1996; WNA 2010

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

concentrate toward the cylinder's outer edge while the lighter $^{235}\text{UF}_6$ molecules concentrate toward the center (Clark et al. 2006; WNA 2011). At the same time, a countercurrent circulation flow along the length of the rotor creates a vertical separation of the isotopes as well allowing for them to be drawn off at separate ends (Clark et al. 2006; WNA 2011). The two major advantages of the gas centrifuge are that it is much more efficient in both its energy requirements and its ability to separate the isotopes than gas diffusion enrichment (WNA 2011). A third technology, laser separation, is currently under development (DOE 1995b; WNA 2011). A fourth technology, thermal separation, is inefficient and no longer used.

Fuel Fabrication. In most cases, the enriched UF_6 is oxidized to uranium dioxide and formed into pellets of ceramic uranium dioxide (UO_2). The pellets are then stacked and sealed inside metal tubes that are mounted into special fuel assemblies ready for use in a nuclear reactor (DOE 1995b; Uranium Institute 1996; WNA 2011).

Product Fabrication. Uranium metal has commercial and industrial uses due to its great density and strength. It is alloyed with a range of metals to meet other commercial and industrial needs (Clark et al. 2006). As with steel, uranium can be formed and fashioned by drop forging, dye casting, and machining and is often painted to minimize oxidation. Some well-known uses for these products are military armor and armor piercing munitions, helicopter rotor blade counterbalances, weights in airplane control surfaces, and radiation shields for high radioactivity sources (e.g., industrial radiography) (Parkhurst and Guilmette 2009a; WNA 2011).

Production. Uranium production from 1975 to 2009 is shown in Table 5-2. Peak production of uranium occurred in 1980 at 21,852 short tons (1.98×10^7 kg) and decreased until 1993. This was the same period when the planning and construction of new nuclear power plants ceased in the United States. Production of U_3O_8 had decreased to 4,443 short tons (4.03×10^6 kg) in 1990 and to 1,534 short tons (1.39×10^6 kg) in 1993, a 65% reduction (ABMS 1994; EPA 1985a). In 1996, U.S. uranium production was 3,160 short tons (2.87×10^6 kg), an increase of 5% from the 1995 level and the highest level since 1991 (DOE 1996a). Underground and open-pit mining have been the two most commonly used methods of mining uranium ores. However, by 1994, uranium was produced primarily by *in situ* leaching methods. A summary of U.S. mine production from 1985 through 1996 (see Table 5-3) illustrates the shift from underground and open-pit mining to *in situ* leaching. U.S. uranium production fell to a low of 1,100 short tons in 2003 before climbing back to just over 2,000 short tons by the end of the decade (EIA 2010b).

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Table 5-2. Uranium Production in the United States by Uranium Mills and Other Sources

Year	Short tons ^a of U ₃ O ₈	Kilograms of U ₃ O ₈
1975	11,600	1.05x10 ⁷
1976	12,747	1.16x10 ⁷
1977	14,939	1.35x10 ⁷
1978	18,486	1.68x10 ⁷
1979	18,736	1.70x10 ⁷
1980	21,852	1.97x10 ⁷
1981	19,237	1.74x10 ⁷
1982	13,434	1.22x10 ⁷
1983	1,0579	9.60x10 ⁶
1989	6,919	6.28x10 ⁶
1990	4,443	4.03x10 ⁶
1991	3,976	3.61x10 ⁶
1992	2,823	2.56x10 ⁶
1993	1,534	1.39x10 ⁶
1994	1,676	1.52x10 ⁶
1995	3,022	2.74x10 ⁶
1996	3,160	2.87x10 ⁶
1997	2,820	2.56x10 ⁶
1998	2,550	2.13x10 ⁶
1999	2,250	2.04x10 ⁶
2000	1,550	1.41x10 ⁶
2001	1,300	1.18x10 ⁶
2002	1,200	1.09x10 ⁶
2003	1,100	9.98x10 ⁵
2004	1,250	1.13x10 ⁶
2005	1,500	1.36x10 ⁶
2006	2,350	2.13x10 ⁶
2007	2,250	2.04x10 ⁶
2008	1,950	1.77x10 ⁶
2009	2,050	1.86x10 ⁶

^aShort ton = 2,000 lbs = 907 kg.

