6.4.1 Air

For airborne particles collected for the RadNet program, ^{234}U, ^{235}U, and ^{238}U analyses are performed on semiannually composited air filters collected from continuously operating airborne particulate samplers. Following chemical separation, the uranium is quantified by α-spectroscopy.

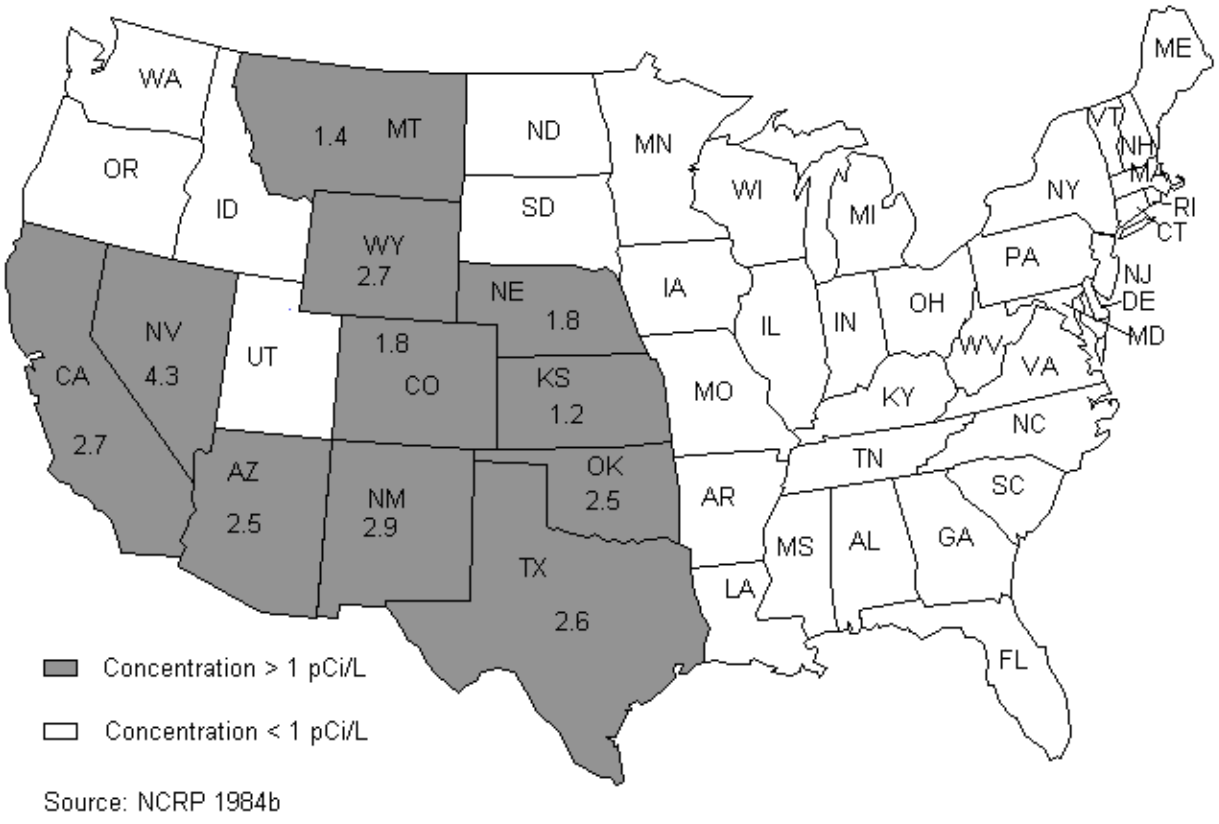
Table 6-2 shows the results of monitoring for uranium in airborne particles for the October to December 2007 composites as published in Report 132 (EPA 2007). Results from October through December 1997 are included as well (EPA 1997b). The locations of air samples with the highest total uranium concentrations were Las Vegas, Nevada; El Paso, Texas; Ross, Ohio; Lynchburg, Virginia; and Phoenix, Arizona (listed in descending concentrations of airborne total uranium). In all cases, atmospheric levels of total uranium were low, in the attocurie/m^3 range. The airborne data show ^{234}U to ^{238}U ratios that range from 1.0 to 7.4, many of which are significantly different from the one-to-one ratio found in crustal rock.

Uranium in airborne dust appears to result from resuspension of soil and, consequently, airborne dust has the same uranium concentration as the soil particles that produce it. Airborne dust near uranium mining or milling operations would be expected to contain higher than background levels of total uranium and have an isotope ratio the same as crustal rock as long as the surface material from which it originated had not experienced significant weathering by moisture. Some examples of airborne uranium levels near mining and milling operations when the industry was actively producing uranium ore are included below for comparison with EPA values in Table 6-2. The annual average concentration of uranium in ambient air taken near the Jackpile Open Pit mine (New Mexico) was 2.4 fCi/m^3 (EPA 1979a), and the concentration of uranium in air measured near a Canadian refinery ranged between 1.3 and 134 fCi/m^3 (2–200 ng/m^3) with a geometric mean of 13 fCi/m^3 (20 ng/m^3) (Tracy and Meyerhof 1987). Air samples taken near a uranium mill tailings pile showed a uranium concentration of 1 pCi/m^3 (NCRP 1984a). Near the Paducah Gaseous Diffusion Plant in Kentucky, where uranium enrichment is performed, the maximum total air alpha activity in 1979 at one location was 0.7 pCi/m^3 (DOE 1981a).

6.4.2 Water

Until the early 1980s, uranium in drinking water was not often measured except when contamination was suspected. Welford and Baird (1967) found a concentration of 0.02 pCi/L in New York City tap water. UNSCEAR (1977) reported that tap water usually contains <0.03 pCi/L.

Figure 6-3. Average Uranium Concentrations in Drinking Water for States Where Concentration Exceeds 1 pCi/L



Source: NCRP 1984b

Table 6-3. Uranium in Drinking Water (Composites)

	pCi/L±2*u*					
	January–December 1997			January–December 2006*		
Location	^{234}U	^{235}U	^{238}U	^{234}U	^{235}U	^{238}U
Los Angeles, California	1.78±0.19	0.098±0.043	1.48±0.17	1.48±0.2	0.071±0.044	1.14±0.17
Tampa, Florida	—	—	—	0.174±0.061	0.009±0.024	0.134±0.052
Baxley, Georgia	0.144±0.042	0.035±0.022	0.065±0.028	0.086±0.045	0.027±0.032	0.018±0.025
Idaho Falls, Idaho	0.8±0.13	0.027±0.025	0.306±0.075	—	—	—
Morris, Illinois	0.6±0.11	0.033±0.027	0.03±0.024	0.58±0.11	0.009±0.024	0.078±0.041
W. Chicago, Illinois	1.42±0.24	0.04±0.04	0.14±0.07	0.114±0.051	0.002±0.018	0.024±0.027
New Orleans, Louisiana	—	—	—	1.05±0.16	0.052±0.041	0.69±0.13
Augusta, Maine	—	—	—	1.11±0.16	0.035±0.033	0.93±0.14
Red Wing, Minnesota	0.43±0.12	0.028±0.039	0.113±0.062	—	—	—
Port Gibson, Mississippi	—	—	—	0.131±0.049	0.010±0.018	0.044±0.032
Lincoln, Nebraska	5.11±0.46	0.358±0.099	3.26±0.33	2.96±0.32	0.097±0.05	1.98±0.24
Santa Fe, New Mexico	6.57±0.52	0.285±0.077	3.65±0.33	6.52±0.57	0.123±0.053	2.64±0.28
Las Vegas, Nevada	2.76±0.32	0.061±0.043	1.55±0.22	3.12±0.32	0.089±0.045	1.69±0.21
Jenkinsville, South Carolina	0.596±0.089	0.027±0.02	0.277±0.059	—	—	—
Genoa, Wisconsin	0.63±0.12	0.115±0.056	0.345±0.088	—	—	—
Madison, Wisconsin	1.25±0.17	0.016±0.018	0.255±0.069	—	—	—

Sources: EPA 1997b, 2006c

Table 6-4. Uranium Analyses of Select Precipitation Composite Samples March–May 1996

