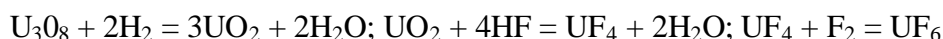


Annex 1 Process of uranium enrichment

After mineral extraction, processed uranium ore (or more exceptionally uranium generated from the recycling of nuclear fuel or reactor materials) undergoes a variety of chemical processes leading to enhancement with respect to both the total concentration and chemical purity of the produced uranium compounds. Following this chemical treatment, the purified uranium may be isotopically enriched, if required, by a number of processes including gaseous diffusion, centrifugation or laser excitation (e.g. Weigel, 1983). Such enrichment is now almost exclusively for the nuclear power industry. Depleted uranium is produced in various forms as a by-product of the isotopic enrichment of uranium (Figure A1.1). In the most common isotopic enrichment process (gaseous diffusion) uranium is required in the form of uranium hexafluoride (UF₆) which may be produced via the following chemical reactions:



At atmospheric pressure, UF₆ exists as a gas above 57°C, and as a solid below this temperature. It sublimes, as does carbon dioxide without passing through a liquid state.

Chemically, UF₆ is highly reactive with water forming water soluble hydrofluoric acid (HF) and uranyl fluoride (UO₂F₂), the former of which is considered to be highly toxic. For this reason DU, produced as a by-product of the enrichment processes in the form of UF₆, is often re-converted to less hazardous forms. These include uranium oxides (UO₂ or U₃O₈) which are more chemically stable and suitable for long-term storage or disposal, or to U metal (AEPI, 1995).

