# Chapter 1.  Introduction

Uranium is a common element in nature that has for centuries been used as a coloring agent in decorative glass and ceramics. Uranium and its radioactive decay products are ubiquitous in nature, and contribute to natural background radiation found everywhere. In fact, it is important to note that many of the natural occurrences of uranium present radiation hazards without any disturbance from miners. By far, the greatest uses of uranium have been defense and electric power generation. The advent of nuclear weapons and nuclear power in the United States resulted in a full-blown exploration and mining boom starting immediately after World War II, making uranium the most important commodity in the mining industry. The uranium production peak spanned from approximately 1948 to the early 1980s (U.S. DOE/EIA 1992). Some uranium mining continues in the United States, and relatively high-grade resources in other parts of the world are being mined to meet continued demand. Through the first half of 2005 the industry had generated over 358,000 metric tons (MTs) of uranium ($U_3O_8$) to foster U.S. dominance in nuclear weapons technology, and later to feed the growing number of commercial power plants that utilized the enormous energy contained in the uranium nucleus.[1]

Another legacy of uranium exploration, mining, and ore processing were many unreclaimed land workings left behind where the uranium concentration in rock was either found or thought to be economically recoverable. Thousands of miners and prospectors, as well as large mining companies, searched the United States for mineral deposits concentrating the valuable metal, echoing the California gold rush 100 years earlier. In many instances before the 1970s, they left behind unreclaimed and exposed wastes elevated in radioactivity from uranium and its radioactive decay progeny, potentially exposing people and the environment to its hazards.

In this report, Naturally Occurring Radioactive Material (NORM) is defined as: **Materials which may contain any of the primordial radionuclides or radioactive elements as they occur in nature, such as radium, uranium, thorium, potassium, and their radioactive decay products, that are undisturbed as a result of human activities.** Radiation levels presented by NORM are generally referred to as a component of "natural background radiation".

The term Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) is defined as: **Naturally occurring radioactive materials that have been concentrated or exposed to the accessible environment as a result of human activities such as manufacturing, mineral extraction, or water processing.** "Technologically enhanced" means that the radiological, physical, and chemical properties of the radioactive material have been altered by having been processed, or beneficiated, or disturbed in a way that increases the potential for human and/or environmental exposures. This definition differs somewhat from other definitions provided by the National Academy of Sciences (1999a) and the Conference of Radiation Control Protection Directors (CRCPD 2004) in that it further amplifies the need to include materials which have not been modified by human activities, yet have been disturbed in such ways that they can be misused by humans, or affect the environment[2]; it does not include a

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[1]  Data compiled from U.S. DOE/EIA 2003a, 2003b, 2005b.

[2]  The National Academy of Sciences (1999a) defined TENORM as "…any naturally occurring radioactive materials not subject to regulation under the Atomic Energy Act whose radionuclide concentrations or potential for human exposure have been increased above levels encountered in the natural state by human activities." The International Atomic Energy Agency (2003), although referring to this class of wastes and products as "NORMs", defined them as encompassing "all naturally occurring radioactive materials where human activities have increased the potential for exposure in comparison with the unaltered

reference to Atomic Energy Act materials as the definitions are changing (see further below and Appendix VI).

Under the Atomic Energy Act, the U.S. Nuclear Regulatory Commission (NRC) regulates operations which produce and concentrate uranium and thorium. In accordance with terminology of the Act, the NRC has defined in 10 CFR 40.4 "source materials" **as (1) uranium or thorium, or any combination thereof, in any physical or chemical form or (2) ores which contain by weight one-twentieth of one percent (0.05%) or more of: (i) uranium, (ii) thorium or (iii) any combination thereof. Source material does not include special nuclear material.** It also defines the "by-product materials" (wastes) of those operations **as tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes. Underground ore bodies depleted by such solution extraction operations do not constitute "byproduct material" within this definition.** Byproduct materials are also regulated by the NRC.

However, certain types of waste from conventional mining of uranium (surface and underground mining) are not subject to NRC regulation, and are considered to be TENORM. Thus, while this report includes information about uranium extraction, processing methods and wastes, only the wastes from conventional mining are considered to be TENORM, and subject to U.S. Environmental Protection Agency (EPA) and State agency oversight. Those distinctions will be made clear below, and elsewhere in this report.

Under the Energy Policy Act of 2005, the Atomic Energy Act was amended to place additional discrete (highly radioactive in small quantities) sources of TENORM under NRC jurisdiction which had the potential for use in a radioactive weapon. The definition of byproduct materials was further modified to include discrete sources of radium-226, any material made radioactive by use of a particle accelerator for use for a commercial, medical or research activity**,** or materials which might pose a similar threat if used to make a radioactive weapon. Specific requirements were provided for determining the appropriate waste disposal methods for these materials. The NRC regulatory definitions of byproduct materials to accommodate these amendments have not been revised to reflect the recent amendments as of this writing. While these products and wastes are not the subject of this report, further discussion on these changes to the Atomic Energy Act are included in Appendix VI.

Other important acronyms and definitions of key terms in this report can be found in Appendix I.

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situation. Concentrations of radionuclides (i.e. TENORM) may or may not have been increased." Alternatively, the Conference of Radiation Control Program Directors (CRCPD 2004) has defined them as a naturally occurring radioactive material whose radionuclide concentrations are increased by or as a result of past or present human practices. TENORM does not include background radiation or the natural radioactivity of rocks or soils. TENORM does not include "source material" or "byproduct material" as both are defined in the Atomic Energy Act of 1954, as amended (AEA 42 USC §2011 *et seq*.) and relevant regulations implemented by the NRC. EPA believes the definition should include materials which were disturbed, but not further concentrated by human activities; by not including this slightly broader definition, not only a significant amount of radioactive waste, but nearly all products which include TENORM would be exempted from regulation.

## Previous EPA Reports

The U.S. Environmental Protection Agency has previously issued reports on the uranium mining industry in response to congressional mandates and programmatic needs. In 1983, EPA published its *Report to Congress on the Potential Health and Environmental Hazards of Uranium Mine Wastes* (U.S. EPA 1983 a, b, c), as required by the Uranium Mill Tailings Radiation Control Act of 1978. This study provided an important overview of the characteristics and generation of uranium mining TENORM wastes during a period when the uranium mining industry was still near its production peak. A subsequent 1985 *Report to Congress on Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale* (U.S. EPA 1985), carried out pursuant to requirements of the Resource Conservation and Recovery Act of 1976 (RCRA), as amended, provided additional risk information and characterization of uranium mining waste. In 1995, EPA issued the *Technical Resource Document: Extraction and Beneficiation of Ores and Minerals: Uranium* as a technical update to provide a means of evaluating wastes that were exempt from or subject to regulation under RCRA (U.S. EPA 1995a).

During the period 1989 to 1993, EPA worked on a draft scoping report (SC&A 1993), now out of print, which compiled information on TENORM in several industries, including uranium mining. A preliminary risk assessment was also developed for certain public and occupational exposure scenarios to the known radiation levels in those industries. Comments received on the draft from industry, as well as EPA's Science Advisory Board (U.S. EPA 1994), resulted in further revisions of the scoping draft, though it was ultimately decided that a final report would not be issued.

Following a review of EPA's guidance for TENORM by the National Academy of Sciences (NAS 1999a), EPA's response to the NAS study (U.S. EPA 2000b), and discussions with EPA's Science Advisory Board (SAB), EPA's Radiation Protection Division decided that a further review of the current hazards associated with uranium mining TENORM was warranted.

