

## 4. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

### 4.1 PRODUCTION

Uranium is present in the earth's crust at approximately 3 ppm (2 pCi/g) (du Preez 1989). Although there are more than 100 uranium ores, carnotite, pitchblende, coffinite, uraninite, tobernite, autunite, tyuyamunite, and a few others are the main ores of commercial interest. The main ores are described in Table 4-1. The most economically attractive uranium ores have uranium concentrations in excess of 1,000 ppm (700 pCi/g) (Stokinger 1981; Weigel 1983). 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 ( $UF_6$ ), 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). 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 1994). The two most commonly used mining methods are open-pit and underground mining. The choice of method is influenced by factors such as the size, shape, grade, depth, and thickness of the ore deposits (Grey 1993). *In situ* leaching involves leaching (or dissolving) uranium from the host rock with liquids without removing the rock from the 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).

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**Table 4-1. Uranium Ores**

| Ore         | Composition  | Description   |
|-------------|--|---|
| Uraninite   | $UO_2 + UO_3$  | A major ore of uranium and radium; can dissolve in acids              |
| Pitchblende | $UO_2 + UO_3$  | Essentially the same as uraninite                                     |
| Carnotite   | $K_2O \cdot 2U_2O_3 \cdot V_2O_5 \cdot 3 H_2O$<br>(uranium potassium vanadate) |   |
| Autunite    | $Ca (UO_2)_2 (PO_4)_2 \cdot 10 H_2O$   | Can lose water to form meta-autunite; dissolves in acids              |
| Torbernite  | $Cu (UO_2)_2 (PO_4)_2 \cdot 10 H_2O$   | Loses water easily in air forming meta-torbernite; dissolves in acids |
| Coffinite   | $U(SiO_4)_{1-x} (OH)_{4x}$<br>(uranium silicate)                               |   |
| Tyuyamunite | $Ca(UO_2)_2 (VO_4)_2 \cdot 5-8 H_2O$<br>(uranium calcium vanadate)             | Closely related to carnotite  |

