Appendix F

Human Health Impacts Primer and Details for Estimating Health Impacts to Workers from Yucca Mountain Repository Operations

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APPENDIX F. HUMAN HEALTH IMPACTS PRIMER AND DETAILS FOR ESTIMATING HEALTH IMPACTS TO WORKERS FROM YUCCA MOUNTAIN REPOSITORY OPERATIONS

Section F.1 of this appendix contains information that supports the estimates of human health and safety impacts in this environmental impact statement (EIS). Specifically, Section F.1 is a primer that explains the natures of radiation and toxic materials, where radiation comes from in the context of the radiological impacts discussed in this EIS, how radiation interacts with the human body to produce health impacts, and how toxic materials interact with the body to produce health impacts. The remainder of the appendix discusses the methodology that was used to estimate worker health impacts and the input data to the analysis, and presents the detailed results of the analysis of worker health impacts.

Section F.2 discusses the methodology and data that the U.S. Department of Energy (DOE) used to estimate worker health and safety impacts for the Proposed Action. It also discusses the detailed results of the impact analysis.

Section F.3 discusses the methodologies and data that DOE used to estimate worker health and safety impacts for Inventory Modules 1 and 2. It also discusses the detailed results of the impact analysis.

Section F.4 discusses the methodology and data that DOE used to estimate worker health and safety impacts for retrieval, should such action become necessary. In addition, it discusses the detailed results from the impact analysis.

Radiological impacts to the public from operations at the Yucca Mountain site could result from release of naturally occurring radon-222 and its decay products in the ventilation exhaust from the subsurface repository operations. The methodology and input data used in the estimates of radiological dose to the public are presented in Appendix G, Air Quality. Outside of the radiation primer, health impacts to the public are not treated in this appendix.

F.1 Human Health Impacts from Exposure to Radioactive and Toxic Materials

This section introduces the concepts of human health impacts as a result of exposure to radiation and potentially toxic materials.

F.1.1 RADIATION AND HUMAN HEALTH

F.1.1.1 Radiation

Radiation is the emission and propagation of energy through space or through a material in the form of waves or bundles of energy called photons, or in the form of high-energy subatomic particles. Radiation generally results from atomic or subatomic processes that occur naturally. The most common kind of radiation is *electromagnetic radiation*, which is transmitted as photons. Electromagnetic radiation is emitted over a range of wavelengths and energies. We are most commonly aware of visible light, which is part of the spectrum of electromagnetic radiation. Radiation of longer wavelengths and lower energy includes infrared radiation, which heats material when the material and the radiation interact, and radio waves. Electromagnetic radiation of shorter wavelengths and higher energy (which are more penetrating) includes ultraviolet radiation, which causes sunburn, X-rays, and gamma radiation.

RADIATION

Radiation occurs on Earth in many forms, either naturally or as the result of human activities. Natural forms include light, heat from the sun, and the decay of unstable radioactive elements in the Earth and the environment. Some elements that exist naturally in the human body and in the environment are radioactive and emit ionizing radiation. For example, one of the naturally occurring isotopes of potassium (essential for health) is radioactive. In addition, isotopes of the naturally occurring uranium and thorium decay series are widespread in the human environment. Human activities have also led to sources of ionizing radiation for various uses, such as diagnostic and therapeutic medicine and nondestructive testing of pipes and welds. Nuclear power generation produces ionizing radiation as well as radioactive materials, which undergo radioactive decay and can continue to emit ionizing radiation for long periods of time.

Ionizing radiation is radiation that has sufficient energy to displace electrons from atoms or molecules to create ions. It can be electromagnetic (for example, X-rays or gamma radiation) or subatomic particles (for example, alpha and beta radiation). The ions have the ability to interact with other atoms or molecules; in biological systems, this interaction can cause damage in the tissue or organism.

F.1.1.2 Radioactivity, Ionizing Radiation, Radioactive Decay, and Fission

Radioactivity is the property or characteristic of an unstable atom to undergo spontaneous transformation (to *disintegrate* or *decay*) with the emission of energy as radiation. Usually the emitted radiation is ionizing radiation. The result of the process, called *radioactive decay*, is the transformation of an unstable atom (a *radionuclide*) into a different atom, accompanied by the release of energy (as radiation) as the atom reaches a more stable, lower energy configuration.

Radioactive decay produces three main types of ionizing radiation—alpha particles, beta particles, and gamma or X-rays—but our senses cannot detect them. These types of ionizing radiation can have different characteristics and levels of energy and, thus, varying abilities to penetrate and interact with atoms in the human body. Because each type has different characteristics, each requires different amounts of material to stop (shield) the radiation. Alpha particles are the least penetrating and can be stopped by a thin layer of material such as a single sheet of paper. However, if radioactive atoms (called radionuclides) emit alpha particles in the body when they decay, there is a concentrated deposition of energy near the point where the radioactive decay occurs. Shielding for beta particles requires thicker layers of material such as several reams of paper or several inches of wood or water. Shielding from gamma rays, which are highly penetrating, requires very thick material such as several inches to several feet of heavy material (for example, concrete or lead). Deposition of the energy by gamma rays is dispersed across the body in contrast to the local energy deposition by an alpha particle. In fact, some gamma radiation will pass through the body without interacting with it.

In a nuclear reactor, heavy atoms such as uranium and plutonium can undergo another process, called *fission*, after the absorption of a subatomic particle (usually a neutron). In fission, a heavy atom splits into two lighter atoms and releases energy in the form of radiation and the kinetic energy of the two new lighter atoms. The new lighter atoms are called fission products. The fission products are usually unstable and undergo radioactive decay to reach a more stable state.

Some of the heavy atoms might not fission after absorbing a subatomic particle. Rather, a new nucleus is formed that tends to be unstable (like fission products) and undergo radioactive decay.

The radioactive decay of fission products and unstable heavy atoms is the source of the radiation from spent nuclear fuel and high-level radioactive waste that makes these materials hazardous in terms of potential human health impacts.

F.1.1.3 Exposure to Radiation and Radiation Dose

Radiation that originates outside an individual's body is called *external* or *direct radiation*. Such radiation can come from an X-ray machine or from *radioactive materials* (materials or substances that contain radionuclides), such as radioactive waste or radionuclides in soil. *Internal radiation* originates inside a person's body following intake of radioactive material or radionuclides through ingestion or inhalation. Once in the body, the fate of a radioactive material is determined by its chemical behavior and how it is metabolized. If the material is soluble, it might be dissolved in bodily fluids and be transported to and deposited in various body organs; if it is insoluble, it might move rapidly through the gastrointestinal tract or be deposited in the lungs.

Exposure to ionizing radiation is expressed in terms of *absorbed dose,* which is the amount of energy imparted to matter per unit mass. Often simply called *dose,* it is a fundamental concept in measuring and quantifying the effects of exposure to radiation. The unit of absorbed dose is the *rad.* The different types of radiation mentioned above have different effects in damaging the cells of biological systems. *Dose equivalent* is a concept that considers (1) the absorbed dose and (2) the relative effectiveness of the type of ionizing radiation in damaging biological systems, using a radiation-specific quality factor. The unit of dose equivalent is the *rem.* In quantifying the effects of radiation on humans, other types of concepts are also used. The concept of *effective dose equivalent* is used to quantify effects of radionuclides in the body. It involves estimating the susceptibility of the different tissue in the body to radiation to produce a tissue-specific weighting factor. The weighting factor is based on the susceptibility of that tissue to cancer. The sum of the products of each affected tissue's estimated dose equivalent multiplied by its specific weighting factor is the *effective dose equivalent.* The potential effects from a one-time ingestion or inhalation of radioactive material are calculated over a period of 50 years to account for radionuclides that have long half-lives and long residence time in the body. The result is called the *committed effective dose equivalent.* The unit of effective dose equivalent is also the *rem. Total effective dose equivalent* is the sum of the committed effective dose equivalent from radionuclides in the body plus the dose equivalent from radiation sources external to the body (also in rem). All estimates of dose presented in this environmental impact statement, unless specifically noted as something else, are total effective dose equivalents, which are quantified in terms of rem or millirem (which is one one-thousandth of a rem).

More detailed information on the concepts of radiation dose and dose equivalent are presented in publications of the National Council on Radiation Protection and Measurements (DIRS 101857-NCRP 1993, p. 16-25) and the International Commission on Radiological Protection (DIRS 101836-ICRP 1991, p. 4-11). The DOE implementation guide for occupational exposure assessment (DIRS 138429-DOE 1998, pp. 3 to 11) also provides additional information.

FISSION

Fission is the process whereby a large nucleus (for example, uranium-235) absorbs a neutron, becomes unstable, and splits into two fragments, resulting in the release of large amounts of energy per unit of mass. Each fission releases an average of two or three neutrons that can go on to produce fissions in nearby nuclei. If one or more of the released neutrons on the average causes additional fissions, the process keeps repeating. The result is a self-sustaining chain reaction and a condition called criticality. When the energy released in fission is controlled (as in a nuclear reactor), it can be used for various benefits such as to propel submarines or to provide electricity that can light and heat homes.

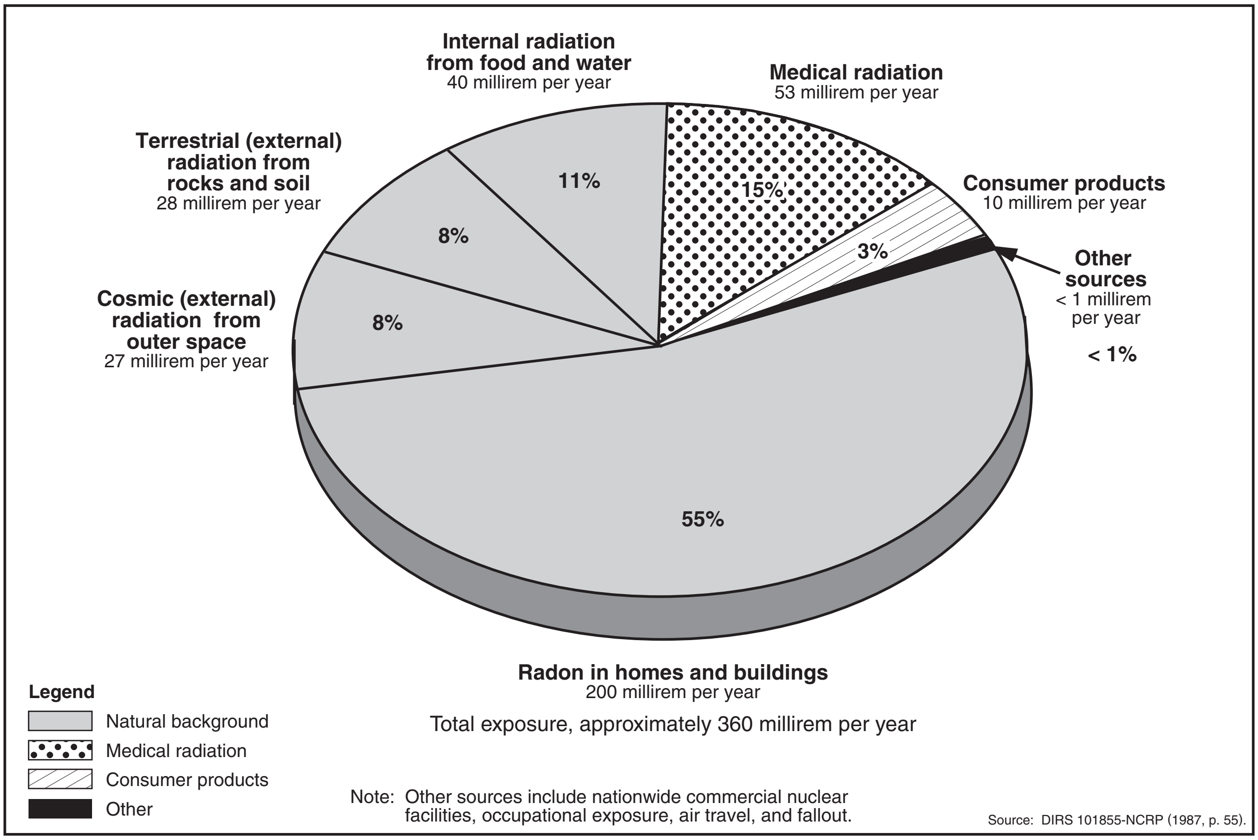
The factors used to convert estimates of radionuclide intake (by inhalation or ingestion) to dose are called *dose conversion factors*. The National Council on Radiation Protection and Measurements and Federal agencies such as the U.S. Environmental Protection Agency publish these factors (DIRS 101882 and 101883-NCRP 1996, all; DIRS 107684-Eckerman and Ryman 1993, all; DIRS 101069-Eckerman, Wolbarst, and Richardson 1988, all). They are based on original recommendations of the International Commission on Radiological Protection (DIRS 101075-ICRP 1977, all).

The radiation dose to an individual or to a group of people can be expressed as the total dose received or as a dose rate, which is dose per unit time (usually an hour or a year).

Collective dose is the total dose to an exposed population. *Person-rem* is the unit of collective dose. Collective dose is calculated by summing the individual dose to each member of a population. For example, if 100 workers each received 0.1 rem, then the collective dose would be 10 person-rem (100 × 0.1 rem).

F.1.1.4 Background Radiation from Natural Sources

Nationwide, on average, members of the public are exposed to approximately 360 millirem per year from natural and manmade sources (DIRS 101855-NCRP 1987, p. 53). Figure F-1 shows the relative contributions by radiation sources to people living in the United States (DIRS 101855-NCRP 1987, p. 55).



Note: Other sources include nationwide commercial nuclear facilities, occupational exposure, air travel, and fallout.

Source: DIRS 101855-NCRP (1987, p. 55).

Figure F-1. Sources of radiation exposure.

The estimated average annual dose rate from natural sources is only about 300 millirem per year. This represents about 80 percent of the annual dose received by an average member of the U.S. public. The largest natural sources are radon-222 and its radioactive decay products in homes and buildings, which contribute about 200 millirem per year. Additional natural sources include radioactive material in the Earth (primarily the uranium and thorium decay series, and potassium-40) and cosmic rays from space filtered through the atmosphere. With respect to exposures resulting from human activities, medical exposure accounts for 15 percent of the annual dose, and the combined doses from weapons testing fallout, consumer and industrial products, and air travel (cosmic radiation) account for the remaining 3 percent of the total annual dose. Nuclear fuel-cycle facilities contribute less than 0.1 percent (0.005 millirem per year per person) of the total dose (DIRS 101855-NCRP 1987, pp. 52 to 56).

F.1.1.5 Impacts to Human Health from Exposure to Radiation

Exposures to radiation or radionuclides are often categorized as being either acute or chronic. Acute exposures occur over a short period. Chronic exposures occur over longer periods (months to years); they are usually continuous over the period, even though the dose rate might vary. For a given dose of radiation, chronic radiation exposure is usually less harmful to the body than an acute exposure because the dose rate (dose per unit time, such as rem per hour) is lower, providing more opportunity for the body to repair the damaged cells (DIRS 101836-ICRP 1991, p. 107).

Acute Exposures at High Dose Rates

Exposure to high levels of radiation at high dose rates over a short period, typically 24 hours or less, can result in acute radiation effects, called *radiation sickness*. If the dose is sufficiently high, death is the eventual result of radiation sickness. At lower doses, recovery can occur, depending on the dose rate and the extent of medical intervention. External (rather than internal) exposures are generally of most concern during a high dose rate, acute exposure event. In such a situation, the biological effects depend more on absorbed dose received than on dose equivalent (DIRS 155674-Hall 1978, p. 106-107).

For external exposures, minor changes in blood characteristics might occur at doses in the range of 25 to 50 rad. The external symptoms of radiation sickness begin to appear when exposures are about 100 rads or greater. Symptoms can include anorexia, nausea, and vomiting. More severe symptoms occur at higher doses and can include death at doses higher than 200 to 300 rad of total body irradiation, depending on the level of medical treatment received. Information on the effects on humans of acute exposures can be obtained from studies of the survivors of the Hiroshima and Nagasaki bombings during World War II and from studies following a number of acute external exposure events (DIRS 102185-Mettler and Moseley 1985, pp. 276-280).

Other effects can follow acute exposures to specific portions of the body. Temporary sterility in men and women has been observed following irradiation of the gonads to doses in the tens to hundreds of rads. Erythema (reddening of the skin) can occur when the skin is exposed to high doses of low-energy radiation (DIRS 108074-Cember 1983, pp. 181-184). In patients treated with external radiation beams for cancer therapy, pulmonary fibrosis or other lung disorders can occur.

As noted above, acute exposures have occurred following detonations of nuclear weapons, both in wartime and during weapons testing, and in other events involving testing of nuclear materials. In addition, there is a potential for acute exposures in the event of an accident at an operating nuclear electric generating station, although Nuclear Regulatory Commission regulations require that the electric utilities design their stations such that these events are extremely unlikely. Such exposures could occur only if there were a highly unlikely failure of the containment vessel surrounding the nuclear reactor and a large release of fission products from the generating station following an accident.

In contrast, accidents during the shipment of spent nuclear fuel or high-level radioactive waste do not have the potential to release sufficient fission products to lead to acute exposures that might immediately threaten the life of the surrounding public. This is because the fission product source term in the spent nuclear fuel would have decayed by a factor of 10,000 or more by the time DOE shipped the material to the proposed repository. Thus, there would not be sufficient energy generated by the fission products in the spent nuclear fuel being shipped to melt the fuel elements and vaporize fission products, as postulated for an accident at an operating nuclear electric generating station.

In the highly unlikely event of an accident during shipment of spent nuclear fuel that is severe enough to breach the shipping cask and rupture the contained spent nuclear fuel, there would be a potential to release fission products to the environment, as discussed in Chapter 6. Following such an event, the principal human exposure pathways would be inhalation or ingestion of released long-lived radioactive fission products. Such an intake of radioactivity could result in a continuing chronic exposure to an individual, but not an acute exposure. Continuing chronic exposures are discussed in the following subsection.

Exposures at Low Dose Rates Including Chronic Exposures

The radiation dose estimates discussed in this EIS are associated with exposure to radiation at low dose rates. Such exposures can be chronic (continuous or nearly continuous), such as those to workers during repository operation, or those to members of the public from the low concentrations of radon-222 and its decay products released in the exhaust from the repository. In some instances, exposures to low levels of radiation would be intermittent (for example, infrequent exposures to an individual from radiation emitted from shipping casks as they are transported). Cancer induction is the principal potential risk to human health from exposure to low levels of radiation. This cancer induction is a statistical process, however, in that exposure to radiation conveys only a chance of incurring cancer, not a certainty. Further, cancer induction in individuals can occur from other causes, such as exposure to chemical agents or natural causes.

Health effects other than fatal cancers can result from exposure to radiation. The International Commission on Radiological Protection suggested the use of detriment weighting factors that consider the curability rate of nonfatal cancers and the reduced quality of life associated with nonfatal cancers and possible hereditary effects (DIRS 101836-ICRP 1991, p. 22). These effects are very difficult to quantify because nonfatal cancers and hereditary effects can be induced from several other causes. Further, hereditary effects have not been demonstrated in humans as a result of exposure to radiation, even in the Japanese atomic bomb survivor population (DIRS 157315-Boice 1990, all). The risk of both of these life-detriment factors, taken together, is believed to be much smaller than the fatal cancer risk. In addition, the National Research Council Committee on Biological Effects of Ionizing Radiation has stated that cancer induction is the most important somatic effect (DIRS 153007-National Research Council 1980, pp. 2 and 136). While DOE recognizes the existence of health effects other than fatal cancers, DOE acknowledges that these effects are extremely difficult to quantify because of all the other factors in life that can cause these effects; accordingly, these effects are not included in the Final EIS. The Final EIS does present human health effects from exposure to radiation based on the potential for induction of fatal cancers.

