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Health Risks to Distant Populations from Uranium Mill Tailings Radon

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PREFACE

This document was first drafted in June 1974 as part of a program to determine which measures to use to control radioactivity from tailings piles at inactive uranium mills. In the interim more sophisticated analyses methods have become available; but the basic conclusions remain valid. This revised and updated version is published now in support of environmental and public health protection standards developed by the Environmental Protection Agency under the Uranium Mill Tailings Radiation Control Act of 1978.

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1: INTRODUCTION

1.1 Purpose of this Report

This paper has several purposes: to illustrate the effects of tailings piles on a variety of local and regional populations, to assess the effects of the tailings on distant populations, and to compare our methods and results with assessments by others.

1.2 Background

Uranium mill tailing piles can expose the population to radiation by several pathways. We believe the air pathway to be the most important. Radon-222, which is produced in the pile and released to the air, is the principal radionuclide.

Uranium-238 undergoes radioactive decay with a long half-life, 4.47 billion years, producing a series of other radionuclides, including radium-226 (half-life 1600 years) and its decay product, radon-222 (half-life 3.82 days). Thus, radium-226 and radon-222 are commonly found with uranium ore and with the waste, i.e. tailings, from the mills that separate uranium from the ore. Radon is a gas, but when it is created, it may or may not be trapped inside grains of tailings. The emanating fraction,[1] i.e., the fraction of the radon-222 that is released from the grains, is about 0.2 (Fo78). The radon-222 gas that is released into the spaces between the grains of tailings material diffuses toward the overlying tailings surface; some reaches the surface and some undergoes radioactive decay enroute.

The radioactive products of radon-222 decay are not noble gases, and they interact with and remain in the tailings. The radon-222 that reaches the surface escapes into the air above, where it is mixed into the passing airstream by normal local air turbulence. The wind carries the radon-222 with it and continually decreases the concentration by further mixing and dilution. The radon-222 concentration is also decreased by its radioactive decay.

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[1]The release of radon into interstitial spaces in the tailings is called "emanation;" the release of the radon from the tailings surface into the air is sometimes called "exhalation," but we are not using that term because inhalation and exhalation are performed by people at the other end of this pathway.

Radioactive products of the decay, as free ionized atoms, are carried along in the air currents where they tend to attach to dust particles. Thus, persons breathing air downwind of the tailings pile will be exposed to radon-222 and also to its radioactive decay products, which may be either free ions or carried by dust particles.

Air entering a building downwind of the tailings pile remains inside it for a time that depends on the rate at which air enters and leaves the building. Radon-222 in the air continues its normal rate of radioactive decay, forming the series of radioactive decay products that may be inhaled by persons in the building.

Some of the radioactive decay products of radon-222 are retained in the tracheobronchial region of the lungs, irradiating the fluids and tissues, and thus increasing the chance that cancer will form there. In contrast, persons exposed outdoors to the same concentration of radon-222 from a nearby tailings pile (e.g., within 1 km), may receive exposure to the lungs from the associated radon decay products that is appreciably smaller (e.g., a factor of 10) than that received indoors, because a delay time is lacking for decay products to accumulate (Sc74, Sw76). At long distances from the pile, when the decay products have "grown in," exposures resulting from the released radon will be similar indoors and outdoors.

In March 1974, the U.S. Environmental Protection Agency and the U.S. Atomic Energy Commission testified at hearings before the Joint Committee on Atomic Energy on pending bills to provide a remedial action program for a tailings pile at an inactive uranium mill site on the edge of Salt Lake City, Utah. Both Federal agencies acknowledged that there are other uranium tailings sites that present public health problems and that legislation to deal with all inactive mill sites would provide more effective control.

After the March 1974 hearings, these agencies began a cooperative study, involving the concerned States and Federal agencies, to determine the current situation at the inactive uranium mill sites and to evaluate remedial measures for each site. The results of the study were published in a series of reports by the main contractor, Ford, Bacon & Davis Utah, Inc. (References Fo76-Fo77g are from this series, which includes reports numbered GJT-1 through GJT-20.) Shortly thereafter, the Uranium Mill Tailings Radiation Control Act of 1978 (PL 95-604) created a joint Federal/State remedial action program for most inactive mill sites.

In the early stages of the cooperative study of the inactive sites and as a contribution to determining which aspects of the tailings piles should be investigated, a report—"Potential Radiological Impact of Airborne Releases and Direct Gamma Radiation to Individuals Living Near Inactive Uranium Mill Tailings Piles"-- (Sw76) was published. This report (Sw76) addressed certain radiation exposure pathways for people within a few kilometers of the tailings piles, including inhaling airborne short-lived radon decay products. During this same period, the first draft of this present document was prepared. It provided a preliminary estimate of the comparative potential radiation exposures of populations at various distances due to inhaled short-lived radioactive decay products of radon-222 released by the tailings piles to the air.

The most significant change here from that early draft is presenting the results in terms of health risk rather than dose equivalent.

2: RADON RELEASE RATE

For the air pathway, in which the lung is exposed to inhaled, short-lived radioactive products of the decay of radon-222 released from the piles, the long-term average radiation exposure is assumed to be proportional to the total amount of radon released to the air.

We take the amount released by each pile to be a constant (see below) times the product of the concentration of radon-226 (the precursor of radon-222) in the pile and of the surface area of the pile.

Table 2-1 lists inactive uranium mill sites and estimates the surface area and radium-226 concentration for the tailings piles at each site (En80). Changes in these data may occur as piles may be reworked to extract more uranium or vanadium, or perhaps reshaped.

