FINAL REPORT

METHOD OF SCREENING OF RADIONUCLIDES RELEASED TO THE ATMOSPHERE FROM FACILITIES AT INEL

Contract No. 200-2002-00367
Task Order 1, Subtask 4

A report to the
Centers for Disease Control and Prevention
Atlanta, Georgia 30335

SC&A, Inc.
6858 Old Dominion Drive, Suite 301
McLean, Virginia 22101

SENES Oak Ridge, Inc.
102 Donner Drive
Oak Ridge, Tennessee 37830

Author:

David C. Kocher
SENES Oak Ridge, Inc.

July 2005

TABLE OF CONTENTS

LIST OF TABLES

1.0 INTRODUCTION

The purpose of this report is to develop a method of screening of historical releases of radionuclides to the atmosphere from various facilities at Idaho National Engineering Laboratory (INEL).[1] The method of screening will be used to select radionuclides that were released in amounts sufficient to warrant further analysis in a dose reconstruction for members of the public who were exposed to past releases at INEL. Screening is useful because a large number of radionuclides, mainly fission products, were released, but many of these radionuclides probably were unimportant in regard to potential doses and health risks to the public. The benefit of screening is that the dose reconstruction can focus on radionuclides that could have been important, without expending unwarranted time and resources on an analysis of unimportant radionuclides.

The method of screening of radionuclides released to the atmosphere developed in this report is intended to be applied to the following releases: (1) routine releases from the Idaho Chemical Processing Plant (ICPP) during the years 1957-1959, when releases of radioactive iodine as a result of RaLa process operations were the highest (DOE 1991; Wichner et al. 2005);[2] (2) releases due to a criticality accident at the ICPP on October 16, 1959; and (3) episodic releases during selected initial engine tests that were conducted as part of the Aircraft Nuclear Propulsion (ANP) Program between February 1956 and March 1958. Of all the airborne releases that have occurred at INEL since operations began in 1952, it is expected that potential doses and risks to members of the public were among the highest for these three (DOE 1991).

The method of screening of radionuclides released to the atmosphere developed in this report has two basic elements: (1) a set of models to calculate the lifetime risk of cancer to a hypothetical member of the public per unit release of any radionuclide, and (2) an assumed cancer risk of concern (i.e., a screening criterion). Based on estimates of the activities of different radionuclides released during an operation or event of concern (the source term), radionuclide-specific cancer risks can be calculated using the screening models, and the results can be compared with the assumed screening criterion. If the calculated risk from the estimated release of a radionuclide exceeds the screening criterion, the radionuclide would be selected for further analysis in a dose reconstruction; otherwise, the radionuclide would be given a lower priority for further investigation.

In order to meet its intended purpose, the method of screening must satisfy two conditions. First, the models used to calculate cancer risks to a hypothetical member of the public per unit release of radionuclides must clearly overestimate actual radiation doses and cancer risks to members of the public that could have resulted from a unit release of each radionuclide of concern. Second, the assumed cancer risk criterion must correspond to a risk to a member of the public that

[1] In this report, we refer to the site by its historical name at the time the releases of concern to this report occurred..

[2] In these operations, irradiated nuclear fuel was processed within a few days after removal from a reactor to extract Ba-140, which has a half-life of 12.75 days and produces the desired high-energy photon-emitting isotope La-140, which has a half-life of 1.678 days. The RaLa process took its name from the desired end product, which was radioactive lanthanum.

generally would be considered negligible. If the method of screening satisfies these conditions, and if the assumed releases of radionuclides do not substantially underestimate actual releases, it is assured that any radionuclide that is assigned a lower priority for further consideration in a dose reconstruction would be unimportant in regard to potential doses and health risks to the public.

The following section discusses the assumed risk criterion to be used for purposes of screening of radionuclides. Section 3 then presents the models used to estimate lifetime risks of cancer per unit release of radionuclides. Based on assumptions about the locations of exposed individuals relative to the locations of releases, so-called "screening factors," which give the cancer risk per unit release of each radionuclide of concern, are developed in Section 4. These screening factors are the quantities to be applied to estimated releases from sources of concern to select radionuclides for further analysis in a dose reconstruction. Section 5 provides further discussion of the screening methodology and resulting screening factors.

2.0 ASSUMED RISK CRITERION FOR PURPOSES OF SCREENING

As emphasized in Section 1, the risk criterion used in a screening method to identify radionuclides to be given a lower priority for further consideration in a dose reconstruction must correspond to a risk to a member of the public that is generally considered negligible. In this analysis, a lifetime risk of cancer incidence of 10^{-5}, taking into account all relevant exposure pathways, is assumed to be an appropriate screening criterion.

Based on an assumed lifetime risk of cancer incidence per unit equivalent dose from uniform irradiation of the whole body on the order of 0.1 Sv^{-1} (0.001 rem^{-1}), the screening risk criterion of 10^{-5} corresponds to a lifetime dose to the whole body of about 0.1 mSv (10 mrem); the assumed risk per unit dose is a representative value for a general population of all ages (EPA 1994; 1999). This lifetime dose is the same as the current limit on annual dose due to airborne releases of radionuclides from U.S. Department of Energy (DOE) facilities, excluding the dose from radon and its decay products, as established by the U.S. Environmental Protection Agency (EPA) in *Code of Federal Regulations*, Title 40, Part 61 (40 CFR 61), and it is approximately 10% of the average annual dose from exposure to natural background radiation, excluding the dose from indoor radon (NCRP 1987). A lifetime cancer risk of 10^{-5} also is within the range of lifetime risks of 10^{-4} to 10^{-6} that has been established by the EPA in 40 CFR 300 as a goal for remediation of sites contaminated with hazardous materials, and it is a factor of 10 less than the risk goal of 10^{-4} that normally is applied in remediating radioactively contaminated sites (Clay 1991; Luftig and Weinstock 1997).

Based on the comparisons described above, we believe it is reasonable to assume that a lifetime risk of cancer incidence of 10^{-5} corresponds to a risk to a member of the public that is generally considered negligible and, thus, is appropriate for use in screening of radionuclides released to the atmosphere at INEL.

3.0 DEVELOPMENT OF SCREENING MODEL TO CALCULATE LIFETIME CANCER RISKS FROM ASSUMED RELEASES

3.1 Formulation of Conceptual Screening Model

For purposes of screening, the lifetime risk of cancer incidence due to a given activity[3] of a radionuclide released to the atmosphere (i.e., a release rate in Bq/s corresponding to a total release in Bq over a specified period of time) is calculated using the following simple model:

$$\begin{aligned}\text{Risk} = {} & \text{Release (Bq/s)} \times \text{Atmospheric dispersion factor (Bq/m}^3\text{ per Bq/s)} \\ & \times \text{Exposure factor (Sv per Bq/m}^3\text{)} \\ & \times \text{Risk coefficient (risk per Sv)} \end{aligned} \quad (1)$$

The atmospheric dispersion factor, which is often denoted by χ/Q, gives the concentration in air at the assumed location of an exposed individual (Bq/m^3) per unit release (Bq/s). The product of the release rate and the dispersion factor thus gives the calculated concentration in air at the receptor location. The exposure factor converts the airborne concentration of a radionuclide at the receptor location to an estimate of effective dose[4] (Sv) from all relevant exposure pathways, including the effective dose received from external exposure to radionuclides in the air and deposited on the ground, and the committed effective dose from inhalation and from ingestion of contaminated foods, including vegetables, milk, and meat. Thus, the exposure factor includes the exposure per unit concentration in air for each pathway and the associated dose coefficient (i.e., effective dose per unit exposure). The risk coefficient converts the estimated effective dose from all exposure pathways combined to an estimate of the lifetime risk of cancer incidence.

From Equation 1, the radionuclide-specific screening factor (i.e., the cancer risk per unit release of a radionuclide) is given by the product of the atmospheric dispersion factor (χ/Q), the radionuclide-dependent exposure factor, and the risk coefficient.

3.2 Identification of Radionuclides of Concern

This section identifies the radionuclides of potential concern in historical releases to the atmosphere from facilities at INEL. As noted in Section 1, the method of screening will be applied to releases from routine operations at the ICPP during 1957-1959, releases during a

[3] In the screening model, activities of radionuclides are expressed in becquerel (Bq). The conventional unit of activity is the curie (Ci), and 1 Ci = 3.7×10^{10} Bq.

[4] In the screening model, effective dose is expressed in sieverts (Sv); 1 Sv = 100 rem. The effective dose is a weighted average of doses to different organs or tissues of the body developed by the International Commission on Radiological Protection (ICRP 1991) for purposes of radiation protection and assessment of health risks from radiation exposure in general terms; the effective dose replaces the effective dose equivalent developed previously (ICRP 1977). In a dose reconstruction, health risks would be estimated based on estimates of absorbed dose to specific organs and consideration of the biological effectiveness of different radiations that deliver the dose, rather than the effective dose.

criticality accident at the ICPP in 1959, and episodic releases during selected initial engine tests in the ANP Program between February 1956 and March 1958.