There are no data that show a clear link between low levels of radiation exposure and cancer. Most of the data on induction of cancer by radiation comes from studying relatively small numbers of people who have received acute exposures to higher doses of radiation (more than 10 rem over a short period), such as atomic bomb survivors. Utilizing the information obtained at these higher exposure rates to estimate effects at low dose rates requires the assumption of a relationship between the overall exposure and the probability of a health effect. The approach generally used is called the *linear dose effect hypothesis*. This concept is shown in Figure F-2, which uses a hypothetical line to extrapolate dose effects at high dose rates to what might occur at low dose rates. It is obvious from the figure that more than one line or curve could be used to fit the data, all of which was obtained at dose rates above 10 rem. Because there is not a statistically significant number of observed effects in the low-dose-rate region, radiation protection organizations, such as the International Commission on Radiological Protection, have assumed a linear-no-threshold response (DIRS 101857-NCRP 1993, p. 112; DIRS 101836-ICRP 1991, p. 22). Under this

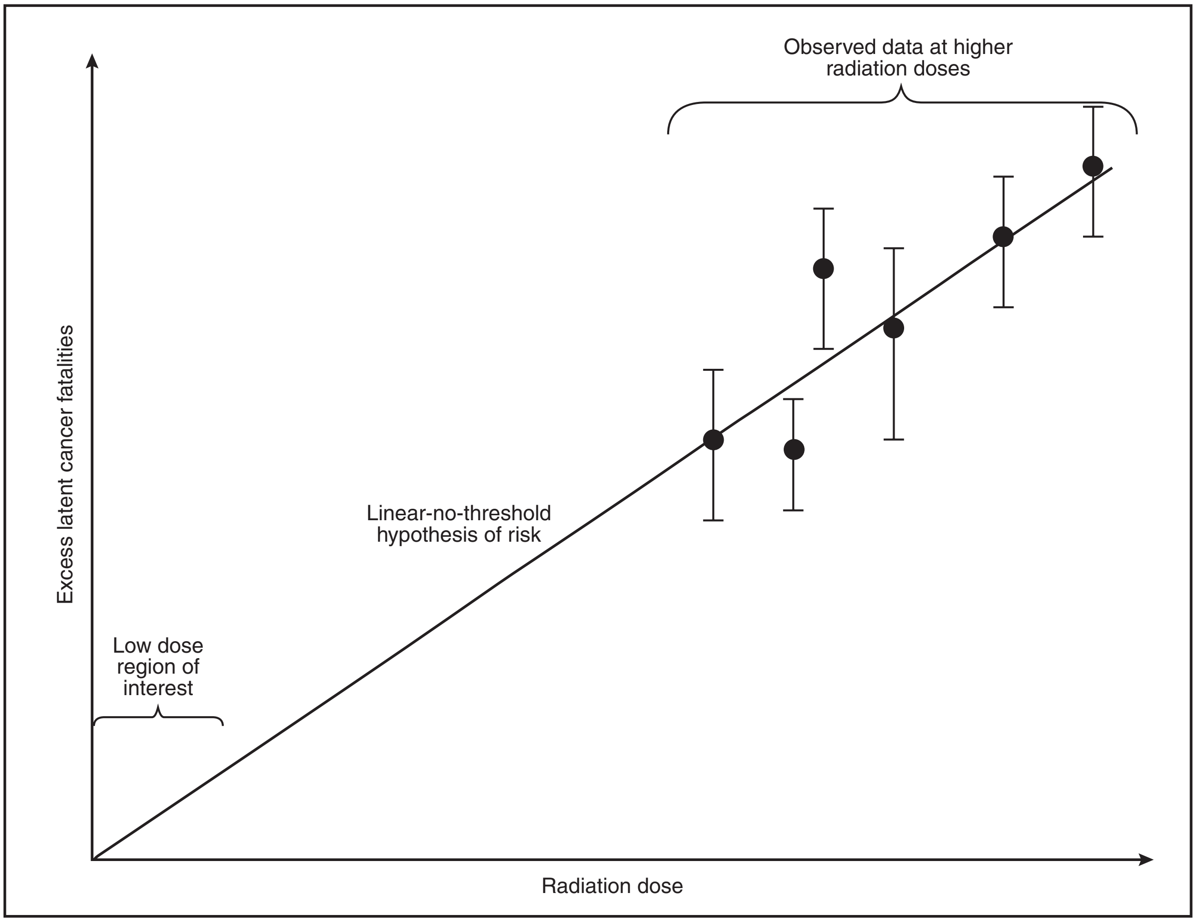


Figure F-2. Assumed linear hypothesis of radiation risks at low doses.

hypothesis, all radiation exposure, no matter how small, involves some risk for inducing cancer and risk increases in proportion to the received dose.

In this EIS, radiological health impacts are expressed as incremental changes in the number of expected fatal cancers (latent cancer fatalities) for the offsite public and for repository workers. Because of the uncertainties in dose response in the low-dose-rate region, the impact estimates provide a general indication of possible health impacts (the potential number of induced cancers) but should not be interpreted as the exact number of induced cancers or as an indication of the individuals in whom cancers might be induced.

Factors Used in this EIS To Convert Accumulated Doses to Health Effects

The factors used to estimate potential health impacts from radiation exposures at low dose rates are based on the dose-to-health-effects conversion factors recommended by the International Commission on Radiological Protection (DIRS 101836-ICRP 1991, p. 22). The Commission estimated that, for the general population, a collective dose of 1 person-rem could yield about 0.0005 excess latent cancer fatality in the exposed population. Because young children are more sensitive to radiation than adults, and because children make up a large part of the general population, the risk conversion factor for the general population is greater than that for a population that includes only workers. Thus, a separate, smaller dose-to-risk conversion factor was recommended for workers (only people older than 18 were considered). The risk factor for workers recommended by the National Council on Radiation Protection and Measurements is 0.0004 excess latent cancer fatality per rem of population exposure (DIRS 101857-NCRP 1993, p. 3).

These concepts can be used to estimate the effects of exposing a population to radiation. For example, if each of 100,000 people was exposed only to background radiation (0.3 rem per year), 15 latent cancer fatalities would be estimated to occur as a result of 1 year of exposure (100,000 persons multiplied by 0.3 rem per year multiplied by 0.0005 latent cancer fatality per person-rem equals 15 latent cancer fatalities per year).

Calculations of the number of latent cancer fatalities associated with radiation exposure normally do not yield whole numbers and, especially in environmental applications, can yield numbers less than 1.0. For example, if each of 100,000 people was exposed to a total dose of 1 millirem (0.001 rem), the population dose would be 100 person-rem, and the corresponding estimated number of latent cancer fatalities would be 0.05 (100,000 persons multiplied by 0.001 rem multiplied by 0.0005 latent cancer fatality per person-rem equals 0.05 latent cancer fatality).

The average number of deaths that would result if the same exposure situation applied to many different groups of 100,000 people is 0.05 for each such group. In most groups, nobody (zero people) would incur a latent cancer fatality from the 1-millirem dose to each member of the group. In a small fraction of the groups, one latent fatal cancer would result; in exceptionally few groups, two or more latent fatal cancers would occur. The average number of deaths over all the groups would be 0.05 latent fatal cancer (just as the average of 0, 0, 0, and 1 is 0.25). The most likely outcome is no latent cancer fatalities in these different groups.

The same concepts apply to estimating the effects of radiation exposure on a single individual. Consider the effects, for example, of exposure to background radiation of 0.3 rem per year over a lifetime. The corresponding likelihood that an individual would experience a radiation-induced latent cancer fatality in that individual’s 70-year lifetime is:

$$
\begin{aligned}
\text{Latent cancer fatality} &= 1 \text{ person} \times 0.3 \text{ rem per year} \times 70 \text{ years} \\
&\quad \times 0.0005 \text{ latent cancer fatality per person-rem} \\
&= 0.011 \text{ latent cancer fatality.}
\end{aligned}
$$

This result must be interpreted in a statistical sense; that is, the estimated effect of background radiation exposure on the exposed individual would produce a 1.1-percent chance that the individual would incur a latent fatal cancer over a 70-year lifetime.

Uncertainty in the Risk Factors for Estimating Health Effects from Low Dose Rate Exposures

The National Council on Radiation Protection and Measurements has stated, “This work indicates that given the sources of uncertainties considered here, together with an allowance for unspecified uncertainties, the values for the lifetime risk can range from about one-fourth or so to about twice the nominal values” (DIRS 101884-NCRP 1997, p. 75). These uncertainties are due, in part, to the fact that the epidemiological studies have been unable to demonstrate that adverse health effects have occurred in individuals exposed to small chronic doses of radiation (less than 10 rem per year) over many years, and to the fact that the extent to which cellular repair mechanisms reduce the likelihood of cancers is unknown. Therefore, the uncertainties indicate that the values used in this EIS probably overestimate the impacts that could occur.

The Environmental Protection Agency recently published an age-specific risk factor of 5.75 chances in 10 million per millirem for fatal cancer (DIRS 153733-EPA 2000, Table 7.3, p. 179). However, DOE currently uses the value of 5.0 and 4.0 chances in 10 million per millirem for fatal cancer for members of the public and workers, respectively, as recommended by the International Commission on Radiological Protection (DIRS 101836-ICRP 1991, p. 22). When recommending these risk factors, the International Commission on Radiological Protection also expressed the desirability, for purposes of radiation protection, of using the same nominal risk factors for both men and women and for a representative population with wide ranges in age. The Commission stated that although there are differences between the sexes and populations of different age-specific mortality rates, these differences are not so large as to necessitate the use of different nominal risk factors. However, the higher risk factor for members of the public compared to that recommended for workers accounts for the fact that children comprise a relatively large part of the population and are more sensitive to the effects of radiation (cancer induction) than adults. Although the embryo-fetus is more radiosensitive (with a radiation risk factor about two times that for the whole population), it is protected by the body of the mother and comprises a small part of the overall population. Pregnant women are not unduly radiosensitive, especially to low levels of radiation.

Both the Environmental Protection Agency and DOE recognize that there are large uncertainties associated with these risk factors, as expressed by the National Council on Radiation Protection and Measurements comment on the result of their uncertainty analysis in the risk coefficients that ". . . show a range (90 percent confidence intervals) of uncertainty values for the lifetime risk for both a population of all ages and an adult worker population from about a factor of 2.5 to 3 below and above the 50th percentile value" (DIRS 101884-NCRP 1997, p. 74). DOE believes that the 15-percent difference in these risk factors is well within other uncertainties and would provide little additional information to the decisionmaking process that this document informs.

Perspectives on Risk

While the risk factors cited above are useful for calculations, comparing them to other risks helps to interpret their meaning. For example, according to statistics published by the Centers for Disease Control, during 1995 the death rate due to cancer in Nevada was 202 cancer deaths per 100,000 persons. The death rate from all causes during that same year was 828 deaths per 100,000; therefore, cancer was responsible for 24 percent of deaths during 1998 (DIRS 153066-Murphy 2000, p. 83).

The long-term risk from exposure to radiation can be placed in perspective by comparison to other risks that are encountered on a daily basis. One method for comparison is the *Loss of Life Expectancy*, which is an estimate of the average number of days of life lost for a given risk factor for a population.

Table F-1 lists Loss of Life Expectancy values for a variety of activities and circumstances. At the bottom of the table is the estimate of Loss of Life Expectancy for several different radiation exposure scenarios.

As discussed in the preceding section, the risk factor (and hence the Loss of Life Expectancy) for radiation exposure is based on an assumption that all radiation exposure carries some risk, even though that assumption has not been proven and might overestimate the true risk from low-level exposure.

F.1.1.6 Exposures from Naturally Occurring Radionuclides in the Subsurface Environment

The estimates of worker doses from inhalation of radon-222 and its decay products while in the subsurface environment and from the ambient radiation fields in the subsurface environment were based on measurements taken in the existing Exploratory Studies Facility drifts. The measurements and the annual dose rates derived from them are discussed below.

Table F-1. Loss of Life Expectancy for causes of death for average citizens of the United States.[a]

Risk factor	Loss of life expectancy (days)
Disease	
Cardiovascular diseases	2,043
Cancer – all types	1,247
Chronic pulmonary	164
Pneumonia	103
Diabetes	82
Tuberculosis	4.7
Influenza	2.3
Accidents	
Motor vehicle accidents	207
Homicide	93
Accidents at home	74
Accidents at work	60
Agriculture	320
Construction	227
Services	27
Radiation exposure	
Lifetime of continuous exposure (100 millirem per year)	15[b]
Single acute exposure of 1 millirem	0.002[b]
Single acute exposure of 1,000 millirem	2.3[b]

a. Tabulated by DIRS 155797-Cohen (1991, Table 3, p. 319).

b. Adapted from methodology presented by DIRS 155797-Cohen (1991, all).

Annual Dose Rate for Subsurface Facility Worker from Inhalation of Radon-222

The annual dose rate for a subsurface worker from inhalation of radon-222 and its decay products was estimated using information developed from radon concentration observations made in the Exploratory Studies Facility subsurface areas during site characterization and subsequent analyses of this data. Two reports (DIRS 152046-DOE 2000, all; DIRS 154176-CRWMS M&O 2000, all) have significantly expanded the available information on radon-222 flux into the repository, radon concentrations in the repository atmosphere, and radon releases from the repository. Additional information on radon release is in Appendix G, Section G.2.3.1.

Recent investigations of radon levels in the repository have led to estimates of radon exposure in Working Level units (DIRS 154176-CRWMS M&O 2000, Attachment 4). The Working Level is the common unit for expressing radon decay product exposure rates. The Working Level was originally developed for use in uranium mines but now is used for environmental exposures as well. Numerically, the Working Level is any combination of short-lived decay products in 1 liter of air that will result in the emission of 1.3×10^5 million electron volts of potential alpha energy. When radon is in complete equilibrium with its short-lived decay products, one Working Level equals 100 picocuries per liter (DIRS 153691-NCRP 1988, p. 17); that is, 100 picocuries per liter each of radon-222 and short-lived decay products polonium-218, lead-214, bismuth-214, and polonium-214. The advantage of the Working Level concept is that different equilibrium levels and different concentrations of radon decay products can be expressed and compared in a common unit. Differences in the activity concentrations between radon-222 and the short-lived decay products are considered using an equilibrium factor (DIRS 103279-ICRP 1994, p. 4). The degree of equilibrium is a critical factor for estimating inhalation exposure and is as important as the radon concentration itself (DIRS 153691-NCRP 1998, p. 19). The Working Level unit considers this factor.

The exposure of workers can be expressed in units of Working-Level Months, which is an exposure rate of 1 Working Level for a working month of 170 hours (DIRS 153691-NCRP 1988, p. 17). Working-Level Months can be converted to more familiar dose units of millirem or rem using a conversion factor of 0.5 rem (500 millirem) per Working-Level Month for inhalation of radon decay products by workers (DIRS 103279-ICRP 1994, p. 24). This dose conversion factor corresponds to 0.029 millirem per picocurie per liter per hour for radon decay products in complete equilibrium with the radon-222 parent (DIRS 103279-ICRP 1994, p. 5).

Average hourly dose rates were estimated for workers in the access mains and ramps, the emplacement drifts and similar 5.5-meter- (18-foot)- diameter drifts, and the overall repository with and without concrete liners, which would reduce the radon flux into the repository. The 5.5-meter drifts would not have concrete liners. These would be the main areas of the repository occupied by workers. Hourly dose rate estimates were developed for involved and noninvolved workers based on their likely work locations, which would also depend on the project phase or activity. Estimated hourly dose rates for involved and noninvolved workers, as well as estimates of the annual dose from radon based on 2,000 hours of occupational exposure in the repository, are listed in Table F-2.

Table F-2. Estimated dose rates to subsurface workers from inhalation of radon.[a]

Project phase and activity	Hourly dose rate (millirem per hour)	Annual dose rate (millirem per year)[b]
Construction		
Involved worker	0.10	200
Noninvolved worker	0.03	60
Operation and Monitoring		
Development		
Involved worker	0.10	200
Noninvolved worker	0.03	60
Emplacement		
Involved worker	0.06	120
Noninvolved worker	0.010	20
Monitoring		
Involved worker	0.050	100
Noninvolved worker	0.010	20
Closure		
Involved worker	0.010	20
Noninvolved worker	0.010	20

a. Numbers are rounded to two significant figures.
b. Based on 2,000 hours per year of occupational exposure in the repository.

In general, workers spending time in subsurface areas without concrete liners and with ventilation flow would have the highest exposures to radon and its decay products. These would be the involved workers during the construction phase and during the drift development period of the operation and monitoring phase. Noninvolved workers would spend more time in the access mains and ramps, with correspondingly less exposure from inhalation of radon decay products. By the end of the development period, all concrete liners would be in place, and exposures to radon decay products would be lower for workers during monitoring and closure. Involved workers during the monitoring period would receive moderate doses because they would be in all areas of the repository, including areas with exhaust from unlined drifts [such as emplacement drifts and other 5.5-meter (18-foot)-diameter drifts].

Annual Dose for Subsurface Facility Worker from Ambient External Radiation in Drifts

Workers in the subsurface facility would be exposed to external radiation from naturally occurring radionuclides in the rock. Measured exposure rates for the subsurface facility ranged from 0.014 to 0.038

millirem per hour (DIRS 104544-CRWMS M&O 1999, p. 12). As for inhalation dose estimates, the analysis assumed an underground exposure time of 2,000 hours per year. The estimated dose range to a worker in the repository from ambient external radiation would be from 28 to 76 millirem per year, with the center of the range being 50 millirem per year. This central estimate was used in this appendix for calculating worker dose estimates from ambient external radiation.

F.1.2 EXPOSURE TO TOXIC OR HAZARDOUS MATERIALS

When certain natural or manmade materials or substances have harmful effects that are not random or do not occur solely at the site of contact, the materials or substances are described as toxic. Toxicology is the branch of science dealing with the toxic effects that chemicals or other substances might have on living organisms.

Chemicals can be toxic for many reasons, including their ability to cause cancer, to harm or destroy tissue or organs, or to harm body systems such as the reproductive, immune, blood-forming, or nervous systems. The following list provides examples of substances that can be toxic:

- Carcinogens, which are substances known to cause cancer in humans or in animals. If cancers have been observed in animals, they could occur in humans. Examples of generally accepted human carcinogens include asbestos, benzene, and vinyl chloride (DIRS 103672-Kamrin 1988, pp. 37 and 38 and Chapter 6).

- Chemicals that controlled studies have shown to cause a harmful or fatal effect. Examples include metals such as cadmium, lead, and mercury; strong acids such as nitric acid and sulfuric acid; some welding fumes; coal dust; sulfur dioxide; and some solvents.

- Some biological materials, including various body fluids and tissues and infectious agents, are toxic.

Even though chemicals might be toxic, many factors influence whether or not a particular substance has a toxic effect on humans. These factors include (1) the amount of the substance with which the person comes in contact, (2) whether the person inhales or ingests a relatively large amount of the substance in a short time (acute exposure) or repeatedly ingests or inhales a relatively small amount over a longer time (chronic exposure), and (3) the period of time over which the exposure occurs.

Scientists determine a substance's toxic effect (or toxicity) by performing controlled tests on animals. In addition to environmental and physical factors, these tests help establish three other important factors for measuring toxicity—dose-response relationship, threshold concept, and margin of safety. The dose-response relationship relates the percentage of test animals that experience observable toxic effects to the doses administered. After the administration of an initial dose, the dose is increased or decreased until, at the upper end, all animals are affected and, at the lower end, no animals are affected. Thus, there is a threshold concentration below which there is no effect. The margin of safety is an arbitrary separation between the highest concentration or exposure level that produces no adverse effect in a test animal species and the concentration or exposure level designated safe for humans. There is no universal margin of safety. For some chemicals, a small margin of safety is sufficient; others require a larger margin.

Two substances in the rock at Yucca Mountain, crystalline silica and erionite, are of concern as potentially toxic or hazardous materials. Both of these naturally occurring compounds occur in the parent rock at the repository site, and excavation activities could encounter them. The following paragraphs contain additional information on these.

Crystalline Silica

Crystalline silica is a naturally occurring, highly structured form of silica (silicon dioxide, SiO_2). Because it can occur in several different forms, including quartz, cristobalite, and tridymite, it is called a *polymorph*. These three forms occur in the welded tuff parent rock at Yucca Mountain (DIRS 104494-CRWMS M&O 1998, p. 25). Crystalline silica is a known causative agent for *silicosis*, a destructive lung condition caused by deposition of particulate matter in the lungs and characterized by scarring of lung tissue. It is contracted by prolonged exposure to high levels of respirable silica dust or an acute exposure to even higher levels of respirable silica dust (DIRS 103243-EPA 1996, Chapter 8). Accordingly, DOE considers worker inhalation of respirable crystalline silica dust particles to be hazardous to worker health. Current standards for crystalline silica have been established to prevent silicosis in workers.

Cristobalite and tridymite have a lower exposure limit than does quartz. The limits for these forms of silica include the Permissible Exposure Limits established by the Occupational Safety and Health Administration and the Threshold Limit Value defined by the American Conference of Governmental Industrial Hygienists. The Occupational Safety and Health Administration Permissible Exposure Limit for cristobalite or tridymite is 50 micrograms per cubic meter averaged over a 10-hour work shift. The American Conference of Governmental Industrial Hygienists Threshold Limit Value is also 50 micrograms per cubic meter, but it is averaged over an 8-hour work shift (DIRS 103674-NJDHSS 1996, all). Thus, the two limits are essentially the same. In accordance with DOE Order 440.1A (DIRS 138429-DOE 1998, p. 5), the more restrictive value provided by the American Conference of Governmental Industrial Hygienists will be applied. In addition, the National Institute for Occupational Safety and Health has established Immediately-Dangerous-to-Life-and-Health concentration limits at levels of 50,000 and 25,000 micrograms per cubic meter for quartz and cristobalite, respectively (DIRS 147940-NIOSH 1996, p. 2). These limits are based on the maximum airborne concentrations an individual could tolerate for 30 minutes without suffering symptoms that could impair escape from the contaminated area or irreversible acute health effects.