The SAB (U.S. EPA 2001d) agreed with EPA's intent to make TENORM documents useful to a broad audience, but also recommended that the whole life cycle of a TENORM source, in this case uranium extraction, be considered beyond regulatory or inter-agency considerations, and that the impacts of non-radiological contaminants also be examined in the Agency's technical reports. In addition to most sources of TENORM, EPA has authorities for environmental standard setting under the Uranium Mill Tailings Radiation Control Act, cleanup of hazardous waste sites which currently include some former uranium mines, and assistance to Native Americans that has included assistance in environmental reviews of proposed *in situ* leach (ISL) facilities. This report will provide limited background materials on uranium milling and ISL operations and waste generated by those processes, even though they may not be considered TENORM by virtue of their regulation under the Atomic Energy Act and its amendments; information will also be provided on the regulatory agencies responsible for oversight of those operations.

Uranium mills and mill tailings impoundments are regulated by the NRC or its Agreement States. Many of the physical and chemical processes used at uranium mills are the same as those which extract uranium at ISL operations. While the tailings are not legally considered TENORM in the United States, this phase of the uranium fuel cycle is described in the report in part because radiation protection standards for the tailings impoundments may have applicability to waste disposal for uranium mine TENORM wastes. Additionally, the NRC has decided to allow mill operators to dispose of wastes other than tailings in the impoundments, which is a possible disposal route for some currently unreclaimed conventional uranium mine TENORM.

This report is the first of two volumes on uranium mining TENORM. It provides background information on the occurrence, mining, and reclamation of uranium mines and mills. Chapter 1 examines the occurrence of uranium in nature, its uses, and its contribution to background radiation in the United States. Chapter 2 provides an overview of mining and milling methods used to extract uranium from its host rocks, while Chapter 3 provides an evaluation of the volume and characteristics of uranium mining TENORM wastes in the United States. Chapter 4 provides a process-oriented review of reclamation[3] and remediation[4] techniques and goals to clean up uranium mines and extraction facilities to reduce their hazards to the environment, while Chapter 5 summarizes the key information developed in the report. The second volume entitled *Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) from Uranium Mining: Volume II: Investigation of Potential Health, Geographic, and Environmental Issues of Abandoned Uranium Mines (2006a)*, will evaluate, in a general way, potential radiogenic cancer and environmental risks posed by abandoned uranium mines. A technical report entitled *Uranium Location Database* (EPA 2006b) in concert with these volumes will provide information on an EPA generated digital spatial database on mines with uranium, and mill locations.

Information on uranium mining waste characteristics for this report has been obtained from several sources, including industries, EPA contractors, federal, state, and Tribal agencies, and scientific literature published by various national and international organizations. EPA's own field studies on a number of uranium mining sites around the United States, several of which are described in the case studies of the Appendix, have contributed to a better understanding of the physical, geographic, and chemical aspects of these wastes. The draft of this report underwent an outside peer review following the Agency's peer review process, and was provided to member agencies of the Interagency Steering Committee on Radiation Standards (ISCORS) Subcommittee on NORM, as well as other selected knowledgeable individuals and organizations, for comment.

Based on reviewers' comments received on the draft reports as well as meetings with stakeholders, the Agency will make a determination on what further steps may be necessary for the purpose of radiation protection from this source of waste material. The specific wastes of EPA concern from this report and study are from conventional open-pit and underground uranium mines, and include overburden, unreclaimed subeconomic ores (protore), waste rock[5], core hole and drill cuttings, mine and pit (or pit lake) water.

As a result of the review comments, significant new information was added to the report on uranium geochemistry and radionuclide environmental transport, as well as on uranium mine, ISL, and mill tailings reclamation methods and requirements. Waste and mining terminology was made more consistent across the report, more definitions of geological, mining, and radiological terms were provided and also included as a glossary in Appendix I, the report tone was changed, and several new references and figures were added. New text was added to this chapter (see above) to clarify the reasons information is included in this report on ISL and milling operations, even though they are for the most part overseen by agencies other than EPA. Responding to

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[3] Reclamation is the restoration of mined land to its original contour, use or condition.

[4] Remediation is the cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a Superfund site or uranium mine or extraction facility, including those included under the Uranium Mill Tailings Radiation Control Act (UMTRCA).

[5] Rock void of uranium ore which may have been set aside as waste after removal of top-soil, overburden and uranium ore or veins. Waste rock is defined as barren or submarginal rock or ore that has been mined, but is not of sufficient value to warrant treatment and is therefore removed ahead of the milling processes.

reviewers' comments, we have clarified in each chapter where specific wastes described are not considered TENORM and are subject to other agency regulations, and have added a new Appendix (VI) which provides information on the regulatory authorities of the principal federal and other agencies which oversee various aspects of uranium extraction and production. Errors in fact and numbers cited which we could verify were corrected throughout the report. Uranium price trends and mine production and reclamation status/ownership information was also updated as of early 2006.

## *Origins of Uranium*

Uranium has been around a long time. Cosmologists believe uranium was formed in supernovae billions of years ago. Uranium is a metal found in most rocks on Earth in concentrations of one to four parts per million. Uranium is in fact more abundant than gold, silver, mercury, antimony, or cadmium, and more or less as common as tin, cobalt, lead, molybdenum, and arsenic (CRC 1994). And contrary to popular perception that uranium is somehow far away and isolated in high-security facilities, traces occur almost everywhere—in plants, soil, rock, seawater, and animals (including humans).

The German chemist Martin Klaproth is credited with discovering uranium in samples of the mineral pitchblende in 1789. He named it for the planet Uranus, discovered only eight years prior. Uranium was first isolated as a metal in 1841 by Eugene-Melchior Peligot. French scientist Henri Becquerel is noted for (among other things) discovering the property of radioactivity while observing radiation from the highly radioactive decay progeny (called radium) closely associated in uranium-bearing rock (Ewing 1999).[6] While "discovered" in the late 18th century, uranium had nevertheless been used for many centuries as a colorant in glass and ceramics. Yellow-colored glass containing one percent uranium oxide has been found in Italy dating to 79 A.D. (CRC 1994).

## *Physical Nature of Uranium*

Uranium, a naturally occurring element with the atomic number 92, contributes to low levels of natural background radiation in the environment. Uranium in ores can be extracted and chemically converted into uranium dioxide ($UO_2$) or other chemical forms usable in industry. When refined, uranium is a silvery-white metal with very high density—65 percent denser than lead (CRC 1994).

Uranium is found naturally as three different isotopes[7]: U-238, U-235, and U-234. Other isotopes can be synthesized (created by humans), but all uranium isotopes are radioactive to varying degrees. Almost all uranium as found in nature is the isotope U-238 (Table 1.1). While in this report, general reference to uranium will be to uranium in its natural isotopic proportion, unless otherwise stated, it should also be noted that these proportions are not in fact entirely fixed.

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[6]  See Appendix II for uranium decay series.

[7]  An isotope is a variant of an element (having the same number of protons) but a different number of neutrons in the nucleus. For example, uranium has 92 protons. But uranium-238 has 146 neutrons, and uranium-235 has 143 neutrons.

**Table 1.1.  Percentage of Natural Abundance and Half-Lives[8]
of Uranium Isotopes by Total Weight**

*Almost all uranium as found in nature is the isotope U-238.*

| Isotope | Natural Abundance (% ) | Half-Life (years) |
|---|---|---|
| U-238 | 99.2740 | 4.47 billion |
| U-235 | 0.7200 | 700 million |
| U-234 | 0.0055 | 246,000 |

*Source: Eisenbud and Gesell 1997.*

Uranium-238 undergoes radioactive decay into a long series of 13 different radionuclides before finally reaching a stable state in lead-206. These radionuclides emit alpha or beta radiation and some also emit gamma radiation of widely varying energies. EPA's glossary of radiation terms[9], defines radioactivity as "*the process of undergoing spontaneous transformation of the nucleus, generally with the emission of alpha or beta particles often accompanied by gamma rays*." Some of these progeny radionuclides are very radioactive and can pose human health risks. One of the radionuclides in the series is actually a radioactive gas, radon-222, while the others are all solids.

