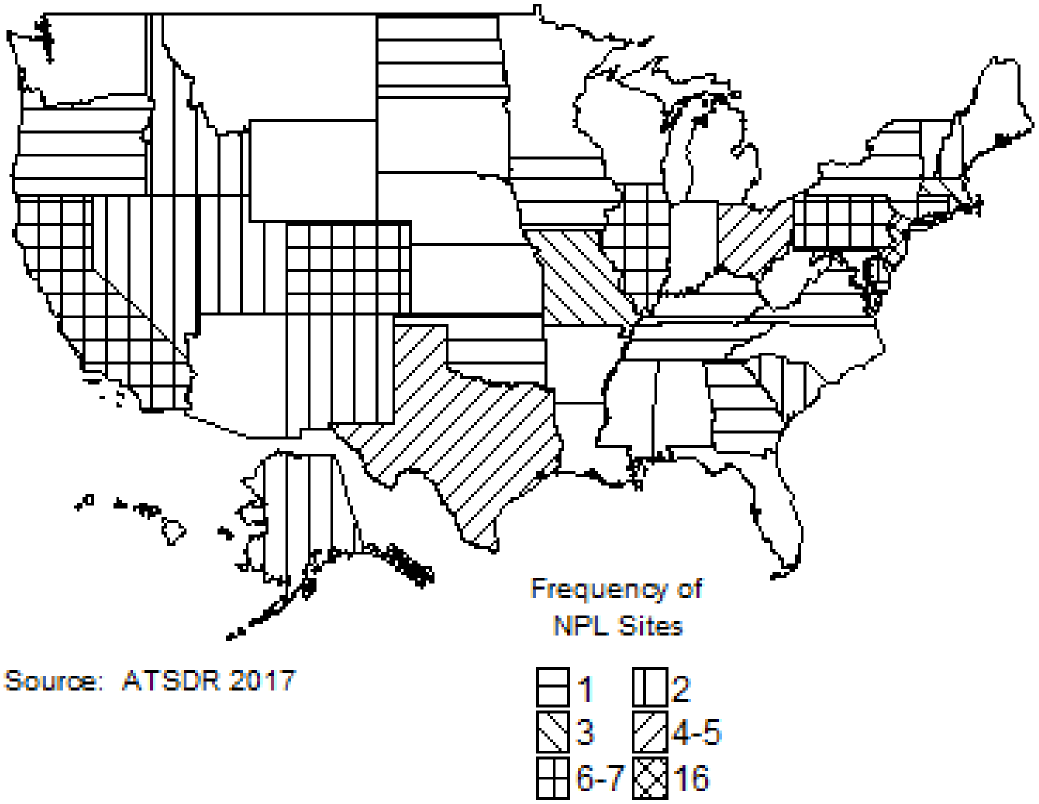
# CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

## 5.1 OVERVIEW

Thorium has been identified in at least 81 of the 1,854 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2017). However, the number of sites in which thorium has been evaluated is not known. The number of sites in each state is shown in Figure 5-1. Of these sites, 81 are located within the United States.

**Figure 5-1. Number of NPL Sites with Thorium and Thorium Compounds Contamination**



Source: ATSDR 2017

- The general population may be exposed to thorium from inhalation of air and ingestion of food and drinking water containing thorium.
- Workers are exposed to higher levels of thorium and other radionuclides in certain thorium industries, as measured in exhaled breath and tissue levels of these chemicals
- Thorium occurs naturally in the environment; thus, background levels occur in air, water, and soil.

- Atmospheric thorium levels above natural background levels occur mainly from mining, milling, and processing operations; phosphate rock processing and phosphate fertilizer production; and coal-fired utilities and industrial boilers.

- Concentrations of thorium in air, food, and/or drinking water are normally very low and thorium-containing substances are not generally readily absorbed by the body.

- Wet and dry deposition are expected to be mechanisms for removal of atmospheric thorium. The rate of deposition will depend on the meteorological conditions, the particle size and density, and the chemical form of thorium particles.

- In water, thorium will be present in suspended matters and sediment and the concentration of soluble thorium will be low.

- Thorium will remain strongly sorbed to soil and its mobility will be very slow.

- Thorium in soil will not bioconcentrate in plants.

Thorium is ubiquitous in our environment. Release of thorium to the atmosphere can occur both from natural and anthropogenic sources, and emissions from the latter sources can produce locally elevated atmospheric levels of thorium over the background. Windblown terrestrial dust and volcanic eruptions are two important natural sources of thorium in the air (Fruchter et al. 1980; Kuroda et al. 1987). Uranium and thorium mining, milling and processing, tin processing, phosphate rock processing and phosphate fertilizer production, and coal fired utilities and industrial boilers are the primary anthropogenic sources of thorium in the atmosphere (Hu and Kandaiya 1985; McNabb et al. 1979; Nakoaka et al. 1984; Sill 1977). The major industrial releases of thorium to surface waters are effluent discharges from uranium and thorium mining, milling and processing, tin processing, phosphate rock processing, and phosphate fertilizer production facilities (Hart et al. 1986; McKee et al. 1987; Moffett and Tellier 1978; Platford and Joshi 1988). The primary sources of thorium at the Superfund sites are perhaps from the processing and extraction of thorium, uranium, and radium from ores and concentrates (EPA 1988a).

Data regarding the fate and transport of thorium in the air are limited. Wet and dry deposition are expected to be mechanisms for removal of atmospheric thorium. The rate of deposition will depend on the meteorological conditions, the particle size and density, and the chemical form of thorium particles. Although atmospheric residence times for thorium and compounds were not located, judging from residence times of other metals (e.g., lead) and their compounds, they are likely to be a few days. Thorium particles with small aerodynamic diameters (<10 micron aerodynamic diameter) will travel long distances from their sources of emission. In water, thorium will be present in suspended matters and sediment and the concentration of soluble thorium will be low (Platford and Joshi 1987). Sediment resuspension and mixing may control the transport of particle-sorbed thorium in water. The concentration of dissolved thorium in some waters may increase due to formation of soluble complexes with carbonate, humic materials, or other ligands in the water (LaFlamme and Murray 1987). Thorium has been found to show significant bioconcentration in lower trophic animals in water, but the bioconcentration factors decrease as the trophic level of aquatic animals increases (Fisher et al. 1987; Poston 1982). The fate and mobility of thorium in soil will be governed by the same principles as in water. In most cases, thorium will remain strongly sorbed to soil and its mobility will be very slow (Torstenfelt 1986). However, leaching into groundwater is possible in some soils with low sorption capacity and the ability to form soluble complexes. The plant/soil transfer ratio for thorium is <0.01 (Garten 1978), indicating that it will not bioconcentrate in plants from soil. However, plants grown at the edge of impoundments of uranium tailings containing elevated levels of thorium had a plant/soil concentration ratio of about 3 (Ibrahim and Whicker 1988).

The atmospheric mass concentration of thorium ranged from 0.2 to 1.0 ng/m$^3$, with a mean value of 0.3 ng/m$^3$ in air samples collected from 250 sites in the United States (Lambert and Wilshire 1979). In another study, the mean activity concentrations of $^{228}$Th, $^{230}$Th, and $^{232}$Th in New York City air were 36, 36, and 37 aCi/m$^3$ (aCi=10$^{-18}$ Ci), respectively (Wrenn et al. 1981). The average population-weighted concentrations of $^{232}$Th and $^{230}$Th in United States community water supplies derived both from surface and groundwater were <0.01 and <0.04 pCi/L, respectively (Cothern 1987; Cothern et al. 1986). The maximum concentration of $^{232}$Th in several fruits, vegetables, and other type of foods from New York City was reported to be <0.01 pCi/g (Fisenne et al. 1987). The daily intakes of $^{230}$Th and $^{232}$Th for residents of New York City were estimated to be 0.17 and 0.11 pCi, respectively. Significant exposure to thorium requires special exposure scenarios (Fisenne et al. 1987). People who consume foods grown in high background areas, reside in homes with high thorium background levels, or live near radioactive waste disposal sites may be exposed to higher than normal background levels of thorium. Workers in uranium, thorium, tin, and phosphate mining, milling, and processing industries, and gas mantle manufacture may also be exposed to higher than normal background levels of thorium (Bulman 1976; Hannibal 1982; Hu et al. 1984; Kotrappa et al. 1976; Metzger et al. 1980).

## 5.2 PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

### 5.2.1 Production

Table 5-1 summarizes information on U.S. companies that reported the manufacture or use of thorium dioxide in 2016 (TRI16 2017). Toxics Release Inventory (TRI) data should be used with caution since only certain types of industrial facilities are required to report. This is not an exhaustive list.

