4. CHEMICAL, PHYSICAL, AND RADIOLOGICAL INFORMATION

4.1 CHEMICAL IDENTITY

Uranium is a naturally occurring element that makes up approximately 2–4 ppm of the earth's crust. It is more plentiful than silver and about as abundant as molybdenum or arsenic. Uranium is an actinide element, and has the highest atomic mass of any naturally occurring element. In its refined state, it is a heavy, silvery-white metal that is malleable, ductile, slightly paramagnetic, and very dense, second only to tungsten. In nature, it is found in rocks and ores throughout the earth, with the greatest concentrations in the United States in the western states of Colorado, Arizona, Wyoming, Texas, Utah, and New Mexico (Lide 2008). In its natural state, crustal uranium occurs as a component of several minerals, such as carnotite, uraninite, and pitchblend, but is not found in the metallic state. The chemical information for uranium metal is listed in Table 4-1.

4.2 PHYSICAL, CHEMICAL, AND RADIOLOGICAL PROPERTIES

The physical properties of uranium and uranium compounds important in the nuclear fuel cycle and defense programs are listed in Table 4-2. The percent occurrence and radioactive properties of naturally occurring isotopes of uranium are listed in Table 4-3. The two decay series for the naturally occurring isotopes of uranium are shown in Table 4-4.

Metallurgically, uranium metal may exist in three allotropic forms: orthorhombic, tetragonal, or body-centered cubic (Lide 2008), and may be alloyed with other metals to alter its structural and physical properties to suit the application. Like aluminum metal powder, uranium metal powder is autopyrophoric and can burn spontaneously at room temperature in the presence of air, oxygen, and water. In the same manner, the surface of bulk metal, when first exposed to the atmosphere, rapidly oxidizes and produces a thin surface layer of UO_2, which resists oxygen penetration and protects the inner metal from oxidation. At temperatures of 200–400°C, uranium powder may self-ignite in atmospheres of CO_2 and N_2. In order to prevent autoignition, uranium machining chips can be stored in open containers and under machine oil or water to prevent hydrogen gas buildup. Burning uranium may be placed under water until extinguished, which may be delayed by hydrolysis of the water, which provides some oxygen and hydrogen for continued burning. Water spray, CO_2, and halon are ineffective, and halon discharge can be explosive and produce toxic gases (DOE 2001).

Table 4-1. Chemical Identity of Uranium Metal

	Value	Reference
Chemical name	Uranium	
Natural isotopes	Uranium-238; uranium-235; uranium-234	HSDB 2011
Synonyms	Uranium; 238U; 238U element; uranium-238; uranium-234; uranium-235; uranium, elemental; uranium, metal, pyrophoric; uranium, radioactive; uranium, natural	HSDB 2011
Trade names	No data	
Chemical formula	U	HSDB 2011
Chemical structure	Not applicable	
Identification numbers		
CAS registry	7440-61-1	HSDB 2011
NIOSH RTECS	NIOSH/YR3490000	NIOSH 2010a
EPA hazardous waste	No data	HSDB 2011
OHM/TADS	7217196	HSDB 1995
DOT/UN/NA/IMO shipping	UN2979; uranium metal, pyrophoric	HSDB 2011
HSDB	2553; 7404, uranium, radioactive	HSDB 2011
NCI	No data	HSDB 2011
STCC	4926187; uranium metal, pyrophoric (uranium metal scrap, neither irradiated nor requiring protective shielding)	HSDB 1995

CAS = Chemical Abstracts Service; DOT/UN/NA/IMCO = Department of Transportation/United Nations/North America/International Maritime Dangerous Goods Code; EPA = Environmental Protection Agency; HSDB = Hazardous Substances Data Bank; NCI = National Cancer Institute; NIOSH = National Institute for Occupational Safety and Health; OHM/TADS = Oil and Hazardous Materials/Technical Assistance Data System; RTECS = Registry of Toxic Effects of Chemical Substances; STCC = Standard Transportation Commodity Code