For the estimate of radon release in Table 2-1, we assume that radon-222 is released to the air at an average rate of 1.0 pCi/m^2 each second for each pCi of radium-226 per gram of tailings. Our estimate comes from treating the tailings as if they are homogeneous and are not covered by much other material, such as soil or water. The release rate is assumed to be uniform and continuous throughout the year. Measurements of the radon release rate from any of these piles taken over short periods have differed appreciably from the estimates used here, e.g., from one-fourth to two times as great (Fo76, Fo77a-Fo77g). We consider these measurements to be no more reliable representations of the average releases than our estimates (see Section 6.2).

Ford, Bacon & Davis Utah, Inc. (Fo76, Fo77a-Fo77g) report that the tailings at some sites are in more than one pile and that different portions of the tailings at a site can have different characteristics. Such nonuniformities may make the local radon release rate greater or smaller than we estimate.

A number of the piles have soil covering the tailings, and some are quite wet (e.g., at Falls City, Fo77a), conditions that tend to reduce radon release rates. Some of the tailings at inactive mill sites also have been subjected to a variety of treatments that might (at least temporarily) change their release rates. In the present work, we make no attempt to account for the effects of the treatments.

Table 2-1. Estimated Surface Areas and Radium-226 Concentrations of Uranium Tailings Located at Inactive Mill Sites

Tailings Site	Average Ra-226 Concentration[a] (pCi/g)	Tailings Area[a] ($10^5 m^2$)	Estimated Annual Rn-222 Release (Ci)
Monument Valley, Ariz.	50	1.21	200
Tuba City, Ariz.	924	0.89	2600
Durango, Colo.	700	0.85	1900
Grand Junction, Colo.	784	2.39	5900
Gunnison, Colo.	420	1.58	2100
Maybell, Colo.	274	3.24	2800
Naturita, Colo.	800	0.93	2300
Rifle, Colo. (new)	868	1.30	3600
Rifle, Colo. (old)	1008	0.53	1700
Slick Rock, Colo. (1)	784	0.77	1900
Slick Rock, Colo. (2)	686	0.24	500
Lowman, Idaho	532	0.20	300
Ambrosia Lake, N.M.	644	4.25	8600
Shiprock, N.M.	700	2.91	6400
Lakeview, Ore.	420	1.21	1600
Canonsburg, Pa.	unknown	0.73	--
Falls City, Texas	448	5.91	8400
Ray Point, Texas	518	1.90	3100
Green River, Utah	812	0.36	900
Mexican Hat, Utah	784	2.75	6800
Monticello, Utah	910	1.62	4700
Salt Lake City, Utah	896	4.05	11500
Converse County, Wyo.	336	0.20	200
Riverton, Wyo.	560	2.91	5100

[a](En80).

3: DISPERSION OF RADON

We have treated the dispersion of radon-222 from its release at a tailings pile until the exposure of populations to its decay products in several phases.

The first phase estimates dispersion within 80 km of the tailings pile; the second estimates dispersion while the radon is windborne over the North American continent until it departs eastward over the North Atlantic Ocean; and the final phase considers the worldwide dispersion.

For all distances greater than 12 km, the dispersion was estimated using techniques adapted from Machta, Ferber, and Heffter (Ma73). We assume that once it is released to the atmosphere, radon is dispersed by the wind and is removed only by its intrinsic radioactive decay and not by any other process (e.g., sorption).

3.1 Within Eighty Kilometers

Dispersion to 12 km from a pile was calculated with the AIREM code (Ma74), using a standard sector-averaged equation (equation 3.144 in Slade (Sl68)). For locations within a few kilometers of a pile, an adjustment was made for the size of the pile (see Appendix B). As in (Sw76), meteorological data from the Fort St. Vrain reactor site in Colorado (Re70) was used for exposures out to 12 km, because accurate site-specific data for the individual tailings piles are lacking (see Section 6.2).

From 12 km to 80 km, the dispersion model of Machta et al. (Ma73) (for a source located at Morris, Illinois) was used, averaged over all directions. Machta's data for exposures in the 12 to 80 km range were approximately one-fourth those of the AIREM calculation, but were used in order to be consistent with the exposures at greater distances. Table 3-1 gives the annual average dispersion in seconds per cubic meter, averaged over all compass directions, for distances ranging out to 80 km from the tailings center.

We used the annual average dispersion, averaged over all directions, for simplicity and because of insufficient data to justify greater sophistication. Long-term measurements of radon concentrations near tailings piles (He69) show large variations with the direction from the pile.

These variations may be caused by topography, diurnal wind patterns, diurnal variations in radon release rate, or other factors, and are strongly site-specific within a few kilometers of the tailings. Data from the tailings location itself are required for a better estimate, but are not available (see Section 6.2).

3.2 Nationwide

Over periods of a year or more, winds will carry radon in all directions from a tailings site. The four-day half-life of radon-222 is sufficiently long that exposure to this radon source is national (and even hemispherical) in extent. Prevailing winds generally carry the radon to the east, so that annual exposures from a tailings pile diminish more rapidly in other directions from the pile.

Machta, Ferber, and Heffter have estimated regional, national, and worldwide pollutant concentrations from continuous releases (Ma73). There had been several earlier calculations of national exposure levels following release of gaseous effluents from a single site. For example, Knox and Peterson (Kn72) had estimated population exposures over large areas of the United States and worldwide, following releases of krypton-85 from nuclear power plants and nuclear fuel processing plants.

The data from (Ma73) were adapted for the estimate presented here. We adjusted the concentration isopleths from (Ma73) for North America for radon-222 decay during its travel time, using mean wind speeds. The resulting isopleth pattern was superimposed on the map of the United States at each tailings pile location, providing annual average concentrations for the 48 contiguous States.