**Table 5-1. Facilities that Produce, Process, or Use Thorium Dioxide**

| State[a] | Number of facilities | Minimum amount on site in pounds[b] | Maximum amount on site in pounds[b] | Activities and uses[c] |
|---|---|---|---|---|
| TX | 2 | 10,000 | 99,999 | 10, 12 |

[a] Post office state abbreviations used.
[b] Amounts on site reported by facilities in each state.
[c] Activities/Uses:

1. Produce
2. Import
3. Used Processing
4. Sale/Distribution
5. Byproduct
6. Reactant
7. Formulation Component
8. Article Component
9. Repackaging
10. Chemical Processing Aid
11. Manufacture Aid
12. Ancillary
13. Manufacture Impurity
14. Process Impurity

Source: TRI16 2017 (Data are from 2016)

The principal source of thorium is monazite (phosphate of rare earth metals, usually with thorium), a mineral produced as a byproduct of mineral sands mined for titanium and zirconium. Thorium compounds are extracted from monazite by acid and alkali treatment processes (Hedrick 1985). Associated Minerals, a subsidiary of the Australian-owned firm Associated Minerals Consolidated Ltd., was the only commercial operation in the United States to produce purified monazite in 1987. This company produced monazite as a byproduct of mineral sands mined for titanium and zirconium minerals at Green Cove Springs, Florida. The monazite produced in the United States was exported. Thorium products used domestically were obtained from imported material, existing company stocks, and thorium nitrate previously released from the National Defense Stockpile (Hedrick 1987). In 1984, the mine production capacity for thorium in the United States was 20 metric tons of thorium oxide equivalent (Hedrick 1985). Actual mine production data have not been released over the years to avoid disclosure of proprietary information. Nevertheless, the domestic mine production volume of monazite or other thorium ore is expected to be approximately the same as the U.S. export volume. The principal processors of thorium-containing ores in the United States during 1987 were W.R Grace & Co. in

Chattanooga, Tennessee, and Rhone-Poulenc Inc. in Freeport, Texas (Hedrick 1987). United States companies that had thorium processing and fabricating capacities in 1987 are listed in Table 5-2.

**Table 5-2. United States Companies with Thorium Processing and Fabricating Capacity**

| Company | Plant location | Operations and products |
|---|---|---|
| Atomergic Chemetals Corporation | Plainview, New York | Produces oxide, flouride, metal |
| Bettis Atomic Power Laboratory | West Mifflin, Pennsylvania | Nuclear fuels; Government research and development |
| Cerac Inc. | Milwaukee, Wisconsin | Produces ceramics |
| Ceradyne Inc. | Santa Ana, California | Produces advanced technical ceramics |
| Chicago Magnesium Castings Co. | Blue Island, Illinois | Magnesium-thorium alloys |
| Coleman Co., Inc. | Wichita, Kansas | Produces thoriated mantles |
| GA Technologies, Inc. | San Diego, California | Nuclear fuels |
| W.R. Grace & Co., Davison Chemical Division | Chattanooga, Tennessee | Produces thorium from compounds in monazite |
| GTE Sylvania | Towanda, Pennsylvania | Produces thoriated welding rods |
| Hitchcock Industries Inc. | South Bloomington, Minnesota | Magnesium-thorium alloys |
| Philips Elmet | Lewiston, Maine | Produces thoriated welding rods |
| Rhône-Poulenc, Inc. | Freeport, Texas | Produces thorium nitrate from an intermediate compound of monazite |
| Spectrulite Consortium, Inc. | Madison, Illinois | Magnesium-thorium alloys |
| Teledyne Cast Products | Pomona, California | Magnesium-thorium alloys |
| Teledyne Wah Chang | Huntsville, Alabama | Produces thoriated welding rods |
| Union Carbide Corporation, Nuclear Division | Oak Ridge, Tennessee | Nuclear fuels; test quantities |
| Wellman Dynamics Corporation | Creston, Iowa | Magnesium-thorium alloys |
| Westinghouse Materials Co. of Ohio[b] | Cincinnati, Ohio | Produces compounds and metals; manages Department of Energy thorium stocks |

[a] Manager of U.S. Department of Energy stocks; formerly NLO, Inc., prior to January 1, 1986.

Source: Hedrick 1987

### 5.2.2 Import/Export

Imports of thorium into the United States in metric tons of thorium oxide equivalent were 45.8 in 1983, 45.4 in 1984, 69.3 in 1985, 19.7 in 1986, and 30.7 in 1987. Additionally, concentrated monazite containing 350–550 tons of $ThO_2$ has been imported annually (Hedrick 1987). Imports of thorium by the

United States may decrease as a result of increased costs of processing thorium. These increased costs are primarily due to increasing concerns about the radiological risks of handling, storing, and disposing of thorium, thereby encouraging the search for nonradioactive substitutes (Hedrick 1987). Exports of thorium metal, waste, and scrap from the United States in metric tons of thorium oxide equivalent were 1.1 in 1983, 1.0 in 1984, 1.6 in 1985, 17.0 in 1986, and 20.4 in 1987 (Hedrick 1987).

### 5.2.3 Use

Thorium can be used as fuel in the generation of nuclear energy. However, there was only one plant in the United States in 1987 that was using thorium for the production of energy (Hedrick 1987). In 1983, 3 metric tons of thorium oxide equivalent were used for energy uses in the United States (Hedrick 1985). Nonenergy uses accounted for almost all of the thorium used in the United States during 1987. The 1987 use pattern for thorium was as follows: refractory applications (57%); lamp mantles (18%); aerospace alloys (15%); welding electrodes (5%); nuclear weapon production; and other applications including ceramics and special use lighting (5%). Specific applications include production of investment molds for casting high-temperature metals and alloys, crucibles, and alloys of special shapes for use in high-temperature vacuum or oxidizing furnaces. Other special applications include production of core-retention beds used in nuclear reactors to contain and possibly diffuse heat generated by accidental core meltdown; magnesium-thorium alloys for strategic aircraft such as military jet fighters and bombers; mantles for incandescent lanterns such as those used on camping trips; thoriated tungsten electrodes used to join stainless steels and other alloys that require controlled weld applications; special lighting such as airport runway lighting; computer memory components; photoconductive film; and target material for x-rays (Hedrick 1985). Natural thorium is also used in ceramic tableware glaze and in flints for lighters (UNSCEAR 1977). Domestic nonenergy thorium consumption was estimated to be 39.4 metric tons of thorium oxide equivalent in 1987, a decrease of 33 metric tons from 1986 usage. The drop in consumption was primarily the result of reduced demand for thorium oxide in high-temperature refractory molds, because suitable substitutes had been developed (Hedrick 1987).

Trastuzumab is a humanized monoclonal antibody approved by the Food and Drug Administration for treating metastatic breast cancer in individuals who overexpress the human epidermal growth factor receptor 2 (HER2) oncogene. Heyerdahl et al. (2012) evaluated the relative efficacy of subcutaneously-injected single dose (1 MBq/kg; 27.02 μCi/kg) versus fractionated dose (4x0.25 MBq/kg; 4x6.76 μCi/kg) therapy with $^{227}$Th-DOTA-pbenzyl-trastuzumab ($^{227}$Th-trastuzumab) for cancer treatment in nude mice. Fractionating the dose of $^{227}$Th-trastuzumab reduced toxicity while maintaining therapeutic value, indicating that fractionation might allow for increased treatment doses aimed at improving cancer therapy. Heyerdahl et al. (2011) also found that $^{227}$Th-trastuzumab at clinically relevant concentrations inhibited cell growth, decreased cell survival, and increased apoptosis in human breast cancer cell lines (BT-474 and SKBR-3) as well as in an ovarian cancer cell line (SKOV-3) in a dose-dependent manner.

$^{227}$Th has been proposed for the palliative treatment of skeletal pain associated with cancers metastasized from other organs so as to improve the quality of life. $^{227}$Th deposits on bone surfaces based on its chemical properties independent of its radiological properties and radioactive progeny. Deposition sites receive 28 MeV of localized alpha energy (within micrometers of the deposition sites) over a short period of weeks resulting from its 18.7-day half-life and rapidly-approached secular equilibrium with its alpha-emitting progeny. Ogawa and Washiyama (2012) suggested that bonding $^{227}$Th to ethylenediaminetetramethylenephosphonic acid (EDTPM) should enhance the efficacy of pain treatment since the complex increases the skeletal deposition and retention of thorium and its progeny. It also speeds excretion from soft tissue and blood, thus reducing radiation dose to those tissues. Similar $^{227}$Th complexes involve bonding with diethylenetriaminepentamethylenephosphonic acid (DTPMP) and 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetramethylenephosphonic acid (DOTMP).

In addition to DTPA being tested as a thorium chelator, it has been studied as a radiotherapy agent. Le Du et al. (2012) identified that DTPA could be labeled *in vitro* with $^{226}$Th to produce a complex with thorium. When injected, the thorium would interact strongly with human serum transferrin such that the complex might be used as a delivery system in targeted alpha therapy.