Table 4-2. Physical and Chemical Properties of Selected Uranium Compounds

Property	Uranium	Uranium dioxide	Uranium trioxide	Triuranium octaoxide	Uranium tetrafluoride
Atomic/molecular weight	238.0289[a]	270.028	286.027	842.08	314.023
Chemical formula	U	UO_2	UO_3	U_3O_8	UF_4
Synonyms	Uranium I[a]	Uranium(IV) oxide	Uranyl(VI) oxide	Uranium octaoxide; uranium oxide	Uranium(IV) fluoride[a]
Common names		Brown oxide	Orange oxide	Yellow cake; Block oxide	Green salt[a]
CAS Registry No.	7440-61-1[a]	1344-57-6	1344-58-7	1344-59-8	10049-14-6
Color	Silvery-white	Brown	Orange-yellow	Olive green-black	Green
Physical state	Solid[a]	Solid crystal	Solid crystal	Solid	Solid crystal
Odor	No data	No data	No data	No data	No data
Melting point, °C	1,135[a]	2,847	Decomposes	Decomposes at 1,300	1,036
Boiling point, °C	4,131[a]	~3,800°K	Not relevant	Not relevant	1,417
Autoignition temperature	20°C (cloud), 100°C [a] (layer)[a]	Not relevant	Not relevant	Not relevant	Not relevant
Solubility:					
Water	Insoluble	Insoluble	Insoluble	Insoluble	0.01 g/100 g H_2O
Other solvents	Soluble in concentrated acids; insoluble in alkalis, alcohols[a]	Soluble in concentrated acids	Soluble in acid	Soluble in HNO_3, H_2SO_4	Soluble in concentrated acids and alkalis
Density, g/cm^3	18.06–19.1[a]	10.97	~7.3	8.30	6.7
Partition coefficients	Not relevant	Not relevant	Not relevant	Not relevant	No data
Vapor pressure	0 mmHg at 20°C; 1 mmHg at 2,450°C [a]	0.463 atm at 2,847°C	Not relevant	Not relevant	Not relevant
Henry's law constant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Refractive index	No data	No data	No data	No data	No data
Flashpoint	No data	No data	No data	No data	No data
Flammability limits	Not relevant[a]	No data	No data	No data	No data
Conversion factor[b]	1 μg=0.69 pCi	1 μg=0.61 pCi	1 μg=0.57 pCi	1 μg=0.59 pCi	1 μg=0.45 pCi

Table 4-2. Physical and Chemical Properties of Selected Uranium Compounds

Property	Uranium hexafluoride	Uranium tetrachloride	Uranyl fluoride[c]	Uranyl acetate, dihydrate	Uranyl nitrate hexahydrate
Atomic/molecular weight	352.019	379.841	308.0245	424.146	502.129
Chemical formula	UF_6	UCl_4	UO_2F_2	$UO_2(CH_3COO)_2{\bullet}2H_2O$	$UO_2(NO_3)_2{\bullet}6H_2O$
Synonyms	Uranium(VI) fluoride	Uranium (IV) chloride	Uranium oxyfluoride; uranium fluoride oxide	bis(Acetate-B) dioxouranium	bis(Nitrate-O) dioxouranium; hexahydrate
Common names	No data	Green salt	No data	No data	No data
CAS Registry No.	7783-81-5	10026-10-5	13536-84-0[a]	6159-44-0	13520-83-7
Color	White crystalline[a]	Green	Yellow[a]	Yellow	Yellow
Physical state	Solid[a]	Octahedral crystal	Solid[a]	Solid crystal	Solid crystal
Odor	No data	No data	No data	No data	No data
Melting point, °C	64.5 at 2 atm[a]	590°C	Decomposes at 300	Loses $2H_2O$ at 110	60
Boiling point, °C	56.2 sublimation point[a]	791	Not relevant	Decomposes at 275	Decomposes at 118
Autoignition temperature	No data	No data	No data	No data	No data
Solubility:					
Water	Reacts with H_2O	Reacts with water	64.4 g/100 g at 20 °C	7.7 g/100 mL at 15 °C	127 g/100 gH_2O
Other solvents	Soluble in CCl_4, TCE, and chloroform[a]	Soluble in ethanol	Soluble in ethanol and benzene[a]	Soluble in ethanol	Soluble in ethanol and ether
Density g/cm^3	5.09 at 20.7°C; 3.595 at 70°C	4.72	6.37	2.893 g/cm^3 at 15°C	2.81 g/cm^3 at 13°C
Partition coefficients	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Vapor pressure	115 mmHg at 25°C [c]	No data	No data	No data	No data
Henry's law constant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Refractive index	No data	No data	No data	No data	1.4967
Flashpoint	No data	No data	No data	No data	No data
Flammability limits	No data	No data	No data	No data	No data
Conversion factor[b]	1 µg=0.47 pCi	1 µg=0.43 pCi	1 µg=0.53 pCi	1 µg=0.39 pCi	1 µg=0.33 pCi