A similar approach was used for Canada and Mexico, although the population data (Ne74) were not as detailed as that for the United States. Figure 3-1 shows the isopleth pattern using the Salt Lake City tailings pile as the source. The source strength from which the isopleths were developed is a continuous release rate of one curie per year. If the concentration varied greatly within a State near the tailings pile, concentration isopleths were fitted to a map of the State so that county-by-county exposures could be estimated.

After we performed this relatively simple estimation process, more accurate methods were developed and applied (Tr79). We will compare the methods and results in Chapter 6.

Table 3-1. Annual Average Dispersion of Radon-222 from Uranium Tailings Piles to Distances of 80 kilometers (averaged over all compass directions)

Average Distance from Pile Center (km)	Annual Average Dispersion[a,b] (s/m^3)
0.25	2.4×10^{-5}
0.5	6.9×10^{-6}
0.6	4.7×10^{-6}
0.75	2.9×10^{-6}
1.25	8.2×10^{-7}
1.5	6.3×10^{-7}
1.75	5.0×10^{-7}
2.0	4.1×10^{-7}
2.25	3.5×10^{-7}
2.5	3.0×10^{-7}
2.75	2.6×10^{-7}
3.25	2.1×10^{-7}
3.5	1.8×10^{-7}
3.75	1.6×10^{-7}
4.5	1.2×10^{-7}
7.5	4.9×10^{-8}
9.6	3.5×10^{-8}
15	1.3×10^{-8}
24	3.9×10^{-9}
30	2.3×10^{-9}
40	1.4×10^{-9}
50	1.0×10^{-9}
60	8.2×10^{-10}
70	6.6×10^{-10}
80	5.7×10^{-10}

[a](s/m^3) = seconds per cubic meter. If the annual average release rate to the air is given in picocuries per second, the product of it and the annual average dispersion will be an annual average concentration in the air in units of picocuries per cubic meter.

[b]An average over all directions, of the annual averages for 16 compass directions.

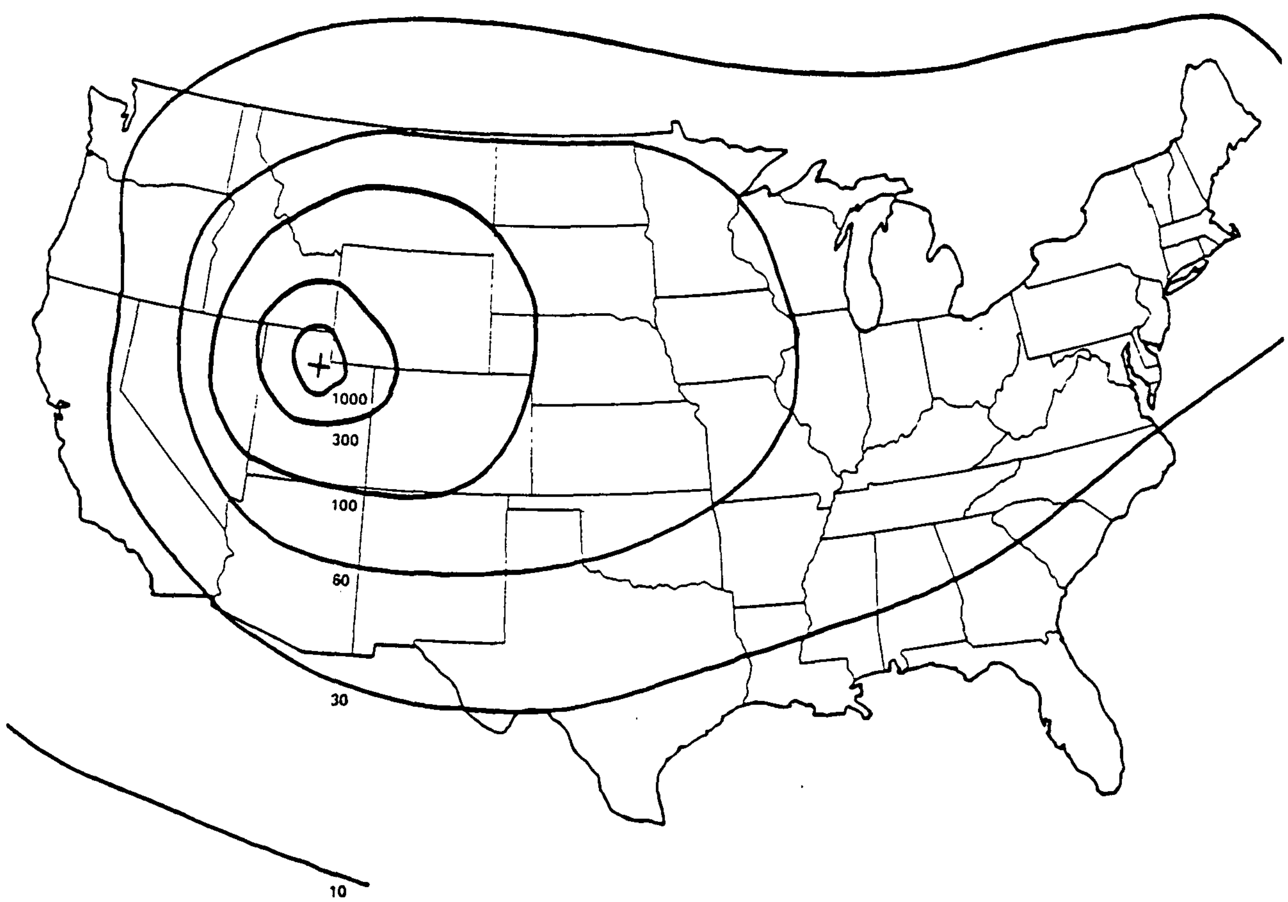

Figure 3-1. Annual Average Radon-222 Concentrations (Units of 10^{-20} Ci/m^3) Due to a Continuous Release of One Curie per Year from the Salt Lake City, Utah, Tailings Location

