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Principal Radioactive Minerals Encountered in Mining and Associated Environmental Concerns

by

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INTRODUCTION

The most common radioactive minerals are of uranium and thorium; radium does not form minerals of its own and resides mainly in uranium minerals and more sparsely in thorium minerals. Radon is a gas produced by radioactive decay of radium (Otton, 1992). Uranium is three times less abundant than thorium in the earth's crust, whereas radium is present in infinitesimal amounts, on the order of $1x10^{-7}$ less abundant than uranium (Tyler, 1930). Radon derived from soils, rocks, and water is common in high levels in many buildings throughout the United States. Radon also is present in very high levels in uranium mines.

The purpose of this paper is to present background on the geologic and mineralogic occurrence of radioactive minerals encountered mainly in uranium mining and on the potential environmental concerns relative to mining and associated recovery of uranium. This paper primarily emphasizes the critical aspects of mining uranium deposits, and less attention is given to mining of thorium and radium.

This paper is prepared as the introduction to Chapter 13 "Radioactive Materials Mining" for the "SME* Mining Environmental Handbook". Other parts of Chapter 13 will discuss details of radiological concerns, environmental impact pathways (water, air, mechanical), mining methods and environmental impacts, and the milling, processing, and waste disposal practices.

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URANIUM

The mean crustal abundance of uranium is about 2 ppm U, and mineable ores contain about 250-2,500 times this amount. Uranium consists of three semi-stable radioactive isotopes: about 99.3 percent $_{238}U$, 0.7 percent $_{235}U$, and 0.005 percent $_{234}U$ (Finch, 1986). Deposits, natural concentrations, occur in nearly every major rock type, but identified mineable resources are few in kind.

Uranium occurs only in minerals that contain oxygen. Uranium in unoxidized black ores is tetravalent, and in most uranium ores, it occurs as uraninite [UO_2, pitchblende is not an accepted mineral name but is used to describe massive uraninite (Fleischer, 1986)] and/or coffinite [$U(SiO_4)_{1-x}(OH)_{4x}$] with pyrite as a common gangue mineral. Under oxidizing conditions, tetravalent uranium changes to hexavalent uranium and forms oxide, vanadate, arsenate, silicate, sulfate, and carbonate compounds, most of which are hydrous, and many are bright yellow or green. The vanadates, carnotite and tyuyamunite, are the most common and abundant. Brannerite [$(U,Ca,Y,Ce)(Ti,Fe)_2O_6$], a less common tetravalent uranium-bearing mineral formed in igneous rocks, is limited mostly to placer concentrations.

Mining of uranium has affected the environment in many ways. Uranium itself has had little effect, but radium and radon have had large effects on surface water and in particular in ground water. A study was made of the radioactivity in surface water, suspended sediment, and ground water two years after all mining stopped near the Puerco River that drains the eastern part of the Grants Mineral Belt, notably the area of several large uranium mines including the North Church Rock (Wirt, in press-a). It was found that after three decades of uranium mining in the headwaters of the Puerco River, the distribution of radioactivity in streamflow downstream from mining appears to be related to geographic differences of geology rather than to the effects of uranium mining. For this study, Wirt (in press-b) developed a method utilizing the ratio of $_{234}U$ to $_{238}U$ to distinguish uranium in ground water derived from uranium ores from that naturally present in country rocks.

MAJOR ORE METALS ASSOCIATED WITH URANIUM DEPOSITS

The major non-uraniferous metals that constitute ore minerals associated with uranium ores are vanadium, copper, and gold, which have been recovered either as co-products or as the major product from mining of some types of uranium deposits (example: Rifle mine, Colorado vanadium with by-product uranium). Less common are molybdenum, silver, cobalt, and nickel, which are rarely in large enough bodies to be recovered. Molybdenum has been recovered from some sandstone ores where it interferes with the recovery of uranium, such as roll front ores in Texas. Silver has been recovered from the Silver Reef District. Utah, where uranium, vanadium, copper, and vanadium also occur. Cobalt and nickel have not been recovered from domestic uranium ores.

VANADIUM

Vanadium ore occurs in tabular sandstone uranium ores mainly in the Jurassic Morrison and Entrada Formations on the Colorado Plateau (Finch, 1967). The principal minerals are roscoelite [$K(Al,V)_2(Al,Si_3)O_{10}(OH,F)_2$] and montroseite [VO(OH)]. These and other vanadium minerals provide vanadium for the common yellow vanadates. Vanadium, itself, presents minor, if any, environmental concerns relative to human health (Health Effects Research Laboratory, 1977). Vanadium that combines with uranium to form insoluble vanadates stabilizes uranium in the oxidizing environment.