3.2.1 Routine Releases from the Idaho Chemical Processing Plant

The radionuclides that are assumed to have been released from routine operations at the ICPP during the years 1957-1959 are listed in Table 3-1. This list is based on source terms previously developed for the releases during these years (DOE 1991). A re-analysis of these source terms conducted as part of the Dose Reconstruction Project (Wichner et al. 2005) focused on estimating releases of isotopes of iodine, and no additional radionuclides that were not considered previously (DOE 1991) were identified. Only I-131, I-132, and I-133 were observed directly in monitoring of stack effluents, and the presence of other radionuclides in the releases was inferred based on process knowledge and calculations of the activities of different radionuclides in processed nuclear fuel.

Table 3-1 Radionuclides assumed to be present in routine airborne releases from the Idaho Chemical Processing Plant for years 1957-1959*

H-3 (12.33 y)†	Zr-95 (64.02 d)	I-135 (6.57 h)	Ba-140 (12.75 d)
Kr-85m (4.48 h)	Nb-95 (35 d)	Xe-131m (11.93 d)	La-140 (1.678 d)
Kr-85 (10.8 y)	Ru-103 (39.26 d)	Xe-133m (2.19 d)	Ce-141 (32.50 d)
Kr-87 (76.3 min)	Ru-106 (373.6 d)	Xe-133 (5.243 d)	Ce-144 (284.89 d)
Kr-88 (2.84 h)	Te-132 (3.20 d)	Xe-135m (15.29 min)	Pr-143 (13.57 d)
Sr-89 (50.53 d)	I-129 (1.57×10^7 y)	Xe-135 (9.14 h)	Pm-147 (2.623 y)
Sr-90 (28.79 y)	I-131 (8.02 d)	Cs-134 (2.07 y)	Eu-154 (8.592 y)
Sr-91 (9.63 h)	I-132 (2.295 h)	Cs-136 (13.16 d)	Pu-238 (87.7 y)
Y-91 (58.51 d)	I-133 (20.8 h)	Cs-137 (30.07 y)	Pu-239/240‡

* Radionuclides are listed in Tables A-14 and A-15 of DOE (1991).
† Entry in parentheses is radionuclide half-life (Tuli 2000).
‡ Half-lives are 24,110 y for Pu-239 and 6564 y for Pu-240.

3.2.2 Releases from 1959 Criticality Accident at the Idaho Chemical Processing Plant

On October 16, 1959, a criticality accident occurred at the ICPP that resulted in releases of radionuclides to the atmosphere. The radionuclides that are assumed to have been released during the accident are listed in Table 3-2. This list is based on the source terms previously developed (DOE 1991) and the few additional radionuclides that were identified in a re-analysis of the source terms conducted as part of the Dose Reconstruction Project (Wichner et al. 2005). Both analyses assume that only noble gases and isotopes of iodine and bromine were released as a result of the criticality accident (DOE 1991; Wichner et al. 2005). The other radionuclides listed in Table 3-2 are decay products of short-lived noble-gas radionuclides that presumably were formed after release of the parent.

Table 3-2 Radionuclides assumed to be present in airborne releases from 1959 criticality accident at the Idaho Chemical Processing Plant*

Br-83 (2.40 h)†, ‡	Sr-89 (50.53 d)	I-134 (52.5 min)	Cs-138 (33.41 min)
Br-84 (31.8 min)	Sr-90 (28.79 y)	I-135 (6.57 h)	Ba-139 (83.06 min)
Br-85 (2.90 min)‡	Sr-91 (9.63 h)	Xe-129m (8.88 d)	Ba-140 (12.75 d)
Kr-83m (1.83 h)‡	Sr-92 (2.71 h)	Xe-133 (5.243 d)‡	Ba-141 (18.27 min)
Kr-85m (4.48 h)	Y-91 (58.51 d)	Xe-135m (15.29 min)	Ba-142 (10.6 min)
Kr-87 (76.3 min)	Y-92 (3.54 h)	Xe-135 (9.14 h)	La-141 (3.92 h)
Kr-88 (2.84 h)	I-131 (8.02 d)	Xe-137 (3.818 min)‡	La-142 (91.1 min)
Kr-89 (3.15 min)‡	I-132 (2.295 h)	Xe-138 (14.08 min)	Ce-141 (32.50 d)
Rb-89 (15.15 min)	I-133 (20.8 h)	Cs-137 (30.07 y)	

* Radionuclides are listed in Table A-41 of DOE (1991), except as noted. Radionuclides other than noble gases and isotopes of iodine and bromine are assumed to have been produced by decay of short-lived noble gases after their release.
† Entry in parentheses is radionuclide half-life (Tuli 2000).
‡ Radionuclide identified in re-analysis of releases by Wichner et al. (2005).

3.2.3 Episodic Releases from Selected Initial Engine Tests in the Aircraft Nuclear Propulsion Program

As part of the Dose Reconstruction Project, episodic releases of radionuclides to the atmosphere during three initial engine tests (IETs) in the ANP Program are being evaluated. The three tests occurred between February 1956 and March 1958 and are designated as IET #3, #4, and #10. These tests are expected to be the most important of all the initial engine tests that took place between February 1956 and March 1961 in regard to the quantities of radionuclides released and potential doses and risks to members of the public (DOE 1991).

The radionuclides that are assumed to have been released during the selected IETs are listed in Table 3-3. This list is based on the source terms previously developed for the releases during these tests (DOE 1991). A re-analysis of these source terms conducted as part of the Dose Reconstruction Project (Behling and Mauro 2005) did not identify any additional radionuclides in the releases. The radionuclides listed in Table 3-3 were identified based on a combination of measurements and modeling.

Table 3-3 Radionuclides assumed to be present in airborne releases from selected initial engine tests in Aircraft Nuclear Propulsion Program*

Ar-41 (109.34 min)†	Zr-95 (64.02 d)	I-131 (8.02 d)	Ba-141 (18.27 min)
Br-84 (31.8 min)	Zr-97 (16.744 h)	I-132 (2.295 h)	Ba-142 (10.6 min)
Kr-85m (4.48 h)	Nb-96 (23.35 h)	I-133 (20.8 h)	La-141 (3.92 h)
Kr-87 (76.3 min)	Mo-99 (65.94 h)	I-134 (52.5 min)	La-142 (91.1 min)
Kr-88 (2.84 h)	Ru-103 (39.26 d)	I-135 (6.57 h)	Ce-141 (32.50 d)
Rb-89 (15.15 min)	Ru-105 (4.44 h)	Xe-129m (8.88 d)	Ce-143 (33.039 h)
Sr-89 (50.53 d)	Ru-106 (373.6 d)	Xe-135 (9.14 h)	Ce-144 (284.89 d)
Sr-90 (28.79 y)	Sb-129 (4.40 h)	Xe-135m (15.29 min)	Pr-143 (13.57 d)
Sr-91 (9.63 h)	Te-131 (25.0 min)	Xe-138 (14.08 min)	Pr-144 (17.28 min)
Sr-92 (2.71 h)	Te-131m (30 h)	Cs-137 (30.07 y)	U-234 (2.46 H 10^5 y)
Y-91 (58.51 d)	Te-132 (3.20 d)	Cs-138 (33.41 min)	U-235 (7.04 H 10^8 y)
Y-92 (3.54 h)	Te-133m (55.4 min)	Ba-139 (83.06 min)	U-238 (4.47 H 10^8 y)
Y-93 (10.18 h)	Te-134 (41.8 min)	Ba-140 (12.75 d)	

* Radionuclides are listed in Table A-41 of DOE (1991).
† Entry in parentheses is radionuclide half-life (Tuli 2000).

3.3 Atmospheric Dispersion Factors

For purposes of screening of radionuclides released to the atmosphere, a 22.5^o (16-point wind rose) sector-averaged, straight-line Gaussian plume model of atmospheric transport is assumed (e.g., see Miller 1984). This type of model has been used in screening models developed by the National Council on Radiation Protection and Measurements (NCRP 1996) and the International Atomic Energy Agency (IAEA 2001). In applying the model, it is assumed that all releases occurred at ground level and that there was no depletion of radionuclides in the plume by radioactive decay or deposition onto the ground surface during transport to the receptor location. The assumption of ground-level releases results in overestimates of airborne concentrations at the ground surface for all radionuclides, because stack releases from facilities at INEL were elevated and the highest calculated airborne concentrations in the Gaussian plume model occur at the same height as the release (or higher if the release is assumed to be buoyant). The assumption of no plume depletion by radioactive decay results in overestimates of airborne concentrations for all shorter-lived radionuclides, and the assumption of no plume depletion by deposition onto the ground surface results in overestimates of airborne concentrations for all radionuclides except noble gases (isotopes of argon, krypton, and xenon).

Based on the assumptions described above, the concentration of a radionuclide in air, χ(Bq/m^3), at an assumed receptor location due to a given release Q(Bq/s) is given by

$$\chi = \frac{2.032\, fQ}{xu\sigma_z} \qquad (2)$$

where f is the fraction of the time the wind direction is toward the receptor location during a release, x is the downwind distance to the receptor location in meters (m), u is the average wind speed in m/s, and σ_z is the standard deviation of a Gaussian (normal) distribution of air concentration in the vertical (z) direction in meters (Miller 1984). The atmospheric dispersion factor in Equation 1 is given by χ/Q.

