APPENDIX C
EVALUATION OF RADIOLOGICAL AND HAZARDOUS CHEMICAL HUMAN HEALTH IMPACTS FROM ROUTINE NORMAL OPERATIONS AND ACCIDENT CONDITIONS

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C.1 Introduction

This appendix provides a brief general discussion of radiation and its health effects. It also describes the methods and assumptions used for estimating the potential impacts and risks to individuals and the general public from exposure to releases of radioactivity during normal operations and postulated accidents involving releases of radioactivity or hazardous chemicals at facilities used for the production of radioisotope power systems (RPS).

This appendix presents numerical information using engineering and/or scientific notation. For example, the number 100,000 also can be expressed as 1×10^5. The fraction 0.001 can be expressed as 1×10^{-3}. The following chart defines the equivalent numerical notations that may be used in this appendix.

Fractions and Multiples of Units

Multiple	*Decimal Equivalent*	*Prefix*	*Symbol*
1×10^6	1,000,000	mega-	M
1×10^3	1,000	kilo-	k
1×10^2	100	hecto-	h
1×10	10	deka-	da
1×10^{-1}	0.1	deci-	d
1×10^{-2}	0.01	centi-	c
1×10^{-3}	0.001	milli-	m
1×10^{-6}	0.000001	micro-	μ

C.1.1 Radiological Impacts on Human Health

Radiation exposure and its consequences are topics of interest to the general public. For this reason, this environmental impact statement (EIS) places emphasis on the consequences of exposure to radiation, provides the reader with information on the nature of radiation, and explains the basic concepts used in the evaluation of radiation health effects.

C.1.1.1 Nature of Radiation and Its Effects on Humans

What Is Radiation?

Radiation is energy transferred in the form of particles or waves. Globally, human beings are exposed constantly to radiation from the solar system and the Earth's rocks and soil. This radiation contributes to the natural background radiation that always surrounds us. Manmade sources of radiation also exist, including medical and dental x-rays, household smoke detectors, and materials released from nuclear and coal-fired power plants.

All matter in the universe is composed of atoms. Radiation comes from the activity of tiny particles within an atom. An atom consists of a positively charged nucleus (central part of an atom) with a number of negatively

charged electron particles in various orbits around the nucleus. There are two types of particles in the nucleus: neutrons that are electrically neutral and protons that are positively charged. Atoms of different types are known as elements. There are more than 100 natural and manmade elements. An element has equal numbers of electrons and protons. When atoms of an element differ in their number of neutrons, they are called isotopes of that element. All elements have three or more isotopes, some or all of which could be unstable (i.e., decay with time).

Unstable isotopes undergo spontaneous change, known as radioactive disintegration or radioactive decay. The process of continuously undergoing spontaneous disintegration is called radioactivity. The radioactivity of a material decreases with time. The time it takes a material to lose half of its original radioactivity is its half-life. An isotope's half-life is a measure of its decay rate. For example, an isotope with a half-life of 8 days will lose one-half of its radioactivity in that amount of time. In 8 more days, one-half of the remaining radioactivity will be lost, and so on. Each radioactive element has a characteristic half-life. The half-lives of various radioactive elements may vary from millionths of a second to millions of years.

As unstable isotopes change into more stable forms, they emit electrically charged particles. These particles may be either alpha particles (a helium nucleus) or beta particles (an electron), with various levels of kinetic energy. Sometimes these particles are emitted in conjunction with gamma rays. The alpha and beta particles are frequently referred to as ionizing radiation. Ionizing radiation refers to the fact that the charged particle energy force can ionize, or electrically charge, an atom by stripping off one of its electrons. Gamma rays, even though they do not carry an electric charge as they pass through an element, can ionize atoms by ejecting electrons. Thus, they cause ionization indirectly. Ionizing radiation can cause a change in the chemical composition of many things, including living tissue (organs), which can affect the way they function.

When a radioactive isotope of an element emits a particle, it changes to an entirely different element, one that may or may not be radioactive. Eventually, a stable element is formed. This transformation, which may take several steps, is known as a decay chain. For example, radium, which is a member of the radioactive decay chain of uranium, has a half-life of 1,622 years. It emits an alpha particle and becomes radon, a radioactive gas with a half-life of only 3.8 days. Radon decays first to polonium, then through a series of further decay steps to bismuth, and ultimately to a stable isotope of lead. Meanwhile, the decay products will build up and eventually die away as time progresses.

The characteristics of various forms of ionizing radiation are briefly described below and in the box to the right.

Alpha (α)—Alpha particles are the heaviest type of ionizing radiation. They can travel only a few centimeters in air. Alpha particles lose their energy almost as soon as they collide with anything. They can be stopped easily by a sheet of paper or by the skin's surface.

Radiation Type	***Typical Travel Distance in Air***	***Barrier***
α	Few centimeters	Sheet of paper or skin's surface
β	Few meters	Thin sheet of aluminum foil or glass
γ	Very large	Thick wall of concrete, lead, or steel
η	Very large	Water, paraffin, graphite

Beta (β)—Beta particles are much (7,330 times) lighter than alpha particles. They can travel a longer distance than alpha particles in the air. A high-energy beta particle can travel a few meters in the air. Beta particles can pass through a sheet of paper, but can be stopped by a thin sheet of aluminum foil or glass.

Gamma (γ)—Gamma rays (and x-rays), unlike alpha or beta particles, are waves of pure energy. Gamma rays travel at the speed of light. Gamma radiation is very penetrating and requires a thick wall of concrete, lead, or steel to stop it.

Neutrons (n)—Neutrons are particles that contribute to radiation exposure both directly and indirectly. The most prolific source of neutrons is a nuclear reactor. Indirect radiation exposure occurs when gamma rays and alpha particles are emitted following neutron capture in matter. A neutron has about one-quarter the weight of an alpha particle. It will travel in the air until it is absorbed in another element.

Units for Measuring Radiation

During the early days of radiological experience, there was no precise unit for radiation measure. Therefore, a variety of units were used to measure radiation. These units were used to determine the amount, type, and intensity of radiation. Just as heat can be measured in terms of its intensity or effects using units of calories or degrees, amounts of radiation or its effects can be measured in units of curies, radiation absorbed dose (rad), or dose equivalent (roentgen equivalent man, or rem). The following summarizes those units.

Curie—The curie, named after French scientists Marie and Pierre Curie, describes the "intensity" of a sample of radioactive material. The rate of decay of 1 gram of radium was the basis of this unit of measure. Because the measured decay rate kept changing slightly as measurement techniques became more accurate, the curie was subsequently defined as exactly 3.7×10^{10} disintegrations (decays) per second.

Rad—The rad is the unit of measurement for the physical absorption of radiation. The total energy absorbed per unit quantity of tissue is referred to as absorbed dose (or simply dose). As sunlight heats pavement by giving up an amount of energy to it, radiation similarly gives up energy to objects in its path. One rad is equal to the amount of radiation that leads to the deposition of 0.01 joule of energy per kilogram of absorbing material.

Radiation Units and Conversions to International System of Units

1 curie	= 3.7×10^{10} disintegrations per second
	= 3.7×10^{10} becquerels
1 becquerel	= 1 disintegration per second
1 rad	= 0.01 gray
1 rem	= 0.01 sievert
1 gray	= 1 joule per kilogram

Rem—A rem is a measurement of the dose equivalent from radiation based on its biological effects. The rem is used in measuring the effects of radiation on the body as degrees Centigrade are used in measuring the effects of sunlight heating pavement. Thus, 1 rem of one type of radiation is presumed to have the same biological effects as 1 rem of any other kind of radiation. This allows comparison of the biological effects of radionuclides that emit different types of radiation.

The units of radiation measure in the International System of Units are: becquerel (a measure of source intensity [activity]), gray (a measure of absorbed dose), and sievert (a measure of dose equivalent).

An individual may be exposed to ionizing radiation externally (from a radioactive source outside the body) or internally (from ingesting or inhaling radioactive material). The external dose is different from the internal dose because an external dose is delivered only during the actual time of exposure to the external radiation source, while an internal dose continues to be delivered as long as the radioactive source is in the body. The dose from internal exposure is calculated over 50 years following the initial exposure. Both radioactive decay and elimination of the radionuclide by ordinary metabolic processes decrease the dose rate with the passage of time.

Sources of Radiation

The average American receives a total of approximately 360 millirem per year from all sources of radiation, both natural and manmade, of which approximately 300 millirem per year are from natural sources. The sources of radiation can be divided into six different categories: cosmic radiation, terrestrial radiation, internal radiation, consumer products, medical diagnosis and therapy, and other sources (NCRP 1987). These categories are discussed in the following paragraphs.

Cosmic Radiation—Cosmic radiation is ionizing radiation resulting from energetic charged particles from space continuously hitting the Earth's atmosphere. These particles and the secondary particles and photons they create comprise cosmic radiation. Because the atmosphere provides some shielding against cosmic radiation, the intensity of this radiation increases with the altitude above sea level. The average dose to people in the United States from this source is approximately 27 millirem per year.

External Terrestrial Radiation—External terrestrial radiation is the radiation emitted from the radioactive materials in the Earth's rocks and soils. The average dose from external terrestrial radiation is approximately 28 millirem per year.

Internal Radiation—Internal radiation results from the human body metabolizing natural radioactive material that has entered the body by inhalation or ingestion. Natural radionuclides in the body include isotopes of uranium, thorium, radium, radon, polonium, bismuth, potassium, rubidium, and carbon. The major contributors to the annual dose equivalent for internal radioactivity are the short-lived decay products of radon, which contribute approximately 200 millirem per year. The average dose from other internal radionuclides is approximately 39 millirem per year.

Consumer Products—Consumer products also contain sources of ionizing radiation. In some products, such as smoke detectors and airport x-ray machines, the radiation source is essential to the product's operation. In other products, such as televisions and tobacco, the radiation occurs as the products function. The average dose from consumer products is approximately 10 millirem per year.

Medical Diagnosis and Therapy—Radiation is an important diagnostic medical tool and cancer treatment. Diagnostic x-rays result in an average exposure of 39 millirem per year. Nuclear medical procedures result in an average exposure of 14 millirem per year.

Other Sources—There are a few additional sources of radiation that contribute minor doses to individuals in the United States. The dose from nuclear fuel cycle facilities (e.g., uranium mines, mills, and fuel processing plants) and nuclear power plants has been estimated to be less than 1 millirem per year. Radioactive fallout from atmospheric atomic bomb tests, emissions from certain mineral extraction facilities, and transportation of radioactive materials contribute less than 1 millirem per year to the average dose to an individual. Air travel contributes approximately 1 millirem per year to the average dose.

Exposure Pathways

As stated earlier, an individual may be exposed to ionizing radiation both externally and internally. The different ways that could result in radiation exposure to an individual are called exposure pathways. Each type of exposure is discussed separately in the following paragraphs.

External Exposure—External exposure can result from several different pathways, all resulting from radiation that is external to the body. Such pathways include exposure to a cloud of radiation passing over the receptor (an exposed individual), standing on ground that is contaminated with radioactivity, and swimming or boating in contaminated water. If the receptor leaves the source of radiation exposure, the dose rate will be reduced. It is assumed that external exposure occurs uniformly during the year. The appropriate dose measure is called the effective dose equivalent.

Internal Exposure—Internal exposure results from a radiation source entering the human body through either inhalation of contaminated air or ingestion of contaminated food or water. In contrast to external exposure, once a radiation source enters the body, it remains there for a period of time that varies depending on decay and biological half-life. The absorbed dose to each organ of the body is calculated for a period of 50 years following the intake. The calculated absorbed dose is called the committed dose equivalent. Various organs

have different susceptibilities to damage from radiation. The quantity that takes these different susceptibilities into account is called the committed effective dose equivalent, and it provides a broad indicator of the risk to the health of an individual from radiation. The committed effective dose equivalent is a weighted sum of the committed dose equivalent in each major organ or tissue. The concept of committed effective dose equivalent applies only to internal pathways.

Radiation Protection Guides

Several organizations have issued radiation protection guides. The responsibilities of the main radiation safety organizations, particularly those that affect policies in the United States, are summarized below.

International Commission on Radiological Protection (ICRP)—This Commission has the responsibility for providing guidance in matters of radiation safety. The operating policy of this organization is to prepare recommendations to deal with basic principles of radiation protection and to leave to the various national protection committees the responsibility of introducing the detailed technical regulations, recommendations, or codes of practice best suited to the needs of their countries.

National Council on Radiation Protection and Measurements (NCRP)—In the United States, this Council is the national organization that has the responsibility for adapting and providing detailed technical guidelines for implementing the ICRP recommendations. The Council consists of technical experts who are specialists in radiation protection and scientists who are experts in disciplines that form the basis for radiation protection.

