Comparison of Potential Radiological Consequences From a Spent-Fuel Repository and Natural Uranium Deposits

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September 1980

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**Pacific Northwest Laboratory
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SUMMARY

A general criterion has been suggested for deep geologic repositories containing spent fuel--the repositories should impose no greater radiological risk than that due to naturally occurring uranium deposits. The following analysis investigates the rationale of that suggestion and determines whether current expectations of spent-fuel repository performance are consistent with such a criterion.

In this study, conducted by the Pacific Northwest Laboratory for the Office of Nuclear Waste Isolation (ONWI) under its contact with the U.S. Department of Energy, reference spent-fuel repositories were compared to natural uranium-ore deposits. Comparisons were based on 1) intrinsic characteristics, such as radionuclide inventory, depth, proximity to aquifers, and regional distribution, and 2) actual and potential radiological consequences that are now occurring from some ore deposits and that may eventually occur from repositories and other ore deposits.

The comparison results show that the repositories are quite comparable to the natural ore deposits and, in some cases, present less radiological hazard than their natural counterparts.

On the basis of the first comparison, placing spent fuel in a deep geologic repository apparently reduces the hazard from natural radioactive materials occurring in the earth's crust by locating the waste in impermeable strata without access to oxidizing conditions.

On the basis of the second comparison, a repository constructed within reasonable constraints presents no greater hazard than a large ore deposit. Even without such constraints, however, the natural hazard due to some observed radioactive releases to the biosphere in the United States far exceeds any hazard that could reasonably be expected from a spent-fuel repository.

It is recommended that if the naturally radioactive environment is to be used as a basis for a criterion regarding repositories, then this criterion should be carefully constructed. The criterion should be based on the

radiological quality of the waters in the immediate region of a specific repository, and it should be in terms of an acceptable potential increase in the radiological content of those waters due to the existence of the repository.

In every drop of water or breath of air there is the full potential for all life and all death and everything in between. It is good when all of the elements are in balance and somewhat worse when they are not.

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INTRODUCTION

A general criterion has been suggested for deep geologic repositories containing spent fuel—the repositories should impose no greater radiological risk than that due to naturally occurring uranium deposits. The following analysis investigates the rationale of that suggestion and determines whether current expectations of spent-fuel repository performance are consistent with such a criterion.

The analysis, conducted by the Pacific Northwest Laboratory (PNL) for the Office of Nuclear Waste Isolation (ONWI) under its contract with the U.S. Department of Energy (DOE), has two main parts. The first part compares natural ore deposits with reference geologic repositories. This comparison is based on intrinsic characteristics such as total radionuclide inventory, proximity to the earth's surface and aquifers, geographic and crustal distribution, and local average and point-specific concentration of key radionuclides. The second part compares the potential radiological consequences from reference geologic repositories with the potential and current radiological releases from natural deposits.

The earth's environment is naturally radioactive due to its original inventory of elements including uranium and its daughters. Since creation, geological processes have been transferring uranium from the earth's core to the surface by magmatic differentiation. Surface processes have further concentrated some uranium into economic deposits. The natural radioactivity varies from place to place as a result of all these processes.

The disposal of radioactive waste back to the environment, in the long term, does not change the natural inventory of uranium and its daughters, disregarding the fraction fissioned in a nuclear reactor. In the short term, the short-lived radioactive fission products add significantly to the radioactive inventory. However, uranium and its daughter radium-226 (and its daughters) are the toxic elements of major long-term concern and share this property with natural deposits. Also of long-term concern for the repository are the long-lived fission products ^{99}Tc , ^{14}C , and ^{129}I , and the actinide ^{237}Np and its precursor ^{241}Am , which, for all practical purposes, do not exist in the natural deposits.

Natural uranium deposits are analogous in many respects to the proposed geologic disposal of radioactive waste. Therefore the characteristics of natural deposits have been reviewed for comparison to similar characteristics of an engineered waste-disposal site.

The tools for performing a classical risk analysis on a geologic repository or a natural uranium deposit are not yet available. The basis for the second part of the analysis was methodology developed (Burkholder et al. 1976) for estimating the potential radiologic consequences due to a scenario involving ground-water intrusion, leaching, and nuclide transport. This methodology was applied in a limited manner to predict the potential radioactive release from large uranium deposits and further to compare these predictive calculations with earlier calculations (Cloninger, Cole and Washburn 1980; Cloninger and Cole 1980) for spent-fuel repositories. The potential radiological consequences from the ore deposits were then compared to those from the repository on an equivalent basis.

The radiological consequences from measured uranium and radium concentrations from several U.S. ground and surface waters were calculated to check on the rationale of the ore deposits' release calculations and to provide actual and current data for the comparisons.

Measured uranium and radium concentrations in these waters were input to the biosphere/dose model to determine the potential consequences of using these sources. Uranium concentrations were converted to equilibrium radium concentrations to predict the potential radiological consequences. The comparison is based on potential long-term radiological consequences to man resulting from an assumed failure of a repository versus both 1) existing consequences from exposure to waters containing isotopes from natural deposits and 2) potential consequences from large, natural ore deposits.

The biological effects are expressed in terms of annual, total-body dose and lifetime, critical-organ dose to a "maximum individual" in order to be consistent with the prior analyses of the reference repositories (Cloninger, Cole and Washburn 1980; Cloninger and Cole 1980).

CONCLUSIONS

The reference spent-fuel repositories were compared to natural uranium ore deposits 1) in terms of intrinsic characteristics, such as radionuclide inventory, depth, proximity to aquifers, and regional distribution, and 2) in terms of the calculated actual and potential radiological consequences that are occurring from some ore deposits and that may eventually occur from repositories and other ore deposits. The comparison results show that the repositories are quite comparable to the natural ore deposits and, in some cases, present less radiological hazard than their natural counterparts.

On the basis of the first comparison, placing spent fuel in a deep geologic repository apparently reduces the hazard from natural radioactive materials occurring in the earth's crust by locating the waste in impermeable strata without access to oxidizing conditions. Under such conditions, even in the event of containment failure, the limited solubility of material exposed to limited quantities of water permeating through geologic materials with high adsorptive capacities would restrict migration to less than the 0.1 to 1.4 cm/yr, which is the estimated migration rate for natural uranium deposits under conditions of oxygen-saturated ground water and permeable strata.

On the basis of the second comparison, a repository constructed within reasonable constraints presents no greater hazard than a large ore deposit. Even without such constraints, however, the natural hazard due to some observed radioactive releases to the biosphere in the United States far exceeds any hazard that could reasonably be expected from a spent-fuel repository.

Therefore, while at first intuition it is reasonable to use natural ore deposits as a basis for criteria for nuclear waste repositories, the variability in the natural system is so great that it does not allow a specific criterion to be stated in absolute terms.

It is suggested that if the naturally radioactive environment is to be used as a basis for a criterion regarding repositories, then this criterion should be carefully constructed. The criterion should be based on the

radiological quality of the waters in the immediate region of a specific repository, and the criterion should be in terms of an acceptable potential increase in the radiological content of those waters due to the existence of the repository. This criterion could then be used as a basis for developing, through experimentation and modeling, specific criteria for a repository system design that is reasonably assured of meeting the environmental criteria.

INTRINSIC PROPERTIES COMPARISON

A perspective on uranium deposits versus waste repositories requires an understanding of the quantity and distribution of naturally occurring uranium and other radioactive elements in the environment. The crustal abundance of natural radioactive nuclides is briefly presented. This is followed by a tabular presentation of the distribution of uranium in the earth's core, mantle, crust, and hydrosphere. The levels of radioactive elements in ground and surface waters are reviewed. An understanding of the processes leading to formation of uranium ore deposits is developed by reviewing 1) the source rocks that provide the uranium, 2) the host rocks in which the uranium deposits occur, and 3) a summation of the total uranium occurrences and the associated radiological activity. A more detailed description is given of economic deposits containing appreciable reserves of uranium, and data is presented on ground-water movements and uranium migration associated with these deposits. The hydrogeology of uranium deposits is discussed with information on the solubility of uranium minerals and the chemical composition of ground water from uranium-containing aquifers. A review is included of 1) the current depth of uranium mining in the United States and 2) the relation of depth to the permeability of host rocks and to the presence of water, which is necessary for the transport of uranium.

Finally, radioactive decay charts are included (see the Appendix) because of the radiological importance of daughter products. Also included in the Appendix tables are factors for the conversion from curies to grams of the various elements. This conversion is important since radiological effects are considered in terms of curies while physical resources are based in mass units of grams or tons.

CHARACTERISTICS OF A NUCLEAR WASTE REPOSITORY

A proposed repository for spent-fuel elements from pressurized water reactors (PWR) is compared with natural uranium occurrences. The inventory of radioactive nuclides contained in the repository at various times after closure is shown in Appendix Table A.1 (U.S. Department of Energy 1979). Repository

characteristics and the assumed conditions controlling the release of radioactive elements to the environment in the event of containment-system failure are given in the following list.

Inventory of radionuclides per repository	24,000 Ci ^{238}U 72,000 tonne ^{238}U
Equivalent number of spent PWR fuel elements	156,000
Number of spent PWR fuel elements per acre	92
Area of repository	1690 acre (2.64 mi ²)
Area per fuel element	0.01 acre
Depth of repository below surface	600 m (1969 ft)
Inventory of ^{238}U per fuel element	0.462 tonne
Inventory of ^{238}U per acre	42.5 tonne
Thickness of zone occupied by fuel elements	3.8 m (12.47 ft)
Integrated ^{238}U density	0.16%
Containment-system failure	1.0 to 10 ⁶ yr
Ground-water velocity	1.5 x 10 ⁻² to 11.0 m/yr
Migration path length	0.2 to 64 km
Ground-water travel time	15 to 10 ⁶ yr
Release rate	1.0 to 10 ⁻⁶ %/yr

NATURAL RADIOACTIVE MINERAL OCCURRENCES

The principal, natural radioactive nuclides found in the earth's crust are uranium-238, uranium-235, thorium-232, potassium-40, and rubidium-87. Radioactive decay of these nuclides results in radioactive daughter products such as radium-226 and radon-222. Other natural radioactive nuclides result from cosmic-ray bombardment of stable nitrogen-14, oxygen-16, and argon-40, producing tritium, (^3H) and carbon-14 among others. The crustal abundance of radioactive elements is shown in Table 1 (Brobst and Pratt 1973; Rohrmann 1969; Weast 1974).

The natural distribution of uranium in the earth's core, mantle, and crust, as well as uranium distribution between the continental and oceanic crust and in the hydrosphere is shown in Appendix Table A.2 (Deffeyes and Macgregor 1978).