Location	pCi/L±2*u*		
	^{234}U	^{235}U	^{238}U
Montgomery, Alabama	0.0163±0.008	0.004±0.0044	0.0036±0.0042
Little Rock, Arkansas	0.0096±0.0062	0.0044±0.0044	0.0065±0.0049
Berkeley, California	0.0153±0.0074	0.0038±0.0042	0.0043±0.0048
Denver, Colorado	0.092±0.019	0.026±0.01	0.044±0.013
Hartford, Connecticut	0.0169±0.0089	0.0012±0.0038	0.0045±0.0053
Wilmington, Delaware	0.02±0.0079	0.0025±0.0032	0.0023±0.0027
Jacksonville, Florida	0.008±0.0054	0.0067±0.0051	0.0051±0.0043
Miami, Florida	0.022±0.01	0.0027±0.0038	0.0086±0.0064
Honolulu, Hawaii	0.0156±0.0086	0.0037±0.0051	0.0014±0.003
Boise, Idaho	0.0114±0.0071	0.01±0.0073	0.0057±0.005
Idaho Falls, Idaho	0.0311±0.0099	0.0111±0.0066	0.0065±0.0046
Augusta, Maine	0.023±0.011	0.0067±0.006	0.0086±0.0064
Lansing, Michigan	0.0138±0.0067	0.0016±0.0028	0.0097±0.0056
Minneapolis, Minnesota	0.0202±0.0092	0.002±0.0044	0.0132±0.0075
Welch, Minnesota	0.047±0.02	0.013±0.012	0.024±0.015
Jackson, Mississippi	0.0145±0.008	0.0134±0.0084	0.0137±0.0081
Charlotte, North Carolina	0.0101±0.0062	0.0085±0.0060	0.0151±0.0074
Wilmington, North Carolina	0.0218±0.0086	0.0047±0.0045	0.0106±0.0061
Bismarck, North Dakota	0.079±0.02	0.019±0.011	0.043±0.014
Lincoln, Nebraska	0.049±0.016	0.0129±0.0087	0.028±0.011
Concord, New Hampshire	0.0195±0.0087	0.0113±0.0074	0.024±0.0098
Trenton, New Jersey	0.0123±0.0069	0.0018±0.0031	0.0044±0.0044
Las Vegas, Nevada	0.261±0.066	0.018±0.02	0.101±0.042
Albany, New York	0.0229±0.0082	0.0043±0.0039	0.0094±0.0052
Yaphank, New York	0.0141±0.0068	0.0051±0.0048	0.0077±0.0051
Painesville, Ohio	0.0077±0.0063	0.0083±0.0071	0.0035±0.0045
Portland, Oregon	0.03±0.0095	0.0111±0.0064	0.0129±0.0063
Harrisburg, Pennsylvania	0.038±0.012	0.0103±0.0065	0.0098±0.0060
Barnwell, South Carolina	0.0153±0.0072	0.0069±0.0052	0.0085±0.0055
Columbia, South Carolina	0.0126±0.0065	0.007±0.0053	0.0039±0.0038
Knoxville, Tennessee	0.0111±0.0057	0.0043±0.0038	0.0043±0.0035
Nashville, Tennessee	0.0074±0.0068	0.0014±0.0043	0.0016±0.0044
Austin, Texas	0.0119±0.0066	0.0017±0.003	0.0061±0.0054
El Paso, Texas	0.043±0.022	0.012±0.014	0.036±0.02
Salt Lake City, Utah	0.0196±0.0078	0.0021±0.0032	0.0102±0.0056
Lynchburg, Virginia	0.05±0.013	0.0083±0.0056	0.008±0.0052
Olympia, Washington	0.0176±0.0072	0.0051±0.0042	0.0052±0.0041
Madison, Wisconsin	0.0209±0.0098	0.0039±0.0045	0.0065±0.0053

Source: EPA 1996b

In some surface waters that have been contaminated by waste discharge and in groundwaters from natural uranium-bearing aquifers, the concentrations of uranium may be higher than the average natural background levels for that area. For example, higher levels of uranium have been observed in water from Ambrosia Lake in New Mexico (uranium milling and mining) (Lapham et al. 1989), the agricultural draining and evaporation pond water of the San Joaquin Valley in California (Bradford et al. 1990), groundwater from Rocky Flats, Colorado (Laul 1994), and groundwater from the Nambe region of northern New Mexico (Hakonson-Hayes et al. 2002). The concentration of uranium in creek waters that lead to the Ohio River near the Paducah Gaseous Diffusion Plant in Kentucky ranged from <0.7 to 470 pCi/L (1–700 µg/L) (DOE 1981a). Mono Lake, a natural alkaline, saline lake in California, contained 185 pCi/L ^{238}U and 222 pCi/L ^{234}U during the period 1978–1980 (Simpson et al. 1982). Analysis of water from the Colorado River and its tributaries during 1985 and 1986 showed that the levels of total uranium ranged from 3.4 to 60 pCi/L (Stewart et al. 1988).

Higher levels of uranium can be found in groundwater. Orloff et al. (2004) found elevated levels of uranium in well water in a South Carolina community (range of 1.7–5,830 pCi/L, equivalent to 1.8–7,780 mg/L, and a mean of 620 µg/L based on isotopic content). The U.S. Geological Service measured uranium concentrations above 30 µg/L in 65 out of 350 wells (19%) located in the Eastern San Joaquin Valley, California during sampling from 2004 to 2008 (Jurgens et al. 2010). Median and maximum concentrations were 18.0 and 2,500 µg/L in 98 observation wells, 8.7 and 503 µg/L, respectively, in 122 domestic wells, and 1.8 and 41.3 µg/L, respectively, in 121 public supply wells.

As part of the Navajo Uranium Assessment and Kidney Health Project, EPA (2013a) analyzed water from 240 unregulated wells on Navajo land. Uranium levels in 29 sources exceeded the MCL of 30 µg/L; the uranium concentrations in these 29 sources ranged from 31 to 700 µg/L.

Discharge of dewatering effluents from underground uranium mines and runoff from uranium mine tailings piles have contaminated surface waters and aquifers in New Mexico with elevated levels of gross alpha activity and uranium (NMHED 1989). The concentration of uranium in mine discharge water in New Mexico was 31,500 µg/L (equivalent to 22,680 pCi/L, assuming that the uranium content is natural uranium) (EPA 1985c). Groundwater from an aquifer adjacent to a uranium mill tailings pile in Falls City, Texas, was also found to have concentrations of uranium above natural background levels (DOE 1994).

The concentrations of ^{234}U and ^{238}U in groundwater from Cambrian-Ordovician sandstone aquifers in Illinois range from <0.1 to 8.0 pCi/L (Gilkeson and Cowart 1987). The ratio of the activity of ^{234}U to ^{238}U ranged from 2.0 to >40. The lowest ratios were found in unconfined aquifers in primary recharge zones, while ratios >20 were found in the confined zones aquifer. It was suggested that glacial recharge in unconfined zones might be responsible for the high ^{234}U to ^{238}U ratios (Gilkeson and Cowart 1987). Fifty-five groundwater samples from the Lockatong and Passaic Formation in the Newark Basin in New Jersey were analyzed during 1985–1987. These samples were found to contain 0.1–40 pCi/L total uranium, with a median value of 2.1 pCi/L (Szabo and Zapecza 1987). Uranium concentrations measured in seven samples of groundwater from the Raymond Basin in California ranged from 5.3 to 43.7 pCi/L (Wiegand et al. 1987).

Water in a private well in Maine, thought to be of geologic origin, was reported to contain as much as 403 µg/L uranium (approximately 270 pCi/L) (Lowry et al. 1987). Uranium concentrations as high as 1,160 µg/L were measured in drinking water from a home in northwestern Connecticut (Magdo et al. 2007). The source of the uranium was found to be a 500-foot well carrying groundwater from the Brookfield Gneiss geological formation. Hughes et al. (2005) measured elevated uranium concentrations ranging from 44.3 to 5,570 µg/L in water from nine private wells located near Simpsonville, South Carolina. Elevated levels of uranium measured in waters from private wells in northern and northeastern Nebraska were thought to be due to the upward migration of uranium from bedrock and heavy use of phosphate fertilizers. Uranium values up to 110 pCi/L were measured (NEDH 1989). The concentrations of uranium in U.S. groundwaters were estimated using a conceptual model based on the geochemical and hydrological characteristics of aquifers.

The population-weighted average uranium concentration in groundwaters used as sources of drinking water in all 50 states was found to range from 0.05 to 4.6 pCi/L, with a mean value of 0.55 pCi/L (Longtin 1988). This mean is lower than the population-weighted uranium value for finished waters of 0.8 pCi/L (NCRP 1984a). Some methods that may be suitable for reducing the concentration of uranium in drinking water include lime softening, coagulation/precipitation, and filtering; however, these methods may not efficiently remove the uranium.

Concentrations of ^{238}U and ^{234}U measured in bottled water samples from 17 locations in Italy were generally <120 mBq/kg (Forte et al. 2001). The highest reported concentrations of these isotopes were 1,936 and 2,842 mBq/kg, respectively.