National Research Council/National Academy of Sciences—The National Research Council is an organization within the National Academy of Sciences that associates the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the Federal Government.

U.S. Environmental Protection Agency (EPA)—The EPA has published a series of documents, *Radiation Protection Guidance to Federal Agencies*. This guidance is used as a regulatory benchmark by a number of Federal agencies, including the U.S. Department of Energy (DOE), in the realm of limiting public and occupational work force exposures to the greatest extent possible.

The Interagency Steering Committee on Radiation Standards (ISCORS), issued a technical report entitled "*A Method for Estimating Radiation Risk from TEDE.*" ISCORS technical reports serve as guidance to Federal agencies to assist them in preparing and reporting the results of analyses and implementing radiation protection standards in a consistent and uniform manner. This report provides dose-to-risk conversion factors where doses are estimated using total effective dose equivalent (TEDE). It is recommended for use by DOE personnel and contractors when computing potential radiation risk from calculated radiation dose for comparison purposes. However, for situations in which a radiation risk assessment is required for making risk management decisions, the radionuclide-specific risk coefficients in the EPA's *Federal Radiation Guidance Report No. 13,* "*Cancer Risk Coefficients for Environmental Exposure to Radionuclides,*" should be used.

Limits of Radiation Exposure

Limits of exposure to members of the public and radiation workers are derived from ICRP recommendations. The EPA uses the NCRP and Measurements and the ICRP recommendations and sets specific annual exposure limits (usually less than those specified by the Commission) in *Radiation Protection Guidance to Federal Agencies* documents. Each regulatory organization then establishes its own set of radiation standards. The various exposure limits set by DOE and the EPA for radiation workers and members of the public are given in **Table C–1**.

Table C–1 Exposure Limits for Members of the Public and Radiation Workers

Guidance Criteria (Organization)	*Public Exposure Limits at the Site Boundary*	*Worker Exposure Limits*
10 CFR 835 (DOE)	–	5 rem per year [a]
10 CFR 835.1002 (DOE)	–	1 rem per year [b]
DOE Order 5400.5 (DOE) [c]	0.01 rem per year (all air pathways) 0.004 rem per year (drinking water pathway) 0.1 rem per year (all pathways)	–
40 CFR 61 (EPA)	0.01 rem per year (all air pathways)	–
40 CFR 141 (EPA)	0.004 rem per year (drinking water pathways)	–

CFR = *Code of Federal Regulations.*

[a] Although this is a limit (or level) that is enforced by DOE, worker doses must be managed in accordance with as low as is reasonably achievable principles. Refer to footnote b.

[b] This is a control level. It was established by DOE to assist in achieving its goal to maintain radiological doses as low as is reasonably achievable. DOE recommends that facilities adopt a more limiting 0.5 rem per year Administrative Control Level (DOE 1999). Reasonable attempts have to be made by the site to maintain individual worker doses below these levels.

[c] Derived from 40 CFR 61, 40 CFR 141, and 10 CFR 20.

C.1.1.2 Health Effects

Radiation exposure and its consequences are topics of interest to the general public. To provide the background for discussions of impacts, this section explains the basic concepts used in the evaluation of radiation effects.

Radiation can cause a variety of damaging health effects in people. The most significant effects are induced cancer fatalities. These effects are referred to as "latent" cancer fatalities because the cancer may take many years to develop. In the discussions that follow, all fatal cancers are considered latent; therefore, the term "latent" is not used.

The National Research Council's Committee on the Biological Effects of Ionizing Radiation (BEIR) has prepared a series of reports to advise the U.S. Government on the health consequences of radiation exposures. *Health Effects of Exposure to Low Levels of Ionizing Radiation*, BEIR V (NRC 1990), provides current estimates for excess mortality from leukemia and other cancers that are expected to result from exposure to ionizing radiation. BEIR V provides estimates that are consistently higher than those in its predecessor, BEIR III. This increase is attributed to several factors, including the use of a linear dose response model for cancers other than leukemia, revised dosimetry for the Japanese atomic bomb survivors, and additional followup studies of the atomic bomb survivors and associated others. BEIR III employs constant, relative, and absolute risk models, with separate coefficients for each of several sex and age-at-exposure groups. BEIR V develops models in which the excess relative risk is expressed as a function of age at exposure, time after exposure, and sex for each of several cancer categories. The BEIR III models were based on the assumption that absolute risks are comparable between the atomic bomb survivors and the U.S. population. BEIR V models were based on the assumption that the relative risks are comparable. For a disease such as lung cancer, where baseline risks in the United States are much larger than those in Japan, the BEIR V approach leads to larger risk estimates than the BEIR III approach.

The models and risk coefficients in BEIR V were derived through analyses of relevant epidemiologic data that included the Japanese atomic bomb survivors, ankylosis spondylitis patients, Canadian and Massachusetts fluoroscopy (breast cancer) patients, New York postpartum mastitis (breast cancer) patients, Israeli tinea capitis (thyroid cancer) patients, and Rochester thymus (thyroid cancer) patients. Models for leukemia, respiratory cancer, digestive cancer, and other cancers used only the atomic bomb survivor data, although results of analyses of the ankylosis spondylitis patients were considered. Atomic bomb survivor analyses were based on

revised dosimetry, with an assumed relative biological effectiveness of 20 for neutrons, and were restricted to doses less than 400 rads. Estimates of risks of fatal cancers, other than leukemia, were obtained by totaling the estimates for breast cancer, respiratory cancer, digestive cancer, and other cancers.

The NCRP (NCRP 1993), based on the radiation risk estimates provided in BEIR V, and the ICRP (ICRP 1991), estimates the total detriment resulting from low dose or low dose rate exposure to ionizing radiation to be 0.00056 per rem for the working population and 0.00073 per rem for the general population. The total detriment includes fatal and nonfatal cancers as well as severe hereditary (genetic) effects. The major contribution to the total detriment is from fatal cancer, estimated to be 0.0006 per rem for both radiation workers and the general population, respectively. The breakdowns of the risk estimators for both workers and the general population are given in **Table C–2**. Nonfatal cancers and genetic effects are less probable consequences of radiation exposure.

Table C–2 Nominal Health Risk Estimators Associated with Exposure to 1 Rem of Ionizing Radiation

Exposed Individual	*Fatal Cancer* [a, c]	*Nonfatal Cancer* [b]	*Genetic Disorders* [b]	*Total*
Worker	0.0004	0.00008	0.00008	0.00056
Public	0.0005	0.0001	0.00013	0.00073

[a] For fatal cancer, the health effect coefficient is the same as the probability coefficient. When applied to an individual, the units are the lifetime probability of a cancer fatality per rem of radiation dose. When applied to a population of individuals, the units are the excess number of fatal cancers per person-rem of radiation dose.

[b] In determining a means of assessing health effects from radiation exposure, the ICRP has developed a weighting method for nonfatal cancers and genetic effects.

[c] For high individual exposures (greater than or equal to 20 rem), the health factors are multiplied by a factor of 2.

Source: NCRP 1993.

The EPA, in coordination with other Federal agencies involved in radiation protection, has issued *Federal Radiation Guidance Report No. 13*, "Cancer Risk Coefficients for Environmental Exposure to Radionuclides," September 1999. This document is a compilation of risk factors for doses from external gamma radiation and internal intakes of radionuclides. *Federal Radiation Guidance Report No. 13* is the basis of the radionuclide risk coefficients used in the *EPA Health Effects Assessment Summary Tables* (EPA 2001) and in computer dose codes such as the DOE Argonne Residual Radiation (RESRAD) code.

However, the Department and other agencies regularly conduct dose assessments with models and codes that calculate radiation dose from exposure or intake using dose conversion factors and do not compute risk directly. In these cases, where it is necessary or desirable to estimate risk for comparative purposes (e.g., comparing the risk associated with alternative actions), it is common practice to simply multiply the calculated TEDE by a risk-to-dose factor. DOE previously recommended a TEDE-to-fatal cancer risk factor of 5×10^{-4} per rem for the public and 4×10^{-4} per rem for working-age populations. These values were based upon recommendations of the former Committee on Interagency Radiation Research and Policy Coordination (CIRRPC). The ISCORS guidance supersedes the 1992 CIRRPC guidance and recommends that agencies use a conversion factor of 6×10^{-4} fatal cancers per TEDE (rem) for mortality and 8×10^{-4} cancers per rem for morbidity when making qualitative or semi-quantitative estimates of risk from radiation exposure to members of the general public[1] (DOE 2002).

[1] *Such estimates should not be stated with more than one significant digit.*

The TEDE-to-risk factor provided by ISCORS in *Technical Report 1* is based upon a static population with characteristics consistent with the U.S. population. There are no separate ISCORS recommendations for workers. For workers (adults), a risk of fatal cancer of 5×10^{-4} per rem and a morbidity risk of 7×10^{-4} per rem may be used. However, given the uncertainties in the risk estimates, for most estimates the value for the general population of 6×10^{-4} per rem could be used for workers (DOE 2002).

The DOE Office of Environmental Policy and Guidance recommends use of these values, but we also emphasize that they are principally suited for comparative analyses and where it would be impractical to calculate risk using the *Federal Radiation Guidance Report No. 13*. If risk estimates for specific radionuclides are needed, the cancer risk coefficients in the *Federal Radiation Guidance Report No. 13* should be used (DOE 2002).

The ISCORS report notes that the recommended risk coefficients used with TEDE dose estimates generally produce conservative radiation risk estimates (i.e., they overestimate risk)[2]. For the ingestion pathway of 11 radionuclides compared, risks would be overestimated compared to the *Federal Radiation Guidance Report No. 13* values for about 8 radionuclides and significantly overestimated (by up to a factor of 6) for 4 of these. The DOE Office of Environmental Policy and Guidance also compared the TEDE multiplying the conversion factor approach to *Federal Radiation Guidance Report No. 13* for the inhalation pathway and found a bias toward overestimation of risk, although it was not as severe as for ingestion. For 16 radionuclides/chemical states evaluated, 7 were significantly overestimated (by more than a factor of 2), 5 were significantly underestimated, and the remainder agreed within about a factor of 2. Generally, these differences are within the uncertainty of transport and uptake portions of dose or risk modeling and, therefore, the approach recommended is fully acceptable for comparative assessments. That notwithstanding, it is strongly recommended that, wherever possible, the more rigorous approach with *Federal Radiation Guidance Report No. 13* cancer risk coefficients be used (DOE 2002).

The values in Table C–2 are "nominal" cancer and genetic disorder probability coefficients. They are based on an idealized population receiving a uniform dose over whole body. Recent studies by the EPA, based on age-dependent dose coefficients for members of the public, indicate that the product of the effective dose and the probability coefficient could overestimate or underestimate radiological risks (EPA 1999b). The risk coefficient provided in *Federal Guidance Report No. 13* eliminates the need for separate probability coefficients for cancer incidence and mortalities (EPA 1999b). In support of the risk results provided in *Federal Guidance Report No. 13*, the EPA performed an uncertainty analysis on the effects of uniform whole body exposures. The analysis resulted in an increase in the estimated nominal risk coefficient from 0.051 fatal cancers per gray (0.00051 fatal cancers per rad) to 0.0575 fatal cancers per gray (0.000575 fatal cancers per rad) (EPA 1999a). This result indicates an increase in nominal risk coefficient of about 20 percent over that provided in NCRP 1993 for the public (given in Table C–2).

Based on review of the recent EPA reports, the ISCORS recommended that a risk factor of 0.06 fatal cancers per sievert (0.0006 fatal cancers per rem) be used for estimating risks when using calculated dose (ISCORS 2002). The DOE Office of NEPA Policy and Compliance recommended that the 0.0006 fatal cancers per rem be used for both the workers and members of the public (DOE 2003).

[2]*This statement presumes that Federal Radiation Guidance Report No. 13 is a more accurate measure of potential risk than multiplying the TEDE by a single average risk factor. The numerical estimate of cancer deaths is based upon the linear extrapolation of risk estimates for total cancer mortality derived at radiation doses above 10 rad (0.1 gray). Other methods of extrapolation would yield higher or lower risk estimates at low doses. Epidemiological studies of human radiation exposure are not sufficiently sensitive to determine the actual level of risk. There is scientific uncertainty about cancer risk in the low-dose region and the possibility of zero risk cannot be excluded.*

The numerical estimates of fatal cancers presented in this EIS were obtained using a linear extrapolation from the nominal risk estimated for lifetime total cancer mortality that results from a dose of 0.1 gray (10 rad). Other methods of extrapolation to the low-dose region could yield higher or lower numerical estimates of fatal cancers. Studies of human populations exposed to low doses are inadequate to demonstrate the actual level of risk. There is scientific uncertainty about cancer risk in the low-dose region below the range of epidemiologic observation, and the possibility of no risk cannot be excluded (CIRRPC 1992).