## Uses of Uranium in Industry

Uranium has more uses than many people are aware of, though most of them are fairly esoteric (Table 1.2). By far, the greatest uses have been in nuclear weapons production and electric power generation. Uranium has the rare property of being "fissionable." Its nucleus can be split, or fissioned, and in the process, releases enormous amounts of energy (as well as significant volumes of highly radioactive by-products). This realization in the late 1930s and early 1940s led to a race by U.S. scientists to produce an atomic bomb during World War II. However, U-238, the predominant isotope, is only nominally fissionable—not enough so for a workable bomb. Of the three natural isotopes of uranium, U-235 is by far the most fissionable. (see Appendix II for uranium-235 (actinium) decay series. There have been reported occurrences of uranium deposits in Africa which underwent spontaneous nuclear fission, and which were detected based on discrepancies in the ratios of uranium isotopes present in the geological deposit (Meshik 2005).

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[8] A half-life is the time in which one-half of the atoms of a radioactive isotope decay into another nuclear form. Half-lives vary from less than a billionth of a second to billions of years. Also called the physical or radiological half-life. Isotopes with longer half-lives tend to be more stable and less radioactive.

[9] See on the Internet the following site: http://www.epa.gov/radiation/terms/termqr.htm#r .

**Table 1.2  Multiple Industrial Uses of Uranium**

*Uranium has more uses than many people are aware of.*

| Types of Uranium | Industrial Uses |
|---|---|
| *Primary Uses* | |
| Uranium | Nuclear weapons production and electric power generation. |
| *Lesser-Known Uses* | |
| Uranium | For production of copper, nickel, and steel alloys to enhance specific properties.<br>For dating the Earth by making calculations based on the rate of decay of uranium and the relative proportion of its stable progeny lead-206.<br>Incorporated into dental porcelain used for false teeth to simulate the fluorescence of natural teeth (a relatively minor historical use). |
| Depleted uranium | For inertial guidance systems and gyro compasses.<br>Armor piercing conventional munitions, tank armor, and nuclear waste casks. |
| Refined uranium metal | For production of high-energy X-rays. |
| Uranyl nitrate | As a colored glaze for porcelain and glass and for manufacturing pigments (this practice has more or less ceased in the United States). |
| Uranyl acetate | In dry-copying inks and as a reagent in chemistry. |
| Uranium salts | As mordants for dyeing silk and wool. |
| Compounds of uranium | For photographic toning, and staining and dyeing leather and wood. |

*Sources: NCRP 1987a; USGS 1973; U.S. NRC 2001.*

To produce a functional uranium-based atom bomb, U.S. scientists needed a high concentration of the isotope U-235. With great difficulty and cost, they separated the natural uranium isotopes to increase the concentration of U-235 relative to U-238. This process is called enrichment, because the extracted fraction is enriched in U-235 (to 90 percent or more for bombs). The highly fissionable U-235 is also used to produce nuclear energy, but is typically enriched only to about three percent (U.S. DOE 2002).

In addition to fission, atomic nuclei, such as uranium, can undergo a process called neutron capture, which permits the generation of plutonium (Pu) isotopes. One of these, Pu-239, is even more fissionable than U-235 and has very high energy outputs. Plutonium is made by bombarding uranium-238 targets in specially designed reactors (Rhodes 1987).

The enrichment process produces huge quantities of remnant, depleted uranium that is almost pure U-238. Depleted uranium is very stable and very dense, has poor fission properties, and is only very weakly radioactive. Decades of uranium enrichment have generated enormous quantities of depleted uranium. The U.S. Department of Energy has over 500,000 metric tons (MTs) of surplus depleted uranium stored on site at two of its large enrichment facilities (U.S. DOE 2002).

The uses of and markets for depleted uranium are fairly limited and are typically unrelated to any nuclear properties. As such, its value is low. Perhaps the most notable use is in military munitions and armored shielding. Like many other metals (e.g., magnesium), uranium is pyrophoric, which means that it reacts quickly with oxygen. As a result, the rapid oxidation of small particles (which have a relatively larger ratio of surface area to volume) of uranium can generate sufficient heat to cause ignition. Consequently, due to this pyrophoric nature and high density, projectiles made of depleted uranium burn on high impact and penetrate enemy armored tanks with ease. As shielding, thick plates of depleted uranium effectively inhibit penetration from projectiles. Due to its high density, depleted uranium finds domestic application in the keels of yachts, as ship ballast, and as counterweights for control surfaces (rudders and elevators) in airplanes and

helicopters. Also because of their high density, depleted uranium blocks are used for shielding gamma radiation in research facilities.

## *Geology and Distribution of Uranium*

The very large ionic size and chemical properties of uranium tend to allocate it to certain mineral assemblages, and lend to fractionation and concentration of uranium in particular rock types. Common uranium minerals include uraninite, coffinite, brannerite, carnotite, uranophane, autunite, pitchblende, and torbernite. Of these, uraninite (nominally $UO_{2+x}$) is the most widespread and significant economically, followed by coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$), and brannerite ($U^{4+}Ti_2O_6$) (Finch and Murakami 1999).

Most deposits of uranium in the U.S. were formed when oxidizing groundwater, which dissolves and transports uranium in a hexavalent[10] state, combines with carbonate, sulfate, and phosphate, and were subsequently reduced in their oxidation state by the presence of either organic matter or iron disulfide in the rock formations. If this occurred, uraninite or coffinite would have precipitated in a quadrivalent (four net positive ions) phase (Burns and Finch 1999). The inverse of this reaction (i.e., dissolution of uranium in mineral form) is used for ISL and hydrometallurgical processing of uranium (see Chapter 2), and introduction of bisulfide or hydrogen sulfide is a process used in aquifer restoration (see Chapter 4).

As a result of its size and charge, the uranium atom does not tend to fit well into typical igneous rock-forming minerals (such as feldspars, quartz, micas, amphiboles, pyroxenes, olivine, and titanomagnetite) and tends to be concentrated in silica-rich magmas such as rhyolites and granites (Burns and Finch 1999). Chemical weathering of these rocks is the likely process that leached out uranium that was later deposited in sandstone-type uranium deposits (see below).

Where uranium is in sufficient concentration in rock to be economically recoverable, it is called an ore body. More detailed information on ore deposit geology can be found in Guilbert and Park (1996) and Edwards and Atkinson (1986). Uranium resources of U.S. economic interest are primarily found in four main types of geologic deposits:

**Sandstone Deposits**
Sandstones contain approximately 33 percent of uranium resources worldwide, whereas they constitute the main source of uranium (over 95% of reserves and production) in the United States. The principal U.S. sandstone deposits of uranium are in the Colorado Plateau, the Wyoming Basin, the Texas Coastal Plain, and Nebraska. Sandstone uranium deposits in the United States were mostly commonly formed when uranium was introduced after the sediment was deposited, whereas some sandstone uranium deposits in other parts of the world (most notably in Canada and South Africa) are paleoplacers, in which uranium minerals were concentrated as heavy minerals in the sediments as they were deposited.