TABLE 1. Crustal Abundance of Radioactive Elements

<u>Element</u>	<u>Abundance, ppm</u>	<u>Radioactive Isotope</u>	<u>Percent of Natural Abundance</u>	<u>Half-life, yr</u>	<u>Decay</u>	<u>Abundance of Isotope, ppb</u>
Uranium	1.7	Uranium-235	0.72	7.1×10^8	α	12
		Uranium-238	99.27	4.51×10^9	α	1,700
Thorium	5.8	Thorium-232	100	1.39×10^{10}	α	5,800
Potassium	25,900	Potassium-40	0.00118	1.28×10^9	β	306
Rubidium	310	Rubidium-87	27.85	5×10^{11}	β	86,000

Decay of Natural Radioactive Nuclides

All radioactive elements spontaneously decay to stable elements in a series of stages. Once equilibrium is established the radioactivity associated with every stage is equal. Thus the decay chain of uranium-238 consists of 14 stages and the total radioactivity at equilibrium is 14 times that associated with uranium-238 decay to thorium-234. The decay chains of uranium-235, uranium-238, and thorium-232 are shown respectively in Figures A.1, A.2, and A.3, in the Appendix. The radioactive decay products of natural uranium are listed in Table A.3 (Benedict and Pigford 1957), and the radioactive decay products of thorium are listed in Table A.4 (Benedict and Pigford 1957).

Background Levels of Radioactive Minerals

The concentration of radioactive elements in the earth's crust is subject to wide variation depending upon the rock type, basic rock chemistry, and the rock's geographic location. According to a survey of over 2000 analyses of rocks from around the world, by H. A. Wollenberg of Lawrence Berkley Laboratory, University of California, the concentration of uranium in rocks ranges from 30 ppb to 720 ppm and of thorium from 0 to 880 ppm. The range and mean

value of uranium and thorium content for different rock classes is shown in Table A.5 (according to A. A. Wollenberg).

Source Rocks

Uranium content of the whole earth is estimated to be 10.5 ppb. However, most of this uranium has been concentrated in the mantle and crust by geological processes. Igneous processes (melting) have further transported uranium from the mantle to the crust and have deposited it in veins or have distributed it in intrusive and extrusive rocks. Sedimentary processes have further distributed uranium by erosion, leaching, and precipitation. Under favorable conditions uranium was concentrated in stream beds before the earth's atmosphere became oxidizing (~1.8 billion years before present) creating the fossil placers of the Witwatersrand in South Africa and Elliott Lake in Canada. Under later oxidizing conditions, uranium was leached by surface and ground waters and transported eventually to the ocean; in the process uranium was precipitated where reducing conditions were encountered. Most U.S. uranium deposits originated from this process.

Effusive Rocks (Volcanic tuffs, breccias). Volcanic tuffs and breccias are important sources of uranium found in the environment and in many commercial sandstone deposits and uraniferous lignites. These acidic rocks containing from 5 to 300 ppm uranium have been ejected into the atmosphere from volcanos and deposited in thin layers over thousands of square miles. The uranium in these permeable fragmented rocks is leached by surface and ground water and transported ultimately to the sea except where reducing conditions are encountered and uranium is deposited. An example of a volcanic source rock is the tuff from the Absaroka volcanic field in Wyoming. The volcanic field covered 40,000 mi² of Wyoming, Montana, North Dakota and South Dakota and contained ~5 ppm uranium or ~20 x 10⁶ tons uranium (Denson and Gill 1965). Water draining these rocks contains 20 ppb or more uranium. The average uranium content of 12 samples of spring and well water from tuff beds was 33 ppb. The average of 6 samples of spring and well water near known uranium occurrences was 153 ppb while 5 samples from nontuffaceous rocks averaged 3 ppb uranium. The area covered is indicated in Figure 1.

FIGURE 1. Area Containing Detritus from Absaroka Volcanic Field

The volcanic rocks of the San Juan Mountains in Colorado cover an area of about 8000 mi² and contain from 1.3 to 5.5 ppm uranium or $\sim 1.26 \times 10^8$ tons uranium as itemized in Table A.6 (Larsen et al. 1958).

Intrusive Rocks (granites, etc.). Granitic rocks exposed over large areas and containing from 5 to 30 ppm uranium are credited as the source of many uranium deposits near the rock outcrops. Some of the granitic rocks are regarded as ultimate resources of uranium and thorium that could be exploited at tolerable costs. Some of these occurrences are listed in Table A.7 (Waldepohl 1969, p. 92-I-1).

Host Rocks

The original source of most of the uranium in the earth's crust is magmas and igneous rocks (Finch 1967). Ground water leaches uranium from these sources and transports it via permeable rocks where it may encounter reducing conditions and be precipitated. Otherwise uranium remains in solution and moves ultimately to the oceans. Sandstones, because of their permeability, are favorable channels for ground water circulation and become host rocks for uranium deposition where they contain carbonaceous matter, sulfides, or other reducing materials. Uranium in the oceans is precipitated in organic muds or phosphate sediments—examples of these are the black shales, Chattanooga shale, Phosphoria formation, and the Florida phosphate beds.

Sandstones. Approximately 4600 uranium deposits in sandstone are known in the United States. Most occur in the west central states of New Mexico, Colorado, and Wyoming and are the major source of U.S. mined uranium and uranium reserves. Sandstone host rocks outcrop or underlie huge areas of the West as indicated by the outlines of sedimentary basins in Figure 2 (Finch 1967, p. 68).

Shales. Marine shales are exposed or underlie large areas in the central and eastern United States. Many contain more than average uranium content and are potential economic deposits (see Figure 3) (Cathcard 1956; Mapel 1956; McKelvey and Carswell 1956; Swanson 1956). The Chattanooga shale and correlatives occupy an area of 800,000 mi² in Tennessee, Kentucky, Alabama, Georgia, Ohio, and Indiana and extend to Texas and Montana. The beds average 40 ft

FIGURE 2. Distribution of Eocene Uranium Deposits in Sandstone

thick, contain 30 ppm uranium, and contain 1.9×10^9 tons uranium. The Gassaway member of the Chatanooga shale contains twice the average amount of uranium or about 60 ppm, is 12 to 18 ft thick, and contains 5.7×10^6 tons uranium. The Gassaway member also contains 8.7 ppm thorium, which is equivalent to 8.4×10^5 tons thorium.

FIGURE 3. Some Uraniferous Areas and Source Rocks in the United States

The marine Phosphoria formation underlies or outcrops in 135,000 mi² of Idaho, Wyoming, and Montana (see Figures 3 and 4) (McKelvey and Carswell 1956). It contains 100 ppm uranium, which is equivalent to 600,000 tons uranium.

The Land Pebble Phosphate District in Florida covers 1000 mi² with uranium concentrations of 150 ppm in some areas (see Figure 3). The Bone Valley formation in the district covers several hundred square miles and contains 100 ppm uranium, which is equivalent to 254,000 tons uranium.

Total Uranium Occurrences in the United States

The total uranium inventory of the earth is estimated as 6.3×10^{13} tonne (Deffeyes and Macgregor 1978) or 2×10^{13} Ci. This is equivalent to the uranium inventory in 877 million standard repositories. The uranium inventory of the United States is estimated as 2.4×10^{12} tonne (Deffeyes and Macgregor 1978) or 8×10^{11} Ci and is equivalent to the uranium in 34 million repositories. If currently mineable-grade uranium is 300 ppm or greater, the cumulative amount of uranium in the United States is 19 million tonne (Deffeyes and Macgregor 1978) or 6.3 million Ci and is equivalent to the uranium in 264 repositories. January 1, 1978 DOE estimates of potential uranium resources available at \$50 per pound of U₃O₈ is 2.7 million tonne uranium (U.S. Department of Energy 1978) or 0.9 million Ci, which is equivalent to the uranium content of 37 repositories.

Thus the inventories of natural uranium are orders of magnitude greater than the inventories that are contemplated for spent-fuel repositories. This information is summarized in Figure 5.

Uranium Ore Deposits

The principal uranium ore deposits in the United States occur in the western states as shown in Figure 6 (U.S. Department of Energy 1978). The largest uranium ore deposits are in New Mexico, Colorado, Utah, and Wyoming. A detailed description of some of the large deposits follows.

Grants Mineral Belt

The Grants Mineral Belt is a series of related uranium deposits occurring in a band extending some 100 mi across northwestern New Mexico as outlined in

FIGURE 4. Generalized Maximum Uranium Content (percent) of Rocks from the Phosphoria Formation and Stratigraphic Correlatives

FIGURE 5. Comparative Uranium Inventory of Waste Repository with Inventory of Naturally Occurring Uranium Deposits

Figure 7 (Barnes, Geller and Hill 1977; Hilpert 1969). The belt has a cumulative production plus \$50 reserves of 684,000 tonne of uranium (Arnold and Hill 1980) equivalent to 228,000 Ci. The uranium occurs in sandstones and limestones that served as channels for uranium-bearing ground water. Uranium deposited where reducing conditions were encountered, generally in a series of lens-like concentrations. Figure 8 is an example of the areal distribution of ore while Figure 9 illustrates the distribution in cross section (Kelley 1963). Uranium occurs near the surface where it is mined by open pit methods. It also occurs at depths as much as 1500 ft where it is mined by underground methods.

FIGURE 6. Significant Areas of Uranium Production in the United States

FIGURE 8. Ore Distribution and Structure Contour Map of the Southeastern Ambrosia Lake Area

FIGURE 9. Relationship of Uranium Deposits to the Stratigraphic Units

Individual lenses of ore have migrated over time by dissolution and reprecipitation, and there is evidence the process is continuing in some areas at present (Kelley 1963).

Shirley Basin

The uranium deposits of the Shirley Basin in Wyoming are associated with two large tongues of altered sandstone (see Figure 10) (Harshmann 1968). The source of the uranium is believed to be from the Granite Mountains and tuffaceous beds of the White River Formation. Ground water issuing from the tuffaceous beds contains 10 to 20 ppb uranium, and ground water present in the Wind

FIGURE 10. Upper and Lower Altered Sandstone Tongues of the Shirley Basin in Wyoming

River Formation contains 20 ppb uranium, 10 pCi/L radium, with a pH of 7.5 to 8.0. The ground-water table is at depths of a few feet to 300 ft below surface and the ground-water gradient is 10 to 30 ft/mi (0.19% to 0.57%). The principal anions in the ground water are bicarbonate ± 200 ppm and sulfate 1000 ppm (Harshmann 1968).

