LMS/S11072

Defense-Related Uranium Mines Assessment of Radiological Risk to Human Health and the Environment Topic Report

Final

June 2014

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Abbreviations

Ac	actinium
AEC	U.S. Atomic Energy Commission
AH	absolute humidity
ARAR	applicable or relevant and appropriate requirement
ATV	all-terrain vehicle
BLM	U.S. Bureau of Land Management
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	contaminant of concern
CSM	conceptual site model
CWA	Clean Water Act
DOE	U.S. Department of Energy
EE/CA	Engineering Evaluation/Cost Analysis
EPA	U.S. Environmental Protection Agency
GIS	geographic information system
HRS	hazard ranking system
HUC	hydrologic unit code
ICRP	International Commission on Radiation Protection
MCL	maximum contaminant level
NCDC	National Climatic Data Center
NECR	Northeast Church Rock
NHD	National Hydrography Dataset
NNEPA	Navajo Nation Environmental Protection Agency
NPL	National Priorities List
NWIS	National Water Information System
Pa	protactinium
Pb	lead
RH	relative humidity
ROD	Record of Decision
RSC	Regional Screening Criteria
STAR	star array
TENORM	technologically enhanced naturally occurring radiological material
Th	thorium
U	uranium

UNC	United Nuclear Corporation
USACE	U.S. Army Corps of Engineers
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
WL	working level
WLM	working level month
WRCC	Western Regional Climate Center

Units of Measure

Ci	curie(s)
cm	centimeter(s)
ft	foot (feet)
g	gram(s)
gal	gallon(s)
h	hour(s)
kg	kilogram(s)
L	liter(s)
lb	pound(s)
m	meter(s)
µg	microgram(s)
µrem	microrem
µR	microroentgen
mg	milligrams
mGy	milligrays
mrem	millirems
pCi	picocurie(s)
R	roentgen
s	second(s)
T	ton(s)
yr	year(s)

Executive Summary

Introduction

The National Defense Authorization Act for Fiscal Year 2013, enacted January 2013, mandates that the U.S. Department of Energy (DOE) prepare a report on abandoned uranium mines. Specifically, Section 3151 of the legislation requests, in part, that "The Secretary of Energy, in consultation with the Secretary of the Interior and the Administrator of the Environmental Protection Agency, shall undertake a review of, and prepare a report on, abandoned uranium mines in the United States that provided uranium ore for atomic energy defense activities of the United States." The Act also requires consultation with other relevant federal agencies, affected states and tribes, and the interested public.

DOE defines an abandoned uranium mine as a named mine or complex developed to extract uranium ore for atomic energy defense-related activities of the United States from 1947 to 1970, as verified by purchase of ore by the U.S. Atomic Energy Commission (AEC) or other means. Since the primary basis of the abandoned mine database is the AEC production records, a mine is generally associated with a patented or unpatented mining claim (established under the General Mining Act of 1872) or a lease of federal, state, tribal, or private lands. By this definition these mines might not be abandoned (some have existing permits) and some mines have been reclaimed or remediated. Mines in any of these categories are included in the set of legacy mines that were considered for evaluation as part of the congressional request for this report. The entire set is labeled as abandoned uranium mines, and additional information in the topic reports and final report identify the status of these mines.

An abandoned mine may be a single feature such as a surface or underground excavation, or it may include an area containing a complex of multiple, interrelated excavations. A mine may include associated mining-related features such as mine adits and portals, surface pits and trenches, highwalls, overburden or spoils piles, mine-waste rock dumps, structures, ventilation shafts, stockpile pads, mine-water retention basins or treatment ponds, close-spaced development drill holes, trash and debris piles, and onsite roads.

For this report, a mine does not include offsite impacts or features such as ore-buying stations, ore transfer stations, or ore used in structures, roads, and general fill.

DOE is required to submit a Report to Congress no later than July 2014. That report will describe and analyze:

- The location of abandoned uranium mines on federal, state, tribal, and private lands, and the status of efforts to remediate or reclaim these mines
- The extent to which these mines pose a significant radiation hazard or other public health and safety threat, and cause, or have caused, water or other environmental degradation
- A priority ranking for the reclamation and remediation of abandoned uranium mines
- The potential cost and feasibility of reclamation and remediation in accordance with federal law

Methodology, Scope, and Results

This topic report addresses (1) the potential human health risk from radiation, (2) potential physical hazards, (3) potential water quality degradation, and (4) potential ecological impacts from mines. The 4,225 mine locations identified for evaluation for this project are grouped into six production-size categories, based on the known tonnage of uranium ore generated from these mines. This topic report evaluates five of the production-size categories but not the sixth category (the Very Large category). The 37 mines in the Very Large category either have been reclaimed or are currently being reclaimed or remediated. A summary of several human-health and ecological risk assessments done by other agencies for inactive uranium mines is also included to provide perspective as to the approaches taken relative to risk assessments.

Radiological Human Health Risk

To provide estimates of the potential radiological risk to human health from the mines, a conceptual site model (CSM) was developed to identify potential sources of contamination, plausible receptors, and exposure pathways. One CSM was used for all five production-size categories of mines evaluated, as the components (i.e., source, receptors, and exposure pathways) examined would be similar regardless of tonnage generated. The following potential sources of contamination were considered: waste-rock piles or dumps, potential ground surface contamination (including surface contamination of mine workings or structures), and adits or other mine openings. The receptors evaluated included an onsite resident, an offsite resident, a recreational visitor, reclamation workers, and an occasional visitor. The scenarios evaluated were intended to provide a range of exposures for comparison purposes only. The scenarios are not unique and other variations and assumptions are possible.

Potential pathways of exposure evaluated include inhalation of radon and particulates, external gamma, incidental ingestion of soil, and ingestion of plant foods, meat, and milk (for both onsite and offsite resident receptors). The risk evaluation followed U.S. Environmental Protection Agency's (EPA's) four components (i.e., data collection and evaluation, exposure assessment, toxicity assessment, and risk characterization) for conducting a risk assessment. Risk estimates were derived using a computer code capable of multiple pathways analysis. Gamma rate and radon working level measurement data were obtained by DOE personnel at a selected number of mines in the DOE mine database for use in the evaluation discussed in this topic report. Calculations for the external radiation and radon inhalation pathways involved the use of conversion factors to convert the measurement data into exposure amounts, which were then multiplied by given risk factors established by the regulatory agencies for use in such calculations. The risk estimates were based on an exposure concentration of 70 picocuries per gram for radium-226 (Ra-226) in the waste-rock pile.

The greatest risks for all receptors were from inhalation of radon. For receptors spending time onsite, risks from external radiation from waste-rock piles and contaminated soil was also significant; risks from other pathways (e.g., ingestion of plants, meat, milk, and soil) were less important. Of the five receptors evaluated, only the onsite resident and reclamation worker risks exceed 1×10^{-4}, which is the upper end of EPA's acceptable risk range. Although mines have been and are being reclaimed and remediated under a variety of authorities, this risk range is broadly used here as a point of comparison.

For the onsite resident scenarios, the estimated risks would result primarily from the inhalation of radon that emanates from the waste-rock pile or foundation material and diffuses into the house. Risks associated with indoor radon range from 9×10^{-2} to 1×10^{-1}. Risks from external radiation through exposure to waste rock and contaminated soils ranged from 2×10^{-3} to 1×10^{-2}. Risks for residential use for all pathways combined range from 9×10^{-2} to 1×10^{-1} (dominated by indoor radon). For an offsite resident living 100 meters from a mine, risk estimates from all pathways evaluated ranged from $<1 \times 10^{-5}$ to $<1 \times 10^{-4}$ and resulted primarily from the inhalation of radon that emanates from the waste-rock pile and then is transported to the offsite location by wind.

For the recreational visitor, occasional visitor, and reclamation workers, risks were calculated for exposures at mine adits and waste-rock piles. Risks from spending one hour at a mine adit ranged from 2×10^{-6} to 4×10^{-5} and would apply to either a recreational or occasional visitor. For a recreational visitor camping on a waste-rock pile at a mine location for two weeks, the external radiation risk is 2×10^{-5}. External radiation risks for one hour of exposure to a waste-rock pile by an occasional visitor ranged from 5×10^{-8} to 7×10^{-8}. If recreational or occasional visitors spent time at both waste-rock piles and adits, total risks would be additive.

Risk estimates for a reclamation worker conducting reclamation activities at mine adits for 20 days range from 3×10^{-4} to 6×10^{-3}. Risk estimates for reclamation workers reclaiming waste-rock piles for 20 days ranged from 9×10^{-6} to 1×10^{-5} for external radiation. If a worker spent 20 days at adits and 20 days at waste-rock piles, risks would be additive and dominated by exposure at adits (i.e., total risks would range from 3×10^{-4} to 6×10^{-3}). However, these results are conservative because no credit is taken for required worker protection measures that workers would use that would reduce their exposure.

Potential Physical Hazards

In considering the potential physical hazards, mines where the information on the exact location, land ownership, or tonnage produced was unknown were excluded, as were mines that were designated as reclaimed or remediated. The remaining 3,085 mine locations were evaluated relative to the potential hazards at each site (e.g., open shafts, unsafe structures) and their distances (within 0.25 mile, 0.5 mile, etc.) from schools, roads, and population centers. The five production-size categories of the 3,085 mines were also further sorted into two land ownership categories (i.e., federal and tribal/state/private). The majority of mines are located on federal public lands (e.g., U.S. Bureau of Land Management and U.S. Forest Service). It is recognized that in addition to proximity to schools, roads, and population centers, proximity of the mines to recreational facilities or areas and the usage of such facilities or areas by recreational visitors could lead to increased potential for exposure to physical hazards at mines.

Of the 3,085 mines evaluated for potential physical hazards about 72 percent (2,213) of them have 100 or fewer people living within a 5-mile radius of the mine. Another 24 percent (747) of the mines have between 101 and 1,000 residents living within a 5-mile radius of the mine, leaving only about 4 percent that have more than 1.000 residents within a 5-mile radius of the mine. If local population is a primary concern, it can be seen that eight mines are in an area in which more than 1,000 people live within a 1-mile radius of the mine, and that 24 mines are in an area in which more than 10,000 people live within a 5-mile radius. No mines have a population greater than 1,000 people within a 0.25-mile radius of the mine location, and only

14 mines have a public school that is within half a mile of the mine. There is relatively easy access to the 248 mines that are within half a mile of a road. While it is assumed that physical hazards are associated with all the mine production-size categories used in this analysis, many of the actual mines included in the DOE mine database may, in reality, have no associated physical hazards.

Water Quality

For surface water, the mine locations were evaluated by comparing the mine locations against locations of relevant impaired water bodies identified by the various states and submitted to EPA for the 303(d) impaired water list as required by the Clean Water Act. The impaired water bodies are defined as any surface water bodies (streams, lakes, and reservoirs) that do not meet water quality standards according to their classified water uses. The extent of assessed water bodies varies by state and may not include all intermittent/ephemeral streams and isolated surface water bodies that have little connection to streams, lakes, and reservoirs. However, water quality information in the 303(d) database reflects water quality issues for those intermittent/ephemeral streams and isolated water bodies that currently have apparent impacts on water quality in streams, lakes, and reservoirs. For groundwater, the mine locations were screened against locations that are included in the U.S. Geological Survey (USGS) National Water Information System (NWIS) groundwater quality measurement database with measurement data indicating elevated contaminant levels (based on the 4.4 million historical water quality analyses that are compiled in the database). The screening made use of several criteria that included distance and groundwater concentration information for uranium and several metals (which are known to be associated with uranium mines but are also associated with other mineral mines and other non-mining activities). This evaluation was done for comparison purposes only; no cause-and-effect relationship between the mines and impaired waters is implied.

The impaired surface water bodies identified in the 19 states with uranium mines comprise about 169 watersheds, as defined by the USGS 8-digit hydrologic unit code for water basin. (As a note, there are more than 2,000 USGS-defined 8-digit watersheds in the entire U.S.) The comparison of the mine locations against the impaired water bodies indicate that 45 mines (about 1 percent of the mines analyzed) are located near or immediately upstream from the impaired surface water bodies. Further, these 45 mines are located in only 10 USGS-defined watersheds, with 43 percent of the 45 mines occurring within one watershed.

Similarly, the evaluation of groundwater quality indicated that 44 mines (about 1 percent) are located within 1 mile of a USGS NWIS measurement site that has indications of degraded groundwater quality. These 44 mines are located within 10 USGS-defined watersheds, with 75 percent of the 44 mines occurring in four watersheds. All of the watersheds above occur in areas of the U.S. where other types of mining are prevalent, and therefore no conclusion is drawn about the link between water impairment and mine sites. These screening-level results are not to be interpreted as indicating that the mines have impacted or would impact the impaired surface water bodies or degrade groundwater further. Rather, they are intended to provide an approach for focusing any further analysis of the mines relative to the potential for water quality degradation, as appropriate.

Potential Ecological Impacts

Potential impacts of the mines on ecological resources were evaluated by a review of (1) the radiological risks to ecological receptors exposed to potentially contaminated soils, waste-rock piles, and water, and (2) the use of underground uranium mines by bats. This task included a review of ecological risk assessments in reports prepared by other agencies for various inactive uranium mine sites. The task also involved a comparison of the protection levels developed by various agencies and organizations (e.g., DOE and the International Commission on Radiological Protection [ICRP]) for ecological species with the radionuclide concentrations used in the human health risk evaluation for this report.

A review of ecological risk assessments conducted at several inactive mines indicated that both radioactive and chemical contaminants may have a localized adverse impact on biota. However, such results are rather conservative, in that impacts are generally based on concentrations in waste piles or in onsite drainages, which do not provide optimal habitat conditions.

Many underground uranium mines have characteristics similar to caves, making them important habitat sites for bats. Therefore, bats are typically the ecological component that influences mine closure and mitigation efforts. A brief review of bat use of abandoned mines was also prepared, focusing on the beneficial use of mines for bat habitat balanced against potential concerns for public safety. Bat gates, rather than sealing off the opening, are recommended for mines that provide important maternity or hibernation sites (e.g., if no other habitat exists in the area and the mine is used by many individual bats and/or by a federally listed species).

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1.0 Introduction

The National Defense Authorization Act for Fiscal Year 2013, enacted January 2013, mandates that the U.S. Department of Energy (DOE) prepare a report on abandoned uranium mines. Specifically, Section 3151 of the legislation requests, in part, that “The Secretary of Energy, in consultation with the Secretary of the Interior and the Administrator of the Environmental Protection Agency, shall undertake a review of, and prepare a report on, abandoned uranium mines in the United States that provided uranium ore for atomic energy defense activities of the United States.” The Act also requires consultation with other relevant federal agencies, affected states and tribes, and the interested public.

DOE defines an abandoned uranium mine as a named mine or complex developed to extract uranium ore for atomic energy defense-related activities of the United States from 1947 to 1970, as verified by purchase of ore by the U.S. Atomic Energy Commission (AEC) or other means. Since the primary basis of the abandoned uranium mines database is the AEC production records, a uranium mine is generally associated with a patented or unpatented mining claim (established under the 1872 Mining Law) or a lease of federal, state, tribal, or private lands. By this definition these mines might not be abandoned (some have existing permits) and some mines have been reclaimed or remediated. Mines in any of these categories are included in the set of legacy mines that were considered for evaluation as part of the congressional request for this report. The entire set is labeled as abandoned uranium mines, and additional information in the topic reports and final report identify the status of these mines.

A mine may be a single feature such as a surface or underground excavation, or it may include an area containing a complex of multiple, interrelated excavations. A mine may include associated mining-related features such as mine adits and portals, surface pits and trenches, highwalls, overburden or spoils piles, mine-waste rock dumps, structures, ventilation shafts, stockpile pads, mine-water retention basins or treatment ponds, close-spaced development drill holes, trash and debris piles, and onsite roads.

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DOE is required to submit a Report to Congress no later than July 2014. That report will describe and analyze:

- The location of abandoned uranium mines on federal, state, tribal, and private lands, and the status of efforts to remediate or reclaim these mines
- The extent to which these mines pose a significant radiation hazard or other public health and safety threat, and cause, or have caused, water or other environmental degradation
- A priority ranking for the reclamation and remediation of abandoned uranium mines
- The potential cost and feasibility of reclamation and remediation in accordance with federal law

This topic report was prepared to address the second area above. Specifically, it evaluates the potential of abandoned uranium mines to pose a radiation hazard to human health, pose physical hazards, have adverse effects on surface water and groundwater, and have adverse effects on ecological resources (i.e., bats and other wildlife). (Note that this report focuses on evaluating radiation hazards to human health in accordance with the authorizing legislation, and this report does not include an evaluation of the potential risk from chemical constituents associated with uranium mining.)

Consistent with the three other topic reports that DOE has prepared to support its preparation of the Report to Congress, this topic report addresses the 4,225 locations contained in the DOE abandoned uranium mine database. The scope of this topic report is discussed in Section 1.1 below, and the report objective is discussed in Section 1.2.

1.1 Scope and Methodology Used for This Topic Report

This topic report addresses (1) the potential human health risk from radiation, (2) potential physical hazards, (3) potential water quality degradation, and (4) potential ecological impacts from abandoned uranium mines. This section summarizes how many defense-related uranium mines were included in the evaluations for various aspects discussed in this report, and it describes the methodologies used in the evaluations. A summary of several human-health and ecological risk assessments done by other agencies for inactive uranium mines is also included to provide perspective as to the approaches taken relative to risk assessments.

1.1.1 Number of Abandoned Uranium Mines Evaluated

There are 4,225 mines in the DOE mines database, although not all were included the various evaluations in this topic report.

The 4,225 uranium mines are grouped into six production-size categories (see Table 1), based on the known tonnage of uranium ore generated from the mines. This topic report evaluates five of the production-size categories but not the sixth category (the Very Large category), because the 37 mines in that production-size category have either been reclaimed or are currently being reclaimed or remediated. This topic report also does not evaluate the 50 mines with no known tonnage information, so the maximum number of mines considered for any evaluation in this report is 4,138. A smaller number of mines are considered for certain evaluations, such as the 3,085 mines considered in the physical-hazards evaluations described in Section 4.0.

Table 1 presents the 4,225 mine sites by production-size category and by state. Figure 1 to Figure 5 show the locations of mines in each of the five production-size categories evaluated. The production-size categorization facilitates the generation of input parameters and assumptions that can be used to evaluate the potential for (1) human health exposure to radiation emanating from the mines, (2) physical hazards, (3) water quality degradation potential, and (4) adverse environmental (ecological) effects.

The methodology for evaluating these four aspects of risk is discussed below in Sections 1.1.2 through 1.1.5.

Table 1. Summary of Mines by Production-Size Category and State[a]

State	Small Less than 100 T	Small/Medium 100–1,000 T	Medium 1,000–10,000 T	Medium/Large 10,000–100,000 T	Large 100,000–500,000 T	Very Large >500,000 T[a]	Unknown Output[a]	Total
Alaska	0	0	0	1	0	0	0	**1**
Arizona	162	110	83	28	4	1	25	**413**
California	21	3	2	0	0	0	0	**26**
Colorado	621	378	348	167	22	3	0	**1539**
Florida	1	0	0	0	0	0	0	**1**
Idaho	1	2	4	0	0	0	0	**7**
Montana	10	8	1	0	0	0	0	**19**
Nevada	12	8	3	1	0	0	0	**24**
New Jersey	1	0	0	0	0	0	0	**1**
New Mexico	78	39	40	33	17	19	21	**247**
North Dakota	2	2	5	3	0	0	2	**14**
Oklahoma	2	0	0	0	0	0	0	**2**
Oregon	1	0	2	0	1	0	0	**4**
Pennsylvania	0	1	0	0	0	0	0	**1**
South Dakota	71	35	34	13	2	0	0	**155**
Texas	6	4	8	8	3	0	0	**29**
Unknown	24	2	0	0	0	0	0	**26**
Utah	788	278	190	100	17	5	2	**1380**
Washington	0	11	3	2	0	1	0	**17**
Wyoming	135	57	61	42	16	8	0	**319**
Grand Total	**1936**	**938**	**784**	**398**	**82**	**37**	**50**	**4225**

[a] This category of mines is included in this table for completeness but is not included in the analysis discussed in this topic report.

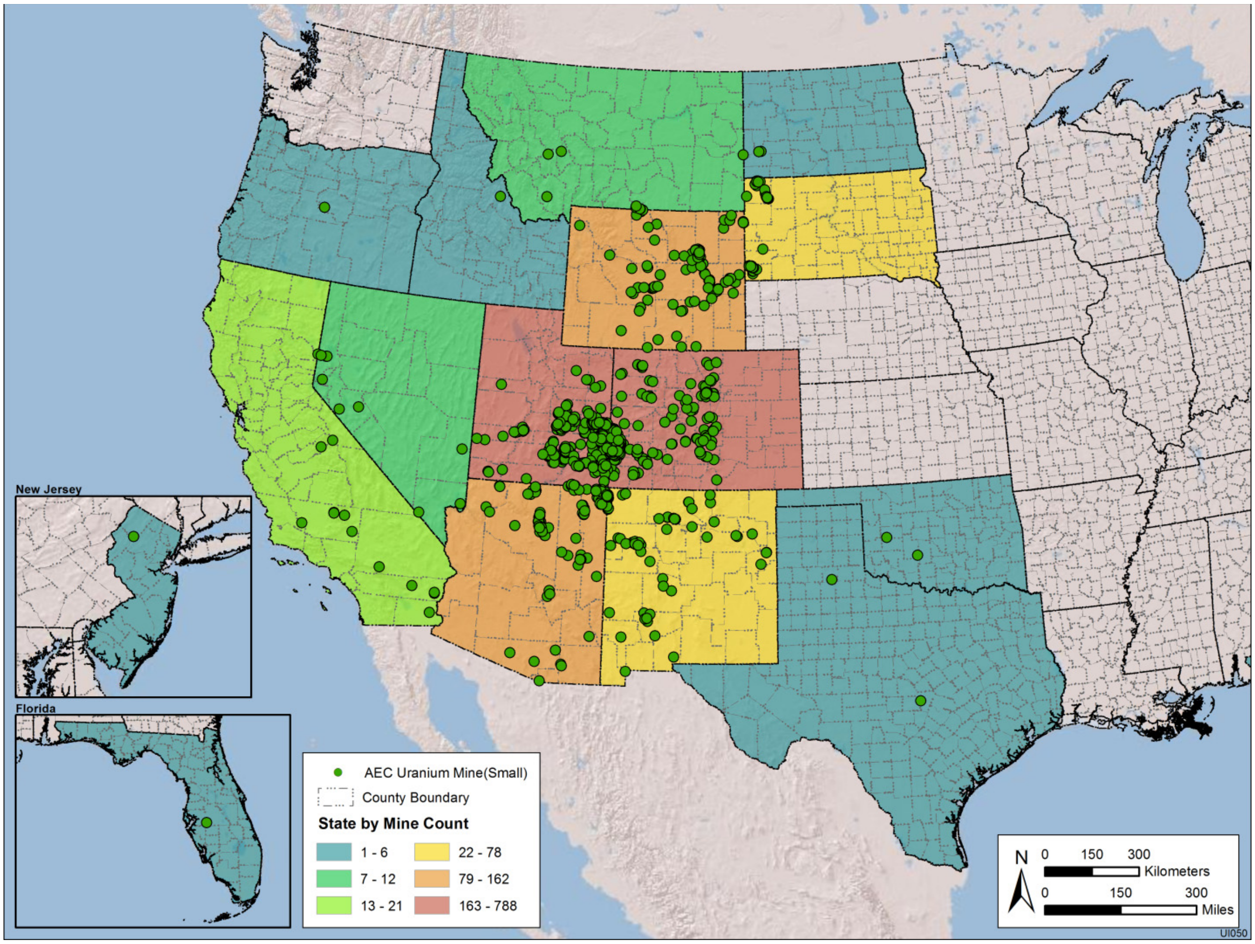


Figure 1. Mines in the Small Production-Size Category (Less than 100 Tons Generated)

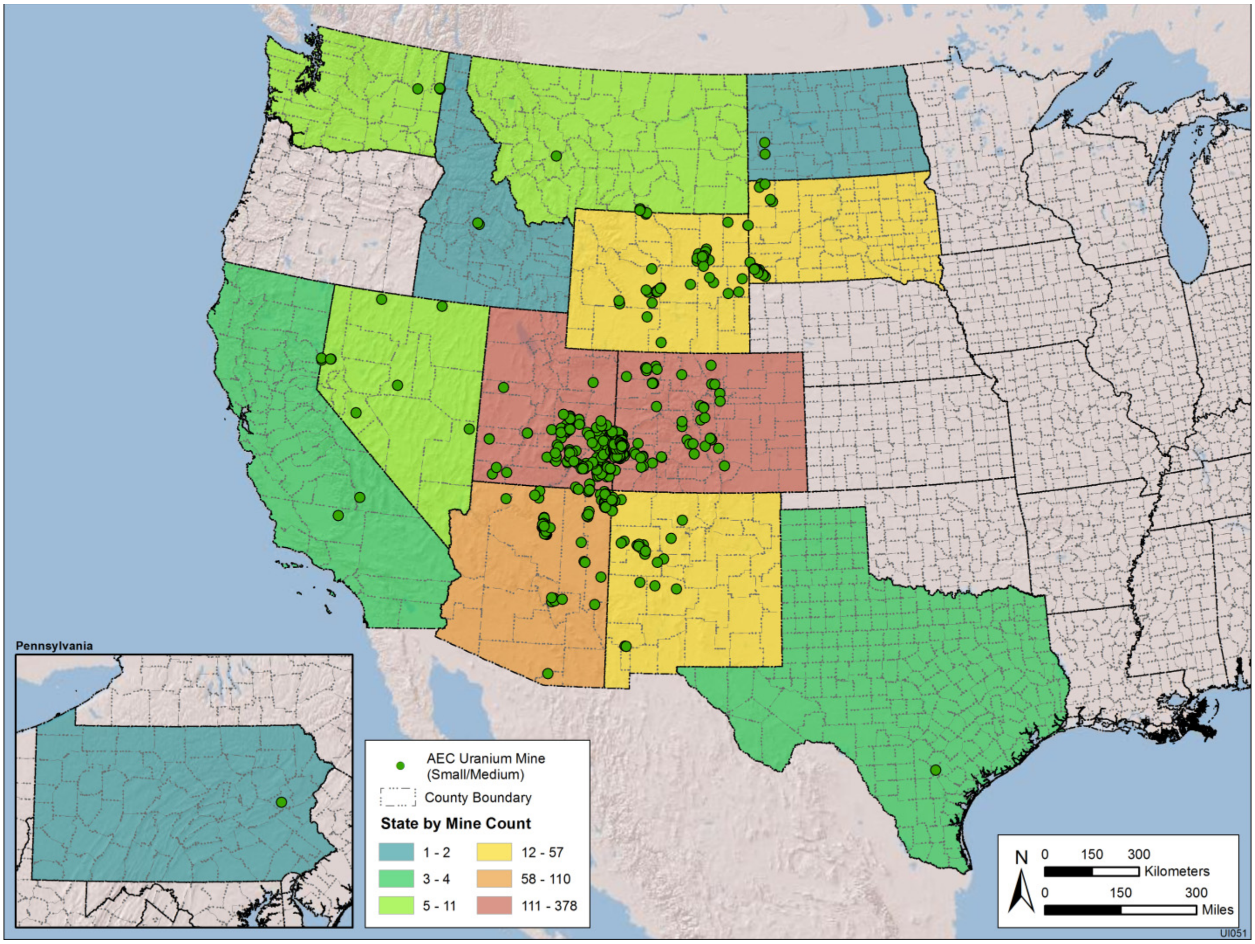


Figure 2. Mines in the Small/Medium Production-Size Category (100 to 1,000 Tons Generated)

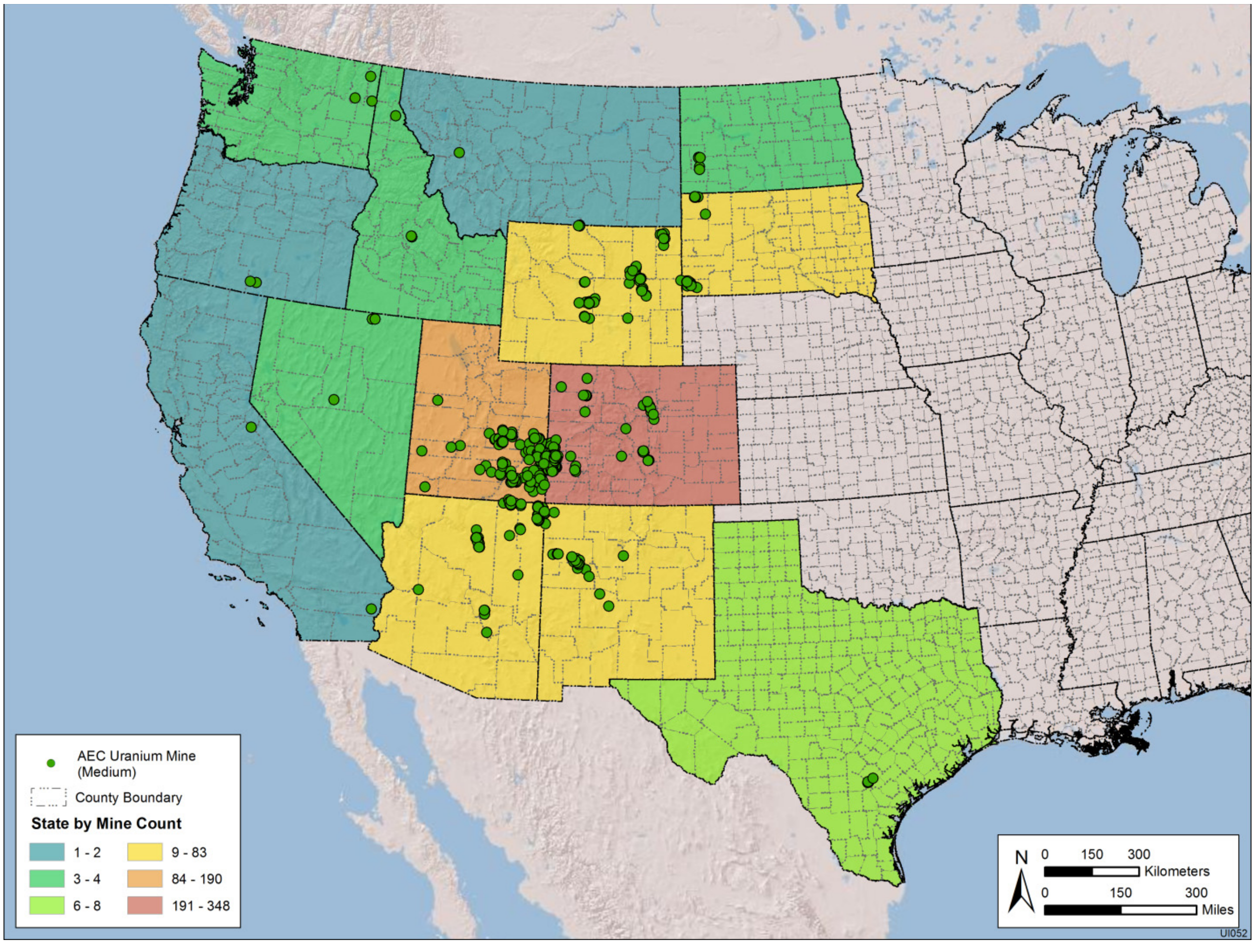


Figure 3. Mines in the Medium Production-Size Category (>1000 to ≤10,000 Tons Generated)

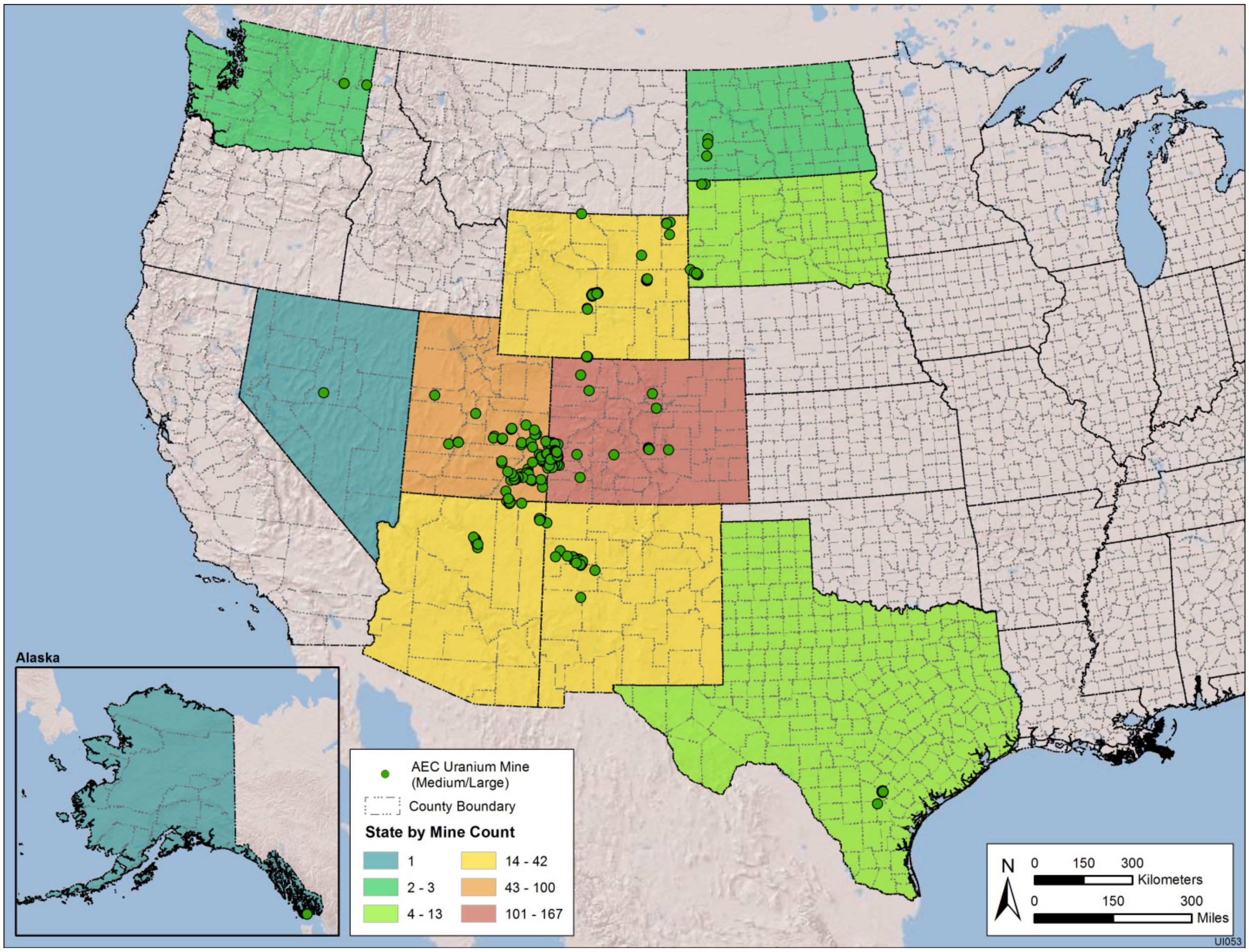


Figure 4. Mines in the Medium/Large Production-Size Category (>10,000 to ≤100,000 Tons Generated)

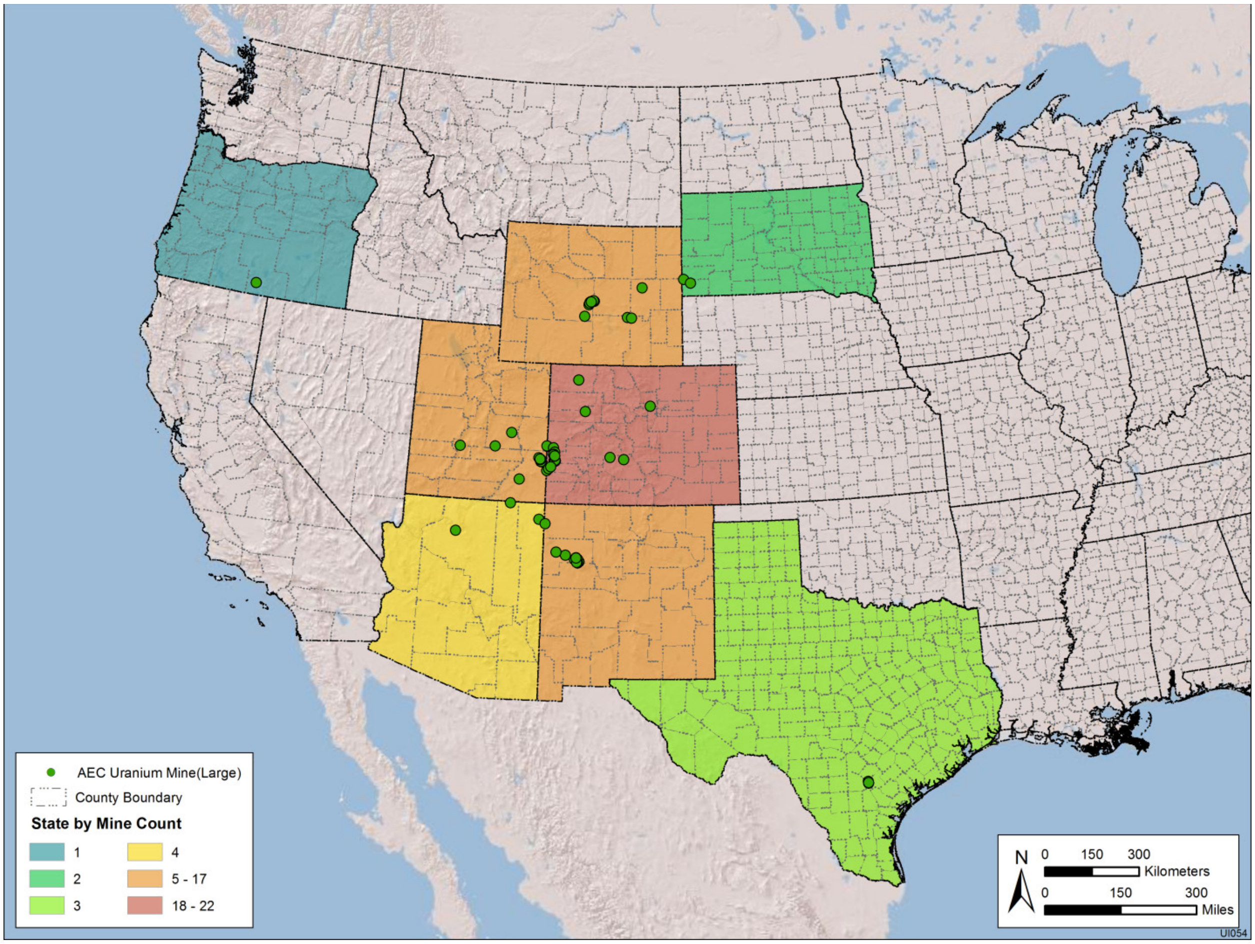


Figure 5. Mines in the Large Production-Size Category (>100,000 and ≤500,000 Tons Generated)

1.1.2 Radiological Human Health Risk

To provide estimates of the potential radiological risk to human health from the mines, a conceptual site model (CSM) was developed to identify potential sources of contamination, plausible receptors, and exposure pathways. One CSM was used for all five production-size categories of mines evaluated, as the components (i.e., source, receptors, and exposure pathways) examined would be similar regardless of tonnage generated. The following potential sources of contamination were considered: waste-rock piles or dumps, potential ground surface contamination (including surface contamination of mine workings or structures), and adits or mine openings. The receptors evaluated included an onsite resident, an offsite resident, a recreational visitor, a reclamation worker, and an occasional visitor. Potential pathways of exposure evaluated include inhalation of radon and particulates, external gamma, incidental ingestion of soil, and ingestion of plant foods, meat, and milk (for both onsite and off-resident receptors). The risk estimates were derived following U.S. Environmental Protection Agency (EPA) methodology in its *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual,* Interim Final (EPA 1989) and exposure parameter values. Risk estimates were derived using a computer code capable of multiple pathways analysis (RESRAD Version 6.7). For perspective, the risk estimates presented in Chapter 3 of this report are compared to EPA's acceptable risk range of 10^{-6} to 10^{-4}, although mines undergoing reclamation or remediation are being done so under a variety of authorities in addition to CERCLA.