Jia et al. (2006) measured concentrations of 0.27–16.2 mBq/L for ^{238}U, 0.41–15.6 mBq/L for ^{234}U, and 0.012–0.695 mBq/L for ^{235}U in water samples collected in Bosnia and Herzegovina. Two water samples were reported to contain depleted uranium. Carvalho and Oliveira (2010) reported mean uranium concentrations of 0.5 and 0.4 mg/kg measured in public drinking water supplies from Kosovo and Bosnia-Herzegovina during 2001. These levels are similar to those reported in other countries and do not reflect enhanced presence of uranium resulting from the use of depleted uranium in these areas during the 1999 military conflict (Carvalho and Oliveira 2010; Sahoo et al. 2007).

6.4.3 Sediment and Soil

Table 6-5 shows the average concentrations of uranium in several types of rocks and soils (NCRP 1984a). The radioactivity in soils is similar to that in the rocks, usually bedrock, from which it derives. The average soil concentration of ^{234}U from Table 6-5 is 0.6 pCi/g. Since the activity of ^{234}U accounts for approximately one-half of the total activity in natural uranium (see Chapter 4), the value in Table 6-5 may be multiplied by two to obtain the total uranium in soils (approximately 1.2 pCi/g).

There are wide variations from the values presented in the table, particularly in areas where uranium minerals are more concentrated. Concentrations of uranium in Louisiana soils ranged from 2.35 to 3.98 μg/g (1.6–2.7 pCi/g) (Meriwether et al. 1988), while uranium concentrations in phosphate rock in north and central Florida ranged from 4.5 to 83.4 pCi/g (6.8–124 μg/g) (EPA 1985c).

Soil samples adjacent to Los Alamos, New Mexico, taken during 1974–1977 contained total uranium in the range of 0.1–5.1 μg/g (0.067–3.4 pCi/g), with a mean concentration of 1.6 pCi/g (2.4 μg/g) (Purtymun et al. 1987). The concentrations of uranium in soils adjacent to the Hanford Fuel Fabrication Facility near Richland, Washington, that were collected during 1978–1981 ranged from 0.51 to 3.1 pCi/g (0.76–4.6 μg/g), with a median value of 1.2 pCi/g (1.8 μg/g). The control samples for the Hanford Fuel Fabrication Study contained uranium at concentrations of 0.21–0.86 pCi/g (0.32–1.128 μg/g), with a median value of 0.49 pCi/g (0.73 μg/g) (Price and Kinnison 1982). Uranium in the soil within the property boundary of the Paducah Gaseous Diffusion Plant in Kentucky ranged from 3.3 to 4.8 pCi/g (4.9–7.1 μg/g), whereas off-site samples taken as far as 12 miles away contained uranium at levels of 3.8–6.0 pCi/g (6.4–9.0 μg/g) (DOE 1981a). Soil monitoring data from the area surrounding the Feed Material Production Center at Fernald, Ohio, showed that the uranium concentrations within an 8-km^2 area were between 3 and 23 pCi/g (4.5–34 μg/g) compared to an mean of 2.2 pCi/g (3.3 μg/g) for natural background levels (Stevenson and Hardy 1993). Other investigators have detected uranium levels in

Table 6-5. Uranium in Rocks and Soils

Material	pCi/g ^{238}U[a]
Igneous rocks	
Basalt (crustal average)	0.2–0.3
Mafic[b]	0.2–0.3
Salic[b]	1.3–1.6
Granite (crustal average)	1
Sedimentary rocks	
Shale	1
Sandstones	
Clean quartz	<0.3
Dirty quartz	1.0[c]
Arkose	0.3–0.7[c]
Beach sands (unconsolidated)	1
Carbonate rocks	0.7
Soils	0.6

[a]To obtain the series equilibrium radioactivity for total alpha, beta, or approximate gamma emission (excluding bremsstrahlung and x-rays), multiply by 8, 6, or 3, respectively.
[b]The median and mean value are given.
[c]Indicates that the values are not well defined.

Source: NCRP 1975

surface soils at the Fernald site as high as 50 times natural background levels (Miller et al. 1994). Moon et al. (2006) measured uranium concentrations as high as 300 µg/g at a soil depth of 6 inches at the Oak Ridge Reservation in Oak Ridge, Tennessee. The contamination was attributed to past waste disposal activities at the site.

Carvalho and Oliveira (2010) reported mean uranium concentrations of 1.8 and 3 mg/kg measured in soils from Kosovo and Bosnia-Herzegovina during 2001. Higher uranium concentrations were localized to areas impacted by depleted uranium ammunition (Carvalho and Oliveira 2010; Sansone et al. 2001).

6.4.4 Other Environmental Media

Concentrations of uranium have been determined in meat and fish (Table 6-6). The uranium content measured in tissues of cattle herds grazing in pastures close to the Rocky Flats Plant in Colorado was slightly higher than in other cattle, reflecting possible contamination from this source (Smith and Black 1975). The average concentrations of uranium in game fish (surface feeders) collected from a reservoir at locations upstream and downstream from the Los Alamos National Laboratory were 2.9 ng/g dry weight (dw) (0.0019 pCi/g) and 4.9 ng/g dw (0.0033 pCi/g), respectively (Fresquez et al. 1994). The corresponding values in nongame, bottom-feeding fish were 7.9 ng/g dw (0.0058 pCi/g) and 17.7 ng/g dw (0.012 pCi/g), respectively. The concentrations of uranium in fish muscle (dw) from a Canadian lake receiving uranium mill effluents were 7–11 times higher than in fish caught in uncontaminated lakes, but this uranium may have only been attached to the gills (Swanson 1985).

The mean uranium concentration in vegetation from Ambrosia Lake, New Mexico (a site of mining and milling activities) was measured at 0.3 pCi/g dw compared to 4 fCi/g dw for vegetation from a control site (Lapham et al. 1989). Although the concentrations of uranium in muscle from exposed cattle were indistinguishable from uranium levels in muscle from control cattle, levels of uranium in liver and kidney tissues were 4 times higher in exposed cattle than in control cattle, and levels of uranium in femur samples were 13 times higher than in controls, indicating that kidney and liver slightly bioconcentrate uranium while muscle does not (Lapham et al. 1989). Thomas et al. (2005) detected uranium concentrations >1 µg/g in bone, liver, kidney, muscle, and rumen content samples from 14 out of 45 Saskatchewan moose and 4 out of 4 Saskatchewan cattle.

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

General population exposure to uranium occurs by ingestion of food and drinking water and by inhalation of air. The pathways are shown in Figure 6-2.

Table 6-6 depicts uranium levels in various types of food in the United States. Measurements of normal levels of dietary ^{234}U and ^{238}U indicate that foods consumed contain about 0.3–0.5 pCi/day for each uranium isotope (0.6–1.0 pCi/day [0.9–1.5 μg/day] total uranium) (EPA 1985c; Welford and Baird 1967).

Based on consumption rates, root crops such as potatoes, parsnips, turnips, and sweet potatoes contribute approximately 38% of total dietary intake of uranium (EPA 1985c).

Ingestion of food grown in the vicinity of a uranium mill may lead to an intake up to 3 pCi/day uranium (Rayno 1983). Other investigators have estimated a dietary intake of 2.86–4.55 mg/day for individuals living near a uranium mine (Yamamoto et al. 1971).

An alternate method for estimating uranium intake is to measure the daily excretion of uranium in urine and feces. Using this method in a study of 12 subjects in Utah, it was estimated that the average dietary intake for the Salt Lake City population was 4.4±0.6 μg, an intake that is higher than that reported for New York City, Chicago, and San Francisco residents (1.3–1.4 μg) (Singh et al. 1990).

Intakes of uranium in food may also increase when certain ceramic glazed dishes are used for serving or storing food (Landa and Councell 1992). Leaching occurs on contact with acidic foods or beverages. Experiments show that when a ceramic glazed plate was kept in contact with a 4% acetic acid solution for 24 hours, the concentration of uranium in the leachate was 31.8 mg/L (Landa and Councell 1992).

Uranium glazed commercial ceramic dinnerware is no longer made and sold because it was determined that the uranium is leachable by acidic foods and beverages (Landa and Councell 1992). Experiments show that when a Fiesta tableware plate was kept in contact with 20 mL of 4% acetic acid solution for 24 hours, the quantity of uranium in the leachate was 600 μg (400 pCi). Other liquids were much less effective at leaching uranium, with water giving a value over 3 orders of magnitude lower, and other uranium glazed ceramics were much less leachable (Landa and Councell 1992).