There is also evidence that silica may be a carcinogen. The International Agency for Research on Cancer has classified crystalline silica and cristobalite as a Class I (known) carcinogen (DIRS 100046-IARC 1997, pp. 205 to 210). The National Institute for Occupational Safety and Health considers crystalline silica to be a potential carcinogen, as defined by the Occupational Safety and Health Administration's carcinogen policy (29 CFR Part 1990). The National Institute for Occupational Safety and Health is reviewing data on carcinogenicity, which could result in a revised limit for crystalline silica. The Environmental Protection Agency has noted an increase in cancer risk to humans who have already developed the adverse noncancer effects of silicosis, but the cancer risk to otherwise healthy individuals is not clear (DIRS 103243-EPA 1996, pp. 1 to 5).

Because there are no specific limits for exposure of members of the public to crystalline silica, this analysis used a comparative benchmark of 10 micrograms per cubic meter, based on a cumulative lifetime exposure limit of 1,000 micrograms per (cubic meter multiplied by years). At this level, an Environmental Protection Agency health assessment has stated that there is a less than 1-percent chance of silicosis (DIRS 103243-EPA 1996, Chapter 1, p. 5, and Chapter 7, p. 5). Over a 70-year lifetime, this cumulative exposure benchmark would correspond to an annual average exposure concentration of about 14 micrograms per cubic meter, which was rounded down to 10 micrograms per cubic meter to establish the benchmark. Appendix G, Section G.1 contains additional information on public exposure to crystalline silica.

Samples of the welded tuff parent rock from four boreholes at Yucca Mountain have an average quartz content of 15.7 percent, an average cristobalite content of 16.3 percent, and an average tridymite content of 3.5 percent (DIRS 104494-CRWMS M&O 1998, p. I-1). Worker protection during excavation in the subsurface would be based on the more restrictive Threshold Limit Value for cristobalite. The analysis assumed that the parent rock and dust would have a cristobalite content of 28 percent, which is the higher end of the concentration range reported in DIRS 104523-CRWMS M&O (1999, p. 4-81). Thus, the assumed percentage of cristobalite in dust probably overestimated the airborne cristobalite concentration. Also, studies of both ambient and occupational airborne crystalline silica have shown that most of the airborne crystalline silica is coarse and not respirable (greater than 5 micrometers aerodynamic diameter), and the larger particles deposit rapidly on the surface (DIRS 103243-EPA 1996, p. 3-26).

Erionite

Erionite is a natural fibrous zeolite that occurs in the rock layers below the proposed repository level in the hollows of rhyolitic tuffs and in basalts. It might also occur in rock layers above the repository level but has not been found in those layers. Erionite is a rare tectosilicate zeolite with hexagonal symmetry that forms wool-like fibrous masses (with a maximum fiber length of about 50 microns, which is generally shorter than asbestos fibers) (DIRS 102057-HHS 1994, p. 134).

There are no specific limits for exposure to erionite. Descriptive studies have shown very high mortality from cancer [malignant mesothelioma, mainly of the pleura (a lung membrane)] in the population of three Turkish villages in Cappadocia where erionite is mined. The International Agency for Research on Cancer has indicated that these studies demonstrate the carcinogenicity of erionite to humans. The Agency classifies erionite as a Group 1 (known) carcinogen (DIRS 103278-IARC 1987, all).

Erionite could become a potential hazard during excavation of access tunnels to the lower block and to offset areas for all operating modes or during vertical boring operations necessary to excavate ventilation shafts. DOE does not expect to encounter erionite layers during the vertical boring operations, which would be through rock layers above known erionite layers, or during excavation of access tunnels to the lower block or offset Area 5, where any identified layers of erionite would likely be avoided (DIRS 104532-McKenzie 1998, all). In accordance with the Erionite Protocol (DIRS 104527-YMP 1995, all), a task-specific health and safety plan would be prepared before the start of boring operations to identify this material and prevent worker inhalation exposures from unconfined material.

The Los Alamos National Laboratory is studying the mineralogy and geochemistry of the deposition of erionite under authorization from the DOE Office of Science. Laboratory researchers are applying geochemical modeling so they can understand the factors responsible for the formation of zeolite assemblages in volcanic tuffs. The results of this modeling will be used to predict the distribution of erionite at Yucca Mountain and to assist in the planning of excavation operations so erionite layers are avoided.

F.1.3 EXPOSURE PATHWAYS

Four conditions must exist for there to be a pathway from the source of released radiological or toxic material to a person or population (DIRS 102174-Maheras and Thorne 1993, p. 1):

- A source term: The material released to the environment, including the amount of radioactivity (if any) or mass of material, the physical form (solid, liquid, gas), particle size distribution, and chemical form
- An environmental transport medium: Air, surface water, groundwater, or a food chain
- An exposure route: The method by which a person can come in contact with the material (for example, external exposure from contaminated ground, immersion in contaminated air or internal exposure from inhalation or ingestion of radioactive or toxic material)
- A human receptor: The person or persons potentially exposed; the level of exposure depends on such factors as location, duration of exposure, time spent outdoors, and dietary intake

These four elements define an exposure pathway. For example, one exposure scenario might involve release of contaminated gas from a stack (source term); transport via the airborne pathway (transport medium); external gamma exposure from the passing cloud (exposure route); and an onsite worker (human receptor). Another exposure scenario might involve a volatile organic compound as the source term, release to groundwater as the transport medium, ingestion of contaminated drinking water as the exposure route, and offsite members of the public as the human receptors. No matter which pathway the scenario involves, local factors such as water sources, agriculture, and weather patterns play roles in determining the importance of the pathway when assessing potential human health effects.

Worker exposure to crystalline silica (and possibly erionite) in the subsurface could occur from a rather unique exposure pathway. Mechanical drift excavation, shaft boring, and broken rock management activities could create airborne dust comprising a range of particles sizes. Dust particles smaller than 10 micrometers have little mass and inertia in comparison to their surface area; therefore, these small particles could remain suspended in dry air for long periods. Airborne dust concentrations could increase if the ventilation system recirculated the air or if airflow velocity in the subsurface facilities became high enough to entrain dust previously deposited on drift or equipment surfaces. As tunnel boring machines or road headers break the rock from the working face, water would be applied to wet both the working face and the broken rock to minimize airborne dust levels. Wet or dry dust scrubbers would capture dust that was not suppressed by the water sprays. To prevent air recirculation, which would lead to an increase of airborne dust loads, the fresh air intake and the exhaust air streams would be separated. Finally, the subsurface ventilation system would be designed and operated to control ambient air velocities to minimize dust reentrainment. If these engineering controls did not maintain dust concentrations below the Threshold Limit Value concentration, workers would have to wear respirators until engineering controls established habitable conditions.

F.2 Worker Human Health and Safety Impact Analysis for the Proposed Action Inventory

This section discusses the methodologies and data used to estimate industrial and radiological health and safety impacts to workers that would result from the construction, operation and monitoring, and closure of the Yucca Mountain Repository, as well as the detailed results from the impact calculations. Section F.2.1 describes the methods used to estimate impacts, Section F.2.2 contains tabulations of the detailed data used in the impact calculations and references to the data sources, and Section F.2.3 contains a detailed tabulation of results.

For members of the public, the EIS uses the analysis methods in Appendix G, Section G.2, to estimate radiation dose from radon-222 and crystalline silica released in the subsurface ventilation system exhaust. The radiation dose estimates were converted to estimates of human health impacts using the dose conversion factors discussed in Section F.1.1.5. These impacts are expressed as the probability of a latent cancer fatality for a maximally exposed individual and as the number of latent cancer fatalities among members of the public within about 80 kilometers (50 miles) for the Proposed Action, the retrieval contingency, and the inventory modules. The results are listed in Chapter 4, Section 4.1.7.

Health and safety impacts to workers have been estimated for two worker groups: involved workers and noninvolved workers. Involved workers are craft and operations personnel who would be directly involved in activities related to facility construction and operations, including excavation activities; receipt, handling, packaging, and emplacement of spent nuclear fuel and high-level radioactive waste material; monitoring of conditions and performance of the waste packages; and those directly involved in closure activities. Noninvolved workers are managerial, technical, supervisory, and administrative personnel who would not be directly involved in construction, excavation, operations, monitoring, and closure activities. The analysis did not consider project workers who would not be located at the repository site.

DOE considered two spent nuclear fuel packaging scenarios: (1) receipt in an uncanistered form, and (2) receipt in dual-purpose canisters. These two scenarios bound the impacts from packaging scenarios involving canistered forms.

Health and safety impacts to workers were ascertained to be largest for the uncanistered packaging scenarios in the Draft EIS (see Tables 4-32 and 4-33). Thus, the uncanistered scenarios bound the health and safety impacts to workers.

In this appendix, worker impacts are listed for the uncanistered and dual-purpose canister packaging scenarios. DOE analyzed each scenario under a higher-temperature repository operating mode and a range of lower-temperature operating mode scenarios. The lower-temperature scenarios evaluated conservative and realistic combinations of waste package spacing; commercial spent nuclear fuel aging and blending; use of derated packages; and ventilation operating parameters (method and duration). For the lower-temperature operating mode, DOE limited the analysis for dual-purpose canisters to the scenario with the longest ventilation period without aging. The results show that the combination of uncanistered packaging and lower-temperature operating scenarios would have the highest worker health and safety impacts.

Radiological health impacts to the public are independent of the spent nuclear fuel packaging scenarios. Thus, only one set of radiological health impacts to the public was developed and presented in Chapter 4.

F.2.1 METHODOLOGY FOR CALCULATING OCCUPATIONAL HEALTH AND SAFETY IMPACTS

To estimate the impacts to workers from industrial hazards common to the workplace, values for the full-time equivalent work years for each phase of the project were multiplied by the statistic (occurrence per 10,000 full-time equivalent work years) for the impact being considered. Values for the number of full-time equivalent workers for each phase of the project are listed in Section F.2.2.1. The statistics for industrial impacts for each of the phases are listed in Section F.2.2.2 for involved and noninvolved workers.

Two kinds of radiological health impacts to workers are provided in this EIS. The first is an estimate of the latent cancer fatalities to the worker group involved in a particular project phase. The second is the incremental increase in latent cancer fatality probability attributable to occupational radiation for a maximally exposed individual in the worker population for each project phase.

To calculate the expected number of worker latent cancer fatalities during a phase of the project, the collective dose to the worker group, in person-rem, was multiplied by a standard factor for converting the collective worker dose to projected latent cancer fatalities (see Section F.1.1.5). As discussed in Section F.1.1.5, the value of this factor for radiation workers is 0.0004 excess latent cancer fatality per person-rem of dose.

The collective dose for a particular phase of the operation is calculated as the product of the number of exposed full-time equivalent workers for the project phase (see Section F.2.2.1), the average dose over the exposure period, and the fraction of the working time that a worker is in an environment where there is a source of radiation exposure. Values for exposure rates for both involved and noninvolved workers are presented in Section F.2.2.3 as are the fractional occupancy factors. The calculation of collective dose to subsurface workers from exposure to the radiation emanating from the loaded waste packages is an exception. Collective worker doses from this source of exposure were calculated using the methodology described in Subsurface Engineering File, (DIRS 150941-CRWMS M&O 2000, Appendix G). Estimates of annual exposure rates for subsurface workers from radiation emanating from the waste packages are contained in Table G-5 of that document. Tables G-1 through G-4 of that document contain information that supports the annual exposure rates estimates in Table G-5.

To estimate the incremental increase in the likelihood of death from a latent cancer for the maximally exposed individual, the estimated dose to the maximally exposed worker was multiplied by the factor for converting radiation dose to latent cancers. The factor applied for workers was 0.0004 latent cancer fatality per rem, as discussed above and in Section F.1.1.5. Thus, if a person were to receive a dose of 1 rem, the incremental increase in the probability that person would suffer a latent cancer fatality is 1 in 2,500 or 0.0004.

To estimate the dose for a hypothetical maximally exposed individual, the analysis generally assumed that this individual would be exposed to the radiation fields over the entire duration of a project phase or for 50 years, whichever would be shorter (see Section F.2.2.3). Other sources of exposure while working underground would be ambient radiation coming from the radionuclides in the drift walls and from inhalation of radon-222 and its decay products. The radiation from the waste package is usually the dominant component when these three dose contributors are added. Doses for the maximally exposed subsurface worker were estimated by adding the three dose components because they would occur simultaneously.

F.2.2 DATA SOURCES AND TABULATIONS

F.2.2.1 Work Hours for the Repository Phases

Table F-3 lists the number of workers involved in the various repository phases in terms of full-time equivalent work years. Each full-time equivalent work year represents 2,000 work hours (the number of hours assumed for a normal work year). The sources of the values in the table are indicated by the table references and footnotes. The primary sources of the values are the surface and subsurface engineering files.

In estimating work hours for each of the phases, the duration of the phase is one of the important factors. The durations of the monitoring and closure phases are variable for the different designs analyzed. Values for the phase durations for each of the design cases are presented in the footnotes to Table F-3.

F.2.2.2 Workplace Health and Safety Statistics

The analysis selected health and safety statistics for three impact categories—total recordable cases, lost workday cases, and fatalities. Total recordable cases are occupational injuries or illnesses that result in:

- Fatalities, regardless of the time between the injury and death, or the length of the illness
- Lost workday cases, other than fatalities, that result in lost workdays
- Nonfatal cases without lost workdays that result in transfer to another job, termination of employment, medical treatment (other than first aid), loss of consciousness, or restriction of work or motion

Lost workday cases, which are described above, include cases that result in the loss of more than half a workday. These statistical categories, which have been standardized by the U.S. Department of Labor and the Bureau of Labor Statistics, must be reported annually by employers with 11 or more employees. Table F-4 summarizes the health and safety impact statistics used for this analysis.

Table F-4 cites three sets of statistics that were used to estimate total recordable cases and lost workday cases for workers during activities at the Yucca Mountain site. In addition, there is a fourth statistic related to the occupational fatality projections for the Yucca Mountain site activities. The source of information from which the sets of impact statistics were derived is discussed below. All of the statistics are based on DOE experience for similar types of activities and were derived from the DOE CAIRS

Table F-3. Estimated full-time equivalent worker years for repository phases[a] (page 1 of 2).

				Operating mode			
				Higher-temperature		Lower-temperature	
Phase	Subphase	Period	Worker group	UC[b]	DPC[c]	UC (range)	DPC[d]
Construction	Surface[e]	44 months	Involved	2,800	2,500	2,600 - 2,900	2,500
			Noninvolved	1,100	940	990 - 1,100	940
	Subsurface	5 years	Involved	2,700	2,700	2,700	2,700
			Noninvolved	560	560	560	560
	Solar power generating facility	6 years	Involved	76	76	76	76
			Noninvolved	26	26	26	26
	Aging facilities[f]	16 years	Involved	NA[g]	NA	1,300	NA
			Noninvolved	NA	NA	500	NA
	Construction subtotals			7,300	6,800	7,300 - 8,800	6,800
Operations	Surface handling	First 24 years	Involved	23,000	15,000	23,000 - 24,000	15,000
			Noninvolved	8,200	9,300	8,200	9,300
		Last 26 years (aging only)[h]	Involved	NA	NA	13,000	NA
			Noninvolved	NA	NA	4,400	NA
	Subsurface emplacement	First 24 years[i]	Involved	1,800	1,800	1,800 - 2,500	1,800
			Noninvolved	380	380	380 - 530	380
		Last 26 years (aging only)[j]	Involved	NA	NA	1,900	NA
			Noninvolved	NA	NA	420	NA
	Subsurface development	22 years[k]	Involved	6,200	6,200	6,600 - 7,500	6,600
			Noninvolved	2,000	2,000	2200	2,200
	Operations subtotals			4,2000	34,000	42,000 - 63,000	35,000
Monitoring	Surface facility decontamination	3 years	Involved	2,700	2,000	2,200 - 2,700	2,000
			Noninvolved	690	610	610 - 690	610
	Surface	Variable[l]	Involved	2,600	2,600	3,400 - 10,000	10,000
			Noninvolved	0	0	0	0
	Subsurface	Variable[m]	Involved	5,200	5,200	6,800 - 21,000	21,000
			Noninvolved	990	990	1,300 - 3,900	3,900
	Solar panel maintenance	Variable[n]	Involved	180	180	270 - 580	580
	Solar panel replacement	Every 20 years[o]	Involved	36	36	63 - 140	140
	Monitoring subtotals			12,000	12,000	15,000 - 39,000	38,000
Closure	Surface facilities	6 years	Involved	2,900	2,500	2,900	2,500
			Noninvolved	1,100	950	1,100	950
	Subsurface	Variable[p]	Involved	2,400	2,400	2,600 - 4,000	2,600
			Noninvolved	450	450	500 - 770	500
	Solar power generating facility	6 years	Involved	62	62	62	62
			Noninvolved	24	24	24	24
	Closure subtotals			6,900	6,400	7,100 - 8,800	6,700
Totals				***68,000***	***59,000***	***77,000 - 110,000***	***87,000***

Table F-3. Estimated full-time equivalent worker years for repository phases[a] (page 2 of 2).

a. Sources: Derived from DIRS 152010-CRWMS M&O (2000, all); DIRS 150941-CRWMS M&O (2000, all); DIRS 155516-Williams (2001, all); DIRS 155515-Williams (2001, all); DIRS 153882-Griffith (2001, all); DIRS 154758-Lane (2000, all); DIRS 153958-Morton (2000, all).
b. UC = uncanistered packaging scenario.
c. DPC = dual-purpose canister packaging scenario.
d. Values are for the lower-temperature long-term ventilation scenario without aging, which would require the greatest number of worker-years for the dual-purpose canister packaging scenario among the lower-temperature scenarios.
e. For the aging and derated waste package scenarios, the analysis applied the ratios of total buildings size between the higher-temperature scenario and the aging and derated waste package scenarios to calculate worker-year values for surface construction in those scenarios. Those ratios are 0.94 for aging scenarios and 1.04 for the derated waste package scenario.
f. For aging scenarios, the analysis assumed that the worker-year values for construction of the surface aging facility would be four-sevenths of those for a 70,000-MTHM retrieval facility. The analysis further assumed that initial construction of one-eighth of the aging pads would occur over 2 years from 2008 to 2010, and that the remaining aging pads would be constructed over the next 14 years, as needed.
g. NA = not applicable.
h. For the last 26 years of surface handling for the aging scenarios, the scale of waste handling operations in the surface facilities would decrease because no more waste would be received. The analysis assumed that the annual number of workers would be one-half of that for the first 24 years.
i. For the derated waste package scenario, the analysis assumed that the ratio of the number of derated waste packages to the number of higher-temperature mode full-size packages (15,600 : 11,300, or 1.38) would apply to the number of involved and noninvolved workers emplacing those waste packages.
j. For the last 26 years of emplacement for the aging scenarios, while the emplacement rate would be substantially reduced, the analysis conservatively assumed no reduction in annual staffing levels.
k. Though the subsurface development period would remain 22 years, annual staffing would be increased to meet the additional excavation demands for the lower-temperature repository operating mode. For the aging scenarios, the development period could be longer, but the number of worker-years would be the same because the amount of excavation would be the same with or without aging.
l. Surface monitoring periods would extend from the end of surface decontamination to the beginning of closure: higher-temperature, 73 years; lower-temperature with long-term ventilation without aging, 297 years; lower-temperature with long-term ventilation with aging, 271 years; lower-temperature with maximum spacing without aging, 122 years; lower-temperature with maximum spacing with aging, 96 years. For scenarios with aging, monitoring and emplacement activities could overlap for part of the last 26 years of the 50-year aging emplacement period.
m. Subsurface monitoring periods would extend from the end of emplacement to the beginning of closure: higher-temperature, 76 years; lower-temperature with long-term ventilation without aging, 300 years; lower-temperature with long-term ventilation with aging, 274 years; lower-temperature with maximum spacing without aging, 125 years; lower-temperature with maximum spacing with aging, 99 years. For scenarios with aging, monitoring and emplacement activities could overlap for part of the last 26 years of the 50-year aging emplacement period.
n. Solar power facility operations would extend from the beginning of emplacement to the end of monitoring: higher-temperature, 100 years; lower-temperature with long-term ventilation, 324 years; lower-temperature with maximum spacing, 149 years.
o. Solar panels would require replacement every 20 years, involving about 9 worker-years per replacement (6 workers for 3 months for each of 6 arrays). Panels would be replaced 4 times for the 100-year higher-temperature mode operating-period, 16 times during the 324-year lower-temperature with long-term ventilation operating-period, and 7 times during the 149-year lower-temperature with maximum spacing operating-period.
p. Subsurface closure periods: Higher-temperature operating mode, 10 years; lower-temperature operating mode with long-term ventilation with or without aging and with natural ventilation, 11 years; lower-temperature operating mode with long-term ventilation with derated waste packages, 12 years; lower-temperature operating mode with maximum spacing, 17 years.