For purposes of screening, an average wind speed (u) of 2 m/s, or about 4.5 miles per hour, is assumed; this value has been used in screening models developed by the NCRP (1996) and IAEA (2001). The assumed wind speed is substantially lower than the average wind speed at INEL (DOE 1991), and it is much lower than the known wind speed during the 1959 criticality accident at the ICPP (DOE 1991). An assumption of a lower-than-expected wind speed results in an overestimate of χ/Q, since χ/Q varies inversely with wind speed. With this assumption, the atmospheric dispersion factor is given by

$$\chi / Q = \frac{1.016\, f}{x \sigma_z} \tag{3}$$

The assumed fraction of the time the wind direction is toward the receptor location, f, depends on whether the releases were routine or accidental. For routine releases, including episodic releases that occurred over a period of at least a few days, f is assumed to be 0.25. This assumption has been used in screening models developed by the NCRP (1996) and IAEA (2001), and it should overestimate the fraction of the time the wind blows in any direction at INEL by nearly a factor of two (SENES 2002). For accidental (short-term) releases, however, the wind is assumed to blow toward the receptor location during the entire time of a release, and f is assumed to be 1.0. The atmospheric dispersion factors for the two cases thus are given by

$$\chi / Q = \frac{0.254}{x \sigma_z}, \quad \textit{routine or episodic releases} \tag{4}$$

$$\chi / Q = \frac{1.016}{x \sigma_z}, \quad \textit{accidental releases} \tag{5}$$

The vertical dispersion parameter σ_z is calculated by assuming that atmospheric transport occurred under neutral conditions described by Pasquill-Gifford stability category D. Although this choice does not minimize dispersion and, thus, does not maximize calculated air concentrations at an assumed receptor location (stability categories E and F give plumes with less dispersion), an assumption of neutral stability was used in screening models developed by the NCRP (1996) and IAEA (2001). Stability category D is a reasonable choice for use in screening of routine or episodic releases at INEL because it probably overestimates the average atmospheric stability at the site, especially during daylight hours (Barr and Clements 1984). Neutral stability also is a reasonable choice for use in screening of releases from the criticality accident at the ICPP, due to the high wind speeds at the time of the accident (DOE 1991), which normally are associated with stability category C or D (Barr and Clements 1984), and the possibility that substantial releases occurred for several days after the accident (Wichner et al. 2005). An assumption that the plume stays within a single 22.5° sector during transport also should result in overestimates of airborne concentrations when the receptor location is far from

the source and the terrain is uneven, as is the case at INEL, and, as discussed later, the assumed fraction of the time the wind blows toward the receptor location should be a considerable overestimate in cases of releases from the ICPP.

In this analysis, we use the Briggs formulation for dispersion parameters during atmospheric transport over open country (Barr and Clements 1984). In this formulation, the dispersion parameter σ_z for Pasquill-Gifford stability category D is given by

$$\sigma_z = \frac{0.06x}{\sqrt{1+0.0015x}} \quad (6)$$

where x again is the downwind distance in meters. This representation of σ_z was used by the NCRP (1996) and IAEA (2001).

3.4 Radionuclide-Specific Exposure Factors

The exposure factor in Equation 1 gives the effective dose per unit activity concentration of a radionuclide in air at an assumed receptor location (Sv per Bq/m^3), and it is based on an assumption that exposure occurs throughout the duration of a release. The exposure factors used in this analysis are values obtained using screening models developed by the IAEA (2001) or, when a radionuclide of concern at INEL is not included in the IAEA analysis, the exposure factor is calculated based mainly on models and parameter values used in the IAEA analysis. The radionuclides listed in Tables 3-1 through 3-3 that were not considered by the IAEA include noble gases (isotopes of argon, krypton, and xenon), Br-83, Br-84, Br-85, Rb-89, Sr-91, Sr-92, Y-92, Y-93, Zr-97, Nb-96, Ru-105, Sb-129, Te-131, Te-133m, Te-134, Cs-138, Ba-139, Ba-140, Ba-141, Ba-142, La-140, La-141, La-142, Ce-143, Pr-143, and Pr-144.

The exposure factors developed by the IAEA (2001) take into account several exposure pathways resulting from airborne releases of radionuclides, including the following:

- External exposure due to immersion in the atmospheric plume
- Inhalation of radionuclides in the atmospheric plume
- External exposure due to deposition of radionuclides onto the ground surface
- Ingestion of radionuclides in terrestrial foods (vegetables, milk, and meat) following deposition onto the ground surface[5]

In estimating dose from external exposure to radionuclides deposited on the ground and from terrestrial foodchain pathways, concentrations of radionuclides on the ground surface are calculated by assuming that atmospheric releases and deposition have occurred continuously over a period of 30 years and that deposited activity is removed from surface soil by radioactive decay or, for certain radionuclides (e.g., isotopes of iodine, strontium, and cesium), by other

[5]The terrestrial foodchain pathways include assumptions about inadvertent ingestion of contaminated surface soil (IAEA 2001).

processes, such as downward migration in infiltrating water (IAEA 2001). Thus, for radionuclides with a half-life of about a year or longer, contributions to the exposure factor from pathways of external and ingestion exposure involving deposition onto the ground surface should be overestimated when releases occurred over a time period much shorter than 30 years, and the extent of overestimation of dose from these pathways increases with increasing radionuclide half-life.[6]

When a radionuclide has radioactive decay products, significant contributions from all decay products are included in the exposure factor for the parent calculated by the IAEA (2001). Examples of important decay products include Y-90 produced in decay of Sr-90, Ba-137m produced in decay of Cs-137, and Pr-144 produced in decay of Ce-144. When the half-lives of a radionuclide and its decay products are much longer than the assumed transport time to a receptor location, buildup of the decay products during transport is negligible and only the pathways of external and ingestion exposure following deposition of the parent onto the ground surface are considered for the decay products. For example, buildup of Nb-95 following deposition of Zr-95 is considered in developing the exposure factor for Zr-95 (IAEA 2001).

Exposure factors developed by the NCRP (1996) also could be used in a screening analysis. The exposure pathways and models for estimating dose from each pathway used by the NCRP are largely the same as those used by the IAEA (2001), and many parameter values in the exposure pathway models are similar. An advantage of using exposure factors developed by the NCRP would be that nearly all radionuclides of concern to this analysis (see Tables 3-1 through 3-3) were considered. For the following reasons, however, exposure factors developed by the NCRP are not used in this analysis.

First, in modeling transfers of radionuclides deposited onto the ground surface into vegetables, milk, and meat, the transfer coefficients assumed by the IAEA (2001) often are higher than values assumed by the NCRP (1996), thus yielding higher estimates of dose from terrestrial foodchain pathways. In addition, the IAEA assumed slightly longer exposure times in estimating doses from the two pathways of external exposure.

Second, the IAEA (2001) used current values of dose coefficients for internal and external exposure (i.e., committed effective doses per unit activity intake of radionuclides by inhalation and ingestion, and effective dose rates from external exposure per unit activity concentration of radionuclides in air or on the ground surface), whereas the NCRP (1996) used dose coefficients that are now outdated. External dose coefficients used by the IAEA were obtained from Federal Guidance Report No. 12 (Eckerman and Ryman 1993), and dose coefficients for inhalation and ingestion were obtained from current ICRP recommendations for exposure of the public

[6]For longer-lived radionuclides, an assumption of deposition over 30 years results in the greatest overestimates of dose for the external exposure pathway. For terrestrial foodchain pathways, the dose often is dominated by contributions due to deposition of radionuclides onto plant surfaces, and long-term buildup of radionuclides on plant surfaces is limited by assumptions that the half-time for removal by weathering is 14 days and that food crops and pasture grass are harvested after 60 days and 30 days, respectively (IAEA 2001). Contributions to ingestion doses due to root uptake of radionuclides from surface soil into food crops or pasture grass often are unimportant—even after 30 years of deposition—due to the substantial dilution of deposited activity in the soil root zone and the low plant-to-soil concentration ratios for many radionuclides (IAEA 2001).

compiled in ICRP Publication 72 (ICRP 1996). In contrast, the NCRP used external dose coefficients calculated by Kocher (1983) and dose coefficients for inhalation and ingestion that were calculated based mainly on recommendations in ICRP Publication 30 (ICRP 1979). Differences in external dose coefficients are minor—generally a few tens of percent or less—with the values used by the IAEA usually higher. For some radionuclides, however, current dose coefficients for inhalation and ingestion used by the IAEA are substantially different from earlier values used by the NCRP, due mainly to changes in biokinetic models describing the behavior of inhaled and ingested radionuclides in the body.

Finally, in calculating doses from inhalation and ingestion pathways, the IAEA (2001) considered exposures of infants of age 1 to 2 years as well as adults, whereas the analysis by the NCRP (1996) considered exposures of adults only. For a given radionuclide, the exposure factor recommended by the IAEA for use in screening is the higher of the calculated values for infants and adults. The IAEA's approach is advantageous because it takes into account that the general public consists of individuals of all ages.

Given that age-dependent inhalation and ingestion doses are incorporated in the analysis by the IAEA (2001), it should be noted that the external dose coefficients used by the IAEA (2001) and NCRP (1996) apply to adults (Eckerman and Ryman 1993; Kocher 1983). However, at photon energies above about 0.1 MeV, which are of greatest concern in estimating external dose, effective doses to adults are only about 20% less than values that apply to infants (ICRP 1997).[7] Such small differences are unimportant in a screening analysis, and available external dose coefficients are assumed to apply to infants as well as adults.