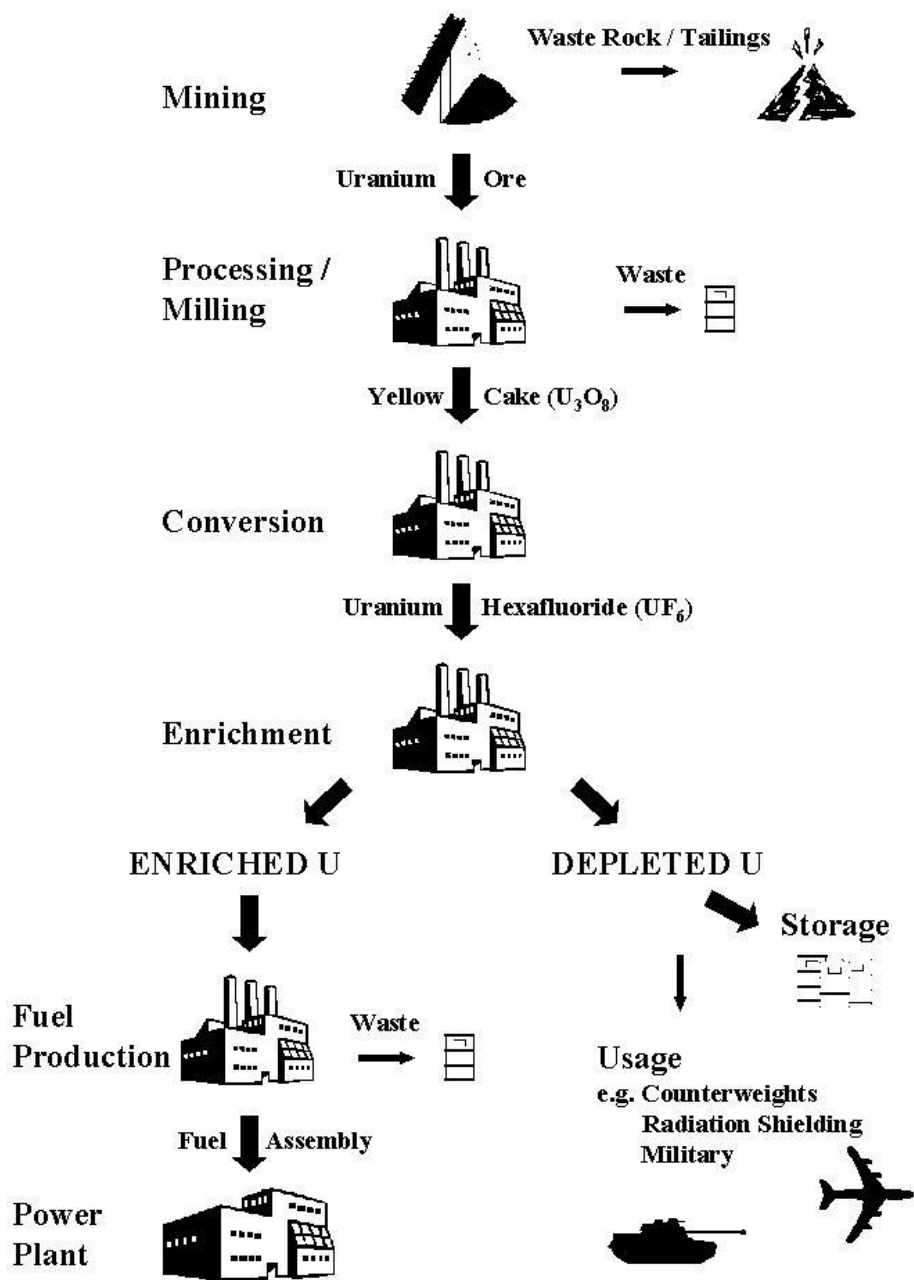


Figure A1.1 Schematic diagram showing various manufacturing routes leading to the production and use of enriched and DU. Note (a) DU is often stored as UF_6 and typically converted to metallic DU prior to the production of fuel, weapons, counterweights etc. (b) yellowcake is a generic term and is often used to describe other uranium compounds such as diuranate or mixtures of diuranate and oxides, (c) reprocessed uranium may enter the process at the enrichment stage.

Annex 2 Radiological dose due to other nuclides

The OSAGWI report has stated that the trace levels of transuranics and fission products in DU contribute less than 1% of the total dose. A simple assessment has been carried out based on measurements of the specific activity of ^{99}Tc , ^{237}Np , ^{238}Pu , $^{239/240}\text{Pu}$ and ^{241}Am given by TACOM (Bhat, 2000). TACOM analysed 60 samples of DU from three different sources, in this assessment the highest measured value is used for each radionuclide, even though these values did not usually occur in the same sample. Committed effective doses were calculated on the basis of the default dose coefficients given in ICRP-68 (1994b), assuming Type M solubility and an aerosol of 5m AMAD. It is found that the dose from transuranics and fission products is about 0.1% of the dose from DU itself, thus confirming the OSAGWI assertion. Although ^{99}Tc has by far the highest specific activity (as high as 500 pCi/g DU compared to less than 3 pCi/g DU for ^{239}Pu), its lower dose coefficient means that it is not as important as the transuranics. Each of the transuranic radionuclides given above contributes roughly equal parts to the total dose from transuranics.

Table A2.1 Radioactive dose from transuranics and fission product contaminants in DU (for inhalation by worker of 5 μm ; Type M particles)

Nuclide	pCi/g*	Bq/mg	e(50)**	E/mg DU
^{241}Am	19	7.03×10^{-4}	2.70×10^{-5}	1.90×10^{-8}
^{237}Np	3.7	1.37×10^{-4}	1.50×10^{-5}	2.05×10^{-9}
^{238}Pu	2	7.40×10^{-5}	3.00×10^{-5}	2.22×10^{-9}
$^{239/240}\text{Pu}$	2.7	9.99×10^{-5}	3.20×10^{-5}	3.20×10^{-9}
^{99}Tc	540	2.00×10^{-2}	3.20×10^{-9}	6.39×10^{-11}
Total				2.62×10^{-8}
% of DU dose				0.11%
DU		14.8	1.68×10^{-6}	2.49×10^{-5}

* highest of highest values of the 3 billets (R K Bhat, Encl. 1; Bhat, 2000)

** ICRP-68, Inhalation, Type M, 5 μm AMAD

Note: % of total DU dose for (a) worker 1 μm particle Type M = 0.13% and (b) member of the public 1 μm particle, Type M = 0.09%

Annex 3 Uranium in the environment, food and reference data.

