3. CHEMICAL AND PHYSICAL INFORMATION

3.1 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 (EPA 1991; Lide 1994). 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 3-1.

3.2 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 3-2. The percent occurrence and radioactive properties of naturally occurring isotopes of uranium are listed in Table 3-3. The two decay series for the naturally occurring isotopes of uranium are shown in Table 3-4.

Metallurgically, uranium metal may exist in three allotropic forms: orthorhombic, tetragonal, or body-centered cubic (EPA 1991), 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 EC, uranium powder may self-ignite in atmospheres of CO_2 and N_2. Oxidation of uranium under certain conditions may generate sufficient energy to cause a chemical explosion (Gindler 1973).

Table 3-1. Chemical Identity of Uranium Metal

	Value	Reference
Chemical name	Uranium	
Natural isotopes	Uranium-238; uranium-235; uranium-234	EPA 1985j
Synonyms	uranium-238; uranium-234; uranium-235; U	HSDB 1995
Trade names	No data	
Chemical formula	U	HSDB 1995
Chemical structure	Not applicable	
Identification numbers		
CAS registry	7440-61-1	HSDB 1995
NIOSH RTECS	NIOSH/YR3490000	HSDB 1995
EPA hazardous waste	No data	HSDB 1995
OHM/TADS	7217196	HSDB 1995
DOT/UN/NA/IMO shipping	UN2979; uranium metal, pyrophoric	HSDB 1995
HSDB	2553	HSDB 1995
NCI	No data	HSDB 1995
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 Commercial Code

Table 3-2. Physical and Chemical Properties of Selected Uranium Compounds

Property	Value				
	Uranium	Uranium dioxide	Uranium trioxide	Triuranium octaoxide	Uranium tetrafluoride
Atomic/molecular weight	238.0289	270.03	286.03	842.08	314.02
Chemical formula	U	UO_2	UO_3	U_3O_8	UF_4
Synonyms[a]	Uranium I	Uranium oxide	Uranyl oxide	Uranium octaoxide	Uranium fluoride
Common names		Brown oxide	Orange oxide	Yellow cake; Block oxide	
Chemical Abstracts Service Registry No.	7440-61-1	1344-57-6	1344-58-7	1344-59-8	10049-14-6
Color	Silvery	Brown-black	Yellow-red	Olive green-black	Green
Physical state	Solid	Solid	Solid	Solid	Solid
Odor	No data	No data	No data	No data	No data
Melting point, °C	1135	2878	Decomposes	Decomposes at 1300	960
Boiling point, °C	4131	No data	Not relevant	Not relevant	No data
Autoignition temperature	20% (cloud), 100 °C[e] (layer)	Not relevant	Not relevant	Not relevant	Not relevant
Solubility:					
Water	Insoluble	Insoluble	Insoluble	Insoluble	Very slightly soluble
Other solvents	Soluble in acids	Soluble in HNO_3	Soluble in HNO_3, HCl	Soluble in HNO_3, H_2SO_4	Soluble in concentrated acids and alkalis
Density, g/cm^3	18.95	10.96	7.29	8.30	6.70
Partition coefficients	Not relevant	Not relevant	Not relevant	Not relevant	No data
Vapor pressure	1 mmHg at 2450° C	Not relevant	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	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Flammability limits	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Conversion factor	1 µg = 0.67 pCi[d]	1 µg = 0.59 pCi[d]	1 µg = 0.56 pCi[d]	1 µg = 0.57 pCi[d]	1 µg = 0.45 pCi[d]

Table 3-2. Physical and Chemical Properties of Selected Uranium Compounds (continued)

Property	Value				
	Uranium hexafluoride	Uranium tetrachloride	Uranyl[c] fluoride	Uranyl acetate, dihydrate	Uranyl nitrate hexahydrate
Atomic/molecular weight	352.02	379.84	308.03	424.15	502.13
Chemical formula	UF_6	UCl_4	UO_2F_2	$UO_2(CH_3COO)_2 \cdot 2H_2O$	$UO_2(NO_3)_2 \cdot 6H_2O$
Synonyms[b]	UN2977; uranium fluoride (fissle)	Uranium (IV) chloride	Uranium oxyfluoride; uranium fluoride oxide	bis(Acetate-B) dioxouranium	bis(Nitrate-O) dioxouranium; hexahydrate
Common names		Green salt			
CAS Registry No.	7783-81-5	10026-10-5	13536-84-0	541-09-3	13520-83-7
Color	Colorless	Dark green	Pale Yellow	Yellow	Yellow
Physical state	Solid	Solid	Solid	Solid	Solid
Odor	No data	No data	No data	No data	No data
Melting point, °C	64.5–64.8	590	Decomposes at 300 °C	Loses $2H_2O$ at 110	60.2
Boiling point, °C	56.2	792	Not relevant	Decomposes at 275	Decomposes at 100
Autoignition temperature	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Solubility:					
Water	Decomposes	Soluble	Soluble	7.7 g/100 mL at 15 °C	Miscible in water at 60 °C
Other solvents	Soluble in CCl_4 and chloroform	Soluble in ethanol	Soluble in ethanol	Soluble in ethanol	Soluble in ethanol
Density, g/cm^3	4.68 at 21 °C	4.87	6.37	2.893 at 15 °C	2.807 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	Not relevant	No data	Not relevant	Not relevant
Flammability limits	No data	Not relevant	No data	Not relevant	Not relevant
Conversion factor	1 µg ≡ 0.45 pCi[d]	1 µg ≡ 0.42 pCi[d]	1 µg ≡ 0.52 pCi[d]	1 µg ≡ 0.38 pCi[d]	1 µg ≡ 0.32 pCi[d]