In February 1976, the European Union made it illegal to commercially export African elephant raw tusk ivory. Schmied et al. (2012) determined that the ratio of $^{228}$Th/$^{232}$Th in the ivory can be used in conjunction with $^{14}$C and $^{90}$Sr dating to help confirm the time of death. One method involves removing ~10 g of ivory from the base (the area of newest growth) and analyzing the ashed, extracted, and electrodeposited sample by alpha spectroscopy. The accuracy and relevance of this approach was validated using standard reference materials.

### 5.2.4 Disposal

Disposal of radioactive wastes is a serious environmental problem for which there is, as yet, no completely satisfactory solution. Intensive research is being conducted by both government and industry for the disposal of this type of waste. Small amounts of low-level wastes containing radioisotopes can be diluted with an inert material sufficiently to reduce its activity to an acceptable level for further storage or disposal. At one nuclear waste disposal site, high-level reactor wastes are stored in concrete tanks lined with steel, which are buried under a foot of concrete and 5–6 feet of soil. Use of compressed alumina (corundum) containers has been recommended, since this material remains impervious to water indefinitely. The Department of Energy has recommended disposal in deep geologic formations. Disposal in salt formations is being considered since they are self-sealing and free from water (Hawley 1981). The Department of Defense Authorization Act of 1987 (Public Law 99-661) authorized 4,536 kg (10,000 pounds) of thorium nitrate for disposal in fiscal year 1987. Further information regarding the amount of thorium disposed of in the United States was not located. Regulations established by the EPA regarding release limits that apply to the storage and disposal of spent nuclear fuel, high-level radioactive wastes, and transuranic radioactive wastes can be found in 40 CFR 191 and 40 CFR 192.

Akkaya (2013) synthesized a polymerized derivative of pumice (poly-hydroxyethylmethacrylate-pumice or P(HEMA-Pum)) and evaluated its effectiveness in adsorbing $Th^{4+}$ ions from solution in order to assess its potential for decontaminating ground and surface water. A total of 0.1 g of adsorbent was agitated for 24 hours in 10 mL of thorium nitrate solution of various concentrations and pH. The adsorption process was endothermic, increased system entropy, was spontaneous, and peaked at pH 3.0. Results demonstrated that P(HEMA)Pum has the potential to adsorb up to 0.21 μmol Th/g medium from a liquid solution. Repetitive testing and cleaning demonstrated the medium to be reusable at least 5 times.

Chandramouleeswaran et al. (2011) tested two boroaluminosilicate glasses with surface area 102 $cm^2/g$ for their ability to adsorb thorium from a solution containing thorium nitrate with or without uranium. Such glasses are used to vitrify and immobilize high level liquid radioactive waste. The glass with the lower $B_2O_3{:}Na_2O$ ratio (0.23 versus 9.8) was more effective at removing thorium. Its thorium uptake peaked at pH 7.5–8, reached saturation at 12 mg Th/g glass, and was selective against uranium.

Li et al. (2011) evaluated 15 plant species for ability to bioaccumulate thorium and other metals from a uranium mill tailings repository in South China. *Phragmites australis* was found to have the greatest capability for removing uranium, thorium, barium, and lead, with respective “phytoremediation factors” of 17, 9, 10, and 10. However, none of the species were classified as hyperaccumulators for these metals.

## 5.3 RELEASES TO THE ENVIRONMENT

The Toxics Release Inventory (TRI) data should be used with caution because only certain types of facilities are required to report (EPA 2005). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ ≥10 full-time employees; if their facility is included in Standard Industrial Classification (SIC) Codes 10 (except 1011, 1081, and 1094), 12 (except 1241), 20–39, 4911 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4931 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4939 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4953 (limited to facilities regulated under RCRA Subtitle C, 42 U.S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited to facilities primarily engaged in solvents recovery services on a contract or fee basis**); and if their facility produces, imports, or processes ≥25,000 pounds of any TRI chemical or otherwise uses >10,000 pounds of a TRI chemical in a calendar year (EPA 2005).**

### 5.3.1 Air

The data in Table 5-3 are the reported releases of thorium to the atmosphere from the two domestic manufacturing and processing facilities in 2016 required to report to the TRI (TRI16 2017; see Table 5-3).

Releases of thorium to the atmosphere can occur from both natural and anthropogenic sources. The release of thorium in volcanic ash containing as much as 0.116 pCi/g (1.06 μg/g) of $^{232}$Th was reported by Fruchter et al. (1980). Increased concentrations of thorium in rain water following a volcanic eruption have also been observed (Kuroda et al. 1987). Since the average level of thorium in soil is about 6 μg/g of thorium (Harmsen and De Haan 1980), windblown terrestrial dust is also a likely natural source of thorium in the atmosphere. Since coal contains 0.5–7.3 μg/g thorium (Nakaoka et al. 1984), burning of coal for power generation produces thorium in the fly ash and is a man-made source of this chemical in the atmosphere. The amount of thorium in the fly ash from coal-burning power plants depends on the nature of coal burned and the emission control devices of the plant, but concentrations usually range from 4.5 to 37 μg/g (Abel et al. 1984; Coles et al. 1979; Tadmor 1986; Weissman et al. 1983). However, the concentrations of all natural radioactive isotopes in (including thorium isotopes) the stack effluents from coal-fired power plants are usually much lower than those from the natural background concentrations of these radionuclides (Nakaoka et al. 1984; Roeck et al. 1987). Similarly, fly ash from oil- and peat-fired power plants can also be atmospheric sources of thorium (Mustonen and Jantunen 1985).

**Table 5-3. Releases to the Environment from Facilities that Produce, Process, or Use Thorium Dioxide[a]**

| | | Reported amounts released in pounds per year[b] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Total release | | |
| State[c] | RF[d] | Air[e] | Water[f] | UI[g] | Land[h] | Other[i] | On-site[j] | Off-site[k] | On- and off-site |
| TX | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

[a] The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number.
[b] Data in TRI are maximum amounts released by each facility.
[c] Post office state abbreviations are used.
[d] Number of reporting facilities.
[e] The sum of fugitive and point source releases are included in releases to air by a given facility.
[f] Surface water discharges, waste water treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g] Class I wells, Class II-V wells, and underground injection.
[h] Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i] Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.
[j] The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k] Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI16 2017 (Data are from 2016)

$^{230}$Th has been detected in air dust from uranium ore processing and mill tailings. These concentrations of $^{230}$Th (a decay product of $^{238}$U) may be particularly high in ore crushing areas (Sill 1977). Similarly, processing of thorium ores is expected to be an atmospheric source of thorium. Elevated levels of thoron (thoron or $^{220}$Rn originating from $^{232}$Th) daughters, such as bismuth-212 ($^{212}$Bi) and polonium-216 ($^{216}$Po), were present at a former thorium and rare-earth extraction facility waste site, although the concentrations of thorium in air particulate samples were not significant (Jensen et al. 1984). Since phosphate ores usually contain $^{230}$Th, phosphate-ore processing plants are also atmospheric sources of $^{230}$Th (McNabb et al. 1979; Metzger et al. 1980). The byproducts obtained during processing of tin ores usually contain $^{232}$Th. Therefore, tin processing industries are sources of atmospheric $^{232}$Th emissions (Hu and Kandaiya 1985; Hu et al. 1981, 1984).

EPA (1984) estimated that about 0.2 Ci of $^{230}$Th is annually emitted into the air from uranium mill facilities, coal-fired utilities and industrial boilers, phosphate rock processing and wet-process fertilizer production facilities, and other mineral extraction and processing facilities. About 0.084 Ci of $^{234}$Th from uranium fuel cycle facilities and 0.0003 Ci of $^{232}$Th from underground uranium mines are emitted into the atmosphere annually (EPA 1984).

### 5.3.2 Water

The data in Table 5-3 are the reported releases of thorium to water from the two domestic manufacturing and processing facilities in 2016 required to report to the TRI (TRI16 2017; see Table 5-3).

The acidic leaching of uranium tailing piles in certain areas is a source of $^{230}$Th in surface water and groundwater (Moffett and Tellier 1978; Platford and Joshi 1988). The contamination of surface waters and benthic organisms by $^{230}$Th (a decay product of $^{238}$U) from uranium mining and milling operations and from radium and uranium recovery plants has been reported (Hart et al. 1986; McKee et al. 1987). Similarly, effluents from thorium mining, milling, and recovery plants are expected to be sources of thorium in water. Other industrial processes that are expected to be sources of thorium contamination into water are phosphorus and phosphate fertilizer production and processing of some tin ores. Since both phosphate rocks and the tailings from tin ore processing contain thorium mainly as $^{230}$Th and $^{232}$Th, respectively, discharges of processed or unprocessed effluents and leaching from tailing piles can be sources of thorium in water. Leaching from landfill sites containing uranium and thorium may result in the contamination of surface water and groundwater with thorium (Cottrell et al. 1981).

### 5.3.3 Soil

The data in Table 5-3 are the reported releases of thorium to the soil from the two domestic manufacturing and processing facilities in 2016 required to report to the TRI (TRI16 2017; see Table 5-3).