Health Effect Risk Estimators Used in this EIS

Health impacts from radiation exposure, whether from external or internal sources, generally are identified as "somatic" (i.e., affecting the exposed individual) or "genetic" (i.e., affecting descendants of the exposed individual). Radiation is more likely to produce somatic effects than genetic effects. The somatic risks of most importance are induced cancers. Except for leukemia, which can have an induction period (time between exposure to carcinogen and cancer diagnosis) of as little as 2 to 7 years, most cancers have an induction period of more than 20 years.

For a uniform irradiation of the body, the incidence of cancer varies among organs and tissues; the thyroid and skin demonstrate a greater sensitivity than other organs. Such cancers, however, also produce relatively low mortality rates because they are relatively amenable to medical treatment. Because fatal cancer is the most probable serious effect of environmental and occupational radiation exposures, estimates of cancer fatalities rather than cancer incidence are presented in this EIS. The numbers of fatal cancers can be used to compare the risks among the various alternatives.

Based on the preceding discussion, the number of fatal cancers to workers and the general public during normal operations and for postulated accidents in which individual doses are less than 20 rem are calculated using a health risk estimator of 0.0006 per person-rem. (The risk estimators are lifetime probabilities that an individual would develop a fatal cancer per rem of radiation received.) The risk estimators associated with total cancer incidence among the public is 0.0008 per person-rem (ISCORS 2002).

Recent analysis by EPA (EPA 1999a and 1999b) address the effects of low dose and dose rate exposure to ionizing radiation. Consistent with the conclusion in NCRP 1993, the risk to individuals receiving doses of 20 rem or more are double those associated with doses of less than 20 rem.

The fatal cancer estimators are used to calculate the statistical expectation of the effects of exposing a population to radiation. For example, if 100,000 people were each exposed to a one-time radiation dose of 100 millirem (0.1 rem), the collective dose would be 10,000 person-rem. The exposed population would then be expected to experience 6 additional cancer fatalities from the radiation (10,000 person-rem × 0.0006 lifetime probability of cancer fatalities per person-rem = 6 cancer fatalities).

Calculations of the number of excess fatal cancers associated with radiation exposure do not always yield whole numbers. These calculations may yield numbers less than one, especially in environmental impact applications. For example, if a population of 100,000 were exposed to a total dose of only 0.001 rem per person, the collective dose would be 100 person-rem (100,000 persons × 0.001 rem = 100 person-rem). The corresponding estimated number of cancer fatalities would be 0.06 (100 person-rem × 0.0006 cancer fatalities per person-rem = 0.06 cancer fatalities). The 0.06 means that there is 1 chance in 16.6 that the exposed population would experience 1 fatal cancer. In other words, the 0.06 cancer fatalities is the *expected* number of deaths that would result if the same exposure situation were applied to many different groups of 100,000 people. In most groups, no person would incur a fatal cancer from the 0.001 rem dose each member received. In a small fraction of the groups, one cancer fatality would result; in exceptionally few groups, two or more cancer fatalities would occur. The *average* expected number of deaths over all the groups would be

0.06 cancer fatalities (just as the average of 0, 0, and 0, added to 1 is 1/4, or 0.25). The most likely outcome is no cancer fatalities.

The same concept is applied to estimate the effects of radiation exposure on an individual member of the public. Consider the effects of an individual's exposure to a 360-millirem (0.36 rem) annual dose from all radiation sources. The probability that the individual will develop a fatal cancer from continuous exposure to this radiation over an average life of 72 years (presumed) is 0.016 (1 person × 0.36 rem per year × 72 years × 0.0006 cancer fatalities per person-rem = 0.016). This corresponds to 1 chance in 64 that the individual would develop a fatal cancer in a lifetime.

C.2 Methodology for Estimating Normal Operation Radiological and Hazardous Chemical Impacts

C.2.1 GENII Computer Code, a Generic Description

The radiological impacts from releases during normal operation of the facilities used to perform RPS production operations were calculated using Version 1.485 of the GENII computer code (PNL 1988). Site-specific input data were used, including location, meteorology, population, and source terms. This section briefly describes GENII and outlines the approach used for normal operations.

C.2.1.1 Description of the Code

The GENII computer model, developed by Pacific Northwest National Laboratory, is an integrated system of various computer modules that analyze environmental contamination resulting from acute or chronic releases to, or initial contamination in, air, water, or soil. The model calculates radiation doses to individuals and populations. The GENII computer model is well documented for assumptions, technical approach, method, and quality assurance issues. The GENII computer model has gone through extensive quality assurance and quality control steps, including comparing results from model computations with those from hand calculations and performing internal and external peer reviews (PNL 1988).

The GENII code consists of several modules for various applications as described in the code manual (PNL 1988). For this EIS, only the ENVIN, ENV, and DOSE computer modules were used. The output of one module is stored in a file that can be used by the next module in the system. The functions of the three GENII computer modules used in this EIS are discussed below.

ENVIN

The ENVIN module of the GENII code controls the reading of input files and organizes the input for optimal use in the environmental transport and exposure module, ENV. The ENVIN code interprets the basic input, reads the basic GENII data libraries and other optional input files, and organizes the input into sequential segments based on radionuclide decay chains.

A standardized file that contains scenario, control, and inventory parameters is used as input to ENVIN. Radionuclide inventories can be entered as functions of releases to air or water, concentrations in basic environmental media (air, soil, or water), or concentrations in foods. If certain atmospheric dispersion options have been selected, this module would generate tables of atmospheric dispersion parameters that are used in later calculations. If the finite plume air submersion option is selected in addition to the atmospheric dispersion calculations, preliminary energy-dependent finite plume dose factors can be prepared as well. The ENVIN module prepares the data transfer files that are used as input by the ENV module; ENVIN generates the first portion of the calculation documentation—the run input parameters report.

ENV

The ENV module calculates the environmental transfer, uptake, and human exposure to radionuclides that result from the chosen scenario for the user-specified source term. The code reads the input files from ENVIN and then, for each radionuclide chain, sequentially performs the precalculations to establish the conditions at the start of the exposure scenario. Environmental concentrations of radionuclides are established at the beginning of the scenario by assuming decay of pre-existing sources, considering biotic transport of existing subsurface contamination, and defining soil contamination from continuing atmospheric or irrigation depositions. For each year of postulated exposure, the code then estimates the air, surface soil, deep soil, groundwater, and surface water concentrations of each radionuclide in the chain. Human exposures and intakes of each radionuclide are calculated for pathways of external exposure from finite or infinite atmospheric plumes; inhalation; external exposure from contaminated soil, sediments, and water; external exposure from special geometries; and internal exposures from consumption of terrestrial foods, aquatic foods, drinking water, animal products, and inadvertent intake of soil. The intermediate information on annual media concentrations and intake rates is written to data transfer files. Although these may be accessed directly, they are usually used as input to the DOSE module of GENII.

DOSE

The DOSE module reads the intake and exposure rates defined by the ENV module and converts the data to radiation dose.

C.2.1.2 Data and General Assumptions

To perform the dose assessments for this EIS, different types of data were collected and generated. This section discusses the various data, along with the assumptions made for performing the dose assessments.

Dose assessments were performed for members of the general public at Oak Ridge National Laboratory (ORNL), Idaho National Laboratory (INL), and Los Alamos National Laboratory (LANL) to determine the incremental doses that would be associated with the alternatives addressed in this EIS. Incremental doses for members of the public were calculated (via GENII) for two different types of receptors:

- *Maximally Exposed Individual (MEI)*—The MEI was assumed to be an individual member of the public located at a position on the site boundary, including public roads inside the site, that would yield the highest impacts during normal operations. For this EIS, the MEI is located 4,550 meters (2.8 miles) east-northeast from the High Flux Isotope Reactor (HFIR) and the Radiochemical Engineering Development Center (REDC) at ORNL; 5,200 meters (3.2 miles) south-southeast from the Materials and Fuels Complex (MFC); and 900 meters (0.6 miles) from the Plutonium Facility at LANL.

- *Population*—The general population living within 80 kilometers (50 miles) of the facility. An average dose to a member of this population was also calculated.

Meteorological Data

The meteorological data used for all normal operational scenarios discussed in this EIS were in the form of joint frequency data files. A joint frequency data file is a table listing the fractions of time the wind blows in a certain direction, at a certain speed, and within a certain atmospheric stability class. The joint frequency data files were based on measurements taken over a period of several years at ORNL, INL, and LANL.

Population Data

Population distributions were based on U.S. Department of Commerce state population Census numbers (DOC 2001). Estimates were determined for the years 2010 and 2050 for areas within 80 kilometers (50 miles) of the release locations. The 2010 projection was used for the bridge period under the Consolidation with Bridge Alternative. The 2050 projection was used for all other alternatives. The estimated site-specific population was used in the impact assessments. The population was spatially distributed on a circular grid with 16 directions and 10 radial distances up to 80 kilometers (50 miles). The grid was centered at the location from which the radionuclides were assumed to be released. The following total populations were projected. For 2010: 245,000 at MFC at INL; 1,129,000 at ORNL; and 357,400 at LANL. For 2050: 355,000 at MFC at INL, 1,438,000 at ORNL; and 608,800 at LANL.

Source Term Data

The source terms used to calculate the impacts of normal operations are provided in Section C.2.1.4.

Food Production and Consumption Data

Generic food consumption rates are available as default values in GENII. The default values are comparable to those established in the U.S. Nuclear Regulatory Commission (NRC) *Regulatory Guide 1.109* (NRC 1977). This regulatory guide provides guidance for evaluating ingestion doses from consuming contaminated terrestrial and animal food products using a standard set of assumptions for crop and livestock growth and harvesting characteristics.

Basic Assumptions

To estimate annual radiological impacts to the public from normal operations, the following additional assumptions and factors were considered in using GENII:

- Radiological airborne emissions were assumed to be released to the atmosphere at a height of 76.2 meters (250 feet) at REDC, 15.9 meters (52 feet) at the Plutonium Facility at Technical Area 55 (TA-55), and 12.8 meters (42 feet) at MFC at INL.

- Emission of the plume was assumed to continue throughout the year. Plume and ground deposition exposure parameters used in the GENII model for the exposed offsite individual and the general population are provided in **Table C–3**.

- The exposed individual or population was assumed to have the characteristics and habits of an adult human.

- A semi-infinite plume model was used for the air immersion doses.

Worker doses associated with RPS production operations were determined from historical data.

Table C–3 GENII Parameters for Exposure to Plumes (Normal Operations)

Maximally Exposed Offsite Individual				*General Population*			
External Exposure		*Inhalation of Plume*		*External Exposure*		*Inhalation of Plume*	
Plume (hours)	*Ground Contamination (hours)*	*Exposure Time (hours)*	*Breathing Rate (cubic centimeters per second)*	*Plume (hours)*	*Ground Contamination (hours)*	*Exposure Time (hours)*	*Breathing Rate (cubic centimeters per second)*
6,136	6,136	8,766	270	4,383	4,383	8,766	270

Sources: PNL 1988, NRC 1977.

C.2.1.3 Uncertainties

The sequence of analyses performed to generate the radiological impact estimates from normal operations include selection of normal operational modes, estimation of source terms, estimation of environmental transport and uptake of radionuclides, calculation of radiation doses to exposed individuals, and estimation of health effects. There are uncertainties associated with each of these steps. Uncertainties exist in the way the physical systems being analyzed are represented by the computational models and in the data required to exercise the models (due to measurement, sampling, or natural variability).

In principle, one can estimate the uncertainty associated with each source and predict the remaining uncertainty in the results of each set of calculations. Thus, one can propagate the uncertainties from one set of calculations to the next and estimate the uncertainty in the final results. However, conducting such a full-scale quantitative uncertainty analysis is neither practical nor a standard practice for a study of this type. Instead, the analysis is designed to ensure—through judicious selection of release scenarios, models, and parameters—that the results represent the potential risks. This is accomplished by making conservative assumptions in the calculations at each step. The models, parameters, and release scenarios used in the calculations are selected in such a way that most intermediate results and, consequently, the final estimates of impacts are greater than would be expected. As a result, even though the range of uncertainty in a quantity might be large, the value calculated for the quantity would be close to one of the extremes in the range of possible values, so the chance of the actual quantity being greater than the calculated value would be low. Conservative assumptions in this analysis bound all uncertainties.