A3.1 Uranium production

Table A3.1 Uranium production in 1998 (British Geological Survey, 2000)

Country	Tonnes
Argentina	35
Australia	4 901
Canada	11 041
China	500
Czech Republic	611
France	508
Gabon	731
India	200
Kazakhstan	1 250
Namibia	2 778
Niger	3 713
Pakistan	23
Portugal	19
Romania	100
Russia	2 000
South Africa	965
Spain	255
Ukraine	500
USA	1 872
Uzbekistan	1 930
World Total	33 900

A3.2 Uranium levels in the environment

Table A3.2 A selection of typical data on uranium concentrations determined in groundwaters, surface waters and drinking waters post-1980.

Country	Comments
Argentina	Bomben et al. (1996) determined the uranium concentrations in bottled mineral waters from Argentina to lie in the range 0.04 to 11 µg/l with a mean of 1.3 µg/l.
Brazil	DeCamargo and Mazzilli (1996) determined the concentrations of uranium in mineral waters from a high background region in Brazil to be 0.08 to 2.0 µg/l.
USA	Fisenne et al., (1987) determined the mean concentration of uranium in drinking water from New York City, USA, to range from 0.03 to 0.08 µg/l. A mean uranium concentration of 2.55 µg/l was reported in drinking water from 978 sites in the USA surveyed during the 1980s (US EPA, 1990; 1991). In Salt Lake City, USA the mean intake of uranium per day from drinking water has been estimated to be 1.5 µg (Singh, 1990).
Canada	In a survey of 130 sites in Ontario Canada conducted between 1990 and 1995, the mean of the average uranium concentrations in treated drinking water was 0.40 µg/l with a range of 0.05 to 4.2 µg/l (OMEE, 1996). In other areas of Canada private water supplies have been found with concentrations of up to 700 µg/l (Moss et al., 1983 and Moss, 1985). On the basis of the results from the OMEE survey of Ontario in 1996 the average daily intake of uranium from drinking water in Canada was estimated to be 0.8 µg (i.e. that based on the consumption of two litres of drinking water per day).
Himalayas	Virk, (1997) determined uranium concentrations in waters (springs, groundwaters and surface streams) from the western Himalayas to range from 0.89 to 63.4 µg/l.

