**Special Analysis of the
Area 3 Radioactive Waste Management Site
at the Nevada National Security Site, Nye County, Nevada**

September 2012

Prepared by

**National Security Technologies, LLC
Las Vegas, Nevada**

Prepared for

**U.S. Department of Energy
National Nuclear Security Administration
Nevada Site Office
Under Contract Number DE-AC52-06NA25946**

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EXECUTIVE SUMMARY

This report describes the methods and results of a special analysis (SA) of the Area 3 Radioactive Waste Management Site (RWMS) on the Nevada National Security Site (NNSS). The purpose of the SA is to determine if the approved performance assessment (PA) and composite analysis (CA) (Shott et al., 2001) remain valid. The Area 3 RWMS PA and CA were prepared as a single document and received conditional approval on October 6, 1999. A conditional Disposal Authorization Statement (DAS) for the Area 3 RWMS was issued on October 20, 1999.

Since preparation of the approved PA and CA, new information and additional environmental monitoring data have been used to update the PA and CA. At the same time, continual advancements in computer processors and software have allowed improvement to the PA and CA models. Annual reviews of the PA and CA required by U.S. Department of Energy (DOE) Order DOE O 435.1 (DOE, 2001a) have documented multiple changes occurring since preparation of the PA and CA. Potentially important changes include:

- Development of a new and improved baseline PA and CA model implemented in the probabilistic GoldSim simulation platform.
- A significant increase in the waste inventory disposed at the site.
- Revision and updating of model parameters based on additional years of site monitoring data and new research and development results.

Although changes have occurred, many important PA/CA issues remain unchanged, including the site conceptual model, important features, events, and processes, and the points of compliance. The SA is performed to document the current status of the PA/CA model and to quantitatively assess the impact of cumulative changes on the PA and CA results. The results of the SA are used to assess the validity of the approved PA/CA and make a determination if revision of the PA or CA is necessary.

The SA was performed using the Area 3 RWMS, version 2.102, GoldSim model, the current baseline PA/CA model. Comparison of the maximum SA results with the PA performance objectives indicates that there continues to be a reasonable expectation of compliance. The resident exposure scenario was evaluated for compliance with the air pathway and all-pathways annual total effective dose (TED) performance objectives. The maximum mean air pathway TED, 7E-6 millisievert (mSv) at 1,000 years (y) has decreased relative to the approved PA and is significantly less than the 0.1 mSv limit. The maximum mean all-pathways annual TED, 7E-5 mSv at 1,000 y has increased but remains a small fraction of the 0.25 mSv limit. The SA maximum mean radon-222 (^{222}Rn) flux density, 0.03 becquerel per square meter per second ($\text{Bq m}^{-2} \text{s}^{-1}$), has increased relative to the PA results but is significantly less than the 0.74 $\text{Bq m}^{-2} \text{s}^{-1}$ limit.

The SA results continue to support a conclusion that the disposed waste inventory is protective of intruders and groundwater resources. The maximum mean intruder TED, 0.01 mSv for an acute construction scenario at the U-3ah/at disposal unit, was less than the 5 mSv performance

measure. Site monitoring data and research results continue to support a conclusion that a groundwater pathway will not exist within the 1,000 y compliance period.

Projected releases to the environment are a small fraction of the performance objectives. Cost-effective options for reducing releases further are unlikely to exist. Therefore, releases from the Area 3 RWMS are judged to be as low as reasonably achievable.

Comparison of the maximum CA result with the 0.3 mSv CA dose constraint indicates that no action is required to reduce the dose from the Area 3 RWMS and all interacting sources of residual radioactive contamination. The SA maximum mean CA annual TED, 0.02 mSv at 1,000 y, has increased from the approved CA result but remains less than 10% of the dose constraint. The CA TED continues to be due predominantly to inhalation of plutonium-239 resuspended from soils contaminated by nuclear weapons tests conducted near the Area 3 RWMS.

The SA results estimated with the Area 3 RWMS version 2.102 model indicate that changes to the PA and CA do not significantly alter the PA/CA results or conclusions. Although increases occur for the all-pathways annual TED, the ²²²Rn flux density, and the CA annual TED, all PA and CA results are a small fraction of the performance objectives or dose constraints. The same conclusion was reached for the approved PA and CA. The SA results continue to support a conclusion that there is a reasonable expectation of meeting all performance objectives and the CA dose constraint. There is no need to revise the DAS at this time. The SA results support a conclusion that the Area 3 RWMS PA and CA remain valid, and revision is not necessary at this time.

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ACRONYMS and ABBREVIATIONS

ac	acre(s)
ALARA	as low as reasonably achievable
Am	americium
Ar	argon
BN	Bechtel Nevada
Bq	becquerel(s)
C	carbon
CA	composite analysis
CADD/CAP	correction action decision document/corrective action plan
CAU	corrective action unit
CFR	Code of Federal Regulations
CR	concentration ratio
Cs	cesium
DAS	Disposal Authorization Statement
DCF	dose conversion factor
DOE	U.S. Department of Energy
ecdf	empirical cumulative distribution function
ET	evapotranspirative
FGR	Federal Guidance Report
ft	foot(feet)
FY	fiscal year
GBM	generalized boosted model
GZ	ground zero
³ H	tritium
ha	hectare(s)
HTO	tritiated water
IC	institutional control
Kr	krypton
LHS	Latin hypercube sampling
LLW	low-level radioactive waste
LWIS	Low-Level Waste Information System
m	meter(s)

m ²	square meter(s)
m ³	cubic meter(s)
MFP	mixed fission product
MOP	member of the public
mSv	millisievert(s)
NCRP	National Council on Radiation Protection and Measurements
NLFB	no-liquid-flux boundary
NNSA/NSO	U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office
NNSS	Nevada National Security Site
NRC	U.S. Nuclear Regulatory Commission
NSTec	National Security Technologies, LLC
PA	performance assessment
Pb	lead
pdf	probability density function
Pu	plutonium
Ra	radium
Rn	radon
RIDP	Radionuclide Inventory and Distribution Program
RWMS	Radioactive Waste Management Site
s	second(s)
SA	special analysis
SI	sensitivity index
SME	subject matter expert
SQAP	Software Quality Assurance Plan
Sr	strontium
TBq	terabequerel(s)
Tc	technetium
TED	total effective dose
Th	thorium
U	uranium
UGTA	underground test area
WAC	waste acceptance criteria
WMDB	waste management data base
y	year(s)

1.0 Introduction

This report describes a special analysis (SA) performed to assess the continuing adequacy of the Area 3 Radioactive Waste Management Site (RWMS) performance assessment (PA) and composite analysis (CA). The Area 3 RWMS is a low-level radioactive waste (LLW) disposal site operated in central Yucca Flat on the Nevada National Security Site (NNSS), formerly the Nevada Test Site, by the U.S. Department of Energy (DOE), National Nuclear Security Administration Nevada Site Office (NNSA/NSO). The Area 3 RWMS began disposal of LLW and mixed LLW in 1966 and was placed in standby on July 1, 2006.

The Area 3 RWMS PA and CA were prepared as a single document and received conditional approval on October 6, 1999. A conditional Disposal Authorization Statement (DAS) for the Area 3 RWMS was issued on October 20, 1999 (DOE, 1999). All DAS conditions were removed in 2002 (DOE, 2002) with acceptance of the final PA/CA document, referred to throughout as the approved PA/CA (Shott et al., 2001).

1.1 Purpose and Approach

The Area 3 RWMS PA and CA are supported and maintained by monitoring, research and development, and a maintenance program as required by DOE Manual DOE M 435.1-1 (National Security Technologies, LLC [NSTec], 2007a; DOE, 2001b). The PA and CA model are continuously updated and improved as new data and modeling capabilities become available. Reviews of the PA and CA conducted annually under the maintenance program have documented that potentially significant changes have occurred since preparation of the approved PA and CA. Potentially important changes include:

- Development of a new and improved baseline PA and CA model implemented in the probabilistic GoldSim simulation platform.
- A significant increase in the waste inventory disposed at the site.
- Revision and updating of model parameters based on additional years of site monitoring data and new research and development results.

Although changes have occurred, many important PA/CA issues remain unchanged, including the site conceptual model, important features, events, and processes, and the points of compliance. The SA is performed to document the current status of the PA/CA model and to quantitatively assess the impact of cumulative changes on the PA and CA results and conclusions. The results of the SA are used to assess the validity of the approved PA/CA and make a determination if revision of the PA or CA is necessary.

The approach of the SA is to document in detail PA and CA results obtained with the current model. The current Area 3 RWMS PA/CA model, version 2.102 (NNSA/NSO, 2011) referred to throughout as the Model, is implemented in GoldSim, a dynamic, probabilistic simulation platform (GoldSim Technology Group, 2010). The object-orientated structure of GoldSim allows visual presentation of model structure and supporting documentation of model assumptions and input distributions using a combination of graphics, diagrams, photographs, notes, comments, and hyperlinks to web content or external documents. Changes are documented in the Model and

in external documents in the accompanying reference folder. This SA report summarizes major PA/CA model changes but does not document all changes in detail or provide justification for changes. The reader is referred to the Model and its documentation if more details are required.

The SA results are not significantly different from the approved PA/CA results. Although some results increase, all PA and CA results remain a small fraction of their performance objective or dose constraint. The SA results confirm that no revision of the PA or CA is necessary at this time.

The report is organized into six chapters, described briefly below:

- Chapter 1: Summarizes the purpose, scope, and approach of the SA.
- Chapter 2: Describes the methods of the SA and summarizes significant changes and revisions to the Area RWMS PA/CA model.
- Chapter 3: Summarizes the results for the SA and presents the uncertainty and sensitivity of the results.
- Chapter 4: Compares the SA results with approved PA/CA results, interprets the SA results, and evaluates the need for PA/CA revision.
- Chapter 5: Compares the SA results with the performance objectives and assesses whether the current results still support a conclusion of compliance. Compares the CA with the dose constraint and limit and evaluates the need for an options analysis.
- Chapter 6: Lists references cited.

1.2 Disposal Site Description

The Area 3 RWMS covers approximately 48 hectare (ha) (119 acre [ac]) within the Yucca Flat Underground Test Area (UGTA) and includes seven craters formed from surface subsidence above underground nuclear tests (Figure 1.1).

Figure 1.1 Aerial photograph of the Area 3 RWMS

The RWMS consists of two trailers used as an administrative office and a change facility, a drainage lysimeter facility, and three waste disposal units. The entire facility is surrounded by a wire fence and a non-engineered flood control berm.

Eight belowground nuclear events, forming seven subsidence craters, were conducted within the Area 3 RWMS boundaries before the RWMS was sited (Table 1.1). Five craters were excavated to create three waste disposal units: U-3ax/bl, U-3ah/at, and U-3bh. Two craters, U-3az and U-3bg, have not been used for waste disposal. There are currently no plans to dispose of waste in these craters. The event conducted in the U-3bm borehole caused minimal subsidence and is not available for waste disposal.

Table 1.1 Subsidence craters within the Area 3 RWMS

Borehole	Event	Date	Event Depth (m)	Crater Radius (m)
U-3ah	FISHER	12/3/1961	363	89
U-3az	DORMOUSE PRIME	4/5/1962	260	80
U-3ax	PACA	5/7/1962	258	70
U-3bl	BOBAC	8/24/1962	195	61
U-3bh	HYRAX	9/14/1962	216	78
U-3bm	GUNDI	11/15/1962	248	Unsubsided
U-3bg	ACUSHI	2/8/1963	260	79
U-3at	JERBOA	3/1/1963	301	85

Nuclear subsidence craters within the Area 3 RWMS were initially used to dispose of bulk wastes generated by nuclear testing on the NNSS. Each disposal unit has received bulk uncontainerized waste or soft sided containers (e.g., supersacks, burrito wraps) at some point during its operation. Since the opening of the NNSS to offsite waste disposal, each disposal unit has also disposed containerized waste from offsite generators.

Wastes are disposed in tiers of various thicknesses separated by alluvium fill (Figure 1.2). Containerized and bulk wastes are disposed in layers 1.2 to 3.0 meters (m) (4 to 10 feet [ft]) thick and separated by 0.4 to 0.9 m (1.3 to 3 ft) fill layers. Thicker waste layers, 2.4 to 3.0 m (8 to 10 ft), are the norm, but these thicknesses cannot be achieved for all waste forms or container types.

Figure 1.2 Photograph of U-3ah/at showing partially completed tier of steel Sealand containers and supersacks

In July 2006, the Area 3 RWMS was placed in standby mode and all disposal activity ceased. All active disposal units were covered with 1.2- to 2.4-m (4- to 8-ft) operational covers. Operational covers in U-3ah/at and U-3bh are currently below existing grade. The Area 3 RWMS remains in standby to allow use of remaining waste disposal capacity if it should be needed.

2.0 Method of Analysis

The SA calculates all PA and CA results using version 2.102 of the Area 3 RWMS PA/CA model. Version 2.102 is a baseline version using the best available methods and parameter distributions available at the end of fiscal year (FY) 2011.

The Model is a probabilistic model where parameter uncertainty is propagated through the Model by Monte Carlo simulation using Latin hypercube sampling (LHS) to obtain results as a probability distribution. Studies were conducted to determine the relationship between the number of model realizations, ranging from 500 to 10,000 realizations, and the stability of the mean and 95th percentile model results. Result stability was evaluated by calculating the coefficient of variation and examining the distribution of the bootstrapped mean and 95th percentile. A sample size of 3,000 was sufficient to stabilize the mean, while 5,000 or more realizations were required to stabilize the 95th percentile. An LHS sample size of 5,000 realizations was selected as a compromise between result stability and computational costs.

2.1 The GoldSim Model

The Area 3 RWMS PA/CA model is implemented in the GoldSim probabilistic simulation platform. Implementation of the PA/CA model in GoldSim allows integration of almost all PA/CA models into a single probabilistic model. In the approved PA/CA, multiple submodels were run with a mix of deterministic and probabilistic input parameter definitions. Outputs from one model, including probabilistic distributions, were passed by script or hand entry to the next model in the sequence. Integration into a single model saves labor, reduces the potential for data transcription errors, and facilitates the use of more powerful sensitivity analysis methods that can be applied to the total model.

The first GoldSim implementation of the Area 3 RWMS PA/CA model (version 1.0) was developed with the intent of matching the models used in the approved PA/CA as closely as possible to demonstrate the feasibility of using GoldSim as a PA platform. Version 1.0 was benchmarked against the approved PA/CA results, and key results were found to agree within a few percent.

Subsequent to the benchmarking against the PA, the PA/CA model has evolved to incorporate updated methods and new information, including updated site inventory. Important changes are summarized in the following sections. Model development and evolution has been performed under a documented quality assurance plan (see Appendix A1).

The cumulative effect of model improvements occurring between the models used in the approved PA/CA and the Model is assessed by comparing the results of the two models using the approved PA/CA radionuclide inventory distributions and waste volumes. Results of the comparison are described in Appendix A2.

Although the PA/CA model has changed, it is important to note that many important components of the PA/CA data and models remain unchanged. The basic conceptual foundations of the disposal site evolution and performance, important feature events and processes, and the site

conceptual model are unchanged. The member of the public (MOP) exposure scenarios, the point of compliance, the closure plan, and many input parameters also remain unchanged.

2.2 Summary of Important Changes

2.2.1 Time Periods of Concern

The approved PA/CA evaluated disposal site performance for a 1,000-year (y) compliance period beginning at final site closure in FY 2013. Exposure of the MOP or intruder was assumed to begin once institutional control (IC) ended. The approved PA/CA assumed a fixed 250-y period of institutional control.

The SA assumes a 1,000-y period of compliance but assumes closure will occur in FY 2025. Since preparation of the approved PA/CA, a new IC policy to maintain IC of the NNSS indefinitely has been adopted (NNSA/NSO, 2008). The Area 3 RWMS is also within the Yucca Flat UGTA (Corrective Action Unit [CAU] 97) that will be subject to a 1,000-y groundwater use restriction under NNSA/NSO policies.

Although a formal policy has been adopted to maintain ICs indefinitely, controls may become less effective over time. The SA uses an active and passive IC period for the MOP and intruder developed from an elicitation of subject matter experts (SMEs) (Black et al., 2001). The IC periods are probability density functions (pdfs) that represent uncertainty in the SMEs' opinions (Black et al., 2001) (Figure 2.1). The passive IC period begins at the end of active ICs and is based on site knowledge or the collective memory and records of the site's past uses held by society. The active and passive IC periods are lognormally distributed with median durations of 245 and 99 y, respectively. The median duration of the combined IC periods is 402 y. The pdf for the combined IC periods implies that there is a 97% chance that ICs will be effective 100 y and an 11% chance that ICs will continue more than 1,000 y. DOE M 435.1-1 specifies an IC period of at least 100 y for establishing waste acceptance criteria (WAC) with intruder analyses. Therefore, ICs are assumed to be 100% effective for 100 y, and the probabilistic ICs are applied only if they exceed 100 y. Once ICs become ineffective, it is assumed possible that a MOP may be at the 100-m (330-ft) RWMS boundary and that intruders may temporarily intrude at the site.