Radionuclide-specific exposure factors used in the screening analysis for releases at INEL are given in Table 3-4. When a radionuclide was considered by the IAEA, the exposure factor is four times the value given in Table I-I of IAEA (2001). This adjustment is needed because exposure factors calculated by the IAEA include an assumption that the fraction of the time the wind is blowing toward the receptor location [the parameter *f* in Equations 2 and 3] is 0.25, whereas exposure factors desired in this analysis are values that do not incorporate assumptions about the atmospheric dispersion factor [see Equation 1].

[7] Greater differences between external doses to adults and infants can occur at photon energies less than 0.1 MeV (ICRP 1997). However, when the spectrum of photons produced in decay of a radionuclide is dominated by photons of such low energies, external doses per unit concentration in air or on the ground surface are relatively low, and doses from inhalation and ingestion exposures often are more important than doses from external exposure.

Table 3-4 Exposure factors assumed in screening analysis for radionuclides released to atmosphere from facilities at the Idaho National Engineering Laboratory[*]

Nuclide[†]	Exposure factor (Sv per Bq/m^3)	Nuclide[†]	Exposure factor (Sv per Bq/m^3)
H-3[‡] (12.33 y)	4.3 H 10$^{!6}$	Kr-85m[‡] (4.48 h)	2.4 H 10$^{!7}$
Ar-41[‡] (109.34 min)	2.1 H 10$^{!6}$	Kr-85[‡] (10.77 y)	7.9 H 10$^{!9}$
Br-83[‡] (2.40 h)	3.0 H 10$^{!7}$	Kr-87[‡] (76.3 min)	1.3 H 10$^{!6}$
Br-84[‡] (31.8 min)	8.1 H 10$^{!6}$	Kr-88[‡] (2.84 h)	5.0 H 10$^{!6}$
Br-85[‡,§] (2.90 min)	1.4 H 10$^{!7}$	Kr-89[‡, §] (3.15 min)	3.7 H 10$^{!6}$
Kr-83m[‡] (1.83 h)	5.9 H 10$^{!11}$	Rb-89[‡] (15.15 min)	4.5 H 10$^{!6}$
Sr-89 (50.53 d)	2.2 H 10$^{!2}$	Xe-133m[‡] (2.19 d)	4.6 H 10$^{!8}$
Sr-90 (28.79 y)	6.8 H 10$^{!1}$	Xe-133[‡] (5.243 d)	5.1 H 10$^{!8}$
Sr-91[‡] (9.63 h)	1.5 H 10$^{!4}$	Xe-135m[‡] (15.29 min)	6.5 H 10$^{!7}$
Sr-92[‡] (2.71 h)	1.3 H 10$^{!5}$	Xe-135[‡] (9.14 h)	3.8 H 10$^{!7}$
Y-91 (58.51 d)	1.4 H 10$^{!2}$	Xe-137[‡, §] (3.818 min)	3.4 H 10$^{!7}$
Y-92[‡] (3.54 h)	4.8 H 10$^{!6}$	Xe-138[‡] (14.08 min)	4.6 H 10$^{!6}$
Y-93[‡] (10.18 h)	5.4 H 10$^{!5}$	Cs-134[¶] (2.07 y)	1.9 H 10$^{!1}$
Zr-95 (64.02 d)	8.0 H 10$^{!3}$	Cs-136 (13.16 d)	6.4 H 10$^{!3}$
Zr-97[‡] (16.744 h)	3.0 H 10$^{!4}$	Cs-137[¶] (30.07 y)	1.8 H 10$^{!1}$
Nb-95 (34.997 d)	2.8 H 10$^{!3}$	Cs-138[‡] (33.41 min)	6.6 H 10$^{!6}$
Nb-96[‡] (23.35 h)	3.0 H 10$^{!4}$	Ba-139[‡] (83.06 min)	8.1 H 10$^{!7}$
Mo-99 (65.94 h)	5.2 H 10$^{!4}$	Ba-140[‡] (12.752 d)	2.5 H 10$^{!2}$
Ru-103 (39.26 d)	5.6 H 10$^{!3}$	Ba-141[‡] (18.27 min)	3.3 H 10$^{!6}$
Ru-105[‡] (4.44 h)	1.3 H 10$^{!5}$	Ba-142[‡] (10.6 min)	3.6 H 10$^{!6}$
Ru-106 (373.59 d)	9.6 H 10$^{!2}$	La-140[‡] (1.6781 d)	1.2 H 10$^{!3}$
Sb-129[‡] (4.40 h)	5.8 H 10$^{!5}$	La-141[‡] (3.92 h)	1.6 H 10$^{!5}$
Te-131m (30 h)	8.0 H 10$^{!4}$	La-142[‡] (91.1 min)	1.3 H 10$^{!5}$
Te-131[‡] (25.0 min)	3.2 H 10$^{!4}$	Ce-141 (32.501 d)	2.7 H 10$^{!3}$
Te-132 (3.20 d)	5.6 H 10$^{!3}$	Ce-143[‡] (33.039 h)	6.4 H 10$^{!4}$
Te-133m[‡] (55.4 min)	1.2 H 10$^{!4}$	Ce-144 (284.893 d)	3.6 H 10$^{!2}$
Te-134[‡] (41.8 min)	1.0 H 10$^{!5}$	Pr-143[‡] (13.57 d)	3.9 H 10$^{!3}$
I-129 (1.57 H 10^7 y)	9.2 H 10$^{!1}$	Pr-144[‡] (17.28 min)	3.5 H 10$^{!7}$
I-131 (8.0207 d)	1.5 H 10$^{!1}$	Pm-147 (2.6234 y)	1.7 H 10$^{!3}$
I-132 (2.295 h)	1.5 H 10$^{!5}$	Eu-154 (8.592 y)	1.7 H 10$^{!1}$
I-133 (20.8 h)	2.4 H 10$^{!3}$	U-234[¶] (2.46 H 10^5 y)	8.4 H 10$^{!1}$
I-134 (52.5 min)	9.2 H 10$^{!6}$	U-235[¶] (7.04 H 10^8 y)	2.7 H 10$^{!1}$

Table is continued on following page.

Table 3-4 Exposure factors assumed in screening analysis for radionuclides released to atmosphere from facilities at the Idaho National Engineering Laboratory* (continued)

Nuclide†	Exposure factor (Sv per Bq/m^3)	Nuclide†	Exposure factor (Sv per Bq/m^3)
I-135 (6.57 h)	5.6 H 10$^{!5}$	U-238¶ (4.47 H 10^9 y)	8.8 H 10$^{!11}$
Xe-129m‡ (8.88 d)	3.6 H 10$^{!8}$	Pu-238¶ (87.7 y)	9.2 H 10$^{!11}$
Xe-131m‡ (11.934 d)	1.4 H 10$^{!8}$	Pu-239/240¶, **	1.0

* Except as noted, exposure factors are entries in Table I-I in Annex I of IAEA (2001), multiplied by a factor of four (see text), and are based on exposures of infants (1 to 2 years old) as limiting group.
† Entry in parentheses is radionuclide half-life (Tuli 2000).
‡ Exposure factor is based mainly on models and parameter data sets used by IAEA (2001), except as noted, and is calculated as described in the text.
§ Exposure factor is calculated using external dose coefficients given by Kocher (1983).
¶ Exposure factor is based on exposures of adults as limiting group.
** Half-lives are 24,110 y for Pu-239 and 6,564 y for Pu-240.

For most of the radionuclides listed in Tables 3-1 through 3-3 that were not considered by the IAEA, exposure factors were calculated based mainly on the models and parameter data sets used by the IAEA (2001). For the short-lived radionuclides Br-85, Kr-89, and Xe-137, however, exposure factors were calculated using external dose coefficients given by Kocher (1983), since these radionuclides were not considered by Eckerman and Ryman (1993); inhalation and ingestion are unimportant for such short-lived radionuclides. The following assumptions were used for all radionuclides not considered by the IAEA. First, any shorter-lived decay products of a radionuclide of concern are assumed to be in activity equilibrium with the parent in air at the receptor location, except as noted in the discussions of exposure factors for specific radionuclides given below. Second, activities of any longer-lived decay products in air and on the ground surface relative to activities of the parent are assumed to be at their maximum values given by the ratio of the half-lives of the parent and decay product. Third, in estimating doses from terrestrial foodchain pathways, the delay time between production and consumption of food crops and milk is assumed to be one day and the delay time between slaughter and consumption of meat is assumed to be seven days. Additional information about the assumed exposure factors for specific radionuclides that were not considered by the IAEA is given as follows.

- H-3: The specific activity of H-3 in body water (i.e., activity of H-3 per unit mass of body water) is assumed to be in equilibrium with the specific activity of atmospheric water vapor (IAEA 2001). This assumption and the assumed absolute humidity of the atmosphere of 6 H 10$^{!3}$ kg/m^3 should result in substantial overestimates of dose from exposure to H-3 in air at INEL.