An important subset of sandstone deposits are breccia pipe deposits found primarily in northern Arizona; collapse structures in bedded sedimentary rocks resulted in the accumulation of uranium in circular deposits mimicking volcanic rock structures. The presence of uranium, copper, silver, vanadium and other valuable metals may occur in breccia pipes—the Orphan Mine (see

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[10] The oxidation state or oxidation number is defined as the sum of negative and positive charges in an atom, which indirectly indicates the number of electrons it has accepted or donated. Hexavalent means that the uranium atom has six more protons than electrons, and thus a net positive charge of +6.

Appendix III) is an example of this type of deposit in which structural geologic features controlled mineral accumulations in sandstones and mudstones.

**Vein Deposits**
Typically, these deposits occur in or near structures (faults, fractures, shear zones, etc.). Uranium is mineralized in cavities, fissures, cracks, and similar porous openings in veins (as well as breccias and pipes) usually cross-cutting the enclosing rock, and is usually present with accumulations of ore minerals and gangue (non-ore minerals) distinctly different from the surrounding rock. The dimensions of cracks and vesicles (openings or cavities in volcanic rocks) may vary considerably, as can the overall size of the vein ore body. Some ore bodies have been very small (several tons), but rich in uranium. Uraninite and pitchblende are the dominant minerals, with some accessory minerals.

**Phosphate Deposits**
Sedimentary marine phosphorite is the primary source of uranium in this category. An estimated four million tons of uranium could be extracted from U.S. phosphate deposits. While marketable phosphatic material obtained from phosphate deposits typically contains only 50–200 ppm uranium, the large quantity (approximately 150 million MTs per year) of crude ore rock produced in the United States (Jasinski 2003) makes it a potentially significant source of uranium.

**Disseminated Deposits**
Typically, these deposits are associated with granites, pegmatites, and syenites. The size, shape, and concentration of the ore bodies vary significantly. Secondary enrichment of the primary mineralization helped to form the ore grade that typically ranges between 0.05 and 0.15 percent. Deposits near Spokane, Washington, and Bokan Mountain in Alaska, are the most prominent disseminated deposits in the United States, though their production was insignificant in comparison to that derived from other types of deposits such as sandstones.

A fifth type of deposit is important to production in Canada:

**Unconformity Deposits**
This type of deposit is high-grade ore that occurs along and just below major Precambrian unconformities. Ore is often associated with graphite schists.

In defining what is ore, assumptions are made about the concentration in the rock; the cost of mining, processing, refinement, waste management, and site restoration; and the market value of the metal. Material too low in uranium to merit processing and refinement is often called protore, a nominal material that is currently uneconomical. Soil and rock that is otherwise essentially at background uranium and radiation levels, which is removed to gain access to underlying ore, is called overburden.

Most uranium mining in the United States has taken place in the expansive Colorado Plateau region straddling the Four Corners where Utah, Colorado, New Mexico, and Arizona meet. Figure 1.1 illustrates the extent of the Colorado Plateau and the general locations of uranium mines within the Colorado Plateau, although not all mines are shown; for example, numerous watersheds have over 100 mines by themselves. The source of the mine information used for this map is the Minerals Availability System/Mineral Industry Location System database (MAS/MILS) developed by the U.S. Bureau of Mines (McFaul et al. 2000), which has been included as a portion of the EPA Uranium Location Database (U.S. EPA 2006b). These mines have documented production, and represent over 4000 records contained within the larger EPA database, which contains over 14,000 records. Other mine location information in the EPA

database has been collected from several cooperating state, Tribal, and federal agencies. Mine locations in the EPA database, including MAS/MILS sites, were compared to U.S. Geological Survey topographic maps and one another in order to obtain an indication of accuracy and reliability. While the MAS/MILS data has known flaws, and sites shown in Figure 1.1 do not constitute all known uranium mines and fields, it provides a general overview of uranium mine geographic distributions in the western U.S. The larger data sets that comprise the EPA Uranium Location Database are discussed in the database documentation (U.S. EPA 2006b).

Major geologic formations noted for high uranium are the sedimentary Chinle (Triassic) and Morrison (Jurassic) Formations. The Chinle and Morrison are characterized by permeable streambed deposits of highly variable sized and sorted pebbles and sands, with associated concentrated pockets of organic matter from trees, branches, grasses, etc. Later blankets of volcanic ash provided a source of uranium to leach into the permeable rocks of the Chinle and Morrison. The uranium-laden leachate followed the highly permeable stream channel and mudstone formations, and upon reaching the reducing environment caused by high organic matter, precipitated uranium into void spaces, typically as uraninite. The association with organics resulted in some locales where very small—but very high-concentration—uranium deposits have been found, including as petrified logs. Thus, one-man mining operations could target small, rich deposits profitably.

## *Uranium's Contribution to Natural Background Radiation*

Uranium is found in all rock types in varying, but usually small concentrations. Naturally occurring elemental radium and its radioactive decay products can emit radon to the Earth's atmosphere. This section provides a basic discussion on natural background radiation.

### Background Gamma Radiation

Numerous studies have examined the occurrence of uranium and its radioactive decay products in U.S. soils. Table 1.3 presents average concentrations of some radionuclides found in igneous and sedimentary rocks that are the principal radionuclides referred to as NORM. There can be more than an order of magnitude difference in radionuclide contents among common igneous rocks. Similarly, deposits known as black shales, found in the eastern U.S. along the Appalachian Mountain front, are not uncommon rocks but are not similar to other U.S. shales as they typically have elevated uranium concentrations.

**Figure 1.1. U.S. Geographic Areas Rich in Uranium**

*Most uranium mining in the United States took place in the expansive Colorado Plateau region straddling the Four Corners where Utah, Colorado, New Mexico, and Arizona meet. This map shows mine locations plotted from McFaul et al. (2000) MAS/MILS database; not all known mine locations are included in that database, so some fields may not be represented. Readers looking for more complete information on state mine locations should refer to U.S. EPA (2006b).*