Years Since Closure	$p(\text{IC period} > \text{years since closure})$		
	Active	Passive	Combined
10	1.00	1.00	1.00
100	0.82	0.50	0.97
250	0.49	0.14	0.74
500	0.23	0.03	0.38
750	0.13	0.01	0.20
1000	0.08	0.00	0.11

Figure 2.1 Probability of the length of IC at the Area 3 RWMS as estimated by elicitation of SMEs

In addition to IC periods, an independent period of active site maintenance is also assumed. During active site maintenance, damage to the cover caused by erosion or subsidence is assumed to be repaired. Active site maintenance is assumed to continue for 30 y after closure based on Title 40 Code of Federal Regulations (CFR) Part 264.117 requirements for post-closure care and maintenance.

2.2.2 Disposal Unit Configuration

Closure Cover Design and Performance

The SA closure cover design is unchanged from the basic concepts in the approved PA/CA. Detail in model assumptions about subsidence and cover performance has increased as detail in closure plans has increased. Similar closure cover designs are planned for all Area 3 RWMS disposal units. The U-3ax/bl disposal unit is closed with a 3-m (9.8-ft) vegetated monolithic evapotranspirative (ET) cover. The current conceptual design for U-3ah/at and U-3bh closure covers calls for installation of a similar vegetated monolithic ET cover over existing operational covers (NSTec, 2007b). The cover will be constructed from local alluvial soils.

The cover's effectiveness to reduce infiltration and resist human and biotic intrusion is based on the cover's thickness. A 3-m (9.8-ft) cover is sufficient to eliminate the potential for infiltration, most biointrusion, and human intrusion by construction excavations. Stable isotope profiles, hydrological modeling studies, and site moisture monitoring all indicate that a 3-m (9.8-ft) vegetated cover is sufficiently thick to retain all infiltrated precipitation and return it to the atmosphere by evapotranspiration before reaching buried waste (Shott et al., 1998, 2001; Kwicklis et al., 2006).

A 3-m (9.8-ft) cover is also sufficiently thick to eliminate most biointrusion by plants, insects, and mammals. A 3-m (9.8-ft) cover is as thick or thicker than the depth of septic systems, basements, and swimming pools, the most common construction excavations in southern Nevada (Bechtel Nevada [BN], 2001), thereby reducing the potential for direct contact of waste by an intruder constructing a residence on the site.

The cover is assumed to return to natural conditions resembling the surrounding undisturbed areas. The closure cover will be vegetated with native plants at the time of closure and is assumed to have a plant community characteristic of the transitional desert communities occurring in similar undisturbed areas. Fauna characteristic of communities surrounding the site are assumed to naturally repopulate the cover. Burrowing animals are assumed to increase the porosity of the upper 1.5 to 2.5 m (5 to 8 ft) of cover.

Subsidence

The U-3ah/at and U-3bh disposal units are not full, and the final height of the closure cover above grade will not be known until final closure. Current plans are to close both disposal units above grade. Preliminary grading sections indicate that the U-3ah/at and U-3bh closure covers will be approximately 1.8 m (6 ft) and 0.6 m (2 ft), respectively, above grade (NSTec, 2007b).

The closure covers are assumed to subside over time as waste containers collapse, voids within and between containers are filled, and waste is compressed. Since preparation of the approved PA/CA, a probabilistic and dynamic model of subsidence based on a detailed review of data base records of waste containers and waste forms has been developed. Subsidence estimates are calculated for U-3ah/at and U-bh only. The U-3ax/bl disposal unit is assumed to have negligible subsidence due to the rarity of containerized waste.

The closure covers are assumed to remain above grade throughout the period of active maintenance. Once maintenance ends, the U-3ah/at and U-3bh closure covers will likely subside below grade before the end of the 1,000-y compliance period. The total amount of subsidence is modeled by sampling a disposal unit specific settlement ratio distribution that is the ratio of the disposed waste bulk density to the weighted mean compacted bulk density of the waste forms.

Subsidence occurs gradually over a finite time interval based on a schedule of subsidence estimated by a panel of SMEs (DOE, 1998). Uncertainty in the subsidence schedule is accounted for by a probabilistic acceleration factor that may positively or negatively accelerate the subsidence process. During active site maintenance the cover is maintained at its closure height above grade. Any subsidence occurring during the maintenance period is compensated for by increasing the cover thickness. Once maintenance ends, cover thickness is constant and the cover may subside below grade if subsidence continues beyond the maintenance period. Unrepaired subsidence is expected to occur at U-3ah/at and U-3bh in most model realizations.

Based on results of the subsidence model, the U-3ah/at disposal unit is expected to form a shallow saucer-shaped depression with a secondary deeper depression over the U-at cater (Figure 2.2). The maximum elevation below grade without any repair is estimated to be approximately 9.6 m (31 ft).

Figure 2.2 Conceptual cross-section of U-3ah/at at closure (above) and after complete subsidence (below)

The U-3bh disposal unit is expected to form a shallower saucer-shaped depression (Figure 2.3). The maximum unrepaired subsidence is estimated to be 9 m (29 ft) for U-3bh. Subsidence at U-3ax/bl is assumed to be minimal.

Figure 2.3 Conceptual cross-section of U-3bh at closure (above) and after complete subsidence (below)

The above grade cover may erode over time, but previous analyses (Shott et al., 1998; DOE, 1998) suggest that erosion will be insignificant over 1,000 y. After subsidence below grade, the crater may begin to accumulate sediment. Sediment accumulation is expected to improve long-term performance by increasing cover thickness and reducing infiltration. The accumulation of fine grained sediments, which is observed in other NNSS subsidence craters (Hokett and French, 1998), may reduce infiltration from small runoff events. Although sediment accumulation may reduce infiltration of runoff by plugging the crater bottom with fine grained sediments and eventually physically filling the crater, these processes are not included in the Model.

While the cover is above grade, infiltration is assumed to be limited to direct precipitation. The unsubsided cover is assumed to have the same water content as natural undisturbed areas surrounding the site. After subsidence below grade, craters are assumed to experience increased infiltration due to focusing of runoff in the bottom of the craters. Cover water content is assumed to increase to the level observed in alluvium below the Area 3 RWMS subsidence craters, which have been capturing runoff from the time of their formation in the early 1960s to the present.

Increased water content is assumed to affect radionuclide transport. Increased water content is assumed to reduce the diffusivity of radon-222 (^{222}Rn) through the cover. Biological properties potentially impacted by water content, such as plant rooting depth and animal population

densities, are assumed to be the same as in undisturbed areas. Plant productivity is assumed to increase after subsidence. Subsidence is assumed to have no impact on cover integrity and thickness except through repair of subsidence during the active maintenance period. Cracks formed as waste subsides are assumed to be filled in by the natural flow of unconsolidated cover material.

When the cap elevation subsides below grade, transport parameters instantaneously change to their subsided values. Parameters that change with subsidence are the liquid advection rate, alluvium and waste water content, the ^{222}Rn diffusion coefficient calibration factor, and the plant primary productivity.

Waste Disposal Capacity

Since preparation of the approved PA/CA, new estimates have been made of the dimensions and volumes of the Area 3 RWMS disposal units. The three disposal units with waste at the Area 3 RWMS have a combined total volume of approximately 1.1 million cubic meters (m^3) (Table 2.1). Disposal unit volume is considered approximate as no data exists on the excavated dimensions of the disposal units.

Table 2.1 Updated Area 3 RWMS disposal unit status, dimensions, and volume

Disposal Unit	Status on 7/1/2006	Area (m^2)	Maximum Depth (m)	Disposal Unit Volume (m^3)	Waste Capacity (m^3)
U-3ax/bl	Closed	35,977	19	3.1E5	2.3E5
U-3ah/at	Partially Full	34,820	24	6.0E5	3.1E5
U-3bh	Partially Full	18,986	20	1.7E5	7.5E4

Waste capacity, the volume of waste that a disposal unit can hold, is a fraction of disposal unit volume, as some volume is filled with backfill soil and void space. The total waste capacity of the three disposal units with waste is estimated to be 0.62 million m^3 . The fraction of disposal unit volume that is waste, or the facility design factor, varies with disposal unit. Containerized wastes tend to decrease the facility design factor. The U-3ax/bl disposal unit, which contains uncontainerized bulk waste, has the highest facility design factor, 0.73. U-3bh, which contains more containerized waste, has the lowest, 0.44.

As of July 1, 2006, the Area 3 RWMS had received approximately 0.56 million m^3 of waste (Figure 2.4). Approximately 60% of the waste volume was disposed after September 26, 1988, and is regulated by DOE O 435.1, "Radioactive Waste Management" (DOE, 2001a). Disposal rates were comparatively low from the start of operations in 1966 to 1978. After 1978 when receipt of offsite waste began, disposal rates increased and remained relatively constant until 2002. Disposal rates increased again in 2002 and continued until the suspension of operations in 2006.

Figure 2.4 Area 3 RWMS volume disposal rate and cumulative volume over the operational period

Most of the radionuclide activity was disposed after September 26, 1988 (Figure 2.5). The largest increase in disposed activity occurred from 2002 to 2006, after preparation of the Area 3 RWMS PA/CA.

Figure 2.5 Area 3 RWMS activity disposal rate and cumulative activity over the operational period

2.2.3 Waste Inventory

The Area 3 RWMS inventory is estimated from three data sources that were in use during different periods. The three sources, the Waste Management Logbook, the Waste Management Data Base (WMDB), and the Low-Level Waste Information System (LWIS), are the same data sources as used in the approved PA/CA. Important changes relative to the approved PA/CA that affect the inventory estimate include the following:

- Development of a new probabilistic inventory model using GoldSim
- Disposal of significant additional waste inventory
- The delay of the planned closure date from 2013 to 2025, allowing additional time for decay of short-lived radionuclides
- Inclusion of radioactive decay during the operational period in the inventory estimate
- Minor changes in the methods used to correct for unreported or under-reported radionuclides

The inventory estimates are distributions (i.e., pdfs) produced by the probabilistic Area 3 RWMS GoldSim inventory model, version 2.012. A description of the model and its results are presented in Appendix A3.

The source of the U-3ax/bl inventory is mostly nuclear testing operations on the NNSS. The near-term inventory is dominated by the short-lived radionuclides tritium (^3H), strontium-90 (^{90}Sr), and cesium-137 (^{137}Cs) (Figure 2.6). After 100 y, the inventory is predominately plutonium-239 (^{239}Pu) and the total activity is relatively constant over the remainder of the 1,000-y compliance period. The total U-3ax/bl inventory is slightly less than the other two disposal units.

Figure 2.6 U-3ax/bl geometric mean radionuclide inventory over time. Time-zero corresponds with 2025 final closure date.

The source of the U-3ah/at inventory is mostly offsite DOE generators. The near-term inventory is dominated by ^3H , ^{90}Sr , and ^{137}Cs (Figure 2.7). After 150 y, the inventory is relatively constant over time and is predominantly uranium-234 (^{234}U) and uranium-238 (^{238}U).

Figure 2.7 U-3ah/at geometric mean radionuclide inventory over time

Waste disposed in U-3bh has originated from offsite DOE generators and remediation of NNSS Pu-contaminated soils from safety tests. For 150 y after closure, the U-3bh inventory is predominantly ^3H (Figure 2.8). Afterwards, ^{238}U and ^{239}Pu are the most abundant radionuclides.

Figure 2.8 U-3bh geometric mean radionuclide inventory over time

2.2.4 CA Inventories

The approved CA considered four categories of residual radioactive material that may interact with the Area 3 RWMS. The sources were Waste Management Projects, residual radioactive contamination from underground testing (UGTAs), residual soil contamination from aboveground testing (Soil Sites), and contaminated sites formerly used to support testing operations (Industrial Sites). Among these sources, Soil Sites and UGTAs have the greatest potential to contribute dose to future residents, and they were the only sources considered in the CA. Inclusion of the Yucca Flat UGTA (CAU 97) in the CA is awaiting additional characterization and modeling.

Contaminated Soil Sites, potentially interacting with the Area 3 RWMS, exist throughout Yucca Flat. The Soil Sites were contaminated by aboveground nuclear testing, underground nuclear testing, and safety experiments where a nuclear weapon is destroyed usually resulting in no or a very slight fission yield. No additional characterization or cleanup of Soil Sites has occurred since preparation of the Area 3 RWMS CA. The Area 3 RWMS CA used Soil Site inventories estimated by the Radioisotope Inventory and Distribution Program (RIDP) (McArthur, 1991). McArthur (1991) reported inventories for 28 contaminated areas in Yucca Flat and one site in Plutonium Valley. The SA uses the same data but includes one additional minor site, an unsurveyed site in Area 2, which was not included in the Area 3 RWMS CA. Complete details of the Soil Site inventories and their estimation can be found in Appendix A3. The Area 3 RWMS is located within the RIDP HORNET ground zero (GZ) site. The HORNET GZ site inventory is dominated by ^{239}Pu throughout the post-closure period (Figure 2.9).

Figure 2.9 HORNET GZ geometric mean radionuclide inventory over time

2.2.5 Transport Model

Diffusive Transport of Radon

Diffusion of the noble gas ^{222}Rn through the cap and the resulting ground surface flux density (a performance objective) was modeled in the approved PA using the method described in the U.S. Nuclear Regulatory Commission (NRC) *Regulatory Guide 3.64* (NRC, 1989). The NRC method estimates the radon ground surface flux, which is directly proportional to the concentration of the ^{222}Rn parent, radium-226 (^{226}Ra), in the waste below.

The Model now simulates the diffusion of ^{222}Rn through the cover, the upward transport of radon parents into the cover, and the deposition of radon progeny in cover soil. Radon decay products can be a significant source of dose to individuals exposed directly to cover soil. The Model estimates a correction factor for the diffusion coefficient based on a calibration to the surface flux density calculated using the NRC *Regulatory Guide 3.64* method. The calibration factor corrects for numerical dispersion caused by too few GoldSim cells being used in the Model. The short half-life of ^{222}Rn , 3.8 days, requires more cells than can be efficiently included in the Model. Separate correction factors are estimated for the subsided and unsubsided model configurations. Once diffusive transport is calibrated, the Model allows radon, its parents, and its progeny to migrate freely throughout the waste and cap layers.

Liquid Phase Transport

The liquid phase transport model used in the approved PA/CA simulated upward liquid advection with linear adsorption on the solid phase. GoldSim simulation capabilities include liquid advection with linear adsorption but also allow easy implementation of additional

processes, including liquid phase diffusion of dissolved solutes and precipitation/dissolution of solid phases. The approved PA/CA acknowledged that these processes were likely to occur but concluded that they were insignificant relative to other processes.

The Model simulates a full suite of liquid transport processes, including upward liquid advection, linear reversible adsorption on the solid phase, liquid phase diffusion, and precipitation/dissolution of solids for a limited set of elements. The upward liquid advection rates are also updated in the Model. The Model assumes upward liquid advection during the unsubsided phase. The upward liquid flux pdf is estimated from probabilistic process model simulations calibrated with water content and environmental tracer profiles observed at the Area 3 RWMS (Kwicklis et al., 2006). After subsidence below grade, increased infiltration from ponding of runoff is assumed to initiate small downward liquid fluxes. The upward flux is assumed to be zero during the subsided phase.

Biotic Transport

The basic concepts of biotic contaminant transport have not changed from the approved PA/CA to the current Model. Biotic transport between model compartments is modeled using transfer rates based on the following processes:

- Animal burrow excavation and collapse, moving fractions of contaminated materials (i.e., waste and soil) from deeper layers to the ground surface. Excavated burrows are assumed to eventually collapse and be filled with alluvium from the overlying layer to maintain mass balance of bulk materials.
- Plant root uptake from sub-surface soil and waste layers and translocation of radionuclides to aboveground plant parts, followed by incorporation into the topmost alluvium layer assuming complete plant senescence. Plant transfer rates are based on plant-soil concentration ratios (CRs) and aboveground primary productivity rates.

The transfer rates in the current Model are calculated for groups of plants and animals with similar characteristics. The parameterization of important plant and animal groups (especially ants and perennial grasses) is supported by field data gathered at various sites, including Area 3, on the NNSS under the PA maintenance program.

Radiological Assessment Method

The Model calculates the MOP annual total effective dose (TED) for a transient occupant, resident, and resident with agriculture scenarios. The radiological assessment methods used for the resident and resident with agriculture scenarios are the same as the community and community with agriculture scenarios evaluated in the approved PA/CA (Shott et al., 2001). The transient occupant scenario uses the same methods as the Area 5 RWMS PA (BN, 2006). All scenarios use updated dose conversion factors (DCFs) for adults from Federal Guidance Report (FGR) 13 (U.S. Environmental Protection Agency, 1999).

The Model evaluates two new acute intruder scenarios, the drilling and the construction scenarios. The chronic intruder scenarios in the approved PA/CA are replaced by the acute

scenarios based on the assumption that the new IC policy will prevent chronic intrusion. Complete details of the intruder scenarios can be found in the Model documentation.

2.3 Summary of Analysis

This SA provides an update to the analysis of radionuclide transport and estimation of dose from LLW disposed at the Area 3 RWMS. Moving the analysis to the GoldSim platform allows for stochastic analysis, which, when coupled with sensitivity analysis of the probabilistic results, offers insight into what parts of the model are most significant. Such insight has informed the direction of investigations supporting the model, providing defensible support where it is most needed.