Sources: ABMS 1994; DOE 1996a, 1997b, 1999a; EIA 2010b; EPA 1985a

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Table 5-3. Uranium Mining Production, 1985–2009^a

Mining method	Percentage of total													
	1985	1986	1987	1988	1990	1991	1992	1994	1996	1998	2003	2005	2006	2009
Underground	52.3	77.8	81.7	56.8	W ^b	W	W	0	W	W	W	W	W	W
Open-pit	23.3	W	W	W	32.0	48.8	W	0	0	0	0	0	0	0
<i>In situ</i> leaching	No data	No data	W	W	W	W	W	96.9	93.1	77.8	W	88.0	90.8	W

^aDoes not include uranium sources such as mine water, mill site cleanup, mill tailings, or well field restoration.

^bData withheld.

Sources: DOE 1995, 1996a, 1997b, 1999b; EIA 2010b

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Leached uranium concentrate was produced in 1996 in Wyoming, Louisiana, Nebraska, New Mexico, and Texas. At the end of 1996, two phosphate byproduct plants and five *in situ* leaching plants were in operation. In addition, seven phosphate byproduct and *in situ* leaching plants were inactive, and seven conventional uranium mills were being maintained in stand-by mode (DOE 1997b). During 2010, one conventional uranium mill and four uranium *in situ* leach plants were reported to be in operation in the United States (EIA 2010b).

5.2 IMPORT/EXPORT

The importation of uranium increased significantly in the 1980s (EPA 1985a). In 1983, 3,960 short tons of U_3O_8 equivalent were imported into the United States (USDOC 1984), which was about 37% of the domestic production. In 1987, the amount of U_3O_8 equivalent imported into the United States was 5,630 short tons (USDOC 1988). The amounts of uranium and uranium compounds imported into the United States during the period 1989–1997 are presented in Table 5-4 (USDOC 1995, 1997). The importation of uranium and uranium compounds peaked in 1990 at about 23 million kg (about 1 million tons) and has remained approximately the same, with some fluctuation, since that time. Actual uranium import values for more recent years have not been located; however, amounts of foreign-origin uranium purchased by U.S. suppliers and owners and operators of U.S. Civilian Nuclear Power Reactors are available (EIA 2010a). These data (located in Table 5-6) suggest uranium imports have remained steady over the previous two decades. Close to 27 million kg of foreign-origin uranium was purchased in 2009.

The amount of uranium and uranium compounds exported from the United States during 1989–1993 is shown in Table 5-5. The total volume of uranium and uranium compounds exported during 1989–1993 was 2 orders of magnitude lower than the quantities imported during this same time period. Exports in 1996 were 5.2 million kg. Most of the foreign sales (Canada, France, Germany, Japan, South Korea, United Kingdom) occurred after the uranium entered the U.S. market as imports (DOE 1999b). Amounts of uranium sold to firms located outside the United States (Table 5-6) suggest exports have remained steady since the mid 1990s (EIA 2010a). Approximately 10 million kg of uranium were sold in 2009.

5.3 USE

Uranium has been produced for use in the commercial nuclear power industry as low-enriched metal or ceramic UO_2 fuel pellets; smaller quantities of high-enriched fuel are produced for U.S. Navy ships and for weapons manufacture (Clayton and Clayton 1981; EPA 1985b; Peehs et al. 2007; WNA 2011). Uranium fuel lasts months to years before refueling is needed, and then only a small fraction of the

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Table 5-4. Import of Uranium and Compounds (in kg) into the United States (1990–1998)^a

Substance	Year								
	1990	1991	1992	1993	1994	1995	1996	1997	1998
U-metal (depleted)	18,343	9,673	9,008	4,458	1,735	792	1,572	36,359	508
U-alloys, dispersions, and ceramic materials	5	2,444	9	25	No data	No data	309,681	10	2
U-oxide (natural)	8,459,924	12,630,433	10,043,472	7,925,762	9,713,406	8,992,532	8,880,669	9,259,002	No data
U-oxide (enriched)	204,592	200,733	63,875	35,779	14,214	97,976	57,241	158,082	36,121
U-oxide (depleted)	886,853	19,410	608,472	495	0	0	11,253	0	0
U-fluoride (natural)	9,432,470	8,109,402	5,844,985	10,827,786	9,583,669	11,140,026	10,936,114	12,210,369	12,965,093
U-fluoride (enriched)	598,763	874,251	875,831	868,652	1,000,950	934,046	1,024,148	858,807	1,252,438
U-fluoride (depleted)	479,601	4,523	125,466	0	0	58,000	0	0	147,691
U-compounds (not otherwise stated)	42,277	191,221	847,425	1,275,137	121,439	86,935	324	446,812	253,211
U-compounds (enriched)	159,220	28,950	6	6	69,063	0	6,800	29,682	No data
U-compounds (depleted)	4,731	294	1,666	107	0	122	245	100	248
Ores and concentrates	2,763,185	1,344,927	0	0	No data	No data	0	212,434	0
Mixture (depleted)	0	0	0	4,431	No data	No data	No data	No data	No data
Spent fuel	16,401	5,033	0	115	45	0	23	306	No data

^aImport data for more recent years were not located. See Table 5-6 for amounts of uranium sold to firms located outside the United States in recent years.