Thorium occurs naturally in the earth's crust at an average lithospheric concentration of 8–12 μg/g (ppm). The typical concentration range of naturally-occurring thorium in soil is 2–12 μg/g, with an average value of 6 μg/g (Harmsen and De Haan 1980). Man-made sources of thorium contamination in soil are mining, milling, and processing operations and uranium, thorium, tin, and phosphate fertilizer production (Chong et al. 1985; Hu and Kandaiya 1985; Joshi 1987; McNabb et al. 1979; Sill 1977). The two principal processes that can contaminate soil from these industries are precipitation of airborne dusts and land disposal of uranium or thorium-containing wastes.

According to EPA (1988a), the primary sources of thorium at the Superfund sites are processing and extraction of thorium, uranium and radium from ores or ore-concentrates. The following radioactive waste Superfund sites were found to contain one or more isotopes of thorium (VIEW 1989): Shpack and adjacent landfills, Norton, Massachusetts; Maywood Chemical Co., Sears Property, Maywood, New Jersey; W.R. Grace and Co., Wayne, New Jersey; West Chicago Sewage Treatment Plant, West Chicago, Illinois; Reed-Keppler Park, West Chicago, Illinois; Kerr-McGee (Residential Areas), West Chicago, Illinois; Kress Creek and the West Branch of the DuPage River, West Chicago, Illinois; United Nuclear Corporation, Church Rock, New Mexico; Homestake Mining Co., Milan, New Mexico; Kearsarge Metallurgical Corporation, Conway, New Hampshire; Naval Air Engineering Center, Lakehurst, New Jersey: Teledyne Wah Chang, Albany, Oregon; Woodland Route 72 Dump, Woodland Township, New Jersey; Weldon Spring Quarry, St. Charles City, Missouri; Monticello Radioactivity-Contaminated Properties, Monticello, Utah; and Uravan Uranium Project, Montrose City, Colorado. Disposal of incandescent lights and lanterns containing $^{232}$Th will be an additional source of thorium at waste disposal sites.

## 5.4 ENVIRONMENTAL FATE

Thorium occurs in nature in four isotopic forms, $^{228}$Th, $^{230}$Th, $^{232}$Th, and $^{234}$Th. Of these, $^{228}$Th is the decay product of naturally-occurring $^{232}$Th, and both $^{234}$Th and $^{230}$Th are decay products of natural $^{238}$U. To assess the environmental fate of thorium, these isotopes of thorium, with the exception of $^{234}$Th, which has a short half-life (24.1 days), should be considered.

### 5.4.1 Transport and Partitioning

**Air.** Data regarding the transport and partitioning of thorium in the atmosphere are limited. Release of atmospheric thorium from mining, milling, and processing operations of thorium will mainly consist of $^{232}$Th particulate matter. Emissions from mining, milling, and processing of uranium and the airblown dust from uranium tailing piles will contribute to the presence of $^{230}$Th as an atmospheric particulate aerosol. The aerodynamic diameters of both $^{230}$Th and $^{232}$Th in atmospheric aerosols are >2.5 μm. The aerodynamic diameter of $^{228}$Th, however, is <1.6 pm (Hirose and Sugimura 1987) and $^{228}$Th may therefore travel longer distances than both $^{230}$Th and $^{232}$Th. Like other particulate matter in the atmosphere, thorium will be transported from the atmosphere to soil and water by wet and dry deposition.

The deposition of thorium through snow and rain water has been observed (Jiang and Kuroda 1987). Dry deposition of thorium through impaction and gravitational settling has also been observed. The atmospheric residence time of thorium depends on the aerodynamic diameter of the particles. Those with small diameters are likely to be transported longer distances. For example, high $^{230}Th/^{232}Th$ activity ratios observed in surface air of the Western North Pacific Ocean are thought to be due to long distance transport of small particles of $^{228}Th$ (Hirose and Sugimura 1987).

The dry deposition velocity of $^{212}Pb$, a thoron (thoron or $^{220}Rn$ itself originating from $^{232}Th$) decay product has been reported to be in the range 0.03–0.6 cm/set (Bigu 1985; Rangarajan et al. 1986). These low deposition velocities indicate that the thoron daughter, stable lead, may have a long residence time in the atmosphere with respect to dry deposition.

Thorium discharged as $ThO_2$ into surface waters from mining, milling, and processing will be present as suspended particles or sediments in water because of the low solubility of thorium in water (Platford and Joshi 1986). Other soluble thorium ions will hydrolyze at pH >5, forming $Th(OH)_4$ precipitate or hydroxy complexes; for example, $Th(OH)_{2+2}$, $Th_2(OH)_2^{+6}$, and $Th_3(OH)_5^{+7}$ (Bodek et al. 1988; Hunter et al. 1988; Milic and Suranji 1982). The hydroxy complexes will be adsorbed by particulate matter in water, e.g., goethite (alpha-FeOOH), with the result that most of the thorium will be present in suspended matter or sediment, and the concentration of soluble thorium in water will be low (Hunter et al. 1988; Sheppard 1980). The adsorption of thorium to suspended particles or sediment in water depends on the particle size, and the adsorption and subsequent removal from aqueous phase is expected to be higher for finer grained particles (Carpenter et al. 1987). The residence times for thorium with respect to removal by adsorption onto particles were reported to be shorter in nearshore waters than in deeper waters, probably because of the availability of more adsorbents (particulate matter). The residence time may vary from 1 to 70 days (Cochran 1984). The scavenging rate varied seasonally and was inversely related to the sediment resuspension rate. Therefore, the removal rate was found to be dependent on both sediment resuspension rate and the concentration of iron and manganese compounds (good adsorption properties) in water (Cochran 1984).

**Water.** The transport of thorium in water is principally controlled by the particle flux in the water, i.e., most of the thorium will be carried in the particle-sorbed state (Santschi 1984), and sediment resuspension and mixing may control the transport of particle-sorbed thorium in water (Santschi et al. 1983). Although the concentration of dissolved thorium is low in most waters, its value could be higher in some waters. For example, the concentration of dissolved thorium in an alkaline lake was up to 4.9 dpm/L (2.21 pCi/L) compared to about $1.3x10^{-5}$ dpm/L ($0.59x10^{-5}$ pCi/L) in sea water (LaFlanune and Murray 1987). The dissolved thorium concentration can increase by the formation of soluble complexes. The anions or ligands likely to form complexes with thorium in natural water are $CO_3^{-2}$ and humic materials, although some of the thorium-citrate complexes may be stable at pH >5 (LaFlamme and Murray 1987; Miekeley and Kuchler 1987; Platford and Joshi 1986; Raymond et al. 1987; Simpson et al. 1984).

The transport of thorium from water to aquatic species has been reported. The bioconcentration factor (concentration in dry organism/concentration in water) (dry weight basis) in algae may be as high as $975 \times 10^4$, but the maximum value in zooplankton (calanoids and cyclopoids) may be $2 \times 10^4$ (Fisher et al. 1987). Fisher et al. (1987) suggested that sinking plankton and their debris may account for the sedimentation of most of the thorium from oceanic surface waters. The highest observed thorium bioconcentration factor in the whole body of rainbow trout (*Salmo gairdneri*) was 465 (Poston 1982). The succeedingly lower bioconcentration factors in higher trophic animals indicate that thorium will not biomagnify in the aquatic environment. It was also noted that the majority of thorium body burden in fish is in the gastrointestinal tract (Poston 1982).

**Sediment and Soil.** The mobility of thorium in soil will be governed by the same principles as in water. In most soil, thorium will remain strongly sorbed onto soil and the mobility will be very slow (Torstenfelt 1986). The presence of ions or ligands ($CO_3^{-2}$, humic matter) that can form soluble complexes with thorium should increase its mobility in soil. The contamination of groundwater through the transport of thorium from soil to groundwater will not occur in most soils, except soils that have low sorption characteristics and have the capability to form soluble complexes. Chelating agents produced by certain microorganisms (*Pseudomonas aeruginosa*) present in soils may enhance the dissolution of thorium in soils (Premuzic et al. 1985).

The transport of atmospherically deposited thorium from soil to plants is low. The soil to plant transfer coefficients (concentration in dry plant to concentration in dry soil) were estimated to be $10^{-4}$–$7 \times 10^{-3}$ by Garten (1978) and $0.6 \times 10^{-4}$ for $^{232}$Th by Linsalata et al. (1989). The root systems of grasses and weeds adsorb thorium from the soil but the transport of thorium from the root to the above-ground parts of the plant is not very extensive, as indicated by l00-fold higher concentrations of all three isotopes ($^{228}$Th, $^{230}$Th, and $^{232}$Th) in the root than in the above-ground parts of the plant (Taskayev et al. 1986). However, Ibrahim and Whicker (1988) showed that under certain conditions, vegetation can accumulate $^{230}$Th, as indicated by the plant/soil concentration ratio (dry weight) of 1.9–2.9 for mixed grasses, mixed forbs, and sagebrush plants grown at the edge of uranium tailings impoundments. Vegetation concentration ratios for $^{232}$Th (a concentration ratio of about 0.1) and $^{228}$Th (a maximum concentration ratio of about 0.4) were lower than that of $^{230}$Th. It was postulated that the acidity and wet conditions at this site enhanced the solubility of thorium in soil and that the difference in solubility was responsible for the difference in plant uptake of the three thorium isotopes (Ibrahim and Whicker 1988). However, it is possible that the observed difference in the uptake of the three isotopes by plants is due to a difference in the chemical compounds formed by the isotopes, making one more leachable than the other (therefore more available for uptake) under the prevailing local conditions.