Important model changes since preparation of the approved PA/CA include the following:

- Increased model transparency afforded by the GoldSim platform
- Fully probabilistic Monte Carlo simulation
- Probabilistic periods of active and passive institutional control based on elicitation of SMEs
- A revised dynamic subsidence model based on a probabilistic analysis of waste composition and compacted bulk density
- Updated disposal unit dimension estimates
- Increased estimate of closure inventory due to higher concentrations of wastes disposed since preparation of the approved PA
- Simulation of radon diffusive transport, coupled with radon parent radionuclide transport processes
- New coupled biotic transport models for plant uptake and animal burrowing, backed up by NNSS field data
- New upward liquid water flux estimates, supported by probabilistic external process model analysis of site characterization data
- Analysis of acute intruder scenarios
- Improved quantitative global sensitivity analysis of the total PA/CA model

The Model was used to generate complete PA and CA results presented in the following chapter. PA and CA results are generated from 5,000 model realizations produced by LHS.

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3.0 Results of Analysis

3.1 Performance Assessment Results

3.1.1 Environmental Transport of Radionuclides

Concentration in Air

Two gaseous radionuclides, ^3H and ^{222}Rn , are projected to reach the highest concentrations in air at the Area 3 RWMS (Figure 3.1). The ^{222}Rn concentration is relatively constant throughout the compliance period, while ^3H has a peak at approximately 44 y and decreases rapidly afterwards. The peak ^3H concentration is a small fraction of the $7.8\text{E}3 \text{ Bq m}^{-3}$ DOE O 458.1 Derived Concentration (DOE, 2011). The highest ^{222}Rn concentration, 1.1 becquerels per cubic meter (Bq m^{-3}), is less than the alternative performance objective limit of 18.5 Bq m^{-3} . Several gaseous radionuclides, carbon-14 (^{14}C), argon-39 (^{39}Ar), ^{42}Ar , and krypton-85 (^{85}Kr), are assumed to be released from waste at the time of closure and rapidly diffuse out of the waste zone to the atmosphere.

Figure 3.1 Activity concentration of radionuclides in air above the Area 3 RWMS as a function of time

Particulate radionuclides, resuspended to air, are projected to be present at concentrations many orders of magnitude less than gaseous species. The airborne concentration of particulate radionuclides rises slowly as they accumulate in surface soils. Particulate lead-210 (^{210}Pb) and technetium-99 (^{99}Tc) reach the highest concentrations.

Comparison of model results with air monitoring results is feasible only for ^3H and ^{222}Rn . All other radionuclides are projected to be present in air at levels that are difficult or impossible to detect. An additional complication for comparisons is that conditions during the monitored

operational phase are different than assumed for the post-closure period. A significant difference is the presence of waste containers and waste forms in the disposal units that will reduce release rates. The Model assumes immediate release of the entire inventory and should tend to overestimate concentrations in the near-term when waste containers and forms are still intact.

In 2010 tritiated water vapor (HTO) concentrations at the Area 3 RMWS ranged from 0.0004 to 0.4 Bq m⁻³ (NSTec, 2011b). Model results for the post-closure period peak at 0.97 Bq m⁻³ at 44 y. Current HTO monitoring results are less than the peak projected for the post-closure period. The monitoring results are consistent with the expectation that Model results will overestimate actual concentrations.

Measurement of ²²²Rn in air was performed over 4 years at six locations within the Area 3 RWMS and at two nearby control sites (BN, 2003). No significant difference was observed between the RWMS and the control sites. The Model results are a small fraction of the measured background concentrations and would be difficult to detect. The monitoring results confirm the Model prediction that ²²²Rn concentrations in air are low.

Concentration in Soil

The PA soil concentrations are averaged over the surface soil layer of the U-3ah/at and U-3bh disposal units. Radionuclides that diffuse in the gas phase or that have gaseous parents, ³H, ²¹⁰Pb, and ²²²Rn, appear most rapidly in surface soil. Tritium reaches a peak in approximately 44 y that exceeds all other nuclides by several orders of magnitude. The concentration of ²²²Rn increases very gradually over time, reflecting ingrowth of the source term. After 300 y, ²¹⁰Pb becomes the highest concentration radionuclide in soil.

Figure 3.2 Activity concentration of radionuclides in surface cover soil as a function of time

Particulate radionuclides accumulate gradually in surface soil over time. By 850 y, ^{99}Tc , which is highly concentrated by plants, reaches the highest concentrations and slightly exceeds the ^{210}Pb concentration.

Radionuclide monitoring in cover soils at the Area 3 RWMS is limited to gamma-emitting radionuclides, ^{238}Pu , $^{239+240}\text{Pu}$, and americium-241 (^{241}Am) at U-3ax/bl, the only closed disposal cell. In 2009, U-3ax/bl soil concentrations were below the detection limit or not different than detected in control samples. This is consistent with the Model which estimates concentrations for particulate radionuclides that would be undetectable.

3.1.2 Dose Results for the Air Pathway

The air pathway annual TED is evaluated for the resident exposure scenario using 5,000 LHS realizations. Doses are calculated for a period of 1,000 y after closure. The annual TED is zero until 100 y when ICs are assumed to be 100% effective. After 100 y, ICs begin to fail probabilistically.

All realizations of the air pathway annual TED are a small fraction of the 0.1 millisievert (mSv) limit throughout the 1,000-y compliance period (Figure 3.3). At 100 y, many realizations indicate the TED is decreasing as short-lived radionuclides decay. The mean and 95th percentile TEDs, however, initially increase due to the increasing probability of IC failure. The mean and 95th percentile TEDs are averages that include realizations with zero dose due to ICs remaining effective. The maximum mean annual TED, $6.5\text{E-}6$ mSv, occurs at 1,000 y after closure (Table 3.1). The 5th percentile TED is zero throughout the compliance period due to a greater than 5% probability that ICs will remain effective for 1,000 y or more.

Figure 3.3 Resident air pathway annual TED time history

Table 3.1 Maximum air pathway annual TED for the resident scenario

Performance Objective/Scenario	Performance Objective (mSv)	Mean Annual TED (mSv)	95 th Percentile (mSv)	Time of Maximum
Air Pathway/Resident	0.1	6.5E-6	1.7E-5	1,000 y

At 100 y when ICs begin to fail, the air pathway dose is approximately equally from ^3H (43%) and $^{210}\text{Pb}+\text{P}$ (57%), where “+P” indicates that dose from short-lived progeny in secular equilibrium are included (Figure 3.4). Over time as ^3H decays away, the air pathway dose becomes completely dominated by $^{210}\text{Pb}+\text{P}$ (92%). Minor contributions are made by $^{238}\text{U}+\text{P}$, ^{234}U , ^{239}Pu , and ^{240}Pu resuspended from soil.

Figure 3.4 Mean annual air pathway TED time history by radionuclide

3.1.3 Dose Results for All-Pathways

The all-pathways TED is also calculated for the resident exposure scenario. All 5,000 realizations are a small fraction of the 0.25 mSv annual TED performance objective throughout the 1,000-y compliance period (Figure 3.5). Individual realizations of the all-pathways annual TED are generally increasing throughout the compliance period. The mean and 95th percentile all-pathways TEDs also increase throughout the compliance period. The increase is more rapid after 100 y as ICs begin to fail. The maximum mean annual TED, 7.1E-5 mSv, occurs at 1,000 y (Table 3.2).

Figure 3.5 Resident all-pathway annual TED time history

Table 3.2 Maximum all-pathways annual TED for the resident scenario

Performance Objective/Scenario	Performance Objective (mSv)	Mean Annual TED (mSv)	95 th Percentile (mSv)	Time of Maximum
All-Pathways/Resident	0.25	7.1E-5	2.0E-4	1,000 y

At 100 y, the all-pathways TED is predominantly from $^{210}\text{Pb}+\text{P}$ (90%) and ^3H (9%) (Figure 3.6). The all-pathways TED continues to be dominated by ^{210}Pb throughout the compliance period. By 1,000 y, $^{210}\text{Pb}+\text{P}$ contributes 96% of the dose with $^{238}\text{U}+\text{P}$ as the next most important source of dose, contributing only 2%.

Figure 3.6 Mean annual all-pathway TED time history by radionuclide

3.1.4 Results for ^{222}Rn Flux Density

The ^{222}Rn flux density is averaged over the area of the post-1988 disposal units, U-3ah/at and U-3bh. All 5,000 realizations are less than the $0.74 \text{ Bq m}^{-2} \text{ s}^{-1}$ performance objective (Figure 3.7). The time dependency of the ^{222}Rn flux density for the first few hundred years after closure is complex, reflecting the effects of the differing source terms and subsidence rates in the U-3ah/at and U-3bh disposal units. For individual realizations, the flux is initially relatively constant until subsidence begins. Repair of subsidence during the maintenance period increases cover thickness, causing the flux to decrease. Once maintenance ends, the flux begins to increase again as ingrowth of ^{226}Ra increases ^{222}Rn production and radon parents are transported into the cover. The mean and 95th percentile ^{222}Rn flux densities are relatively stable throughout the compliance period. The maximum mean ^{222}Rn flux density, $0.029 \text{ Bq m}^{-2} \text{ s}^{-1}$, occurs at 1,000 y (Table 3.3).

Figure 3.7 ^{222}Rn flux density time history

Table 3.3 Maximum ^{222}Rn flux density results

Performance Objective/Disposal Unit	Performance Objective ($\text{Bq m}^{-2} \text{s}^{-1}$)	Mean ^{222}Rn Flux Density ($\text{Bq m}^{-2} \text{s}^{-1}$)	95 th Percentile ($\text{Bq m}^{-2} \text{s}^{-1}$)	Time of Maximum
^{222}Rn Flux Density/ U-3ah/at and U-3bh	0.74	0.029	0.070	1,000 y

3.1.5 Results for Acute Intruder Scenarios

Acute Construction Scenario

The acute construction scenario estimates the TED to construction workers building a home on a disposal unit. A home constructed at the Area 3 RWMS might involve excavation of a basement, swimming pool, or septic tank. The construction scenario assumed a basement is excavated as in previous PAs.

All 5,000 realizations of the acute construction scenario for the U-3ah/at disposal unit are less than the 5 mSv performance measure (Figure 3.8). The intruder TED appears to increase throughout the compliance period. The mean and 95th percentile intruder TEDs increase for several hundred years after closure as ICs begin to fail. The maximum mean acute construction intruder TED, 0.014 mSv, occurs at 1,000 y for the U-3ah/at disposal unit (Table 3.4).

Figure 3.8 Intruder TED time history for the acute construction scenario at U-3ah/at

Table 3.4 Maximum acute construction scenario TED results

Scenario/Disposal Unit	Performance Measure (mSv)	Mean TED (mSv)	95 th Percentile (mSv)	Time of Maximum
Construction/U-3ah/at	5	0.014	0.036	1,000 y
Construction/U-3bh	5	0.016	0.037	1,000 y

The predominant source of the acute construction TED throughout the compliance period is external irradiation by progeny of ^{222}Rn deposited in cover soil. At 1,000 y, the U-3ah/at acute construction TED is predominantly from $^{222}\text{Rn}+\text{P}$ (46%), ^{239}Pu (29%), and $^{238}\text{U}+\text{P}$ (12%).

A small number of individual realizations of the acute construction TED for the U-3bh disposal unit exceed the performance measure (Figure 3.9). The individual realizations of the acute construction TED for U-3bh appear to fall into two distinct populations. Examination of individual realizations from the two groups indicates that the difference is related to the final cover thickness after subsidence. Containers disposed in U-3bh are mostly boxes and Sealand containers, which are assumed to degrade more slowly than drums. This delays subsidence in U-3bh relative to U-3ah/at and increases the likelihood that subsidence occurs after the 30-y active maintenance period. The realizations with higher TEDs are composed of cases where subsidence occurs after the maintenance period and the cover remains 3 m (9.8 ft) thick throughout the compliance period. In these cases, the construction excavation exposes buried waste and causes higher doses. In the lower dose U-3bh realizations, and all realizations for U-3ah/at, the cover thickness is increased by repair of subsidence occurring during the active maintenance period. When intrusion occurs, the cover thickness is greater than the construction excavation depth and waste is not directly exposed.

Figure 3.9 Intruder TED time history for the acute construction scenario at U-3bh

The mean and 95th percentile acute construction intruder TEDs at U-3bh are less than the performance measure for 1,000 y after closure. The mean is increasing throughout the compliance period, and the maximum TED, 0.016 mSv, occurs at 1,000 y (Table 3.4).

At 100 y, the U-3bh construction intruder TED is predominantly from thorium-228 (^{228}Th)+P (28%), ^{222}Rn +P (23%), and ^{228}Ra +P (17%). By 1,000 y, the most important source of dose is ^{222}Rn +P (31%), ^{228}Th +P (23%), ^{239}Pu (17%), and ^{228}Ra +P (14%).

Acute Drilling Scenario

The acute drilling scenario estimates the TED to a drill crew drilling a water well through a disposal unit. Exposure to contaminated drill cuttings occurs while augering a surface casing for the well. Results for the acute drilling scenario are less than estimated for the acute construction scenario.

All 5,000 realizations of the U-3ah/at acute drilling scenario TED are less than the 5 mSv performance measure (Figure 3.10). Individual realizations of TED decrease until 200 y, after which it remains relatively constant. Many individual realizations have a maximum from 100 to 200 y. The mean TED, however, increases throughout the compliance period and reaches its maximum of 2.3E-4 mSv at 1,000 y (Table 3.5). The maximum of the 95th percentile, 5.5E-4 mSv, occurs at 140 y.

Figure 3.10 Intruder TED time history for the acute drilling scenario at U-3ah/at

Table 3.5 Maximum acute drilling scenario TED results

Scenario/Disposal Unit	Performance Measure (mSv)	Mean TED (mSv)	95 th Percentile (mSv)	Time of Maximum
Drilling/U-3ah/at	5	2.3E-4	4.5E-5 [†]	1,000 y
Drilling/U-3bh	5	4.2E-4	1.2E-3	1,000 y

[†] - Maximum 95th percentile value occurs at 140 y

At 100 y, the U-3ah/at acute drilling TED is predominantly from ¹³⁷Cs+P (84%). The 1,000-y TED is predominantly from ²²²Rn+P (43%), ²³⁸U+P (22%), and ²³⁹Pu (15%).

All realizations of the acute drilling scenario at the U-3bh disposal unit are less than the performance measure (Figure 3.11). Individual realizations of TED are relatively constant throughout the compliance period. The mean TED increases throughout the compliance period, reaching a maximum of 4.2E-4 mSv at 1,000 y (Table 3.5).

Figure 3.11 Intruder TED time history for the acute drilling scenario at U-3bh

The U-3bh acute drilling TED is predominantly from $^{228}\text{Th}+\text{P}$ and $^{228}\text{Ra}+\text{P}$ throughout the compliance period.

3.2 Performance Assessment Uncertainty Analysis

3.2.1 Air Pathway Dose Uncertainty

Parameter Uncertainty

Parameter uncertainty is assessed by evaluating probabilistic model outputs produced by Monte Carlo simulation. Sensitive input parameters are assigned pdfs describing uncertainty in the average parameter value over the time, region, or population modeled. The pdfs are repeatedly sampled using LHS and propagated through the Model to obtain a result. The process is repeated until a stable distribution of Model outputs is obtained. The output distributions represent the contribution of parameter uncertainty to output uncertainty.

The maximum of the mean air pathway annual TED occurs at 1,000 y. The distribution of the annual air pathway TED at 1,000 y indicates that there is a high probability that the dose is less than the 0.1 mSv performance objective (Figure 3.12). The empirical cumulative distribution function (ecdf), plotted on the right, is the fraction of model outputs that are equal to or less than the value on the x-axis. The ecdf indicates that no realization out of 5,000 exceeds the performance objective. The step in the ecdf indicates that there is an 11% chance of a negligible dose to the member of public due to ICs remaining effective for more than 1,000 y.

Figure 3.12 Histogram of non-zero doses (left) and ecdf (right) of the air pathway annual TED at 1,000 y

Exposure Scenario Uncertainty

Compliance with the air pathway performance objective is evaluated for the resident scenario based on the opinions of SMEs that this was the most likely scenario for receptors on or near the RWMS. Exposure scenario uncertainty is evaluated by estimating the annual TED for reasonable, but less likely, alternative scenarios.

The resident with agriculture scenario evaluates the dose to a resident engaged in part-time non-commercial agricultural activities. The resident is assumed to ingest limited amounts of vegetables, fruits, milk, beef, eggs, and poultry produced on the site. The addition of agriculture slightly increases the resident's dose through the air pathway at all times (Figure 3.13). The mean and 95th percentile TED for a resident with agriculture is less than the performance objective throughout the 1,000-y compliance period (Table 3.6).

Figure 3.13 Time history of the mean (solid) and 95th percentile (dashed) air pathway annual TED for the resident and alternative exposure scenarios

Table 3.6 Maximum air pathway alternative scenarios annual TED results

Performance Objective/Scenario	Performance Objective (mSv)	Mean TED (mSv)	95 th Percentile (mSv)	Time of Maximum
Air Pathway/Resident with Agriculture	0.1	7.3E-6	1.9E-5	1,000 y
Air Pathway/Transient Occupant	0.1	2.6E-6	7.3E-6	1,000 y

The transient occupant scenario evaluates the dose to a MOP on the site 2,000 hours per year (hr y^{-1}). The air pathway dose to a transient occupant is less than to a resident after approximately 150 y. At earlier times the transient occupant dose is slightly greater than the resident dose due to onsite exposure to ^3H .

The mean and 95th percentile annual TED is less than the performance objective for all alternative scenarios for 1,000 y after closure. Although scenario uncertainty is a potentially significant source of uncertainty, evaluation of a range of credible scenarios indicates that there is still a high likelihood of meeting the air pathway performance objective.

