6. POTENTIAL FOR HUMAN EXPOSURE

6.1 OVERVIEW

Strontium and ^{90}Sr have been identified in at least 102 and 12, respectively, of the 1,636 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2003). However, the number of sites evaluated for strontium and strontium-90 are not known. The frequency of these sites can be seen in Figures 6-1 and 6-2, respectively. Of these sites, all are located within the United States and none are located in the Commonwealth of Puerto Rico.

Strontium is widely distributed in the earth's crust and oceans. Strontium is released into the atmosphere primarily as a result of natural sources, such as entrainment of dust particles and resuspension of soil. Radioactive strontium is released into the environment as a direct result of anthropogenic activities. Stable strontium can neither be created nor destroyed. However, strontium compounds may transform into other chemical compounds. Radioactive strontium is formed by nuclear reactions. Radioactive decay is the only mechanism for decreasing the concentration of radiostrontium. The half-life of ^{90}Sr is 29 years. Eventually, all of the radioactive strontium will be converted to stable zirconium (see Section 4.2).

Strontium present in the atmosphere is in the form of wet or dry aerosols. The principal chemical species in the air is strontium oxide (SrO). Strontium oxide will react rapidly in the presence of moisture to form Sr^{+2} and $SrOH^{+}$ ions. Strontium is dispersed by atmospheric cycling and is subsequently deposited by wet deposition on the earth's surface. In surface water and groundwater, strontium exists primarily as a hydrated ion. Strontium can form ionic complexes with other inorganic or organic substances. Strontium is relatively mobile in water. However, the formation of insoluble complexes or sorption of strontium to soils can reduce its mobility in water. Strontium sorbs to soils by ion exchange, and tends to be more mobile in soils with a high concentration of exchangeable ions or in soils with low cation exchange capacities. Strontium is taken up and retained by aquatic and terrestrial plants and is concentrated in the boney tissues of animals that eat contaminated vegetation. The average concentration of strontium in urban air is 20 ng/m^3 (Dzubay and Stevens 1975). The concentration of ^{90}Sr in the atmosphere has steadily decreased since its maximum concentration in 1963. The mean concentration of strontium in U.S. surface water is <1 mg/L. Dissolved strontium has been detected in groundwater and surface water used for drinking water supplies with average concentrations of 0.81 and 1.1 mg/L, respectively (EPA

Figure 6-1. Frequency of NPL Sites with Strontium Contamination

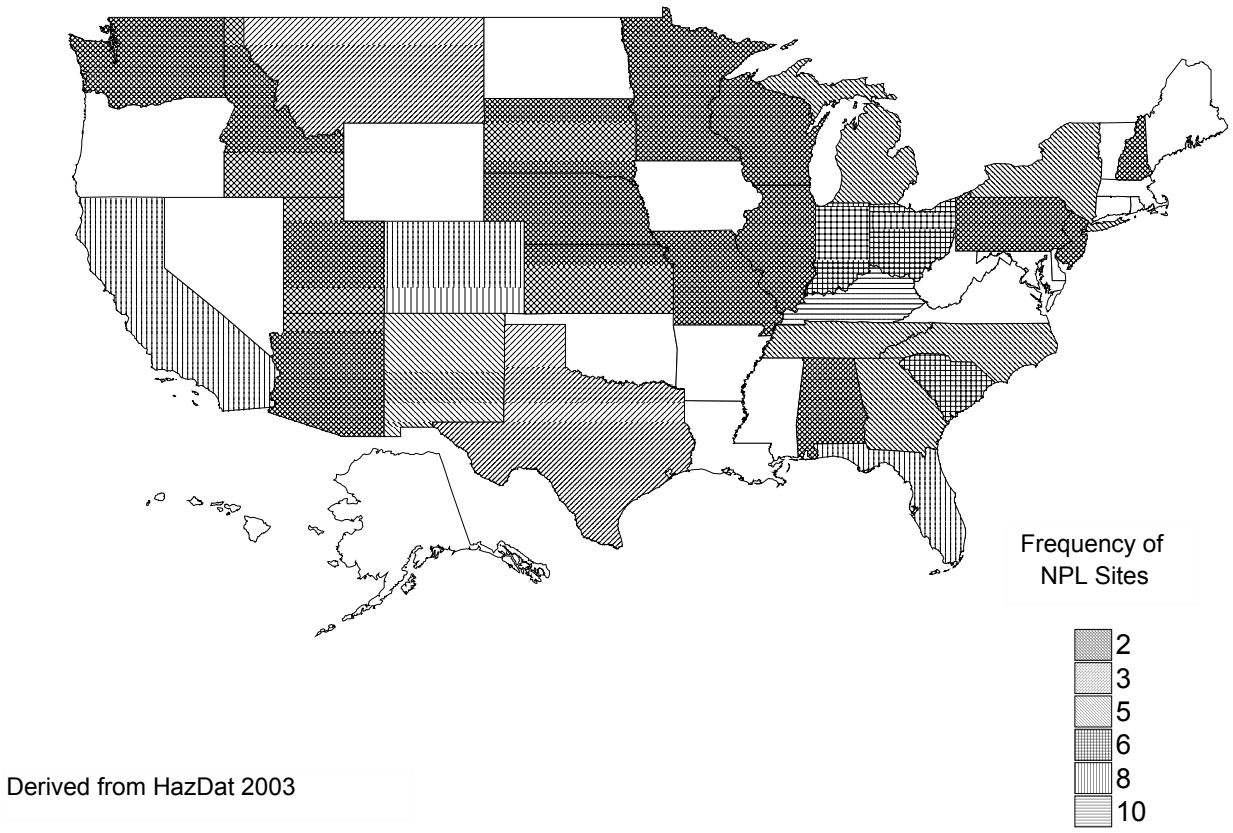

Figure 6-2. Frequency of NPL Sites with Strontium-90 Contamination

Derived from HazDat 2003

2002b). The median concentration of ^{90}Sr in drinking water for 1995 was 0.1 pCi/L (3.7 mBq/L). Human exposure to strontium and radiostrontium can result from consumption of food, drinking water, or incidental ingestion of soil or dust contaminated with strontium. Food and drinking water are the largest sources of exposure to strontium and radiostrontium. Grain, leafy vegetables, and dairy products contribute the greatest percentage of dietary strontium and radiostrontium to humans.

6.2 RELEASES TO THE ENVIRONMENT

The TRI data should be used with caution because only certain types of facilities are required to report. This is not an exhaustive list.

6.2.1 Air

Strontium naturally occurs in the earth's crust and is released into the atmosphere as a result of natural processes such as entrainment of dust particles, resuspension of soil by wind, and sea spray. Entrainment of soil and dust particles with significant concentrations of strontium would be most significant in areas with higher soil strontium concentrations. Coastal regions have higher concentrations of strontium due to sea spray (Capo et al. 1998). Human activities, including milling and processing of strontium compounds, burning of coal, land application of phosphate fertilizers, and using pyrotechnic devices, release strontium into the atmosphere (Lee and von Lehmden 1973; Ondov et al. 1989; Perry 1999; Que Hee et al. 1982; Raven and Loeppert 1997). The effect of these activities is illustrated by the deposition rates of strontium measured in peat cores of northern Indiana. Deposition has increased by a factor of 7 from 8.1 mg strontium/m^2/year in presettlement times (1339–1656) to 57.0 mg strontium/m^2/year between 1970 and 1973 (Cole et al. 1990).

Strontium discharged into the atmosphere from the operation of coal fired power plants depends on the strontium concentration in coal, the amount of coal burned, and the efficiency of fly ash recovery. Approximately 90% of coal mass is consumed during the combustion process, leaving 10% as a residual nonvolatile material (fly ash) containing 100–4,000 ppm (or mg/kg) of strontium (Furr et al. 1977). Atmospheric concentrations of strontium emitted from coal fired power plants have been found to range from 17 to 2,718 µg/m^3 in the western United States and are approximately 9,786 µg/m^3 in the eastern United States (Ondov et al. 1989; Que Hee et al. 1982). Phosphate fertilizers are known to contain between 20 and 4,000 µg strontium/g solid by weight (Lee and von Lehmden 1973; Raven and Loeppert

1997). Strontium can be released into the atmosphere in windblown soil to which phosphate fertilizers have been applied. Pyrotechnic displays release low levels of strontium on the order of 9 ng/m^3 in the immediate environment of the display (Perry 1999).

Strontium has been identified in air at 9 sites collected from the 102 NPL hazardous waste sites where it was detected in some environmental media (HazDat 2003).

Radioactive strontium (e.g., ^{90}Sr) was released into the atmosphere from aboveground testing of nuclear weapons during the period of 1945–1980. Nuclear weapon testing injects radioactive material into the stratosphere, which results in wide dispersal of radionuclides. However, atmospheric deposition of ^{90}Sr has steadily decreased from a high in 1963 of approximately 1.10x10^8 GBq (3.0 MCi) to <3,000 Ci in 1990, which suggests that global concentrations of ^{90}Sr in the atmosphere have declined (DOE 1996c). Other sources of regional contamination from radiostrontium include large-scale nuclear power plant accidents such as the Chernobyl disaster in the Ukraine (April 1986), which resulted in releases of about 2.2 MCi (8.1x10^7 GBq) of ^{89}Sr and 0.22 MCi (8.1x10^6 GBq) of ^{90}Sr into the atmosphere (Eisenbud 1987). However, although some ^{90}Sr reached the upper atmosphere and was subsequently transported around the world, most of the radiostrontium was deposited as regional fallout in eastern Europe (Eisenbud 1987). Routine releases of radiostrontium in 1993 from the operation of nuclear power plants around the United States are summarized in Table 6-1 (USNRC 1993a). In 1993, releases of radiostrontium (i.e., ^{89}Sr, ^{90}Sr, and ^{91}Sr) for boiling water reactors (BWR) and pressurized water reactors (PWR) (the two common designs of nuclear reactors in the United States) were 72.1 and 3.3 mCi (2.67 and 0.12 GBq), respectively. The total annual releases of radiostrontium from nuclear power plants in the United States (75.4 mCi or 2.79 GBq) are insignificant compared to releases of ^{90}Sr from the testing of nuclear weapons. In the former Soviet Union between the years 1949 and 1956, large-scale environmental contamination occurred in the region surrounding the Mayak plutonium production complex in the Ural region of Russia (Eisenbud and Gesell 1997). Releases of radioactive liquid wastes into the Techa River, both planned and accidental, of about 10^{17} Bq (2.7 MCi) resulted. ^{90}Sr contributed about 12% (or 0.23 MCi) to the total activity released (Tokareva et al. 2000). Other minor releases of ^{90}Sr have involved accidents with rockets or satellites that have disintegrated in the atmosphere. The Soviet satellite Cosmos 954 powered by a plutonium fueled nuclear reactor released 3.1x10^3 GBq (83 Ci) of ^{90}Sr to the regional atmosphere in northern Canada in 1978 (Eisenbud 1987). The Department of Energy (DOE) and its predecessor agencies have been involved in operations that have released radiostrontium into the atmosphere. Over the 43-year operating period at the DOE Savannah River Site in South Carolina, about 1.1x10^2 GBq (3 Ci) of ^{90}Sr were released into the atmosphere, primarily from the chemical separation and