Table 6-6. Concentrations of Uranium in Some Foods

Type of food	Uranium concentration (ng/g raw weight)	Reference
Whole grain products	1.45	NCRP 1984a
Potatoes	2.66–2.92; 15–18	EPA 1985c; NCRP 1984a
Carrots	7.7	EPA 1985c
Root vegetables	0.94–1.20	NCRP 1984a
Cabbage	4.7	EPA 1985c
Meat	0.58–1.32; 20	EPA 1985c; NCRP 1984a
Poultry	0.14–0.42	NCRP 1984a
Beef	14	EPA 1985c
Beef liver	26	EPA 1985c
Beef kidney	70	EPA 1985c
Eggs	0.23; 9.6	EPA 1985c; NCRP 1984a
Dairy products	0.08–0.31	NCRP 1984a
Cow milk	4	EPA 1985c
Milk	1–2	EPA 1985c
Fresh fish	0.43–0.85; 11	EPA 1985c; NCRP 1984a
Shellfish	9.5–31.0	NCRP 1984a
Welsh onion	69	EPA 1985c
Flour	0.25–0.68	NCRP 1984a
Wheat bread	19	EPA 1985c
Baked products	1.32–1.5; 12	EPA 1985c; NCRP 1984a
Polished rice	1.43–6.0; 15	EPA 1985c; NCRP 1984a
Macaroni	0.4–0.63	NCRP 1984a
Tea	5	EPA 1985c
Coffee	6	EPA 1985c
Parsley	60	EPA 1985c
Red pepper	5	EPA 1985c
Mustard	0.2	EPA 1985c
Table salt	40	EPA 1985c
Canned vegetables	0.09–0.18	NCRP 1984a
Fruit juices	0.04–0.12	NCRP 1984a
Canned fruits	0.18–0.29	NCRP 1984a
Fresh fruits	0.71–1.29	NCRP 1984a
Dried beans	1.5–3.67	NCRP 1984a
Fresh vegetables	0.52–0.92	NCRP 1984a

Uranium intakes from food in Japanese diets from two control areas ranged from 0.86 to 1.02 µg/day (Yamamoto et al. 1971). Another study reported a mean value of 0.71 µg/day for Japanese males from 31 prefectures (Shiraishi et al. 1992). Galletti et al. (2003) estimated a total dietary intake of uranium in the range of 2.9–4.8 µg/day for the Italian population. Worldwide intake values for uranium have been reported at an average of 1 pCi/day (1.5 µg/day) (range 0.6–3.2 pCi/day [0.9–4.8 µg/day]) (Linsalata 1994).

Concentrations of uranium from selected drinking water supplies in the United States were analyzed by the EPA laboratories and found to be generally <1 pCi/L (EPA 1985c, 1997b, 2005a, 2010b). Based on data obtained from the NURE program plus data prepared for the EPA (DOE 1981b; USGS 2006), a population-weighted average of 0.8 pCi/L uranium was determined. In another study, Ohanian (1989) reported population-weighted average concentrations of uranium in U.S. community drinking water ranging from 0.3 to 2.0 pCi/L. Considering an individual water intake of approximately 1.7 L/day, and an average intake of uranium from drinking water of 0.8 pCi/L as reported in the EPA study, the total intake of uranium for an individual from drinking water each day is approximately 1.4 pCi.

Uranium is also taken into the body by the inhalation route. The average daily intake of uranium from inhalation of air has been estimated to range from 0.007 pCi/day (0.010 µg/day) (Cothern 1987) to 0.0007 pCi/day (0.0010 µg/day) (UNSCEAR 1988). This value may be somewhat higher for persons living near sources of uranium emission. Glass makers and potters who use uranium-containing enamels may be exposed to small amounts of uranium from handling the powder or from fuming operations in glass making (Rossol 1997). In general, however, exposure to uranium from inhalation is small compared to exposure from food and drinking water.

Measurements of concentrations of uranium have been made in human tissues and body fluids resulting from consumption of food and water and from natural background sources. Levels of uranium measured between 1999 and 2008 in the urine of members of the general U.S. population from the National Health and Nutrition Examination Survey (NHANES) are listed in Tables 6-7 and 6-8 (CDC 2012). The range of geometric mean values is 0.006–0.009 µg U/g creatinine (or 0.005–0.010 µg U/L urine), respectively.

Two longtime residents of Los Alamos, New Mexico (one a smoker and one nonsmoker) were shown to have uranium tissue concentrations for the skeleton (average 5.8 µg/g wet weight) and liver (average 0.08 µg/kg) in closer agreement with the Reference Man (Kathren 1997; ICRP 1975) than those reported in New York City residents (Fisenne and Welford 1986). Values of uranium in whole blood measured in

Table 6-7. Geometric Mean and Selected Percentile of Urinary Concentrations of Uranium (µg/g Creatinine) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES)

	Survey years	Geometric mean (95% confidence interval)	Selected percentiles (95% confidence interval)			Sample size
			50th	75th	90th	95th	
Total	99–00	**0.007** (0.006–0.009)	**0.007** (0.006–0.009)	**0.013** (0.010–0.016)	**0.024** (0.019–0.030)	**0.034** (0.027–0.053)	2,464
	01–02	**0.008** (0.007–0.010)	**0.007** (0.006–0.009)	**0.014** (0.011–0.018)	**0.026** (0.020–0.034)	**0.040** (0.028–0.058)	2,689
	03–04	**0.008** (0.007–0.008)	**0.007** (0.006–0.008)	**0.012** (0.010–0.014)	**0.021** (0.017–0.025)	**0.029** (0.023–0.039)	2,557
	05–06	**0.006** (0.005–0.006)	**0.005** (0.005–0.006)	**0.009** (0.008–0.010)	**0.017** (0.014–0.020)	**0.026** (0.020–0.039)	2,576
	07–08	**0.007** (0.006–0.009)	**0.006** (0.005–0.008)	**0.012** (0.009–0.016)	**0.024** (0.016–0.038)	**0.038** (0.025–0.065)	2,627
Age group							
6–11 years	99–00	**0.009** (0.007–0.012)	**0.008** (0.006–0.011)	**0.015** (0.010–0.024)	**0.030** (0.016–0.044)	**0.037** (0.030–0.077)	340
	01–02	**0.010** (0.008–0.011)	**0.010** (0.008–0.012)	**0.015** (0.013–0.019)	**0.027** (0.018–0.032)	**0.033** (0.027–0.048)	368
	03–04	**0.009** (0.008–0.010)	**0.008** (0.007–0.010)	**0.013** (0.011–0.017)	**0.024** (0.016–0.039)	**0.033** (0.022–0.050)	289
	05–06	**0.007** (0.006–0.008)	**0.006** (0.005–0.008)	**0.010** (0.008–0.014)	**0.018** (0.013–0.035)	**0.034** (0.018–0.048)	355
	07–08	**0.009** (0.007–0.011)	**0.008** (0.007–0.010)	**0.014** (0.010–0.022)	**0.026** (0.016–0.053)	**0.042** (0.023–0.065)	394
12–19 years	99–00	**0.007** (0.006–0.008)	**0.006** (0.005–0.008)	**0.010** (0.009–0.014)	**0.020** (0.014–0.030)	**0.030** (0.019–0.074)	719
	01–02	**0.007** (0.006–0.008)	**0.007** (0.006–0.008)	**0.012** (0.009–0.016)	**0.020** (0.015–0.026)	**0.026** (0.020–0.042)	762
	03–04	**0.007** (0.006–0.008)	**0.006** (0.005–0.007)	**0.010** (0.008–0.013)	**0.019** (0.015–0.027)	**0.034** (0.022–0.041)	725
	05–06	**0.006** (0.005–0.007)	**0.005** (0.005–0.006)	**0.009** (0.007–0.012)	**0.017** (0.013–0.022)	**0.023** (0.019–0.026)	701
	07–08	**0.007** (0.006–0.009)	**0.006** (0.005–0.008)	**0.012** (0.009–0.016)	**0.025** (0.013–0.050)	**0.033** (0.022–0.077)	376
≥20 years	99–00	**0.007** (0.006–0.009)	**0.007** (0.006–0.009)	**0.013** (0.010–0.016)	**0.024** (0.019–0.029)	**0.034** (0.025–0.051)	1,405
	01–02	**0.008** (0.007–0.010)	**0.007** (0.006–0.009)	**0.014** (0.011–0.019)	**0.027** (0.020–0.039)	**0.043** (0.030–0.063)	1,559
	03–04	[a]	**0.007** (0.006–0.008)	**0.012** (0.010–0.014)	**0.020** (0.017–0.024)	**0.028** (0.022–0.038)	1,543
	05–06	**0.006** (0.005–0.006)	**0.005** (0.005–0.006)	**0.009** (0.008–0.010)	**0.016** (0.014–0.019)	**0.026** (0.020–0.039)	1,520
	07–08	**0.007** (0.006–0.008)	**0.006** (0.005–0.008)	**0.012** (0.009–0.016)	**0.024** (0.016–0.036)	**0.037** (0.025–0.065)	1,857
Gender							
Males	99–00	**0.007** (0.006–0.009)	**0.006** (0.005–0.008)	**0.011** (0.009–0.015)	**0.021** (0.017–0.028)	**0.035** (0.024–0.056)	1,227
	01–02	**0.007** (0.006–0.008)	**0.007** (0.006–0.008)	**0.012** (0.010–0.015)	**0.022** (0.018–0.028)	**0.033** (0.025–0.047)	1,334
	03–04	**0.007** (0.006–0.008)	**0.006** (0.006–0.007)	**0.010** (0.009–0.012)	**0.019** (0.015–0.024)	**0.026** (0.019–0.039)	1,280