3.3 Worldwide

Worldwide exposure estimates were based on data from Machta et al. (Ma73), where the source term is a continuous release of one curie per year of krypton-85. When adjustments are made for the more rapid decay of radon-222, only the earlier phases of worldwide dispersion are of interest. In a manipulation similar to that applied to the regional and national isopleths, we shifted the isopleth pattern for the early worldwide dispersion phase to the west (about 20 degrees of longitude for the tailings pile at Salt Lake City). The concentration over each individual country was multiplied by the population of that country, and the product was corrected for the radioactive decay of radon-222 while it travels to that location.

Windborne radon circles the world in about 30 days. After 30 days, about 0.004 times the original amount of radon remains, which is insignificant when compared to the uncertainty in the estimate of worldwide exposures. Therefore, there is no need for longer-term assessment of worldwide dispersion of radon-222, as Machta et al. (Ma73) did for krypton-85. We made only one estimate of collective exposures in Europe and Asia because the dispersion would be virtually the same for any pile located in the western United States.

Machta's work (Ma73), from which we derived the dispersion beyond 12 km, represents an initial effort at calculating nationwide and worldwide dispersion. Their computer program was not available for general use at the time this document was drafted. The approximation we used, of translating the isopleths from the source location at Morris, Illinois (used by Machta, et al.) to the various tailings pile locations, does not incorporate differences from site to site in regional wind patterns.

Therefore, our results show a smaller variation in collective exposures per 1,000 curies released than recent site-specific calculations (Tr79). Because we use the same isopleth pattern at each tailings location, our estimates reflect primarily differences in population distributions. In Chapter 6 we compare the results of this simple procedure with the recent, more accurate calculations (Tr79).

4: EXPOSURE TO RADON DECAY PRODUCTS

Population data from the 1970 census are shown in Tables 4-1 through 4-7 for various distant sectors around uranium mill tailings pile locations (See Appendix A). We use the population data combined with radon concentration levels to estimate annual average population exposures as a function of their distances from a tailings pile.

Census Bureau data indicate no one is living in the immediate vicinity of certain tailings piles. Because the census data were compiled by adding small groups of people together and assigning them a collective location, this is not the actual case. There are occupied dwellings and even small population groups where none are shown by the census. However, people are unlikely to be mislocated by more than a few kilometers. Other sources (e.g., Fo77a-Fo77g) have provided estimates of nearby populations which we have added to the Census Bureau data where the latter showed zero population.

For the populations exposed at distances greater than 80 km, we used 1970 census data for cities, counties, and States (Ne74).

We estimate the population exposure to radon and its decay products similarly as in (Sw76). When radon is first released from the tailings pile, it may be regarded as unaccompanied by its decay products. Because it does not react chemically, radon is retained in the body only in negligible amounts when inhaled, and causes only a small radiation exposure of the lungs. Thus, the radon from a tailings pile may add little to outdoor background radiation exposures immediately downwind. However, when radon enters a building and is given time to decay by the slow rate at which indoor air is exchanged for outside air, a buildup of decay products of radon-222 will occur in the air.

We assume that delay in the building air exchange provides time for the buildup of short-lived radon decay products to about 70 percent of the radioactive decay equilibrium value (Un77). We also assume that in outdoor air, far from the pile, approximately the same 70 percent equilibrium ratio of decay products is eventually obtained (Un77).

At this level of decay product buildup, one pCi of radon-222 per cubic meter of air is accompanied by approximately 7×10^{-6} Working

Levels (WL) of the principal short-lived decay products, polonium-218, lead-214, and bismuth-214. (The Working Level is defined (32 FR 11183) as any combination of the short-lived radon decay products in one liter of air that will result in the ultimate emission of 1.3×10^{-5} MeV of potential alpha energy.)

In Tables 4-1 to 4-7, we present the collective exposures in person Working-Level years (person-WL-years). We consider this a more appropriate unit than the rem for estimating risks due to radon decay products because the WL has been related to the incidence of lung cancers observed in uranium miners exposed to those decay products. Yearly exposure is more appropriate for the exposure circumstances considered here than the Working Level Month (WLM) used for uranium miners. Continuous exposure to one WL for a year is roughly equivalent to 27 WLM, for a member of the general population (Gu79).

We assume that, on the average, the exposed population spends 75 percent of the time indoors. Therefore, for exposures within 40 km of the tailings, we assumed that 75 percent of the exposure was at 7×10^{-6} WL per pCi/m^3 (indoors) and 25 percent at 5×10^{-6} WL per pCi/m^3 (outdoors). At greater distances, we assume that decay products have accumulated so that exposures are about the same indoors and outdoors, at 7×10^{-6} WL per pCi/m^3.

Tables 4-1 through 4-7 show the estimated collective exposures at various distances from the tailings piles, covering the local and regional populations. The estimated collective exposure to the national population for a long-term (to average over fluctuations) release of 1000 curies is 0.7 person-WL-year, averaged over the seven locations.

The estimated collective exposure to the adjacent countries of Canada and Mexico is about 0.1 person-WL-year for a long-term release of 1000 curies, and to the rest of the world also about 0.1 person-WL-year. About 60 percent of this latter amount is experienced in western Europe, and radioactive decay makes the collective exposure smaller in India and eastward.