- All isotopes of argon, krypton, and xenon, except Kr-88, Kr-89, and Xe-138: External exposure due to immersion in the atmospheric plume is the only relevant exposure pathway. In addition, contributions to exposure factors from any longer-lived noble-gas decay products (e.g., Xe-131m produced in decay of I-131) are unimportant in all cases,

due either to the much longer half-life of the decay product or the long half-life of the parent compared with the transit time to the receptor location.

- Br-83, Br-85: Due to the short half-lives of these radionuclides, terrestrial foodchain pathways are unimportant and inhalation also is unimportant for Br-85. Contributions to the exposure factors due to immersion in the atmospheric plume from the respective longer-lived noble-gas decay products Kr-83m (1.83 h) and Kr-85m (4.48 h) are taken into account.

- Br-84, Y-92, Cs-138, Ba-139, La-142, Pr-144: Due to the short half-lives of these radionuclides, terrestrial foodchain pathways are unimportant, and only inhalation and the two external exposure pathways contribute significantly to the exposure factors. None of these radionuclides has radioactive decay products.

- Kr-88, Kr-89: In addition to external exposure due to immersion in the atmospheric plume, contributions to the exposure factors from the respective decay products Rb-88 (17.78 min) and Rb-89 (15.15 min) are taken into account. Due to the short half-lives of the decay products, terrestrial foodchain pathways are unimportant.

- Rb-89: Due to the short half-life of this radionuclide, terrestrial foodchain pathways are unimportant. The contribution to the exposure factor from the longer-lived decay product Sr-89 (50.53 d) is taken into account.

- Sr-91: Contributions to the exposure factor from the shorter-lived decay product Y-91m (49.71 min), which is produced in 57.4% of Sr-91 decays (Kocher 1981), and the longer-lived decay product Y-91 (58.51 d) are taken into account.

- Sr-92, Te-134, Ba-142: Contributions to the exposure factors from the respective longer-lived decay products Y-92, I-134, and La-142 are taken into account. Due to the short half-lives of these radionuclides and their decay products, terrestrial foodchain pathways are unimportant.

- Y-93, Nb-96: None of these radionuclides has important radioactive decay products.

- Zr-97: Contributions to the exposure factor from the shorter-lived decay products Nb-97m (58.7 s), which is produced in 94.7% of Zr-97 decays (Kocher 1981), and Nb-97 (72.1 min) are taken into account.

- Ru-105: Contributions to the exposure factor from the shorter-lived decay product Rh-105m (43 s), which is produced in 24.5% of Ru-105 decays (Kocher 1981), and the longer-lived decay product Rh-105 (35.36 h) are taken into account.

- Sb-129: Contributions to the exposure factor from the shorter-lived decay product Te-129 (69.6 min), which is produced in 83.4% of Sb-129 decays (Kocher 1981), and the longer-lived decay product Te-129m (33.6 d), which is produced in 16.6% of Sb-129

decays (Kocher 1981), are taken into account. Terrestrial foodchain pathways are important only for Te-129m.

- Te-131: The contribution to the exposure factor from the longer-lived decay product I-131 (8.02 d) is taken into account. Terrestrial foodchain pathways are important only for I-131.

- Te-133m: Contributions to the exposure factor from the shorter-lived decay product Te-133 (12.5 min), which is produced in 13% of Te-133m decays (Kocher 1981), and the longer-lived decay product I-133 (20.8 h) are taken into account. Terrestrial foodchain pathways are important only for I-133.

- Xe-137, Xe-138: In addition to external exposure due to immersion in the atmospheric plume, contributions to the exposure factor from the respective longer-lived decay products Cs-137 (30.07 y) and Cs-138 (33.41 min) are taken into account. Terrestrial foodchain pathways are important only for Cs-137.

- Ba-140: The exposure factor takes into account buildup of the shorter-lived decay product La-140 (1.678 days). In all exposure pathways involving activity deposited on the ground surface, La-140 is assumed to be in activity equilibrium with the parent. However, based on an assumed travel time to the receptor location of 2.6 hours,[8] the activity of La-140 in air is assumed to be 7% of the activity of the parent. In modeling terrestrial foodchain pathways for La-140, the transfer coefficient from soil to food crops is assumed to be 5 times the value used by the NCRP (1996), and the transfer coefficients from intake by a cow to milk and meat are assumed to be 10 times the respective values used by the NCRP (1996); these assumptions are consistent with the transfer coefficients for Ba used by the IAEA (2001) relative to the values used by the NCRP. The transfer coefficient from soil to pasture grass is assumed to be 0.1; this value is used for all radionuclides with low plant-to-soil concentration ratios to account for the substantial ingestion of contaminated soil by grazing livestock (IAEA 2001).

- Ba-141: Contributions to the exposure factor from the longer-lived decay products La-141 (3.92 h) and Ce-141 (32.5 d) are taken into account. Terrestrial foodchain pathways are unimportant for Ba-141, due to its short half-life. Assumed transfer coefficients in terrestrial foodchain pathways for La-141 are described in the discussion of the exposure factor for Ba-140.

- La-140: Assumed transfer coefficients in terrestrial foodchain pathways are described in the discussion of the exposure factor for Ba-140.

- La-141: The contribution to the exposure factor from the longer-lived decay product Ce-141 (32.5 d) is taken into account. Assumed transfer coefficients in terrestrial foodchain pathways for La-141 are described in the discussion of the exposure factor for Ba-140.

[8] This assumption is based on an assumed distance to the receptor location of 19 km, as described in later sections, and an average wind speed of 2 m/s, as described previously.

- Ce-143: The contribution to the exposure factor from the longer-lived decay product Pr-143 (13.57 d) is taken into account. Assumed transfer coefficients in terrestrial foodchain pathways for Pr-143 are the same as the values for Pm used by the IAEA (2001).

- Pr-143: Assumed transfer coefficients in terrestrial foodchain pathways are described in the discussion of the exposure factor for Ce-143.

3.5 Assumed Risk Coefficient for Purposes of Screening

For purposes of screening, the lifetime risk of cancer incidence per unit effective dose is assumed to be 0.1 Sv^{-1}. This value is based on a central estimate of 0.076 Sv^{-1} developed by the EPA (1994) for purposes of assessing average lifetime risks of cancer incidence in exposed populations with a normal age distribution. The increase above the central estimate of the risk coefficient takes into account its uncertainty (EPA 1999). Thus, the assumed risk coefficient is intended to be somewhat above the average value in a normal population.

3.6 Assumed Screening Cancer Risk Due to a Given Release

With reference to the screening model in Equation 1, and using the assumed atmospheric dispersion factor in Equation 4 or Equation 5 and the assumed risk coefficient of 0.1 Sv^{-1}, the lifetime risk of cancer incidence due to an assumed release of a radionuclide to the atmosphere from facilities at INEL is given by one of the following equations:

Routine or episodic releases –

$$\text{Risk} = \text{Release (Bq/s)} \times \frac{0.0254}{x\sigma_z} \times \text{Exposure factor (Sv per Bq/m}^3\text{)}, \quad (7)$$

Accidental releases –

$$\text{Risk} = \text{Release (Bq/s)} \times \frac{0.1016}{x\sigma_z} \times \text{Exposure factor (Sv per Bq/m}^3\text{)}, \quad (8)$$

where x again is the distance between the source and receptor locations in meters and the dispersion parameter, σ_z, is given in Equation 6.

4.0 SCREENING FACTORS FOR RELEASES AT THE IDAHO NATIONAL ENGINEERING LABORATORY

The following sections give the screening factors that are intended to be applied to routine releases from the ICPP in 1957-1959, releases from the 1959 criticality accident at the ICPP, and episodic releases from the selected initial engine tests in the ANP Program between February 1956 and March 1958. As discussed in Section 1, screening factors give lifetime risks of cancer incidence per unit activity of radionuclides released to be used for purposes of selecting radionuclides that warrant further analysis in a dose reconstruction.

4.1 Routine Releases from the Idaho Chemical Processing Plant

For purposes of screening of routine releases from the ICPP, we assume that an exposed individual resided at the closest populated location beyond the INEL site boundary, which is Atomic City, Idaho. The distance between the ICPP and Atomic City is 19 km, or 1.9×10^4 m (DOE 1991). At this distance, the dispersion parameter, F_z, in Equation 6 is 210 m, and the calculated lifetime risk of cancer incidence for routine releases in Equation 7 becomes

$$\text{Risk} = (6.4 \times 10^{-9}) \times \text{Release rate (Bq/s)} \times \text{Exposure factor (Sv per Bq/m}^3\text{)}. \quad (9)$$

In applying Equation 9 to routine releases from the ICPP during the years 1957-1959, the total releases for the three years can be assumed to occur during a single year and at a constant rate. This is a valid simplification since the lifetime cancer risk depends only on the total activity of a radionuclide released when exposures are assumed to occur throughout the duration of a release, as is the case in the screening model developed in this report. Estimated activities of radionuclides released from facilities at INEL generally are reported in curies (Ci), rather than Bq (DOE 1991; Behling and Mauro 2005; Wichner et al. 2005). Thus, the desired release rate in Bq/s for use in Equation 9 is given by

$$\text{Release (Bq/s)} = \text{Release (Ci)} \times (3.7 \times 10^{10}\ \text{Bq/Ci})/(3.15 \times 10^7\ \text{s/y}), \quad (10)$$

and the screening factor becomes

$$\text{Risk per Ci released} = (7.5 \times 10^{-6}) \times \text{Exposure factor (Sv per Bq/m}^3\text{)}. \quad (11)$$

Using Equation 11 and the exposure factors in Table 3-4, the screening factors for routine releases from the ICPP given in Table 4-1 are obtained. Multiplication of the screening factors in Table 4-1 by estimated total routine releases in Ci during the years 1957-1959 would give estimates of the lifetime risk of cancer incidence that can be compared with the screening risk criterion of 10^{-5} to select those radionuclides that warrant further analysis in a dose reconstruction.