The human health impacts from routine normal activities may have different impacts on specific populations such as American Indians or Hispanics whose cultural heritage can result in special pathways of exposure that are different than those modeled to evaluate the doses to the general population and MEI. Although the analyses performed to evaluate the public impacts of the alternatives did include normally significant pathways and were designed to be conservative, no pathways were included to specifically address local population use of local resources. Therefore, there is potentially more uncertainty in the effects of activities on these specific population groups. A qualitative evaluation of the potential impacts on these specific groups was performed based on the nuclides emitted and an understanding of the most significant pathways.

Parameter selection and practices of the population and MEI were chosen to be conservative. For example, it was assumed that the population breathed contaminated air all the time (spent no time away from the local area) and that all food was produced in the potentially affected area (no food from outside the local area). The dose to a member of the public was dominated by internal exposures from inhalation and ingestion. Typically, about one-third of the dose was from inhalation and two thirds was from ingestion. Inhalation of ambient air and the resulting dose would be about the same for all members of population surrounding the locations of interest.

C.2.1.4 Radiological Releases During Routine Normal Operations

The estimated radiological releases to the environment associated with routine normal operations are discussed below and are based on the methodology provided in Section C.2.1.2. The resulting impacts to the public and to workers associated with each alternative are presented and discussed in Chapter 4 of this EIS.

Routine radiological releases during normal operations are presented in **Table C–4** for each of the alternatives. These are incremental releases (i.e., releases due to the Proposed Action only). They do not include releases from other activities that might occur at the same facility or complex.

Table C–4 Normal Operation Incremental Radiological Releases

	No Action Alternative (curies per year plutonium-238)	*Consolidation Alternative (curies per year plutonium-238)*	*Consolidation with Bridge Alternative (curies per year plutonium-238)*	
Storage of Target Material				
Location	FMF at MFC at INL	FMF at MFC at INL	FMF at MFC at INL	
Emissions	1.7×10^{-8} [a]	1.7×10^{-8} [a]	1.7×10^{-8} [a]	
Target Fabrication and Post-Irradiation Processing				
Location	REDC at ORNL	Plutonium-238 Facility at MFC at INL	REDC at ORNL (2007-2011)	Plutonium-238 Facility at MFC at INL (2012-2047)
Emissions	1.7×10^{-7}	1.7×10^{-7}	6.8×10^{-8}	1.7×10^{-7}
Target Irradiation [b]				
Location	ATR at INL and HFIR at ORNL	ATR at INL	HFIR at ORNL (2007-2011)	ATR at INL (2012-2047)
Emissions	No Change	No Change	No Change	No Change
Purification, Pelletization, and Encapsulation				
Location	Plutonium Facility at LANL	Plutonium Facility at LANL (2007-2011) MFC at INL (2012-2047)	Plutonium Facility at LANL (2007-2011)	MFC at INL (2012-2047)
Emissions	1.0×10^{-8}	1.0×10^{-8}	1.0×10^{-8}	1.0×10^{-8}
RPS Assembly and Testing				
Location	Assembly and Testing Facility at MFC at INL	Assembly and Testing Facility at MFC at INL	Assembly and Testing Facility at MFC at INL	
Emissions	None	None	None	

FMF = Fuel Manufacturing Facility, MFC = Materials and Fuels Complex, INL = Idaho National Laboratory, REDC = Radiochemical Engineering Development Center, ORNL = Oak Ridge National Laboratory, ATR = Advanced Test Reactor, HFIR = High Flux Isotope Reactor, LANL = Los Alamos National Laboratory, RPS = radioisotope power systems.

[a] Releases associated with storage of neptunium-237 would be expected to be essentially zero because it is stored in licensed and shielded containers. However, it has been assumed that the doses due to storage would be 10 percent of the doses due to processing activities.

[b] The incremental emissions from ATR and HFIR are zero because it is assumed that they are in operation regardless of the Proposed Action, and the Proposed Action does not increase their emissions.

Target Material Storage—Release associated with the storage of neptunium-237 would be expected to be essentially zero. However, the *Final Programmatic Environmental Impact Statement for Accomplishing Expanded Civilian Nuclear Energy Research and Development and Isotope Production Missions in the United States, Including the Role of the Fast Flux Test Facility (NI PEIS)*, DOE/EIS-0310, has conservatively assumed that the doses due to storage would be 10 percent of the doses due to processing activities. That is why this EIS assumes a normal operation release due to storage of target material equivalent to 10 percent of the release due to target fabrication and post-irradiation activities.

Target Fabrication and Post-irradiation—Normal operational releases to the environment from target fabrication and post-irradiation processing activities were determined based on the conservative assumption made in the *NI PEIS* (DOE 2000) that a 5-kilogram (11-pound) inventory of plutonium-238 is processed on an annual basis. Employing a processing facility emission factor of 1.98×10^{-12}, and a specific activity of 17 curies per gram, a resulting annual release quantity of 1.7×10^{-7} curies is calculated as shown below:

(5,000 grams per year of plutonium-238) × (17 curies of plutonium-238 per gram of plutonium-238) × (1.98×10^{-12}) = 1.7×10^{-7} curies per year of plutonium-238

For a production of 2 kilograms per year of plutonium-238, the normal operation releases from target fabrication and post-irradiation activities would be $(2/5) \times (1.7 \times 10^{-7}) = 6.8 \times 10^{-8}$ curies per year of plutonium-238.

Target Irradiation—Normal operational release to the environment from Advanced Test Reactor (ATR) and/or HFIR for the purpose of calculating incremental dose would be zero because there would be no increase in activities in those reactors due to the additional target irradiation.

Purification, Pelletization, and Encapsulation—Normal operation releases from purification, pelletization, and encapsulation were based on stack monitoring data from the operations at LANL's Plutonium Facility at TA-55. Plutonium-238 emissions from the LANL Plutonium Facility between 1997 and 2003 ranged between 4.7×10^{-9} to 8.63×10^{-9} curies per year. These emissions from TA-55 of the facility containing the plutonium-238 operations are exhausted through Stack "ES-15," which is filtered by four stages of high-efficiency particulate air (HEPA) filters, with a control efficiency of 99.95 percent for each stage (LANL 2005a).

This EIS conservatively assumes an upper bound of 1.0×10^{-8} curies of plutonium-238 per year.

RPS Assembly and Testing—Normal operation releases are not expected from the RPS assembly and testing activities because the facility would only handle fully encapsulated radioactive material.

Storage of Available Inventory—Normal operation releases are not expected from the storage of the available and usable inventory of plutonium-238 because this inventory would be in the form of fully encapsulated radioactive material.

C.2.1.5 Occupational (Worker) Health Impacts

Health impacts from radiological exposure due to normal facility operation were determined for the facility worker directly involved in the fabrication, irradiation, processing, and storage of plutonium-238 targets. The *NI PEIS* (DOE 2000) provides number of workers, collective dose, and individual worker dose for processing activities at REDC. The *NI PEIS* also assumes that the worker dose due to storage of target materials is 10 percent of that due to processing activities. They were duplicated in this EIS.

Worker doses due to plutonium-238 purification, pelletization, and encapsulation activities at LANL's Plutonium Facility at TA-55 were obtained from 12 years (1993 to 2004) exposure data for workers involved in plutonium-238 operations (LANL 2005b). These doses are total measured internal and external radiation dose based on actual worker dosimetry data and by periodic worker biosafety monitoring. This data showed that an average of 79 workers have received 0.24[3] rem each annually for a collective dose of 19 person-rem per year.

[3] *During peak plutonium-238 production years, a few workers at the LANL TA-55 Plutonium Facility received total annual doses of up to 2 rem each, which was the worker maximum dose administrative limit.*

C.2.1.6 Impacts of Exposures to Hazardous Chemicals on Human Health

The potential impacts of exposure to hazardous chemicals released to the atmosphere due to plutonium-238 production activities were evaluated for routine operations in the *NI PEIS* (DOE 2000). The results of the analysis are reproduced in Chapter 4 of this EIS. The methodology appears in Appendix H, Section H.3 of the *NI PEIS*.

C.3 Accident Analysis

Accident scenarios were divided into two categories: neptunium-237 target fabrication and processing and plutonium-238 purification, pelletization, and encapsulation. The identical accidents are evaluated for the No Action and Proposed Action alternatives, with the difference being the location of the accident. In the No Action case, target fabrication processing was analyzed in the *NI PEIS* for the REDC at ORNL. Also, the No Action Alternative analyzed the purification, pelletization, and encapsulation accidents at the Plutonium Facility at LANL. For the Proposed Action alternatives (i.e., Consolidation Alternative and Consolidation with Bridge Alternative), both sets of accidents were analyzed for the new facility at INL. The new facility at INL, currently in the conceptual design phase, will meet or exceed all safety design features of the REDC and LANL Plutonium Facility. This includes four separate dry HEPA filters for all air exhausted through the stack. Therefore, it is conservative to use the accident scenarios from these existing facilities for the new facility at INL in the Proposed Action alternatives.

Dose assessments were performed for members of the general public and noninvolved workers at ORNL, INL, and LANL to determine the doses that would be associated with the alternatives addressed in this EIS. Doses for members of the public and noninvolved workers were calculated (via MACCS2) for three different types of receptors:

- *Maximally Exposed Individual*—The MEI was assumed to be an individual member of the public located at a position on the site boundary, including public roads inside the site, that would yield the highest impacts from the postulated accident. For this EIS, the MEI is located 4,550 meters (2.8 miles) east-northeast from HFIR and REDC at ORNL; 5,200 meters (3.2 miles) south-southeast from MFC; and 900 meters (0.6 miles) from the Plutonium Facility at LANL.

- *Population*—The general population living within 80 kilometers (50 miles) of the facility.

- *Noninvolved worker*–A worker located 640 meters (2,100 feet) from the accident source term plume release location.

C.3.1 MACCS2 Code Description

The MACCS2 computer code is used to estimate the radiological doses and health effects that could result from postulated accidental releases of radioactive materials to the atmosphere. The specification of the release characteristics, designated a "source term," can consist of up to four Gaussian plumes that are often referred to simply as "plumes."

The radioactive materials released are modeled as being dispersed in the atmosphere while being transported by the prevailing wind. During transport, whether or not there is precipitation, particulate material can be modeled as being deposited on the ground. If contamination levels exceed a user-specified criterion, mitigating actions can be triggered to limit radiation exposures.

There are two aspects of the code's structure basic to understanding its calculations: (1) the calculations are divided into modules and phases, and (2) the region surrounding the facility is divided into a polar-coordinate grid. These concepts are described in the following sections.

MACCS2 is divided into three primary modules: ATMOS, EARLY, and CHRONC. Three phases are defined as the emergency, intermediate, and long-term phases. The relationship among the code's three modules and the three phases of exposure are summarized below.

The ATMOS module performs all of the calculations pertaining to atmospheric transport, dispersion, and deposition, as well as the radioactive decay that occurs before release and while the material is in the atmosphere. It uses a Gaussian plume model with Pasquill-Gifford dispersion parameters. The phenomena treated include building wake effects, buoyant plume rise, plume dispersion during transport, wet and dry deposition, and radioactive decay and in-growth. The results of the calculations are stored for use by EARLY and CHRONC. In addition to the air and ground concentrations, ATMOS stores information on wind direction, arrival and departure times, and plume dimensions.

The EARLY module models the period immediately following a radioactive release. This period is commonly referred to as the emergency phase. The emergency phase begins at each successive downwind distance point when the first plume of the release arrives. The duration of the emergency phase is specified by the user, and it can range between 1 and 7 days. The exposure pathways considered during this period are direct external exposure to radioactive material in the plume (cloud shine), exposure from inhalation of radionuclides in the cloud (cloud inhalation), exposure to radioactive material deposited on the ground (ground shine), inhalation of resuspended material (resuspension inhalation), and skin dose from material deposited on the skin. Mitigating actions that can be specified for the emergency phase include evacuation, sheltering, and dose-dependent relocation. All MACCS2 calculations for this EIS assumed no mitigating actions.

The CHRONC module performs all of the calculations pertaining to the intermediate and long-term phases. CHRONC calculates the individual health effects that result from both direct exposures to contaminated ground and from inhalation of resuspended materials, as well as indirect health effects caused by the consumption of contaminated food and water by individuals who reside both on and off the computational grid.

The intermediate phase begins at each successive downwind distance point upon conclusion of the emergency phase. The user can configure the calculations with an intermediate phase that has a duration as short as zero or as long as 1 year. In the zero-duration case, there is essentially no intermediate phase and a long-term phase, begins immediately upon conclusion of the emergency phase.