Country	Comments
India	Singh et al (1995) Measured uranium in drinking waters from Punjab (Bathinda and Amritsar). Observed concentrations ranged from 11 to 113 µg/l. Singh et al, (1996) Measured uranium concentrations in 24 water samples collected from various important sources of drinking water in Upper Pradesh. Concentrations were found to lie between 0.87 and 11 µg/l.
Finland	The daily intake of uranium from waters in Finland, that are often sourced from fractured aquifers in granitic rocks or overlying sediments, has been estimated to be 2.1 µg (Kahlos and Asikainen, 1980). Salonen (1988) measured natural radionuclides in groundwaters in Finland and recorded an arithmetic mean concentration of uranium of 166 µg/l, a geometric mean of 26 µg/l and a maximum of 2900 µg/l amongst 58 water samples derived from wells drilled into bedrock.
Norway	A survey of groundwater derived from 28 private water supplies in Norway yielded uranium concentrations in the range <0.02 to 170 µg/l (Banks et al., 1995) An investigation of 145 hard-rock groundwater samples collected from private drinking water wells in the area of Oslo and Bergen yielded a median uranium concentration of 3.514 µg/l. The median values for the Oslo and Bergen areas were 3.378 µg/l and 3.720 µg/l respectively (Reimann et al., 1996).
Japan	In five Japanese cities, a mean uranium concentration of 0.009 µg/l was determined in potable drinking water supplies (Nozaki, 1970).
Jordan	Studies by Gedeon et al. (1994) and Smith et al. (2000) of 168 drinking water supply boreholes, principally in karstic limestone aquifers, gave a mean uranium concentration in drinking water supply wells of 2.4 µg/l with a wide range of <0.04 to 1400 µg/l. Average intakes were considered to be inappropriate because of the supply system in which supply to one area was often fed directly from a limited number of wells.
Cyprus	Studies undertaken in Cyprus in a variety of underground aquifers hosted in limestone, sandstone and alluvial deposits indicated an average uranium concentration in 215 drinking water and agricultural supply wells of 0.86 µg/l with a range of <0.005 to 38 µg/l Smith et al. (2000).
Kuwait	Studies by Bou-Rabee (1995) measured uranium concentrations in six drinking waters following the Gulf War (1991). Concentrations ranged from 0.02 to 2.48 µg/l and all samples had a ²³⁵ U/ ²³⁸ U ratio of 0.007 (typical for natural uranium = 0.007 25).
UK	Surveys of 35 groundwaters and spring waters in the United Kingdom (Edmunds et al., 1989) showed uranium concentrations in the range <0.1 to 10 µg/l across a variety of aquifers including those developed in sandstones, millstone grits, chalk, limestone and greensand. A high degree of variation was observed in most aquifers. Analysis of spring-waters from Derbyshire and closely associated millstone grits have shown ranges of <2 to 13 µg/l (Banks et al., 1997). The mean uranium concentration in over 100 000 surface waters throughout the UK has been determined to be 0.65 µg/l with a maximum observed concentration of 233 µg/l.
Pakistan	In the analysis of 16 groundwaters from Pakistan, an average uranium concentration of 1.6 µg/l was measured with a range of <0.05 to 5 µg/l (British Geological Survey, unpublished data)
Sea Water	Uranium is present in sea water at concentrations of about 3.3 µg/l (Kaye and Laby, 1993). In estuaries concentrations are generally positively correlated with salinity and in open Oceans range from 3.0 to 3.6 µg/l (Ivanovich and Harmon, 1982). Experimentation has shown it may be removed by a number of techniques such as ion exchange, ultra-filtration and reverse osmosis (Pramauro et al., 1996; Raff and Wilken, 1999).
Spain	Herranz et al. (1997, 1999) determined the mean uranium content of drinking water at four treatment plants serving municipalities in northern Spain to be 0.11 µg/l. The same authors observed a 60% drop in the uranium content of sewage effluent during the treatment process, indicating an increased uranium content in the sewage sludge.
Syria	Othman and Yassine (1996) measured uranium in drinking waters from 48 sites in Southern and Middle Syria. Highest observed values (approximately 14 µg/l) were observed in the vicinity of phosphate mines.
Uganda	Analysis of water samples collected from 139 drinking water supplies, mainly sited in highly weathered terrains overlying undifferentiated granitic basement rocks during studies of water quality in Uganda (Smith et al., 1996; Smith et al., 1998) indicate a range of uranium concentrations <0.05 to 17 µg/l with a mean of 0.59 µg/l (British Geological Survey, unpublished data).
Europe (Bottled Waters)	In a survey of 56 randomly selected bottled mineral waters Misund et al. (1999) observed uranium concentrations to range from 0.0104 to 9.45 µg/l.

Table A3.3 Concentrations of uranium observed in soils during recent studies.

