DOE/NV/0000939-25

Approximating Dose and Risk for Contaminants in Groundwater from the Underground Nuclear Test Areas of the Nevada National Security Site (NNSS)

Prepared by

Jeffrey I. Daniels, Jenny Chapman, and Karl F. Pohlmann

Submitted to

Nevada Field Office
National Nuclear Security Administration
U.S. Department of Energy
Las Vegas, Nevada

March 2015

Publication No. 45262

Nevada System of Higher Education

DOE/NV/0000939-25

Approximating Dose and Risk for Contaminants in Groundwater from the Underground Nuclear Test Areas of the Nevada National Security Site (NNSS)

Prepared by

Jeffrey I. Daniels, Jenny Chapman, and Karl F. Pohlmann

Division of Hydrologic Sciences
Desert Research Institute
Nevada System of Higher Education

Publication No. 45262

Submitted to

Nevada Field Office
National Nuclear Security Administration
U.S. Department of Energy
Las Vegas, Nevada

March 2015

The work upon which this report is based was supported by the U.S. Department of Energy under Contract #DE-NA0000939. Approved for public release; further dissemination unlimited.

THIS PAGE LEFT INTENTIONALLY BLANK

ACKNOWLEDGEMENTS

The authors express their gratitude to Chuck Russell at DRI; Kathryn Knapp at the U.S. Department of Energy, Nevada Field Office (Las Vegas, Nevada); Andrew Tompson at Lawrence Livermore National Laboratory (Livermore, California); and Jena M. Huntington at United States Geological Survey (Carson City, Nevada) for their expertise and reviews from which this document benefited greatly. The editing and production assistance provided by Nicole Damon at DRI were also especially meaningful contributions to this document.

THIS PAGE LEFT INTENTIONALLY BLANK

EXECUTIVE SUMMARY

As part of the Environmental Management Program at the Nevada National Security Site (NNSS), the Underground Test Area (UGTA) Activity investigates the potential impacts of radionuclides that were introduced into groundwater from the underground nuclear tests conducted near or below the NNSS water table between 1951 and 1992. Groundwater models are being used to simulate contaminant transport and forecast contaminant boundaries that encompass areas where the groundwater has a five percent or greater probability of containing contaminants above the Safe Drinking Water Act Maximum Contaminant Levels (SDWA MCLs) at any time during the next 1,000 years. Transport modeling conducted for the Frenchman Flat Corrective Action Unit (CAU) at the NNSS identified the beta/photon-emitting radionuclides tritium (^{3}H), carbon-14 (^{14}C), chlorine-36 (^{36}Cl), technetium-99 (^{99}Tc), and iodine-129 (^{129}I) as having the greatest influence in defining the farthest extent of the modeled CAU contaminant boundary. These same radionuclides are assumed here as the contaminants of concern (COCs) for all underground nuclear tests at the NNSS because models are not yet complete for the other CAUs.

Potential public exposure to the COCs will only occur and be of concern if the COCs migrate into the groundwater beneath public or private lands at levels that exceed either individual SDWA MCLs or dose and risk limits. Groundwater flow directions strongly suggest that any contaminant boundary predicted by contaminant fate and transport modeling to overlap public or private lands is more likely to occur to the west and/or southwest of the NNSS and the adjacent Nevada Test and Training Range (NTTR). Well-established, rural communities exist in these directions. Estimates of representative activity concentrations at the applicable SDWA MCL were developed for the five COCs. It is assumed that these COC concentrations may collectively occur at some public or private location in the future, but that situation does not exist today. These representative activity concentrations are evaluated with respect to conforming collectively to a modern annual committed effective dose (CED) and lifetime excess cancer morbidity risk for a hypothetical reasonably maximally exposed individual (RMEI). This approach goes beyond the SDWA MCL focus of the contaminant boundary because individual COC concentrations may comply with the SDWA MCL but not collectively meet the modern health-protection metrics and the SDWA language, especially if future modeling studies or monitoring activities show multiple radionuclides from different SDWA MCL categories to be COCs.

For the drinking water exposure pathway alone, the annual committed effective dose (CED) for the RMEI from all five COCs that are collectively at estimated activity concentrations equal to their SDWA MCL is well below the U.S. Department of Energy health-protective CED limit of 100 millirem (mrem)/yr. This is consistent using both the NNSS unclassified, 1992 decay-corrected radionuclide atom inventory and the atom inventory based on radionuclides measured in groundwater obtained from the ALMENDRO cavity in 2009 to calculate the SDWA MCL activity concentrations in groundwater. The RMEI's total lifetime excess cancer risk from the drinking water exposure pathway for both atom inventories is within the range of 1×10^{-4} to $\leq 1 \times 10^{-6}$, which is considered health protective according to modern SDWA MCL regulatory language.

The biosphere exposure pathways are drinking water, garden produce, animal products, inadvertent soil ingestion, and indoor and outdoor air inhalation. The exposure parameters for communities west and southwest of the NNSS were developed when the Yucca Mountain high-level, nuclear-waste disposal facility was under consideration. For all biosphere exposure pathways, calculations of the annual CED and lifetime excess cancer morbidity risk for the RMEI revealed that:

1) The annual CED is well within health-protective guidance ($<< 100$ $mrem_{CED}/yr$) for the COC activity concentrations at the SDWA MCL, regardless of the atom inventory used.

2) The calculated 70-year lifetime excess cancer morbidity risk (6×10^{-5}) is within the health-protective range when the five COC activity concentrations are derived using the NNSS 1992 atom inventory, but it is at the upper limit of the acceptable range (1×10^{-4}) using the ALMENDRO 2009 atom inventory.

3) Tritium (^{3}H) is the principal COC for producing annual dose and lifetime excess cancer risk, regardless of the atom inventory used.

4) Overall, the drinking water ingestion pathway is the dominant exposure pathway contributing to the total annual CED and lifetime excess cancer risk, followed by eating locally grown produce and animal products.

5) When tritium completely decays (after about 100 years), the RMEI's lifetime risk will fall well within the health-protective range (i.e., 1×10^{-4} to $\leq 1 \times 10^{-6}$) and ^{36}Cl will then become the most important contributor to the RMEI's total annual CED and lifetime excess cancer morbidity risk from eating local produce and animal products.

In the event that radionuclide concentrations begin to approach SDWA MCLs, a reasonable risk-management strategy for keeping lifetime risk more in compliance with regulatory guidance would be to use local sources of groundwater that are below SDWA MCLs or to limit the consumption of local produce and animal products that have ingested COC-contaminated groundwater. The viability of the latter strategy increases where the annual CED due to ^{36}Cl approaches that of ^{3}H.

The dose and risk values calculated here for an RMEI are specific to the assumption that the five COCs occur in groundwater beneath public or private lands at concentrations that are collectively at the SDWA MCL. Currently, these COCs are essentially absent from groundwater beneath public or private lands beyond the boundaries of the NNSS and NTTR other than at very low, naturally occurring concentrations. The analyses presented here can be readily applied to determine dose and risk for COC concentrations actually measured in any future monitoring samples.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

A_i/vol	Radioactivity per unit volume, herein referred to as activity concentration
BDCF	Biosphere dose conversion factors
Bq	Becquerel (one disintegration per second)
CAU	Corrective Action Unit
CED	Committed effective dose
Ci	Curie (3.7×10^{10} disintegrations per second)
COC	Contaminant of concern (radionuclide of interest)
CRITORG	Critical organ dose
D_T	Total annual dose
DVRFS	Death Valley Regional (Groundwater) Flow System
ED	Exposure duration
eDC_i	Committed effective dose coefficient for radionuclide *i*
FFACO	Federal Facilities Agreement and Consent Order
L	Liter
MCL	Maximum contaminant level
mrem	Millirem (10^{-3} rem)
mSv	Millisievert (10^{-3} Sv)
µg	Microgram (10^{-6} g)
N_i	Number of atoms of radionuclide *i*
NNSS	Nevada National Security Site (formerly the Nevada Test Site [NTS])
NPDWR	National Primary Drinking Water Regulation
NTTR	Nevada Test and Training Range
p_i	Relative atom abundance of radionuclide *i* expressed as proportion
pCi	Picocurie (10^{-12} Ci or 0.037 Bq)
RMEI	Reasonably maximally exposed individual
RC_i	Risk coefficient for radionuclide *i*
R_T	Total lifetime excess cancer morbidity risk
SDWA	Safe Drinking Water Act
SNL	Sandia National Laboratories
SI	International System of Units
UGTA	Underground Test Area
USDoD	United States Department of Defense
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency

INTRODUCTION

The Underground Test Area (UGTA) Activity is part of the Environmental Management Program at the Nevada National Security Site (NNSS). This Activity investigates the potential impacts of radionuclides introduced into groundwater from the underground nuclear tests conducted near or below the NNSS water table between 1951 and 1992. The sources of the radionuclides are centered in each of the nuclear-test cavities that constitute a corrective action site (CAS) located within the NNSS Corrective Action Units (CAUs): Frenchman Flat, Yucca Flat/Climax Mine, Central and Western Pahute Mesa, and Rainier Mesa/Shoshone Mountain (Figure 1). The communities of Beatty (near Oasis Valley) and Amargosa Valley are approximately 30 miles beyond the western and southwestern boundaries of the NNSS, respectively, and in the general directions of groundwater flow. Because there is no feasible method for removing radioactive contamination from groundwater at the NNSS, the objective of the UGTA Activity is to forecast the farthest extent of a probabilistic contaminant boundary (defined below) for radionuclides in the groundwater over a 1,000 year time period. This boundary will be used in combination with monitoring and institutional controls to protect the public.

The approach for calculating a contaminant boundary is prescribed by the Federal Facilities Agreement and Consent Order (FFACO, 1996; as amended in 2010) and is agreed to by the Department of Energy and the State of Nevada. The contaminant boundary delineates the surface projection of a volume of groundwater downgradient from one (or more) underground nuclear tests that is, or will potentially become contaminated at any time over the next 1,000 years. By "potentially," we mean that inside the boundary, there is at least a five percent probability of exceeding the concentrations allowed by the regulatory standards over the next 1,000 years. Outside the boundary, there is at least a 95 percent probability of not exceeding those standards over the next 1,000 years. The idealized example in Figure 2 shows that activity (meaning radionuclide concentration) in the groundwater will decrease as the distance from the source increases because of the effects of dispersion, nuclear decay, matrix diffusion, and retardation. Therefore, contours farther from the source reflect greater levels of confidence that the activity in groundwater beyond them will be equal to or less than the regulatory standard. The activity in the groundwater is ionizing radiation—such as alpha or beta particles and/or gamma rays—emitted from the nucleus of an unstable, radioactive atom as it decays to a lower energy state.

The National Primary Drinking Water Regulations (NPDWRs) for radionuclides are the Safe Drinking Water Act Maximum Contaminant Levels (SDWA MCLs) (USEPA, 2000c and 2001) and are applicable to the contaminant boundary calculation. The NPDWRs constitute the regulatory standards that are considered to protect public health, specifically for the drinking water ingestion exposure pathway. The SDWA MCLs combine radionuclides into three categories: alpha emitters, beta/photon emitters, and uranium. The MCLs were established using the "critical organ" philosophy for radiation protection in which radionuclide accumulation is greatest for the exposure pathway. Different metrics were used to define each MCL category (Table 1). Current federal regulatory guidance (e.g., USDOE, 2011, and USEPA, 1999) focuses on the total radiation detriment for the whole body and the linear no-threshold, dose-risk relationship instead of relying on the "critical organ" philosophy. This means that under the modern concept of CED, the total radiation

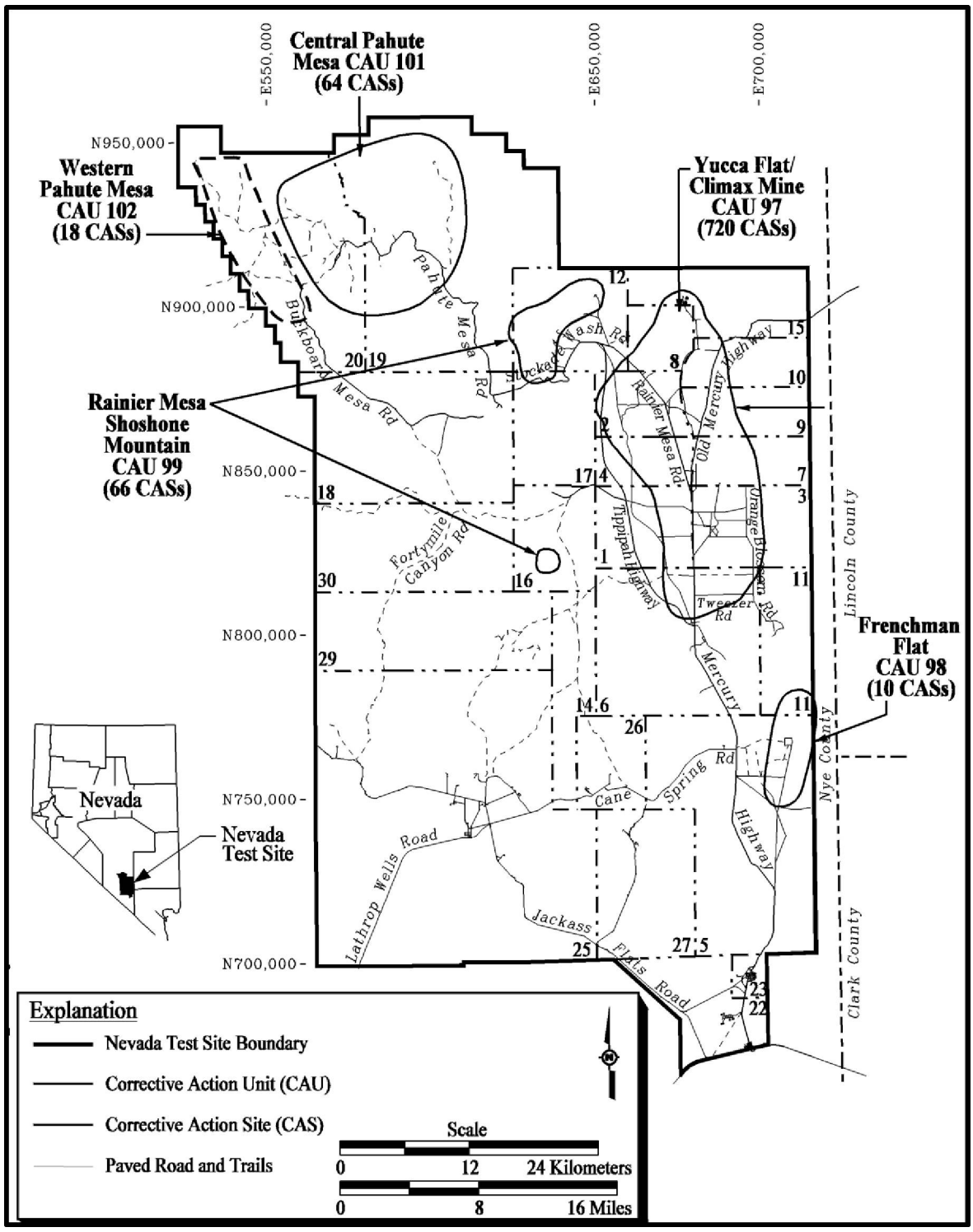


Figure 1. Nevada National Security Site (NNSS; formerly the Nevada Test Site) area map showing Underground Test Area (UGTA) Corrective Action Units (CAUs) and the individual nuclear-test cavities (the Corrective Action Sites [CASs]) at each CAU (from SNJV, 2005; Figure 1-1).

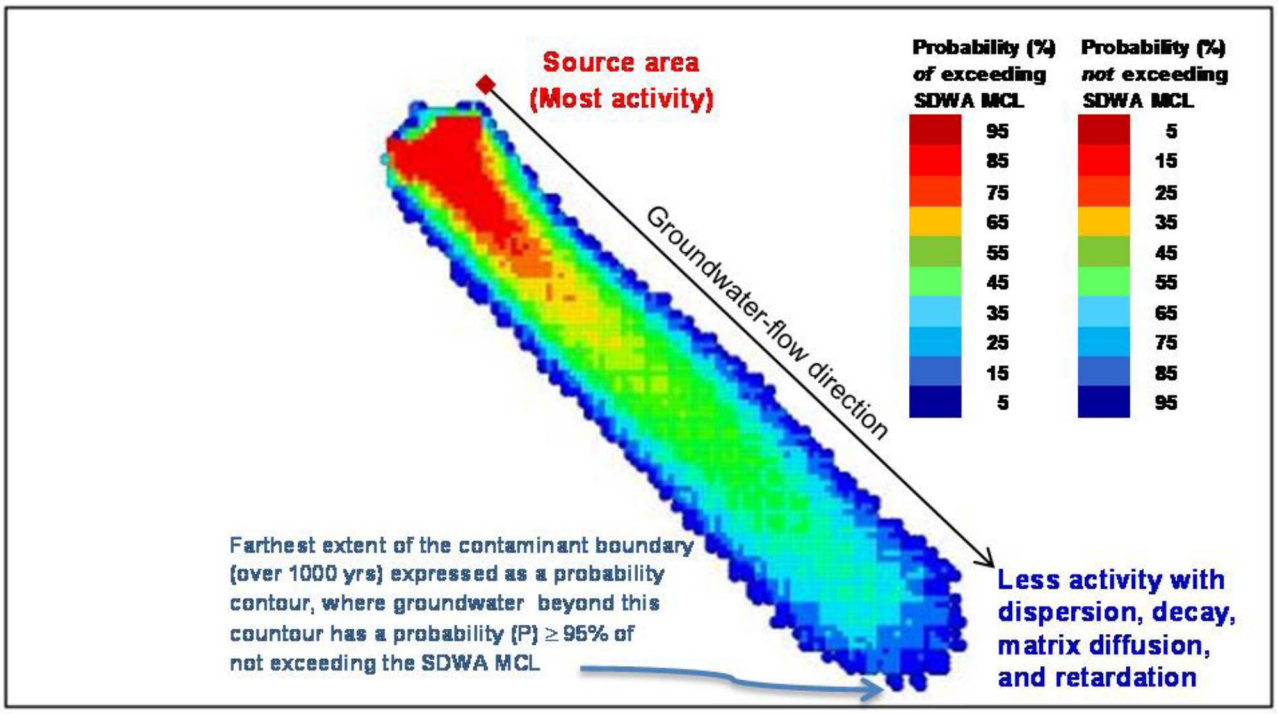


Figure 2. An idealized contaminant boundary (adapted from Figure 3-3 in FFACO, 1996; as amended in 2010) developed from computer simulations of the maximum extent of radionuclide transport. The red area indicates where the SDWA MCL will not be exceeded with a probability of at least 5 percent and the blue area indicates where the SDWA MCL will not be exceeded with a probability of at least 95 percent. The groundwater outside the contaminant boundary (the dark blue perimeter) has more than a 95 percent probability of not exceeding the SDWA MCL over 1,000 years.

detriment for the whole body is expressed as the sum of radiation detriments to individual organs based on their radiosensitivity. This is conceptually important for addressing activity concentrations when multiple co-occurring contaminants of concern (COCs) are present and collectively contribute to their respective SDWA MCLs. To ensure that the SDWA MCLs at a predicted contaminant boundary meet the modern metrics, the COCs contributing to the SDWA MCLs require evaluation for compliance with health-protective modern dose and risk limits both individually and collectively (Daniels and Tompson, 2003). Demonstrating conformity between SDWA MCLs and federal guidelines for annual CED and lifetime excess cancer risk will guarantee that the activity concentrations of the COCs at the contaminant boundary comply with the "health protection clause" language of the latest amendments to the SDWA (USEPA, 2000b; USEPA, 2000c).

The NNSS and the adjoining Nevada Test and Training Range (NTTR) are institutionally controlled federal lands (by the U.S. Department of Energy [USDOE] and the U.S. Department of Defense [USDoD], respectively) with limited public access. Therefore, potential public exposure to anthropogenic radionuclides migrating in the groundwater from the NNSS will only be of concern if a contaminant boundary extends to public or private lands beyond the confines of the NNSS and the NTTR. Should this occur, it will be important to know if the contaminant boundary containing COCs at the SDWA MCLs will also

Table 1. National Primary Drinking Water Regulations (NPDWRs) for radionuclides, which are the Safe Drinking Water Act Maximum Contaminant Levels (SDWA MCLs).[a]

Radionuclide regulatory category	Regulatory category maximum contaminant level (MCL)	
Beta/photon emitters	4	$mrem_{CRITORG}$/yr (*total annual dose limit)* based on dosimetric methodology cited by USEPA[b,c] and corresponding to either the activity concentration determined for an individual beta/photon-emitting radionuclide that is present or to the sum of the fractions of the activity concentration for each co-occurring, beta/photon-emitting radionuclide that is present so that the total annual dose limit is not exceeded
Gross alpha particle	15	pCi/L (*total activity concentration limit*) applicable to either an individual alpha-emitting radionuclide that is present[d] or to the sum of the fractions of the activity concentration for each co-occurring, alpha-particle-emitting radionuclide that is present so that the total activity concentration limit is not exceeded[d]
Uranium	30	µg/L (*mass concentration limit*) applicable to an individual uranium isotope that is present or to the sum of the fractions of the mass concentrations for each co-occurring uranium isotope that is present so that the total mass concentration limit is not exceeded[e]

[a] Described in USEPA (2000c) and summarized in USEPA (2001).

[b] The "critical organ" philosophy of radiation protection adopted in the 1960s still serves as the basis for the units of the SDWA MCL for beta/photon-emitting radionuclides. However, the health protection clause of the SDWA requires that activity concentrations corresponding to such metrics be evaluated in terms of modern science, which was done by USEPA in a series of publications (USEPA, 1991, and 2000a,b) and led to the most recent Final Rule for radionuclides (USEPA, 2000c) discussed in the text.

[c] The SDWA MCL activity concentrations for individual beta/photon-emitting radionuclides are assembled together in USEPA (2002) from Tables IV-2A and IV-2B appearing in USEPA (1976; Appendix IV).

[d] The SDWA MCL activity concentration for gross-alpha-emitting radionuclides limits the critical organ dose to bone (USEPA 1976; Appendix B).

[e] The SDWA MCL mass concentration limit for uranium is considered protective of kidney toxicity, as well as cancer for the general population, including children and the elderly (USEPA, 2000c).

conform with current USDOE (2011 and 2013) and USEPA (2000c) federal guidelines for the annual CED (100 $mrem_{CED}$), and lifetime excess cancer morbidity risk (a range, above background, from 1/10,000 [10^{-4}] to 1/1,000,000 [10^{-6}] or less individual cases of cancer per total exposed population).

The COCs evaluated for compliance with the SDWA MCLs are those most likely to migrate in groundwater away from the nuclear-test cavities. Identification of the COCs and their relative concentrations is based on studies performed as part of the UGTA Activity. The UGTA hydrologic flow and transport modeling has not yet fully evaluated contaminant transport in groundwater over the next 1,000 years for all of the CAUs across the NNSS. Therefore, it is not yet known whether a contaminant boundary may extend beyond federal properties to public or private lands over this time. This report hypothesizes that COCs migrate in groundwater beneath a local community downgradient from the NNSS and NTTR and occur at a contaminant boundary at activity concentrations equal to the applicable SDWA MCLs.

For this analysis, a hypothetical reasonably maximally exposed individual (RMEI) is considered to access water from the contaminant boundary. The RMEI is a conceptual reference person used to conservatively approximate human exposure to the COCs in groundwater at this boundary. Annual CED and lifetime excess cancer morbidity risk corresponding to such exposure is then computed for the RMEI and used to determine whether the activity concentrations for the COCs at the SDWA MCLs individually and collectively will comply with current federal regulatory thresholds for annual CED (USDOE, 2011 and 2013) and lifetime excess cancer morbidity risk (USEPA, 2000c). The method used for this evaluation is described for future application. In addition to the drinking water ingestion pathway inherent in the SDWA, the annual CED and lifetime excess cancer morbidity risk for the RMEI are also determined for alternative biosphere exposure scenarios. The agricultural and consumption characteristics of Amargosa Valley that were developed for the Yucca Mountain Project (SNL, 2007) are used to address these alternative exposure scenarios.

The assessment described above is conducted as follows:

1) **Identify the COCs.** The COCs are determined based on UGTA transport modeling for the Frenchman Flat CAU (NNES, 2010).

2) **Identify the general location of the RMEI.** The evaluation of groundwater flow directions beneath the NNSS is used to determine most likely locations of RMEIs on public or private lands down hydraulic gradient of the NNSS and NTTR.

3) **Estimate the activity/concentrations of the COCs at the SDWA MCL.** These COCs are assumed to be present at concentrations that together produce their SDWA MCL at the location of a hypothetical RMEI. Because the SDWA MCLs for radionuclides prescribe limits for combinations of radionuclides of a specific type, the relative activity concentrations of the categories of radionuclides must be estimated. Two suitable alternative combinations of COCs that cumulatively produce the SDWA MCL were determined using the atom inventory for underground tests at the NNSS compiled and decay corrected to 1992 (Bowen *et al.*, 2001), and the atom inventory that uses the activity concentrations measured in water obtained in 2009 from the ALMENDRO nuclear-test cavity on Central Pahute Mesa (Zavarin, 2012). In the absence of completed transport modeling results, these two inventories are used to derive atom-based, relative-abundance (mass-conservative) approximations of representative activity concentrations for co-occurring COCs at a contaminant boundary at the applicable SDWA MCLs (Table 1).

4) **Calculate the annual CED and the lifetime excess cancer morbidity risk for the RMEI from ingestion exposure to drinking water with COCs at the SDWA MCL.** Committed effective dose coefficients (i.e., CED/pCi) from the USDOE (2011) and lifetime excess cancer morbidity risk coefficients (Risk/pCi) from the United States Environmental Protection Agency (USEPA, 1999) are compiled to calculate both the annual CED and the lifetime excess cancer morbidity risk for a hypothetical RMEI who is assumed to be routinely ingesting groundwater containing concentrations of co-occurring COCs at the applicable SDWA MCLs (Appendix Table A-2).

5) **Calculate the annual CED and the lifetime excess cancer morbidity risk for the RMEI due to all reasonable biosphere exposure pathways in addition to drinking water ingestion.** Other exposure pathways include inadvertent soil ingestion, consumption of produce and animal products, inhalation of contaminated outdoor air, and inhalation of contaminated indoor air from using an evaporative cooler unit. The biosphere exposure model developed by Sandia National Laboratories (SNL, 2007) for Amargosa Valley residents as part of the Yucca Mountain Project is used to calculate the CED and risk for exposure to most of the COCs. The approaches of Baker *et al.* (1976) and Yu *et al.* (2001) are used to calculate exposure to ^{3}H through biosphere pathways. The exposure pathways and applicable dose and risk coefficients are described in Appendix B and its accompanying tables.

6) **Compare the CED and risk results to pertinent benchmarks.** Health-protective annual CED ($mrem_{CED}/yr$) and 70-year lifetime excess cancer morbidity (i.e., lethal and nonlethal) risk ($R/lifetime_{70yr}$) associated with USDOE Orders and USEPA regulatory language, respectively, are specified as comparisons for the values obtained in steps 4 and 5.

The method and findings of each of these steps is described in detail in the following sections.

CONTAMINANTS OF CONCERN (COCs)

The unclassified NNSS inventory of 43 longer-lived radionuclides (half-lives of 10 years or more) compiled by Bowen *et al.* (2001) for underground nuclear tests are considered for potential groundwater transport from the UGTA CAUs. Based on information in the externally peer-reviewed transport modeling documentation for the Frenchman Flat CAU (NNES, 2010), only five of these 43 radionuclides will have the greatest influence in defining the farthest extent of a modeled contaminant boundary (over the FFACO prescribed 1,000-year period of model performance). These five COCs are applied here to all of the CAUs because only the Frenchman Flat models are complete and approved. The COCs are all beta/photon-emitting radionuclides:

1) tritium (^{3}H; half-life = 12.32 years),
2) carbon-14 (^{14}C; half-life = 5,720 years),
3) chlorine-36 (^{36}Cl; half-life = 301,000 years),
4) technetium-99 (^{99}Tc; half-life = 213,000 years), and
5) iodine-129 (^{129}I; half-life = 15,700,000 years).

The introduction of the COCs into the geohydrologic media are described by Bowen *et al.* (2001). The presence of ^{3}H activity is a function of its use as a device component, fission processes, and neutron interactions with the geohydrologic characteristics of the detonation site. The ^{14}C and ^{36}Cl activities occur as a result of the neutron activation of device parts, external hardware, and surrounding geologic and hydrologic media. The ^{99}Tc and ^{129}I activities are present as fission products.

Following are the four principal reasons these beta/photon-emitting radionuclides will define the farthest extent of the contaminant boundary and are therefore the radionuclides that constitute the COCs for this analysis:

1) All five COCs are considered nonsorbing in the modeling calculations (NNES, 2010).
2) At Frenchman Flat, these radionuclides collectively constitute about 90 percent of the inventory in terms of activity (Bowen *et al.*, 2001) and they all are found primarily in cavity rubble and groundwater—in contrast to the relatively insoluble nuclear melt glass—which makes them immediately available for groundwater transport (NNES, 2010).
3) In terms of activity, the majority of the remaining approximately ten percent of the Frenchman Flat inventory are sorbing radionuclide species, and therefore are relatively immobile and not present at high enough activities to impact the location of a contaminant boundary (NNES, 2010).
4) Cavity melt glass contains between 95 and 100 percent of the actinide (e.g., U, Pu, and Am) and Eu isotopes, as well as significant amounts of all other radionuclides in the inventory described by Bowen *et al.* (2001), with the exception of ^{3}H, ^{14}C, ^{36}Cl, ^{99}Tc, and ^{129}I. The availability of these other radionuclides for transport depends on the rate of melt glass dissolution, which generally tends to be very slow (N-I, 2013; Rose *et al.*, 2011; and IAEA, 1998).