Table F-4. Health and safety statistics for estimating industrial safety impacts common to the workplace.

Phase	Total recordable cases incidents per 100 FTEs[a]		Lost workday cases per 100 FTEs		Fatalities per 100,000 FTEs (involved and noninvolved)[b]	Data set for TRCs and LWCs[c,d]
	Involved	Noninvolved	Involved	Noninvolved		
Construction						
Surface	6.1	3.3	2.9	1.6	2.9	(1)
Subsurface	6.1	3.3	2.9	1.6	2.9	(1)
Operation and Monitoring						
Operation period						
Surface	3	3.3	1.2	1.6	2.9	(3)
Subsurface - emplacement	3	3.3	1.2	1.6	2.9	(3)
Subsurface - drift development	6.8	1.1	4.8	0.7	2.9	(2)
Monitoring period						
Surface	3	3.3	1.2	1.6	2.9	(3)
Subsurface	3	3.3	1.2	1.6	2.9	(3)
Closure						
Surface	6.1	3.3	2.9	1.6	2.9	(1)
Subsurface	6.1	3.3	2.9	1.6	2.9	(1)

a. FTEs = full-time equivalent worker years.

b. See the discussion about Data Set 4 for source of fatality statistic for normal industrial activities.

c. TRCs = total recordable cases; LWCs = lost workday cases.

d. See text below for source of data in Data Sets 1, 2, and 3.

(Computerized Accident/Incident Reporting and Recordkeeping System) database (DIRS 147938-DOE 1999, all).

Data Set 1, Construction and Construction-Like Activities

This set of statistics from the DOE CAIRS database was applied to construction or construction-like activities. Specifically, it was used for both surface and subsurface workers during the construction phase and the closure phase (closure phase activities were deemed to be construction-like activities). The statistics were based on a 6.75-year period (1992 through the third quarter of 1998).

For involved workers the impact statistic numbers were derived from the totals for all of the DOE construction activities over the period. For noninvolved workers, the values were derived from the combined government and services contractor noninvolved groups for the same period. The noninvolved worker statistic, then, is representative of impacts for oversight personnel who would not be involved in the actual operation of equipment or resources. The basic statistics derived from the CAIRS database for each of the groups include:

- Involved worker total recordable cases: 764 recordable cases for approximately 12,400 full-time equivalent work years
- Involved worker lost workday cases: 367 lost workday cases for approximately 12,400 full-time equivalent work years
- Noninvolved worker total recordable cases: 1,333 recordable cases for approximately 40,600 full-time equivalent work years
- Noninvolved worker lost workday cases: 657 lost workday cases for approximately 40,600 full-time equivalent work years

Data Set 2, Excavation Activities

This set of statistics was derived from experience at the Yucca Mountain Project over a 30-month period (fourth quarter of 1994 though the first quarter of 1997). DOE selected this period because it coincided with the exploratory tunnel boring machine operations at Yucca Mountain, reflecting a high level of worker activity during ongoing excavation activities. This statistic was applied for the Yucca Mountain Project subsurface development period, which principally involves drift development activities. The Yucca Mountain Project experience from which the statistic is derived is presented in Table F-5. DIRS 104543-Stewart (1998, all) contains the Yucca Mountain statistics, which were derived from the CAIRS database (DIRS 147938-DOE 1999, all).

Table F-5. Yucca Mountain Project worker industrial safety loss experience.[a]

Factor	Value[b]	Basis
TRCs[c] per 100 FTEs[d]		
Involved worker	6.8	56 TRCs for 825 construction FTEs
Noninvolved worker	1.1	23 TRCs for 2,015 nonconstruction FTEs
LWCs[e] per 100 FTEs		
Involved worker	4.8	40 LWCs for 825 construction FTEs
Noninvolved worker	0.7	14 LWCs for 2,015 nonconstruction FTEs
Fatality rate occurrence per 100,000 FTEs		
Involved worker	0.0	No fatalities for 825 construction FTEs
Noninvolved worker	0.0	No fatalities for 2,015 nonconstruction FTEs

a. Fourth quarter 1994 through first quarter 1997.
b. Source: Adapted from the CAIRS database (DIRS 147938-DOE 1999, all) by DIRS 104543-Stewart (1998, all) for the fourth quarter of 1994 through the first quarter of 1997.
c. TRCs = total recordable cases.
d. FTEs = full-time equivalent worker years.
e. LWCs = lost workday cases.

Data Set 3, Activities Involving Work in a Radiological Environment

This set of statistics is from the DOE CAIRS database (DIRS 147938-DOE 1999, all). In arriving at the statistics listed in Table F-4, information from the Savannah River Site, the Hanford Site, and the Idaho National Engineering and Environmental Laboratory was averaged individually for the 6.5 years from 1992 through the second quarter of 1998. The averages were then combined to produce an overall average. The reason these three sites were selected as the basis for this set of statistics is that the DOE Savannah River, Hanford, and Idaho National Engineering and Environmental Laboratory sites currently conduct most of the operations in the DOE complex involving handling, sorting, storing, and inspecting spent nuclear fuel and high-level radioactive waste materials, as well as similar activities for low-level radioactive waste materials. The Yucca Mountain Repository phases for which this set of statistics was applied included the receipt, handling, and packaging of spent nuclear fuel and high-level radioactive waste in the surface facilities; subsurface emplacement activities; and surface and subsurface monitoring activities, including decontamination of the surface facilities. These activities involve handling, storing, and inspecting spent nuclear fuel and high-level radioactive waste. The worker activities at the Yucca Mountain site are expected to be similar to those cited above for the other sites in the DOE complex.

The basic statistics for the involved and noninvolved workers include:

- Involved worker total recordable cases: 1,246 for about 41,600 full-time equivalent work years
- Involved worker lost workday cases: 538 for about 41,600 full-time equivalent work years
- Noninvolved worker total recordable cases: 1,333 for about 40,600 full-time equivalent work years
- Noninvolved worker lost workday cases: 657 for about 40,600 full-time equivalent work years

Data Set 4, Statistics for Worker Fatalities from Industrial Hazards

There have been no reported fatalities as a result of workplace activities for the Yucca Mountain project. Similarly, there are no fatalities listed in the Mine Safety and Health Administration database for stone mining workers (DIRS 147939-MSHA n.d., all). Because fatalities in industrial operations sometimes occur, the more extensive overall DOE database was used to estimate a fatality rate for the activities at the Yucca Mountain site. Statistics for the DOE facility complex for the 10 years between 1988 and 1997 were used (DIRS 147938-DOE 1999, all). These fatality statistics are for both government and contractor personnel working in the DOE complex who were involved in the operation of equipment and resources (involved workers). The activities in the DOE complex covered by this statistic were governed by safety and administrative controls (under the DOE Order System) that are similar to the safety and administrative controls that would be applied for Yucca Mountain Repository work. These fatality statistics were also applied to the noninvolved worker population because they are the most inclusive statistics in the CAIRS database. However, the statistics probably are conservatively high for the noninvolved worker group.

F.2.2.3 Estimates of Radiological Exposures

DOE considered the following potential sources of radiation exposure for assessing radiological health impacts to workers:

- Inhalation of gaseous radon-222 and its decay products. Subsurface workers could inhale the radon-222 present in the air in the repository drifts. Workers on the surface could inhale radon-222 released to the environment in the exhaust air from the subsurface ventilation system.

- External exposure of surface workers to radioactive gaseous fission products that could be released during handling and packaging of spent nuclear fuel with failed cladding for emplacement in the repository. Such impacts would be of most concern for the uncanistered packaging scenario.

- Direct external exposure of workers in the repository drifts as a result of naturally occurring radionuclides in the walls of the drifts (primarily potassium-40 and radionuclides of the naturally occurring uranium and thorium decay series).

- External exposure of workers to direct radiation emanating from the waste packages containing spent nuclear fuel and high-level radioactive waste either during handling and packaging (surface facility workers) or after it is placed within the waste package (largely subsurface workers).

Section F.1.1.6 describes the approach taken to estimate exposures to workers as a result of inhalation of gaseous radon-222 released from the drift walls to the subsurface atmosphere. For radon exposures to subsurface workers, the analysis assumed a subsurface occupancy factor of 1.0 for involved workers, an occupancy factor of 0.6 for noninvolved workers for construction and drift development activities, and an occupancy factor of 0.4 for noninvolved workers for emplacement, monitoring, and closure (DIRS 104533-Rasmussen 1998, all; DIRS 104536-Rasmussen 1999, all; DIRS 104528-Jessen 1999, all).

As discussed in Section F.1.1.6, the average concentration of radon-222 and its progeny in the subsurface atmosphere varies with factors such as location within the repository (main drifts or emplacement drifts), whether or not concrete lining is in place in the main drifts, the subsurface ventilation rate, and the repository volume. Table F-2 lists estimated doses to subsurface workers from inhalation of radon-222 and its progeny.

Appendix G, Section G.2.3.2, describes the approach taken to estimate source terms and associated doses to workers from the potential release of gaseous fission products from spent nuclear fuel with failed cladding.

Subsurface workers would also be exposed to background gamma radiation from naturally occurring radionuclides in the subsurface rock (largely from the thorium and uranium-238 decay series radionuclides and from potassium-40, all in the rock). DOE has based its projection of worker external gamma dose rates on the data obtained during Exploratory Studies Facility operations (Sections F.1.1.6 and G.2.3.1). The collective ambient radiation exposures for subsurface workers were calculated assuming occupancy factors cited in the previous paragraph for subsurface workers for emplacement and monitoring activities (DIRS 104533-Rasmussen 1998, all; DIRS 104536-Rasmussen 1999, all; DIRS 104528-Jessen 1999, all). The average exposure level, as listed in Table F-7, is 50 millirem per year.

Estimates of subsurface worker exposure as a result of radiation emanating from the waste packages are developed in subsurface facility engineering file (DIRS 150941-CRWMS M&O 2000, Appendix G). Specifically, Tables G-1, G-2, and G-3 of this engineering file list estimates of exposures from the waste packages in the various repository regions. Table G-5 of this engineering file lists manpower distributions for involved workers who would be exposed to radiation emanating from the waste packages. Tables G-4 and G-6 of the engineering file list estimates of annual exposures from radiation emanating from the waste packages. Table F-6 below summarizes the estimates of subsurface worker exposures from radiation emanating from the waste packages during the operation and monitoring and closure phases.

Table F-6. Estimated annual subsurface worker exposures to radiation emanating from waste packages.[a]

	Operating mode				
		Lower-temperature			
Operations phase	Higher-temperature	Long-term ventilation	Long-term ventilation (natural ventilation after 50 years)	Derated waste packages	Maximum spacing
Emplacement					
First 24 years (person-rem per year)[b]	6.0	6.0	6.0	8.3	6.0
Latter period of emplacement for aging cases (person-rem per year)[c]	N/A[d]	6.0	N/A	N/A	6.0
Monitoring (person-rem per year)[e]	3.7	3.7	3.7	3.7	3.7
Monitoring for natural ventilation period (person-rem per year)[f]	N/A	N/A	1.07	N/A	N/A
Closure (overall exposure in person-rem)[g]	270	300	300	330	460

a. Numbers are rounded to two significant figures.

b. Sources: Tables G-4 and G-6 of the Subsurface Engineering File (DIRS 150941-CRWMS M&O 2000).

c. For aging cases, it is assumed that 90 full-time equivalent workers are retained for emplacement. Annual exposure levels are assumed to be the same as for the first 24 years.

d. N/A = not applicable.

e. Source: Table G-6 of the Subsurface Engineering File (DIRS 150941-CRWMS M&O 2000).

f. It is assumed that the annual exposure from radiation emanating from the waste packages is reduced by the ratio of full-time equivalent workers for the forced ventilation period to those for the 250-year natural ventilation period. See Tables I-18 and I-18a for long-term ventilation in letter update to the Subsurface Engineering File (DIRS 155515-Williams 2001, all).

g. Values derived from Appendixes G and H of the Subsurface Engineering File (DIRS 150941-CRWMS M&O 2000).

Table F-7 summarizes the exposure values used in this appendix for estimating overall worker exposures. Values are presented for both the uncanistered packaging scenario and for the dual-purpose canister packaging scenario where appropriate. The table also lists the references or sources from which the data were obtained.

Table F-8 contains estimates of overall annual radiation exposure to surface workers during the waste package handling and packaging operations in preparation for emplacement. The values for the design case with blending are derived from the values listed in Table 6-2 of the Surface Engineering File (DIRS 152010-CRWMS M&O 2000). The estimates for design cases with surface aging prior to emplacement and for the derated waste package design cases were derived from the supplemental information provided in the surface facilities EIS letter report (DIRS 155516-Williams 2001, Section 3.1).

Table F-7. Radiological exposure data used to calculate worker radiological health impacts[a] (page 1 of 2).

Phase and worker group	Exposure source[b]	Occupancy factor[c]	Annual dose (millirem, except where noted)	Annual full-time equivalent workers[d]			Data source[g]
				Derated waste package	UC[e]	DPC[f]	
Construction							
Surface							
Involved	Radon-222 inhalation	1.0	Small relative to subsurface worker exposures				h
Noninvolved	Radon-222 inhalation	1.0	Small relative to subsurface worker exposures				h
Subsurface							
Involved	Drift ambient	1.0	50				g(1)
	Radon-222 inhalation	1.0	200				Table F-2, g(2)
Noninvolved	Drift ambient	0.6	50				g(1), g(5), g(6)
	Radon-222 inhalation	0.6	60				Table F-2, g(5), g(6)
Surface handling and loading operations							
Involved	Receipt, handling and packaging of spent nuclear fuel and high-level radioactive waste	1.0	Table F-8				See Table F-8
Noninvolved	Receipt, handling and packaging of spent nuclear fuel and high-level radioactive waste	1.0	0				g(7)
Surface							
Involved only	Radon-222 inhalation	1.0	Small relative to subsurface workers				i
Subsurface emplacement							
Involved	Waste package	1.0	Table F-6				Table F-6
	Drift ambient	1.0	50				g(1)
	Radon-222	1.0	120				Table F-2
Noninvolved	Waste package	0.04	200				g(2)
	Drift ambient	0.4	50				g(1), g(5), g(6)
	Radon-222 inhalation	0.4	20				Table F-2, g(5), g(6)
Subsurface drift development							
Involved	Drift ambient	1.0	50				g(1)
	Radon-222 inhalation	1.0	200				Table F-2
Noninvolved	Drift ambient	0.6	50				g(1), g(5), g(6)
	Radon-222 inhalation	0.6	60				Table F-2, g(5), g(6)
Monitoring							
Surface decontamination (postemplacement)							
Involved		1.0	25	2,190	2,663	1,993	g(4), g(8)
Noninvolved		1.0	0	605	689	583	
Subsurface							
Involved	Waste package	1.0	Table F-6				Table F-6
	Drift ambient	1.0	50				g(1)
	Radon-222 inhalation	1.0	100				Table F-2, g(5), g(6)
Noninvolved	Waste package	0.04	200				g(2)
	Drift ambient	0.4	50				g(1), g(5), g(6)
	Radon-222 inhalation	0.4	20				Table F-2, g(5), g(6)
Surface monitoring							
Involved only	Radon-222 inhalation	1.0	Small relative to subsurface workers				j

Table F-7. Radiological exposure data used to calculate worker radiological health impacts[a] (page 2 of 2).

				Annual full-time equivalent workers[d]			
Phase and worker group	Exposure source[b]	Occupancy factor[c]	Annual dose (millirem, except where noted)	Derated waste package	UC[e]	DPC[f]	Data source[g]
Closure							
Surface							
Involved		1.0	Small relative to subsurface worker exposures				k
Noninvolved		1.0	Small relative to subsurface worker exposures				k
Subsurface							
Involved	Waste package	1.0	Table F-6				Table F-6
	Drift ambient	1.0	50				g(1)
	Radon-222 inhalation	1.0	20				Table F-2
Noninvolved	Waste package	0.04	200				g(2)
	Drift ambient	0.4	50				g(1), g(5), g(6)
	Radon-22 inhalation	0.4	20				Table F-2, g(5), g(6)

a. Numbers are rounded to two significant figures.
b. Exposure sources include radiation from spent nuclear fuel and high-level radioactive waste packages to surface and subsurface workers, the ambient exposure to subsurface workers from naturally occurring radiation in the drift walls, and internal exposures from inhalation of radon-222 and its decay products in the drift atmosphere by subsurface workers.
c. Fraction of 8-hour workday that workers are exposed.
d. Number of annual full-time equivalent workers for surface facility activities when the number of workers in each exposure category would vary with packaging scenario.
e. UC = uncanistered packaging scenario.
f. DPC = dual-purpose canister packaging scenario.
g. Sources:
    (1) Section F.1.1.6.
    (2) DIRS 104533-Rasmussen (1998, all).
    (3) DIRS 150941-CRWMS M&O (2000 Subsurface Facility Engineering File, Table G-6).
    (4) DIRS 152010-CRWMS M&O (2000 Surface Engineering File, Table 6-4).
    (5) DIRS 104536-Rasmussen (1999, all).
    (6) DIRS 104528-Jessen (1999, all).
    (7) DIRS 152010-CRWMS M&O (2000 Surface Engineering File, Table 6-2).
    (8) DIRS 155516-Williams (2001, Section 3.1).
h. Comparison of information in Chapter 4, Table 4-2 (surface workers) and Table F-11 (subsurface workers).
i. Comparison of information in Chapter 4, Table 4-5 (surface workers) and Tables F-20 and F-21 (subsurface workers).
j. Comparison of information in Chapter 4, Table 4-7 (surface workers) and Table F-30 (subsurface workers).
k. Comparison of information in Chapter 4, Table 4-5 (surface workers) and Table F-37 (subsurface workers).

Table F-8. Estimates of annual exposures (person-rem per year) for surface facility workers during handling and packaging of waste material for emplacement.[a]

Period	Packaging scenario	Blending	Aging via surface storage	Derated waste packages
First 24 years	Uncanistered	230[b]	240[c]	240[c]
	Dual-purpose canister	120[b]	NA[d]	NA
Latter period for aging cases	NA	NA	160[e]	NA

a. Numbers are rounded to two significant figures.
b. DIRS 152010-CRWMS M&O (2000, Table 6-2).
c. DIRS 155516-Williams (2001, Section 3.1); values adjusted upward by a ratio of 119/117 for the uncanistered case.
d. NA = not applicable to the operation listed.
e. For surface storage cases (aging), it is assumed that the annual average cumulative exposure to surface facility workers is two-thirds that for the first 24 years based on handling of about 2,000 MTHM per year rather than 3,000 MTHM per year.

F.2.3 COMPILATION OF DETAILED RESULTS FOR OCCUPATIONAL HEALTH AND SAFETY IMPACTS

F.2.3.1 Occupational Health and Safety Impacts During the Construction Phase

F.2.3.1.1 *Industrial Hazards to Workers*

Tables F-9 and F-10 list health and safety impacts from industrial hazards to surface and subsurface workers, respectively, for construction activities.

Table F-9. Industrial hazard health and safety impacts to surface facility workers during construction phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	180	160	180 - 210	160
Lost workday cases	84	74	84 - 99	74
Fatalities	0.084	0.074	0.084 - 0.099	0.074
Noninvolved				
Total recordable cases of injury and illness	36	32	36 - 43	32
Lost workday cases	18	16	18 - 21	16
Fatalities	0.032	0.028	0.032 - 0.038	0.028
All workers (totals)[e]				
Total recordable cases of injury and illness	220	190	220 - 250	190
Lost workday cases	100	90	100 - 120	90
Fatalities	0.12	0.10	0.12 - 0.14	0.10

a. Source: Impact rates from Table F-4; includes all construction activities.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-10. Industrial hazard health and safety impacts to subsurface facility workers during construction phase.[a,b]

Worker group	All operating modes
Involved	
Total recordable cases of injury and illness	170
Lost workday cases	79
Fatalities	0.079
Noninvolved	
Total recordable cases of injury and illness	18
Lost workday cases	9
Fatalities	0.016
All workers (totals)[c]	
Total recordable cases of injury and illness	190
Lost workday cases	88
Fatalities	0.095

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. Totals might differ from sums of values due to rounding.

F.2.3.1.2 *Radiological Health Impacts to Workers*

Table F-11 lists subsurface worker health impacts from inhalation of radon-222 in the subsurface atmosphere and from ambient radiation exposure from radionuclides in the rock of the drift walls. The radiological health impacts to surface workers from inhalation of radon-222 would be small in comparison to those for subsurface workers; therefore, they were not tabulated in this appendix (see Table F-7, Footnotes h to k for sources of comparison).