Table 6-1. Radiostrontium Releases from Nuclear Power Plants for 1993

		Annual total site environmental releases for 1993						
		Water				Air		
Installation	Location[a]	^{89}Sr, mCi	^{90}Sr, mCi	^{91}Sr, mCi	^{92}Sr, mCi	^{89}Sr, mCi	^{90}Sr, mCi	^{91}Sr, mCi
Boiling Water Reactors								
Browns Ferry[b]	Decatur, AL	41.1	2.05	No data	0.40	0.19	No data	No data
Brunswick[b]	Wilmington, NC	No data	No data	No data	0.0062	0.099	0.0027	No data
Clinton	Clinton, IL	No data	No data	No data	No data	0.06	No data	No data
Cooper	Omaha, NE	4.69	15.8	No data	0.082	No data	No data	No data
Dresden[b]	Joliet, IL	0.056	0.085	No data	No data	0.67	0.004	No data
Duane Arnold	Cedar Rapids, IA	No data	No data	No data	No data	0.018	0.0009	No data
Edwin I. Hatch	Baxley, GA	6.29	0.43	5.20	0.65	12.0	0.24	No data
Fermi	Laguna Beach, MI	0.19	No data	No data	No data	0.14	0.0003	4.0
Grand Gulf	Vicksburg, MS	0.32	0.29	No data	No data	0.003	0.002	No data
Hope Creek	Wilmington, DE	No data	No data	No data	No data	No data	No data	No data
Humbolt Bay[b]	Eureka, CA	No data	36.5	No data	No data	No data	0.002	No data
James A. Fitzpatrick	Syracuse, NY	0.44	No data	No data	No data	0.045	7.3×10^{-7}	No data
LaCrosse[b]	LaCross, WI	No data	0.28	No data	No data	No data	0.0003	No data
LaSalle	Ottawa, IL	No data	No data	No data	No data	No data	No data	No data
Limerick	Phildelphia, PA	20.0	0.44	No data	No data	16.4	0.31	No data
Millstone	New London, CT	3.30	0.15	No data	0.55	0.22	0.0006	No data
Monticello	St.Cloud, MN	No data	No data	No data	No data	0.59	0.003	No data
Nine Mile Point	Oswego, NY	<0.0001	No data	No data	No data	5.90	0.004	No data
Oyster Creek	Toms River, NJ	No data	No data	No data	No data	1.17	0.014	No data
Peach Bottom	Lancaster. PA	0.19	0.056	No data	No data	4.9	0.021	3.76
Perry	Painesville, OH	0.22	0.008	No data	No data	1.8	0.009	4.87
Pilgram	Boston, MA	1.63	0.086	No data	No data	5.8	0.024	No data
Quad-Cites	Moline, IL	0.050	0.018	No data	0.12	0.61	0.0014	No data
River Bend	Baton Rouge, LA	5.3	0.31	No data	No data	0.30	0.0095	No data
Shoreham	Brookhaven, NY	0.025	No data	No data	No data	No data	No data	No data
Susquehanna	Berwick, PA	0.0088	No data	No data	0.0011	0.0003	No data	No data
Vermont Yankee	Brattleboro, VT	No data	No data	No data	No data	2.83	0.054	No data
WNP-2	Richland, WA	0.55	0.057	No data	No data	3.5	0.012	1.61

Table 6-1. Radiostrontium Releases from Nuclear Power Plants for 1993

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		Water				Air		
Installation	Location[a]	^{89}Sr, mCi	^{90}Sr, mCi	^{91}Sr, mCi	^{92}Sr, mCi	^{89}Sr, mCi	^{90}Sr, mCi	^{91}Sr, mCi
Total		84.4	56.6	5.20	1.81	57.2	0.72	14.2
Pressurized Water Reactors								
Arkansas One	Russellville, AR	2.81	1.17	No data	0.59	0.000955	No data	No data
Beaver Valley	Shippingport, PA	No data	No data	No data	0.08	No data	No data	No data
Big Rock Point	Charlevoix, MI	0.02	0.17	No data	No data	0.21	0.006	2.73
Braidwood	Joliet, IL	3.68	158.4	No data	0.017	No data	No data	No data
Byron	Byron, IL	152.4	0.56	No data	No data	No data	No data	No data
Callaway	Fulton, MO	17.6	1.12	No data	No data	0.004	No data	No data
Calvert Cliffs	Washington, DC	0.83	0.37	No data	No data	No data	No data	No data
Catawaba	Rock Hill, SC	No data	No data	No data	0.41	No data	No data	No data
Comache Peak	Glen Rose, TX	No data	No data	No data	0.029	No data	No data	No data
Crystal River	Tampa, FL	3.03	10.2	No data	3.57	0.001	0.001	No data
Davis-Besse	Toledo, OH	No data	No data	No data	No data	No data	No data	No data
Diablo Canyon	San Luis Obispo, CA	0.16	0.057	No data	0.003	No data	No data	No data
Donald C. Cook	St. Joseph, MI	No data	0.029	No data	No data	0.080	0.0005	No data
Fort Calhoun	Omaha, NE	0.61	0.77	No data	No data	No data	0.0007	No data
H.B. Robinson	Hartsville, SC	No data	No data	No data	No data	No data	No data	No data
Haddam Neck	Middletown, CT	0.076	1.52	No data	No data	0.0002	0.0002	No data
Harris[b]	Raleigh, NC	No data	No data	No data	No data	No data	No data	No data
Indian Point[b]	Peekskill, NY	0.077	0.007	No data	No data	No data	No data	No data
Joseph M. Farley	Dothan, AL	No data	0.028	No data	0.10	No data	No data	No data
Kewaunee	Green Bay, WI	0.92	0.051	No data	No data	No data	No data	No data
Maine Yankee	Wicassett, ME	0.15	No data	No data	No data	No data	No data	No data
McGuire	Charlotte, NC	0.20	No data	No data	No data	No data	No data	No data
North Anna[c]	NW Richmond, VA	No data	No data	No data	No data	No data	No data	No data
Oconee	Greenville, SC	No data	No data	No data	No data	No data	No data	No data
Palisades	South Haven, MI	0.003	0.012	No data	No data	0.011	0.0042	No data
Palo Verde	Phoenix, AZ	No data	No data	No data	No data	0.19	0.0009	No data
Point Beach	Manitowoc, WI	0.012	0.11	0.0052	No data	No data	0.0001	No data
Prairie Island	Minneapolis, MN	No data	No data	No data	0.029	0.0006	0.0003	No data
R.E. Ginna	Rochester, NY	0.30	0.090	No data	No data	No data	No data	No data

Table 6-1. Radiostrontium Releases from Nuclear Power Plants for 1993

		Annual total site environmental releases for 1993						
		Water				Air		
Installation	Location[a]	^{89}Sr, mCi	^{90}Sr, mCi	^{91}Sr, mCi	^{92}Sr, mCi	^{89}Sr, mCi	^{90}Sr, mCi	^{91}Sr, mCi
Rancho Seco[b]	Sacramento, CA	No data	0.0013	No data	No data	No data	No data	No data
San Onofre[b]	San Clemente, CA	4.26	0.36	No data	0.48	No data	No data	No data
Seabrook	Portsmouth, NH	No data	No data	No data	No data	No data	No data	No data
Sequoyah	Daisy, TN	0.35	0.29	0.023	0.54	No data	No data	No data
South Texas	Bay City, TX	No data	No data	No data	No data	No data	No data	No data
St. Lucie	Ft. Pierce, FL	1.21	1.83	No data	No data	No data	0.0012	No data
Summer	Columbia, SC	0.0007	0.021	No data	No data	No data	No data	No data
Surry	Newport News, VA	No data	No data	No data	No data	No data	No data	No data
Three Mile Island[b]	Harrisburg, PA	0.034	0.83	No data	No data	No data	0.0003	No data
Trojan[b]	Portland, OR	0.24	0.029	No data	No data	No data	No data	No data
Turkey Point[b]	Florida City, FL	12.7	3.55	No data	No data	No data	No data	No data
Vogtle	Augusta, GA	1.64	0.19	No data	No data	0.0025	0.0003	No data
Waterford	New Orleans, LA	No data	No data	No data	0.23	No data	No data	No data
Wolf Creek	Burlington, KS	No data	0.092	0.0087	No data	No data	No data	No data
Yankee Rowe[b]	Greenfield, MA	No data	No data	No data	No data	No data	No data	No data
Zion	Waukegan, IL	No data	No data	No data	5.93	No data	No data	No data
Total		207.1	182.8	0.04	11.5	0.50	0.02	2.73

[a]Post office state abbreviations used
[b]Facilities that are permanently or indefinitely shut down
[c]Air ^{85}Sr 8.17×10^{6}

Source: NRC 1993b

reprocessing of nuclear fuel (Carlton et al. 1998, 1999). Between 1944 and 1972, about 64 Ci ($2.4x10^3$ GBq) of ^{90}Sr and 700 Ci ($2.6x10^4$ GBq) of ^{89}Sr was released into the atmosphere at the DOE Hanford site in Washington state from the routine operation of chemical plants used to separate plutonium from spent reactor fuel (CDC 1994).

^{90}Sr has been identified in air at 3 sites collected from the 12 NPL hazardous waste sites where it was detected in some environmental media (HazDat 2003).

6.2.2 Water

Releases of strontium to surface water and groundwater results from the natural weathering of rocks and soils and from the discharge of waste water directly into streams and aquifers. Intentional and unintentional releases of radioactive strontium directly into streams have occurred at DOE sites across the country. Over the period of 1954–1989, about 104 Ci ($3.8x10^3$ GBq) of ^{90}Sr and 216 Ci ($8.0x10^3$ GBq) of ^{89}Sr were released to streams in the vicinity of the Savannah River Site (Carlton et al. 1998; Cummins et al. 1991). During the period from 1952 to 1991, >129 Ci of ^{90}Sr in waste water was discharged into pits, wells, and infiltration ponds at the Idaho Chemical Processing Plant in Idaho, some of which may have found its way into surface or groundwater (Bartholomay et al. 1995). Minor releases of radioactive strontium to water occur annually from nuclear power plants. Table 6-1 summarizes the releases of radioactive strontium from nuclear power plants into surface waters in 1993 (USNRC 1993a). Releases of radiostrontium (i.e., ^{89}Sr, ^{90}Sr, ^{91}Sr, and ^{92}Sr) into surface waters in 1993 from BWR and PWR were 146.2 mCi (5.41 GBq) and 401.4 mCi (14.9 GBq), respectively.

Strontium has been identified in surface water and groundwater at 25 and 55 sites, respectively, collected from the 102 NPL hazardous waste sites where it was detected in some environmental media. ^{90}Sr has been identified in surface water and groundwater at 3 and 7 sites, respectively, collected from the 12 NPL hazardous waste sites where it was detected in some environmental media (HazDat 2003).

6.2.3 Soil

Strontium is ubiquitous in the environment and is present in nearly all rocks and soils. It is released to land in solid waste and from the use of phosphate fertilizers. ^{90}Sr is found in nearly all soils in the United States. ^{90}Sr that is deposited at a specific site varies widely, depending primarily on rainfall. Intentional

and unintentional releases of radioactive strontium have occurred at DOE sites across the country. Between 1954 and 1989 at the Savannah River Site, 105 Ci ($3.9x10^3$ GBq) of ^{89}Sr and 299 Ci ($1.1x10^4$ GBq) of ^{90}Sr were released into onsite seepage basins (DOE 1991). About 100 million gallons of liquid HLW are stored in underground tanks in Hanford, Washington, Savannah River, South Carolina, Idaho National Engineering Laboratory, Idaho, and West Valley, New York; these tanks contain a variety of radioactive liquids, solids, and sludges with unknown characteristics. Sixty-seven tanks at the Hanford site have suspected leaks of HLW into the surrounding soil. The largest three confirmed leaks at the Hanford site have released 115,000, 70,000, and 55,000 gallons of HLW, respectively, which may contain ^{90}Sr as well as other radionuclides (DOE 1996a).