All five beta/photon-emitting COCs are considered to be co-occurring and transported in groundwater together. For groundwater at a contaminant boundary containing these five COCs to meet the SDWA MCL regulatory standard (Table 1), their activity concentrations should collectively produce an annual dose that is equal to 4 mrem to the critical organ (CRITORG). Tritium is by far the most abundant of the radionuclides generated by an underground nuclear test (Bowen *et al.*, 2001) and it is also the most mobile, replacing a hydrogen atom to become part of the water molecule itself. Tritium also decays relatively rapidly with a 12.32 year half-life, so as time progresses, its importance as a COC will diminish.

Derived activity concentrations for beta/photon-emitting radionuclides individually contributing to the SDWA MCL annual dose of 4 $mrem_{CRITORG}$ are tabulated in USEPA (1976 and 2002) and are presented in Table 2. The USEPA used risk coefficients (USEPA, 1999) based on modern dosimetry models to demonstrate that each activity concentration in Table 2 falls within the regulatory target range of 10^{-4} to 10^{-6} lifetime excess cancer morbidity (and mortality) risk (USEPA, 2000b,c).

Table 2. USEPA derived activity concentrations (pCi/L) for individual beta/photon emitters in drinking water, representing the five contaminants of concern (COCs).[a]

Beta/photon-emitting radionuclides representing contaminants of concern (COCs)	Activity concentration (pCi/L) equating to SDWA MCL (annual dose = 4 $mrem_{CRITORG}$/yr)
Tritium (^{3}H)	20,000
Carbon-14 (^{14}C)	2,000
Chlorine-36 (^{36}Cl)	700
Technetium-99 (^{99}Tc)	900
Iodine-129 (^{129}I)	1

[a] The data and methods used for deriving the activity concentrations equating to an annual dose of 4 $mrem_{CRITORG}$ appear in USEPA (1976; Appendix IV) and employ information from United States Bureau of Standards (USNBS) Handbook 69 (USNBS, 1963). These resulting activity concentrations are tabulated in both USEPA (1976) and USEPA (2002). Note: Using the cancer morbidity (and mortality) risk coefficients from Federal Guidance Report No. 13 (USEPA, 1999), which are based on modern dosimetry models that replace the critical organ philosophy, USEPA found that lifetime cancer risk(s) for each activity concentration falls mostly within the regulatory target range of 10^{-4} to 10^{-6}. Therefore, USEPA ratified them as protective of public health and retained the current SDWA MCL. This action was taken under the health protection clause of the 1996 Amendments to the Safe Drinking Water Act (SDWA), which requires USEPA to ensure that " … any revision to a drinking water regulation maintains or provides for greater protection of the health of persons" (USEPA, 2000c).

LOCATIONS FOR ASSESSMENT OF RMEI EXPOSURE

The NNSS lies within the Death Valley regional groundwater flow system (DVRFS), which encompasses approximately 100,000 km^2 (38,610 mi^2) in southwestern Nevada and southeastern California (Belcher and Sweetkind, 2010). As summarized by Faunt *et al.* (2010), most recharge to the DVRFS originates as precipitation at higher elevations in mountain ranges and in the northern portions of the region. The majority of natural discharge occurs in areas of wetlands, springs, and playas located at lower elevations in Death Valley, California, and Amargosa Valley and Sarcobatus Flat, Nevada. Because of this geographic configuration, groundwater flows in a generally southward direction, moving from recharge areas to discharge areas. Comprehensive regional hydrogeologic investigations (Winograd and Thordarson, 1975; Laczniak *et al.*, 1996; and Fenelon *et al.*, 2010), regional groundwater flow modeling (Belcher and Sweetkind, 2010), and ongoing investigations at individual UGTA CAUs suggest that groundwater flow systems within the NNSS are consistent with this regional flow pattern. These studies also indicate that groundwater flow from the underground test areas is generally south to southwestward with most discharge occurring in three areas: Oasis Valley (near the community of Beatty, Nevada), Ash Meadows (near the community of Amargosa Valley, Nevada), and

Death Valley, California (Figure 3). The discharge to Sarcobatus Flat, which is northwest of Oasis Valley near the community of Scotty's Junction, is thought to originate from flow paths west of and not on the NNSS.

Figure 3 shows that of the three discharge areas, the shortest path for groundwater to reach a discharge region is from the Central and Western Pahute Mesa underground test areas toward Oasis Valley to the west of the NNSS. The straight-line distance from the NNSS boundary on Western Pahute Mesa to public lands at the northeast end of Oasis Valley is approximately 26 km (16.2 mi). Groundwater at Pahute Mesa flows through fractured volcanic aquifers at rates estimated to be in the range of 2 to 60 meters per year (Wolfsberg *et al.*, 2002; Kwicklis *et al.*, 2005; and SNJV, 2009).

Ash Meadows is the closest discharge area for underground testing areas on the eastern side of the NNSS and it is approximately 42 km (26.1 mi) downgradient and to the southwest of Frenchman Flat (Figure 3). The rural community of Amargosa Valley is in the Ash Meadows area. The groundwater velocities in the eastern basins are much lower than those in the western basins due to lower hydraulic gradients and shallower aquifer systems that generally occur above thick sequences of low-permeability confining units overlying the regional groundwater flow paths. For example, mean groundwater velocities below Frenchman Flat are estimated to be less than 1.7 m/yr (SNJV, 2006; NNES, 2010), which is up to 35 times lower than the groundwater velocities estimated for the western side of the NNSS.

The regional model (Belcher and Sweetkind, 2010) indicates that groundwater pathways from Rainier Mesa, Yucca Flat, and Shoshone Mountain to public and private lands are longer than from the other CAUs and flow through low-permeability confining units that reduce groundwater velocity. In many cases, groundwater will flow through neighboring CAUs before exiting the NNSS. Therefore, the flow paths from these CAUs to the public and private lands surrounding the NNSS will have longer travel times. The groundwater-flow directions shown in Figure 3 strongly suggest that any contaminant boundary predicted using the fate and transport modeling currently underway is most likely to overlap public and private lands to the west and/or southwest of the NNSS and NTTR borders. This reasoning is reinforced by evaluating the distances to public and private lands from the testing areas on the NNSS and estimating the groundwater-flow velocities that move the COCs through the groundwater-flow systems beneath these testing areas. Communities with well-established populations lie to the west and/or southwest, so public and private lands in these directions are postulated as locations that might have access to groundwater within a contaminant boundary.

ESTIMATING RELATIVE COC CONTRIBUTIONS TO THE SDWA MCL

Representative activity concentrations for each co-occurring, beta/photon-emitting COC contributing to the SDWA MCL at the location of the RMEI are approximated using radionuclide atom inventory data. Atom fractions for ^{3}H, ^{14}C, ^{36}Cl, ^{99}Tc, and ^{129}I can be derived using the atom abundance for each one of these radionuclides documented individually in the Bowen *et al.* (2001) inventory and the sum of the atom abundance for all five of these individual beta/photon-emitting COC values compiled in this inventory.

The relative atom-abundance approach for deriving atom fractions is mass conservative. Therefore, the results are consistent with mass-transport modeling practice and the presence of long-lived radionuclides, such as ^{129}I (half-life of 15.7 million years), for which radioactive

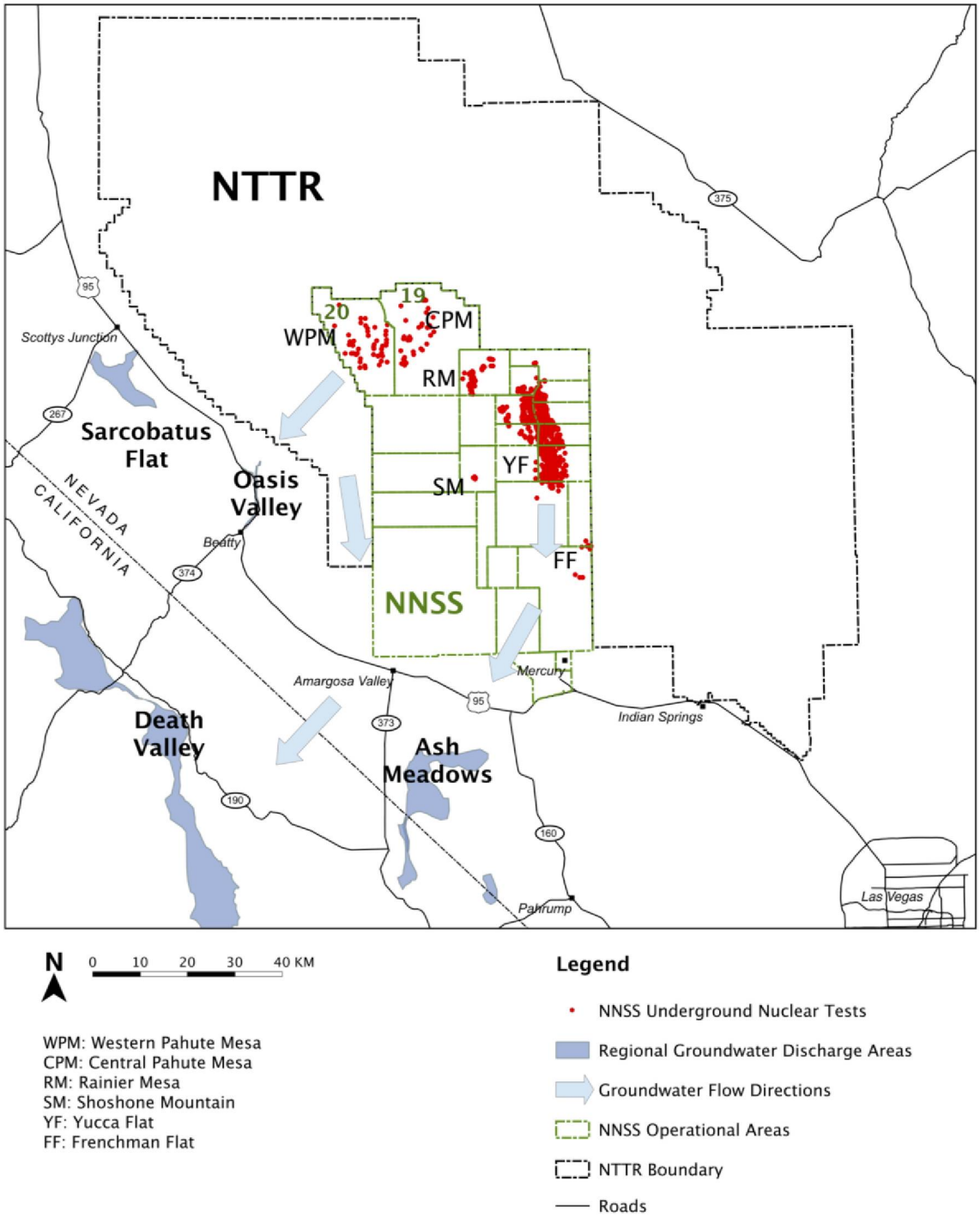


Figure 3. Map showing the general directions of regional groundwater flow from testing areas on the Nevada National Security Site (NNSS) based on comprehensive investigations of regional hydrogeology. Note: The population and commercial agriculture areas of Amargosa Valley are disperse and located south of U.S. Route 95 and north of the Nevada-California border.

decay is not relevant over the modeling duration of 1,000 years. Because the sum of the atom fractions for the co-occurring COCs is equal to one for the inventory (i.e., $\Sigma(A_i/A_T) = 1.0$), the sum of the products of each atom fraction and the annual dose limit at the SDWA MCL for the beta/photon-emitting COCs will total the target annual dose limit that is not to exceed 4 $mrem_{CRITORG}$ (i.e., $\Sigma[(A_i/A_T) \times 4.0] = 4.0$).

Similarly, for each co-occurring, beta/photon-emitting COC, the product of its atom fraction (A_i/A_T) and individual activity concentration (pCi/L) corresponding to the SDWA MCL dose limit (Table 2) will yield an adjusted activity concentration. These adjusted activity concentrations for all co-occurring, beta/photon-emitting COCs will be collectively dose limiting when they are all present at the adjusted levels in water that is consumed at the rate of 2 L/d. For example, daily ingestion exposure to 2 L of drinking water that contains the beta/photon-emitting COCs at their adjusted activity concentrations will produce an annual dose limit for the RMEI that does not exceed the SDWA MCL for beta/photon-emitting radionuclides of 4 $mrem_{CRITORG}$.

To ensure that the final results are representative, atom fractions for the co-occurring, beta/photon-emitting COCs are derived from two atom inventory sources for comparison. The first is the unclassified atom inventory of 43 long-lived radionuclides associated with all underground tests at the NNSS that was compiled by Bowen *et al.* (2001) and decay corrected to 1992, which is identified here as "NNSS 1992." The NNSS 1992 atom inventory for the five co-occurring, beta/photon-emitting COCs covers all geographic areas of the NNSS, and therefore all CAUs. Although there are subtle differences between the NNSS 1992 inventory and CAU-specific inventories, including the inventories applicable to Pahute Mesa, the differences are considered negligible for the purposes of this analysis and the NNSS 1992 inventory is considered representative. The second source of information is the activity concentrations measured by Zavarin (2012) in water collected in 2009 from the ALMENDRO nuclear-test cavity using a post-shot sampling well (U-19v-PS#1ds). These activity concentrations are equated to an atom inventory, which is identified here as "ALMENDRO 2009." The ALMENDRO 2009 atom inventory is the result of the ALMENDRO nuclear test conducted on Central Pahute Mesa in June 1973. This nuclear test created a cavity that has unique conditions, which is suggested by its persistent elevated temperature more than 30 years after detonation. This indicates these cavity fluids may be isolated from surrounding cooler groundwater, so fluids and radionuclides are likely being retained within the cavity (Kersting and Zavarin, 2011; Zavarin, 2012). Therefore, the samples collected within the ALMENDRO cavity have been relatively unaffected by transport or dilution processes attributable to groundwater flow or hydrodynamic dispersion. This suggests that the individual radionuclide activities measured could represent a real-world alternative to NNSS 1992 for determining the relative concentrations of the COCs.

Figure 4 and Table 3 (columns five and eight) contain the atom fractions in terms of derived relative atom abundance for each of the five COCs in both the NNSS 1992 atom inventory and the ALMENDRO 2009 atom inventory. The calculated relative atom abundance for each inventory is explained in the Table 3 footnotes. The mathematical formulas for converting between activity concentrations and atoms are also presented in the Table 3 footnotes, as well as in Appendix Equations A-1 and A-2. The atom fractions from the NNSS 1992 and ALMENDRO 2009 atom inventories are generally similar. For example, ^{3}H is overwhelmingly abundant and is the dominant atom fraction in both cases. However, it is

notable that the derived atom fraction for ^{3}H in the ALMENDRO 2009 atom inventory is approximately 17 percent greater than the derived atom fraction for ^{3}H in the NNSS 1992 atom inventory. This is also true for the corresponding activity concentrations estimated from these two atom fractions. The differences between the atom fractions for the COCs in the two inventories are helpful for bounding the estimated ^{3}H contribution.

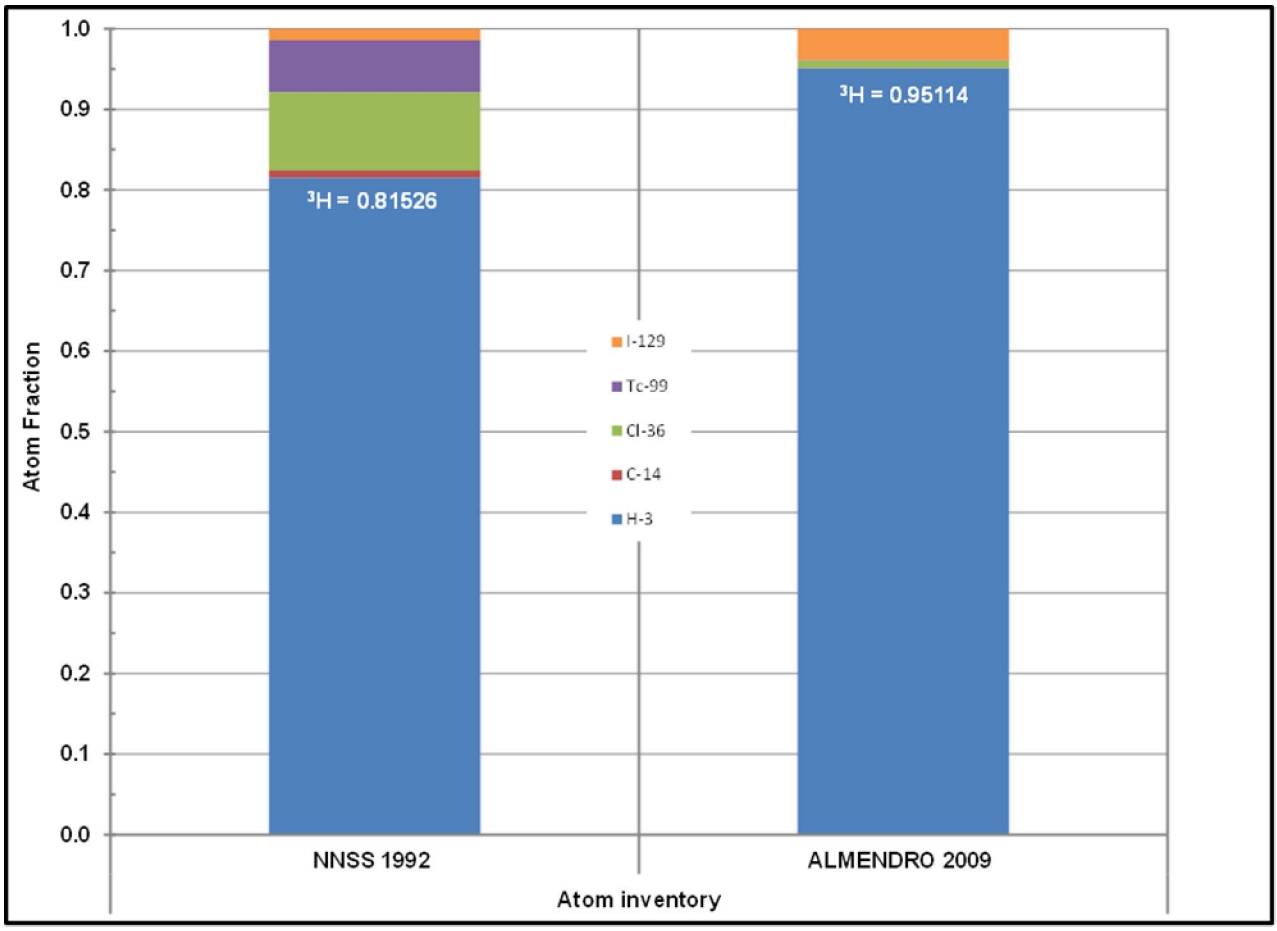


Figure 4. Relative atom abundance for each of the five co-occurring, beta/photon-emitting radionuclides that are the contaminants of concern (COCs) and collectively contribute to the SDWA MCL based on the NNSS 1992 (Bowen *et al.*, 2001) and ALMENDRO 2009 (Zavarin, 2012) atom inventories.

Table 3. Derived relative atom abundance for the five beta/photon-emitting radionuclides that are the contaminants of concern (COCs) based on the NNSS 1992[a] compiled atom inventory and the ALMENDRO 2009[b] atom inventory derived from measured activity concentrations.

			NNSS 1992[a]		ALMENDRO 2009[b]		
COC	**Half-life ($t_{1/2}$; yr)**	**Decay constant (λ; 1/s)[c]**	**Reported atom inventory [$N_{i(1992)}$]**	**Derived relative atom abundance [atom fraction; $p_{i(1992)}$][d]**	**Reported measured activity [pCi/L; $A_{i(2009)}$]**	**Derived atom inventory in one liter [$N_{i(2009)}$][e]**	**Derived relative atom abundance [atom fraction; $p_{i(2009)}$][d]**
^{3}H	1.23×10^{1}	1.78×10^{-09}	2.61×10^{27}	0.815	8.49×10^{7}	1.76×10^{15}	0.9511
^{14}C	5.72×10^{3}	3.85×10^{-12}	2.74×10^{25}	0.009	7.64×10^{1}	7.35×10^{11}	0.0004
^{36}Cl	3.01×10^{5}	7.30×10^{-14}	3.12×10^{26}	0.098	3.26×10^{1}	1.65×10^{13}	0.0089
^{99}Tc	2.13×10^{5}	1.03×10^{-13}	2.05×10^{26}	0.064	2.89×10^{0}	1.04×10^{12}	0.0006
^{129}I	1.57×10^{7}	1.40×10^{-15}	4.65×10^{25}	0.014	2.73×10^{0}	7.22×10^{13}	0.0390
Σ_i			3.20×10^{27}	1.000	8.49×10^{7}	1.85×10^{15}	1.0000

[a] Bowen *et al.* (2001; Errata Table VI).

[b] Zavarin (2012; Radiochemistry for September 2009 in Analytical Results, Table 1).

[c] λ (1/s) = [ln(2)]/[$t_{1/2}$ (yr) × 365 (d/yr) × 24 (h/d) × 60 (min/h) × 60 (sec/min)] = 2.198×10^{-8} (yr/s)/[$t_{1/2}$ (yr)].

[d] $p_{i(\mathrm{yr})} = N_{i(yr)}/\Sigma N_{i(yr)}$, where i is a specific COC in the applicable atom inventory (yr: 1992 for NNSS; and 2009 for ALMENDRO); p = atom fraction of COC; and N = atoms. Adjusted activity concentrations are the product of p_I and the corresponding COC activity concentration equating to 4 $\mathrm{mrem}_{\mathrm{CRITORG}}$/y from Table 2 (see Table 4).

[e] $N_{i(2009)}$ = [$A_{i(2009)}$ (pCi/L) × 0.037 (Bq/pCi)]/[λ (1/s)], where Bq = atoms transformed (disintegrations) per second; i is a specific COC in the ALMENDRO 2009 inventory; $N_{i(yr)}$ = atoms of COC i at yr; and $A_{i(yr)}$ = activity concentration of COC i at yr (pCi/L). Adjusted activity concentrations are the product of N_I and the corresponding COC activity concentration equating to 4 $\mathrm{mrem}_{\mathrm{CRITORG}}$/y from Table 2 (see Table 4).

POTENTIAL ANNUAL DOSE AND LIFETIME RISK FOR AN RMEI FROM DRINKING WATER

Table 4 contains the potential annual doses and lifetime excess cancer morbidity risk estimated for an RMEI. The RMEI is assumed to drink groundwater containing adjusted activity concentrations for the five co-occurring, beta/photon-emitting COCs that together equal the SDWA MCL. The adjusted activity concentrations for the COCs are derived using the relative atom abundance for each COC obtained from either the NNSS 1992 reported atom inventory or the atom inventory derived from the ALMENDRO 2009 cavity water measurements (Table 3, columns 5 and 8). Because the ALMENDRO 2009 measured activity concentrations are from groundwater directly in the nuclear-test cavity, it is not surprising that those concentrations exceed the SDWA MCL (see Table 3, column 6). The concentrations used here are adjusted to comply with the SDWA MCL, while retaining the original relative atom abundances.

Appendix Table A-1 contains the derived daily water intake (L/d) and derived annual water intake (L/yr) for a U.S. reference person based on the U.S. population and usage data recommended for computing the annual dose according to USDOE guidance (Technical Standard DOE-STD-1196-2011 [USDOE, 2011] and USDOE O458.1 [2013]). Appendix Table A-2 contains the CED coefficients ($mrem_{CED}$/pCi, in column 3) from USDOE (2011) and the lifetime excess cancer morbidity risk coefficients (R/pCi, in column 4) from USEPA (1999) for each of the COCs with respect to drinking water ingestion. The respective drinking water ingestion rates that are appropriate for computing either annual effective dose or lifetime excess cancer risk are both presented in Appendix Table A-3. These factors are incorporated into Appendix Equations A-3 and A-4 with the activity concentration (pCi/L) for each co-occurring COC contributing to the SDWA MCL (from Table 4) and they are used to compute either the total annual CED or the total lifetime excess cancer morbidity risk, respectively, for the RMEI.

Regardless of atom inventory, the atom-fraction-based activity concentrations for the five COCs yield a 4 $mrem_{CRITORG}$/yr target annual dose limit for the RMEI (Table 4, also see "Total(s)" for "atom inventory and critical organ dose" in Figure 5) because that was a constraint in the calculations. However, these atom-fraction-based activity concentrations will yield different annual effective doses for the RMEI depending on the atom inventory that is used. For example, the activity concentrations estimated from the NNSS 1992 and ALMENDRO 2009 atom inventories (Table 4) produced an annual effective dose for the RMEI of 1.24 and 1.04 $mrem_{CED}$/yr, respectively (Table 4, also see "Total(s)" for "atom inventory and committed effective dose" in Figure 5). Nevertheless, these annual effective doses remain well below the USDOE radiation protection annual dose limit of 100 $mrem_{CED}$/yr (USDOE, 2011 and 2013). Tritium is the overwhelmingly dominant contributor to annual dose from drinking water ingestion. Depending on the dosimetry (the previous CRITORG or modern CED) and inventory (NNSS 1992 or ALMENDRO 2009) used, it represents approximately 70 to 97 percent of the total annual dose.

Table 4. Potential annual doses and lifetime excess cancer morbidity risks for a reasonably maximally exposed individual (RMEI) ingesting drinking water containing the five co-occurring, beta/photon-emitting contaminants of concern (COCs) at activity concentrations collectively contributing to the SDWA MCL and derived from atom fractions in the NNSS 1992 (Bowen *et al.*, 2001) and the ALMENDRO 2009 (Zavarin, 2012) atom inventories.

	Inventory-specific relative atom abundance (atom fraction)[a]		**Adjusted activity concentration (pCi/L)[b]**		**SDWA MCL based critical organ annual dose ($mrem_{CRITORG}$/yr)[c]**		**USDOE (committed) effective annual dose ($mrem_{CED}$/yr)[d]**		**Lifetime excess cancer morbidity risk[e]**	
COC	**NNSS 1992**	**ALMENDRO 2009**	**NNSS 1992**	**ALMENDRO 2009**	**NNSS 1992**	**ALMENDRO 2009**	**NNSS 1992**	**ALMENDRO 2009**	**NNSS 1992**	**ALMENDRO 2009**
^{3}H	0.815	0.9511	16,305	19,023	3.261	3.8045	0.861	1.005	4.2×10^{-5}	4.9×10^{-5}
^{14}C	0.009	0.0004	17	0.79	0.034	0.0016	0.027	0.001	1.4×10^{-6}	6.3×10^{-8}
^{36}Cl	0.098	0.0089	68	6.24	0.390	0.0357	0.212	0.019	1.2×10^{-5}	1.0×10^{-6}
^{99}Tc	0.064	0.0006	58	0.50	0.256	0.0022	0.131	0.001	8.2×10^{-6}	7.0×10^{-8}
^{129}I	0.014	0.0390	0.01	0.04	0.058	0.1559	0.004	0.012	1.1×10^{-7}	3.0×10^{-7}
Σ	1.000	1.0000			4.000	4.000	1.236	1.038	6.3×10^{-5}	5.1×10^{-5}

[a] Presented in Table 3 and illustrated graphically in Figure 4.

[b] Product of the activity concentration (pCi/L) from Table 2 for an individual beta/photon-emitting contaminant of concern (COC) that is derived by USEPA to equate to an annual dose for that beta/photon-emitting radionuclide that is equal to the SDWA MCL annual dose limit of 4 $mrem_{CRITORG}$/yr and the corresponding inventory-specific atom fraction, which appears in this table and also in Table 3 and Figure 4.

[c] Product of the SDWA MCL for beta/photon-emitting radionuclides equal to an annual dose of 4 $mrem_{CRITORG}$/yr (USEPA, 2001) and the corresponding inventory-specific atom proportion that appears in this table. These tabulated results are illustrated in Figure 5.

[d] The USDOE dose ($mrem_{CED}$/yr) is the product of the COC activity concentration appearing in this table (pCi/L), the COC effective dose coefficient expressed as mrem committed effective dose ($mrem_{CED}$) per pCi for ingested water by a reference person (Table A-1 in DOE-STD-1196-2011; USDOE, 2011) and the drinking-water annual consumption rate for a reference person is derived from US population and usage data (see Table 3 in DOE-STD-1196-2011; USDOE, 2011) and equal to 679.8 L/y (also see Appendix). These tabulated results also are illustrated in Figure 5.

[e] The lifetime excess cancer morbidity risk corresponding to the SDWA MCL is calculated as the product of the COC activity concentration (pCi/L) appearing in this table, the COC lifetime cancer risk morbidity coefficient obtained from the USEPA (1999) and expressed as Risk/pCi, and the drinking water consumption rate equal to 2 L/d for 365 d/yr over a 70-year exposure duration (i.e., 51,100 L/lifetime; also see Appendix). These tabulated results are illustrated graphically in Figure 6.

The lifetime excess cancer morbidity risks for the RMEI corresponding to the five COCs at the farthest extent of the contaminant boundary are presented in the last two columns of Table 4 (columns 10 and 11) and are shown in Figure 6. Regardless of the inventory used, the total lifetime excess cancer morbidity risk for the RMEI at this location is compliant with the acceptable risk levels that were considered by the USEPA (2000c) when establishing the SDWA MCLs (i.e., ideally less than 1×10^{-6} to 1×10^{-4}). Tritium again dominates the COC contributions to total lifetime excess cancer morbidity risk from drinking water ingestion at 67 to 97 percent depending on the inventory used.