The estimated known resource of uranium in the Shirley Basin upper tongue is 32,000 tonne, equivalent to 11,000 Ci; in the lower tongue it is 7000 tonne, equivalent to 2300 Ci. The deposits were formed in a sandstone host rock with a median thickness of 30 ft and a median width of 19,800 ft for the upper tongue and 15,800 ft for the lower tongue. The median permeability of the strata is 750 ft/yr, and the median gradient is 1.7%. Ground water flowing through the strata at a rate of 12.8 ft/yr for 17 million years carried 44,000 tonne of uranium and precipitated an estimated 75% in the upper tongue. An estimated 20% from 35,000 tonne uranium flowing through that system was precipitated in the lower tongue (Golabi and Lamont 1978).

Gas Hills

The uranium deposits of the Gas Hills District in Wyoming occur in a coarse-grained arkosic sandstone of the Wind River Formation. The source of the host rock was the granitic core of the Granite Mountains (Love 1970). The estimated known resource of uranium in the Gas Hills District is 68,000 tonne (~23,000 Ci U-238). The median thickness of the host sandstone is 150 ft, the median width of the aquifer is 53,000 ft. The median permeability of the strata is 750 ft/yr with a median gradient of 1.7%. Ore formation occurred over 20 million years by precipitation from ground water containing 15 ppb uranium and flowing at a rate of 12.8 ft/yr. An estimated 10% to 30% of the uranium was precipitated in mineable deposits of economic value (Golabi and Lamont 1978).

Granite Mountain Deposit

The Granite Mountains in Wyoming, represent a granitic source rock that contained 20 to 30 ppm uranium 60 million years ago but today contains only 2 to 5 ppm uranium. The total uranium content originally present is estimated to be between 7.0 to 10×10^7 tonne in an area of 1600 to 4800 km² and 390 m thick (Rosholt and Bartel 1969).

Rössing Deposit

The Rössing deposit in Namibia (formerly South West Africa) produces nearly 4000 tonne/yr uranium from 44,400 tonne/day of ore containing 300 ppm uranium. The total uranium content in the deposit is about 6×10^7 kg. The deposit is about 700 m in diameter and has a thickness of about 300 m, containing a volume of $1.2 \times 10^8 \text{ m}^3$ of uranium-bearing granite. The deposit is in the Namib Desert, a very dry location (annual rainfall is about 1 in./yr). The deposit is near the edge of the Khan River Basin, but the river contains water only when there is runoff from the infrequent rains. The leaching of uranium from the deposit is included here because it approximates the inventory of a waste repository, is an example of a granitic deposit, and is being commercially mined.

Uranium Deposits at Depth

Uranium deposits can occur at the surface or at any distance below the surface. Uranium is being recovered from depths in excess of 10,000 ft as a by-product of gold mining in South Africa. The uranium deposits at Oklo, Gabon are thought to have been buried as deep as 30 km by sediments before being exposed near surface by uplift and erosion. Knowledge of uranium at great depth is limited because exploration is not economical. However, in 1977 underground mines produced 80% of U.S. uranium, and 18.6% of the uranium came from 800 to 2600 ft below the surface. The distribution of uranium production in 1977 by depth of ore is shown in Table 2 (U.S. Department of Energy 1978). The locations of some significant underground uranium mines in the United States are shown in Figure 11 and some are listed in Table 3 (Dayton 1978, p. 73, 76, 99, 100, 105, and 137; Arnold and Hill 1980).

RADIOACTIVE ELEMENTS IN GROUND AND SURFACE WATERS

The concentration of uranium and radium in ground water in the United States ranges from 0.1 to 120 $\mu\text{g/L}$ (ppb) with a median of about 1.5 ppb (Davis and DeWiest 1966) for uranium and from 0.1 to 29 pCi/L with a median close to 0.3 pCi/L (Davis and DeWiest 1966) for radium. Averages for ten geotectonic regions in the United States are shown in Table 4 (Scott and Barker 1962, p. 12), and the corresponding geotectonic regions are shown in Figure 12.

TABLE 2. Distribution by Depth of Ore of 1977 U.S. Uranium Production

<u>Depth of Ore, ft</u>	<u>Uranium, tons</u>	<u>Percent of Total</u>	<u>No. of Sources</u>
0-100	760	5	105
100-200	3,480	25	60
200-300	1,780	13	35
300-400	1,870	13	20
400-500	850	6	20
500-600	1,190	8	7
600-700	930	7	15
700-800	340	2	4
800-2,600	2,630	19	11
Others	<u>340</u>	<u>2</u>	<u>37</u>
Total	14,160	100	314

Surface waters (rivers/lakes) have an average uranium content of 0.1 ppb and the oceans about 1 ppb (Deffeyes and Macgregor 1978).

Hydrogeology of Uranium Deposits

The mobility of uranium and its daughters in the environment depends primarily on ground and surface waters as vehicles. The chemical composition of the water governs the uranium solubility, and the permeability of aquifers and hydraulic gradients controls the rate of movement.

Solubility of Uranium Minerals

The most important component of ground water in solubilizing uranium is its dissolved oxygen content. The solubility of oxygen in water is 8 ppm at sea level, reducing to 7 ppm at 5000 ft equivalent atmospheric pressure.

The natural uranium concentration in ground water from strata in or adjacent to ore bodies within the Grants Mineral Belt is on the order of 60 ppb or less. The concentration of radium rarely exceeds 10 pCi/L and is commonly less than 5 pCi/L (EPA 1975). Analysis of well water from the Westwater Canyon Member of the Morrison Formation is shown in Table 5 (Hiss 1977, p. 51).

FIGURE 11. Significant Underground Uranium Mines

Figure 13 shows the solubility of UO_2 in water at various values of pH (Langmuir 1978) and the range of pH values for Grants Mineral Belt ground water (EPA 1975). Also shown are individual values of uranium concentration and pH for water from wells and other sources in Grants Mineral Belt (EPA 1975). While UO_2 is very insoluble, U^{+6} in oxidizing water is quite soluble as uranyl complexes with fluoride, phosphate, or carbonate ions.

TABLE 3. Underground Uranium Mines in the United States

Uranium Mining Co. and Mine Location	Depth, ft	Ore Grade Δ Uranium
United Nuclear Corporation Churchrock, New Mexico	1,800	---
Kerr-McGee Churchrock, New Mexico	1,850	0.17
Rio Algom Big Indian District, Utah	2,800	---
Western Nuclear Golden Goose Mine, Crooks Gap, Wyoming	400	---
Kerr-McGee Powder River Basin, Wyoming	950	---
Union Carbide Uravan Mineral Belt, Colorado	100-800	---
United Nuclear Ambrosia Lake, New Mexico	850	---
Bokum Resources Corporation Marquez Mine, New Mexico	2,150	---
Phillips Petroleum Company Nose Rock, New Mexico	3,400	---
Mobil Crownpoint in situ leach, New Mexico	2,000	---
Gulf Mt. Taylor Mine, New Mexico	3,370	---
Sohio J. J. No. 1 Mine, Laguna, New Mexico	672	0.13
Exxon Highland Mine, Powder River Basin, Wyoming	700	---
Pathfinder Mines Corporation West Gas Hills Mine, Shirley Basin, Wyoming	300	---
Western Nuclear Sheep Mt. No. 1, Crook Gap, Wyoming	1,400	---
Federal American Partners Wyoming	1,050	---
United Nuclear Morton Ranch, Wyoming	630	---
Kerr-McGee Powder River Basin, Wyoming	870	---
Union Carbide Deremo Mine, Colorado-Utah	750	---
Union Carbide King Solomon Mine, Uravan, Colorado	156	---
Cotter Corporation Schwartzwalder Mine, Golden, Colorado	2,000	0.27

TABLE 4. Concentration of Uranium and Radium in U.S. Ground Water

Geotectonic Region (Figure 12)	Number of Samples	Uranium ($\mu\text{g/L}$)		Radium (pCi/L)	
		Range	Median	Range	Median
I	86	0.1-15	0.2	0.1-8.6	0.2
II	77	0.1-24	0.5	0.1-3.3	0.1
III	17	0.1-1.5	0.5	0.1-1.5	0.1
IV	7	0.2-4.3	1.1	0.1-2.6	0.1
V	75	0.1-8.9	0.5	0.1-22	0.6
VI	72	0.1-120	2.2	0.1-11	0.3
VII	12	0.1-0.6	0.3	0.1-2.3	1.0
VIII	108	0.1-37	1.7	0.1-29	0.1
IX	13	0.1-6.1	0.8	0.1-5.5	0.1
X	42	0.1-7.6	0.2	0.1-2.5	0.1

Formation of Uranium Deposits

The formation and migration of uranium ore deposits are shown pictorially in Figure 14. Oxygenated ground water carrying dissolved uranium derived from nearby source rocks enters a sandstone aquifer in its recharge area. Ground-water flows in the sandstone under influence of gradient and the permeability of the aquifer. Carbonaceous matter and sulfides react with and deplete oxygen dissolved in the ground water. Dissolved uranium is then reduced by carbonaceous matter and by sulfides; the reduced form is insoluble and precipitates forming a deposit. Oxygenated ground water from the recharge area flows through the oxidized rock with loss of oxygen until encountering the roll front where oxygen is then consumed. Eventually, uranium is dissolved at the trailing edge of the roll front and transported to the advancing edge where it again precipitates. The advance rate of a roll front, measured by Russian geologists with similar rates accepted by American geologists, is on the order of

FIGURE 12. Median Concentration of Uranium and Radium in Ground Water in the Geotectonic Regions of the Conterminous United States

0.1 cm/yr. At this rate, roll fronts in Wyoming, which are found 11 to 13 km from the nearest recharge area, have been migrating for 11 to 13 million years.

Presence of Water at Depth

The primary long-term hazard from either a spent-fuel repository or a large ore deposit is due to the possibility that ground water may transport radioactive elements to the surface. The presence of water, its quantity, flow rate, and chemical composition are factors that govern the extent of the hazard. If exclusion of water could be assured, no such hazard would exist. Water is present in rock at considerable depths occupying pores and fractures. Sedimentary rocks contain water at depths of 50,000 ft and hard igneous rocks

TABLE 5. Dissolved Chemical Constituents in Water from Grants Mineral Belt^(a)

<u>Chemical Constituents</u>	<u>Concentration, ppm</u>
SiO ₂	18 to 43
Fe	0 to 0.01
Mn	0 to 0.16
Ca	1.9 to 39
Mg	0 to 0.5
Na	120 to 250
K	1.1 to 2.5
HCO ₃	166 to 244
CO ₃	0 to 12
CO ₂	0.5 to 2.1
Alkalinity as CaO ₃ Total	220 to 136
SO ₄	55 to 490
Cl	5.3 to 17
F	0.3 to 1
Nitrate + Nitrate as N	0.03 to 0.05
Orthophosphate as P	0.13 to 0.14
Orthophosphate as PO ₄	0.40 to 0.43
Natural Uranium	0.07 to 0.09 ^(b)
Radium-226	0.05 to 0.24 ^(c)

(a) The pH is 8.1 to 8.9.