Table 4-1 Screening factors for radionuclides assumed to be present in routine airborne releases from the Idaho Chemical Processing Plant for years 1957-1959 *

Nuclide	Screening factor (Risk per Ci)	Nuclide	Screening factor (Risk per Ci)
H-3 (12.33 y)†	3.2×10^{-11}	I-135 (6.57 h)	4.2×10^{-10}
Kr-85m (4.48 h)	1.8×10^{-12}	Xe-131m (11.93 d)	1.1×10^{-13}
Kr-85 (10.8 y)	5.9×10^{-14}	Xe-133m (2.19 d)	3.5×10^{-13}
Kr-87 (76.3 min)	9.8×10^{-12}	Xe-133 (5.243 d)	3.8×10^{-13}
Kr-88 (2.84 h)	3.8×10^{-11}	Xe-135m (15.29 min)	4.9×10^{-12}
Sr-89 (50.53 d)	1.7×10^{-7}	Xe-135 (9.14 h)	2.9×10^{-12}
Sr-90 (28.79 y)	5.1×10^{-6}	Cs-134 (2.07 y)	1.4×10^{-6}
Sr-91 (9.63 h)	1.1×10^{-9}	Cs-136 (13.16 d)	4.8×10^{-8}
Y-91 (58.51 d)	1.1×10^{-7}	Cs-137 (30.07 y)	1.4×10^{-6}
Zr-95 (64.02 d)	6.0×10^{-8}	Ba-140 (12.75 d)	1.9×10^{-7}
Nb-95 (35 d)	2.1×10^{-8}	La-140 (1.678 d)	9.0×10^{-9}
Ru-103 (39.26 d)	4.2×10^{-8}	Ce-141 (32.50 d)	2.0×10^{-8}
Ru-106 (373.6 d)	7.2×10^{-7}	Ce-144 (284.89 d)	2.7×10^{-7}
Te-132 (3.20 d)	4.2×10^{-8}	Pr-143 (13.57 d)	2.9×10^{-8}
I-129 (1.57×10^{7} y)	6.9×10^{-6}	Pm-147 (2.623 y)	1.3×10^{-8}
I-131 (8.02 d)	1.1×10^{-6}	Eu-154 (8.592 y)	1.3×10^{-6}
I-132 (2.295 h)	1.1×10^{-10}	Pu-238 (87.7 y)	6.9×10^{-6}
I-133 (20.8 h)	1.8×10^{-8}	Pu-239/240‡	7.5×10^{-6}

* Screening factors give lifetime risk of cancer incidence per unit activity of radionuclides released, and are calculated using Equation 11 and exposure factors given in Table 3-4; assumed distance from source to receptor location is 19 km, and other assumptions used in calculations are described in the text.

† Entry in parentheses is radionuclide half-life (Tuli 2000).

‡ Half-lives are 24,110 y for Pu-239 and 6,564 y for Pu-240.

4.2 Releases from 1959 Criticality Accident at the Idaho Chemical Processing Plant

For purposes of screening of releases from the 1959 criticality accident at the ICPP, we assume, as in the analysis for routine releases, that an exposed individual resided at a distance from the source of 1.9×10^{4} m, and that the dispersion parameter, σ_z, in Equation 6 is 210 m. The calculated lifetime risk of cancer incidence for accidental releases in Equation 8 becomes

$$\text{Risk} = (2.5 \times 10^{-8}) \times \text{Release rate (Bq/s)} \times \text{Exposure factor (Sv per Bq/m}^3\text{)} \qquad (12)$$

In applying Equation 12 to releases from the criticality accident, the total releases can be assumed to occur at a constant rate over an entire year, to be consistent with the assumption in the models used to calculate exposure factors that exposure occurs over an entire year. Again,

this is a valid assumption when exposure is assumed to occur throughout the duration of a release. Taking into account the conversion from total release in Ci to release rate in Bq/s given in Equation 10, the screening factor becomes

$$\text{Risk per Ci released} = (3.0 \times 10^{-5}) \times \text{Exposure factor (Sv per Bq/m}^3\text{)}. \quad (13)$$

Using Equation 13 and the exposure factors in Table 3-4, the screening factors for the 1959 criticality accident at the ICPP given in Table 4-2 are obtained. Multiplication of the screening factors in Table 4-2 by estimated total released in Ci duing the criticality accident would give estimates of the lifetime risk of cancer incidence that can be compared with the screening risk criterion of 10^{-5} to select those radionuclides that warrant further analysis in a dose reconstruction.

Table 4-2 Screening factors for radionuclides assumed to be present in airborne releases from the 1959 criticality accident at the Idaho Chemical Processing Plant*

Nuclide	Screening factor (Risk per Ci)	Nuclide	Screening factor (Risk per Ci)
Br-83 (2.40 h)†	9.0×10^{-12}	I-134 (52.5 min)	2.8×10^{-10}
Br-84 (31.8 min)	2.4×10^{-10}	I-135 (6.57 h)	1.7×10^{-9}
Br-85 (2.90 min)	4.2×10^{-12}	Xe-129m (8.88 d)	1.1×10^{-12}
Kr-83m (1.83 h)	1.8×10^{-15}	Xe-133 (5.243 d)	1.5×10^{-12}
Kr-85m (4.48 h)	7.2×10^{-12}	Xe-135m (15.29 min)	2.0×10^{-11}
Kr-87 (76.3 min)	3.9×10^{-11}	Xe-135 (9.14 h)	1.1×10^{-11}
Kr-88 (2.84 h)	1.5×10^{-10}	Xe-137 (3.818 min)	1.0×10^{-11}
Kr-89 (3.15 min)	1.1×10^{-10}	Xe-138 (14.08 min)	1.4×10^{-10}
Rb-89 (15.15 min)	1.4×10^{-10}	Cs-137 (30.07 y)	5.4×10^{-6}
Sr-89 (50.53 d)	6.6×10^{-7}	Cs-138 (33.41 min)	2.0×10^{-10}
Sr-90 (28.79 y)	2.0×10^{-5}	Ba-139 (83.06 min)	2.4×10^{-11}
Sr-91 (9.63 h)	4.5×10^{-9}	Ba-140 (12.75 d)	7.5×10^{-7}
Sr-92 (2.71 h)	3.9×10^{-10}	Ba-141 (18.27 min)	9.9×10^{-11}
Y-91 (58.51 d)	4.2×10^{-7}	Ba-142 (10.6 min)	1.1×10^{-10}
Y-92 (3.54 h)	1.4×10^{-10}	La-141 (3.92 h)	4.8×10^{-10}
I-131 (8.02 d)	4.5×10^{-6}	La-142 (91.1 min)	3.9×10^{-10}
I-132 (2.295 h)	4.5×10^{-10}	Ce-141 (32.50 d)	8.1×10^{-8}
I-133 (20.8 h)	7.2×10^{-8}		

* Screening factors give lifetime risk of cancer incidence per unit activity of radionuclides released, and are calculated using Equation 13 and exposure factors given in Table 3-4; assumed distance from source to receptor location is 19 km, and other assumptions used in calculations are described in the text.

† Entry in parentheses is radionuclide half-life (Tuli 2000).

4.3 Episodic Releases from Selected Initial Engine Tests in Aircraft Nuclear Propulsion Program

For purposes of screening of episodic releases from selected IETs in the ANP Program, we assume that an exposed individual resided at the closest populated location beyond the INEL site boundary, which is Monteview, Idaho. The distance to the receptor location in this case is 19 km (DOE 1991), which is the same as the distance from the ICPP to its closest receptor location beyond the site boundary (see Section 4.1). Therefore, the screening model that applies to episodic releases from the initial engine tests is given by Equation 9 above, and the screening factors are calculated using Equation 11. This model can be applied to the initial engine tests because all releases occurred over a period of at least a few days (DOE 1991), and significant changes in wind direction should have occurred during the releases.

In applying the screening model to the initial engine tests, estimated releases from all selected tests combined can be assumed to have occurred at a constant rate during a single year, to be consistent with the models used to obtain the exposure factors. Using Equation 11 and the exposure factors in Table 3-4, the screening factors for episodic releases from the selected initial engine tests given in Table 4-3 are obtained. Multiplication of the screening factors in Table 4-3 by estimated total releases in Ci during the selected IETs would give estimates of the lifetime risk of cancer incidence that can be compared with the screening risk criterion of 10^{-5} to select those radionuclides that warrant further analysis in a dose reconstruction.