The contribution of ^{3}H to total lifetime excess cancer morbidity risk becomes even more evident as ^{3}H decays from the system. When ^{3}H completely decays, the level of total lifetime excess cancer morbidity risk at the farthest extent of the contaminant boundary will decrease by either a factor of approximately 3 (from approximately 6×10^{-5} to about 2×10^{-5} for NNSS 1992) or over 30 (from approximately 5×10^{-5} to about 1.5×10^{-6} for ALMENDRO 2009). Chlorine-36 will then become the relatively more dominant contributor to the lower total lifetime excess cancer risk (i.e., responsible for 57 to 67 percent of total risk for NNSS 1992 and ALMENDRO 2009, respectively).

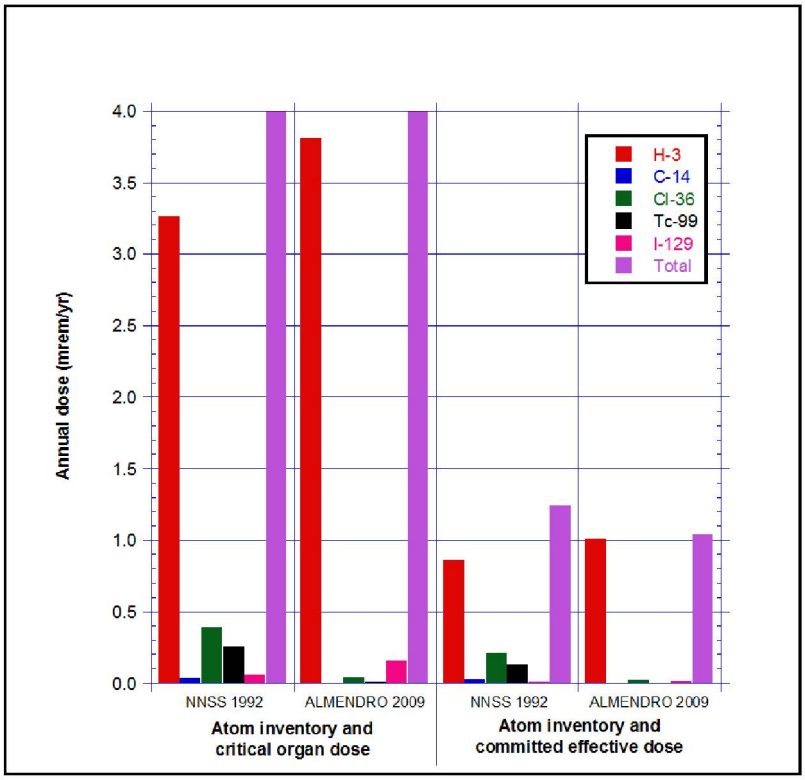


Figure 5. Atom-inventory proportioned annual critical organ dose (SDWA MCL) and activity concentration computed annual (committed) effective dose for the RMEI from ingestion exposure to drinking water containing the activity concentrations of the five co-occurring, beta/photon-emitting COCs collectively at the SDWA MCL. Activity concentrations are determined using atom fractions from the NNSS 1992 (Bowen *et al.*, 2001) and ALMENDRO 2009 (Zavarin, 2012) atom inventories (see Figure 4). For comparison, the SDWA MCL target annual dose limit is 4 $mrem_{CRITORG}$/yr and the USDOE target annual effective dose limit for the public is 100 $mrem_{CED}$/yr (USDOE, 2011 and 2013).

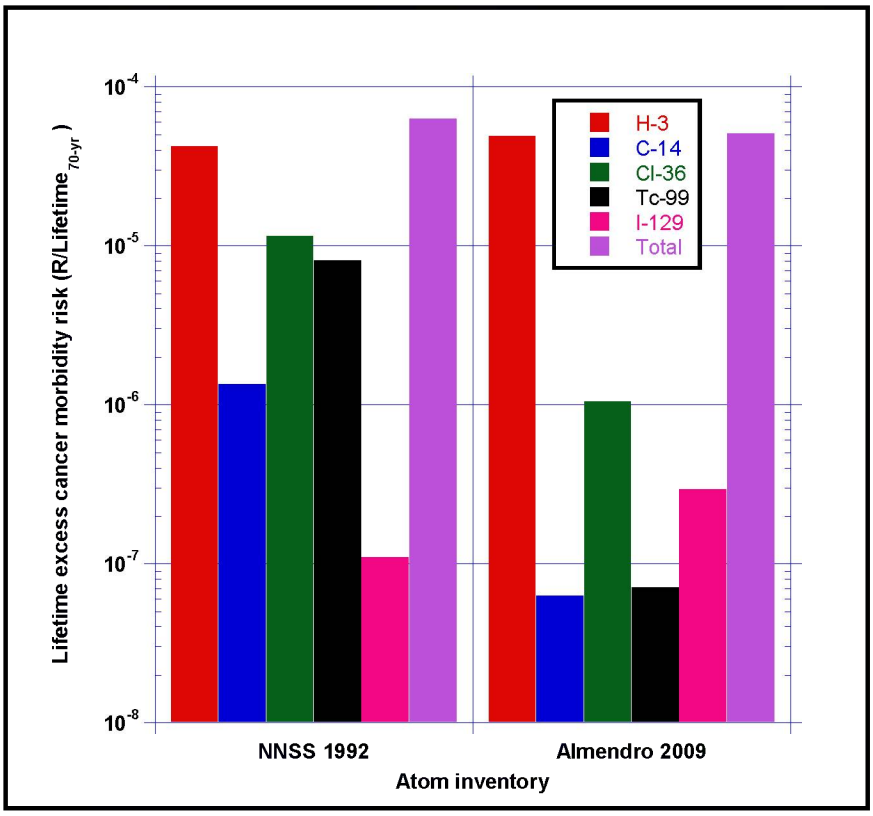


Figure 6. Atom-inventory proportioned lifetime excess cancer morbidity risk from the ingestion of drinking water containing the five co-occurring, beta/photon-emitting COCs contributing to the SDWA MCL. The activity concentrations are determined using atom fractions from the NNSS 1992 (Bowen *et al.*, 2001) and ALMENDRO 2009 (Zavarin, 2012) atom inventories (see Figures 4 and 5). For comparison, an acceptable level of lifetime excess cancer risk is considered to be ideally less than 1×10^{-4} to $\leq 1 \times 10^{-6}$ (USEPA, 2000c).

POTENTIAL ANNUAL DOSE AND LIFETIME RISK FROM ALL RELEVANT EXPOSURE PATHWAYS

Biosphere modeling allows the annual dose and lifetime excess cancer morbidity risk to be evaluated for a hypothetical RMEI for the other relevant COC exposure pathways in addition to drinking water. The model uses groundwater as the source medium of exposure and Oasis Valley, near Beatty, as the RMEI's location. The biosphere parameters for Oasis Valley are assumed to be similar to the Amargosa Valley parameters that were developed and approved for the Yucca Mountain Project (SNL, 2007). Although exposure pathways developed in the biosphere model for an RMEI will be stylized because the RMEI and the community are hypothetical, they will be based on the realistic parameters that characterize the residents of Amargosa Valley. Figure 7 depicts the general Amargosa Valley groundwater biosphere model.

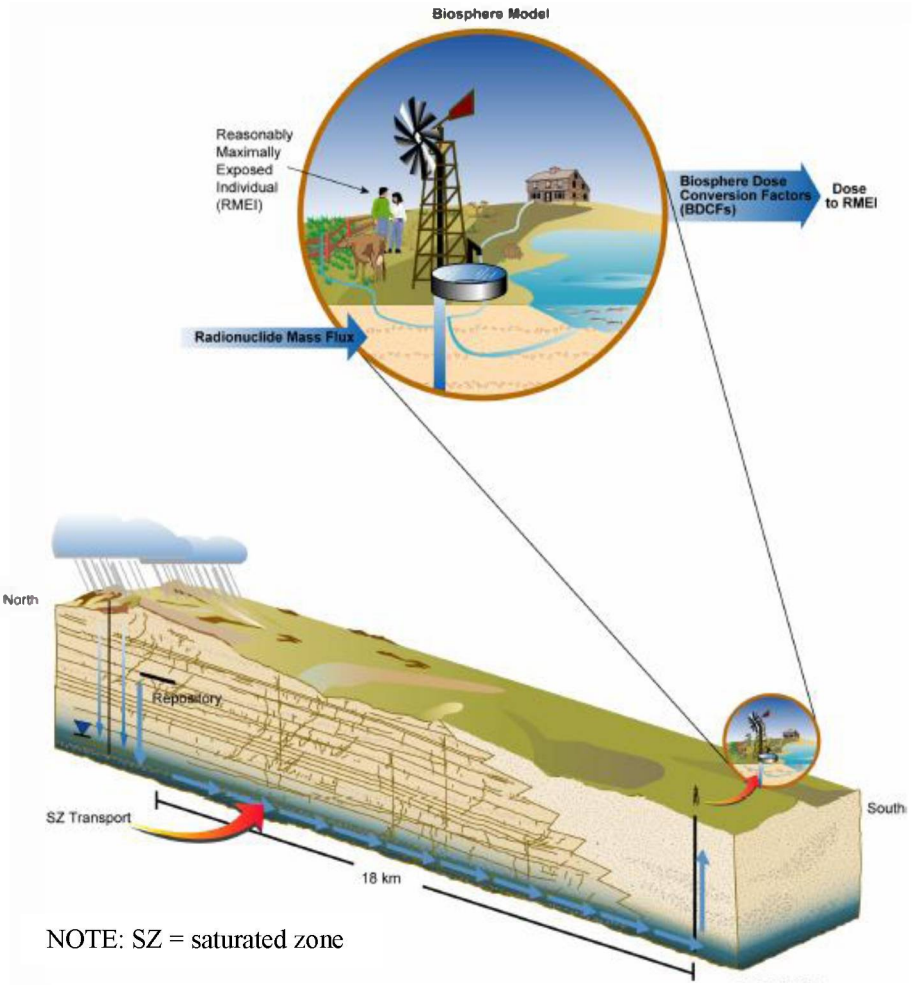


Figure 7. The general biosphere model developed by the Yucca Mountain Project for a resident of Amargosa Valley (the RMEI) exposed to radionuclides in groundwater (from SNL, 2007; §6). The model elements used for this analysis include groundwater pumped for domestic, agricultural, and livestock use. Biosphere dose conversion factors (BDCFs) are not specifically incorporated into the analytical process used for this study.

The biosphere components consist of the environmental source medium that contains the COCs (groundwater), the environmental media it contaminates (i.e., soil, air, plants, and animals), and the RMEI exposed to such media. The characteristics of the biosphere include the specific process parameters for transfer/uptake of the COCs from groundwater into the media and the RMEI's exposure rates to these media as a consequence of specific biosphere characteristics (e.g., tritium uptake into garden vegetables from irrigating with contaminated well water, the RMEI's rate of consuming those vegetables, and the RMEI's contaminant uptake through ingestion). For this exercise, all RMEI ingested crops and animal products are considered to be grown locally and irrigated or watered using groundwater with COCs at activity concentrations that equal the MCL.

The RMEI's exposure to the COCs assumed to be present in the groundwater occurs through the following activities:

1) Direct ingestion of contaminated groundwater that has an activity concentration (pCi/L) that remains constant for the entire period of exposure.
2) Inadvertent ingestion of soil from gardens irrigated with contaminated groundwater.
3) Ingestion of food crops from gardens irrigated with contaminated groundwater.
4) Ingestion of animal products from animals that directly consume contaminated groundwater as well as feed (forage and grains) and soil irrigated with contaminated groundwater.
5) Inhalation of indoor air containing aerosols produced by evaporative cooler units that operate using contaminated groundwater, which are typical of residential units in the biosphere.
6) Inhalation of outdoor air in which COCs have been released as gases from soil or resuspended in the air column on soil particles from gardens and fields irrigated with contaminated groundwater.

Tables 5 and 6 summarize the annual CED and lifetime excess cancer morbidity risk estimates for the RMEI from all relevant biosphere exposure pathways for both the NNSS 1992 and ALMENDRO 2009 derived concentrations of COCs (see also Table 4, columns 4 and 5). The biosphere exposure modeling for the COCs is obtained from Baker *et al.* (1976) and Yu *et al.* (2001) for ^{3}H and from Sandia National Laboratories (SNL, 2007; §6) for ^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I. Appendix B contains the data used with the models and the model results that are summarized in Tables 5 and 6. The biosphere exposure pathway data tabulated in the appendix constitute central (nominal or accepted) values that are recommended by regulatory guidance (e.g., the annual drinking water consumption and inhalation rate described in DOE-STD-1196-2011 [DOE, 2011] for computing the RMEI's annual CED or a lifetime drinking-water consumption rate for 70 years based on 2 L/d, which is consistent with USEPA guidance). The total annual CED for either set of COC activity concentrations is substantially below the standard of 100 $mrem_{CED}$/yr (DOE, 2011) and range from approximately 1 to 2 $mrem_{CED}$/yr (Table 5). The total dose is dominated by drinking water ingestion. The dietary dose from produce and animal products is approximately 55 percent of the annual dose from drinking water alone for the NNSS 1992 atom inventory and 10 percent of the annual dose from drinking water alone for the ALMENDRO 2009 atom inventory. For activity concentrations of COCs derived from both the NNSS 1992 and ALMENDRO 2009 atom inventories, tritium is the dominant COC, contributing 47 percent to the total annual CED for the NNSS 1992 atom inventory, and 92 percent to the total annual CED for the ALMENDRO 2009 atom inventory.

Table 5. Estimated committed effective annual dose (CED) from all relevant biosphere exposure pathways. Federal guidelines specify a health-protective annual dose limit to be 100 $mrem_{CED}$/yr (USDOE, 2011 and 2013).

NNSS 1992

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathways (annual committed effective dose; $mrem_{CED}$/yr)				Inhalation exposure pathways (annual committed effective dose; $mrem_{CED}$/yr)		TOTAL (annual committed effective dose; ($mrem_{CED}$/yr)
		Drinking water	Inadvertent soil	Local garden produce[a]	Local animal products	Indoor air	Outdoor air	
^{3}H	16,305	8.61×10^{-1}	6.17×10^{-6}	2.47×10^{-2}	1.58×10^{-2}	1.44×10^{-2}	5.35×10^{-3}	9.21×10^{-1}
^{14}C	17	2.70×10^{-2}	1.14×10^{-5}	7.56×10^{-4}	7.87×10^{-3}	2.32×10^{-5}	4.80×10^{-6}	3.57×10^{-2}
^{36}Cl	68	2.12×10^{-1}	3.14×10^{-6}	1.64×10^{-1}	4.23×10^{-1}	9.09×10^{-3}	6.04×10^{-7}	8.09×10^{-1}
^{99}Tc	58	1.31×10^{-1}	1.94×10^{-6}	2.03×10^{-2}	1.91×10^{-2}	4.26×10^{-3}	5.82×10^{-8}	1.75×10^{-1}
^{129}I	0.01	4.42×10^{-3}	8.63×10^{-6}	1.99×10^{-4}	6.10×10^{-4}	6.74×10^{-6}	1.56×10^{-9}	5.24×10^{-3}
	Σ	$1.24 \times 10^{+0}$	3.13×10^{-5}	2.10×10^{-1}	4.66×10^{-1}	2.78×10^{-2}	5.35×10^{-3}	$1.95 \times 10^{+0}$

ALMENDRO 2009

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathways (annual committed effective dose; $mrem_{CED}$/yr)				Inhalation exposure pathways (annual committed effective dose; $mrem_{CED}$/yr)		TOTAL (annual committed effective dose; ($mrem_{CED}$/yr)
		Drinking water	Inadvertent soil	Local garden produce[a]	Local animal products	Indoor air	Outdoor air	
^{3}H	19,023	$1.00 \times 10^{+0}$	7.19×10^{-6}	2.88×10^{-2}	1.84×10^{-2}	1.68×10^{-2}	6.24×10^{-3}	$1.08 \times 10^{+0}$
^{14}C	0.79	1.26×10^{-3}	5.29×10^{-7}	3.51×10^{-5}	3.66×10^{-4}	1.08×10^{-6}	2.23×10^{-7}	1.66×10^{-3}
^{36}Cl	6.24	1.95×10^{-2}	2.88×10^{-7}	1.51×10^{-2}	3.88×10^{-2}	8.34×10^{-4}	5.54×10^{-8}	7.42×10^{-2}
^{99}Tc	0.50	1.13×10^{-3}	1.67×10^{-8}	1.75×10^{-4}	1.65×10^{-4}	3.67×10^{-5}	5.02×10^{-10}	1.51×10^{-3}
^{129}I	0.04	1.22×10^{-2}	3.05×10^{-6}	7.96×10^{-4}	2.44×10^{-3}	2.70×10^{-5}	6.25×10^{-9}	1.54×10^{-2}
	Σ	$1.04 \times 10^{+0}$	1.11×10^{-5}	4.48×10^{-2}	6.02×10^{-2}	1.77×10^{-2}	6.24×10^{-3}	$1.17 \times 10^{+0}$

[a] Includes small amount of grain (i.e., considered a field crop based on biosphere characteristics), see Appendix Table B-21.

Table 6. Estimated lifetime excess cancer morbidity risk from all relevant biosphere exposure pathways. Federal guidelines specify the health-protective range for lifetime cancer risk to be from 1×10^{-4} to $\leq 1 \times 10^{-6}$ per lifetime (USEPA, 2000c).

NNSS 1992

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathways (Risk/Lifetime$_{70\ yr}$)				Inhalation exposure pathways (Risk/Lifetime$_{70\ yr}$)		TOTAL (Risk/Lifetime$_{70\ yr}$)
		Drinking water	Inadvertent soil	Local garden produce[a]	Local animal products	Indoor air	Outdoor air	
^{3}H	16,305	4.2×10^{-5}	8.0×10^{-10}	3.2×10^{-6}	2.0×10^{-6}	2.7×10^{-8}	7.1×10^{-9}	4.7×10^{-5}
^{14}C	17	1.4×10^{-6}	6.8×10^{-10}	4.5×10^{-8}	4.7×10^{-7}	3.7×10^{-11}	6.6×10^{-12}	1.9×10^{-6}
^{36}Cl	68	1.2×10^{-5}	2.1×10^{-10}	1.1×10^{-5}	2.9×10^{-5}	1.4×10^{-8}	8.6×10^{-13}	5.1×10^{-5}
^{99}Tc	58	8.2×10^{-6}	1.6×10^{-10}	1.7×10^{-6}	1.6×10^{-6}	6.7×10^{-9}	4.1×10^{-13}	1.2×10^{-5}
^{129}I	0.01	1.1×10^{-7}	2.3×10^{-11}	6.0×10^{-9}	1.8×10^{-8}	5.0×10^{-12}	5.2×10^{-15}	1.3×10^{-7}
	Σ	6.3×10^{-5}	1.9×10^{-9}	1.6×10^{-5}	3.3×10^{-5}	4.8×10^{-8}	7.1×10^{-9}	1.1×10^{-4}

ALMENDRO 2009

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathways (Risk/Lifetime$_{70\ yr}$)				Inhalation exposure pathways (Risk/Lifetime$_{70\ yr}$)		TOTAL (Risk/Lifetime$_{70\ yr}$)
		Drinking water	Inadvertent soil	Local garden produce[a]	Local animal products	Indoor air	Outdoor air	
^{3}H	19,023	4.9×10^{-5}	9.3×10^{-10}	3.7×10^{-6}	2.4×10^{-6}	3.1×10^{-8}	8.3×10^{-9}	5.5×10^{-5}
^{14}C	0.79	6.3×10^{-8}	3.2×10^{-11}	2.1×10^{-9}	2.2×10^{-8}	1.7×10^{-12}	3.1×10^{-13}	8.7×10^{-8}
^{36}Cl	6.24	1.0×10^{-6}	2.0×10^{-11}	1.0×10^{-6}	2.6×10^{-6}	1.3×10^{-9}	7.9×10^{-14}	4.7×10^{-6}
^{99}Tc	0.50	7.0×10^{-8}	1.4×10^{-12}	1.5×10^{-8}	1.4×10^{-8}	5.8×10^{-11}	3.5×10^{-15}	9.9×10^{-8}
^{129}I	0.04	3.0×10^{-7}	9.2×10^{-11}	2.4×10^{-8}	7.4×10^{-8}	2.0×10^{-11}	2.1×10^{-14}	4.0×10^{-7}
	Σ	5.1×10^{-5}	1.1×10^{-9}	4.8×10^{-6}	5.1×10^{-6}	3.3×10^{-8}	8.3×10^{-9}	6.1×10^{-5}

[a] Includes small amount of grain (i.e., considered a field crop based on biosphere characteristics), see Appendix Table B-23.

When tritium disappears from the biosphere due to radioactive decay, the total annual committed effective dose significantly decreases. In the absence of ^{3}H, this total dose from all other COCs becomes 1.03 $mrem_{CED}$/yr for the NNSS 1992 atom inventory and 0.09 $mrem_{CED}$/yr for the ALMENDRO 2009 atom inventory, respectively (see Table 5, last column). Both atom inventories are then expected to be dominated by the total dose from ^{36}Cl, particularly from ingesting local produce and animal products. However, in both cases the annual CED is well below the standard of 100 $mrem_{CED}$/yr (USDOE, 2011). In both cases, the ^{36}Cl contribution to total dose is greater from eating local produce and animal products than from any of the other pathways, including drinking water ingestion, because the modeled uptake of ^{36}Cl activity is highest from this pathway and the effective dose coefficient is larger than for any other COC.

Both the NNSS 1992 and the ALMENDRO 2009 atom-inventory ratios of COCs lead to respective MCL activity concentrations that produce total lifetime excess cancer risk values (expressed as additional individuals with cancer per population of exposed individuals) from all exposure pathways that are also within the acceptable range of 1×10^{-4} to $\leq 1 \times 10^{-6}$. However, the NNSS 1992 total risk from all exposure pathways (Table 6) is at the upper end of the acceptable range (i.e., 1×10^{-4}), whereas the ALMENDRO 2009 total risk from all exposure pathways (Table 6) is a lower value (i.e., 6×10^{-5}). Although both inventories are considered reasonable, the ALMENDRO 2009 inventory may be more realistic because it is based on recent measurements of COC activity concentrations in groundwater that has been isolated in a cavity since detonation on Pahute Mesa in 1973. The NNSS 1992 inventory was determined using source-physics calculations.

As in the case of total annual dose (Table 5), drinking water ingestion dominates the total lifetime risk (Table 6). Also, for activity concentrations of COCs derived from both the NNSS 1992 and ALMENDRO 2009 atom inventories, ^{3}H is the overwhelmingly dominant COC contributing to the drinking water ingestion risk (Table 6, column 3). However, for the NNSS 1992 atom inventory, the ^{36}Cl contribution to total risk is more than that from ^{3}H (Table 6) because:

1) The ^{36}Cl activity concentration estimated at the SDWA MCL in groundwater water from this atom inventory is a factor of 10 greater than from the ALMENDRO 2009 atom inventory (Table 6, column 2).
2) The ^{3}H activity concentration for this atom inventory is also approximately 20 percent lower than for the ALMENDRO 2009 atom inventory (Table 6, column 2).
3) This atom inventory yields an uptake of ^{36}Cl activity from eating local produce and animal products by a factor of 10 over the ALMENDRO 2009 atom inventory (see Appendix B, Tables B-20 and B-21, the rows containing ^{36}Cl annual consumption for NNSS 1992 and ALMENDRO 2009).
4) The ^{36}Cl risk coefficient is greater than that for ^{3}H for both drinking water and dietary ingestion (see the last columns of Table A-2 for drinking water ingestion in Appendix A and Table B-5 for dietary ingestion in Appendix B).

When tritium completely decays, the total lifetime risk is reduced and will be nearly a factor of 2 lower for the NNSS 1992 inventory and about a factor of 10 lower for the ALMENDRO 2009 inventory (as computed from data in the last column of Table 6). This means that for the NNSS 1992 inventory, when ^{3}H disappears the total lifetime excess cancer risk will be lowered from the peak of the acceptable range for risk of 1×10^{-4} to a more compliant level of risk equal to 6×10^{-5}. For the ALMENDRO 2009 inventory, when ^{3}H disappears the total lifetime excess cancer risk will go from 6×10^{-5} to 6×10^{-6}, which is closer to the lower end of the acceptable range for risk ($\leq 1 \times 10^{-6}$). The dominant COC contributing to risk for both inventories will then be ^{36}Cl due to local produce and animal product ingestion (Table 6). This is because both the ^{36}Cl ingested activity and risk coefficient for the RMEI associated with this dietary pathway are greater than the ingested activity and risk coefficient for drinking water ingestion.

The different timescales of exposure (annual versus 70-year lifetime) result in different model outcomes for yielding an acceptable annual dose level and a level of lifetime risk that approaches or is just at the upper bound of acceptability. The CED is a recommended dose limit for exposure during one year. The risk calculation assumes a 70-year lifetime of exposure. However, once COCs are recognized in publically accessible groundwater, efforts to minimize exposure over longer time periods will effectively reduce risk. For example, the calculations suggest that switching to local sources of groundwater that have not yet reached SDWA MCLs or reducing the consumption of locally grown produce and animal products can be an important risk-reduction action. The latter strategy is particularly effective for scenarios in which the committed effective annual dose due to ^{36}Cl approaches that of ^{3}H.

ASSESSMENT OF UNCERTAINTY

The values of each parameter in each biosphere modeling equation are central (nominal, accepted, or expected) values. However, there is some degree of uncertainty in each of the parameters that are used because there is natural variability and/or a lack of complete knowledge. One way to evaluate this uncertainty when calculating the annual dose and lifetime risk is to use a range for each parameter and perform the calculation hundreds or thousands of times. In such procedures, values from all of the parameter ranges are randomly selected, which generates a new statistical distribution of the possible results. This was done in preliminary risk assessments for the ingestion pathway alone and multiple radionuclides (Daniels *et al.*, 1993), as well as for multiple exposure pathways and ^{3}H alone (USDOE/NVO, 1997). Such a numerical analysis was not used for this study because the multiple biosphere exposure pathways examined here are applied to a hypothetical RMEI under assumed conditions that collectively produce a compounded conservatism. For example, it would be extraordinary to observe a 2 L/d consumption rate for a 365-day duration over a 70-year lifetime for the drinking water pathway alone. Applying such conservatism means that annual dose and lifetime risk may actually be lower for a real individual exposed to the estimated activity concentrations. Therefore, uncertainty in the computed annual dose and lifetime risk is examined by identifying the exposure pathways and COCs that are making the greatest contribution. This information will help effectively focus future resources to reduce uncertainty in the parameters that are important for assessing exposure, annual dose, and lifetime risk.

The data in Tables 7 and 8 show the fractional contributions to total annual CED and total 70-year lifetime excess cancer morbidity risk, respectively, for the RMEI from COC activity concentrations derived from either the NNSS 1992 or ALMENDRO 2009 atom inventory and biosphere exposure pathways. The table rows contain each COC activity concentration with respect to every biosphere exposure pathway both individually and collectively. The table columns contain each biosphere exposure pathway with respect to every COC both individually and collectively. The footnotes at the bottom of Tables 7 and 8 explain how the proportions presented in the body of these tables are derived from the tabulated data in Tables 5 and 6.

For this analysis, the consumption rates for drinking water are meaningfully representative for assessing compliance with the regulatory annual CED (i.e., 1.862 L/d) and lifetime cancer risk (i.e., 2 L/d). Although the RMEI's exposure durations are quite different for these two consumption rates (365 d/y for the former and 70 years for the latter), the consumption rates themselves are approximately the same. However, the dietary ingestion rates used are from the diet survey underlying the biosphere exposure model for the Yucca Mountain Nevada Project, which found that a significant portion of the Amargosa population actually did not consume locally produced vegetables (Figure 8). Therefore, although these dietary ingestion rates are representative of and applicable to an RMEI in the community of interest, the values used are interpreted as being conservative based on the information conveyed by Figure 8.

The greater contributors to uncertainty in the calculations of annual dose and lifetime risk are the approximated activity concentrations for the COCs. The relative COC activity concentrations derived from ALMENDRO 2009 are arguably more realistic than those of NNSS 1992, because they are based on measurements rather than source-physics calculations.

The parameters supporting the inadvertent soil ingestion and inhalation exposure calculations yield contributions from these pathways to overall annual dose and lifetime risk that are not very significant (see Tables 5 through 8). Therefore, the contributions of these parameter values to uncertainty are deemed not very important.

For both the NNSS 1992-based and ALMENDRO 2009-based activity concentrations in groundwater, ^{3}H is the greatest contributor to the total annual CED and it is overwhelmingly so for the ALMENDRO 2009-based activity concentrations (see last column in Table 7). Drinking water ingestion is also the dominant exposure pathway for the total annual dose from all COCs for both the NNSS 1992-based and ALMENDRO 2009-based activity concentrations. The fractional contributions corresponding to 64 percent and 89 percent, respectively, are shown in Table 7 under the drinking water column in the "Exposure pathway" row. After ^{3}H disappears from radioactive decay, ^{36}Cl is the most significant COC contributor to the total annual CED, but in the case of ^{36}Cl, dietary ingestion (local produce and animal products) is the dominant exposure pathway because both the activity ingested through diet and the size of the water/dietary ingestion dose conversion factor are high. For example, the ^{36}Cl dose coefficient for water and dietary ingestion is about 60 times greater than that for ^{3}H, which has the lowest value for water and dietary ingestion (see Appendix A, Table A-2, column 3; and Appendix B; Table B-5, column 3).