Table 4-2. Physical and Chemical Properties of Selected Uranium Compounds

Property	Uranyl nitrate (not hexahydrate)	Ammonium diuranate	Uranium peroxide	Uranyl acetate
Atomic/molecular weight	394.037	624.131	302.03[a]	388.12[a]
Chemical formula	$(UO_2)(NO_3)_2$	$(NH_4)_2U_2O_7$	UO_4[a]	$C_4H_6O_6U$[a]
Synonyms	No data	Ammonium uranate(VI)	No data	No data
Common names	No data	No data	No data	No data
CAS Registry No.	10102-06-4	7783-22-4	19525-15-6[a]	541-09-3[a]
Color	Yellow	Reddish yellow	Pale yellow[a]	Yellow[a]
Physical state	Solid crystal	Amorphous powder	Solid	Solid crystals[a]
Odor	No data	No data	No data	Vinegar-like[a]
Melting point, °C	No data	No data	Decomposes at 90–195°C [a]	No data
Boiling point, °C	No data	No data	No data	Decomposes at <275[a]
Autoignition temperature	Not relevant	Not relevant	Not relevant	Not relevant
Solubility:				
Water	127 g/100 g H_2O	Insoluble	0.0006 g/100 cc at 20°C; 0.008 g/cc at 90°C [a]	7.694/100 mL at 15°C[a]
Other solvents	Soluble in ether	Insoluble in alkali; soluble in acids	No data	Very soluble in alcohol[a]
Density g/cm^3	No data	No data	11.66 (calculated)[a]	2.893 at 15°C[a]
Partition coefficients	No data	No data	No data	No data
Vapor pressure	No data	No data	No data	No data
Henry's law constant	No data	No data	No data	No data
Refractive index	No data	No data	No data	No data
Flashpoint	No data	No data	No data	No data
Flammability limits	No data	No data	No data	No data
Conversion factor[b]	1 μg ≡ 0.42 pCi	1 μg ≡ 0.52 pCi	1 μg ≡ 0.54 pCi	1 μg ≡ 0.42 pCi

[a]HSDB (2011).
[b]Calculated from National Nuclear Data Center data (NNDC 2011).
[c]Argonne National Laboratory (2011).

Source: Lide (2008), unless annotated

Table 4-3. Percent Occurrence and Radioactive Properties of Naturally Occurring Isotopes of Uranium

Isotope	Percent of total uranium in crustal rock		Alpha energies, keV (abundance)		Gamma energies, keV (abundance)		Half-life (years)
	By weight	By radioactivity					
^{234}U	0.0054	49.03	4772.4	(28.42%)	13.0	(10.0%)	2.455×10^5
			4774.6	(71.38%)			
^{235}U	0.7204	2.27	4214.7	(5.7%)	13.0	(37.00%)	7.038×10^8
			4366.1	(17.0%)	93.35	(5.60%)	
			4397.8	(55%)	143.76	(10.96%)	
			4556.0	(4.2%)	163.33	(5.08%)	
			4596.4	(5.0%)	185.715	(57.20%)	
			Others	(13.1%)	205.311	(5.01%)	
^{238}U	99.2742	48.70	4151	(21%)	4772.4	(28.42%)	4.468×10^9
			4198	(79%)	4774.6	(71.38%)	