Gamma rate and radon working level measurement data were obtained by DOE personnel at a selected number of mines in the DOE mines database for use in the evaluations discussed in this topic report. Calculations for the external radiation and radon inhalation pathways involved the use of conversion factors to convert the measurement data into exposure amounts, which were then multiplied by given risk factors established by the regulatory agencies for use in such calculations.

> ***Box 1-1. EPA's Acceptable Risk Range of 10^{-6} to 10^{-4}***
>
> To guide plans for managing contaminated sites, EPA established an acceptable risk range that represents the increased probability (above a background rate) of a hypothetical person developing cancer over their lifetime from assumed exposures to site contaminants. This acceptable range for an incremental lifetime cancer risk is between one in a million (1×10^{-6}, or 0.000001) and one in ten thousand (1×10^{-4}, or 0.0001). As general perspective from the American Cancer Society, for men, the risk of developing cancer over their lifetime from all causes combined is nearly 1 in 2 (5×10^{-1}, or 0.5), while the risk for women is slightly more than 1 in 3 (3×10^{-1}, or 0.3). Thus, the acceptable risk range represents a small fraction (0.0002% to 0.03%) of the U.S. average risk of getting cancer from all causes over a lifetime.

1.1.3 Potential Physical Hazards

Potential physical hazards associated with each production-size category were estimated (e.g., numbers of shafts, adits). To evaluate potential for exposure to physical hazards, mine locations were reviewed for their distances from schools, roads, and population centers. The five production-size categories were also further sorted into two land ownership categories (i.e., federal and tribal/state/private).

1.1.4 Water Quality

The mine locations were evaluated for potential effects on surface water and groundwater quality. For surface water, the mines were evaluated by comparing the locations against locations of relevant impaired water bodies identified by the various states and submitted to EPA for the 303(d) impaired water list as required by the Clean Water Act. The impaired water bodies are defined as any surface water bodies (streams, lakes, and reservoirs) that do not meet water quality standards according to their classified water uses. For groundwater, the mines were screened against locations included in the U.S. Geological Survey (USGS) National Water Information System (NWIS) groundwater quality measurement database with measurement data indicating elevated contaminant levels (based on the 4.4 million historical water quality analyses that are compiled in the database). The screening made use of several

> ***Box 1-2. U.S. Average Annual Radiation Dose From Natural and Man-Made Sources***
>
> As further perspective for the radionuclides, the National Council on Radiation Protection and Measurements estimates the U.S. average annual radiation dose is about 620 millirems (mrem), with natural and man-made sources (which include medical procedures and consumer products) each contributing half. For natural sources, about two-thirds of the dose (200 mrem/year) is due to indoor radon-222 gas and its short-lived radioactive decay products. This average natural background dose corresponds to a lifetime cancer risk of about 3×10^{-2}, or about 3 chances in 100 of getting cancer over a lifetime (based on a risk factor of 1.16×10^{-6} per mrem for the likelihood of developing a radiogenic cancer and assuming a lifetime of 70 years).

criteria that included distance and groundwater concentration information for uranium and several metals (which are known to be associated with uranium mines but are also associated with other mineral mines).

1.1.5 Potential Ecological Impacts

Potential impacts of the mines on ecological resources were evaluated by a review of (1) the radiological risks to ecological receptors exposed to potentially contaminated soils, waste-rock piles, and water, and (2) the use of underground uranium mines by bats. This task included a review of ecological risk assessments in reports prepared by other agencies for various inactive uranium mine sites. The task also involved a comparison of the protection levels developed by various agencies and organizations (e.g., DOE and the International Commission on Radiological Protection [ICRP]) with the radionuclide concentrations used in the human health risk evaluation for this report. Many abandoned underground mines have characteristics similar to caves, making them important habitat sites for bats. Therefore, bats are typically the ecological component that influences mine closure and mitigation efforts. A brief review of bat use of abandoned mines was also prepared, focusing on the beneficial use of mines for bat habitat balanced against potential concerns for public safety.

2.0 Risk Assessments for Uranium Mines by Other Agencies

Over 60 percent of the 4,225 mine sites are on federal lands, and many federal agencies have been involved in addressing uranium mines. EPA has been evaluating uranium mines since it prepared its initial 1983 Report to Congress (EPA 1983). Other involved agencies include the U.S. Forest Service (USFS), the National Park Service, and the U.S. Bureau of Land Management (BLM). There are also many mines on tribal lands, particularly the Navajo Nation, so tribal governments have also been involved.

EPA is tasked with protecting human health and the environment from hazardous material releases. Its involvement with uranium mines started in 1983, when Congress tasked it to investigate the potential risks. In addition, EPA is often concerned with surface mining sites and underground mining sites because of their status as technologically enhanced naturally occurring radiological material (TENORM) sites. As part of its investigations of Superfund sites, EPA studied the uranium mines on Navajo Nation land by collecting data, performing a hazard rank assessment, and performing remediation. Sections 2.1, 2.2, and 2.3 provide brief summaries of the risk assessment components of the EPA 1983 Report to Congress, TENORM, and the project addressing the Navajo Nation land, respectively.

Finally, risk assessments for various inactive uranium mine sites have been conducted by several oversight agencies. The risk assessments summarized in Section 2.4 provide a historical perspective on the human health and ecological risk assessment methodologies that have been used for uranium mine sites.

2.1 EPA 1983 Report to Congress

EPA (1983) constructed model mines and then calculated annual release rates for use in estimating health effects. Airborne releases of radon and particulates with radon progeny were estimated. Water pathways were considered, but their contribution was found to be relatively small when compared with the air pathways. Both surface and underground mines are assumed to emit about 8 curies per year (Ci/yr) of radon. Particulate emissions of uranium and thorium were about 0.0015 and 0.00001 Ci/yr, respectively, from the surface mines and about an order of magnitude less from the underground mines. The radon-222 progeny contributed most of the dose, with lifetime cancer risks of about 5×10^{-7} for the maximally exposed individual (about 1 mile downwind) and about 1×10^{-9} for the average individual residing within a 50-mile radius of the mine.

2.2 EPA TENORM Report

In Volume II of the EPA's TENORM report (EPA 2008b), Section 3, "Cancer Risks from On-Site Exposure," the potential scenarios for the exposure of the general public are identified as (1) onsite recreational users, (2) use of contaminated materials for buildings, (3) onsite residents, and (4) nearby residents. The primary exposure pathways for the onsite recreational users were the external exposure, inhalation, and drinking-water pathways. Two recreational scenarios were considered: an individual camping at the site for 2 weeks and an all-terrain vehicle (ATV) rider visiting the site 60 times a year. The potential drinking-water concentration was based on applying a soil-water distribution coefficient of 50 liters per kilogram (L/kg) for uranium and then a dilution factor of 20 to derive the maximum concentration level of 21 picocuries per gram (pCi/g). The scenario of using contaminated building materials was analyzed with RESRAD-BUILD. The major exposure pathway for onsite and nearby residents was radon inhalation, with a contribution from external exposure for onsite residents.

2.3 Navajo Nation Atlas Project

This screening assessment report and atlas were prepared by EPA in 2007 (TerraSpectra Geomatics 2007). The land covered included 27,000 square miles in Arizona, New Mexico, and Utah. More than 600 uranium mines on or within 1 mile of the Navajo Nation were identified. Data were collected to implement the EPA's 2002 hazard ranking system (HRS) designed by the Superfund Site Assessment and Technical Support Team and modified, as needed. The HRS was designed not to evaluate risks but instead to prioritize sites for future investigation and actions. The HRS was based on groundwater pathways, surface water pathways, dust dispersion through the air, and dust accumulation on soil. For each of these four pathways, the HRS index was constructed by summing points per structure, well, or surface water body. For the air and soil pathways, structures closer than 200 feet (ft) were assigned 100 points. The number of points assigned diminished with distance, so that structures beyond 1 mile away did not contribute. The corresponding distances for wells (and surface water bodies, respectively) were 1,320 ft (and 1 mile) for 100 points, with contributions up to 4 miles (and 15 miles). The HRS model is based on these proximities but not on the amount of waste at the mines. Therefore, some mines with little waste that were close to human structures and supplies scored high.

2.4 Risk Assessments Conducted for Various Inactive Uranium Mine Sites

Human health and/or ecological risk assessments have been conducted for a number of inactive uranium mine sites. These risk assessments are often a component of short-term removal action or a long-term response action. Removal actions are evaluated through preparation of an Engineering Evaluation/Cost Analysis (EE/CA); long-term actions are generally evaluated in a Remedial Investigation/Feasibility Study. These documents include an evaluation of alternatives for addressing contaminants at a mine (e.g., in waste-rock piles and mine drainage) to minimize or eliminate endangerment to public health, welfare, or the environment (MSE 2005). Risk assessments at uranium mines have been performed using a variety of approaches and using different assumptions and reference radiation dose rates (SENES Consultants Limited 2007). Sections 2.4.1 through 2.4.13 summarize human health and ecological risk assessments from select EE/CAs and other historical assessments of inactive uranium mines. It should be noted that the conditions described in the studies discussed below are not representative of all uranium mines, but only those where some type of remedial action was deemed necessary. Therefore these examples likely illustrate mines at the high end of the complete risk spectrum (human health and ecological) for uranium mines.

2.4.1 Browns Hole

Marston et al. (2011) analyzed samples from abandoned uranium waste dumps, undisturbed geologic background sites, and adjacent streambeds in Browns Hole, a 36-square-mile area in San Juan County, Utah. The objectives of the study were to (1) assess impacts on human health from exposure to radium, uranium, and thorium during recreational activities on and around the uranium waste dumps; (2) compare concentrations of trace elements associated with mine waste dumps to background concentrations; (3) assess the nonpoint-source chemical loading potential of ephemeral and perennial watersheds from uranium waste dumps; and (4) assess the transfer of contaminants from waste dumps to local perennial stream water in Muleshoe Creek (a perennial stream that bisects Browns Hole) (Marston et al. 2011).

Human Health Risk Assessment. USFS, along with USGS, took measurements at waste dumps associated with 20 uranium mine adits at Browns Hole, Utah (Marston et al. 2011). They developed soil levels based on the RESRAD code for radionuclides of radium, uranium, and thorium. Radium was found to contribute the highest risk to recreational off-road ATV riders. Three exposure pathways for this scenario were considered: external gamma, inhalation, and incidental ingestion. The soil guidelines equivalent to a 15 mrem/yr dose from concentrations above background were 33 pCi/g of radium-226 (Ra-226) for an exposure duration of 14 days. Shorter exposure durations of 3.6 and 7 days were also considered. None of the 20 soil samples had radium concentrations that exceeded the limit for a 3.6-day exposure scenario (96 pCi/g), while two sites exceeded the limit for a 7-day exposure scenario (66 pCi/g). An additional seven sites exceeded the 14-day scenario limit. The potential transport of radionuclides through ephemeral streams was also analyzed, resulting in the identification of one site that had a high potential for radionuclide transport due to 2-, 100-, and 500-year peak flow events. The water pathways were not considered in the RESRAD analysis.

Ecological Risk Assessment. An ecological risk assessment was not conducted for the Browns Hole uranium waste dumps.

2.4.2 Butterfly and Burrell Mines

An EE/CA has been prepared under CERCLA authority for the Butterfly and Burrell mines located in the White River National Forest in Rio Blanco County, Colorado. The EE/CA addressed physical hazards and all reasonable exposure pathways (soil, surface water, and direct exposure) to human and ecological receptors (CH2MHILL 2011). Soil and surface water contaminants of concern (COCs) identified in a 2005 site assessment included arsenic, antimony, calcium, chromium, copper, iron, magnesium, mercury, molybdenum, nickel, potassium, selenium, silver, sodium, uranium, and vanadium. Arsenic regional screening concentrations in the BLM Rocky Mountain Region have been determined to be much higher than the "12 mg/kg RSC concentration" as noted by EPA in *Region 8 Background Soil Arsenic Concentrations (XLS)* **(**http://www2.epa.gov/region8/hh-exposure-assessment**).**

Radiological concerns included gross alpha, gross beta, Ra-226, Ra-228, thorium-228 (Th-228), Th-230, and Th-232. The 2005 site assessment did not identify groundwater as an exposure pathway (CH2MHILL 2011). Removal action objectives identified for the mine sites include reducing offsite migration of contaminated sediments from the waste-rock piles and reducing risk to ecological receptors from exposure to contaminated soil and water. The proposed actions to achieve these objectives include partially excavating and flattening the waste-rock dump, using the material to backfill and flatten the high wall, adding storm-water control, and limiting access to and use of the bench areas (CH2MHILL 2011).

The Butterfly mine includes 1.3 acres of waste rock with a bench area of 1.4 acres. Only the primary adit remains open (the secondary and ancillary adits were closed in 2010). Runoff from the Butterfly mine flows about 800 ft into an unnamed tributary, with the tributary flowing about 1,900 ft to its confluence with Coal Creek (CH2MHILL 2011). The Burrell mine includes about

0.8 acre of waste rock with a bench area of about 1.3 acres. The only adit at the mine was backfilled in 2010. Runoff from the Burrell mine flows about 1,800 ft to Coal Creek (CH2MHILL 2011). Because of heavy snowpack, both mine sites are generally accessible only from June through September (CH2MHILL 2011).

The primary risks at the mines are physical hazards from the high wall and adit and direct exposure to metals and radioactivity (both at the mines and from sediments migrating offsite) (CH2MHILL 2011). Removal action objectives for the Butterfly and Burrell mines include reducing physical hazards to site users, reducing offsite migration of contaminants from the waste-rock piles, and reducing risk to human and ecological receptors from exposure to contaminated soil and water (CH2MHILL 2011).

Human Health Risk Assessment. The human health evaluation used a streamlined approach by comparing soil and surface water concentrations to BLM Regional Screening Criteria (RSC) for campers, ATV drivers, workers, and surveyors. Radon and gamma exposure were compared to EPA's maximum contaminant levels (MCLs). Arsenic in soil exceeded the RSC for a worker, with soil concentrations at 22 to 104 milligrams per kilogram (mg/kg) compared to the RSC of 12 mg/kg. The Ra-226 concentration of 7.3 picocuries per liter (pCi/L) in surface water was slightly elevated when compared to the MCL of 5 pCi/L.

Ecological Risk Assessment. A streamlined ecological risk assessment was performed for the Butterfly and Burrell mines to evaluate potential risk to ecological receptors. Soil risk screening criteria for ecological receptors (robin, Canada goose, mallard, trumpeter swan, white-tailed deer, mule deer, and elk) were compared to 2005 site assessment soil-sampling results for arsenic, cadmium, copper, lead, and/or zinc; while for surface waters, exposure criteria for copper and mercury were compared to the highest concentrations detected in the 2005 site assessment (CH2MHILL 2011). Comparisons indicated risks to the ecological receptors from arsenic, cadmium, copper, lead, and zinc due to soil exposure. Comparisons also indicated that some surface water samples exceeded acute and chronic exposure criteria for copper and chronic exposure criteria for mercury. In addition, it was concluded that a risk to ecological resources existed from radiological exposure.

2.4.3 Juniper Uranium Mine

An EE/CA has been prepared under CERCLA authority for the Juniper uranium mine located in Tuolumne County, California (Tetra Tech EM Inc. 2005). The mine is located within the Stanislaus National Forest. Sources of contamination at the Juniper uranium mine include the mine pit and waste-rock piles (Tetra Tech EM Inc. 2005). Human health and ecological benchmarks were used to identify COCs. The COCs included Ra-228, uranium-234/235/238 (U-234/235/238), Th-228/230, lead-210 (Pb-210), polonium-210, arsenic, and total uranium in the mine pit and waste rock. Ra-226, U-234/238, Th-228, Pb-210, arsenic, manganese, thallium, and total uranium were identified as COCs in creeks that received mine drainage (Tetra Tech EM Inc. 2005). Concentrations of Ra-226, U-234/238, Pb-210, arsenic, and uranium were similar in shallow groundwater upgradient and downgradient of the mine and in the pit spring (Tetra Tech EM Inc. 2005). Radon was identified as a contaminant of potential concern in air. The recommended response action for the Juniper uranium mine was excavation of mine waste and consolidation in an onsite repository and treatment of groundwater discharges (Tetra Tech EM Inc. 2005).

Human Health Risk Assessment. Several recreational visitor scenarios (target shooters, hikers, campers, and off-road vehicle users) were evaluated. Identification of an imminent threat to human health was based on a cumulative excess cancer risk greater than 10^{-4} for the identified receptors. Human health risk from contamination in soil and waste rock ranged from 10^{-5} to 10^{-3} with risk from soil background concentrations at the 10^{-5} level. Risk associated with the sediment at or downstream of the site ranged from 10^{-5} to 10^{-4} with background sediment concentrations resulting in a 10^{-6} to 10^{-5} risk. Ra-226 was the primary contributor to the estimated risk for soil, waste rock, and sediment. Waste rock concentrations of uranium and Ra-226 were reported to be as high as 3,170 mg/kg and 1,750 pCi/g, respectively. Risk from surface water was as high as 10^{-5} (with background at 10^{-8}) with uranium as the primary COC. Uranium concentrations were reported to be as high as 160 micrograms per liter (µg/L) in surface water. Groundwater risk was reported to be about 10^{-5} with uranium, Ra-226, and a few metals as primary COCs. A uranium concentration of 210 µg/L was reported for groundwater at a seep below a waste-rock pile.

Ecological Risk Assessment. Identification of imminent threats to ecological receptors was based on metal and radionuclide concentrations greater than two orders of magnitude above ecological benchmarks (Tetra Tech EM Inc. 2005). Arsenic concentrations in waste rock at the Juniper uranium mine were up to 12 times greater than the ecological benchmark. Uranium concentrations in the waste rock were up to 635 times greater than the ecological benchmark, and Ra-226 concentrations of 1,750 pCi/g in the waste rock (Tetra Tech EM Inc. 2005) were above the soil biota concentration guideline of 50.6 pCi/g. None of the sediment, surface water, or groundwater samples exceeded the ecological benchmark for Ra-226. Cadmium concentrations were up to 5 times greater than the ecological benchmark. However, site concentrations of cadmium were similar to area background concentrations (Tetra Tech EM Inc. 2005).

2.4.4 King Edward Mine

An EE/CA has been prepared under CERCLA authority for the King Edward mine (MSE 2005). The site includes three distinct uranium mine site areas totaling about 18 acres in the Manti-La Sal National Forest of southeastern Utah. The King Edward mine site is located in an area where uranium production occurred from numerous small mines (MSE 2005). The site includes three waste-rock piles and two discharging adits. The adits discharge between one and two gallons per minute. The proposed action for the King Edward mine site is to consolidate and recontour the waste-rock piles, cap the piles with native soil, construct infiltration trenches for the mine discharge, construct earthen entrainment barriers parallel to the infiltration trenches, and close the adits to eliminate safety hazards associated with mine entry by site visitors (MSE 2005).

Contaminants of concern for the media investigated at the King Edward mine area are as follows: arsenic, potassium-40, Pb-210, Ra-226, Th-230, and U-234/235/238 in waste rock; cadmium, copper, lead, mercury, selenium, uranium, zinc, gross alpha, gross beta, Ra-226/228, Th-230/232, and U-234/238 in water; and radon in air (MSE 2005). The waste-rock piles cover about 1.4 acres and are sparsely vegetated. Therefore, sediment from the piles could reach South Cottonwood Creek, a perennial stream near the site (MSE 2005). Streamlined human health and ecological risk assessments were performed to address potential risks associated with the adits, waste-rock piles, and mine drainage on the King Edward mine site. The assessments are based on a qualitative comparison of collected samples to applicable or relevant and appropriate requirements (ARARs).

Human Health Risk Assessment. Gamma measurements taken at the waste-rock pile and access roads indicate readings from 30 to 1,200 microroentgens per hour (μR/h). An average dose for a visitor (with exposure duration of 16 days and 24 h/day) was estimated to be 115 mrem. However, at one location, this visitor receptor could receive a dose of 460 mrem. Background gamma reading was assumed to be 15 μR/h or 6 mrem/yr.

Ecological Risk Assessment. Based only on the concentrations of contaminants, the EE/CA states that metal concentrations in the waste-rock piles present a low to moderate risk to biota. Copper and possibly arsenic concentrations in the waste-rock piles could be hazardous to most mammals, while copper, arsenic, and, possibly, zinc are potential COCs for invertebrates, soil microbes, and terrestrial plants (MSE 2005). The steep slopes of the waste-rock piles also present a low-risk physical hazard to wildlife. However, the variable concentrations of metals in the piles and the limited exposure durations for most ecological receptors—caused by the small area covered by waste rock, sparseness of vegetation, lack of obvious burrows or nests, seasonal migratory patterns of large mammals, and/or other considerations—effectively reduce the overall risk for ecological receptors (MSE 2005).

The mine discharges contained concentrations of cadmium, copper, iron, lead, mercury, selenium, uranium, and zinc that pose a moderate to very high risk to ecological receptors, based on exceedance of state and federal standards (MSE 2005). However, the discharge channels are shallow, poorly defined, and less than 200 ft long, which makes them generally unsuitable habitats for aquatic biota (MSE 2005).

MSE (2005) did not include a detailed assessment of ecological risks posed by uranium or radioisotopes. It was stated that radioactivity from mining waste at other sites with dry environments indicates that radionuclides present a minimal risk to ecological receptors (MSE 2005). In a bat survey of the South Cottonwood Creek area conducted in 1996, six bat species were found in the King Edward mine adits. However, an ecological risk assessment of the adits was not part of the EE/CA conducted for the site (MSE 2005). Nevertheless, the preferred implementation at the King Edward mine site is to close the mine adits rather than install bat gates (MSE 2005).

2.4.5 Manti-La Sal Mines

A Preliminary Assessment Report was prepared for nine inactive uranium mines in the Manti-La Sal National Forest, Utah (UNC Geotech 1989). Mine waste dumps were analyzed for gamma and radon exposures and for near-surface equivalent Ra-226 concentrations. Surface water samples were analyzed for gross alpha and beta radiation, total uranium, Ra-226/228, arsenic, barium, molybdenum, lead, selenium, and vanadium (UNC Geotech 1989).

Preliminary results indicate that most of the mines had elevated gamma and equivalent radium concentrations, that some of the mine drainages exceeded EPA drinking-water standards (for gross alpha, Ra-226, arsenic, and/or selenium), and that onsite radiation might have been significant in some areas. Some of the mines may have been causing radionuclide contamination of groundwater (UNC Geotech 1989).

Human Health Risk Assessment. A human health risk assessment was not prepared as part of the Preliminary Assessment Report for the nine inactive uranium mines in the Manti-La Sal National Forest (UNC Geotech 1989). Nevertheless, exposure to gamma radiation and radon was significant at several locations, and could have been exceeding occupational standards (UNC Geotech 1989).

Ecological Risk Assessment. An ecological risk assessment was not prepared as part of the Preliminary Assessment Report for the nine inactive uranium mines in the Manti-La Sal National Forest (UNC Geotech 1989). Nevertheless, radionuclide contamination in the waste dumps ranged upwards of 1,000 pCi/g equivalent radium (UNC Geotech 1989), which is well above the soil biota concentration guideline of 50.6 pCi/g from RESRAD-BIOTA.

2.4.6 Midnite Mine

The Midnite mine is located on the Spokane Indian Reservation in eastern Washington. The mine is on the National Priorities List (NPL) and is being cleaned up under CERCLA authority. The site includes an inactive open pit uranium mine, with areas and media impacted by mine-related contaminants (radionuclides and heavy metals). The contaminants at the site have been mobilized as a result of mining activities and environmental processes such as acid mine drainage, radioactive decay, and particulate transport in air, surface water, and groundwater (EPA 2006). The mined area consists of about 350 acres of land physically disturbed by mining, including open mine pits (two partially filled with water), interconnected pits filled with waste rock, waste-rock fill and piles, piles of stockpiled ore or protore, a seep collection area, and surface water conveyances. The mining-affected area encompasses areas and media affected by the mined-area sources (e.g., spilled ore along the haul route, gravel roads at and near the mine, groundwater, surface water, sediments, and soils) (EPA 2006).

Cleanup levels for metals and radionuclides in surface water, surface material, groundwater, and sediments at the Midnite mine site are based on tribal regulatory standards in some instances. However, in many cases the site-specific background levels exceeded site-specific or tribal regulatory risk-based concentrations, and in these cases background was the basis for the cleanup level. The cleanup level for air is the Uranium Mill Tailings Radiation Control Act (UMTRCA) radon flux limit of 20 picocuries per square meter per second (EPA 2006). The selected remedy for the Midnite mine site included (1) consolidation and containment of mine waste in pits, (2) water collection and treatment, (3) offsite residuals management, (4) surface water and sediment management, (5) monitored natural attenuation of groundwater, (6) institutional controls and access restrictions, (7) long-term site management, and (8) contingent actions (EPA 2006).

Human Health Risk and Public Health Assessments. In 2005, EPA completed a human health risk assessment as part of the Remedial Investigation/Feasibility Study. The risk assessment considered tribal traditional and subsistence activities and other exposure scenarios. The resulting risk-based concentrations were compared to background and regulator targets to develop cleanup levels. The Midnite Mine Public Health Assessment (ATSDR 2010) by the Agency for Toxic Substances and Disease Registry (ATSDR) compared site contaminant radionuclide concentrations to health-based dose guidelines for groundwater, soil, surface water, and sediment. This assessment updates ATSDR's preliminary assessment of the Midnite Mine in

2000 and includes findings from ATSDR's 2007 public health assessment of radioactive contaminants from the Midnite Mine Site (see ATSDR 2010).

Ecological Risk Assessment. A baseline ecological risk assessment was conducted for the Midnite mine site. The assessment evaluated endpoints selected to represent ecological communities, as follows: aquatic periphyton, benthic macroinvertebrates, and fish; terrestrial soil and plant communities; mammals and birds (herbivores, carnivores, omnivores, piscivores, and soil invertebrate-feeding species); amphibians; and wetland plant and invertebrate communities (EPA 2006). Contaminant exposure pathways evaluated included direct contact (e.g., dermal exposure), ingestion, inhalation, and external radiation (EPA 2006).

Metals generally drove the ecological risk. Metal contaminants that contributed most to site risks were identified on the basis of considerations of background levels and the magnitude of the hazard quotients. In most cases, maximum contaminant concentrations for a given exposure area were used as exposure point concentrations (EPA 2006). Results of dietary modeling for mammals and birds indicated that site risks were very high in some areas, and in no area could it be stated that there were no ecological effects. Risks were generally higher in the mined area and in mine drainages. Areas exceeding radiological risk thresholds were generally limited to the mined-area pits and impoundments and mine drainages (EPA 2006).

Contaminants in surface water, groundwater, soils and rock, sediments, and air represent a threat to ecological receptors (EPA 2006). The COCs included aluminum, barium, beryllium, cobalt, copper, lead, manganese, nickel, silver, uranium, and zinc in surface water; cadmium, lead, and uranium in surface materials; and chromium, manganese, selenium, uranium, and vanadium in sediments. For total ionizing radiation exposure, DOE risk assessment methods were used, based on risk thresholds of 1 rad/day (10 milligrays per day [mGy/day]) for aquatic organisms and terrestrial plants and 0.1 rad/day (1 mGy/day) for terrestrial animals (EPA 2006).

2.4.7 Northeast Church Rock

An EE/CA was prepared under CERCLA authority for the Northeast Church Rock (NECR) mine site located in McKinley County, New Mexico. The 125-acre mine site is located within Navajo Nation Tribal Trust Lands (EPA 2009). The mine site includes two mine shafts, mine vent holes, wastewater processing ponds, roads, and a water supply well. Wastes at the site include protore, waste rock, overburden, and contaminated water from dewatering activities (EPA 2009). Contaminants analyzed included Ra-226 and uranium, which are co-located. Other stable metals associated with the mineral belt such as arsenic, molybdenum, selenium, and vanadium were below their preliminary removal goals and appear to be within the range observed in the background area. Radium was present in significantly elevated concentrations in soil and sediment. Owing to transport by wind and water processes to areas around and adjacent to the site, human and ecological receptors experienced exposures through the food chain, air, surface water, and/or groundwater (EPA 2009). The principal threat waste at the NECR mine site was defined as any waste containing either 200 pCi/g or more of Ra-226 or 500 mg/kg or more of total uranium.

Human Health Risk Assessment. Radium and uranium are the primary radionuclide contaminants in soils from historical mining practices that may contribute to human health risks. Human receptors may be exposed to these contaminants through ambient air, soil, surface water, or sediment, or by eating plants or animals that are impacted by the site. Activities considered for exposure scenarios include walking or hiking, livestock grazing, ATV use, motorcycling, and horseback riding. Transport of contamination to offsite locations may result in exposure pathways including inhalation or ingestion. Traditional uses of plants also may result in secondary exposure.

EPA has developed a cleanup plan to address potential exposure risks posed by the NECR mine site contaminants to protect human health and the environment. EPA's preference is to move all the mine-contaminated material to the United Nuclear Corporation mill tailings cells, to cap and line the waste disposal cell, and to restore the mine site for grazing.

EPA provided further clarification of this human health risk assessment in comments to a draft of this topic report saying, "the assessment of risk does not address the ground water exposure pathway. Billions of gallons of mine water were discharged to the local arroyo over the years, which ultimately flowed to the Rio Puerco. This mine discharge water significantly resaturated the shallow alluvium (known as the Southwest Alluvium at the UNC [United Nuclear Corporation] NPL mill site). Such re-saturation actually raised the water level in the alluvium over 100 feet at one time. The ongoing ground water remediation (pump and treat) at the NPL site included tailing seepage in the Southwest Alluvium. However, the cleanup was not fully successful for the alluvium and pumping was discontinued. The residual saturation in the alluvium today consists mostly of mine water and some natural recharge. The furthest downgradient extent of the slug of mine water in the Rio Puerco alluvium is not known, but may have reached Gallup. There was concern that the Navajo people may use the alluvial ground water for consumption. EPA Region 6 met with the Navajo Nation Environmental Protection Agency (NNEPA) in Window Rock, AZ, in the early 2000s to discuss the establishment of government controls for restricting the use of this water. The NNEPA decided not to do so."

Ecological Risk Assessment. An ecological risk assessment was not conducted at the NECR site.

2.4.8 Quivira

Bain (2010) prepared an Action Memorandum under CERCLA authority to describe hazardous conditions at the Quivira mine site in McKinley County, New Mexico. The site is located within the Navajo Nation Indian Reservation. Uranium mines are considered to be the major sources of soil contamination at the site. The site includes a mine shaft, a uranium waste pile, several mine vent holes, treatment ponds, and a production well that dewatered the mine workings during past operations. Contaminants are spread by wind and water erosion during weather events (Bain 2010). The site poses a threat of potential future releases of Ra-226 (Bain 2010). The proposed interim response actions for the site include fencing, road paving, and soil stabilization in specified areas of concern prior to implementing a site-wide characterization and time-critical removal action involving the rest of the site (Bain 2010). This mine is adjacent to the NECR and the UNC NPL sites. According to EPA, it was also a wet mine, like the NECR mine, with mine water discharges to surface drainages. EPA has verbally proposed locating the Quivira mine waste to the mill tailings cell, similar to what is proposed for the NECR mine waste.

Human Health Risk Assessment. The primary COC is Ra-226, with exposure pathways including ingestion and/or inhalation of the original contamination or secondary contamination through potential future releases and migration. Scenarios include both onsite and offsite residents along with activities like hiking, livestock grazing, and recreational vehicle use.

Ecological Risk Assessment. An ecological risk assessment was not conducted for the Quivira mine.

2.4.9 Riley Pass

The Riley Pass uranium mines are strip mines located in Harding County, South Dakota, that are being cleaned up under CERCLA authority. Most of the mined lands are within the Custer National Forest. The mines cover about 250 acres of high walls, pit floor, and spoils. Historical mining activities spread elevated concentrations of chemical and radionuclides throughout the soils and surface waters at the mining area. Storm events and wind readily disperse contaminants both onsite and offsite. In 1989, USFS constructed five sediment ponds to minimize the travel of eroded sediments to offsite lands and access roads. Contractors periodically clean out the ponds and return eroded wastes back to upgrade mined areas (Portage Environmental Inc. 2006). The risks to humans and ecological receptors, measured background concentrations, and EPA preliminary remediation goals were developed. These goals are intended to be protective of human health and the environment, while ensuring that the remedies do not seek to clean-up any contaminants that are below natural background levels (Portage Environmental Inc. 2006).