More recent studies provide support to previous findings that thorium in soil can adhere to plant roots (Shtangeeva 2010), while relatively little transfers to the upper parts and is slowly taken up by plants (Chen et al. 2005; Morton et al. 2002; Pulhani et al. 2005; Rayno 1989; Shtangeeva 2010; Shtangeeva et al. 2005). Baeza and Guillen (2006) reported that mushrooms remove thorium from soil, with uptake being an order of magnitude higher for Munõveros than Bazagona mushrooms. For both varieties combined, the soil-to-mushroom transfer factors (the ratio of meat to gross soil concentration) ranged from 0.030 to 0.62, which is comparable to factors for uranium, strontium-90 ($^{90}$Sr), americium-241 ($^{241}$Am), and plutonium-239+240 ($^{239+240}$Pu). The available transfer factor (considering only that portion of the thorium in soil that is available for transfer to plants) was 2 orders of magnitude higher and ranged from 3 to 371 (which is comparable to factors for cesium-137 [$^{137}$Cs]).

The presence of EDTA in soil (e.g., at a mill or waste disposal site) can increase the rate at which a thorium plume moves through the earth. Abdel-Fattah et al. (2013) passed mixtures of thorium (0.4–4 mM) and EDTA (4–40 mM) with Th:EDTA ratios of 1:1 to 10:1 through sand at rates of 20–100 m/year to simulate conditions at the U.K. low level waste repository at Drigg. May et al. (2012) studied the migration of thorium-EDTA mixtures through sand-packed columns. Thorium migrated very slowly when EDTA was absent. Migration rate changed as functions of thorium and EDTA concentration, as well as with thorium species. The relative abundances of 10 identified thorium species depended on the thorium:EDTA concentration ratio. At low thorium concentrations, the thorium-EDTA complex was considered to interact with sand surfaces, and transport depended on groundwater flow rate. But at higher thorium concentrations, plume flow was higher than expected. This might be due to the formation of a thorium colloid associated with natural minerals and not necessarily with EDTA, as has been reported for plutonium colloids.

**Other Media.** Ishikawa et al. (2004) observed relatively high concentrations of $^{234}$Th in livers (50–400 Bq/kg dry; 1.35–10.81 nCi/kg) and excrement (2,000–2,900 Bq/kg dry; 54.05–78.38 nCi/kg) from marine ascidians, whereas parent $^{238}$U concentrations were <3 Bq/kg dry (<0.081 nCi/kg). These findings indicate biomagnification of $^{234}$Th in the liver.

Historical soil-to-plant transfer coefficients (concentration in dry plant to concentration in dry soil) were reported in the range of $10^{-4}$–$7x10^{-3}$, but could be as high as 2.9 for mixed grasses under certain conditions. Jeambrun et al. (2012) conducted a study of uranium and thorium uptake in plants from five French areas. Soil-to-plant transfer factors were lower for $^{232}$Th than $^{238}$U, and those factors for $^{232}$Th were lower in wheat (mean 0.0014) than in lettuce (0.013).

Soudek et al. (2013) artificially exposed the roots of hydroponically grown tobacco plant seedlings (*Nicotiana tabacum* cv. La Burley 21) over a 16-day period to media containing thorium nitrate (50, 100, 250, or 500 μM) with various concentrations of organic acid chelators (citric, tartaric, and oxalic) or in the absence of phosphate or iron. The absence of phosphate most significantly affected thorium uptake. Levels in all plant parts increased gradually as a function of thorium concentration and extent of phosphate and iron depletion. The highest thorium dose with no phosphate resulted in thorium levels of 82 μg/kg dry weight in roots, 6 μg/kg dry weight in stems, and 1 μg/kg dry weight in leaves, while the addition of 2 mM phosphate retarded thorium uptake. Effects of iron deprivation were less, while the impact of acids peaked for 0.5 mM citric or tartaric acids resulted in thorium increases in roots and stems, but not in leaves. The phosphate deficient thorium uptake factor for tobacco seedling leaves can be calculated as 0.002.

### 5.4.2 Transformation and Degradation

**Air.** Thorium may change from one chemical species to another in the atmosphere (such as $ThO_2$ to $Th(SO_4)_2$) as a result of chemical reactions, but nothing definitive is known about the atmospheric chemical reactions of thorium. The chemical forms in which thorium may reside in the atmosphere are also not known, but it is likely to be present mostly as $ThO_2$.

**Water.** The principal abiotic processes that may transform thorium compounds in water are complexation by anions/organic ligands and hydroxylation. The increase in the mobility of thorium through the formation of soluble complexes with $CO_3^{-2}$, humic materials, and other anions or ligands and the decrease in the mobility due to formation of $Th(OH)_4$ or anionic thorium-hydroxide complexes were discussed in Section 5.4.1. In a model experiment with seawater at pH 8.2 and freshwater at pH 6 and pH 9, it was estimated that almost 100% of the thorium resides as hydroxo complexes (Boniforti 1987).

**Sediment and Soil.** No published data were located referencing biotic transformation of thorium in soil. Abiotic transformation processes that can convert immobile thorium in soil into mobile forms through the formation of complexes were discussed in Section 5.4.1.

## 5.5 LEVELS IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to thorium depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of thorium in unpolluted atmospheres and in pristine surface waters are often so low as to be near the limits of current analytical methods. In reviewing data on thorium levels monitored or estimated in the environment, it should also be noted that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable.

Table 5-4 shows the lowest limit of detections for thorium that are achieved by analytical analysis in environmental media. An overview summary of the range of concentrations detected in environmental media is presented in Table 5-5.

**Table 5-4. Lowest Limit of Detection Based on Standards[a]**

| Media | Detection limit | Reference |
|---|---|---|
| Air | 5 fCi/m$^3$ | Percival and Martin 1974 |
| Drinking water | Not available | |
| Surface water and groundwater | <1 ng/g<br>0.03 pCi/L | ASTM 1986<br>Lauria and Godoy 1988 |
| Soil | 0.01 pCi | Singh and Wrenn 1988 |
| Sediment | Not available | |
| Whole blood | <0.2 pg/mL | Picer and Strohal 1968 |

[a] Detection limits based on using appropriate preparation and analytics. These limits may not be possible in all situations.

**Table 5-5. Summary of Environmental Levels of Thorium**

| Media | Low | High | For more information |
|---|---|---|---|
| Outdoor air (pCi/$m^3$) | $36 \times 10^{-6}$ | $0.66 \times 10^{-3}$ | Section 5.5.1 |
| Indoor air (pCi/$m^3$) | No data | No data | |
| Surface water (pCi/L) | $0.23 \times 10^{-6}$ | 1.4 | Section 5.5.2 |
| Ground water (pCi/L) | 0.009 | 1.3 | Section 5.5.2 |
| Drinking water (pCi/L) | <0.1 | 1.3 | Section 5.5.2 |
| Food (pCi/g) | $1 \times 10^{-3}$ | $9.8 \times 10^{-2}$ | Table 5-6 |
| Soil (pCi/g) | 0.716 | 16,000 | Section 5.2.3 |

No data are available on levels of thorium and thorium compounds in air, water, and soil at NPL sites (ATSDR 2017).

### 5.5.1 Air

The level of thorium in air has not been measured as frequently as it has for uranium. The concentration of thorium in the atmosphere of the South Pole measured in 1970 ranged between 18 and 83 fg/$m^3$, with a mean value of 59 fg/$m^3$ (1 fg=$10^{-15}$ g). The origin of thorium in the polar atmosphere was speculated to be either crustal weathering or the ocean water (Zoller et al. 1974). The thorium level in the air of Algonquin Park, Ontario, Canada was reported to be 7.1 pg/$m^3$ (Sheppard 1980). The level of thorium measured in 1969 in East Chicago, Indiana, a heavily polluted industrial area, was 1.3 ng/$m^3$ compared to a value of 0.27 ng/$m^3$ at a rural location in Niles, Michigan (Dams et al. 1970). The air particulate samples collected from 250 sites in the United States by the National Air Surveillance Network (NASN) of EPA during 1975 and 1976 were analyzed for $^{232}$Th by neutron activation analysis. The measured concentrations at 250 urban and nonurban sites in the United States ranged from 0.2 to 1.0 ng/$m^3$, with a mean concentration of 0.3 ng/$m^3$ (Lambert and Wilshire 1979). The mean concentrations of $^{228}$Th, $^{230}$Th, and $^{232}$Th in New York City air (sample collected on the roof above the 14th floor) were 36, 36, and 37 aCi/$m^3$, respectively (Wrenn et al. 1981).