Country	Comments
Czech Republic	Ledvina et al. (1996) undertook an analysis of uranium within soils in the former state farm of Trebon in Southern Bohemia which was felt to be potentially contaminated with uranium from a uranium processing plant and from naturally mineralized soils. Concentrations in the range of 14 to 50 mg/kg were observed in the most contaminated soils with an apparent baseline concentration of 2 to 4 mg/kg.
Brazil	Perez et al. (1998) determined the total uranium concentration in the A and B horizons of 15 Brazilian soils and found positive correlation between uranium concentration and the proportion of clay and iron oxides. A range of 0.001 to 2.115 mg/kg and 0.003 to 2.298 mg/kg were observed for A and B horizon soils respectively.
India	Singh et al. (1998) determined the uranium concentration in a range of contaminated soils (due to releases from fertilizer and thermal power plants) and soils from background areas of Uttar Pradesh, Rajasthan and Kerala (India). Their results indicated levels of between 0.24 and 9.20 mg/kg with the most elevated levels being recorded in the proximity of a coal-fired power plant.
Central Barents Region	Reimann et al. (1998) collected a suite of geochemical samples from 617 catchment areas 132 in Norway, 191 in Finland and 294 in Russia. Topsoil concentrations (0-5cm) were in the range of <0.5 to 30 mg/kg with a median of less than 0.5 mg/kg.
Lithuania	A geochemical survey of Lithuania by Kadunas et al. (1999), analysed 2700 topsoil samples which indicated levels across the country of between 0.7 and 5.0 mg/kg with a median of 1.7 mg/kg.
Kuwait	Bou-Rabee (1995) measured uranium in 12 soil samples collected following the gulf war. Uranium concentrations ranged from 0.30 to 1.85 mg/kg and had $^{235}\text{U}/^{238}\text{U}$ isotopic ratios in the range 0.006 to 0.007. Samples of dry deposition and oil fly-ash were also measured. In these samples concentrations of uranium ranged between 0.19 and 0.25 mg/kg in the fly-ash samples and 0.95 to 1.79 mg/kg in the dry deposition samples $^{235}\text{U}/^{238}\text{U}$ ratios ranged between 0.006 and 0.007 (typical natural uranium = 0.007 25).
Slovenia	Brajnik et al., (1988) measured natural radioactivity at a number of locations in Slovenia. Sites studied included soils associated with the underground uranium mine at Zirovski vrh, natural radioactivity associated with the coal-fired power stations at Ljubljana, Trbovlje and Sostanj and natural radioactivity (U, Ra and Rn) associated with phosphogypsum wastes. The latter source was found to dominate with respect to the contamination of sediment and water of the river Sava even in comparison with the impact of the uranium mine.
United Kingdom	Uranium concentrations in rural topsoils and profile soils have been determined as part of the British Geological Surveys G-BASE programme. Concentrations of uranium ranged from 0.05 to 76 mg/kg in profile soils over central and eastern England. Urban soils sampled in 5 major UK cities ranged from 0.25 to 5.50 mg/kg in topsoils and 0.25 to 9.2 mg/kg in profile soils (e.g. British Geological Survey, 1997)

A3.3 Uranium levels in food

Table A3.4 Average concentrations of uranium in various foodstuffs from New York City, adapted from (¹Fisenne et al., 1987; ²NCRP, 1984; ³US EPA, 1985).

Food Stuff	Concentration U (ng/kg)
Fresh vegetables	1900 ¹ 520–920 ²
Canned vegetables	340 ¹ 90–180 ²
Root vegetables	620 ¹ 940–1200 ²
Potatoes	72 ¹ 2660–2920 ² 15 000–18 000 ³
Dry Beans	2200 ¹ 1500–3670 ²
Fresh fruit	160 ² 710–1290 ²
Canned fruit	81 ¹ 180–290 ²
Fruit juice	49 ¹ 40–120 ²
Bakery products	1900 ¹ 1320–1500 ² 12000 ³
Flour	390 ¹ 250–680 ²
Whole grain products	1400 ¹ 1450 ²
Macaroni	300 ¹ 400–630 ²
Rice	240 ¹ 1430–6000 ² 15000 ³
Meat	190 ¹ 580–1320 ² 20000 ³
Poultry	64 ¹ 140–420 ²
Eggs	150 ¹ 230 ² 9600 ³
Fresh fish	110 ¹ 430–850 ² 11 000 ³
Shellfish	160 000 ¹ 9500–31 000 ²
Dairy products	59 ¹ 80–310 ²
Tea	5000 ³
Coffee	6000 ³
Drinking Water	49

Table A3.5 Typical concentrations of uranium in various foodstuffs and animal feed (wet weight) sampled in the United Kingdom, adapted from MAFF (1999). Where possible data, with the exception of grass and silage, refers to sampling sites remote from nuclear facilities.