Strontium has been identified in soil and sediment at 32 and 16 sites, respectively, collected from the 102 NPL hazardous waste sites where it was detected in some environmental media. ^{90}Sr has been identified in soil and sediment at 3 and 1 sites, respectively, collected from the 12 NPL hazardous waste sites where it was detected in some environmental media (HazDat 2003).

6.3 ENVIRONMENTAL FATE

6.3.1 Transport and Partitioning

Strontium, present in crustal materials, is released by the weathering force of wind and water. Strontium leaves the oceans, the largest reservoir of dissolved strontium, by deposition in marine carbonate sediment. Some strontium is transported from oceans to the atmosphere in sea spray, returning to the terrestrial environment in the form of precipitation (Capo et al. 1998).

Strontium released into the atmosphere from natural and anthropogenetic activities is transported and redeposited on the earth by dry or wet deposition. Dry deposition results from gravitational settling, impact, and sorption on surfaces (NCRP 1984). Experimental data on dry deposition of strontium, present in the ambient atmosphere, is limited. Rain, sleet, snow, or other forms of moisture can wash airborne particles containing strontium from the atmosphere by the process of wet deposition. Wet deposition depends on conditions such as particle solubility, air concentration, rain drop size distribution, and rain fall rate (NCRP 1984). Hirose et al. (1993) examined the mechanism of aerial deposition of ^{90}Sr derived from the Chernobyl accident, and found that 96% of atmospheric ^{90}Sr returned to earth as wet deposition.

Like calcium, strontium has moderate mobility in soils and sediments, and sorbs moderately to metal oxides and clays (Hayes and Traina 1998). The Sr^{2+} ion is strongly hydrated and is firmly coordinated with six or more water molecules in aqueous solution. When Sr^{2+} ions sorb on negatively charged mineral surface sites, the hydration sphere is retained (O'Day et al. 2000). Strontium sorbs as hydrated ions on the surface of clay minerals (kaolinite), weathered minerals (amorphous silica), and iron oxides (Sahai et al. 2000). Sorbed carbonate on iron oxides enhances the sorption of Sr^{2+} and permits the nucleation of Sr^{2+} as strontium carbonate (Sahai et al. 2000). On calcite (calcium carbonate), Sr^{2+} sorption occurs by electrostatic attraction as hydrated ions. However, at higher concentrations, precipitation of strontianite (strontium carbonate) occurs, and strontium is likely to be less mobile (Parkman et al. 1998).

A wide variation of K_d values have been published in the literature for Sr^{2+} sorption (NCRP 1984) that reflect differences in soil and sediment conditions as well as the analytical techniques used (Bunde et al. 1997). The *in situ* K_d values of stable strontium and ^{90}Sr determined in soil cores taken from the fallout area of the 1945 blast in Nagasaki, Japan were 496 and 300 L/kg, respectively (Mahara 1993). Migration rates for ^{90}Sr in soils from this area were estimated to be 4.2 mm/year when the percolation rate of soil water was 2,500 mm/year. Most ^{90}Sr remained close to the soil surface in these soils. In 1996, at most sites in the contaminated zone near Chernobyl, the main content of ^{90}Sr (more than 95% of activity) was located in the upper 30-cm layer. Only at a few sites (<1% of all sites) had a significant part of the ^{90}Sr (>20%) migrate deeper than 30 cm (Kashparov et al. 2001). A high migration ability of ^{90}Sr is observed only in low-humus sands. In soils from Belarus near the Chernobyl accident site, K_d values were 43, 59, and 150 L/kg for soddy-podzolic, soddy-loamy sandy, and peaty-gley soils, respectively (Sokolik et al. 2001). Organic matter in soils has a substantial effect on the transport of strontium through soils into groundwater. K_d values decreased down the soil profile in Podzol forest soil with an organic rich top soil and lower clay layers, from 140 to 44 L/kg (Bunzl and Schimmack 1989). Sr^{2+} chemically complexes with organic matter by partially neutralizing exchangeable sites on organic matter resulting in the precipitation of organic matter-Sr^{2+} complexes (Helal et al. 1998a). High concentrations of ion exchangeable Ca^{2+} in soil enhances the complexation of Sr^{2+} with organic matter and increases the removal of Sr^{2+} from solution, which results in reduced Sr^{2+} mobility (Helal et al. 1998a). However, nitrate fertilizers inhibit the formation of Sr^{2+}-organic matter complexes and increase Sr^{2+} mobility (Helal et al. 1998b). K_d values of 15–40 L/kg were measured for $^{90}Sr^{2+}$ in aquifer sediments near Liquid Waste Disposal Facilities at the Hanford site in Washington, where rapid ion exchange dominates (DOE 1996d). K_d was measured for $^{90}Sr^{2+}$ in aquifer sediments beneath waste water ponds that contained high salt concentrations at the Idaho National Environmental and Engineering Laboratory (INEEL) (Bunde et al.

1998); and values ranged from 56 to 62 L/kg at initial concentrations of sodium and potassium of 300 and 150 mg/L, respectively. For initial aqueous concentrations of sodium between 1,000 and 5,000 mg/L, K_d values were 4.7 and 19 L/kg, respectively. At the Chalk River Nuclear Laboratory in Ontario, Canada, a ^{90}Sr waste plume in groundwater initially advanced rapidly as ^{90}Sr was out competed by high concentrations of Ca^{2+} and Mg^{2+} for sorption sites in sediments, and as concentrations of Ca^{2+} and Mg^{2+} declined, the migration of the ^{90}Sr plume slowed (Toran 1994). High salt concentrations (marine, brines, or high salinity water) can increase the mobility of $^{90}Sr^{2+}$ by decreasing strontium sorption to sediments (Bunde et al. 1997, 1998) and increase the transport of strontium with the environmental cycling of water.

Strontium is not necessary for growth or reproduction for most plants, but is typically absorbed to satisfy the plant's metabolic requirements for calcium (NCRP 1984). Soil to plant concentration ratios for strontium (the ratio of the concentration of strontium in wet vegetation to the concentration of strontium in dry soil) are 0.017–1.0 (NCRP 1984), and indicate that strontium can be easily absorbed into plants from soil. The uptake of strontium by plants is greatest in sandy soils having low clay and organic matter content (Baes et al. 1986). The concentration of nutritive mineral elements in soil such as calcium lower the intake of strontium to the aboveground phytomass. The average reduction of the soil-to-plant concentration ratios for ^{90}Sr caused by amendment with Ca or K is around 50–60% (Lembrechts 1993).

Strontium may be deposited on plant surfaces from the atmosphere, remain on the plant, be washed off, or be absorbed directly into the plant through leaves. Contamination by direct deposition on foliage surfaces is predominantly a short-term mechanism with a weathering half-life of approximately 14 days (Lassey 1979). Carini et al. (1999) examined the mechanism of translocation in three species of fruit-bearing plants exposed to aerial deposition of ^{85}Sr and found that translocation of ^{85}Sr is localized to the area of contamination on the plant. However, uptake of strontium through the leaves is minor compared to root uptake. Once absorbed in the plant, strontium translocates to other parts of the plant, such as the leaves or fruit. Translocation of strontium in plants is affected by the particular species and stage of organism growth, and the most metabolically active parts (growing) will accumulate higher concentrations of strontium (Kodaira et al. 1973).

Strontium, taken up by plants and translocated to the aboveground plant compartments, has been observed for deep-rooted plants such as chasima *(Chrysothamnus nauseosus)*, mulberry vegetation *(Morus alba)*, quaking aspen *(Populus tremuloides)*, and red maple *(Acer rubrum)* growing on top of low level waste burial sites or contaminated soils (Cooper and Rahman 1994; DOE 1995; Fresquez et al. 1996a). The top growth of the plant material releases strontium to the soil surface through leaf fall. Downward migration

of ^{90}Sr is slowed by recycling of the contaminated litter by vegetation (Cooper and Rahman 1994). Subsurface ^{90}Sr can be transported from soil to top soil by burrowing animals, and is spread to the surrounding environment via animal tissues and fecal deposits. At the Subsurface Disposal Area at the INEL, deer mice had the highest contamination of all animals from ingestion of ^{90}Sr-contaminated low level nuclear waste. In addition, the biotic intrusion of soils covering the waste site brings water infiltration into buried LLW (Arthur and Janke 1986).

The uptake or bioaccumulation of strontium by plants and organisms is the mechanism by which strontium in air, water, and soil enters into the food chain of humans. Bioconcentration factors (BCFs) have been measured by several investigators in both aquatic and terrestrial organisms for ^{90}Sr (NCRP 1984). BCF values for ^{90}Sr in aquatic, terrestrial, and wetland ecosystems at the Savannah River Site were reported by Friday (1996) and are summarized in Table 6-2. The study illustrates that the organisms with the highest uptake are aquatic organisms such as fish (large-mouthed bass), macroinvertebrates (insects), macrophytes (white-water lilies and bladderwort), and zooplankton. Because of the similarity of strontium to calcium, boney fish had a very high BCF, with a value >50,000 measured in the boney tissue (Friday 1996). In the muscle tissue of boney fish, BCF values for ^{90}Sr ranged from high (benthic invertebrate and fish feeders; 610) to very high (piscivores; 3,400). Because strontium and calcium are chemically similar, the concentration of calcium in water can influence the bioaccumulation of strontium in biota. Organisms such as fish bioaccumulate strontium with an inverse correlation to levels of calcium in water. However, this correlation is not universal and does not apply to other organisms such as algae and plants (NCRP 1984).

6.3.2 Transformation and Degradation

Because strontium is an element, its atoms do not degrade by environmental processes such as hydrolysis or biodegradation. However, radioactive strontium will be subject to radioactive decay and transformation to other elements. Eventually, all of the radioactive strontium will be transformed into stable zirconium by the process of radioactive decay (see Section 4.2):

$$^{90}\text{Sr}\ (t_{½} = 29\ \text{years}) - {}^{90}\text{Y}\ (t_{½} = 64\ \text{hours}) + \beta^{-} - {}^{90}\text{Zr}\ (\text{stable}) + \beta^{-}$$

Both radioactive and nonradioactive strontium compounds are subject to both biotic and abiotic transformation mechanisms.