Table 7. Contribution to committed effective annual dose by contaminant of concern (COC) and exposure pathway.[a,b]

NNSS 1992

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathway				Inhalation exposure pathways		TOTAL
		Drinking water	Inadvertent soil	Garden produce	Animal products	Indoor air	Outdoor air	
^{3}H	16,305	0.70	0.20	0.12	0.03	0.52	0.999	0.47
^{14}C	17	0.02	0.36	0.004	0.02	0.0008	0.0009	0.02
^{36}Cl	68	0.17	0.10	0.78	0.91	0.33	0.0001	0.42
^{99}Tc	58	0.11	0.06	0.097	0.041	0.15	0.00001	0.09
^{129}I	0.01	0.004	0.28	0.001	0.0013	0.0002	0.0000003	0.003
	Σ	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Exposure pathway	0.64	0.00002	0.11	0.24	0.014	0.003	

ALMENDRO 2009

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathway				Inhalation exposure pathways		TOTAL
		Drinking water	Inadvertent soil	Garden produce	Animal products	Indoor air	Outdoor air	
^{3}H	19,023	0.97	0.65	0.64	0.31	0.95	0.999	0.920
^{14}C	0.79	0.001	0.05	0.0008	0.01	0.00006	0.00004	0.001
^{36}Cl	6.24	0.02	0.03	0.336	0.64	0.05	0.000009	0.064
^{99}Tc	0.50	0.001	0.002	0.004	0.0027	0.002	0.00000008	0.0013
^{129}I	0.04	0.01	0.28	0.018	0.0405	0.002	0.000001	0.0132
	Σ	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Exposure pathway	0.89	0.00001	0.038	0.052	0.015	0.0053	

[a] The values appearing in each of the seven exposure pathway *columns* above the summation (Σ) row correspond to the quotient of the $[(mrem_{CED}/yr)_{COC}/\Sigma(mrem_{CED}/yr)_{COC}]_{EXPOSURE\ PATHWAY}$ from Table 5.

[b] The values appearing in the Exposure pathway *row* are equal to the quotient of $[\Sigma(mrem_{CED}/yr)_{COC}]_{EXPOSURE\ PATHWAY}/[\Sigma(mrem_{CED}/yr)_{EXPOSURE\ PATHWAYS}]_{TOTAL}$ from Table 5.

Table 8. Contribution to lifetime excess cancer morbidity risk by contaminant of concern (COC) and exposure pathway.[a,b]

NNSS 1992

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathway				Inhalation exposure pathways		TOTAL
		Drinking water	Inadvertent soil	Garden produce	Animal products	Indoor air	Outdoor air	
^{3}H	16,305	0.67	0.43	0.199	0.06	0.56	0.999	0.423
^{14}C	17	0.02	0.36	0.003	0.01	0.001	0.0009	0.017
^{36}Cl	68	0.18	0.11	0.692	0.87	0.29	0.0001	0.457
^{99}Tc	58	0.13	0.09	0.106	0.05	0.14	0.00006	0.102
^{129}I	0.01	0.002	0.012	0.0004	0.0006	0.0001	0.0000007	0.001
	Σ	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Exposure pathway		0.56	0.00002	0.14	0.29	0.0004	0.00006	

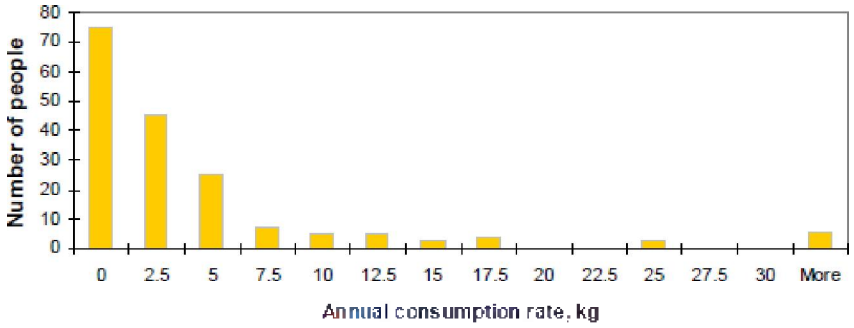
ALMENDRO 2009

COC	Activity concentration in water (pCi/L)	Ingestion exposure pathways				Inhalation exposure pathways		TOTAL
		Drinking water	Inadvertent soil	Garden produce	Animal products	Indoor air	Outdoor air	
^{3}H	19,023	0.97	0.87	0.778	0.466	0.96	0.999	0.913
^{14}C	0.79	0.001	0.03	0.0004	0.004	0.0001	0.00005	0.001
^{36}Cl	6.24	0.02	0.02	0.213	0.512	0.04	0.000009	0.077
^{99}Tc	0.50	0.001	0.0013	0.003	0.003	0.002	0.0000004	0.002
^{129}I	0.04	0.006	0.08	0.005	0.014	0.0006	0.000002	0.007
	Σ	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Exposure pathway		0.84	0.00002	0.08	0.08	0.0005	0.0001	

[a] The values appearing in each of the seven exposure pathway *columns* above the summation (Σ) row correspond to the quotient of the $[(\text{Risk/lifetime})_{COC}/\Sigma(\text{Risk/lifetime})_{COC}]_{EXPOSURE\ PATHWAY}$ from Table 6.

[b] The values appearing in the Exposure pathway *row* are equal to the quotient of $[\Sigma(\text{Risk/lifetime})_{COC}]_{EXPOSURE\ PATHWAY}/[\Sigma(\text{Risk/lifetime})_{EXPOSURE\ PATHWAYS}]_{TOTAL}$ from Table 6.

a) Leafy vegetables



b) Other vegetables

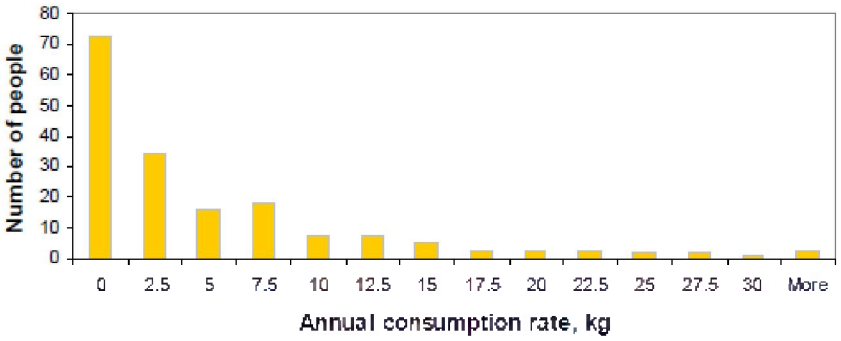


Figure 8. Amargosa survey results for consumption of locally produced a) leafy vegetables and b) other vegetables (from Bechtel SAIC, 2005).

However, for the ALMENDRO 2009-based activity concentrations of COCs in groundwater, ^{3}H is overwhelmingly the greatest contributor to the total lifetime risk at 91 percent and the drinking water ingestion pathway is the dominant contributor to total risk at 84 percent (Table 8). In this case, the ^{3}H activity concentration (i.e., above 19,000 pCi/L) and the ^{36}Cl activity concentration (6.24 pCi/L) are greater by 20 percent and lower by over a factor of 10, respectively, than in the NNSS 1992-based case. These differences are so significant that the differences in magnitude between risk coefficients for ^{36}Cl and ^{3}H (see Tables A-2 and B-5, last columns) are insufficient to make ^{36}Cl the more significant contributor to lifetime risk. After ^{3}H disappears from radioactive decay, ^{36}Cl becomes the greatest contributor to lifetime risk and ingestion of local produce and animal products becomes the dominant exposure pathway.

Two additional points are worth mentioning concerning the calculations of annual dose and lifetime risk and uncertainty. Ciffroy *et al.* (2006) observed that when ^{3}H was modeled to be the most significant contributor to total dose from contaminated drinking water, the ingestion of contaminated produce and animal products that had been irrigated and watered with ^{3}H contaminated water could account for as much as one-third of the total ^{3}H dose. Although the drinking water exposure pathway for the ^{3}H activity concentrations derived from the NNSS 1992 and ALMENDRO 2009 atom inventories was shown to be the most important contributor to total ^{3}H dose (Table 7, last column), the ingestion of produce and animal products irrigated and watered with contaminated groundwater contributed only

four percent to the total annual ^{3}H dose. These results were derived by inserting the appropriate data (shown in the ^{3}H rows of Table 5 for NNSS 1992 and ALMENDRO 2009) into the quotient equal to $[(\Sigma mrem_{CED}/yr)_{\text{"FOODS"}}/(\Sigma mrem_{CED}/yr)_{\text{"TOTAL"}}]_{TRITIUM}$.

The factors influencing the ^{3}H results and the results for the other COCs are the RMEI's consumption rate of the produce and animal products, the variability in the uptake of COCs into the irrigated plants and watered animals, and the distribution of the COCs into the RMEI after consumption. Note that an individual would not be subject to the exposures calculated here if he or she consumed bottled water or obtained water for drinking and irrigation from the Beatty municipal supply, which is currently available at wells such as well W07 that is south of the town in the northern Amargosa Desert. These sources are far more likely to contain background level activity concentrations of COCs that are below SDWA MCLs and are therefore in regulatory compliance for use as drinking water.

The hypothetical nature of the activity concentrations used in these calculations means that the greater uncertainty related to the calculation of annual dose and lifetime risk remains the activity concentrations of the COCs at the MCL. Therefore, current efforts devoted to defining these activity concentrations and their precise locations in time and space in relation to the communities in the direction of groundwater flow are an appropriate focus of attention and resources before other less-important contributors to uncertainty are investigated, such as the parameters related to the ingestion of local produce and animal products.

CONCLUSIONS

Groundwater flow and contaminant transport modeling for the Frenchman Flat CAU (NNES, 2010) determined that of the 43 radionuclides in the NNSS inventory (Bowen *et al.*, 2001), the beta/photon-emitting radionuclides ^{3}H, ^{14}C, ^{36}Cl, ^{99}Tc, and ^{129}I are the most likely to influence the farthest extent of the contaminant boundary calculated for that CAU. For this assessment, the COCs considered for human exposure to groundwater contaminated by NNSS nuclear testing are those identified from the Frenchman Flat CAU modeling results. These five nonsorbing, isotopes collectively constitute 92 percent of the inventory at Frenchman Flat and are found mostly in cavity rubble, which makes them more readily available for groundwater transport (NNES, 2010). With groundwater models currently in process for the other CAUs, alternative or additional COCs may be identified and the analyses described here can be updated to consider them.

Based on the consideration of groundwater-flow systems beneath the NNSS, the closest location of private or public lands downgradient from the NNSS and beyond the NTTR is to the west (in the direction of the Oasis Valley discharge area near Beatty) and/or southwest (in the direction of the Ash Meadows discharge area near Amargosa Valley). The shortest path for groundwater to move from an NNSS underground test area to a discharge area at accessible public or private lands is westerly, from Central and Western Pahute Mesa to Oasis Valley, which is a straight-line distance of approximately 26 km (16.2 miles). Additionally, groundwater velocities through the basins on the western side of the NNSS are estimated to be much higher than those through the basins on the eastern side. Therefore, the Oasis Valley discharge area and nearby community of Beatty are considered to be a realistic location for the RMEI. The RMEI's location is based solely on groundwater flow directions and general groundwater velocity information. The actual transport of radionuclides is

assumed for the analysis, but it should not be implied. Many factors control the fate and transport of radionuclides, some of which move much slower than groundwater because of processes such as sorption and matrix diffusion. The CAU flow and transport models in progress are needed to estimate how far radionuclides may migrate and at what concentrations.

In advance of completed CAU groundwater flow and transport modeling, this analysis assumes that the RMEI is exposed to the COCs assumed here at concentrations equivalent to the SDWA MCLs. Current health-protective regulatory guidance is also considered that establishes limits for both annual effective dose and lifetime excess cancer morbidity risk for the RMEI. The current regulatory guidance for the annual effective dose limit for the public is defined by USDOE (2011 and 2013) to be ≤ 100 $mrem_{CED}$/yr. The health-protective lifetime excess cancer risk that USEPA (2000c) used to establish the SDWA MCLs is no greater than 1×10^{-4} and preferably less than 1×10^{-6}. To assess the dose and risk, the RMEI is assumed to ingest groundwater that contains activity concentrations for the COCs that correspond to the applicable SDWA MCL.

This assessment was performed by approximating the representative activity concentrations for the co-occurring, beta/photon-emitting COCs that collectively contribute to the SDWA MCL. This was done using the relative atom abundances for the five beta/photon-emitting COCs in the NNSS 1992 (Bowen *et al.*, 2001) and ALMENDRO 2009 (Zavarin, 2012) atom inventories. The NNSS 1992 inventory represents data from all of the CAUs, but it includes the entire testing inventory, not just the portion that may dissolve in groundwater. The ALMENDRO 2009 inventory may be more realistic because it is specific to a test on Pahute Mesa, which is upgradient of the RMEI's location, and is based on measurements of radionuclides in groundwater within a test cavity. Considering both sources allows the sensitivity of the relative atom abundance to be assessed.

The total annual effective doses for the RMEI from drinking water exposure to activity concentrations for each of the five COCs derived from atom fractions in the two atom inventories are relatively comparable: 1.04 $mrem_{CED}$/yr (ALMENDRO 2009) and 1.24 $mrem_{CED}$/yr (NNSS 1992). Furthermore, both of these annual effective doses are well below the health-protective effective dose limit of 100 $mrem_{CED}$/yr described in the USDOE (2011 and 2013) guidance. The total 70-year lifetime excess cancer morbidity risks for the RMEI from drinking water exposure to these same activity concentrations for each of the five COCs are also relatively comparable, 5.1×10^{-5} (ALMENDRO 2009) and 6.3×10^{-5} (NNSS 1992). Both of the total lifetime excess cancer risks are also within the range of 1×10^{-4} to $\leq 1 \times 10^{-6}$, which is considered to be health protective according to current USEPA (2000c) regulatory language establishing the SDWA MCLs.

Radioactive decay reduces the mass of ^{3}H by half every 12.5 years, which will effectively remove NNSS 1992-derived ^{3}H from groundwater within the next 100 years. The decay for the four remaining beta/photon-emitting COCs is not significant compared with that of ^{3}H over the time assessed (their half-lives are long and their concentrations will not markedly decline during the next few hundreds of years). Without the ^{3}H contribution, the activity concentrations of the remaining COCs are less than the SDWA MCL. The resulting total lifetime excess cancer morbidity risk without ^{3}H decreases by a factor of approximately two to a factor of more than 11 based on the activity concentrations derived

from the NNSS 1992 and ALMENDRO 2009 atom inventories, respectively (Table 6, last column). These differences occur because the activity concentration for ^{3}H computed from the ALMENDRO 2009 atom inventory is 17 percent greater than the activity concentration computed from the NNSS 1992 atom inventory. The activity concentrations of the remaining co-occurring, beta/photon-emitting COCs are much lower in the ALMENDRO 2009 atom inventory than in the NNSS 1992 atom inventory with the exception of ^{129}I, which is only slightly higher in the ALMENDRO 2009 atom inventory.

Calculations for the annual CED and lifetime excess cancer morbidity risk show that ^{3}H is the dominant COC for producing annual dose and lifetime risk from all biosphere exposure pathways, drinking water ingestion is the dominant pathway contributing to dose and risk, and the CED from all biosphere pathways is well within health-protective guidance. The calculated lifetime excess cancer morbidity risk is also within the acceptable range, though the NNSS 1992 risk is at the upper end of the acceptable range (1×10^{-4}) and the ALMENDRO 2009 risk is lower (6×10^{-5}). The ALMENDRO 2009 risk can be considered more realistic because it is based on groundwater measurements from Pahute Mesa rather than source-physics calculations. The longer time frame for assumed exposure for the risk calculation (70 years) relative to the annual CED accounts for the risk being at or near the upper value for the recommended range. Switching to local sources of groundwater that are at background COC levels below SDWA MCLs or reducing or eliminating the food exposure pathway during the 70-year lifetime could readily reduce risk to levels consistent with regulatory guidance.

The calculations presented for analysis of the health-protective limits for the CED and lifetime excess cancer morbidity risk are meant to be descriptive in terms of process and illustrative in terms of results. The methodology is readily adaptable and updatable for application to activity concentrations for the five co-occurring, beta/photon-emitting COCs collectively contributing to the SDWA MCL. This methodology can be adapted to evaluate COC concentrations forecasted by ongoing groundwater modeling activities or measured during groundwater monitoring and by considering other RMEI locations and characteristics. The results also suggest that as ^{3}H nears 20,000 pCi/L, where the accompanying COCs are at low activity concentrations and all correspond to the SDWA MCL, compliance should be achieved with the health protective standards for both annual dose and the range of lifetime excess cancer morbidity risk.

REFERENCES

Baker, D.A., G.R. Hoenes, and J.K. Soldat, 1976. "FOOD—An Interactive Code to Calculate Internal Radiation Doses from Contaminated Food Products," in *Proceedings of the Conference on Environmental Modeling and Simulation,* W.R. Ott, Ed., held April 19-22, 1976, in Cincinnati, OH, Office of Research and Development and Office of Planning and Management, U.S. Environmental Protection Agency, Washington, DC, EPA 600/9-76-016 (July 1976), pp. 204–208.

Bechtel SAIC, 2005. Characteristics of the Receptor for the Biosphere Model. ANL-MGR-MD-000005 REV 04, DOC.20050405.0005. Available at http://pbadupws.nrc.gov/docs/ML0907/ML090720248.pdf .

Belcher, W.R. and D.S. Sweetkind, Eds., 2010. *Death Valley Regional Groundwater Flow System, Nevada and California–Hydrogeologic Framework and Transient Groundwater Flow Model,* U.S. Department of the Interior, U.S. Geological Survey, Reston, VA, USGS Professional Paper 1711. Available at http://pubs.usgs.gov/pp/1711/. Accessed 27 February 2014.

Bowen, S.M., D.L. Finnegan, J.L. Thompson, C.M. Miller, P.L. Baca, L.F. Olivas, C.G. Geoffrion, D.K. Smith, W. Goishi, B.K. Esser, J.W. Meadows, N. Namboodiri, and J.F. Wild, 2001. *Nevada Test Site Radionuclide Inventory, 1951-1992 (and Errata Tables V and VI),* Los Alamos National Laboratory, Los Alamos, NM, LA-13859-MS; also published as Smith, D.K., D.L. Finnegan, and S.M. Bowen (2003), "An Inventory of Long-Lived Radionuclides Residual From Underground Nuclear Testing at the Nevada Test Site, 1951-1992," *Journal of Environmental Radioactivity,* 67, 35-51.

Ciffroy, P., F. Siclet, C. Damois, M. Luck, 2006. "A Dynamic Model for Assessing Radiological Consequences of Tritium Routinely Released in Rivers. Application to the Loire River," *Journal of Environmental Radioactivity,* 90, 110–139.

Daniels, J.I., R. Andricevic, L.R. Anspaugh, and R.L. Jacobson, 1993. "Risk Based Screening Analysis of Ground Water Contaminated by Radionuclides Introduced at the Nevada Test Site (NTS)," in Pilot Study Risk Assessment for Selected Problems at the Nevada Test Site (NTS), J.I. Daniels, Ed., Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-113891, pp. 69–97.

Daniels, J.I. and A.F.B. Tompson, 2003. *Technical Basis for Also Using Health-Risk Assessment to Establish Corrective Action Units (CAUs) of the Underground Test Area (UGTA) at the Nevada Test Site (NTS),* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-TR-201702.

Faunt, C.C., F.A. D'Agnese, and G.M. O'Brien, 2010. "Hydrology, Chapter D," in W.R. Belcher and D.S. Sweetkind, Eds., *Death Valley Regional Ground-Water Flow System, Nevada and California—Hydrogeologic Framework and Transient Groundwater Flow Model,* U.S. Geological Survey Professional Paper 1711. Available at http://pubs.usgs.gov/pp/1711/. Accessed 20 January 2015.

Federal Facility Agreement and Consent Order, 1996 (as amended March 2010). Agreed to by the State of Nevada; U.S. Department of Energy, Environmental Management; U.S. Department of Defense; and U.S. Department of Energy, Legacy Management. Appendix VI, which contains the Underground Test Area Strategy, was last modified May 2011, Revision Number 4 (Tri-party agreement administered through Nevada Division of Environmental Protection (NDEP), United States Department of Defense (DoD), and National Nuclear Security Administration Nevada Field Office (NNSA/NFO), Las Vegas, NV (pp. 22–25).

Fenelon, J.M., D.S. Sweetkind, and R.J. Laczniak, 2010. *Groundwater Flow Systems at the Nevada Test Site, Nevada: A Synthesis of Potentiometric Contours, Hydrostratigraphy, and Geologic Structures,* U.S. Geological Survey, Reston, VA, USGS Professional 1771. Available at http://pubs.usgs.gov/pp/1771/. Accessed 27 February 2014.

International Atomic Energy Agency (IAEA) International Advisory Committee, 1998. *The Radiological Situation at the Atolls of Mururoa and Fangataufa,* Technical Report, Volume 3: *Inventory of Radionuclides Underground at the Atolls,* International Atomic Energy Agency, Vienna, Austria, IAEA-MFTR-3; also *The Radiological Situation at the Atolls of Mururoa and Fangataufa Proceedings of an IAEA Conference (*to present the results of the International Study) and held in Vienna, Austria, June 30 to July 3, 1998, International Atomic Energy Agency, Vienna, Austria, IAEA-MFCP.

Kersting, A.B. and M. Zavarin, 2011. "Colloid-Facilitated Transport of Plutonium at the Nevada Test Site, NV, USA," in *Actinide Nanoparticle Research,* S.N. Kalmykov and M.A. Denecke, Eds. (Springer-Verlag, Berlin and Heidelberg, Germany), pp. 399–412.

Kwicklis, E.M., T.P. Rose, and F.C. Benedict, Jr., 2005. Evaluation of Groundwater Flow in the Pahute Mesa—Oasis Valley Flow System Using Groundwater Chemical and Isotopic Data, Los Alamos National Laboratory (LANL), Los Alamos, NM, LA-UR-05-4344.

Laczniak, R.J., J.C. Cole, D.A. Sawyer, and D.A. Trudeau, 1996. Summary of Hydrogeologic Controls on Ground-Water Flow at the Nevada Test Site, Nye County, Nevada, U.S. Geological Survey, Las Vegas, NV, Water-Resources Investigations Report 96–4109. Available at http://pubs.usgs.gov/wri/wri964109/index.html. Accessed 27 February 2014.

Navarro-Intera, LLC (N-I), 2013. "Appendix C: Yucca Flat/Climax Mine CAU Hydrologic Source Term Allocation and Screening," in *Phase I Flow and Transport Model Document for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada National Security Site, Nye County, Nevada,* United States Department of Energy (U.S. DOE), Las Vegas, NV, N-I/28091-080, Revision Number 1 (September 2013).

Navarro Nevada Environmental Services, LLC (NNES), 2010. *Phase II Transport Model of Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nye County, Nevada,* Prepared for U.S. Department of Energy (USDOE), Las Vegas, NV, January 2010, Revision Number 1, N-I/28091-004 and S-N/99205-2.

Rose, T.P., Q. Hu, P. Zhao, C.L. Conrado, R. Dickerson, G.F. Eaton, A.B. Kersting, J.E. Moran, G. Nimz, B.A. Powell, E.C. Ramon, F.J. Ryerson, R.W. Williams, P.T. Woody, and M. Zavarin, 2011. *Radionuclide Partitioning in an Underground Nuclear Test Cavity,* Lawrence Livermore National Laboratory, Livermore, CA, LLNL-TR-409817.

Sandia National Laboratories (SNL), 2007. "Model Discussion," Section 6 in *Biosphere Model Report,* prepared for U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Project, Las Vegas, NV; DOC.20070830.0007/MDL-MGR-MD-000001 REV 02, August 2007. Available at http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/references.html (see Document No. ML090720287). Accessed on 30 June 2014.

Stoller-Navarro Joint Venture (SNJV), 2005. Unclassified Source Term and Radionuclide Data for Corrective Action Unit 98: Frenchman Flat Nevada Test Site. Prepared for U.S. Department of Energy, Stoller-Navarro Joint Venture, Las Vegas, NV, S-N/99205–058 (Revision Number 0; September 2005). Available at http://www.osti.gov/scitech/biblio/876140. Accessed 31 December 2014.

Stoller-Navarro Joint Venture (SNJV), 2006. Phase II Groundwater Flow Model of Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nye County, Nevada. Prepared for U.S. Department of Energy, Stoller-Navarro Joint Venture, Las Vegas, NV, S-N/99205–074 (Revision Number 0; May 2006). Available at http://www.osti.gov/scitech/biblio/891955. Accessed 27 February 2014.

Stoller-Navarro Joint Venture (SNJV), 2009. Phase I Transport Model of Corrective Action Units 101 and 102: Central and Western Pahute Mesa, Nevada Test Site, Nye County, Nevada with Errata Sheet 1, 2,3, Prepared for U.S. Department of Energy, Stoller-Navarro Joint Venture, Las Vegas, NV, S-N/99205–111 (Revision Number 1; February 2009). Available at http://www.osti.gov/scitech/biblio/948559. Accessed 27 February 2014.

United States Department of Energy (USDOE), 2011. *DOE STANDARD: Derived Concentration Technical Standard (AREA ENVR),* U.S. Department of Energy, Washington, DC, DOE-STD-1196-2011 (April 2011). Available at http://energy.gov/hss/information-center/department-energy-technical-standards-program/doe-approved-technical. Accessed 27 February 2014.

United States Department of Energy (USDOE), 2013. Radiation Protection of the Public and the Environment, The Office of Health, Safety and Security, Washington, DC, DOE O458.1; Chg 3: 1-15-2013. Available at https://www.directives.doe.gov/directives/0458.1-BOrder-AdmChg3/view. Accessed 27 February 2014.

United States Department of Energy, Nevada Operations Office (USDOE/NVO), 1997. *Regional Groundwater Flow and Tritium Transport Modeling and Risk Assessment of the Underground Test Area, Nevada Test Site, Nevada,* Nevada Environmental Restoration Project, United States Department of Energy, Nevada Operations Office, Las Vegas, NV, DOE/NV–477, UC-700.

United States Environmental Protection Agency (USEPA), 1976. "Appendix IV: Dosimetric Calculations for Man-Made Radioactivity," in *National Primary Drinking Water Regulations,* United States Environmental Protection Agency, Office of Water Supply, Washington, DC, EPA-570/9-76-003 (January 1976), NTIS Accession Number PB-267630. Available at http://yosemite.epa.gov/water/owrccatalog.nsf/9da204a4b4406ef885256ae0007a79c7/490344d9eaf40d4e85256b0600724162!OpenDocument . Accessed 27 February 2014.

United States Environmental Protection Agency (USEPA), 1991. "National Primary Drinking Water Regulations; Radionuclides (40 CFR Parts 141 and 142)—Notice of Proposed Rule Making (NPRM)," *Federal Register*, 56(138), 33050–33127 (July 18, 1991, Proposal). Available at http://water.epa.gov/lawsregs/rulesregs/sdwa/radionuclides/regulation.cfm. Accessed 05 September 2014.

United States Environmental Protection Agency (USEPA), 1999. Federal Guidance Report Number 13, Cancer Risk Coefficients for Environmental Exposure to Radionuclides, In: Radionuclide Carcinogenicity Slope Factors: HEAST (Table 4), User's Guide and Radionuclide Health Effects Assessment Summary Tables, Washington, DC: Office of Radiation and Indoor Air; Report Number EPA 402-R-99-001; 1999. Available at http://www.epa.gov/rpdweb00/heast/. Accessed 27 February 2014.

United States Environmental Protection Agency (USEPA), 2000a. *Radionuclides Notice of Data Availability Technical Support Document,* prepared by United States Environmental Protection Agency (USEPA) Office of Ground Water and Drinking Water in collaboration with USEPA Office of Indoor Air and Radiation and United States Geological Survey (USGS), Targeting and Analysis Branch Standards and Risk Management Division, Office of Ground Water and Drinking Water, United States Environmental Protection Agency, Washington, DC (March 2000, NODA Technical Document). Available at http://water.epa.gov/lawsregs/rulesregs/sdwa/radionuclides/regulation.cfm. Accessed 05 September 2014.

United States Environmental Protection Agency (USEPA), 2000b. "National Primary Drinking Water Regulations; Radionuclides (40 CFR 141, and 142)—Notice of Data Availability (NODA)," *Federal Register,* 65(78), 21576–21628 (April 21, 2000, NODA for Proposed Rule); Available at http://water.epa.gov/lawsregs/rulesregs/sdwa/radionuclides/regulation.cfm. Accessed 05 September 2014.

United States Environmental Protection Agency (USEPA), 2000c. "National Primary Drinking Water Regulations; Radionuclides; Final Rule (40 CFR Parts 9, 141, and 142)," *Federal Register,* 65(236), 76708–76753 (December 7, 2000, Final); Available at http://www.gpo.gov/fdsys/pkg/FR-2000-12-07/pdf/00-30421.pdf. Accessed 27 February 2014.

United States Environmental Protection Agency (USEPA), 2001. Radionuclide Rule: A Quick Reference Guide (see Regulated [Radionuclide] Contaminants), Office of Water, Washington, DC, EPA 816-F-01-003 (June 2001). Available at http://water.epa.gov/lawsregs/rulesregs/sdwa/radionuclides/regulation.cfm. Accessed 27 February 2014.

United States Environmental Protection Agency (USEPA), 2002. "Derived Concentrations (pCi/L) of Beta and Photon Emitters in Drinking Water (yielding dose of 4 mrem/yr based on NBS Handbook 69 dosimetrics)," in *Radionuclides in Drinking Water: A Small Entity Compliance Guide,* Office of Ground Water and Drinking Water, Washington, DC, EPA 815-R-02-001. Available at http://water.epa.gov/lawsregs/rulesregs/sdwa/radionuclides/compliancehelp.cfm. Accessed 27 February 2014.