COPPER

In the U.S., copper occurs mainly in tabular sandstone uranium ores (as well as tabular copper ores with essentially no uranium) and in porphyry copper deposits. The tabular copper-uranium ores occur mainly in Triassic and Permian formations in the western States. Copper has been recovered chiefly from copper-uranium ores at the Happy Jack and other mines in the White Canyon District, Utah. Porphyry copper ores contain traces of uranium in quartz monzonite stocks. Uranium has been recovered as a by-product of heap leaching of low-grade copper tailings from Bingham Canyon, Utah (NUEXCO, written communication, 1993). Other porphyry copper deposits contain traces of uranium, such as at Yerington, Nevada, and Twin Buttes, Arizona. One of the largest copper resources in the world occurs in the breccia complex Cu-U-Au-Ag deposit at Olympic Dam, Australia (Oreskes and Einaudi, 1990). Copper in itself is of little environmental concern to human health in uranium mining.

GOLD

Gold is found mainly in quartz-pebble conglomerate uranium deposits and the Cu-U-Au-Ag deposit, Olympic Dam, Australia and only in trace to small amounts in other types of uranium deposits, such as collapse breccia uranium deposits. In the Witwatersrand, South Africa, deposits, gold is the primary product and uranium is a sometimes recovered by-product depending upon uranium grade and the market price. Gold is one of the most inert elements and, therefore, is not of environmental concern. However, chemicals, such as cyanide, used to extract gold may present serious environmental impacts.

NON-METALS ASSOCIATED WITH URANIUM ORES

Although not metals, several elements associated with uranium ores in significant amounts deserve mention here because of their environmental concerns. They are sulfur, arsenic, and selenium.

SULFUR

Sulfur in uranium deposits occurs mainly as pyrite (FeS_2), which is found in nearly all primary uranium ores; in some, it is present in excess of 10 percent pyrite. Sulfur becomes liberated in oxidation of primary uranium ores and is in places expressed by high-sulfur bearing

plants found on mine dumps. The environmental impact of sulfur at most uranium mines is generally low, but in some places, mining has generated acid mine waters that mobilized uranium and associated radionuclides. Acidic mill-process liquid is a special environmental problem. A catastrophic spill of uranium mill-process liquid and tailings in the Church Rock Mining District, New Mexico, is discussed by Wirt (in press a). This spill had a pH <2 and 27,000 mg/L of SO_4, which mobilized uranium, radium, and thorium until the pH was neutralized downstream.

ARSENIC

Arsenic is less common and abundant than sulfur; it commonly associated with uranium ores containing copper, notably in collapse breccia pipe ores. Its main mineral is arsenopyrite (FeAsS). Secondary arsenic minerals were observed associated with vanadium-uranium sandstone ores at the Temple Mountain pipe, Utah. Arsenic is a very toxic element and has a high potential for isolated environmental concerns, particularly in open-pit mines and at mine dumps from underground mines. The EPA maximum contaminant level in drinking water is 0.05 mg/L As.

SELENIUM

Selenium is common in tabular sandstone uranium ores, particularly in the Morrison Formation in the Colorado Plateau. It is most commonly associated with galena as clausthalite (PbSe). Selenium weathers out easily and has a very distinctive odor at open-pit mine faces. It was noted in the early days of uranium prospecting because selenium indicator plants grew where it was abundant (Cannon, 1960, 1964). These plants were used as prospecting guides to uranium. Selenium is both beneficial and toxic to plants and animals (McNeal and Balistrieri, 1989; Herring, 1991) but in large amounts is very toxic to cattle and humans. In uranium mining it has high potential for environmental concerns. An example is the elevated levels of selenium found in ground water in 1983 downstream from the large mill tailings embankments at the Homestake Mining Company mill near Milan, New Mexico (Environmental Protection Agency, 1989). The EPA maximum contaminant level in drinking water is 0.05 mg/L Se.