Table 4-1. Collective Radon-222 Decay Product Exposure to the Population within 80 km of the Uranium Tailings Pile at Grand Junction, Colorado

Distance from center of pile[a] (km)	Population in increments of distance	Annual collective exposure[b] (person-WL-years)
0.5	166	1
1.0	1,022	4
1.5	5,024	5
2.0	3,611	2
2.5	6,224	3
3.0	7,001	2
3.5	3,697	0.9
4.0	800	0.2
5.0	4,022	0.6
10	8,401	0.5
20	8,684	0.1
40	3,851	0.01
80	18,084	0.02
Total	70,421	19

[a]Outer radius of an annulus whose inner radius is the next smaller distance.

[b]For an annual release of 5,900 Ci radon-222.

Table 4-2. Collective Radon-222 Decay Product Exposure to the Population within 80 km of the Uranium Tailings Pile at Gunnison, Colorado

Distance from center of pile[a] (km)	Population in increments of distance	Annual collective exposure[b] (person-WL-years)
1	738	2
2	2,237	0.6
3	1,738	0.2
4	0	0
5	0	0
10	345	0.007
20	938	0.005
40	1,529	0.002
60	318	0.0001
80	14,379	0.004
Total	22,122	2.8

[a]Outer radius of an annulus whose inner radius is the next smaller distance.

[b]For an annual release of 2,100 Ci radon-222.

Table 4-3. Collective Radon-222 Decay Product Exposure to the Population within 80 km of the Newer Uranium Tailings Pile at Rifle, Colorado

Distance from center of pile[a] (km)	Population in increments of distance	Annual collective exposure[b] (person-WL-years)
1	42	0.1
2	2,108	1
3	0	0
4	0	0
5	548	0.05
10	0	0
20	1,397	0.01
40	2,621	0.004
60	11,939	0.01
80	19,976	0.01
Total	38,631	1.2

[a]Outer radius of an annulus whose inner radius is the next smaller distance.

[b]For an annual release of 3,600 Ci radon-222 from the newer tailings location at Rifle, Colorado.

Table 4-4. Collective Radon-222 Decay Product Exposure to the Population within 80 km of the Uranium Tailings Pile at Shiprock, New Mexico

Distance from center of pile[a] (km)	Population in increments of distance[b]	Annual collective exposure[c] (person-WL-years)
0.8	0	0.0
1.6	2,550	3
2.4	0	0
3.2	0	0
16	4,671	0.2
32	4,625	0.02
40	[d]11,822	0.02
48	[d]14,449	0.02
64	15,857	0.02
80	16,794	0.02
Total	70,768	3.3

[a]Outer radius of an annulus whose inner radius is the next smaller distance.

[b]Population data out to 1.6 km from Ford, Bacon & Davis Utah, Inc. (Fo78).

[c]For an annual release of 6,400 Ci Radon-222.

[d]Population count between 32 and 48 km divided into 32 to 40 km and 40 to 48 km according to the ratio of the areas of the annuli.

Table 4-5. Collective Radon-222 Decay Product Exposure to the Population within 80 km of the Uranium Tailings Pile at Falls City, Texas

Distance from center of pile[a] (km)	Population in increments of distance	Annual collective exposure[b] (person-WL-years)
1	[c]50	0.3
2	50	0.04
3	90	0.04
3.5	160	0.04
4	200	0.04
5	200	0.04
10	600	0.05
20	4,196	0.09
40	28,448	0.1
60	67,876	0.1
80	821,665	1
Total	923,535	1.8

[a]Outer radius of an annulus whose inner radius is the next smaller distance.

[b]For an annual release of 8,400 Ci radon-222.

[c]Population data to 10 km from Ford, Bacon & Davis Utah, Inc. (Fo78).

Table 4-6. Collective Radon-222 Decay Product Exposure to the Population within 80 km of the Uranium Tailings Pile at Mexican Hat, Utah

Distance from center of pile[a] (km)	Population in increments of distance	Annual collective exposure[b] (person-WL-years)
0.5	[c]2	0.02
1.0	10	0.04
1.5	47	0.05
1.8	143	0.1
2.0	115	0.08
10	0	0
20	2,681	0.05
40	1,235	0.004
80	10,212	0.01
Total	14,445	0.4

[a]Outer radius of an annulus whose inner radius is the next smaller distance.

[b]For an annual release of 6,800 Ci of radon-222.

[c]Population data out to 2 km from Ford, Bacon & Davis Utah, Inc. (Fo78).

Table 4-7. Collective Radon-222 Decay Product Exposure to the Population within 80 km of the Uranium Tailings Pile at Salt Lake City, Utah

Distance from center of pile[a] (km)	Population in increments of distance	Annual collective exposure[b] (person-WL-years)
0.5	7	0.1[c]
1.0	156	1[c]
1.5	397	0.8
2.0	735	0.9
2.5	8,986	7
3.0	4,228	3
3.5	11,594	6
4.0	12,050	5
5.0	42,679	10
10	280,000	30
20	106,000	3
40	80,000	0.4
80	308,000	0.06
Total	854,832	68[c]

[a]Outer radius of an annulus whose inner radius is the next smaller distance.

[b]For an annual release of 11,500 Ci radon-222.

[c]Table C.2 in reference Fo78 indicates a greater population near the tailings; it includes, within 0.5 miles of the pile's edge, 1400 residents and 3200 employed persons whose exposure would increase these values by about 13 person-WL-years.

5: HEALTH RISKS

The principal radiological health risk from exposure to radon-222 is lung cancer from irradiation of the bronchial epithelium of the lung by the short-lived radon decay products. From more extensive assessments (Tr79, McD79) we have concluded that the effects of the longer-lived decay products are less significant than the incidence of lung cancer caused by inhaling short-lived decay products. The following comparison of health risks does not consider the risks from long-lived decay products, such as lead-210, or any other radiation risk associated with tailings piles.