## Extent of Colorado Plateau

Legend
- Colorado Plateau Boundary
- × Uranium Mines W/Past Production
- State Boundaries
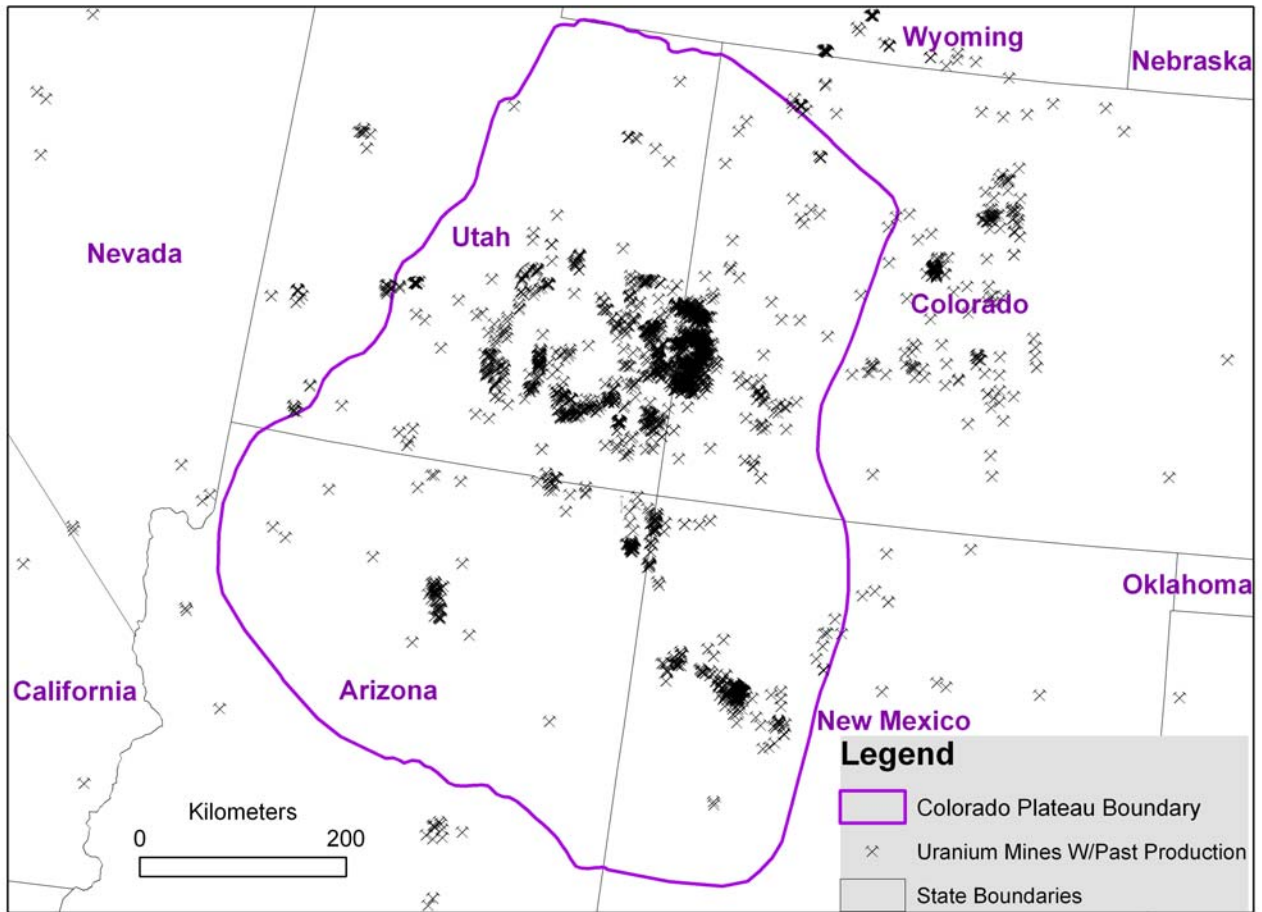
**Table 1.3  Concentrations of Certain Natural Radionuclides
in Igneous and Sedimentary Rocks**

*A concentrating effect can occur as a result of weathering and erosion of igneous rocks. With the
exception of uranium-238, concentrations of radionuclides are generally higher in sedimentary
rocks. The radionuclides listed are principal NORM radionuclides. The radionuclide contents
shown here should be considered average values. Individual rock deposits can have radionuclide
contents that may differ significantly from the numbers shown.*

| Rock type | Radium | | Uranium | | Thorium | | Potassium | |
|---|---|---|---|---|---|---|---|---|
| | Ra-226 pCi/g | Ra-226 Bq/kg | U-238 pCi/g | U-238 Bq/kg | Th-232 pCi/g | Th-232 Bq/kg | K-40 pCi/g | K-40 Bq/kg |
| Igneous | 1.30 | 48 | 1.30 | 48 | 1.30 | 48 | 22.0 | 810 |
| Sedimentary | | | | | | | | |
| Sandstone | 0.71 | 26 | 0.40 | 15 | 0.65 | 24 | 8.8 | 330 |
| Shale | 1.08 | 40 | 0.40 | 15 | 1.10 | 41 | 22.0 | 810 |
| Limestone | 0.42 | 16 | 0.40 | 15 | 0.14 | 5 | 2.2 | 81 |

*Note: Units are in picocuries/gram and Becquerels/kilogram.*
*Source: Eisenbud and Gesell 1997.*

Radium (a decay product of uranium) primarily decays by alpha particle emission. Its own short-lived radioactive decay products, such as polonium-210 or bismuth-214, yield more gamma ray emissions over time, making radium an important contributor to overall human and environmental exposure to radiation, or radiation dose. In general, concentrations of radium-226 in U.S. soils range from 0.4 to 1.3 pCi/g (16 to 48 Bq/kg) (Eisenbud and Gesell 1997), with lower concentrations found in the eastern part of the country, and higher concentrations in the West. Higher concentrations may also be found in locations with uraniferous igneous and sedimentary rocks, as well as phosphatic rock deposits. In addition to radium-226, uranium-238, uranium-235, and thorium-232, there are radioactive decay products that may substantially add to the radioactivity present where these radionuclides are in equilibrium to their decay products in uranium deposits, and mine or mine waste locations

Primary contributors of radiation from the natural environment are soil gamma ray radiation and inhaled radon. A 1987 study (NCRP 1987b), citing a 1972 review by Oakley, estimated gamma radiation doses to the U.S. population from terrestrial sources, based on aerial radiological measuring surveys by the U.S. Atomic Energy Commission (Table 1.4 and Figure 1.2). Annual doses for people living in brick homes may increase up to 10 milliRems/year (mRem/yr) due to naturally occurring thorium, uranium, and radium found in clays often used to make bricks. Additional data on the distribution of radium in the U.S. can be found in Myrick et al. (1981). Two additional studies of the National Council for Radiation Protection (NRCP 1993, 1984) examined the impacts of exposure to uranium and it's radon daughter decay products, and radiation protection in the mineral extraction industry, respectively.

**Table 1.4  Absorbed Dose Rate in Air from Terrestrial Radiation Sources
(in milliRems/year, milliSieverts/year and microGrays/year)**

*Natural geologic accumulations of radionuclides in the Colorado Plateau,
the principal mining area for uranium in the United States,
result in increased exposure rates for humans living in that environment.*

| region | 1960 Population Covered by Surveys | Absorbed Dose Rate in Air (microGy/yr) | Dose in mrem/yr (mSv/yr) |
|---|---|---|---|
| Coastal Plain | 6,759,772 | 230 | 23 (0.23) |
| Non-coastal Plain (excluding Denver) | 46,781,330 | 460 | 46 (0.46) |
| Colorado Plateau (Denver) | 1,073,624 | 900 | 90 (0.90) |
| **Population-Weighted Average** | | **440** | **44 (0.44)** |

*Note: Results are based on population-weighted aerial radiological survey data.
100 microGy/yr x 0.1 = 0.10 mSv/yr = 10 mRem/yr. Rem = Roentgen equivalent in man.
Sources: NCRP 1987b; Oakley 1972.*


**Figure 1.2  Gamma Ray Radiation Across the United States**
*Terrestrial Gamma-Ray Exposure at 1m above ground.*
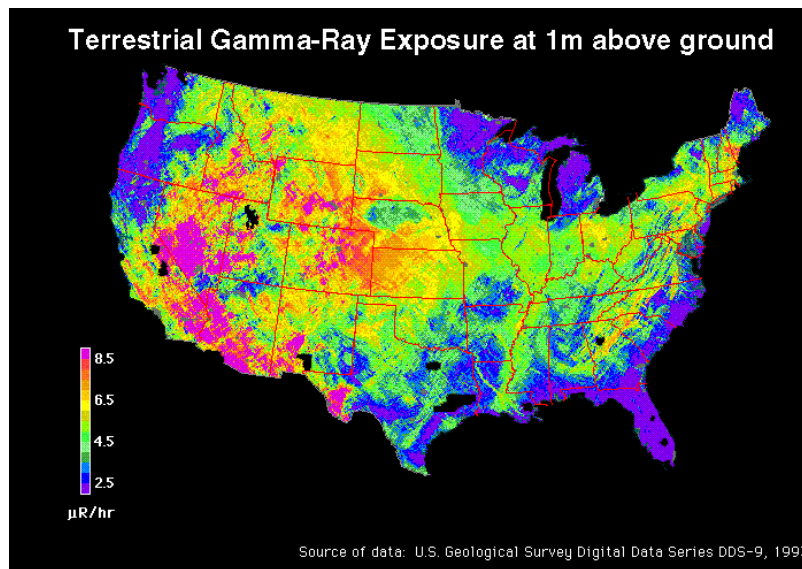