Human Health Risk Assessment. Four receptors were identified for the human health risk assessment (not including the onsite resident or offsite resident scenarios), with exposure to contaminated soil as the primary focus. Field data collection for radionuclides relied on gamma scans correlated to radionuclide concentrations from historical samples. These gamma scans predicted concentrations of 2.3 to 88 pCi/g of Ra-226. High radionuclide contaminated areas correlated well with high arsenic areas. Background for Ra-226 is reported to be about 1.8 pCi/g.

Ecological Risk Assessment. Chemical (arsenic, molybdenum, and selenium) and radiological (Ra-226, U-234, U-235, and U-238) ecological risk assessments were conducted for the Riley Pass uranium mines. Risks were characterized by comparing quantitative estimates of exposure with the quantitative estimate of toxicity. Toxicity values for ecological risk were obtained from a variety of commonly used and accepted sources. Chemical exposure pathways not analyzed included inhalation, exposure to offsite surface soils potentially impacted by windblown dust, and groundwater (Portage Environmental Inc. 2006).

Significant potential for ecological impacts from chemicals was determined for the Riley Pass uranium mines. Key findings included the following: (1) concentrations of contaminants of potential concern were well above area background concentrations and exceeded various benchmark concentrations, indicating the potential for adverse ecological effects; (2) the contaminants of potential concern were distributed throughout all of the mined areas, with large areas showing elevated concentrations; (3) hazard quotients were well above 1.0 for most species evaluated (i.e., moderate or greater impacts); and (4) concentrations of contaminants of potential concern in soil, water, and sediment all were contributing to potential ecological hazards (Portage Environmental Inc. 2006).

Radiological risks for aquatic biota were dismissed, as the radiological biota concentration guides for water were found to be much greater than the observed maximum concentrations for the radionuclides in water at the Riley Pass uranium mines. A potential risk to terrestrial plants and animals was noted in some areas for Ra-226. However, owing to several uncertainty factors, it was difficult to categorically state that ecological risks from Ra-226 were real (Portage Environmental Inc. 2006).

The extent to which ecological harm is occurring is uncertain. Many species may avoid the mined areas, owing to instability of mine wastes and lack of vegetation. However, the lack of vegetation (representing a tangible loss of habitat), combined with the potential for exposure to mine wastes (particularly chemicals), results in overall reduced ecosystem vitality (Portage Environmental Inc. 2006).

2.4.10 Ross-Adams

A Site Characterization Report was prepared in order to obtain information needed to prepare the proposed EE/CA for the Ross-Adams mine site (Tetra Tech 2010). The Ross-Adams mine site is an inactive uranium mine located in the Tongass National Forest near the southern end of Prince of Wales Island, Alaska, that is being cleaned up under CERCLA authority. The Ross-Adams mine was initially developed by open-pit mining in 1957 and later by underground mining operations from three portals opened at different elevations. The site includes the mine with associated mine rock piles, haul roads, an ore staging area, a former barge loading area, and downstream potentially impacted areas, including a creek delta. Observations at the site indicated that the mine rock piles and road embankments were relatively stable and not susceptible to offsite migration by wind and water erosion processes (Tetra Tech 2010).

Data collection to characterize the chemical and radiological conditions of the site included gamma radiation surveys, radon air monitoring, and sampling of potential contaminants in soil, surface water, stream sediment, and marine sediment at the site and background locations. Soil contaminants analyzed included arsenic, lead, Ra-226, and total uranium; surface water and sediment samples were analyzed for aluminum, arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, Ra-226, selenium, uranium, and zinc. Owing to the shallow nature of groundwater at the site, the quality of groundwater was represented by surface water quality information (Tetra Tech 2010).

The results of the Site Characterization Report indicated that the influences of mining activities related to the Ross-Adams mine are limited to the vicinity of the mine feature areas (Tetra Tech 2010).

Human Health Risk Assessment. A human health risk assessment has not been prepared for the Ross-Adams mine site (one will be prepared as part of the EE/CA). A land use evaluation was conducted to identify human receptors that could potentially be exposed to mine-related contaminants. Radiological and chemical data collected for the Site Characterization Report indicated a potential for human health risks (Tetra Tech 2010). Radionuclides (of interest for human health risk) in the mine rock piles and other site areas described above include uranium and Ra-226. Gamma correlation with radionuclide soil concentrations provides reasonable estimates of the Ra-226 concentrations and other radionuclides in areas for which soil sample data are not available.

Ecological Risk Assessment. An ecological risk assessment has not been prepared for the Ross-Adams mine site (one will be prepared as part of the EE/CA). A biological assessment of the site was conducted to identify main habitat types and associated ecological receptors for use in the exposure pathways analyses for the proposed ecological risk assessment. Radiological and chemical data collected for the Site Characterization Report indicated that ecological receptors were at potential risk (Tetra Tech 2010). For example, median Ra-226 concentrations in soil were as high as 351 pCi/g (Tetra Tech 2010), which is about 7 times the soil biota concentration guideline of 50.6 pCi/g from RESRAD-BIOTA.

2.4.11 San Mateo Uranium Mine

An EE/CA was prepared under CERCLA authority for the inactive San Mateo uranium mine in the Cibola National Forest, Cibola County, New Mexico, in order to address potential contaminant exposure to humans and ecological resources. The mine site includes a 10-acre waste-rock pile, a 1.2-acre north pad (consisting of material similar to the main waste-rock pile), three small settling ponds (now full of sediment and totaling about 0.4 acre), and a sheet wash area that consists of materials that have eroded off the waste-rock pile. The mine road also remains at the mine site. The main shaft and any emergency/air shafts associated with the mine are apparently sealed (SAIC 2009). The primary radionuclide COCs include Ra-226, Ra-228, and Th-232. Metal COCs are uranium and selenium. Wind and water erosion of the uncovered wastes has led to contaminant migration into air, soil, and sediment with resultant potential inhalation, ingestion, and dermal contact exposure pathways (SAIC 2009).

Potential migration/exposure pathways at the San Mateo mine include direct exposure to waste rock/soil, surface water/sediment, air, and groundwater pathways. However, the groundwater pathway is believed to be incomplete in that there is no indication of a significant hydraulic connection between contaminated surface materials and deep groundwater aquifers, and no shallow groundwater has been identified at the site (SAIC 2009). Radionuclide levels and uranium and selenium concentrations in the waste-rock pile are as much as 100 times higher than background levels, indicating a high level of contamination. The north pad and settling ponds also have elevated concentrations of radionuclides and metals. In addition to uranium and selenium, the settling ponds have elevated levels of copper and vanadium (SAIC 2009). According to EPA, the San Mateo Uranium Mine was operated as a wet mine. The mine water was discharged to surface drainage features that flowed to nearby San Mateo Creek. Like at other mines within the basin, the mine water resaturated the shallow alluvium. The hydraulic connection between the mine and groundwater is via this flow path. There may be no shallow groundwater at the site today, but the mine water discharged from the site has moved down San Mateo Creek drainage within the alluvium. Thus, there could be potential risk through the exposure to contaminated groundwater via consumption.

The removal action objectives developed for the San Mateo mine site include the following: (1) reduce onsite gamma radiation exposure for onsite human receptors to below a 10^{-4} increased cancer risk; (2) minimize or eliminate the potential for exposure via direct contact of human and ecological receptors to unacceptable concentrations of radionuclides in waste material, and for release of contaminants from the site into the San Mateo Creek watershed or onto nearby private land via the surface water pathway; (3) reduce or eliminate migration of radionuclides from the site via the air pathway; and (4) minimize ingestion and uptake of radionuclides by plants and animals (SAIC 2009).

Human Health Risk Assessment. The shallow alluvial aquifer along San Mateo Creek contains molybdenum, selenium, and gross alpha concentrations sufficiently high to make the groundwater unsuitable for domestic and agricultural use. The New Mexico Environment Department issued an advisory to private well owners in the San Mateo Creek Basin in Cibola and McKinley Counties in January 2009. Groundwater may exceed federal and state standards for several contaminants including Ra-226, Ra-228, selenium, and uranium. The contamination may be related to naturally occurring ore deposits or to former uranium mine and mill activities in the area.

A streamlined human health risk assessment used BLM risk management criteria to compare contaminant concentrations found. These criteria were based on reducing the risk to 10^{-4} for the receptors considered.

Ecological Risk Assessment. A streamlined ecological risk assessment was conducted for the San Mateo mine, emphasizing the risk posed by metal concentrations to cattle, deer, and small songbirds (SAIC 2009). Metal concentrations in waste rock, pad material, and soil/sediment were compared to BLM risk management criteria for metals (Ford 2004). The following criteria were applied to evaluate the degree of risk: low risk (less than or equal to the criteria), moderate risk (>1 to 10 times the criteria), high risk (>10 to 100 times the criteria), and extremely high risk (>100 times the criteria) (Ford 2004). A moderate risk to robins was indicated for arsenic, cadmium, copper, lead, and zinc concentrations in soil, waste rock, and sediment samples. The assessment was considered to be conservative because it did not take into account the home range of the species. An ecological risk assessment was not conducted for radionuclides.

2.4.12 White King and Lucky Lass Uranium Mines

The White King/Lucky Lass uranium mine site is located in the Fremont National Forest, Lake County, Oregon. The site is listed on the National Priorities List and is being cleaned up under CERCLA authority. The site encompasses about 140 acres on both USFS and private lands (EPA 2001). Contaminated areas at the site include soils, waste rock, and groundwater at both the White King and Lucky Lass mines, and contaminated water and sediments at the water-filled excavation pit (pond) located at the White King mine. The major features at the White King mine are a 13.4-acre water-filled excavation pit, a 17-acre protore stockpile, and a 24-acre overburden stockpile. The major features at the Lucky Lass mine are a 5-acre water-filled excavation pit and a 14-acre overburden stockpile (EPA 2001).

The primary COCs at the White King/Lucky Lass uranium mine site are arsenic, U-234/238, Ra-226/228, and radon. The proposed action for the site is to consolidate and cover the most contaminated soils from both mines at White King mine area and continue neutralization of the acidity in the White King pond (EPA 2001).

The selected remedy chosen for the White King/Lucky Lass uranium mine site included reconfiguration, consolidation, and covering the stockpiles with a clay-like material followed by a soil cover. Other disturbed areas will be reclaimed and revegetated. The site will also have storm water management, pond maintenance, routine monitoring, inspection and maintenance of the mine waste repository, institutional controls, and physical access restrictions (EPA 2001).

Human Health Risk Assessment. A Record of Decision (ROD) was developed with concurrence by the U.S. Department of Agriculture's USFS, the State of Oregon's Department of Environmental Quality, and the Oregon Office of Energy (EPA 2001). COCs were both chemical (e.g., arsenic) and radiological (e.g., Ra-226). Scenario receptors included workers, recreational users, trespassers, and potential residents exposed to contaminants (but not to radon, since it is at background levels) through external radiation and dust inhalation. Risk levels were set at 10^{-6} from an individual COC and 10^{-5} from the cumulative COCs. The selected remedy in the ROD was to consolidate contaminated soils and place a clean cover over them and to continue acid neutralization in ponds.

Ecological Risk Assessment. A baseline ecological risk assessment was performed for the White King/Lucky Lass uranium mine site. All constituents that were determined to be above background concentrations were included as contaminants of potential concern for the ecological risk assessment. On the basis of the ecological risk assessment, the final COCs were aluminum and arsenic in the White King pond surface waters; arsenic, manganese, and mercury in the Auger Creek and White King pond sediments; and arsenic, antimony, mercury, and selenium in the White King and Lucky Lass soils (EPA 2001).

To estimate ecological receptor exposure to radionuclides, the absorbed doses (Gy/day) were calculated for each receptor. Radionuclide-specific factors were based on those for Ra-226 and U-238 (EPA 2001).

Ecological risks were determined for plants and animals exposed primarily to antimony, arsenic, lead, mercury, and selenium in surface and subsurface soils. Risks were also indicated for aquatic invertebrates exposed to mine sediments, owing primarily to arsenic (EPA 2001). No adverse impacts on ecological receptors were predicted for radionuclides in the water of the mine ponds or offsite streams (EPA 2001). The groundwater pathway was not analyzed for ecological risks. The groundwater in the area has elevated natural background levels of arsenic, radon, and other constituents (EPA 2001).

2.4.13 Workman Creek

An EE/CA was performed under CERCLA authority for the Workman Creek uranium mines site in the Tonto National Forest in Gila County, Arizona (Weston Solutions Inc. 2008). Open adits, waste-rock piles, and areas of mixed waste rock and road-cut materials are present throughout the Workman Creek watershed (Weston Solutions Inc. 2008). Radiological risks from gamma radiation and elevated levels of arsenic, cadmium, copper, and lead may exist at various locations within the watershed (Weston Solutions Inc. 2008).

The overall removal action goal for the Workman Creek uranium mines site is to minimize the risk to human health and the environment from COCs and gamma radiation associated with ore staging areas, open adits, and waste-rock piles (Weston Solutions Inc. 2008). The following removal action objectives were developed for the Workman Creek uranium mines site: (1) reduce human exposure to gamma radiation on ATV roads to levels that do not result in unacceptable site-related risks, (2) reduce exposure of human and ecological receptors to COCs in soils at campgrounds to levels that do not result in unacceptable site-related risks, (3) reduce exposure of human and ecological receptors to COCs in soils and waste-rock areas that do not result in unacceptable site-related risks and reduce contaminant transport from waste-rock material to drainage areas, and (4) reduce the physical hazards posed by open or partially open adits present in the mining areas (Weston Solutions Inc. 2008).

The recommended alternative actions for the Workman Creek uranium mines site include the following:

- **Campgrounds:** Excavation of hot-spot areas and onsite disposal in a consolidated disposal cell
- **ATV Roads:** Rerouting of ATV traffic to eliminate access to the most highly affected road segments
- **Mine Groups:** Excavation and onsite disposal that include a combination of closing adits with surrounding waste rock or with a steel plate, consolidating and capping waste-rock piles, and/or capping waste rock in place (Weston Solutions Inc. 2008)

Human Health Risk Assessment. Human health risk to recreational visitors (camper, hiker, ATV user) was evaluated via a streamlined risk assessment process. The primary pathway of exposure is external gamma radiation. BLM risk management criteria, State of Arizona non-residential soil remediation levels, and State drinking-water standards were used to compare to contaminant concentrations and for the determination of potential risk. Gamma rates of 90 µR/h were reported for campgrounds; and a hot spot gamma reading of 1,100 µR/h was reported on a road leading to the mine.

Ecological Risk Assessment. A streamlined ecological risk assessment was conducted at the Workman Creek uranium mines site. The concentrations of COCs in soil, waste rock, surface water, and sediments were compared to potential chemical-specific ARARs and/or risk-based chemical concentrations (Weston Solutions Inc. 2008). Concentrations of uranium in surface waters from Workman Creek and one of the mine adit pools presented a moderate risk to ecological resources during low-flow conditions but only a low risk during high-flow conditions (Weston Solutions Inc. 2008). Metals in Workman Creek and mine site drainage sediments revealed a low to moderate risk to ecological receptors. Metals in soils at two campgrounds also posed a low to moderate risk to ecological receptors. Similarly, soils and waste rock at the various mines presented a low to moderate risk to ecological receptors. Concentrations of uranium at one of the mine sites and mercury at another represented a high risk to ecological receptors (Weston Solutions Inc. 2008).

Radionuclides present in surface waters and sediments did not indicate a risk to ecological receptors. Ra-226 concentrations in soils and/or waste rock at some of the mine sites exceeded the ecological risk criteria, representing an increased risk to ecological receptors (Weston Solutions Inc. 2008). Groundwater did not appear to pose a chemical or radiological risk to ecological receptors (Weston Solutions Inc. 2008).

2.5 Summary

The review of the reports summarized in Sections 2.1 through 2.4 indicates that similar types of radionuclides and chemical contaminants (primarily metals) occur at inactive uranium mines. Again, it should be noted that this analysis is not meant to imply that these conditions are typical for all uranium mines. These mines are those that were problematic enough for action to be taken. For those mines having risk data associated with them, localized human health and ecological risks are identified for most mine sites on the basis of elevated levels of radionuclides and metal concentrations. On the basis of human health and ecological risk assessments done at inactive uranium mine sites, proposed remedies generally involve reducing risk from the ingestion and inhalation of contaminants of potential concern, reducing the risk of exposure to gamma radiation, minimizing air emissions of radon, and minimizing offsite transport of contaminants of potential concern. EPA CERCLA guidance and policy do not recommend that cleanup levels be established at levels below background, even if background level exceeds an ARAR or a risk-based concentration. Where a regulatory standard or risk-based concentration is greater than the background level, the standard or risk-based concentration is the appropriate one to use as the cleanup level at CERCLA sites.

ICRP (2007) concluded that there was a need to develop a comprehensive approach to study the effects on, and protection of, biota from radionuclides. Therefore, ICRP (2008) introduced the concept of reference animals and plants, which are hypothetical entities with the assumed basic biological characteristics of a particular type of animal or plant that has defined anatomical, physiological, and life-history properties, and which can be used for the purpose of relating exposure to dose, and dose to effects, for that type of living organism. A set of 12 reference animal and plants were developed (ICRP 2008). Those that would be most appropriate for use in evaluating ecological risks to biota at uranium mines that are the subject of this report include deer, rat, duck, frog, trout, bee, earthworm, pine tree, and wild grass. Ecological evaluations conducted for uranium mines should consider the use of reference animals and plants (ICRP 2008) and the use of equilibrium concentration ratios reported for the reference animals and plants in order to model the transfer of radionuclides through the environment (ICRP 2009).

In contrast to human health assessments, for which excess risk to an individual is important, ecological risk assessments are more often concerned with maintaining general ecosystem health and productivity. Guidance has been developed for conducting ecological risk assessments (e.g., EPA 1997a, EPA 1998). As most ecological risk assessments are based on conservative exposure assumptions and toxicological data from laboratory studies, coupled with limited site-specific biological data, there are a number of uncertainties associated with the assessments. All of the ecological risk assessments have uncertainties regarding chemistry and sampling analysis, fate and transport parameters, exposure assumptions, and toxicological data. The use of very conservative exposure assumptions and the use of weak toxicological data from laboratory studies rather than site-specific toxicity data are the largest sources of uncertainty (see EPA 2001, 2006). For example, using maximum values as exposure point concentrations, assuming that a species only inhabits the impacted areas, and assuming 100 percent bioavailability of contaminants tend to overestimate risk.

3.0 Evaluate Potential Radiological Risk from Mines

To provide estimates of the potential radiological risk to human health from the mines, a CSM was developed. One CSM was used for all five production-size categories of mines evaluated, as the components (i.e., source, receptors, and exposure pathways) examined would be the same regardless of the mine size evaluated. The risk evaluation for the mines was conducted for an average mine for each of the five production-size categories and not for individual mines, as this was not possible due to data limitations for individual mines.

The number of mines considered in this evaluation is 4,174, compared to the total number of 4,225 mines in the DOE mines database. That is because this evaluation does not consider the mines in the Very Large production-size category. The 37 mines in that production-size category either have been reclaimed or are being reclaimed or remediated.

The potential sources of contamination considered were (1) waste-rock piles or dumps; (2) potential ground surface contamination (including surface contamination of mine workings or structures, stockpile pads, and onsite roads); and (3) radon gas and residual ores at mine adits.

Five receptors were evaluated that represented varying degrees of exposure, from longer duration (resident scenarios) to shorter duration (visitor scenarios), along with the range of plausible exposures (addressing pathways of exposure to the potential sources identified above) at the mines. These five receptors are (1) an onsite resident, (2) an offsite resident, (3) a recreational visitor, (4) an occasional visitor, and (5) a reclamation worker.

For the onsite resident receptor, two variations of the scenario were analyzed in this report. The first onsite resident receptor (Onsite Resident Receptor A) lives on a house built on top of a waste-rock pile. The second onsite resident receptor (Onsite Resident Receptor B) lives on an open area on the mine site and made use of waste-rock material to construct the house foundation. The risk estimates were based on an exposure concentration of 70 picocuries per gram (pCi/g) for radium-226 (Ra-226) in the waste-rock pile. The potential cancer risk for Onsite Resident Receptor A would result primarily from indoor radon exposure (followed by external radiation exposure). Estimates that assumed the addition of a layer of cover material (such as soil or dirt) on the waste-rock pile indicated a reduction of the external gamma radiation pathway. However, the potential risk associated with indoor radon exposure would be reduced only slightly. Risk estimates are slightly lower for Onsite Resident Receptor B, because the addition of the cover material below the foundation only slightly reduces the estimated risk.

For both onsite and offsite resident receptors, the potential pathways of exposure evaluated include (1) inhalation of radon and particulates, (2) external gamma, (3) incidental ingestion of soil, and (4) ingestion of plant foods, meat, and milk. The potential exposure to surface water and groundwater was not evaluated for this report as the risk from exposure to potential radionuclide water contamination would be lower than the risk from exposure to air contaminants (inhalation to radon) and external gamma radiation.

The exposure parameter values (e.g., exposure duration of 30 years for the resident scenario, inhalation rates, and ingestion amounts) used as input for the risk estimates provided in this report are those recommended by EPA in its exposure factors handbook (EPA 1997b).

The greatest risks for all receptors were from inhalation of radon. For receptors spending time onsite, risks from external radiation from waste-rock piles and contaminated soil was also significant; risks from other pathways (e.g., ingestion of plants, meat, milk, and soil) were less important. Of the five receptors evaluated, only the onsite resident and reclamation worker risks exceed 10^{-4}, which is the upper end of EPA's acceptable risk range that is broadly used in the U.S. for point of comparison.

For the onsite resident scenarios, the estimated risks would result primarily from the inhalation of radon that emanates from the waste-rock pile or foundation material and diffuses into the house. Risks associated with indoor radon range from 8×10^{-2} to 1×10^{-1}. Risks from external radiation through exposure to waste rock and contaminated soils ranged from 2×10^{-3} to 1×10^{-2}. Risks for residential use for all pathways combined range from 9×10^{-2} to 1×10^{-1} (dominated by indoor radon). For an offsite resident living 100 meters from a mine, risk estimates from all pathways evaluated ranged from $<1 \times 10^{-5}$ to $<1 \times 10^{-4}$ and resulted primarily from the inhalation of radon that emanates from the waste-rock pile and then is transported to the offsite location by wind.

For the recreational visitor, occasional visitor, and reclamation workers, risks were calculated for exposures at mine adits and waste-rock piles. Risks from spending one hour at a mine adit ranged from 2×10^{-6} to 4×10^{-5} and would apply to either a recreational or occasional visitor. For a recreational visitor camping on a waste-rock pile at a mine for 2 weeks, the external radiation risk is 2×10^{-5}. External radiation risks for one hour of exposure to a waste-rock pile by an occasional visitor ranged from 5×10^{-8} to 7×10^{-8}. If recreational or occasional visitors spent time at both waste-rock piles and adits, total risks would be additive.

Risks to a reclamation worker conducting reclamation activities at mine adits for 20 days range from 3×10^{-4} to 6×10^{-3}. Risks to reclamation workers reclaiming waste-rock piles for 20 days ranged from 9×10^{-6} to 1×10^{-5} for external radiation. If a worker spent 20 days at adits and 20 days at waste-rock piles, risks would be additive and dominated by exposure at adits (i.e., total risks would range from 3×10^{-4} to 6×10^{-3}). These risks estimates do not take into account the health and safety protocols required for reclamation workers conducting reclamation activities. The requirements would reduce potential risks to workers to as low as reasonably achievable levels. The estimates presented in this report indicate that following existing health and safety requirements for workers is essential for worker protection.

Further discussion regarding the evaluation is provided in Sections 3.1 through 3.5. Section 3.1 discusses the methodology used for this assessment and presents the CSM developed. Sections 3.2 through 3.5 further elaborate on the components of the risk evaluation process presented in this chapter. These components address the sources of exposure, identification of exposure point concentrations (or contaminant concentrations at the point of exposure), potential pathways and receptors, and risk estimates. A brief conclusion is provided in Section 3.6.

3.1 Risk Assessment Methodology and Conceptual Site Model

The assessment performed for this report involves the following steps: (1) identify sources of exposure (this report focuses on radiation sources at the uranium mines), (2) determine release and transport mechanisms in order to identify the potential exposure location and contaminant concentrations at this location, (3) identify plausible receptors and exposure pathways, and (4) quantify and characterize risk. These steps are consistent with those provided in EPA's guidance for risk assessments in *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual,* Interim Final (EPA 1989).

The CSM shown in Figure 6 illustrates the primary components of the evaluation. All completed pathways were evaluated. For the onsite resident, exposure to mine adits was not calculated because it was assumed that if the resident would visit the adits, it would be occasional and would be reflected by the risk estimates for the recreational/occasional visitor. The groundwater pathways were not calculated due to limited time available to evaluate data for mines considered for this report.

For the offsite resident, due to the distance of these receptors to the mines, the external gamma and soil ingestion of contaminated surface and the waste-rock piles were not estimated; and if these receptors do visit onsite, the estimates for the recreational visitors would reflect that potential exposure. For offsite resident inhalation, the airborne particulates and radon from the waste-rock piles would be the primary source of exposure. For the offsite resident ingestion pathway, risk estimates were derived assuming that livestock would graze in an open contaminated area at the mines and, subsequently, meat and milk products from the livestock could be ingested by the offsite resident. Plants or vegetation grown on the open contaminated area were also assumed to be ingested and are included in the risk estimates.

For the recreational, occasional, and reclamation workers, risk estimates for the external gamma, inhalation, and soil ingestion pathways were calculated for the waste-rock piles because the estimates would be more conservative than risk estimates for the contaminated ground surface and it was assumed that the entire exposure duration was for exposure to the waste-rock piles.

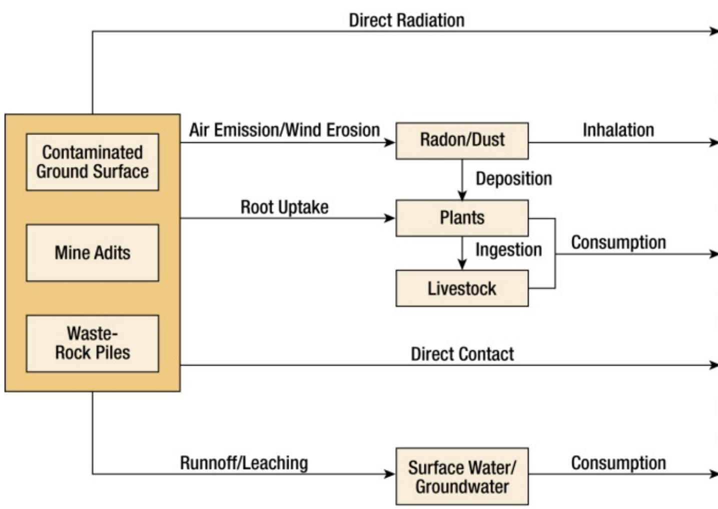
As previously mentioned, this CSM is applicable for the five production-size categories evaluated, as the components of the model shown are valid regardless of mine size. In addition, naturally occurring processes, such as accumulation of a natural calcium carbonate crust on a waste pile, can reduce erosion and radon flux, thereby reducing the potential for a completed pathway for exposure to the waste-rock piles.

3.2 Potential Radiation Sources at Mines

The primary radiation sources identified at mines for evaluation in this report include (1) waste-rock piles or dumps, (2) contaminated soils or ground surface, and (3) radon gas and residual uranium ores at mine adits.

Waste-rock piles can contain uranium isotopes and their decay products (such as U-238, U-235, U-234, Th-230, and Ra-226) because (1) uranium ores were inadvertently mixed with surrounding overburden rocks during the mining process and/or (2) ore materials were judged to be “waste” because they did not meet the uranium-content requirement for uranium ores that were transported for processing.

The ground surface in uranium mining areas can become contaminated through the area being used for mine-water retention or treatment, the area being used for stockpiling uranium ores, or from spills when transporting uranium ores or waste rocks from the mine opening to the stockpile locations at the mine sites. Also, through precipitation-runoff events, human activities, and vehicular traffic, the area of ground surface contamination could expand. In addition to the ground surface, surfaces of above-ground workings or mining structures can be contaminated



Exposure	Source	On-site Resident	Off-site Resident	Recreational Visitor	Occasional Visitor	Reclamation Worker
External Exposure	Contaminated Ground	⊙	•	•	•	•
	Waste-Rock Piles	⊙	•	⊙	⊙	⊙
	Mine Adit	•	—	⊙	⊙	⊙
Inhalation Exposure	Contaminated Ground	⊙	•	•	•	•
	Waste-Rock Piles	⊙	⊙	⊙	⊙	⊙
	Mine Adit	•	•	⊙	⊙	⊙
Ingestion Exposure	Contaminated Ground	⊙	⊙	—	—	—
	Waste-Rock Piles	•	•	—	—	—
	Mine Adit	—	—	—	—	—
Soil Ingestion Exposure	Contaminated Ground	⊙	•	•	•	•
	Waste-Rock Piles	⊙	•	⊙	•	⊙
	Mine Adit	•	—	•	•	⊙
Water Ingestion Exposure	Contaminated Ground	•	•	—	—	—
	Waste-Rock Piles	•	•	—	—	—
	Mine Adit	—	—	—	—	—

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• Complete pathway   ⊙ Calculated pathway   — Incomplete pathway

Figure 6. Conceptual Site Model for the Receptors at the Five Mine Production Categories

because of handling of uranium ores at these locations. For this report, the contaminated structure surfaces are addressed by the analyses of contamination on ground surfaces, as the potential radiation exposure emanating from structural surface contamination would result in similar exposures.

For underground mining in particular, some uranium ores can remain after mining, thus creating a source of radon gas that could diffuse out to mine adits. In addition, waste rocks and uranium ores from underground tunnels carried through the mine adits during mining can leave behind residual uranium ores or waste rocks near the adits, resulting in external gamma radiation exposure.

Radionuclides that are expected to be present in waste-rocks, contaminated ground surface, or residual uranium ores at mine adits include U-238, U-235, U-234, and their decay products. The decay products include Th-230, Ra-226, and Pb-210 for U-238 and U-234; and protactinium-231 (Pa-231) and actinium-227 (Ac-227) for U-235.

3.3 Exposure Point Concentrations

In deriving exposure concentrations of the potential contaminants for input into the risk estimates, several aspects of the sources discussed in Section 3.1 need to be considered.

Waste-Rock Piles. The potential radiological risks associated with waste-rock piles are dependent on their dimensions, in addition to the concentrations of radionuclides present in the waste rocks. Essentially, the larger the size of the pile, the larger the footprint, or the taller the height, the higher the risk estimates. For each of the five production-size categories of mines evaluated in this report, a representative waste-rock pile size was developed. Further, for this analysis and as a conservative approach, potential multiple waste-rock piles are aggregated as one pile since, as stated before, a larger pile size would result in higher potential risk than the risk from several smaller piles all located in approximately the same area. Table 2 lists the area footprint and height assumed for the representative waste-rock piles. These dimensions were developed by the DOE team on the basis of information on mines included in the DOE mines database. The thickness of the contaminated ground surface is assumed to be 1 centimeter (cm) (0.39 inch) but spread out over a larger area thereby providing greater accessibility for exposure. This approach provides a more conservative (higher) risk estimate than were it assumed that the contamination disseminated deeper into the soil column over time.

Table 3 presents a compilation of U-238 concentration in waste rocks as presented or indicated in several literature references consulted. The data indicate that there would be variability of uranium data from site to site. The 36 discrete measurement data (See Appendix A, Table A-2, for the individual measurements) collated from these literature references provided an overall mean concentration of 50.2 pCi/g for U-238. The 95th percentile of mean concentration for U-238 was calculated to be 61.8 pCi/g and 78.3 pCi/g using two statistical methods (i.e., the central limit theory and Chebyshev inequality method, respectively; both methods are recommended by EPA [2002a]). The average of the two 95th percentile values, which is 70 pCi/g, was used as the U-238 concentration for the risk estimates discussed in this report. Because very limited data are available with regards to radionuclide concentrations in the contaminated soils on ground surface, the 70 pCi/g value was also used as the concentration of U-238 in the ground surface soil at a mine site.

Table 2. Assumed Dimensions of Waste-Rock Piles and Contaminated Ground Surface Areas for the Five Production-Size Categories

Size of Uranium Mines	Small	Small/ Medium	Medium	Medium/ Large	Large
Range of Ore Produced (tons)	0–100	>100–1,000	>1,000–10,000	>10,000–100,000	>100,000–500,000
Waste-Rock Pile Footprint Area (m^2)	100	175	400	2,300	10,000
Waste-Rock Pile Footprint Area (acre)	0.025	0.043	0.099	0.57	2.47
Waste-Rock Pile Height (m)	0.61	1.07	4.00	8.00	9.00
Waste-Rock Pile Height (ft)	2.0	3.5	13.1	26.3	29.5
Contaminated Ground Surface Area (m^2)	150	263	600	3,450	15,000
Contaminated Ground Surface Area (acre)	0.037	0.065	0.15	0.85	3.71
Contaminated Ground Surface Thickness (m)/(inches)	0.01/ 0.39	0.01/ 0.39	0.01/ 0.39	0.01/ 0.39	0.01/ 0.39

Abbreviations:
m = meters

Table 3. Compilation of U-238 Concentration in Waste-Rock Piles for Determining Source Concentration

Source of Data	Value (pCi/g)
DOE Uranium Leasing Program JD-6 Mine (Whetstone Associates 2012)[a]	52.6
DOE Uranium Leasing Program JD-8 Mine (Whetstone Associates 2011)[a]	30–70
Whirlwind Mine (BLM 2008)[a]	2.8–4.2
Butterfly Mine (CH2MHill 2011)[a]	35.7–151
Burrell Mine (CH2MHill 2011)[a]	9.06–136
Browns Hole Mine (Marston, et al., 2012)	7.5–120.5
Overall–Range	2.8–151
– Mean	50.2
– 95th percentile (central limit theory)	61.8
– 95th percentile (Chebyshev inequality method)	78.3

[a] U-238 concentration was obtained from measured total uranium concentration (mg/kg) and the activity ratio of uranium isotopes in natural uranium.

In the estimates discussed in this report, the secular equilibrium assumption was applied to derive the concentrations of the remaining suite of associated nuclides (this approach is often used in radiological risk assessments to obtain conservative dose/risk results). Using the secular equilibrium assumption, U-234, Th-230, Ra-226, and Pb-210 were assumed to be at the same concentration as U-238. However, the concentration assumed for U-235, 3.22 pCi/g, was determined on the basis of the radioactivity ratio of 1:0.046:1 among U-234, U-235, and U-238 for natural uranium. The same concentration of 3.22 pCi/g was assumed for the decay products of U-235, i.e., Pa-231 and Ac-227. The bulk density of waste-rock piles was assumed to be 2.8 g/cm^3 (EPA 2008a, 2008b).

Concentrations of radionuclides in waste rocks at the various mine sites could vary from the concentrations assumed for this report. However, the results presented in this report can be scaled linearly, as needed, to determine risk estimates for other concentrations. For example, the risk estimate for a concentration of 1 pCi/g could be derived by dividing the results presented in this report (for 70 pCi/g) by 70. Essentially, the risk would be about two orders of magnitude less (e.g., risk from inhalation of radon to the Onsite Resident Receptor A discussed previously would be at about 10^{-3} instead of 10^{-1}). Conversely, if Ra-226 concentrations were higher than the 70 pCi/g assumed for this report, the risk estimates would increase accordingly.

Ground Surface Contamination. The size of the contaminated area is assumed to depend on the cumulative uranium ore production in the past, with a higher uranium ore production resulting in the generation of larger amounts of uranium ore and waste rock. The larger production tonnage would require more handling and transportation across the mine area and larger areas for stockpiling them onsite, resulting in more runoff during rain events that could spread to larger areas. The area of the contaminated ground surface was assumed to be about 1.5 times the footprint of the waste-rock pile assumed for each of the five production-size categories of mine sites. This means that if the waste-rock pile occupies a footprint of 1 acre, the contaminated ground surface would be around 1.5 acres. This is consistent information found in the review of various inactive mine sites discussed in Section 2.4; for example, at the Juniper uranium mine in Toulumne County, California (Tetra Tech EM Inc. 2005), the waste-rock pile was said to occupy an area of about 1.4 acres and the contaminated ground surface (including access roads) was said to be about 2.5 acres. The sizes of the contaminated ground surface areas assumed for mines of different production-size categories are listed in Table 2.