Sources: NNDC 2011

Table 4-4. ^{235}U and ^{238}U Decay Series Showing Sources and Decay Products

	^{238}Uranium-238 series, includes uranium-234 series							Uranium-235 series				
Np												
U	^{238}U 4.47x 10^{9} y		^{234}U 2.46x 10^{5} y					^{235}U 7.04x 10^{8} y				
Pa	↓	^{234m}Pa 1.16 m	↓					↓	^{231}Pa 3.28x 10^{4} y			
Th	^{234}Th 24.1 d		^{230}Th 7.54x 10^{4} y					^{231}Th 25.5 h	↓	^{227}Th 18.7 d		
Ac			↓						^{227}Ac 21.8 y	↓		
Ra			^{226}Ra 1,600 y						↓	^{223}Ra 11.4 d		
Fr			↓						^{223}Fr 22.0 m	↓		
Rn			^{222}Rn 3.82 d							^{219}Rn 3.96 s		
At			↓	^{218}At 1.5 s						↓	^{215}At 1x10^{-4} s	
Po			^{218}Po 3.10 m		^{214}Po 1.64x 10^{-4} s		^{210}Po 138 d			^{215}Po 17.8x 10^{-3} s	↓	^{211}Po 0.5 s
Bi			↓	^{214}Bi 19.9 m	↓	^{210}Bi 5.01 d	↓			↓	^{211}Bi 2.14 m	↓
Pb			^{214}Pb 26.8 m	↓	^{210}Pb 22.2 y	↓	^{206}Pb stable			^{211}Pb 36.1 m	↓	^{207}Pb stable
Tl				^{210}Tl 1.30 m		^{206}Tl 4.20 m					^{207}Tl 4.77 m	

↓ = alpha decay; ↗ = beta decay; half-life (d = days; h = hours; m = minutes; s = seconds; y = years)

Sources: Aieta et al. 1987; Argonne National Laboratory 2005; half-life data from NNDC 2011

Uranium can exist in five oxidation states: +2, +3, +4, +5, and +6 (Lide 2008); however, only the +4 and +6 states are stable enough to be of practical importance. Tetravalent uranium is reasonably stable and forms hydroxides, hydrated fluorides, and phosphates of low solubility. Hexavalent uranium is the most stable state, and the most commonly occurring state is U_3O_8, although there are a few localized storage locations for anthropogenic uranium hexafluoride (UF_6) in the United States (DOE 2011a). Major compounds of uranium include oxides, fluorides, carbides, nitrates, chlorides, acetates, and others. One of the characteristics of UO_2^{+2} ions is their ability to fluoresce under ultraviolet light.

Although the element uranium was discovered in 1789 by Klaproth, who named it "uranium" after the newly discovered planet Uranus, it was not until 1896 that Becquerel discovered that uranium is radioactive. There are 22 known isotopes of uranium, only 3 of which occur naturally (NNDC 2011). These three isotopes, ^{234}U, ^{235}U, and ^{238}U, have relative mass abundances within the earth's undisturbed crustal rock of 0.005, 0.72, and 99.275%, respectively. One gram of natural uranium having this relative isotopic abundance has an activity of 0.69 μCi. Of this 0.69 μCi, 49.0% of the activity is attributable to ^{234}U, 2.27% of the activity is attributable to ^{235}U, and 48.7% of the activity is attributable to ^{238}U (Agency for Toxic Substances and Disease Registry 2011). This ratio is for undisturbed crustal rock only. Although the relative mass abundance of ^{234}U is only 0.005%, it accounts for approximately one-half of the total activity. The relative isotopic abundances given above can be altered to some extent by natural processes that are not fully understood, but which can cause different ratios in air, water, and soil as demonstrated in EPA reports (EPA 1994a, 2007).