Sources: USDOC 1995, 1997, 1999

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Table 5-5. Export of Uranium and Compounds (in kg) (1990–1998)^a

Substance	Year									
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
U-oxide (natural)	6,302	318	0	96,748	6,196	690,449	351,169	192,296	250,443	0
U-oxide (enriched)	0	0	85	26,596	64	418,873	299,175	323,990	903,810	646,984
U-fluoride (natural)	85	0	20,175	186,530	4,231	No data	No data	0	688,873	53,800
U-fluoride (enriched)	15,698	39,262	0	175,445	90,459	No data	No data	No data	No data	No data
U-compounds (not otherwise stated)	0	9,801	12,596	8,019	0	No data	No data	No data	No data	No data
U-compounds (enriched)	28,221	0	6,609	3	0	0	66,893	418,447	10,506	99,456
U-compounds (depleted)	0	90	160	0	0	246,765	379,530	406,079	30,426	41,674
U-metal	No data	No data	No data	No data	No data	270	496	299,117	3,159	0
U-ores and concentrates	No data	No data	No data	No data	No data	59,461	0	0	0	0
Alloys, dispersions, ceramics ^b	No data	No data	No data	No data	No data	74,712	45,424	29,759	152,920	0
Spent fuel	0	21,576	0	0	0	No data	No data	No data	No data	No data

^aExport data for more recent years were not located. See Table 5-6 for amounts of uranium purchased from firms located outside the United States in recent years.

^bAlloys, dispersions (including cermets), ceramic products, and mixtures containing natural uranium compounds, Nesoi (SIC2819).

Sources: USDOC 1995, 1999

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

Table 5-6. Foreign Purchases and Foreign Sales of Uranium (kg U₃O₈ Equivalent) by U.S. Suppliers and Owners and Operators of U.S. Civilian Nuclear Power Reactors, 1994–2009

Year	Foreign purchases ^a	Foreign sales ^b
1994	1.66x10 ⁷	8.03x10 ⁶
1995	1.87x10 ⁷	4.44x10 ⁶
1996	2.06x10 ⁷	5.22x10 ⁶
1997	1.95x10 ⁷	7.71x10 ⁶
1998	1.98x10 ⁷	6.85x10 ⁶
1999	2.16x10 ⁷	3.85x10 ⁶
2000	2.04x10 ⁷	6.17x10 ⁶
2001	2.12x10 ⁷	5.31x10 ⁶
2002	2.39x10 ⁷	6.98x10 ⁶
2003	2.40x10 ⁷	5.99x10 ⁶
2004	3.00x10 ⁷	5.99x10 ⁶
2005	2.97x10 ⁷	9.30x10 ⁶
2006	2.94x10 ⁷	8.48x10 ⁶
2007	2.45x10 ⁷	6.71x10 ⁶
2008	2.59x10 ⁷	7.80x10 ⁶
2009	2.67x10 ⁷	1.07x10 ⁷

^aPurchases of foreign origin uranium from a firm located outside the United States.

^bSales of uranium to a firm located outside the United States.

Sources: EIA 2010a

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

uranium has actually been fissioned, making fuel reprocessing an option used in other countries (WNA 2011). One pound of completely fissioned uranium produces the same amount of energy as 1,500 tons of coal (Lide and Frederikse 1994). Depleted uranium is used in the manufacture of armor-piercing ammunition for the military, in inertial guidance devices and gyro compasses, as counterbalances for helicopter rotors, as counterweights for aircraft control surfaces, as radiation shielding material, and as x-ray targets (EPA 1985b; Parkhurst and Guilmette 2009a; Peehs et al. 2007; USDI 1980; WNA 2011). In the past, uranium salts have been used to produce colored ceramics and glasses (Clark et al. 2006). Additionally, uranium was used in dental porcelains for many years, but this practice has been discontinued (FDA 1976; WNA 2011). According to the USDI (1980), the major uses of depleted uranium in 1978 were military ammunition, 71.8%; counterweights, 11.4%; radiation shielding, 13.6%; and chemical catalysts, 3.2%, although this ratio may shift to support war efforts.