Table 6-7. Geometric Mean and Selected Percentile of Urinary Concentrations of Uranium (µg/g Creatinine) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES)

	Survey years	Geometric mean (95% confidence interval)	Selected percentiles (95% confidence interval)			Sample size
			50th	75th	90th	95th	
Females	05–06	**0.005** (0.005–0.005)	**0.005** (0.004–0.005)	**0.008** (0.007–0.009)	**0.014** (0.013–0.016)	**0.021** (0.016–0.031)	1,271
	07–08	**0.007** (0.005–0.008)	**0.006** (0.005–0.007)	**0.012** (0.009–0.015)	**0.022** (0.016–0.031)	**0.032** (0.024–0.056)	1,327
	99–00	**0.008** (0.007–0.010)	**0.007** (0.006–0.010)	**0.013** (0.010–0.017)	**0.025** (0.019–0.033)	**0.034** (0.027–0.054)	1,237
	01–02	**0.009** (0.008–0.011)	**0.009** (0.007–0.011)	**0.016** (0.012–0.021)	**0.029** (0.021–0.042)	**0.045** (0.031–0.067)	1,355
	03–04	[a]	**0.008** (0.007–0.009)	**0.013** (0.011–0.016)	**0.022** (0.018–0.028)	**0.031** (0.025–0.041)	1,277
	05–06	**0.006** (0.006–0.007)	**0.006** (0.005–0.006)	**0.010** (0.009–0.011)	**0.019** (0.015–0.024)	**0.035** (0.022–0.041)	1,305
	07–08	**0.008** (0.006–0.009)	**0.007** (0.006–0.008)	**0.013** (0.010–0.018)	**0.026** (0.016–0.043)	**0.042** (0.024–0.083)	1,300
Race/ethnicity							
Mexican Americans	99–00	**0.015** (0.011–0.022)	**0.015** (0.011–0.020)	**0.029** (0.016–0.058)	**0.059** (0.027–0.146)	**0.100** (0.042–0.270)	883
	01–02	**0.012** (0.010–0.016)	**0.012** (0.009–0.016)	**0.021** (0.015–0.028)	**0.033** (0.024–0.053)	**0.050** (0.034–0.080)	682
	03–04	**0.013** (0.010–0.016)	**0.013** (0.009–0.017)	**0.022** (0.016–0.029)	**0.035** (0.026–0.051)	**0.051** (0.034–0.061)	618
	05–06	**0.008** (0.007–0.009)	**0.007** (0.006–0.008)	**0.013** (0.010–0.015)	**0.022** (0.016–0.031)	**0.035** (0.025–0.060)	652
	07–08	**0.009** (0.008–0.012)	**0.009** (0.007–0.011)	**0.017** (0.014–0.021)	**0.031** (0.021–0.048)	**0.042** (0.027–0.097)	515
Non-Hispanic blacks	99–00	**0.006** (0.004–0.007)	**0.005** (0.004–0.006)	**0.008** (0.006–0.013)	**0.017** (0.011–0.029)	**0.028** (0.018–0.048)	568
	01–02	**0.005** (0.005–0.006)	**0.005** (0.005–0.006)	**0.008** (0.007–0.010)	**0.013** (0.011–0.014)	**0.017** (0.014–0.029)	667
	03–04	**0.006** (0.005–0.006)	**0.005** (0.005–0.006)	**0.009** (0.008–0.009)	**0.013** (0.012–0.015)	**0.018** (0.014–0.024)	722
	05–06	**0.004** (0.004–0.005)	**0.004** (0.003–0.005)	**0.006** (0.006–0.007)	**0.011** (0.009–0.015)	**0.017** (0.012–0.021)	692
	07–08	**0.005** (0.005–0.006)	**0.005** (0.004–0.006)	**0.009** (0.007–0.011)	**0.014** (0.011–0.017)	**0.018** (0.014–0.041)	589
Non-Hispanic whites	99–00	**0.007** (0.006–0.009)	**0.007** (0.006–0.009)	**0.012** (0.010–0.015)	**0.021** (0.017–0.027)	**0.030** (0.024–0.050)	822
	01–02	**0.008** (0.007–0.009)	**0.007** (0.006–0.009)	**0.013** (0.011–0.016)	**0.025** (0.018–0.032)	**0.034** (0.025–0.051)	1,132
	03–04	[a]	**0.007** (0.006–0.008)	**0.011** (0.010–0.013)	**0.019** (0.015–0.024)	**0.027** (0.020–0.040)	1,074
	05–06	**0.006** (0.005–0.006)	**0.005** (0.005–0.006)	**0.009** (0.008–0.010)	**0.016** (0.013–0.020)	**0.024** (0.019–0.039)	1,041
	07–08	**0.007** (0.006–0.009)	**0.006** (0.005–0.008)	**0.012** (0.009–0.019)	**0.025** (0.015–0.043)	**0.039** (0.024–0.081)	1,095

[a]Not calculated: proportion of results below limit of detection was too high to provide a valid result.

Source: CDC 2012

Table 6-8. Geometric Mean and Selected Percentile of Urinary Concentrations of Uranium (µg/L) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES)

	Survey years	Geometric mean (95% confidence interval)		Selected percentiles (95% confidence interval)								Sample size
				50th		75th		90th		95th		
Total	99–00	**0.008**	(0.007–0.009)	**0.007**	(0.006–0.008)	**0.013**	(0.010–0.017)	**0.027**	(0.021–0.038)	**0.046**	(0.037–0.056)	2,464
	01–02	**0.009**	(0.007–0.010)	**0.008**	(0.007–0.009)	**0.014**	(0.012–0.018)	**0.030**	(0.023–0.039)	**0.046**	(0.034–0.062)	2,690
	03–04	**0.008**	(0.007–0.008)	**0.007**	(0.006–0.007)	**0.011**	(0.010–0.013)	**0.021**	(0.017–0.026)	**0.031**	(0.026–0.037)	2,557
	05–06	**0.006**	(0.005–0.006)	**0.005**	(0.005–0.006)	**0.010**	(0.009–0.012)	**0.019**	(0.016–0.022)	**0.033**	(0.023–0.041)	2,576
	07–08	**0.007**	(0.006–0.008)	**0.007**	(0.005–0.008)	**0.013**	(0.011–0.015)	**0.024**	(0.018–0.033)	**0.039**	(0.026–0.057)	2,627
Age group												
6–11 years	99–00	**0.009**	(0.007–0.011)	**0.007**	(0.006–0.009)	**0.013**	(0.009–0.022)	**0.032**	(0.019–0.048)	**0.048**	(0.033–0.066)	340
	01–02	**0.008**	(0.007–0.010)	**0.008**	(0.006–0.010)	**0.014**	(0.010–0.020)	**0.026**	(0.020–0.036)	**0.040**	(0.025–0.049)	368
	03–04	**0.008**	(0.007–0.009)	**0.007**	(0.006–0.009)	**0.012**	(0.009–0.016)	**0.020**	(0.016–0.026)	**0.028**	(0.020–0.039)	289
	05–06	**0.006**	(0.005–0.007)	**0.005**	(0.004–0.007)	**0.010**	(0.008–0.011)	**0.015**	(0.012–0.031)	**0.031**	(0.013–0.051)	355
	07–08	**0.007**	(0.006–0.008)	**0.006**	(0.005–0.008)	**0.012**	(0.009–0.016)	**0.021**	(0.016–0.027)	**0.030**	(0.022–0.039)	394
12–19 years	99–00	**0.009**	(0.008–0.011)	**0.009**	(0.008–0.010)	**0.015**	(0.012–0.018)	**0.026**	(0.020–0.043)	**0.044**	(0.028–0.072)	719
	01–02	**0.010**	(0.008–0.012)	**0.010**	(0.008–0.012)	**0.017**	(0.013–0.023)	**0.030**	(0.022–0.042)	**0.042**	(0.027–0.088)	762
	03–04	**0.010**	(0.009–0.011)	**0.009**	(0.008–0.010)	**0.015**	(0.012–0.018)	**0.028**	(0.023–0.036)	**0.038**	(0.036–0.053)	725
	05–06	**0.007**	(0.006–0.008)	**0.007**	(0.006–0.008)	**0.013**	(0.011–0.015)	**0.023**	(0.018–0.032)	**0.034**	(0.027–0.045)	701
	07–08	**0.009**	(0.007–0.011)	**0.008**	(0.007–0.011)	**0.016**	(0.014–0.020)	**0.029**	(0.022–0.056)	**0.056**	(0.027–0.156)	376
≥20 years	99–00	**0.008**	(0.006–0.009)	**0.007**	(0.005–0.008)	**0.013**	(0.010–0.017)	**0.027**	(0.021–0.040)	**0.046**	(0.036–0.056)	1,405
	01–02	**0.009**	(0.007–0.010)	**0.008**	(0.007–0.009)	**0.014**	(0.012–0.017)	**0.031**	(0.022–0.040)	**0.046**	(0.034–0.065)	1,560
	03–04	[a]		**0.006**	(0.005–0.007)	**0.011**	(0.009–0.012)	**0.019**	(0.016–0.026)	**0.029**	(0.024–0.038)	1,543
	05–06	**0.006**	(0.005–0.006)	**0.005**	(0.005–0.006)	**0.010**	(0.008–0.012)	**0.019**	(0.015–0.022)	**0.032**	(0.022–0.041)	1,520
	07–08	**0.007**	(0.005–0.008)	**0.006**	(0.005–0.008)	**0.013**	(0.010–0.015)	**0.024**	(0.017–0.035)	**0.039**	(0.026–0.052)	1,857
Gender												
Males	99–00	**0.009**	(0.008–0.011)	**0.008**	(0.007–0.010)	**0.015**	(0.012–0.021)	**0.036**	(0.024–0.046)	**0.053**	(0.040–0.067)	1,227
	01–02	**0.009**	(0.008–0.011)	**0.009**	(0.007–0.010)	**0.015**	(0.013–0.021)	**0.033**	(0.024–0.045)	**0.047**	(0.035–0.065)	1,335