Source: Amethyst Galleries 1995; Stockinger 1981; Uranium Institute 1996

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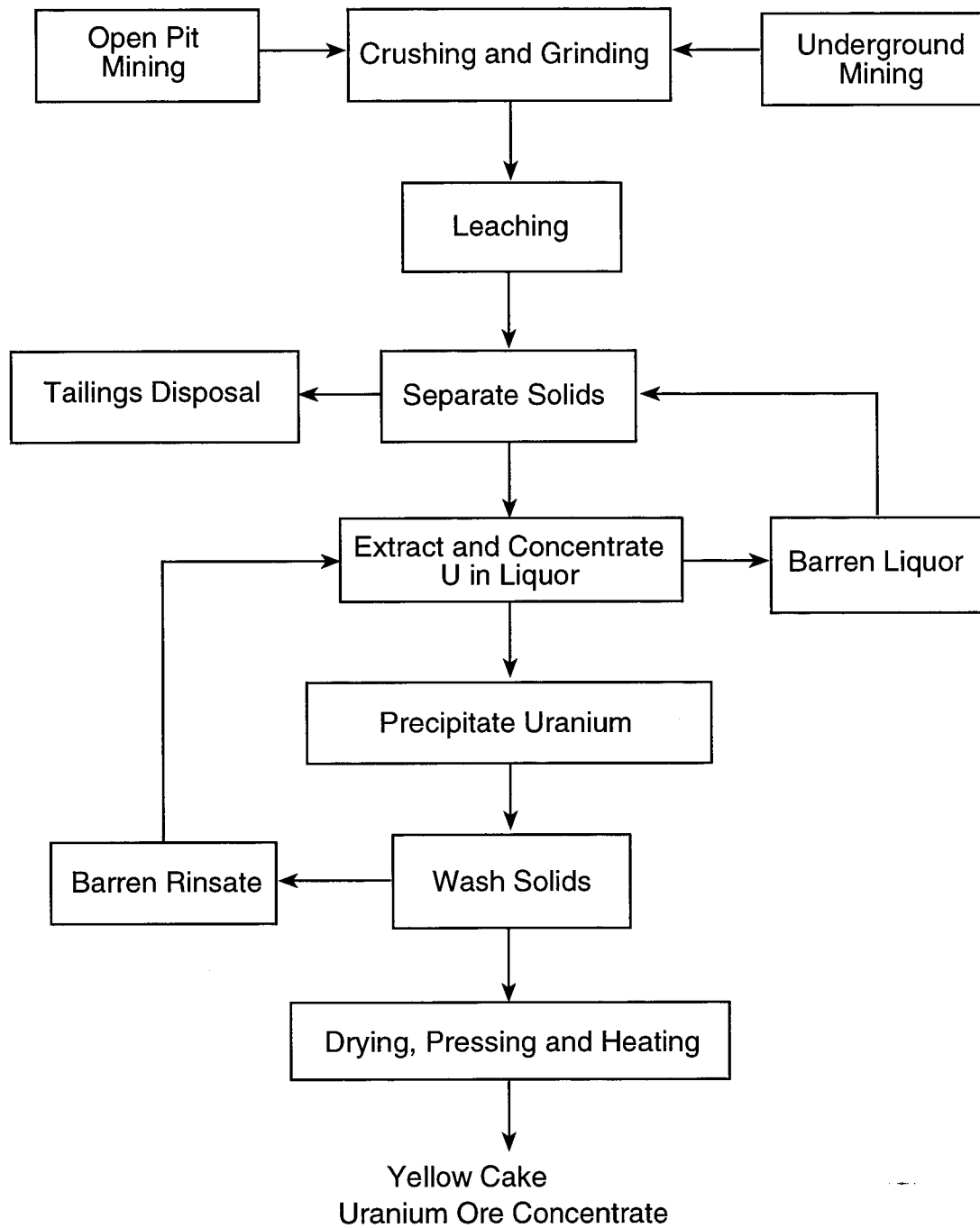
**Milling.** Ore mined in an open-pit or underground mine is crushed and leached in a uranium mill. The initial step in conventional milling involves crushing, grinding, and wet and/or dry classification of the crude ore to produce uniformly sized particles that are similar in size to beach sand. A slurry generated in the grinding circuit is transferred to a series of tanks for leaching by either an alkaline or acid process. 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  $U_3O_8$  (EPA 1995d). Yellowcake is pressed, dried, banded, and shipped for refinement and enrichment. Some of the process streams can also be used to extract other oxides, such as vanadium pentoxide. The byproduct of this process is the leftover sand, known as tailings. Thus, tailings are the original sand minus much of the uranium plus residual process chemicals and tailings are less radioactive than the original ore. (Uranium metal production in a conversion facility is done post-enrichment.) Generalized flow charts for the alkaline and acid leaching processes for ore concentration and uranium production are shown in Figure 4-1.

**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  $^{234}U$ . In the United States, the process used for enrichment is 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  $^{238}U$ . 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 560,000 metric tons of depleted uranium currently in storage as  $UF_6$ . A second enrichment technology, gas centrifuge separation, has been used in Europe. A third technology, laser separation, is currently under development (DOE 1995b). A fourth technology, thermal separation, is inefficient and no longer used.

**Fuel fabrication.** The enriched  $UF_6$  is either reduced to metallic uranium and machined to the appropriate shape, or 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).

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**Figure 4-1. Flow Chart of Uranium Ore Processing**



Source: ATSDR 1997; Uranium Institute 1996

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**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. As with steel, uranium can be formed and fashioned by drop forging, die casting, and machining and is often painted to minimize oxidation. Some well known uses for these products are gyroscopic wheels in guidance systems, helicopter rotor blade counterbalances, weights in airplane control surfaces, and radiation shields for high radioactivity sources (e.g. industrial radiography).

**Production.** Uranium production from 1975 to 1996 is shown in Table 4-2. Peak production of uranium occurred in 1980 at 21,852 short tons ( $1.98 \times 10^7$  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 ( $4.03 \times 10^6$  kg) in 1990 and to 1,534 short tons ( $1.39 \times 10^6$  kg) in 1993, a 65% reduction (ABMS 1994; EPA 1985a). In 1996, U.S. uranium production was 3,160 ( $2.87 \times 10^6$  kg) short tons, 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 4-3) illustrates the shift from underground and open-pit mining to *in situ* leaching.