Food Stuff	Concentration U (ng/kg)
Milk ¹	< 291 (max = 433)
Lettuce ²	5500
Potatoes ²	<1300
Strawberries ²	<670
Cabbage ²	<790 - 5500
Grass ³ (Drigg soil mean [U] = 1380000)	3000 (max = 3250)
Grass ³ (Capenhurst soil mean [U] = 1575000)	7100 (max = 18 500)
Grass ³ (Springfields soil mean [U] = 3900000)	78 700 (max = 300 000)
Silage ³ (Capenhurst)	5100 (max = 8700)
Silage ³ (Springfields)	95 000 (max = 283 000)
Sea Fish ⁴	150
Crustaceans ⁴	1400
Crabs ⁴	1800
Lobsters ⁴	1400
Molluscs ⁴	35 000
Winkles ⁴	35 000

¹From MAFF (1999, table 11.7)

²From MAFF (1999, table 11.8)

³From MAFF (1999, tables 4.10, 4.15 and 4.16)

⁴From MAFF (1999, table A6.1)

A3.4 Dietary information for exposure assessment

Table A3.6 Typical per capita food consumption levels (Muir et al., 1995), based on North American families as used in US EPA risk assessment calculations. For information on regional diets and associated variations the reader should consult WHO (1997) – Food consumption and exposure assessment of chemicals) and WHO (1998c) – GEMS/FOOD Regional Diets.

Foodstuff	Consumer Group	Consumption (kg/y)
Vegetables (spring mix)	Average American Family	96
Vegetables (summer mix)	Average American Family	160
Vegetables (autumn mix)	Average American Family	430
Vegetables (winter mix)	Average American Family	160
Fruit (spring mix)	Average American Family	66
Fruit (summer mix)	Average American Family	170
Fruit (autumn mix)	Average American Family	95
Fruit (winter mix)	Average American Family	73
Total milk	Average Infant (age under 8)	180
Total milk	Average Adult (age 19–64)	110
Total meat	Average Infant (age under 8)	40
Total meat	Average Adult (age 19–64)	86
Total poultry	Average Infant (age under 8)	5.1
Total poultry	Average Adult (age 19–64)	10

Table A3.7 Consumption rates for terrestrial foods in the United Kingdom based on national statistics (MAFF, 1999) For more detailed information on regional diets and associated variations see WHO (1997) – Food consumption and exposure assessment of chemicals) and WHO (1998c) – GEMS/FOOD Regional Diets.

Foodstuff	Average / Above Average Consumption rates (kg/y) (Above Average = 97.5 th percentile across all consumers)	
	Adult	Infant
Beef	15 / 45	3 / 10
Cereals	50 / 100	15 / 30
Eggs	8.5 / 25	5 / 15
Fruit	20 / 75	9 / 35
Game	6 / 15	0.8 / 2.1
Green vegetables	15 / 45	3.5 / 10
Honey	2.5 / 9.5	2 / 7.5
Lamb	8 / 25	0.8 / 3
Legumes	20 / 50	3 / 10
Milk	95 / 240	130 / 320
Mushrooms	3 / 10	0.6 / 1.5
Nuts	3 / 10	1 / 2
Offal	5.5 / 20	1 / 5.5
Pork	15 / 40	1.5 / 5.5
Potatoes	50 / 120	10 / 35
Poultry	10 / 30	2 / 5.5
Root crops	10 / 40	5 / 15
Wild fruit	7 / 25	1 / 2

Table A3.8 Body weights and volumes for intake for 'reference man' to be used when site specific data is unavailable as described in WHO (1994). Note: these data are based on ICRP-23, (1974) unless otherwise indicated.