Table 6-8. Geometric Mean and Selected Percentile of Urinary Concentrations of Uranium (µg/L) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES)

	Survey years	Geometric mean (95% confidence interval)		Selected percentiles (95% confidence interval)								Sample size
				50th		75th		90th		95th		
	03–04	**0.008**	(0.007–0.009)	**0.007**	(0.006–0.008)	**0.013**	(0.011–0.016)	**0.023**	(0.019–0.027)	**0.031**	(0.027–0.035)	1,280
	05–06	**0.006**	(0.006–0.007)	**0.006**	(0.005–0.006)	**0.011**	(0.009–0.012)	**0.019**	(0.015–0.022)	**0.030**	(0.021–0.043)	1,271
	07–08	**0.007**	(0.006–0.009)	**0.007**	(0.006–0.009)	**0.014**	(0.013–0.016)	**0.026**	(0.021–0.037)	**0.046**	(0.030–0.056)	1,327
Females	99–00	**0.007**	(0.006–0.008)	**0.006**	(0.005–0.007)	**0.012**	(0.009–0.015)	**0.023**	(0.016–0.033)	**0.036**	(0.026–0.050)	1,237
	01–02	**0.008**	(0.007–0.010)	**0.008**	(0.006–0.009)	**0.014**	(0.011–0.017)	**0.027**	(0.019–0.037)	**0.041**	(0.029–0.063)	1,355
	03–04	[a]		**0.006**	(0.005–0.007)	**0.010**	(0.009–0.011)	**0.018**	(0.013–0.027)	**0.031**	(0.022–0.039)	1,277
	05–06	**0.005**	(0.005–0.006)	**0.005**	(0.004–0.006)	**0.010**	(0.008–0.011)	**0.019**	(0.016–0.023)	**0.034**	(0.025–0.040)	1,305
	07–08	**0.006**	(0.005–0.008)	**0.006**	(0.005–0.007)	**0.011**	(0.009–0.015)	**0.024**	(0.016–0.033)	**0.035**	(0.022–0.067)	1,300
Race/ethnicity												
Mexican Americans	99–00	**0.017**	(0.012–0.023)	**0.016**	(0.011–0.021)	**0.033**	(0.020–0.054)	**0.060**	(0.040–0.127)	**0.114**	(0.054–0.279)	883
	01–02	**0.013**	(0.010–0.016)	**0.012**	(0.009–0.016)	**0.022**	(0.017–0.030)	**0.040**	(0.031–0.054)	**0.055**	(0.046–0.069)	683
	03–04	**0.014**	(0.011–0.017)	**0.013**	(0.009–0.018)	**0.024**	(0.017–0.034)	**0.041**	(0.028–0.073)	**0.064**	(0.039–0.158)	618
	05–06	**0.008**	(0.007–0.009)	**0.009**	(0.007–0.010)	**0.014**	(0.013–0.017)	**0.025**	(0.021–0.033)	**0.042**	(0.028–0.051)	652
	07–08	**0.009**	(0.008–0.011)	**0.009**	(0.008–0.010)	**0.017**	(0.014–0.022)	**0.032**	(0.026–0.039)	**0.047**	(0.032–0.073)	515
Non-Hispanic blacks	99–00	**0.009**	(0.007–0.011)	**0.008**	(0.006–0.010)	**0.014**	(0.010–0.020)	**0.028**	(0.018–0.049)	**0.052**	(0.030–0.067)	568
	01–02	**0.008**	(0.007–0.009)	**0.008**	(0.007–0.009)	**0.012**	(0.011–0.015)	**0.021**	(0.017–0.027)	**0.030**	(0.023–0.037)	667
	03–04	**0.008**	(0.008–0.009)	**0.007**	(0.007–0.008)	**0.012**	(0.011–0.013)	**0.021**	(0.017–0.027)	**0.031**	(0.023–0.045)	722
	05–06	**0.006**	(0.005–0.007)	**0.006**	(0.005–0.007)	**0.010**	(0.009–0.011)	**0.016**	(0.014–0.020)	**0.023**	(0.018–0.031)	692
	07–08	**0.007**	(0.006–0.009)	**0.007**	(0.006–0.008)	**0.013**	(0.010–0.016)	**0.024**	(0.016–0.038)	**0.038**	(0.025–0.055)	589

Table 6-8. Geometric Mean and Selected Percentile of Urinary Concentrations of Uranium (µg/L) for the U.S. Population from the National Health and Nutrition Examination Survey (NHANES)

	Survey years	Geometric mean (95% confidence interval)		Selected percentiles (95% confidence interval)								Sample size
				50th		75th		90th		95th		
Non-Hispanic whites	99–00	**0.007**	(0.006–0.009)	**0.007**	(0.006–0.007)	**0.012**	(0.009–0.016)	**0.023**	(0.017–0.037)	**0.043**	(0.027–0.051)	822
	01–02	**0.008**	(0.007–0.009)	**0.007**	(0.006–0.009)	**0.013**	(0.011–0.016)	**0.026**	(0.019–0.035)	**0.037**	(0.029–0.050)	1,132
	03–04	[a]		**0.006**	(0.005–0.007)	**0.010**	(0.009–0.012)	**0.018**	(0.015–0.023)	**0.027**	(0.020–0.036)	1,074
	05–06	**0.005**	(0.005–0.006)	**0.005**	(0.004–0.006)	**0.010**	(0.008–0.012)	**0.018**	(0.014–0.022)	**0.033**	(0.021–0.043)	1,041
	07–08	**0.006**	(0.005–0.008)	**0.006**	(0.005–0.008)	**0.013**	(0.009–0.016)	**0.023**	(0.015–0.039)	**0.038**	(0.022–0.086)	1,095

[a]Not calculated: proportion of results below limit of detection was too high to provide a valid result.

Note: Limit of detection for survey years 99–00, 01–02, 03–04, 05–06, and 07–08 are 0.004, 0.004, 0.005, 0.002, and 0.002, respectively

Source: CDC 2012

New York City residents and Illinois residents averaged 0.14 µg/kg (0.09 pCi/kg) and 0.1 µg/kg (0.07 pCi/kg), respectively, compared to a mean value worldwide of 0.58 µg/kg (Fisenne 1988). Mean concentrations of uranium were measured in the organs of persons representing all age groups from different parts of the United States. The uranium values for lungs, liver, kidney, and bone (vertebrae, rib, and skeleton) were 0.5–1.17 µg/kg (0.34–0.78 pCi/kg), 0.12–0.33 µg/kg (0.08–0.22 pCi/kg), 0.39–1.00 µg/kg (0.26–0.67 pCi/kg), and 0.25–1.9 µg/kg (0.17–1.3 pCi/kg), respectively (Fisenne and Welford 1986; Fisenne 1988; Singh et al. 1986b). These differences reflect dietary variations.

Workers engaged in the extraction and processing of uranium are occupationally exposed to uranium. Industries where uranium exposures are known to have occurred are uranium mining and milling, uranium conversion and enrichment, uranium fuel fabrication, and nuclear weapons production.