Future Inventory

The U-3ah/at and U-3bh disposal units are partially filled and are not expected to be filled at closure. The future inventory analysis evaluates the impacts of additional waste disposal in the U-3ah/at and U-3bh disposal units.

Future inventories are estimated by assuming that U-3ah/at and U-3bh are filled to capacity. Future waste for each disposal unit is assumed to have an activity concentration similar to

disposed waste. Therefore, addition of future waste has little impact on waste activity concentration but increases the total inventory.

Disposal of future waste is estimated to slightly increase the resident's air pathway annual TED at all times (Figure 3.14). The mean and 95th percentile air pathway annual TEDs remain less than the performance objective with disposal of future waste throughout the 1,000-y compliance period.

Figure 3.14 Time history of the mean (solid) and 95th percentile (dashed) air pathway annual TED for the base case inventory and the base case plus future inventory

Performance after the Compliance Period

The Model duration was increased to 10,000 y to evaluate performance beyond the period of compliance. A period of 10,000 y is judged as the maximum period where the conceptual model might remain valid. All parameters remain constant after 1,000 y.

The mean and 95th percentile resident's air pathways annual TEDs continue to increase from 1,000 to 10,000 y (Figure 3.15). Uncertainty appears to increase after approximately 1,000 y. All realizations, however, of the air pathway TED remain below the performance objective for 10,000 y.

Figure 3.15 Time history of air pathway annual TED for 10,000 y after closure

Doses are expected to increase gradually after the compliance period as progeny activities increase and transport process lead to a slow accumulation of radionuclides in surface soils. The peak in the Model TED was obtained by increasing the duration of a deterministic model run to 3 million y. During 3 million y, however, many Model assumptions, such as site water balance and biotic communities, are expected to become invalid. The results of the 3 million y run simply represent Model behavior rather than site performance.

The air pathway annual TED reaches a broad peak at 2.2 million y associated with the ^{238}U decay chain approaching secular equilibrium (Figure 3.16). The air pathway TED decreases very slowly thereafter as ^{238}U decays. The air pathway peak annual TED is less than the 0.1 mSv performance objective.

Figure 3.16 Time history of the air pathway annual TED for 3E6 y after closure

3.2.2 All-Pathways Dose Uncertainty

Parameter Uncertainty

Parameter uncertainty for the resident all-pathways annual TED is assessed by Monte Carlo simulation using 5,000 LHS realizations. The maximum of the mean all-pathway annual TED occurs at 1,000 y. Parameter uncertainty is evaluated at the 1,000-y maximum.

The distribution of the all-pathways annual TED at 1,000 y indicates that there is a high probability that the dose is less than the 0.25 mSv performance objective (Figure 3.17). The log-transformed all-pathways annual TED is reasonably symmetrically distributed, indicating a slight skew toward lower dose. All 5,000 realizations are less than the performance objective. The ecdf indicates that there is an 11% chance of a negligible dose to the MOP due to ICs remaining effective for more than 1,000 y.

Figure 3.17 Histogram of non-zero doses (left) and ecdf (right) of the all-pathway annual TED at 1,000 y

Exposure Scenario Uncertainty

Uncertainty contributed by the exposure scenario is investigated by evaluating two alternative scenarios, the resident with agriculture scenario and the transient occupant scenario. Both alternative scenarios doses are greater than the resident scenario dose (Figure 3.18). The resident with agriculture scenario all-pathways annual TED is initially several orders of magnitude greater than the resident dose. By approximately 200 y, the resident with agriculture TED decreases to a level similar to the transient occupant's dose. The higher resident with agriculture dose after closure is due to ingestion of ^3H in agricultural products. At 1,000 y, the resident with agriculture annual TED is due predominantly to ingestion of $^{210}\text{Pb}+\text{P}$ and ^{99}Tc . The most important source of dose for the transient occupant, who is assumed to be on site, is external irradiation from ^{222}Rn progeny (i.e., ^{214}Pb and ^{214}Bi) in cover soil.

The TED for the alternative scenarios is greater than for the resident scenario. The mean and 95th percentile TEDs of the alternative scenarios remain less than the performance objective throughout the compliance period (Table 3.7). Although scenarios may be an important source of uncertainty in the all-pathways TED result, there is a high likelihood of compliance with the performance objective for all scenarios evaluated.

Figure 3.18 Time history of the mean (solid) and 95th percentile (dashed) all-pathways annual TED for the resident and alternative exposure scenarios

Table 3.7 Maximum all-pathways alternative scenario annual TED results

Performance Objective/Scenario	Performance Objective (mSv)	Mean TED (mSv)	95 th Percentile (mSv)	Time of Maximum
All-Pathway/Resident with Agriculture	0.25	1.2E-3	3.6E-3	1,000 y
All-Pathway/Transient Occupant	0.25	1.3E-3	3.4E-3	1,000 y

Future Inventory

Including future inventory in the all-pathways analysis causes a slight increase in the annual TED (Figure 3.19). The increase is constant throughout the compliance period. The activity concentration of future waste is similar to that of disposed waste.

The mean and 95th percentile all-pathways annual TEDs remain less than the 0.25 mSv performance objective for 1,000 y after closure. Filling available capacity at the Area 3 RWMS with waste similar to disposed waste does not alter the conclusion that there is a reasonable expectation of compliance with the all-pathways performance objective.

Figure 3.19 Time history of the mean (solid) and 95th percentile (dashed) all-pathways annual TED for the base case inventory and the base case plus future inventory

Length of IC Period

The importance of the probabilistic period of IC was investigated by comparing the base case results with a case using a constant 100-y IC period.

The mean and 95th percentile resident's all-pathways annual TED increases gradually from 100 to 1,000 y with the use of a 100-y IC period (Figure 3.20). Although the deterministic 100-y IC period increases the TED, all realizations remain significantly less than the performance objective.

Figure 3.20 Time history of the resident's all-pathway annual TED with a constant 100-y period of IC

Performance after the Compliance Period

The Model duration was increased to 10,000 y to evaluate the all-pathways performance beyond the period of compliance. A period of 10,000 y was judged as the maximum period where the conceptual model would remain valid. All parameter values remain constant over the 1,000 to 10,000 y period.

The mean and 95th percentile resident all-pathways annual TEDs continue to increase from 1,000 to 10,000 y (Figure 3.21). Uncertainty appears to increase at approximately 1,000 y. All realizations of the all-pathways TED remain below the performance objective for 10,000 y.

Figure 3.21 Time history of all-pathways annual TED for 10,000 y after closure

The resident all-pathways TED reaches a broad peak beginning at 2.2E6 y when the ^{238}U decay chain approaches secular equilibrium. The dose decays very slowly thereafter with the half-life of ^{238}U (Figure 3.22). The annual TED remains below the 0.25 mSv performance objective throughout the entire period.

Figure 3.22 Time history of the all-pathway annual TED for 3E6 y after closure

3.2.3 ^{222}Rn Flux Density Uncertainty

Parameter Uncertainty

Parameter uncertainty for the ^{222}Rn flux density is assessed by Monte Carlo simulation using 5,000 LHS realizations. The maximum flux density during the compliance period occurs at 1,000 y. Therefore, parameter uncertainty is evaluated at 1,000 y.

The distribution of the ^{222}Rn flux density at 1,000 y indicates that there is a high probability that the flux is less than the $0.74 \text{ Bq m}^{-2} \text{ s}^{-1}$ performance objective (Figure 3.23). The log-transformed flux density is reasonably symmetrically distributed, indicating a slight skew toward lower flux. All 5,000 realizations are less than the performance objective.

Figure 3.23 Histogram of non-zero values (left) and ecdf (right) of the ^{222}Rn flux density at 1,000 y

Future Inventory

Including future inventory in the ^{222}Rn flux analysis causes an increase in the flux (Figure 3.24). The increase is relatively constant throughout the compliance period. The mean and 95th percentile ^{222}Rn flux densities with future waste remain less than the $0.74 \text{ Bq m}^{-2} \text{ s}^{-1}$ performance objective throughout the compliance period.

Figure 3.24 Time history of the mean (solid) and 95th percentile (dashed) ^{222}Rn flux density for the base case inventory and the base case plus future inventory

Performance after the Compliance Period

The Model duration was increased to 10,000 y to evaluate the ^{222}Rn flux density after the period of compliance. A period of 10,000 y was judged to be the maximum period where the conceptual model was likely to remain valid. All parameter values remain constant over the period from 1,000 to 10,000 y.

The mean and 95th percentile ^{222}Rn flux densities continue to increase from 1,000 to 10,000 y (Figure 3.25). Uncertainty is initially high for a few hundred years after closure when subsidence is occurring. A few individual realizations exceed the $0.74 \text{ Bq m}^{-2} \text{ s}^{-1}$ flux density limit by approximately 5,000 y. The mean and 95th percentile remain less than the performance objective throughout the 10,000-y period. Overall, a high likelihood of compliance with the performance objective continues for a period of 10,000 y.

Figure 3.25 Time history of the ^{222}Rn flux density for 10,000 y after closure

A deterministic evaluation of ^{222}Rn flux density for 3 million y was performed. The deterministic ^{222}Rn flux density exceeds the $0.74 \text{ Bq m}^{-2} \text{ s}^{-1}$ performance objective by 56,000 y (Figure 3.26). The ^{222}Rn flux density reaches a peak flux at $2.2\text{E}6 \text{ y}$ when ^{226}Ra is in secular equilibrium with ^{238}U .

Figure 3.26 Time history of the ^{222}Rn flux density for 3E6 y after closure

Nuclear subsidence craters in Yucca Flat have been observed to accumulate alluvial sediment over the few decades of their existence. Subsided disposal units within the Area 3 RWMS may also accumulate alluvium after subsidence below grade. This process is not in the Model. Increased cover thickness caused by sediment accumulation would delay the time that the ^{222}Rn flux density exceeds the performance objective.

3.2.4 Maintaining Releases As Low As Reasonably Achievable

A PA is required to demonstrate that radionuclide releases to the environment are as low as reasonably achievable (ALARA). Releases are maintained ALARA by optimizing the disposal facility design considering costs associated with the facility's construction, operation, and health detriment. The Area 3 RWMS is an operational facility that has already disposed a significant inventory of waste. Optimizing releases from the Area 3 RWMS entails determining if there are cost-effective ICs, closure, or remediation options that can reduce MOP doses further. Cost-effective options must reduce costs, most likely health detriment costs, by an amount at least equal to the cost of implementation.

The value of health detriment is determined by calculating the collective dose and multiplying by a dollar per person-Sv conversion factor. The collective dose is the sum of all the individual doses of exposed persons. The number of exposed persons is a function of the area assumed to be impacted. Spatial limits must be imposed on the collective dose calculation to avoid decision making with collective doses composed of large numbers of trivial individual doses (International Commission on Radiological Protection, 2007). Individual doses that are a small fraction of background can be considered trivial as few individuals would take action to avoid them. The maximum mean all-pathways annual TED, $7\text{E-}5$ mSv, is 0.007% of natural background, excluding radon (National Council on Radiation Protection and Measurements [NCRP], 2009), and represents the dose to the most exposed persons. Because the maximum individual doses at the site boundary are so low, the spatial limits for the Area 3 RWMS collective dose must be confined to the immediate vicinity of the site. Considering the Area 3 RWMS's remote location, lack of water resources, and location within a nuclear testing area, the population of exposed persons is likely to be small. The low individual doses and small exposed population indicate that value of the health detriment from the Area 3 RWMS is likely so low that cost-effective measures for reducing dose do not exist. This supports a conclusion that releases from the Area 3 RWMS are ALARA.

3.3 Sensitivity Analysis of Performance Assessment Results

The sensitivity of the air pathway annual TED, the all-pathways annual TED, and the ^{222}Rn flux density were evaluated at 1,000 y when the maximum result was obtained. A boosted regression tree model, known as a generalized boosted model (GBM) (Ridgeway, 2010), was fit for each of the three PA Model endpoints using the R Project GBM package (R Development Core Team, 2011). The GBMs achieved good to excellent fits for the three Model endpoints. The sensitivity of the GBMs was evaluated by calculating the Monte Carlo estimate of the first-order and total effects Sobol's sensitivity indexes (SIs) (Sobol', 2001). Sobol's first-order SI measures the fraction of total Model variance attributable to one parameter in isolation. The total effects SI measures the fraction of total Model variance attributable to a parameter and all of its interactions with other parameters. Complete details of the sensitivity analysis method and results are presented in Appendix A4.

The air pathway annual TED at 1,000 y was found to be weakly sensitive to multiple parameters related to the ^{222}Rn source term (i.e., Rn parent inventories and Rn emanation coefficient) and the length of the active IC period (Table 3.8). The air pathway model is weakly sensitive to multiple parameters because the ^{222}Rn source term is affected by multiple disposal units (U-3ah/at and U-3bh) and multiple radon parents. Although interactions are apparent for several parameters, interactions are especially important for the depth where upward liquid advection ceases (i.e., the no-liquid-flux boundary [NLFB]), whose sensitivity ranking increases from fifth to third when interactions are included.

Table 3.8 First-order and total effects Sobol's SIs for the air pathway annual TED at 1,000 y

Rank	Parameter	First-Order SI	Parameter	Total Effects SI
1	U-3ah/at ^{226}Ra Inventory	0.19	U-3ah/at Rn Emanation Coefficient	0.24
2	U-3ah/at Rn Emanation Coefficient	0.18	U-3ah/at ^{226}Ra Inventory	0.23
3	Period of Active IC	0.11	Depth of NLFB	0.21
4	U-3bh ^{230}Th Inventory	0.10	U-3bh ^{230}Th Inventory	0.12
5	Depth of NLFB	0.06	Period of Active IC	0.12
6	Outdoor Mass Loading	0.03	Rodent Burrow Shape	0.06
7	Rodent Burrow Shape	0.03	U-3bh Rn Emanation Coefficient	0.04
8	U-3ah/at Settlement Ratio	0.03	U Solubility Limit	0.03

The all-pathways annual TED at 1,000 y was also found to be weakly sensitive to multiple parameters related to the ^{222}Rn source term and the length of the IC period (Table 3.9). The rate of inadvertent soil ingestion also appears among the more sensitive parameters. Interactions are apparent mostly for the ^{222}Rn source term related parameters. Interactions between Rn parent inventories and the Rn emanation coefficient are expected.

Table 3.9 First-order and total effects Sobol's SIs for the all-pathways annual TED at 1,000 y

Rank	Parameter	First-Order SI	Parameter	Total Effects SI
1	U-3ah/at ^{226}Ra Inventory	0.20	U-3ah/at ^{226}Ra Inventory	0.30
2	U-3ah/at Rn Emanation Coefficient	0.18	U-3ah/at Rn Emanation Coefficient	0.30
3	Period of Active IC	0.10	Inadvertent Soil Ingestion Rate	0.17
4	Inadvertent Soil Ingestion Rate	0.10	Period of Active IC	0.15
5	U-3bh ^{230}Th Inventory	0.09	U-3bh ^{230}Th Inventory	0.14
6	U-3ah/at Settlement Ratio	0.02	U-3bh Rn Emanation Coefficient	0.05
7	U-3ah/at ^{230}Th Inventory	0.02	Depth of NLFB	0.04
8	Depth of NLFB	0.02	U-3ah/at Settlement Ratio	0.03

The ^{222}Rn flux density at 1,000 y was found to be moderately sensitive to the U-3ah/at ^{226}Ra inventory and the U-3ah/at Rn emanation coefficient (Table 3.10). Weak sensitivity to the U-3bh thorium-230 (^{230}Th) inventory and emanation coefficient is observed.

Table 3.10 First-order and total effects Sobol's SIs for the ^{222}Rn flux density at 1,000 y

Rank	Parameter	First-Order SI	Parameter	Total Effects SI
1	U-3ah/at ^{226}Ra Inventory	0.31	U-3ah/at Rn Emanation Coefficient	0.43
2	U-3ah/at Rn Emanation Coefficient	0.30	U-3ah/at ^{226}Ra Inventory	0.41
3	U-3bh ^{230}Th Inventory	0.14	U-3bh ^{230}Th Inventory	0.20
4	U-3bh Rn Emanation Coefficient	0.02	U-3bh Rn Emanation Coefficient	0.07
5	U-3ah/at ^{230}Th Inventory	0.02	U-3ah/at ^{230}Th Inventory	0.03
6	U-3ah/at Settlement Ratio	0.01	U-3ah/at Settlement Ratio	0.03
7	U-3ah/at ^{234}U Inventory	0.01	U-3ah/at ^{234}U Inventory	0.02

3.4 Composite Analysis Results

3.4.1 Environmental Transport of Radionuclides

Air Concentration

The highest concentrations of radionuclides in air above the Area 3 RWMS are gaseous radionuclides released from the Area 3 RWMS disposal units (Figures 3.27). ^{222}Rn , released mostly from the U-3ax/bl disposal unit, is the highest concentration radionuclide. The peak ^{222}Rn concentration, 7 Bq m^{-3} , is less than a typical outdoor background concentration of 9 Bq m^{-3} (NCRP, 1988). HTO released from the Area 3 RWMS is the next most abundant airborne radionuclide. The peak HTO concentration, 0.8 Bq m^{-3} , occurs at 44 y. The highest concentration particulate radionuclides are present at closure, indicating that they are resuspended from the Soil Sites rather than released from Area 3 RWMS disposal units.