Body weight, kg: Adult male = 70; Adult Female = 58; Average = 64a

Daily fluid intake (milk, tap water, other beverages), ml/day

Normal conditions:

Adults = 1000–2400, representative figure = 1900^b (excluding milk: 1400^c)

Adult male = 1950

Adult female = 1400

Child (10 years) = 1400

High average temperature (32° C):

Adults = 2840–3410

Moderate activity:

Adults = 3700

Respiratory volumes

8-h respiratory volume, m³

Resting Light/non-occupational activity:

Adult man = 3.6

Adult man = 9.6

Adult woman = 2.9

Adult woman = 9.1

Child (10 years) = 2.3

Child (10 years) = 6.24

Daily inhalation volume, m³

(8-h resting, 16-h light/non-occupational activity)

Adult male = 23

Adult female = 21

Child (10 years) = 15

Average adult = 22

Proportion of time spent indoors^c = 20 h/day

Amount of soil ingested^d: 20 mg/day

Dietary intake^d

Cereals = 323 g/day (flour and milled rice)

Starchy roots = 225 g/day (sweet potatoes, cassava and other)

Sugar = 72 g/day (includes raw sugar, excludes syrups and honey)

Pulses and nuts = 33 g/day (includes cocoa beans)

Vegetables and fruits = 325 g/day (fresh equivalent)

Meat = 125 g/day (includes offal, poultry and game in terms of carcass weight)

Eggs = 19 g/day (fresh equivalent)

Fish = 23 g/day (landed weight)

Milk = 360 g/day (excludes butter; includes milk products as milk equivalent)

Fats and oils = 31 g/day (pure fat content)

Footnotes:

^a WHO uses 60 kg for calculation of acceptable daily intakes and water quality guidelines (WHO, 1987, 1993).

^b WHO uses a daily per capita drinking-water consumption of two litres in calculating water quality guidelines (WHO, 1993)

^c from Health and Welfare Canada (1992)

^d based on average of estimates for seven geographical regions (ICRP, 1974)

A3.5 Uranium chemistry

Table A3.9 Details of some selected uranium and uranium compounds.

Compound	CAS	NIOSH/ RTECS	UN	Molecular formula	Molecular weight	Solubility * in cold water	Solubility class**
Uranium	7440-61-1	YR3490000	2979	U	238	i	Insoluble
Uranium dioxide	1344-57-6			UO ₂	270	i	Moderately soluble
Uranium hexafluoride	7783-81-5	YR4720000	2977	UF ₆	352	s	Highly soluble
Uranium peroxide	19525-15-9			UO ₄	302	-	Moderately soluble
Triuranium octaoxide	1317-99-3	YR3400000		U ₃ O ₈	842	i	-
Uranium tetrachloride	10026-10-5	YR4025000		UCl ₄	380	-	-
Uranium tetrafluoride	10049-14-6	YR4710000		UF ₄	314	-	Highly to moderately soluble
Uranium trioxide	1344-58-7			UO ₃	286	i	Moderately soluble
Uranyl acetate	541-09-3	YR3675000	9180	UO ₂ (C ₂ H ₃ O ₂) ₂	388	8	Moderately soluble
Uranyl chloride	7791-26-6	YR420000	2981	UO ₂ Cl ₂	341	320	Moderately soluble
Uranyl nitrate	10102-06-4	YR3805000		UO ₂ (NO ₃) ₂	394	119	Highly soluble
Uranyl sulphate	1314-64-3			UO ₂ SO ₄	366	19	Slightly soluble
Uranium carbonate				UO ₂ CO ₃	330	-	Highly soluble

i = insoluble

s = soluble

* The solubility (S) are expressed as 100 times the mass of anhydrous compound soluble in a unit mass of water at a temperature between 13 and 20 °C (data from Kaye and Laby, 1986). Note the solubility in biological fluids may differ significantly from those observed in pure water.

** These solubility classes are taken from Mirto et al., (1999).