*Note: Results are based on national aerial gamma ray surveys.
Colors/shading reflect exposure in μR per hour (micro Roentgens per hour) according to the map.
Source: USGS 1993.*

<u>Radon in Homes</u>

The average radiation dose to an individual in the United States from all sources is about 360 mRem/yr (3.6 milliSieverts). Typical values for annual exposure to radiation within the United States are summarized in Table 1.5. Radon occurs in the environment and is listed separately in that table because of radon's significant contribution to radiation exposure: 200 mRem (two mSv) of the estimated average dose from all sources.[11]  Most of the radon dose comes from indoor exposure in homes, schools, and other buildings. The radon is generated by rocks and soil underlying the man-made structures; it seeps into the buildings through cracks and pore spaces of the foundations. Some radon is also generated from the building materials used in construction. Figure 1.3 presents short-term screening average U.S. indoor air concentrations of radon by county.[12]

**Table 1.5  Average Annual Human Exposure to Radiation**
*Natural sources of human exposure to radiation, primarily in the form of radon,*
*usually outweigh manmade sources, though medical exposures have*
*become more prominent in recent years.*

| Sources of Radiation | Average Exposure in mRem/yr (mSv/yr) | Typical Range of Variability in mRem/yr (mSv/yr) |
|---|---|---|
| **Natural Sources** | **300** (3) | |
| Radon | 200 (2) | 30–800 (0.3-8) |
| Internal | 40 (0.4) | 20–100 (0.02-1.0) |
| Cosmic | 30 (0.3) | 30–80 (0.3-0.8) |
| Terrestrial | 30 (0.3) | 10–80 (0.1-0.8) |
| **Man-made Sources** | **61** (0.61) | |
| Medical | 50 (0.5) | |
| Consumer products | 10 (0.1) | |
| Other (nuclear fuel cycle and occupational exposure) | 1 (0.01) | |
| **Total** | **361** (3.6) | **90–1,060** (0.9-10.6) |

*Sources: NCRP 1987b for average exposure values;*
*U.S. NRC 1994 for ranges of variability; Fisher 2003 for radon.*

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[11] Cosmic radiation comes from outer space. Some of it penetrates through the atmosphere covering the Earth. The amount of cosmic radiation will vary, depending on the altitude and latitude where one lives. Internal radiation comes primarily from ingested natural radioactive substances, such as potassium-40.

[12] See http://www.epa.gov/radon for more information.

**Figure 1.3 Average Indoor Air Screening-Level Concentrations
of Radon in the United States**

*The highest radon levels are generally reflected in counties located along
the Appalachian Mountains, Rocky Mountains, and north central states.*

EPA Map of Radon Zones



Legend
Zone 1
Zone 2
Zone 3
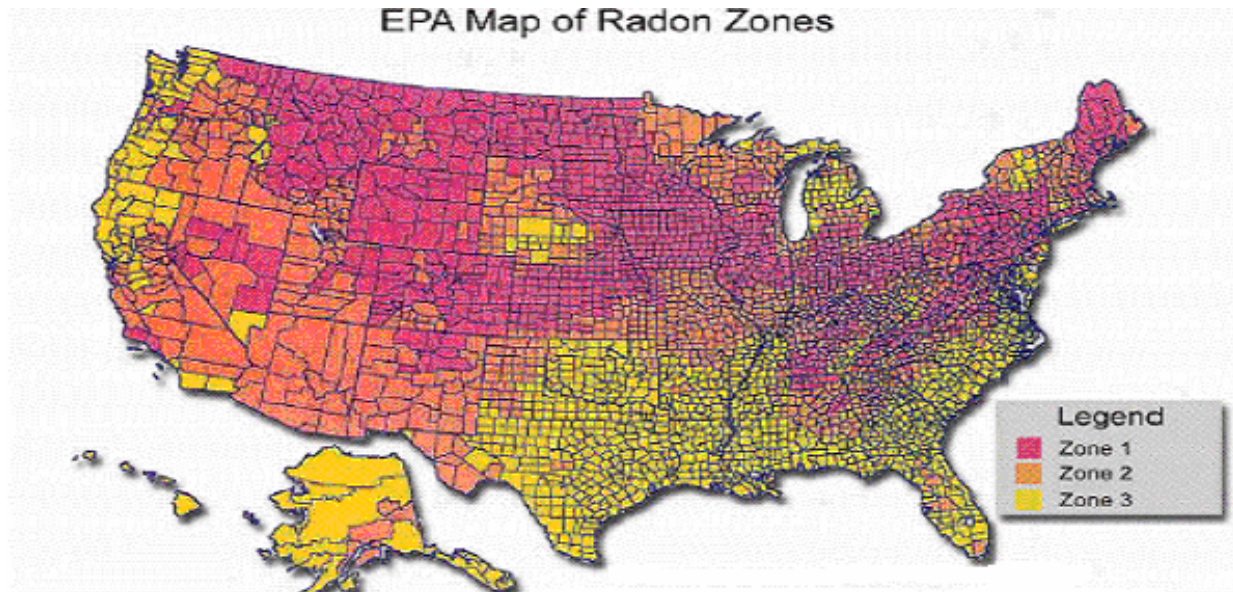
**Average Indoor Screening Levels**
Zone 1 counties: greater than 4 pCi/L (0.148 Bq/L)
Zone 2 counties: between 2 and 4 pCi/L (0.074 and 0.148 Bq/L)
Zone 3 counties: less than 2 pCi/L (less than 0.074 Bq/L)

*Note: See http://www.epa.gov/iaq/radon/zonemap.html to access an on-line
version of this figure, which allows county-by-county information.
Source: U.S. EPA 1993c*
.

Uranium in Water

Just as uranium is found in virtually all rock and soil, it is essentially ubiquitous in groundwater.
Groundwater concentrations tend to reflect overall bedrock averages and can vary widely. While
surface waters, originating primarily from rain and snow melt, are typically very low in uranium
and other TENORM radionuclides, to the point where they cannot be measured, groundwater can
be relatively high in radionuclides of both primary and anthropogenic origin.

Water is perhaps the most significant means of dispersal of uranium and related TENORM in the
environment from mines and mine wastes. Surface waters contaminated by surface erosion of
mines and wastes maypercolate into groundwater, and contaminated water travels underground
through mines or drill holes into the groundwater. Uranium is very soluble in acidic and alkaline
waters and can be transported easily from a mine site. Radium may be leachable as well as carried
in particulate form by flowing water (Eisenbud and Gesell 1997). More detail on this topic can be
found in Chapter 3. Occurrence of uranium and radium in water has been detailed in case studies
on the Orphan Mine, Midnite Mine, Bluewater, and Yazzie-312 Mine (see Appendix III).

EPA has updated its standards for maximum contaminant levels for radionuclides in drinking
water (40 CFR 141.66), including a new standard for uranium (65 FR2000a 76708, December 7,
2000), as required by the 1986 amendments to the Safe Drinking Water Act. The standards are:

combined radium 226/228 internal (five pCi/L) (0.185 Bq/L); man-made beta emitters (four mRem annual dose equivalent to the total body or any organ) (0.04 mSv); gross alpha (excluding uranium and radon) standard (15 pCi/L) (0.56 Bq/L); and uranium (30 μg/L). The reader should understand that the uranium standard was based on its identified toxicity to the kidney, and not its potential for causing cancer.