Figure 3.27 Activity concentration of radionuclides in air at the 100-m (330-ft) boundary for all CA sources as a function of time

The Area 3 RWMS environmental monitoring program routinely detects HTO, ^{241}Am , and $^{239+240}\text{Pu}$ in air at the site. In 2010, most HTO concentrations were less than the 0.04 Bq m^{-3} minimum detectable concentration (NSTec, 2011a). The highest HTO concentrations in 2010, approximately 0.4 Bq m^{-3} , were less than the maximum Model result of 0.8 Bq m^{-3} . In 2010, $^{239+240}\text{Pu}$ concentrations ranged from $4\text{E-}7$ to $4\text{E-}6 \text{ Bq m}^{-3}$, which is an order of magnitude less than the Model estimate of $3\text{E-}5 \text{ Bq m}^{-3}$ at closure. Typically measured ^{241}Am concentrations, $4\text{E-}7 \text{ Bq m}^{-3}$, are similarly bounded by the Model projection of $5\text{E-}6 \text{ Bq m}^{-3}$ at closure. Environmental monitoring data confirm that the Model provides conservative estimates of radionuclide concentrations in air from all sources as used in the CA.

Radionuclide ratios may also be used to test the CA Model and identify the source of radionuclides found in environmental samples. The mean $^{241}\text{Am}/^{239+240}\text{Pu}$ activity ratio for air samples collected at the Area 3 RWMS in 2010 was 12.4% (NSTec, 2011b). A 12% ratio is consistent with the ratio observed for HORNET GZ (McArthur, 1991). This suggests that transuranics in air at the Area 3 RWMS are currently being resuspended from contaminated Soil Sites surrounding the Area 3 RWMS.

The CA Model airborne $^{241}\text{Am}/^{239+240}\text{Pu}$ activity ratio is 17% at 10 y post-closure, slightly higher than the observed ratio of 12%. The Model's higher $^{241}\text{Am}/^{239+240}\text{Pu}$ activity ratio suggests that the ingrowth of ^{241}Am from plutonium-241 (^{241}Pu) in the HORNET GZ inventory is overestimated. The overestimate is likely due to uncertainty concerning the initial concentration of ^{241}Am and ^{241}Pu in plutonium and the age of the plutonium.

The Model estimate of the $^{241}\text{Am}/^{239+240}\text{Pu}$ activity ratio in Area 3 RWMS cover soil, 0.2% at 10 y, is much less than observed in air samples at the RWMS or in contaminated soils

surrounding the RWMS. The ratio in disposed waste is estimated to be 18%. The lower ratio in cover soil is caused by large differences between Am and Pu K_d s and plant-soil CRs, which favor release of plutonium. The Model results suggest that the $^{241}\text{Am}/^{239+240}\text{Pu}$ activity ratio might provide a gross screening method for identifying releases from the Area 3 RWMS. A significant decrease in the $^{241}\text{Am}/^{239+240}\text{Pu}$ activity ratio in air or soil surface samples at the RWMS might provide an indication of significant releases from disposed waste.

Soil Concentration

Radionuclide concentrations in soil at the 100-m (330-ft) site boundary, estimated for the CA, are predominantly from the HORNET GZ Soil Site and HTO from the Area 3 RWMS (Figure 3.28). The HTO concentration reaches a peak at 44 y and decreases rapidly afterwards. By 120 y, ^{239}Pu becomes the highest concentration radionuclide.

Figure 3.28 Activity concentration of radionuclides in surface soil at the 100-m (330-ft) site boundary for the CA as a function of time

3.4.2 Results for the Composite Analysis

The SA calculates the CA annual TED for a resident exposure scenario. The resident is assumed to live at the 100-m (330-ft) RWMS boundary within the HORNET GZ Soil Site. The resident is exposed to radionuclides from the HORNET GZ source, the Area 3 RWMS, and from other more distant Soil Sites throughout Yucca Flat.

All 5,000 realizations of the CA annual TED are less than the 0.3 mSv dose constraint and the 1 mSv dose limit (Figure 3.29). The CA annual TED is relatively constant over time for each individual realization. The maximum value of individual TED realizations occurs at the time ICs fail.

Figure 3.29 Time history of composite analysis annual TED

The mean and 95th percentile TEDs increase after 100 y due to the increasing probability that ICs have failed. The maximum mean annual TED, 0.021 mSv, occurs at 1,000 y after closure (Table 3.11).

Table 3.11 Maximum CA annual TED results

Scenario	Dose Constraint (mSv)	Mean TED (mSv)	95 th Percentile (mSv)	Time of Maximum
Resident	0.30	0.021	0.031	1,000 y

The most important radionuclide source for the CA annual TED is the HORNET GZ (Figure 3.30). The annual TED from the HORNET GZ decreases over time as the source term slowly undergoes radioactive decay. The mean annual TED increases over time as the probability of a resident at the site boundary increases.

Figure 3.30 Time history of composite analysis annual TED by source

The other sources are minor contributors to the CA TED over the 1,000-y compliance period. The second most important source is the Yucca Flat Soil Sites. The Area 3 RWMS makes a comparatively minor contribution to the CA annual TED.

The TED from the HORNET GZ and Yucca Flat Soil Sites is predominantly from ^{239}Pu and ^{240}Pu throughout the compliance period. Dose from the Area 3 RWMS disposal units is almost entirely from inadvertent ingestion of soil contaminated with $^{210}\text{Pb}+\text{P}$.

3.4.3 Options Analysis

The CA requires an options analysis if the dose from all interacting sources of radioactive materials is greater than the 0.3 mSv dose constraint and less than the 1 mSv dose limit. The maximum mean CA result, 0.021 mSv in a year, is significantly less than the dose constraint; therefore, no options analysis is necessary.

3.5 Composite Analysis Uncertainty Analysis

CA parameter uncertainty is assessed by propagating 5,000 LHS input parameter values through the Model by Monte Carlo simulation. The maximum mean CA annual TED occurs at 1,000 y. Therefore, CA parameter uncertainty is evaluated at 1,000 y.

The distribution of the CA annual TED at 1,000 y indicates that there is a high probability that the dose is less than the 0.3 dose constraint (Figure 3.31). The log-transformed dose is reasonably symmetrically distributed, indicating a slight skew toward higher dose. All 5,000 realizations are less than the dose constraint.

Figure 3.31 Histogram of non-zero values (left) and ecdf (right) of the CA annual TED from all sources at 1,000 y

3.6 Composite Analysis Sensitivity Analysis

The sensitivity of the CA annual TED was evaluated at 1,000 y. A GBM was fit using 5,000 LHS realizations. A very good fit was obtained with an r-squared of 0.97. The GBM was found to be moderately sensitive to the HORNET GZ enrichment factor, the HORNET GZ ^{239}Pu inventory, and the length of the active IC period (Table 3.12). The enrichment factor is the ratio of the radionuclide concentration in resuspended particulates to concentration in bulk soil. Higher order interactions were observed for the three most sensitive parameters. The HORNET GZ enrichment factor and the HORNET GZ ^{239}Pu inventory were found to have an increasing linear relationship with the CA annual TED. Weak sensitivity to the indoor and outdoor mass loading and the ^{240}Pu inventory was also observed. Uncertainty in the CA annual TED appears to be related to uncertainty in the HORNET GZ $^{239+240}\text{Pu}$ source term and the probability that a MOP will be present. Complete results for the CA sensitivity analysis are presented in Appendix A4.

Table 3.12 First-order and total effects Sobol's SIs for the CA annual TED at 1,000 y

Rank	Parameter	First-Order SI	Parameter	Total Effects SI
1	HORNET GZ Enrichment Factor	0.36	HORNET GZ Enrichment Factor	0.47
2	HORNET GZ ^{239}Pu Inventory	0.22	HORNET GZ ^{239}Pu Inventory	0.30
3	Period of Active IC	0.20	Period of Active IC	0.27
4	Outdoor Mass Loading	0.04	Outdoor Mass Loading	0.04
5	HORNET GZ ^{240}Pu Inventory	0.03	Period of Passive IC	0.02
6	Period of Passive IC	0.03	Indoor Mass Loading	0.02
7	Indoor Mass Loading	0.02	HORNET GZ ^{240}Pu Inventory	0.02
8	Inadvertent Soil Ingestion Rate	0.02	Inadvertent Soil Ingestion Rate	0.01

4.0 Interpretation of Results

4.1 Performance Assessment Results

The purpose of the SA is to update the PA results using the current baseline model (i.e., the Area 3 RWMS v2.102 model or the Model) and evaluate the continuing adequacy of the approved PA. The Model was used to probabilistically estimate the air pathway annual TED, the all-pathways annual TED, and the ^{222}Rn flux density.

The Model maximum mean result was found to occur at 1,000 y for all three PA performance objectives, as was found for the approved PA. Comparison of the Model results with the approved PA results indicates a reduction for the air pathway TED and an increase for the all-pathways annual TED (Table 4.1). The current ^{222}Rn flux density result shows a significant increase over the approved PA results.

Table 4.1 Comparison of the approved PA and A3 RWMS v2.102 Model results.

Performance Objective	Approved PA Mean	A3 RWMS v2.102 Mean [‡]
Air Pathway/Resident Scenario	4E-5 mSv (U-3bh)	7E-6 mSv
All-Pathways/Resident Scenario	4E-5 mSv [†]	7E-5 mSv
Radon Flux Density	4E-4 Bq m ⁻² s ⁻¹ (U-3ah/at)	0.03 Bq m ⁻² s ⁻¹
Intruder Protection/Chronic Intruder-Agriculture	3E-4 mSv (U-3bh)	Excluded by ICs
Intruder Protection/Acute Construction	NA	0.016 (U-3bh)
Protection of Groundwater Resources	No Release to Aquifer in 1,000 y	No Release to Aquifer in 1,000 y

[†] - Same result obtained for U-3ah/at and U-3bh

[‡] - Updated results are for U-3ah/at and U-3bh combined, unless noted otherwise

NA – not available

The differences above are the result of cumulative changes to the model and its input parameters. A comparison of the two models where the inventory was held constant indicates that the Model produces lower doses for the air pathway and all-pathways TED and similar ^{222}Rn flux densities (see Appendix A2). Therefore, the increases in the all-pathways TED and the ^{222}Rn flux density in Table 4.1 must in part be due to inventory increases occurring since preparation of the approved PA.

Review of the GoldSim model development documentation suggests that several changes during the model development process had significant impacts on all model endpoints. These important changes have affected all dose endpoints in the same way (i.e., increase or decrease) but affect different endpoints to different degrees. The increased site inventory and updated subsidence model have increased the dose estimates, while the addition of a passive IC period has decreased the mean dose. The effects of the subsidence model changes are caused in part by the shorter maintenance period. The shorter maintenance period allows less cover repair, resulting in a thinner cover. A thinner cover allows increased releases of ^{210}Pb to surface soil, which increases the all-pathways dose. The ^{222}Rn flux density appears to be affected most significantly by the increased radionuclide inventory.

In addition to the GoldSim model changes discussed above, which are recorded in the Model development records, there are potentially important differences between the approved PA and the initial (version 1.0) GoldSim model. Among these changes is the revised ^{222}Rn transport model, which tracks the deposition of ^{222}Rn progeny, including ^{210}Pb , in cover soil. The Model results indicate that ^{210}Pb in cover soil is an important source of dose, while the approved PA models only estimated ^{222}Rn surface flux and did not include progeny transport. Another change occurring with migration to GoldSim was implementation of a revised biotic transport model with updated transport rates.

Although significant changes have occurred, the Model results for the air pathway and all-pathways annual TED indicate there is a reasonable expectation that the doses are a small fraction of the performance objectives. The ^{222}Rn maximum mean flux density is approximately 4% of the performance objective.

The Model results also indicate that the disposed inventory is protective of intruders and groundwater resources. Chronic intruder results are replaced by acute intruder scenarios. The maximum acute intruder dose is a small fraction of the performance measure. Releases to the uppermost aquifer are still considered unlikely.

The PA model and its input parameters have been improved and updated since preparation of the Area 3 RWMS PA/CA based on additional site operations, new site characterization and monitoring data, new process model results, and new literature reports. The conceptual model of site performance remains unchanged. The SA conclusions are essentially the same as the approved PA's conclusions that all results are a small fraction of the performance objectives and there is a high likelihood of compliance. Revision of the PA appears to be unnecessary until the closure plan is finalized or unless a resumption of operations significantly alters site conditions.

4.1.1 Key Results

Key radionuclides are defined as long-lived nuclides that contribute significantly to the air pathway dose, all-pathways dose, or ^{222}Rn flux density. Selection of key radionuclides is a function not only of the radionuclide's behavior in the waste disposal system, but also its inventory in disposed waste.

Tritium is identified as a key radionuclide that contributes significantly to the MOP dose early in the post-closure period. The importance of ^3H depends on the duration of ICs. Early failure of ICs favors the importance of ^3H as a key radionuclide. Key radionuclides contributing to long-term risks include ^{238}U , ^{234}U , ^{230}Th , ^{226}Ra , and ^{239}Pu . Although ^{210}Pb is a major contributor to long-term dose, it is not considered a key radionuclide because it is produced by decay of its parents in disposed waste. Key radionuclides contributing to the production of ^{210}Pb and ^{222}Rn flux density are ^{238}U , ^{234}U , ^{230}Th , and ^{226}Ra .

Key uncertainties are defined as uncertainties contributing most significantly to uncertainty in the SA results. Sensitivity analysis is important for identifying potential key uncertainties, but the key assumptions must also be considered for their potential contribution to uncertainty. Sensitivity analysis indicates that key uncertainties are the U-3ah/at ^{226}Ra inventory, the U-3bh ^{230}Th inventory, the Rn emanation coefficient, and the duration of the IC period. A key uncertainty arising from the assumptions is the hydrologic performance of subsided disposal units. Subsidence is assumed to initiate downward liquid fluxes, but recharge of the aquifer is

assumed not to occur. The magnitude of future downward fluxes and their potential to reach the aquifer within 1,000 y is a significant source of uncertainty.

Key operational conditions are requirements for operations and closure that are considered essential to ensure that PA conclusions remain valid. The Area 3 RWMS is near its waste volume capacity and currently in standby mode. A key operational condition would be the control of any future inventory to ensure compliance with the performance objectives. Other key operational conditions are related to ICs and the assumption of no groundwater pathway after subsidence. Assumed closure conditions are important to the latter condition. Key operational conditions impacting the groundwater pathways assumption would include closure with a 3-m (9.8-ft) vegetated ET cover constructed from native alluvium, a final closure cover elevation above surrounding grade, and effective controls for eliminating run-on into subsided disposal units. Implementation of land use controls for the Yucca Flat UGTA (CAU 97) is also seen as a key operational condition ensuring that ICs remain effective.

4.2 Composite Analysis Results

The purpose of the SA is to update the CA results using the Model and evaluate the continuing adequacy of the approved CA. The Model was used to probabilistically estimate the annual TED to a resident at the 100-m (330-ft) site boundary from the Area 3 RWMS and contaminated Soil Sites throughout Yucca Flat.

The Model maximum mean CA result was found to occur at 1,000 y, while the approved CA found a maximum dose at 250 y. Comparison of the Model results with the approved CA results indicates an increase in the annual TED (Table 4.2). The major source of dose continues to be inhalation of ^{239}Pu resuspended from the HORNET GZ contaminated Soil Site.

Table 4.2 Comparison of the approved CA and A3 RWMS v2.102 Model results.

Performance Measure	Approved CA Mean	A3 RWMS v2.102 Mean
All-Pathways/Resident Scenario	0.01 mSv	0.02 mSv

The shift in the time of the maximum mean dose from 250 to 1,000 y is a result of the new probabilistic IC period. The combined active and passive IC period in the Model is longer than the deterministic 250-y period assumed in the prior CA. The probabilistic IC period reduces the mean dose in the near-term. The increase in the CA annual TED is likely due to changes in parameters influencing the dose from ^{239}Pu resuspended from the HORNET GZ contaminated Soil Site. Important parameters that have been updated include the HORNET GZ resuspension enrichment factor and the inhalation DCFs.

The SA results for the CA annual TED indicate that the dose is a small fraction of the 0.3 mSv dose constraint and due predominantly to the HORNET GZ site. The SA results are similar to the approved CA results. The CA conceptual and mathematical models have changed little from the approved version. Some input parameters, however, have been updated. The SA results support a conclusion that there is a reasonable expectation that the dose from all sources of radioactive materials is less than the dose constraint and the dose limit. Revision of the CA appears to be unnecessary until plans for closure are finalized, operations resume, or groundwater concentration estimates become available from UGTA activities. The CA was approved with a condition that a revision be prepared when UGTA groundwater concentration estimates are available.

4.2.1 Key Results

Key nuclides for the CA are nuclides resuspended from the HORNET GZ contaminated Soil Site. The key radionuclides from the HORNET site are ^{239}Pu , ^{240}Pu , ^{241}Am , and ^{137}Cs .

Key uncertainties for the CA are related to the HORNET GZ site source term and the length of the active IC period. Sensitivity analysis identifies key CA uncertainties related to the HORNET GZ source term are the resuspension enrichment factor and the ^{239}Pu inventory.

Key operational conditions for the CA are the implementation of the NNSS IC policy and the Yucca Flat UGTA (CAU 97) land use restrictions. The controls are expected to indefinitely prevent development at the 100-m (330-ft) site boundary.