TYPES OF URANIUM ORE DEPOSITS AND THEIR UNIQUE CHARACTERISTICS RELATIVE TO ENVIRONMENTAL CONCERNS

The International Atomic Energy Agency (IAEA) (Nuclear Energy Agency and International Atomic Energy Agency, 1992) defines 14 types of uranium deposits on the basis of their geologic occurrence. The top eleven deposit-types listed in about their economic importance in world resources and with an example of a major mine or mining district are 1) unconformity related, Athabasca Basin, Canada; 2) sandstone, Colorado Plateau, USA; 3) quartz-pebble conglomerate, Elliot Lake, Canada; 4) vein, Schwartzwalder mine, Colorado; 5) breccia complex, Olympic Dam, Australia; 6) intrusive, Rössing, Namibia; 7) phosphorite, Florida; 8) collapse-breccia pipe, Grand Canyon, Arizona; 9) volcanic, Peña Blanca, Mexico; 10) surficial, Yeelerrie, Australia; and 11) lignite, North and South Dakota. Of these, sandstone, vein, intrusive, phosphorite, collapse-

breccia pipe, volcanic, surficial, and lignite ores have been mined to various extents in the United States (Nash and others, 1981).

SANDSTONE URANIUM DEPOSITS

Sandstone uranium deposits are epigenetic concentrations of uranium minerals that formed after sedimentation and that occur as uneven impregnations in sandstone and associated sedimentary rocks formed in fluvial and marginal marine environments of Permian, Triassic, Jurassic, Cretaceous, and Tertiary ages. They are the major uranium resource in the United States; the Colorado Plateau is the type area for these deposits (Nash and others, 1981; Finch, 1991). The host sandstones of Tertiary age are characteristically unconsolidated whereas the older hosts are generally well-cemented with calcareous and siliceous minerals. The form of most sandstone uranium deposits is either tabular or roll front. Tabular deposits are in rocks of all ages mentioned above, but are most common in Jurassic and older ages. On the other hand, roll-front deposits seem to be limited to Cretaceous and Tertiary host rocks; some tabular deposits in older rocks have been modified into roll-front deposits by Tertiary remobilization.

The mining of tabular deposits is mainly by open-pit and underground mining, rarely by in-situ-leach because of relatively poor permeability. The largest open-pit was the Jackpile in the Morrison Formation in the San Juan Basin, New Mexico. Part of it was worked by underground and the pit is now completely reclaimed. The Mt. Taylor deposit, also in the Morrison Formation and in New Mexico, is being worked underground; this deposit is over 6 miles long, a mile or more wide, and more than 1,000 feet deep. Unlike tabular deposits, roll-front deposits are well suited to in-situ-leach mining. An example of a large roll-front deposit is the Christensen Ranch deposit in the Tertiary Wasatch Formation in Wyoming; it is more than one mile wide, nearly 20 miles long, and several hundred feet deep. Human exposure to radioactivity is greatest in underground mines due to confined surroundings. Exposures in open-pit mines are usually lower, except where the ore is very high-grade (>1 percent U_3O_8), such as at Slave Lake Mine, Northern Territories, Canada (Michael Drozd, written communication, July 1993). Direct human exposure to radiation is negligible in in-situ-leach operations.

VEIN URANIUM DEPOSITS

Vein uranium deposits typically occur in faulted, tectonically brecciated, and fractured brittle hard rocks, generally either igneous or metamorphic, but also in hard sedimentary rocks like limestone. Deposits in veins in tuffaceous rocks are commonly characteristic of some volcanic deposits. The principal examples of vein uranium deposits in the United States are in the Schwartzwalder mine in Precambrian metasedimentary rocks and the Pitch mine in the Leadville Limestone, both in Colorado. These two deposits were mined by deep underground operations. The Pitch mine area has been reclaimed, but the Schwartzwalder was in a holding pattern in 1993.

The average grades of vein uranium deposits are mostly high (>1%U_3O_8) and thus attendant high radium and radon intensify environmental human health concerns in mining and associated activities.

INTRUSIVE URANIUM DEPOSITS

Intrusive uranium deposits occur in alaskite, granite, monzonite, peralakaline syenite, carbonatite, and pegmatite bodies. The largest deposit consists of uraninite disseminated in lower Cambrian pegmatitic alaskite intruded into Upper Proterozoic metasedimentary rocks in the Rössing District, Namibia. The main examples of intrusive uranium deposits in the United States are the very large porphyry copper deposits, such as Bingham Canyon mine, Utah, where uranium has been recovered by heap-leaching of tailings, and pegmatites, which are rarely mined because they small although rich deposits. Because of the uranium in porphyry copper deposits, they have a potential radon problem.

Uranium minerals occur in rich concentrations (>1 percent U_3O_8) in many pegmatites, but rarely are ore bodies large enough to be mined for uranium. Uranium has been recovered from the pegmatites in the Bancroft area, Ontario, Canada (Alexander, 1986).