Table F-11. Radiological health impacts to subsurface facility workers from radon exposure and ambient radiation during construction phase.[a,b]

Worker group	Radon	Ambient radiation	Total[c]
Involved worker			
Dose to maximally exposed worker (millirem)	1,000	250	1,300
Probability of latent cancer fatality	0.0004	0.0001	0.00052
Collective dose (person-rem)	550	140	680
Number of latent cancer fatalities	0.22	0.056	0.27
Noninvolved worker			
Dose to maximally exposed worker (millirem)	180	150	330
Probability of latent cancer fatality	0.000072	0.00006	0.00013
Collective dose (person-rem)	20	17	37
Number of latent cancer fatalities	0.008	0.0068	0.015
All workers (totals)[c]			
Dose to maximally exposed worker (millirem)	1,180	400	1,630
Probability of latent cancer fatality	0.000472	0.00016	0.00065
Collective dose (person-rem)	570	160	720
Number of latent cancer fatalities	0.23	0.064	0.29

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. Totals might differ from sums of values due to rounding.

F.2.3.1.3 *Summary of Impacts for Construction Phase*

Table F-12 summarizes the estimated health and safety impacts from industrial hazards. The radiological health impacts were summarized in Table F-11.

Table F-12. Summary of estimated impacts to workers from industrial hazards during construction phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	340	320	340 - 370	320
Lost workday cases	160	150	160 - 180	150
Fatalities	0.16	0.15	0.16 - 0.18	0.15
Noninvolved				
Total recordable cases of injury and illness	55	50	55 - 61	50
Lost workday cases	27	24	27 - 30	24
Fatalities	0.048	0.044	0.048 - 0.054	0.044
All workers (total)[e]				
Total recordable cases of injury and illness	400	370	400 - 430	370
Lost workday cases	190	170	190 - 210	170
Fatalities	0.21	0.19	0.21 - 0.23	0.19

a. Values are sums of values in Tables F-9 and F-10.
b. Includes all construction activities.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.2 Occupational Health and Safety Impacts During the Operations Period

F.2.3.2.1 *Industrial Safety Hazards to Workers*

Table F-13 lists the estimated impacts from industrial hazards for the surface facility workers during waste receipt and packaging, surface storage of waste, retrieval of the waste from surface storage, and preparation of the stored waste for emplacement. Table F-14 lists the estimated impacts from industrial hazards to subsurface workers involved in drift development activities, and Table F-15 lists estimated impacts from industrial hazards to subsurface workers involved in emplacement activities.

Table F-13. Industrial hazard health and safety impacts to surface facility workers involved in waste receipt and packaging activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	690	440	690 - 1,100	440
Lost workday cases	280	180	280 - 430	180
Fatalities	0.67	0.43	0.67 - 1.1	0.43
Noninvolved				
Total recordable cases of injury and illness	270	310	270 - 420	310
Lost workday cases	130	150	130 - 200	150
Fatalities	0.24	0.27	0.24 - 0.37	0.27
All workers (total)[e]				
Total recordable cases of injury and illness	960	750	960 - 1500	750
Lost workday cases	410	330	410 - 630	330
Fatalities	0.91	0.7	0.91 - 1.5	0.7

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-14. Industrial hazard health and safety impacts to subsurface workers involved in drift development activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	420	420	450 - 510	450
Lost workday cases	300	300	320 - 360	320
Fatalities	0.18	0.18	0.19 - 0.22	0.19
Noninvolved				
Total recordable cases of injury and illness	22	22	24	24
Lost workday cases	14	14	15	15
Fatalities	0.058	0.058	0.064	0.064
All workers (total)[e]				
Total recordable cases of injury and illness	440	440	470 - 530	470
Lost workday cases	310	310	340 - 380	340
Fatalities	0.24	0.24	0.25 - 0.28	0.25

a. Source: Calculated using impact rates from Tables F-4 and F-5.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-15. Industrial health hazard and safety impacts to subsurface facility workers involved in emplacement activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	53	53	53 - 110	53
Lost workday cases	21	21	21 - 44	21
Fatalities	0.052	0.052	0.052 - 0.11	0.052
Noninvolved				
Total recordable cases of injury and illness	13	13	13 - 26	13
Lost workday cases	6.1	6.1	6.1 - 13	6.1
Fatalities	0.011	0.011	0.011 - 0.023	0.011
All workers (total)[e]				
Total recordable cases of injury and illness	66	66	66 - 140	66
Lost workday cases	27	27	27 - 57	27
Fatalities	0.063	0.063	0.063 - 0.13	0.063

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.2.2 *Radiological Health Impacts to Workers*

Radiological health impacts to surface and subsurface workers are listed in Tables F-16 through F-21.

- Table F-16 summarizes the radiological health impacts to surface facility workers involved in handling and packaging of incoming waste materials, surface storage of materials, and recovery and repackaging of the stored materials.
- Table F-17 lists radiological health impacts from radiation emanating from waste packages to subsurface workers involved in emplacement activities.
- Table F-18 lists radiological health impacts from ambient radiation emanating from drift walls to subsurface facility workers involved in emplacement activities.
- Table F-19 lists radiological health impacts from ambient radiation emanating from the drift walls to subsurface workers involved in drift development activities.
- Table F-20 lists radiological health impacts from inhalation of radon-222 and its decay products to subsurface workers involved in emplacement activities.
- Table F-21 lists radiological health impacts from inhalation of radon-222 and its decay products to subsurface workers involved in drift development activities.

Table F-16. Estimated exposures and radiological health impacts to surface facility workers during the operations period.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	9,600	9,600	9,600 - 18,000	9,600
Probability of latent cancer fatality	0.0038	0.0038	0.0038 - 0.0072	0.0038
Collective dose (person-rem)	5,500	2,800	5,500 - 9,100	2,800
Number of latent cancer fatalities	2.2	1.1	2.2 - 3.6	1.1
Noninvolved worker				
Dose to maximally exposed worker (millirem)	0	0	0	0
Probability of latent cancer fatality	0	0	0	0
Collective dose (person-rem)	0	0	0	0
Number of latent cancer fatalities	0	0	0	0
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	9,600	9,600	9,600 - 18,000	9,600
Probability of latent cancer fatality	0.0038	0.0038	0.0038 - 0.0072	0.0038
Collective dose (person-rem)	5,500	2,800	5,500 - 9,100	2,800
Number of latent cancer fatalities	2.2	1.1	2.2 - 3.6	1.1

a. Source: Exposure values from Table F-10.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-17. Radiological health impacts from radiation emanating from waste packages to subsurface facility workers involved in emplacement activities.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)[e]	11,000	11,000	11,000 - 22,000	11,000
Probability of latent cancer fatality	0.0044	0.0044	0.0044 - 0.0088	0.0044
Collective dose (person-rem)	140	140	140 - 290	140
Number of latent cancer fatalities	0.056	0.056	0.056 - 0.12	0.056
Noninvolved worker				
Dose to maximally exposed worker (millirem)	190	190	190 - 400	190
Probability of latent cancer fatality	0.000076	0.000076	0.000076 - 0.00016	0.000076
Collective dose (person-rem)	3.1	3.1	3.1 - 6.4	3.1
Number of latent cancer fatalities	0.0012	0.0012	0.0012 - 0.0026	0.0012
All workers (totals)[f]				
Dose to maximally exposed worker (millirem)	11,190	11,190	11,190 - 22,400	11,190
Probability of latent cancer fatality	0.004476	0.004476	0.004476 - 0.00896	0.004476
Collective dose (person-rem)	140	140	140 - 300	140
Number of latent cancer fatalities	0.056	0.056	0.056 - 0.12	0.056

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Maximally exposed individual, (DIRS 150941-CRWMS M&O 2000, Table G-4).
f. Totals might differ from sums of values due to rounding.

Table F-18. Radiological health impacts from ambient radiation to subsurface facility workers involved in emplacement activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	1,200	1,200	1,200 - 2,500	1,200
Probability of latent cancer fatality	0.00048	0.00048	0.00048 - 0.001	0.00048
Collective dose (person-rem)	89	89	89 - 190	89
Number of latent cancer fatalities	0.036	0.036	0.036 - 0.076	0.036
Noninvolved worker				
Dose to maximally exposed worker (millirem)	480	480	480 - 1,000	480
Probability of latent cancer fatality	0.00019	0.00019	0.00019 - 0.0004	0.00019
Collective dose (person-rem)	7.7	7.7	7.7 - 16	7.7
Number of latent cancer fatalities	0.0031	0.0031	0.0031 - 0.006	0.0031
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	1,680	1,680	1,680 - 3,500	1,680
Probability of latent cancer fatality	0.00067	0.00067	0.00067 - 0.0014	0.00067
Collective dose (person-rem)	97	97	97 - 210	97
Number of latent cancer fatalities	0.039	0.039	0.039 - 0.08	0.039

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-19. Radiological impacts from ambient radiation to subsurface workers involved in development activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	1,100	1,100	1,100	1,100
Probability of latent cancer fatality	0.00044	0.00044	0.0004	0.00044
Collective dose (person-rem)	310	310	330 - 370	330
Number of latent cancer fatalities	0.12	0.12	0.13 - 0.15	0.13
Noninvolved worker				
Dose to maximally exposed worker (millirem)	660	660	660	660
Probability of latent cancer fatality	0.00026	0.00026	0.00026	0.00026
Collective dose (person-rem)	60	60	66	66
Number of latent cancer fatalities	0.024	0.024	0.026	0.026
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	1,760	1,760	1,760	1,760
Probability of latent cancer fatality	0.0007	0.0007	0.00066	0.0007
Collective dose (person-rem)	370	370	400 - 440	400
Number of latent cancer fatalities	0.15	0.15	0.16 - 0.18	0.16

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-20. Radiological health impacts from airborne radon-222 to subsurface facility workers involved in emplacement activities.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	2,900	2,900	2,900 - 6,000	2,900
Probability of latent cancer fatality	0.0012	0.0012	0.0012 - 0.0024	0.0012
Collective dose (person-rem)	210	210	210 - 440	210
Number of latent cancer fatalities	0.084	0.084	0.084 - 0.18	0.084
Noninvolved worker				
Dose to maximally exposed worker (millirem)	190	190	190 - 400	190
Probability of latent cancer fatality	0.000076	0.000076	0.000076 - 0.00016	0.000076
Collective dose (person-rem)	3.1	3.1	3.1 - 6.4	3.1
Number of latent cancer fatalities	0.0012	0.0012	0.0012 - 0.0026	0.0012
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	3,090	3,090	3,090 - 6,400	3,090
Probability of latent cancer fatality	0.001276	0.001276	0.001276 - 0.00256	0.001276
Collective dose (person-rem)	210	210	210 - 450	210
Number of latent cancer fatalities	0.084	0.084	0.084 - 0.18	0.084

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-21. Radiological health impacts from airborne radon-222 to subsurface facility workers involved in development activities.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	4,400	4,400	4,400	4,400
Probability of latent cancer fatality	0.0018	0.0018	0.0018	0.0018
Collective dose (person-rem)	1,200	1,200	1,300 - 1,500	1,300
Number of latent cancer fatalities	0.48	0.48	0.52 - 0.60	0.52
Noninvolved worker				
Dose to maximally exposed worker (millirem)	790	790	790	790
Probability of latent cancer fatality	0.00032	0.00032	0.00032	0.00032
Collective dose (person-rem)	72	72	79	79
Number of latent cancer fatalities	0.029	0.029	0.032	0.032
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	5,190	5,190	5,190	5,190
Probability of latent cancer fatality	0.00212	0.00212	0.00212	0.00212
Collective dose (person-rem)	1,300	1,300	1,400 - 1,600	1,400
Number of latent cancer fatalities	0.52	0.52	0.55 - 0.64	0.56

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.2.3 *Summary of Impacts for the Operations Period*

Tables F-22 and F-23 summarize the estimated safety and health impacts to workers during the operations period from industrial hazards and from radiological hazards, respectively.

Table F-22. Estimated impacts to workers from industrial hazards during the operations period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	1,200	910	1,200 - 1,700	940
Lost workday cases	590	490	620 - 840	510
Fatalities	0.9	0.66	0.91 - 1.4	0.67
Noninvolved				
Total recordable cases of injury and illness	300	340	310 - 470	340
Lost workday cases	150	170	150 - 230	170
Fatalities	0.31	0.34	0.31 - 0.45	0.35
All workers (totals)[e]				
Total recordable cases of injury and illness	1,500	1,300	1,500 - 2,200	1,300
Lost workday cases	740	660	770 - 1,100	680
Fatalities	1.2	1.0	1.2 - 1.9	1.0

a. Source: Sum of impacts listed in Tables F-13, F-14, and F-15.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = disposal canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-23. Summary of estimated dose and radiological health impacts to workers for the repository operations period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	15,000	15,000	15,000 - 30,000	15,000
Probability of latent cancer fatality	0.006	0.006	0.006 - 0.012	0.006
Collective dose (person-rem)	7,500	4,800	7,600 - 12,000	4,900
Number of latent cancer fatalities	3	1.9	3 - 4.8	2
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,500	1,500	1,500 - 1,800	1,500
Probability of latent cancer fatality	0.0006	0.0006	0.0006 - 0.00072	0.0006
Collective dose (person-rem)	150	150	160 - 170	160
Number of latent cancer fatalities	0.06	0.06	0.064 - 0.068	0.064
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	16,500	16,500	16,500 - 31,800	16,500
Probability of latent cancer fatality	0.0066	0.0066	0.0066 - 0.01272	0.0066
Collective dose (person-rem)	7,700	5,000	7,800 - 12,000	5,100
Number of latent cancer fatalities	3.1	2	3.1 - 4.8	2.0

a. Source: Sum of impacts listed in Tables F-16, F-17, F-18, F-19, F-20, and F-21.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.3 Occupational Health and Safety Impacts to Workers During the Monitoring and Caretaking Period

F.2.3.3.1 *Health and Safety Impacts to Workers from Workplace Industrial Hazards*

Health and safety impacts from industrial hazards common to the workplace for the monitoring period consist of the following:

- Impacts to surface facility workers for the 3-year surface facility decontamination period (Table F-24)
- Impacts to surface facility workers for monitoring support activities (Table F-25)
- Impacts to subsurface facility workers for monitoring and maintenance activities (Table F-26)

Table F-24. Industrial hazard health and safety impacts to surface facility workers during the decontamination period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	80	59	66 - 80	59
Lost workday cases	32	24	26 - 32	24
Fatalities	0.077	0.057	0.064 - 0.077	0.057
Noninvolved				
Total recordable cases of injury and illness	23	20	20 - 23	20
Lost workday cases	11	9.7	9.7 - 11	9.7
Fatalities	0.02	0.018	0.018 - 0.02	0.018
All workers (total)[e]				
Total recordable cases of injury and illness	100	79	86 - 100	79
Lost workday cases	43	34	36 - 43	34
Fatalities	0.097	0.075	0.082 - 0.97	0.075

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.3.2 *Radiological Health Impacts to Workers*

F.2.3.3.2.1 Surface Facility Workers. During monitoring, surface facility workers would be involved in two types of activities with the potential for worker exposure. They are (a) a three-year decontamination operation after the completion of emplacement, and (b) support of subsurface monitoring and caretaking activities by surface facility workers for an additional 73 years for the higher-temperature scenarios. For the lower-temperature scenarios, the lengths of the support period for monitoring and caretaking activities by surface facility workers would be 122 years for the maximum spacing scenarios and 297 years for the long-term ventilation scenarios.

Surface facility workers providing support for the subsurface monitoring and caretaking activities would receive very little exposure in comparison to their counterparts involved in the subsurface monitoring and caretaking activities (see Table F-7, footnote j).

Radiological health impacts for the workers involved in surface facility decontamination activities are listed in Table F-27.

Table F-25. Industrial hazard health and safety impacts to surface facility workers during the monitoring and caretaking period.[a,b,c,d]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[e]	DPC[f]	UC range	DPC
Involved				
Total recordable cases of injury and illness	83	83	110 - 330	330
Lost workday cases	33	33	44 - 130	130
Fatalities	0.08	0.08	0.11 - 0.32	0.32
Noninvolved				
Total recordable cases of injury and illness	0	0	0	0
Lost workday cases	0	0	0	0
Fatalities	0	0	0	0
All workers (total)[g]				
Total recordable cases of injury and illness	83	83	110 - 330	330
Lost workday cases	33	33	44 - 130	130
Fatalities	0.08	0.08	0.11 - 0.32	0.32

a. Source: Calculated using impact rates from Table F-4.
b. All workers are considered to be involved workers.
c. Includes full-time equivalent worker years for solar power generating facility monitoring and maintenance.
d. Numbers are rounded to two significant figures.
e. UC = uncanistered packaging scenario.
f. DPC = dual-purpose canister packaging scenario.
g. Totals might differ from sums of values due to rounding.

Table F-26. Industrial hazard health and safety impacts for subsurface workers during the monitoring period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	160	160	200 - 620	620
Lost workday cases	63	63	82 - 250	250
Fatalities	0.15	0.15	0.20 - 0.60	0.60
Noninvolved				
Total recordable cases of injury and illness	33	33	42 - 130	130
Lost workday cases	16	16	21 - 62	62
Fatalities	0.029	0.029	0.037 - 0.11	0.11
All workers (total)[e]				
Total recordable cases of injury and illness	190	190	240 - 750	750
Lost workday cases	79	79	100 - 310	310
Fatalities	0.18	0.18	0.24 - 0.71	0.71

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-27. Radiological health impacts to surface facility workers during facility decontamination.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Dose to maximally exposed worker (millirem)	75	75	75	75
Probability of latent cancer fatality	0.000030	0.000030	0.000030	0.000030
Collective dose (person-rem)	67	49	55 - 67	49
Number of latent cancer fatalities	0.027	0.020	0.022 - 0.027	0.020

a. Source: Dose rates from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.

F.2.3.3.2.2 Subsurface Facility Workers. There are three exposure components which contribute to radiological health impacts to subsurface facility workers during the monitoring and caretaking phase. They are exposure from radiation emanating from the waste packages, exposure from the ambient radiation emanating from the drift walls, and exposure from inhalation of radon-222 and its progeny which are present in the subsurface atmosphere. Exposures to the subsurface workers during the monitoring and caretaking phase for each of these three components are listed in Tables F-28, F-29, and F-30, respectively. Exposures to the maximally exposed individual worker were based on a maximum work period of 50 years for an individual worker when the length of the monitoring periods is longer than 50 years.

Table F-28. Radiological health impacts to subsurface facility workers from waste package exposure during the monitoring and caretaking period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	10,000	10,000	10,000	10,000
Probability of latent cancer fatality	0.0040	0.0040	0.0040	0.0040
Collective dose (person-rem)	280	280	370 - 1,100	1,100
Number of latent cancer fatalities	0.11	0.11	0.15 - 0.44	0.44
Noninvolved worker				
Dose to maximally exposed worker (millirem)	400	400	400	400
Probability of latent cancer fatality	0.00016	0.00016	0.00016	0.00016
Collective dose (person-rem)	7.9	7.9	10 - 31	31
Number of latent cancer fatalities	0.0032	0.0032	0.004 - 0.012	0.012
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	10,400	10,400	10,400	10,400
Probability of latent cancer fatality	0.00416	0.00416	0.00416	0.00416
Collective dose (person-rem)	290	290	380 - 1,100	1,100
Number of latent cancer fatalities	0.12	0.12	0.15 - 0.44	0.44

a. Source: Exposure data from Table F-6.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-29. Radiological health impacts to subsurface facility workers from ambient radiation during the monitoring and caretaking period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	2,500	2,500	2,500	2,500
Probability of latent cancer fatality	0.001	0.001	0.001	0.001
Collective dose (person-rem)	260	260	340 - 1,000	1,000
Number of latent cancer fatalities	0.10	0.10	0.14 - 0.40	0.40
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,000	1,000	1,000	1,000
Probability of latent cancer fatality	0.0004	0.0004	0.0004	0.0004
Collective dose (person-rem)	20	20	26 - 78	78
Number of latent cancer fatalities	0.008	0.008	0.01 - 0.031	0.031
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	3,500	3,500	3,500	3,500
Probability of latent cancer fatality	0.0014	0.0014	0.0014	0.0014
Collective dose (person-rem)	280	280	370 - 1,100	1,100
Number of latent cancer fatalities	0.11	0.11	0.15 - 0.44	0.44

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-30. Radiological health impacts to subsurface facility workers from inhalation of radon-222 during the monitoring and caretaking period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	5,000	5,000	5,000	5,000
Probability of latent cancer fatality	0.002	0.002	0.002	0.002
Collective dose (person-rem)	520	520	680 - 2,100	2,100
Number of latent cancer fatalities	0.21	0.21	0.27 - 0.84	0.84
Noninvolved worker				
Dose to maximally exposed worker (millirem)	400	400	400	400
Probability of latent cancer fatality	0.00016	0.00016	0.00016	0.00016
Collective dose (person-rem)	7.9	7.9	10 - 31	31
Number of latent cancer fatalities	0.0032	0.0032	0.004 - 0.012	0.012
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	5,400	5,400	5,400	5,400
Probability of latent cancer fatality	0.00216	0.00216	0.00216	0.00216
Collective dose (person-rem)	530	530	690 - 2,100	2,100
Number of latent cancer fatalities	0.21	0.21	0.28 - 0.84	0.84

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.3.3 *Summary of Health Impacts for the Monitoring Phase*

Tables F-31 and F-32 summarize health and safety impacts from industrial hazards and from radiological hazards, respectively.