(b) Concentration is in ppb.

(c) Concentration is in pCi/L.

at perhaps 10,000 ft. Depths greater than 100,000 ft are at temperatures and pressures that close all pores and openings, and water is present only in chemical combination with rock minerals. At the 100,000-ft (30.5-km) depth, the pressure is about 165,000 psi and the temperature is about 550°C. At this temperature sediments are converted to granite (granitization). Depths at which entry of water is precluded are too great for practical consideration.

FIGURE 13. Solubility of Uranium Minerals at 25°C Under Air at Atmospheric Pressure.
 NOTE: Solubility curves are based on research by Langmuir (1978).
 Atmospheric pressure of CO_2 is $10^{-3.5} \text{ atm}$; oxygen is $10^{-0.68} \text{ atm}$.

FIGURE 14. Formation and Migration of Uranium Deposits in Sandstone Host Rocks

COMPARISON OF NATURAL DEPOSITS AND WASTE REPOSITORIES

The inventory of uranium-238 in the reference nuclear-waste repository is 24,000 Ci or 72,000 tonne of uranium. This quantity of uranium is dispersed over 2,000 acres (3.13 mi²) in the form of 156,000 spent PWR fuel elements with a density of 92 fuel elements per acre or approximately 1/100 acre per each 460-kg fuel element. The zone occupied by the fuel elements is 3.8 m thick; if the uranium were uniformly distributed throughout the zone, its average concentration would be 0.16%.

The uranium inventory of a natural deposit can be as large or larger than that specified for a nuclear-waste repository. However, the distribution of natural deposits is controlled by chemical and geological factors and, therefore, does not simulate the precise arrangement of an engineered waste repository. Also, the full extent of natural uranium occurrences is not known nor does uranium concentration in natural deposits ever approach the concentration in a fuel element.

The Grants Mineral Belt in New Mexico has an inventory of 423,000 tonne of uranium. The Shirley Basin in Wyoming has known uranium resources of

39,000 tonne while the Gas Hills Wyoming District has an inventory of 68,000 tonne. The Grants Mineral Belt is spread over an area of about 90 mi² while the Shirley Basin deposit occurs over an area of 15 mi². The Gas Hills deposit occupies some 10 mi².

The uranium occurs in concentrations of ore pods or roll fronts often along the interface between an oxidized and reduced area of sandstone (see Figure 14). Uranium concentrations in the ore range from a lower economic mining limit of perhaps 0.05% up to as much as 14% U₃O₈. Individual ore pods may vary from an average of 3000 tonne of ore containing perhaps 5 tonne of uranium to single, large ore bodies of up to 10 million tonne of ore containing 1000 tonne of uranium. Thus the mineable concentrations of uranium ore are as large or larger than the quantity of uranium dispersed in the storage zone of a nuclear-waste repository. A single, small ore pod containing 6 tonne of uranium is equivalent to the uranium in 12 fuel elements and may have a projected area of 0.10 acre versus 0.12 acre for 12 fuel elements.

Natural uranium occurs at the surface and at depths of 3000 to 4000 ft. Most U.S. deposits occur in highly permeable aquifers which is unlike the location of an engineered waste repository that is away from the surface and in impermeous material. The modeling of a nuclear-waste repository assumes containment failure for any time from 1 to 10⁶ years. Natural uranium ore occurrences can be said to be in a state of failure for the past 30, 40 or 50 million years in that they are exposed to ground water in aquifers and have migrated considerable distances since their formation.

Ground water velocity assumed for the waste-repository studies range from 0.1 to 11 m/yr, whereas actual ground-water velocities in natural uranium ore systems are in the range of 12 ft/yr. Release rates from spent fuel have been assumed at 1 to 10⁻⁶%/yr, whereas the migration of natural uranium deposits indicate leach rates of approximately 0.15%/yr. Uranium concentrations in ground water in areas of natural uranium deposits are of the order of 60 ppb and the natural concentration of radium is commonly less than 5 pCi/L. The natural concentrations of radium in surface water and ground water, in areas near uranium ore deposits and in regions throughout the United States, frequently exceed the EPA maximum drinking water standard concentration of

5 pCi/L. The concentration of uranium in ground water also is anomalous in many areas of the United States that are quite remote from uranium mining areas.

On the basis of this analysis, placing spent fuel in a deep geological repository appears to reduce the hazard from natural radioactive materials occurring in the earth's crust by locating the uranium in impermeable strata without access to oxidizing conditions. Under such conditions even in the event of containment failure the limited solubility of material exposed to limited quantities of water permeating through geologic materials with high adsorptive capacities would restrict migration to less than 0.1 to 1.4 cm/yr for most isotopes. This is the estimated migration rate for natural uranium deposits under conditions of oxygen-saturated ground water and permeable strata.

RADIOLOGICAL CONSEQUENCES COMPARISON

The first comparison was based on similarities and differences between the intrinsic properties of ore deposits and the proposed reference repositories. This second comparison is based on the potential radiological consequences that may occur from the repositories and the actual and potential radiological consequences from natural ore deposits.

APPROACH AND METHODOLOGY

This part of the analysis involved three major tasks. The first task attempted to define a "reference" uranium ore deposit, or, failing that, attempted to adequately define one or more large uranium deposits so that the release analysis could be performed. The second task simplified the uranium-deposit descriptive data to accomplish the release calculations and analyzed the potential release based on dose to a maximally exposed individual ("maximum individual"). The third task compiled data on naturally occurring uranium and radium concentrations in U.S. surface and subsurface waters and converted that data into an equivalent radiological dose to a maximum individual. The dose was based on the same dose model as used in the repository and ore deposit analyses.

In order to partially eliminate uncertainties due to calculated (via transport models) potential nuclide releases versus measured nuclide concentrations, two large ore deposits were treated in the same manner as the reference repositories. Calculated potential consequences from these deposits were then compared to the equivalent calculations for the repositories and to the measured radionuclide concentrations in actual U.S. water resources.

Ore Deposit Definition

To develop a representative scenario for naturally occurring uranium ore deposits, a literature search was conducted and contacts were made with members of the U.S. Geologic Survey and DOE Grand Junction office. There is a wealth of information concerning uranium deposits and uranium/radium concentrations in ground and surface waters. Two uranium deposits briefly described earlier were

selected to serve as references. The two are Granite Mountain in Wyoming and Rössing in South West Africa. These two sites were picked due to their large inventories of uranium. The Granite Mountain deposit is a widely distributed, lower specific concentration deposit, while the Rössing deposit is a more compact, higher specific concentration deposit.

Granite Mountain Deposit

The characteristics of this deposit are assumed to be those present nearly 60 million years ago. It has been determined that some granite samples from the Granite Mountain region have lost nearly 80% of the uranium originally contained in them (Stuckley et al. 1977). This uranium has been leached away during the last 60 million years. Very little of the leached uranium is present in the area surrounding the Granite Mountain region. It was determined that the granite lost 1000 times as much uranium as there is known to be in reserves in the surrounding sedimentary Wyoming deposits (Rosholt and Bartel 1969).

Assuming that all the leached uranium was returned to the area, the uranium content of the deposit would be about 10^{11} kg. The uranium is spread over an area of between 1600 and 4800 km². The thickness of the leached granite is about 390 m, containing a volume of uranium-bearing granite of about 10^{12} m³. It was assumed that the ²³⁸U, ²³⁴U, ²³⁰Th, and ²²⁶Ra concentrations are in decay equilibrium. The total curies inventory for the deposit is given in Table 6. The flow rate for water through the deposit is not known, but studies have determined the rate through Conway Granite has a range of 0.01 to 0.05 m/yr (Fehm, Cathles and Holland 1978).

Rössing Deposit

The Rössing deposit of South West Africa was chosen due to its high specific activity--between ten and one hundred times that of Granite Mountain. The total uranium content in the deposit is about 6×10^7 kg. The deposit is about 700 m in diameter, has a thickness of about 300 m, and contains a volume of 1.2×10^8 m³ of uranium-bearing granite. The total curie inventory is given in Table A.1. The leaching of uranium from the deposit is slow due to the lack of moisture in the area.

TABLE 6. Radionuclide Inventories

Nuclide	Initial Inventories, Ci		
	Reference Repositories	Granite Mountain	Rössing Deposit
^{238}U	2.4E4	3.4E7	1.9E4
^{234}U	1.3E5 ^(a)	3.4E7	1.9E4
^{230}Th	2.9E1	3.4E7	1.9E4
^{226}Ra	2.9E-1	3.4E7	1.9E4
^{129}I	2.5E3	--	--
^{99}Tc	9.6E5	--	--
^{14}C	2.5E4	--	--
^{241}Am	2.3E8	--	--
^{237}Np	2.5E4	--	--

(a) Includes ingrowth from ^{238}Pu during first 1000 years.

Potential Consequences Analysis

The descriptive data for the uranium ore deposits were combined with other data needed for the nuclide-transport calculations. The methodology applied was identical to that of Burkholder et al. (1976), Cloninger, Cole and Washburn (1980), and Cloninger and Cole (1980), using a new FORTRAN version of the GETOUT (DeMier et al. 1979) nuclide-transport code. The biosphere-transport code, PABLM (Napier, Kennedy and Soldat 1980), is the same as that used in the Commercial Waste Management/Generic Environmental Impact Statement (CWM/GEIS) (U.S. Department of Energy 1979). These models were applied to predict the potential radiological consequences from the two example ore deposits in a manner consistent with the analyses of the reference repositories. A brief description follows giving the models, the scenario, and the development of the remaining descriptive data for the ore deposits.

The Models

The geosphere transport model is a second-generation FORTRAN version of the GETOUT code (DeMier et al. 1979). The model is a one-dimensional

analytical type that 1) simulates the radionuclide release from a repository through contact and leaching by flowing ground water with simultaneous transport of the nuclides in the ground water (including the effects of convection, hydrodynamic dispersion, reversible sorption and mineralization, and radioactive decay), and 2) predicts the ultimate time and rate of nuclide release to the surface water (lake or river) or water well intake.