Epidemiologic surveys were initiated in the United States as early as 1950 to study the effects of uranium exposure on uranium millers, and similar studies were performed of workers at the Oak Ridge Gaseous Diffusion Plant in Oak Ridge, Tennessee, where uranium conversion and enrichment were performed. Those studies attributed the health decrement to radon progeny and other toxicants and not directly to the uranium (BEIR IV 1988).

Exposure to enriched uranium, used as a uranium fuel in nuclear energy production, may present a combined chemical and radiological health hazard. However, access to enriched or high specific activity uranium is strictly regulated by the USNRC and the DOE. Therefore, the potential for significant human exposure to enriched uranium should be limited to rare accidental releases in the workplace.

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 Section 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 (NRC 1993).

As for adults in the general population, small exposures occur from normal ingestion of food and drinking water and inhaling air. These exposures may be higher in areas with naturally high uranium soil levels or near uranium processing sites and hazardous waste sites containing uranium. Levels of uranium measured between 1999 and 2008 in the urine of various ages of the U.S. population from NHANES are listed in Tables 6-7 and 6-8 (CDC 2012). Concentrations measured in children aged 6–11 and 12–19 years were similar to those measured in adults aged ≥20 years, across all years.

A study of uranium content in bone from three age groups (<13, 13–20, and 20–25 years old) reported somewhat higher uranium content in the youngest compared to the oldest age group (approximately 1.5–3-fold); however, there were only 2–4 subjects in each group and the results were not statistically significant (Broadway and Strong 1983). No information on uranium levels in amniotic fluid, meconium, cord blood, neonatal blood, or breast milk was located.

At hazardous waste sites, uranium 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 and eating contaminated dirt will result in oral exposure to uranium. The hazard in this case depends on the form of uranium present at the waste site. Soluble uranium compounds (e.g., uranyl nitrate) are absorbed by the gastrointestinal tract to a much greater degree than insoluble uranium compounds (e.g., insoluble oxides of uranium), and a large toxicity database in animals supports the higher toxicity of the soluble forms (see Chapter 3). Uranium in soil at non-hazardous waste sites is almost entirely (>99%) in the form of insoluble oxides of uranium, which have very low bioavailability.

As for adults, the potential for uranium exposure is greater for children who consume foods grown in areas with elevated concentrations of uranium in the soil and for children with elevated concentrations of uranium in their drinking water (EPA 1985c; NCRP 1984a). Other home exposures are unlikely since no household products or products used in crafts, hobbies, or cottage industries contain significant amounts of uranium, except in cases where uranium-bearing rocks are used in and around the home for decorative, collection, or construction purposes (Agency for Toxic Substances and Disease Registry 1997).

No information is available on whether children differ from adults in their weight-adjusted intake of uranium. The fractional absorption of uranium (as uranyl nitrate and uranyl citrate) by the oral route was

higher in neonatal than in adult rats and swine (Sullivan 1980b; Sullivan and Gorham 1982). In a mathematical model developed by the ICRP for risk assessment, one of the assumptions is that the fractional absorption of ingested uranium is twice as high in children under the age of 1 year compared to adults.

Uranium exposure to children from parents' work clothes, skin, hair, tools, or other objects from the workplace is possible if the parent uses uranium at work. However, in a comprehensive review of incidents of home contamination by workers (NIOSH 1997), no cases of uranium contamination were described.

As a radionuclide, uranium is potentially genotoxic and thus, it is important to know if parental exposure to uranium could affect the developing fetus or germ cells. However, epidemiological studies of workers exposed to uranium show no evidence of genotoxic effects. This is most likely due to the very low specific activity, the low systemic absorption of uranium, and the lack of concentration of uranium in the germ cells. Genotoxic effects to parental germ cells or to a developing fetus are not likely at probable levels of exposure to uranium from the environment or at hazardous waste sites. Some uranium is stored in bone, but it is not known if this uranium is released during pregnancy and lactation, when it could result in exposure to the fetus or infant.

6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Higher rates of uranium exposure have been reported for some populations. The potential for uranium exposure is greater for individuals who consume foods grown in areas with elevated concentrations of uranium in the soil, and for individuals with elevated concentrations of uranium in their drinking water (EPA 1985c; NCRP 1984a; Orloff et al. 2004). Industries where higher exposures to uranium are known to occur include uranium mining and milling, uranium conversion and enrichment, uranium fuel fabrication, and nuclear weapons production (BEIR IV 1988; Miller 1977; NCRP 1984a; West et al. 1979). Other groups with the potentially higher exposures include persons involved in producing and using phosphate fertilizers and individuals living and working near fossil fuel plants (Jaworowski and Grzybowska 1977; NCRP 1984a; Tadmor 1986; Weissman et al. 1983). Uranium compounds were previously used in dental appliances, and individuals with dental work of this kind have potentially higher exposures (Sairenji et al. 1980).

The use of depleted uranium in high-density tank armor and armor piercing munitions may result in higher exposures of military personnel who are located in, or nearby, an armored vehicle penetrated by a depleted uranium munition (kinetic energy penetrator) during combat. The primary routes of exposure to depleted uranium include inhalation of aerosols formed during the high energy collisions of depleted uranium munitions with vehicle armor, embedding of depleted uranium fragments in wounds to the body, and ingestion resulting from contact with depleted uranium residue on contaminated surfaces (Parkhurst and Guilmette 2009a; Szrom et al. 2009). The handling of coated and intact depleted uranium plates and unfired depleted uranium munitions should not result in exposure to uranium.

The Capstone Depleted Uranium Aerosol Characterization and Risk Assessment Study, begun in November 2000, was conducted to determine the level of exposure to depleted uranium aerosols resulting from perforation of armored Abrams Tanks and Bradley Fighting Vehicles with large caliber depleted uranium munitions (Guilmette and Parkhurst 2007; Parkhurst and Guilmette 2009a). Results of the Capstone study show mean depleted uranium concentrations measured inside the unventilated combat vehicles ranging from 3.0 to 16 g/m^3 10 seconds after perforation and falling to 0.020–0.15 g/m^3 within 30 minutes (Parkhurst et al. 2009). Levels were much lower in a ventilated Abrams tank with a maximum concentration of 0.22 g/m^3 measured 1 minute after perforation and 0.011 g/m^3 after 30 minutes (Guilmette and Parkhurst 2007; Parkhurst et al. 2009). Based on the aerosol measurements, median inhalation intakes of depleted uranium were determined to be 10–280 mg for a combat vehicle crew member exiting 1 minute after perforation, 43–710 mg for a combat vehicle crew member exiting 5 minutes after perforation, and 27–200 mg for a first responder entering 5 minutes after perforation and remaining in the combat vehicle for 10 minutes (Guilmette et al. 2009; Parkhurst and Guilmette 2009b). A depleted uranium inhalation intake rate ranging from 0.447 to 14.5 mg/hour was estimated for military personnel and civilian employees located near vehicles containing depleted uranium fragments but not directly involved in the perforation incident (Szrom et al. 2009). Ingestion intake rates for these individuals were estimated to be 1.78–38.9 mg/hour resulting from hand-to-mouth transfer from contact with depleted uranium contaminated surfaces (Szrom et al. 2009).

Depleted uranium was reportedly used in the military conflicts in Iraq during 1991 and 2003, in Bosnia during 1994, and in Kosovo during 1999 (Oeh et al. 2007b). Several studies have monitored the levels of uranium in the urine of individuals with reported exposure to the depleted uranium used during these conflicts (Hooper et al. 1999; McDiarmid et al. 1999b, 2001b, 2004a; Miller et al. 2008; Oeh et al. 2007a, 2007b; Toohey 2003). Table 6-9 lists urinary concentrations measured in these studies. In general, the levels of uranium measured in the urine of individuals reporting exposure were not different than levels in

Table 6-9. Urinary Levels of Uranium in Individuals Exposed through Military Use of Depleted Uranium

Location	Number of individuals	Concentration (µg U/g creatinine)			Reference
		Mean	Minimum	Maximum	
U.S. Gulf War veterans, 1993–1994					Hooper et al. 1999
Reported depleted uranium exposure without embedded fragments	10	0.03	—	—	
With embedded depleted uranium fragments	15	4.47	—	22.48	
1997					McDiarmid et al. 1999b; Toohey 2003
Non-exposed	22	0.02	0.01	0.05	
Reported depleted uranium exposure[a]	29	3.59	0.01	30.74[a]	
1997–1999					Toohey 2003
With embedded depleted uranium fragments (30–840 mg)	7	—	0.46	24.77	
1998–1999					McDiarmid et al. 2001b
Reported depleted uranium exposure	169	0.01[b]	0.001	0.432	
1998–2002					McDiarmid et al. 2004a
Reported depleted uranium exposure without embedded fragments	440	0.001	0.005[c]	0.042[d]	
With embedded depleted uranium fragments	6	0.083	0.008[c]	2.895	
Peacekeepers and residents in Kosovo, 1999–2006					Oeh et al. 2007a, 2007b
German peacekeepers	726	0.0139	0.006	0.1715	
Kosovo residents	25	0.0251	0.00292	0.2668	
Unexposed controls from southern Germany	63	0.0128	0.0014	0.775	
British Forces					Miller et al. 2008
Military personnel not having served in Iraq	732	0.0027[b]	<0.001	0.556	

[a]All values >1.0 µg U/g creatinine occurred in nine veterans containing embedded fragments.
[b]Median value.
[c]10th percentile value.
[d]95th percentile value.

non-exposed individuals. A notable exception is seen with individuals having depleted uranium-containing fragments embedded within their bodies (Hooper et al. 1999; McDiarmid et al. 1999b, 2004a; Toohey 2003). Measured urinary uranium levels in these individuals are consistently elevated, reaching as high as 30 μg U/g creatinine.