5.0 Compliance Evaluation

The approved Area 3 RWMS PA/CA reached a conclusion that the PA results were in compliance with the performance objectives and that the CA results supported continuing waste disposal operations without any remediation or operational changes. This section evaluates if the SA results continue to support a conclusion of compliance with the appropriate PA and CA requirements.

5.1 Performance Assessment

Compliance with the PA performance objectives is provided by demonstrating there is a reasonable expectation that the performance objectives can be met for a period of 1,000 y after final closure. Reasonable expectation of compliance is assumed to be demonstrated if the maximum of the mean and median are less than the performance objective throughout the compliance period. The mean was found to be greater than the median for all performance objectives and is used for the comparisons.

Comparison of the maximum mean SA results with the performance objectives indicates that Model results support a conclusion of compliance with all requirements. The resident exposure scenario was evaluated for compliance with the air pathway and all-pathways annual TED performance objectives. The maximum mean and 95th percentile results were found to be a small fraction of the performance objectives for both the air pathway and all-pathways annual TED (Table 5.1).

Table 5.1 Summary of maximum PA results

Performance Objective	Limit	Limiting Result			Conclusion
		Scenario	Mean	95 th Percentile	
Air Pathway Annual TED	0.1 mSv	Resident	7E-6 mSv	2E-5 mSv	Complies
All-Pathways Annual TED	0.25 mSv	Resident	7E-5 mSv	2E-4 mSv	Complies
²²² Rn Flux Density	0.74 Bq m ⁻² s ⁻¹	All Disposal Units	0.03 Bq m ⁻² s ⁻¹	0.07 Bq m ⁻² s ⁻¹	Complies
Intruder Protection	5 mSv	Acute Construction U-3ah/at	0.01 mSv	0.04 mSv	Complies
Groundwater Protection	40 CFR 141	No groundwater pathway in 1,000 y			Complies
Releases ALARA	No Limit	No cost effective options			ALARA

The maximum mean and 95th percentile ²²²Rn flux density is less than the performance objective. The result supports a conclusion of reasonable expectation of compliance.

Chronic exposure of intruders is assumed unlikely based on long-term land use plans for Yucca Flat. Land use plans are assumed to ensure compliance with the chronic intrusion performance measure. The maximum mean and 95th percentile TED for an acute intruder was found to be less than the performance measure. This provides assurance of compliance with the intruder protection requirements.

Site characterization data indicate that there is no groundwater pathway under current climatic conditions. Control of run-on after disposal unit subsidence is assumed to maintain infiltration at levels where recharge of the aquifer within 1,000 y is unlikely. The lack of a groundwater pathway ensures that groundwater protection requirements can be met.

Projected releases to the environment are a small fraction of the performance objectives. Cost-effective options for reducing releases further are unlikely to exist. Therefore, releases from Area 3 RWMS are judged ALARA.

5.2 Composite Analysis

The purpose of the CA is to guide decision making concerning the management of the LLW disposal facility and other interacting sources of residual radioactive material. The CA annual TED is compared with the 0.3 mSv dose constraint. If the dose is less than 0.3 mSv, no action is necessary to reduce doses further. A CA result greater than 0.3 mSv but less than 1 mSv requires an options analysis to identify cost-effective options for reducing doses. A dose greater than 1 mSv requires remediation.

Comparison of the maximum mean SA result with the 0.3 mSv dose constraint indicates that no action is required to reduce the dose from interacting sources. The same conclusion was reached in the approved CA. The resident exposure scenario was evaluated for compliance with the dose constraint. The maximum mean and 95th percentile result were found to be significantly less than the dose constraint (Table 5.2).

Table 5.2 Summary of maximum CA result

Performance Measure	Constraint	Limiting Result			Conclusion
		Scenario	Mean	95 th Percentile	
Dose Constraint	0.3 mSv	Resident	0.02 mSv	0.03 mSv	Options Analysis not Required

5.3 Application of SA Results

5.3.1 Future Work

Future work is defined as additional research that can increase confidence in the PA/CA conclusions and reduce uncertainty. Key PA uncertainties were identified as the ²²²Rn waste source term, the duration of ICs, and the consequences of subsidence of closure covers below grade. Key CA uncertainties were related to the HORNET GZ ²³⁹Pu source term, the duration of ICs, and implementation of UGTA derived land use restrictions.

Not all of these uncertainties are equally amenable to additional research. The hydrologic consequence of subsidence stands out as an uncertainty that would benefit from future work. Proposed revisions to DOE O 435.1, which would require analyses for a period of 10,000 y, are likely to increase the significance of this issue if implemented. Future work that could potentially decrease uncertainty in the hydrologic consequences of subsidence includes:

- Continue Area 3 RWMS Lysimeter studies to better understand the biotic and hydrologic consequences of increased infiltration.
- Conduct upstream flood evaluations of the Area 3 RWMS to develop estimates of potential run-on and understand the impacts of flood control berms.

- Assess the long-term sediment transport potential of alluvial fans upstream of the Area 3 RWMS and the associated impacts on the closure cover.
- Perform additional vadose zone modeling to understand the long-term consequences of multiple but infrequent infiltration events. Calibrate vadose models using available data sources including the Area 3 RWMS Lysimeter data and U-3bh characterization data.
- Evaluate the existing Area 3 RWMS closure plan, considering the potential consequences of subsidence.
- Conduct a groundwater resource evaluation to assess the potential impacts of aquifer recharge, should it occur.

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Appendix A1: Software Quality Assurance

Software used to prepare the special analysis (SA) for the Area 3 Radioactive Waste Management Site (RWMS) was developed and controlled under the National Security Technologies, LLC (NSTec), Software Quality Assurance Plan (SQAP), *Software Quality Assurance Plan for the GoldSim Models Supporting the Area 3 and Area 5 Radioactive Waste Management Site Performance Assessment Program* (NSTec, 2007). The SQAP implements quality requirements described in the NSTec Company Directive CD-3500.009, “Software Quality Assurance,” and Requirements Document RD-3200.001, “Quality Assurance Requirements Document.” These NSTec documents implement the requirements of U.S. Department of Energy (DOE) Order DOE O 414.1C, “Quality Assurance” (DOE, 2005). The following sections briefly summarize important features of the SQAP.

A1.1 Model Development

The Area 3 GoldSim inventory, performance assessment (PA), and composite analysis (CA) models are subject to a continuous process of review and improvement under the PA/CA maintenance plan. Annual reviews of site operations, monitoring program results, research results, and the results of sensitivity analyses are used to identify model components and input parameters that need revision or updating. Major revisions or changes are initiated only after consensus is reached among the PA/CA task team and the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office (NNSA/NSO).

The model development process is controlled by restricting model revisions to a single copy maintained in a model repository. Revisions are documented within the model and in external documentation maintained in the model repository and linked to the model. Model revisions are independently reviewed and verified. At least annually, baseline revisions are released for routine applications in support of waste management decisions. Baseline models are subject to a formal acceptability review by NNSA/NSO.

A1.1.1 Model Custody

The current version of each GoldSim model is maintained throughout the development process as a single file in a network model repository. Write privileges for the model repository are granted to a single person designated as the model custodian. A custody log is maintained that records the custodian’s identity and the version number of the current version over time. When a new version number is assigned with the GoldSim versioning feature, a copy is saved in an archive folder in the model repository.

Periodically after completing acceptance testing, the current model version is issued as a baseline model for routine application. Approved baseline models are maintained in a separate write protected repository file. Baseline models are also issued to project members on a compact disk for archival purposes. Analysts performing calculations for the SA obtain a copy of the baseline model from the repository and document their analysis in an Engineering Analysis/Calculation package, which includes a copy of all models and their results.

A1.1.2 Documentation and Records

Multiple records document the model development process. The GoldSim software includes a versioning feature that automatically records model changes. Periodically during the model

development process, the model custodian will create a new model version and save a copy in the model repository archive. Each archived version represents a snapshot of the model at a particular time in the development process. The GoldSim software can generate a report listing changes between any two model versions and can highlight changed model elements in the model browser window.

In addition to GoldSim's automatic change tracking, model developers record changes manually in multiple records within and external to the model. Whenever an element is changed or created, a version change note pane attached to the element is available where the analyst can record his or her name, date, and description of the changes. The text entered in version change notes is included in the GoldSim version report described above.

A higher level, chronological history of changes is recorded in a note pane (associated with the \Documentation container for the PA model and top level container for the inventory model). A brief summary of the most significant changes for each version is maintained in the \Whats_New container in the PA/CA model.

The effects of model changes on important results (e.g., scenario dose, surface soil concentrations) are recorded in the run log, maintained in an Excel spreadsheet linked to the model. The model run log records how model results have changed over time in response to model changes and improvements.

Additional notes can be recorded in the note pane associated with each model element. These notes are used to explain the function or performance of an element, the data source for data or stochastic input elements, and record quality assurance checks made by reviewers. Complex model components or data inputs may be supported by reports or Engineering Analysis/Calculation packages maintained in the model reference folder. External support documents are hot-linked to the model by icons located throughout the model and in the model parameter file (e.g., Area 3 RWMS Parameters.doc).

A1.1.3 Data Traceability

All input data are traceable to their original source and a data analysis package if any preprocessing was conducted. Each PA/CA model has a parameters document in the references folder (e.g., Area 3 RWMS Parameters.doc) that lists each input, its value or distribution, and data source. All inputs in the parameters document are hot-linked to the original data sources. The original data sources and data analysis packages are maintained in the model references folder.

A1.2 Model Review and Acceptability Testing

Throughout the model development process, model changes are checked by a reviewer for correctness and completeness and approved by the PA/CA task leader. PA/CA model versions prepared as baseline models for release are submitted to NNSA/NSO for acceptability testing. Acceptability testing produces a report summarizing the model's performance and describing appropriate application and limitations on use of the model. Models found to be acceptable by NNSA/NSO are committed to the write protected baseline model repository.

A1.3 Model Application

The PA/CA model is routinely used for waste management decision support, SAs, and the preparation of PA and CA reports. Analysts performing routine applications use a baseline version obtained from the model repository. Routine model applications are documented in an Engineering Analysis/Calculation package. The analyst prepares the calculation documenting the software version used, supporting references, assumptions, input data, calculations, and results. Any model changes required for the application are also documented in the Analysis/Calculation package. The model used for the analysis is maintained as part of the Analysis/Calculation package. Each Engineering Analysis/Calculation package is checked by a subject matter expert and approved for use by the responsible manager.

A1.4 References

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Appendix A2: Model Development and Comparison

A2.1 Model Development Process

Development of the Area 3 Radioactive Waste Management Site (RWMS) performance assessment (PA) and composite analysis (CA) model continued after approval of the PA/CA under the maintenance plan and software quality assurance plans. The approved PA/CA was performed using probabilistic spreadsheet calculations and FORTRAN computer programs as described in the PA/CA document (Shott et al., 2001).

The first step in model development was the integration of nearly all PA/CA model calculations into a single probabilistic model using the GoldSim simulation platform. An initial model was prepared from the Area 5 RWMS version 3.124 (v3.124) model, revised to simulate the Area 3 RWMS disposal units and include subsidence. Although the intention for the initial model was to reproduce the original Area 3 RWMS PA/CA models, starting with the existing Area 5 RWMS PA model introduced additional transport processes, such as solubility limits and liquid phase diffusion, that were assumed to be insignificant in the Area 3 PA/CA model but are easily accommodated in GoldSim. The Area 5 RWMS model also included a biotic transport model that was somewhat different from the Area 3 PA/CA model. Nevertheless, this model was benchmarked against PA/CA results for the U-3ah/at disposal unit and found to be in good agreement.

A summary of important changes to the Area 3 RWMS PA/CA model occurring since the approved PA/CA version includes:

- A revised institutional control (IC) period is assumed, which includes a regulatory-based minimum period of 100 years (y), followed by probabilistic periods of active and passive IC based on an elicitation of subject matter experts.
- Subsidence is simulated for U-3ah/at and U-3bh. The subsidence simulation is probabilistic and dynamic. A 30-y period of active maintenance is assumed when subsidence is repaired. Subsidence estimates are based on a new probabilistic analysis of database records of disposed waste bulk density and waste composition. Some release and transport parameters change upon subsidence.
- The diffusion of radon-222 (^{222}Rn) in the cover gas phase is explicitly modeled so that the concentration of ^{222}Rn and its progeny in cover soil is available. ^{222}Rn diffusion is calibrated to reproduce the surface flux density results that would be obtained using U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 3.64 methods (NRC, 1989). Calibration factors are determined for each disposal unit in the subsided and unsubsidized state.
- Cracks formed by subsidence are assumed to close by the natural flow of the alluvial sediments. Diffusion of ^{222}Rn occurs only in the air-filled pores of the cover.
- Upward advection rates are updated for the unsubsidized period with rates estimated by the probabilistic process model simulations of Kwicklis et al. (2006).
- Vadose zone transport processes include diffusion of dissolved solutes in soil pore water.
- Aqueous phase solubility limits are assumed for some heavy elements, including uranium.

- Plant uptake is calculated for four groups of plants. Parameters for plant uptake, excluding plant-soil concentration ratios (CRs), are based on site specific studies.
- Animal burrow excavation rates are calculated for two ant species and two groups of mammals. Burrow excavation rates, burrow depth, and burrow depth distribution is based on site specific studies.
- Chronic intrusion scenarios are replaced by an acute drilling scenario and an acute construction scenario.
- Waste inventories are updated through the end of active disposal in July 2006. Future inventories are estimated assuming that U-3ah/at and U-3bh will be filled to capacity with waste similar to disposed waste.
- Dose conversion factors (DCFs) are updated with factors for adults obtained from the Federal Guidance Report 13 Supplemental CD (U.S. Environmental Protection Agency, 1999).
- All Area 3 RWMS disposal unit areas and volumes are updated based analysis of crater dimensions.
- Some radiological assessment parameter distributions are updated (see the Model documentation for details).

A2.2 Comparison of PA Model Results

The cumulative effect of model structure and parameter value changes occurring since preparation of the Area 3 RWMS PA and CA is assessed by comparing the approved PA/CA results with results from the Area 3 RWMS v2.102 GoldSim Model. The Area 3 RWMS v2.102 Model was prepared for the comparison by entering the waste inventory used in the Area 3 RWMS PA, Table 2.7 (Shott et al., 2001). The inventories are assumed to be triangularly distributed with mode equal to the Table 2.7 value (Shott et al., 2001) and range equal to 0.1 and 10 times the mode. Comparisons are made at the time the maximum result was observed for the approved PA/CA. The comparison, therefore, represents the cumulative effect of model structure and parameter value changes, excluding inventory changes. The model and parameter changes are significant, and significant changes in the results are expected.

Performance assessment results for U-3ah/at indicate significantly lower total effective doses (TEDs) for all scenarios for the Model (Table A2.1). The time dependency of the atmospheric and all-pathways TED is similar for the two models after a few hundred years, showing a gradual increase in TED with time. Results for a few hundred years after closure are different as the two models use different IC assumptions. The PA assumed a fixed 250-y period of IC, while the current version assumes a probabilistic period of active and passive IC.

Table A2.1 Comparison of model results for U-3ah/at at 1,000 y

Performance Objective/Exposure Scenario	Approved PA		A3 RWMS v2.102 Model	
	Mean (mSv)	95 th Percentile (mSv)	Mean (mSv)	95 th Percentile (mSv)
Air Pathway/Resident	2E-5	6E-5	4E-7	8E-7
Air Pathway/Resident with Agriculture	2E-5	9E-5	4E-7	9E-7
All-Pathways/Resident	4E-5	1E-4	2E-6	6E-6
All-Pathways/Resident with Agriculture	3E-4	7E-4	2E-5	7E-5

Important radionuclides for the U-3ah/at air pathway are similar for the two models. The PA found that the air pathway TED was due predominantly to uranium-238 (^{238}U)+P and uranium-234 (^{234}U). The Model indicates that the air TED is from these two radionuclides plus lead-210 (^{210}Pb +P). The importance of ^{210}Pb +P was underestimated in the approved PA/CA models because it only calculated the radon surface flux density, whereas the Model estimates the concentration of ^{222}Rn and its daughters in cover soil. Similar differences for important radionuclides are observed for the U-3ah/at all-pathways results.

Performance assessment results for U-3bh indicate significantly lower TEDs for all scenarios for the Model (Table A2.2). The time dependency of the air pathways and all-pathways TED is similar for the two models after a few hundred years, showing a gradual increase in TED with time. Results for a few hundred years after closure are different as the two models use different assumptions about IC. The PA assumed a fixed 250-y period of IC, while the current version assumes a probabilistic period of active and passive IC.

Table A2.2 Comparison of model results for U-3bh at 1,000 y

Performance Objective/Exposure Scenario	Approved PA		A3 RWMS v2.102 Model	
	Mean (mSv)	95 th Percentile (mSv)	Mean (mSv)	95 th Percentile (mSv)
Air Pathway/Resident	4E-5	9E-5	1E-6	3E-6
Air Pathway/Resident with Agriculture	5E-5	1E-4	1E-6	4E-6
All-Pathways/Resident	4E-5	1E-4	2E-6	5E-6
All-Pathways/Resident with Agriculture	1E-4	2E-4	1E-5	3E-5

Important radionuclides for the U-3bh air pathway are similar for the two models. The PA found that the U-3bh air pathway TED was due predominantly to plutonium-239 (^{239}Pu), plutonium-240 (^{240}Pu), and americium-241 (^{241}Am). The Model indicates that the air pathway TED is predominately from ^{239}Pu and ^{240}Pu , with ^{241}Am being an unimportant radionuclide. The decreased importance of ^{241}Am may in part be due to an increase in the Pu inhalation DCF and decrease in the Am inhalation DCF. Similar differences in important radionuclides are observed for the U-3bh all-pathways dose.