The air concentrations of thorium and other airborne radioactivity near a former thorium and rare-earth extraction facility in the United States were measured. The maximum radioactivity due to all three isotopes of thorium at a site about 450 feet from the primary waste pile was 0.66 fCi/$m^3$. Although the background thorium radioactivity was not reported, the total radioactivity at a site about 4,000 feet south of the waste pile was about 3.5 times lower than a site 450 feet from the pile (Jensen et al. 1984).

The concentrations of thorium in rainwater over Fayetteville, Arkansas were 2.8–123 fCi/L for $^{228}$Th, 1.7–123 fCi/L for $^{230}$Th, and 0.8118 fCi/L for $^{232}$Th. The peak values in thorium concentrations correlated well with the 1980 eruption of Mount St. Helen and the 1982 eruption of El Chichon (Jiang and Kuroda 1987; Jiang et al. 1986; Salaymeh and Kuroda 1987).

The natural decay of $^{238}$U and $^{232}$Th will produce $^{222}$Rn and thoron ($^{220}$Rn). The indoor air levels of radon ($^{222}$Rn) and thoron ($^{220}$Rn) daughters arising from some building materials and the soil have been reported by several authors. It was generally believed that the effective dose equivalent from $^{220}$Rn (thoron) daughters (originating from $^{232}$Th) might average about one-fifth of that due to $^{222}$Rn daughters (originating from $^{238}$U) in the temperate regions (Schery 1985). However, more recent measurements at varied indoor locations within the United States and Germany have shown that the potential alpha energy concentrations from $^{220}$Rn daughters may be as high as 60% of that originating from $^{222}$Rn. It has also been shown that the concentrations of thoron ($^{220}$Rn) and $^{222}$Rn daughters in the indoor air are dependent on the air exchange rate in the dwellings and that the indoor concentrations are about 3–4 times higher than the outdoor concentrations (Keller and Folkerts 1984; Schery 1985).

### 5.5.2 Water

Compared to uranium, relatively less information was located on the levels of thorium in natural waters. The concentrations of dissolved thorium in water with high pH (more than 8) are expected to be very low, and the concentration may increase with the decrease of pH (Harmsen and De Haan 1980). Cothern et al. (1986) reported $^{232}$Th concentrations rarely exceed 0.1 pCi/L in natural waters, but that the concentrations of $^{230}$Th, a progeny of $^{238}$U, may be as high as 0.4 pCi/L. In a natural surface water in Austria, the concentration of thorium (isotope undefined) was reported to be 1.24–2.90 μg/L (Harmsen and De Haan 1980). The concentration of thorium (isotope undefined but probably $^{230}$Th) in water under low pH conditions, which may occur from the leaching of uranium tailings, may be as high as 38 mg/L (Harmsen and De Haan 1980). The individual concentrations of $^{228}$Th, $^{230}$Th, and $^{232}$Th in an area of Great Bear Lake in Canada contaminated with mine wastes (silver and uranium mines) were <0.5 pCi/L (Moore and Sutherland 1981). The concentrations of $^{228}$Th, $^{230}$Th, and $^{232}$Th in a highly alkaline (pH of about 10) lake (Mono Lake) in California have been reported to be as high as 1.02, 1.41, and 0.7 pCi/L, respectively (Anderson et al. 1982; Simpson et al. 1982).

The concentrations of thorium in seawater at various depths and locations have been reported by several authors. Because of the very low concentrations of thorium and the differences in location and the varying characteristics of the water, the reported results are different. The concentration of total thorium in seawater ranges from $4 \times 10^{-5}$ to <0.5 μg/kg (Greenberg and Kinston 1982; Sheppard 1980) and the world average concentration in seawater is 0.05 μg/L (Harmsen and De Haan 1980). The concentrations of the individual isotopes $^{232}$Th, $^{230}$Th, and $^{228}$Th in seawater have been reported to be 0.00023–0.032, 0.014–0.72, and 0.023–3.153 fCi/L, respectively (Anderson et al. 1982; Hirose 1988; Huh and Bacon 1985; Livingston and Cochran 1987; Simpson et al. 1982). The concentrations of thorium in sediments are much higher than in seawater. In several sediments, concentrations of $^{232}$Th, $^{230}$Th, and $^{228}$Th were 0.52–1.96, 1.01–30.77, and 0.36–1.93 pCi/g, respectively (Huh et al. 1987; Yang et al. 1986).

Thorium has also been detected in groundwaters. In groundwater in Austria, concentrations ranged from 0.5 to 2.90 μg/L (Harmsen and De Haan 1980). Briny groundwater from a well in Palo Duro Basin, Washington, contained 0.009, 0.1, and 0.59 pCi/L of $^{232}$Th, $^{230}$Th, and $^{228}$Th, respectively (Laul et al. 1987). In a California well, $^{230}$Th was detected at a concentration as high as 1.3 pCi/L (Aieta et al. 1987). The average population-weighted concentrations of $^{232}$Th and $^{230}$Th in U.S. community water supplies derived from both surface water and groundwater are <0.01 and <0.04 pCi/L, respectively (Cothern 1987; Cothern et al. 1986).

### 5.5.3 Sediment and Soil

The typical concentration range of thorium in soil is 2–12 μg/g (ppm), with an average value of 6 μg/g (Harmsen and De Haan 1980). The thorium content of soil normally increases with an increase in clay content of soil (Harmsen and De Haan 1980). The thorium contents in most soils from the Superfund sites listed in Section 5.3.3 were above background levels. The soil concentrations of $^{232}$Th at the Reed-Keppler Park, West Chicago, Illinois, site and the Kerr-McGee Residential areas in West Chicago, Illinois, were 11,000 and 16,000 pCi/g, respectively (EPA 1988a). Soils near processing and milling operations, and concentrations of uranium and thorium ores, phosphate ores, and tin ores may contain thorium at concentrations higher than the background levels. Higher concentrations of thorium in soils near uranium ore crushing facilities have been reported (Jensen et al. 1984; Sill 1977).

Gallegos (1995) reported mean $^{232}$Th levels of 0.0265, 0.0259, and 0.0351 Bq/g dry (0.716, 0.7, and 0.949 pCi/g dry) in soil samples taken from sampling sites in the vicinity of the Lawrence Livermore National Laboratory in California. Powell et al. (2007) found much higher levels in sediment samples taken from the Reedy River and surrounding creeks in Simpsonville, South Carolina that averaged 45.3 Bq/kg (1.22 pCi/g).

Hydraulic fracturing (fracking) operations to enhance natural gas production use water and additives injected under pressure and the process results in pits, ponds, and impoundments, referred to as reserve pits, on the surface. Rich and Crosby (2013) collected water and residual sludge from two reserve pits in the Barnett Shale East Newark Field and found $^{228}$Th concentrations ranging from 0.36 to 0.72 pCi/g. Water concentrations were not reported.

Coal combustion residues (CCRs) from coal-fired power plants contain thorium, uranium, and a range of other substances. Spills from containment impoundments, such as the one in Kingston, Tennessee in 2008, can adversely affect the environment, so EPA undertook evaluation of such sites. Roper et al. (2013) analyzed samples from a 74-site subset of that larger EPA study. The concentration of $^{232}$Th in fly ash averaged 73±26 Bq/kg (1.97±0.70 nCi/kg) for bituminous coals and 81±18 Bq/kg (2.19±0.49 nCi/kg) for subbituminous coals, 10±6 Bq/kg (0.27±0.16 nCi/kg) in scrubber sludges, and 1±1 Bq/kg (0.027±0.027 nCi/kg) in flue gas desulfurization gypsum.

Normally, thorium concentrations in drinking water are low and EPA does not require levels to be measured. Since thorium and other elements can become trapped in solids that deposit on sediment and walls of distribution system piping, levels can build up over time. Lytle et al. (2014) collected and analyzed samples of solids from the flushing of deposits (primarily from fire hydrants) in 25 distribution systems from 12 water utilities. Total thorium averaged 40±25 pCi/g and consisted of >90% $^{228}$Th (36±24 pCi/g), ~8% $^{230}$Th (3.3±3.0 pCi/g), and ~3% $^{232}$Th (1.2±1.1 pCi/g). The flushing of water distribution systems can remove thorium and result in lower levels at the tap, especially if the system is otherwise undisturbed.