Table F-31. Estimated impacts to workers from industrial hazards during the monitoring and caretaking period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	320	300	400 - 1,000	1,000
Lost workday cases	130	120	160 - 410	410
Fatalities	0.31	0.29	0.38 - 1.0	0.98
Noninvolved				
Total recordable cases of injury and illness	55	53	65 - 150	150
Lost workday cases	27	25	32 - 73	72
Fatalities	0.049	0.046	0.057 - 0.13	0.13
All workers (total)[e]				
Total recordable cases of injury and illness	380	350	470 - 1,200	1,200
Lost workday cases	160	150	190 - 480	480
Fatalities	0.36	0.34	0.44 - 1.1	1.1

a. Values presented in this table are the sum of the estimates from Tables F-24, F-25, and F-26.
b. Values are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-32. Radiological health impacts to workers for the monitoring and caretaking period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	18,000	18,000	18,000	18,000
Probability of latent cancer fatality	0.0072	0.0072	0.0072	0.0072
Collective dose (person-rem)	1,100	1,100	1,500 - 4,300	4,300
Number of latent cancer fatalities	0.44	0.44	0.6 - 1.7	1.7
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,800	1,800	1,800	1,800
Probability of latent cancer fatality	0.00072	0.00072	0.00072	0.00072
Collective dose (person-rem)	36	36	46 - 140	140
Number of latent cancer fatalities	0.014	0.014	0.018 - 0.056	0.056
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	19,800	19,800	19,800	19,800
Probability of latent cancer fatality	0.00792	0.00792	0.00792	0.00792
Collective dose (person-rem)	1,100	1,100	1,500 - 4,400	4,400
Number of latent cancer fatalities	0.44	0.44	0.6 - 1.8	1.8

a. Values in this table are the sum of the values in Tables F-27, F-28, F-29, and F-30.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.4 Occupational Health and Safety Impacts During the Closure Phase

F.2.3.4.1 *Health and Safety Impacts to Workers from Workplace Industrial Hazards*

Health and safety impacts to workers from industrial hazards common to the workplace for the closure phase are listed in Table F-33 for surface facility workers and Table F-34 for subsurface facility workers.

Table F-33. Industrial hazard health and safety impacts to surface facility workers during the closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	180	160	180	160
Lost workday cases	85	75	85	75
Fatalities	0.085	0.075	0.085	0.075
Noninvolved				
Total recordable cases of injury and illness	37	32	37	32
Lost workday cases	18	16	18	16
Fatalities	0.032	0.028	0.032	0.028
All workers (total)[e]				
Total recordable cases of injury and illness	220	190	220	190
Lost workday cases	100	91	100	91
Fatalities	0.12	0.10	0.12	0.10

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-34. Industrial hazard health and safety impacts to subsurface facility workers during the closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	150	150	160 - 250	160
Lost workday cases	69	69	76 - 120	76
Fatalities	0.069	0.069	0.076 - 0.12	0.076
Noninvolved				
Total recordable cases of injury and illness	15	15	16 - 25	16
Lost workday cases	7.2	7.2	7.9 - 12	7.9
Fatalities	0.013	0.013	0.014 - 0.022	0.014
All workers (total)[e]				
Total recordable cases of injury and illness	170	170	180 - 280	180
Lost workday cases	76	76	84 - 130	84
Fatalities	0.082	0.082	0.09 - 0.14	0.09

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.2.3.4.2 *Radiological Health Impacts to Workers*

Radiological health impact to workers from closure activities are the sum of the following components:

- Radiological health impacts to subsurface workers from radiation emanating from the waste packages during the closure phase (Table F-35)
- Radiological impacts to subsurface workers from the ambient radiation field in the drifts during the closure phase (Table F-36)
- Radiological impacts to subsurface workers from inhalation of radon-222 in the drift atmosphere during the closure phase (Table F-37)

Table F-35. Radiological health impacts to subsurface workers from radiation emanating from waste packages during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	6,000	6,000	7,100 - 12,000	7,100
Probability of latent cancer fatality	0.0024	0.0024	0.0028 - 0.0048	0.0028
Collective dose (person-rem)	270	270	300 - 460	300
Number of latent cancer fatalities	0.11	0.11	0.12 - 0.18	0.12
Noninvolved worker				
Dose to maximally exposed worker (millirem)	80	80	88 - 140	88
Probability of latent cancer fatality	0.000032	0.000032	0.000035 - 0.000056	0.000035
Collective dose (person-rem)	3.6	3.6	4 - 6.1	4
Number of latent cancer fatalities	0.0014	0.0014	0.0016 - 0.0024	0.0016
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	6,080	6,080	7,188 - 12,140	7,188
Probability of latent cancer fatality	0.002432	0.002432	0.002835 - 0.004856	0.002835
Collective dose (person-rem)	270	270	300 - 470	300
Number of latent cancer fatalities	0.11	0.11	0.12 - 0.19	0.12

a. Source: Exposure data from Table F-6.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Because the surface facilities would be largely decontaminated at the beginning of the monitoring period (the exception would be a small facility retained to handle an operations emergency), radiological health impacts to surface facility workers during closure would be small in comparison to those to the subsurface facility workers and so are not included here.

F.2.3.4.3 *Summary of Impacts for Closure Phase*

Tables F-38 and F-39 summarize the estimated health and safety impacts from industrial hazards and from radiological hazards, respectively.

F.2.3.5 Summary of Occupational Health and Safety Impacts for All Repository Phases

The occupational health and safety impacts for all of the repository phases have been summarized in Tables F-40 (impacts from industrial safety hazards) and F-41 (impacts from radiological health hazards).

Table F-36. Radiological health impacts to subsurface workers from ambient radiation during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	500	500	550 - 850	550
Probability of latent cancer fatality	0.0002	0.0002	0.00022 - 0.00034	0.00022
Collective dose (person-rem)	120	120	130 - 200	130
Number of latent cancer fatalities	0.048	0.048	0.052 - 0.08	0.052
Noninvolved worker				
Dose to maximally exposed worker (millirem)	200	200	220 - 340	220
Probability of latent cancer fatality	0.00008	0.00008	0.000088 - 0.00014	0.000088
Collective dose (person-rem)	9	9	9.9 - 15	9.9
Number of latent cancer fatalities	0.0036	0.0036	0.004 - 0.006	0.004
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	700	700	770 - 1,190	770
Probability of latent cancer fatality	0.00028	0.00028	0.000308 - 0.00048	0.000308
Collective dose (person-rem)	130	130	140 - 220	140
Number of latent cancer fatalities	0.052	0.052	0.056 - 0.088	0.056

a. Source: Exposure values from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-37. Radiological health impacts to subsurface workers from inhalation of radon-222 during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	200	200	220 - 340	220
Probability of latent cancer fatality	0.00008	0.00008	0.000088 - 0.00014	0.000088
Collective dose (person-rem)	48	48	52 - 81	52
Number of latent cancer fatalities	0.019	0.019	0.021 - 0.032	0.021
Noninvolved worker				
Dose to maximally exposed worker (millirem)	80	80	88 - 140	88
Probability of latent cancer fatality	0.000032	0.000032	0.000035 - 0.000056	0.000035
Collective dose (person-rem)	3.6	3.6	4 - 6.1	4
Number of latent cancer fatalities	0.0014	0.0014	0.0016 - 0.0024	0.0016
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	280	280	308 - 480	308
Probability of latent cancer fatality	0.000112	0.000112	0.000123- 0.000196	0.000123
Collective dose (person-rem)	52	52	56 - 87	56
Number of latent cancer fatalities	0.021	0.021	0.022 - 0.035	0.022

a. Source: Exposure values from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-38. Summary of estimates of impacts to workers from industrial hazards for the closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	320	300	340 - 420	320
Lost workday cases	150	140	160 - 200	150
Fatalities	0.15	0.14	0.16 - 0.2	0.15
Noninvolved				
Total recordable cases of injury and illness	51	47	53 - 62	49
Lost workday cases	25	23	26 - 30	24
Fatalities	0.045	0.041	0.047 - 0.054	0.043
All workers (total)[e]				
Total recordable cases of injury and illness	370	350	390 - 480	370
Lost workday cases	180	160	190 - 230	170
Fatalities	0.20	0.18	0.21 - 0.25	0.19

a. Data in this table are the sum of the impacts in Tables F-33 and F-34.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-39. Summary of radiological health impacts to subsurface workers for the closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	6,700	6,700	7,900 - 13,000	7,900
Probability of latent cancer fatality	0.0027	0.0027	0.0032 - 0.0052	0.0032
Collective dose (person-rem)	430	430	480 - 740	480
Number of latent cancer fatalities	0.17	0.17	0.19 - 0.3	0.19
Noninvolved worker				
Dose to maximally exposed worker (millirem)	360	360	400 - 610	400
Probability of latent cancer fatality	0.00014	0.00014	0.00016 - 0.00024	0.00016
Collective dose (person-rem)	16	16	18 - 28	18
Number of latent cancer fatalities	0.0064	0.0064	0.0072 - 0.011	0.0072
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	7,060	7,060	8,300 - 13,610	8,300
Probability of latent cancer fatality	0.00284	0.00284	0.00336 - 0.00544	0.00336
Collective dose (person-rem)	450	450	500 - 770	500
Number of latent cancer fatalities	0.18	0.18	0.2 - 0.31	0.2

a. Data in this table are the sum of the impacts presented in Tables F-35, F-36, and F-37, except for impacts to maximally exposed individuals.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-package canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-40. Summary of impacts to workers from industrial hazards for all phases.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved				
Total recordable cases of injury and illness	2,200	1,800	2,500 - 3,300	2,600
Lost workday cases	1,000	910	1,200 - 1,500	1,200
Fatalities	1.5	1.2	1.8 - 2.6	2
Noninvolved				
Total recordable cases of injury and illness	470	490	500 - 720	590
Lost workday cases	230	240	250 - 350	290
Fatalities	0.45	0.47	0.48 - 0.68	0.56
All workers (total)[e]				
Total recordable cases of injury and illness	2,700	2,300	3,000 - 4,000	3,200
Lost workday cases	1,200	1,200	1,500 - 1,900	1,500
Fatalities	2.0	1.7	2.3 - 3.3	2.6

a. Estimated impacts in this table are the sums of impacts listed in Tables F-12, F-22, F-31, and F-38.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-41. Summary of radiological health impacts to workers for all phases.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC range	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	18,000	18,000	18,000 - 30,000	18,000
Probability of latent cancer fatality	0.0072	0.0072	0.0072 - 0.012	0.0072
Collective dose (person-rem)	9,800	7,000	11,000 - 17,000	10,000
Number of latent cancer fatalities	3.9	2.8	4.4 - 6.8	4
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,800	1,800	1,800	1,800
Probability of latent cancer fatality	0.00072	0.00072	0.00072	0.00072
Collective dose (person-rem)	230	230	280 - 360	350
Number of latent cancer fatalities	0.092	0.092	0.11 - 0.14	0.14
All workers (totals)[e]				
Dose to maximally exposed worker (millirem)	20,000	20,000	20,000 - 30,000	20,000
Probability of latent cancer fatality	0.0079	0.0079	0.0079 - 0.012	0.0079
Collective dose (person-rem)	10,000	7,200	11,000 - 17,000	10,000
Number of latent cancer fatalities	4.0	2.9	4.4 - 6.8	4.0

a. Estimated impacts in this table are the sums of the impacts listed in Tables F-11, F-23, F-32, and F-39.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3 Worker Human Health and Safety Impact Analysis for Inventory Modules 1 and 2

DOE performed the same analyses used for the Proposed Action to estimate the occupational and public health and safety impacts from the emplacement of Inventory Module 1 or 2. Module 1 would involve the emplacement of additional spent nuclear fuel and high-level radioactive waste in the repository; Inventory Module 2 would emplace commercial Greater-Than-Class-C waste and DOE Special-Performance-Assessment-Required waste, which is equivalent to commercial Greater-Than-Class-C waste, in addition to the inventory from Module 1. The volumes of Greater-Than-Class-C and Special-Performance-Assessment-Required waste would be less than that for spent nuclear fuel and high-level radioactive waste (DIRS 104508-CRWMS M&O 1999, Table 3.1). Waste packages containing these materials would be placed between the waste packages containing spent nuclear fuel and high-level radioactive waste (see Chapter 8, Section 8.1.2.1).

With regard to estimating heath and safety impacts for the inventory modules, the characteristics of the spent nuclear fuel and high-level radioactive waste were taken to be the same as those for the Proposed Action, but there would be more material to emplace (see Appendix A, Section A.2). As described in Appendix A, the radiological content of the Greater-Than-Class-C waste and Special-Performance-Assessment-Required waste, which is the additional material in Module 2, is much less than that for spent nuclear fuel and high-level radioactive waste. Therefore, the emplacement of the Module 2 material would not meaningfully increase radiological impacts to workers over those estimated for the Module 1 inventory. Further, the facility design parameters, on which the impact estimates are based, are extrapolations from existing designs and have some uncertainty associated with them [see, for example, DIRS 104508-CRWMS M&O (1999), Section 6.2, first paragraph]. Therefore, separate occupational and public health and safety impact analyses were not performed for Module 2 because the impacts for Inventory Modules 1 and 2 would not differ meaningfully.

The calculation of health and safety impacts to workers assumed that the throughput rate of materials for the facility would remain the same as that assumed for the Proposed Action during repository operations (that is, the 70,000-MTHM case). In addition, for the inventory modules the period of operations would be extended to accommodate the additional materials, and the monitoring period would be reduced such that the Yucca Mountain repository operations and monitoring activities would be the same as those for the Proposed Action.

This section discusses the methodologies and data used to estimate occupational radiological health and safety impacts resulting from construction, operation and monitoring, and closure of the Yucca Mountain Repository for Inventory Modules 1 and 2, and presents the detailed results. Section F.3.1 describes the methods DOE used to estimate impacts. Section F.3.2 contains tabulations of the detailed data used in the impact calculations and references to the data sources. Section F.3.3 contains detailed tabulations of results.

F.3.1 METHODOLOGY FOR CALCULATING HUMAN HEALTH AND SAFETY IMPACTS

DOE used the methodology described in Section F.2.1 to estimate health and safety impacts for the inventory modules. This methodology involved assembling data for the number of full-time equivalent workers for each repository phase. These numbers were used with statistics for the likelihood of an impact (industrial hazards) or the expected dose rate in the worker environment to calculate health and safety impacts. The way in which the input data was combined in the calculation of health and safety impacts is described in more detail in Section F.2.1. Some of the input data for the calculations for the inventory modules are different from those for the Proposed Action, as discussed in the next section.

F.3.2 DATA SOURCES AND TABULATIONS

F.3.2.1 Full-Time Equivalent Worker-Year Estimates for the Repository Phases for Inventory Modules 1 and 2

The full-time equivalent worker-year estimates for the inventory modules are different from those for the Proposed Action. Table F-42 lists the number of full-time equivalent work years for the various repository phases for the inventory modules. Each full-time equivalent work year represents 2,000 work hours, the hours assumed to be worked in a normal work year.

This analysis divides the repository workforce into two groups—involved and noninvolved workers (see Section F.2 for definitions of involved and noninvolved workers). It did not consider workers whose place of employment would be other than at the repository site.

F.3.2.2 Statistics on Health and Safety Impacts from Industrial Hazards in the Workplace

DOE used the same statistics for health and safety impacts from industrial hazards common to the workplace that were used for the Proposed Action (70,000 MTHM) for analyzing the inventory module impacts (see Tables F-4 and F-5).

F.3.2.3 Estimates of Radiological Exposure Rates and Times for Inventory Modules 1 and 2

DOE used the values in Tables F-6 through F-8 (Proposed Action) for exposure rates, occupancy times, and the fraction of the workforce that would be exposed to estimate radiological health impacts for the inventory module cases, except for doses from the waste packages and from radon-222 inhalation for the subsurface emplacement, monitoring, and closure phases.

F.3.3 DETAILED HUMAN HEALTH AND SAFETY IMPACTS TO WORKERS–INVENTORY MODULES 1 AND 2

F.3.3.1 Construction Phase

F.3.3.1.1 *Industrial Hazards to Workers*

This section details health and safety impacts to workers from industrial hazards common to the workplace for the construction phase. Because the activities for construction would be the same for the Inventory Modules as they would for the Proposed Action, the industrial safety impacts would also be the same. Impact values for surface workers are presented in Table F-9, while impacts for subsurface workers are presented in Table F-10. Further, Table F-12 summarizes the impacts listed in Tables F-9 and F-10.

F.3.3.1.2 *Radiological Health Impacts to Workers*

Because the activities for construction would be the same for the Inventory Modules as for the Proposed Action, the radiological impacts are also the same. Table F-11 lists subsurface worker health impacts from inhalation of radon-222 and its decay products in the subsurface atmosphere and from exposure to natural radiation from radionuclides in the drift walls, respectively. The radiological health impacts to surface workers from radon-222 and ambient radiation contribute negligibly to the overall impact from these natural sources. Therefore, separate tables are not presented for surface workers.

Table F-42. Full-time equivalent worker years for various repository periods for Inventory Modules 1 and 2 (page 1 of 2).[a]

				Operating mode			
				Higher-temperature		Lower-temperature	
Phase	Subphase	Period	Worker group	UC[b]	DPC[c]	UC (range)	DPC
Construction	Surface	44 months	Involved	2,800	2,500	2,600 - 2,900	2,500
			Noninvolved	1,100	940	990 - 1,100	940
	Subsurface	5 years	Involved	2,700	2,700	2,700	2,700
			Noninvolved	560	560	560	560
	Solar power facility	6 years	Involved	76	76	76	76
			Noninvolved	26	26	26	26
	Aging facilities	16 years	Involved	N/A[d]	N/A	750	N/A
			Noninvolved	N/A	N/A	290	N/A
	Construction subtotals			7,300	6,800	7,300 - 8,000	6,800
Operations	Surface handling	First 38 years	Involved	37,000	23,000	37,000 - 38,000	23,000
			Noninvolved	13,000	15,000	13,000	15,000
		Last 13 years (aging only)	Involved	N/A	N/A	6,400	N/A
			Noninvolved	N/A	N/A	2,200	N/A
	Subsurface emplacement	First 38 years	Involved	2,800	2,800	2,800 - 4,300	2,800
			Noninvolved	610	610	610 - 930	610
		Last 13 years (aging only)	Involved	N/A	N/A	960	N/A
			Noninvolved	N/A	N/A	210	N/A
	Subsurface development	36 years	Involved	10,000	10,000	10,000 - 11,000	10,000
			Noninvolved	2,400	2,400	2,400	2,400
	Operations subtotals			66,000	54,000	66,000 - 77,000	54,000
Monitoring	Surface facility decontamination	3 years	Involved	2,700	2,000	2,200 - 2,700	2,000
			Noninvolved	690	610	610 - 690	610
	Surface	Variable[e]	Involved	2,100	2,100	3,800 - 10,000	10,000
			Noninvolved	0	0	0	0
	Subsurface	Variable[f]	Involved	4,700	4,700	8,100 - 23,000	23,000
			Noninvolved	870	870	1,600 - 4,200	4,200
	Solar panel maintenance	Variable[g]	Involved	180	180	290 - 610	610
	Solar panel replacement	Every 20 years	Involved	36	36	72 - 140	140
	Monitoring subtotals			11,000	10,000	17,000 - 41,000	40,000

Table F-42. Full-time equivalent worker years for various repository periods for Inventory Modules 1 and 2 (page 2 of 2).[a]

				Operating mode			
				Higher-temperature		Lower-temperature	
Phase	Subphase	Period	Worker group	UC[b]	DPC[c]	UC (range)	DPC
Closure	Surface facilities	6 years	Involved	2,900	2,500	2,900	2,500
			Noninvolved	1,100	950	1,100	950
	Subsurface	Variable[h]	Involved	2,900	2,900	3,600 - 6,900	3,800
			Noninvolved	540	540	680 - 1,400	720
	Solar power facility	6 years	Involved	62	62	62	62
			Noninvolved	24	24	24	24
	Closure subtotals			7,400	6,900	8,300 - 12,000	8,100
Totals				***92,000***	***78,000***	***110,000 - 130,000***	***110,000***

a. Sources: Derived from DIRS 152010-CRWMS M&O (2000, all); DIRS 150941-CRWMS M&O (2000, all); DIRS 155515-Williams (2001, all); DIRS 155516-Williams (2001, all); DIRS 153882-Griffith (2001, all); DIRS 154758-Lane (2000, all); DIRS 153958-Morton (2000, all).

b. UC = uncanistered packaging scenario.

c. DPC = dual-purpose canister packaging scenario.

d. N/A = not applicable.

e. Surface monitoring periods are 73 years for the higher-temperature cases (UC and DPC), 297 years for the lower-temperature DPC case, and ranges from 96 to 271 years for the remaining cases.

f. Subsurface monitoring periods are 76 years for the higher-temperature cases (UC and DPC), 300 years for the lower-temperature DPC case, and ranges from 99 to 274 years for the remaining cases.

g. Solar power maintenance periods are 100 years for the higher-temperature cases (UC and DPC), 324 years for the lower-temperature DPC case, and either 149 or 324 years for the remaining cases.

h. Subsurface closure periods are 10 years for the higher-temperature cases (UC and DPC), 11 years for the lower-temperature DPC case, and either 12 or 17 years for the remaining cases.