Table 6-2. Selected Bioconcentration Factors for ^{90}Sr in Aquatic, Wetland, and Terrestrial Ecosystems at the Savannah River Site

Organism	Bioconcentration factors for ^{90}Sr		
	Minimum	Maximum	Mean
Algae		600	
Clam, shell		1,300	
Fish muscle			
Insect and bottom invertebrate feeders		<48	
Piscivores		3,400	
Benthic invertebrate and fish feeders		610	
Fish bone			
Insect and bottom invertebrate feeders		2,400	
Piscivores		63,000	
Benthic invertebrate and fish feeders		57,000	
Detritus and plankton feeders		51,000	
Macroinvertebrates, larvae	520	54,000	27,300
Macrohytes (rooted vascular)	2,100	8,500	5,500
Macrophytes (floating vascular)		9,400	
Zooplankton		3,900	
Corn			
Grain		0.15	
Leaves		13.1	
Pine tree, leaves	0.88	1.69	1.29
Soybeans		2.51	
Tree (maple, sweetgum, and poplar)			
Wood		0.81	
Bark		11	
Leaf		3.8	

Source: Friday 1996

6.3.2.1 Air

The presence of strontium and radioactive strontium compounds in the atmosphere results from both natural and anthropogenetic activities (see Section 6.2.1). Strontium is emitted into the atmosphere as strontium oxide (SrO) during thermal processes. SrO is unstable and reacts with moisture or carbon dioxide in the air to form strontium hydroxide ($Sr[OH]_2$) or strontium carbonate ($SrCO_3$), respectively. $Sr[OH]_2$ in contact with water in clouds or during washout by rain will ionize to form Sr^{2+} and $SrOH^+$ ions. There is no evidence in the literature for interaction of SrO with other compounds in the atmosphere.

6.3.2.2 Water

Strontium exists almost exclusively in the environment as a +2 cation, and will form different species, some of which are more soluble than others. Because the different species have different solubilities, they will have different mobilities in the environment and different exposure potentials. Strontium exists as a hydrated cation, an ionic solution complex, or an ionic salt. In the environment, typical solution species for strontium are Sr^{2+} and $SrOH^+$, and some strontium compounds ($SrCO_3$ and $SrSO_4$) are practically insoluble in neutral water (Cotton and Wilkenson 1980; see Table 4-2).

6.3.2.3 Sediment and Soil

The principal abiotic processes that transform strontium in soils and sediments are mediated by sorption and desorption reactions between the soil solution and matrix (precipitation, complexation, and ion exchange), and controlled by pH, ionic strength, solution speciation, mineral composition, organic matter, biological organisms, and temperature (see Section 6.3.1). For many soil systems, in the short term, strontium sorption is dominated by simple ion exchange, and strontium ions are readily exchangeable. At longer timescales, however, strontium ions may relocated into sterically hindered sites that are not readily exchangeable (Bunker et al. 2000).

In the vicinity of the Chernobyl accident site, ^{90}Sr has leached from “hot” fuel particles (which have dissolved) and now may interact with natural soil components (Sokolik et al. 2001). In situations where soil is incorporated into a nuclear fireball (e.g., Semipalatinsk Nuclear Test Site, Kazakhstan), the resulting fused silicates that form are usually comparatively insoluble. Typically, ^{90}Sr in these particles

are tightly bound with the majority of ^{90}Sr undergoing radioactive decay before being released by weathering (Gastberger et al. 2000).

6.3.2.4 Other Media

No data were located in the literature on the transport or degradation of stable or radioactive strontium in other media.

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Strontium is widely distributed throughout the earth and has continuously cycled between the atmosphere, biosphere, hydrosphere, and lithosphere for many millions of years. Table 6-3 illustrates the average or range of concentrations of strontium in earth materials (Capo et al. 1998). Anthropogenic activities have increased local concentrations of strontium as a consequence of the development of an industrialized human society. Before the 1940s, radioactive strontium was not present in the environment at any measurable levels.

In the United States, commercial nuclear power plant operators are required to monitor and report any detectable quantities of radioactive materials released to the environment (USNRC 1996). Table 6-1 summarizes releases of radiostrontium isotopes with half-lives >8 hours to the atmosphere and water for 1993 from PWR and BWR nuclear power plants. Nearly all of the radioactive material reported as released in effluents are from planned releases from normal plant operation or anticipated operational occurrences. The latter includes unplanned releases of radioactive materials from miscellaneous actions such as equipment failure, operator error, or procedure error, and are not of such consequence as to be considered an accident (USNRC 1993a).

6.4.1 Air

According to two surveys, the strontium content in urban air ranges from 4 to 100 ng/m^3 and averages 20 ng/m^3 (Dzubay and Stevens 1975). The arithmetic mean concentration of strontium in urban air was measured as 29.1 ng/m^3 in the Los Angeles basin during 1985 (Witz et al. 1986). Urban air in Illinois between 1985 and 1988 averaged 0.9–4.8 ng/m^3 (Sweet et al. 1993). Areas where higher strontium

Table 6-3. Average or Ranges of Concentration of Strontium in Earth Materials

Material	Concentration of strontium
Geologic	(ppm)
Average crust	370
Exposed upper crust	337
Soil:	
Soil minerals	240
Soil (labile)	0.2–20
Individual rock types:	
Basalt	465
Carbonate	610
High-Ca granite	440
Low-Ca granite	100
Sandstone	20
Shale	300
Biologic	(ppm)
Wood	8–2,500
Roots (spruce)	19
Conifer needles	2–20
Hydrologic	(µg/L)
Seawater	7,620
Rivers	6–800
Rain	0.7–383
Snow	0.01–0.76

Source: Capo et al. 1998

concentrations are prevalent are near coal burning plants where strontium can be released with stack emissions (as discussed in Section 6.2.1).

Before the 1940s, radiostrontium was not present in the air at any significant concentrations. Concentrations of ^{90}Sr in the atmosphere peaked at about 10 MCi (0.37 GBq) in 1963 coincident with the period of extensive atmospheric nuclear weapons testing. Since the signing of the Nuclear Test Ban Treaty of 1963, the concentration of ^{90}Sr has steadily dropped through the latter 35 years by deposition and radioactive decay (DOE 1996c; Eisenbud 1987). Recent levels of ^{90}Sr in air were not located.

6.4.2 Water

Surveys of strontium in surface waters and municipal water supplies across the United States show that strontium is present in nearly all fresh waters in amounts <1 mg/L (USGS 1963). The National Drinking Water Contaminant Occurrence Database (NDOD), which contains data from public water supplies (PWS), where testing is performed at many points in the system, including the intake and at various points in the treatment and distribution systems, as well as at the point where the drinking water can be labeled "finished", lists the number of detections and concentrations of strontium. The average concentrations of strontium in PWS waters from the United States derived from surface water and groundwater were 1.10 (range, 0.2–3.68 mg/L) and 0.81 mg/L (range, 0.010–3.5 mg/L), respectively (EPA 2002b). The average concentrations of strontium in streams of the United States are between 0.5 and 1.5 mg/L. Strontium concentrations >1 mg/L are found in streams of the southwest, where the total dissolved solids content is the highest of any area of the continental United States. Streams of most of the Atlantic slope basins, southern United States, upper Great Lakes region, and Pacific northwest contain concentrations of strontium that are generally <0.5 mg/L strontium (USGS 1963). Some exceptions are areas where there are celestite-rich limestone deposits, such as regions of northwestern Ohio and eastern Florida (USGS 1963). The average concentration of strontium in sea water is approximately 8 mg/L (Demayo 1986). In groundwater, the average concentration of strontium is <0.5 mg/L. High concentrations of strontium, >1 mg/L, have been in observed in the southwestern United States. Unusually high concentrations of strontium, >20 mg/L, have been observed for some wells in central Wisconsin (USGS 1963). The NDOD lists the number of detections and concentrations of strontium in groundwater and surface water at several locations around the United States from ambient water samples (EPA 2002b). Dissolved strontium was detected in groundwater at 4,353 of 4,383 sites (99.3% of sites), with an average concentration of 1.6 mg/L (range, 0.0009–200 mg/L). The average dissolved strontium concentration in lake/reservoirs and springs were 1.09 mg/L (97.6% of sites; range, 0.002–170 mg/L) and

0.64 mg/L (100% of sites; range, 0.028–3.2 mg/L), respectively. In other surface waters, dissolved strontium was detected at 1,572 of 1,595 sites (98.6% of sites), with an average concentration of 362 µg/L (range, 0.0005–30 mg/L). The concentration of dissolved strontium in publicly owned treatment works (POTW) influents was between 0.025 and 0.45 mg/L (EPA 1981). The average concentrations of strontium in rain and snow were 0.7–383 and 0.01–0.76 µg/L, respectively (Capo et al. 1998).

^{90}Sr concentration in surface waters of the north Pacific Ocean has decreased steadily since the early 1960s to present day levels of approximately 23–81 pCi/m^3 (1–3 Bq ^{90}Sr/m^3) sea water. This value is estimated by dividing the concentration levels for ^{137}Cs by the global fallout activity ratio measured for ^{137}Cs/^{90}Sr of 1.5 (Hamilton et al. 1996). The EPA ERAMS program monitors ambient concentrations of ^{90}Sr in drinking water at 78 sites. ERAMS data serve to assess trends and anomalies in concentrations, and to compare with standards set forth in the EPA National Interim Primary Drinking Water Regulations. Table 6-4 summarizes drinking water composite samples for the period of January–December in 1995 taken at the 78 sites in major population centers or near selected nuclear facilities (EPA 2000a). The median concentration of ^{90}Sr in drinking water for this period was 0.1 pCi/L (4 mBq). Sites with above average levels of ^{90}Sr, Detroit and Niagara Falls, recorded levels of 0.4 and 0.5 pCi/L (~15 mBq/L), respectively. In a 1974 study, a concentration of 0.09 pCi/L ^{90}Sr (3 mBq/L) in drinking water was measured in Los Angeles, California (Kraybill 1983). In a survey that examined 169 wells used for public drinking water in California (Storm 1994), 16 wells measured recordable concentrations of ^{90}Sr, with an average concentration of 105 pCi/L (4 Bq/L). The NDOD lists the number of detections of ^{90}Sr in ambient groundwater at several locations around the United States. Dissolved ^{90}Sr was detected in groundwater at 18 out of 104 sites (17%), with an average concentration of 1.46 nCi/L (53.9 Bq) (EPA 2002b). The concentrations of ^{90}Sr in groundwater at the 91 waste sites located at 18 DOE facilities were between 0.05 and 231,000 pCi/L (2 mBq and 9 kBq) (DOE 1992). River water taken from the Ebro River basin (Northeast Spain) during 1994 had a mean ^{90}Sr level of 6.6 mBq (0.18 pCi) and ranged from 5.9 to 7.6 mBq/L (0.16 to 0.21 pCi/L) (Pujol and Sanchez-Cabeza 2000). ^{90}Sr in the Ebro River waters could be attributed solely to global fallout. The DOE Environmental Measurements Laboratory program measures the ^{90}Sr content of wet deposition in selected sites across the world to determine global trends in ^{90}Sr deposition. The data for the year 1990 are presented in Table 6-5 for cities in the United States. The average total annual wet deposition of ^{90}Sr in the United States was 5 pCi/m^2 (0.2 Bq/m^2) during this period. The precipitation samples with the highest total ^{90}Sr concentrations were obtained from New York City and Nome, Alaska with annual totals of 10 and 8 pCi/m^2 (0.4 and 0.3 Bq/m^2), respectively. In all cases, the ^{90}Sr concentrations in rain were low, which suggests that the atmospheric content of ^{90}Sr in 1990 was small and decreasing (DOE 1996c).