We have estimated risks based only on radon released directly from tailings piles and have not included radon from tailings that have blown off a pile or been used in construction. Windblown tailings are secondary radon sources that could be significant, but are difficult to assess. Tailings used in building construction, as in building foundations, can expose people occupying the buildings to increased indoor radon and radon decay product concentrations (En79). The effects of tailings used in construction are beyond the scope of this paper, however.

We estimated the risk by assuming an increased incidence of lung cancer proportional to the level and duration of increased exposure to short-lived radon decay products, and proportional to the natural incidence of lung cancer (a so-called "relative risk" assessment).

Our risk estimates are based primarily on studies of underground miners. Although there is considerable agreement on the risks from radon to underground miners, there is some uncertainty on how to apply these risk estimates to the general public. The relative risk estimate we used (En79) gives the same result as the most recent estimate by the National Academy of Sciences (Na80), which is calculated on the basis of age-dependent absolute risk. Nevertheless, these remain estimates on which there still exists disagreement in the scientific community (Ra80).

The value we use, 2.3 committed fatal lung cancers per 100 person-WL-years, depends on the lung cancer incidence in the United States as a whole. For certain States, the local lung cancer rate is smaller than the national average. The health risks to the local, regional, and total populations of these States are estimated by multiplying 2.3 by a corresponding reduction factor. This reduction factor is, for Texas, 0.967; for New Mexico, 0.537; for Colorado, 0.657; and for Utah, 0.392 (El79). (Some minor inconsistency results where a site is less than 80 km from a site in another State.)

The risk estimates for the rest of the United States, for Canada and Mexico, and for the rest of the world are based on 2.3 committed fatal lung cancers per 100 person-WL-years. This probably overestimates the very small health risks calculated for most other countries, because their lung cancer rates are generally somewhat below that in the United States.

Table 5-1 shows the estimated fatal lung cancer commitment in the populations at various distances from the the seven tailings piles addressed in this document. Table 5-2 shows the corresponding estimates with the source strength at each pile normalized to 1,000 curies of radon-222 released per year. We have assumed that for fairly constant releases over periods of a year or longer, the exposure in person-WL-years will be approximately directly proportional to the quantity of radon released.

Table 5-1. Comparison of the Estimated Fatal Lung Cancer Commitment[a] at Selected Distances Due to Radon-222 from Tailings at Seven Inactive Uranium Mill Sites

Distance increment	Grand Junction Colo.	Gunnison Colo.	Rifle Colo.	Shiprock N.M.[b]	Falls City Texas	Mexican Hat Utah	Salt Lake City Utah
0.0 to 5 km	0.3	0.04	0.02	0.03	0.01	0.003	0.3
5 to 10	0.008	1×10^{-4}	0.0	0.0	0.001	0.0	0.3
10 to 20	0.002	8×10^{-5}	2x10-4	---	0.002	4×10^{-4}	0.03
20 to 40	2×10^{-4}	3×10^{-5}	6×10^{-5}	6×10^{-4}	0.002	4×10^{-5}	0.004
40 to 80	3×10^{-4}	7×10^{-5}	3×10^{-4}	7×10^{-5}	0.02	9×10^{-5}	0.005
Subtotal	0.3	0.04	0.02	0.03	0.04	0.003	0.6
Rest of USA	0.09	0.03	0.06	0.1	0.1	0.1	0.2
Total USA	0.4	0.07	0.08	0.1	0.1	0.1	0.8
Canada & Mexico	0.02	0.007	0.01	0.02	0.03	0.02	0.04
Rest of World	0.02	0.006	0.01	0.02	0.02	0.02	0.03
Total	0.4	0.08	0.1	0.1	0.2	0.1	0.9

[a]Annual commitment of fatal lung cancers due to inhalation of radioactive short-lived decay products of radon-222.

[b]Distance increments for Shiprock are: 0.0 to 3.2 km; 3.2 to 16 km; 16 to 40 km; and 40 to 80 km; instead of the respective increments given in the left column.

Table 5-2. Comparison of the Estimated Fatal Lung Cancer Commitment at Selected Distances Due to Release of 1000 Curies of Radon-222 from Tailings at Seven Inactive Uranium Mill Sites

Distance increment	Grand Junction Colo.	Gunnison Colo.	Rifle Colo.	Shiprock N.M.[a]	Falls City Texas	Mexican Hat Utah	Salt Lake City Utah
0.0 to 5 km	0.05	0.02	0.005	0.005	0.001	$4x10^{-4}$	0.03
5 to 10	0.001	$4x10^{-5}$	0.0	0.0	$1x10^{-4}$	0.0	0.02
10 to 20	$3x10^{-4}$	$3x10^{-5}$	$6x10^{-5}$	---	$2x10^{-4}$	$5x10^{-5}$	0.003
20 to 40	$3x10^{-5}$	$2x10^{-5}$	$2x10^{-5}$	$9x10^{-5}$	$2x10^{-4}$	$5x10^{-6}$	$3x10^{-4}$
40 to 80	$4x10^{-5}$	$3x10^{-5}$	$9x10^{-5}$	$1x10^{-4}$	0.003	$2x10^{-5}$	$4x10^{-4}$
Subtotal	0.05	0.02	0.005	0.005	0.004	$5x10^{-4}$	0.05
Rest of USA	0.01	0.02	0.02	0.02	0.02	0.02	0.01
Total USA	0.06	0.04	0.02	0.03	0.02	0.02	0.06
Canada & Mexico	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Rest of World	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Total	0.07	0.05	0.03	0.04	0.03	0.03	0.07

[a]Distance increments for Shiprock are: 0.0 to 3.2 km; 3.2 to 16 km; 16 to 40 km; and 40 to 80 km; instead of the respective increments given in the left column.