F.3.3.2 Operations Period

F.3.3.2.1 *Health and Safety Impacts to Workers from Industrial Hazards*

This section details health and safety impacts to workers from industrial hazards common to the workplace for the operations period. These impacts would consist of three components:

- Health and safety impacts to surface workers for operations (Table F-43)
- Health and safety impacts to subsurface workers for drift development (Table F-44)
- Health and safety impacts to subsurface workers for emplacement (Table F-45)

Table F-43. Industrial hazard health and safety impacts for surface facility workers during the operations period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	1,100	700	1,100 - 1,300	700
Lost workday cases	440	280	440 - 520	280
Fatalities	1.1	0.68	1.1 - 1.3	0.68
Noninvolved workers				
Total recordable cases of injury and illness	430	490	430 - 500	490
Lost workday cases	210	240	210 - 240	240
Fatalities	0.38	0.43	0.38 - 0.44	0.43
All workers[e]				
Total recordable cases of injury and illness	1,500	1,200	1,500 - 1,800	1,200
Lost workday cases	650	520	650 - 760	520
Fatalities	1.5	1.1	1.5 - 1.7	1.1

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.2.2 *Radiological Health Impacts to Workers*

This section details radiological health impacts to workers during the operation and monitoring phase for the inventory modules. These impacts consist of three components:

- Radiological health impacts to surface workers from waste packages during operations (Table F-46)

- Radiological health impacts to subsurface workers involved in drift development activities (Tables F-47 and F-48)

- Radiological health impacts to subsurface workers involved in emplacement activities (Tables F-49 through F-51)

Table F-44. Industrial hazard health and safety impacts to subsurface facility workers involved in drift development activities.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	700	700	700 - 760	700
Lost workday cases	490	490	490 - 540	490
Fatalities	0.3	0.3	0.3 - 0.33	0.3
Noninvolved workers				
Total recordable cases of injury and illness	27	27	27	27
Lost workday cases	17	17	17	17
Fatalities	0.071	0.071	0.071	0.071
All workers[e]				
Total recordable cases of injury and illness	730	730	730 - 790	730
Lost workday cases	510	510	510 - 560	510
Fatalities	0.37	0.37	0.37 - 0.4	0.37

a. Source: Calculated using impact rates from Table F-5.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-45. Industrial hazard health and safety impacts to subsurface facility workers involved in emplacement activities.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	84	84	84 - 130	84
Lost workday cases	34	34	34 - 51	34
Fatalities	0.082	0.082	0.082 - 0.12	0.082
Noninvolved workers				
Total recordable cases of injury and illness	20	20	20 - 31	20
Lost workday cases	9.7	9.7	9.7 - 15	9.7
Fatalities	0.018	0.018	0.018 - 0.027	0.018
All workers[e]				
Total recordable cases of injury and illness	100	100	100 - 160	100
Lost workday cases	44	44	44 - 66	44
Fatalities	0.1	0.1	0.1 - 0.15	0.1

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-46. Radiological health impacts from waste packages to surface facility workers during operations period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	15,000	15,000	15,000 - 20,000	15,000
Probability of latent cancer fatality	0.006	0.006	0.006 - 0.008	0.006
Collective dose (person-rem)	8,800	4,400	8,800 - 11,000	4,400
Number of latent cancer fatalities	3.5	1.8	3.5 - 4.4	1.8
Noninvolved worker				
Dose to maximally exposed worker (millirem)	0	0	0	0
Probability of latent cancer fatality	0	0	0	0
Collective dose (person-rem)	0	0	0	0
Number of latent cancer fatalities	0	0	0	0
All workers[e]				
Collective dose (person-rem)	8,800	4,400	8,800 - 11,000	4,400
Number of latent cancer fatalities	3.5	1.8	3.5 - 4.4	1.8

a. Source: Calculated using exposure rate from Table F-8.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-47. Radiological health impacts from ambient radiation to subsurface facility workers involved in drift development activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	1,800	1,800	1,800	1,800
Probability of latent cancer fatality	0.00072	0.00072	0.00072	0.00072
Collective dose (person-rem)	510	510	510 - 560	510
Number of latent cancer fatalities	0.2	0.2	0.2 - 0.22	0.2
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,100	1,100	1,100	1,100
Probability of latent cancer fatality	0.00044	0.00044	0.00044	0.00044
Collective dose (person-rem)	73	73	73	73
Number of latent cancer fatalities	0.029	0.029	0.029	0.029
All workers[e]				
Collective dose (person-rem)	580	580	580 - 630	580
Number of latent cancer fatalities	0.23	0.23	0.23 - 0.25	0.23

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-48. Radiological health impacts from radon exposure to subsurface facility workers involved in drift development activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	7,200	7,200	7,200	7,200
Probability of latent cancer fatality	0.0029	0.0029	0.0029	0.0029
Collective dose (person-rem)	2,100	2,100	2,100 - 2,200	2,100
Number of latent cancer fatalities	0.84	0.84	0.84 - 0.88	0.84
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,300	1,300	1,300	1,300
Probability of latent cancer fatality	0.00052	0.00052	0.00052	0.00052
Collective dose (person-rem)	88	88	88	88
Number of latent cancer fatalities	0.035	0.035	0.035	0.035
All workers[e]				
Collective dose (person-rem)	2,200	2,200	2,200 - 2,300	2,200
Number of latent cancer fatalities	0.88	0.88	0.88 - 0.92	0.88

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-49. Radiological health impacts from waste packages to subsurface facility workers involved in emplacement activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	18,000	18,000	18,000 - 24,000	18,000
Probability of latent cancer fatality	0.0072	0.0072	0.0072 - 0.0096	0.0072
Collective dose (person-rem)	230	230	230 - 340	230
Number of latent cancer fatalities	0.092	0.092	0.092 - 0.14	0.092
Noninvolved worker				
Dose to maximally exposed worker (millirem)	300	300	300 - 410	300
Probability of latent cancer fatality	0.00012	0.00012	0.00012 - 0.00016	0.00012
Collective dose (person-rem)	4.9	4.9	4.9 - 7.4	4.9
Number of latent cancer fatalities	0.002	0.002	0.002 - 0.003	0.002
All workers[e]				
Collective dose (person-rem)	230	230	230 - 350	230
Number of latent cancer fatalities	0.092	0.092	0.092 - 0.14	0.092

a. Source: Exposure data from Table F-6.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-50. Radiological health impacts from ambient radiation to subsurface facility workers involved in emplacement activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	1,900	1,900	1,900 - 2,600	1,900
Probability of latent cancer fatality	0.00076	0.00076	0.00076 - 0.001	0.00076
Collective dose (person-rem)	140	140	140 - 210	140
Number of latent cancer fatalities	0.056	0.056	0.056 - 0.084	0.056
Noninvolved worker				
Dose to maximally exposed worker (millirem)	760	760	760 - 1,000	760
Probability of latent cancer fatality	0.0003	0.0003	0.0003 - 0.0004	0.0003
Collective dose (person-rem)	12	12	12 - 19	12
Number of latent cancer fatalities	0.0048	0.0048	0.0048 - 0.0076	0.0048
All workers[e]				
Collective dose (person-rem)	150	150	150 - 230	150
Number of latent cancer fatalities	0.06	0.06	0.06 - 0.092	0.06

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-51. Radiological health impacts from radon exposure to subsurface facility workers involved in emplacement activities.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	4,600	4,600	4,600 - 6,100	4,600
Probability of latent cancer fatality	0.0018	0.0018	0.0018 - 0.0024	0.0018
Collective dose (person-rem)	340	340	340 - 510	340
Number of latent cancer fatalities	0.14	0.14	0.14 - 0.2	0.14
Noninvolved worker				
Dose to maximally exposed worker (millirem)	300	300	300 - 410	300
Probability of latent cancer fatality	0.00012	0.00012	0.00012 - 0.00016	0.00012
Collective dose (person-rem)	4.9	4.9	4.9 - 7.4	4.9
Number of latent cancer fatalities	0.002	0.002	0.002 - 0.003	0.002
All workers[e]				
Collective dose (person-rem)	340	340	340 - 520	340
Number of latent cancer fatalities	0.14	0.14	0.14 - 0.21	0.14

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.2.3 *Summary of Impacts for the Operations Period*

Tables F-52 and F-53 present the occupational and radiological impacts, respectively, to all workers from operations activities. In each table, impacts are presented for the higher-temperature repository operating mode uncanistered and dual-purpose canister packaging scenarios; in addition, the range of impacts for the lower-temperature mode (uncanistered packaging scenario) is presented along with the impacts for the dual-purpose canister scenario that uses long-term ventilation without aging.

Table F-52. Summary of industrial hazard health and safety impacts to facility workers during operations period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Impact	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	1,900	1,500	1,900 - 2,200	1,500
Lost workday cases	970	810	970 - 1,100	810
Fatalities	1.4	1.1	1.4 - 1.7	1.1
Noninvolved workers				
Total recordable cases of injury and illness	470	530	470 - 560	530
Lost workday cases	230	260	230 - 270	260
Fatalities	0.46	0.52	0.46 - 0.54	0.52
All workers[e]				
Total recordable cases of injury and illness	2,400	2,000	2,400 - 2,800	2,000
Lost workday cases	1,200	1,100	1,200 - 1,400	1,100
Fatalities	1.9	1.6	1.9 - 2.2	1.6

a. Sources: Tables F-43, F-44, and F-45.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-53. Summary of radiological health impacts to workers from all activities during operations period.

	Operating mode			
	Higher-temperature		Lower-temperature	
Impact	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	24,000	24,000	24,000 - 33,000	24,000
Probability of latent cancer fatality	0.0096	0.0096	0.0096 - 0.013	0.0096
Collective dose (person-rem)	12,000	7,700	12,000 - 15,000	7,700
Number of latent cancer fatalities	4.8	3.1	4.8 - 6	3.1
Noninvolved worker				
Dose to maximally exposed worker (millirem)	2,400	2,400	2,400	2,400
Probability of latent cancer fatality	0.00096	0.00096	0.00096	0.00096
Collective dose (person-rem)	180	180	180 - 190	180
Number of latent cancer fatalities	0.072	0.072	0.072 - 0.076	0.072
All workers[e]				
Collective dose (person-rem)	12,000	7,900	12,000 - 15,000	7,900
Number of latent cancer fatalities	4.8	3.2	4.8 - 6	3.2

a. Sources: Tables F-46, F-47, F-48, F-49, and F-50.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.3 Occupational Health and Safety Impacts to Workers During the Monitoring and Caretaking Period

F.3.3.3.1 *Health and Safety Impacts to Workers from Workplace Industrial Hazards*

Health and safety impacts from industrial hazards common to the workplace for the monitoring period consist of the following:

- Impacts to surface facility workers for the 3-year surface facility decontamination period. These values, which are the same as those for the Proposed Action, are listed in Table F-24.
- Impacts to surface facility workers for monitoring support activities (Table F-54)
- Impacts to subsurface facility workers for monitoring and maintenance activities (Table F-55)

Table F-54. Industrial hazard health and safety impacts to surface facility workers during the monitoring period.[a,b]

Worker group	Operating mode: Higher-temperature: UC[c]	Higher-temperature: DPC[d]	Lower-temperature: UC (range)	Lower-temperature: DPC
Involved workers				
Total recordable cases of injury and illness	68	68	130 - 330	330
Lost workday cases	27	27	50 - 130	130
Fatalities	0.066	0.066	0.12 - 0.32	0.32
Noninvolved workers				
Total recordable cases of injury and illness	0	0	0	0
Lost workday cases	0	0	0	0
Fatalities	0	0	0	0
All workers[e]				
Total recordable cases of injury and illness	68	68	130 - 330	330
Lost workday cases	27	27	50 - 130	130
Fatalities	0.066	0.066	0.12 - 0.32	0.32

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.3.2 *Radiological Health Impacts to Workers*

F.3.3.3.2.1 Surface Facility Workers. During monitoring, surface facility workers would be involved in two types of activities with the potential for worker exposure. They are (a) the decontamination operation after the completion of emplacement, and (b) support of subsurface monitoring and caretaking activities by surface facility workers. Surface facility workers providing support for the subsurface monitoring and caretaking activities would receive very little radiological dose in comparison to their counterparts involved in the subsurface monitoring and caretaking activities because the greatest source of radiation exposure would be in the subsurface areas.

Radiological health impacts for the workers involved in surface facility decontamination activities, which are the same for the Inventory Modules as those for the Proposed Action, are listed in Table F-27.

Table F-55. Industrial hazard health and safety impacts to subsurface facility workers during the monitoring period.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	140	140	240 - 680	680
Lost workday cases	56	56	97 - 270	270
Fatalities	0.13	0.13	0.23 - 0.65	0.65
Noninvolved workers				
Total recordable cases of injury and illness	29	29	52 - 140	140
Lost workday cases	14	14	25 - 67	67
Fatalities	0.025	0.025	0.045 - 0.12	0.12
All workers[e]				
Total recordable cases of injury and illness	170	170	290 - 820	820
Lost workday cases	70	70	120 - 340	340
Fatalities	0.16	0.16	0.28 - 0.77	0.77

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.3.2.2 Subsurface Facility Workers. There are three exposure components which contribute to radiological health impacts to subsurface facility workers during the monitoring and caretaking phase. They are exposure from radiation emanating from the waste packages, exposure from the ambient radiation emanating from the drift walls, and exposure from inhalation of radon-222 and its progeny which are present in the subsurface atmosphere. Exposures to the subsurface workers during the monitoring and caretaking phase for each of these three components are listed in Tables F-56, F-57, and F-58, respectively. Exposures to the maximally exposed worker were based on a maximum work period of 50 years for an individual worker when the length of the monitoring periods was longer than 50 years.

Table F-56. Radiological health impacts to subsurface facility workers from exposure to waste packages during the monitoring and caretaking period.[a,b]

Worker group	Operating mode			
	Higher-temperature		Lower-temperature	
	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	10,000	10,000	10,000	10,000
Probability of latent cancer fatality	0.004	0.004	0.004	0.004
Collective dose (person-rem)	230	230	410 - 1,100	1,100
Number of latent cancer fatalities	0.092	0.092	0.16 - 0.44	0.44
Noninvolved worker				
Dose to maximally exposed worker (millirem)	400	400	400	400
Probability of latent cancer fatality	0.00016	0.00016	0.00016	0.00016
Collective dose (person-rem)	6.9	6.9	13 - 34	34
Number of latent cancer fatalities	0.0028	0.0028	0.0052 - 0.014	0.014
All workers[e]				
Collective dose (person-rem)	240	240	420 - 1,100	1,100
Number of latent cancer fatalities	0.096	0.096	0.17 - 0.44	0.44

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-57. Radiological health impacts to subsurface facility workers from ambient radiation exposure during the monitoring and caretaking period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	2,500	2,500	2,500	2,500
Probability of latent cancer fatality	0.001	0.001	0.001	0.001
Collective dose (person-rem)	230	230	400 - 1,100	1,100
Number of latent cancer fatalities	0.092	0.092	0.16 - 0.44	0.44
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,000	1,000	1,000	1,000
Probability of latent cancer fatality	0.0004	0.0004	0.0004	0.0004
Collective dose (person-rem)	17	17	31 - 84	84
Number of latent cancer fatalities	0.0068	0.0068	0.012 - 0.034	0.034
All workers[e]				
Collective dose (person-rem)	250	250	430 - 1,200	1,200
Number of latent cancer fatalities	0.1	0.1	0.17 - 0.48	0.48

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-58. Radiological health impacts to subsurface facility workers from radon exposure during the monitoring and caretaking period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	5,000	5,000	5,000	5,000
Probability of latent cancer fatality	0.002	0.002	0.002	0.002
Collective dose (person-rem)	470	470	810 - 2,300	2,300
Number of latent cancer fatalities	0.19	0.19	0.32 - 0.92	0.92
Noninvolved worker				
Dose to maximally exposed worker (millirem)	400	400	400	400
Probability of latent cancer fatality	0.00016	0.00016	0.00016	0.00016
Collective dose (person-rem)	6.9	6.9	13 - 34	34
Number of latent cancer fatalities	0.0028	0.0028	0.0052 - 0.014	0.014
All workers[e]				
Collective dose (person-rem)	480	480	820 - 2,300	2,300
Number of latent cancer fatalities	0.19	0.19	0.33 - 0.92	0.92

a. Source: Exposure data from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.3.3 *Summary of Health Impacts for the Monitoring and Caretaking Period*

Tables F-59 and F-60 present the occupational and radiological impacts, respectively, to all workers from monitoring and caretaking activities. In each table, impacts are presented for the higher-temperature uncanistered and dual-purpose canister packaging scenarios; in addition, the range of impacts for the lower-temperature uncanistered packaging scenario is presented along with the impacts for the dual-purpose canister packaging scenario with long-term ventilation.

Table F-59. Summary of industrial hazard health and safety impacts to facility workers during monitoring period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	290	270	450 - 1,100	1,100
Lost workday cases	120	110	180 - 440	430
Fatalities	0.28	0.26	0.43 - 1.1	1
Noninvolved workers				
Total recordable cases of injury and illness	51	49	74 - 160	160
Lost workday cases	25	24	36 - 78	77
Fatalities	0.045	0.043	0.065 - 0.14	0.14
All workers[e]				
Total recordable cases of injury and illness	340	320	520 - 1,300	1,300
Lost workday cases	150	130	220 - 520	510
Fatalities	0.33	0.3	0.5 - 1.2	1.1

a. Sources: Calculated using impact rates from Tables F-24, F-54, and F-55.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-60. Summary of radiological health impacts to workers from all activities during monitoring period.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	18,000	18,000	18,000	18,000
Probability of latent cancer fatality	0.0072	0.0072	0.0072	0.0072
Collective dose (person-rem)	990	980	1,700 - 4,500	4,500
Number of latent cancer fatalities	0.4	0.39	0.68 - 1.8	1.8
Noninvolved worker				
Dose to maximally exposed worker (millirem)	1,800	1,800	1,800	1,800
Probability of latent cancer fatality	0.00072	0.00072	0.00072	0.00072
Collective dose (person-rem)	31	31	56 - 150	150
Number of latent cancer fatalities	0.012	0.012	0.022 - 0.06	0.06
All workers[e]				
Collective dose (person-rem)	1,000	1,000	1,800 - 4,700	4,700
Number of latent cancer fatalities	0.4	0.4	0.72 - 1.9	1.9

a. Sources: Calculated using impact rates from Tables F-27, F-56, F-57, and F-58.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.4 Closure Phase

F.3.3.4.1 *Health and Safety Impacts to Workers from Industrial Hazards*

This section details health and safety impacts to workers from industrial hazards common to the workplace for the closure phase. The impacts would consist of two components—impacts to surface workers supporting the closure operations, and impacts to subsurface workers during the closure phase. These impacts are listed in Tables F-61 and F-62, respectively.