United States National Bureau of Standards (USNBS), 1963. *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure*, United States Department of Commerce, Washington, DC, Handbook 69 (August 1963). Available at http://www.orau.org/ptp/Library/NBS/NBS%2069.pdf. Accessed 27 February 2014.

Winograd, I.J. and W. Thordarson, 1975. Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site, U.S. Geological Survey Professional Paper 712-C. Available at http://pubs.er.usgs.gov/publication/pp712C. Accessed 27 February 2014.

Wolfsberg, A.V., L. Glascoe, G. Lu, A. Olson, P. Lichtner, M. McGraw, T. Cherry, and G. Roemer, 2002. TYBO/BENHAM: Model Analysis of Groundwater Flow and Radionuclide Migration from Underground Nuclear Tests in Southwestern Pahute Mesa, Nevada. Los Alamos National Laboratory, Los Alamos, NM, LA-13977. Available at http://www.osti.gov/scitech/biblio/821548. Accessed 27 February 2014.

Yu, C., Zielen, A.J., J.-J. Cheng. D.J. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo III, W.A. Williams, and H. Peterson, 2001. *User's Manual for RESRAD Version 6, Environmental Assessment Division,* Argonne National Laboratory, Argonne, IL, ANL/EAD-4 (July 2001).

Zavarin, M., 2012. *Isotopic Analyses: Environmental Monitoring Well U-19v PS #1ds, Environmental Chemistry Group,* Lawrence Livermore National Laboratory, Livermore, CA; Letter-Report to Bill Wilborn, Federal Sub-Project Director, UGTA Sub-Project, USDOE/NNSA/NFO, Las Vegas, NV (24 May 2012).

APPENDIX A: COMPUTATION OF ANNUAL DOSE AND LIFETIME EXCESS CANCER MORBIDITY RISK

Water intakes for computing the total annual committed effective dose (D_T) and total excess lifetime cancer morbidity risk (R_T) are presented in this appendix along with the data and equations suitable for converting between activity and atoms, and for calculating both D_T and R_T. Table A-1 contains the U.S. population and usage data from DOE-STD-1196-2011 (USDOE, 2011) and the derivation of the annual and lifetime drinking water ingestion rates for the reference person considered to be an aggregate member of the U.S. population and corresponding to the representative reasonably maximally exposed individual (RMEI) for purposes of dose estimation. Table A-2 contains the committed effective dose (CED) and excess lifetime cancer morbidity risk coefficients for the five radionuclides that are used here as the contaminants of concern (COCs: ^{3}H, ^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I). Table A-3 contains the drinking water ingestion rates used to derive annual effective dose and lifetime cancer morbidity risk in units of $mrem_{CED}$/yr and Risk/$lifetime_{70yr}$. Equation A-1 converts activity, expressed as pCi (or activity concentration, pCi/L) to atoms (or atoms/L). Equation A-2 converts atoms (or atoms/L) to activity (pCi or pCi/L). Radioactivity can be expressed as pCi or Bq with pCi = 0.037 Bq. A curie (Ci) is defined as the quantity of any radioactive nuclide in which the number of disintegrations (atom transformations) is 3.700×10^{10} per second; a pCi is 10^{-12} Ci. A Bq is activity expressed as atoms (transformed)/s; and the decay constant (λ) for a radionuclide is in units of 1/s.

$$\textit{Atoms}\ (N_i) = [\textit{Activity}\ (\text{pCi})/\ \lambda\ (1/\text{s})] \times [0.037\ \text{Bq (atoms/s)/pCi}] \quad \text{(A-1)}$$

$$\textit{Activity}\ (\text{pCi}) = [\textit{Atoms}\ (N_i) \times \lambda\ (1/\text{s})] \times [\text{pCi}/0.037\ \text{Bq (atoms/s)}] \quad \text{(A-2)}$$

Total annual committed effective dose (D_T) is calculated according to equation A-3 and total lifetime excess cancer morbidity risk (R_T) is calculated according to equation A-4.

$$D_T = IR \times ED \times [\Sigma(A_i \times eDC_i) \quad \text{(A-3)}$$

where:

D_T = Total annual committed effective dose ($mrem_{CED}$/yr);

IR = U.S. reference person daily drinking water ingestion rate (1.862 L/d from Table A-1);

ED = exposure duration (365 d/yr from Table A-1);

A_i = activity concentration for COC, i (pCi/L from Table 4 in text); and

eDC_i = committed effective dose (CED) coefficient for COC, i ($mrem_{CED}$/pCi from Table A-2).

$$R_T = IR \times ED \times [\Sigma(Ai \times RCi)] \quad \text{(A-4)}$$

where:

R_T = Total lifetime excess cancer morbidity risk (R/lifetime70yr);

IR = daily drinking water ingestion rate (2 L/d; applicable to USEPA SDWA MCLs);

ED = exposure duration (365 d/yr × 70 yr/lifetime);

A_i = activity concentration for COC, i (pCi/L from Table 4 in text); and

RC_i = risk coefficient for COC, i (R/pCi from Table A-2).

Table A-1. Daily water intake (L/d) for a U.S. reference person[a] based on U.S. population and usage data in DOE-STD-1196-2011.[b]

Reference age category	Time period (yr)	Population fraction		Gender-specific water intake (L/d)[b]		Reference person (weighted average; L/d)
		Male	Female	Male	Female	
Newborn	$0 \le x < 1$	6.930×10^{-03}	6.6000×10^{-03}	1.07	1.07	1.448×10^{-02}
1 yr	$1 \le x < 3$	1.383×10^{-02}	1.3210×10^{-02}	1.12	1.12	3.028×10^{-02}
5 yr	$3 \le x < 7$	2.864×10^{-02}	2.7310×10^{-02}	1.27	1.27	7.106×10^{-02}
10 yr	$7 \le x < 12$	3.814×10^{-02}	3.6320×10^{-02}	1.50	1.50	1.117×10^{-01}
15 yr	$12 \le x < 17$	3.672×10^{-02}	3.4820×10^{-02}	2.02	1.52	1.271×10^{-01}
Adult	$x \ge 17$	3.663×10^{-01}	3.9118×10^{-01}	2.29	1.71	$1.508 \times 10^{+00}$
Reference person[a] drinking water ingestion rate(s):					Daily [Σ L/d] =	$1.862 \times 10^{+00}$
					Annual (L/y)= 365 d/y × [Σ (L/d)] =	$6.798 \times 10^{+02}$

[a] Reference person is an age and gender composite individual, aggregate member of the U.S. population, and representative reasonably maximally exposed individual (RMEI). Reference person ingestion rate (weighted average; L/d)$_{\text{Age-category}}$ = [(Population Fraction)$_{\text{MALE}}$ × (Gender-specific ingestion rate; L/d)$_{\text{MALE}}$ +[(Population Fraction)$_{\text{FEMALE}}$ × (Gender-specific ingestion rate; L/d)]$_{\text{FEMALE}}$

[b] USDOE (2011, Table 3).

Table A-2. Committed effective dose (CED) and lifetime excess cancer morbidity risk coefficients for ingestion (ing) exposure pathway for the five contaminants of concern (COCs).

COC	USDOE committed effective dose (CED) coefficient ($Sv_{CED}/Bq)_{ing}$[a]	USDOE committed effective dose (CED) coefficient ($mrem_{CED}/pCi)_{ing}$[b]	USEPA lifetime excess risk coefficient $(Risk/pCi)_{ing}$[c]
^{3}H	2.10×10^{-11}	7.77×10^{-08}	5.07×10^{-14}
^{14}C	6.33×10^{-10}	2.34×10^{-06}	1.55×10^{-12}
^{36}Cl	1.24×10^{-09}	4.59×10^{-06}	3.30×10^{-12}
^{99}Tc	9.00×10^{-10}	3.33×10^{-06}	2.75×10^{-12}
^{129}I	1.21×10^{-07}	4.48×10^{-04}	1.48×10^{-10}

[a] From DOE-STD-1196-2011 (USDOE, 2011; Table A-1: Effective Dose Coefficients for Ingested Water).

[b] Unit conversion: $mrem_{CED}/pCi = Sv_{CED}/Bq \times 100\ rem_{CED}/Sv_{CED} \times 1{,}000\ mrem_{CED}/rem_{CED} \times 0.037\ Bq/pCi = Sv_{CED}/Bq \times 3{,}700$.

[c] From USEPA (1999).

Table A-3. Drinking water ingestion rates used to derive annual dose and lifetime excess cancer morbidity risk for reasonably maximally exposed individual (RMEI) corresponding to reference person.

Metric	**RMEI (reference person) drinking water ingestion rate**
Annual dose	$6.798 \times 10^{+02}$ L/yr (= 1.862 L/d × 365 d/yr)
Lifetime excess cancer morbidity risk	$5.110 \times 10^{+04}$ L/lifetime$_{70y}$ (= 2 L/d × 365 d/yr × 70-yr/lifetime)

APPENDIX B: BIOSPHERE MODELING PARAMETERS AND RESULTS OF CALCULATIONS

Biosphere modeling describes radionuclide transport processes in the biosphere and associated human exposure that may arise from radionuclide releases into the accessible environment. The modeling allows the estimation of annual dose and lifetime excess cancer morbidity risk for a hypothetical reasonably maximally exposed individual (RMEI). In the case of the Underground Test Area (UGTA) at the Nevada National Security Site (NNSS), groundwater is the fundamental radionuclide transport process and the first step in an exposure pathway. The groundwater contaminants of concern (COCs) considered here are from the Frenchman Flat Corrective Action Unit (CAU) model results and are the radionuclides tritium (^{3}H), carbon-14 (^{14}C), chlorine-36 (^{36}Cl), technetium-99 (^{99}Tc), and iodine-129 (^{129}I). The RMEI is located in Oasis Valley, a rural community near Beatty, Nevada, which is downgradient from the Pahute Mesa testing area on the NNSS (Figure 3 in text). A comprehensive biosphere model was developed for the community of Amargosa Valley as part of the Yucca Mountain Project (SNL, 2007). Amargosa Valley is located approximately 30 miles southeast of the Oasis Valley area. Both valleys reside in Nye County and are characterized by a sparsely populated, rural Nevada culture and are subject to similar geographic and climatic conditions. Amargosa Valley is also in the general direction of regional groundwater flow from testing areas on the NNSS. Therefore, the parameters developed for characterizing the biosphere of Amargosa Valley are considered applicable for an RMEI for contaminants related to the UGTA.

The biosphere parameters related to Amargosa Valley were developed for the Yucca Mountain Project in order "[…] to limit speculation about possible futures so that the performance assessments can provide meaningful input into the decision process and the decision process itself is not confounded with speculative alternatives" (SNL, 2007; §6). The exposure pathways developed in the biosphere model for an RMEI will be stylized because the RMEI and the community are hypothetical, but they will be based on the realistic parameters that characterize the biosphere of the community of interest. The overall philosophy of the Yucca Mountain biosphere model was to be cautious while being reasonable (SNL, 2007).

Local wells in the region provide water for household, agriculture, horticulture, and animal husbandry use. Many residences have gardens with vegetable plots and some have a few cattle, sheep, chickens, and other farm animals. A survey of Amargosa Valley residents determined that some people in the region consume locally produced vegetables, fruit, grain, meat, poultry, fish, eggs, and milk (SNL, 2007). The survey also found that almost 75 percent of residents use evaporative coolers during a significant part of the year (average of 5 months).

With groundwater as the migration pathway to the RMEI, radionuclides enter the biosphere in the model from wells that extract contaminated groundwater from an aquifer. The Yucca Mountain evaluation of Amargosa Valley did not include surface discharge of groundwater at springs, which is a process that occurs in Oasis Valley, but notes that wells and springs are equivalent sources of contamination in the biosphere. Groundwater is assumed to be the sole source for all water needs. Human exposure occurs from using contaminated water for domestic and agricultural purposes. The biosphere model includes

direct ingestion through drinking water and food preparation; the consumption of locally produced crops, animals, and freshwater fish (aquaculture is not considered applicable in this analysis) that consumed contaminated groundwater; the inhalation of water vapor and particulates from evaporative coolers and elsewhere; and the ingestion of soil or external exposure to soil contaminated by water (Table B-1). These various and interrelated processes are displayed graphically in Figure B-1.

The biosphere models for all relevant exposure pathways applicable to the RMEI for ^{14}C, ^{36}Cl, ^{99}Tc, and ^{129}I in the groundwater are described in a Sandia National Laboratories report (SNL, 2007; §6). The central (nominal or accepted) values for the model parameters are presented in either the text or Table 6.6-3 of that report. These parameters are used here with the exception that the annual average precipitation for Beatty is used. The radionuclides of interest for the Yucca Mountain biosphere analysis did not include ^{3}H. For biosphere modeling of ^{3}H exposure pathways for the RMEI, the derivation of the soil concentration and outdoor (garden and field) air concentration for outdoor inhalation were obtained using equations and supplementary data from Yu *et al.* (2001). The concentration in vegetation and animal products was obtained using equations and supplementary data from Baker *et al.* (1976). Human intake of all COCs from water, food, and animal products is modeled according to the equations presented in the report by Sandia National Laboratories (SNL, 2007; §6). The data appearing in Tables B-2 to B-25 of this appendix were used to construct the summary Tables 5 through 8 in the text of this report.

Table B-1. Biosphere exposure pathways (taken from SNL, 2007) and applicable to the transport of relevant COCs in groundwater from the underground test area (UGTA) of the Nevada National Security Site (NNSS).

Environmental Medium	Exposure Mode	Exposure Pathways	Examples of Typical Activities
Water	Ingestion	Water intake	Drinking water and water-based beverages and water used in food preparation
Soil	Ingestion	Inadvertent soil ingestion	Recreational activities, occupational activities, gardening, and consumption of fresh fruit and vegetables
Air	Inhalation	Breathing resuspended particles, gases e.g., $^{14}CO_2$), and aerosols from evaporative coolers	Outdoor activities, including soil-disturbing activities related to work and recreation; and domestic activities in residences, including sleeping.
Plants	Ingestion	Consumption of locally produced crops: leafy vegetables, other vegetables, fruit, and grain	Eating contaminated crop foodstuffs
Animals	Ingestion	Consumption of locally produced animal products: meat, poultry, milk, and eggs	Eating contaminated animal product foodstuffs

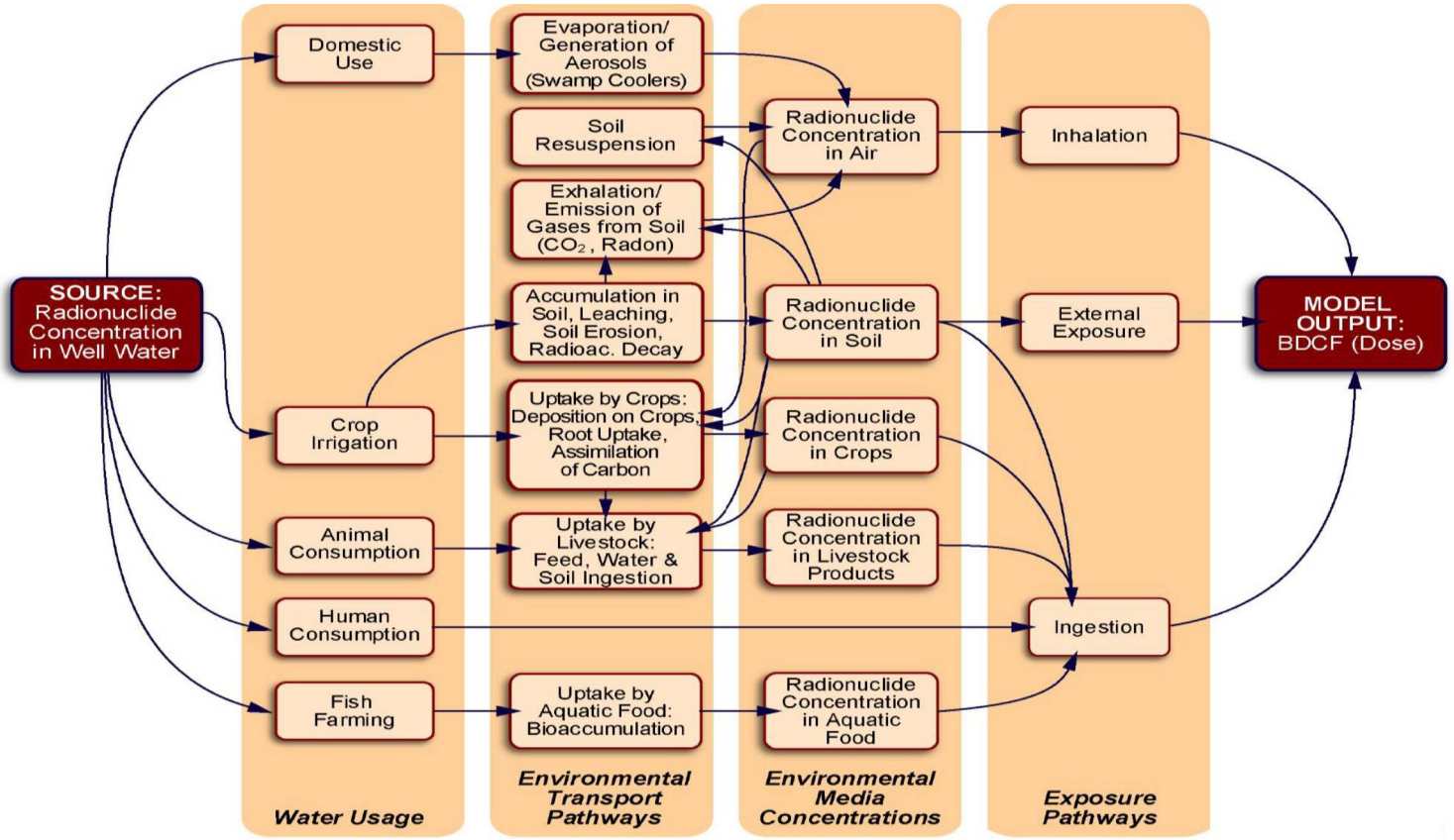


Figure B-1. Conceptual representation of a biosphere model for the groundwater exposure scenario used for the Yucca Mountain Program (from SNL, 2007; Figure 6.6-3). Elements relevant to this assessment were adapted for use. The biosphere dose conversion factor (BDCF) is not specifically incorporated into the analytical process used for this study.

Table B-2. Water activity concentrations for the contaminants of concern (COCs) presented in equivalent units for NNSS 1992 and ALMENDRO 2009 atom inventory derived activity concentrations.

	NNSS 1992				ALMENDRO 2009			
COC	(pCi/L)	(Bq/m^3)	(Bq/L)	(Bq/kg)	(pCi/L)	(Bq/m^3)	(Bq/L)	(Bq/kg)
^{3}H	16,305	$6.03\times 10^{+5}$	603	603	19,023	$7.04\times 10^{+5}$	704	704
^{14}C	17	$6.29 \times 10^{+2}$	0.629	0.629	0.79	$2.92 \times 10^{+1}$	0.0292	0.0292
^{36}Cl	68	$2.52 \times 10^{+3}$	2.52	2.52	6.24	$2.31 \times 10^{+2}$	0.231	0.231
^{99}Tc	58	$2.15 \times 10^{+3}$	2.15	2.15	0.50	$1.85 \times 10^{+1}$	0.0185	0.0185
^{129}I	0.01	3.70×10^{-1}	0.00037	0.00037	0.04	$1.48 \times 10^{+0}$	0.00148	0.00148

Table B-3. Daily inhalation rate for a U.S. reference person[a] based on U.S. population and usage data in DOE-STD-1196-2011.[b]

Reference age category	Time period (yr)	Population fraction		Gender-specific inhalation (m^3/d)		Reference Person (weighted average; m^3/d)
		Male	Female	Male	Female	
Newborn	$0 \le x < 1$	6.930×10^{-3}	6.6000×10^{-3}	4.15	4.15	5.615×10^{-2}
1 yr	$1 \le x < 3$	1.383×10^{-2}	1.3210×10^{-2}	5.89	5.89	1.593×10^{-1}
5 yr	$3 \le x < 7$	2.864×10^{-2}	2.7310×10^{-2}	9.00	9.08	5.057×10^{-1}
10 yr	$7 \le x < 12$	3.814×10^{-2}	3.6320×10^{-2}	15.20	15.00	1.125×10^{0}
15 yr	$12 \le x < 17$	3.672×10^{-2}	3.4820×10^{-2}	20.00	15.80	1.285×10^{0}
Adult	$x \ge 17$	3.663×10^{-1}	3.9118×10^{-1}	22.20	17.70	$1.506 \times 10^{+1}$
Reference person[a] air inhalation rate(s):					Daily [Σ $(m^3/d)_{air}$] =	$1.819 \times 10^{+1}$
					Annual $(m^3/yr)_{air}$ = 365 d/yr × [Σ $(m^3/d)_{air}$] =	$6.638 \times 10^{+3}$

[a] Reference person is an age and gender composite individual, aggregate member of the U.S. population, and representative reasonably maximally exposed individual (RMEI). Reference person (weighted average; $m^3/d)_{Age\text{-}category}$ = [(Population Fraction)$_{MALE}$ × (Gender-specific inhalation rate; $m^3/d)_{MALE}$ +[(Population Fraction)$_{FEMALE}$ × (Gender-specific inhalation rate; $m^3/d)]_{FEMALE}$

[b] USDOE (2011, Table 3).

Table B-4. Inhalation committed effective dose and lifetime excess cancer morbidity risk coefficients.

COC	USDOE committed effective dose (CED) coefficient (Sv_{CED}/Bq)	Lung absorption type	USDOE[a] committed effective dose (CED) coefficient $(mrem_{CED}/pCi)_{inh}$	USEPA[b] lifetime excess risk coefficient $(Risk/pCi)_{inh}$
^{3}H	5.33×10^{-11}	Medium	1.97×10^{-7}	1.99×10^{-13}
HTO(vapor)	1.93×10^{-11}	Water vapor	7.14×10^{-8}	5.62×10^{-14}
^{14}C	2.22×10^{-9}	Medium	8.21×10^{-6}	7.07×10^{-12}
$^{14}CO_2$(vapor)	6.70×10^{-12}	CO_2 vapor	2.48×10^{-8}	1.99×10^{-14}
^{36}Cl	8.05×10^{-9}	Medium	2.98×10^{-5}	2.50×10^{-11}
^{99}Tc	4.42×10^{-9}	Medium	1.64×10^{-5}	1.41×10^{-11}
^{129}I	4.06×10^{-8}	Fast	1.50×10^{-4}	6.07×10^{-11}

[a] From DOE-STD-1196-2011 (USDOE, 2011; Table A-1: Effective Dose Coefficients for Ingested Water).
[b] From USEPA (1999).

Table B-5. Dietary ingestion, committed effective dose (CED), and lifetime excess cancer morbidity risk coefficients.

COC	USDOE committed effective dose (CED) coefficient $(Sv_{CED}/Bq)_{dietary\ ing}$	USDOE[a] committed effective dose (CED) coefficient $(mrem_{CED}/pCi)_{dietary\ ing}$	USEPA[b] lifetime excess risk coefficient $(Risk/pCi)_{dietary\ ing}$
^{3}H	2.10×10^{-11}	7.77×10^{-8}	1.44×10^{-13}
^{14}C	6.33×10^{-10}	2.34×10^{-6}	2.00×10^{-12}
^{36}Cl	1.24×10^{-9}	4.59×10^{-6}	4.44×10^{-12}
^{99}Tc	9.00×10^{-10}	3.33×10^{-6}	4.00×10^{-12}
^{129}I	1.21×10^{-7}	4.48×10^{-4}	1.93×10^{-10}

[a] From DOE-STD-1196-2011 (USDOE, 2011; Table A-1: Effective Dose Coefficients for Ingested Water) are considered applicable.
[b] From Federal Guidance Report No.13 (USEPA, 1999; corresponding specifically to "Dietary Intakes" in Table 2.2a).

Table B-6. Central (nominal or accepted) values for soil and radionuclide specific parameters.[a]

COC	Irrigation rate (IR; m/yr)		Irrigation duration (T_{irr}; yr)		Erosion rate (ER; kg/[m^2/yr])	Soil bulk density (ρ; kg/m^3)	Tillage depth (d_t; m)	Critical thickness (or resuspendable) depth (d_c; m)	Volumetric water content (θ; dimensionless)	Solid liquid partition coefficient (K_d; m^3/kg)
	Garden	Field	Garden	Field						
^{3}H	0.91	1.78	25	100	0.2	1,500	0.25	0.002	0.2	0
^{14}C	0.91	1.78	25	100	0.2	1,500	0.25	0.002	0.2	1.4×10^{-4}
^{36}Cl	0.91	1.78	25	100	0.2	1,500	0.25	0.002	0.2	1.4×10^{-4}
^{99}Tc	0.91	1.78	25	100	0.2	1,500	0.25	0.002	0.2	1.4×10^{-4}
^{129}I	0.91	1.78	25	100	0.2	1,500	0.25	0.002	0.2	1.4×10^{-4}

[a] From data are from Table 6.6.-3 and §6: Model Discussion in SNL (2007).

Table B-6. Central (nominal or accepted) values for soil and radionuclide specific parameters [a] (continued).

COC	Overwatering rate (OW; m/yr) for			Radionuclide decay constant (λ_d)	Rate constants (λ; 1/yr)					
					Leaching (λ_ℓ)				Erosion (λ_e; garden and field)	
	Tillage depth (*garden and field*)	Critical thickness depth			Surface above tillage (*garden and field*)	Critical thickness depth		Vapor emission for $^{14}CO_2$		
		Garden	*Field*			*Garden*	*Field*		Soil surface	Critical thickness depth
					$(\lambda_\ell)_{surface}$	$(\lambda_\ell)_{garden\ crit}$	$(\lambda_\ell)_{field\ crit}$	$(\lambda_v)_{surface}$	$(\lambda_e)_{surface}$	$(\lambda_e)_{crit}$
^{3}H	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
^{14}C	0.079	0.903	1.77	1.21×10^{-4}	1.16×10^{-2}	$1.66 \times 10^{+1}$	$3.25 \times 10^{+1}$	$2.2 \times 10^{+1}$	5.33×10^{-4}	6.67×10^{-2}
^{36}Cl	0.079	0.903	1.77	2.30×10^{-6}	7.71×10^{-1}	$1.10 \times 10^{+3}$	$2.15 \times 10^{+3}$	NA	5.33×10^{-4}	6.67×10^{-2}
^{99}Tc	0.079	0.903	1.77	3.25×10^{-6}	7.71×10^{-1}	$1.10 \times 10^{+3}$	$2.15 \times 10^{+3}$	NA	5.33×10^{-4}	6.67×10^{-2}
^{129}I	0.079	0.903	1.77	4.41×10^{-8}	4.55×10^{-2}	$6.50 \times 10^{+1}$	$1.27 \times 10^{+2}$	NA	5.33×10^{-4}	6.67×10^{-2}

[a] From data are from Table 6.6.-3 and §6: Model Discussion in SNL (2007).
NA = not applicable.

Table B-7. Calculated effective removal rates for contaminants of concern at soil surface above tillage and critical thickness (resuspendable) depths.[a]

	Effective removal rate (λ_{eff} ; 1/yr)		
	Critical thickness depth		
COC	Garden and Field: $(\lambda_{eff})_{surface}$ = $\lambda_d + (\lambda_\ell)_{surface} + (\lambda_e)_{surface}$ [+ $(\lambda_v)_{surface}$][b]	Garden: $(\lambda_{eff})_{garden\ crit}$ = $\lambda_d + (\lambda_\ell)_{garden\ crit} + (\lambda_e)_{crit}$ [+ $(\lambda_v)_{surface}$][b]	Field: $(\lambda_{eff})_{field\ crit}$ = $\lambda_d + (\lambda_\ell)_{field\ crit} + (\lambda_e)_{surface}$ [+ $(\lambda_v)_{surface}$][b]
^{3}H	NA	NA	NA
^{14}C	$2.2 \times 10^{+1}$	$3.87 \times 10^{+1}$	$5.4 \times 10^{+5}$
^{36}Cl	7.7×10^{-1}	$1.1 \times 10^{+3}$	$2.2 \times 10^{+3}$
^{99}Tc	7.7×10^{-1}	$1.1 \times 10^{+3}$	$2.2 \times 10^{+3}$
^{129}I	4.6×10^{-2}	$6.5 \times 10^{+1}$	$1.3 \times 10^{+2}$

[a] Derived from equations presented in §6: Model Discussion of SNL (2007).

[b] (λ_v) is used only for determining (λ_{eff}) for ^{14}C, because ^{14}C is also lost significantly by vapor-phase emission (as $^{14}CO_2$) SNL (2007),

NA = not applicable.

Table B-8. Soil concentrations derived from nominal values for soil and radionuclide specific parameters with respect to equilibrium conditions.