6: DISCUSSION

6.1 Comparison with Other Estimates

Our evaluation was performed primarily to assess the relative effects of radon from tailings piles on local, regional, and national populations, rather than to make accurate estimates of the health risk around individual tailings locations.

However, we will compare here our results with those of Ford, Bacon & Davis Utah, Inc. (FBDU), which has compiled such data (Fo78) from its series of reports on most of the inactive uranium mill sites, including the seven sites we selected.

FBDU's radon-222 annual average concentration exposures compared to ours are: at Grand Junction, Colorado, 1870 vs. 3000 person-pCi/liter-year; at Gunnison, Colorado, 325 vs. 400 person-pCi/liter-year; at the newer Rifle, Colorado location, 289.6 vs. 200 person-pCi/liter-year; at Shiprock, New Mexico, 2550 vs. 400 person-pCi/liter-year; at Falls City, Texas, 120.7 vs. 80 person-pCi/liter-year; at Mexican Hat, Utah, 127.2 vs. 40 person-pCi/liter-year; and at Salt Lake City, Utah, 13,200 vs. 10,000 person-pCi/liter-year. (FBDU's values are as given in (Fo78); our values are to one significant figure).

Most of these pairs of values match within the uncertainties. At Shiprock, Falls City, and Mexican Hat, we have used the Ford, Bacon & Davis Utah population data, so the comparison mainly reflects differences in estimating radon concentrations. These comparisons are for exposures to the local populations, within a few miles, as treated in (Fo78).

The procedures used by Ford, Bacon & Davis Utah, Inc. appear to differ appreciably in thoroughness and sophistication from site to site, perhaps due in part to the paucity of data for some sites. For most sites, we believe their results and ours are of comparable accuracy.

Travis et al. (Tr79) estimated population exposures from four uranium mill sites using theoretical atmospheric concentration gradients for North America (provided by the National Oceanic and Atmospheric Administration) for a unit release from each tailings location. Of the four sites, only one (Falls City, Texas) coincides with our selection. At Falls City, Travis et al. estimated, for a nominal release of 1,000 Ci radon-222 per year, collective exposures of 108 person-pCi/liter-year to the national population, 1.2 person-pCi/liter-year to the Canadian population, and 5.2 person-pCi/liter-year to the population of Mexico. They did not include the population within 50 miles (about 80 km) in this calculation. Our estimates for the same areas are: 100 person-pCi/liter-year to the national population, 1 person-pCi/liter-year to the Canadian population, and 20 person-pCi/liter-year to the population of Mexico. We consider the methods of Travis et al. more accurate, but the results are very similar.

The differences in (Tr79) among collective national exposures for the four sites they examined is greater than differences over the seven we examined, most likely because Travis et al. used more site-specific data; their smallest value is about 56 percent of their largest (Falls City), whereas our smallest value is about 82 percent of our largest (Gunnison). In view of the overall uncertainties in such estimates (see below), however, our simpler methods appear adequate.

6.2 Uncertainties

All segments of the radiation exposure pathway have appreciable uncertainties. The quantities of radon-222 released each year from the tailings locations are estimated from data derived from the uranium production records of the now-inactive mills.

Although measurements of the radon release rate have been made, for most piles only a few scattered measurements were made and those only over short time periods (Fo76, Fo77a-Fo77g); such measurements give broad indications of the radon release rates from tailings piles. We believe our method of estimating radon release rates based on the tailings composition is as reliable as any when data from comprehensive, long-term sampling is lacking. The relatively sparse direct measurements of radon-222 release rates of tailings piles (e.g., Fo76, Fo77a-Fo77g) show a few samples indicating slightly higher release rates, and a greater number indicating lower release rates than our estimates.

The annual release from a tailings pile could be firmly established only by a long-term monitoring program, sampling fairly continuously the radon release rate per unit area at a number of points on the pile. This expensive program is not likely to be carried out because no specific need for such accurate data has been determined.

The dispersion of the radon-222 in air has many sources of uncertainty. Little and Miller (Li79) estimate uncertainties of one or two orders of magnitude for complex terrain or meterorology using a Gaussian-plume model like that employed here. Furthermore, our use of uniform dispersion in all directions, with one set of meteorological data for all sites, ignores differences between site-specific data and data from a distant location, and differences in meteorology among regions of the country.

Although the climate at Fort St. Vrain, in central Colorado, is similar to other locations in western United States, there are regional differences in large scale weather movements. When the specific directions are removed from consideration, the differences may not be as significant. If dispersion calculations are made using the Fort St. Vrain meteorological data (Re70) and again, using the Farmington data (Ha79), the ratio of the calculated concentrations (Fort St. Vrain to Farmington) ranges from 0.76 to 0.28 within 12 km and is 0.13 at 40 km.

The Farmington data indicate that the concentrations in individual compass sectors deviate from the directional average by factors of 0.2 to 3 at 10.8 km; the Fort St. Vrain data indicate deviations by factors of 0.3 to 2 at 12 km.

These values do not include any consideration of the effects of complex terrain, a characteristic of most of these tailings locations. Dispersion, particularly within a few kilometers, is influenced by local factors such as topography. This is especially true for low wind-speed inversion conditions which produce peak concentrations of radon per unit released. Of the tailings sites we considered, it is likely that only Gunnison, Colorado, would have site-specific meteorological data available because the tailings are adjacent to the airport.