5.4 DISPOSAL

Radioactive waste containing uranium is usually grouped into three categories: uranium mill tailings, low-level waste, and, in the case of spent reactor fuel, high-level waste (USNRC 2002, 2007).

Uranium mill tailings are the residual sand and trace chemicals from the processing of uranium ore. About 150 tons of enriched uranium are required per year to fuel a 1,000-megawatt electric nuclear power reactor, and about 500 times that amount of ore is required to obtain the uranium. The total accumulation of uranium in licensed mill tailings piles in the United States is approximately 200 million tons (EPA 2011ee; Murray 1994). Tailings from mines and mills that process other metals should also be expected to contain elevated concentrations of uranium and its progeny, although this may not be readily recognized.

Disposal methods for processed uranium tailings have been discussed by Bearman (1979). In the late 1940s, mainly unconfined disposal systems were used. Untreated solid wastes were stored as open piles and, in some cases, were spread in urban areas where they were used as fill and as the sand in concrete used to build roads, walks, drives, and concrete block, and in brick mortar. As a result of the Animas River Survey in the United States, tailing control programs were instituted in 1959 to prevent airborne and waterborne dispersal of the wastes. Confined disposal methods were devised to reduce the exposure and dispersion of wastes and to reduce seepage of toxic materials into groundwater to the maximum extent reasonably achievable. Under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, the U.S. Department of Energy (DOE) designated 24 inactive tailings piles for cleanup. These

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

24 sites contained a total of about 28 million tons of tailings and covered a total of approximately 1,000 acres (EPA 1985b). Two of the sites have been withdrawn from the list and others have combined tailings piles, reducing the number of sites to 19 (USNRC 2006). According to a report by the USNRC (2006), cleanup has been completed at all but two of these locations.

In 1977, the EPA issued Environmental Radiation Protection Standards to limit the total individual radiation dose due to emissions from uranium fuel cycle facilities, including licensed uranium mills. This standard specified that the “annual dose equivalent does not exceed 25 millirems (0.25 mSv) to the whole body, 75 millirems (0.75 mSv) to the thyroid, and 25 millirems (0.25 mSv) to any other organ of any member of the public as the result of exposures of planned discharges of radioactive materials “to the general environment” (40 CFR 190). The EPA also established environmental standards for cleanup of open lands and buildings contaminated with residual radioactivity from inactive uranium processing sites (40 CFR 192).

Low-level radioactive waste (LLRW), which may contain uranium, is disposed of at DOE facilities and at commercial disposal facilities (USNRC 2002, 2007). Since 1963, seven commercial LLRW facilities have operated, but only three are currently receiving waste for disposal (USNRC 2007). A 1992 report listed the total volume of LLRW buried at six of the sites to be approximately 50 million cubic feet (Murray 1994). The current total amount of LLRW stored at the seven LLRW facilities was not located; however, the yearly total amount stored at the three operating locations was reported to be 4.01, 4.05, 2.63, and 2.09 million cubic feet in 2005, 2006, 2007, and 2008, respectively (USNRC 2011). Only a small fraction of the LLRW contains uranium. The method of disposal for commercial and DOE LLRW has been shallow land burial, in which the waste is disposed of in large trenches and covered. This method of disposal relies upon natural features to isolate the waste. Although USNRC regulations for LLRW disposal (10 CFR 61) permit shallow land burial, many states have enacted more stringent regulations that require artificial containment of the waste in addition to natural containment (Murray 1994; USNRC 2002, 2007).

High-level radioactive waste (HLRW) includes spent fuel, which is the uranium fuel rods that have been used in a nuclear reactor (USNRC 2007). When the fuel rods are removed from the reactor for refueling, they still contain most of the original unfissioned uranium. However, the hazard from the large activity of fission products and plutonium that have been produced in the fuel rods overshadows that of uranium. Approximately 47,000 metric tons of spent fuel have been removed from U.S. power reactors through 2002 (EIA 2010d). There is currently no permanent disposal facility for HLRW in the United States;

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

these wastes are being stored at commercial nuclear power plants and DOE facilities where they were produced (EIA 2010d). The USNRC has issued standards for the disposal of HLRW (10 CFR 60), and the DOE is pursuing the establishment of an HLRW facility. Efforts to establish an HLRW facility, which began over 2 decades ago, have experienced many delays.