Table 6-4. ^{90}Sr in Drinking Water (Composites) for January–December 1995

			^{90}Sr	
State[a]	City	Total solids (mg/L)	pCi/L	±2σ
AK	Fairbanks	162.0	0.0	0.2
AL	Dothan	160.0	0.1	0.1
AL	Montgomery	55.2	0.1	0.2
AL	Muscle Shoals	82.0	0.2	0.2
AL	Scottsboro	87.0	0.2	0.2
AR	Little Rock	28.8	0.0	0.2
CA	Berkeley	8.0	0.1	0.2
CA	Los Angeles	318.0	0.0	0.1
CO	Denver	140.0	0.0	0.2
CO	Platteville	138.0	0.0	0.2
CT	Hartford	36.6	0.3	0.2
DE	Dover	191.0	ND	—
FL	Miami	150.0	0.2	0.2
FL	Tampa	252.0	0.3	0.2
GA	Baxley	165.0	0.0	0.2
GA	Savannah	147.0	ND	—
HI	Honolulu	208.0	0.1	0.1
IA	Cedar Rapids	121.0	0.1	0.2
ID	Boise	95.5	ND	—
ID	Idaho Falls	219.0	ND	—
IL	Morris	474.0	ND	—
IL	West Chicago	337.0	0.1	0.1
KS	Topeka	364.0	0.2	0.2
LA	New Orleans	226.0	0.2	0.2
MA	Lawrence	93.8	0.2	0.2
MD	Baltimore	89.8	0.1	0.2
MD	Conowingo	155.0	0.1	0.2
ME	Augusta	85.2	0.3	0.2

Table 6-4. ^{90}Sr in Drinking Water (Composites) for January–December 1995

			^{90}Sr	
State[a]	City	Total solids (mg/L)	pCi/L	±2σ
MI	Detroit	79.8	0.4	0.2
MI	Grand Rapids	125.0	0.3	0.2
MN	Minneapolis	93.8	0.3	0.2
MN	Red Wing	238.0	0.0	0.2
MO	Jefferson City	283.0	0.0	0.2
MS	Jackson	86.8	0.2	0.2
MS	Port Gibson	313.0	0.0	0.1
MT	Helena	61.8	0.1	0.2
NC	Charlotte	46.8	0.1	0.2
NC	Wilmington	110.0	0.2	0.2
ND	Bismarck	329.0	0.0	0.2
NE	Lincoln	305.0	0.1	0.2
NH	Concord	81.2	0.1	0.2
NJ	Trenton	92.7	0.1	0.2
NJ	Waretown	52.0	0.0	0.2
NM	Santa Fe	279.0	ND	—
NV	Las Vegas	248.0	0.1	0.2
NY	Albany	68.8	0.3	0.2
NY	New York City	44.5	0.0	0.2
NY	Niagara Falls	99.2	0.5	0.2
NY	Syracuse	94.8	0.3	0.2
OH	Cincinnati	198.0	0.2	0.2
OH	Columbus	362.0	0.0	0.3
OH	East Liverpool	215.0	0.3	0.2
OH	Painesville	126.0	0.2	0.3
OH	Toledo	148.0	0.3	0.3
OK	Oklahoma City	62.6	0.3	0.2
OR	Portland	19.2	0.1	0.2

Table 6-4. ^{90}Sr in Drinking Water (Composites) for January–December 1995

			^{90}Sr	
State[a]	City	Total solids (mg/L)	pCi/L	±2σ
PA	Columbia	121.0	0.1	0.2
PA	Harrisburg	51.2	0.1	0.2
PA	Philadelphia	165.0	0.0	0.2
PA	Philadelphia-Queen	207.0	0.1	0.2
PA	Philadelphia-Baxter	101.0	0.2	0.2
PA	Pittsburgh	178.0	0.2	0.2
PC	Corozal	71.6	0.1	0.2
RI	Providence	52.8	0.3	0.2
SC	Barnwell	73.6	0.0	0.2
SC	Columbia	28.2	0.0	0.2
SC	Jenkinsville	165.0	ND	—
SC	Seneca	35.2	0.1	0.2
TN	Chattanooga	82.2	0.2	0.2
TN	Knoxville	93.8	0.0	0.2
TX	Austin	180.0	0.0	0.2
VA	Doswell	193.0	0.0	0.2
VA	Lynchburg	45.2	0.1	0.2
VA	Virginia Beach	91.2	0.3	0.2
WA	Richland	77.2	0.1	0.2
WA	Seattle	29.8	0.0	0.2
WI	Genoa City	194.0	ND	—
WI	Madison	234.0	ND	—

[a]Post office state abbreviations used

ND = not detected;
2σ = counting error term reported at the 2σ (95%) confidence level

Source: EPA 1995

Table 6-5. Quarterly and Annual Deposition of ^{90}Sr in Selected U.S. Cites for the Year 1990

	Quarter								Annual total	
	First		Second		Third		Fourth			
Location	^{90}Sr Deposition[a]	Precipitation[b]	^{90}Sr Deposition[a]	Precipitation[b]	^{90}Sr Deposition[a]	Precipitation[b]	^{90}Sr Deposition[a]	Precipitation[b]	^{90}Sr Deposition[a]	Precipitation[b]
Anchorage, Alaska	0.0	8.5	0.0	6.5	—	15.9	—	29.7	0.0	60.5
Argonne, Illinois	0.1	18.6	0.1	33.4	0.1	26.9	0.0	29.5	0.2	108.4
Birmingham, Alabama	0.1	50.6	0.0	22.2	0.0	14.7	0.0	31.7	0.1	119.3
Chester, New Jersey	0.0	23.2	0.1	44.7	0.1	39.2	0.1	39.3	0.2	146.4
Cold Bay, Alaska	0.0	20.3	0.0	14.7	0.1	29.5	0.0	31.1	0.1	95.5
Fairbanks, Alaska	0.0	3.4	0.0	5.6	0.1	25.9	0.1	12.1	0.2	47.1
Houston, Texas	0.0	31.4	0.0	26.0	0.0	22.0	0.0	21.8	0.0	101.2
Lihue, Hawaii	0.0	36.7	0.0	14.5	0.0	12.2	0.1	36.6	0.1	100.0
Mauna Loa, Hawaii	0.0	54.5	0.0	0.3	0.1	7.5	0.0	44.9	0.1	107.2
Miami, Florida	0.0	9.4	0.0	54.8	0.0	48.0	0.1	19.1	0.2	131.1
New York, New York	—	28.7	0.1	42.5	0.1	46.0	0.1	37.5	0.4	154.7
Nome, Alaska	0.1	5.4	0.0	10.8	0.2	27.0	0.1	13.2	0.3	56.3
Vermillion, South Dakota	0.0	5.5	0.0	28.7	0.0	20.6	0.0	6.0	0.1	60.7
West Los Angeles, California	0.1	16.7	0.1	5.3	0.1	0.1	0.0	4.1	0.2	26.2
Wooster, Ohio	0.0	16.5	0.1	28.0	0.0	43.5	0.0	36.9	0.1	124.8
Average	0.03	22.0	0.03	22.5	0.06	25.3	0.04	26.2	0.2	96.0

[a]In Bq/m^3
[b]In cm

Source: DOE 1996d

6.4.3 Sediment and Soil

Table 6-3 summarizes the average or range of concentrations of strontium in soils and bedrock minerals. The average concentrations of strontium in the earth's crust and the exposed upper crust are 370 and 337 mg/kg, respectively. Soils, on average, have approximately 240 mg/kg Sr (Capo et al. 1998; EPA 1995a). Some materials, such as soil amendments, are routinely applied to agricultural lands. Typical concentrations of strontium in soil amendments are: POTW sewage sludges, 250±192 ppm (mg/kg dry weight); phosphate fertilizers, 610 mg/kg; limestone, 610 mg/kg; and manure, 80 mg/kg dry weight (EPA 1995a; Mumma et al. 1984).

The background level of ^{90}Sr in soils of the United States from global fallout will depend upon the historical transport and deposition inventory at that particular location. The mean regional background concentration of ^{90}Sr in soils in proximity to the Los Alamos National Laboratory from 1974 to 1994 was 320±250 pCi/kg dry weight soil (Fresquez et al. 1996b). This value has decreased with time due to radioactive decay of ^{90}Sr. The range of concentrations for ^{90}Sr in soils and sediments at 91 waste sites located at the 18 DOE facilities around the United States was 0.02–540,000 pCi/kg (DOE 1992). The total content of ^{90}Sr on surface soil in the 30 km contaminated zone around Chernobyl accident site in the Ukraine (not including the reactor site and waste storage) was about $8.1x10^{14}$ Bq ($2.2x10^{7}$ Ci) in 1997, which corresponds to about 0.4–0.5% of the Chernobyl reactor inventory at the time of the accident (Kashparov et al. 2001). Ten years after the accident, about 95% of the ^{90}Sr activity is associated with the upper 10–20 cm layer of soil for most of the soils in this area. Mean ^{90}Sr activity in soil at a Chernobyl-contaminated field site in the Ukraine was 36 Bq dry weight (0.97 nCi dry weight) (Malek et al. 2002). Levels of ^{90}Sr in soils from Belarus situated at a distance of ~40 km from the Chernobyl accident site ranged from 50 to 640 kBq/m^2 (1.4–17 μCi/m^2), while levels at a distance of 200–250 km ranged from 10–80 kBq/m^2 (270–2,200 nCi/m^2) (Sokolik et al. 2001).

The mean activity of ^{90}Sr in lacustrine and marine sediments from Antarctica in 1989–1996 ranged from 0.17 to 0.76 Bq/kg dry weight (4.59–20.5 pCi/kg dry weight) and from <0.10 to 0.21 Bq/kg dry weight (<2.7–5.78 pCi/kg dry weight), respectively (Jia et al. 1999). The ^{90}Sr activities in marine sediments ranged from 117 to 1,277 mBq/kg (3.16 and 34.5 pCi/kg) and from 304 to 1,799 mBq/kg (8.21–48.6 pCi/kg) at two sites off atomic power stations in South Korea (Yang et al. 2002). $^{90}Sr^{2+}$ ions in sediments are characterized by reversible ion exchange processes that lead to low ^{90}Sr activity in sediments (Jia et al. 1999).

6.4.4 Other Environmental Media

The range of concentrations of strontium in fruits and vegetables is summarized in Table 6-6 (Barnes 1997). The highest concentrations are observed in leafy vegetables, such as cabbage (64.2 mg Sr/kg dry weight) (USGS 1980).

The range of concentrations of ^{90}Sr in food stuffs is summarized in Table 6-7. The highest concentrations were observed in fresh vegetables (8.8 pCi/kg dry weight=0.33 Bq/kg dry weight) and dry beans (15.9 pCi/kg dry weight=0.59 Bq/kg dry weight) (Eisenbud 1987). The U.S. Food and Drug Administration Radionuclides in Foods program monitors radionuclides (e.g., ^{90}Sr) in the food supply as part of the Total Diet Study (TDS). For the years 1994 and 1995, about 60 foods with historically high ^{90}Sr levels were analyzed (Capar and Cunningham 2000). ^{90}Sr was detected in about 65% of these foods. The greatest concentration was in mixed nuts at 2 Bq/kg (50 pCi). Approximately 200 reactor-survey food test portions, including raw vegetables, food crops (primarily fruits), fish, and milk, were collected in the vicinities of 33 nuclear reactors (Cunningham et al. 1994). Ninety-four percent of the reactor-survey food test portions had ^{90}Sr activities between 0 and 0.74 Bq/kg (0 and 20 pCi), and 6% had activity concentration between 0.74 and 7.4 Bq/kg (20 and 200 pCi/kg). The EPA ERAMS program monitors ambient concentrations of ^{90}Sr in pasteurized milk at 42 sites in major population centers, and is used to assess trends and anomalies in concentrations. Table 6-8 summaries pasteurized milk samples for the period of July 1997 (EPA 2002b). The average concentration of ^{90}Sr in pasteurized milk during this period for the 42 sites was 0.9 pCi/L (33 mBq/L). Sites with above average levels of ^{90}Sr in pasteurized milk were observed at (listed in order of decreasing activity of ^{90}Sr): Minot, North Dakota; Grand Rapids, Michigan; Spokane, Washington; Cleveland, Ohio; Cincinnati, Ohio; Memphis, Tennessee; St. Paul, Minnesota; Chicago, Illinois; Detroit, Michigan; San Francisco, California; Baltimore, Maryland; and Wilmington, Delaware. Dietary intake of ^{90}Sr peaked in 1965 at 1.1 Bq/day (30 pCi/day), during a period of atmospheric testing of nuclear weapons, and has continued to decline to <0.05 Bq/day (<1.2 pCi/day) after 1987 (Cunningham et al. 1989). Dietary intake of ^{90}Sr in the United States from 1961 to 1991 is illustrated in Figure 6-3.