It is our view that for most of these tailings locations, data from a more distant location, even one as close as 5 km, has little directional significance. Therefore, we believe that our use of generalized meteorological data is appropriate, and using data from the nearest weather station generally would not appreciably improve the accuracy of the results.

The path airborne pollution travels over the northern hemisphere after leaving the east coast is uncertain. An article in Science suggests that some pollution may travel north across the polar regions rather than east across Asia (Ke79). There is also uncertainty in the amounts of radioactive decay products accompanying the radon-222, both outdoors and indoors (En80, Gu79, and Un77).

Another source of uncertainty is the relation between the exposure, in person-WL-years, and health risk. The more we extrapolate risk data for underground miners to other groups (e.g., the general population), the greater the uncertainties. A primary example is converting the same way for the United States, Great Britain, Europe, and all of Asia. We doubt, however, that using more representative values for Great Britain, Europe, and Asia would significantly alter the values in Tables 5-1 and 5-2 for "Rest of World."

In our estimate, about six-tenths of the collective exposure to the world outside North America occurs in western Europe and relatively negligible amounts in Asia. Therefore, much of the collective exposure occurs in Europe where the lung cancer incidence is not greatly different from that in the United States.

In spite of many sources of uncertainty and potential inaccuracy, the principal objective of this evaluation has been achieved. Evaluating the exposures with the linear, nonthreshold health risk model indicates that the cumulative health risks for distant populations are comparable to the risks for populations near the tailings piles.

The relatively few people who live within a few kilometers of tailings piles may receive individual exposures as much as a hundred times the exposures to individuals at greater distances (as indicated by Table 3-1). However, when collective exposures are estimated, the larger number of people at greater distances leads to collective exposures comparable to those within 5 km, in spite of the much smaller individual exposures. This can be seen in the summary given in Table 6-1 (taken from Table 5-1), even though the seven cases include a wide range in population densities and distributions within 80 km.

Thus, moving a tailings pile away from a relatively populous area to a more remote site will reduce local radiation exposures to individuals, but the collective exposures to distant populations can only be appreciably changed by measures that suppress the release of radon-222.

Table 6-1. Summary of the Estimated Fatal Lung Cancer[a] Commitment at Selected Distances Due to Radon-222 from Tailings at Seven Inactive Uranium Mill Sites (From Table 5-1)

Site	Distance Increement 0-5 km	USA (From 5 km out)	World Total
Grand Junction, Colo.	0.3	0.01	0.4
Gunnison, Colo.	0.04	0.03	0.08
Rifle, Colo.	0.02	0.06	0.1
Shiprock, N.M.	0.03	0.07	0.1
Falls City, Texas	0.01	0.1	0.2
Mexican Hat, Utah	0.003	0.1	0.1
Salt Lake City, Utah	0.3	0.5	0.9

[a]Annual commitment of fatal lung cancers due to inhalation of radioactive short-lived decay products of radon-222.

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Appendix A: TAILINGS COORDINATES

Records and reports of the seven tailings piles gave the coordinates of the mill buildings rather than the tailings. We determined the locations of the tailings from U.S. Geological Survey maps and the aerial photographs and site maps in the reports of Ford, Bacon & Davis Utah, Inc.

The locations listed here represent the centers of the tailings piles and are believed to be accurate to within ±2 seconds of latitude or longitude. In some cases (e.g., at Falls City, Texas, where there are six tailings locations) selection of a "center" represents a judgment.

Grand Junction, Colo.	39° 03' 17"N, 108° 32' 59"W
Gunnison, Colo.	38° 31' 48"N, 106° 56' 30"W
Rifle, Colo. (new)	39° 31' 26"N, 107° 48' 57"W
Rifle, Colo. (old)	39° 31' 45"N, 107° 46' 20"W
Shiprock, N.M.	36° 46' 09"N, 108° 41' 02"W
Falls City, Texas	28° 54' 16"N, 98° 07' 46"W
Ray Point, Texas	28° 31' 15"N, 98° 06' 12"W
Mexican Hat, Utah	37° 08' 04"N, 109° 52' 32"W
Salt Lake City, UT	40° 42' 11"N, 111° 54' 44"W

Appendix B: ADJUSTMENT FOR AREA SOURCE

We used calculations from (Sw76) to determine the dispersion in the range to 12 km from the tailings location center. An equivalent line-source perpendicular to the wind direction through the tailings center is substituted for the point source generally used in the AIREM code.

When the wind is in a sector adjacent to that of the receptor and tailings center, if the receptor is sufficiently close to the tailings it can still be within the sector of the tailings' plume (i.e., the plume from the equivalent line source). The exposure from this fractional overlap is added to that of the receptor's sector according to the fractional area of the overlap and the wind direction frequency in the adjacent sector.

The equivalent line source was calibrated against a calculation in which a circular (200 m radius) model tailings pile was subdivided into a two-dimensional array of point sources whose monodirectional, single Gaussian plumes were superimposed on a crosswind row of receptor locations. Use of the equivalent line source with the AIREM calculation is consistent with the assumptions concerning concentrations in adjacent sectors that are intrinsic to the sector-averaged equation, equation 3.144 in Slade (Sl68).

For receptors at downwind distances greater than ten times the diameter of one tailings pile (a few kilometers), we used a point-source, which is adequate.

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16. ABSTRACT

Uranium mill tailing piles can expose the population to radiation by several pathways. The author believes the air pathway to be the most important and radon-222 to be the principal nuclide. The report illustrates the effects of tailings piles on a variety of local and regional populations, assesses the effects of the tailings on distant populations, and compares EPA methods and results with assessments by others.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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