The environmental concerns of mining pegmatite uranium ores are similar to those of vein uranium deposits.

PHOSPHORITE URANIUM DEPOSITS

Phosphorite is a marine sedimentary rock that contains syngenetic uranium in most places in low concentrations of uranium on the order of 0.009 percent U_3O_8; it may be locally enriched by weathering. It occurs in fine-grained apatite minerals. The principal large phosphorite deposits in the United States are Tertiary rocks in Florida and in South and North Carolina and the Permian Phosphoria Formation in Idaho, Montana, and Utah. Large deposits of phosphorite also occur in North Africa and Middle Eastern countries. Production of phosphorite in the United States has come mostly from Florida and North Carolina, and only a small amount from the western states. Uranium has been recovered as a by-product of phosphorite manufacture mostly from Florida, and a very small amount of uranium has been recovered from phosphorite in the western areas (Stowasser, 1991). Uranium travels with phosphorous in the mining and manufacture of various fertilizer products. Uranium can be recovered from the manufacture of phosphoric acid. Most of the uranium not recovered goes with the acid, whereas radium and various daughters go with the "fines" (slime) (Strain and others, 1979). Some entrained phosphoric acid and uranium are retained in gypsum, the solid reaction product, during the phosphoric acid manufacture. This gypsum is considered to be a toxic waste because of its low pH and radon emanations (J.R. Herring, U.S. Geological Survey, personal communication, July 1993). Other uranium is retained in the "sand" separated by floatation before the chemical treatment, and this "sand" is returned to the mine workings, which in actuality cleans up the environment. The amount of uranium and

associated radionuclides, including radium and radon, is very small (de Jesus, 1984) in these various waste products. The clay resulting from drying of "fines", however, poses a potential radium and radon problem. In Polk County, the clay fields total about 100,000 acres. Research sponsored by the Florida Institute of Phosphate Research showed that less than one percent of the radium-226 found in the soil was taken up by plants grown in the clay fields (Striker, 1993).

COLLAPSE BRECCIA PIPE URANIUM DEPOSITS

Collapse breccia pipe uranium deposits occur only in the Grand Canyon region in Arizona and adjacent Utah (Wenrich, 1985). The pipes have a small diameter (about 300 feet) but extend through as much as 2,500 feet of section above the Mississippian Redwall Limestone. The ore occurs in breccia whose wall rocks are Permian and Pennsylvanian rocks. The primary ores are high grade (0.65 percent U_3O_8) and commonly contain copper and silver. In deeply eroded and weathered pipes, copper and silver are supergene enriched, and uranium content has been lowered in remnant deposits, and some of these have been mined for copper, gold, and silver (Chenoweth, 1988). These abandoned mines pose a radon problem.

VOLCANIC URANIUM DEPOSITS

Volcanic uranium deposits in felsic igneous rocks are generally related to calderas; they are commonly of mixed forms similar to tabular sandstone deposits and veins. The host rocks are mostly Tertiary in age. Uranium is commonly associated with molybdenum, fluorine, and mercury. In the United States, the major deposits are at McDermitt, Nevada-Oregon border; Marysvale, Utah; and Date Creek Basin, Arizona, all in the Basin and Range Uranium Province (Finch, 1992). Further south in this Province, major volcanic deposits are in the Chihuahua District, Mexico. Mines for all of these deposits are an environmental problem for not only uranium and radon but some also for mercury.

SURFICIAL URANIUM DEPOSITS

Surficial uranium deposits occur in sediments, mostly of Quaternary and Tertiary ages, which have not been deeply buried and may or may not have been calcified to some degree (Otton, 1984a). Surficial deposits most commonly form in either arid or wetland surficial environments. The common host rock in arid environments is calcrete, and carnotite is the most common uranium mineral, which is primary in the sense it is the first to form. The most prominent deposit in the arid environment is the Yeelirrie deposit in desert of Western Australia. In the United States, carnotite occurs in calcrete layers in the Miocene Ogallala Formation in the Southern High Plains of west Texas (Otton, 1984b). In wetland deposits, uranium, generally absorbed and not in a uranium species, occurs mostly in peat formed in Holocene organic-rich, poorly drained, fluvial-lacustrine environments related to present-day drainages underlain by granitic rocks. These deposits are difficult to identify because they are only slightly radioactive due to the young age of the uranium concentration. They are very common in wetland environments in the United States.