Leached uranium concentrate was produced in 1996 in Wyoming, Louisiana, Nebraska, New Mexico, and Texas. At the end of 1996, two phosphate by-product plants and five *in situ* leaching plants were in operation. In addition, seven phosphate by-product and *in situ* leaching plants were inactive, and seven conventional uranium mills were being maintained in stand-by mode (DOE 1996b).

## 4.2 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 (USDOD 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 (USDOD 1988). The amounts of uranium and uranium compounds imported into the United States during the period 1989–1997 are presented in Table 4-4 (USDOD 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.

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**Table 4-2. Uranium Production in the United States  
by Uranium Mills and Other Sources**

| Year | Short tons of U <sub>3</sub> O <sub>8</sub> | Kilograms of U <sub>3</sub> O <sub>8</sub> |
|------|---|--|
| 1975 | 11600                                       | 1.05x10 <sup>7</sup>                       |
| 1976 | 12747                                       | 1.16x10 <sup>7</sup>                       |
| 1977 | 14939                                       | 1.35x10 <sup>7</sup>                       |
| 1978 | 18486                                       | 1.68x10 <sup>7</sup>                       |
| 1979 | 18736                                       | 1.70x10 <sup>7</sup>                       |
| 1980 | 21852                                       | 1.97x10 <sup>7</sup>                       |
| 1981 | 19237                                       | 1.74x10 <sup>7</sup>                       |
| 1982 | 13434                                       | 1.22x10 <sup>7</sup>                       |
| 1983 | 10579                                       | 9.60x10 <sup>6</sup>                       |
| 1989 | 6919  | 6.28x10 <sup>6</sup>                       |
| 1990 | 4443  | 4.03x10 <sup>6</sup>                       |
| 1991 | 3976  | 3.61x10 <sup>6</sup>                       |
| 1992 | 2823  | 2.56x10 <sup>6</sup>                       |
| 1993 | 1534  | 1.39x10 <sup>6</sup>                       |
| 1994 | 1676  | 1.52x10 <sup>6</sup>                       |
| 1995 | 3022  | 2.74x10 <sup>6</sup>                       |
| 1996 | 3160  | 2.87x10 <sup>6</sup>                       |
| 1997 | 2820  | 2.56x10 <sup>6</sup>                       |
| 1998 | 2550  | 2.13x10 <sup>6</sup>                       |

Source: ABMS 1994; DOE 1996a, 1996b, 1999a; EPA 1985a

<sup>a</sup>Short ton = 2,000 pounds = 907 kilograms

Table 4-3. Uranium Mining Production, 1985–1998

| Mining method           | Percentage of total |                   |                   |                   |                   |                   |                   |                  |                  |                  |                  |                  |      |      |
|-------------------------|---------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|------------------|------------------|------------------|------------------|------------------|------|------|
|                         | 1985                | 1986              | 1987              | 1988              | 1989              | 1990              | 1991              | 1992             | 1993             | 1994             | 1995             | 1996             | 1997 | 1998 |
| Underground             | 52.3                | 77.8              | 81.7              | 56.8              | 54.4              | W <sup>a</sup>    | W                 | W                | 0                | 0                | 0                | W                | W    | W    |
| Open-pit                | 23.3                | W                 | W                 | W                 | W                 | 32.0              | 48.8              | W                | 0                | 0                | 0                | 0                | 0    | 0    |
| <i>In situ</i> leaching | No data             | No data           | W                 | W                 | W                 | W                 | W                 | W                | W                | 96.9             | 95.6             | 93.1             | 86.7 | 77.8 |
| Other                   | 24.4 <sup>b</sup>   | 22.2 <sup>c</sup> | 18.3 <sup>c</sup> | 43.2 <sup>c</sup> | 45.6 <sup>c</sup> | 68.0 <sup>d</sup> | 51.2 <sup>d</sup> | 100 <sup>e</sup> | 100 <sup>f</sup> | 3.1 <sup>g</sup> | 4.4 <sup>g</sup> | 6.9 <sup>h</sup> | 13.3 | 22.2 |

