

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

### 5.1 PRODUCTION

No information is available in the TRI database on facilities that manufacture or process plutonium 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 1998).

Plutonium was the first human-made element to be synthesized in weighable amounts.  $^{238}\text{Pu}$  was discovered in 1940 by Seaborg and co-workers; it was synthesized by the bombardment of uranium with neutrons ( $^1_0\text{H}$ ). Isotopes with mass numbers 228–247 have been identified; all are radioactive (Clark et al. 2006). Trace amounts of plutonium are found worldwide, mostly due to fall-out from atmospheric nuclear testing, which ended in 1980 and released several isotopes of plutonium, including  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}$  (Clark et al. 2006; DOE 2005a; Eisenbud and Gesell 1997). Plutonium is not considered a naturally occurring element; however, trace amounts of  $^{239}\text{Pu}$  are found in naturally occurring uranium ores, but the amounts are in such small amounts that extraction is not practical (Clark et al. 2006; EPA 2006b; Lide 2008). Small amounts of  $^{244}\text{Pu}$  exist in nature from remnants of primordial stellar nucleosynthesis (Clark et al. 2006). Small amounts of plutonium were produced in natural reactors, such as the Oklo natural reactor in Gabon, which existed about 2 billion years ago (DOE 2005a). The most common form of plutonium found in the environment is  $^{239}\text{Pu}$ , followed by  $^{240}\text{Pu}$  (DOE 1999a).

Large quantities of plutonium were first produced during the 1940's as part of the Manhattan Project in order to produce the atomic bomb. Production continued throughout the years of the Cold War (DOE 2005a). The United States built and operated 14 plutonium-production reactors at the Hanford and Savannah River Sites starting in 1944 and ending in 1988 with the shutdown of the last reactor. A total of approximately 100 metric tons of plutonium was produced during this time (DOE 1996b). Currently,  $^{238,239,240,241,242}\text{Pu}$  are commercially available from Oak Ridge National Laboratory for laboratory research (DOE 2007a).

Plutonium is a byproduct of nuclear energy generation. Most plutonium isotopes are produced in uranium-fueled reactors through neutron capture by  $^{238}\text{U}$  (Clark et al. 2006; Koch 2005). Approximately 1,855 metric tons of plutonium were estimated to exist worldwide at the end of 2003. Most of the plutonium (1,370 metric tons) was found in irradiated fuel from nuclear power plants. A plutonium

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production rate of 70–75 metric tons/year was estimated for reactors worldwide at the end of 2003 (Albright and Kramer 2004; Clark et al. 2006).

Plutonium from spent nuclear fuel is recovered by the PUREX (Plutonium, Uranium, Reduction, Extraction) liquid-liquid extraction process (Clark et al. 2006; Koch 2005). This process is the main method to separate plutonium and uranium from used reactor fuel and neutron-irradiated actinide material (Clark et al. 2006). The basis of the PUREX process involves the selective extraction of U(VI) and Pu(IV) from a nitric acid solution of dissolved irradiated fuel into an aliphatic hydrocarbon solvent that contains tri(*n*-butyl)phosphate. Most of the fission products are left in the acid solution (Clark et al. 2006). Other processes (e.g., the bismuth phosphate process at the Hanford site) have been used to separate and purify plutonium from irradiated fuels; however, many of these are now of only historical interest (Clark et al. 2006).

Modern plutonium metal production involves recovery and recycling of residues and scrap (Clark et al. 2006). Plutonium metal is produced by pyrochemical processes in either centrifugal or stationary bombs. The major pyrochemical processes used by large facilities are bomb reduction of plutonium tetrafluoride, direct oxide reduction (DOR), molten salt extraction (MSE), anode casting, electrorefining (ER), and pyroredox. In DOR, plutonium dioxide is reduced with calcium metal to produce plutonium metal and calcium oxide. The MSE process reduces the amount of  $^{241}\text{Am}$ , which is a decay product of  $^{241}\text{Pu}$ , in plutonium metal. It also separates the more reactive elements (e.g., rare earth (lanthanide), alkali, and alkaline-earth metals) from the plutonium metal. In the ER process, liquid plutonium oxidizes from the anode ingot, which is cast from the plutonium metal derived from the MSE process, into a molten-salt electrolyte. The Pu(III) ions are transported through the salt to the cathode where they are reduced to the metal. The pyroredox process recovers plutonium metal from impure scrap material and from spent anode heels from the ER process (Clark et al. 2006).