Sato et al. (1977) determined the concentration of strontium in tobacco leaves as 141 μg/g. The average concentration of strontium in the ash of 12 brands of cigarettes was measured as 373 μg/g (Iskander 1986). No significant difference was observed in the concentration of strontium in the cigarette filter before and after smoking (Sato et al. 1977). The ranges of concentrations of strontium in waste materials are: municipal solid waste (MSW) 11–35 μg/g; incineration fly ash 110–220 μg/g (Lisk 1988); coal fly

Table 6-6. Concentration of Strontium in Fruit Juices and Produce

Fruit juice and produce	Average liquid concentration (µg/L)[a]	Average solid concentration (ppm)[b]
Apple		13.58
Apple juice	0.1271	
Banana	0.1297	
Bean:		
Dry		6.63
Snap		21.7
Blackberry	0.2619	
Boysenberry	0.9523	
Cabbage		64.17
Corn:		
Sweet		0.416
Cucumber		24
Currant:		
Red	1.251	
Grape:		
American		25.6
Concord	0.3661	
European		38.4
Red	0.1086	
White	0.6318	
Kiwi	1.744	
Lemon products:		
Lemon	0.0986	
Bottled	0.5334	
Lemonade	0.1653	
Lettuce		22.26
Lime	0.3464	
Mango	0.5121	
Orange		25.56
Orange juice		
Brazilian	0.0417	
California	0.5368	
Florida	0.0933	
Navel	0.5209	
Pineapple	0.1612	
Papaya	1.690	
Peach		3.082
Pear	0.5912	
Pineapple	0.0604	

Table 6-6. Concentration of Strontium in Fruit Juices and Produce

Fruit juice and produce	Average liquid concentration (µg/L)[a]	Average solid concentration (ppm)[b]
Potato		2.562
Raspberry	2.232	
Strawberry	0.3001	
Tangerine	0.0828	
Tomato		9.96
Tomato sauce	0.8894	

[a]Barnes 1997
[b]USGS 1980; values are parts per million, dry weight

Table 6-7. ^{90}Sr in the Human Diets During 1982

				New York City			San Francisco		
Diet category	Intake kg/year	g Ca/year	Percent yearly intake Ca	pCi ^{90}Sr/kg	pCi ^{90}Sr/year	Percent yearly intake ^{90}Sr	pCi ^{90}Sr/kg	pCi ^{90}Sr/year	Percent yearly intake ^{90}Sr
Dairy products	200	216.0	58	3.2	641	32	1.0	200	21
Fresh vegetables	48	18.7		8.8	422		2.4	116	
Canned vegetables	22	4.4		5.4	119		2.9	64	
Root vegetables	10	3.8		3.4	34		3.8	38	
Potatoes	38	3.8		2.3	88		2.1	79	
Dry beans	3	2.1		15.9	48		7.9	54	
Total (vegetables)			9			36			36
Fresh fruit	59	9.4		2.6	152		1.3	77	
Canned fruit	11	0.6		1.1	12		0.8	9	
Fruit juice	28	2.5		1.7	48		1.4	40	
Total (fruits)			3			11			13
Bakery products	44	53.7		3.0	131		1.9	84	
Flour	34	6.5		4.5	153		3.5	119	
Whole grain products	11	10.3		6.2	69		2.9	32	
Macaroni	3	0.6		2.4	7		2.3	7	
Rice	3	1.1		0.6	2		0.8	2	
Total (grains)			20			18			25
Meat	79	12.6		0.4	35		0.4	31	
Poultry	20	6.0		0.3	6		0.3	5	
Eggs	15	8.7		0.6	10		0.6	8	
Fresh fish	8	7.6		0.2	1		0.1	1	
Shell fish	1	1.6		0.2	<1		0.7	1	
Total (meat, eggs, and fish)	-	-	10	-	-	3	-	-	5
Yearly intake									
Ca (total)		370 g							
^{90}Sr (total)					1978 pCi			967 pCi	
Ratio of ^{90}Sr/Ca					5.3 pCi ^{90}Sr/g Ca			2.6 pCi ^{90}Sr/g Ca	
Daily intake					54 pCi/day			2.6 pCi/day	

1 pCi=37 mBq (conversion factor)
Source: DOE 1984

Table 6-8. ^{90}Sr in Pasteurized Milk in July 1997

State[a]	City	^{90}Sr (pCi/L)
AL	Montgomery	0.98
CA	Los Angeles	0.66
CA	Sacramento	0.26
CA	San Francisco	1.24
CO	Denver	0.41
CT	Hartford	1.31
DE	Wilmington	1.00
FL	Tampa	0.59
GA	Atlanta	0.56
HI	Honolulu	0.38
IA	Des Moines	0.40
IL	Chicago	1.38
IN	Indianapolis	0.96
KY	Louisville	0.20
MA	Boston	0.77
MD	Baltimore	1.06
MI	Detroit	1.34
MN	Grand Rapids	1.78
MN	St. Paul	1.44
MO	Kansas City	1.14
MS	Jackson	—
NC	Charlotte	1.25
ND	Minot	2.12
NJ	Trenton	0.75
NM	Albuquerque	0.53
NV	Las Vegas	0.20
NY	Buffalo	0.75
NY	Syracuse	0.94
OH	Cincinnati	1.60

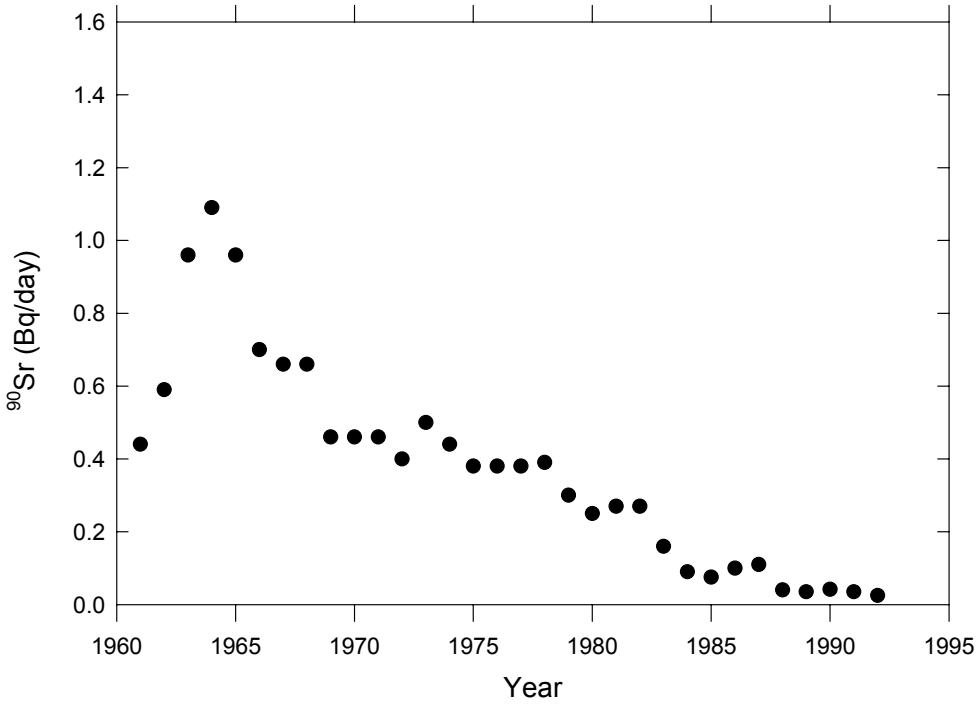
Table 6-8. ^{90}Sr in Pasteurized Milk in July 1997

State[a]	City	^{90}Sr (pCi/L)
OH	Cleveland	1.60
OR	Portland	0.79
PA	Philadelphia	0.84
PA	Pittsburgh	0.23
PC	Cristobal	0.27
PR	San Juan	0.51
SC	Charleston	0.73
TN	Memphis	1.54
TX	Austin	0.29
TX	Ft. Worth	0.50
VA	Norfolk	0.89
VT	Burlington	1.10
WA	Seattle	0.49
WA	Spokane	1.71

[a]Post office state abbreviations used

Source: EPA 2000b

Figure 6-3. U.S. Daily Dietary Intake of ^{90}Sr, 1961–1992



Source: Cunningham et al. 1994

ash 30–7,600 µg/g; coal bottom ash 170–6,400 µg/g; flue-gas desulfurization by-products 70–3,000 µg/g; oil ash 50–920 µg/g; (Eary et al. 1990); and compost 260–420 µg/g (Evans and Tan 1998).

Levels of ^{90}Sr were measured in tissue samples of animals killed by motorists near the low-level radioactive disposal site at Los Alamos National Laboratory and from background locations. The mean concentration of ^{90}Sr in tissues from deer and elk killed near the low-level radioactive disposal site were 460 and 230 mBq/kg (12 and 7.0 pCi), respectively, while concentrations at background locations were 130 and 6.3 mBq/kg (3.5 and 1.7 pCi), respectively (Ferenbaugh et al. 2002). Between 1994 and 1996, levels of skeletal ^{90}Sr in small mammals in the Exclusion Zone at Chernobyl, Ukraine averaged 297 Bq/g (8.0 nCi/g) (Chesser et al. 2000).

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

The primary routes of human exposure to strontium are from inhalation of aerosols and ingestion of food and drinking water containing strontium. The intake of strontium, therefore, depends upon the concentration of strontium in air, drinking water, and in the food items that comprise a person's diet, which may be highly variable. The average concentration of strontium in urban air is about 20 ng strontium/m^3 (see Section 6.4.1). Assuming that an adult breathes approximately 20 m^3 of air per day, the inhalation exposure would be 400 ng strontium/day. This value may be somewhat higher for persons living near sources of strontium emission. Workers employed at industrial facilities that produce, process, and use strontium and strontium compounds will have higher exposures. Similarly, strontium is taken into the body by ingestion of drinking water. Using the concentration of strontium in U.S. drinking water to be 1 mg/L (see Section 6.4.2), and the consumption rate as 2 L/day, the strontium intake from drinking water would be 2 mg/day. In a 1994 total diet study in the United Kingdom, the total dietary exposure to stable strontium was estimated at 1.3 mg/day (Ysart et al. 1999). As part of an Australian Market Basket Survey in 1994, the estimated daily intakes of strontium for female adults ranged from 0.89 to 1.2 mg/day (Gulson et al. 2001). Combining air, water, and diet exposures estimates, the total daily exposure to strontium is ~3.3 mg/day.