COC	Field-soil activity per unit soil area with respect to *tillage* (Bq/m^2)	Field-soil activity per unit soil mass with respect to *tillage* and applicable to plant and animal uptakes (Bq/kg)	Garden-soil activity per unit area (Bq/m^2)		Garden-soil activity per unit soil mass (Bq/kg)	
			Tillage	*Critical thickness*	*Tillage*	*Critical thickness*
NNSS 1992						
^{3}H	NA	$8.04 \times 10^{+1}$	NA	NA	NA	$8.04 \times 10^{+1}$
^{14}C	$5.09 \times 10^{+1}$	1.36×10^{-1}	$2.60 \times 10^{+1}$	$1.48 \times 10^{+1}$	6.93×10^{-2}	$4.93 \times 10^{+0}$
^{36}Cl	$5.81 \times 10^{+3}$	$1.55 \times 10^{+1}$	$2.97 \times 10^{+3}$	$2.08 \times 10^{+0}$	$7.92 \times 10^{+0}$	6.93×10^{-1}
^{99}Tc	$4.95 \times 10^{+3}$	$1.32 \times 10^{+1}$	$2.53 \times 10^{+3}$	$1.77 \times 10^{+0}$	$6.75 \times 10^{+0}$	5.91×10^{-1}
^{129}I	$1.43\times 10^{+1}$	3.82×10^{-2}	$7.32 \times 10^{+0}$	5.18×10^{-3}	1.95×10^{-2}	1.73×10^{-3}
ALMENDRO 2009						
^{3}H	NA	$9.38 \times 10^{+1}$	NA	NA	NA	$9.38 \times 10^{+1}$
^{14}C	$2.36 \times 10^{+0}$	6.30×10^{-3}	$1.21 \times 10^{+0}$	6.88×10^{-1}	3.22×10^{-3}	2.29×10^{-1}
^{36}Cl	$5.33 \times 10^{+2}$	$1.42 \times 10^{+0}$	$2.72 \times 10^{+2}$	1.91×10^{-1}	7.26×10^{-1}	6.36×10^{-2}
^{99}Tc	$4.27 \times 10^{+1}$	1.14×10^{-1}	$2.18 \times 10^{+1}$	1.53×10^{-2}	5.82×10^{-2}	5.09×10^{-3}
^{129}I	$5.73 \times 10^{+1}$	1.53×10^{-1}	$2.93 \times 10^{+1}$	2.07×10^{-2}	7.81×10^{-2}	6.90×10^{-3}

NA = not applicable.

Table B-9. Nominal values of parameters for determining particle resuspension and deriving air concentrations.

COC	Garden-soil activity per unit soil mass with respect to *critical thickness* and applicable to plant and human exposure pathways (Bq/kg)		Mass loading factor for resuspended particulates from cultivated landscape (S; kg/m^3)	Critical thickness activity concentration of particulates in air and applicable to plants (C_p; Bq/m^3)		Enhancement factor (E; dimensionless)		Activity concentration in outdoor (garden) air from resuspended particulates and applicable to human inhalation (C_h; Bq/m^3)	
	NNSS 1992	ALMENDRO 2009		NNSS 1992	ALMENDRO 2009	Indoor	Outdoor	NNSS 1992	ALMENDRO 2009
^{3}H	$8.04 \times 10^{+1}$	$9.38 \times 10^{+1}$	1.2×10^{-7}	9.65×10^{-6}	1.13×10^{-5}	1	4	3.86×10^{-5}	4.50×10^{-5}
^{14}C	$4.93 \times 10^{+0}$	2.29×10^{-1}	1.2×10^{-7}	5.92×10^{-7}	2.75×10^{-8}	1	4	2.37×10^{-6}	1.10×10^{-7}
^{36}Cl	6.93×10^{-1}	6.36×10^{-2}	1.2×10^{-7}	8.31×10^{-8}	7.63×10^{-9}	1	4	3.33×10^{-7}	3.05×10^{-8}
^{99}Tc	5.91×10^{-3}	5.09×10^{-3}	1.2×10^{-7}	7.09×10^{-8}	6.11×10^{-10}	1	4	2.84×10^{-7}	2.44×10^{-9}
^{129}I	1.73×10^{-3}	6.90×10^{-3}	1.2×10^{-7}	2.07×10^{-10}	8.28×10^{-10}	1	4	8.28×10^{-10}	3.31×10^{-9}

Table B-10. Data for evaporative cooler units used in residential structures of biosphere and the indoor air inhalation concentrations that result for contaminants of concern (COCs).

COC	Activity concentration in groundwater (Bq/m^3)	Water-to-indoor-air transfer factor (M; dimensionless)	Water evaporation rate [f_{evap}; $(m^3/h)_{water}$]	Airflow rate through evaporative cooling unit [F_{air}; $(m^3/h)_{air}$]	Activity concentration in *indoor air* from evaporative cooling applicable to human inhalation (C_h; Bq/m^3)
NNSS 1992					
^{3}H	$6.03\times 10^{+5}$	0.5	0.017	8300	6.18×10^{-1}
^{14}C	$6.29 \times 10^{+2}$	0.5	0.017	8300	6.44×10^{-4}
^{36}Cl	$2.52 \times 10^{+3}$	0.5	0.017	8300	2.58×10^{-3}
^{99}Tc	$2.15 \times 10^{+3}$	0.5	0.017	8300	2.20×10^{-3}
^{129}I	3.70×10^{-1}	0.5	0.017	8300	3.79×10^{-7}
ALMENDRO 2009					
^{3}H	$7.04\times 10^{+5}$	0.5	0.017	8300	7.21×10^{-1}
^{14}C	$2.92 \times 10^{+1}$	0.5	0.017	8300	2.99×10^{-5}
^{36}Cl	$2.31 \times 10^{+2}$	0.5	0.017	8300	2.36×10^{-4}
^{99}Tc	$1.85 \times 10^{+1}$	0.5	0.017	8300	1.89×10^{-5}
^{129}I	$1.48 \times 10^{+0}$	0.5	0.017	8300	1.52×10^{-6}

Table B-11A. ^{14}C data and results applicable to outdoor (garden and field) air activity concentration for inhalation by RMEI.

			Garden crops			Field crops	
			Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Activity concentration in groundwater	NNSS 1992	(C_w; Bq/m^3)	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$
	ALMENDRO 2009	(C_w; Bq/m^3)	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$
Irrigation rates (average annual)	Garden	(IR; m/yr)	9.10×10^{-1}	9.10×10^{-1}	9.10×10^{-1}	9.10×10^{-1}	9.10×10^{-1}
	Field	(IR; m/yr)	$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$
Landscape area	Garden	(A; m^2)	$2.00 \times 10^{+3}$	$2.00 \times 10^{+3}$	$2.00 \times 10^{+3}$	NA	NA
	Field	(A; m^2)	NA	NA	NA	$2.30 \times 10^{+6}$	$2.30 \times 10^{+6}$
Emission rate constant of $^{14}CO_2$ from soil		($\lambda_{a(C\text{-}14)}$; 1/yr)	22	22	22	22	22
Effective removal rate constant for ^{14}C from soil (tillage), including gas emission		($\lambda_{eff[C\text{-}14(garden)]}$; 1/yr)	22.012	22.012	22.012	22.012	22.012
Activity concentration per unit area in surface soil (tillage)	**NNSS 1992**(C_s; Bq/m^2)		$2.6 \times 10^{+1}$	$2.6 \times 10^{+1}$	$2.6 \times 10^{+1}$	$5.09 \times 10^{+1}$	$5.09 \times 10^{+1}$
	ALMENDRO 2009 (C_s; Bq/m^2)		$1.21 \times 10^{+0}$	$1.21 \times 10^{+0}$	$1.21 \times 10^{+0}$	$2.36 \times 10^{+0}$	$2.36 \times 10^{+0}$
Annual average wind speed for 2 m above surface		(U; m/s)	2.45	2.45	2.45	2.45	2.45
		Unit conversion factor (s/yr)	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$
$^{14}CO_{2(gas)}$ mixing height (m)			2	2	2	2	2
NNSS 1992 flux density of $CO_{2(gas)}$ from soil	Garden	[EVSN; Bq/(m^2·yr)]	$5.72 \times 10^{+2}$	$5.72 \times 10^{+2}$	$5.72 \times 10^{+2}$	$5.72 \times 10^{+2}$	$5.72 \times 10^{+2}$
	Field	[EVSN; Bq/(m^2·yr)]	$1.12 \times 10^{+3}$	$1.12 \times 10^{+3}$	$1.12 \times 10^{+3}$	$1.12 \times 10^{+3}$	$1.12 \times 10^{+3}$
ALMENDRO 2009 flux density of $CO_{2(gas)}$ from soil	Garden	[EVSN; Bq/(m^2·yr)]	$1.21 \times 10^{+0}$	$1.21 \times 10^{+0}$	$1.21 \times 10^{+0}$	$1.21 \times 10^{+0}$	$1.21 \times 10^{+0}$
	Field	[EVSN; Bq/(m^2·yr)]	$2.36 \times 10^{+0}$	$2.36 \times 10^{+0}$	$2.36 \times 10^{+0}$	$2.36 \times 10^{+0}$	$2.36 \times 10^{+0}$
NNSS 1992 activity concentration applicable to human inhalation of $^{14}CO_2$	Garden	($C_{gas(C\text{-}14)}$; Bq/m^3)$_{CO2}$	1.65×10^{-4}	1.65×10^{-4}	1.65×10^{-4}	NA	NA
	Field	($C_{gas(C\text{-}14)}$; Bq/m^3)$_{CO2}$	NA	NA	NA	1.10×10^{-2}	1.10×10^{-2}
ALMENDRO 2009 activity concentration applicable to human inhalation of $^{14}CO_2$	Garden	($C_{gas(C\text{-}14)}$; Bq/m^3)$_{CO2}$	7.96×10^{-6}	7.96×10^{-6}	7.96×10^{-6}	NA	NA
	Field	($C_{gas(C\text{-}14)}$; Bq/m^3)$_{CO2}$	NA	NA	NA	5.09×10^{-4}	5.09×10^{-4}

NA = not applicable.

Table B-11B. ^{14}C data, outdoor air (garden and field) activity concentration of $^{14}CO_2$, and uptake by garden and field crops.

Parameter			Garden crops: Leafy vegetable	Garden crops: Other vegetable	Garden crops: Fruit	Field crops: Grain	Field crops: Forage
Activity concentration in groundwater	NNSS 1992	(C_w; Bq/m^3)	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$	$6.29 \times 10^{+2}$
	ALMENDRO 2009	(C_w; Bq/m^3)	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$	$2.92 \times 10^{+1}$
Crop specific irrigation rates daily		(IRD; m/d)	5.41×10^{-3}	7.71×10^{-3}	7.41×10^{-3}	4.64×10^{-3}	6.55×10^{-3}
Crop specific growing time		(t_g; d/y)	$7.5 \times 10^{+1}$	$8.0 \times 10^{+1}$	$1.6 \times 10^{+2}$	$2.0 \times 10^{+2}$	$7.5 \times 10^{+1}$
Crop specific annual irrigation rate		(IR_p; m/y)	4.06×10^{-1}	6.17×10^{-1}	$1.19 \times 10^{+0}$	9.28×10^{-1}	4.91×10^{-1}
Effective removal rate constant for ^{14}C from soil (tillage), including gas emission		($\lambda_{eff[C\text{-}14(garden)]}$; 1/yr)	22.012	22.012	22.012	22.012	22.012
Activity concentration per unit area in surface soil (tillage) (C_s; Bq/m^2)$_{crop\ specific}$	**NNSS 1992**		$1.16 \times 10^{+1}$	$1.76 \times 10^{+1}$	$3.39 \times 10^{+1}$	$2.65 \times 10^{+1}$	$1.40 \times 10^{+1}$
	ALMENDRO 2009		5.39×10^{-1}	8.19×10^{-1}	$1.57 \times 10^{+0}$	$1.23 \times 10^{+0}$	6.52×10^{-1}
Emission rate constant of $^{14}CO_2$ from soil		($\lambda_{a(C\text{-}14)}$; 1/yr)	22	22	22	22	22
Flux density of $CO_{2(gas)}$ from soil [EVSN; Bq/(m^2·yr)]	**NNSS 1992**		$2.55 \times 10^{+2}$	$3.88 \times 10^{+2}$	$7.45 \times 10^{+2}$	$5.83 \times 10^{+2}$	$3.09 \times 10^{+2}$
	ALMENDRO 2009		$1.19 \times 10^{+1}$	$1.80 \times 10^{+1}$	$3.46 \times 10^{+1}$	$2.71\times 10^{+1}$	$1.44 \times 10^{+1}$
Landscape area	Garden	(A; m^2)	$2.00 \times 10^{+3}$	$2.00 \times 10^{+3}$	$2.00 \times 10^{+3}$	NA	NA
	Field	(A; m^2)	NA	NA	NA	$2.30 \times 10^{+6}$	$2.30 \times 10^{+6}$
Annual average wind speed for crops		(U; m/s)	1.9	1.9	1.9	1.9	1.9
	Unit conversion factor (s/yr)		$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$
$^{14}CO_{2(gas)}$ mixing height (m)			1	1	1	1	1
NNSS 1992 activity concentration of $^{14}CO_2$ *applicable to plants*	($C_{gas(C\text{-}14)}$; Bq/m^3)$_{CO2}$		1.90×10^{-4}	2.89×10^{-4}	5.56×10^{-4}	1.47×10^{-2}	7.80×10^{-3}
ALMENDRO 2009 activity concentration of $^{14}CO_2$ *applicable to plants*	($C_{gas(C\text{-}14)}$; Bq/m^3)$_{CO2}$		8.84×10^{-6}	1.34×10^{-5}	2.58×10^{-5}	6.85×10^{-4}	3.63×10^{-4}

NA = not applicable.

Table B-11B. ^{14}C data, outdoor air (garden and field) activity concentration of $^{14}CO_2$, and uptake by crops (continued).

Parameter		Garden crops			Field crops	
		Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Fraction of air-derived carbon in plant crop	(Fa; dimensionless)	0.98	0.98	0.98	0.98	0.98
Fraction of soil-derived carbon in plant crop	[Fs = (1–Fa); dimensionless]	0.02	0.02	0.02	0.02	0.02
Crop-specific (plant) stable carbon fraction	(Fcp; $kg_{carbon}/kg_{wet\ plant}$)	0.09	0.09	0.09	0.4	0.09
Soil stable-carbon fraction	(Fcs; kg_{carbon}/kg_{soil})	0.03	0.03	0.03	0.03	0.03
Air stable-carbon fraction	(Fca; kg_{carbon}/kg_{air})	1.8×10^{-4}	1.8×10^{-4}	1.8×10^{-4}	1.8×10^{-4}	1.8×10^{-4}
Areal density of soil [ρ_s; kg/m^2 = soil bulk density (1500 kg/m^3) × tillage depth (0.25 m)]		$3.75\times 10^{+2}$	$3.75\times 10^{+2}$	$3.75\times 10^{+2}$	$3.75\times 10^{+2}$	$3.75\times 10^{+2}$
NNSS 1992						
Activity concentration of ^{14}C in plant crop root	($C_{p(root)}$; Bq/kg_{wet})	1.86×10^{-3}	2.82×10^{-3}	5.42×10^{-3}	1.89×10^{-2}	2.25×10^{-3}
Activity concentration of ^{14}C in leaf	($C_{p(leaf)}$; Bq/kg_{wet})	9.32×10^{-2}	1.42×10^{-1}	2.72×10^{-1}	$3.21 \times 10^{+1}$	$3.82 \times 10^{+0}$
Activity concentration in edible plant root and leaf	[($C_{p(edible)}$; Bq/kg_{wet}) = $C_{p(root)} + C_{p(leaf)}$]	9.51×10^{-2}	1.45×10^{-1}	2.78×10^{-1}	$3.21 \times 10^{+1}$	$3.83 \times 10^{+0}$
ALMENDRO 2009						
Activity concentration of ^{14}C in plant crop root	($C_{p(root)}$; Bq/kg_{wet})	8.62×10^{-5}	1.31×10^{-4}	2.52×10^{-4}	8.76×10^{-4}	1.04×10^{-4}
Activity concentration of ^{14}C in leaf	($C_{p(leaf)}$; Bq/kg_{wet})	4.33×10^{-3}	6.59×10^{-3}	1.27×10^{-2}	$1.49 \times 10^{+0}$	1.78×10^{-1}
Activity concentration in edible plant root and leaf	[($C_{p(edible)}$; Bq/kg_{wet}) = $C_{p(root)} + C_{p(leaf)}$]	4.42×10^{-3}	6.72×10^{-3}	1.29×10^{-2}	$1.49 \times 10^{+0}$	$1,78 \times 10^{-1}$

Table B-11C. ^{14}C data and uptake by animals from forage and grain feeds.

Parameter		Animal feed [a]		Animal products			
		Forage (vegetables and grass)	Grain (fodder)	Beef (cattle)	Milk (dairy cows)	Poultry	Eggs (hens)
Water stable-carbon concentration	(F_{wc}; kg_{carbon}/L)	2.0×10^{-5}	2.0×10^{-5}	2.0×10^{-5}	2.0×10^{-5}	2.0×10^{-5}	2.0×10^{-5}
Soil stable-carbon concentration	(F_{sc}; kg_{carbon}/kg_{soil})	0.03	0.03	0.03	0.03	0.03	0.03
Feed stable-carbon concentration	(F_{fc}; kg_{carbon}/kg_{feed})	0.09	0.4	NA	NA	NA	NA
Animal stable-carbon concentration	(F_{ac}; kg_{carbon}/kg_{animal})	NA	NA	2.4×10^{-1}	7.0×10^{-2}	2.0×10^{-1}	1.5×10^{-1}
Animal consumption rates (Q)	Feed (Q_f; kg/d)	NA	NA	48.5	61.5	0.26	0.26
	Water (Q_w; L/d = kg/d)	NA	NA	60.0	80.0	0.5	0.5
	Soil (Q_s; kg/d)	NA	NA	0.70	0.95	0.02	0.02
NNSS 1992							
Activity concentration of ^{14}C in groundwater	(C_w; Bq/L_{water})	6.29×10^{-1}	6.29×10^{-1}	6.29×10^{-1}	6.29×10^{-1}	6.29×10^{-1}	6.29×10^{-1}
Activity concentration of ^{14}C in soil	(C_s; Bq/kg_{soil})	1.36×10^{-1}	1.36×10^{-1}	1.36×10^{-1}	1.36×10^{-1}	1.36×10^{-1}	1.36×10^{-1}
Activity concentration in animal feed	(C_f; Bq/kg_{wet})	$3.83 \times 10^{+0}$	$3.21 \times 10^{+1}$	(forage)	(forage)	(grain)	(grain)
$[\Sigma (Q \times C)]_{animal} = (Q_f \times C_f)_{animal} + (Q_w \times C_w)_{animal} + (Q_s \times C_s)_{animal}$	(Bq/d)	NA	NA	$2.23 \times 10^{+2}$	$2.86 \times 10^{+2}$	$8.67 \times 10^{+0}$	$8.67 \times 10^{+0}$
$[\Sigma (Q \times F)]_{animal} = (Q_f \times F_{fc})_{animal} + (Q_w \times F_{wc})_{animal} + (Q_s \times F_{sc})_{animal}$	(kg/d)	NA	NA	$4.39 \times 10^{+0}$	$5.57 \times 10^{+0}$	1.05×10^{-1}	1.05×10^{-1}
$[\Sigma (Q \times C)/\Sigma (Q \times F)]_{animal} \times F_{ac(animal)}$	($C_{dc(animal)}$; Bq/kg)	NA	NA	$1.22 \times 10^{+1}$	$3.59 \times 10^{+0}$	$1.66 \times 10^{+1}$	$1.24 \times 10^{+1}$

NA = not applicable.

Table B-11C. ^{14}C data and uptake by animals from forage and grain feeds (continued).

ALMENDRO 2009							
		Animal feed [a]		Animal products			
Parameter		Forage (vegetables and grass)	Grain (fodder)	Beef (cattle)	Milk (dairy cows)	Poultry	Eggs (hens)
Activity concentration of ^{14}C in groundwater	(C_w; Bq/L_{water})	2.92×10^{-2}	2.92×10^{-2}	2.92×10^{-2}	2.92×10^{-2}	2.92×10^{-2}	2.92×10^{-2}
Activity concentration of ^{14}C in soil	(C_s; Bq/kg_{soil})	6.30×10^{-3}	6.30×10^{-3}	6.30×10^{-3}	6.30×10^{-3}	6.30×10^{-3}	6.30×10^{-3}
Activity concentration in animal feed	(C_f; Bq/kg_{wet})	1.78×10^{-1}	$1.49 \times 10^{+0}$	(forage)	(forage)	(grain)	(grain)
$[\Sigma (Q \times C)]_{animal} = (Q_f \times C_f)_{animal} + (Q_w \times C_w)_{animal} + (Q_s \times C_s)_{animal}$	(Bq/d)	NA	NA	$1.04 \times 10^{+1}$	$1.33 \times 10^{+1}$	4.03×10^{-1}	4.03×10^{-1}
$[\Sigma (Q \times F)]_{animal} = (Q_f \times F_{fc})_{animal} + (Q_w \times F_{wc})_{animal} + (Q_s \times F_{sc})_{animal}$	(kg/d)	NA	NA	$4.39 \times 10^{+0}$	$5.57 \times 10^{+0}$	1.05×10^{-1}	1.05×10^{-1}
$[\Sigma (Q \times C)/\Sigma (Q \times F)]_{animal} \times F_{ac(animal)}$	($C_{dc(animal)}$; Bq/kg)	NA	NA	5.68×10^{-1}	1.67×10^{-1}	7.70×10^{-1}	5.78×10^{-1}

[a] Forage applicable to beef (cattle) and milk (dairy cows) and grain applicable to poultry and eggs (hens).
NA = not applicable.

Table B-12A. ^{3}H data and activity concentration in air applicable to human inhalation.

			Garden crops			Field crops	
			Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Activity concentration in groundwater (C_w; Bq/m^3)	NNSS 1992		$6.03 \times 10^{+5}$	$6.03 \times 10^{+5}$	$6.03 \times 10^{+5}$	$6.03 \times 10^{+5}$	$6.03 \times 10^{+5}$
	ALMENDRO 2009		$7.04 \times 10^{+5}$	$7.04 \times 10^{+5}$	$7.04 \times 10^{+5}$	$7.04 \times 10^{+5}$	$7.04 \times 10^{+5}$
Irrigation rates (IR; m/yr)	Garden		9.10×10^{-1}	9.10×10^{-1}	9.10×10^{-1}	9.10×10^{-1}	9.10×10^{-1}
	Field		$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$	$1.78 \times 10^{+0}$
Landscape area (A; m^2)	Garden		$2.00 \times 10^{+3}$	$2.00 \times 10^{+3}$	$2.00 \times 10^{+3}$	NA	NA
	Field		NA	NA	NA	$2.30 \times 10^{+6}$	$2.30 \times 10^{+6}$
Annual average wind speed for 2 m above surface (U; m/s)			2.45	2.45	2.45	2.45	2.45
Unit conversion factor (s/yr)			$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$	$3.156 \times 10^{+7}$
HTO_{vapor} mixing height (m)			2	2	2	2	2
Evapotransportation coefficient (T; dimensionless)			0.5	0.5	0.5	0.5	0.5
Runoff coefficient (R; dimensionless)			0.2	0.2	0.2	0.2	0.2
Precipitation rate (characteristic of Beatty, NV; m/yr)			0.15	0.15	0.15	0.15	0.15
Evapotransportation rate (E_t; m/yr)		Garden	5.15×10^{-1}	5.15×10^{-1}	5.15×10^{-1}	5.15×10^{-1}	5.15×10^{-1}
		Field	9.50×10^{-1}	9.50×10^{-1}	9.50×10^{-1}	9.50×10^{-1}	9.50×10^{-1}
Flux density of vapor from soil [EVSN; Bq/(m^2·yr)]	NNSS 1992	Garden	$3.11 \times 10^{+5}$	$3.11 \times 10^{+5}$	$3.11 \times 10^{+5}$	$3.11 \times 10^{+5}$	$3.11 \times 10^{+5}$
		Field	$5.73 \times 10^{+5}$	$5.73 \times 10^{+5}$	$5.73 \times 10^{+5}$	$5.73 \times 10^{+5}$	$5.73 \times 10^{+5}$
	ALMENDRO 2009	Garden	$3.62 \times 10^{+5}$	$3.62 \times 10^{+5}$	$3.62 \times 10^{+5}$	$3.62 \times 10^{+5}$	$3.62 \times 10^{+5}$
		Field	$6.69 \times 10^{+5}$	$6.69 \times 10^{+5}$	$6.69 \times 10^{+5}$	$6.69 \times 10^{+5}$	$6.69 \times 10^{+5}$

Table B-12A. ^{3}H data and activity concentration in air applicable to human inhalation (continued).

		Garden crops			Field crops	
		Leafy vegetable	Other vegetable	Fruit	Grain	Forage
NNSS 1992 activity concentration applicable to human inhalation (C_{vapor}; $Bq/m^3)_{air}$	Garden	8.99×10^{-2}	8.99×10^{-2}	8.99×10^{-2}	NA	NA
	Field	NA	NA	NA	$5.61\times 10^{+0}$	$5.61\times 10^{+0}$
ALMENDRO 2009 activity concentration applicable to human inhalation (C_{vapor}; $Bq/m^3)_{air}$	Garden	1.05×10^{-1}	1.05×10^{-1}	1.05×10^{-1}	NA	NA
	Field	NA	NA	NA	$6.55\times 10^{+0}$	$6.55\times 10^{+0}$
Mass fraction of hydrogen in plant (dimensionless)		0.10	0.10	0.10	0.10	0.10
Mass fraction of hydrogen in water ($2_H/18_{H2O}$ = 1/9; dimensionless)		0.111	0.111	0.111	0.111	0.111
NNSS 1992 activity concentration in garden and field crops applicable to human dietary ingestion of plants (C_{plant}; Bq/kg_{crop})	Garden	$5.50 \times 10^{+2}$	$5.50 \times 10^{+2}$	$5.50 \times 10^{+2}$	NA	NA
	Field	NA	NA	NA	$3.69 \times 10^{+2}$	$5.50 \times 10^{+2}$
ALMENDRO 2009 activity concentration in garden and field crops applicable to human dietary ingestion of plants (C_{plant}; Bq/kg_{crop})	Garden	$6.42 \times 10^{+2}$	$6.42 \times 10^{+2}$	$6.42 \times 10^{+2}$		
	Field				$4.30 \times 10^{+2}$	$6.42 \times 10^{+2}$

NA = not applicable.

Table B-12B. ^{3}H data and uptake into animal products from forage or grain feeds (based on NNSS 1992 atom inventory).

NNSS 1992							
		Animal feed		Animal products			
Parameter		Forage (vegetables and grass)	Grain (fodder)	Beef (cattle)	Milk (dairy cows)	Poultry	Eggs (hens)
Activity concentration in groundwater	(C_w; Bq/kg)	603	603	603	603	603	603
Activity concentration in soil	(C_s; Bq/kg)	80.4	80.4	80.4	80.4	80.4	80.4
Dietary item water fraction	(F_{dw}; dimensionless)	0.80	0.12	0.60	0.88	0.70	0.75
Dietary item (dry) hydrogen fraction	(F_{dh}; dimensionless)	0.062	0.062	0.094	0.083	0.087	0.092
Dietary item (edible) hydrogen fraction	(F_{de}; dimensionless) = $(F_{dw}/9) + [F_{dh} \times (1-F_{dw})]$	0.10	0.068	0.10	0.11	0.10	0.11
Water and soil-water hydrogen fraction	(F_{hs}; dimensionless)	1/9	1/9	1/9	1/9	1/9	1/9
Activity concentration in feed	(C_f; Bq/kg)	$5.50 \times 10^{+2}$	$3.69 \times 10^{+2}$	(forage)	(forage)	(grain)	(grain)
Animal consumption rates (Q)	Feed (Q_f; kg/d)	NA	NA	48.5	61.5	0.26	0.26
	Water (Q_w; L/d = kg/d)	NA	NA	60.0	80.0	0.5	0.5
	Soil (Q_s; kg/d)	NA	NA	0.70	0.95	0.02	0.02
$[\Sigma (Q \times C)]_{animal} = (Q_{(f)eed} \times C_{(f)eed}) + (Q_{w(animal)} \times C_w) + (Q_{s(animal)} \times C_s)$	(Bq/d)	NA	NA	$6.29 \times 10^{+4}$	$8.22 \times 10^{+4}$	$3.99 \times 10^{+2}$	$3.99 \times 10^{+2}$
$[\Sigma (Q \times F)]_{animal} = (Q_{f(feed)} \times F_{de(feed)}) + (Q_{w(animal)} \times F_{hs}) + (Q_{s(animal)} \times F_{hs})$	(kg/d)	NA	NA	$1.17 \times 10^{+1}$	$1.52 \times 10^{+1}$	7.54×10^{-2}	7.54×10^{-2}
$[\Sigma (Q \times C)/\Sigma (Q \times F)]_{animal} \times F_{de(animal)}$	($C_{d(animal)}$; Bq/kg)	NA	NA	$5.63 \times 10^{+2}$	$5.81 \times 10^{+2}$	$5.50 \times 10^{+2}$	$5.63 \times 10^{+2}$

NA = not applicable.

Table B-12B. ^{3}H data and uptake into animal products from forage or grain feeds (based on ALMENDRO 2009 atom inventory) (continued).