^{235}U is an isotope of particular interest because it is fissile (capable of being fissioned) and, consequently, can sustain a nuclear chain reaction in the presence of appropriate energy neutrons. The predominant isotope of uranium found in nature, ^{238}U, is not readily fissionable, but a small portion of its transformations result in spontaneous fission rather than the typical alpha decay; these neutrons can be sufficient to initiate a chain reaction under appropriate concentration, mass, and neutron thermalization conditions. Consequently, for uranium to be used as a fuel in nuclear reactors, the ratio of ^{235}U to ^{238}U is increased from 0.72 to 2–4% by a process called enrichment. The enrichment process most used in the United States is called gaseous diffusion, but other enrichment processes involving thermal, centrifuge, and laser methods can be used, and other countries are actively involved in producing enriched uranium. Uranium ore is processed to uranium oxide (U_3O_8) and then fluorinated to UF_6; next, a stream of UF_6 gas containing all three isotopic compounds is passed through a long series of diffusion stages through which the ^{234}U and ^{235}U pass more quickly than the ^{238}U. Thus, the front end of the stream has an enhanced ^{235}U concentration and is called enriched uranium hexafluoride, while the back end of the stream has a reduced

^{235}U concentration and is called depleted uranium hexafluoride. The percent enrichment is a measure of the mass percentage of ^{235}U in the final product, and the degree of enrichment is determined by the use. Enriched UF_6 is typically converted to uranium metal or oxide for power reactor fuel or to metal for weapons applications. Depleted UF_6 is either converted to uranium metal for a variety of civilian and military applications or stored for future use. Low enriched uranium (2–4% enriched) is used in civilian nuclear power reactors (DOE 2000), while high enriched uranium (>90% enriched) is used in special research reactors (most of which have been removed from operation), nuclear submarine reactor cores, and nuclear weapons. Depleted uranium metal is used as radiation shielding, missile projectiles, target elements in plutonium production reactors, a gyroscope component, and counterweights or stabilizers in aircraft.

Uranium continuously undergoes transformation through the decay process whereby it releases energy to ultimately become a stable or nonradioactive element. For the uranium isotopes, this is a complex process involving the serial production of a chain of decay products, called progeny, until a final stable element is formed. The decay products of the uranium isotopes, which are also radioactive, are shown in Table 4-4. ^{238}U is the parent isotope of the uranium series (^{234}U is a decay product of ^{238}U), while ^{235}U is the parent isotope of the actinium decay series. All natural uranium isotopes and some of their progeny decay by emission of alpha particles; the other members of both series decay by emission of beta particles and gamma rays (NNDC 2011). Both the uranium and the actinium decay series have three features in common. Each series begins with a long-lived parent, ^{235}U or ^{238}U, each series contains an isotope of the noble gas radon, and each series ends with a stable isotope of lead, ^{207}Pb or ^{206}Pb.

The amount of time required for one-half of the atoms of a radionuclide to transform is called its radioactive half-life. The rate of decay, and thus the half-life, for each radionuclide is unique. The half-life of ^{238}U is very long, $4.5x10^9$ years; the half-lives of ^{235}U and ^{234}U are orders of magnitude lower, $7.0x10^8$ and $2.5x10^5$ years, respectively. Since the activity of a given mass of uranium depends on the mass and half-life of each isotope present, the greater the relative abundance of the more rapidly decaying ^{234}U and ^{235}U, the higher the activity will be. Thus, depleted uranium is less radioactive than natural uranium and enriched uranium is more radioactive.

Uranium is unusual among the elements because it is both a chemical and a radioactive material. The hazards associated with uranium are dependent upon uranium's chemical and physical form, route of intake, and level of enrichment. The chemical form of uranium determines its solubility and, thus, transportability in body fluids as well as retention in the body and various organs. Uranium's chemical toxicity is the principal health concern, because soluble uranium compounds cause heavy metal damage to renal tissue. The radiological hazards of uranium may be a primary concern when inhaled, enriched (DOE 2001) and insoluble uranium compounds are retained long-term in the lungs and associated lymphatics.