The major hydrologic parameters are the dispersivity, ground-water flow rates, and total pathlength to the biosphere. These parameters are functions of geologic media factors such as porosity, permeability, net hydraulic head and gradient, and fracture patterns. For this analysis, these parameters have been reduced to net ground-water flow velocity, total migration pathlength, and a net dispersion coefficient. The flow velocity and pathlength, though modeled separately, are combined for graphic presentation into a single parameter, ground-water travel time (pathlength/flow velocity).

Output data of the geosphere model are the input data for the biosphere model, PABLM (Napier, Kennedy and Soldat 1980). The biosphere model predicts the human radiation dose from the nuclide release to surface waters via several pathways, including direct ingestion of water, aquatic foods and irrigated food products, as well as irradiation from shoreline deposition and swimming. Food chain reconcentration/accumulation effects are included.

The Scenario

The highest risk path from the ore deposit and repository through the geosphere to the biosphere is assumed to be the leach-incident pathway. While the relative risks of the various pathways have not all been evaluated, the leach incident appears to be the highest probability release process.

The leach-incident scenario involves the following steps:

- penetration of the repository by ground water
- failure of the waste container
- leaching of the radionuclides from the waste form
- transport of the nuclides through the surrounding geology to the biosphere

- transport of the nuclides through the biosphere to man
- interaction of the nuclides with man.

A pictorial representation of this scenario is shown in Figure 15 (Cloninger, Cole and Washburn 1980).

One difference between a repository and an ore deposit in the scenario is that the failure of the waste container is not part of the ore deposit release. The "waste form" in the case of the ore deposit is the ore itself.

The scenario has two subsets, a general scenario and an intrusion water well scenario. The general scenario consists of the six steps above with release to surface water (lake or river) as the biosphere entry point. The human-caused intrusion water well scenario can essentially short-circuit the protection that the geologic system provides from nuclides already dissolved in the ground water. The intrusion-well scenario was chosen as a limiting case of the leach-incident pathway.

The biosphere parameters for the general scenario are identical to those used in the CWM/GEIS (U.S. Department of Energy 1979) and in the studies by Cloninger, Cole and Washburn (1980) and Cloninger and Cole (1980). The parameters for the well scenario are those used by Cloninger and Cole (1980).

Uranium-Radium Concentrations in U.S. Waters

Uranium and radium are found in almost every source of surface or subsurface water. The levels of activity differ from location to location, with the water sources that traverse uranium-bearing formations containing a higher concentration. It has been proposed that these high-concentration water sources be used as an indicator of potentially mineable uranium deposits. Table 7 lists some uranium and radium concentrations that have been found in ground or surface waters of the United States. These concentrations were used in conjunction with the biosphere model to estimate the potential dose consequences due to a maximum individual's use of these waters for all of his water needs.

FIGURE 15. Pictorial Representation of the Leach-Incident Scenario

TABLE 7. Reported Nuclide Concentrations in
U.S. Surface and Subsurface Waters

Location	Uranium Content, ppb	Radium Content, ppb	Reference
Hudson River	2.2×10^{-2}	3.3×10^{-8}	Rona and Urry 1952
St. Lawrence	1.6×10^{-2}	2.5×10^{-8}	Rona and Urry 1952
Mississippi River (near Delta)	9.7×10^{-1}	--	Spaulding and Sackett 1972
Rio Grande	3.5×10^0	--	Spaulding and Sackett 1972
Camden, AL	2.0×10^{-1}	2.1×10^{-6}	Scott and Barker 1962
Long Beach, CA	1.8×10^0	1.0×10^{-7}	Scott and Barker 1962
Santa Barbara, CA	6.6×10^2	1.6×10^{-6}	Scott and Barker 1962
Curie Springs, CO	--	2.7×10^{-1}	Smith et al. 1961
Warm Springs, CO	4.6×10^0	--	Judson and Osmond 1955
Florida ground water	1.0×10^0	--	Handbook of Geochemistry 1969
Tallahassee, FL	1.2×10^0	2.0×10^{-7}	Scott and Barker 1962
Ohio River, IL	5.0×10^{-1}	--	Judson and Osmond 1955
South Windham, MA	1.1×10^1	3.3×10^{-6}	Scott and Barker 1962
Bishop Creek, MT	3.2×10^1	--	Fix 1956
Dover, NH	--	3.9×10^{-6}	Smith et al. 1961
North Conway, NH	2.0×10^{-1}	1.0×10^{-7}	Scott and Barker 1962
Princeton, NJ	2.3×10^0	1.6×10^{-6}	Scott and Barker 1962
Cement, OK	1.2×10^2	2.0×10^{-6}	Scott and Barker 1962
Icebox Creek, PA	6.0×10^0	--	Rose, Keith and Suhr 1976
Lehigh River, PA	9.0×10^0	--	Rose, Keith and Suhr 1976
Canadian River, TX	3.5×10^0	--	Judson and Osmond 1955
Llana Estacado, TX	6.2×10^0	1.0×10^{-7}	Barker and Scott 1958
Sevier River, UT	4.0×10^1	--	Fix 1956
Yellow Cat Springs, UT	8.0×10^2	--	Gabelmayer 1970
Mt. Spokane, WA			
Surface	1.5×10^0	--	Illsley 1957
Spring	4.5×10^0	--	Illsley 1957
Fox River, WI	5.0×10^{-1}	--	Judson and Osmond 1955
Pigeon River, WI	3.0×10^0	--	Judson and Osmond 1955
Crow Creek, WY	1.5×10^2	--	Murphy 1956
Muskrat Creek, WY	3.4×10^2	--	Murphy 1956
Average Wyoming areal surface waters	6.5×10^{-1}	--	Fix 1956
Columbia River maximum upstream of Hanford, WA	2.1×10^0	8.1×10^{-8}	Houston and Blumer 1979
downstream of Hanford, WA	2.5×10^0	6.1×10^{-8}	Houston and Blumer 1979

APPLICATION TO THE ORE DEPOSITS

The ground water velocity used for the Granite Mountain calculations was a factor of five times the maximum estimated for the Conway Granite System (0.05 m/yr), a value of 0.22 m/yr (0.72 ft/yr). This value was used in order to avoid numerical difficulties in the dispersion ground-water transport model. At first it was thought that this would lead to an excessively conservative result, however it was found that the result was relatively insensitive to ground-water travel rates due to the extremely long leach duration (7.7 to 77 million years) used. In other words, the dispersive effect of the long release duration (low leach rate) was far greater than the convective dispersion effects during ground-water transport.

The sorption coefficients (K_d) for both the Granite Mountain and the Rossing analysis are based on a geologic media which is a hybrid of Swedish bedrock and Nevada Test Site Climax Stock granite quartz monzonite porphyry. The ground water basis for the K_d s is similar to Swedish (Rennerfelt 1977) and Los Alamos Scientific Laboratory's analysis of Climax Stock ground water (Serne 1977). The sorption coefficients are listed in Table 8.

TABLE 8. Uranium Deposits Sorption Coefficients, K_d

<u>Element</u>	<u>Oxic Condition, ml/g (0.2 atm O₂)</u>	<u>Anoxic, ml/g (negligible O₂)</u>
Ra	80	80
Th	500 ^(a)	500
U	6-10 ^(a) (8) ^(b)	50

(a) Measured values, others estimated.

(b) Value used where range given.

For application in the GETOUT model, the K_d values were incorporated as "K-values" according to the equation:

$$K = 1 + \beta K_d$$

where β represents the ratio of geologic material available for sorption to the specific volume available for saturated ground-water flow. The values of β assumed for this work were

Granite Mountain $\beta = 3.5$

Rössing $\beta = 9.0$.

In the general scenario, the distance that the ground water traveled from the uranium ore deposit to the surface waters (biosphere entry point) was varied from 1.0 km to (0.62 mi) to 32 km (20 mi) for Granite Mountain to cover a range of possibilities due to the size of the system; it was constant at 3.2 km (2 mi) for the Rössing analysis.

For the limiting well scenario, the pathlengths were reduced to 0.23 km (0.14 mi) for Granite Mountain and 0.55 km (0.34 mi) for Rössing, and the ground-water velocity for Granite Mountain was increased to 0.45 m/yr (1.5 ft/yr).

The inventories of dose-significant nuclides for the two uranium deposits and the reference repositories are listed in Table 6. The inventory of the repositories was based on the CWM/GEIS no-recycle nuclear power industry accumulation of spent fuel, with 1/5 of the total spent fuel sealed into one repository in the year 2050 (U.S. Department of Energy 1979), and is listed in detail in Table A.1. A summary of the descriptive data for the geologic transport calculations is given in Table 9.

RESULTS AND DISCUSSION

Results were compiled from 1) the reference repository studies (Cloninger, Cole and Washburn 1980; Cloninger and Cole 1980), 2) the ore deposits consequence calculations, and 3) the measured nuclide concentrations in U.S. waters. This section explains how these study results were combined for the comparison on potential radiological consequences, and it discusses the significance of the results in relating natural ore deposits to radioactive waste repositories.

TABLE 9. System Parameters for Geologic Transport Calculations

Site	Ground Water Velocity, m/yr	Migration Pathlength, km	Ground Water Travel Time, yr	Leach Rate, Fraction/yr
Reference Granite Repository	1.5E-2 to 2.0E+0	1.0E+0 to 1.5E+1	5.0E+2 to 1.0E+6	1.0E-2 to 1.0E-6
Reference Salt Repository	1.7E-1 to 1.1E+1	5.6E+0 to 6.4E+1	5.0E+2 to 3.7E+5	1.0E-2 to 1.0E-6
Granite Mountain	2.2E-1 to 4.5E-1	2.3E-1 to 3.2E+1	5.0E+2 to 1.5E+5	1.3E-7 to 1.3E-8
Rössing	1.1E+0	5.5E-1 to 3.2E+0	5.0E+2 to 2.9E+3	1.0E-7

Application of the Results

The reported uranium and radium concentrations in U.S. waters (see Table 7) have been converted to a resultant average, annual, total-body dose to the maximum individual (see Table 10) and to a lifetime, critical-organ (bone, in all cases) dose commitment to the maximum individual (see Table 11).