As with the distributions of radionuclides in waste-rock piles, the actual distribution of radionuclides on the ground surface of a mine site may be nonhomogeneous, likely with some higher concentrations intermingled with lower and/or background concentrations. To evaluate potential radiological risks associated with this ground surface radiation source, a U-238 concentration of 70 pCi/g (70 pCi/g for U-234, Th-230, Ra-226, and Pb-210, and 3.22 pCi/g for U-235, Pa-231, and Ac-227) was assumed for the entire open area for each of the five production-size categories of mines. In addition to the assumed radionuclide concentrations, a thickness of 1 cm for the contamination was assumed. The bulk density of the 1-cm-thick layer of contamination was set at 2.8 g/cm^3, the same as the bulk density assumed for waste-rock piles (EPA 2008a, 2008b). The actual concentrations of radionuclides remaining on the ground surface of existing mine sites would most likely be lower than the concentrations assumed for this evaluation. Again, the estimated results can be linearly scaled to determine a specific estimate with corresponding concentrations.

Radon Measured at Adits. The potential radiological risks at adits were estimated using the gamma rate and radon level measurements collected at mines visited in six states in August 2013. This was a small sample of the total population of mines and may not be representative. However, the maximum values for this dataset were consistent with maximum measurements in other available datasets. Maximum values were used in the risk calculations to be conservative. The measured data were used to derive estimates for onsite receptors as potential exposure to radon and external gamma at adits would occur primarily for a receptor in close proximity to these adits.

Air Concentrations of Radionuclides at Offsite Locations. Radionuclides in onsite radiation sources could be blown to downwind locations and result in radiation exposures of offsite residents. Because waste-rock piles could be the largest above-ground radiation sources at a mine site, they were the focus of analysis when evaluating airborne emissions. The emissions from waste-rock piles include loose particulates on the surface, which could contain uranium isotopes and their decay products, and radon gas, which is generated in waste rocks as Ra-226 (a decay product of U-238 and U-234) decays and diffuses through the pore space to the surface of waste-rock piles.

Emission rates of radon from the surface of waste-rock piles were calculated with the use of RESRAD code Version 6.7 (Yu et al. 2001), which provides estimates of radon flux in terms of picocuries per meters squared per second ($pCi/m^2/s$) on the basis of input information on waste-rock piles, such as dimensions and radionuclide concentrations, the radon diffusion coefficient (the default value was used), and the radon emanation coefficient (0.15, based on measurement data taken from rock samples [Ferry et al. 2002; Sakoda et al. 2010]). The radon flux estimated by RESRAD was multiplied by the footprint areas of waste-rock piles (listed in Table 2) to obtain radon emission rates.

The emission rates of particulates were estimated following the guidance from Regulatory Guide 3.59 (NRC 1987) concerning emission of dust particles from exposed uranium mill tailing sands due to wind erosion. The use of the NRC guidance is expected to generate higher than actual emission rates from waste-rock piles, because uranium mill tailing sands would be more susceptible to wind erosion than fine particulates of waste rocks. The emission rate of particulates is dependent on the wind speed, with a higher wind speed eroding more particles from exposed surfaces than a lower wind speed. Because weather conditions could vary at different locations, the emission rates of particulates from waste-rock piles could also vary depending on location. For this evaluation, meteorological data from various weather stations in 19 states with existing mines were obtained and analyzed for the distributions of wind speeds of different eroding categories and then used for the particulate emission rate calculations.

After airborne emission rates of particulates and radon were obtained, the emission rates were input to the air dispersion model to calculate radionuclide concentrations and radon levels at different downwind locations. The air dispersion model used in this evaluation is CAP88-PC (Trinity Engineering Associates Inc. 2007). CAP88-PC is a state-of-the-art computer code employed by various agencies including DOE, NRC, and EPA for calculating air emissions.

Appendix A provides further discussion on the evaluation of the radon and particulate emission rates and the use of computer code CAP88-PC for calculating the radon levels and air concentrations of radionuclides at downwind locations.

3.4 Potential Receptors and Exposure Pathways

As shown in Figure 6, the five receptors evaluated are onsite residents, offsite residents, recreational visitors, occasional visitors, and reclamation workers. The “visitor” scenarios (recreational and occasional) evaluated likely encompass other similar shorter duration exposures, such exposures experienced by off-road vehicle users, hikers, and others. Depending on the receptor, potential exposure pathways considered in this radiological risk evaluation include external radiation, inhalation of radon, inhalation of airborne particulates containing radionuclides, ingestion of contaminated plant and meat/milk products, and incidental ingestion of contaminated soil particles.

Depending on the distance to the radiation source and the nature of receptor activities (including living patterns such as the amount of time spent inside or outside the home, how long one resides in the same residence, and whether or not one plants vegetables for consumption or raises cattle for milk and meat), exposures to radiation for a receptor could be incurred through multiple pathways. The plausible exposure pathways could also vary among the receptors evaluated.

The uranium isotopes and their decay products contained in a radiation source could emit gamma rays and cause direct external radiation exposure to a receptor located nearby. In addition to direct radiation, the emanation and diffusion of radon gas (generated by the decay of Ra-226, a decay product of uranium isotopes) and the erosion of surface particles by wind from a radiation source would result in air contamination at onsite as well as offsite locations, leading to inhalation exposures. Vegetation such as grass or crops could be planted and grown in contaminated soil and could take up radionuclides through the root systems and become contaminated. If the contaminated vegetation were consumed by a receptor, or by livestock that produces meat and milk consumed by a receptor, exposures to radiation through the ingestion of plant foods or meat/milk pathways could occur. Exposures through soil ingestion could be incurred if a receptor inadvertently ingested contaminated soil/dust particles sticking to his hands as a result of either direct contact with a radiation source or deposition of airborne contaminated particles originating from a radiation source.

The exposure parameters and input values assumed for the five receptors are summarized in Table 4, and are further described in the text that follows for each receptor.

Table 4. Exposure Parameters Used for Evaluating the Potential Radiological Risks to Uranium Mine Receptors

Parameter	Onsite Resident	Offsite Resident	Recreational Visitor	Occasional Visitor	Reclamation Worker
Exposure duration (yr)	30[a]	30[a]	1	1	1
Exposure frequency (days/yr)	350[a]	350[a]	14 (piles)[b] 1 (adits)	1 (piles)[b] 1 (adits)	20 (piles)[b] 20 (adits)
Exposure time					
Indoor (h/day)	16[c]	16[c]	—[d]	—[d]	—[d]
Outdoor (h/day)	8[c]	8[c]	24 (piles)[b,e] 1 (adits)	1 (piles)[b] 1 (adits)	8 (piles)[b,f] 8 (adits)
Inhalation rate (m^3/yr)	8,000[g]	8,000[g]	8,000[g]	8,000[g]	8,000[g]
Ingestion rate					
Soil (mg/day)	100[h]	100[h]	100[h]	—[d]	100[h]
Meat (kg/yr)/(lb/yr)	63 / 139[i]	63 / 139[i]	—[d]	—[d]	—[d]
Milk (L/yr)/(gal/yr)	92 / 24[i]	92 / 24[i]	—[d]	—[d]	—[d]
Leafy vegetables (kg/yr)/(lb/yr)	14 / 31[i]	—[d]	—[d]	—[d]	—[d]
Fruits, vegetables, and grain (kg/yr)/(lb/yr)	160 / 352[i]	—[d]	—[d]	—[d]	—[d]
Depth of roots–grass (m)/(inches)	0.15 / 6[j]	0.15 / 6	—[d]	—[d]	—[d]
Depth of roots—fruits, vegetables, and grains (m)/(ft)	0.9 / 3[i]	—[d]	—[d]	—[d]	—[d]

Notes:

[a] The exposure duration and exposure frequency assumed are the typical values used for residential scenarios (EPA 1989, EPA 2002).

[b] Information in parenthesis indicates the exposure location, on a waste-rock pile or at a mine adit.

[c] The EPA-recommended value for residential time spent indoors is 16.4 hours per day (EPA 1997), rounded here to 16 hours per day. To obtain conservative estimates of the potential cancer risk, the remaining time was assumed to be spent outdoors in the contaminated area.

[d] "—" indicates the parameter is not applicable to the scenario under consideration.

[e] The recreational visitors were assumed to camp outdoors for 14 days; therefore, the outdoor exposure time was 24 hours per day.

[f] The reclamation workers were assumed to work 8 hours per day.

[g] Default value from CAP88-PC (Trinity Engineering Associates Inc. 2007). The corresponding daily inhalation rate of 21.9 m^3 is about the same as (1) the 95th percentile value recommended by EPA (2011a) for assessing long-term exposure of adults aged 20–60 and (2) the average value recommended by ICRP (1975) for a "reference man." For the reclamation worker, the risk from inhalation is mitigated by safety requirements that would be implemented.

[h] Value recommended by EPA (1989) for adults in residential settings. The recommended value for adults in occupational setting is 50 mg/day (EPA 1991). However, assuming reclamation activities would result in more contact with soils, the ingestion rate that was assumed for residents was used for reclamation workers as well. For recreational visitors, using the same ingestion rate provides a more conservative estimate of the potential risk. For the reclamation worker, the risk from ingestion is mitigated by safety requirements that would be implemented.

[i] RESRAD default values (Yu et al. 2001).

[j] Determined based empirical information and to provide conservative estimates.

Abbreviations:

gal/yr gallons per year
lb/yr pounds per year
m^3/yr meters cubed per year

3.4.1 Onsite Residents

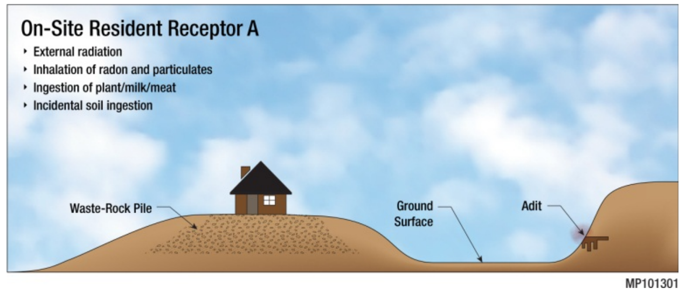


Figure 7. Onsite Resident Receptor A

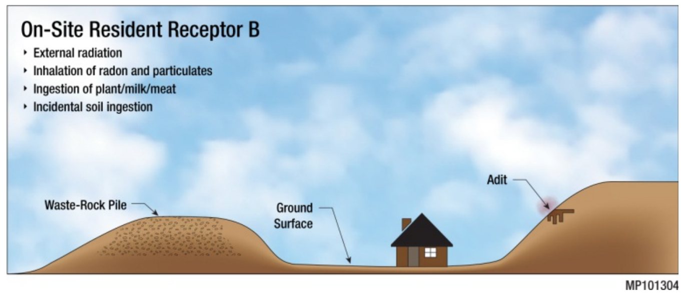


Figure 8. Onsite Resident Receptor B

Potential onsite residential use of a mine is most likely for mines on private and tribal land; this scenario would not apply to the majority of mines that are located on federal public lands. Two variations of the onsite resident scenario were analyzed in this report. These scenarios were selected for comparison purposes only for the generic CSMs. Other variations of an onsite residential scenario are possible. The first onsite resident receptor (Onsite Resident Receptor A, see Figure 7) lives on a house built on top of a waste-rock pile. The second onsite resident receptor (Onsite Resident Receptor B, see Figure 8) lives on an open area on the mine site and made use of waste-rock material to construct the house foundation. These residents grow crops and vegetables for their own consumption and graze cattle in the open area within the mine site for the meat and milk they consume. The pathways evaluated are external gamma radiation, inhalation of radon and particulates, incidental ingestion of soil, and ingestion of plant foods and meat/milk pathways. Note that inclusion of the plant foods and meat/milk ingestions pathways would overestimate potential risks for residents obtaining their food from other sources.

For estimating the potential cancer risks associated with the inhalation pathway, the onsite outdoor air concentrations of radionuclides and radon associated with the waste-rock pile and the contaminated ground surface source were calculated separately. Because the radon and airborne particulates could be blown from waste-rock pile area to the open area and vice versa, the larger of the calculated outdoor air concentrations (either from the waste-rock pile or the ground surface source) was used for potential risk estimation.

In addition to emanating to the outdoor environment, the radon gas generated from the waste-rock pile could diffuse into the house from the house foundation. For Onsite Resident Receptor A, the thickness of the waste rocks under the house was determined by the dimensions assumed for the waste-rock pile. For Onsite Resident Receptor B, the foundation constructed with waste rocks was assumed to have a thickness of 1 meter (m).

3.4.2 Offsite Residents

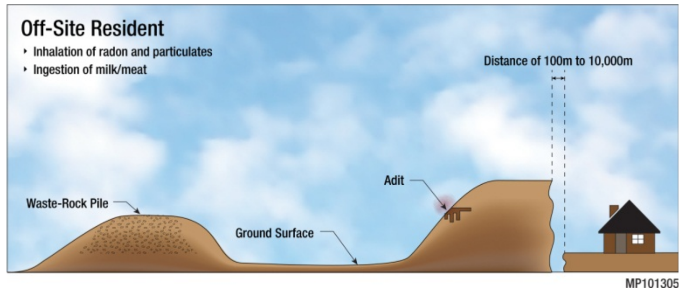


Figure 9. Offsite Resident

Residents who live outside the boundary of a mine site (see Figure 9) could be exposed to radiation as a result of radioactive particulates and radon gas emanating from above-ground radiation sources located within the mine site. Because waste-rock piles could be significantly larger sources of exposure than the other potential radiation sources at mine sites, the evaluation of potential radiological risks to offsite residents focused on airborne emissions from waste-rock piles. This is a potential scenario for any mine where residential use is permitted on adjacent lands. This analysis calculates exposures for distances ranging from 100 m to 10,000 m from a mine. Note that the closer distances are unlikely to apply for the vast majority of mines, particularly those located on federal public land. Based on the analysis discussed in Section 4.2.3 of this topic report, only a small percentage of mines are located within one-half mile of a roadway. The remoteness of many mines reduces the possibility that residences will be constructed nearby.

The airborne particulates containing radionuclides could be deposited to the ground surface along the wind path; the ground deposition could form a secondary radiation source and result in subsequent radiation exposures through direct external radiation, soil ingestion, and ingestion of plant/meat/milk pathways. Air dispersion modeling results obtained with CAP88-PC indicated that the exposure through the inhalation pathway accounted for more than 95 percent of the total exposure (through the inhalation and the subsequent pathways). The potential inhalation exposure an offsite resident incurred would depend on the relative direction and distance between the receptor and the representative waste-rock pile at a mine site. The maximum air concentration (over different sectors of direction) at each distance selected for evaluation from the waste-rock pile was obtained and used to estimate the potential cancer risk to an offsite resident.

As discussed in the previous paragraph, subsequent radiation exposures associated with the secondary ground source at offsite locations are relatively small compared with the exposures associated with the inhalation of radon and particulate pathways. Therefore, an exposure scenario that assumed an offsite resident owned livestock that grazed on the mine area, rather than at the offsite location, was considered. This offsite receptor was then assumed to consume the meat and milk produced by the livestock. It was considered unlikely that vegetation would thrive on bare waste-rock piles (i.e., waste-rock piles that are not covered with a top layer of cover material); even with cover material, the root systems of the vegetation would most likely be limited to the cover layer, resulting in little contamination of the vegetation. To evaluate potential risks associated with this scenario, it was assumed that livestock would graze in the open area of mine sites where ground surface was contaminated with residual radioactivity to a thickness of 1 cm. The assumptions made for the meat/milk ingestion pathway are highly conservative as it is unlikely that cattle would be confined to and graze exclusively on a mine site.

3.4.3 Recreational Visitors

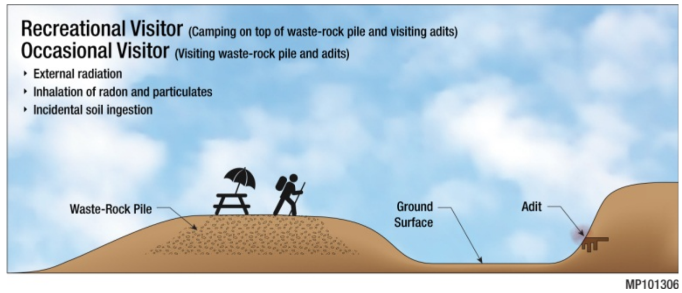


Figure 10. Recreational Visitor

A recreational visitor who entered a mine site could be exposed to radiation from contaminated ground surface and waste-rock piles. This recreational visitor was assumed to camp on top of a waste-rock pile for 2 weeks (see Figure 10). This scenario is used because the two major federal public land management agencies, BLM and USFS, allow dispersed camping in a single location for a maximum of 2 weeks before requiring campers to move camps. Exposures to radiation could be incurred through the external radiation, inhalation of radon and particulate, and ingestion of soil pathways.

Additional radon and external radiation exposure might be incurred by the recreational visitor if he spent some time at mine adits. The amount of time a recreational visitor would spend at these locations was considered to be much shorter than the 2 weeks he would spend camping at a mine site. To evaluate the additional exposures, an exposure time of 1 hour (over the 2-week camping period) was assumed. However, exposure durations longer than the 1 hour evaluated and for multiple occurrences could be possible. The estimates presented for this receptor in this report can be extrapolated to determine the risk for these other exposure durations and occurrences.

3.4.4 Occasional Visitors

In the evaluation, an occasional visitor was assumed to enter a mine site and spend 1 hour on top of waste-rock piles or 1 hour at a mine adit (see Figure 10). Similar to the recreational visitor, exposure durations longer than the 1 hour evaluated and for multiple occurrences could be possible. The estimates presented for this receptor in this report can be extrapolated to determine the risk for these other exposure durations and occurrences.

The exposures were considered to result mainly from external radiation and inhalation of radon and particulates. This scenario could occur at any mine where access is possible, regardless of land ownership.

3.4.5 Reclamation Workers

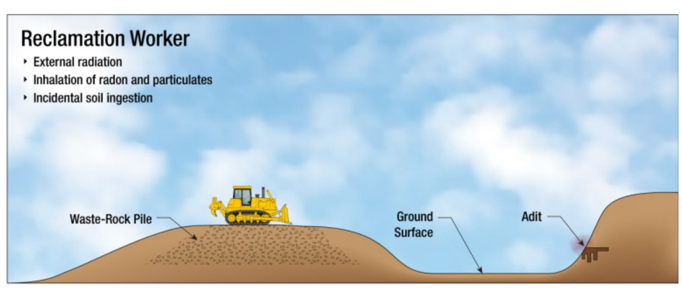


Figure 11. Reclamation Workers

For the purpose of this evaluation, it was assumed that reclamation would involve primarily grading and placing a layer of cover material on top of waste-rock piles and closing the mine adits. Therefore, the reclamation worker (see Figure 11) was assumed to incur radiation exposures primarily from working on or near a waste-rock pile. Potential radiation exposures could result from the following pathways: direct external radiation, inhalation of radon and particulates, and incidental ingestion of soil/dust particles.

Potential radiation exposures incurred from closing the mine adits were evaluated by considering that a worker would work 20 days at these locations. Although the number of days required for reclaiming a larger mine would be greater than that required for reclaiming a smaller mine, the potential dose/risk incurred by a reclamation worker would be proportional to the number of days of exposure; hence, the estimates presented can be used to derive an estimate for another assumption.

The potential risks associated with the external radiation and inhalation of radon pathways near a mine adit were estimated with the use of available gamma rate and radon level monitoring data at these locations. To calculate radiation exposure from the ingestion of soil/dust pathway associated with closing the mine adits, a concentration of 70 pCi/g for U-238 was assumed for the dust/soil ingested. Other associated radionuclides were assumed to be in secular equilibrium or at the natural activity ratio to U-238.

3.5 Risk Estimates for the Five Receptors

Risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to potential carcinogens (i.e., incremental or excess individual lifetime cancer risk). This approach is consistent with the risk assessment methodology provided by EPA in its risk assessment guidance (EPA 1989). The radionuclides evaluated for the uranium mines have the potential to cause cancer. The slope factors (see Table 5) convert estimated daily intakes (of the nuclides) averaged over a lifetime of exposure directly to incremental risk of an individual developing cancer. EPA considers an incremental or excess individual lifetime cancer risk of 10^{-6} to 10^{-4} as acceptable for CERCLA cleanups. This risk range is used in this report for perspective.

Table 5. Slope Factors for Uranium Isotopes and Their Decay Products

Pathway	U-238+D[a]	U-234	Th-230	Ra-226+D[a]	Pb-210+D[a]	U-235+D[a]	Pa-231	Ac-227+D[a]
External radiation [(1/yr)/(pCi/g)][b,c]	1.14E-07	2.52E-10	8.19E-10	8.49E-06	4.21E-09	5.43E-07	1.39E-07	1.47E-06
Inhalation (1/pCi)[c]	2.36E-08	2.78E-08	3.40E-08	2.83E-08	3.08E-08	2.50E-08	7.62E-08	2.13E-07
Ingestion (1/pCi)[c]	1.21E-10	9.55E-11	1.19E-10	5.15E-10	3.44E-09	9.76E-11	2.26E-10	6.53E-10

[a] "+D" indicates that the slope factor listed includes contributions from short-lived progenies that have a radioactive decay half-life of less than 180 days. These short-lived progenies were assumed to be in secular equilibrium with the parent nuclide.

[b] The external radiation slope factors listed are for a radiation source of infinite dimensions. The RESRAD code adjusts the listed slope factors for the finite dimensions of a radiation source according to the input specifications, then uses the adjusted slope factors for cancer risk estimation.

[c] The slope factors for individual radionuclides are from Federal Guidance Report No. 13 (Eckerman et al. 1999) for cancer morbidity risks. For radionuclides with a "+D" suffix, the slope factors listed were calculated by adding slope factors of short-lived progenies to that of the parent radionuclide, adding a level of conservatism in calculating risk.

To estimate the radiation exposures and associated potential cancer risks for the five receptors from the waste-rock piles and potential contaminated surface areas for the various pathways discussed in Section 3.4, the RESRAD computer code was used. The RESRAD code (Yu et al 2007) was used to evaluate the external radiation, inhalation of particulates, inhalation of radon, ingestion of soil, and ingestion of plant/meat/milk pathways considered for the onsite receptors in this evaluation. The code incorporates slope factors (see Table 5) obtained from Federal Guidance Report No. 13 (Eckerman et al. 1999) to convert estimated exposure to risks.

For exposure to mine adits, the potential risk to onsite receptors (i.e., Onsite Resident Receptors A and B, recreational and occasional visitors, and the reclamation worker) were estimated using gamma rate and radon data collected by DOE from several mine sites representative of the five production-size categories evaluated in this report. These measured data were converted to cancer risks with appropriate (exposure-to-risk) conversion factors (see discussion in Section 3.5.1).

For the offsite resident, the RESRAD code was used to calculate the emission rates of radon from waste-rock piles. The conversion factors discussed in Section 3.5.1 were also used (as was done for the onsite receptors). The values obtained were then used as input to the CAP88-PC model (Trinity Engineering Associates Inc. 2007) to obtain air concentrations of radionuclides and radon levels at the offsite locations.

Emission of radon from waste-rock piles could be reduced by adding a cover layer. Particulate emissions from waste-rock piles could be eliminated completely if the cover materials would prevent the waste rocks from being exposed to suspension at the surface. To evaluate the effectiveness of covering waste-rock piles, two cover thicknesses, 6 inches (0.15 m) and 12 inches (0.3 m), were assumed in the evaluation.

CAP88-PC (Trinity Engineering Associates Inc. 2007) was designed specifically for evaluating airborne emissions of radionuclides and radon. It is supported and maintained by EPA and was granted prior approval for use to demonstrate compliance with the national standards for emissions of radionuclides other than radon from DOE facilities (Title 40 *Code of Federal Regulations* Part 61 [40 CFR 50], Subpart H). Because of its capability to evaluate area sources and to maintain consistency in the evaluation methodology, the CAP88-PC was also used to evaluate radon emissions. The use of CAP88-PC to calculate the air concentrations of radionuclides and radon levels at offsite locations are detailed in Appendix A.

Section 3.5.1 below provides a discussion of the conversion factors utilized for this evaluation. Sections 3.5.2 to 3.5.6 detail risk-estimation results obtained for each of the five receptors. Section 3.5.7 presents a comparison of risk results estimated for the external radiation pathway for this report. External radiation risk can be determined two ways: either by using radionuclide concentrations to calculate them (as done in this evaluation using the RESRAD code with assumed concentrations for the nuclides for the waste-rock piles and the potentially contaminated ground surface) or by using gamma rate measurement data (collected by DOE for the mines in this case).

3.5.1 Conversion Factors

Potential exposures to radionuclides were converted to cancer risk estimates with the use of the slope factors obtained from Federal Guidance Report No. 13 (Eckerman et al. 1999). Table 5 lists the slope factors used in this evaluation.

Radon concentration is usually expressed in terms of working level (WL), which is a measure of the release of radiation (or alpha energy) by radon decay. The radon exposures are quantified in terms of working-level months (WLMs). One WLM is equivalent to an exposure of 170 hours to a concentration of radon of 1 WL. The ICRP (2011) indicates that, on the basis of the pooled results from studies of radon-exposed miners, a lifetime excess risk of 5×10^{-4} per WLM should be used for estimating radon-induced lung cancer incidence.

When estimating cancer risks using gamma rate monitoring data, the gamma rate data reported in μR/h were converted to effective external dose rates by multiplying by a factor of 0.0007 (for 0.001 millirem per microrem [mrem/μrem] and 0.7 rem per roentgen [rem/R]). The effective external dose rates were then multiplied by a dose-to-risk conversion factor of 1.16×10^{-6} per mrem (EPA 2011b). This dose-to-risk conversion factor was used because information on the radionuclides responsible for the gamma radiation and the concentrations associated with the radionuclides could not be inferred from the monitoring data. Therefore, the nuclide-specific slope factors could not be applied to estimate the corresponding cancer risks.

3.5.2 Risk Estimates for the Onsite Resident

For Onsite Resident Receptor A (with a house built on top of a waste-rock pile), the potential estimated radiological risks are presented in Table 6. The inhalation of indoor radon is the dominant pathway, resulting in a cancer risk estimate ranging from 8×10^{-2} to 1×10^{-1} for the Small to Large production-size categories. Assuming a cover layer is added to the top of the waste-rock pile before the house is constructed, the risk estimates range from 7×10^{-2} to 8×10^{-2} for a cover thickness of 0.15 m (6 inches) and from 5×10^{-2} to 7×10^{-2} for a cover thickness of 0.3 m (12 inches).

The next most dominant pathway (after inhalation of radon) is external radiation, which could be effectively reduced by placing a cover layer on the waste-rock piles. The estimated risk associated with the external radiation pathway could be reduced from 1×10^{-2} to 2×10^{-3} with a cover thickness of 0.15 m (6 inches), and from 1×10^{-2} to 4×10^{-4} with a cover thickness of 0.3 m (12 inches) at a Small mine site. At a Large mine site, the estimated cancer risk could be reduced from 1×10^{-2} to about the same estimates as given for the Small mine site above.

Potential cancer risk estimates from the ingestion pathways (plant, meat, milk, and soil) are lower than the indoor radon and external radiation pathways (i.e., at less than 2×10^{-4}).

Table 7 presents the estimates for Onsite Resident Receptor B. Excluding the contribution associated with inhalation of indoor radon, the external radiation pathway contributes to more than 95 percent and 85 percent of the total cancer risk for Onsite Resident Receptor B at a Small and Large category mine site, respectively. Without a layer of cover material on top of the waste rock used for the house foundation, the total cancer risk (without indoor radon) was estimated to range from 2×10^{-3} at a Small mine site to 4×10^{-3} at a Large mine site. The addition of a cover would reduce the potential radiation exposure only slightly (i.e., too small to be noted with the rounding of results shown in Table 7).

Radon accumulation inside the house for the Onsite Resident Receptor B would be less than that for Onsite Resident Receptor A with the assumption that the waste-rock material used for the Receptor B house foundation is about 1 m thick (as opposed to a larger thickness associated with a house constructed right on top of waste rock, as is assumed for Onsite Resident Receptor A). Radon gas generated from the waste-rock foundation and diffusing into the house could result in an indoor radon level as high as 0.21 WL. For comparison, the radon level in the active working area of an underground uranium mine is not to exceed 0.3 WL (30 CFR Part 57). The estimated risk (for the indoor-radon inhalation pathway) for the Onsite Resident Receptor B is 9×10^{-2}. This estimate was based on a Ra-226 and U-238 concentration of 70 pCi/g in the waste rock.

Table 6. Risk Estimates for Onsite Resident Receptor A (House Built on Top of Waste-Rock Pile) at the Five Mine Production-Size Categories

Exposure Pathway	Cancer Risk				
	Small	Small/Medium	Medium	Medium/Large	Large
Without Cover Layer					
External radiation[a]	1E-02	1E-02	1E-02	1E-02	1E-02
Inhalation[b]	3E-05	4E-05	6E-05	1E-04	2E-04
Ingestion of plant[c]	2E-05	3E-05	7E-05	1E-04	1E-04
Ingestion of meat[c]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[c]	2E-07	4E-07	1E-06	6E-06	2E-05
Ingestion of soil[c]	3E-06	6E-06	1E-05	2E-05	2E-05
Inhalation (indoor radon)[d]	8E-02	9E-02	9E-02	9E-02	1E-01
Total	**9E-02**	**1E-01**	**1E-01**	**1E-01**	**1E-01**
With 6-inch cover on waste-rock piles					
External radiation[a]	2E-03	2E-03	2E-03	2E-03	2E-03
Inhalation[b]	1E-05	2E-05	3E-05	8-05	2E-04
Ingestion of plant[c]	2E-05	3E-05	7E-05	1E-04	1E-04
Ingestion of meat[c]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[c]	2E-07	4E-07	1E-06	6E-06	2E-05
Ingestion of soil[c]	3E-06	6E-06	1E-05	2E-05	2E-05
Inhalation (indoor radon)[d]	8E-02	9E-02	9E-02	9E-02	1E-01
Total	**8E-02**	**9E-02**	**1E-01**	**1E-01**	**1E-01**
With 12-inch cover on waste-rock piles					
External radiation[a]	4E-04	4E-04	4E-04	4E-04	4E-04
Inhalation[b]	1E-05	2E-05	3E-05	7E-05	2E-04
Ingestion of plant[c]	2E-05	3E-05	7E-05	1E-04	1E-04
Ingestion of meat[c]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[c]	2E-07	4E-07	1E-06	6E-06	2E-05
Ingestion of soil[c]	3E-06	6E-06	1E-05	2E-05	2E-05
Inhalation (indoor radon)[d]	8E-02	9E-02	9E-02	9E-02	1E-01
Total	**8E-02**	**9E-02**	**9E-02**	**9E-02**	**1E-01**

[a] The cancer risks listed for the external radiation pathway are associated with waste-rock piles.
[b] The cancer risks listed for the inhalation pathway considered inhalation of radon and particulates emitted from waste-rock piles as well as from contaminated ground surface. The values listed are the bounding values.
[c] The cancer risks listed for the ingestion pathway are associated with ground surface contamination.
[d] The cancer risks listed for the inhalation of indoor-radon pathway are associated with waste-rock piles, assuming the onsite residence was constructed on a waste-rock pile such that the bottom of the house would contact the top of the waste rocks.

Table 7. Risk Estimates for the Onsite Resident Receptor B (Waste-Rock Material for House Foundation, with House Located in an Open Area) at the Five Mine Production-Size Categories

Exposure Pathway	**Estimated Risk**[a]				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
With No Cover on Waste-Rock Pile					
External radiation[a]	2E-03	2E-03	3E-03	3E-03	4E-03
Inhalation[b]	3E-05	4E-05	6E-05	1E-04	2E-04
Ingestion of plant[a]	2E-05	3E-05	7E-05	1E-04	1E-04
Ingestion of meat[a]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[a]	2E-07	4E-07	1E-06	6E-06	2E-05
Ingestion of soil[a]	3E-06	6E-06	1E-05	2E-05	2E-05
Inhalation (indoor radon)[c]	9E-02	9E-02	9E-02	9E-02	9E-02
Total (without indoor radon)	**2E-03**	**2E-03**	**3E-03**	**3E-03**	**4E-03**
Total (with indoor radon)	**9E-02**	**9E-02**	**9E-02**	**9E-02**	**9E-02**
With 6-inch cover on waste-rock piles					
External radiation[a]	2E-03	2E-03	3E-03	3E-03	4E-03
Inhalation[b]	1E-05	2E-05	3E-05	8-05	2E-04
Ingestion of plant[a]	2E-05	3E-05	7E-05	1E-04	1E-04
Ingestion of meat[a]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[a]	2E-07	4E-07	1E-06	6E-06	2E-05
Ingestion of soil[a]	3E-06	6E-06	1E-05	2E-05	2E-05
Inhalation (indoor radon)[c]	9E-02	9E-02	9E-02	9E-02	9E-02
Total (without indoor radon)	**2E-03**	**2E-03**	**3E-03**	**3E-03**	**4E-03**
Total (with indoor radon)	**9E-02**	**9E-02**	**9E-02**	**9E-02**	**9E-02**
With 12-inch cover on waste-rock piles					
External radiation[a]	2E-03	2E-03	3E-03	3E-03	4E-03
Inhalation[b]	1E-05	2E-05	3E-05	7E-05	2E-04
Ingestion of plant[a]	2E-05	3E-05	7E-05	1E-04	1E-04
Ingestion of meat[a]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[a]	2E-07	4E-07	1E-06	6E-06	2E-05
Ingestion of soil[a]	3E-06	6E-06	1E-05	2E-05	2E-05
Inhalation (indoor radon)[c]	9E-02	9E-02	9E-02	9E-02	9E-02
Total (without indoor radon)	**2E-03**	**2E-03**	**3E-03**	**3E-03**	**4.-03**
Total (with indoor radon)	**9E-02**	**9E-02**	**9E-02**	**9E-02**	**9E-02**

[a] The risk estimates are the same with or without cover material on top of the waste-rock piles. Risk estimates for the external radiation and ingestion pathways are associated with ground surface contamination.
[b] The cancer risks listed for the inhalation pathway considered inhalation of radon and particulates emitted from waste-rock piles as well as from contaminated ground surface. The values listed are the bounding values.
[c] The cancer risks listed for the inhalation of indoor-radon pathway are associated with waste rocks, which were assumed in the modeling to be used as the foundation materials.

3.5.3 Risk Estimates for the Offsite Resident

Table 8 through Table 10 summarize the estimated maximum cancer risks to the offsite receptors at different downwind locations contributed by particulate emissions, radon emissions, and combined particulate and radon emissions. The estimated emissions are from the representative waste-rock piles considered for mine sites in different production-size categories. The maximum cancer risks were determined after analyzing the calculated results obtained with 134 sets of wind data from the selected weather stations located in the 19 states identified as having mines. The state-specific cancer risk results for the six states with the most mines are provided in Appendix A. These six states are Arizona, Colorado, New Mexico, South Dakota, Utah, and Wyoming.

The potential radiation exposures for the offsite resident due to particulate and radon emissions from waste-rock piles vary with the locations of the mine sites. However, no matter where the mine sites are located, on the basis of the estimates in Table 8 through Table 10, the maximum cancer risk incurred by an offsite resident living outside a mine site ranges from 10^{-8} to 10^{-5} (without a cover layer on the waste-rock pile; for Small to Large mines; at a distance of about 1,500 m or about a mile). All risk estimates (including scenarios that assumed no cover for the waste piles) are below 10^{-4} which is the upper end of EPA's acceptable risk range. These results are consistent with those discussed in the EPA 1983 Report to Congress (EPA 1983). It is stated in that report that the maximally exposed individual from inhalation of radon would incur a risk of about 10^{-7}.

The potential cancer risks associated with particulate emissions can be reduced or even eliminated by covering the surfaces of waste-rock piles with a cover layer to prevent the waste rocks from being exposed to wind erosion. Although radon emissions cannot be eliminated completely, they are likely reduced slightly by the addition of a cover layer. On the basis of the estimates, a cover thickness of 6 inches (0.15 m) would reduce the cancer risk to an offsite receptor by about 60 percent at a distance of 100 m and by about 80 percent at a distance of 10,000 m. Increasing the thickness to 12 inches (0.3 m) would reduce the cancer risk by another 5–8 percent at a distance of 100 m and by another 7–10 percent at a distance of 10,000 m.