ALMENDRO 2009							
		Animal feed		Animal products			
Parameter		Forage (vegetables and grass)	Grain (fodder)	Beef (cattle)	Milk (dairy cows)	Poultry	Eggs (hens)
Activity concentration in groundwater	(C_w; Bq/kg)	704	704	704	704	704	704
Activity concentration in soil	(C_s; Bq/kg)	93.8	93.8	93.8	93.8	93.8	93.8
Dietary item water fraction	(F_{dw}; dimensionless)	0.80	0.12	0.60	0.88	0.70	0.75
Dietary item (dry) hydrogen fraction	(F_{dh}; dimensionless)	0.062	0.062	0.094	0.083	0.087	0.092
Dietary item (edible) hydrogen fraction	(F_{de}; dimensionless) = $(F_{dw}/9) + [F_{dh} \times (1-F_{dw})]$	0.10	0.068	0.10	0.11	0.10	0.11
Water and soil-water hydrogen fraction	(F_h; dimensionless)	1/9	1/9	1/9	1/9	1/9	1/9
Activity concentration in vegetation	(C_f; Bq/kg)	$6.42 \times 10^{+5}$	$4.30 \times 10^{+5}$	(forage)	(forage)	(grain)	(grain)
Animal consumption rates (Q)	Feed (Q_f; kg/d)	NA	NA	48.5	61.5	0.26	0.26
	Water (Q_w; L/d = kg/d)	NA	NA	60.0	80.0	0.5	0.5
	Soil (Q_s; kg/d)	NA	NA	0.70	0.95	0.02	0.02
$[\Sigma (Q \times C)]_{animal} = (Q_{(f)eed} \times C_{(f)eed}) + (Q_{w(animal)} \times C_w) + (Q_{s(animal)} \times C_s)$	(Bq/d)	NA	NA	$7.34 \times 10^{+4}$	$9.59 \times 10^{+4}$	$4.66 \times 10^{+2}$	$4.66 \times 10^{+2}$
$[\Sigma (Q \times F)]_{animal} = (Q_{f(feed)} \times F_{de(feed)}) + (Q_{w(animal)} \times F_{hs}) + (Q_{s(animal)} \times F_{hs})$	(kg/d)	NA	NA	$1.17 \times 10^{+1}$	$1.52 \times 10^{+1}$	7.54×10^{-2}	7.54×10^{-2}
$[\Sigma (Q \times C)/\Sigma (Q \times F)]_{animal} \times F_{de(animal)}$	($C_{d(animal)}$; Bq/kg)	NA	NA	$6.57 \times 10^{+2}$	$6.78 \times 10^{+2}$	$6.41 \times 10^{+2}$	$6.56 \times 10^{+2}$

NA = not applicable.

Table B-13A. ^{36}Cl data and activity concentration in garden and field crops.

		Garden crops			Field crops	
		Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Activity concentration in groundwater (C_w; Bq/m^3)	**NNSS 1992**	$2.52 \times 10^{+3}$	$2.52 \times 10^{+3}$	$2.52 \times 10^{+3}$	$2.52 \times 10^{+3}$	$2.52 \times 10^{+3}$
	ALMENDRO 2009	$2.31 \times 10^{+2}$	$2.31 \times 10^{+2}$	$2.31 \times 10^{+2}$	$2.31 \times 10^{+2}$	$2.31 \times 10^{+2}$
Crop specific soil-to-plant transfer factor (tf; Bq/kg$_{dry\ plant}$/Bq/kg$_{dry\ air}$)		$6.40 \times 10^{+1}$	$6.40 \times 10^{+1}$	$6.40 \times 10^{+1}$	$2.40 \times 10^{+1}$	$7.50 \times 10^{+1}$
Dry-to-wet mass ratio (dwr; kg$_{dry\ plant}$/kg$_{wet\ plant}$)		0.070	0.103	0.120	0.903	0.220
Soil activity concentration with respect to tillage (Bq/kg$_{soil}$)	**NNSS 1992**	7.92	7.92	7.92	15.5	15.5
	ALMENDRO 2009	0.726	0.726	0.726	1.42	1.42
Root activity concentration for plant crop ($C_{p(root)}$; Bq/kg$_{wet}$)	**NNSS 1992**	$3.55 \times 10^{+1}$	$5.22 \times 10^{+1}$	$6.08 \times 10^{+1}$	$3.36 \times 10^{+2}$	$2.55 \times 10^{+2}$
	ALMENDRO 2009	$3.25 \times 10^{+0}$	$4.79 \times 10^{+0}$	$5.58 \times 10^{+0}$	$3.08 \times 10^{+1}$	$2.34 \times 10^{+1}$
Irrigation rate daily (IRD; m/d)		5.41×10^{-3}	7.71×10^{-3}	7.41×10^{-3}	4.64×10^{-3}	6.55×10^{-3}
Irrigation water deposition rate on foliar surface (δ; Bq/(m^2·d)	**NNSS 1992**	$1.36 \times 10^{+1}$	$1.94 \times 10^{+1}$	$1.86 \times 10^{+1}$	$1.17 \times 10^{+1}$	$1.65 \times 10^{+1}$
	ALMENDRO 2009	$1.25 \times 10^{+0}$	$1.78 \times 10^{+0}$	$1.71 \times 10^{+0}$	$1.07 \times 10^{+0}$	$1.51 \times 10^{+0}$
Overhead irrigation factor (dimensionless)		0.75	0.75	0.50	0.90	0.90
Factors for deriving interception factor (R_w): $K_1 = 2.29$; $K_2 = 0.695$; $K_3 = -0.29$; $K_4 = -0.341$: where $R_w = K_1 \times DB^K2 \times IA^K3 \times I^K4$, and						
Standing biomass (DB; kg$_{dry}$/m^2)		0.21	0.43	0.62	1.13	0.48
Irrigation per application event (IA; mm)		14.7	26	33.9	56.7	57.8
Irrigation intensity (I; cm/h)		4.3	4.3	4.3	4.3	4.3
Interception fraction of irrigation water (R_w; dimensionless)		0.22	0.30	0.36	0.47	0.26

Table B-13A. ^{36}Cl data and activity concentration in garden and field crops (continued).

		Garden crops			Field crops	
		Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Translocation factor (M; dimensionless)		1.00	0.10	0.10	0.10	1.00
Weathering constant derived from 14-d weathering half-life; [λ_w; 1/d = ln(2)/(14-d)]		0.05	0.05	0.05	0.05	0.05
Wet biomass crop yield (Y; kg_{wet}/m^2)		3.30	4.13	2.75	0.59	2.14
Crop growing time (t_g = d)		75.00	80.00	160.00	200.00	75.00
Multiplier [dimensionless; $1–exp(–\lambda_w \cdot t_g)$]		0.98	0.98	1.00	1.00	0.98
Crop leaf activity concentration ($C_{p(leaf)}$; Bq/kg_{wet})	NNSS 1992	13.16	2.10	2.46	16.91	35.21
	ALMENDRO 2009	1.21	0.19	0.23	1.55	3.23
Critical thickness air particulate activity concentration (Bq/m^3)	NNSS 1992	8.31×10^{-8}	8.31×10^{-8}	8.31×10^{-8}	8.31×10^{-8}	8.31×10^{-8}
	ALMENDRO 2009	7.63×10^{-9}	7.63×10^{-9}	7.63×10^{-9}	7.63×10^{-9}	7.63×10^{-9}
Aerosol particulate (dry) deposition velocity (V_d; m/s)		0.008	0.008	0.008	0.008	0.008
Unit conversion (s/d)		$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$
Aerosol particulate (dry dust) deposition rate [Da; $Bq/(m^2 \cdot d)$]	NNSS 1992	5.75×10^{-5}	5.75×10^{-5}	5.75×10^{-5}	5.75×10^{-5}	5.75×10^{-5}
	ALMENDRO 2009	5.27×10^{-6}	5.27×10^{-6}	5.27×10^{-6}	5.27×10^{-6}	5.27×10^{-6}
Empirical factor (a; m^2/kg)		2.9	3.6	3.6	2.9	2.9
Multiplier [$1–exp(–a \cdot DB)$; dimensionless]		0.456	0.787	0.893	0.962	0.751
Interception fraction for airborne particles (R_a = 1–Multiplier; dimensionless)		0.544	0.213	0.107	0.038	0.249
Crop activity concentration from dust uptake ($C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992	1.87×10^{-4}	5.86×10^{-6}	4.53×10^{-6}	7.42×10^{-6}	1.32×10^{-4}
	ALMENDRO 2009	1.71×10^{-5}	5.38×10^{-7}	4.15×10^{-7}	6.81×10^{-7}	1.21×10^{-5}
Total activity concentration in crop plant ($C_{p(total)} = C_{p(root)} + C_{p(leaf)} + C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992	$4.86 \times 10^{+1}$	$5.43 \times 10^{+1}$	$6.33 \times 10^{+1}$	$3.52 \times 10^{+2}$	$2.91 \times 10^{+2}$
	ALMENDRO 2009	$4.46 \times 10^{+0}$	$4.98 \times 10^{+0}$	$5.80 \times 10^{+0}$	$3.23 \times 10^{+1}$	$2.67 \times 10^{+1}$

Table B-13B. ^{36}Cl data and activity concentration in animal products from forage and grain feeds.

Parameter			Animal feed: Forage (vegetables and grass)	Animal feed: Grain (fodder)	Animal products: Beef (cattle); from forage	Animal products: Milk (dairy cows); from forage	Animal products: Poultry; from grain	Animal products: Eggs (hens); from grain
Activity concentration in groundwater (C_w; Bq/L)	NNSS 1992		$2.52 \times 10^{+0}$	$2.52 \times 10^{+0}$	$2.52 \times 10^{+0}$	$2.52 \times 10^{+0}$	$2.52 \times 10^{+0}$	$2.52 \times 10^{+0}$
	ALMENDRO 2009		2.31×10^{-1}	2.31×10^{-1}	2.31×10^{-1}	2.31×10^{-1}	2.31×10^{-1}	2.31×10^{-1}
Activity concentration in soil relative to tillage (C_s; Bq/kg)	NNSS 1992		$1.55 \times 10^{+1}$	$1.55 \times 10^{+1}$	$1.55 \times 10^{+1}$	$1.55 \times 10^{+1}$	$1.55 \times 10^{+1}$	$1.55 \times 10^{+1}$
	ALMENDRO 2009		$1.42 \times 10^{+0}$	$1.42 \times 10^{+0}$	$1.42 \times 10^{+0}$	$1.42 \times 10^{+0}$	$1.42 \times 10^{+0}$	$1.42 \times 10^{+0}$
Total activity concentration in feed (forage and grain plants) ($C_f = C_{p(root)} + C_{p(leaf)} + C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992		$3.52 \times 10^{+2}$	$2.91 \times 10^{+2}$	NA	NA	NA	NA
	ALMENDRO 2009		$3.23 \times 10^{+1}$	$2.67 \times 10^{+1}$	NA	NA	NA	NA
Animal intake to animal product transfer coefficient (F_m; $d/kg_{fresh(wet)}$ and $d/L_{milk} = d/kg_{milk}$)			NA	NA	4.6×10^{-2}	1.8×10^{-2}	3.0×10^{-2}	4.4×10^{-2}
Animal consumption rates (Q)	Feed	(Q_f; kg/d)	NA	NA	48.5	61.5	0.26	0.26
	Water	(Q_w; L/d = kg/d)	NA	NA	60	80	0.5	0.5
	Soil	(Q_s; kg/d)	NA	NA	0.7	0.95	0.02	0.02
Activity concentration in animal product $[C_{d(animal)} = \{(Q_f \times C_f)_{animal} + (Q_w \times C_w)_{animal} + (Q_s \times C_s)_{animal}\} \times F_m$; Bq/d]	NNSS 1992		NA	NA	$6.56 \times 10^{+2}$	$3.26 \times 10^{+2}$	$2.80 \times 10^{+0}$	$4.10 \times 10^{+0}$
	ALMENDRO 2009		NA	NA	$6.02 \times 10^{+1}$	$2.99 \times 10^{+1}$	2.57×10^{-1}	3.76×10^{-1}

NA = not applicable.

Table B-14A. ^{99}Tc data and activity concentration in garden and field crops.

		Garden crops			Field crops	
		Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Activity concentration in groundwater (C_w; Bq/m^3)	NNSS 1992	$2.15 \times 10^{+3}$	$2.15 \times 10^{+3}$	$2.15 \times 10^{+3}$	$2.15 \times 10^{+3}$	$2.15 \times 10^{+3}$
	ALMENDRO 2009	$1.85 \times 10^{+1}$	$1.85 \times 10^{+1}$	$1.85 \times 10^{+1}$	$1.85 \times 10^{+1}$	$1.85 \times 10^{+1}$
Crop specific soil-to-plant transfer factor (tf; Bq/kg$_{dry\ plant}$/Bq/kg$_{dry\ air}$)		$4.60 \times 10^{+1}$	$4.40 \times 10^{+0}$	$4.30 \times 10^{+0}$	$1.60 \times 10^{+0}$	$2.70 \times 10^{+1}$
Dry-to-wet mass ratio (dwr; kg$_{dry\ plant}$/kg$_{wet\ plant}$)		0.070	0.103	0.120	0.903	0.220
Soil activity concentration with respect to tillage (Bq/kg$_{soil}$)	NNSS 1992	6.75	6.75	6.75	13.2	13.2
	ALMENDRO 2009	0.0582	0.0582	0.0582	0.114	0.114
Root activity concentration for plant crop ($C_{p(root)}$; Bq/kg$_{wet}$)	NNSS 1992	$2.17 \times 10^{+1}$	$3.06 \times 10^{+0}$	$3.48 \times 10^{+0}$	$1.91 \times 10^{+1}$	$7.85 \times 10^{+1}$
	ALMENDRO 2009	1.87×10^{-1}	2.64×10^{-2}	3.00×10^{-2}	1.64×10^{-1}	6.76×10^{-1}
Irrigation rate daily (IRD; m/d)		5.41×10^{-3}	7.71×10^{-3}	7.41×10^{-3}	4.64×10^{-3}	6.55×10^{-3}
Irrigation water deposition rate on foliar surface (δ; Bq/(m^2·d)	NNSS 1992	$1.16 \times 10^{+1}$	$1.65 \times 10^{+1}$	$1.59 \times 10^{+1}$	$9.96\times 10^{+0}$	$1.41 \times 10^{+1}$
	ALMENDRO 2009	1.00×10^{-1}	1.43×10^{-1}	1.37×10^{-1}	8.58×10^{-2}	1.21×10^{-1}
Overhead irrigation factor (dimensionless)		0.75	0.75	0.50	0.90	0.90
Factors for deriving interception factor (R_w): $K_1 = 2.29$; $K_2 = 0.695$; $K_3 = -0.29$; $K_4 = -0.341$: where $R_w = K_1 \times DB^K2 \times IA^K3 \times I^K4$, and						
Standing biomass (DB; kg$_{dry}$/m^2)		0.21	0.43	0.62	1.13	0.48
Irrigation per application event (IA; mm)		14.7	26	33.9	56.7	57.8
Irrigation intensity (I; cm/h)		4.3	4.3	4.3	4.3	4.3
Interception fraction of irrigation water (R_w; dimensionless)		0.22	0.30	0.36	0.47	0.26

Table B-14A. ^{99}Tc data and activity concentration in garden and field crops (continued).

		Garden crops			Field crops	
		Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Translocation factor (M; dimensionless)		1.00	0.10	0.10	0.10	1.00
Weathering constant derived from 14-d weathering half-life; [λ_w; 1/d = ln(2)/(14-d)]		0.05	0.05	0.05	0.05	0.05
Wet biomass crop yield (Y; kg_{wet}/m^2)		3.30	4.13	2.75	0.59	2.14
Crop growing time (t_g = d)		75.00	80.00	160.00	200.00	75.00
Multiplier [dimensionless; $1-exp(-\lambda_w \cdot t_g)$]		0.98	0.98	1.00	1.00	0.98
Crop leaf activity concentration ($C_{p(leaf)}$; Bq/kg_{wet})	NNSS 1992	11.23	1.79	2.10	14.42	30.03
	ALMENDRO 2009	0.0968	0.0155	0.0181	0.1243	0.2589
Critical thickness air particulate activity concentration (Bq/m^3)	NNSS 1992	7.09×10^{-8}	7.09×10^{-8}	7.09×10^{-8}	7.09×10^{-8}	7.09×10^{-8}
	ALMENDRO 2009	6.11×10^{-10}	6.11×10^{-10}	6.11×10^{-10}	6.11×10^{-10}	6.11×10^{-10}
Aerosol particulate (dry) deposition velocity (V_d; m/s)		0.008	0.008	0.008	0.008	0.008
Unit conversion (s/d)		$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$
Aerosol particulate (dry dust) deposition rate [Da; $Bq/(m^2 \cdot d)$]	NNSS 1992	4.90×10^{-5}	4.90×10^{-5}	4.90×10^{-5}	4.90×10^{-5}	4.90×10^{-5}
	ALMENDRO 2009	4.22×10^{-7}	4.22×10^{-7}	4.22×10^{-7}	4.22×10^{-7}	4.22×10^{-7}
Empirical factor (a; m^2/kg)		2.9	3.6	3.6	2.9	2.9
Multiplier [$1-exp(-a \cdot DB)$; dimensionless]		0.456	0.787	0.893	0.962	0.751
Interception fraction for airborne particles (R_a = 1–Multiplier; dimensionless)		0.544	0.213	0.107	0.038	0.249
Crop activity concentration from dust uptake ($C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992	1.59×10^{-4}	5.00×10^{-6}	3.86×10^{-6}	6.33×10^{-6}	1.12×10^{-4}
	ALMENDRO 2009	1.37×10^{-6}	4.31×10^{-8}	3.33×10^{-8}	5.46×10^{-8}	9.67×10^{-7}
Total activity concentration in crop plant ($C_{p(total)}$ = $C_{p(root)} + C_{p(leaf)} + C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992	$3.30 \times 10^{+1}$	$4.85 \times 10^{+0}$	$5.58 \times 10^{+0}$	$3.35\times 10^{+1}$	$1.08 \times 10^{+2}$
	ALMENDRO 2009	2.84×10^{-1}	4.18×10^{-2}	4.81×10^{-2}	2.89×10^{-1}	9.35×10^{-1}

Table B-14B. ^{99}Tc data and activity concentration in animal products from forage and grain feeds.

Parameter		Animal feed: Forage (vegetables and grass)	Animal feed: Grain (fodder)	Animal products: Beef (cattle); from forage	Animal products: Milk (dairy cows); from forage	Animal products: Poultry; from grain	Animal products: Eggs (hens); from grain
Activity concentration in groundwater (C_w; Bq/L)	NNSS 1992	$2.15 \times 10^{+0}$	$2.15 \times 10^{+0}$	$2.15 \times 10^{+0}$	$2.15 \times 10^{+0}$	$2.15 \times 10^{+0}$	$2.15 \times 10^{+0}$
	ALMENDRO 2009	1.85×10^{-2}	1.85×10^{-2}	1.85×10^{-2}	1.85×10^{-2}	1.85×10^{-2}	1.85×10^{-2}
Activity concentration in soil relative to tillage (C_s; Bq/kg)	NNSS 1992	$1.32 \times 10^{+1}$	$1.32 \times 10^{+1}$	$1.32 \times 10^{+1}$	$1.32 \times 10^{+1}$	$1.32 \times 10^{+1}$	$1.32 \times 10^{+1}$
	ALMENDRO 2009	1.14×10^{-1}	1.14×10^{-1}	1.14×10^{-1}	1.14×10^{-1}	1.14×10^{-1}	1.14×10^{-1}
Total activity concentration in feed (forage and grain plants) ($C_f = C_{p(root)} + C_{p(leaf)} + C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992	$1.08 \times 10^{+2}$	$3.35 \times 10^{+1}$	NA	NA	NA	NA
	ALMENDRO 2009	9.35×10^{-1}	2.89×10^{-1}	NA	NA	NA	NA
Animal intake to animal product transfer coefficient (F_m; $d/kg_{fresh(wet)}$ and $d/L_{milk} = d/kg_{milk}$)		NA	NA	1.1×10^{-3}	2.1×10^{-3}	6.3×10^{-2}	$2.4 \times 10^{+0}$
Animal consumption rates (Q)	Feed (Q_f; kg/d)	NA	NA	48.5	61.5	0.26	0.26
	Water (Q_w; L/d = kg/d)	NA	NA	60	80	0.5	0.5
	Soil (Q_s; kg/d)	NA	NA	0.7	0.95	0.02	0.02
Activity concentration in animal product $[C_{d(animal)} = \{(Q_f \times C_f)_{animal} + (Q_w \times C_w)_{animal} + (Q_s \times C_s)_{animal}\} \times F_m$; Bq/d]	NNSS 1992	NA	NA	$5.94 \times 10^{+0}$	$1.44 \times 10^{+1}$	6.33×10^{-1}	$2.41 \times 10^{+1}$
	ALMENDRO 2009	NA	NA	5.12×10^{-2}	1.24×10^{-1}	5.46×10^{-3}	2.08×10^{-1}

NA = not applicable.

Table B-15A. ^{129}I data and activity concentration in garden and field crops.

		Garden crops			Field crops	
		Leafy vegetables	Other vegetables	Fruit	Grain	Forage
Activity concentration in groundwater (C_w; Bq/m^3)	NNSS 1992	3.70×10^{-1}	3.70×10^{-1}	3.70×10^{-1}	3.70×10^{-1}	3.70×10^{-1}
	ALMENDRO 2009	$1.48 \times 10^{+0}$	$1.48 \times 10^{+0}$	$1.48 \times 10^{+0}$	$1.48 \times 10^{+0}$	$1.48 \times 10^{+0}$
Crop specific soil-to-plant transfer factor (tf; Bq/kg$_{dry\ plant}$/Bq/kg$_{dry\ air}$)		2.60×10^{-2}	5.00×10^{-2}	5.70×10^{-2}	2.5×10^{-2}	4.00×10^{-2}
Dry-to-wet mass ratio (dwr; kg$_{dry\ plant}$/kg$_{wet\ plant}$)		0.070	0.103	0.120	0.903	0.220
Soil activity concentration with respect to tillage (Bq/kg$_{soil}$)	NNSS 1992	0.0195	0.0195	0.0195	0.0382	0.0382
	ALMENDRO 2009	0.0781	0.0781	0.0781	0.153	0.153
Root activity concentration for plant crop ($C_{p(root)}$; Bq/kg$_{wet}$)	NNSS 1992	3.55×10^{-5}	1.04×10^{-4}	1.34×10^{-4}	8.62×10^{-4}	3.36×10^{-4}
	ALMENDRO 2009	1.42×10^{-4}	4.02×10^{-4}	5.34×10^{-4}	3.45×10^{-3}	1.34×10^{-3}
Irrigation rate daily (IRD; m/d)		5.41×10^{-3}	7.71×10^{-3}	7.41×10^{-3}	4.64×10^{-3}	6.55×10^{-3}
Irrigation water deposition rate on foliar surface (δ; Bq/(m^2·d)	NNSS 1992	2.00×10^{-3}	2.85×10^{-3}	2.74×10^{-3}	1.72×10^{-3}	2.42×10^{-3}
	ALMENDRO 2009	8.01×10^{-3}	1.14×10^{-2}	1.10×10^{-2}	6.87×10^{-3}	9.69×10^{-3}
Overhead irrigation factor (dimensionless)		0.75	0.75	0.50	0.90	0.90
Factors for deriving interception factor (R_w): $K_1 = 2.29$; $K_2 = 0.695$; $K_3 = -0.29$; $K_4 = -0.341$: where $R_w = K_1 \times DB^K2 \times IA^K3 \times I^K4$, and						
Standing biomass (DB; kg$_{dry}$/m^2)		0.21	0.43	0.62	1.13	0.48
Irrigation per application event (IA; mm)		14.7	26	33.9	56.7	57.8
Irrigation intensity (I; cm/h)		4.3	4.3	4.3	4.3	4.3
Interception fraction of irrigation water (R_w; dimensionless)		0.22	0.30	0.36	0.47	0.26

Table B-15A. ^{129}I data and activity concentration in garden and field crops (continued).

		Garden crops			Field crops	
		Leafy vegetable	Other vegetable	Fruit	Grain	Forage
Translocation factor (M; dimensionless)		1.00	0.10	0.10	0.10	1.00
Weathering constant derived from 14-d weathering half-life; [λ_w; 1/d = ln(2)/(14-d)]		0.05	0.05	0.05	0.05	0.05
Wet biomass crop yield (Y; kg_{wet}/m^2)		3.30	4.13	2.75	0.59	2.14
Crop growing time (t_g = d)		75.00	80.00	160.00	200.00	75.00
Multiplier [dimensionless; $1-exp(-\lambda_w \cdot t_g)$]		0.98	0.98	1.00	1.00	0.98
Crop leaf activity concentration ($C_{p(leaf)}$; Bq/kg_{wet})	NNSS 1992	0.00194	0.00031	0.00036	0.00249	0.00518
	ALMENDRO 2009	0.00774	0.00124	0.00145	0.00995	0.02071
Critical thickness air particulate activity concentration (Bq/m^3)	NNSS 1992	2.07×10^{-10}	2.07×10^{-10}	2.07×10^{-10}	2.07×10^{-10}	2.07×10^{-10}
	ALMENDRO 2009	8.28×10^{-10}	8.28×10^{-10}	8.28×10^{-10}	8.29×10^{-10}	8.29×10^{-10}
Aerosol particulate (dry) deposition velocity (V_d; m/s)		0.008	0.008	0.008	0.008	0.008
Unit conversion (s/d)		$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$	$8.64 \times 10^{+4}$
Aerosol particulate (dry dust) deposition rate [Da; $Bq/(m^2 \cdot d)$]	NNSS 1992	1.43×10^{-7}	1.43×10^{-7}	1.43×10^{-7}	1.43×10^{-7}	1.43×10^{-7}
	ALMENDRO 2009	5.27×10^{-7}	5.27×10^{-7}	5.27×10^{-7}	5.27×10^{-7}	5.27×10^{-7}
Empirical factor (a; m^2/kg)		2.9	3.6	3.6	2.9	2.9
Multiplier [$1-exp(-a \cdot DB)$; dimensionless]		0.456	0.787	0.893	0.962	0.751
Interception fraction for airborne particles (R_a = 1–Multiplier; dimensionless)		0.544	0.213	0.107	0.038	0.249
Crop activity concentration from dust uptake ($C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992	4.65×10^{-7}	1.46×10^{-8}	1.13×10^{-8}	1.85×10^{-8}	3.28×10^{-7}
	ALMENDRO 2009	1.86×10^{-6}	5.84×10^{-8}	4.51×10^{-8}	7.39×10^{-8}	1.31×10^{-6}
Total activity concentration in crop plant ($C_{p(total)}$ = $C_{p(root)} + C_{p(leaf)} + C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992	1.97×10^{-3}	4.10×10^{-4}	4.95×10^{-4}	3.35×10^{-3}	5.51×10^{-3}
	ALMENDRO 2009	7.89×10^{-3}	1.64×10^{-3}	1.98×10^{-3}	1.34×10^{-2}	2.20×10^{-2}

Table B-15B. ^{129}I data and activity concentration in animal products from forage and grain feeds.

Parameter			Animal feed: Forage (vegetables and grass)	Animal feed: Grain (fodder)	Animal products: Beef (cattle); from forage	Animal products: Milk (dairy cows); from forage	Animal products: Poultry; from grain	Animal products: Eggs (hens); from grain
Activity concentration in groundwater (C_w; Bq/L)	NNSS 1992		3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}	3.70×10^{-4}
	ALMENDRO 2009		1.48×10^{-3}	1.48×10^{-3}	1.48×10^{-3}	1.48×10^{-3}	1.48×10^{-3}	1.48×10^{-3}
Activity concentration in soil relative to tillage (C_s; Bq/kg)	NNSS 1992		3.82×10^{-2}	3.82×10^{-2}	3.82×10^{-2}	3.82×10^{-2}	3.82×10^{-2}	3.82×10^{-2}
	ALMENDRO 2009		1.53×10^{-1}	1.53×10^{-1}	1.53×10^{-1}	1.53×10^{-1}	1.53×10^{-1}	1.53×10^{-1}
Total activity concentration in feed (forage and grain plants) ($C_f = C_{p(root)} + C_{p(leaf)} + C_{p(dust)}$; Bq/kg_{wet})	NNSS 1992		5.51×10^{-3}	3.34×10^{-3}	NA	NA	NA	NA
	ALMENDRO 2009		2.20×10^{-2}	1.34×10^{-2}	NA	NA	NA	NA
Animal intake to animal product transfer coefficient (F_m; $d/kg_{fresh(wet)}$ and $d/L_{milk} = d/kg_{milk}$)			NA	NA	1.0×10^{-2}	9.1×10^{-3}	5.5×10^{-2}	$2.6 \times 10^{+0}$
Animal consumption rates (Q)	Feed	(Q_f; kg/d)	NA	NA	48.5	61.5	0.26	0.26
	Water	(Q_w; L/d = kg/d)	NA	NA	60	80	0.5	0.5
	Soil	(Q_s; kg/d)	NA	NA	0.7	0.95	0.02	0.02
Activity concentration in animal product [$C_{d(animal)} = \{(Q_f \times C_f)_{animal} + (Q_w \times C_w)_{animal} + (Q_s \times C_s)_{animal}\} \times F_m$; Bq/d]	NNSS 1992		NA	NA	2.11×10^{-3}	2.47×10^{-3}	1.31×10^{-4}	6.19×10^{-3}
	ALMENDRO 2009		NA	NA	8.44×10^{-3}	9.87×10^{-3}	5.24×10^{-4}	2.48×10^{-2}

NA = not applicable.

Table B-16. Drinking water ingestion annual committed effective dose (CED) and lifetime excess cancer morbidity risk for RMEI.