Table 4-3 Screening factors for radionuclides assumed to be present in episodic releases from selected initial engine tests in Aircraft Nuclear Propulsion Program between February 1956 and March 1958*

Nuclide	Screening factor (Risk per Ci)	Nuclide	Screening factor (Risk per Ci)
Ar-41 (109.34 min)†	1.6×10^{-11}	I-131 (8.02 d)	1.1×10^{-6}
Br-84 (31.8 min)	6.1×10^{-11}	I-132 (2.295 h)	1.1×10^{-10}
Kr-85m (4.48 h)	1.8×10^{-12}	I-133 (20.8 h)	1.8×10^{-8}
Kr-87 (76.3 min)	9.0×10^{-12}	I-134 (52.5 min)	6.9×10^{-11}
Kr-88 (2.84 h)	3.8×10^{-11}	I-135 (6.57 h)	4.2×10^{-10}
Rb-89 (15.15 min)	3.4×10^{-11}	Xe-129m (8.88 d)	2.7×10^{-13}
Sr-89 (50.53 d)	1.7×10^{-7}	Xe-135 (9.14 h)	2.9×10^{-12}
Sr-90 (28.79 y)	5.1×10^{-6}	Xe-135m (15.29 min)	4.9×10^{-12}
Sr-91 (9.63 h)	1.1×10^{-9}	Xe-138 (14.08 min)	3.5×10^{-11}
Sr-92 (2.71 h)	9.8×10^{-11}	Cs-137 (30.07 y)	1.4×10^{-6}
Y-91 (58.51 d)	1.1×10^{-7}	Cs-138 (33.41 min)	5.0×10^{-11}
Y-92 (3.54 h)	3.6×10^{-11}	Ba-139 (83.06 min)	6.1×10^{-12}
Y-93 (10.18 h)	4.1×10^{-10}	Ba-140 (12.75 d)	1.9×10^{-7}
Zr-95 (64.02 d)	6.0×10^{-8}	Ba-141 (18.27 min)	2.5×10^{-11}
Zr-97 (16.744 h)	2.3×10^{-9}	Ba-142 (10.6 min)	2.7×10^{-11}
Nb-96 (23.35 h)	2.3×10^{-9}	La-141 (3.92 h)	1.2×10^{-10}
Mo-99 (65.94 h)	3.9×10^{-9}	La-142 (91.1 min)	9.8×10^{-11}
Ru-103 (39.26 d)	4.2×10^{-8}	Ce-141 (32.50 d)	2.0×10^{-8}
Ru-105 (4.44 h)	9.8×10^{-11}	Ce-143 (33.039 h)	4.8×10^{-9}
Ru-106 (373.6 d)	7.2×10^{-7}	Ce-144 (284.89 d)	2.7×10^{-7}
Sb-129 (4.40 h)	4.4×10^{-10}	Pr-143 (13.57 d)	2.9×10^{-8}
Te-131 (25.0 min)	2.4×10^{-9}	Pr-144 (17.28 min)	2.6×10^{-12}
Te-131m (30 h)	6.0×10^{-9}	U-234 (2.46×10^{5} y)	6.3×10^{-6}
Te-132 (3.20 d)	4.2×10^{-8}	U-235 (7.04×10^{8} y)	2.0×10^{-6}
Te-133m (55.4 min)	9.0×10^{-10}	U-238 (4.47×10^{8} y)	6.6×10^{-6}
Te-134 (41.8 min)	7.5×10^{-11}		

* Selected initial engine tests include IET #3, #4, and #10 (DOE 1991; Behling and Mauro 2005). Screening factors give lifetime risk of cancer incidence per unit activity of radionuclides released, and are calculated using Equation 11 and exposure factors given in Table 3-4; assumed distance from source to receptor location is 19 km, and other assumptions used in calculations are described in text.

† Entry in parentheses is radionuclide half-life (Tuli 2000).

4.4 Consideration of Alternative Exposure Scenarios

The screening factors obtained in this analysis, as given in Tables 4-1 through 4-3, are based on an assumption that a maximally exposed individual was a largely self-sufficient homesteader who resided permanently at the closest populated location beyond the INEL site boundary. For the releases of concern to this analysis, the distance to the assumed receptor locations is 19 km (see Sections 4.1 and 4.3). As indicated in eqs. (3) and (6), the large distance to the receptor locations has a considerable effect on reducing calculated concentrations in air compared with concentrations near the sources.

Exposure scenarios that were considered for use in a more detailed and realistic dose reconstruction for historical releases at INEL are discussed in another report (Apostoaei and Reed 2005). These scenarios include some that involve exposure of members of the public within the INEL site boundary. One of these scenarios involves an individual who makes regular deliveries of items (e.g., food and drink) to office or service buildings located relatively close to a release. Compared with other scenarios for onsite exposure, this scenario involves exposures closest to a release, and the exposure time could be appreciable.

As an example, we assume that an individual made regular deliveries to the Central Facilities Area (CFA), which is located approximately 4 km from the ICPP (Bowman et al. 1984). At this distance, the atmospheric dispersion factor in Equation 6 is about a factor of 10 higher than the value at the assumed receptor locations beyond the INEL site boundary. We also assume that a delivery person spent 5% of the time during a year, or about one working day per week, at the CFA. Based on these assumptions, the product of the atmospheric dispersion factor and the exposure time would be about a factor of two less than the value that is assumed to apply to a member of the public who resided beyond the INEL site boundary. Therefore, consideration of this scenario should not increase the number of radionuclides that would warrant further analysis in a dose reconstruction.

It also is possible that a member of the public, such as a delivery person, was exposed at locations much closer to a release than the distance of 4 km assumed in the example discussed above. In such cases, airborne concentrations of radionuclides at locations of exposure could have been considerably higher. For example, regular deliveries could have been made to the facilities where the releases occurred. However, we believe that members of the public probably were not exposed at the facilities where releases occurred. Since these facilities were operated under conditions of strict security and were designated as radiation areas, it seems highly unlikely that anyone would have been allowed into the facilities without wearing a badge and a personal dosimeter. Therefore, persons entering the facilities would be considered radiation workers, and would not be of concern in a dose reconstruction for members of the public.

A screening analysis based on the types of scenarios for onsite exposure discussed above should take into account that only external and inhalation exposures could occur, and that terrestrial foodchain pathways are not relevant. Terrestrial foodchain pathways do not contribute to exposure factors for noble-gas radionuclides and other radionuclides with half-lives less than a few hours, but these pathways can contribute 90% or more of the total dose from all exposure pathways combined for some longer-lived radionuclides considered in this analysis (IAEA 2001). Furthermore, the assumptions that most shorter-lived decay products are in activity

equilibrium with their parent radionuclides and that the activities of longer-lived decay products are at their maximum values relative to the activities of the parents, which were used in calculating exposure factors at locations beyond the INEL site boundary, probably do not apply at locations close to a release, and these assumptions should result in considerable overestimates of exposure factors in many such cases. Finally, if exposure at locations within a few hundred meters of a release were a credible occurrence, the assumption used in the screening models that releases occurred at ground level should result in considerable overestimates of exposure to airborne radionuclides, because releases at the facilities of concern occurred through elevated stacks and concentrations at ground level at close-in locations should have been substantially less than concentrations along the centerline of the plume.

Based on these considerations, we believe that scenarios for onsite exposure of members of the public do not need to be included in a screening analysis to select radionuclides of greatest concern to a dose reconstruction at INEL. It appears unlikely that calculated cancer risks based on credible scenarios for onsite exposure and the screening models developed in this report would be substantially higher than calculated cancer risks at locations beyond the INEL site boundary, due to the limited number of relevant exposure pathways and much shorter exposure times. Furthermore, given that the lifetime cancer risk of $10^{!5}$ used as the screening criterion in this analysis is very low, it is highly unlikely that any radionuclides that would not be selected for further analysis based on assumed exposures beyond the INEL site boundary could have resulted in significant doses and risks to members of the public who might have been exposed within the site boundary.

5.0 DISCUSSION OF SCREENING METHODOLOGY AND RESULTS

This report has presented simple screening models that are intended for use in selecting radionuclides that warrant inclusion in a dose reconstruction for historical releases to the atmosphere from facilities at INEL. The method of screening of radionuclides assumes that a maximally exposed member of the public was a resident homesteader at the closest populated locations to the releases beyond the INEL site boundary. The screening models apply to routine airborne releases from the ICPP during the years 1957-1959, to airborne releases that occurred following a criticality accident at the ICPP in 1959, and to episodic airborne releases that occurred during selected IETs in the ANP Program between February 1956 and March 1958. The results of the screening analysis are presented as screening factors, which give calculated lifetime risks of cancer incidence per unit activity release of radionuclides. These screening factors are intended to be applied to estimated releases of radionuclides from the operations and events of concern to select those radionuclides for which the calculated lifetime cancer risk exceeds the screening criterion of 10^{-5}.