Under the Clean Water Act (See Appendix VI for more detail), mines and mills that discharge must obtain a permit, and must monitor twice a year for specific pollutants determined by the type of ore they mine or process. EPA regulations in 40 CFR 440, Part C, are applicable to discharges from (a) mines either open-pit or underground (ISL operations are excluded), from which uranium, radium and vanadium ores are produced; and (b) mills using the acid leach, alkaline leach, or combined acid and alkaline leach process for the extraction of uranium, radium and vanadium. Only vanadium byproduct from uranium ores is covered under this subpart. With certain exceptions, primarily concerning unusually high storm water events, for existing and new point source dischargers, the maximum concentration for one day of dissolved radium-226 allowed to be discharged is 10 pCi/L with an average 30 day value of three pCi/l, for total radium-226 the amount allowed to be discharged for one day is 30 pCi/L and 10 pCi/L for an average 30 day concentration. For uranium discharges, the maximum allowable discharge for one day is four milligrams/L, while an average of no more than two milligrams/L is allowed to be discharged over a 30 day period. The same numerical standards for radium apply to uranium mills, though there is no uranium discharge standard.

## *Industrial Processes and Activities*

TENORM may be generated during extraction, processing, treatment, and purification of minerals, petroleum products, or other substances obtained from NORM-containing parent materials. TENORM also includes any radioactive materials made more accessible by human activities. Several hundred million metric tons (MTs) of TENORM are generated each year by a wide variety of industrial processes, ranging from uranium and phosphate mining to the treatment of drinking water. Although conventional uranium mining is the central focus of this report and will be discussed in more detail in Chapter 2, the section below briefly discusses activities or processes, other than uranium mining, that produce TENORM as a result of the co-occurrence of uranium and its daughter radionuclides in the source rock, soil, or water. However, not all ores of these commodities contain uranium or radium at concentrations above natural background levels in associated rocks. In some instances, the radioactive wastes from mineral processing other than uranium mines have been used as source rock for uranium extraction under NRC license.

Uranium Associations with Other Metal Mining

Quite typically, beginning in the 1940s, uranium mines would open based on the detection of radioactivity at the site and identification of uraniferous mineralization. While some deposits were mined solely for their uranium content, others produced a variety of other minerals, which co-exist with the uranium minerals (Table 1.6). In some cases, exploitation of uranium minerals was secondary to producing another mineral found in greater abundance, commanding a better market price, or less expensive to produce; nevertheless, their combined economic value contributed to the success of the mining venture.

The presence of radioactive minerals was sometimes unexpected, unknown, or ignored in producing one or more minerals at a mine. Many mine sites operated prior to the 1940s, and even after, have not been recognized for the inherent hazards potentially posed by radioactivity in the discarded waste rock or subeconomic ore piles. The geological emplacement or geothermal phenomena that formed other valuable minerals may have concentrated radioactive minerals as well, or the process of mining, beneficiation, and milling may have resulted in a concentration of the radioactive minerals in the waste. In some instances, the mineral(s) being mined may have radioactive elements included in their molecular structure that impart radioactivity to the ore or even the finished product. The EPA (U.S. EPA 2006b) *Uranium Location Database* provides the location of mines with uranium occurrence including those that may have been mined primarily for other minerals.

**Table 1.6  Mineral Commodities with Uranium Associations**

*Several mineral ores often, though not always, have TENORM-associated wastes resulting from the co-occurrence of uranium and radium.*

| | |
|---|---|
| Aluminum (bauxite) | Potassium (potash) |
| Coal (and coal ash) | Precious metals (gold, silver) |
| Copper | Rare earths: yttrium, lanthanum, monazite, bastanite, etc. |
| Fluorospar (fluorite) | Tin |
| Gypsum | Titanium (leucoxene, ilmenite, rutile) |
| Molybdenum | Tungsten |
| Niobium | Vanadium |
| Phosphate (phosphorus) | Zircon |

*Source: U.S. EPA 2003b.*

**Copper Mining**

Copper mines have long known to be associated with uranium occurrences internationally, as well as in the U.S. The Bingham Canyon copper mine in Utah produced 150,000 pounds of uranium per year from 1978-1985 and 10,000 pounds per month from February 1987 through the end of 1989 (Chenoweth 1991). The Orphan Mine in Arizona (see Appendix III) was originally claimed for its copper mineralization, but only began production in the 1950s as a result of its rich uranium occurrence. Other mines in the southwest, such as the Yerington Mine in Nevada and Anaconda Mine in Utah have also been reported to have uranium mineralization or production. Uranium recovery from copper leaching is described in McGinley (1980). EPA's report (U.S. EPA 1999) on copper mining in Arizona provides extensive information on TENORM radiation associated with copper mine wastes and groundwater impacts, both from conventional and ISL extraction facilities in that state. Some of the mines listed also were licensed by the Atomic Energy Commission (precursor to the NRC) to produce uranium in addition to copper.

**Phosphate Production**

Uranium is known to associate with phosphatic deposits primarily because hexavalent uranium complexes well with dissolved phosphate. Phosphate rock contains phosphorite, a form of the mineral apatite, which is known to accommodate uranium. Phosphate rock is the sixth largest mining industry in the United States in terms of volume of material mined. It is mined for the production of phosphoric acid, the great majority of which is used in agricultural fertilizer. About 80 percent of U.S. phosphate mining occurs in south central Florida, though some mining also has occurred in North Carolina, Utah, Idaho, Wyoming, Tennessee, and a few other states (U.S. EPA 1989b; Jasinski 2003).

The phosphate fertilizer industry is a major generator of TENORM. Uranium concentrations in phosphate rock range from 14 to 200 pCi/g (20 to 300 ppm, or about 0.5 Bq/g to 7 Bq/g), and radium concentrations are 18 to 84 pCi/g (about 0.7 to 3 Bq/g) (DeVoto and Stevens 1979). In the United States alone, some 150 million MTs of phosphate ore are produced each year, which contain radioactive thorium and its decay progeny, in addition to uranium TENORM. Mineral processing sometimes exposes workers to measurable doses of radioactivity.

Phosphate ore is crushed and digested in sulfuric acid to produce orthophosphoric acid and phosphogypsum. Phosphogypsum is a complex mixture of gypsum ($CaSO_4 \cdot 2H_2O$), silica, and anhydrite ($CaSO_4$). In the process, various other wastes are also formed. Between 80 and 100 percent of the radium in phosphate rock is transported to the phosphogypsum, while about 70 percent of the uranium (and thorium) remains in the phosphoric acid (however, the fractionation of uranium and thorium is variable and still not well characterized) (Guimond 1975; Hull and Burnett 1996; FIPR 1995).

Though uranium concentrations in phosphate ore are low compared to typical uranium ores, the low cost of uranium recovery from secondary phosphate products sometimes makes it profitable to extract uranium as a by-product of phosphate production. Phosphate rock and tailings containing up to 120 ppm of uranium have been mined as a source of uranium (DeVoto and Stevens 1979).

Before EPA required placement of phosphogypsum in environmentally isolated waste piles, called "stacks", to control radon emissions (40 CFR 61, Subpart R), phosphogypsum and waste rock containing uranium and thorium were often used to refill and reclaim open mine pits. Due to pressures to find available land for home building, several of these reclaimed mine pits were subsequently sold as home sites. In 1975, EPA reported that more than 1,000 houses were built over these sites in one Florida county alone. While it has not been determined if this housing may pose a radiation hazard to the occupants, during its study EPA found some elevated levels of radiation and radon (U.S. EPA 1975).