Intermediate models are implemented on the assumption that the radioactive plume has passed and the only exposure sources (ground shine and resuspension inhalation) are from ground-deposited material. It is for this reason that MACCS2 requires the total duration of a radioactive release be limited to no more than 4 days. Potential doses from food and water during this period are not considered.

The mitigating action model for the intermediate phase is very simple. If the intermediate phase dose criterion is satisfied, the resident population is assumed present and subject to radiation exposure from ground shine and resuspension for the entire intermediate phase. If the intermediate phase exposure exceeds the dose criterion, then the population is assumed relocated to uncontaminated areas for the entire intermediate phase. No mitigating actions were assumed for MACCS2 calculations in support of this EIS.

The long-term phase begins at each successive downwind distance point upon conclusion of the intermediate phase. The exposure pathways considered during this period are ground shine, resuspension inhalation, and food and water ingestion.

The exposure pathways considered are those resulting from ground-deposited material. A number of protective measures, such as decontamination, temporary interdiction, and condemnation, can be modeled in the long-term phase to reduce doses to user-specified levels. The decisions on mitigating action in the long-term phase are based on two sets of independent actions: (1) decisions relating to whether land at a specific location and time is suitable for human habitation (habitability), and (2) decisions relating to whether land at a specific location and time is suitable for agricultural production (ability to farm). MACCS2 calculations in support of this EIS assumed no protective measures.

All of the calculations of MACCS2 are stored based on a polar-coordinate spatial grid with a treatment that differs somewhat between calculations of the emergency phase and calculations of the intermediate and long-term phases. The region potentially affected by a release is represented with an (r, Θ) grid system centered on the location of the release. Downwind distance is represented by the radius "r". The angle, Θ, is the angular offset from the north, going clockwise.

The user specifies the number of radial divisions as well as their endpoint distances. The angular divisions used to define the spatial grid are fixed in the code. They correspond to the 16 points of the compass, each being 22.5 degrees wide. The 16 points of the compass are used in the United States to express wind direction. The compass sectors are referred to as the coarse grid.

Since emergency phase calculations use dose-response models for early fatalities and injuries that can be highly nonlinear, these calculations are performed on a finer grid basis than the calculations of the intermediate and long-term phases. For this reason, the calculations of the emergency phase are performed with the 16 compass sectors divided into 3, 5, or 7 equal, angular subdivisions. The subdivided compass sectors are referred to as the fine grid.

Two types of doses may be calculated by the code, "acute" and "lifetime."

Acute doses are calculated to estimate deterministic health effects that can result from high doses delivered at high dose rates. Such conditions may occur in the immediate vicinity of a nuclear facility following hypothetical severe accidents where confinement and/or containment failure has been assumed to occur. Examples of the health effects based on acute doses are early fatality, prodromal vomiting, and hypothyroidism.

Lifetime doses are the conventional measure of detriment used for radiological protection. These are 50-year dose commitments to either specific tissues (e.g., red marrow and lungs) or a weighted sum of tissue doses defined by ICRP and referred to as "effective dose." Lifetime doses may be used to calculate the stochastic health effect risk resulting from exposure to radiation. MACCS2 uses the calculated lifetime dose in cancer risk calculations.

C.3.2 ALOHA Code Description

Consequences of accidental chemical releases were determined using the Areal Locations of Hazardous Atmospheres (ALOHA) computer code (NOAA 1999). ALOHA is an EPA/National Oceanic and Atmospheric Administration-sponsored computer code that has been widely used in support of chemical accident responses and also in support of safety and National Environmental Policy Act (NEPA) documentation for DOE facilities. The ALOHA code is a deterministic representation of atmospheric releases of toxic and hazardous chemicals. The code can predict the rate at which chemical vapors escape (e.g., from puddles or leaking tanks) into the atmosphere; a specified direct release rate is also an option.

ALOHA performs calculations for chemical source terms and resulting downwind concentrations. Source term calculations determine the rate at which the chemical material is released to the atmosphere, release duration,

and the physical form of the chemical upon release. The term "cloud" is used in this document to refer to the volume that encompasses the chemical emission. In general, the released chemical may be a gas, a vapor, or an aerosol. An aerosol release may consist of either solid (e.g., fume, dust) or liquid (e.g., fog, mist, spray) particles that are suspended in a gas or vapor medium. Liquid particles are also referred to as "droplets". The analyst specifies the chemical and then characterizes the initial boundary conditions of the chemical with respect to the environment through the source configuration input. The ALOHA code allows for the source to be defined in one of four ways (i.e., direct source, puddle source, tank source, or pipe source) in order to model various accident scenarios. The source configuration input is used to either specify the chemical source term or to provide ALOHA with the necessary information and data to calculate transient chemical release rates and physical state of the chemical upon release. ALOHA calculates time-dependent release rates for up to 150 time steps (NOAA 1999). ALOHA then averages the release rates from the individual time steps over one to five averaging periods, each lasting at least 1 minute (NOAA 1999). The five averaging periods are selected to most accurately portray the peak emissions. The five average release rates are inputs to the ALOHA algorithms for atmospheric transport and dispersion (NOAA 1999). ALOHA tracks the evolution of the mean concentration field of the five separate chemical clouds and calculates the concentration at a given time and location through superposition. ALOHA limits releases to 1 hour.

Evolution of the mean concentration field of the chemical cloud is calculated through algorithms that model turbulent flow phenomena of the atmosphere. The prevailing wind flows and associated atmospheric turbulence serve to transport, disperse, and dilute the chemical cloud that initially forms at the source. For an instantaneous release or release of short duration, the chemical cloud will travel downwind as a puff. In contrast, a plume will form for a sustained or continuous release.

The wind velocity is a vector term defined by a direction and magnitude (i.e., wind speed). The wind direction and wind speed determine where the puff or plume will go and how long it will take to reach a given downwind location. For sustained or continuous releases, the wind speed has the additional effect of stretching out the plume and establishing the initial dilution of the plume (i.e., determines the relative proportion of ambient air that initially mixes with the chemical source emission). Atmospheric turbulence causes the puff or plume to increasingly mix with ambient air and grow (disperse) in the lateral and vertical direction as it travels downwind. Longitudinal expansion also occurs for a puff. These dispersion effects further enhance the dilution of the puff or plume. The two sources of atmospheric turbulence are mechanical turbulence and buoyant turbulence. Mechanical turbulence is generated from shear forces that result when adjacent parcels of air move at different velocities (i.e., either at different speeds or directions). Fixed objects on the ground such as trees or buildings increase the ground roughness and enhance mechanical turbulence in proportion to their size. Buoyant turbulence arises from vertical convection and is greatly enhanced by the formation of thermal updrafts that are generated from solar heating of the ground.

The ALOHA code considers two classes of atmospheric transport and dispersion based upon the assumed interaction of the released cloud with the atmospheric wind flow.

- For airborne releases in which the initial chemical cloud density is less than or equal to that of the ambient air, ALOHA treats the released chemical as neutrally buoyant. A neutrally buoyant chemical cloud that is released to the atmosphere does not alter the atmospheric wind flow, and therefore, the term "passive" is used to describe the phenomenological characteristics associated with its atmospheric transport and dispersion. As a passive contaminant, the released chemical follows the bulk movements and behavior of the atmospheric wind flow.

- Conversely, if the density of the initial chemical cloud is greater than that of the ambient air, then the possibility exists for either neutrally buoyant or dense-gas type of atmospheric transport and dispersion. In dense-gas atmospheric transport and dispersion, the dense-gas cloud resists the influences of the hydraulic pressure field associated with the atmospheric wind, and the cloud alters

> the atmospheric wind field in its vicinity. Dense-gas releases can potentially occur with gases that have a density greater than air due to either a high molecular weight or from being sufficiently cooled. A chemical cloud with sufficient aerosol content can also result in the bulk cloud density being greater than that of the ambient air. Dense-gas releases undergo what has been described in the literature as "gravitational slumping."

Gravitational slumping is characterized by significantly greater lateral (crosswind) spreading and reduced vertical spreading as compared to the spreading that occurs with a neutrally buoyant release.

In addition to the source term and downwind concentration calculations, ALOHA allows for the specification of concentration limits for the purpose of consequence assessment (e.g., assessment of human health risks from contaminant plume exposure). ALOHA refers to these concentration limits as level-of-concern (LOC) concentrations. Safety analysis work uses the Emergency Response Planning Guidelines (ERPGs) and Temporary Emergency Exposure Limits (TEELs) for assessing human health effects for both facility workers and the general public. While ERPGs and TEELs are not explicitly a part of the ALOHA chemical database, ALOHA allows the user to input any value, including an ERPG or TEEL value, as the LOC concentration. The LOC value is superimposed on the ALOHA generated plot of downwind concentration as a function of time to facilitate comparison. In addition, ALOHA will generate a footprint that shows the area (in terms of longitudinal and lateral boundaries) where the ground-level concentration reached or exceeded the LOC during puff or plume passage (the footprint is most useful for emergency response applications).

The ALOHA code uses a constant set of meteorological conditions (e.g., wind speed, stability class) to determine the downwind atmospheric concentrations. The sequential meteorological data sets used for the radiological accident analyses were re-ordered from high to low dispersion by applying a Gaussian dispersion model (such as that used by ALOHA) at a representative downwind distance for each site. The median set of hourly conditions for each site (i.e., wind speed and stability corresponding to the median concentration) was used for the analysis; this is roughly equivalent to the conditions corresponding to the mean radiological dose estimates of MACCS2.

ALOHA contains physical and toxicological properties for the chemical spills included in this EIS and for approximately 1,000 additional chemicals. The physical properties were used to determine which of the dispersion models and accompanying parameters were applied. The toxicological properties were used to determine the levels of concern. Atmospheric concentrations at which health effects are of concern (e.g., ERPG-2) are used to define the footprint of concern. Because the meteorological conditions specified do not account for wind direction (i.e., it is not known *a priori* in which direction the wind would be blowing in the event of an accident), the areas of concern are defined by a circle of radius equivalent to the downwind distance at which the concentration decreases to levels less than the level of concern. In addition, the concentration at 640 meters (2,100 feet) (potential exposure to a noninvolved worker) and at the nearest site boundary distance (exposure to maximum exposed offsite individual) are calculated and presented.

C.3.3 Radiological Accident Scenarios

An evaluation of past accidents at INL, LANL, and ORNL documented in EIS Sections 3.2.9.4, 3.3.9.4, and 3.4.9.4, respectively, concluded that, although these accidents may have had a significant radiological impact on involved workers, they did not result in significant or, in some cases, measurable impacts on the public and noninvolved workers. The accidents analyzed in this EIS have greater impacts than the past accidents. For the processing facilities, a spectrum of accidents was developed that considered a full range of accidents that could affect noninvolved workers and the public associated with such facilities. The scenarios evaluated, however, represent cases that are considered to bound the risk profile for noninvolved workers and the public.

C.3.3.1 Neptunium-237 Target Processing Accident Scenario Selection and Description

The processing facility accidents presented in the *ORNL REDC Safety Analysis Report for Building 7920* (ORNL 1999) were reviewed for evaluation in this *Draft Environmental Impact Statement for the Proposed Consolidation of Nuclear Operations Related to Production of Radioisotope Power Systems (Consolidation EIS)*. Process and facility details were based on the preconceptual design study to support plutonium-238 production (Wham et al. 1998). Since process details at the new building at INL are essentially the same as those at REDC, the same spectrum of accidents was evaluated for all the processing facilities. However, facility differences were accounted for in evaluating the consequences of these accidents.

Several evaluation-basis accidents were selected for inclusion in this *Consolidation EIS*. These include:

- A postulated explosion in a glovebox during neptunium-237 target fabrication, representing the glovebox-handling accident having the largest potential consequences;
- A postulated failure of the target dissolver tank containing both neptunium-237 and plutonium-238, representing the accidental spill having the greatest consequences; and
- A postulated explosion of an ion exchange column during plutonium-238 purification, which has the potential to release more plutonium-238 than any other processing facility design-basis accident.

A fire in a hot cell was judged to have lower consequences than an explosion, and was not included in this *Consolidation EIS*. This is based on an extensive experimental investigation (Hasegawa et al. 1992), which concluded that a fire in a hot cell would not represent a threat to the effectiveness of the facility roughing or HEPA filters and would be self-extinguishing within a short time from lack of oxygen.

Both neptunium-237 and plutonium-238 would be stored in shielded containers in quantities and configurations that preclude criticality. Target preparation and post-irradiation processing would be carried out in batches involving quantities well below those at which criticality could occur. As a result, a criticality accident could occur only as a result of a series of gross, deliberate violations of established controls.