The screening models developed in this report incorporate many assumptions that should tend to result in overestimates of actual doses and risks to members of the public at any location beyond the INEL site boundary due to an atmospheric release of concern. In the atmospheric dispersion factor, the assumed average wind speed of 2 m/s should underestimate average wind speeds at the site by approximately a factor of two (DOE 1991), with the result that average airborne concentrations of radionuclides at any receptor location would be overestimated by the same factor. The assumption that routine releases from the ICPP and episodic releases from the IETs were carried by the wind in a direction toward the receptor locations for 25% of the time should overestimate the true frequency of the wind in any direction by nearly a factor of two (SENES 2002). Furthermore, for releases from the ICPP, the assumed location of exposure at Atomic City is in a direction perpendicular to the prevailing wind direction, i.e., the wind blows toward Atomic City only a small fraction of the time (SENES 2002; DOE 1991), which greatly reduces potential exposures at that location; this conclusion does not necessarily apply during the criticality accident at the ICPP or to episodic releases from IETs. If exposures due to routine releases from the ICPP were assumed to occur at the INEL site boundary in the prevailing wind direction, the distance to the nearest receptor location would increase substantially, and the atmospheric dispersion factor would decrease with increasing distance more rapidly than $1/x$ [see eqs. (4) and (6)]. Airborne concentrations of radionuclides are assumed not to be depleted by radioactive decay or deposition onto the ground during transport to the receptor location. The assumption of no decay results in substantial overestimates of potential exposures for radionuclides with half-lives of a few hours or less, and the assumption of no deposition onto the ground results in overestimates of exposures for all radionuclides except noble gases (argon, krypton, and xenon). Assumptions about the activities of any radioactive decay products are intended to maximize potential exposures to decay products that are formed after release of the parent. Finally, the assumption of Pasquill-Gifford stability category D in the model of atmospheric transport should tend to result in overestimates of airborne concentrations of radionuclides at assumed receptor locations.

The models used to estimate exposure factors also incorporate several assumptions that should result in overestimates of doses and risks to members of the public. An exposed individual is assumed to reside at the closest populated location beyond the INEL site boundary for 100% of

the time during a year, and no credit is taken for reductions in external and inhalation doses during the substantial fraction of the time spent indoors. Assumed intakes of vegetables, milk, and meat that are contaminated as a result of deposition of radionuclides from an atmospheric plume onto the ground surface should overestimate actual intakes of locally grown foods by most individuals. Transfer coefficients used in the models for terrestrial foodchain pathways, which give concentrations of radionuclides in food crops or forage per unit concentration in surface soil or concentrations in milk and meat per unit activity intake by dairy and beef cattle, also were selected with the intent that they would not substantially underestimate actual values at any site (IAEA 2001). Finally, the models for estimating dose due to radionuclides deposited on the ground surface (i.e., external dose due to deposited activity and ingestion dose from terrestrial foodchain pathways) assume that deposition occurred continually for 30 years, and this assumption often results in considerable overestimates of dose following deposition for radionuclides with half-lives of a few years or greater.

We also note that for many radionuclides with half-lives of several hours or greater, inclusion of terrestrial foodchain pathways in the models used to estimate exposure factors should result in substantial overestimates of dose from all pathways combined when an accidental or episodic release occurred at times outside the normal growing season near INEL. This could be an important consideration for the criticality accident at the ICPP, which occurred on October 16, and for IETs #3 and #10, which occurred in February 1956 and March 1958, respectively. When locally grown vegetables are not being produced or when dairy and beef cattle would be consuming stored feed, doses from terrestrial foodchain pathways would be greatly reduced compared with doses during the growing season, mainly because pathways involving ingestion of radionuclides that were deposited onto plant surfaces would not apply. There would still be some dose from terrestrial foodchain pathways due to deposition onto the ground surface, either directly from the atmosphere or by weathering from plant surfaces, but only when a radionuclide is sufficiently long-lived that it would be retained in surface soil and available for root uptake during the next growing season. Furthermore, doses resulting from root uptake by food crops or pasture grass usually are much less than doses resulting from deposition onto plant surfaces (IAEA 2001). Modifications of exposure factors to account for the time of year when a release occurred could be used in further screening of radionuclides if so desired.

It must be emphasized that **calculated screening factors in Tables 4-1 through 4-3, when applied to estimated releases, are not intended to provide estimates of risk to any member of the public at locations beyond the INEL site boundary during the years 1956-1959**, and they should not be so interpreted. Based on assumptions in the screening models summarized above, calculated screening factors are expected to result in substantial overestimates of risks that were experienced by members of the public beyond the site boundary, provided that assumed source terms for the releases of concern do not substantially underestimate actual releases.

In addition, **calculated screening factors in Tables 4-1 through 4-3, when applied to estimated releases, should not be used to rank the different radionuclides released from the ICPP or the selected IETs in the ANP Program in order of importance**. While calculated risks from a given release can be used to indicate, in a general way, that certain radionuclides should be more important than others, a rank-ordering of the results probably would not be meaningful, mainly because the extent to which the assumed atmospheric dispersion factors and

exposure factors overestimate actual exposure conditions during a release probably is not the same for all radionuclides. The same caution applies to comparisons of calculated risks associated with the different releases from the ICPP and IETs. Any such rank-ordering should be based on a reasonably consistent set of assumptions for all radionuclides and releases, but this condition is not met by the screening models used in this analysis.

REFERENCES

Apostoaei AI, Reed WE, 2005. Exposure Scenarios for Use in Estimating Radiation Doses to the Public from Historical Atmospheric Releases of Radionuclides at INEL. Final Report. SENES Oak Ridge, Inc., Oak Ridge, Tennessee; July 2005.

Barr S, Clements WE, 1984. Diffusion Modeling: Principles of Application, Chapter 13 in Atmospheric Science and Power Production. DOE/TIC-27601, U.S. Department of Energy, Washington, DC; 1984.

Behling UH and Mauro J, 2005. A Critical Review of Source Terms for Selected Initial Engine Tests Associated with the Aircraft Nuclear Propulsion Program at INEL. Final Report. S. Cohen and Associates, McLean, Virginia; July 2005.

Bowman AL, Downs WF, Moor KS, Russell BF, 1984. INEL Environmental Characterization Report. Summary Report and Appendices, EGG-NPR-6688, EG&G Idaho, Inc., Idaho Falls, Idaho; 1984.

Clay DR, 1991. Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions. Directive 9355.0-30, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC; 1991.

DOE (U.S. Department of Energy), 1991. Idaho National Engineering Laboratory Historical Dose Evaluation. Volume 2: Appendices, DOE/ID-12119 Vol 2, U.S. Department of Energy, Idaho Falls, Idaho.

Eckerman KF, Ryman JC, 1993. External Exposure to Radionuclides in Air, Water, and Soil. Federal Guidance Report No. 12, EPA 402-R-93-081, U.S. Environmental Protection Agency, Washington, DC.

EPA (U.S. Environmental Protection Agency), 1994. Estimating Radiogenic Cancer Risks. EPA 402-R-93-076, U.S. Environmental Protection Agency, Washington, DC.

EPA (U.S. Environmental Protection Agency), 1999. Estimating Radiogenic Cancer Risks. Addendum: Uncertainty Analysis, EPA 402-R-99-003, U.S. Environmental Protection Agency, Washington, DC.

IAEA (International Atomic Energy Agency), 2001. Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment. Safety Reports Series No. 19, International Atomic Energy Agency, Vienna, Austria.

ICRP (International Commission on Radiological Protection), 1977. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26, Annals of the ICRP 1, No. 3.

ICRP (International Commission on Radiological Protection), 1979. Limits for Intakes of Radionuclides by Workers. ICRP Publication 30, Part 1, Annals of the ICRP 2, No. 3/4.

ICRP (International Commission on Radiological Protection), 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Annals of the ICRP 21, No. 1-3.

ICRP (International Commission on Radiological Protection), 1996. Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5. Compilation of Ingestion and Inhalation Dose Coefficients, ICRP Publication 72, Annals of the ICRP 26, No. 1.

ICRP (International Commission on Radiological Protection), 1997. Conversion Coefficients for Use in Radiological Protection Against External Radiation. ICRP Publication 74, Annals of the ICRP 26, No. 3/4.

Kocher DC, 1981. Radioactive Decay Data Tables. DOE/TIC-11026, U.S. Department of Energy, Oak Ridge, TN.

Kocher DC, 1983. Dose-Rate Conversion Factors for External Exposure to Photons and Electrons. Health Physics 45:665-686.

Luftig SD, Weinstock L, 1997. Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination. Directive 9200.4-18, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

Miller CW, 1984. Atmospheric Dispersion and Deposition, Chapter 3 in Models and Parameters for Environmental Radiological Assessments. DOE/TIC-11468, U.S. Department of Energy, Oak Ridge, TN.

NCRP (National Council on Radiation Protection and Measurements), 1987. Exposure of the Population in the United States and Canada from Natural Background Radiation. NCRP Report No. 94, National Council on Radiation Protection and Measurements, Bethesda, MD.

NCRP (National Council on Radiation Protection and Measurements), 1996. Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground. NCRP Report No. 123 I, National Council on Radiation Protection and Measurements, Bethesda, MD.

SENES, 2002. I-131 Dose Reconstruction, Progress Report, SENES Consultants Limited, Richmond Hill, Ontario, Canada, and SENES Oak Ridge, Inc., Oak Ridge, Tennessee; October 2002.

Tuli JK, 2000. Nuclear Wallet Cards. 6th edition, Brookhaven National Laboratory, Upton, NY.

Wichner RP, Renier J-P, Anspaugh LR, 2005. Atmospheric Source Terms for the Idaho Chemical Processing Plant, 1957 – 1959. Final Report. SENES Oak Ridge, Inc., Oak Ridge, Tennessee; July 2005.