Table 3-2. Physical and Chemical Properties of Selected Uranium Compounds (continued)

Property	Value	
	Ammonium diuranate	Uranium peroxide
Atomic/molecular weight	624.22	302.03
Chemical formula	$(NH_4)_2U_2O_7$	UO_4
Synonyms[b]	Ammonium uranate(IV)	No data
CAS Registry No.	7783-22-4	19525-15-6
Color	Reddish yellow	Pale yellow
Physical state	Solid	Solid
Odor	No data	No data
Melting point, °C	No data	Decomposes
Boiling point, °C	No data	No data
Autoignition temperature	Not relevant	Not relevant
Solubility:		
Water	Practically insoluble	Decomposes
Other solvents	Soluble in acids	No data
Density, g/cm^3	No data	No data
Partition coefficients	No data	No data
Vapor pressure	No data	No data
Henry's law constant	No data	No data
Refractive index	No data	No data
Flashpoint	No data	Not relevant
Flammability limits	No data	Not relevant
Conversion factor	1 µg = 0.51 pCi[d]	1 µg = 0.53 pCi[d]

Source: Lide 1994, unless otherwise stated
[a]Synonyms were obtained from Chemline 1989
[b]Properties were obtained from HSDB 1989
[c]Cotton and Wilkinson 1980
[d]NCRP (1984) and EPA (1985b), based on natural U (values higher for enriched compounds, lower for depleted compounds)
[e]This value is obtained from HSDB 1995

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

Isotope	Percent of Total Uranium in Crustal Rock		Alpha energies, MeV (abundance)	Half-life (years)
	by weight	by radioactivity		
^{234}U	0.0055	48.9	4.776 (72.5%) 4.723 (27.5%)	2.45×10^{5}
^{235}U	0.720	2.2	4.597 (5%) 4.395 (55%) 4.370 (6%) 4.364 (11%) 4.216 (5.7%) Others (17.3%)	7.04×10^{8}
^{238}U	99.2745	48.9	4.196 (77%) 4.147 (23%)	4.46×10^{9}

Source: Lide 1994

Table 3-4. Uranium Isotope Decay Series Showing the Decay Products of the Naturally Occurring Isotopes of Uranium

	Uranium-238 Series, Includes ^{234}U Series							Uranium-235 Series				
Np												
U	^{238}U 4.5E9		^{234}U 2.5E5y					^{235}U 7.1E8 y				
Pa	↓	^{234}Pa 1.2 m	↓					↓	^{231}Pa 3.3E4 y			
Th	^{234}Th 24 d		^{230}Th 8E4y					^{231}Th 25.5 h	↓	^{227}Th 18.7 d		
Ac			↓						^{227}Ac 21.8 y	↓		
Ra			^{226}Ra 1600 y						↓	^{223}Ra 11.4 d		
Fr			↓						^{223}Fr 21.8 m	↓		
Rn			^{222}Rn 3.82 d							^{219}Rn 4.0 s		
At			↓	^{218}At 2s						↓	^{215}At 1E-4s	
Po			^{218}Po 3.05 m	↓	^{214}Po 1.6E-4s		^{210}Po 138 d			^{215}Po 1.8E-5	↓	^{211}Po 0.5 s
Bi			↓	^{214}Bi 19.7 m	↓	^{210}Bi 5.0 d	↓			↓	^{211}Bi 2.15 m	↓
Pb			^{214}Pb 26.8 m	↓	^{210}Pb 22.3y	↓	^{206}Pb stable			^{211}Pb 36.1 m	↓	^{207}Pb stable
Tl				^{210}Tl 1.3 m		^{206}Tl 4.2 m					^{207}Tl 4.79 m	

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

Source: NCRP 1975

Uranium can exist in five oxidation states: +2, +3, +4, +5, and +6 (Lide 1994); 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) (EPA 1991). 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 radio-active. There are 22 known isotopes of uranium, only 3 of which occur naturally (Parrington et al. 1996). 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 0.67 µCi. Of this 0.67 µCi, 48.9% of the activity is attributable to ^{234}U, 2.2% of the activity is attributable to ^{235}U, and 48.9% of the activity is attributable to ^{238}U (Lide 1994). This ratio is for undisturbed crustal rock only. Although the relative mass abundance of ^{234}U is only 0.005%, it accounts for exactly 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).

^{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% or enriched 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, while high enriched uranium (>90% enriched) is used in special research reactors (most of which have been removed from operation) (Weigel 1983), nuclear submarine reactor cores, and nuclear weapons. Depleted uranium metal (DU) 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 3-4. ^{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 actinide 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 (Cowart and Burnett 1994). Both the uranium and the actinide 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, 4.5×10^{9} years; the half-lives of ^{235}U and ^{234}U are orders of magnitude lower, 7.1×10^{8} years and 2.5×10^{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 (EPA 1991). 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 (>90%) and insoluble uranium compounds are retained long-term in the lungs and associated lymphatics.