They have been identified in northeastern Washington, northern Idaho, Sierra Nevada of California, Colorado Rockies, and the eastern United States. The deposits are generally small but may be as much as a mile or more in length and a few hundred feet wide; the thickness generally equals the depth of the sediment. The grades range from less than 0.01 percent U_3O_8 uranium to as much as 0.15 percent. The only deposit that has been mined is along Flodelle Creek in Stevens County, Washington.

Mining of surficial uranium deposits and returning the waste to original sites decreases the amount of original uraniferous sediment and ultimately improves the surficial environment. Although never tried, in-situ-leach mining would seem to be feasible and very beneficial to the environment.

LIGNITE URANIUM DEPOSITS

Uraniferous lignite deposits in Cretaceous and Tertiary formations are widespread in southeastern Montana, southwestern North Dakota, and northwestern South Dakota (Denson and Gill, 1965). The uranium occurs in very low amounts (0.005-0.02 percent U_3O_8, averages about 0.008 percent) irregularly, disseminated in lignite and in coaly material in associated clay and sandstone beds. The primary uranium in the lignite is present in an organo-uranium complex, but sparse visible secondary minerals, such as copper-uranium arsenate and copper-uranium and calcium-uranium phosphate, have been observed in some outcrops. Uranium has been recovered by mining and ashing the coal; radium, radon, and other radionuclides for the most part accompany the ash. Incidentally, the level of radioactivity in fly ash from burning bituminous coal in electrical power plants is very high; for example, in the United Kingdom plants, radioactivity is 1,400 becquerel per kilogram alpha and 1,100 Bq/kg beta/gamma in the ash compared to 82Bq/kg and 170 Bq/kg, respectively in the coal (Baxter, 1993).

OTHER TYPES OF URANIUM DEPOSITS IN THE UNITED STATES

In the United States, an important type of deposit in the IAEA classification included as "Other deposits" is the limestone uranium deposit. It occurs in the Todilto Limestone Member of the Wanakah Formation in the Grants Mineral Belt, New Mexico. Limestone uranium deposits consist of uraninite and minor coffinite locally accompanied by fluorite, barite, and vanadium-oxide minerals localized along intraformational folds in the limestone. These deposits were an important source of uranium in the 1950's. Their environmental concerns are similar to those of sandstone deposits; no environmental data are available on their reclamation.

THORIUM

Thorium is about three times more abundant than uranium in the earth's crust. Thorium ore deposits are relatively sparse because thorium forms mainly resistate rock minerals, particularly in metamorphic and igneous environments. Thorium occurs widely disseminated mostly in very small quantities of thorium-bearing minerals that are not easily oxidized. Thorium is rarely remobilized

to form ore bodies. In the sedimentary cycle, thorium is not mobile like uranium and remains in residual minerals deposited in fluvial and beach placers. The principal minerals are monazite [(Ce, La, Nd, Th)PO_4], thorite ($ThSiO_4$), uranothorite, and brannerite (Staatz and Olson, 1973). Monazite occurs mainly in beach and fluviatile placers, notably in the United States along the Atlantic Coast; it was mined in the 1930's in the Piedmont of North and South Carolina. Monazite also is concentrated in small deposits in metamorphic and igneous rocks. Carbonatite is the most common host, which account for about 40 percent of world resources (Barthel and Dahlkamp, 1992); notable occurrences in the U.S. are at Mountain Pass, California and Wet Mountains, Colorado. Thorite occurs mainly in veins, which account for about 30 percent of world resources; notable examples are in the Wet Mountains, Colorado; Bokan Mountain, Alaska; and Lemhi Pass and Hall Mountain, Idaho. Brannerite occurs in the Precambrian quartz-pebble conglomerate deposits in the Blind River-Elliot Lake region of Canada, where its thorium content has been recovered as a by-product of uranium mining, although most of the thorium has gone into mill tailings.

Mining of thorium-bearing deposits in the U.S. has been minor and, except for eastern placers, it has not been recovered. The large, rich uranium-thorium deposit at Bokan Mountain, Alaska, was mined for uranium, and the thorium is presumed to have remained in the tailings; the ore was processed in Washington state. Thorium veins in Idaho have been prospected with small open-pit and underground workings. Thorium-230 is the parent of a series of radioactive decay products, including radium-226 and radon-222, which present serious environmental concerns in mining.