In addition to exposures through the inhalation pathway, an offsite resident in the vicinity of a mine site could incur radiation exposure through the meat and milk ingestion pathways, if he raised livestock within the mine site. Table 11 presents the risk estimates associated with these two exposure pathways. On the basis of the estimates, the estimated maximum risk from these two pathways would range from 6×10^{-7} to 6×10^{-5} for mines ranging in size from Small to Large. The radiological risk would be greater for a larger mine site because the area of surface contamination was assumed to be larger, resulting in a higher probability that contaminated meat/milk would be produced. However, as noted previously, these risks are probably an overestimation due to the fact that most livestock would not be confined to and graze exclusively on a mine site.

Table 11 presents the estimated total risk to the offsite resident receptor (summing all pathways evaluated). The estimated total risk ranges from less than 1×10^{-5} to less than 1×10^{-4} for mines ranging in size from Small to Large. With the addition of a top layer of cover material, a slight reduction in the estimated risk was observed, and more so for the smaller production-size categories. The potential risk reduction for the larger production-size categories are not discernible with the estimates presented in Table 11, as rounding to one significant figure (as typically recommended for presentation of risk results) was done for the presentation of estimates in the table. Note that the inhalation risks presented in this table are for a 100 m distance, which is not plausible for the vast majority of mines due to their remoteness.

3.5.4 Risk Estimates for the Recreational Visitor

Table 12 presents the risk estimates for the recreational visitor. The radiation exposure incurred by the recreational visitor would result primarily from external radiation, which could be effectively reduced by adding a layer of cover material on top of the waste-rock pile. Figure 12 illustrates the estimated reduction in potential risk with and without a layer of cover.

The recreational visitor could also be exposed to radiation at the mine adits. Table 13 presents a compilation of radon measurements collected for the project by DOE from adits at several mine sites. These measurements were used to derive risk estimates for the inhalation of radon pathway (risk estimates per hour of exposure are also shown in Table 13). Radon data collected from mine sites with openings that have not been sealed appear to result in a risk of about 10^{-5}, with data for mine sites with sealed openings resulting in risk estimates at one to two orders of magnitude lower (i.e., at 10^{-6} to 10^{-7}). However, it should be recognized that, compared to the concentrations used for the estimates presented in this report, the radon concentrations at the mines could vary from site-to-site and could even vary at different times at a particular mine.

Table 13 also presents gamma rate measurements collected by DOE at the adits at mines visited. These measurements were converted to external radiation dose rates by multiplying by 0.0007. The gamma rates measured at unreclaimed mine sites range from 11.2 to 730 µR/h, which convert to external dose rates of 0.0078 to 0.51 mrem/h. Using a dose-to-risk conversion factor of 1.16×10^{-6}/mrem (EPA 2011b), the corresponding cancer risks range from 9×10^{-9} to 6×10^{-7} per hour of exposure.

The measured gamma rates at reclaimed mine sites ranged from 7 to 400 µR/h, which were converted to external dose rates ranging from 0.0049 to 0.28 mrem/h and cancer risks ranging from 6×10^{-9} to 3×10^{-7} per hour of exposure.

The estimates presented in this report would increase proportionally with increased exposure duration for any of the receptors evaluated. For example, if the recreational visitor evaluated here were to camp on top of the same small waste-rock pile (with 12-inch cover material) for two weeks each time on ten different visits, then the estimated risk for that receptor would be 6×10^{-6} (or 10 times the estimate of 6×10^{-7} shown in Table 12).

3.5.5 Risk Estimates for the Occasional Visitor

For occasional visitors to a mine site, the potential radiation exposures were considered to result mainly from the external radiation and the inhalation of radon and particulate pathways. The potential exposure was to be incurred by spending one hour on top of a waste-rock pile or near the mine adits. The estimates for cancer risks at mine adits (Table 14) were obtained by using radon and gamma rate measurements shown in Table 13. Radon data collected from mine sites that have not been reclaimed appear to result in a risk of about 10^{-5}, with those for reclaimed mine sites one to two orders of magnitude lower. Estimated risk for the occasional visitor, based on the maximum gamma measurements, ranges from 2×10^{-7} to 6×10^{-7}.

3.5.6 Risk Estimates for the Reclamation Worker

Table 15 lists the estimated cancer risk for a reclamation worker. The potential cancer risk (from working on top of the waste rock piles) would result primarily from the external radiation pathway. For the work of reclaiming waste-rock piles, the total cancer risk estimates range from 9×10^{-6} to 1×10^{-5} for mines ranging in size from Small to Large.

In addition to working on top of waste-rock piles, a reclamation worker might also work to close mine adits. To evaluate the potential risk associated with these closure activities, the worker was assumed to also work 20 days at these locations. Table 15 presents the estimated risk. The estimates for the inhalation of radon and external radiation pathways were estimated with the maximum radon level and gamma rate measurement data taken by DOE at mine adits at mines for the various production size categories. Based on estimates shown in Table 15, the total estimated cancer risk for a reclamation worker from working near mine openings for 20 days was estimated to range from 2×10^{-4} to 6×10^{-3}. As the reclamation proceeded, the mine openings would be gradually reduced in size, and so would the radon level. However, this evaluation did not account for improvement of conditions as closure activity progressed or the safety precautions the workers are required to observe in accordance with regulatory requirements. The actual risk for the worker is expected to be less than the estimates presented in Table 15.

3.5.7 Comparison of External Radiation Risk Estimates with Gamma Rate Measurements

For the two assumed above-ground sources (i.e., waste-rock piles and contaminated ground surfaces), the external dose rates calculated using the RESRAD code were compared with those indicated by gamma rate measurement data taken by DOE at representative mine sites in the five production-size categories. Table 16 shows the comparison of these two methods. The table shows the calculation results, in mrem/h, for waste-rock piles for the five production-size categories, for the external radiation pathway for 1-hour exposure of an occasional visitor (see Table A-7 in Appendix A). The calculated external dose rates for “not reclaimed” mines in Table 16 are the results before reclamation in Table A-7, while the calculated external dose rates for “reclaimed” mines in Table 16 are the results after reclamation with 6 inches of cover materials on waste-rock piles in Table A-7. The calculation results for contaminated ground surfaces in mines of different production-size categories were obtained by dividing the external radiation pathway results listed in Table A-4 of Appendix A by a factor of 6,720. Table A-4 concerns radiation doses to onsite residents living in the open area for one year. The dose results associated with the external radiation pathway were estimated by assuming that 350 days per year were spent at mine sites—8 hours per day outdoors and 16 hours per day indoors—and that the structures of the residence attenuated the external radiation from the contaminated ground surface, so that the external radiation level indoors was 70 percent of the outdoor level.

On the basis of these assumptions, the effective exposure hours to the residual ground source would be $6{,}720 = 350 \times (8 + [16 \times 0.7])$. Therefore, the dose results associated with the external radiation pathway, as listed in Table A-4, need to be divided by 6,720 to obtain the outdoor external dose rates in terms of mrem/h.

As shown in Table 16, the calculated external dose rates for waste-rock piles and contaminated ground surfaces for the five production-size categories are within the minimum-to-maximum range of external dose rates indicated by the gamma rate data measured by DOE.

3.6 Summary

Table 17 summarizes risks for all scenarios based on the assumed sources of contamination evaluated as depicted in the conceptual site model in Figure 6. The presence of other sources of exposure could increase the risk estimates, just as the absence of sources could decrease the estimates. Based on the conceptual site model evaluated, only the onsite resident and reclamation worker scenarios exceed EPA's acceptable risk range. The estimates for the five receptors indicate that the inhalation of radon pathway is the primary contributor to the potential risk at mines. Inhalation of radon for the Onsite Resident Receptors (A and B) is due primarily to the radon diffusing up into the house, either (1) from the waste-rock pile that the house for Onsite Receptor A is assumed to be located on, or (B) from the waste-rock material assumed to be used for the house foundation for Onsite Receptor B. For the offsite resident receptor, the inhalation-of-radon pathway is also due to nuclides (Ra-226) in the waste-rock pile. The recreational visitor, occasional visitor, and the reclamation worker would be exposed to radon primarily from the radon present in mine adits. The radon data collected by DOE for several mines did not indicate an increasing trend with larger mine size (see Table 13).

The risk estimates for the inhalation-of-radon pathway for the resident scenarios are influenced by the Ra-226 concentrations that could be in the waste-rock piles. And as indicated in the estimates discussed in Section 3.5, the addition of a cover layer before construction of the residence does not effectively reduce the potential risk from radon.

For the offsite resident, risk estimates indicate that potential risk decreases with distance (i.e., the farther away from the mine location, the less the potential risk). The presence of a cover layer of 6-inch thickness is effective in reducing the potential risk, although the long-term effectiveness of this or a thicker layer of cover could require periodic inspection and maintenance of the site.

The estimates presented in this report are based on the assumption of a 70 pCi/g uranium and Ra-226 concentration in the waste-rock piles at the mines. The actual concentrations could vary. However, the risk estimates presented here could be used to scale proportionally to determine the potential risk for concentrations other than those assumed here.

Table 8. Maximum Risk Estimates for the Offsite Resident from Particulate Emissions from Representative Waste-Rock Piles at Mines of the Five Production-Size Categories

Distance (m)	Small Mines			Small/Medium Mines			Medium Mines			Medium/Large Mines			Large Mines		
	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover
100	4E-06	0	0	7E-06	0	0	5E-06	0	0	1E-05	0	0	3E-05	0	0
200	1E-06	0	0	2E-06	0	0	3E-06	0	0	7E-06	0	0	2E-05	0	0
300	5E-07	0	0	9E-07	0	0	2E-06	0	0	5E-06	0	0	2E-05	0	0
400	3E-07	0	0	5E-07	0	0	1E-06	0	0	4E-06	0	0	1E-05	0	0
500	2E-07	0	0	3E-07	0	0	7E-07	0	0	3E-06	0	0	1E-05	0	0
750	9E-08	0	0	2E-07	0	0	4E-07	0	0	2E-06	0	0	7E-06	0	0
1,000	5E-08	0	0	9E-08	0	0	2E-07	0	0	1E-06	0	0	5E-06	0	0
1,500	3E-08	0	0	5E-08	0	0	1E-07	0	0	6E-07	0	0	3E-06	0	0
2,000	2E-08	0	0	3E-08	0	0	7E-08	0	0	4E-07	0	0	2E-06	0	0
3,000	8E-09	0	0	1E-08	0	0	3E-08	0	0	2E-07	0	0	8E-07	0	0
5,000	4E-09	0	0	6E-09	0	0	2E-08	0	0	9E-08	0	0	4E-07	0	0
7,500	2E-09	0	0	3E-09	0	0	8E-09	0	0	5E-08	0	0	2E-07	0	0
10,000	1E-09	0	0	2E-09	0	0	5E-09	0	0	3E-08	0	0	1E-07	0	0

Table 9. Maximum Risk Estimates for the Offsite Resident from Radon Emissions from Representative Waste-Rock Piles at Mines for the Five Production-Size Categories

Distance (m)	Small Mines			Small/Medium Mines			Medium Mines			Medium/Large Mines			Large Mines		
	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover
100	7E-06	6E-06	6E-06	2E-05	1E-05	1E-05	7E-06	6E-06	5E-06	2E-05	2E-05	2E-05	7E-05	6E-05	5E-05
200	2E-06	2E-06	2E-06	5E-06	4E-06	4E-06	7E-06	6E-06	5E-06	1E-05	9E-06	8E-06	4E-05	3E-05	3E-05
300	1E-06	9E-07	8E-07	2E-06	2E-06	2E-06	5E-06	4E-06	4E-06	9E-06	8E-06	7E-06	3E-05	3E-05	2E-05
400	6E-07	5E-07	5E-07	1E-06	1E-06	1E-06	3E-06	3E-06	2E-06	1E-05	8E-06	7E-06	3E-05	3E-05	2E-05
500	4E-07	4E-07	3E-07	1E-06	9E-07	8E-07	2E-06	2E-06	2E-06	9E-06	7E-06	6E-06	3E-05	3E-05	2E-05
750	2E-07	2E-07	2E-07	5E-07	4E-07	4E-07	1E-06	1E-06	9E-07	6E-06	5E-06	4E-06	2E-05	2E-05	2E-05
1,000	1E-07	1E-07	9E-08	3E-07	3E-07	2E-07	8E-07	7E-07	6E-07	4E-06	3E-06	3E-06	2E-05	1E-05	1E-05
1,500	6E-08	6E-08	5E-08	2E-07	1E-07	1E-07	4E-07	4E-07	3E-07	2E-06	2E-06	2E-06	1E-05	8E-06	7E-06
2,000	4E-08	4E-08	3E-08	1E-07	9E-08	8E-08	3E-07	3E-07	2E-07	2E-06	1E-06	1E-06	7E-06	6E-06	5E-06
3,000	2E-08	2E-08	2E-08	6E-08	5E-08	5E-08	2E-07	1E-07	1E-07	9E-07	8E-07	7E-07	4E-06	3E-06	3E-06
5,000	1E-08	1E-08	1E-08	3E-08	3E-08	3E-08	1E-07	8E-08	7E-08	5E-07	5E-07	4E-07	2E-06	2E-06	2E-06
7,500	9E-09	8E-09	7E-09	2E-08	2E-08	2E-08	6E-08	5E-08	5E-08	4E-07	3E-07	3E-07	2E-06	1E-06	1E-06
10,000	6E-09	6E-09	5E-09	2E-08	1E-08	1E-08	5E-08	4E-08	3E-08	3E-07	2E-07	2E-07	1E-06	1E-06	8E-07

Table 10. Maximum Risk Estimates for the Offsite Resident from Combined Particulate and Radon Emissions from Representative Waste-Rock Piles at Mines for Five Production-Size Categories

Distance (m)	Small Mines			Small/Medium Mines			Medium Mines			Medium/Large Mines			Large Mines		
	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover	Without Cover	With 6-inch Cover	With 12-inch Cover
100	1E-05	6E-06	6E-06	2E-05	1E-05	1E-05	9E-06	6E-06	5E-06	2E-05	2E-05	2E-05	8E-05	6E-05	5E-05
200	3E-06	2E-06	2E-06	6E-06	4E-06	4E-06	8E-06	6E-06	5E-06	1E-05	9E-06	8E-06	4E-05	3E-05	3E-05
300	1E-06	9E-07	8E-07	3E-06	2E-06	2E-06	6E-06	4E-06	4E-06	1E-05	8E-06	7E-06	4E-05	3E-05	2E-05
400	8E-07	5E-07	5E-07	2E-06	1E-06	1E-06	4E-06	3E-06	2E-06	1E-05	8E-06	7E-06	4E-05	3E-05	2E-05
500	5E-07	4E-07	3E-07	1E-06	9E-07	8E-07	3E-06	2E-06	2E-06	1E-05	7E-06	6E-06	4E-05	3E-05	2E-05
750	2E-07	2E-07	2E-07	6E-07	4E-07	4E-07	2E-06	1E-06	9E-07	7E-06	5E-06	4E-06	3E-05	2E-05	2E-05
1,000	1E-07	1E-07	9E-08	3E-07	3E-07	2E-07	9E-07	7E-07	6E-07	5E-06	3E-06	3E-06	2E-05	1E-05	1E-05
1,500	8E-08	6E-08	5E-08	2E-07	1E-07	1E-07	5E-07	4E-07	3E-07	3E-06	2E-06	2E-06	1E-05	8E-06	7E-06
2,000	5E-08	4E-08	3E-08	1E-07	9E-08	8E-08	3E-07	3E-07	2E-07	2E-06	1E-06	1E-06	8E-06	6E-06	5E-06
3,000	3E-08	2E-08	2E-08	7E-08	5E-08	5E-08	2E-07	1E-07	1E-07	1E-06	8E-07	7E-07	4E-06	3E-06	3E-06
5,000	2E-08	1E-08	1E-08	4E-08	3E-08	3E-08	1E-07	8E-08	7E-08	6E-07	5E-07	4E-07	3E-06	2E-06	2E-06
7,500	1E-08	8E-09	7E-09	2E-08	2E-08	2E-08	7E-08	5E-08	5E-08	4E-07	3E-07	3E-07	2E-06	1E-06	1E-06
10,000	7E-09	6E-09	5E-09	2E-08	1E-08	1E-08	5E-08	4E-08	3E-08	3E-07	2E-07	2E-07	1E-06	1E-06	8E-07

Table 11. Risk Estimates for an Offsite Resident in the Vicinity of Mines of the Five Production-Size Categories When Livestock Are Grazed on the Mine Site

Exposure Pathway	**Risk Estimate**				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Without Cover					
Inhalation[a]	< 1E-05	< 2E-05	< 9E-06	< 2E-05	< 8E-05
Ingestion of meat[b]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[b]	3E-07	4E-07	1E-06	6E-06	3E-05
Total	**< 1E-05**	**< 2E-05**	**< 1E-05**	**< 4E-05**	**< 1E-04**
With 6 inch cover on waste-rock piles					
Inhalation[a]	< 7E-06	< 1E-05	< 6E-06	< 2E-05	< 6E-05
Ingestion of meat[b]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[b]	3E-07	4E-07	1E-06	6E-06	3E-05
Total	**< 7E-06**	**< 2E-05**	**< 9E-06**	**< 3E-05**	**< 1E-04**
With 12 inch cover on waste-rock piles					
Inhalation[a]	< 6E-06	< 1E-05	< 5E-06	< 2E-05	< 5E-05
Ingestion of meat[b]	3E-07	6E-07	1E-06	8E-06	3E-05
Ingestion of milk[b]	3E-07	4E-07	1E-06	6E-06	3E-05
Total	**< 6E-06**	**< 1E-05**	**< 8E-06**	**< 3E-05**	**< 1E-04**

[a] The cancer risks listed for the inhalation pathway include contributions from both inhalation of radon and inhalation of particulates, which are associated with waste-rock piles. The listed values are the maximums of the results over all the exposure distances and locations of mine sites considered in the evaluation.
[b] The cancer risks listed for the ingestion pathways are associated with ground-surface contamination.

Table 12. Risk Estimates for a Recreational Visitor at Mines of the Five Production-Size Categories

Exposure Pathway	Risk Estimate				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Waste-rock piles with no cover material					
External radiation[a]	2E-05	2E-05	2E-05	2E-05	2E-05
Inhalation[a,b]	6E-08	8E-08	1E-07	3E-07	5E-07
Ingestion of soil[a]	4E-08	7E-08	2E-07	4E-07	4E-07
Total	**2E-05**	**2E-05**	**2E-05**	**2E-05**	**2E-05**
Waste-rock piles with 6 inch cover material					
External radiation[a]	4E-06	4E-06	4E-06	4E-06	4E-06
Inhalation[a,b]	2E-08	4E-08	7E-08	2E-07	4E-07
Ingestion of soil[a]	0	0	0	0	0
Total	**4E-06**	**4E-06**	**4E-06**	**4E-06**	**6E-06**
Waste-rock piles with 12 inch cover material					
External radiation[a]	6E-07	6E-07	6E-07	6E-07	6E-07
Inhalation[a,b]	2E-08	3E-08	6E-08	2E-07	3E-07
Ingestion of soil[a]	0	0	0	0	0
Total	**6E-07**	**6E-07**	**6E-07**	**6E-07**	**6E-07**
Mine adit before closure					
External radiation[c]	2E-07	3E-07	3E-07	2E-07	6E-07
Inhalation of radon[c]	4E-05	1E-05	2E-05	2E-05[d]	1E-06
Total	**4E-05**	**1E-05**	**2E-05**	**2E-05**	**2E-06**

[a] The estimated cancer risks are based on an exposure of 14 days, i.e., 336 hours, and are associated with waste-rock piles.
[b] The estimated cancer risks for the inhalation pathway are the sums from inhalation of radon and inhalation of particulates.
[c] The cancer risks listed are for an exposure of 1 hour and are associated with mine adits. The risk estimates correspond to the maximum gamma rate or radon level for the five mine categories presented in Table 13.
[d] The radon data for the Medium mines were used for the Medium/Large category as no data was reported.

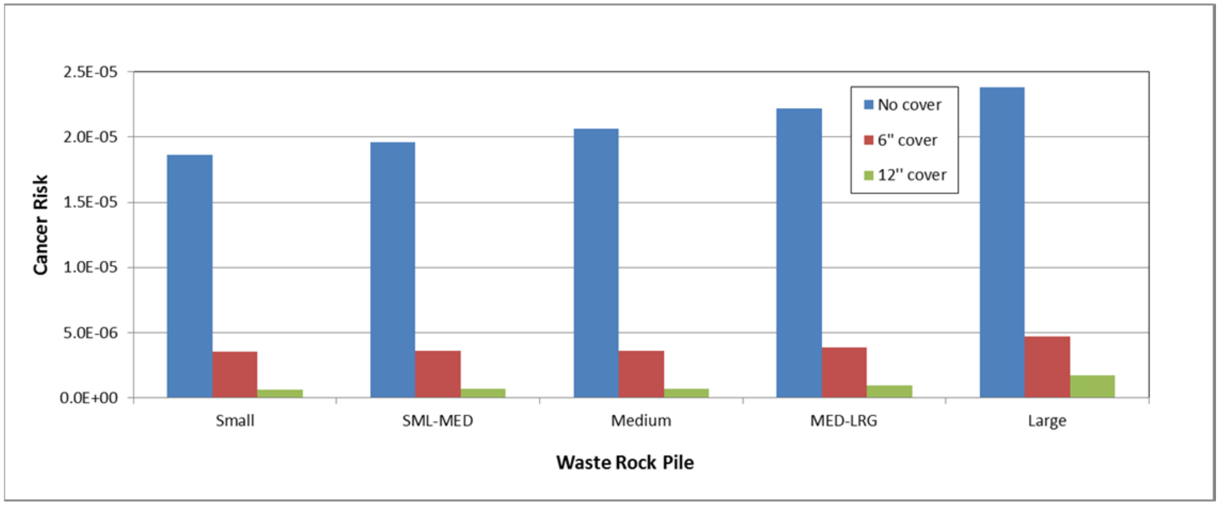


Figure 12. Comparison of Cancer Risk Estimates for a Recreational Visitor Camping on a Waste-Rock Pile at Mines for the Five Production-Size Categories

Table 13. Compilation of Radon Levels and Gamma Rates Measured at Mine Adits/Shafts[a]

Mine Category and Status	Radon Level (WL) Measured at Mine Adits/Shafts[a]		Corresponding Cancer Risk per Hour of Exposure to the Measured Radon Level		Gamma Rate (μR/h) Measured at Mine Adits/Shafts[a]		Converted External Dose Rate (mrem/h) from Measured Gamma Data	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Small								
Reclaimed/closed	0.01	13.24	3E-08	4E-05	10	200	0.007	0.14
Not Reclaimed	4.85[b]	4.85[b]	1E-05	1E-05	12.5	43.7	0.0088	0.031
Small/Medium								
Reclaimed/closed	0.53	3.57	2E-06	1E-05	7	400	0.0049	0.28
Not Reclaimed	—	—	—	—	—	—	—	—
Medium								
Reclaimed/closed	0.06	1.26	2E-07	4E-06	13	200	0.0091	0.14
Not Reclaimed	6.62[b]	6.62[b]	2E-05	2E-05	11.2	375	0.0078	0.26
Medium/Large								
Reclaimed/closed	—	—	—	—	25	180	0.0175	0.13
Not Reclaimed	—	—	—	—	—	—	—	—
Large								
Reclaimed/closed	0.08	0.33	2E-07	1E-06	15	350	0.011	0.25
Not Reclaimed	—	—	—	—	17	730	0.012	0.51

[a] Measured radon levels and gamma rates were collected by DOE as reported in the DOE mines database. DOE also collected radon data for the Mi Vida mine in Utah. The radon levels reported for this mine were about 10 times higher than the maximum radon measured for the rest of the mines included in the sampling event. If the radon data for the Mi Vida mine is included, the risk estimates for radon inhalation presented in this table would be an order of magnitude higher (i.e., 4×10^{-4} instead of the 4×10^{-5} shown for the small reclaimed mine using the maximum radon data of 13.24 WL). The listed values were obtained by grouping the measured data (including contributions from background) for various mines according to the mine production-size category and reclamation status, then analyzing the grouped data to obtain the minimum (Min) and maximum (Max). The measured radon levels and gamma rates were collected from the Maybell, Uravan, and Fremont County mines in Colorado, the Grants Mineral Belt mine in New Mexico, the Black Hills Area and Dakota Lignite Area mines in South Dakota, the Lisbon Valley and Yellow Cat mines in Utah, and the Gas Hills and Crooks Gap mines in Wyoming. The reported background radon levels ranged from 0 to 0.01 WL, while the reported background gamma rates ranged from 10 to 70 μR/h.

[b] Only one measured value was available. Therefore, the measured value was reported as both the minimum and maximum. The state of Colorado Division of Reclamation, Mining and Safety clarified in its comments to this report that this value is not typical for small un-reclaimed adits in the Uravan Mineral Belt in Colorado, which average about 0.1 WL.

Table 14. Risk Estimates for an Occasional Visitor to Mines of the Five Production-Size Categories

Exposure Pathway	Cancer Risk				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
On top of a waste-rock pile without cover					
External radiation[a]	5E-08	6E-08	6E-08	6E-08	7E-08
Inhalation[a,b]	2E-10	2E-10	4E-10	8E-10	2E-09
Total	**6E-08**	**6E-08**	**6E-08**	**6E-08**	**7E-08**
On top of a waste-rock pile with 6 inch cover					
External radiation[a]	1E-08	1E-08	1E-08	1E-08	1E-08
Inhalation[a,b]	6E-11	1E-10	2E-10	5E-10	1E-09
Total	**1E-08**	**1E-08**	**1E-08**	**1E-08**	**1E-08**
On top of a waste-rock pile with 12 inch cover piles					
External radiation[a]	2E-09	2E-09	2E-09	2E-09	2E-09
Inhalation[a,b]	6E-11	1E-10	2E-10	5E-10	1E-09
Total	**2E-09**	**2E-09**	**2E-09**	**2E-09**	**3E-09**
At Mine Adits/Openings					
External radiation[c]	2E-07	3E-07	3E-07	2E-07	6E-07
Inhalation of radon[c]	4E-05	1E-05	2E-05	2E-05[d]	1E-06
Total	**4E-05**	**1E-05**	**2E-05**	**2E-05**	**2E-06**

[a] The cancer risks listed are for an exposure of 1 hour and are associated with waste-rock piles.
[b] The cancer risks listed for the inhalation pathway are the sums from inhalation of radon and inhalation of particulates.
[c] The cancer risk listed are for an exposure of 1 hour and are associated with mine adits/portals/openings. The risk estimate correspond to the maximum gamma rate or radon level for the five production-size categories of mines presented in Table 13.
[d] The radon data for the Medium mines were used for the Medium/Large category as no data was reported.

Table 15. Risk Estimates for a Reclamation Worker at Mines of the Five Production-Size Categories

Exposure Pathway	**Cancer Risk**				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Reclaiming Waste-Rock Piles					
External radiation[a]	9E-06	9E-06	1E-05	1E-05	1E-05
Inhalation[a,b]	3E-08	4E-08	6E-08	1E-07	2E-07
Ingestion of soil[a]	6E-08	1E-07	2E-07	6E-07	6E-07
Total	**9E-06**	**9E-06**	**1E-05**	**1E-05**	**1E-05**
Closing Mine Adits/Openings					
External radiation[c,d]	3E-05	5E-05	5E-05	2E-05	1E-04
Inhalation of radon[c,d]	6E-03	2E-03	3E-03	3E-03[e]	2E-04
Ingestion of soil[c,d]	6E-07	6E-07	6E-07	6E-07	6E-07
Total	**6E-03**	**2E-03**	**3E-03**	**3E-03**	**3E-04**

[a] The cancer risks listed are for an exposure of 20 days and are associated with waste-rock piles.
[b] The inhalation risk includes contributions from the inhalation of radon and the inhalation of particulates pathways.
[c] The cancer risks listed are for an exposure of 20 days. The results listed for the external radiation and inhalation of radon pathways are associated with mine adits/portals/openings, while those listed for the ingestion of soil pathway could be partially associated with the geological materials used for the closure of mine openings. The risk associated with the soil ingestion pathway is very small compared with the risk associated with the external radiation and inhalation of radon pathways.
[d] The risk estimates correspond to the maximum gamma rates or radon levels for the five production-size categories of mines presented in Table 13.
[e] The radon data for the Medium mines were used for the Medium/Large category as no data was reported.

Table 16. Comparison of Calculated External Dose Rates and Measured Gamma Rates for the Mines

Mine Category and Status	Calculated External Dose Rate (mrem/h)		Converted External Dose Rate (mrem/h) from Measured Gamma Rate[a]			Measured Gamma Rate (µR/h)[b]		
	Waste-Rock Pile[c]	Contaminated Ground Surface[d]	Min	Max	Average	Min	Max	Average
Small								
Reclaimed	0.013[e]	0.012[f]	—[g]	—	—	—	—	—
Not Reclaimed	0.069	0.012	0.0098	0.11	—	14	150	—
Small/Medium								
Reclaimed	0.013[e]	0.014[f]	—	—	—	—	—	—
Not Reclaimed	0.072	0.014	0.0060	0.11	0.017–0.050	8.6	163	24.3–72.5
Medium								
Reclaimed	0.013[e]	0.016[f]	0.0098	0.063	—	14[h]	90[h]	—
Not Reclaimed	0.076	0.016	0.0078	0.20	—	11.2	288[h]	—
Medium/Large								
Reclaimed	0.013[e]	0.02[f]	0.0097	0.053	—	13.9[h]	75[h]	—
Not Reclaimed	0.079	0.020	0.011	0.10	0.034	15.9	146[h]	—
Large								
Reclaimed	0.013[e]	0.022[f]	0.019	0.11	0.036–0.053	26.5[h]	151[h]	50.9 -75.2[h]
Not Reclaimed	0.082	0.022	0.020	0.42	—	28	600	—

[a] The converted external dose rates were obtained by multiplying the measured gamma rates by a factor of 0.0007 (mrem/µR).

[b] Measured gamma rates were collected by DOE as reported in the DOE mines database. The listed values were obtained by grouping the measured data (including contributions from background) for various mines according to the mine production-size category and reclamation status, then analyzing the grouped data to obtain the min., max., and average values. The measured gamma rates were collected from the Maybell, Uravan, and Fremont County mines in Colorado, the Grants Mineral Belt mine in New Mexico, the Black Hills Area and Dakota Lignite Area mines in South Dakota, the Lisbon Valley and Yellow Cat mines in Utah, and the Gas Hills and Crooks Gap mines in Wyoming. The reported background gamma rates ranged from 14 to 29 µR/h.

[c] The calculated external dose rate for the waste-rock pile were taken from Table A-7 in Appendix A for an occasional visitor spending one hour on a waste-rock pile.

[d] The calculated external dose rate for contaminated ground surface was obtained by dividing the external doses listed in Table A-4 in Appendix A for onsite residents living in the open area by 6170.

[e] Listed external dose rates for reclaimed waste-rock piles correspond to the assumption that waste-rock piles would be covered by 6 inches of cover materials.

[f] Listed external dose rates associated with the contaminated ground surface in the open area before and after reclamation are the same, because it was assumed that reclamation would not involve activities to reduce the contamination level at ground surface.

[g] "—" indicates that measured data are not available or cannot be determined.

[h] The listed min., max., and averages were obtained by summarizing the measured data for reclaimed mines. However, the activities involved in the reclamation are unknown. The state of Texas provided information indicating that they have maximums higher than the values presented in the table (Medium - not reclaimed at 1,500 µR/h; Medium/Large - not reclaimed at 350 µR/h).

Table 17. Summary of Risk Estimates for the Five Receptors at Mines for the Five Production-Size Categories

Receptor	Radiation Source	Small Mine	Small/Medium Mine	Medium Mine	Medium/Large Mine	Large Mine
Onsite Resident Receptor A (house on top of a waste-rock pile)	Ground surface[a]	2E-05	4E-05	8E-05	2E-04	2E-04
	Waste-rock pile[b]	9E-02	1E-01	1E-01	1E-01	1E-01
Onsite Resident Receptor B (house in the open area on mine site)	Ground surface[c]	2E-03	2E-03	3E-03	3E-03	4E-03
	Waste-rock pile[d]	9E-02	9E-02	9E-02	9E-02	9E-02
Offsite Resident	Ground surface[e]	6E-07	1E-06	2E-06	1E-05	6E-05
	Waste-rock pile[f]	1E-05	2E-05	9E-06	2E-05	8E-05
Recreational Visitor	Adits[g]	4E-5[h]	1E-5[h]	2E-5[h]	2E-5[h]	1E-6[h]
	Waste-rock pile[i]	2E-05	2E-05	2E-05	2E-05	2E-05
Occasional Visitor	Adits[j]	4E-5[k]	1E-5[k]	2E-5[k]	2E-5[k]	1E-6[k]
	Waste-rock pile[j]	6E-08	6E-08	6.E-08	6E-08	7E-08
Reclamation Worker	Adits[k]	6E-3[h]	2E-3[h]	3E-3[h]	3E-3[h]	2E-4[h]
	Waste-rock pile[j]	9E-06	9E-06	1E-05	1E-05	1E-05

[a] Radiation exposures were estimated assuming that the onsite resident planted crops and raised livestock in the open area for meat and milk for 30 years. The cancer risks listed would result from meat and milk ingestion pathways.

[b] Radiation exposures were estimated assuming that the onsite resident lived on top of waste-rock piles for 30 years. The potential risk would result primarily from inhalation of indoor radon. Exposures associated with living in the open area would be less.

[c] The estimates presented would result from the external radiation; inhalation of radon and particulates (associated with outdoor air contamination and outdoor contamination that infiltrates to indoor space); incidental ingestion of soil; and plant, meat, and milk ingestion pathways.

[d] Radiation exposures were estimated assuming exposure to indoor radon for 30 years due to waste rocks being used to construct the foundation of the onsite residence.

[e] Radiation exposures were estimated assuming that the offsite resident raised livestock in the open area and ingested meat and milk produced by the livestock for 30 years.

[f] Radiation exposures were estimated assuming inhalation of radon and particulates emitted from waste-rock piles for 30 years.

[g] Radiation exposures were estimated assuming the recreational visitor ventured to mine adits for an hour. Radon data obtained by DOE at mines for the five production-size categories indicated that there is not an increasing trend with larger mines. As shown in this row, the radon data for the Large mines showed the lowest risk level.

[h] The potential range of exposures was estimated using the radon data and gamma rate measurement data taken by DOE at various mines, as recorded in the DOE mines database.

[i] Radiation exposures were estimated assuming the recreational visitor camped on a waste-rock pile for 2 weeks.

[j] Radiation exposures were estimated assuming the occasional visitor stayed on top of a waste-rock pile or at mine adits for 1 hour.

[k] Radiation exposures were estimated assuming the reclamation worker worked on waste-rock piles or at mine adits for 20 days. The exposures were estimated on the basis of the pre-reclamation conditions; therefore, reduction in external radiation and radon levels as the reclamation proceeded was not taken into account.

4.0 Evaluate Mine Locations for Use in Physical Hazards Determination

4.1 Methodology and Summary of Results

To evaluate physical hazards at mines, the hazards themselves must be delineated and the potential for individuals to encounter such hazards must be understood. Existing available information on mine locations and the number and types of hazards associated with the mines can be used. The likelihood that individuals would access a mine site is a function of a mine's location relative to the nearest inhabited location(s) (e.g., populations centers and schools) and relative to the nearest access point (e.g., road).

The majority of mines (about 84%; 66% on federal land) are more than 1 mile from the nearest road, with more than 99% of the mines more than 1 mile from the nearest school, as shown in Table 20. Of the 14 mines (0.45%) with schools within 0.5 mile, 2 are on federal land. While 72% (2,213; 1,854 on federal land) of the mines have a population less than or equal to 100 people within a 5-mile radius, 24% (747), 3.3% (101), and 0.78% (24) of the mines have populations >100 to 1,000, >1,000 to 10,000, and >10,000, respectively, within a 5-mile radius.

Populations associated with 0.25-, 0.5-, and 1-mile distance ranges are shown in Table 19. No mines are associated with a population greater than 1,000 people within a 0.25-mile radius of the mine location. Only 58 mines (1.9%; 30 on federal land) have a population greater than 100 people within a 1-mile radius.

4.1.1 Mine Hazards

Numerous potential hazards can be present at an underground uranium mine location. Such hazards include exposed or hidden vertical shafts; open portals and adits; subsidence; weakened and degraded supports in the mine; insufficient air supply; dangerous above-ground structures; hazardous chemicals, wastes, and explosives; waste-rock piles; pooled water; and animals.