The dose to the maximum individual calculated for Tables 10 and 11 was based on either the reported ^{226}Ra concentration or on the assumption that ^{226}Ra is in decay equilibrium with the reported uranium concentration. The uranium is assumed to be totally ^{238}U . It has been found that normal ground water generally contains a higher concentration (Ci/L) of radium than uranium (Muzor 1976) partly due to reconcentration (Burkholder and Cloninger 1978), enhanced solubility due to α -recoil and solution chemistry; thus the use of the equilibrium assumption would be considered conservative. However, note that in Table 10, the doses calculated from the equilibrium assumption range from about two orders of magnitude higher (Santa Barbara, California) to about an order of magnitude lower (Camden, Alabama) than those based on the actual ^{226}Ra measurement for the same water. Therefore, the validity of the equilibrium assumption is not strongly supported.

Several of the values from Tables 10 and 11 are shown graphically on Figures 16, 17, 18 and 19 for comparison with calculated potential dose consequences for the reference repositories and the two ore deposits.

TABLE 10. Calculated Average, Annual, Total-Body Dose to Maximum Individual Due to Reported Nuclide Concentrations

Location	²²⁶ Ra Dose ^(a) from Assumed Equilibrium with Uranium	²²⁶ Direct Ra Dose ^(a)
Hudson River	6.0E+0	2.7E+1
St. Lawrence River	4.4E+0	2.0E+1
Mississippi River	2.7E+2	--
Rio Grande	9.6E+2	--
Camden, AL	5.5E+1	1.7E+3
Long Beach, CA	4.9E+2	8.0E+1
Santa Barbara, CA	1.8E+5	1.3E+3
Curie Springs, CO	--	2.2E+8
Warm Springs, CO	1.3E+3	--
Florida ground water	2.7E+2	--
Tallahassee, FL	3.3E+2	1.6E+2
Ohio River, IL	1.4E+2	--
South Windham, MA	3.0E+3	2.7E+3
Bishop Creek, MT	8.7E+3	--
Dover, NH	--	3.1E+3
North Conway, NH	5.5E+1	8.0E+1
Princeton, NJ	6.3E+2	1.3E+3
Cement, OK	3.3E+4	1.6E+3
Icebox Creek, PA	1.6E+3	--
Lehigh River, PA	2.5E+3	--
Canadian River, TX	9.6E+2	--
Llano Estacado, TX	1.7E+3	8.0E+1
Sevier River, UT	1.1E+3	--
Yellow Cat Springs, UT	2.2E+5	--
Mt. Spokane, WA		
Surface water	4.1E+2	--
Spring water	1.2E+3	--
Fox River, WI	1.4E+2	--
Pigeon River, WI	8.2E+2	--
Crow Creek, WY	4.1E+4	--
Muskrat Creek, WY	9.3E+4	--
Average Wyoming area ¹ surface waters	1.8E+2	--
Columbia River maximum upstream of Hanford, WA	5.7E+2	6.5E+1

(a) Dose to maximum individual, mrem/yr, based on reported nuclide concentrations from Table 7.

TABLE 11. Lifetime Critical-Organ Dose Commitment (cumulative) to Maximum Individual Due to Reported Nuclide Concentrations

Location	^{226}Ra Dose ^(a) from Assumed Equilibrium with Uranium	^{226}Ra Direct Dose ^(a)
Hudson River	6.3E-1	2.8E+0
St. Lawrence River	4.6E-1	2.1E+0
Mississippi River	2.8E+1	--
Rio Grande	1.0E+2	--
Camden, AL	5.7E+0	1.8E+2
Long Beach, CA	5.2E+1	8.4E+0
Santa Barbara, CA	1.9E+4	1.4E+2
Curie Springs, CO	--	2.3E+7
Warm Springs, CO	1.3E+2	--
Florida ground water	2.9E+1	--
Tallahassee, FL	3.4E+1	1.7E+1
Ohio River, IL	1.4E+1	--
South Windham, MA	3.2E+2	2.8E+2
Bishop Creek, MT	9.2E+2	--
Dover, NH	--	3.3E+2
North Conway, NH	5.7E+0	8.4E+0
Princeton, NJ	6.6E+1	1.4E+2
Cement, OK	3.4E+3	1.7E+2
Icebox Creek, PA	1.7E+2	--
Lehigh River, PA	2.6E+2	--
Canadian River, TX	1.0E+2	--
Llano Estacado, TX	1.8E+2	8.4E+0
Sevier River, UT	1.1E+2	--
Yellow Cat Springs, UT	2.3E+4	--
Mt. Spokane, WA		
Surface water	4.3E+1	--
Spring water	1.3E+2	--
Fox River, WI	1.4E+1	--
Pigeon River, WI	8.6E+1	--
Crow Creek, WY	4.3E+3	--
Muskrat Creek, WY	9.8E+3	--
Average Wyoming areal surface waters	1.9E+1	--
Columbia River maximum upstream of Hanford, WA	6.0E+1	6.8E+0
downstream of Hanford, WA	7.2E+1	5.1E+0

(a) 70-yr bone dose commitment to maximum individual, rem,
based on reported nuclide concentrations from Table 7.

FIGURE 16. Summary of Calculated Potential Radiological Consequences: Average, Annual, Total-Body Dose, General Scenario

FIGURE 17. Summary of Calculated Potential Radiological Consequences: Average, Annual, Total-Body Dose, Well Scenario

FIGURE 18. Summary of Calculated Potential Radiological Consequences: Lifetime Critical-Organ Dose Commitment, General Scenario

FIGURE 19. Summary of Calculated Potential Radiological Consequences: Lifetime Critical-Organ Dose Commitment, Well Scenario

Figures 16 through 19 show a comparison among the measured radionuclide concentrations in U.S. waters, the calculated potential releases from two large ore deposits, and potential releases from the two reference repositories in four different, but related ways.

Figure 16 shows the results in terms of the average, annual, total-body dose for the general scenario. Figure 17 shows the results in terms of average, annual, total-body dose from the intrusion water well scenario (reference Figure 15), resulting in much higher doses from the repositories and ore deposits since the water is used by the maximum individual prior to dilution into surface waters.

Figure 18 shows the results in terms of maximum lifetime critical-organ dose commitment for the general scenario, and Figure 19 shows the results for lifetime critical-organ dose due to the water well scenario. The critical organ is the organ that receives the greatest cumulative dose commitment (rem), regardless of any arbitrary allowable dose limit differences among the various organs. For all of the dose consequences (Table 11) calculated from the reported nuclide concentrations in U.S. waters (Table 7), the critical organ was bone. Bone was also the critical organ for both the ore deposits and the principle critical organ for the reference repositories. Under some of the more extreme conditions, the critical organs for the repositories were the thyroid (^{129}I) and gastrointestinal tract including the lower large intestine (^{99}Tc), and again bone (^{14}C , ^{90}Sr).

In nearly all cases (Figures 16 through 19), the peak radionuclide releases occur over such long periods of time, thousands to even millions of years, that they can be considered chronic, constant environmental conditions. One exception is the case of the most severe condition of the well scenario for the reference salt repository (see Figures 17 and 19) where the dose was dominated by ^{90}Sr , a short-lived isotope of extreme dose significance. In the cases where ^{90}Sr dominates the dose, the release was limited to a maximum of 300 years.

The ^{90}Sr doses are high in the reference salt and granite site studies (Cloninger, Cole and Washburn 1980 and Cloninger and Cole 1980), because the

authors attempted to push the limits of the repository system to the point where engineered barriers to a release would become absolutely necessary in order to provide reasonable safety. In order to attain such high biosphere releases and the resultant high dose, the natural barriers to a high release rate--such as solubility limits, reasonable ground water velocities, and reasonable transport distances--had to be ignored singly and serially. While the upper limits from the most severe scenarios are indicated on Figures 16 through 19, the reasonable range is also shown (shaded bars) and is the proper basis for the comparison. A reasonable upper limit for the repositories in terms of representative parameters was taken to be a release rate of nuclides into the ground water of no more than 10^{-3} /yr (fractional) and a ground-water travel time from the repository to surface waters of no less than 500 years and to a water well borehole of no less than 100 years (a 500-year minimum was used here for the ore deposit calculations). This 100-year minimum still allows penetration of the well borehole within 30 m of either repository.

The geologic transport model was particularly conservative for the water well scenario since it treats the repository and ore deposit as a point source in the flow field. Its application to the Granite Mountain deposit was extremely conservative due to the immense dimensions of the deposit compared to the transport distance to the well borehole. These results would not be at all valid for Granite Mountain, except that the low release rate (1.3×10^{-7} to 1.3×10^{-8} /yr, fractional), rather than the far-field hydrology, controls the Granite Mountain dose consequences. Therefore, relative to the other calculations on Figures 17 and 19, a more reasonable range of consequences from the well scenario for Granite Mountain is shown by the dashed bar.

The total body dose from the ore deposits and for most of the parameter range of the repositories is dominated by ^{226}Ra created from uranium parents. Included in this dose is the direct dose from ^{226}Ra and its daughters ($^{226}\text{Ra} + \text{D}$), which includes the dose from ^{210}Pb and ^{210}Po created by decay after ingestion of ^{226}Ra plus additional dose from ^{210}Pb and ^{210}Po released to the biosphere in decay equilibrium with ^{226}Ra and subsequently ingested. The uranium itself contributes a minor fraction of the total dose. However, under some conditions for the reference granite repository, ^{234}U plus ^{237}Np from its

original inventory and from its precursor ^{241}Am contribute significantly to the total body dose and can dominate the critical-organ dose. For very extreme release rates of nuclides into the ground water, ^{14}C , ^{99}Tc and ^{129}I can dominate both the total-body and critical-organ dose from both the repositories. As previously mentioned, if this extreme release rate is combined with high ground-water velocity and a short pathlength to a water well (includes no credit for the waste container) and the flowing ground water contacts the waste immediately after the repository is sealed, the dose is dominated entirely by ^{90}Sr .

Discussion of the Results

In Figure 16, the calculated potential dose to a maximum individual from the reference repositories ranges from a high of about 240 mrem/yr to a low of about 0.10 mrem/yr resulting from the general scenario. This compares with a calculated dose that ranges from 23 to 2 mrem/yr for the Granite Mountain deposit and from 0.2 to 0.1 mrem/yr for the Rossing deposit.

With the exception of the upper bounds of potential consequences from the reference salt repository, the results from the repositories are in the same general range as those from the ore deposits. If the waste package release rates for the repositories are less than 10^{-4} /yr (fractional) or if the ^{14}C , ^{99}Tc and ^{129}I are eliminated from the repository-bound waste, the upper limits for the repositories would be the same as for the Granite Mountain deposit (about 20 mrem/yr). Note that in Figure 16, most of the points representing the water sources whose nuclide concentrations were measured lie above the range calculated for both reference repositories and both ore deposits.