The ^{222}Rn flux density results are similar for the two models (Table A2.3). The U-3ah/at flux increases slightly for the Model. The mean U-3bh flux density is unchanged.

Table A2.3 Comparison of ^{222}Rn flux density results at 1,000 y

Disposal Unit	Approved PA		A3 RWMS v2.102 Model	
	Mean ($\text{Bq m}^{-2} \text{ s}^{-1}$)	95 th Percentile ($\text{Bq m}^{-2} \text{ s}^{-1}$)	Mean ($\text{Bq m}^{-2} \text{ s}^{-1}$)	95 th Percentile ($\text{Bq m}^{-2} \text{ s}^{-1}$)
U-3ah/at	4E-4	1E-3	6E-4	2E-3
U-3bh	2E-4	7E-4	2E-4	5E-4

In contrast to the PA results, the intruder results for the Model increase significantly for the chronic intruder scenarios, except for the post-drilling scenario at U-3ah/at (Table A2.4). The time dependency of the intruder TED is similar for the two models after a few hundred years. At earlier times, differences in assumptions concerning ICs cause the Model to give lower results.

Table A2.4 Comparison of model results for the chronic intruder at 1000 y

Performance Objective/Intruder Scenario	Disposal Unit	Mean (mSv) at 1000 y	
		Approved PA	A3 RWMS v2.102 Model
Chronic Intruder/Intruder-Agriculture	U-3ah/at	5E-4	2E-3
	U-3bh	3E-4	8E-3
Chronic Intruder/Postdrilling	U-3ah/at	3E-4	1E-4
	U-3bh	5E-4	2E-3

Important radionuclides for U-3ah/at intruder scenarios are similar for both models. The PA results for the post-drilling scenario are mostly from $^{238}\text{U}+\text{P}$, ^{234}U , and ^{239}Pu , which is the same for the Model except that ^{239}Pu is less important.

Important radionuclides for intruder scenarios at U-3bh have changed significantly. Important radionuclides for the post-drilling scenario have changed from ^{239}Pu , ^{240}Pu , and ^{241}Am for the approved PA models to $^{238}\text{U}+\text{P}$ and ^{234}U for the Model. A similar shift is observed for the intruder-agriculture scenario.

A2.3 Comparison of CA Model Results

The CA results for the Model are less than the approved PA/CA results at 250 y (Table A2.5). The HORNET Ground Zero (GZ) is the most significant source for both models. Much of the CA TED decrease is due to the different IC assumptions. The contribution from the Area 3 RWMS disposal units has decreased significantly for the Model, as observed for the PA all-pathways result. However, because the disposal unit dose is a small fraction of the composite analysis dose, the total CA result is only slightly reduced. The large decrease in the disposal unit TEDs at 250 y is in part due to the different institutional IC assumptions.

Table A2.5 Comparison of model results for the CA at 250 y

Source	Mean TED (mSv) at 250 y	
	Approved CA	A3 RWMS v2.102 Model
HORNET GZ Soil Site	0.02	0.007
Yucca Flat Soil Sites	0.003	4E-4
U-3ax/bl	0.001	1E-9
U-3ah/at	2E-4	3E-8
U-3bh	5E-5	5E-8
Total	0.02	0.008

A2.4 References

- Kwicklis, E., A. Wolfsberg, P. Stauffer, M. Walvoord, and M. Sully, 2006. *Numerical Evaluation of Liquid and Vapor Fluxes at the Nevada Test Site Area 3 Radioactive Waste Management Site Using Hydrologic Data and Natural Environmental Tracers*. Los Alamos, NM: Los Alamos National Laboratory. LA-UR-06-1212.
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- U.S. Environmental Protection Agency, 1999. *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*. Washington, D.C.: U.S. Environmental Protection Agency. EPA-402-R-99-001, Supplemental CD.
- U.S. Nuclear Regulatory Commission, 1989. *Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers*. Washington, D.C.: U.S. Nuclear Regulatory Commission. Regulatory Guide 3.64.

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Appendix A3: Performance Assessment and Composite Analysis Inventories

The Area 3 Radioactive Waste Management Site (RWMS) special analysis (SA) estimates the RWMS inventory at closure using a model developed in the probabilistic GoldSim simulation platform. Version 1.000 of the Area 3 RWMS Inventory GoldSim model (A3 RWMS v1.000) was developed in September 2003 and populated with data from the Waste Management Logbook, Waste Management Data Base (WMDB), and Low-Level Waste Information System (LWIS). The Area 3 RWMS SA inventory is estimated with the A3 RWMS v2.012 inventory model. The inventory of radionuclides in contaminated Soil Sites in Yucca Flat is estimated using different methods.

A3.1 Area 3 RWMS Inventory Model

A3.1.1 Model Overview

The A3 RWMS v2.012 inventory model estimates the inventory of radionuclides disposed in the U-3ax/bl, U-3ah/at, and U-3bh disposal units at the Area 3 RWMS. Inventory uncertainty is estimated by Monte Carlo simulation. Inventory radioactive decay and ingrowth during the operational period is calculated by native GoldSim routines for solution of the Bateman equations. Model input data, data sources, assumptions, and methods are documented in notes, comments, hyperlinks, and graphics included within the model.

Important model inputs are probability density functions (pdfs) representing uncertainty. Input pdfs are sampled and propagated through the model. The process is repeated to produce a distribution of model results.

The inventory model output distributions for radionuclide inventory are well fit by lognormal distributions and are input into the PA/CA Model as lognormal distributions with the geometric mean and standard deviation of the inventory model outputs.

A3.1.2 Data Sources

Inventory records for the Area 3 RWMS are found in three sources: the Waste Management Logbook, the WMDB, and the LWIS. The Waste Management Logbook is a paper record summarizing disposals at the Area 3 RWMS from 1966 until 1978. Beginning in 1976, some disposal records were entered into the WMDB, an electronic database in use until 1993. From 1993 until the present, the LWIS has been in use. In addition to the database records, original records sent by the generator, survey records, and receipt records are maintained in an electronic imaging system. Records of disposals regulated under U.S. Department of Energy (DOE) Order DOE O 435.1 are maintained in the WMDB and LWIS. The Area 3 RWMS inventory model uses the same data sources as the approved Area 3 RWMS performance assessment (PA) and composite analysis (CA).

A3.1.3 Overview of Changes to Inventory Estimation Methods

The Area 3 RWMS inventory model uses similar methods and assumptions as used in the 2001 PA/CA. Important changes are noted below.

Data Sources

- Disposal records used to prepare the 2001 PA/CA inventory and Area 3 RWMS inventory model are the same: the Waste Management Logbook, the WMDB, and the LWIS. Information in these databases is occasionally compared with original shipping records and other records of site operation and revised as necessary. A large radium-226 (^{226}Ra) source ($5.5\text{E}10$ Bq), previously thought to be disposed at the Area 5 RWMS, has been determined to be disposed in U-3ax/bl and is now included in its inventory.
- Since preparation of the 2001 PA/CA, a significant effort was made to repopulate database tables in the WMDB. Queries of the WMDB are now believed to be more complete. The 2001 PA/CA inventory and the Area 3 RWMS inventory model use query results from different queries, prepared on different dates. The query results may be different, but each represents the best information available at the time of preparation. The queries and query results are documented in the Area 3 RWMS inventory model.

Inventory Revisions

- The approved PA/CA assigned gross activity or mixed fission product (MFP) activity to a limited list of high-yield fission products. The fission product scaling factors were estimated from multiple sources based on the expected mode of production. The Area 3 RWMS inventory model assigns activity to individual fission products based on the activity of MFP or gross activity disposed. The list of radionuclides included and their scaling factors are based on an estimate of the radionuclide composition of the Nevada National Security Site Underground Test Areas (UGTAs) (Bowen et al., 2001).
- The 2001 PA/CA estimated the inventory of unreported uranium isotopes by assuming an isotopic mixture for each generator. The current inventory model assumes that uranium-238 (^{238}U) and uranium-235 (^{235}U) disposed before fiscal year (FY) 1994 were depleted and enriched uranium, respectively. Enriched uranium is stochastically divided each FY into low and high enrichment fractions. The level of enrichment in each category (i.e., depleted, low enrichment, high enrichment) is selected randomly each FY. The isotopic composition of each mixture is based on a published empirical relationship between specific activity and enrichment for the gaseous diffusion process (DOE, 2009). In addition to corrections for uranium isotopes, scaling factors for fission product and transuranic contamination from recycled uranium are estimated from generator estimates.
- The 2001 PA estimated the inventory of unreported nuclides in weapons-grade plutonium disposed as PU52. The current inventory model performs similar revisions, but also includes calculations for PU51 and PU57. The inventory of plutonium-239 (^{239}Pu) disposed before FY 1994 is assumed to represent the activity of PU52 weapons-grade Pu, and corrections are made for other transuranic nuclides expected to be present.

Inventory Calculation

- The 2001 PA/CA summed disposal records deterministically. The current inventory model estimates the inventory by Monte Carlo simulation.
- The 2001 PA/CA performed radioactive decay and ingrowth calculation after closure. The current inventory model decays the inventory from the beginning of disposal operations until closure in 2025.

A3.1.4 Area 3 RWMS CA Inventory

The Area 3 RWMS CA inventory is disposed mostly in U-3ax/bl (Table A3.1). A small fraction (i.e., < 3% by volume) of U-3ah/at waste was disposed before September 26, 1988.

Table A3.1 Area 3 RWMS CA waste volumes

Inventory	U-3ax/bl	U-3ah/at
Pre-1988	227,485 m ³	7,696 m ³

The Area 3 RWMS CA inventories are assumed to be lognormally distributed with the geometric means and standard deviations listed in Table A3.2.

Table A3.2 Pre-1988 inventory of U-3ax/bl and U-3ah/at decayed to closure in 2025

Nuclide	U-3ax/bl		U-3ah/at	
	Geometric Mean (Bq)	Geometric Standard Deviation	Geometric Mean (Bq)	Geometric Standard Deviation
³ H	1.3E+14	3.13	7.7E+11	2.17
¹⁴ C	1.0E+11	3.13	1.1E+08	2.88
²⁶ Al	4.0E+06	3.16	4.3E+03	2.90
³⁶ Cl	2.2E+10	3.27	2.4E+07	2.91
³⁹ Ar	1.0E+11	3.16	1.1E+08	2.98
⁴⁰ K	6.0E+09	3.07	6.7E+06	2.65
⁴¹ Ca	1.6E+11	3.07	1.7E+08	3.08
⁶⁰ Co	1.2E+10	3.20	<i>Negligible</i>	
⁵⁹ Ni	4.2E+09	3.13	4.5E+06	2.83
⁶³ Ni	3.4E+11	3.19	4.0E+08	2.85
⁸⁵ Kr	6.4E+10	3.10	1.3E+08	2.67
⁹⁰ Sr	5.2E+12	3.08	7.8E+09	2.53
⁹³ Zr	5.7E+08	3.08	6.3E+05	2.67
^{93m} Nb	7.4E+10	3.31	1.2E+08	2.91
⁹⁴ Nb	1.4E+11	3.26	1.5E+08	3.01
⁹⁹ Tc	1.4E+10	2.45	1.0E+10	3.81
¹⁰⁷ Pd	2.5E+07	3.08	2.8E+04	2.68
^{113m} Cd	6.4E+10	3.17	1.1E+08	2.94
^{121m} Sn	1.4E+12	3.18	1.7E+09	2.93
¹²⁶ Sn	2.5E+08	3.08	2.7E+05	2.66
¹²⁹ I	1.3E+07	3.08	1.4E+04	2.66
¹³⁵ Cs	4.4E+08	3.07	4.9E+05	2.66
¹³⁷ Cs	7.2E+12	3.06	1.0E+10	2.61
¹⁵¹ Sm	5.5E+11	3.07	6.5E+08	2.66
¹⁵⁰ Eu	2.0E+11	3.38	2.3E+08	3.59
¹⁵² Eu	4.9E+11	3.25	8.8E+08	3.02
¹⁵⁴ Eu	8.8E+10	3.26	2.0E+08	3.17

Nuclide	U-3ax/bl		U-3ah/at	
	Geometric Mean (Bq)	Geometric Standard Deviation	Geometric Mean (Bq)	Geometric Standard Deviation
^{166m} Ho	5.4E+09	3.17	5.9E+06	2.92
²¹⁰ Pb	4.0E+11	4.07	1.1E+05	2.19
²²⁶ Ra	5.5E+11	4.07	3.6E+05	2.19
²²⁸ Ra	1.4E+09	2.71	4.8E+05	2.66
²²⁷ Ac	1.3E+06	2.20	1.7E+06	2.22
²²⁸ Th	8.3E+09	2.85	7.8E+06	2.87
²²⁹ Th	1.5E+07	3.05	1.4E+04	2.62
²³⁰ Th	3.6E+07	2.04	4.4E+07	2.19
²³² Th	1.5E+09	2.71	4.9E+05	2.66
²³¹ Pa	3.0E+06	2.21	4.2E+06	2.22
²³² U	5.9E+09	3.24	7.0E+06	2.91
²³³ U	3.5E+09	3.07	3.9E+06	2.60
²³⁴ U	9.3E+10	2.13	1.3E+11	2.19
²³⁵ U	3.6E+09	2.22	5.3E+09	2.22
²³⁶ U	2.5E+09	2.82	2.4E+09	2.84
²³⁸ U	4.3E+10	2.31	1.1E+11	2.55
²³⁷ Np	5.3E+08	2.46	2.3E+08	2.40
²³⁸ Pu	2.0E+11	3.08	1.8E+10	2.61
²³⁹ Pu	1.2E+12	3.05	2.3E+09	2.17
²⁴⁰ Pu	3.1E+11	3.05	5.8E+08	2.11
²⁴¹ Pu	4.6E+11	3.09	1.6E+09	2.02
²⁴² Pu	1.2E+08	3.07	1.6E+05	2.31
²⁴¹ Am	3.8E+11	3.03	7.0E+08	2.07
²⁴³ Am	5.2E+07	3.12	5.7E+04	2.69
²⁴⁴ Cm	9.2E+09	3.10	1.5E+07	2.66
Total	1.5E+14		1.1E+12	

Negligible – Inventory less than 37 Bq

A3.1.5 PA Inventory

The Area 3 RWMS PA inventory is disposed in U-3ah/at and U-3bh (Table A3.3). The available future capacity of U-3ah/at and U-3bh is uncertain due to uncertainty in the disposal unit volume and filled volume. The U-3ah/at disposal unit is estimated to be greater than 90% full while U-3bh is approximately 60% full.

Table A3.3 Area 3 RWMS PA waste volumes

Inventory	U-3ah/at	U-3bh
Disposed Post-1988	289,199 m ³	43,949 m ³
Future	11,836 m ³	31,098 m ³

The post-1988 inventories are assumed to be lognormally distributed with geometric mean and standard deviation as reported in Table A3.4.