External exposure to ^{90}Sr is not a concern because of minor emission of penetrating radiation from ^{90}Sr. No estimate of the concentration of ^{90}Sr in air is available (see Section 6.4.1). However, it is assumed that ambient concentrations of ^{90}Sr in the atmosphere are small relative to exposures from water and diet. If the concentration of ^{90}Sr in average U.S. drinking water is estimated as 0.1 pCi/L (4 mBq/L) or one radiochemical event per 5–10 minutes (see Section 6.4.2), and the consumption rate of drinking water by

a normal adult is assumed to be 2 L/day, then the exposure from drinking water would be 0.2 pCi (7 mBq) per day. Since the inception of the TDS Radionuclides in Foods program in 1961, intake levels of ^{90}Sr in food have steadily declined from a peak level in 1965 of 1.1 Bq/day (30 pCi/day), to below 0.2 Bq/day (5 pCi/day) (Cunningham et al. 1989). A DOE Environmental Measurements Laboratory study estimated the average dietary intake of ^{90}Sr from 19 diet categories for individuals living in the urban areas of New York City and San Francisco. Table 6-6 summarizes the data from this study (DOE 1984). For both locations, vegetables accounted for more than a third of the yearly dietary intake of ^{90}Sr at 36%. In the vegetable group, fresh vegetables were the largest contributors of ^{90}Sr dietary intakes. The next largest contributor of ^{90}Sr was grains and dairy products. Using a conservative estimate of total dietary exposure for ^{90}Sr of 5 pCi/day (0.19 Bq/day) and drinking water exposure of 0.2 pCi/day (7 mBq/day), the total estimated daily exposure to strontium is approximately 5.2 pCi/day (0.19 Bq/day). Current population exposure levels to ^{90}Sr will be lower than this value as a result of decreasing concentrations of ^{90}Sr in the environment. However, this value may be somewhat higher for persons living near sources of ^{90}Sr, such as DOE facilities, and for workers employed at government facilities that produce, process, and use ^{90}Sr and ^{90}Sr waste compounds.

Table 6-9 summarizes measurements of concentrations of strontium in human tissues and body fluids resulting from consumption of food and water and from natural background sources (Tsalev 1984); these are nonoccupationally exposed populations. The highest concentrations of strontium are in the bones and teeth (Iyengar et al. 1978; Tsalev 1984).

The distributions of ^{90}Sr in the body are significantly different for males and females. As expected, the highest concentrations of ^{90}Sr are measured in the boney tissue. Males and females averaged 10.4 and 65 pCi/kg (0.38 and 2.4 Bq/kg) wet weight, respectively. Males had a much higher concentration of ^{90}Sr in the muscular tissue compared to females. The heart and psoas muscles had respective concentrations of ^{90}Sr for men averaging 13.9 and 18.7 pCi/kg (0.51 and 0.69 Bq) wet weight versus respective concentrations of 7.4 and 1.9 pCi/kg (0.27 Bq/kg and 70 mBq/kg) wet weight for females (Baratta and Ferri 1966). Approximately 1,000 human teeth, collected in southern Ukraine in 1990–1991, had ^{90}Sr activities ranging from 1.0 to 16.3 mBq/g ash (0.027–0.44 pCi/q ash) (Kulev et al. 1994).

Strontium can be released into the atmosphere as a result of glass manufacturing. In one study, the median ambient air concentration of strontium that both art glass makers and formers were chronically exposed was 0.1 μg strontium/m^3 (Apostoli et al. 1998). A National Occupational Exposure Survey conducted by NIOSH during 1981–1983 estimated the number of workers potentially exposed to

Table 6-9. Strontium Concentrations in Human Body Fluids and Tissues

Sample	Units[a]	Mean	Range
Blood	µg/L	27	No data
Bone	µg/g	138	63–281
Brain	µg/g	0.08	No data
Dental plaque	µg/g	48	<0.5–1,880
Erythrocytes	µg/L	7.2	No data
Feces	µg/day	1.5	No data
Hair	µg/g	4.2	0.75–10.8
Kidney	µg/g	0.1	No data
Liver	µg/g	0.15	No data
Lung	µg/g	0.38	No data
Milk	µg/L	20	17–295
Muscle	µg/g	0.05	No data
Nails (finger)	µg/g(dry weight)	No data	0.43–0.86
Plasma or serum	µg/L	40	10–70
Saliva	µg/L	11	8–63
Sweat	mg/7 hour	0.96	No data
Tooth (dentin)	µg/g	115	14–286
Tooth (enamel)	µg/g	128	14–286
Urine	µg/L	No data	<0.01–0.03

[a]Values are per wet weight unless otherwise noted.

Source: Tsalev 1984

strontium compounds in the workplace: strontium chloride (8,289), strontium fluoride (5,607), strontium hydroxide (385), and strontium nitrate (1,895) (NOES 1983).

Workers engaged in nuclear fuel cycle operations, such as the handling of radioactive strontium wastes, decontamination and decommissioning workers, contaminated soils, and waters may be potentially exposed to radioactive strontium. A case of accidental inhalation and dermal exposure to strontium titanate contaminated with ^{90}Sr used for lightning rods was recorded, which resulted in an exposure of approximately 10^5 Bq (2.7 mCi) to the workers (Navarro and Lopez 1998).

6.6 EXPOSURES OF CHILDREN

This section focuses on exposures from conception to maturity at 18 years in humans. Differences from adults in susceptibility to hazardous substances are discussed in 3.7 Children's Susceptibility.

Children are not small adults. A child's exposure may differ from an adult's exposure in many ways. Children drink more fluids, eat more food, breathe more air per kilogram of body weight, and have a larger skin surface in proportion to their body volume. A child's diet often differs from that of adults. The developing human's source of nutrition changes with age: from placental nourishment to breast milk or formula to the diet of older children who eat more of certain types of foods than adults. A child's behavior and lifestyle also influence exposure. Children crawl on the floor, put things in their mouths, sometimes eat inappropriate things (such as dirt or paint chips), and spend more time outdoors. Children also are closer to the ground, and they do not use the judgment of adults to avoid hazards (USNRC 1993a).

As part of an Australian Market Basket Survey in 1994, the estimated daily intakes of strontium for 6-month-old infants fed exclusively breast milk or infant formula were 47 and 254 µg/day, respectively (Gulson et al. 2001). The mean concentration of strontium in amniotic fluid and placenta ranged from 0.03 to 0.05 mg/L and from 1.6 to 3.2 µg/L, respectively, for mothers from Portugal (Carvalho et al. 2001). Harrison (1965) notes that strontium in human breast milk is transferred to newborns during breast feeding.

Specific information on the exposure of children to radiostrontium is limited. As for adults in the general population, small exposures to children occur from normal ingestion of food and drinking water and inhaling air. These exposures may be higher in areas near nuclear fuel processing sites and hazardous

waste sites containing radiostrontium. Future accidental exposures could potentially occur from nuclear weapons detonation and consequent contamination of air, water, and food.

Children typically ingest a higher percentage of diary products compared to adults. Levels of ^{90}Sr in body tissues tend to increase with age (Glowiak and Pacyna 1978). In a study in the Soviet Union between 1959 and 1971, children were reported to have elevated levels of ^{90}Sr in bone tissue between the ages of 1 and 4 years (Marei et al. 1976). The elevated levels of ^{90}Sr for children of this age were determined to be a direct result of diet, primarily from ^{90}Sr contaminated cow's milk. In a 1978 study in Poland, females between 0 and 20 years of age had the highest level of ^{90}Sr accumulation in the gonad tissues for all age levels (Glowiak and Pacyna 1978). No explanation as to a cause for this accumulation was provided. For 1979–1994 births, the average concentration of ^{90}Sr in deciduous teeth from children of Western Suffolk County (New York), Eastern Suffolk County (New York), Dade County (Miami, Florida), and Ocean County (New Jersey) were 1.56, 1.02, 2.80, and 1.54 pCi/g calcium, respectively (Gould et al. 2000). No additional information is available on whether children differ from adults in their weight-adjusted intake of strontium. There is no information on ^{90}Sr levels in amniotic fluid, meconium, cord blood, neonatal blood, or breast milk.

At hazardous waste sites, radiostrontium that is found in excess of natural background levels is most likely to be in soil and presents a special hazard for young children. Hand-to-mouth activity resulting in inadvertent soil consumption or intentional consumption of soil (pica behavior) will result in oral exposure to radiostrontium. Young children often play close to the ground and frequently play in dirt, which increases their dermal exposure to radiostrontium in dust and soil. The degree of hazard in each case depends on the form of strontium present at the waste site.

Compared to adults, the potential for radiostrontium exposure is greater for children who consume foods (e.g., milk, grains) produced in areas with elevated concentrations of radiostrontium in the soil and for children with elevated concentrations of radiostrontium in their drinking water. Children are more likely to be exposed to ^{90}Sr in cow's milk produced in contaminated areas. Table 6-8 summaries pasteurized milk samples in the United States for July 1997 (EPA 2002b). The average concentration of ^{90}Sr in pasteurized milk during this period was 0.9 pCi/L (33 mBq/L).

Other home exposures are unlikely since no household products or products used in crafts, hobbies, or cottage industries contain significant amounts of radiostrontium. Radiostrontium exposure to children from parents' work clothes, skin, hair, tools, or other objects from the workplace is possible if the parent

is exposed to radiostrontium at work. However, no specific cases of home contamination with radiostrontium were located in the literature.

6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Cigarettes and tobacco leaves are known to contain strontium, and individuals who smoke may be exposed to higher levels of strontium. Strontium has been found in the tobacco leaves and ash of cigarettes at average levels of 141 and 373 mg/kg, respectively (Iskander 1986).

The potential for ^{90}Sr exposure is greater for individuals who consume foods grown in areas with elevated concentrations of ^{90}Sr in soil, and for individuals with elevated concentrations of ^{90}Sr in drinking water. Industries where higher exposures to ^{90}Sr are known to occur include nuclear weapons test sites, nuclear weapons production, and nuclear reactors facilities. Populations with potentially high exposure include DOE employees involved in heavy construction, decontamination activities, chemical processing, and fabrication.

Populations with a relatively short food chains (e.g., Arctic peoples) and a higher per capita consumption of country foods that have elevated levels of contamination from radionuclides, will have a higher exposure to ^{90}Sr (Barrie et al. 1992). Caribou or reindeer feeding on arctic vegetation are more likely to accumulate higher body burdens of ^{90}Sr in edible tissues than other herbivorous animals with less restrictive diets (Witkamp 1966). Concentrations of ^{90}Sr in caribou meat per gram of calcium were high (150 pCi/g Ca) compared with those of Alaskan-grown cabbage (6 pCi/g Ca) and potatoes (8 pCi/g Ca), marine fish (5 pCi/g Ca), and whale meat (1 pCi/g Ca). Arctic peoples, who depend on caribou and reindeer for sustenance, may have an elevated body burden of ^{90}Sr compared to other people who consume a more varied diet (Witkamp 1966). However, the 1966 peak levels reported in this study are expected to have fallen to minuscule levels since the Test Ban Treaty of 1962.