The postulated beyond-evaluation-basis processing facility accident selected for use in this *Consolidation EIS* is a catastrophic earthquake resulting in a collapse of the nearby stack and failure of the HEPA filter system intended to mitigate the consequences of releases. Two cases involving this accident scenario were evaluated. Case 1 assumed that the facility was only being used to store neptunium-237. Case 2 assumed that the facility was an integrated storage, target fabrication, and irradiated-target-processing facility.

The waste stream from the irradiated targets would be processed in the same facilities as the irradiated targets. Accidents occurring during the processing of the waste stream were not evaluated in this *Consolidation EIS* because their consequences are bounded by the irradiated target accidents that have been evaluated.

Ion Exchange Explosion During Neptunium-237 Target Fabrication Accident

An accident could occur during fabrication of the neptunium-237 targets. As part of the target preparation, 1-kilogram (2.2-pound) quantities of neptunium-237 solution are processed (Wham et al. 1998) to yield neptunium in an oxide form for use as a target material. This operation takes place in a shielded glovebox and involves use of an ion exchange column. This accident scenario postulates an explosion of the ion exchange column in the glovebox. Judging from historical occurrences of this type of accident at radiochemical laboratories and processing facilities, the frequency of this event is "unlikely" (between 1×10^{-2} and 1×10^{-4} per year) (ORNL 1999). For the purpose of this *Consolidation EIS*, the accident frequency was assumed to be 1×10^{-2} per year.

The glovebox is maintained at a slight negative pressure with respect to that portion of the building outside the hot cells, and is continually exhausted to the atmosphere through roughing filters and then through two banks of HEPA filters arranged in series outside the building and then to the environs via a stack. Each bank of HEPA filters is assumed to remove 99.95 percent of all particulates at or above a size of 0.3 microns (Burchsted et al. 1976). (Note: This assumes two HEPA filters are in series and each is 99.95 percent efficient, yielding a 2.5×10^{-7} reduction factor.)

In the accident scenario, an explosion is estimated to release essentially all of the neptunium-237 into the glovebox. Additional data to calculate releases were taken from relevant facility data (ORNL 1999; Green 1998, 1999) and other accepted sources (DOE 1994). Since an explosion involves small quantities of materials, any increase in pressure is expected to be small and is not expected to result in transitory leakage of radioactive material from the glovebox into the operating area.

Airborne releases can be divided into respirable (smaller than about 10 microns) and nonrespirable fractions. Nonrespirable airborne particles can cause localized onsite contamination, but they do not contribute significantly to offsite doses for several reasons. For design-basis accidents, the filter efficiency for the larger, nonrespirable particles is greater than that for all particles of the respirable fractions, and significantly greater than the minimum value of 99.95 percent for 0.3-micron particles. For the beyond-design-basis earthquake, where filters are postulated to be ineffective, leakage from the hot cells is at a low rate, allowing for increased deposition and settling of the larger particles prior to release. Even where large, nonrespirable particles are released to the environment, their atmospheric transport is limited and they will "fall out" within a short distance from the release point.

Table C–5 shows the release fractions and source terms for this accident.

Table C–5 Neptunium-237 Target Preparation Accident Source Terms

Analysis Parameters	*Units*
Neptunium-237 inventory in glovebox	1,000 grams
Neptunium-237 released into glovebox from explosion	1,000 grams
Airborne release fraction times respirable particle fraction	7×10^{-2}
Leak path factor	0.50
Neptunium-237 reaching HEPA filters	35.0 grams
Neptunium-237 released from stack to environs	8.75×10^{-6} grams

HEPA = high-efficiency particulate air.
Source: Calculated results.

Target Dissolver Tank Failure During Plutonium-238 Separation Accident

A hypothetical accident scenario involving the failure of a tank in which irradiated neptunium-237 targets are to be dissolved was analyzed. Irradiated neptunium-237 target processing is planned to be carried out in approximately five batches per year. Each batch of irradiated targets is expected to contain approximately 1 kilogram (2.2 pounds) of plutonium-238 and 8 to 10 kilograms (17.6 to 22 pounds) of neptunium-237. A complete failure of the dissolver tank envelops a spectrum of accidental spills involving plutonium-238 in the hot cells. The complete failure of this tank is judged to be unlikely (between 1×10^{-2} and 1×10^{-4} per year) (ORNL 1999). For the purpose of this *Consolidation EIS*, the accident frequency is assumed to be 1×10^{-2} per year.

This scenario postulates the sudden, complete failure of the dissolver tank and the spilling of its contents onto the floor of the hot cell. The product of the airborne release fraction and the respirable fraction is the sum of

that for a free-fall spill, plus evaporation of a shallow pool and are estimated (DOE 1994) to be 0.00013. A leak path factor of 0.75, applicable for a hot cell (Green 1998), was used.

The cell is exhausted first to roughing filters, then through two stages of HEPA filters in series, and then to the environs via a stack. (Note: This assumes two HEPA filters are in series, and each is 99.95 percent efficient, yielding a 2.5×10^{-7} reduction factor.)

Table C–6 shows the release fractions and source terms for this accident.

Table C–6 Target Dissolver Tank Failure Source Terms

Analysis Parameters	*Neptunium-237*	*Plutonium-238*
Inventory in dissolver tank	9,000 grams	1,000 grams
Spilled onto hot cell floor	9,000 grams	1,000 grams
Airborne release fraction times respirable fraction	0.00013	0.00013
Leak path factor	0.75	0.75
Amount entering HEPA filters	0.88 gram	0.098 gram
Amount released from stack to environs	2.19×10^{-7} gram	2.44×10^{-8} gram

HEPA = high-efficiency particulate air.
Source: Calculated results.

Ion Exchange Explosion During Plutonium-238 Separation Accident

A hypothetical accident scenario was considered based on the postulated explosion of an ion exchange column during plutonium-238 purification in a hot cell. Although plans for plutonium purification call for a solvent extraction process, an alternative method involves the use of an ion exchange process (Wham et al. 1998). In this alternative procedure, 495 grams (1.1 pounds) of plutonium-238 are loaded onto an ion exchange column. Judging from historical occurrences of this type of accident at radiochemical laboratories and processing facilities, the frequency of this event is unlikely (between 1×10^{-2} and 1×10^{-4} per year) (ORNL 1999). For the purpose of this *Consolidation EIS*, the accident frequency is assumed to be 1×10^{-2} per year.

Most of the plutonium would be deposited on the cell walls and floor, along with other explosion debris. The fraction of plutonium estimated to be released in airborne form and respirable size particles is 0.07 (DOE 1994).

The hot cell is maintained at a slight negative pressure with respect to the rest of the building. After effluents are exhausted from the hot cell, they pass first through roughing filters, then through two banks of HEPA filters outside the building. On exiting the HEPA filters, effluents are released to the environs through a stack. At the REDC, the explosion could also result in the generation of a weak shock wave and a momentary pressure increase of up to 10 to 50 kilopascals (several pounds per square inch gage) in the hot cell (ORNL 1999). This accident would not be expected to generate dynamic pressures sufficient to damage the hot cell confinement structure, but could result in some leakage of radioactive materials into the operating areas of the building due to the brief pressurization of the hot cell cubicle (ORNL 1999).

For REDC, the shock wave might impact the HEPA filters, possibly degrading their performance. Although the HEPA filters are tested to retain 99.97 percent efficiency, tornado conditions are estimated (DOE 1994) to reduce their efficiency to approximately 99 percent. This scenario assumes that the efficiency of the first-stage HEPA filters at REDC is partially degraded to 99.5 percent while the second-stage efficiency is 99.95 percent. This yields a reduction factor of 2.5×10^{-6} at REDC. The release to the environment was conservatively assumed to consist of a single "puff" associated with the immediate explosion.

Table C–7 shows the release fractions and source terms for this accident.

Table C–7 Plutonium-238 Ion Exchange Explosion Accident Source Terms

Analysis Parameters	*Units*
Plutonium-238 material at risk	495 grams
Plutonium-238 released into Hot Cell E from explosion	495 grams
Airborne release fraction times respirable particle fraction	7×10^{-2}
Leak path factor	0.75
Plutonium-238 reaching HEPA filters	26.0 grams
Plutonium-238 released to environs	6.50×10^{-5} gram

HEPA = high-efficiency particulate air.
Source: Calculated results.

Beyond-Evaluation-Basis Accident

The postulated beyond-evaluation-basis processing facility accident selected for use in this *Consolidation EIS* is a catastrophic earthquake. Such an event is less likely than the design-basis processing facility accidents, although its consequences could be severe. Its frequency is assumed to be 1×10^{-5} per year.

Case 1—Storage Facility

The earthquake is postulated to collapse the stack, severely damaging the HEPA filter system located nearby. Although the building is expected to collapse, the hot cells are expected to remain intact, but with cracked walls. In addition, one or more of the shielded viewing windows could be cracked or broken. The ventilation systems exhausting from the hot cells are expected to fail. Neptunium-237 is stored in double steel cans, with both the inner and outer cans sealed. The double cans are stacked in an array of robust, seismically supported steel storage tubes inside the hot cell. The analysis postulated the storage tube array would maintain geometry and not be damaged by equipment dislodged within the hot cell during the event. It was postulated that none of the storage cans in the storage tubes would be damaged. The storage cans would not be stressed to a level that would breach the double containment of the can design. No neptunium was postulated to be released from the storage cans during the event.

At INL, neptunium-237 is stored in a vault at the Fuel Manufacturing Facility, which is close to the new facility for the proposed alternative. The neptunium-237 storage cans are located in a rack inside the vault. While the postulated beyond-design-basis earthquake could cause portions of the facility to collapse, none of the storage cans in the vault would be breached. The storage cans would not be stressed to a level that would breach the double containment of the can design. Similarly, storage of available and usable plutonium-238 at the MFC in INL would also utilize sealed double steel cans in robust, seismically supported steel storage tubes. These plutonium-238 storage cans would not be stressed to a level that would breach the double containment of the can design.

Case 2—Processing Facility

The earthquake is postulated to collapse the stack, severely damaging the HEPA filter system located nearby. Although the building is expected to collapse, the hot cells are expected to remain intact, but with cracked walls. In addition, one or more of the shielded viewing windows could be cracked or broken. The ventilation systems exhausting from the hot cells are expected to fail. Radioactive materials in the hot cells will be released as a result of cracks in cell walls and shielded windows, but the rate of leakage is expected to be low, since the hot cells are not pressurized and there is no forced ventilation. The leak path factor (i.e., the mass

fraction of airborne particulates in an enclosure that is released to the environment) under these conditions has been conservatively estimated to be 0.1 (Green 1997).

The plutonium-238 inventory in the facility would be in several different chemical and physical forms. Since processing is carried on in batches that overlap one another (Wham et al. 1998), the total quantity of plutonium-238 considered available for release from the facility is the sum of the amounts in the dissolver tank, the ion exchange column during purification, and in powder form that has not yet been placed into a sealed canister. Any plutonium-238 in irradiated targets awaiting processing is unlikely to be mechanically damaged by the earthquake because of their small size and thus resistance to mechanical breakage. Even if some targets were broken, the plutonium-238 is intimately mixed with the neptunium-237 oxide and an aluminum matrix, rendering it essentially immobile. The earthquake is postulated to result in a massive spill and/or failure of the dissolver tank, an explosion in an ion exchange column, and a spill of any plutonium-238 powder not in a sealed container.

Table C–8 shows the release fractions and the ground-level release source terms for this accident.

Table C–8 Beyond-Design-Basis Earthquake Accident Source Terms

Analysis Parameters	*Plutonium-238 Form and Location*			
	Solution – Dissolver Tank	***Solution – Ion Exchange Column***	***Powder – Hot Cell Cubicle***	***Total***
Material at risk	1,000 grams	495 grams	186 grams	1,681 grams
Released into hot cell	1,000 grams	495 grams	186 grams	1,681 grams
Airborne release fraction times respirable fraction	0.00013	0.07	0.0033	–
Leak path factor	0.1	0.1	0.1	-
Released to environs	0.013 gram	3.47 grams	0.061gram	3.54 grams

Source: Calculated results.

C.3.3.2 Purification, Pelletization, and Encapsulation Accident Scenario Selection and Description

For the processing facilities, a spectrum of accidents was developed that considered a full range of accidents associated with such facilities. The scenarios evaluated, however, represent bounding cases that are considered to envelop the risk profile.