### 5.5.4 Other Media

Because concentrations of thorium in foods are very low, very few data exist. The $^{232}$Th content in fresh fruits, vegetables, and tea was determined (in pCi/g), and the values are listed in Table 5-6. Vegetables grown in an area of high natural activity in Brazil had the following concentrations of thorium (μg/g in dry sample) (Linsalata et al. 1987): brown beans, 0.011; potato, 0.0019; zucchini, 0.011; corn, 0.0022; carrot, 0.0074; and sweet potato, 0.0027. These authors did not observe rapid transport of $^{232}$Th from soil to the edible parts of the plants.

## Table 5-6. $^{232}$Th Content in Fresh Fruits, Vegetables, and Tea

| Food | Concentration in pCi/g (wet weight) |
|---|---|
| Apples | ≤6.9x10$^{-3}$ |
| Asparagus | ≤9.8x10$^{-2}$ |
| Bananas | ≤8.2x10$^{-3}$ |
| Bell peppers | ≤6.7x10$^{-3}$ |
| Brazil nut | <7x10$^{-3}$–9x10$^{-3}$ |
| Broccoli | ≤3.6x10$^{-3}$ |
| Cabbage | ≤3.3x10$^{-3}$ |
| Carrots | ≤4.2x10$^{-3}$ |
| Celery | ≤9.0x10$^{-3}$ |
| Cucumbers | ≤2.9x10$^{-3}$ |
| Egg plant | ≤3.3x10$^{-3}$ |
| Grapefruit | ≤9.8x10$^{-3}$ |
| Green beans | ≤4.9x10$^{-3}$ |
| Green tea | 2x10$^{-3}$–3x10$^{-3}$ |
| Irish potatoes | ≤3.9x10$^{-3}$ |
| Lettuce | ≤2.8x10$^{-3}$ |
| Oranges | ≤4.1x10$^{-3}$ |
| Pears | ≤8.5x10$^{-3}$ |
| Raisins | ≤1.2x10$^{-2}$; 2x10$^{-3}$–3x10$^{-3}$ |
| Sesame seed | 1x10$^{-2}$ |
| Soybean | 1x10$^{-3}$ |
| Sweet potatoes | ≤7.5x10$^{-3}$ |
| Tangelos | ≤2.3x10$^{-3}$ |
| Tangerines | 4.7x10$^{-3}$ |
| Tomatoes | ≤1.1x10$^{-2}$ |
| Turnips | ≤2.6x10$^{-3}$ |
| Yellow squash | ≤3.9x10$^{-3}$ |

Sources: Oakes et al. 1977; Kobashi and Tominaga 1985

The concentrations of thorium in both hard and soft tissues of humans have been determined by a few authors. The concentration of $^{232}$Th in the blood of normal populations (not occupationally or otherwise known to be exposed to levels higher than background level of thorium) in the United Kingdom was 2.42 μg/L. The $^{232}$Th level in the urine of the same population was below the detection limit of 0.001 μg/L, although the concentration in the urine of exposed workers ranged from <0.001 to 2.24 μg/L. The highest value (2.24 μg/L) was found in a worker in the thorium nitrate gas mantle industry (Bulman 1976; Clifton et al. 1971).

The $^{232}$Th concentrations in rib bones from several control humans from the United States ranged from <0.1 to 72 ng/g (ppb) and were found to increase with age (Lucas et al. 1970). A similar increase in thorium concentration with age was seen in bones (primarily vertebral wedges) of a Colorado population (Wrenn et al. 1981). The level of $^{232}$Th in rib bones of individuals in the United Kingdom not occupationally exposed to thorium ranged from 0.8 to 163.8 ng/g, with a mean value of 28.7 ng/g in dry ash (Clifton et al. 1971). The concentration of thorium in the fibula of a Thorotrast patient was reported to be 2.0 μg/g (ppm) (Edgington 1967). Singh et al. (1985) reported more recent measurements of isotopic concentrations of thorium in different human bones from the general population of Colorado and Pennsylvania. These values are shown in Table 5-7. The authors concluded that the concentrations of $^{230}$Th in ribs of the Colorado population were significantly higher (statistically), probably because of exposure to uranium tailings, than those from the Pennsylvania population.

**Table 5-7. Thorium Levels in Bones of Colorado and Pennsylvania Residents**

| Source of bone | Mean thorium levels [(pCi/kg) wet weight] in residents from two locations | | | | | |
|---|---|---|---|---|---|---|
| | Colorado | | | Pennsylvania | | |
| | $^{232}$Th | $^{230}$Th | $^{228}$Th | $^{232}$Th | $^{230}$Th | $^{228}$Th |
| Ribs | 0.50 | 1.57 | 1.0 | 0.20 | 0.54 | 1.19 |
| Vertebrae | 0.096 | 0.96 | 0.88 | 0.10 | 0.27 | 1.31 |
| Sternum | Not detected[a] | Not detected[a] | 0.02[a] | 0.33 | 0.63 | 2.73 |

[a] Only one sample analyzed.

Source: Singh et al. 1985

The levels of thorium in the tissues of a hard-rock miner, a uranium miner, and the levels in two uranium millers ($^{230}$Th is a decay product of $^{238}$U, and $^{228}$Th and $^{232}$Th are impurities in uranium) were compared with the levels in the 50th percentile for the general population (Singh et al. 1987; Wrenn et al. 1981). These data are given in Table 5-8. The levels of $^{230}$Th in the hard-rock miner were about 10 times higher than the median levels in most tissues of the general population. In the case of the uranium miner and millers, the values were >2 orders of magnitude higher than the median tissues levels in the general population.

Wrenn et al. (1981) determined the median concentrations of $^{228}$Th, $^{230}$Th, and $^{232}$Th in the lungs of smokers and nonsmokers; the respective values were 0.22, 0.56, and 0.43 pCi/kg for smokers and 0.37, 0.84, and 0.60 pCi/kg for nonsmokers. The investigators concluded that cigarette smoking had no effect relative to increasing the concentration of thorium isotopes in lungs.

## Table 5-8. Thorium Isotopic Concentration in Three Occupational Cases and the General Population of Grand Junction, Colorado (pCi/kg)

| | Uranium miner[a] | | | Hard rock miner[a] | | | Uranium miller[b] | | | 50th percentile for the general population[a] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $^{228}$Th | $^{230}$Th | $^{232}$Th | $^{228}$Th | $^{230}$Th | $^{232}$Th | $^{228}$Th | $^{230}$Th | $^{232}$Th | $^{228}$Th | $^{230}$Th | $^{232}$Th |
| Lung | 1.1±0.18 | 54.0±0.81 | 1.4±0.13 | 0.70±0.24 | 12.0±0.79 | 0.61±0.18 | 0.49 | 141 | 2.35 | 0.21 | 0.88 | 0.37 |
| Lymph nodes | NA | NA | NA | 12.0±2.4 | 37.0±3.9 | 4.6±1.4 | 168 | 1,687 | 31.7 | 4.8 | 13.0 | 8.1 |
| Liver | 0.25±0.04 | 32.0±0.36 | 0.12±0.2 | 0.05±0.01 | 0.82±0.07 | 0.06±0.02 | 0.73 | 120 | 0.09 | 0.08 | 0.13 | 0.07 |
| Spleen | 0.69±0.18 | 32.0±1.0 | 0.80±0.15 | 0.06±0.02 | 1.5±0.16 | 0.12±0.04 | 1.81 | 1.81 | 0.38 | 0.06 | 0.13 | 0.09 |
| Bone | 0.24±0.3 | 132.0±1.1 | 0.42±0.06 | 0.54±0.13 | 10.0±0.40 | 0.32±0.07 | 1.47 | 86.9 | 0.31 | 0.54 | 0.89 | 0.20 |
| Kidney | 0.11±0.05 | 10.0±0.40 | 0.09±0.04 | 0.09±0.04 | 1.4±0.15 | 0.11±0.04 | 0.82 | 2.80 | 0.18 | 0.09 | 0.23 | 0.07 |

[a] Wrenn et al. 1981.
[b] Singh et al. 1987; the averages of two samples are given.