COC	Activity concentration in groundwater (C_w; pCi/L)	DOE-Std [a] annual drinking water ingestion rate for reference person (L/yr)	DOE-Std Committed effective dose (CED) coefficient for water ingestion ($mrem_{CED}$/pCi)	Annual drinking water ingestion CED ($mrem_{CED}$/yr)	USEPA[b] 70-yr Lifetime ingestion exposure rate ($L/Lifetime_{70yr}$)	USEPA lifetime excess cancer morbidity risk coefficient for ingestion (R/pCi)	70-yr lifetime excess cancer morbidity risk for drinking water ingestion ($R/Lifetime_{70yr}$)
NNSS 1992							
^{3}H	16,305	679.8	7.77×10^{-8}	0.861	$5.11 \times 10^{+4}$	5.07×10^{-14}	4.22×10^{-5}
^{14}C	17	679.8	2.34×10^{-6}	0.027	$5.11 \times 10^{+4}$	1.55×10^{-12}	1.35×10^{-6}
^{36}Cl	68	679.8	4.59×10^{-6}	0.212	$5.11 \times 10^{+4}$	3.30×10^{-12}	1.15×10^{-5}
^{99}Tc	58	679.8	3.33×10^{-6}	0.131	$5.11 \times 10^{+4}$	2.75×10^{-12}	8.16×10^{-6}
^{129}I	0.0145	679.8	4.48×10^{-4}	0.004	$5.11 \times 10^{+4}$	1.48×10^{-10}	1.09×10^{-7}
ALMENDRO 2009							
^{3}H	19,023	679.8	7.77×10^{-8}	1.005	$5.11 \times 10^{+4}$	5.07×10^{-14}	4.93×10^{-5}
^{14}C	0.79	679.8	2.34×10^{-6}	0.001	$5.11 \times 10^{+4}$	1.55×10^{-12}	6.27×10^{-8}
^{36}Cl	6.24	679.8	4.59×10^{-6}	0.019	$5.11 \times 10^{+4}$	3.30×10^{-12}	1.05×10^{-6}
^{99}Tc	0.50	679.8	3.33×10^{-6}	0.001	$5.11 \times 10^{+4}$	2.75×10^{-12}	7.03×10^{-8}
^{129}I	0.04	679.8	4.48×10^{-4}	0.012	$5.11 \times 10^{+4}$	1.48×10^{-10}	3.02×10^{-7}

[a] USDOE (2011; Table 3).

[b] 5.11×10^{4} L/Lifetime = 2 L/d × 365 d/y × 70 yr/Lifetime.

Table B-17. Data and associated indoor aerosol and soil vapor activity concentrations.

COC	Time indoors (yr)	Time outdoors Garden (yr)	Time outdoors Field (yr)	Soil particulate activity concentration in air for garden and field critical thickness (pCi/m^3)	Indoor aerosol particulate activity concentration (pCi/m^3)	Soil vapor activity concentrations Garden (pCi/m^3)	Soil vapor activity concentrations Field (pCi/m^3)
NNSS 1992							
^{3}H	0.66	0.27	0.07	1.04×10^{-3}	$1.67 \times 10^{+1}$	NA	NA
$HTO_{(vapor)}$	NA	0.27	0.07	NA	NA	$2.43 \times 10^{+0}$	$1.52 \times 10^{+2}$
^{14}C	0.66	0.27	0.07	6.40×10^{-5}	6.44×10^{-4}	NA	NA
$^{14}CO_{2(vapor)}$	NA	0.27	0.07	NA	NA	4.47×10^{-3}	2.96×10^{-1}
^{36}Cl	0.66	0.27	0.07	8.99×10^{-6}	6.96×10^{-2}	NA	NA
^{99}Tc	0.66	0.27	0.07	7.67×10^{-6}	5.94×10^{-2}	NA	NA
^{129}I	0.66	0.27	0.07	2.24×10^{-8}	1.02×10^{-5}	NA	NA
ALMENDRO 2009							
^{3}H	0.66	0.27	0.07	1.22×10^{-3}	$1.95 \times 10^{+1}$	NA	NA
$HTO_{(vapor)}$	NA	0.27	0.07	NA	NA	$2.83 \times 10^{+0}$	$1.77 \times 10^{+2}$
^{14}C	0.66	0.27	0.07	2.97×10^{-6}	2.99×10^{-5}	NA	NA
$^{14}CO_{2(vapor)}$	NA	0.27	0.07	NA	NA	2.08×10^{-4}	1.38×10^{-2}
^{36}Cl	0.66	0.27	0.07	8.25×10^{-7}	6.39×10^{-3}	NA	NA
^{99}Tc	0.66	0.27	0.07	6.61×10^{-8}	5.12×10^{-4}	NA	NA
^{129}I	0.66	0.27	0.07	8.95×10^{-8}	4.10×10^{-5}	NA	NA

NA = not applicable.

Table B-18. Data and annual committed effective dose (CED) and lifetime excess cancer morbidity risk from inhalation for RMEI.

COC	DOE-Std overall inhalation rate (m^3/yr)	DOE-Std committed effective dose (CED) ($mrem_{CED}$/pCi)	Indoor inhalation annual CED for reference person ($mrem_{CED}$/yr)	Outdoor inhalation annual CED for reference person ($mrem_{CED}$/yr)	Indoor inhalation rate for active person in biosphere (m^3/yr)	Outdoor inhalation rate for active person in biosphere (m^3/yr)	USEPA inhalation cancer morbidity risk coefficient R/pCi	Indoor inhalation risk for active person in biosphere R/$Lifetime_{70yr}$	Outdoor inhalation risk for active person in biosphere R/$Lifetime_{70yr}$
NNSS 1992									
$^{3}H_{(soil+aerosol)}$	$6.64 \times 10^{+3}$	1.97×10^{-7}	1.44×10^{-2}	4.64×10^{-7}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	1.99×10^{-13}	2.67×10^{-8}	7.90×10^{-13}
$HTO_{(vapor)}$	$6.64 \times 10^{+3}$	7.14×10^{-8}	NA	5.35×10^{-3}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	5.62×10^{-14}	NA	7.10×10^{-9}
$\Sigma\ ^{3}H_{(total)}$	NA	NA	1.44×10^{-2}	5.35×10^{-3}	NA	NA	NA	2.67×10^{-8}	7.10×10^{-9}
$^{14}C_{(soil+aerosol)}$	$6.64 \times 10^{+3}$	8.21×10^{-6}	2.32×10^{-5}	1.19×10^{-6}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	7.07×10^{-12}	3.66×10^{-11}	1.72×10^{-12}
$^{14}CO_{2(gas)}$	$6.64 \times 10^{+3}$	2.48×10^{-8}	NA	3.61×10^{-6}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	1.99×10^{-14}	NA	4.90×10^{-12}
$\Sigma\ ^{14}C_{(total)}$	NA	NA	2.32×10^{-5}	4.80×10^{-6}	NA	NA	NA	3.66×10^{-11}	6.62×10^{-12}
^{36}Cl	$6.64 \times 10^{+3}$	2.98×10^{-5}	9.09×10^{-3}	6.04×10^{-7}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	2.50×10^{-11}	1.40×10^{-8}	8.55×10^{-13}
^{99}Tc	$6.64 \times 10^{+3}$	1.64×10^{-5}	4.26×10^{-3}	5.82×10^{-8}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	1.41×10^{-11}	6.73×10^{-9}	4.11×10^{-13}
^{129}I	$6.64 \times 10^{+3}$	1.50×10^{-4}	6.74×10^{-6}	1.56×10^{-9}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	6.07×10^{-11}	5.00×10^{-12}	5.17×10^{-15}
ALMENDRO 2009									
^{3}H	$6.64 \times 10^{+3}$	1.97×10^{-7}	1.68×10^{-2}	5.42×10^{-7}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	1.99×10^{-13}	3.12×10^{-8}	9.22×10^{-13}
$HTO_{(vapor)}$	$6.64 \times 10^{+3}$	7.14×10^{-8}	NA	6.24×10^{-3}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	5.62×10^{-14}	NA	8.28×10^{-9}
$\Sigma\ ^{3}H_{(total)}$	$6.64 \times 10^{+3}$	NA	1.68×10^{-2}	6.24×10^{-3}	NA	NA	NA	3.12×10^{-8}	8.28×10^{-9}
$^{14}C_{(soil+aerosol)}$	$6.64 \times 10^{+3}$	8.21×10^{-6}	1.08×10^{-6}	5.51×10^{-8}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	7.07×10^{-12}	1.70×10^{-12}	8.00×10^{-14}
$^{14}CO_{2(gas)}$	$6.64 \times 10^{+3}$	2.48×10^{-8}	NA	1.68×10^{-7}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	1.99×10^{-14}	NA	2.28×10^{-13}
$\Sigma\ ^{14}C_{(total)}$	$6.64 \times 10^{+3}$		1.08×10^{-6}	2.23×10^{-7}	NA	NA	NA	1.70×10^{-12}	3.08×10^{-13}
^{36}Cl	$6.64 \times 10^{+3}$	2.98×10^{-5}	8.34×10^{-4}	5.54×10^{-8}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	2.50×10^{-11}	1.29×10^{-9}	7.85×10^{-14}
^{99}Tc	$6.64 \times 10^{+3}$	1.64×10^{-5}	3.67×10^{-5}	5.02×10^{-10}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	1.41×10^{-11}	5.80×10^{-11}	3.54×10^{-15}
^{129}I	$6.64 \times 10^{+3}$	1.50×10^{-4}	2.70×10^{-5}	6.25×10^{-9}	$1.74 \times 10^{+2}$	$1.60 \times 10^{+2}$	6.07×10^{-11}	2.00×10^{-11}	2.07×10^{-14}

NA = not applicable.

Table B-19. Data and annual committed effective dose (CED) and lifetime excess cancer morbidity risk from soil ingestion for RMEI.

COC	Soil critical-layer activity concentration (C_s; pCi/kg)	Inadvertent soil ingestion rate (kg/yr)	DOE-Std Committed effective dose (CED) coefficient for soil ingestion ($mrem_{CED}$/pCi)	Annual inadvertent soil ingestion CED ($mrem_{CED}$/yr)	USEPA 70-yr Lifetime inadvertent soil ingestion exposure rate (kg/$Lifetime_{70yr}$)	USEPA lifetime excess cancer morbidity risk coefficient for ingestion (R/pCi)	70-yr lifetime excess cancer morbidity risk for drinking water ingestion (R/$Lifetime_{70yr}$)
NNSS 1992							
^{3}H	$2.17 \times 10^{+3}$	3.65×10^{-2}	7.77×10^{-8}	6.17×10^{-6}	2.56×10^{0}	1.44×10^{-13}	7.99×10^{-10}
^{14}C	$1.33 \times 10^{+2}$	3.65×10^{-2}	2.34×10^{-6}	1.14×10^{-5}	2.56×10^{0}	2.00×10^{-12}	6.81×10^{-10}
^{36}Cl	$1.87 \times 10^{+1}$	3.65×10^{-2}	4.59×10^{-6}	3.14×10^{-5}	2.56×10^{0}	4.44×10^{-12}	2.12×10^{-10}
^{99}Tc	$1.60 \times 10^{+1}$	3.65×10^{-2}	3.33×10^{-6}	1.94×10^{-6}	2.56×10^{0}	4.00×10^{-12}	1.63×10^{-10}
^{129}I	4.66×10^{-2}	3.65×10^{-2}	4.48×10^{-4}	8.63×10^{-6}	2.56×10^{0}	1.93×10^{-10}	2.30×10^{-11}
ALMENDRO 2009							
^{3}H	$2.54 \times 10^{+3}$	3.65×10^{-2}	7.77×10^{-8}	7.19×10^{-6}	2.56×10^{0}	1.44×10^{-13}	9.33×10^{-10}
^{14}C	$6.20 \times 10^{+0}$	3.65×10^{-2}	2.34×10^{-6}	5.29×10^{-7}	2.56×10^{0}	2.00×10^{-12}	3.16×10^{-11}
^{36}Cl	$1.72 \times 10^{+0}$	3.65×10^{-2}	4.59×10^{-6}	2.88×10^{-7}	2.56×10^{0}	4.44×10^{-12}	1.95×10^{-11}
^{99}Tc	1.38×10^{-1}	3.65×10^{-2}	3.33×10^{-6}	1.67×10^{-8}	2.56×10^{0}	4.00×10^{-12}	1.41×10^{-12}
^{129}I	1.87×10^{-1}	3.65×10^{-2}	4.48×10^{-4}	3.05×10^{-6}	2.56×10^{0}	1.93×10^{-10}	9.19×10^{-11}

Table B-20. Summary of activity concentration in dietary produce and intake of activity (Bq/kg and pCi/yr) by RMEI.

		Garden produce			Field crops	
		Leafy vegetables	Other vegetables	Fruit	Grain	Forage
Garden produce annual consumption rate	(kg/yr)	3.78	4.73	12.68	0.23	NA
COC		**NNSS 1992**				
^{3}H Activity concentration	Bq/kg	$5.50 \times 10^{+2}$	$5.50 \times 10^{+2}$	$5.50 \times 10^{+2}$	$5.50 \times 10^{+2}$	$5.50 \times 10^{+2}$
Annual consumption	pCi/yr	$5.62 \times 10^{+4}$	$7.03 \times 10^{+4}$	$1.88 \times 10^{+5}$	$2.29 \times 10^{+3}$	NA
^{14}C Activity concentration	Bq/kg	9.51×10^{-2}	1.45×10^{-1}	2.78×10^{-1}	$3.21 \times 10^{+1}$	$3.83 \times 10^{+0}$
Annual consumption	pCi/yr	$9.71 \times 10^{+0}$	$1.85 \times 10^{+1}$	$9.25 \times 10^{+1}$	$2.00 \times 10^{+2}$	NA
^{36}Cl Activity concentration	Bq/kg	$4.86 \times 10^{+1}$	$5.43 \times 10^{+1}$	$6.33 \times 10^{+1}$	$3.52 \times 10^{+2}$	$2.91 \times 10^{+2}$
Annual consumption	pCi/yr	$4.97 \times 10^{+3}$	$6.94 \times 10^{+3}$	$2.17 \times 10^{+4}$	$2.19 \times 10^{+3}$	NA
^{99}Tc Activity concentration	Bq/kg	$3.30 \times 10^{+1}$	$4.85 \times 10^{+0}$	$5.58 \times 10^{+0}$	$3.35 \times 10^{+1}$	$1.08 \times 10^{+2}$
Annual consumption	pCi/yr	$3.37 \times 10^{+3}$	$6.20 \times 10^{+2}$	$1.91 \times 10^{+3}$	$2.08 \times 10^{+2}$	NA
^{129}I Activity concentration	Bq/kg	1.97×10^{-3}	4.10×10^{-4}	4.95×10^{-4}	3.34×10^{-3}	5.51×10^{-3}
Annual consumption	pCi/yr	2.01×10^{-1}	5.24×10^{-2}	1.70×10^{-1}	2.08×10^{-2}	NA
COC		**ALMENDRO 2009**				
^{3}H Activity concentration	Bq/kg	$6.42 \times 10^{+2}$	$6.42 \times 10^{+2}$	$6.42 \times 10^{+2}$	$6.42 \times 10^{+2}$	$6.42 \times 10^{+2}$
Annual consumption	pCi/yr	$6.56 \times 10^{+4}$	$8.20 \times 10^{+4}$	$2.20 \times 10^{+5}$	$2.67 \times 10^{+3}$	NA
^{14}C Activity concentration	Bq/kg	4.42×10^{-3}	6.72×10^{-3}	1.29×10^{-2}	$1.49 \times 10^{+0}$	1.78×10^{-1}
Annual consumption	pCi/yr	4.51×10^{-1}	8.59×10^{-1}	$4.42 \times 10^{+0}$	$9.28 \times 10^{+0}$	NA
^{36}Cl Activity concentration	Bq/kg	$4.46 \times 10^{+0}$	$4.98 \times 10^{+0}$	$5.80 \times 10^{+0}$	$3.23 \times 10^{+1}$	$2.67 \times 10^{+1}$
Annual consumption	pCi/yr	$4.56 \times 10^{+2}$	$6.37 \times 10^{+2}$	$1.99 \times 10^{+3}$	$2.01 \times 10^{+2}$	NA
^{99}Tc Activity concentration	Bq/kg	2.84×10^{-1}	4.18×10^{-2}	4.81×10^{-2}	2.89×10^{-1}	9.35×10^{-1}
Annual consumption	pCi/yr	$2.90 \times 10^{+1}$	$5.35 \times 10^{+0}$	$1.65 \times 10^{+1}$	$1.80 \times 10^{+0}$	NA
^{129}I Activity concentration	Bq/kg	7.89×10^{-3}	1.64×10^{-3}	1.98×10^{-3}	1.34×10^{-2}	2.02×10^{-2}
Annual consumption	pCi/yr	8.06×10^{-1}	2.09×10^{-1}	6.79×10^{-1}	8.30×10^{-2}	NA

NA = not applicable.

Table B-21. Summary of activity concentration in dietary animal products and intake of activity (Bq/kg and pCi/y) by RMEI.

		Beef (cattle)	Milk (dairy cows)	Poultry	Eggs (hens)
Garden produce annual consumption rate	(kg/yr)	2.85	4.66	0.42	5.30
COC			**NNSS 1992**		
^{3}H Activity concentration	Bq/kg	$5.63\times 10^{+2}$	$5.81 \times 10^{+2}$	$5.50 \times 10^{+2}$	$5.36 \times 10^{+2}$
Annual consumption	pCi/yr	$4.34 \times 10^{+4}$	$7.32 \times 10^{+4}$	$6.24 \times 10^{+3}$	$8.06 \times 10^{+4}$
^{14}C Activity concentration	Bq/kg	$1.22 \times 10^{+1}$	$3.59 \times 10^{+0}$	$1.66 \times 10^{+1}$	$1.24 \times 10^{+1}$
Annual consumption	pCi/yr	$9.41 \times 10^{+2}$	$4.53 \times 10^{+2}$	$1.88 \times 10^{+2}$	$1.78 \times 10^{+3}$
^{36}Cl Activity concentration	Bq/kg	$6.56 \times 10^{+2}$	$3.26 \times 10^{+2}$	$2.80 \times 10^{+0}$	$4.10 \times 10^{+0}$
Annual consumption	pCi/yr	$5.05 \times 10^{+4}$	$4.10 \times 10^{+4}$	$3.17 \times 10^{+1}$	$5.87 \times 10^{+2}$
^{99}Tc Activity concentration	Bq/kg	$5.94 \times 10^{+0}$	$1.44 \times 10^{+1}$	6.33×10^{-1}	$2.41 \times 10^{+1}$
Annual consumption	pCi/yr	$4.57 \times 10^{+2}$	$1.81 \times 10^{+3}$	$7.19 \times 10^{+0}$	$3.45 \times 10^{+3}$
^{129}I Activity concentration	Bq/kg	2.11×10^{-3}	2.47×10^{-3}	1.31×10^{-4}	6.19×10^{-3}
Annual consumption	pCi/yr	1.63×10^{-1}	3.11×10^{-1}	1.49×10^{-3}	8.87×10^{-1}
COC			**ALMENDRO 2009**		
^{3}H Activity concentration	Bq/kg	$6.57 \times 10^{+2}$	$6.78\times 10^{+2}$	$6.41 \times 10^{+2}$	$6.56 \times 10^{+2}$
Annual consumption	pCi/yr	$5.06 \times 10^{+4}$	$8.54 \times 10^{+4}$	$7.28 \times 10^{+3}$	$9.40 \times 10^{+4}$
^{14}C Activity concentration	Bq/kg	5.68×10^{-1}	1.67×10^{-1}	7.70×10^{-1}	5.78×10^{-1}
Annual consumption	pCi/yr	$4.37 \times 10^{+1}$	$2.10 \times 10^{+1}$	$8.74 \times 10^{+0}$	$8.27 \times 10^{+1}$
^{36}Cl Activity concentration	Bq/kg	$6.02 \times 10^{+1}$	$2.99 \times 10^{+1}$	2.57×10^{-1}	3.76×10^{-1}
Annual consumption	pCi/yr	$4.64 \times 10^{+3}$	$3.76 \times 10^{+3}$	$2.91 \times 10^{+0}$	$5.39 \times 10^{+1}$
^{99}Tc Activity concentration	Bq/kg	5.12×10^{-2}	1.24×10^{-1}	5.46×10^{-3}	2.08×10^{-1}
Annual consumption	pCi/yr	$3.94 \times 10^{+0}$	$1.56 \times 10^{+1}$	6.19×10^{-2}	$2.98 \times 10^{+1}$
^{129}I Activity concentration	Bq/kg	8.44×10^{-3}	9.87×10^{-3}	5.24×10^{-4}	2.47×10^{-2}
Annual consumption	pCi/yr	6.50×10^{-1}	$1.24 \times 10^{+0}$	5.95×10^{-3}	$3.55 \times 10^{+0}$

Table B-22. Summary of RMEI annual dose ($mrem_{CED}$/yr) from ingestion of garden produce and grain.

COC	USDOE committed effective dose (CED) coefficient ($(mrem_{CED}/pCi)_{dietary\ ing}$)	Garden produce			Field crops		Total annual committed effective dose (CED) ($mrem_{CED}$/yr)
		Leafy vegetables	Other vegetables	Fruit	Grain	Forage	
		$mrem_{CED}$/yr			$mrem_{CED}$/yr		
NNSS 1992							
^{3}H	7.77×10^{-8}	4.37×10^{-3}	5.46×10^{-3}	1.46×10^{-2}	1.78×10^{-4}	NA	2.47×10^{-2}
^{14}C	2.34×10^{-6}	2.27×10^{-5}	4.32×10^{-5}	2.23×10^{-4}	4.67×10^{-4}	NA	7.56×10^{-4}
^{36}Cl	4.59×10^{-6}	2.28×10^{-2}	3.19×10^{-2}	9.95×10^{-2}	1.01×10^{-2}	NA	1.64×10^{-1}
^{99}Tc	3.33×10^{-6}	1.12×10^{-2}	2.07×10^{-3}	6.37×10^{-3}	6.94×10^{-4}	NA	2.03×10^{-2}
^{129}I	4.48×10^{-4}	9.02×10^{-5}	2.35×10^{-5}	7.61×10^{-5}	9.30×10^{-6}	NA	1.99×10^{-4}
ALMENDRO 2009							
^{3}H	7.77×10^{-8}	5.09×10^{-3}	6.37×10^{-3}	1.71×10^{-2}	2.08×10^{-4}	NA	2.88×10^{-2}
^{14}C	2.34×10^{-6}	1.06×10^{-6}	2.01×10^{-6}	1.04×10^{-5}	2.17×10^{-5}	NA	3.51×10^{-5}
^{36}Cl	4.59×10^{-6}	2.09×10^{-3}	2.92×10^{-3}	9.13×10^{-3}	9.23×10^{-4}	NA	1.51×10^{-2}
^{99}Tc	3.33×10^{-6}	9.67×10^{-5}	1.78×10^{-5}	5.49×10^{-5}	5.98×10^{-6}	NA	1.75×10^{-4}
^{129}I	4.48×10^{-4}	3.61×10^{-4}	9.38×10^{-5}	3.04×10^{-4}	3.72×10^{-5}	NA	7.96×10^{-4}

NA = not applicable.

Table B-23. Summary of RMEI annual dose ($mrem_{CED}$/yr) from ingestion of animal products.

COC	USDOE committed effective dose (CED) coefficient ($mrem_{CED}/pCi)_{dietary\ ing}$	Beef (cattle)	Milk (dairy cows)	Poultry	Eggs (hens)	Total annual committed effective dose (CED)
		$mrem_{CED}$/yr				$mrem_{CED}$/yr
NNSS 1992						
^{3}H	7.77×10^{-8}	3.37×10^{-3}	5.69×10^{-3}	4.85×10^{-4}	6.26×10^{-3}	1.58×10^{-2}
^{14}C	2.34×10^{-6}	2.20×10^{-3}	1.06×10^{-3}	4.49×10^{-4}	4.17×10^{-3}	7.87×10^{-3}
^{36}Cl	4.59×10^{-6}	2.32×10^{-1}	1.88×10^{-1}	1.46×10^{-4}	2.70×10^{-3}	4.23×10^{-1}
^{99}Tc	3.33×10^{-6}	1.52×10^{-3}	6.04×10^{-3}	2.39×10^{-5}	1.15×10^{-2}	1.91×10^{-2}
^{129}I	4.48×10^{-4}	7.29×10^{-5}	1.40×10^{-4}	6.66×10^{-7}	3.97×10^{-4}	6.11×10^{-4}
ALMENDRO 2009						
^{3}H	7.77×10^{-8}	3.93×10^{-3}	6.64×10^{-3}	5.66×10^{-4}	7.31×10^{-3}	1.84×10^{-2}
^{14}C	2.34×10^{-6}	1.02×10^{-4}	4.92×10^{-5}	2.05×10^{-5}	1.94×10^{-4}	3.66×10^{-4}
^{36}Cl	4.59×10^{-6}	2.13×10^{-2}	1.73×10^{-2}	1.34×10^{-5}	2.47×10^{-4}	3.88×10^{-2}
^{99}Tc	3.33×10^{-6}	1.31×10^{-5}	5.21×10^{-5}	2.06×10^{-7}	9.92×10^{-5}	1.65×10^{-4}
^{129}I	4.48×10^{-4}	2.91×10^{-4}	5.57×10^{-4}	2.66×10^{-6}	1.59×10^{-3}	2.44×10^{-3}

Table B-24. Summary of RMEI lifetime excess cancer morbidity risk ($R/lifetime_{70yr}$) from ingestion of garden produce and grain.

COC	USEPA lifetime excess cancer morbidity risk coefficient $(Risk/pCi)_{dietary\ ing}$	Garden produce: Leafy vegetables $R/lifetime_{70yr}$	Garden produce: Other vegetables $R/lifetime_{70yr}$	Garden produce: Fruit $R/lifetime_{70yr}$	Field crops: Grain $R/lifetime_{70yr}$	Field crops: Forage $R/lifetime_{70yr}$	Total 70-yr lifetime excess cancer morbidity risk $R/lifetime_{70yr}$
NNSS 1992							
^{3}H	1.44×10^{-13}	5.66×10^{-7}	7.08×10^{-7}	1.90×10^{-6}	2.31×10^{-8}	NA	3.20×10^{-6}
^{14}C	2.00×10^{-12}	1.36×10^{-9}	2.58×10^{-9}	1.33×10^{-8}	2.79×10^{-8}	NA	4.52×10^{-8}
^{36}Cl	4.44×10^{-12}	1.54×10^{-6}	2.16×10^{-6}	6.74×10^{-6}	6.81×10^{-7}	NA	1.11×10^{-5}
^{99}Tc	4.00×10^{-12}	9.42×10^{-7}	1.74×10^{-7}	5.35×10^{-7}	5.83×10^{-8}	NA	1.71×10^{-6}
^{129}I	1.93×10^{-10}	2.72×10^{-9}	7.07×10^{-10}	2.29×10^{-9}	2.80×10^{-10}	NA	6.00×10^{-9}
ALMENDRO 2009							
^{3}H	1.44×10^{-13}	6.60×10^{-7}	8.26×10^{-7}	2.22×10^{-6}	2.69×10^{-8}	NA	3.73×10^{-6}
^{14}C	2.00×10^{-12}	6.31×10^{-11}	1.20×10^{-10}	6.19×10^{-10}	1.30×10^{-9}	NA	2.10×10^{-9}
^{36}Cl	4.44×10^{-12}	1.42×10^{-7}	1.98×10^{-7}	6.18×10^{-7}	6.25×10^{-8}	NA	1.02×10^{-6}
^{99}Tc	4.00×10^{-12}	8.12×10^{-9}	1.50×10^{-9}	4.61×10^{-9}	5.02×10^{-10}	NA	1.47×10^{-8}
^{129}I	1.93×10^{-10}	1.09×10^{-8}	2.83×10^{-9}	9.16×10^{-9}	1.12×10^{-9}	NA	2.40×10^{-8}

NA = not applicable.

Table B-25. Summary of RMEI lifetime excess cancer morbidity risk (R/lifetime$_{70yr}$) from ingestion of animal products.

		NNSS 1992				
COC	USEPA lifetime excess cancer morbidity risk coefficient (Risk/pCi)$_{dietary\ ing}$	Beef (cattle)	Milk (dairy cows)	Poultry	Eggs (hens)	Total 70-yr lifetime excess cancer morbidity risk R/lifetime$_{70yr}$/yr
		R/lifetime$_{70yr}$/yr				
^{3}H	1.44×10^{-13}	4.37×10^{-7}	7.38×10^{-7}	6.29×10^{-8}	8.12×10^{-7}	2.05×10^{-6}
^{14}C	2.00×10^{-12}	1.32×10^{-7}	6.33×10^{-8}	2.63×10^{-8}	2.49×10^{-7}	4.70×10^{-7}
^{36}Cl	4.44×10^{-12}	1.57×10^{-5}	1.27×10^{-5}	9.87×10^{-9}	1.83×10^{-7}	2.86×10^{-5}
^{99}Tc	4.00×10^{-12}	1.28×10^{-7}	5.07×10^{-7}	2.01×10^{-9}	9.66×10^{-7}	1.60×10^{-6}
^{129}I	1.93×10^{-10}	2.20×10^{-9}	4.19×10^{-9}	2.01×10^{-11}	1.20×10^{-8}	1.84×10^{-8}
		ALMENDRO 2009				
^{3}H	1.44×10^{-13}	5.10×10^{-7}	8.61×10^{-7}	7.33×10^{-8}	9.47×10^{-7}	2.39×10^{-6}
^{14}C	2.00×10^{-12}	6.12×10^{-9}	2.49×10^{-9}	1.22×10^{-9}	1.16×10^{-8}	2.19×10^{-8}
^{36}Cl	4.44×10^{-12}	1.44×10^{-6}	1.17×10^{-6}	9.05×10^{-10}	1.68×10^{-8}	2.63×10^{-6}
^{99}Tc	4.00×10^{-12}	1.10×10^{-9}	4.37×10^{-9}	1.73×10^{-11}	8.33×10^{-9}	1.38×10^{-8}
^{129}I	1.93×10^{-10}	8.77×10^{-9}	1.68×10^{-8}	8.03×10^{-11}	4.79×10^{-8}	7.35×10^{-8}