The processing facility accidents presented in the LANL *TA-55 Hazard Analysis* (LANL 2002) were reviewed for evaluation in this *Consolidation EIS*. Process and facility details were based on the preconceptual design study to support plutonium-238 production (INL 2005). Since process details at the new INL facility are essentially the same as those at TA-55, the same spectrum of accidents was evaluated for all the processing facilities. However, facility differences were accounted for in evaluating the consequences of these accidents.

Several evaluation-basis accidents were selected for inclusion in this *Consolidation EIS*. These include:

- A postulated evaluation-basis fire adjacent to a glovebox during plutonium-238 powder-to-pellet fabrication, representing the glovebox-handling accident having the largest potential consequences. This accident was analyzed for two separate assumptions denoted as mitigated and unmitigated. Mitigated assumes normal functioning of all heating, ventilating, and air conditioning and fire suppression systems while unmitigated assumes failure of the heating, ventilating, and air conditioning and fire suppression systems.

- A postulated evaluation-basis earthquake (0.3-g acceleration) causing failure of the heating, ventilating, and air conditioning, fire safety equipment, nonsafety class ductwork, and internal nonsafety grade structures, but not the structure shell itself.

- A postulated beyond-evaluation-basis fire similar to the evaluation-basis fire but involving two gloveboxes and the assumption that exterior doors are open for the duration of the fire providing a direct unfiltered release to the environment.

- A postulated beyond-design-basis earthquake (0.5-g) with all the same assumed failures as the evaluation-basis earthquake, but in addition, a 50-percent degradation in HEPA filter removal efficiency.

Calculations of peak HEPA filter temperature for both fire accident scenarios showed that the maximum conservatively calculated air temperature at the HEPA filters would not cause any failure or degradation of the filters' efficiency in removing airborne respirable particles of plutonium-238.

Plutonium-238 would be stored in shielded containers in quantities and configurations that preclude criticality. Target preparation and post-irradiation processing would be carried out in batches involving quantities well below those at which criticality could occur. As a result, a criticality accident could occur only as a result of a series of gross, deliberate violations of established controls.

The waste stream from the irradiated targets would be processed in the same facilities as the irradiated targets. Accidents occurring during the processing of the waste stream were not evaluated in this *Consolidation EIS* because their consequences are bounded by the irradiated target accidents that have been evaluated.

Table C–9 lists the source term and frequency for each of the accident scenarios.

Table C–9 Accident Scenario Source Term and Frequency

Accident Scenario	*Material at Risk (grams of heat source plutonium)*	*Damage Ratio*	*Airborne Release Fraction*	*Respirable Fraction*	*Leak Path Factor*	*Source Term (grams of heat source plutonium)*	*Annual Frequency*
Design-basis fire - mitigated (not analyzed because bounded by unmitigated case)	20.4	1.0	0.01	1.0	0.011	0.0022	$>1 \times 10^{-5}$
Design-basis fire - unmitigated	20.4	1.0	0.01	1.0	1.0	0.2	1×10^{-5}
Design-basis earthquake	(a)	0.0 [b] or 1.0	(c)	(c)	0.06	0.0116	5×10^{-4}
Beyond-design-basis fire	40.8	1.0	0.01	1.0	0.18	0.074	1×10^{-6}
Beyond-design-basis earthquake	(a)	0.0 [b] or 1.0	(c)	(c)	0.06	0.0174	1×10^{-4}

[a] Composite of source terms from different locations containing heat source plutonium.
[b] Damage ratio depends on whether individual component or structure is designed to survive Earthquake.
[c] Depends on physical form of plutonium in the specific apparatus (e.g., powder, oxide, liquid).

Heat source plutonium, in Table C–9, consists of a mix of plutonium and other radioisotopes. A representative specification for heat source plutonium, in weight percent, is 80.2 percent plutonium-238, 15.9 percent plutonium-239, 3 percent plutonium-240, 0.6 percent plutonium-241, 0.1 percent plutonium-242, 0.1 percent neptunium-237, and 0.1 percent uranium-234 (decay product from plutonium-238). Since plutonium-238 has

the highest curies per gram content of all these isotopes, accident analyses conservatively assumed that the heat source plutonium is 100 percent plutonium-238. Aged heat sources like those which would be transported from LANL and Pantex to INL under the Consolidation and Consolidation with Bridge Alternatives, have lower fractions of plutonium-238 in their plutonium because of the 87.8 year half-life of plutonium-238. The reduced plutonium-238 concentration would be replaced with uranium-234, the daughter or decay product of plutonium-238. For example, a heat source with 60 weight percent plutonium-238 would also contain 20.3 weight percent uranium-234 (80.2 − 60 = 20.2 + existing 0.1 = 20.3) along with the same percentages of the other radioisotopes. The much longer half-life of the other constituent radioisotopes results in no significant change in their relative concentrations.

C.3.3.3 Accident Scenario Summary

The accident scenarios described in this section apply to the No Action, Consolidation, and Consolidation with Bridge Alternatives. The principal difference is the location of the accident. This is better explained in **Table C–10**.

Table C–10 Accident Scenario Location for Each Alternative

Accident Scenario	*No Action Alternative and Bridge Period of Consolidation with Bridge Alternative Location*	*Consolidation Alternative and Consolidation Period of Consolidation with Bridge Alternative Location*
Target Fabrication and Processing Facility		
Design-basis neptunium-237 ion exchange explosion	ORNL REDC [a]	New Facility at INL-MFC [b]
Design-basis target dissolver tank failure	ORNL REDC [a]	New Facility at INL-MFC [b]
Design-basis plutonium-238 ion exchange explosion	ORNL REDC [a]	New Facility at INL-MFC [b]
Beyond design-basis earthquake	ORNL REDC [a]	New Facility at INL-MFC [b]
Plutonium-238 Purification, Pelletization, and Encapsulation Facility		
Unmitigated design-basis fire	LANL TA-55 [c]	New Facility at INL-MFC [b]
Design-basis earthquake	LANL TA-55 [c]	New Facility at INL-MFC [b]
Beyond-design-basis fire	LANL TA-55 [c]	New Facility at INL-MFC [b]
Beyond-design-basis earthquake	LANL TA-55 [c]	New Facility at INL-MFC [b]

ORNL = Oak Ridge National Laboratory, REDC = Radiochemical Engineering Development Center, INL = Idaho National Laboratory, MFC = Materials and Fuels Complex, LANL = Los Alamos National Laboratory, TA-55 = Technical Area 55.

[a] Accident analysis results from the *NI PEIS* (DOE 2000).

[b] Accident analysis calculations performed specifically for this EIS.

[c] Some accident analysis results from TA-55 Hazards Analysis (LANL 2002) and some from specific calculations performed for this EIS.

C.3.4 Radiological Accident Impacts

The following tables show the impacts for the Consolidation and Consolidation with Bridge Alternatives for accident scenarios that have been postulated for operations involving target processing and purification, pelletization, and encapsulation at INL. Other operations such as target irradiation in a reactor, RPS assembly and testing, and storage of target materials are also sources of potential accidents that have been considered. However, the expected impacts of these operations would be bounded by accidents that could occur during target processing and plutonium-238 purification, pelletization, and encapsulation.

Tables C–11 and C–12 show the consequences and risks, respectively, for target processing operations at INL under the Consolidation Alternative. **Tables C–13 and C–14** similarly show the Consolidation Alternative consequences and risks for plutonium-238 purification, pelletization, and encapsulation at INL.

Under the Consolidation with Bridge Alternative, target processing and plutonium-238 purification, pelletization, and encapsulation would be conducted sequentially in 5-year and 35-year periods. **Tables C–15 and C–16** show the consequences and risk for accidents postulated to occur during target processing at the REDC facility at ORNL for the first 5-year period and at INL for the next 35-year period. Similarly, for the purification, pelletization, and encapsulation operations, **Tables C–17 and C–18** show the consequences and risks at the Plutonium Facility at LANL for the first 5-years and at INL for the next 35 years. Consequences and risks in the Plutonium Facility at LANL are identical to the No Action Alternative.

Table C–11 Target Processing Accident Consequences Under the Consolidation Alternative at Idaho National Laboratory

Accident	*Maximally Exposed Individual*		*Population to 80 Kilometers (50 miles)*		*Noninvolved Worker*	
	Dose (rem)	*Latent Cancer Fatality* [a]	*Dose (person-rem)*	*Latent Cancer Fatalities* [b]	*Dose (rem)*	*Latent Cancer Fatality* [a]
Neptunium-237 target preparation ion exchange explosion	5.2×10^{-9}	3.1×10^{-12}	7.9×10^{-7}	4.8×10^{-10}	7.2×10^{-8}	4.3×10^{-11}
Plutonium-238 separation tank failure	1.3×10^{-7}	7.5×10^{-11}	2.8×10^{-5}	1.7×10^{-8}	1.9×10^{-6}	1.1×10^{-9}
Plutonium-238 ion exchange explosion	4.9×10^{-4}	3.0×10^{-7}	7.43×10^{-2}	4.5×10^{-5}	6.9×10^{-3}	4.1×10^{-6}
Beyond-evaluation-basis earthquake	8.37	0.005	4,000	2.4	195	0.23

[a] Likelihood of a latent cancer fatality.
[b] Number of latent cancer fatalities.

Table C–12 Target Processing Annual Accident Risks Under the Consolidation Alternative at Idaho National Laboratory

Accident	*Maximally Exposed Individual* [a]	*Population to 80 Kilometers (50 miles)* [b]	*Noninvolved Worker* [a]
Neptunium-237 target preparation ion exchange explosion	3.1×10^{-14}	4.8×10^{-12}	4.3×10^{-13}
Plutonium-238 separation tank failure	7.5×10^{-13}	1.7×10^{-10}	1.1×10^{-11}
Plutonium-238 ion exchange explosion	3.0×10^{-9}	4.5×10^{-7}	4.1×10^{-8}
Beyond-evaluation-basis earthquake	5.0×10^{-8}	2.4×10^{-5}	2.3×10^{-6}

[a] Increased likelihood of a latent cancer fatality.
[b] Increased number of latent cancer fatalities.

Table C–13 Plutonium-238 Purification, Pelletization, and Encapsulation Accident Consequences Under the Consolidation Alternative at Idaho National Laboratory

Accident	*Maximally Exposed Individual*		*Population to 80 Kilometers (50 miles)*		*Noninvolved Worker*	
	Dose (rem)	*Latent Cancer Fatality* [a]	*Dose (person-rem)*	*Latent Cancer Fatalities* [b]	*Dose (rem)*	*Latent Cancer Fatality* [a]
Unmitigated evaluation-basis fire	0.70	0.00042	228	0.14	15.6	0.0094
Unmitigated evaluation-basis earthquake	0.27	0.00016	169	0.10	6.38	0.0038
Beyond-evaluation-basis fire	0.42	0.00025	84.2	0.051	7.87	0.0047
Beyond-evaluation-basis earthquake	0.04	0.000025	20	0.012	0.97	0.00058

[a] Likelihood of a latent cancer fatality.
[b] Number of latent cancer fatalities.

Table C–14 Plutonium-238 Purification, Pelletization, and Encapsulation Annual Accident Risks Under the Consolidation Alternative at Idaho National Laboratory

Accident	*Maximally Exposed Individual* [a]	*Population to 80 Kilometers (50 miles)* [b]	*Noninvolved Worker* [a]
Unmitigated evaluation-basis fire	4.2×10^{-9}	1.4×10^{-6}	9.4×10^{-8}
Unmitigated evaluation-basis earthquake	8.2×10^{-8}	5.1×10^{-5}	1.9×10^{-6}
Beyond-evaluation-basis fire	2.5×10^{-10}	5.1×10^{-8}	4.7×10^{-9}
Beyond-evaluation-basis earthquake	2.5×10^{-9}	1.2×10^{-6}	5.8×10^{-8}

[a] Increased likelihood of a latent cancer fatality.
[b] Increased number of latent cancer fatalities.