<sup>a</sup> Withheld; data included with "Other"

<sup>b</sup> *In situ* leach, mine water, water-treatment plant solutions

<sup>c</sup> Open-pit, *in situ* leach, heap leach, mine water, water-treatment plant solutions

<sup>d</sup> Underground, *in situ* leach, heap leach (1990), restoration

<sup>e</sup> Underground, open-pit, and *in situ* leach mines, uranium-bearing water from mine workings, tailing ponds, restoration

<sup>f</sup> *In situ* leach mines, uranium-bearing water from mine workings and restoration

<sup>g</sup> Production from uranium-bearing water from mine workings and restoration

<sup>h</sup> Production from an underground mine and uranium-bearing water from mine workings and restoration

Source: DOE 1995, 1996a, 1996b, 1999b

**Table 4-4. Import of Uranium and Compounds (in kg) into the United States**

| 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        | 1572       | 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 (NOS)                           | 42,277    | 191,221    | 847,425    | 1,275,137  | 121,439   | 86,935     | 324        | 446,812    | 253,211    |
| U-compounds (NOS) (enriched)                | 159,220   | 28,950     | 6          | 6          | 69,063    | 0          | 6,800      | 29,682     | No data    |
| U-compounds (NOS) (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    |

NOS = Not otherwise stated

Source: USDOC 1995, 1997, 1999



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The amount of uranium and uranium compounds exported from the United States during 1989–1993 is shown in Table 4-5. The total volume of uranium and uranium compounds exported during 1989–1993 was two 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).

### 4.3 USE

Uranium has been produced for use in the commercial nuclear power industry as low-enriched metal or ceramic  $\text{UO}_2$  fuel pellets; smaller quantities of high-enriched fuel are produced for U.S. Navy ships and for weapons manufacture (EPA 1985b; Stokinger 1981). Uranium fuel lasts months to years before refueling is needed, and then only a small fraction of the uranium has actually been fissioned, making fuel reprocessing an option used in other countries. One pound of completely fissioned uranium produces the same amount of energy as 1,500 tons of coal (Lide 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; USDI 1980). Uranium dioxide is used to extend the lives of filaments in large incandescent lamps used in photography and motion picture projectors. Uranium compounds are used in photography for toning, in the leather and wood industries for stains and dyes, and in the silk and wood industries as mordants. Ammonium diuranate is used to produce colored glazes in ceramics. Uranium carbide is a good catalyst for the production of synthetic ammonia (Hawley 1981). Additionally, uranium was used in dental porcelains for many years, but this practice has been discontinued (Thompson 1976). 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.

### 4.4 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.

**Table 4-5. Export of Uranium and Compounds (in kg)**

| 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 (NOS)                          | 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 <sup>a</sup> | 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 |

NOS = Not otherwise stated

<sup>a</sup> Alloys, Dispersions (Including Cermets), Ceramic Products And Mixtures Containing Natural Uranium Compounds, Nesoi (SIC2819)

Source: USDOC 1995, 1999

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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 mill tailings in the United States is approximately 140 million tons (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 24 sites contained a total of about 28 million tons of tailings and covered a total of approximately 1,000 acres (EPA 1985b). Cleanup has been completed at some sites.

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. Since 1963, six commercial LLRW facilities have operated, but only two were in operation in 1995. A 1992 report listed the total volume of LLRW buried at all 6 sites to be approximately 50 million cubic feet (Murray 1994). Only a small fraction of the LLRW contains uranium.

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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 U.S. Nuclear Regulatory Commission (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). The EPA has proposed regulations for LLRW disposal that would apply to DOE facilities (EPA 1998b).

High-level radioactive waste (HLRW) includes spent fuel, which is the uranium fuel rods that have been used in a nuclear reactor. 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 30,000 metric tons of spent fuel have been removed from U.S. power reactors through 1994 (Murray 1994). There is currently no permanent disposal facility for HLRW in the United States; these wastes are being stored at commercial nuclear power plants and DOE facilities where they were produced. The NRC 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 two decades ago, have experienced many delays. A facility for the permanent disposal of HLRW is not projected to be in operation before 2010 (Murray 1994).