In the absence of mine-specific information, the production-size categories provide the basis for a more general analysis. For each of the five production-size categories DOE assigned a given set of hazards, such as portals, pits and trenches, shafts, bored vents, waste-rock piles, and structures. The basis for this assignment is described in the cost topic report. The average number of each characteristic for a given mine category is summarized in Table 18.

4.1.2 Potential for Encountering Hazards

Since the likelihood that individuals would access a mine site could be a function of a mine's location relative to the nearest inhabited locations (e.g., population centers and schools) and relative to the nearest access points (e.g., roads), this evaluation used maps, 2010 U.S. Census data, and other information to analyze the proximity of mines to residences, schools, and roads. Roads included local, county, state, and interstate roadways from the USGS National Atlas database (http://nationalatlas.gov/index.html). However, it is recognized that the increasing non-traditional recreational use of some of the areas near the mines (such as those in the Colorado Plateau) could also create a greater potential for chance encounters with mines by the recreating public. Non-traditional recreational use could include all-terrain vehicle access, four-wheel driving, and mountain biking.

Table 18. Assumed Number of Each Mine Characteristic by Mine Production-Size Category

Characteristic	Small Mine	Small/Medium Mine	Medium Mine	Medium/Large Mine	Large Mine
Portals	3	3	5	8	9
Pits and trenches	1	2	2	2	2
Shafts	0	0	1	1	2
Bored vents	1	1	2	4	5
Waste-rock piles	2	3	3	4	7
Structures	1	1	2	2	1

4.1.3 Mines Evaluated for Physical Hazards

For consideration of potential physical hazards, mines where the information on the exact location, land ownership, or tonnage produced was unknown were excluded, as were mines that were designated as reclaimed or remediated. This left 3,085 mine locations, in five production-size categories, that were evaluated for potential physical hazards. The 3,085 mines evaluated for potential physical hazards are from five production-size categories; (mines in the sixth production-size category, the Very Large category, were excluded from this topic report). The 3,085 mines were also sorted into two land ownership categories (i.e., federal and tribal/state/private). The majority of the mines are located on federal public lands managed by BLM, USFS, and other federal land management agencies.

4.2 Results

4.2.1 Overview of the Proximity of Mines to Residences, Schools, and Roads

Table 19 shows how many people live within a quarter mile, a half mile, and a mile of the mines. No mines are associated with a population greater than 1,000 people within a 0.25-mile radius of the mine location. Only 58 mines (1.9 percent) have a population greater than 100 people within a 1-mile radius.

Table 19. Number of Mines Associated with Selected Population Ranges and Distances

Total Population (persons)	Number of Mines		
	Within 0.25 mile	Within 0.5 mile	Within 1 mile
0	1,770 (57%)	1,526 (49%)	1,306 (42%)
>0 to 1	935 (30%)	691 (22%)	382 (12%)
>1 to 10	328 (11%)	680 (22%)	908 (29%)
>10 to 100	45 (1.5%)	156 (5.0%)	431 (14%)
>100 to 1,000	7 (0.23%)	29 (0.94%)	50 (1.6%)
>1,000	0 (0%)	3 (0.10%)	8 (0.26%)
All	**3,085 (100%)**	**3,085 (100%)**	**3,085 (100%)**

Table 20 shows how many mines have a school within half a mile, within a mile, and so on. The majority of the 3,101 mines (about 84 percent) are more than 1 mile from the nearest road, and more than 99 percent of the mines are more than 1 mile from the nearest school.

Table 20. Overview of Distances from Uranium Mines to the Nearest Roads and Schools

Distance to Nearest Road or School (miles)	Number of Mines	
	Roads	Schools
0.5 or less	248 (8.0%)	14 (0.5%)
>0.5 to 1	242 (7.8%)	9 (0.3%)
>1 to 5	1,518 (49%)	265 (8.6%)
>5 to 10	859 (28%)	826 (27%)
>10	218 (7.1%)	1,971 (64%)
All	**3,085 (100%)**	**3,085 (100%)**

4.2.2 Proximity of Mines to Local Population

Precise information about the number of residents and inhabited places (e.g., workplaces) within the vicinity of mine sites is not available. As an alternative, 2010 U.S. Census block data were used as a basis for estimating the number of people who reside close to a mine site and who might inadvertently find it. The 2010 Census data was used to produce Table 21 through Table 24, which show estimated total populations within 0.25, 0.5, 1, and 5 miles of each mine site; other distances might also be suitable. In all four of those tables, mine sites are divided into two land-ownership categories: sites with federal ownership and sites with tribal (including U.S. Bureau of Indian Affairs), state, and/or private ownership.

Central gathering places in most communities are the local schools, which draw people from the immediate area during a large portion of the year. Table 25 through Table 27 provide information on mine sites and their proximity to private schools, public schools, and colleges and universities.

4.3 Summary

Of the 3,085 mines evaluated for potential physical hazards, about 72 percent (2,213) of the mines have 100 or fewer people living within a 5-mile radius of a mine (Table 24). Another 24 percent (747) of the mines have between 101 and 1,000 residents living within a 5-mile radius, leaving only about 4 percent that have more than 1,000 residents within a 5-mile radius of the mines.

If local population is a primary concern, it can be seen that seven mines are in an area in which more than 1,000 people live within a 1-mile radius of the mine (Table 23), and that 24 mines are in an area in which more than 10,000 people live within a 5-mile radius of the mine (Table 24). No mines have a population greater than 1,000 people within a 0.25-mile radius of the mine location (Table 21), and only 14 mines have a public school that is within half a mile of the mine

(Table 26). There is potentially relatively easy access to the 248 mines that are within half a mile of a road, as shown in Table 28.

A number of states (e.g., Colorado, California [CDOC 2000], Montana [MDEQ 1996], and Nevada [NAC 2013]) and federal agencies (e.g., BLM [DOI 2007]) employ a ranking system in their efforts to protect the public from mine hazards. Most of these systems use a point scoring system that (1) gives more weight to greater hazards (e.g., falling down an open vertical shaft is considered a greater hazard than slipping on loose soil or rocks on a waste-rock pile) and (2) gives consideration to how likely it is that individuals are likely to encounter a mine (e.g., for mines that are nearer to more populated or frequented areas). The Wyoming Abandoned Mine Land (AML) program has developed a prioritization matrix that uses a combination of physical hazards and radiological parameters. The development and use of a similar ranking system would provide a sound basis for determining management options for the mine sites, as needed. See *Abandoned Uranium Mines Prioritization Topic Report* for further details.

Table 21. Population within a Quarter of a Mile of Mines

Total Population	Number of Mines in Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
0	587	154	352	87	301	63	158	32	24	12	**1,770**
>0 to 1	339	89	171	46	140	41	73	22	11	3	**935**
>1 to 10	94	37	40	38	51	20	23	13	7	5	**328**
>10 to 100	6	18	4	7	1	6	1	1	0	1	**45**
>100 to 1,000	0	4	0	2	0	1	0	0	0	0	**7**
>1,000	0	0	0	0	0	0	0	0	0	0	**0**
All	**1,026**	**302**	**567**	**180**	**493**	**131**	**255**	**68**	**42**	**21**	**3,085**

Note:
The majority of "Federal" lands in this table are public lands managed by BLM and USFS.

Table 22. Population within a Half of a Mile of Mines

Total Population	Number of Mines in Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
0	539	101	311	63	271	45	141	20	24	11	**1,526**
>0 to 1	229	83	130	28	110	27	64	15	4	1	**691**
>1 to 10	208	80	106	69	86	42	46	23	14	6	**680**
>10 to 100	50	23	16	12	25	14	4	9	0	3	**156**
>100 to 1,000	0	13	4	7	1	3	0	1	0	0	**29**
>1,000	0	2	0	1	0	0	0	0	0	0	**3**
All	**1,026**	**302**	**550**	**180**	**493**	**131**	**255**	**79**	**42**	**21**	**3,085**

Note:
The majority of federal lands in this table are public lands managed by BLM and USFS.

Table 23. Population within 1 Mile of Mines

Total Population	Number of Mines in Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
0	452	101	264	61	226	42	118	17	19	6	**1,306**
>0 to 1	135	36	64	15	60	17	32	14	6	3	**382**
>1 to 10	297	97	166	59	140	40	75	19	9	6	**908**
>10 to 100	125	56	65	36	64	29	28	14	8	6	**431**
>100 to 1,000	12	12	8	8	3	3	2	2	0	0	**50**
>1,000	5	0	0	1	0	0	0	2	0	0	**8**
All	**1,026**	**302**	**567**	**180**	**493**	**131**	**255**	**68**	**42**	**21**	**3,085**

Note:
The majority of federal lands in this table are public lands managed by BLM and USFS.

Table 24. Population within 5 Miles of Mines

Total Population	Number of Mines in Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
100 or less	767	165	450	89	400	63	209	29	28	13	**2,213**
>100 to 1,000	223	102	110	71	88	58	46	31	12	6	**747**
>1,000 to 10,000	33	28	6	16	2	6	0	6	2	2	**101**
>10,000	3	7	1	4	3	4	0	2	0	0	**24**
All	**1,026**	**302**	**567**	**180**	**493**	**131**	**255**	**68**	**42**	**21**	**3,085**

Note:
The majority of federal lands in this table are public lands managed by BLM and USFS.

Table 25. Distance from Mines to the Nearest Private School

Nearest Private School (miles)	Number of Mines in Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
0.5 or less	0	1	0	0	0	0	0	0	0	0	**1**
>0.5 to 1	0	0	0	1	0	1	0	0	0	0	**2**
>1 to 5	6	15	1	4	5	4	0	3	0	1	**38**
>5 to 10	58	21	14	17	11	11	4	5	0	3	**144**
>10	962	265	552	158	477	115	251	60	42	18	**2,900**
All	**1,026**	**302**	**567**	**180**	**493**	**131**	**255**	**68**	**42**	**21**	**3,085**

Note:
The majority of federal lands in this table are public lands managed by BLM and USFS.

Table 26. Distance from Mines to the Nearest Public School

Nearest Public School (miles)	Number of Mines in Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
0.5 or less	0	6	2	6	0	0	0	0	0	0	**14**
>0.5 to 1	2	1	1	1	2	0	0	1	0	0	**8**
>1 to 5	84	49	23	18	33	12	19	8	7	1	**254**
>5 to 10	257	69	150	51	136	31	60	14	11	3	**782**
>10	683	177	391	104	322	88	176	45	24	17	**2,027**
All	**1,026**	**302**	**567**	**180**	**493**	**131**	**255**	**68**	**42**	**21**	**3,085**

Note:
The majority of federal lands in this table are public lands managed by BLM and USFS.

Table 27. Distance from Mines to the Nearest College/University

Nearest College/ University (miles)	Number of Mines in Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
0.5 or less	0	0	0	0	0	0	0	0	0	0	**0**
>0.5 to 1	0	0	0	0	0	0	0	0	0	0	**0**
>1 to 5	1	2	1	2	2	3	0	1	0	0	**12**
>5 to 10	5	7	2	3	3	3	1	4	0	1	**29**
>10	1020	293	564	175	488	125	254	63	42	20	**3,044**
All	**1,026**	**302**	**567**	**180**	**493**	**131**	**255**	**68**	**42**	**21**	**3,085**

Note:
The majority of federal lands in this table are public lands managed by BLM and USFS.

Table 28. Distance from Mines to the Nearest Road

Nearest Roadway (miles)	Number of Mines in Mine Production-Size Category										
	Small		Small/Medium		Medium		Medium/Large		Large		Total
	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	Federal	Tribal/State/ Private	
0.5 or less	74	39	39	21	33	5	26	10	0	1	**248**
>0.5 to 1	87	29	47	12	41	4	10	2	3	7	**242**
>1 to 5	510	118	279	81	269	48	144	33	29	7	**1,518**
>5 to 10	273	93	162	46	133	61	60	19	8	4	**859**
>10	82	23	40	20	17	13	15	4	2	2	**218**
All	**1,026**	**302**	**567**	**180**	**493**	**131**	**255**	**68**	**42**	**21**	**3,085**

Note:
The majority of federal lands in this table are public lands managed by BLM and USFS.

5.0 Evaluate Potential for Water Quality Degradation

To evaluate the 4,225 mine locations in the DOE mines database with the limited site-specific groundwater and surface water information that exists for each of the mine locations, two distance-based general factors that could characterize the current and historical potential for contamination from uranium mining were considered. These two factors are (1) the presence of impaired water bodies in the current surface water system near and downstream from the mine sites; and (2) any evidence of historical groundwater contamination near the mine sites.

The intent of using the screening approach discussed in this section was not to identify whether any mine site has actually released contaminants to the local water system. Instead, the evaluation was intended to provide information on the proximity or relative location of the mines to identified impaired surface water bodies (as identified in state databases) and to areas of degraded groundwater quality (based on USGS databases). The screening evaluation approach was used because of the large number of mine sites (more than 4,000) that are the subject of this report and the limited data available for surface water and groundwater associated with the mines.

The results of the screening analysis for water quality indicate that a small number of mine sites are located near the impaired water bodies and elevated groundwater contamination. There is only a small likelihood of significant surface water and groundwater impacts from mine sites, and the impact may be confined to smaller, localized portions of the area studied.

5.1 Methodology

Several assessment studies of the mine sites have been conducted in the western United States. These studies have mainly involved two approaches: (1) an assessment to identify the potential level of any mine effects on water quality at the mine sites (Shevenell et al. 1997; USACE et al. 2007) and (2) a site survey to identify actual risk by collecting samples from waste dumps, soil, adjacent streambeds, surface water, and groundwater (Nash 2002; Marston et al. 2012). The Nevada Bureau of Mines and Geology (Shevenell et al. 1997) developed a ranking scheme for the mines in Clark County, Nevada, that considered detailed, site-specific geologic, hydrologic, and physical parameters for each mine. The U.S. Army Corps of Engineers (USACE) applied a set of distance criteria to evaluate a large number of the Navajo Nation mine sites (USACE et al. 2007).

There is no detailed local geologic, hydrologic, and mining data (such as from a site survey with sampling) for the vast majority of the 4,225 mines across 19 states in the DOE mines database. Therefore, a sampling-based evaluation of the actual risk of water-quality degradation caused by the mines is not possible at this time. Accordingly, the evaluation presented in this report mainly focused on a screening assessment to identify the potential of any mine effects on local water systems.

As stated above, this evaluation is a screening study of the 4,225 mines across 19 states in the DOE mines database. This evaluation excluded mines where the information on the exact location or production was unknown, and mines in the sixth production-size category (the Very Large category). The Very Large mines were excluded from the evaluation because they have either been reclaimed or are being reclaimed or remediated. This left approximately

3,500 mine locations, in five production-size categories, that were screened for the potential of water-quality degradation.

To utilize as much information as possible, this evaluation took advantage of (1) existing nationwide monitoring data for surface water and groundwater qualities and (2) national hydrography datasets. This assessment approach considered any evidence of both current and historical contamination that was likely to be associated with uranium mining activities at the mine sites. This assessment included the following components:

- Establish a set of radionuclides and metals (that are associated with uranium mines) and their associated regulatory standards to use as evaluation criteria.
- Identify and locate surface water and groundwater that are contaminated by uranium mine-related constituents by searching the nationwide databases (i.e., the EPA and/or state 303(d) database and the USGS NWIS database).
- Evaluate the potential for surface water and groundwater contamination contribution at each mine site on the basis of the following three criteria: stream network, flow direction, and distance.

The evaluation results were used to create a list of the mines that indicate a spatial relationship with listed or measured impairments.

5.2 Analysis of the Potential for Impact on Water Systems

An analysis was conducted to determine how likely it is that a mine site has had an impact on historical or current water quality. The following datasets were obtained from EPA, USGS, or state agencies and used in the analysis:

- Geographic information system (GIS) data from EPA's recently updated list of impaired water bodies (http://water.epa.gov/scitech/datait/tools/waters/data/), the 303(d) list of impaired waters mandated by the Clean Water Act (CWA), and corresponding state water quality assessment 305(b) reports mandated by the CWA
- USGS NWIS groundwater quality measurement data from 1950 to the present (http://nwis.waterdata.usgs.gov/nwis/qw)
- USGS National Hydrography Dataset (NHD), which contains data on features of water bodies (i.e., streams, rivers, lakes) with vector features (flow lines) representing water flow in the water bodies (http://nhd.usgs.gov/data.html)

The total number of mines included in this analysis is 3,474. Only mines with a specific location (latitude-longitude) and a known production of <500,000 tons of uranium ore were selected. In addition, the mines in the Very Large production-size category (i.e., with >500,000 tons of ore production) have either been reclaimed or are being reclaimed or remediated, and were not included for this evaluation. The detailed analysis is discussed in the following sections.

5.2.1 Constituents Associated with Uranium Mining

On the basis of previous studies and sampling results from various uranium mining sites, several radionuclides and metals could possibly be leached from waste-rock or ore piles into local water systems (Marston et al. 2012). The studies and sampling results identified the following radionuclides and metals at contaminated sites associated with uranium mining: arsenic, cadmium, copper, lead, radium, selenium, and uranium (Karp and Metzler 2006; Mkandawire and Dudel 2005; Muscatello and Janz 2009; Kelly and Janz 2009). The reported results from conducting synthetic precipitation leaching procedure tests of the composite samples from the waste-rock and ore piles at the DOE Uranium Leasing Program mining sites indicate that constituents of arsenic, radium, selenium, and uranium may have a higher potential of being mobilized from the waste-rock or temporary ore stockpile and migrating to the local water system. This evaluation selected these radionuclides and metals (listed in Table 29) as a base of constituents to search for when reviewing relevant contamination from the databases of contaminated water bodies. It is important to note that these metals and radionuclides are also contaminants of gold, silver, copper, iron, lead, and coal mining (Taylor et al. 2005, van Geen et al. 1997, Bech et al. 1997, Williams and Smith 2000, Wang and Mulligan 2006, Johnson 2002). Furthermore, locations of mines are commonly concentrated in areas in which these other types of mining are prevalent (USGS 2013a). Since it is not possible with this analysis to narrow down the specific cause of each impairment in the collected databases, this analysis should only be recognized as a first-order exploration into the spatial relationship between mine sites and databases of water contamination.

Table 29. List of Metal and Radionuclide Constituents and Their Drinking-Water Quality Standards

Constituents	Primary Drinking-Water Quality Standard[a] (µg/L)
Arsenic	10
Cadmium	5
Copper	1,300
Lead	15
Radium	5[b]
Selenium	50
Uranium	30

Notes:
[a] EPA (2013): http://water.epa.gov/drink/contaminants/index.cfm#List.
[b] Radium is in pCi/L.

As a part of the groundwater analysis of this study, the primary drinking-water standards for the seven constituents were applied to the USGS groundwater quality database as screening levels. In many locations in the U.S., especially where uranium mining is prevalent, there are naturally occurring background concentrations of these seven constituents, especially uranium (Orloff et al. 2004). Therefore, in an effort to screen out those groundwater test sites, the primary drinking-water quality standards listed in Table 29 were used. The use of drinking-water standards is not intended to imply that these USGS water quality test samples were taken from drinking-water aquifers, but rather to screen out those test results that might contain background measurements of the seven constituents.

5.2.2 Analysis of Potential for Contributing to Current Impairment of Water Body

Section 303(d) of the CWA, as amended, requires states to develop lists of water bodies that do not meet water quality standards according to their classified water uses and to submit updated lists to EPA every 2 years, along with the integrated report on water quality conditions that is required in Section 305(b). It should be noted that the extent of assessed water bodies varies by state and may not include all intermittent/ephemeral streams and isolated surface water bodies that have little connection to streams, lakes, and reservoirs. However, water quality information in the 303(d) database reflects water quality issues for those intermittent/ephemeral streams and isolated water bodies that currently have apparent impacts on water quality in streams, lakes, and reservoirs.

For all but four states, the latest available 303(d) list was from the most recent survey, in 2010 or 2012. This set of data represents a list of impaired water bodies requiring a Total Maximum Daily Load plan to be formulated by the state. Each impaired water body is listed along with its cause for impairment. The analysis in this report uses this dataset to identify the mine sites that are at or immediately upstream of these 303(d) water bodies. The 2-mile distance criterion, with additional constraints such as stream network near the site and stream flow direction, was used. The concentration of contaminants that are discharging to the nearest streams system typically decreases downstream within the streams owing to dilution, precipitation in response to changing chemical environments, adsorption, and other factors. However, the highest concentration should be captured within the 2-mile stream channel at or near the mine site. Hence, the 2-mile criterion was used to search impaired water bodies relevant to mine site locations. The additional criteria of stream network near the mine sites and stream flow direction were also expected to rule out those mine sites that are at or near the stream but downstream from the impaired water bodies, as it was assumed that the contaminated water will not move upward against flow direction. A GIS tool was used to aid the following procedures carried out for this analysis:

- Collect all GIS data and recent survey results on impaired water bodies based on the state 303(d) list from EPA or state sources. The results for all but four states were from the most recent survey, in 2010 or 2012.
- Extract data for locating impaired water bodies that are currently contaminated with any of the seven constituents listed in Table 29.
- Use medium-resolution NHD datasets to locate all mine sites that are within 2 miles upstream from the impaired waters that have at least one of the seven constituents listed as the cause of exceeding drinking-water standards.

Figure 13 shows a flow chart of this process. Figure 14 shows a map view of this process and illustrates the application of the criteria used.

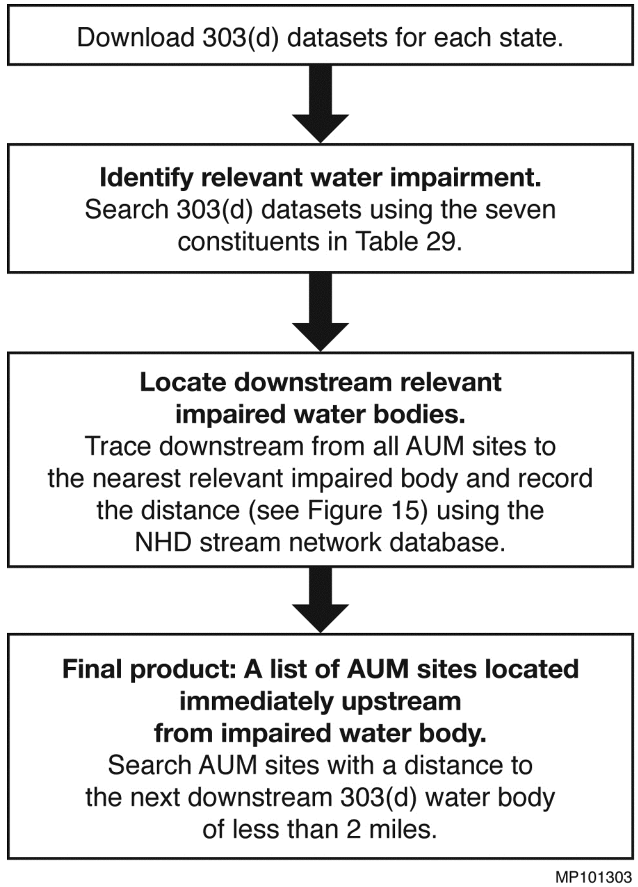
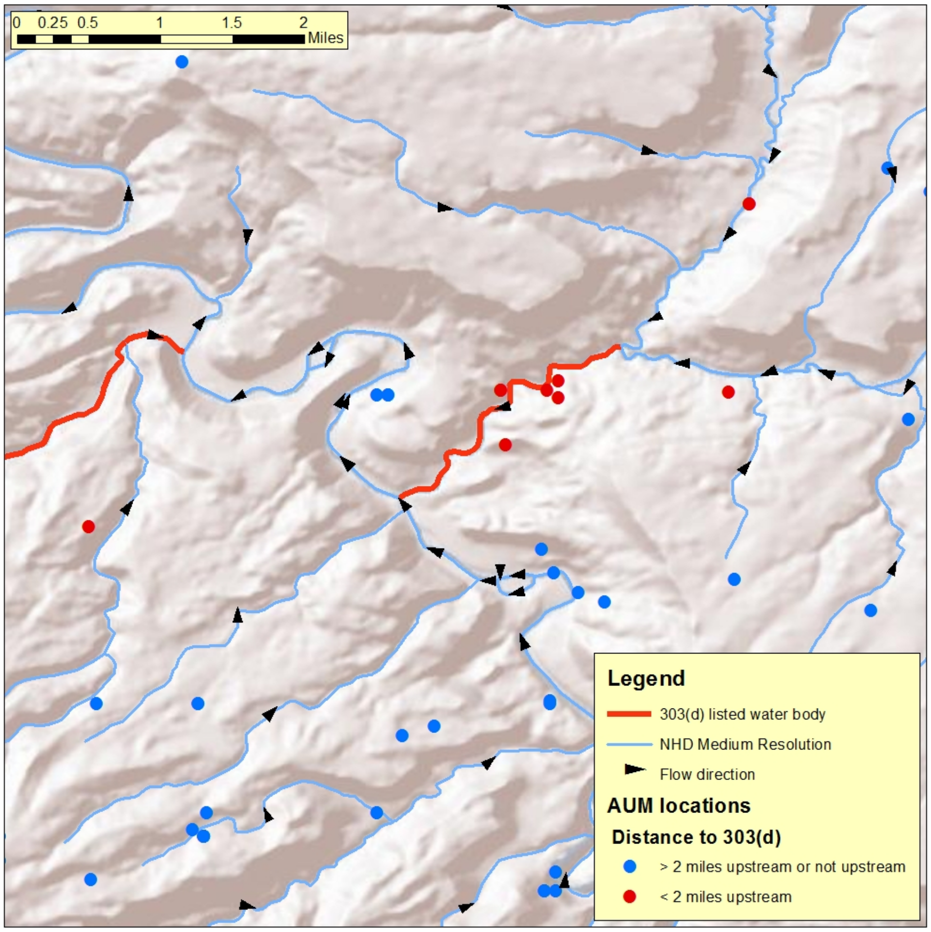


Figure 13. Flow Chart of the Process Used to Associate Mines with 303(d)-listed Water Databases

5.2.3 Analysis of Potential for Contributing to Historical or Current Groundwater Contamination

The USGS collected and analyzed chemical, physical, and biological properties of water across the nation. The water quality dataset from the nationwide discrete-sample database is a compilation of over 4.4 million historical water quality analyses by the USGS through September 2005 (http://nwis.waterdata.usgs.gov/nwis/qw). The discrete sample data were collected in a variety of projects, ranging from national programs to studies in small watersheds. This evaluation used the USGS data set to identify any historical groundwater contamination relevant to contaminants that could be potentially linked to mining activities near the mine sites and to determine the relative potential of the mine sites to contribute to the groundwater contamination. The water quality analyzed in the USGS database does not represent drinking-water sources only, but rather various hydrogeologic settings and uses. The analysis presented here is therefore limited in its ability to conclude any causality between groundwater measurement data and the location of a mine; rather, it represents merely a spatial relationship between the two.



Notes:
The red mine locations are within 2 miles upstream of the 303(d) water body, while the blue mine locations are >2 miles upstream, or not upstream, from a 303(d) water body. Simply being within 2 miles upstream of a 303(d) body does not implicate the red mines as the cause of impairment to the 303(d) body. Flow direction arrows are shown to give an idea of water flow in this particular location. These flow direction arrows are generated using the embedded flow direction information in the NHD dataset.

Figure 14. Map View of the Surface Water Processing Technique

Generally, the greater the distance from the uranium mines or any mineral mines, the more likely that natural processes will reduce the impacts of contamination. Processes such as precipitation (which can change the water chemistry), biological degradation (which sometimes renders contaminants less toxic), adsorption (binding of materials to soil particles), and mixing may take place during transport processes in aquifers. A searching/screening factor of 1 mile has been commonly used for many contaminated sites. For the purpose of this study, a 1-mile search criterion was also used to identify mines that are close to the elevated groundwater concentration of seven constituents. It should be noted that a majority of the mines are located in arid to semi-arid regions. This limits the potential releases of contaminants to the environment, although the types of precipitation events (e.g., a thunderstorm or a rapid snow melt event) may result in transport events in regions that otherwise have comparatively low total annual precipitation.

An analysis procedure using a GIS tool was developed as follows:

- Compile all groundwater quality measurements from the NWIS and relevant GIS data for the USGS groundwater test sites within 1 mile of a mine.
- Extract all measurements that are relevant to the seven constituents of interest.
- Extract the data for USGS sites with groundwater contamination that exhibited a constituent level exceeding the drinking-water standards listed in Table 29. These drinking-water standards were used as a way to screen out background levels of the seven constituents.
- Determine which mines are within 1 mile of the USGS groundwater sites where a measurement exceeded the levels of contaminants listed in Table 29.

See Figure 15 for a flow chart of this process.

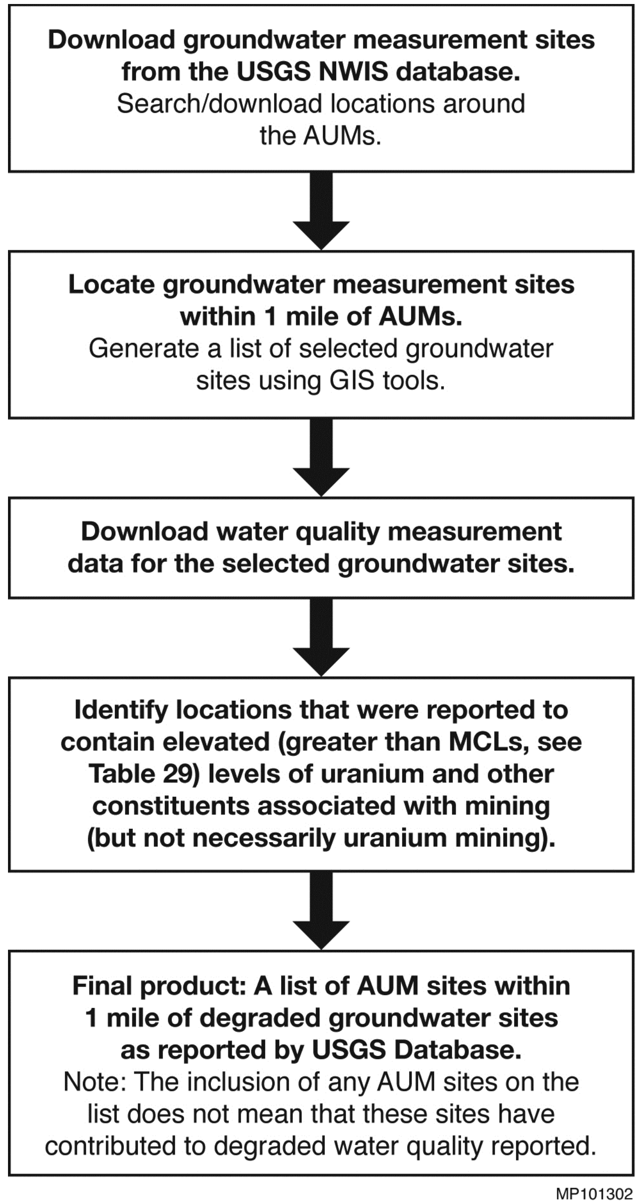


Figure 15. Flow Chart of the Process Used to Associate Mines with USGS Groundwater Measurements

5.3 Results

The impaired surface water bodies identified in the 19 states where the mines are located comprise about 169 watersheds (defined by the USGS 8-digit hydrologic unit code [HUC8] for water basins; see Box 5-1). There are more than 2,000 8-digit watersheds in the entire U.S. It is important to note that the constituents used to screen the water quality databases (Table 29) are also associated with many non-uranium types of mining, and therefore the spatial relationships between the mines and the polluted water in the databases are not sufficient to imply that the mines are the source of the contamination. Therefore, these screening results are not to be interpreted as demonstrating that the mines have impacted the impaired water bodies or groundwater further. Rather, it is intended to provide a means of focusing any further analysis of the mines relative to the potential for water quality degradation, as appropriate. Furthermore, if the metals and radionuclides listed in Table 29 were reduced to only those prevalent as a result of uranium mining—excluding those that are produced by other types of mining as well—the number of mines that fit the final criteria would be nearly zero. As the results show, a very small percentage of the total mines fit the analysis criteria as they stand presently.

Box 5-1. ***What are Hydrologic Unit Codes or HUCs?***

Hydrologic unit codes (HUCs) are a method of dividing the United States into different watersheds. The USGS states: "The United States is divided and sub-divided into successively smaller hydrologic units which are classified into four levels: regions, sub-regions, accounting units, and cataloging units. The hydrologic units are arranged or nested within each other, from the largest geographic area (regions) to the smallest geographic area (cataloging units). Each hydrologic unit is identified by a unique HUC consisting of two to eight digits based on the four levels of classification in the hydrologic unit system." (USGS 2013b).

A summary of the results from these two analyses are displayed in Table 30. A brief conclusion is presented in Section 5.4.

5.3.1 Surface Water

The comparison of the mine locations against the impaired water bodies indicate that 45 mine sites (about 1 percent of the mines analyzed) are located at or immediately upstream (within 2 miles) from the relevant impaired surface water bodies. Further, these 45 mine sites are concentrated in only 10 HUC8 watersheds (Table 31). The 10 watersheds are located in western states that are associated with traditionally large amounts of other types of mining in addition to uranium mining. One of the 10 watersheds in this list contains 21 (47 percent) of the 45 mine sites identified by this analysis, with the other 9 watersheds containing between 1 and 7 mine sites. See Figure 16 for a map of these watersheds.

5.3.2 Groundwater

Similarly, the evaluation of groundwater quality indicated that 44 mine sites (about 1 percent of the mine sites analyzed) are located within 1 mile of the USGS NWIS measurement sites that have indications of elevated levels of any of the seven constituents listed in Table 29. These 44 mine sites are concentrated within 10 HUC8 watersheds (Table 31). Of these 10 watersheds, two are also in the list of 10 watersheds discussed in Section 5.3.1. Forty-three (75 percent) of the identified mine sites are located in four watersheds, and the remaining sites are distributed among six watersheds, with one to three mines in each. The locations of the 10 watersheds are shown in Figure 16.

In addition, 17 of the identified mine sites have been reclaimed or closed. A total of 27 mines remain as having potential to have contributed to the poor groundwater quality indications found in the USGS NWIS database.

Table 30. A Summary of the Results of the Analysis Listed by Mine Production-Size Category

Production-Size Category [a]	Total Number	Within 1 Mile of USGS Groundwater Site[b]		Within 2 Miles Upstream of 303(d)-Listed Water Body[c]	
		Number of Mines	Percent of Total	Number of Mines	Percent of Total
1–Small	1,413	16	1.1%	30	2.1%
2–Small/Medium	842	8	1.0%	5	0.6%
3–Medium	746	12	1.6%	7	0.9%
4–Medium/Large	392	7	1.8%	2	0.5%
5–Large	81	1	1.2%	1	1.2%
Total	**3,474**	**44**	**1.3%**	**45**	**1.3%**

Notes:

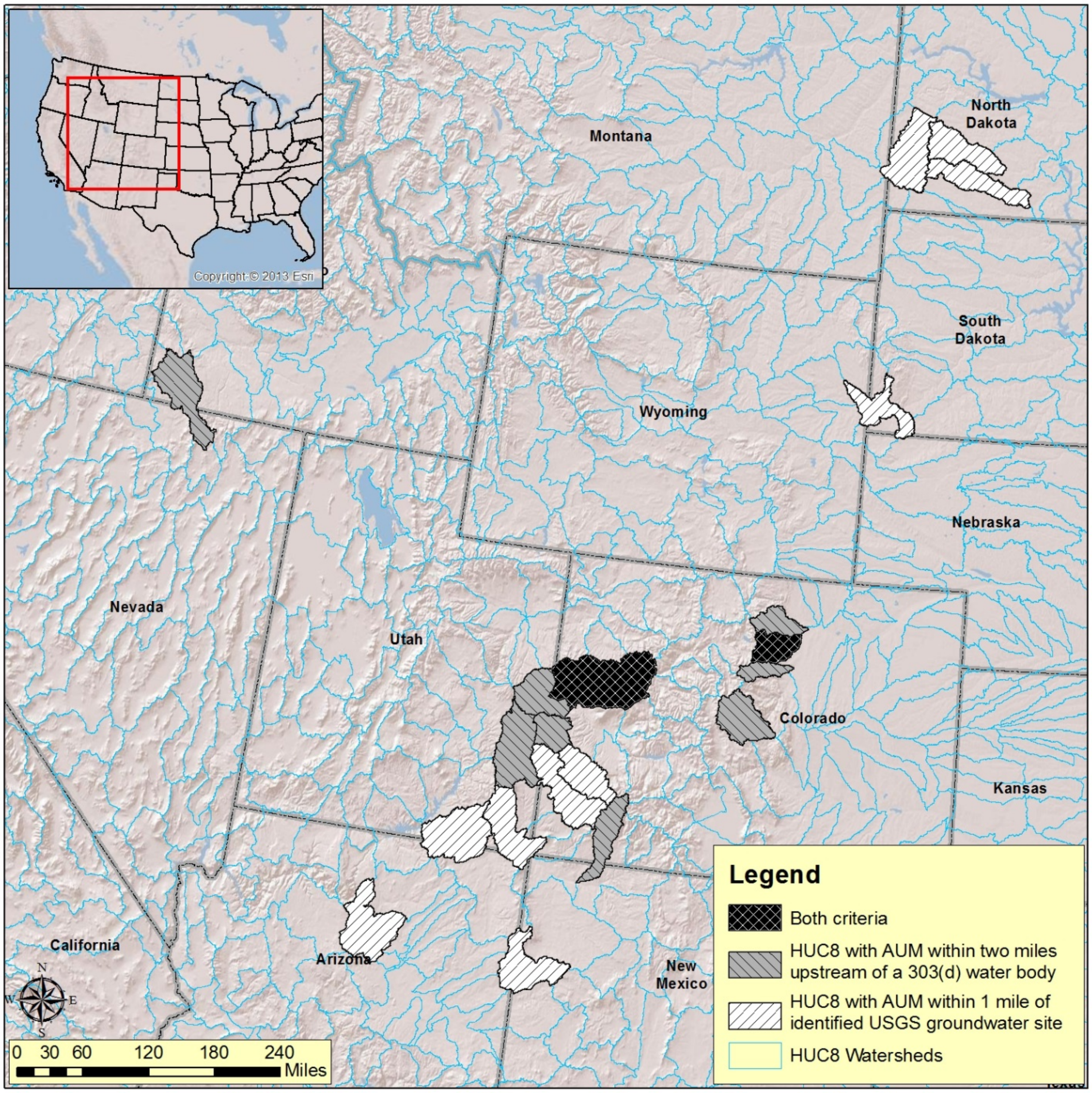
[a] Small (≤100 tons), Small/Medium (>100–1,000 tons), Medium (>1,000–10,000 tons), Medium/Large (>10,000–100,000 tons), and Large (>100,000–500,000 tons).