Table C–15 Target Processing Accident Consequences Under the Consolidation with Bridge Alternative at Idaho National Laboratory and Oak Ridge National Laboratory

Accident	*Maximally Exposed Individual*		*Population to 80 Kilometers (50 miles)*		*Noninvolved Worker*	
	Dose (rem)	*Latent Cancer Fatality* [a]	*Dose (person-rem)*	*Latent Cancer Fatalities* [b]	*Dose (rem)*	*Latent Cancer Fatality* [a]
Neptunium-237 target preparation ion exchange explosion at INL	5.2×10^{-9}	3.1×10^{-12}	7.9×10^{-7}	4.8×10^{-10}	7.2×10^{-8}	4.3×10^{-11}
Plutonium-238 separation tank failure at INL	1.3×10^{-7}	7.5×10^{-11}	2.8×10^{-5}	1.7×10^{-8}	1.9×10^{-6}	1.1×10^{-9}
Plutonium-238 ion exchange explosion at INL	4.9×10^{-4}	3.0×10^{-7}	7.43×10^{-2}	4.5×10^{-5}	6.9×10^{-3}	4.1×10^{-6}
Beyond-evaluation-basis earthquake at INL	8.37	0.005	4,000	2.4	195	0.23
Neptunium-237 target preparation ion exchange explosion at ORNL	9.4×10^{-9}	5.6×10^{-12}	1.0×10^{-5}	6.2×10^{-9}	5.5×10^{-9}	3.3×10^{-12}
Plutonium-238 separation tank failure at ORNL	2.2×10^{-7}	1.3×10^{-10}	3.6×10^{-4}	2.2×10^{-7}	1.2×10^{-7}	7.4×10^{-11}
Plutonium-238 ion exchange explosion at ORNL	0.00089	5.4×10^{-7}	0.98	5.9×10^{-4}	0.00052	3.1×10^{-7}
Beyond-evaluation-basis earthquake at ORNL	54	0.064	29,000	17.3	1,010	1.0

INL = Idaho National Laboratory, ORNL = Oak Ridge National Laboratory.
[a] Likelihood of a latent cancer fatality.
[b] Number of latent cancer fatalities.

Table C–16 Target Processing Annual Accident Risks Under the Consolidation with Bridge Alternative at Idaho National Laboratory and Oak Ridge National Laboratory

Accident	*Maximally Exposed Individual* [a]	*Population to 80 Kilometers (50 miles)* [b]	*Noninvolved Worker* [a]
Neptunium-237 target preparation ion exchange explosion at INL	3.1×10^{-14}	4.8×10^{-12}	4.3×10^{-13}
Plutonium-238 separation tank failure at INL	7.5×10^{-13}	1.7×10^{-10}	1.2×10^{-11}
Plutonium-238 ion exchange explosion at INL	3.0×10^{-9}	4.5×10^{-7}	4.1×10^{-8}
Beyond-evaluation-basis earthquake at INL	5.0×10^{-8}	2.4×10^{-5}	2.3×10^{-6}
Neptunium-237 target preparation ion exchange explosion at ORNL	5.6×10^{-14}	6.2×10^{-11}	3.3×10^{-14}
Plutonium-238 separation tank failure at ORNL	1.3×10^{-12}	2.2×10^{-9}	7.4×10^{-13}
Plutonium-238 ion exchange explosion at ORNL	5.4×10^{-9}	5.9×10^{-6}	3.1×10^{-9}
Beyond-evaluation-basis earthquake at ORNL	6.4×10^{-7}	1.7×10^{-4}	1.2×10^{-5}

INL = Idaho National Laboratory, ORNL = Oak Ridge National Laboratory.
[a] Increased likelihood of a latent cancer fatality.
[b] Increased number of latent cancer fatalities.

Table C–17 Plutonium-238 Purification, Pelletization, and Encapsulation Accident Consequences at Los Alamos National Laboratory and Idaho National Laboratory Under the Consolidation with Bridge Alternative

	Maximally Exposed Individual		*Population to 80 Kilometers (50 miles)*		*Noninvolved Worker*	
Accident	*Dose (rem)*	*Latent Cancer Fatality* [a]	*Dose (person-rem)*	*Latent Cancer Fatalities* [b]	*Dose (rem)*	*Latent Cancer Fatality* [a]
Unmitigated evaluation-basis fire at LANL	10.2	0.0061	1,850	1.11	15.9	0.0095
Unmitigated evaluation-basis earthquake at LANL	4.70	0.0028	834	0.50	7.6	0.0046
Beyond-evaluation-basis fire at LANL	5.37	0.0032	675	0.41	8.0	0.0048
Beyond-evaluation-basis earthquake at LANL	0.72	0.00043	165	0.10	1.2	0.00070
Unmitigated evaluation-basis fire at INL	0.70	0.00042	228	0.14	15.6	0.0094
Unmitigated evaluation-basis earthquake at INL	0.27	0.00016	169	0.10	6.38	0.0038
Beyond-evaluation-basis fire at INL	0.42	0.00025	84.2	0.051	7.87	0.0047
Beyond-evaluation-basis earthquake at INL	0.042	0.000025	20	0.012	0.97	0.00058

LANL = Los Alamos National Laboratory, INL = Idaho National Laboratory.
[a] Likelihood of a latent cancer fatality.
[b] Number of latent cancer fatalities.

Table C–18 Plutonium-238 Purification, Pelletization, and Encapsulation Annual Accident Risks at Los Alamos National Laboratory and Idaho National Laboratory Under the Consolidation with Bridge Alternative

Accident	*Maximally Exposed Individual* [a]	*Population to 80 Kilometers (50 miles)* [b]	*Noninvolved Worker* [a]
Unmitigated evaluation-basis fire at LANL	6.1×10^{-8}	1.1×10^{-5}	9.5×10^{-8}
Unmitigated evaluation-basis earthquake at LANL	1.4×10^{-6}	2.5×10^{-4}	2.3×10^{-6}
Beyond-evaluation-basis fire at LANL	3.2×10^{-9}	4.1×10^{-7}	4.8×10^{-9}
Beyond-evaluation-basis earthquake at LANL	4.3×10^{-8}	9.9×10^{-6}	7.0×10^{-8}
Unmitigated evaluation-basis fire at INL	4.2×10^{-9}	1.4×10^{-6}	9.4×10^{-8}
Unmitigated evaluation-basis earthquake at INL	8.2×10^{-8}	5.1×10^{-5}	1.9×10^{-6}
Beyond-evaluation-basis fire at INL	2.5×10^{-10}	5.1×10^{-8}	4.7×10^{-9}
Beyond-evaluation-basis earthquake at INL	2.5×10^{-9}	1.2×10^{-6}	5.8×10^{-8}

LANL = Los Alamos National Laboratory, INL = Idaho National Laboratory.
[a] Increased likelihood of a latent cancer fatality.
[b] Increased number of latent cancer fatalities.

C.3.5 Chemical Accidents

C.3.5.1 Chemical Accident Scenario

Anticipated annual inventories of chemicals stored onsite for plutonium-238 processing were identified and evaluated in the *NI PEIS* (DOE 2000). Two of the 40 chemicals identified, nitric acid and hydrochloric acid, were selected for evaluation for potential impacts to workers and the public. The stored annual inventories and ERPG levels of concern for these chemicals are shown in **Table C–19**.

Table C–19 Chemicals of Concern Used in Plutonium-238 Processing

Chemical	*Annual Inventory* [a] *(pounds)*	*ERPG-1* [b] *Concentration*	*ERPG-2* [c] *Concentration*	*ERPG-3* [d] *Concentration*
Nitric Acid	2,170	1 ppm	6 ppm	78 ppm
Hydrochloric Acid	321	3 ppm	20 ppm	150 ppm

ERPG = Emergency Response Planning Guideline, ppm = parts per million.
[a] On a daily basis, less than 10 gallons or 5 pounds of these chemicals would be used in plutonium-238 processing.
[b] ERPG-1 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined, objectionable odor (NOAA 1999).
[c] ERPG-2 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action (NOAA 1999).
[d] ERPG-3 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects (NOAA 1999).
Note: To convert pounds to kilograms, multiply by 0.45359; to convert gallons to liters, multiply by 3.78533.
Source: DOE 2000.

The selection of these chemicals was based on their large quantities that are potentially available for release, chemical properties, and health effects. For these chemicals, an accident scenario is postulated in which a break in a tank or piping occurs, allowing the chemical to be released over a short time period. The cause of the break could be mechanical failure, corrosion, mechanical impact, or natural phenomena. The large quantity of these chemicals is used in target processing and would therefore only apply to ORNL for the No Action Alternative and Consolidation with Bridge Alternative and to INL for the Consolidation with Bridge

Alternative and Consolidation Alternative. The frequency of the accident is in the range of 1.0×10^{-5} to 1.0×10^{-4} per year.

Nitric Acid Release

In its concentrated form, nitric acid is an acute inhalation hazard. It is not combustible, but is a strong oxidizer, and its heat of reaction with reducing agents or combustibles may cause irritation. It can react with metals to release flammable hydrogen gas and nitrogen oxides (NO_x). It may react explosively with combustible organic or readily oxidizable materials.

Nitric acid in any concentration would react with any concentration of sodium hydroxide or sodium nitrate to produce heat. The reaction between the highest concentrations of nitric acid and highest concentrations of sodium hydroxide could result in extreme heat generation, resulting in fire. Nitric acid could also react with sodium nitrite to produce toxic gases. The mixture of these two chemicals results in a nitrous acid solution, which decomposes into the toxic gases nitrogen monoxide and nitrogen dioxide.

The accident scenario postulates an unmitigated catastrophic release of 984 kilograms (2,170 pounds) of nitric acid from an outdoor storage tank. The cause of the accident could be a vehicular crash, earthquake, or any similar high-energy event.

Hydrochloric Acid Release

Hydrochloric acid is a very strong acid and its solutions can be extremely corrosive. It is highly reactive with alkaline materials. It is not flammable, but reacts with most metals to form explosive/flammable hydrogen gas. Hydrochloric acid fumes have an acrid, penetrating odor. Aqueous solutions of hydrochloric acid attack and corrode nearly all metals, except mercury, silver, gold, platinum, tantalum, and certain alloys.

Exposure can cause severe burns and eye damage. It is harmful if inhaled and fatal if swallowed. Exposure to hydrochloric acid can cause circulatory collapse, which can cause death including asphyxial death due to glottic edema.

The accident scenario postulates an unmitigated catastrophic release of 147 kilograms (321 pounds) of hydrochloric acid from an outdoor storage tank. The cause of the accident could be a vehicular crash, earthquake, or any similar high-energy event.

C.3.5.2 Impacts

The released chemical forms a pool surrounding the tank and evaporates forming a plume that disperses into the environment. Existing berms surrounding the tanks are conservatively assumed to fail due to the postulated accident. The assumption results in the largest pool area causing the largest plume release. The chemical plume moves away from the point of release in the direction of prevailing wind and potentially impacts workers and the public.

Table C–20 shows the estimated atmospheric concentrations of the chemicals at specified distances for comparison with ERPG-2 and ERPG-3 levels of concern (NOAA 1999). The levels of concern for nitric acid are 6 parts per million for ERPG-2 and 78 parts per million for ERPG-3. The results indicate that, for a nitric acid release at INL or ORNL, ERPG-2 and ERPG-3 limits are not exceeded beyond the nearest site boundary. For the noninvolved worker located at a distance of 640 meters (2,100 feet) from the accident, both the ERPG-2 and ERPG-3 limits would not be exceeded at either INL or ORNL.

The levels of concern for hydrochloric acid are 20 parts per million for ERPG-2 and 150 parts per million for ERPG-3. The results indicate that for a hydrochloric acid release, ERPG-2 and ERPG-3 limits are not exceeded beyond the nearest site boundary at either INL or ORNL. For the noninvolved worker located at a distance of 640 meters (2,100 feet) from the accident, both the ERPG-2 and ERPG-3 limits would not be exceeded at either INL or ORNL.

Table C–20 Chemical Accident Impacts at Idaho National Laboratory and the Radiochemical Engineering Development Center at Oak Ridge National Laboratory

Chemical	*Quantity Released (pounds)*	*ERPG-2* [a]		*ERPG-3* [b]		*Concentration*	
		Limit	*Distance to Limit (meters)*	*Limit*	*Distance to Limit (meters)*	*Noninvolved Worker at 640 Meters*	*Nearest Site Boundary* [c]
Nitric acid at INL	2,170	6 ppm	128	78 ppm	21	0.33 ppm	0.013 ppm
Hydrochloric acid at INL	321	20 ppm	232	150 ppm	80	2.85 ppm	0.037 ppm
Nitric Acid at REDC (ORNL)	2,170	6 ppm	204	78 ppm	39	0.72 ppm	0.027 ppm
Hydrochloric Acid at REDC (ORNL)	321	20 ppm	444	150 ppm	142	9.97 ppm	0.13 ppm

ERPG = Emergency Response Planning Guideline, INL = Idaho National Laboratory, ppm = parts per million,
REDC = Radiochemical Engineering Development Center, ORNL = Oak Ridge National Laboratory.

[a] ERPG-2 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action (NOAA 1999).

[b] ERPG-3 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects (NOAA 1999).

[c] Nearest site boundary is 5,200 meters at INL and 4,600 meters at REDC.

Note: To convert pounds to kilograms, multiply by 0.45359; to convert meters to feet, multiply by 3.2808.

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