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 uranium is available. Where adequate information is not available, ATSDR, in conjunction with 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 uranium.

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. Pertinent data on the physical and chemical properties of uranium and uranium compounds are available in the literature.

Production, Import/Export, Use, Release, and Disposal. According to the Emergency Planning and Community Right-to-Know Act of 1986, 42 U.S.C. Section 11023, industries are required to submit substance release and off-site transfer information to the EPA. The TRI, which contains this information for 2010, became available in May of 2008. This database is updated yearly and should provide a list of industrial production facilities and emissions.

Data regarding the past and present production (ABMS 1994; EPA 1985a) and import/export volumes (USDOC 1995) for uranium are available. The uses of uranium and uranium compounds are well known (Clayton and Clayton 1981; EPA 1985c). Other than glazed ceramic foodware and decorative items (Landa and Councell 1992) and dental appliances (Sairenji et al. 1980), consumer contact with uranium

products is negligible. Since uranium is not covered under SARA, Title III, manufacturers and users are not required to report releases to the EPA. There is a lack of data on the release and disposal of uranium during mining, milling, and chemical processing and its use during fuel cycle operations. The disposal of uranium is governed by the USNRC regulations (10 CFR 61), and releases of uranium to the environment are governed by USNRC and EPA regulations (10 CFR 20, Appendix B; 40 CFR 190; 40 CFR 192). Since significant amounts of depleted uranium are used on modern battlefields, it would be useful to have more information on the export of depleted uranium to other nations, the disposal of related wastes in the United States, and the mass of depleted uranium released to long-distance air transport when projectiles are used against different target types.

Environmental Fate. For solids, there is a need to determine uptake factors into edible portions of plants and not just adherence to the root structure. For the solid-liquid interface, a method is needed to determine a method by which ^{234}U to ^{238}U ratio deviates from unity such that the EPA ERAMS water sample results indicate disequilibrium. Uranium enters the atmosphere in particulate form from natural sources and from uranium mining, milling, and processing. Dry or wet deposition from the atmosphere to soil and water can occur (Essien et al. 1985). Little experimental data on the particle size and residence time of uranium and uranium compounds present in ambient atmospheres are available. Additional data regarding the measured particle size of uranium compounds in ambient air, settling velocity, and knowledge of the chemical forms and lifetime of the particles in air would be useful. Although some studies have characterized the oxidation states and chemical forms of some uranium compounds (UO_2 and UO_3) (Dodge and Francis 1994; Wersin et al. 1994), more data identifying the chemical forms of uranium in the environment are needed to better understand the fate and transport of uranium. Since significant amounts of depleted uranium are used on modern battlefields, it would be useful to have more information on the export of depleted uranium to other nations and the disposal of related wastes in the United States, as well as estimates of projectile quantities that aerosolize to a significant extent and associated downwind air contamination levels.

Bioavailability from Environmental Media. The absorption and distribution of uranium as a result of inhalation and ingestion exposures have been discussed in Sections 3.5.1 and 3.5.2. However, quantitative data relating to physical/chemical properties such as particle size, chemical form, and degree of absorption with the bioavailability of uranium from inhaled air particles and inhaled and/or ingested soil particles, are lacking. Such studies would be useful in assessing potential public health impact of uranium to people living near a hazardous waste site.

Food Chain Bioaccumulation. Information about uranium bioaccumulation in fish (Mahon 1982; Poston 1982; Swanson 1983; Waite et al. 1988) is available. Data concerning levels of uranium in various foods (EPA 1985c) are also available. These data indicate that uranium does not biomagnify in the food chain (Ahsanullah and Williams 1989; Morishima et al. 1977; Swanson 1983, 1985). Data on the levels of uranium in food grown in contaminated areas are limited. Additional data are needed on whether the uptake of uranium in fish is restricted to the gills and how much actually distributes to the meat.

Exposure Levels in Environmental Media. Reliable monitoring data for the levels of uranium in contaminated media at hazardous waste sites are needed so that the information obtained on levels of uranium in the environment can be used in combination with the known body burden of uranium to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

The levels of uranium in airborne particles and precipitation have been monitored since 1973 (EPA 1994). Data from several large studies of uranium in domestic water supplies are available (Cothern and Lappenbusch 1983; DOE 1981b), as are data from studies of groundwater and surface water (NCRP 1984a). The primary source of information on the occurrence of uranium in drinking water is the National Inorganics and Radionuclides Survey (NIRS) conducted by EPA (EPA 1991b). Some monitoring data are available for uranium-contaminated soils and sediments associated with the nuclear fuel cycle. Better information on background levels in the environment and speciation of uranium in soils and sediments would be useful for determining which species lead to actual public exposure.

Exposure Levels in Humans. Although some data on the urinary levels of uranium in humans exposed to natural background levels (food, water, and air) are available (CDC 2012), these data are nationally representative and do not reflect high exposures, such as those experienced in the Southwest area of the United States. Biomonitoring studies are needed in areas with higher natural uranium exposure to develop a baseline for comparison. Additionally, there are limited data on the uranium content in human tissues in the general population and in populations living in areas with higher background uranium levels. The principal source of information about occupationally exposed individuals is the U.S. Transuranium and Uranium Registries (USTUR) Tissue Program and database, established to document uranium levels and distribution in human tissues for occupationally exposed workers (PNL 1981). Several major database files are available. The Radiochemical file contains information about radiochemical analysis of tissue donations from occupationally exposed individuals. The Health Physics file contains bioassay and other health physics data. These two databases are

regularly updated. The Medical file contains abstracted personal, medical, and clinical data; the Pathology file contains autopsy and pathology information; and the Skeletal Estimate file contains estimated actinide concentrations for unanalyzed half skeletons from donors (USTUR 1999).

This information is necessary for assessing the need to conduct health studies on these populations.

Exposures of Children. Children will be exposed to uranium in the same manner as adults in the general population (i.e., ingestion of food and water and inhalation of air). Concentrations measured in the urine of children aged 6–11 and 12–19 years during the National Health and Nutrition Examination Survey (NHANES) were similar to those measured in adults aged 20 years and older (CDC 2012), across all years. A study of uranium content in bone from three age groups (<13, 13–20, and 20–25 years old) reported somewhat higher uranium content in the youngest compared to the oldest age group (approximately 1.5–3-fold); however, there were only 2–4 subjects in each group and the results were not statistically significant (Broadway and Strong 1983). Since the skeletons of children are growing (higher rate of bone formation), it is possible that a higher fraction of circulating uranium will be deposited in bone than in adults. Further information is needed on bone levels of uranium in children to determine if this is the case. Uranium is found in all soil, and at potentially higher levels at some hazardous waste sites. Since children may have oral exposure to soil through hand-to-mouth activity, bioavailability studies of uranium in soil may be useful to assess the risk of this type of exposure. There is some evidence that neonatal animals absorb uranium in the gastrointestinal tract to a greater extent than adults. Experiments to confirm this finding and to determine how long into maturation a difference exists would help refine risk assessment for uranium exposure in children.

Child health data needs relating to susceptibility are discussed in Section 3.12.2, Identification of Data Needs: Children's Susceptibility.

Exposure Registries. A voluntary exposure registry, the USTUR for occupationally exposed individuals, was established at Richland, Washington, in 1968 as the National Plutonium Registry for investigation of the potential hazards for occupational exposure to uranium. In 1971, additional radiochemistry support was provided by Los Alamos National Laboratory. The U.S. Uranium Registry was created as a separate entity in 1978, and the two registries operated in parallel until 1987, when a single director was given responsibility for both registries. In 1992, the management and operation of the registries was combined at Washington State University under a grant from the U.S. DOE. The primary goals are to develop information on the distribution and dose of uranium and transuranic elements in

humans, providing data for verification or development of radiation protection standards, and to determine and evaluate health effects due to exposure to these radioactive elements.

6.8.2 Ongoing Studies

Ongoing studies are examining the levels of potential exposure to depleted uranium used for military purposes.