[b] USGS groundwater sites with measured levels that exceeded the standards of the seven constituents in Table 29.

[c] 303(d)-listed water bodies for which at least one of the seven constituents in Table 29 is listed as the cause for water-body impairment.

Table 31. A List of HUC8s and the Numbers of Mines Identified by the Surface Water and Groundwater Analysis

HUC8	HUC8 Name	States	Groundwater Count	Surface Water Count
10120106	Angostura Reservoir	SD	7	0
10130202	Upper Heart	ND	10	0
10130204	Upper Cannonball	ND	2	0
10190001	South Platte Headwaters	CO	0	1
10190004	Clear	CO	0	7
10190005	St. Vrain	CO	1	5
10190006	Big Thompson	CO	0	1
14010005	Colorado Headwaters-Plateau	CO	1	3
14030001	Westwater Canyon	CO, UT	0	3
14030002	Upper Dolores	CO	12	0
1400003	San Miguel	CO	1	0
14030004	Lower Dolores	CO, UT	0	20
14030005	Upper Colorado-Kane Springs	UT	0	5
14080104	Animas	CO, NM	0	1
14080201	Lower San Juan-Four Corners	AZ, UT	3	0
14080205	Lower San Juan	AZ, UT	3	0
15020016	Lower Little Colorado	AZ	7	0
17050104	Upper Owyhee	ID, NV	0	1



Note:
White watersheds are those identified with a mine within 1 mile of an identified groundwater. Grey watersheds are those identified with a mine within 2 miles upstream of a 303(d) water body. Black watersheds are those that fit both the above criteria. Relief base map is provided by ESRI.

Figure 16. A Map of the Watersheds Identified in This Report

5.4 Conclusion

The results of the screening analysis for water quality indicate that a small number (about 1 percent) of mine sites are located near the impaired water bodies and/or areas of elevated groundwater contamination. The number of watersheds encompassed by the screened mine sites is also limited to a few.

6.0 Evaluation of Potential Radiological Exposure of Ecological Receptors and Bat Use at Abandoned Uranium Mines

Potential impacts of mines on ecological resources include (1) radiological risks to ecological receptors exposed to potentially contaminated soils, waste-rock piles, and water; and (2) the use of underground mines by bats. Both subject areas may be appropriate considerations when evaluating the closure of mines (EPA 2008b) on a site-specific basis. While potential impacts from inorganic contaminants are also of concern at mines, they generally occur at most hardrock mines, and their impacts on terrestrial and aquatic biota have been thoroughly investigated. Therefore, the discussion below focuses only on radiological exposure to biota, which is more typical at mines. Inorganic contaminants are also included in ecological risk assessments conducted at mines (see Section 2.4).

6.1 Evaluation of Potential Radiological Exposure of Ecological Receptors at Abandoned Uranium Mines

As indicated in Section 2.4, mine areas often contain elevated concentrations of radionuclides to which ecological receptors may be exposed. Further human exposure to radionuclides may occur by ingestion of plants and animals; contamination of fur, feathers, skin, and vegetation surfaces; direct uptake from the water column; ingestion from water (including root uptake of water); and inhalation (EPA 2008a, 2008b; ICRP 2009). The aim of environmental protection to biota from radionuclide exposure includes preventing or reducing the frequency of deleterious radiation effects to a level where they would have a negligible impact on biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems (IAEA 1992, ICRP 2008, 2009).

Copplestone et al. (2001) summarized various recommendations on dose limits to biota that stated that dose rates below 40 rad/hr (400 mGy/hr) are generally below the levels that cause significant effects. Adverse impacts to ecological receptors can occur from uranium radionuclide doses of 0.48 to 96 rad/day (4.8 to 960 mGy/day) for terrestrial invertebrates, of 0.34 to 96 rad/day (3.4 to 960 mGy/day) for birds, and of 0.1 to 96 rad/day (1.0 to 960 mGy/day) for mammals (Hinck et al. 2010). Exposure at these dose rates may have detectable effects on individuals; but generally there would be no detrimental effects at the population level (Real et al. 2004). Life history strategies, habitat requirements, and the mass of an organism influence the potential impact magnitude (Hinck et al. 2010). Some birds may be at greater risk of radiation exposure than other wildlife because they forage and ingest grit, which increases the radiation dose (Driver 1994). Species that spend considerable amounts of time underground (e.g., in the underground mine, in the waste-rock pile, or in burrows in contaminated soils) could potentially inhale, ingest, or be directly exposed to radionuclides while digging, eating, preening, and/or sleeping or hibernating.

Howard et al. (2010) concluded that a numeric screening value of 0.024 rad/day (0.24 mGy/day) can be used to identify situations that are below regulatory concerns with regard to preventing biological effects. DOE has suggested that a chronic absorbed dose rate no greater than 1 rad/day (10 mGy/day) for the most sensitive organisms should ensure the protection of populations of aquatic organisms and terrestrial plants; while a chronic dose rate no greater than 0.1 rad/day

(1 mGy/day) should ensure the protection of terrestrial animals (DOE 2002; EPA 2008b). The question remains as to whether these levels are indeed protective to biota (EPA 2008b). ICRP (2008) summarized principal information on mortality for its reference animals and plants. The LD_{50} (lethal dose, 50%; the concentration required to kill half the members of a tested population) generally ranged from several Gy to several hundred Gy. Doses that have an effect on morbidity, fertility, and fecundity are also mostly higher, often by an order of magnitude or more, than the DOE (2002) protection levels (ICRP 2008).

Table 32 presents the assumed concentrations of radionuclides in waste rock and surface soil at mines, as well as soil and water biota concentration guidelines from RESRAD-BIOTA. Similar concentrations may also be expected inside the underground mines. Ra-226 is the only nuclide concentration that exceeds the biota concentration guidelines for soil biota. Where the environmental concentrations exceed biota concentration guidelines, more detailed evaluations may be necessary to investigate whether an actual effect might be possible (SENES Consultants Limited 2007).

Table 32. Assumed Radionuclide Concentrations in Waste Rock and Surface Soils and Biota Concentration Screening Guidelines

Nuclide	Assumed Waste Rock and Surface Soil Concentration (pCi/g)	Soil Biota Concentration Guidelines (pCi/g)	Water Biota Concentration Guidelines (pCi/L)
U-238	70	1,580	223
U-234	70	5,130	202
Th-230	70	9,980	2,570
Ra-226	70	50.6	4.08
Pb-210	70	1,390	601
U-235	3.22	2,770	217
Pa-231	3.22	1,170	2,600
Ac-227	3.22	Not Available	Not Available

Depending on the isotopic composition, uranium can be a greater risk because of its chemical toxicity than its radiological toxicity (Sheppard et al. 2005). Predicted no-effect uranium concentrations for chemical toxicity are 250 mg/kg of dry soil for terrestrial plants, 100 mg/kg of dry soil, and 0.1 mg/kg of body weight for mammals (Sheppard et al. 2005).

An exceedance of a biota concentration guideline alone is not an indication that a mine is a threat to ecological receptors. The lack of resources and disturbed nature of many mines may discourage wildlife use. Use may also occur infrequently due to the large home ranges of many species.

In their review of ecological risk assessments at sites with enhanced radioactivity, SENES Consultants Limited (2007) generally observed the following:

- The non-human biota most likely to receive the highest doses in aquatic habitats are crustaceans, mollusks, and wildlife (birds and mammals that rely on the aquatic environment).
- Vegetation, invertebrates, and small mammals are most likely to receive the highest doses in terrestrial habitats.
- Where dose rates to non-human biota are predicted to exceed the reference dose rate, the areal extent of elevated dose rates is limited and confined to areas in, or in close proximity to, the source of radioactivity within site boundaries.

The representative ecological risk assessments reviewed by SENES Consultants Limited (2007) indicate that standard protective practices for containing radioactive sources, for controlling and limiting radioactive releases to the environment, and for protecting humans have also provided an adequate level of protection to populations of non-human biota. ICRP (2008) voiced a similar conclusion.

6.2 Bat Use of Abandoned Uranium Mines

Although radiological (and chemical) toxicity should be treated as a concern, the closure of mine shafts that have been unreclaimed for a long period of time must also be carefully considered (EPA 2008b). Many abandoned underground mines have similar characteristics to caves, making them important roosting sites for bats (Hinman and Snow 2003). Forty-three species of bats occur within the 19 states (including the Navajo Nation) that contain mines. The majority of these bat species use abandoned mines to some extent; most endangered bat species in North America are cave or mine obligates (Navo 2001). Abandoned mines provide important habitat for bats (e.g., protection from predators, temporary stopovers during migration, day and night roosts, maternity roosts, and/or hibernacula). Therefore, abandoned underground mines can be critical to the continued existence of bats. Concerns about bats are typically the ecological component that programmatically influences mine closure and mitigation efforts (Sherwin et al. 2009). Depending on the design and enactment of reclamation projects, reclamation of mines (including mines) can enhance or destroy bat populations.

Bats typically use trees, human-made structures (e.g., buildings and bridges), and underground sites (e.g., caves and mines) for roosts. Rock crevices, including those present at abandoned surface mine sites, are also commonly used. Some species of bats will make use of the same roost site locations yearly (BCT 2013; Baumgardner 1999).

It cannot be determined how use of man-made structures by bats has compensated for the loss of their natural habitat (Bogan 2000). Nevertheless, as natural habitats for bats are impacted, man-made habitats become increasingly important in bat conservation (Navo 2001). About 30 bat species in the United States make use of abandoned mines. Some species may only occupy a mine for a day or so, using it as a stopover during migration. However, many bats, including individuals of some federally listed species, use mines as their permanent and only residence in both summer and winter (Belwood and Waugh 1991). Published accounts of the proportion of abandoned mines used by bats can run as high as 70 percent in some regions (Sherwin et al. 2009).

However, while abandoned mines can provide important roosting habitat for bats, they also pose a significant public safety hazard. In the early 1990s, many state governments stepped up mine closure efforts in order to address public safety concerns. Impacts on bats were not considered for most of those mine closures. This oversight may have led to the burial of millions of bats (BCI 1994). Large-scale mine closure programs occurring over a short period of time can result in a net loss of bats, as individual colonies are unable to adjust local distributions in response to mine closures (Sherwin et al. 2009).

Not all abandoned underground mines provide the conditions needed for bats to survive. Mine shafts that are relatively shallow or that have no horizontal workings generally provide poor habitat, and the latter also pose a fall hazard to wildlife and the public (CSLC 2012). Also, as discussed elsewhere in this report, uranium mines can expose humans and wildlife to radiological and chemical contaminants through inhalation, ingestion, or direct exposure. Surveys can determine the physical and radiological characteristics of a mine and its actual or potential use as bat habitat, so that a closure technique that is physically possible and best suited for it can be chosen (CSLC 2012). Bats have been reported from locations in mines or caves where medium or low radon concentration levels occur (Espinosa et al. 2013; Schmidt et al. 2013). However, further studies are needed to determine the effects of radon exposure on bats (Schmidt et al. 2013).

The Colorado Bat Working Group discussed the pros and cons of gating uranium mines (CBWG 2005). There has been little study on the effects of radiation on bats. It is reasonable to speculate that high levels of radiation would be deleterious to bats, since they are long-lived. Exposure to continuous low doses of radiation has been shown to adversely affect bats (e.g., cause genetic damage) (Meehan 2001). Thus, unless the mines slated for reclamation have exceptional qualities as hibernacula or maternity roosts, consideration should be given to evicting bats, if present (e.g., determining when the fewest bats would be present in the mine, then adding exclusion barriers that allow bats to exit but not to reenter the mine), and to then permanently sealing the mines in order to remove the threat of the bats' exposure to radionuclides. In response to comments provided on this topic report by the state of Colorado, they provided further information to indicate that the state of Colorado constructs bat accessible mine safety closures where it is safe to do so, given individual site constraints. However, Colorado has determined that the greatest radiation exposure risks are to subsurface habitat evaluators. In order to minimize this risk, Colorado no longer encourages subsurface bat evaluations at underground uranium mines. Instead, surface observations and historic mine documents are relied upon when available to make mine closure method determinations. When a subsurface habitat evaluation is necessary, safety equipment are utilized by the evaluators to protect themselves from undue radon exposures.

The use of underground uranium mines as alternatives to diminishing natural bat habitats may outweigh the risk of exposure to radionuclides. For instance, the majority of Townsend's big-eared bat (*Corynorhinus townsendii*) maternity roosts in Colorado are located in uranium mines, and displacing them could impact the population (CBWG 2005). Currently, research is insufficient to allow a definitive conclusion on whether the beneficial use of underground uranium mines by bats outweighs potential adverse effects from exposure to radiological and chemical contaminants. In many cases, there may be enough natural habitats in the area that could provide suitable bat habitat (e.g., areas with many rock crevices may provide suitable roost habitats similar to those provided by the underground uranium mines). In such instances, closure of a mine may be the best approach. Conversely, an underground uranium mine may provide the only suitable hibernation habitat in an area. In that case, it may be more beneficial to gate the mine rather than sealing it and making it inaccessible to bats.

Decisions on whether to use bat gates or permanently close underground uranium mines should involve mining organizations, government agencies, bat biologists, and conservation groups working together to ensure that bats that roost in mines will be able to do so undisturbed into the future (Belwood and Waugh 1991). Bat Conservation International and BLM have developed a decision matrix tool for determining the most appropriate closure type for a specific mine opening (BCI 2013). Their abandoned mine closure website (http://www.batgating.com/index.php?option=com_content&view=frontpage&1temid=1) provides instructions, required information, background information, and information on the closure process needed to use the decision matrix tool.

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Appendix A

Supporting Information for the Radiological Risk Evaluation of Abandoned Uranium Mines

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This appendix contains supporting information for the radiological risk evaluation in Section 3.0 of this report. Section A.1 presents the airborne emission rates of radionuclides and radon from waste-rock piles and describes the modeling of air concentrations of radionuclide and radon levels at offsite locations (i.e., away from mines) using the CAP88-PC computer code. Section A.2 presents the measurement data of U-238/total uranium concentrations in waste-rock piles that were used to determine the U-238 concentration assumed in the radiological risk evaluation in Section 3 of this report. Potential cancer risks estimated for the various receptors considered in the radiological risk evaluation are presented in Section 3.5 of this report. The corresponding radiation dose results are presented in Section A.3. Finally, Section A.4 presents the radiation dose and cancer risks estimated for offsite residents in each of the six states that comprised about 80 percent of the mines. The radiation doses and cancer risks would result from airborne emissions of radionuclides and radon from waste-rock piles associated with the mines in the production-size categories.

A.1 Modeling of Radionuclide Concentrations and Radon Levels at Offsite Locations

To evaluate potential radiation exposures to offsite residents, air concentrations of radionuclides and radon levels at the exposure locations are needed. The CAP88-PC computer code (Trinity Engineering Associates Inc. 2007) was employed to calculate the concentrations and radon levels at offsite locations, using the airborne emission rates for radionuclides and radon estimated for varying distances away from the mine sites in the five production-size categories.

A.1.1 Airborne Emission Rates of Radionuclides and Radon

Emission rates of radon from the surface of waste-rock piles were calculated with the RESRAD code, Version 6.7 (Yu et al. 2001), which provides estimates of radon flux in terms of picocuries per meters squared per second ($pCi/m^2/s$) with the input information on dimensions of waste-rock piles and radon diffusion and emanation coefficients. The radon flux estimated by RESRAD was multiplied by the surface areas of waste-rock piles, which are listed in Table 2, to obtain radon emission rates.

The emission rates of particulates were estimated following the guidance from Regulatory Guide 3.59 (NRC 1987) concerning emission of dust particles from exposed uranium mill tailings sands due to wind erosion. The use of the NRC guidance is expected to generate conservative (i.e., higher than actual) particulate emission rates from the waste-rock piles. The emission rate of particulates is dependent on the wind speed, with a higher wind speed eroding more particles from exposed surfaces than a lower wind speed. Because weather conditions could vary at different locations, the emission rates of particulates from waste-rock piles could also vary with their locations. For the radiological risk evaluation, wind data from 134 weather stations in 19 states where mines are located were obtained and analyzed for the distribution of wind speeds of several erosion categories and then used for the particulate emission rate calculations. After the particulate emission rates were available, radionuclide emission rates were calculated by multiplying the particulate emission rates by the radionuclide concentrations assumed for waste rocks.

Table A-1 lists the estimated emission rates of radon and radionuclides from the waste-rock pile dimensions assumed for each mine in the five production-size categories. The emission rates were estimated assuming uranium-238 (U-238) concentration in waste rocks to be 70 picocuries per gram (pCi/g), while the other radionuclides are either in secular equilibrium or at natural activity ratio to U-238. The radon emission rates could be reduced by covering waste-rock piles with a layer of cover material. If such cover material could prevent waste rocks from exposure to the surface, the particulate emission could be completely suppressed, and so could be the emission of radionuclides (U-238 and its decay progenies).

A.1.2 Modeling Offsite Air Concentrations with CAP88-PC

The modeling of offsite air concentrations of radon and radionuclides, and subsequently the radiation exposures for an offsite resident, was performed repeatedly for the five mine production-size categories using each of the 134 sets of wind data. The modeling results were then analyzed to obtain the average, minimum, and maximum potential dose/risk associated with each of the five mine production-size categories located in each of the 19 states. The results for each state were then combined and analyzed to obtain the overall average, minimum, and maximum across the 19 states, as presented in Section 3.5.

The computer code CAP88-PC (Trinity Engineering Associates Inc. 2007) was designed specifically for evaluating airborne emissions of radionuclides and radon. It is supported and maintained by EPA and has been used extensively for such applications. For each CAP88-PC modeling activity, the maximum radon levels and radionuclide concentrations calculated over the 16 different sectors at selected distances were identified and recorded and then used for radiation dose/risk calculations.

Wind erosion of particulates and radon emanating from the surface of waste-rock piles would contribute to the total exposure of an offsite resident; however, for most of the locations of mine sites, assumed to have the meteorological characteristics represented by the weather stations selected for this evaluation, the exposures associated with particulate emission are less significant than the exposures associated with radon emission, unless the mine site is situated at a very windy location. This finding is due to the dual effects of wind on particulate emissions. In addition to affecting the dispersion, the speed and frequency of wind also affect the emission rate of particulates from the surfaces of waste-rock piles; the two effects have opposite consequences for the air concentration of particulates. For radon, the wind speed and frequency affect only its dispersion; the radon flux emerging from the surfaces of waste-rock piles stays relatively constant regardless of the wind characteristics. Therefore, at a location where strong wind occurs often, the radon concentrations at near distances from the emission source would decrease relatively fast with the distance, while the decrease in particulate concentration would not be as significant as there are more eroded particulates from the emission source. As a result, radiation exposure associated with particulate emission could exceed the exposure associated with radon emission at near distances. However, particulates would deposit to the ground surface while radon gas would not; furthermore, the short-lived radon decay products, which cause the radiation exposures associated with radon, would be produced along the path to further-downwind locations, and the radiation exposure associated with radon would regain its leading role in comparison to the exposures associated with airborne particulates.

Table A-1. Emission Rates of Radon and Particulates, Based on the Representative Waste-Rock Piles for the Mines in the Five Production-Size Categories in 19 States

Emission Rate	**Production-Size Category**				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Radon (curies per year [Ci/yr])					
No Cover	0.105	0.265	0.759	4.37	19.0
6-inch Cover	0.096	0.234	0.651	3.75	16.3
12-inch Cover	0.086	0.205	0.558	3.21	14.0
Particulate (kilograms per year [kg/yr])—No Cover					
Alaska	35.7	62.5	143	821	3,570
Arizona	6.0–76.1	10.5–133	23.9–304	137–1,750	598–7,610
California	9.3–126	16.3–221	37.3–506	214–2,910	931–12,600
Colorado	8.1–76.5	14.2–134	32.4–306	186–1,760	810–7,650
Florida	5.44	9.52	21.8	125	544
Idaho	7.42–11.7	13.0–20.4	29.7–46.7	171–268	742–1,170
Montana	19.3–102	33.8–179	77.2–408	444–2,350	1,930–10,200
Nevada	16.6–75.2	29.1–132	66.5–301	382–1,730	1,660–7,520
New Jersey	9.0	17.3	39.6	228	990
New Mexico	25.1–200	43.9–350	100–800	577–4,600	2,510–20,000
North Dakota	86.7–107	152–188	347–430	1,990–2,470	8,670–10,700
Oklahoma	63.8–95.6	112–167	255–382	1,470–2,200	6,380–9,560
Oregon	16.6–43.3	29.1–75.7	66.5–173	382–996	1,660–4,330
Pennsylvania	16.40	28.7	65.5	377	1,640
South Dakota	16.5–126	28.9–221	66.2–504	380–2,900	1,650–12,600
Texas	14.9–101	26.1–176	59.7–403	343–2,320	1,490–10,100
Utah	12.4–94.4	21.7–165	49.5–378	285–2,170	1240–9,440
Washington	11.6–41.1	20.3–71.9	46.4–164	267–945	1,160–4,110
Wyoming	25.8–183	45.2–312	103–734	594–4,220	2,580 – 18,300

Table A-1 (continued). Emission Rates of Radon and Particulates, Based on the Representative Waste-Rock Piles for the Five Mine Production-Size Categories in 19 States

Emission Rate	Production-Size Category				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Emission of U-238 (Ci/yr)–No Cover					
Alaska	2.50E-6	4.37E-6	1.00E-5	5.75E-5	2.50E-4
Arizona	4.18E-7–5.33E-6	7.32E-7–9.32E-6	1.67E-6–2.13E-5	9.62E-6–1.23E-4	4.18E-5–5.33E-4
California	6.52E-7–8.85E-6	1.14E-6–1.55E-5	2.61E-6–3.54E-5	1.50E-5–2.04E-4	6.52E-5–8.85E-4
Colorado	5.67E-7–5.36E-6	9.92E-7–9.37E-6	2.27E-6–2.14E-5	1.30E-5–1.23E-4	5.67E-5–5.36E-4
Florida	3.81E-7	6.67E-7	1.52E-6	8.76E-6	3.81E-5
Idaho	5.19E-7–8.17E-6	9.09E-7–1.43E-6	2.08E-6–3.27E-6	1.19E-5–1.88E-5	5.19E-5–8.17E-5
Montana	1.35E-6–7.14E-6	2.36E-6–1.25E-5	5.40E-6–2.86E-5	3.11E-5–1.64E-4	1.35E-4–7.14E-4
Nevada	1.16E-6–5.27E-6	2.04E-6–9.23E-6	4.66E-6–2.11E-5	2.68E-5–1.21E-4	1.16E-4–5.27E-4
New Jersey	6.97E-7	1.21E-6	2.776E-6	1.59E-5	6.93E-5
New Mexico	1.76E-6–1.40E-5	3.08E-6–2.45E-5	7.03E-6–5.61E-5	4.04E-5–3.22E-4	1.76E-4–1.40E-3
North Dakota	6.07E-6–7.52E-6	1.06E-5–1.32E-5	2.43E-5–3.01E-5	1.40E-4–1.73E-4	6.07E-4–7.52E-4
Oklahoma	4.47E-6–6.69E-6	7.82E-6–1.17E-5	1.79E-5–2.68E-5	1.03E-4–1.54E-4	4.47E-4–6.69E-4
Oregon	1.16E-6–3.03E-6	2.04E-6–5.30E-6	4.65E-6–1.21E-5	2.68E-5–6.97E-5	1.16E-4–3.03E-4
Pennsylvania	1.15E-6	2.01E-6	4.59E-6	2.64E-5	1.15E-4
South Dakota	1.16E-6–8.82E-6	2.03E-6–1.54E-5	4.63E-6–3.53E-5	2.66E-5–2.03E-4	1.16E-4–8.82E-4
Texas	1.04E-6–7.05E-6	1.83E-6–1.23E-5	4.18E-6–2.82E-5	2.40E-5–1.62E-4	1.04E-4–7.05E-4
Utah	8.67E-7–6.61E-6	1.52E-6–1.16E-5	3.47E-6–2.64E-5	1.99E-5–1.52E-4	8.67E-5–6.61E-4
Washington	8.12E-7–2.88E-6	1.42E-6–5.03E-6	3.25E-6–1.15E-5	1.87E-5–6.61E-5	8.12E-5–2.88E-4
Wyoming	1.81E-6–1.29E-5	3.17E-6–2.25E-5	7.24E-6–5.14E-5	4.16E-5–2.96E-4	1.81E-4–1.29E-3

To run the CAP88-PC code, a star array (STAR)-formatted wind data file is required, along with several meteorological parameters such as annual precipitation, annual ambient temperature, height of lid (or mixing height), and absolute humidity. The parameters are discussed in the following subsections.

STAR-Formatted file

A three-way joint frequency distribution of wind speed, wind direction, and Pasquill stability class (a so-called STar ARray [STAR] summary table) is needed to run the CAP88-PC code (version 3.0). To generate a STAR-formatted file, integrated surface hourly data available at weather stations at different locations were used. The STAR-formatted files were converted to the Wind file using GETWIND, a utility program included in the CAP88-PC distribution package.

Depending on the spatial distributions of existing mine sites, 1 (for Alaska, Florida, New Jersey, and Pennsylvania) to 19 weather stations (for Colorado) were selected for each state to provide wind data to generate radiological risk estimates representative of the mine sites in that state.

Annual precipitation (in centimeters per year [cm/yr])

Annual precipitation data were obtained from Western Regional Climate Center (WRCC) for the 11 western states (WRCC 2013) and from the National Climatic Data Center (NCDC) for the other eight states (NCDC 2013). If the precipitation data were not available at the location of interest, the meteorological station most representative of that location (on the basis of proximity and elevation) was consulted to obtain the needed data.

Annual ambient temperature (in °C)

Annual-average temperature data were obtained from WRCC (2013) for the 11 western states and from NCDC (2013) for the other eight states. If the temperature data were not available at the location of interest, the meteorological station most representative of that location (on the basis of proximity and elevation) was consulted to obtain the needed data.

Height of lid (m)

Height of lid (or mixing height) is defined as the height above the ground surface through which relatively vigorous vertical mixing occurs, primarily through the action of atmospheric turbulence. The mixing heights were read off from the mean morning and afternoon mixing height contours over the contiguous U.S. (Holzworth 1972). Then the averages of mean morning and afternoon mixing heights annually were estimated to obtain the input value for CAP88-PC calculations.

Absolute humidity (grams per meters cubed [g/m^3])

The absolute humidity (AH) is defined as the density, in g/m^3, of water vapor. The absolute humidity generally is not available, so it was estimated with ambient temperature (T in degrees Celsius) and relative humidity (RH in percent) using the following equation (available at http://carnotcycle.wordpress.com/2012/08/04/how-to-convert-relative-humidity-to-absolute-humidity/):

$$AH = \frac{6.112 \times e^{\frac{(17.67 + T)}{(243.5 + T)}} \times 2.164 \times RH}{(273.15 + T)}$$

For each state, relative humidity data are available only at a few locations, so the meteorological station most representative of that location (on the basis of proximity and elevation) was consulted to obtain the needed data.

A.2 Measurement Data of Radionuclide Concentrations in Waste Rocks

U-238 or total uranium concentrations in waste rocks were measured at various uranium mine sites. The data from these various sources were compiled to develop the U-238 concentration used for the risk evaluation discussed in this report. Table A-2 presents the measurement data. The measurement data reported for total uranium (in terms of mg/kg), were converted to U-238 concentrations (as pCi/g) assuming the natural radioactivity ratio of 1:1:0.046 for U-234, U-235, and U-238, respectively. The calculated U-238 concentrations are also listed in the table.

A.3 Radiation Dose Results for Different Receptors Considered in the Radiological Risk Evaluation

Section 3.5 of this report presents the potential cancer risks estimated for the different receptors considered in the radiological risk evaluation. The corresponding radiation doses are presented in this section. Tables A-3 to A-8 show the radiation doses associated with the radiation sources at the mine sites for Onsite Resident Receptor A (living in a house on top of a waste-rock pile), Onsite Resident Receptor B (living in the adjacent open area), offsite residents, recreational visitors, occasional visitors, and reclamation workers, respectively.

Table A-2. Source Measurement Data of Radionuclide Concentrations in Waste Rocks

Source: Table 3 of DOI and USGS report (Marston, et al., 2012)			
Data taken from 20 uranium mine waste dump sites in Browns Hole, Utah –			
Site ID	**Measurement U-238 (pCi/g)**	**Calculated U-238 (pCi/g)**	**Note**
BH-2	33.2	33.2	
BH-26	89.6	89.6	
BH-27	17.2	17.2	
BH-28	10.1	10.1	
BH-30	119.1	119.1	
BH-32	33.9	33.9	
BH-33	7.5	7.5	
BH-35	33.9	33.9	
BH-36	16.5	16.5	
BH-37	79.9	79.9	
BH-40	27.5	27.5	
BH-46	120.5	120.5	
BH-49	89.9	89.9	
BH-52	69.5	69.5	
BH-54	88.9	88.9	
BH-58	37.6	37.6	
BH-59	38.6	38.6	
BH-60	50.7	50.7	
BH-62	7.9	7.9	
BH-63	7.6	7.6	
Source: Table 2-2 of US Forest Service Report (CH2MHill 2011),			
Soil and waste rock sampling from 2 mines in Rio Blanco County, CO –			
Sample ID	**Measurement Uranium (mg/kg)**	**Calculated U-238 (pCi/g)**	**Note**
BFLY-01	458 (avg. of 479 and 436)	151	
BFLY-02	131	43.3	
BFLY-03	108	35.7	
BUR-01	411	136	
BUR-02	27.4	9.06	
BUR-03	128	42.7	
Source: Table 5 of JD-8 Mine Environmental Protection Plan (Whetstone 2011)			
Whole rock results from waste-rock pile –			
Sample ID	**Measurement Uranium (mg/kg)**	**Calculated U-238 (pCi/g)**	**Note**
JD8-WRC1	212	70	Three samples composited
JD8-WRC1	212	70	
JD8-WRC1	212	70	
Source: Table 7 of JD-8 Mine Environmental Protection Plan (Whetstone 2011),			
Whole rock results from waste-rock pile –			
Sample ID	**Measurement Uranium (mg/kg)**	**Calculated U-238 (pCi/g)**	**Note**
8W1	91	30	

Table A-2 (continued). Source Measurement Data of Radionuclide Concentrations in Waste Rocks

Source: Table 6 of JD-6 Mine Environmental Protection Plan (Whetstone 2012),			
Whole rock results from waste-rock pile –			
Sample ID	**Measurement Uranium (mg/kg)**	**Calculated U-238 (pCi/g)**	**Note**
JD-6 WRP	159	52.6	Three samples composited
JD-6 WRP	159	52.6	
JD-6 WRP	159	52.6	
Source: Section 3.26 of Whirlwind Mine Final Environmental Assessment (BLM 2008),			
Waste rock sampling results –			
Sample ID	**Measurement Ra-226 (pCi/g)**	**Calculated U-238 (pCi/g)**	**Note**
—[a]	2.8	2.8	Three samples ranging from 2.8 - 4.2 pCi/g. Use the mean as the third data.
—[a]	3.5	3.5	
—[a]	4.2	4.2	

[a] Not available.

Table A-3. Dose Estimates for an Onsite Resident Receptor A at Mines in the Five Production-Size Categories

Exposure Pathway	Radiation Dose (mrem/yr)				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Without Cover					
External radiation[a]	460	490	510	530	550
Inhalation[b]	2.3	2.4	2.6	3.3	4.3
Ingestion of plant[c]	1.2	2.1	4.7	7.8	7.8
Ingestion of meat[c]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[c]	0.017	0.029	0.067	0.38	1.7
Ingestion of soil[c]	0.23	0.41	0.93	1.6	1.6
Inhalation (indoor radon)[d]	4,700	5,300	5,500	5,600	5,600
Total	**5,200**	**5,800**	**6,100**	**6,100**	**6,200**
With 6 inch cover on waste-rock piles					
External radiation[a]	88	88	88	88	88
Inhalation[b]	0.15	0.16	0.19	0.33	0.76
Ingestion of plant[c]	1.2	2.1	4.7	7.8	7.8
Ingestion of meat[c]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[c]	0.017	0.029	0.067	0.38	1.7
Ingestion of soil[c]	0.23	0.41	0.93	1.6	1.6
Inhalation (indoor radon)[d]	4,700	5,300	5,500	5,600	5,600
Total	**4,800**	**5,400**	**5,600**	**5,700**	**5,700**
With 12 inch cover on waste-rock piles					
External radiation[a]	15	15	15	15	15
Inhalation[b]	0.15	0.16	0.19	0.31	0.68
Ingestion of plant[c]	1.2	2.1	4.7	7.8	7.8
Ingestion of meat[c]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[c]	0.017	0.029	0.067	0.38	1.7
Ingestion of soil[c]	0.23	0.41	0.93	1.6	1.6
Inhalation (indoor radon)[d]	4,700	5,300	5,500	5,600	5,600
Total	**4,800**	**5,300**	**5,600**	**5,600**	**5,700**

Notes:

[a] The radiation doses listed for the external radiation pathway are associated with waste-rock piles.

[b] The radiation doses listed for the inhalation pathway considered inhalation of radon and particulates emitted from waste-rock piles as well as from contaminated ground surfaces. The values listed are the bounding values.

[c] The radiation doses listed for the ingestion pathway are associated with ground surface contamination.

[d] The radiation doses listed for the inhalation of indoor radon pathway are associated with waste-rock piles, assuming the onsite residence was constructed on a waste-rock pile such that the bottom of the house would contact the top of the waste rocks.