Elemental phosphorus is produced by the thermal process. It is a raw material used primarily in chemical and food production, primarily from ore deposits in Idaho. This process also produces TENORM wastes, such as slags, containing radium and uranium.

**Coal Combustion**

Most coal contains uranium and its progeny radionuclides at levels about the same as, or less than other rocks of the Earth's crust (UNSCEAR 1982). Uranium TENORM emerges from coal-burning plant furnaces predominantly in fly ash, which is fused and chemically stable. Coal fly ash is derived from inorganic materials that were co-deposited with the organic detritus that produced the coal beds. Uranium in coal may be a combination of detrital mineral matter and uranium deposited later through adsorption by, or oxidation of, organic matter in the lignite or coal. In one instance in the 1960s, certain lignitic coals from North Dakota were mined and burned in order to further concentrate the high levels of uranium already present in the coal; the resulting ash was then taken to a uranium mill in Colorado to process into uranium yellowcake[13].

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[13] See http://www.eia.doe.gov/cneaf/nuclear/page/umtra/belfield_title1.html for more information.

Principal nonradioactive ash constituents are the metal oxides of silica and alumina, often comprising 80–90 percent, with smaller percentages of other metal oxides, including iron, calcium, sodium, tin, magnesium, and potassium. Pollution control devices in modern power plants usually capture about 99 percent of fly ash, and devices in some older plants capture about 90 percent. However, those devices do not capture radon gas. In addition to ash, power plants produce slag, sludge, and other waste products that may contain uranium TENORM.

The amount of ash generated is proportional to the amount of coal consumed and the coal ash content. The ash content of coal will vary according to the depositional environment. The average ash content of coal burned by the U.S. electric utility industry is approximately 10 percent, meaning that uranium in coal is concentrated roughly 10 times in the ash. For coal with a 10 percent ash content, a 1,000 megawatt plant may produce over 1,500 tons of ash during a 24-hour period. However, the actual quantity of ash produced also depends on the plant's design and efficiency and the coal's energy content.

Though the concentrations are low, the total amount of TENORM in fly ash is noteworthy (Beck et al. 1980; Beck 1989). For example, in 2004, U.S. electric power plants burned approximately 921 million MTs of coal (U.S. DOE/EIA 2005d). If that amount of coal is burned with 1.5 ppm uranium, 1,381 MTs of uranium would be concentrated, in addition to other TENORM quantities.

Other coals are quoted as ranging from up to 25 ppm of uranium and 80 ppm of thorium. Based on analyses of nearly 7,000 samples, of all coal provinces and coal ranks, an EPA study found that the range of uranium in U.S. coal was 0.010–75 ppm (U.S. EPA 1995b).

Most fly ash is buried, but increasingly fly ash is being used for commercial applications. A significant quantity of fly ash (Class C) is considered cementitious (having the properties of cement, the principal binding agent in concrete) which makes it a very useful material. The relatively uniform small particle size, surface reactivity, and bulk chemical composition—particularly if alkali elements are abundant—lend properties to coal ash, slag, and flue gas waste material that have numerous useful commercial applications. These include: flowable fill, structural fill, road base/subbase, coal mining applications, mineral filler in asphalt, snow and ice road control, blasting grit and roofing granules, grouting, waste solidification and stabilization, and wall board (ACAA 1995, 1996; U.S. DOE/EIA 1993; EPRI 1988).

**Heavy Mineral Sands**
Many of the minerals which make up this commodity contain significant percentages of uranium and thorium. As a result of their inherent hardness, weight (specific gravity), and other physical properties, certain minerals are naturally resistant to erosion and to physical and chemical breakdown over geologic time. Accumulations of these minerals results in sedimentary sand deposits commonly called "heavy mineral sands," or sometimes "black sands," because they are dominated by black minerals. These deposits, if they occur in easily accessible locations and in sufficient size, may be mined to concentrate and extract valuable industrial metals (U.S. EPA 1990).

Typical minerals that may be found in these deposits include garnet; titanium-rich rutile, ilmenite, and leucoxene; thorium-rich monazite; and uranium-rich zircon. All of these minerals, and several others typically occurring in the deposits, are radioactive due to: the presence of uranium, thorium, and radium in their molecular matrix; radioactive coatings washed into the deposits from elsewhere; or the chemical and physical weathering of radioactive mineral grains in the sand deposit. The wastes from extracting these minerals, and often the finished products resulting from mineral processing, may retain some or all of their natural radioactivity (CRCPD 1994).

Although monazite is mined incidentally along with other minerals in heavy mineral sand deposits, it is not currently being used commercially in the United States, and is usually returned to the extraction site as a waste. The uranium oxide content of monazite sands in the Southeast was measured at 0.47 percent (Mertie 1953). Monazite from the Green Cove Springs deposit in Florida, which produced monazite prior to 1995, averaged 4.44 percent thorium oxide (Staatz et al. 1980).

The major U.S. mining operations for titanium sands have been located in Stoney Creek, Virginia, and Simi Valley, California, and along the Trail Ridge formation, an ancient sand dune deposit that extends from northeastern Florida to southeastern Georgia. However, most titanium ore (separated sands mostly, rather than finished titanium dioxide powder) is imported. Although as a metal, titanium is well known for its corrosion resistance and for its high strength-to-weight ratio, approximately 95 percent of titanium is consumed in the form of titanium dioxide pigment in paints, paper, and plastics. Other end uses of titanium include ceramics, chemicals, welding rod coatings, heavy aggregate, and steel furnace flux (USGS 1973). There has been no study on disposal of any residual radioactive wastes from these industries in the U.S.

Zirconium is a silvery-white metal obtained from zircon sands (Brady et al. 1997), while hafnium is a ductile metal, with a brilliant silver luster. Most zirconium minerals contain 1–5 percent hafnium (CRC 1994). Zircon production is usually a byproduct of mining and extracting titanium minerals from ilmenite and rutile ores. Zircon has been produced from dredging operations in Florida, and now Virginia. Major end-use categories for zircon include abrasives, ceramics, refractories, and foundry applications. Zircon is consumed directly for abrasives and welding and as welding flux. Zircon sands and finely ground zircon (termed zircon "flour") are consumed in foundry molds, refractories, and ceramics. Residual radioactive wastes from these industries have been reported to be disposed in industrial landfills, and there have been instances where abandoned barrels of zircon flour, and sites contaminated with zircon wastes have been the subject of Superfund cleanup and removal actions. Table 1.7 presents radioactivity concentrations reported by the CRCPD for zircon and titanium process ore and wastes

### Table 1.7  Radionuclide Concentrations in Process and Waste Samples
*Radium concentrations can be highly variable for titanium
and zircon ores and wastes, and dependent on ore source.*

| Process Ores | $^{226}$Radium Concentrations in pCi/g (Bq/Kg) |
|---|---:|
| **Titanium** | |
| Rutile | 15 (555) |
| Leucoxene | 12 (444) |
| Dry ponds (~5 cm depth) | 45 (1665) |
| Dry ponds (surface) | 20 (740) |
| Settling pond solids | 17 (0.73) |
| Sludge pile | 4–25 (148–925) |
| **Zircon** | |
| Chlorinator residues No. 1 | 150–1,300 (5550–48100) |
| Chlorinator residues No. 2 | 230–890 (8510–32930) |
| Clarifier sludge | 87–150 (3219–5550) |

*Source: CRCPD 1994.*