## 5.2 IMPORT/EXPORT

There is no information on the import or export of plutonium. The import and export of plutonium in the United States is governed by the U.S. Nuclear Regulatory Commission (USNRC 2009b).

## 5.3 USE

$^{239}\text{Pu}$  was first used in fission weapons beginning in 1945 (DOE 2005a). In a reactor of a nuclear power plant, the fissioning of  $^{235}\text{U}$  produce two or three neutrons, which can be absorbed by  $^{238}\text{U}$  to produce

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$^{239}\text{Pu}$ . The  $^{239}\text{Pu}$  formed can also absorb neutrons and undergo fission, which provides about one-third of the total energy produced in a typical commercial nuclear power plant (DOE 2005a).  $^{238}\text{Pu}$  is used as a heat source in nuclear batteries to produce electricity in devices such as unmanned spacecraft, and interplanetary probes (DOE 2005a; Koch 2005). Plutonium is a carefully regulated material under government control. Small quantities are used in research laboratories (Clark et al. 2006) and quantities of plutonium oxides are used in MOX (mixed oxide plutonium and uranium) fuels as an alternative to low enriched uranium fuel used in light water nuclear power reactors (Makhijani 1997).  $^{236}\text{Pu}$  and  $^{242}\text{Pu}$  are used as tracers in plutonium determinations in environmental and biological samples (Brouns 1980; DOE 1997; Kressin et al. 1975).

#### 5.4 DISPOSAL

Plutonium isotopes are classified as hazardous substances under Section 102(a) of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), commonly known as Superfund. Under CERCLA, spills or discharges into the environment of plutonium isotopes of more than 0.01 Ci (370 MBq) ( $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{242}\text{Pu}$ , and  $^{244}\text{Pu}$ ), 1 Ci ( $3.7 \times 10^4$  MBq) ( $^{241}\text{Pu}$ ), or 1,000 Ci ( $3.7 \times 10^7$  MBq) ( $^{237}\text{Pu}$  and  $^{243}\text{Pu}$ ) must be reported immediately to the National Response Center (EPA 2007c). The final reportable quantities for all radionuclides apply to chemical compounds containing the radionuclides and elemental forms regardless of the diameter of pieces of solid material (EPA 2007c).

During 1944–1988, most nuclear fuel rods and targets irradiated in the reactors at the 14 plutonium-production reactors at the Hanford and Savannah River Sites were reprocessed to extract the plutonium. When the Department of Energy stopped reprocessing spent-fuel elements in April 1992, approximately 2,700 metric tons of spent fuel were accumulated in 30 storage ponds. About 99% of this spent fuel is stored at the Hanford Site in Washington, the Savannah River Site in South Carolina, the Idaho National Engineering Laboratory, and West Valley in New York. Approximately 30,000 metric tons of spent fuel from commercial nuclear power plants are stored at more than 100 nuclear reactor sites around the United States (DOE 1996b). Most spent nuclear fuel is stored in specially designed pools at individual reactor sites around the country in 33 states (USNRC 2009a, 2009c).

The disposal of radioactive waste is regulated by the rules of the USNRC and EPA. Spent fuel, which contains approximately 0.88%  $^{239,240,241,242}\text{Pu}$  combined, is considered high-level waste (HLW) (Murray 2005; Murray and Fentiman 2006). Currently, the preferred method for HLW disposal is deep underground burial in a mined cavity; however, no facilities in the United States have been authorized for

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the disposal of HLW. An alternative to burial of spent fuel is to store it for future use as fuel for nuclear reactors. The uranium and plutonium could be extracted from spent fuel to be used as fuel in nuclear power plants.

Transuranic wastes (TRUs) contain significant amounts of plutonium or other transuranic elements. As of 2006, the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico was the only operating geological disposal facility in the world; TRU has been disposed of in the WIPP since 1999 (Murray and Fentiman 2006).

In 2002, Yucca Mountain was approved by the Congress and the President as the site for the nation's first permanent spent nuclear fuel and high-level radioactive waste geologic repository (DOE 2007b). Most of the waste that may be disposed at Yucca Mountain will be spent nuclear fuel and high-level radioactive waste. About 90% of this waste is from commercial nuclear power plants and the rest comes from defense programs. Currently, this waste is stored at facilities in 43 states. By Department of Energy (DOE) projections, the earliest the proposed repository at Yucca Mountain could open and begin accepting waste is 2017; however, various steps must first be met before this can occur (EPA 2009). Spent fuels must be stored in water pools or in dry storage casks at nuclear plant sites until a repository is completed (Murray 2005).