NA = not analyzed; Th = thorium

## 5.6 GENERAL POPULATION EXPOSURE

The general population will be exposed to thorium through the inhalation of air and ingestion of food and drinking water containing trace amounts of the chemical. Because the concentration of thorium is normally very low in air, drinking water, and foods, few studies were located that determined the daily human intake of thorium. According to Cothern (1987), the estimated daily intakes of $^{230}$Th in the United States population through inhalation of air and ingestion of drinking water are 0.0007 and <0.06 pCi, respectively. The corresponding values for $^{232}$Th are 0.0007 and <0.02 pCi. Cothern (1987) assumed that the intake from food would be negligible. Based on these values, the total daily intakes of $^{230}$Th and $^{232}$Th are expected to be <0.06 and <0.02 pCi, respectively. However, other authors estimated the contribution of food to the total human thorium intake may not be negligible and may be the most significant. Based on a survey of the levels of thorium in air, water, and food, Fisenne et al. (1987) estimated the daily intake of $^{230}$Th and $^{232}$Th by New York City residents. The daily dietary, water, and inhalation intake of $^{230}$Th was estimated to be 0.164, 0.005, and 0.0003 pCi, respectively, giving a total daily intake of 0.17 pCi. The corresponding estimated values for $^{232}$Th are 0.110, 0.002, and 0.0002 pCi, with a total daily intake being 0.112 pCi. From the measured values of thorium in feces and the assumed values for uptake and elimination rates, Linsalata et al. (1985) estimated a daily ingestion intake of $^{232}$Th for New York residents to be about 0.08 pCi or 0.7 μg. This value is considerably smaller than the value estimated by Fisenne et al. (1987). The value from Linsalata et al. (1985) is again considerably smaller than the daily dietary, water, and inhalation intakes of 2.24, 0.02, and 0.02 μg, respectively, as estimated for residents of Bombay, India (Dang et al. 1986). It can be concluded from the above discussion that the total intake of thorium by the United States population may vary depending on the thorium content in the consumed food and that no firm U.S. average thorium intake value is yet available. The importance of the intake of thorium from foods is overshadowed by the relative absorption of thorium by lung compared with its uptake by gut.

Occupational exposures to higher levels of thorium isotopes occur primarily to workers in uranium, thorium, tin, and phosphate mining, milling, and processing industries, radium dial workers, and gas lantern mantle workers. From the measurement of airborne thorium concentrations in workplaces of the uranium and thorium industry, it was concluded that radioactive dust, particularly from crushing areas, represents an important route of exposure (Hannibal 1982; Kotrappa et al. 1976). It has also been reported that exposure of workers in the fertilizer industry to natural radioactivity may increase by 100% over normal background (Metzger et al. 1980). Measuring external gamma radiation dosages to a person working 8 hours/day has shown that monazite and xenotime storage rooms of Amang upgrading plants (tin processing) on the west coast of Malaysia exhibited exposure rates exceeding the ICRP recommended maximum value of 5 rem/year (Hu et al. 1984). From the radioactivity released by a burning gas mantle (contains thorium), it was concluded that the user would be at minimal risk unless the person was in a small unventilated room (Leutzelschwab and Googins 1984). However, workers in the gas mantle manufacturing industry are expected to be exposed to higher concentrations of radioactivity than the normal population.

Workers are exposed to higher levels of thorium and other radionuclides in certain thorium industries, as indicated by the measured exhaled breath and tissue levels of these chemicals. The significantly higher level of $^{220}$Rn (a decay product of $^{232}$Th) in the exhaled breath of some thorium plant workers (Mayya et al. 1986) is indirect evidence of higher thorium intakes. Similarly, other authors have found higher tissue and body fluid levels (compared to background) of thorium in workers in the thorium processing industry (Clifton et al. 1971; Mausner 1982; Twitty and Boback 1970), workers in the radium dial industry (Keane et al. 1986), in uranium mill crushermen (Fisher et al. 1983), and in uranium and hard rock miners and uranium millers (Singh et al. 1987; Wrenn et al. 1981).

Thorium-doped glass is also used in the production of some camera lenses (Waligorski et al. 1985). A relatively recent measurement has shown that the external dose rate from exposure to a camera lens can be 10 times higher (as high as 9.25 mrem/hour at the front glass surface of the lens) than previously reported (Waligorski et al. 1985). Therefore, professional photographers and workers in the thorium-doped photographic lens manufacturing industry may be at slightly higher risk of exposure to thorium and its daughter products from inhalation and/or external radiation.

An autopsy study from the U.S. Transuranium and Uranium Registry reported that the maximum concentrations of $^{232}$Th for an individual who was not occupationally exposed to thorium were 20–400 ng/g in lung and 160–400 ng/g in lymph nodes (Hare et al. 2010).

Thorium concentrations in the air of an ore-crushing workshop associated with a rare-earth mine in China ranged from 9.30 to 875 mg/m$^3$ and averaged 188.7 mg/m$^3$ (Chen et al. 2003).

## 5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Neonatal animals have been found to absorb 20–40 times more thorium through the gastrointestinal tract than adult animals (Sullivan 1980a, 1980b; Sullivan et al. 1983), indicating that children may be more susceptible to both the chemical and radiological effects of thorium than adults.

The three groups of the general population that have the potential of exposure to thorium and its decay products at levels higher than background are people who consume large amounts of foods grown in high background areas, people who reside in homes built with high thoron ($^{220}$Rn) emitting building materials and constructed on soil with high background levels of thorium, and people who live near radioactive waste disposal sites. Linsalata et al. (1987) analyzed vegetables grown in two areas near Sao Paulo, Brazil, which contained high natural radioactivity, and found that thorium is not bioaccumulated in the vegetables but maintained a mean concentration ratio (concentration in dry vegetable/concentration in dry soil) of $10^{-4}$. Root vegetables (e.g., carrots and potatoes) showed lower concentration ratios than zucchini and beans. Therefore, it can be concluded that vegetables grown in these soils would contain more thorium than vegetables grown in soil with normal background levels.

Linsalata et al. (1985) also estimated that the intake of thorium by populations residing in these parts of Brazil was 6–10 times higher than the population in New York City, as indicated by the analysis of human bones from the two areas. The concentration of thorium in human bones was found to be 100 times higher in high background monazite areas in India than in areas with normal thorium concentration in soils (Pillai and Matkar 1987).

The building construction materials that contain higher levels of $^{232}$Th are granite, clay bricks, and certain kinds of concrete blocks and gypsum, particularly the materials in which waste products from uranium mining and milling industry are used (Beretka and Mathew 1985; Ettenhuber and Lehmann 1986; Hamilton 1971). Ettenhuber and Lehmann (1986) reported that the indoor gamma radiation dose equivalent in buildings made from bricks and concrete is mainly due to $^{222}$Rn (originating from $^{238}$U) and $^{220}$Rn (originating from $^{232}$Th), and can be over 7 times higher than outdoors.

The effect of soil on the level of thorium and its decay products in indoor air has been discussed by Gunning and Scott (1982). Homes near the Elliot Lake (Canada) uranium mines were suspected to contain higher than normal levels of thoron ($^{220}$Rn) and its daughters, because of higher levels of thorium in the surface soil and building materials used in the town. The ratio of the concentration of decay products of thoron ($^{220}$Rn) to $^{222}$Rn found in these homes was 0.3. Therefore, the concentrations of thoron in decay products originating from $^{232}$Th inside the homes were lower than $^{222}$Rn decay products originating from $^{238}$U, and the levels were insignificant compared with the remedial action limit of 20 mWL (1 WL is the concentration of short-lived radon decay products that will result in 1.3x10$^5$ MeV of potential alpha energy per liter of air) (Gunning and Scott 1982).

The concentrations of $^{232}$Th in soil from several residential lots near the Kerr-McGee ore processing facilities in West Chicago, Illinois, have been determined to be up to 16,000 pCi/g (EPA 1988a). Therefore, homes built on such lots or homes that are close to other radioactive disposal sites may be sources of higher thorium exposure.

Both cigarette tobacco and its smoke contain thorium (Munita and Mazzilli 1986; Neton and Ibrahim 1978). However, the effect of cigarette smoking on potential thorium exposure remains unclear. Joyet (1971) analyzed the lungs of 10 autopsied smokers and two nonsmokers. In 5 of 10 smokers, the lungs contained significantly higher levels of thorium than the nonsmokers, and the thorium levels in the residual five were not significantly different from the nonsmokers. Limited data suggest that cigarette smoking has no effect on the concentration of thorium isotopes in the lungs (Wrenn et al. 1981).

Welders are exposed to elevated airborne thorium levels when using thoriated tungsten welding electrodes during the process of tungsten inert gas (TIG) welding (Gafvert et al. 2003; Ludwig et al. 1999; McElearney and Irvine 1993; Saito et al. 2003), even though the welding process is not intended to consume the electrode. Additional inhalation exposure of those welders could occur while grinding one end of each electrode to a point in preparation for its use.

Firefighters may be exposed to elevated levels of thorium when inhaling smoke from forest fires. Carvalho et al. (2014) found that the complete combustion of plants in the Viesu district of Portugal resulted in fly ash with a thorium concentration of 412 Bq/kg (11.14x10$^3$ pCi/kg), which was >100 times that of the original vegetation, which ranged from 0.023 to 5.5 Bq/kg (0.62 to 148.65 pCi/kg).

Lenka et al. (2013) estimated the ingestion radiation doses from thorium and other environmental radionuclides in food and water to the population of Chhatrapur, Odisha, India. The area is rich in monazite sand, which contains elevated levels of uranium and thorium series radionuclides. The respective average doses from cereals, pulses, and drinking water were 50, 2.4, and 0.2 μSv/year (5,000, 240, and 20 µrem/year). Cereals were highest due to their combined radioactivity concentration (up to 2 mBq/g; 0.054 pCi/g) and intake rate.