RADIUM

Radium occurs in uranium ores at about one part radium to about three million parts uranium (Tyler, 1930). It does not occur as a distinct radium mineral, although radium-bearing barite is a the common mineral in small concentrations. Radium emits gamma radiation and has a half life of over 1,600 years, which makes disposal of radium imperative and its minute concentrations expensive. Radium can be produced as a by-product of uranium milling, but is rarely recovered for economic use in recent times. There is an adequate supply of radium, although there are no quantitative resource data. Man-made radioisotopes have largely replaced radium in its applications. Radium ends up in the tailings piles from mining of uranium, copper, vanadium, fluorspar, and phosphorite (Strain and others, 1979), and from slightly uraniferous metallic ores. The International Atomic Energy Agency (1984) reported on radium studies of uranium mining of sandstone ores in the Grants Mineral Belt, New Mexico; and Tona mine, Japan; Zirovski Vrh, Yugoslavia; surficial deposits at Yeelirrie, Australia; quartz-pebble conglomerates at Witwatersrand, South Africa; and vein deposits at Vendé, France. It was found that in most cases too little pre-mining background data were available to determine if present high levels of

radioactivity were caused by mining. Radium was extracted from high-grade carnotite ores from southwestern Colorado and southeastern Utah from 1906-1926 at plants located in Denver and Boulder, Colorado; Chicago, Illinois; Orange, New Jersey; Sellersville, Lansdowne, Cheswick, and Canonsburg, Pennsylvania (Landa, 1981,1984). Most of these sites are currently on the EPA Superfund list for cleanup (EPA, written communication, 1993).

OPEN-PIT, UNDERGROUND, AND IN-SITU-LEACH MINING CHOICES

The choice of mining method and the subsequent disposal of mine and mill tailings is primarily an economic one governed by governmental regulations and will determine the types of environmental problems. In general, underground mine tailings are piled on the ground surface, are subject to wind and water action, and present a serious radiological health risk. In some modern cases, mine and mill tailings are returned underground and problems are minimized, for example, Energy Fuels Inc. breccia pipe underground (shaft) operations in the Grand Canyon, Arizona (Mathison, I.W., Energy Fuels Nuclear, Inc., oral communication, 1992). In open-pit mining, the tailings may be returned to the pit and environmental concerns are moderated. In 1991, K.A. Dickinson and I attempted to locate in the field an open-pit mine in Karnes County, Texas; instead we found that we could only recognize the site in a field of grain where the grain was noticeably more luxuriant.

In-situ-leach (ISL) mining causes the least environmental radionuclide problems of the three methods of mining because of minor surface disturbance and no mine tailings. However, calcite deposited in ponds must be disposed of in final reclamation (Michael Drozd, written communication, 1993). Monitor wells around the well field insure against radioactive contamination of the ground water aquifer.

The type of uranium deposit and the permeability of the wall rocks will determine in many cases the choice of mining method. Sandstone deposits, particularly roll-front deposits in Cretaceous and Tertiary host rocks, are in permeable rocks and are amenable to ISL mining with a high (~90%) recovery of uranium. Hard-rock deposits are generally not amenable to ISL mining. The average grade of most uranium deposits is 1 percent or less U_3O_8, but a few, such as those of unconformity related type, average several to more than 10 percent and special precautions against radiation need to be taken to underground mine them. The richest known deposit, Cigar Lake at a depth of more than 1,500 feet, in Saskatchewan, Canada, averages about 14 percent U_3O_8 and must be mined by novel remote methods (NUEXCO, 1993, p. 104).

CONCLUSIONS

Mining of deposits of radioactive minerals can be as safe as mining any metal deposits but requires additional safety precautions during mining, milling, and reclamation. Exposure to radiation can be limited using existing technology. Mining of uranium is considered safer than mining of coal, which has explosive gases. Uranium and thorium present less of a health risk than their associated radiogenic daughters and radium. Radon presents the greatest radiological risk in a closed environment (such as a tunnel), but not all problems are related to mining because of radon's general widespread distribution in ordinary soils, rocks, and water.

The grade of uranium deposits influence the intensity of environmental radiological problems. In general, the higher the grade the greater the radon problems. Grades of more than 1 percent require adequate ventilation and other measures to avoid undue exposure to radiation. Grades of more than 10 percent U_3O_8 require remote mining and milling.

Some metals and elements associated with uranium deposits cause additional environmental concerns, especially sulfur, selenium, and arsenic.

The choice of mining method affects the environmental concerns, especially those related to radon. Precautions must be factored into the initial development of explorations, mining and milling of uraniferous ores. Final reclamation can be successful but with added costs.

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