6.8 ADEQUACY OF THE DATABASE

Section 104(i)(5) of CERCLA, as amended, directs the Administrator of ATSDR (in consultation with the Administrator of EPA and agencies and programs of the Public Health Service) to assess whether adequate information on the health effects of strontium is available. Where adequate information is not available, ATSDR, in conjunction with the National Toxicology Program (NTP), is required to assure the

initiation of a program of research designed to determine the health effects (and techniques for developing methods to determine such health effects) of strontium.

The following categories of possible data needs have been identified by a joint team of scientists from ATSDR, NTP, and EPA. They are defined as substance-specific informational needs that if met would reduce the uncertainties of human health assessment. This definition should not be interpreted to mean that all data needs discussed in this section must be filled. In the future, the identified data needs will be evaluated and prioritized, and a substance-specific research agenda will be proposed.

6.8.1 Identification of Data Needs

Physical and Chemical Properties. Relevant data on the physical and chemical properties of strontium and strontium compounds are available in the literature and are sufficient to permit estimation of its environmental fate (ChemFinder 2002; Cotton and Wilkenson 1980; Hibbins 1997; HSDB 2002; Lide 1995, 2000; Merck 1989; Sigma-Aldrich 2000). The physical and chemical properties of radiostrontium and radiostronium compounds are expected to be equivalent to those for stable strontium. Data on the radioactive properties of isotopes of strontium are available (Lide 1995).

Production, Import/Export, Use, Release, and Disposal. Data regarding the past and present production and import/export volumes for strontium are available (Adams 1975; USGS 1998, 1999, 2002). The uses of strontium and strontium compounds are well known with more than 85% of all strontium consumed in the United States used in the manufacture of ceramics and glass products (Hibbins 1997; USGS 1999, 2002). Strontium is found in food products such as fruits and vegetables (Barnes 1997; USGS 1980). Since strontium is not covered under Superfund Amendments and Reauthorization Act (SARA), Title III, manufacturers and users are not required to report releases to the EPA's Toxics Release Inventory (TRI). Most nonradioactive strontium minerals, strontium compounds, and strontium-containing materials do not require special disposal and handling requirements.

Data regarding the past and present production and import/export volumes for radiostrontium are limited (DOE 1996b, 1996c). The uses of radiostrontium and radiostrontium compounds are restricted primarily to medicinal, analytical, and power generation applications (Alimov 2003; Murray 1994). Radioactive strontium (e.g., ^{90}Sr) was released into the atmosphere from aboveground testing of nuclear weapons during the period of 1945–1980. Nuclear weapon testing injects radioactive material into the stratosphere, which results in wide dispersal of radionuclides. However, atmospheric deposition of ^{90}Sr

has steadily decreased from a high in 1963 of approximately $1.10x10^8$ GBq (3.0 MCi) to <3,000 Ci in 1990, which suggests that global concentrations of ^{90}Sr in the atmosphere have declined (DOE 1996c). The disposal of radiostrontium and radiostrontium contaminated wastes is governed by the U.S. Nuclear Regulatory Commission (USNRC) regulations, and releases of radiostrontium and radiostrontium contaminated wastes are governed by USNRC and EPA regulations.

Environmental Fate. Information about the partitioning and mobility of strontium and strontium compounds in the environment is available (Bunde et al. 1997; Bunzl and Schimmack 1989; Hayes and Traina 1998; Helal et al. 1998a, 1998b; O'Day et al. 2000; Parkman et al. 1998; Sahai et al. 2000). Strontium released into the atmosphere from natural and anthropogenetic activities is transported and redeposited on the earth by dry or wet deposition (NCRP 1984). Because strontium is an element, its atoms do not degrade by environmental processes such as hydrolysis or biodegradation.

Information about the partitioning and mobility of ^{90}Sr in environment is available (Bunde et al. 1997, 1998; DOE 1996d; Kashparov et al. 2001; Mahara 1993; Sokolik et al. 2001; Toran 1994). Radiostrontium released into the atmosphere from anthropogenetic activities is transported and redeposited on the earth by dry or wet deposition (NCRP 1984). Radiostrontium does not degrade by environmental processes such as hydrolysis or biodegradation. However, radioactive strontium will be subject to radioactive decay and transformation to other elements. Eventually, all of the radioactive strontium will be transformed into stable zirconium by the process of radioactive decay. Additional information on the environmental fate of ^{90}Sr in different forms of mixed waste may be beneficial. Studies investigating mixed waste matrixes may be useful information for accessing the current and potential risk of the storage of liquid HLW in buried underground tanks. Mixed waste forms that pose the highest potential risk include mixtures such as metals-radiostrontium, metals-radiostrontium-organic acids, metals-radiostrontium-complexing agents, and metals-radiostrontium-ketones (DOE 1992).

Bioavailability from Environmental Media. The absorption and distribution of strontium and radiostrontium as a result of inhalation, dermal, or oral exposures have been discussed in Sections 3.5.1 and 3.5.2. Limited information on the bioavailability of strontium and radiostrontium from environmental media (e.g., plants and animals) is available. Additional studies on the bioavailability of strontium and radiostrontium from environmental media would be useful.

Food Chain Bioaccumulation. The uptake or bioaccumulation of strontium and radiostrontium by plants and organisms is the mechanism by which strontium and radiostrontium in air, water, and soil enter

into the food chain of humans. Information on tissue levels of strontium and radiostrontium indicating storage in the organism as a result of exposure to contaminated media would be useful. Information on whether strontium and radiostrontium are biomagnified (increased levels in predators resulting from the consumption of contaminated prey organisms) would also be helpful.

Exposure Levels in Environmental Media. Strontium has been detected in air (Dzubay and Stevens 1975; Sweet et al. 1993; Witz et al. 1986), water (Capo et al. 1998; EPA 1981, 2002b; USGS 1963), soil (Capo et al. 1998; EPA 1995a), plants (Sato et al. 1977), and foodstuff (Barnes 1997; USGS 1980). Reliable monitoring data for the levels of strontium in contaminated media at hazardous waste sites are needed so that the information obtained on levels of strontium in the environment can be used in combination with the known body burden of strontium to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites. In a 1994 total diet study in the United Kingdom, the total dietary exposure to stable strontium was estimated at 1.3 mg/day (Ysart et al. 1999). As part of an Australian Market Basket Survey in 1994, the estimated daily intakes of strontium for female adults ranged from 0.89 to 1.2 mg/day (Gulson et al. 2001). Combining air, water, and diet exposures estimates, the total daily exposure to strontium is ~3.3 mg/day.

Radiostrontium has been detected in air (DOE 1996c; Eisenbud 1987), water (DOE 1992, 1996c; EPA 2000a, 2002b; Hamilton et al. 1996; Kraybill 1983; Pujol and Sanchez-Cabeza 2000), soil (DOE 1992; Fresquez et al. 1996b; Kashparov et al. 2001; Malek et al. 2002; Sokolik et al. 2001), and foodstuffs (Capar and Cunningham 2000; Cunningham et al. 1989, 1994; Eisenbud 1987; EPA 2002b). Information on levels of radiostrontium is needed. Exposure levels of ^{90}Sr in environmental media have decreased as a result of radioactive decay from a high in the 1960s. However, updated information on the concentration levels in air, water, soil, and food (e.g., milk products) may be useful. Specific monitoring of radiostrontium in airborne particulates may also be beneficial. Reliable monitoring data for the levels of radiostrontium in contaminated media at hazardous waste sites may be useful so that the information obtained on levels of radiostrontium in the environment can be used in combination with the known body burden of radiostrontium to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites. Using a conservative estimate of total dietary exposure for ^{90}Sr of 5 pCi/day (0.19 Bq/day) (Cunningham et al. 1989) and drinking water exposure of 0.2 pCi/day (7 mBq/day) (EPA 2000a), the total estimated daily exposure to strontium is approximately 5.2 pCi/day (0.19 Bq/day).

Exposure Levels in Humans. Strontium has been detected in human tissues, as illustrated in Table 6-9 (Tsalev 1984). The highest concentrations of strontium are in the bones and teeth (Iyengar et al. 1978; Tsalev 1984). However, these data are not current (within 3 years). Additional human tissue monitoring data for strontium is needed for populations surrounding hazardous waste sites. This information is necessary for assessing the need to conduct health studies on these populations.

^{90}Sr has been detected in human tissues with the highest concentrations measured in boney tissues (Baratta and Ferri 1966; Kulev et al. 1994). However, these data are not current (within 3 years). Exposure levels of humans to ^{90}Sr have decreased as a result of radioactive decay from a high in the 1960s. Additional human tissue monitoring data for radiostrontium is needed for populations surrounding hazardous waste sites. This information is necessary for assessing the need to conduct health studies on these populations.

Exposures of Children. Children are exposed to strontium in the same manner as adults, primarily by food and water intake. No information was available on unique exposure pathways for children (e.g., pica children, dermal). However, children typically ingest a higher percentage of diary products compared to adults. Data exist on the levels of strontium in human breast milk (Gulson et al. 2001). Additional body burden studies on children are needed for strontium. Additional studies are needed to determine whether children are different in their weight-adjusted intake of strontium. Better and more recent information on exposure levels of strontium to children may be beneficial.

Children are exposed to radiostrontium in the same manner as adults, primarily by food and water intake. No information was available on unique exposure pathways for children (e.g., pica children, dermal). However, children typically ingest a higher percentage of diary products compared to adults. Exposure levels of children to ^{90}Sr have decreased as a result of radioactive decay from a high in the 1960s. Data exist on the levels of ^{90}Sr in deciduous teeth (Gould et al. 2000). Additional body burden studies on children are needed for radiostrontium. Additional studies are needed to determine whether children are different in their weight-adjusted intake of radiostrontium. Better and more recent information on exposure levels of radiostrontium to children may be beneficial.

Child health data needs relating to susceptibility are discussed in Section 3.13.2 Identification of Data Needs: Children's Susceptibility.

Exposure Registries. No exposure registries for strontium or radiostrontium were located. These substances are not currently compounds for which a subregistry has been established in the National Exposure Registry. These substances will be considered in the future when chemical selection is made for subregistries to be established. The information that is amassed in the National Exposure Registry facilitates the epidemiological research needed to assess adverse health outcomes that may be related to exposure to this substance.

6.8.2 Ongoing Studies

The Federal Research in Progress (FEDRIP 2002) database provides additional information obtainable from a few ongoing studies that may fill in some of the data needs identified in Section 6.8.1. These studies are summarized in Table 6-10.

Table 6-10. Ongoing Studies on the Environmental Effects of Strontium[a]

Investigator	Affiliation	Study	Sponsor
Ron, Elaine	NIH	Studies of populations exposed to occupational sources of radiation	NIH
Helt, JE	ANL	Waste volume reduction using surface characterization and decontamination by laser ablation	DOE-OEM
Todd, Terry A	INEEL	Laboratory radioactive waste solvent extraction and ion exchange	DOE-OEM
Smith, Robert W	INEEL	Calcite precipitation and trace metal partitioning in groundwater and the vadose zone: Remediation of ^{90}Sr and other divalent metals and radionuclides in arid western environments	DOE-OEM
Louie, Gary D	PNNL	Chemical separations for nuclear waste disposal	DOE-OEM
Louie, Gary D	PNNL	Chemical speciation of strontium, americium, and curium in waste	DOE-OEM

ANL = Argonne National Laboratory; DOE-OEM = Department of Energy-Office of Environmental Management; INEEL = Idaho National Engineering and Environmental Laboratory; NIH = National Institute of Health; PNNL = Pacific Northwest National Laboratory

[a]Source: FEDRIP 2002