Table A-4. Dose Estimates for an Onsite Resident Receptor B at Mines in the Five Production-Size Categories

Exposure Pathway	Radiation Dose (mrem/yr)				
	Small	Small/Medium	Medium	Medium/Large	Large
Without Cover					
External radiation[a]	*82*	93	110	130	150
Inhalation[b]	2.3	2.4	2.6	3.3	4.3
Ingestion of plant[a]	1.2	2.1	4.7	7.8	7.8
Ingestion of meat[a]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[a]	0.017	0.029	0.067	0.38	1.7
Ingestion of soil[a]	0.23	0.41	0.93	1.6	1.6
Inhalation (indoor radon)[c]	5,200	5,200	5,200	5,200	5,200
Total (without indoor radon)	**86**	**98**	**120**	**150**	**170**
Total (with indoor radon)	**5,300**	**5,300**	**5,300**	**5,400**	**5,400**
With 6 inch cover on waste-rock piles					
External radiation[a]	82	93	110	130	150
Inhalation[b]	0.15	0.16	0.19	0.33	0.76
Ingestion of plant[a]	1.2	2.1	4.7	7.8	7.8
Ingestion of meat[a]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[a]	0.017	0.029	0.067	0.38	1.7
Ingestion of soil[a]	0.23	0.41	0.93	1.6	1.6
Inhalation (indoor radon)[c]	5,200	5,200	5,200	5,200	5,200
Total (without indoor radon)	**84**	**96**	**110**	**140**	**160**
Total (with indoor radon)	**5,300**	**5,300**	**5,300**	**5,400**	**5,400**
With 12 inch cover on waste-rock piles					
External radiation[a]	82	93	110	130	150
Inhalation[b]	0.15	0.16	0.19	0.31	0.68
Ingestion of plant[a]	1.2	2.1	4.7	7.8	7.8
Ingestion of meat[a]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[a]	0.017	0.029	0.067	0.38	1.7
Ingestion of soil[a]	0.23	0.41	0.93	1.6	1.6
Inhalation (indoor radon)[c]	5,200	5,200	5,200	5,200	5,200
Total (without indoor radon)	**84**	**96**	**110**	**140**	**160**
Total (with indoor radon)	**5,300**	**5,300**	**5,300**	**5,400**	**5,400**

Notes:

[a] The radiation doses listed for the external radiation and ingestion pathways are associated with ground surface contamination.

[b] The radiation doses listed for the inhalation pathway considered inhalation of radon and particulates emitted from waste-rock piles as well as from contaminated ground surfaces. The values listed are the bounding values.

[c] The radiation doses listed for the inhalation of indoor radon pathway are associated with waste rocks that were assumed to be used as the foundation materials for residences.

Table A-5. Dose Estimates for an Offsite Resident Living in the Vicinity of the Mines in the Five Production-Size Categories

Exposure Pathway	Radiation Dose (mrem/yr)				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Without Cover					
Inhalation[a]	< 0.29	< 0.57	< 0.30	< 0.63	< 2.0
Ingestion of meat[b]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[b]	0.017	0.029	0.067	0.38	1.7
Total	**< 0.33**	**< 0.64**	**< 0.47**	**< 1.6**	**< 6.1**
With 6 inch cover on waste-rock piles					
Inhalation[a]	< 0.17	< 0.36	< 0.16	< 0.46	< 1.6
Ingestion of meat[b]	0.024	0.042	0.096	0.55	2.4
Ingestion of milk[b]	0.017	0.029	0.067	0.38	1.7
Total	**< 0.21**	**< 0.43**	**< 0.32**	**< 1.4**	**< 5.6**
With 12 inch cover on waste-rock piles					
Inhalation[a]	< 0.15	< 0.31	< 0.14	< 0.39	< 5E-05
Ingestion of meat[b]	0.024	0.042	0.096	0.55	3E-05
Ingestion of milk[b]	0.017	0.029	0.067	0.38	3E-05
Total	**< 0.19**	**< 0.38**	**< 0.30**	**< 1.3**	**< 1E-04**

Notes:

[a] The radiation doses listed for the inhalation pathway include contributions from both inhalation of radon and inhalation of particulates, which are associated with waste-rock piles. The listed values are the maximums of the results over all the exposure distances and locations of mine sites considered in the evaluation.

[b] The radiation doses listed for the ingestion pathways are associate with ground surface contamination.

Table A-6. Dose Estimates for a Recreational Visitor at Mines in the Five Production-Size Categories

Exposure Pathway	Radiation Dose (mrem)				
	Small	Small/Medium	Medium	Medium/Large	Large
Without cover					
External radiation[a]	23	24	25	27	28
Inhalation[a,b]	0.14	0.15	0.17	0.21	0.27
Ingestion of soil[a]	0.093	0.16	0.37	0.93	0.93
Total	**23**	**25**	**26**	**28**	**29**
With 6 inch cover on waste-rock piles					
External radiation[a]	4.4	4.4	4.4	4.4	4.4
Inhalation[a,b]	0.00021	0.00050	0.0014	0.0080	0.0035
Ingestion of soil[a]	0	0	0	0	0
Total	**4.5**	**4.5**	**4.6**	**5.3**	**8.0**
With 12 inch cover on waste-rock piles					
External radiation[a]	0.75	0.75	0.75	0.75	0.75
Inhalation[a,b]	0.00019	0.00044	0.0012	0.0069	0.030
Ingestion of soil[a]	0	0	0	0	0
Total	**0.75**	**0.75**	**0.75**	**0.75**	**0.75**
Mine adits					
External radiation[c]	0.14	0.28	0.26	0.13	0.51
Inhalation of radon[c]	30	8.4	15	15[d]	1.3
Total	**31**	**8.7**	**16**	**15**	**1.8**

Notes:

[a] The radiation doses listed are for an exposure of 14 days (336 hours) and are associated with waste-rock piles.
[b] The radiation doses listed for the inhalation pathway are the sums from inhalation of radon and inhalation of particulates.
[c] The radiation doses listed are for an exposure of 1 hour and are associated with mine adits/openings. The risk estimates correspond to the maximum gamma rate or radon level for mines in the five production-size categories presented in Table 13.
[d] The radon data for the Medium mines were used for the Medium/Large category as no data was reported.

Table A-7. Dose Estimates for an Occasional Visitor at Mines in the Five Production-Size Categories

Exposure Pathway	Radiation Dose (mrem)				
	Small	Small/Medium	Medium	Medium/Large	Large
Without Cover					
External radiation[a]	0.069	0.072	0.076	0.079	0.082
Inhalation[a,b]	0.00042	0.00045	0.00049	0.00061	0.00080
Total	**0.069**	**0.073**	**0.076**	**0.080**	**0.083**
With 6-inch cover on waste-rock piles					
External radiation[a]	0.013	0.013	0.013	0.013	0.013
Inhalation[a,b]	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.00010
Total	**0.013**	**0.013**	**0.013**	**0.013**	**0.013**
With 12-inch cover on waste-rock piles					
External radiation[a]	0.0022	0.0022	0.0022	0.0022	0.0022
Inhalation[a,b]	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Total	**0.0022**	**0.0022**	**0.0022**	**0.0023**	**0.0023**
Mine adits					
External radiation[c]	0.14	0.28	0.26	0.13	0.51
Inhalation of radon[c]	30	8.4	15	15[d]	1.3
Total	**31**	**8.7**	**16**	**15**	**1.8**

Notes:
[a] The radiation doses listed are for an exposure of 1 hour and are associated with waste-rock piles.
[b] The radiation doses listed for the inhalation pathway are the sums of inhalation of radon and inhalation of particulate.
[c] The radiation doses listed are for an exposure of 1 hour and are associated with mine adits/portals/openings. The risk estimate correspond to the maximum gamma rate or radon level for mines in the five production-size categories presented in Table 13.
[d] The radon data for the Medium mines were used for the Medium/Large category as no data was reported.

Table A-8. Dose Estimates for a Reclamation Worker at Mines in the Five Production-Size Categories

Exposure Pathway	Radiation Dose (mrem)				
	Small	**Small/Medium**	**Medium**	**Medium/Large**	**Large**
Waste-rock piles					
External radiation[a]	11	12	12	13	13
Inhalation[a,b]	0.067	0.072	0.079	0.098	0.13
Ingestion of soil[a]	0.13	0.23	0.53	1.3	1.3
Total	**11**	**12**	**13**	**14**	**15**
Mine adits					
External radiation[c,d]	22	45	42	21	82
Inhalation of radon[c,d]	6,300	1,700	3,200	3,200[e]	160
Ingestion of soil[c,d]	1.3	1.3	1.3	1.3	1.3
Total	**6,300**	**1,700**	**3,200**	**3,200**	**240**

Notes:

[a] The radiation doses listed are for an exposure of 20 days and are associated with waste-rock piles.

[b] The inhalation doses include contributions from the inhalation of radon and the inhalation of particulates pathways.

[c] The radiation doses listed are for an exposure of 20 days. The results listed for the external radiation and inhalation of radon pathways are associated with mine adits/portals/openings, while those listed for the ingestion of soil pathway could be partially associated with the geological materials used for the closure of mine openings. However, the dose associated with the soil ingestion pathway is very small compared with the dose associated with the external radiation and inhalation of radon pathways.

[d] The risk estimates correspond to the maximum gamma rate or radon level for mines in the five production-size categories presented in Table 13.

[e] The radon data for the Medium mines were used for the Medium/Large category as no data was reported.

A.4 Radiological Risks to Offsite Residents around Mines in the Six States with the Most Mines

Detailed calculation results concerning potential radiological risks to offsite residents living around mine sites in the five production-size categories in the six states that have the most number of mines are presented in this section. These six states are Arizona (416), Colorado (1,347), New Mexico (249), South Dakota (155), Utah (1,376), and Wyoming (319). The average and range of the maximum radiation doses (associated with 1 year of exposure) and cancer risks (associated with 30 years of exposure) at different downwind distances from mines of the five production-size categories prior to reclamation are presented in bar-chart figures. The height of each solid bar represents the average value; its error bar represents the range of calculation results that give the average value. The average and range of radiological risk at each downwind distance were determined with the modeling results obtained with numerous sets of wind data from selected weather stations located in the same state under consideration.

Figures A-1 and A-2 present the radiation doses and cancer risks, respectively, associated with mines of the Small production-size category. Figures A-3 and A-4 presents the radiation doses and cancer risks, respectively, associated with mines of the Small/Medium category. Results for mines of the Medium category are presented in Figures A-5 and A-6; those for mines of the Medium/Large category are presented in Figures A-7 and A-8. Colorado has no mines in the Medium/Large category; therefore, no results for Colorado are presented in Figures A-7 and A-8. Figures A-9 and A-10 present results for mines of the Large category.

The potential radiological risks presented in this section are associated with the airborne emissions of particulates and radon from the representative waste-rock pile for mines in the five production-size categories (without a cover layer on top of the waste-rock pile).

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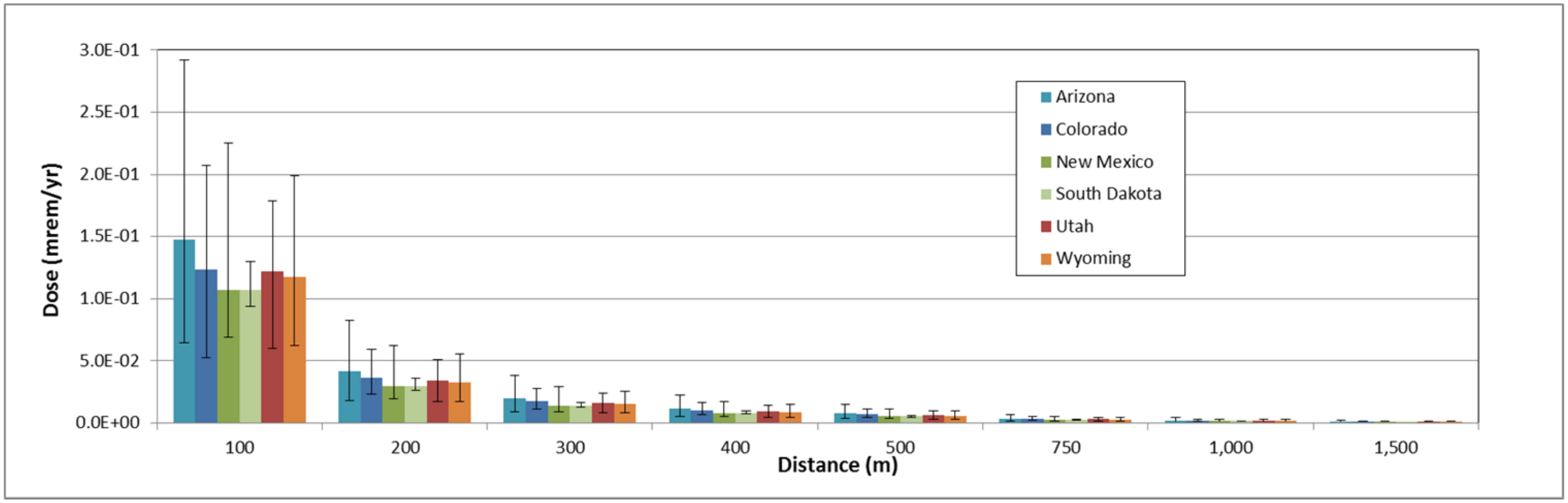

Figure A-1. Average and Range of Maximum Radiation Dose to an Offsite Resident Living in the Vicinity of a Small Mine Site in Different States

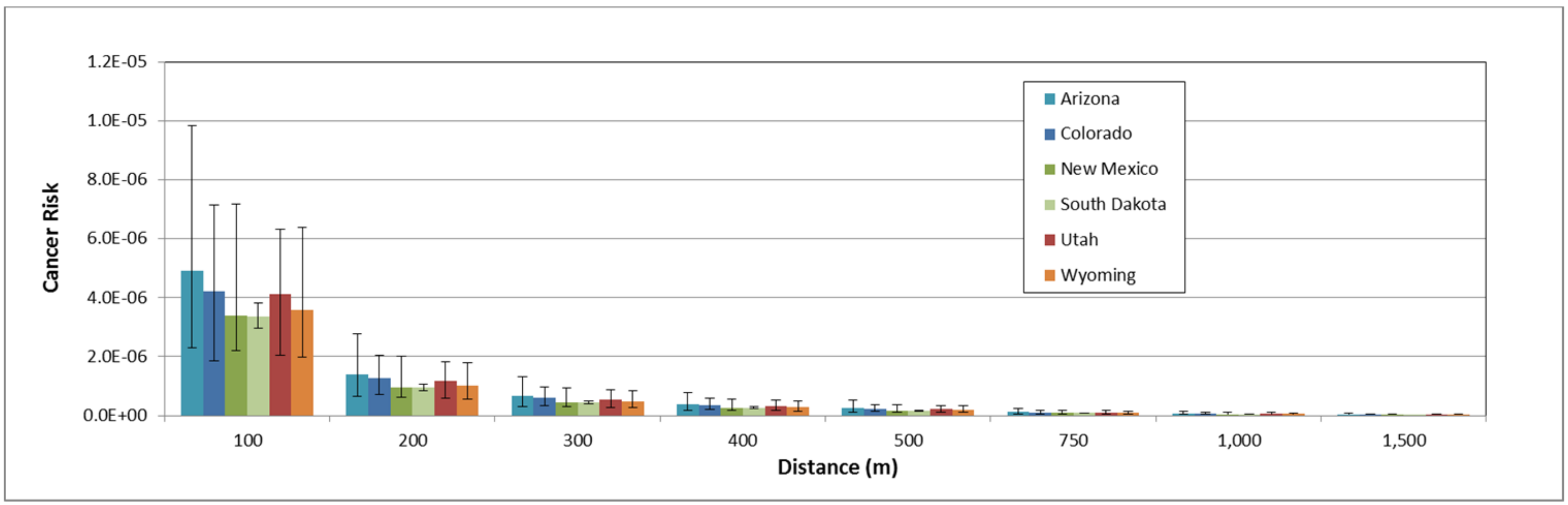

Figure A-2. Average and Range of Maximum Cancer Risk to an Offsite Resident Living in the Vicinity of a Small Mine Site in Different States

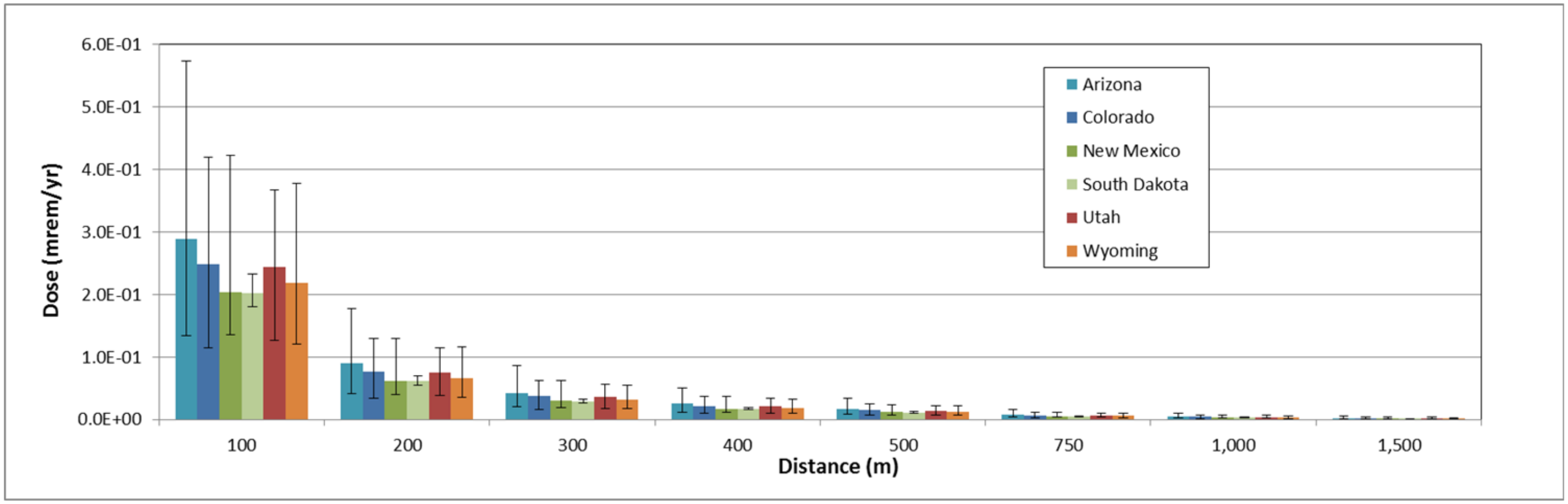

Figure A-3. Average and Range of Maximum Radiation Dose to an Offsite Resident Living in the Vicinity of a Small/Medium Mine Site in Different States

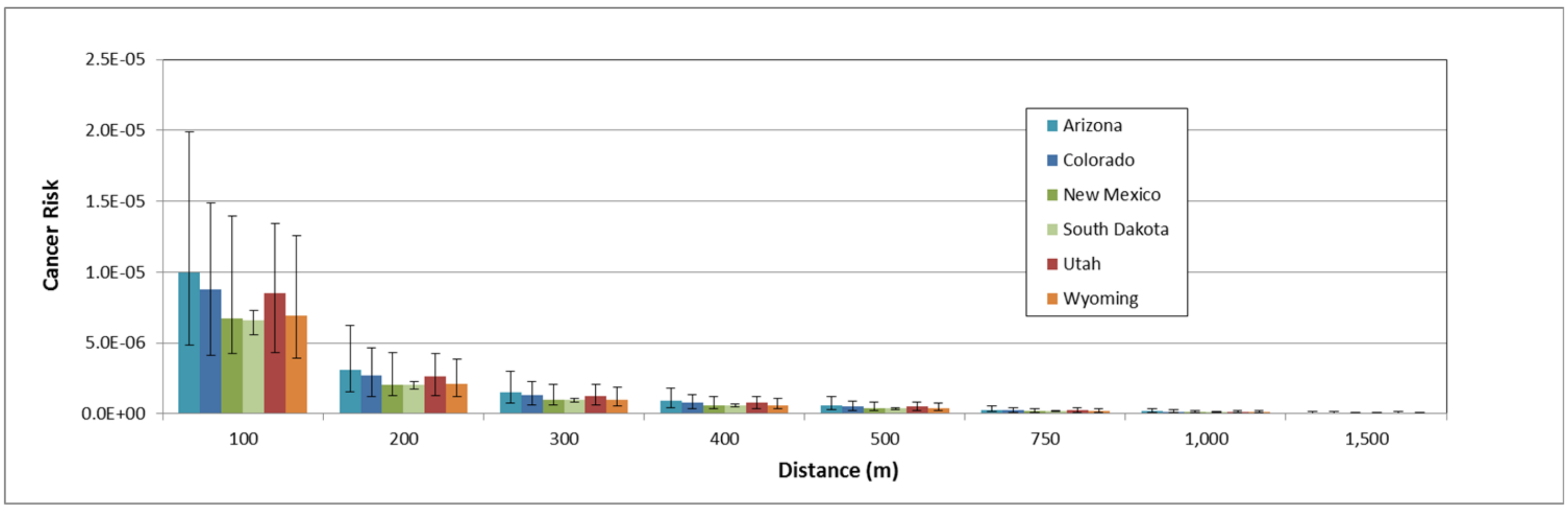

Figure A-4. Average and Range of Maximum Cancer Risk to an Offsite Resident Living in the Vicinity of a Small/Medium Mine Site in Different States

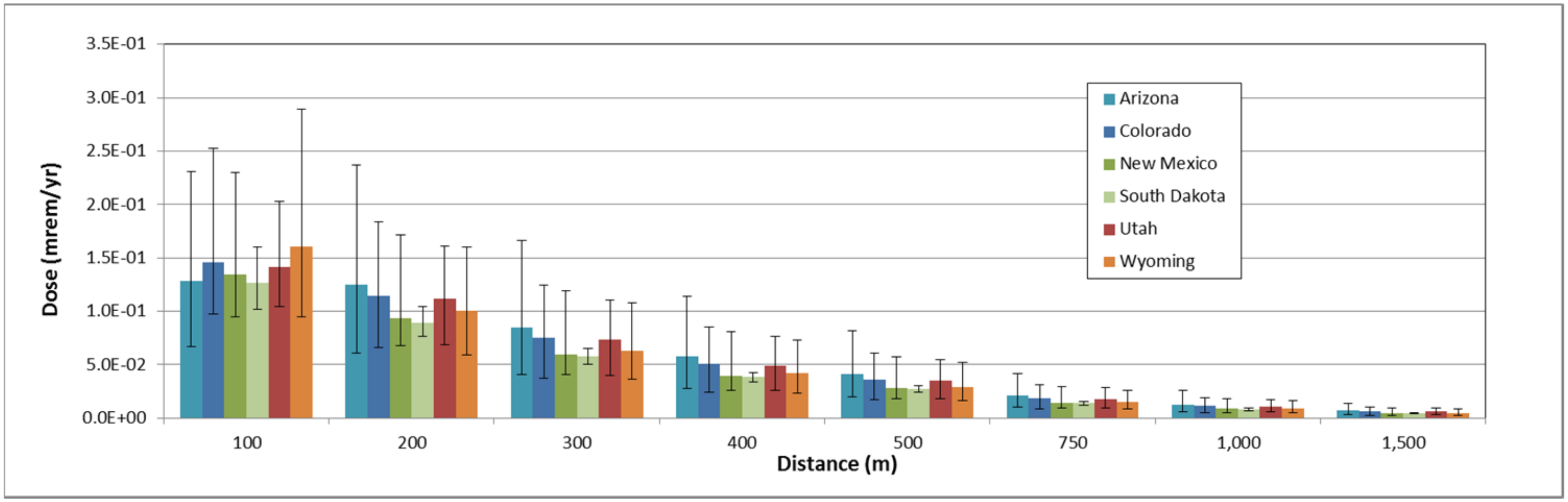

Figure A-5. Average and Range of Maximum Radiation Dose to an Offsite Resident Living In the Vicinity of a Medium Mine Site in Different States

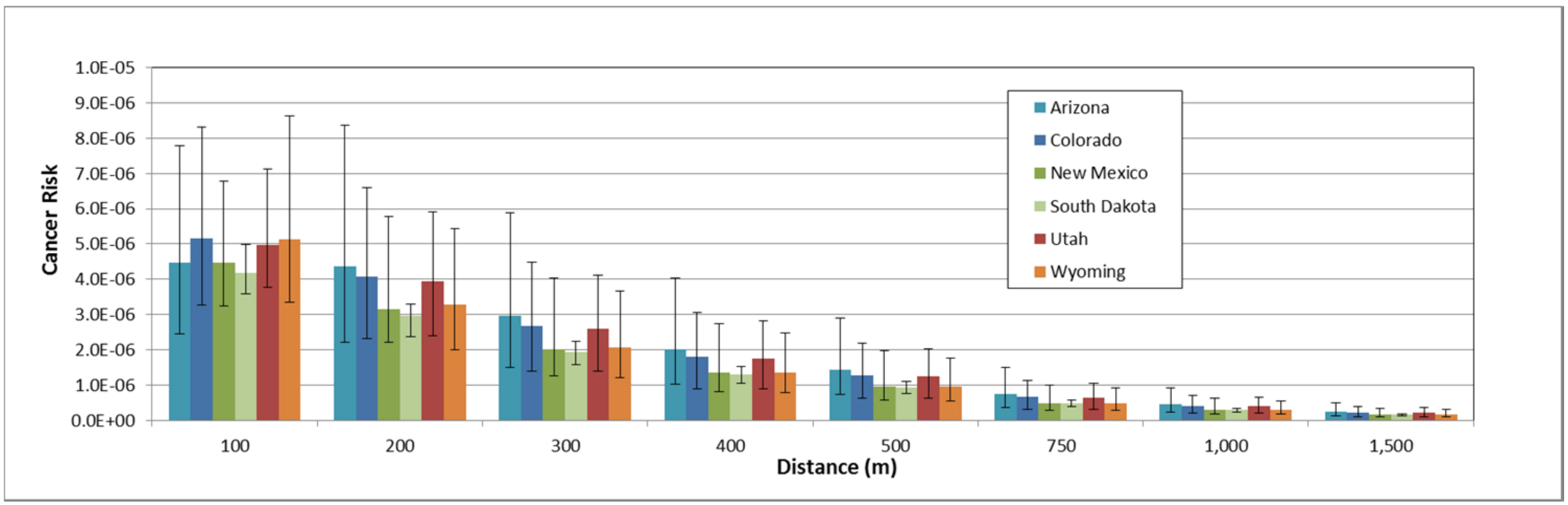

Figure A-6. Average and Range of Maximum Cancer Risk to an Offsite Resident Living in the Vicinity of a Medium Mine Site in Different States

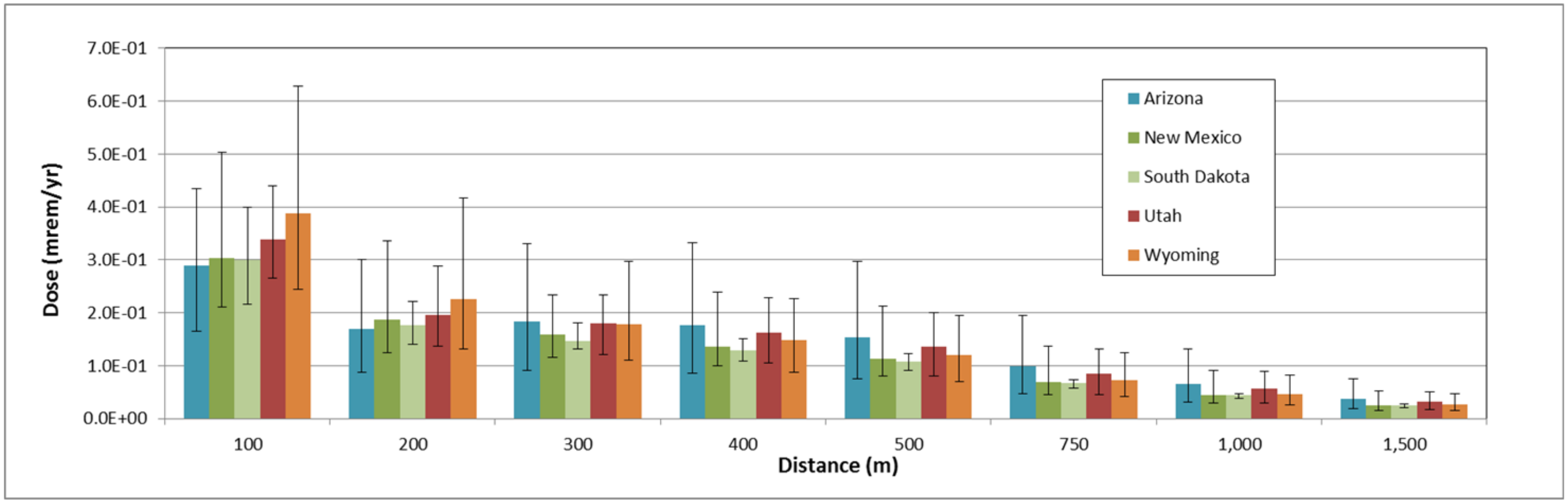

Figure A-7. Average and Range of Maximum Radiation Dose to an Offsite Resident Living in the Vicinity of a Medium/Large Mine Site in Different States

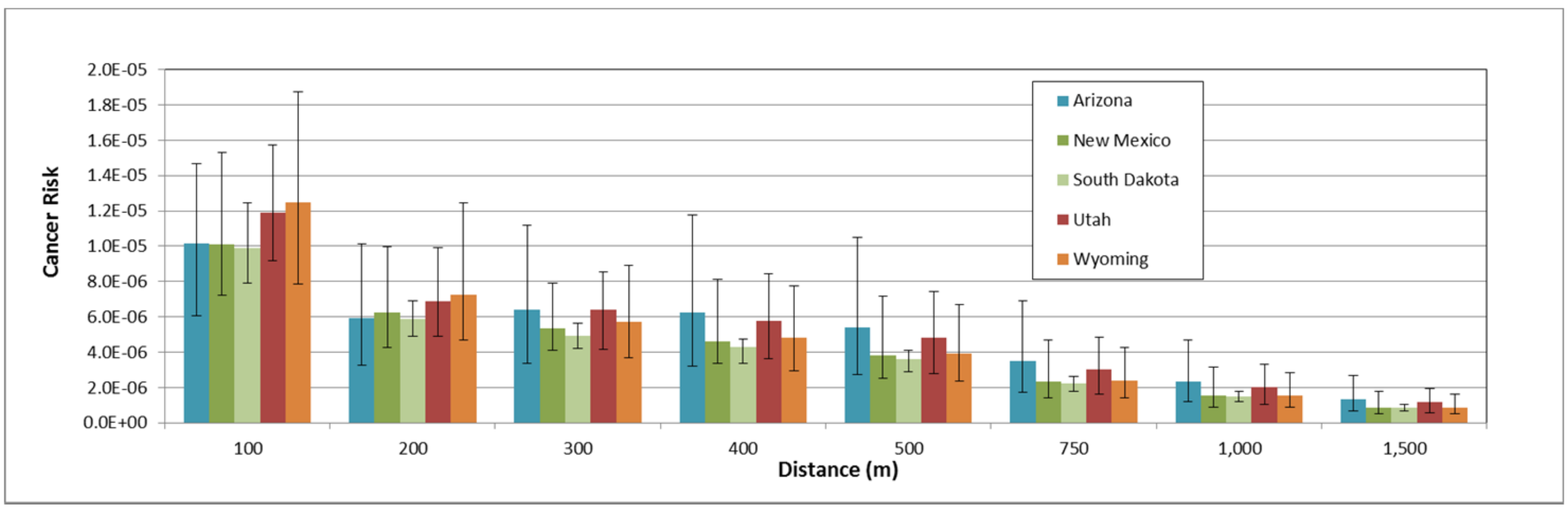

Figure A-8. Average and Range of Maximum Cancer Risk to an Offsite Resident Living in the Vicinity of a Medium/Large Mine Site in Different States

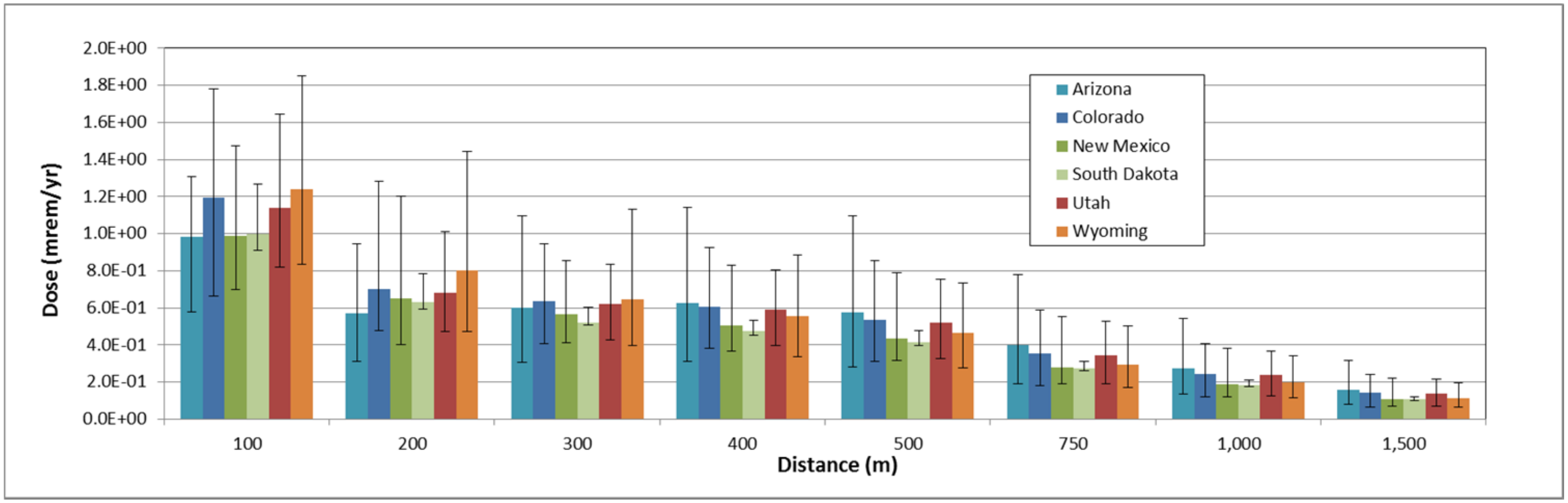

Figure A-9. Average and Range of Maximum Radiation Dose to an Offsite Resident Living in the Vicinity of a Large Mine Site in Different States

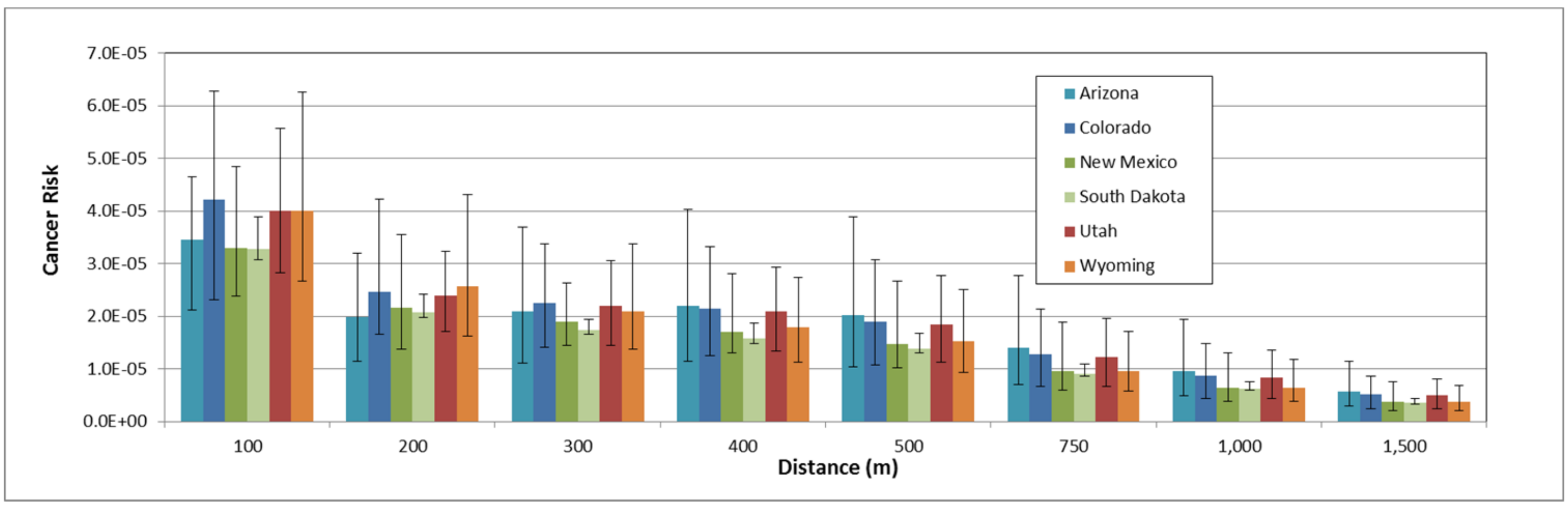

Figure A-10. Average and Range of Maximum Cancer Risk to an Offsite Resident Living in the Vicinity of a Large Mine Site in Different States

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