To explain the relative positions, two reasons are given other than the uncertainties regarding scenarios and the geologic transport calculations. First, these measured values represent resultant consequences from quite a range of actual yet unknown scenarios in terms of release rate from the ore, size and quality of the ore deposit, ground-water velocity, and proximity of the deposit to the discharge point where the measurement was made. Second, many of the measured values probably represent waters whose radionuclide content is not from a single source, as were the calculations for the repositories and ore deposits, but from several in addition to the minerals from the immediate area where the samples were taken.

As might be expected, the dose consequences from the intrusion water well scenario, summarized in Figure 17, are considerably higher for both repositories and both ore deposits, and they generally lie in the higher range of the measured values. Furthermore, the reference repositories and the ore deposits are even more similar in potential consequences from the well scenario than from the general scenario summarized in Figure 16. It is interesting to note that even under the most severe conditions imaginable (but not necessarily reasonable) for this scenario, the maximum consequences from the repositories are at least an order of magnitude less than that calculated from the reported radium concentration of Curie Springs (top of Figure 17 and Table 10).

This is probably a useful place to point out that the extremely high doses for the repositories, ore deposits, and the conversions of reported nuclide concentrations in U.S. waters from Table 7 that are reported here are based on linear extrapolation from dose transfer factors that were determined at much lower dose rates. Thus, the actual upper limits for the well scenario consequences from the reference repositories and the ore deposits as well as those for extremely high reported concentrations of ^{226}Ra (Crow Creek, Yellow Cat Springs, and Curie Springs) would, in reality, be somewhat lower; however, relative to one another, they would still be about the same.

Figures 18 and 19 present the comparison of consequences on a slightly different basis, the lifetime critical-organ dose commitment to the maximum individual. In Figure 18, as in Figure 16, the results are shown for the general scenario and the resultant consequences for the repositories, and the ore deposits are again at the lower range of the measured values. On the basis of critical-organ dose, however, the calculated potential consequences from the repositories run generally higher than those from the ore deposits, although the reasonable range for the reference granite repository is essentially identical to the result for the Granite Mountain deposit.

The critical-organ dose consequences for the well scenario are shown in Figure 19. The calculated results for the repositories and ore deposits span the range of reported U.S. waters nuclide content. Within the predictive accuracy of the methodology and models, the reasonable ranges for the repositories, Granite Mountain, and the Rossing deposit are equivalent.

It may well be said of man in the 20th century that he spent most of his creative genius in trying to dispose of his own wastes.

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APPENDIX

TABLE A.1. Repository Nuclide Inventories (curies) at Various Times after Closure in Year 2050

Isotope	Time (years)									
	1.00+000	100 1.00+002	300 3.00+002	1000 1.00+003	3000 3.00+003	10,000 1.00+004	30,000 3.00+004	100,000 1.00+005	300,000 3.00+005	1,000,000 1.00+006
³ H	4.38+006	1.57+004	7.22-004	1.53-018	0.00	0.00	0.00	0.00	0.00	0.00
⁹⁹ Tc	9.64+005	9.64+005	9.62+005	9.60+005	9.54+005	9.32+005	8.72+005	6.92+005	3.58+005	3.56+004
¹²⁹ I	2.48+003	2.48+003	2.48+003	2.48+003	2.48+003	2.46+003	2.46+003	2.46+003	2.44+003	2.38+003
¹⁴ C	2.50+004	2.46+004	2.38+004	2.22+004	1.74+004	7.46+003	6.64+002	1.40-001	4.44-012	0.00
⁹³ Mo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁴¹ Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁷⁹ Se	2.62+004	2.62+004	2.62+004	2.60+004	2.54+004	2.36+004	1.90+004	9.04+003	1.07+003	6.18-001
⁹⁰ Sr	2.02+009	1.71+008	1.05+005	3.96-002	1.53-023	0.00	0.00	0.00	0.00	0.00
¹⁰ Be	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁶⁰ Co	8.34+006	1.59+001	1.11-016	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁵⁹ Ni	2.30+005	2.30+005	2.28+005	2.28+005	2.24+005	2.10+005	1.77+005	9.66+004	1.71+004	3.98+001
⁶³ Ni	2.72+007	1.28+007	1.34+006	1.47+004	4.22-003	5.46-026	0.00	0.00	0.00	0.00
⁸⁷ Rb	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000
¹³⁵ Cs	2.00+004	2.00+004	2.00+004	2.00+004	2.00+004	2.00+004	1.99+004	1.96+004	1.87+004	1.59+004
¹³⁷ Cs	2.88+009	2.86+008	2.80+005	2.70-001	2.38-021	0.00	0.00	0.00	0.00	0.00
¹⁰⁷ Po	7.32+003	7.32+003	7.32+003	7.32+003	7.32+003	7.32+003	7.30+003	7.26+003	7.10+003	6.64+003
¹²⁶ Sn	3.54+004	3.54+004	3.54+004	3.52+004	3.48+004	3.32+004	2.88+004	1.63+004	4.44+003	3.50+001
¹⁵¹ Sm	6.36+007	2.86+007	2.62+006	2.22+004	2.68+003	1.68-027	0.00	0.00	0.00	0.00
^{166m} Ho	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
¹⁵² Eu	1.33+005	4.14+002	1.25-005	1.14-020	0.00	0.00	0.00	0.00	0.00	0.00
¹⁵⁴ Eu	9.02+007	1.19+006	2.72+000	1.42-011	0.00	0.00	0.00	0.00	0.00	0.00
⁹³ Zr	1.24+005	1.24+005	1.24+005	1.24+005	1.24+005	1.24+005	1.23+005	1.19+005	1.08+005	7.84+004
^{113m} Cd	1.10+005	7.84+002	2.80-004	3.58-017	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁸ Cm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁴ Pu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁴ Cm	2.38+007	5.18+005	5.30+000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁰ Pu	3.38+007	3.34+007	3.24+007	3.04+007	2.48+007	1.21+007	1.56+006	1.19+003	1.47-006	0.00
²³⁶ U	1.69+004	1.70+004	1.73+004	1.78+004	1.88+004	2.30+004	2.46+004	2.64+004	2.62+004	2.58+004
²³² Th	2.04-005	8.66-005	3.16-004	1.30-003	1.99-003	1.01-002	7.30-002	1.88-001	2.84-001	1.27+000

Time (years)

[illegible]

TABLE A.2. Natural Distribution of Uranium

Geological Unit	Mass (Whole Earth) (x 10 ²⁵ gm)	Conc. U ppm	Mass-U (Whole Earth) (x 10 ⁹ tonne U)	Mass-U Cont. U.S.A. (x 10 ⁹ tonne U)
WHOLE EARTH	597.6	0.0105	63,000.00	
CORE	193.6	0.00001	20.00	
MANTLE	401.6	0.005	20,000.00	
CRUST	2.57	1.67	43,000.00	
<u>Continental Crust</u>	2.09	1.93	40,000.00	
Mafic	1.01	1.45	14,625.00	979.975
Sialic	0.99	2.56	25,375.00	1,700.16
<u>Metamorphic</u>	0.43	2.00	8,000.00	536.00
<u>Igneous</u>	0.43	1.93		
<u>Plutonic</u>	0.1754			
Veins/Pegmatites		5,000-10,000	0.0013	0.00012
Veins/Pegmatites		10,000	0.0018	0.000012
U-Granites		5-15	597.00	40.00
Granodiorites	0.1750	3.00	5,000.00	335.00
Diorite/Gabbro	0.0004	1.63	80.00	5.36
<u>Volcanic</u>				
U-Rhyolite		100-300	0.104	0.007
Andesite	0.0437	2.00	800.00	53.60
Basalt	0.0510	1.00	4,100.00	274.70
<u>Sedimentary</u>	0.128		3,200.00	
<u>Fold Belts</u>	0.094		2,200.00	
Sandstones	0.013	1.01	180.00	12.06
Shales	0.037	4.00	1,500.00	100.59
Limestones	0.015	2.2	330.00	22.11
Volcanogenic	0.024	1.0	240.00	16.08
Evaporites	0.0003	0.2	6.00	0.40
<u>Platforms</u>	0.034		940.00	
U-Sandstones		600-1,000		0.004
		1,000-3,000	0.075	0.0080
Sandstones	0.003	1.01	31.00	5.43
Placers		1,000-2,000	0.001	0.00007
Shales	0.017	4.00	680.00	45.56
U-Shales		10-40	29.10	1.95
U-Shales		40-200	0.09	0.006
Phosphorites		120-300	1.94	0.13
Limestones	0.007	2.2	150.00	10.05
Volcanogenic	0.001	1.0	10.00	0.67
Evaporites	0.0007	0.2	14.00	0.94
<u>Oceanic Crust</u>	0.43		2,600.00	
<u>Igneous/Metamorphic</u>	0.38	0.1	380.00	
<u>Sedimentary</u>	0.1005	2.0	2,200.00	
<u>Deep Ocean</u>	0.02	1.0	200.00	
Calcareous oozes	0.008	0.77	60.00	
Siliceous oozes	0.003	0.45	14.00	
Ferruginous Clay	0.001	1.30	13.00	
Red Clay	0.006	3.00	180.00	
Volcanogenic	0.0006	1.00	6.00	
<u>Shallow Ocean</u>		1.92	1,700.00	
Shelf	0.0125	3.02	380.00	
Hemipelagic	0.068	2.0	1,400.00	
<u>Hydrosphere</u>				
Rivers/Lakes	0.000051	0.0001	0.00005	0.0000335
Ground water	0.00051	0.0001	0.0005	0.000335
Oceans	0.141	0.001	14.00	
Ice	0.0023	0.0001	0.0022	