Table F-61. Industrial hazard health and safety impacts to surface facility workers during the closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	180	160	180	160
Lost workday cases	85	75	85	75
Fatalities	0.085	0.075	0.085	0.075
Noninvolved workers				
Total recordable cases of injury and illness	37	32	37	32
Lost workday cases	18	16	18	16
Fatalities	0.032	0.028	0.032	0.028
All workers[e]				
Total recordable cases of injury and illness	220	190	220	190
Lost workday cases	100	91	100	91
Fatalities	0.12	0.1	0.12	0.1

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-62. Health and safety impacts to subsurface facility workers from industrial hazards during the closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	170	170	220 - 420	230
Lost workday cases	83	83	100 - 200	110
Fatalities	0.083	0.083	0.1 - 0.2	0.11
Noninvolved workers				
Total recordable cases of injury and illness	18	18	22 - 46	24
Lost workday cases	8.6	8.6	11 - 22	12
Fatalities	0.016	0.016	0.02 - 0.04	0.021
All workers[e]				
Total recordable cases of injury and illness	190	190	240 - 470	250
Lost workday cases	92	92	110 - 220	120
Fatalities	0.099	0.099	0.12 - 0.24	0.13

a. Source: Calculated using impact rates from Table F-4.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.4.2 *Radiological Health Impacts to Workers*

Radiological health impact to workers from closure activities are the sum of the following components:

- Radiological health impacts to subsurface workers from radiation emanating from the waste packages during the closure phase (Table F-63)
- Radiological impacts to subsurface workers from the ambient radiation field in the drifts during the closure phase (Table F-64)
- Radiological impacts to subsurface workers from inhalation of radon-222 in the drift atmosphere during the closure phase (Table F-65)

Table F-63. Radiological health impacts to subsurface facility workers from waste package exposure during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	7,200	7,200	9,700 - 16,000	10,000
Probability of latent cancer fatality	0.0029	0.0029	0.0039 - 0.0064	0.004
Collective dose (person-rem)	320	320	410 - 620	430
Number of latent cancer fatalities	0.13	0.13	0.16 - 0.25	0.17
Noninvolved worker				
Dose to maximally exposed worker (millirem)	96	96	120 - 180	130
Probability of latent cancer fatality	0.000038	0.000038	0.000048 - 0.000072	0.000052
Collective dose (person-rem)	4.3	4.3	5.4 - 11	5.8
Number of latent cancer fatalities	0.0017	0.0017	0.0022 - 0.0044	0.0023
All workers[e]				
Collective dose (person-rem)	320	320	420 - 630	440
Number of latent cancer fatalities	0.13	0.13	0.17 - 0.25	0.18

a. Source: Exposure rates from Table F-6.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Because the surface facilities would be largely decontaminated at the beginning of the monitoring period (the exception would be a small facility retained to handle an operations emergency), radiological health impacts to surface facility workers during closure would be small in comparison to those to the subsurface facility workers and so are not included here. DOE estimated exposures to subsurface workers from waste packages by increasing those from the Proposed Action by the ratio of the length of closure phases.

F.3.3.4.3 *Summary of Impacts for Closure Phase*

Tables F-66 and F-67 present the occupational and radiological impacts, respectively, to all workers from activities performed during the closure phase. In each table, impacts are presented for the higher-temperature uncanistered and dual-purpose canister packaging scenarios; in addition, the range of impacts for the lower-temperature uncanistered packaging scenario is presented along with the impacts for the dual-purpose canister packaging scenario with long-term ventilation without aging.

Table F-64. Radiological health impacts to subsurface facility workers from ambient radiation exposure during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	600	600	750 - 1,200	800
Probability of latent cancer fatality	0.00024	0.00024	0.0003 - 0.00048	0.00032
Collective dose (person-rem)	140	140	180 - 350	190
Number of latent cancer fatalities	0.056	0.056	0.072 - 0.14	0.076
Noninvolved worker				
Dose to maximally exposed worker (millirem)	240	240	300 - 460	320
Probability of latent cancer fatality	0.000096	0.000096	0.00012 - 0.00018	0.00013
Collective dose (person-rem)	11	11	14 - 28	14
Number of latent cancer fatalities	0.0044	0.0044	0.0056 - 0.011	0.0056
All workers[e]				
Collective dose (person-rem)	150	150	190 - 380	200
Number of latent cancer fatalities	0.06	0.06	0.076 - 0.15	0.08

a. Source: Exposure rates from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-65. Radiological health impacts to subsurface facility workers from radon exposure during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Full-time equivalent worker years[e]	2,900	2,900	3,600 - 6,900	3,800
Dose to maximally exposed worker (millirem)	240	240	300 - 460	320
Probability of latent cancer fatality	0.000096	0.000096	0.00012 - 0.00018	0.00013
Collective dose (person-rem)	57	57	71 - 140	76
Number of latent cancer fatalities	0.023	0.023	0.028 - 0.056	0.03
Noninvolved worker				
Full-time equivalent worker years[e]	540	540	680 - 1,400	720
Dose to maximally exposed worker (millirem)	96	96	120 - 180	130
Probability of latent cancer fatality	0.000038	0.000038	0.000048 - 0.000072	0.000052
Collective dose (person-rem)	4.3	4.3	5.4 - 11	5.8
Number of latent cancer fatalities	0.0017	0.0017	0.0022 - 0.0044	0.0023
All workers[f]				
Full-time equivalent worker years	3,400	3,400	4,300 - 8,300	4,500
Collective dose (person-rem)	61	61	76 - 150	82
Number of latent cancer fatalities	0.024	0.024	0.030 - 0.06	0.033

a. Source: Exposure rates from Table F-7.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Source: Table F-42.
f. Totals might differ from sums of values due to rounding.

Table F-66. Summary of industrial hazard health and safety impacts to facility workers during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	350	330	400 - 600	390
Lost workday cases	170	160	190 - 280	180
Fatalities	0.17	0.16	0.19 - 0.28	0.18
Noninvolved workers				
Total recordable cases of injury and illness	54	50	59 - 82	56
Lost workday cases	26	24	29 - 40	27
Fatalities	0.048	0.044	0.052 - 0.072	0.049
All workers[e]				
Total recordable cases of injury and illness	400	380	460 - 680	450
Lost workday cases	200	180	220 - 320	210
Fatalities	0.22	0.2	0.24 - 0.35	0.23

a. Sources: Tables F-61 and F-62.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-67. Summary of radiological health impacts to workers from all activities during closure phase.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	8,000	8,000	11,000 - 18,000	11,000
Probability of latent cancer fatality	0.0032	0.0032	0.0044 - 0.0072	0.0044
Collective dose (person-rem)	520	520	660 - 1,100	700
Number of latent cancer fatalities	0.21	0.21	0.26 - 0.44	0.28
Noninvolved worker				
Dose to maximally exposed worker (millirem)	430	430	540 - 830	580
Probability of latent cancer fatality	0.00017	0.00017	0.00022 - 0.00033	0.00023
Collective dose (person-rem)	19	19	24 - 50	26
Number of latent cancer fatalities	0.0076	0.0076	0.0096 - 0.02	0.01
All workers[e]				
Collective dose (person-rem)	540	540	680 - 1,200	730
Number of latent cancer fatalities	0.22	0.22	0.27 - 0.48	0.29

a. Sources: Tables F-63, F-64, and F-65.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.3.3.5 Summary of Impacts for All Repository Phases

Tables F-68 and F-69 present the occupational and radiological impacts, respectively, to all workers from all activities performed during all phases. In each table, impacts are presented for the higher-temperature uncanistered and dual-purpose canister packaging scenarios; in addition, the range of impacts for the lower-temperature uncanistered packaging scenario is presented along with the impacts for the dual-purpose canister packaging scenario with long-term ventilation without aging.

Table F-68. Summary of industrial hazard health and safety impacts to facility workers during all phases.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved workers				
Total recordable cases of injury and illness	2,900	2,400	3,400 - 4,000	3,300
Lost workday cases	1,400	1,200	1,600 - 1,900	1,600
Fatalities	2.1	1.6	2.4 - 3.1	2.4
Noninvolved workers				
Total recordable cases of injury and illness	640	680	690 - 830	800
Lost workday cases	310	340	340 - 410	390
Fatalities	0.61	0.65	0.65 - 0.78	0.75
All workers[e]				
Total recordable cases of injury and illness	3,500	3,100	4,100 - 4,800	4,100
Lost workday cases	1,700	1,500	1,900 - 2,300	2,000
Fatalities	2.7	2.3	3.1 - 3.9	3.2

a. Sources: Tables F-12, F-52, F-59, and F-66.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

Table F-69. Summary of radiological health impacts to workers from all activities during all phases.[a,b]

	Operating mode			
	Higher-temperature		Lower-temperature	
Worker group	UC[c]	DPC[d]	UC (range)	DPC
Involved worker				
Dose to maximally exposed worker (millirem)	24,000	24,000	24,000 - 33,000	24,000
Probability of latent cancer fatality	0.0096	0.0096	0.0096 - 0.013	0.0096
Collective dose (person-rem)	14,000	9,900	16,000 - 20,000	14,000
Number of latent cancer fatalities	5.6	4.0	6.4 - 8	5.6
Noninvolved worker				
Dose to maximally exposed worker (millirem)	2,400	2,400	2,400	2,400
Probability of latent cancer fatality	0.00096	0.00096	0.00096	0.00096
Collective dose (person-rem)	270	270	330 - 410	400
Number of latent cancer fatalities	0.11	0.11	0.13 - 0.16	0.16
All workers[e]				
Collective dose (person-rem)	14,000	10,000	16,000 - 20,000	14,000
Number of latent cancer fatalities	5.6	4	6.4 - 8	5.6

a. Source: Sum of values from Tables F-11, F-53, F-60, and F-67.
b. Numbers are rounded to two significant figures.
c. UC = uncanistered packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. Totals might differ from sums of values due to rounding.

F.4 Worker Human Health and Safety Impact Analysis for the Retrieval Contingency

Nuclear Regulatory Commission regulations state that the period for which DOE must maintain the ability to retrieve waste is at least 50 years after the start of emplacement operations [10 CFR 60.111(b)]. Although DOE does not anticipate retrieval and it is not part of the Proposed Action, the Department would maintain the ability to retrieve the waste for at least 100 years and possibly for as long as 300 years after the start of emplacement. Factors that could lead to a decision to retrieve the waste would be (1) to protect the public health and safety or the environment or (2) to recover resources from spent nuclear fuel. This EIS evaluates retrieval as a contingency action and describes potential impacts should it occur. The analysis assumes that under this contingency DOE would retrieve all the waste associated with the Proposed Action and would place it on surface storage pads pending future decisions about its ultimate disposition.

The analysis of health and safety impacts to workers divided the retrieval period into two subperiods, as follows:

- First, a construction subperiod in which DOE would (1) build the surface facilities necessary to handle and enclose retrieved waste packages in concrete storage units in preparation for placement on concrete storage pads, and (2) construct the concrete storage pads.

  No radioactive materials would be involved in the construction subperiod, so health and safety impacts would be limited to those associated with industrial hazards in the workplace. DOE expects this subperiod would last 2 to 3 years, although construction of the concrete storage pads probably would continue on an as-needed basis during most of the operations subperiod. The analysis assumed a 3-year period.

- Second, an operations subperiod during which the waste packages would be retrieved and moved to the Waste Retrieval Transfer Building. Surface facility workers would unload the waste package from the transfer vehicle and place it on a concrete base. The package and concrete base would then be enclosed in a concrete storage unit that would be placed on the concrete storage pad. The analysis assumed an 11-year period.

This section discusses the methodologies and data used to estimate human health and safety impacts resulting from the retrieval contingency. Section F.4.1 describes the methods DOE used to estimate impacts. Section F.4.2 contains tabulations of the detailed data used in the impact calculations and references to the data sources. Section F.4.3 contains detailed tabulations of the results.

F.4.1 METHODOLOGY FOR CALCULATING HUMAN HEALTH AND SAFETY IMPACTS

DOE used the methodology summarized in Section F.2.1 to estimate health and safety impacts for the retrieval contingency. This involved assembling data for the number of full-time equivalent workers for each retrieval activity. These numbers were used with statistics on the likelihood of an impact (industrial hazards), or the estimated radiological dose rate in the worker environment, to calculate health and safety impacts. The way in which the input data were combined to calculate health and safety impacts is described in more detail in Section F.2.1. Some of the input data in the retrieval impact calculations are different from those for the Proposed Action, as described in the next section.

F.4.2 DATA SOURCES AND TABULATIONS

F.4.2.1 Full-Time Equivalent Worker-Year Estimates for the Retrieval Contingency

This analysis divides the repository workforce into two groups—involved and noninvolved workers (see Section F.2 for definitions of involved and noninvolved workers).

Table F-70 lists the number of full-time equivalent work years for the two subperiods of the retrieval operation and the sources of the numbers. Each full-time equivalent worker year represents 2,000 work hours, the hours assumed to be worked in a normal work year. The full-time equivalent worker-year estimates are independent of repository operating mode.

Table F-70. Full-time equivalent worker-year estimates for retrieval.

Subperiod and worker group	Length of subperiod (years)	Full-time equivalent worker years[a]
Surface facilities, construction[b]	3	
Involved		1,300
Noninvolved		500
Surface facilities, retrieval support[c]	11	
Involved		320
Noninvolved		870
Subsurface facility retrieval operations[d]	11	
Involved		810
Noninvolved		180
Total		**4,000**

a. Numbers are rounded to two significant figures.
b. Source: DIRS 154758-Lane (2000, all).
c. Source: DIRS 152010-CRWMS M&O (2000, Table I-3, p. I-20).
d. Source: DIRS 150941-CRWMS M&O (2000, Table 6-29, p. 6-20).

F.4.2.2 Statistics on Health and Safety Impacts from Industrial Hazards in the Workplace

For the retrieval contingency, DOE used the same set of statistics on health and safety impacts from industrial hazards common to the workplace that were used for the Proposed Action (70,000 MTHM) (see Table F-4). The specific statistics that were applied to the retrieval contingency subphases are listed in Table F-71.

F.4.2.3 Estimated Radiological Exposure Rates and Times for the Retrieval Contingency

DOE used the same set of worker exposure rate data as those used for evaluating radiological worker impacts for the Proposed Action. Table F-72 presents the specific application of this data to the retrieval contingency subphases. The source of the information is also referenced. The rates used in the analysis did not take into account radioactive decay for the period between emplacement and retrieval.

Table F-71. Statistics for industrial hazard impacts for retrieval.

Subperiod and worker group	Total recordable incidents (rate per 100 FTEs)[a]	Lost workday cases (rate per 100 FTEs)[a]	Fatalities (rate per 100,000 FTEs)[a,b]
Construction, surface workers[c]			
Involved	6.1	2.9	2.9
Noninvolved	3.3	1.6	
Retrieval, surface workers[d]			
Involved	3.0	1.2	2.9
Noninvolved	3.3	1.6	
Retrieval, subsurface workers[d]			
Involved	3.0	1.2	2.9
Noninvolved	3.3	1.6	

a. FTE = full-time equivalent worker years.
b. Source: Data Set 4, Section F.2.2.
c. Source: Data Set 1, Section F.2.2.
d. Source: Data Set 3, Section F.2.2.

Table F-72. Radiological doses and exposure data used to calculate worker exposures during retrieval.[a]

Subperiod and worker group	Source of exposure	Occupancy factor for exposure rate (fraction of 8-hour workday)	Annual dose (millirem)	Source[b]
Construction				
Surface				
Involved	None			
Noninvolved	None			
Operations				
Surface				
Involved	Waste package	1.0	25	(1)
Noninvolved	Waste package	1.0	0	(1)
Subsurface				
Involved	Waste package	1.0	600	(2)
	Radon-222[c]	1.0	20	Table F-2
	Drift ambient	1.0	50	Section F.1.1.6
Noninvolved	Waste package	0.04 (0.4 for 10% of workers)	200	(3)
	Radon-222	0.4	20	Table F-2
	Drift ambient	0.4	50	Sections F.1.1.6

a. External exposures include radiation from spent nuclear fuel and high-level radioactive waste packages to surface and subsurface workers, the ambient exposure to subsurface workers from naturally occurring radiation in the drift walls, and subsurface worker exposure from inhalation of radon-222.
b. Sources:
   (1) DIRS 152010-CRWMS M&O (2000, Table I-3, p. I-20).
   (2) Table F-6.
   (3) Table F-2; DIRS 104536-Rasmussen (1999, all).
c. Exposure rates from inhalation of radon-222 are assumed to be the same as those for the construction phase.

F.4.3 DETAILED RESULTS FOR THE RETRIEVAL CONTINGENCY

F.4.3.1 Construction Phase

F.4.3.1.1 *Human Health and Safety Impacts to Workers from Industrial Hazards*

The construction phase would entail only surface-facility activities. Table F-73 summarizes health and safety impacts to workers from industrial hazards during construction. There would be no radiological sources present during surface facility construction activities for retrieval and, hence, no radiological health and safety impacts to workers.

Table F-73. Industrial hazard health and safety impacts to workers during construction.[a,b]

Worker group	Impacts
Involved	
Total recordable cases of injury and illness	80
Lost workday cases	38
Fatalities	0.04
Noninvolved	
Total recordable cases of injury and illness	16
Lost workday cases	8
Fatalities	0.01
All workers (totals)	
Total recordable cases of injury and illness	96
Lost workday cases	46
Fatalities	0.05

a. Source: Calculated using impact rates from Table F-71.

b. Numbers are rounded to two significant figures.

F.4.3.2 Operations Period

F.4.3.2.1 *Health and Safety Impacts to Workers from Industrial Hazards*

Chapter 4, Table 4-55, summarizes health and safety impacts to workers from industrial hazards common to the workplace for the retrieval operations period. The impacts in that table consist of two components—health impacts to surface workers and health impacts to subsurface workers. Tables F-74 and F-75 list health impacts from industrial hazards during retrieval operations for these two components, surface and subsurface workers, respectively.

F.4.3.2.2 *Radiological Health and Safety Impacts to Workers*

Potential radiological health impacts to workers during the operations period of retrieval consist of the following components:

- Impacts to surface facility workers involved in handling the waste packages and placing them in concrete storage units

- Impacts to subsurface facilities workers from direct radiation emanating from the waste packages

- Impacts to subsurface workers from inhalation of radon-222 in the atmosphere of the drifts
- Impacts to subsurface workers from ambient radiation from naturally occurring radionuclides in the drift walls

Tables F-76 and F-77 list potential radiological health impacts for each of these component parts.

Table F-74. Industrial hazard health and safety impacts to surface facility workers during retrieval operations.[a,b]

Worker group	Impacts
Involved	
Total recordable cases of injury and illness	10
Lost workday cases	4
Fatalities	0.009
Noninvolved	
Total recordable cases of injury and illness	29
Lost workday cases	14
Fatalities	0.03
All workers (totals)[c]	
Total recordable cases of injury and illness	39
Lost workday cases	18
Fatalities	0.039

a. Source: Impact rates from Table F-71.
b. Numbers are rounded to two significant figures.
c. Totals might differ from sums of values due to rounding.

Table F-75. Industrial hazard health and safety impacts to subsurface facility workers during retrieval operations.[a,b]

Worker group	Impacts
Involved	
Total recordable cases of injury and illness	24
Lost workday cases	11
Fatalities	0.02
Noninvolved	
Total recordable cases of injury and illness	6
Lost workday cases	3
Fatalities	0.01
All workers (totals)[c]	
Total recordable cases of injury and illness	30
Lost workday cases	14
Fatalities	0.03

a. Source: Impact rates from Table F-71.
b. Numbers are rounded to two significant figures.
c. Totals might differ from sums of values due to rounding.

Table F-76. Radiological health impacts to surface facility workers from waste handling during retrieval operations.[a]

Worker group	Impacts
Involved	
Maximally exposed individual dose (millirem)	280
Latent cancer fatality probability for maximally exposed individual	0.0001
Collective dose (person-rem)	8
Latent cancer fatality incidence for overall worker group	0.003
Noninvolved	
Maximally exposed individual dose (millirem)	0
Latent cancer fatality probability for maximally exposed individual	0
Collective dose (person-rem)	0
Latent cancer fatality incidence for overall worker group	0
All workers (totals)[b]	
Collective dose (person-rem)	8
Latent cancer fatality	0.003

a. Source: Exposure rate data from Table F-72.

b. Totals might differ from sums due to rounding.

Table F-77. Components of radiological health impacts to subsurface workers during retrieval operations.[a]

	Source of exposure			
Worker group	Waste packages	Ambient	Radon-222 inhalation	Total[b]
Involved				
Maximally exposed individual dose (millirem)	5,200	550	1,400	5,900
Latent cancer fatality probability for maximally exposed individual	0.002	0.0002	0.0009	0.002
Collective dose (person-rem)	66	41	16	120
Latent cancer fatality incidence for overall worker group	0.08	0.02	0.04	0.05
Noninvolved				
Maximally exposed individual dose (millirem)	88	220	130	440
Latent cancer fatality probability for maximally exposed individual	0.00004	0.00009	0.00005	0.0002
Collective dose (person-rem)	1	4	1	4
Latent cancer fatality incidence for overall worker group	0.0004	0.001	0.0006	0.002
All workers (totals)[c]				
Collective dose (person-rem)	67	45	17	130
Latent cancer fatality incidence for overall worker group	0.08	0.02	0.04	0.05

a. Source: Exposure data from Table F-72.

b. Totals might differ from sums due to rounding.

c. Source: FTE values from Table F-70.

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