TABLE A.3. Radioactive Decay Products of Natural Uranium

Nuclide	Half-life	Radiation	Atom Ratio, ppb in Natural Uranium	Grams Isotope per Curie
²³⁸ U	4.49 x 10 ⁹ yr	α	9.928 x 10 ⁸	3.0 x 10 ⁶
²³⁴ Th	24.1 days	β, r	0.0146	4.32 x 10 ⁻⁵
²³⁴ Pa	1.18 min	β, r	4.94 x 10 ⁻⁷	1.46 x 10 ⁻⁹
²³⁴ U	2.48 x 10 ⁵ yr	α, (r)	5.48 x 10 ⁴	162.2
²³⁰ Th	8.0 x 10 ⁴ yr	α, r	1.77 x 10 ⁴	51.4
²²⁶ Ra	1622 yr	α, r	359	1.02
²²² Rn	3.83 days	α	2.32 x 10 ⁻³	6.50 x 10 ⁻⁶
²¹⁸ Po	3.05 min	α	1.28 x 10 ⁻⁶	3.54 x 10 ⁻⁹
²¹⁴ Pb	26.8 min	β, r	1.13 x 10 ⁻⁵	3.05 x 10 ⁻⁸
²¹⁴ Bi	19.7 min	β, r	8.28 x 10 ⁻⁶	2.24 x 10 ⁻⁸
²¹⁴ Po	1.64 x 10 ⁻⁴ s	α	1.12 x 10 ⁻²¹	3.11 x 10 ⁻¹⁵
²¹⁰ Pb	22 yr	β, r	4.86	0.0129
²¹⁰ Bi	5.02 days	β	3.04 x 10 ⁻³	8.07 x 10 ⁻⁶
²¹⁰ Po	138.3 days	α	0.0838	22.24 x 10 ⁻⁵
²⁰⁶ Pb	Stable	---	---	---
From U-235				
²³⁵ U	7.13 x 10 ⁸ yr	α, r	7.15 x 10 ⁶	468.3 x 10 ³
²³¹ Th	25.64 h	β, r	2.94 x 10 ⁻⁵	1.89 x 10 ⁻⁶
²³¹ Pa	3.43 x 10 ⁴ yr	α, r	344	22.15
²²⁷ Ac	22.0 yr	(α)β (r)	0.221	13.96 x 10 ⁻³
²²⁷ Th	18.6 days	α, r	5.11 x 10 ⁻⁴	32.33 x 10 ⁻⁶
²²³ Ra	11.2 days	α, r	3.08 x 10 ⁻⁴	19.13 x 10 ⁻⁶
²¹⁹ Rn	3.92 s	α, r	1.25 x 10 ⁻⁹	76.09 x 10 ⁻¹²
²¹⁵ Po	1.83 x 10 ⁻³ s	α	5.82 x 10 ⁻¹³	34.87 x 10 ⁻¹⁵
²¹¹ Pb	36.1 min	β, r	6.89 x 10 ⁻⁷	40.51 x 10 ⁻⁹
²¹¹ Bi	2.16 min	α, r	4.12 x 10 ⁻⁸	2.42 x 10 ⁻⁹
²⁰⁷ Tl	4.79 min	β, (r)	9.14 x 10 ⁻⁸	5.27 x 10 ⁻⁹
²⁰⁷ Pb	Stable	---	---	---

TABLE A.4. Radioactive Decay Products of Natural Thorium

Nuclide	Half-life	Radiation	Atom Ratio, ppb	Grams Isotope per Curie
²³² Th	1.39 x 10 ¹⁰ yr	α	10 ⁹	9.01 x 10 ⁶
²²⁸ Ra	6.7 yr	β	0.48	4.27 x 10 ⁻³
²²⁸ Ac	6.13 h	β, r	5.0 x 10 ⁻⁵	4.46 x 10 ⁻⁷
²²⁸ Th	1.90 yr	α, r	0.14	1.21 x 10 ⁻³
²²⁴ Ra	3.64 days	α, r	7.2 x 10 ⁻⁴	6.24 x 10 ⁻⁶
²²⁰ Rn	54.5 s	α	1.2 x 10 ⁻⁷	1.06 x 10 ⁻⁹
²¹⁶ Po	0.16 s	α	3.6 x 10 ⁻¹⁰	3.02 x 10 ⁻¹²
²¹² Pb	10.6 h	β, r	0.87 x 10 ⁻⁴	7.17 x 10 ⁻⁷
²¹² Bi	60.5 min	α, β, r	8.3 x 10 ⁻⁶	6.82 x 10 ⁻⁸
²¹² Po (64%)	3.04 x 10 ⁻⁷ s	α	4.6 x 10 ⁻¹⁶	5.71 x 10 ⁻¹⁸
²⁰⁸ Tl (36%)	3.1 min	β, r	1.4 x 10 ⁻⁷	3.43 x 10 ⁻⁹
²⁰⁸ Pb	Stable	---	---	---

THE SOLID BOXES DENOTE NATURALLY OCCURRING NUCLIDES. ADJACENT NUMBERS INDICATE HALF-LIFE OF ISOTOPE. DIAGONAL ARROWS INDICATE α AND HORIZONTAL ARROWS β DECAY. CHAIN BRANCHES OF <1% OMITTED.

FIGURE A.1. Uranium-235 Decay Chain Series

THE SOLID BOXES DENOTE NATURALLY OCCURRING NUCLIDES. ADJACENT NUMBERS INDICATE HALF-LIFE OF ISOTOPE. DIAGONAL ARROWS INDICATE α AND HORIZONTAL ARROWS β DECAY. CHAIN BRANCHES OF < 1% OMITTED.

FIGURE A.2. Uranium-238 Decay Chain Series

THE SOLID BOXES DENOTE NATURALLY OCCURRING NUCLIDES. ADJACENT NUMBERS INDICATE HALF-LIFE OF ISOTOPE. DIAGONAL ARROWS INDICATE α AND HORIZONTAL ARROWS β DECAY.

FIGURE A.3. Thorium-232 Decay Chain Series

TABLE A.5. Uranium and Thorium Content of Various Rock Classes

Rock Class	Rock Types	U (ppm)			Th (ppm)		
		Mean	Range	n ^(a)	Mean	Range	n ^(a)
Acid Extrusives	rhyolite (obsidian & tuffs), latite, qtz dacite	4.1	0.8-16.4	13	11.9	1.1-41.0	13
Acid Intrusives	aplite, pegmatite, granite, qtz monzonite	4.5	0.1-30.0	489	25.7	0.1-253.1	493
Intermediate Extrusives	dacite, andesite	1.1	0.2-2.6	21	2.4	0.4-6.4	21
Intermediate Intrusives	qtz diorite (tonalite), diorite, granodiorite	3.2	0.1-23.4	271	12.2	0.4-106.0	273
Basic Extrusives	basalts, olivine basalt, tachylite, basaltic glass	0.8	0.03-3.3	55	2.2	0.05-8.8	55
Basic Intrusives	gabbro, diabase, olivine gabbro, olivine diabase	0.8	0.01-5.7	119	2.3	0.03-15.0	110
Ultrabasic	peridotite, pyroxenite, dunite, serpentinite	0.3	0-1.6	31	1.4	0-7.5	30
Alkali Feldspath- oidal Intermed- iate Extrusives	Keratophyre, trachyte, trachyandesite, phondite	29.7	1.9-62.0	138	133.9	9.5-265.0	139
Alkali Feldspath- oidal Intermed- iate Intrusives	Syenite, syenodiorite, monzonite, alkali syenite	55.8	0.3-720.0	75	132.6	0.4-880.0	75

TABLE A.5. (Contd)

Rock Class	Rock Types	U (ppm)			Th (ppm)		
		Mean	Range	n ^(a)	Mean	Range	n ^(a)
Alkali Feldspathoidal Extrusives	nepheline phonolite, leucite phonolite, nepheline basalt Leucite basalt, malilite basalt nepheline tephrite, nepheline basanite	2.4	0.5-12.0	20	8.2	2.1-60.0	20
Alkali Feldspathoidal Basic Intrusives	alkali gabbros incl teschenite, theralite, essexite, picrite, shonlanite, kentellerite, alkali theralite, ijolite	2.3	0.4-5.4	8	8.4	2.8-19.6	8
Chemical Sedimentary Rocks	limestone, dolomite, cherts, evaporites	3.6	0.03-26.7	243	14.9	0.03-132.0	239
Carbonates	carbonates	2.0	0.03-18.0	141	1.3	0.03-10.8	131
Detrital Sedimentary Rocks	sandstone, shale, breccia	4.8	0.1-80.0	412	12.4	0.2-362.0	411
Metamorphosed Igneous Rocks	orthohornfels, orthogneiss, amphibolite	4.0	0.1-148.5	128	14.8	0.1-104.2	128
Metamorphosed Sedimentary Rocks	parahornfels, quartzite, marble	3.0	0.1-53.4	207	12.0	0.1-91.4	208

(a) n = number of analyses.

TABLE A.6. Volume and Uranium Content of Volcanic Rocks
Remaining in Colorado's San Juan Mountains

<u>Formation or series</u>	<u>Volume, mi³</u>	<u>U Content, ppm</u>	<u>Amount of U, tons x 10⁶</u>
Pre-Potosi (east of Conejos)	20	3.3	0.7
Lake Fork quartz latite	40	3.0	1.3
San Juan tuff	250	4.3	12
Silverton	100	5.5	6.1
Conejos	2000	2.2	48
Treasure Mountain rhyolite	300	2.9	9.6
Sheep Mountain quartz latite	80	2.5	2.2
Alboroto rhyolite	600	4.0	26
Huerto quartz latite	90	2.4	2.4
Piedra rhyolite	250	4.0	11
Fisher quartz latite	100	3.7	4.1
Hinsdale	150	1.3	2.2
Approximate volume	4000	--	--
Weighted average--	--	2.9	--
Total uranium content	--	--	126

TABLE A.7. Acid Intrusive Source Rocks for Uranium and Thorium

<u>Source Rocks</u>	<u>Location</u>	<u>Uranium, ppm</u>	<u>Thorium, ppm</u>
Conway Granite	New Hampshire	12-16	56
Westerly Granite	Rhode Island		
Granites	Maine	6.0	
Front Range Granites	Colorado	5.0	
Boulder Creek Batholith	Colorado	2.2	13.4
Front Range Laramide Stocks	Colorado	7.6	
Mount Evans Batholith	Colorado	4.4	13.4
Monarch Batholith	Colorado	2.2	13.4
Silver Plume Batholith	Colorado	3.1	79.1
Indian Creek Batholith	Colorado	4.9	62.7
Longs Peak Batholith	Colorado	5.8	29.0
Kenosha Batholith	Colorado	5.4	42.5
Log Cabin Batholith	Colorado	6.7	24.5
Cripple Creek Batholith	Colorado	3.2	24.0
Sherman Batholith	Colorado	5.7	24.0
Pikes Peak Batholith	Colorado	4.9	25.7
Wind River Uplift	Wyoming	3.1	13.7
Bear Tooth Uplift	Montana	1.6	16.8
Bighorn Uplift	Wyoming	1.4	17.9
Granite Mountains	Wyoming	2-5	--
Enchanted Rock Batholith (Granite)	Texas	3.5	--
Idaho Batholith (Granite)	Idaho	2.5	--
Boulder Batholith (Granite)	Montana	2.5	--
Southern California Batholith (Granite)	California	2.4	--
Sierra Nevada Batholith (Granite)	California	5.4	--

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