Table A3.4 Post-1988 inventory of U-3ah/at and U-3bh decayed to closure in 2025

Nuclide	U-3ah/at		U-3bh	
	Geometric Mean (Bq)	Geometric Standard Deviation	Geometric Mean (Bq)	Geometric Standard Deviation
³ H	7.5E+15	2.06	4.5E+15	2.15
¹⁴ C	9.8E+10	1.76	3.0E+07	2.11
²⁶ Al	9.5E+04	2.40	<i>Negligible</i>	
³⁶ Cl	6.1E+08	2.29	<i>Negligible</i>	
³⁹ Ar	2.6E+09	2.50	<i>Negligible</i>	
⁴² Ar	4.4E+08	2.01	2.4E+08	2.49
⁴⁰ K	2.6E+09	1.82	7.1E+08	2.58
⁴¹ Ca	4.0E+09	2.39	<i>Negligible</i>	
⁴⁴ Ti	1.2E+10	2.04	5.6E+09	2.61
⁶⁰ Co	3.6E+09	1.79	2.4E+09	1.89
⁵⁹ Ni	9.4E+08	2.31	1.7E+08	2.06
⁶³ Ni	2.1E+11	1.77	7.5E+09	1.97
⁷⁹ Se	2.5E+07	2.13	<i>Negligible</i>	
⁸⁵ Kr	3.6E+09	2.13	<i>Negligible</i>	
⁹⁰ Sr	3.1E+14	2.75	4.4E+10	1.94
⁹³ Zr	1.4E+07	2.28	<i>Negligible</i>	
^{93m} Nb	2.8E+09	2.42	<i>Negligible</i>	
⁹⁴ Nb	3.4E+09	2.56	1.8E+08	2.10
⁹⁹ Tc	2.0E+12	1.90	7.7E+10	1.98
¹⁰⁷ Pd	6.2E+05	2.28	<i>Negligible</i>	
^{113m} Cd	2.7E+09	2.41	<i>Negligible</i>	
^{121m} Sn	3.7E+10	2.42	<i>Negligible</i>	
¹²⁶ Sn	5.8E+08	2.15	9.1E+05	2.66
¹²⁹ I	4.7E+08	2.03	2.4E+08	2.63
¹³⁵ Cs	1.1E+07	2.29	<i>Negligible</i>	
¹³⁷ Cs	1.7E+14	1.96	4.9E+10	1.75
¹³³ Ba	5.0E+09	1.99	1.6E+09	2.73
¹⁵¹ Sm	1.5E+10	2.28	1.2E+06	2.23
¹⁵⁰ Eu	6.1E+09	2.76	<i>Negligible</i>	
¹⁵² Eu	3.9E+10	1.87	1.3E+09	2.42
¹⁵⁴ Eu	8.6E+09	1.99	1.6E+08	2.04
^{166m} Ho	1.3E+08	2.38	<i>Negligible</i>	
²¹⁰ Pb	9.6E+10	1.77	4.5E+08	1.86
²⁰⁷ Bi	3.8E+05	2.27	1.8E+07	2.19
^{210m} Bi	6.7E+06	1.96	2.1E+08	2.23

Nuclide	U-3ah/at		U-3bh	
	Geometric Mean (Bq)	Geometric Standard Deviation	Geometric Mean (Bq)	Geometric Standard Deviation
²²⁶ Ra	1.0E+11	1.98	9.4E+08	2.25
²²⁸ Ra	1.3E+10	1.69	1.9E+11	2.70
²²⁷ Ac	2.5E+09	1.85	1.4E+06	2.15
²²⁸ Th	7.2E+10	1.91	1.8E+11	2.70
²²⁹ Th	4.0E+07	1.95	4.8E+07	2.53
²³⁰ Th	4.7E+10	2.00	7.1E+10	2.72
²³² Th	1.4E+10	1.71	2.0E+11	2.70
²³¹ Pa	3.8E+08	1.79	5.0E+06	2.16
²³² U	5.3E+10	2.20	<i>Negligible</i>	
²³³ U	1.6E+10	1.93	2.2E+10	2.52
²³⁴ U	7.4E+12	1.98	1.3E+11	2.08
²³⁵ U	3.4E+11	1.83	1.1E+10	2.18
²³⁶ U	3.6E+11	2.34	9.6E+07	2.71
²³⁸ U	1.3E+13	1.74	5.8E+11	2.32
²³⁷ Np	2.4E+11	2.08	1.5E+08	1.91
²³⁸ Pu	5.6E+11	1.97	1.8E+11	2.07
²³⁹ Pu	2.7E+12	1.68	5.1E+11	1.85
²⁴⁰ Pu	5.4E+11	1.70	8.6E+10	2.07
²⁴¹ Pu	1.5E+12	1.75	1.6E+11	2.00
²⁴² Pu	1.1E+08	1.61	4.0E+07	2.32
²⁴¹ Am	5.3E+11	1.56	8.8E+10	1.84
^{242m} Am	2.3E+08	2.18	3.3E+06	2.84
²⁴³ Am	5.9E+08	1.80	4.3E+07	2.63
²⁴³ Cm	3.1E+06	1.74	9.9E+05	2.61
²⁴⁴ Cm	8.2E+09	1.60	1.1E+08	2.09
²⁴⁵ Cm	5.4E+08	1.90	8.2E+06	2.64
²⁴⁶ Cm	8.8E+07	1.86	<i>Negligible</i>	
²⁴⁷ Cm	7.0E+05	2.72	<i>Negligible</i>	
²⁴⁹ Cf	3.4E+03	2.21	<i>Negligible</i>	
²⁵⁰ Cf	1.3E+03	2.81	<i>Negligible</i>	
²⁵¹ Cf	2.2E+08	2.29	<i>Negligible</i>	
Total	8.0E+15		4.5E+15	

Negligible – Inventory less than 37 Bq

Future inventories are estimated for U-3ah/at and U-bh in the event that the Area 3 RWMS is reactivated in the future (Table A3.5). The future inventories are highly uncertain due to the large temporal variability in past annual activity concentrations and the small number of future years of operation. Future inventories are assumed to be lognormally distributed, but are truncated at the maximum Area 3 RWMS inventory model realization to limit the excessive uncertainty.

Table A3.5 Future inventory of U-3ah/at and U-3bh decayed to closure in 2025

Nuclide	U-3ah/at		U-3bh	
	Geometric Mean (Bq)	Geometric Standard Deviation	Geometric Mean (Bq)	Geometric Standard Deviation
³ H	4.1E+09	1.6E+05	2.5E+12	2.0E+03
¹⁴ C	1.1E+05	1.1E+04	9.0E+06	8.8E+03
³⁶ Cl	3.1E+02	1.2E+02	1.3E+03	3.0E+02
⁴² Ar	3.6E+02	1.9E+02	3.4E+03	8.2E+02
⁴⁰ K	1.1E+04	1.7E+03	4.1E+05	2.2E+03
⁴⁴ Ti	4.8E+02	5.3E+02	4.6E+03	2.8E+03
⁶⁰ Co	3.6E+05	1.6E+03	2.0E+07	5.1E+02
⁵⁹ Ni	7.6E+02	4.0E+02	6.2E+03	1.1E+03
⁶³ Ni	2.9E+05	1.5E+04	3.1E+07	9.8E+03
⁷⁹ Se	1.2E+02	3.6E+01	3.4E+02	1.1E+02
⁸⁵ Kr	2.2E+02	1.2E+02	1.2E+03	5.8E+02
⁹⁰ Sr	9.2E+07	1.0E+04	9.9E+09	1.3E+03
⁹⁴ Nb	5.8E+01	8.4E+00	8.3E+01	1.7E+01
⁹⁹ Tc	6.7E+06	2.8E+04	1.7E+09	2.6E+03
¹²⁶ Sn	1.7E+02	9.3E+01	5.9E+02	3.6E+02
¹²⁹ I	1.4E+03	3.9E+02	2.8E+04	8.4E+02
¹³⁷ Cs	1.1E+09	3.1E+04	1.2E+11	2.6E+03
¹³³ Ba	5.5E+02	5.2E+02	4.8E+03	2.4E+03
¹⁵¹ Sm	1.7E+02	3.0E+01	4.8E+02	6.4E+01
¹⁵² Eu	2.8E+03	2.4E+03	1.1E+05	8.4E+03
¹⁵⁴ Eu	4.9E+03	1.6E+03	2.8E+05	3.0E+03
²¹⁰ Pb	2.7E+07	1.7E+02	5.7E+08	4.4E+01
²⁰⁷ Bi	7.6E+01	1.4E+01	1.3E+02	3.0E+01
^{210m} Bi	1.1E+02	2.8E+01	4.4E+02	1.0E+02
²²⁶ Ra	2.9E+07	1.8E+02	5.7E+08	5.7E+01
²²⁸ Ra	3.6E+06	5.6E+04	5.1E+08	6.2E+01
²²⁷ Ac	1.4E+06	2.1E+01	8.7E+06	2.0E+01
²²⁸ Th	8.8E+07	8.8E+02	1.7E+09	1.1E+01
²²⁹ Th	3.7E+01	1.8E+04	9.1E+03	1.2E+03
²³⁰ Th	1.3E+08	3.3E+01	1.0E+09	1.0E+01
²³² Th	1.9E+06	8.0E+04	3.8E+08	1.1E+02
²³¹ Pa	2.2E+06	7.4E+00	7.4E+06	5.3E+00
²³² U	8.5E+03	2.2E+03	4.2E+05	3.9E+03
²³³ U	2.3E+04	1.4E+04	5.7E+06	1.3E+03
²³⁴ U	3.8E+10	2.3E+01	2.0E+11	7.0E+00
²³⁵ U	4.6E+09	6.0E+00	1.5E+10	4.3E+00
²³⁶ U	9.7E+05	1.5E+05	2.6E+08	4.4E+02
²³⁸ U	2.0E+10	1.9E+03	2.8E+11	1.6E+01

Nuclide	U-3ah/at		U-3bh	
	Geometric Mean (Bq)	Geometric Standard Deviation	Geometric Mean (Bq)	Geometric Standard Deviation
²³⁷ Np	1.5E+06	1.4E+03	1.0E+08	2.8E+02
²³⁸ Pu	2.2E+07	3.0E+03	2.2E+09	2.1E+02
²³⁹ Pu	5.8E+07	4.9E+04	1.0E+10	5.4E+02
²⁴⁰ Pu	5.8E+06	1.4E+05	1.6E+09	2.1E+02
²⁴¹ Pu	2.0E+07	1.6E+04	6.1E+09	7.7E+02
²⁴² Pu	4.6E+03	7.3E+02	8.6E+04	6.4E+02
²⁴¹ Am	3.0E+08	8.8E+02	1.3E+10	2.0E+01
^{242m} Am	3.1E+02	9.1E+01	1.8E+03	2.7E+02
²⁴³ Am	3.7E+03	1.3E+04	1.9E+05	5.9E+03
²⁴³ Cm	6.0E+02	1.1E+02	4.3E+03	2.2E+02
²⁴⁴ Cm	3.1E+04	2.4E+03	3.0E+06	1.8E+03
²⁴⁵ Cm	1.4E+03	8.2E+02	2.9E+04	2.4E+03
²⁴⁶ Cm	9.4E+02	2.5E+02	1.2E+04	5.9E+02
²⁴⁷ Cm	1.5E+01	1.1E+03	4.8E+00	2.4E+04
²⁴⁹ Cf	5.3E+01	2.8E+00	7.0E+01	3.9E+00
²⁵⁰ Cf	4.7E+01	2.4E+00	5.4E+01	2.9E+00
²⁵¹ Cf	1.2E+02	5.6E+01	3.0E+02	1.7E+02
Total	6.9E+10		3.2E+12	

Negligible – Inventory less than 37 Bq

A3.2 CA Inventories

The approved CA considered four categories of residual radioactive material that may interact with the Area 3 RWMS. The source categories were Waste Management Projects, UGTAs, Soil Sites, and Industrial Sites. Among these sources, only Soil Sites were included in the CA.

An Industrial Site, Corrective Action Unit (CAU) 547, was characterized in 2009 and found to have a significant transuranic inventory. CAU 547 includes three sites consisting of piping and gas sampling equipment. Each of the sites is associated with a safety test (i.e., MULLET, TEJON, and PLAYER) located in different operational areas on the NNSS. The MULLET and PLAYER sites are in Yucca Flat, but not within Area 3 and unlikely to interact with the Area 3 RWMS. The TEJON site, which is approximately 350 meters (m) (1,150 feet [ft]) west-northwest of the Area 3 RWMS boundary, is a potential source for the CA.

The TEJON site falls within the HORNET Soil Site and any surface activity would be included with the Radionuclide Inventory and Development Program (RIDP) HORNET inventory estimate. Transuranic contamination contained in belowground pipes at TEJON is likely not included in the HORNET inventory. Steel piping, valves, and gas sampling equipment at TEJON are estimated to contain 0.2 terabequerel (TBq) of ²³⁹Pu (NNSA/NSO, 2011). Most of the pipe is under an earthen berm that is at least 1.2 m (4 ft) thick (NNSA/NSO, 2011). The TEJON corrective action site will be closed in place with a 0.6 m (2 ft) soil cover and land use restrictions.

A radiological assessment was performed for the PLAYER site to support the CAU 547 closure plan. The assessment estimated a maximum mean annual total effective dose of 0.08 mSv at 1,000 years (y) for a transient visitor (NNSA/NSO, 2011). The PLAYER inventory is more than two times the TEJON inventory. Given the lesser inventory and thicker cover at TEJON, dose from this site is likely a small fraction of the HORNET Ground Zero dose. The TEJON CAU 547 source is not included in the CA because it is expected to be a minor contributor to the CA dose.

A3.2.1 Soil Site Inventories

Soil Sites throughout Yucca Flat have been contaminated by atmospheric nuclear testing, underground nuclear testing, and safety experiments where a nuclear weapon is destroyed usually resulting in no or a very slight fission yield. The Area 3 RWMS CA used Soil Site inventories estimated by the Radioisotope Inventory and Distribution Program (McArthur, 1991). No additional characterization or cleanup of Soil Sites has occurred since preparation of the Area 3 RWMS CA. The Area 3 RWMS, version 2.102, CA model uses the same data source for estimation of the Soil Site inventories.

McArthur et al. (1991) reported inventories for 28 contaminated Soil Sites in Yucca Flat and one site in Plutonium Valley. The CA update includes one additional site, an unsurveyed site in Area 2, which was not included in the Area 3 RWMS CA. The inventories reported in McArthur (1991) are assumed to be the median of a lognormal distribution. The 95th percentile of the distribution is estimated as two times the median based on the qualitative uncertainty stated by McArthur (1991). The inventories of ²³⁹Pu, plutonium-240 (²⁴⁰Pu), plutonium-241 (²⁴¹Pu), and plutonium-242 (²⁴²Pu) are estimated from the reported ^{239,240}Pu inventory assuming the composition of weapons-grade Pu and assuming that 5 to 44 y have elapsed since production. The geometric mean activities at the time of characterization, January 1, 1990, appear in Table A3.6.

Table A3.6 Soil Site areas and geometric mean inventories on January 1, 1990

Nuclide	Geometric Mean Activity (MBq)						
	GALILEO 1.24E+07 m ²	HORNET (Area 1) 1.48E+07 m ²	S. Yucca (Area 1) 1.97E+07 m ²	Unsurveyed (Area 1) 2.18E+07 m ²	WHITNEY 6.99E+06 m ²	SHASTA 1.27E+07 m ²	DIABLO 1.04E+07 m ²
²⁴¹ Am	3.70E+01	4.80E+01	4.40E+01	2.60E+01	1.50E+01	2.60E+01	3.70E+01
²³⁸ Pu	7.40E+01	3.30E+01	8.50E+01	4.80E+01	5.20E+01	7.80E+01	1.00E+02
^{239,240} Pu	1.85E+02	3.77E+02	2.18E+02	1.22E+02	1.78E+02	1.96E+02	2.07E+02
⁶⁰ Co	1.04E+02	4.00E+00	4.00E+00	4.00E+00	5.90E+01	2.60E+01	1.50E+01
¹³⁷ Cs	1.78E+02	1.30E+02	3.70E+01	4.10E+01	1.48E+02	3.85E+02	3.33E+02
⁹⁰ Sr	2.66E+02	4.33E+02	5.60E+01	5.90E+01	4.14E+02	9.99E+02	6.66E+02
¹⁵² Eu	7.88E+02	0.00E+00	0.00E+00	0.00E+00	7.18E+02	1.10E+01	1.50E+01
¹⁵⁴ Eu	8.10E+01	0.00E+00	0.00E+00	0.00E+00	2.60E+01	0.00E+00	0.00E+00
²³⁹ Pu	2.00E+02	3.00E+02	2.00E+02	1.00E+02	1.00E+02	2.00E+02	2.00E+02
²⁴⁰ Pu	3.00E+01	7.00E+01	4.00E+01	2.00E+01	3.00E+01	3.00E+01	4.00E+01
²⁴¹ Pu	2.00E+02	3.00E+02	2.00E+02	1.00E+02	2.00E+02	2.00E+02	2.00E+02
²⁴² Pu	3.00E-03	6.00E-03	4.00E-03	2.00E-03	3.00E-03	3.00E-03	4.00E-03

Table A3.6 (Cont.) Soil Site areas and geometric mean inventories on January 1, 1990

Nuclide	Geometric Mean Activity (MBq)						
	SEDAN (Area 2) 1.58E+07 m ²	Unsurveyed (Area 2) 5.18E+06 m ²	HORNET (Area 3) 2.20E+07 m ²	S. Yucca (Area 3) 1.19E+07 m ²	Unsurveyed (Area 3) 4.97E+07 m ²	KEPLER 2.51E+07 m ²	QUAY (Area 4) 1.35E+07 m ²
²⁴¹ Am	1.50E+01	1.50E+01	1.26E+02	7.00E+00	3.70E+01	2.15E+02	1.50E+01
²³⁸ Pu	4.40E+01	4.40E+01	8.50E+01	4.00E+00	2.60E+01	4.29E+02	4.00E+00
^{239,240} Pu	1.22E+02	1.18E+02	1.00E+03	5.60E+01	3.00E+02	1.29E+03	1.11E+02
⁶⁰ Co	7.00E+00	1.90E+01	6.70E+01	4.00E+00	1.50E+01	1.44E+02	4.00E+00
¹³⁷ Cs	1.18E+02	7.80E+01	3.15E+02	2.20E+01	1.85E+02	4.00E+02	7.40E+01
⁹⁰ Sr	2.92E+02	1.92E+02	1.04E+03	7.40E+01	6.07E+02	5.18E+02	1.63E+02
¹⁵² Eu	0.00E+00	0.00E+00	9.03E+02	0.00E+00	0.00E+00	4.81E+02	0.00E+00
¹⁵⁴ Eu	0.00E+00	0.00E+00	4.10E+01	0.00E+00	0.00E+00	3.30E+01	0.00E+00
²³⁹ Pu	1.00E+02	1.00E+02	8.00E+02	5.00E+01	2.00E+02	1.00E+03	9.00E+01
²⁴⁰ Pu	2.00E+01	2.00E+01	2.00E+02	1.00E+01	5.00E+01	2.00E+02	2.00E+01
²⁴¹ Pu	1.00E+02	1.00E+02	9.00E+02	5.00E+01	3.00E+02	1.00E+03	1.00E+02
²⁴² Pu	2.00E-03	2.00E-03	2.00E-02	9.00E-04	5.00E-03	2.00E-02	2.00E-03

Table A3.6 (Cont.) Soil Site areas and geometric mean inventories on January 1, 1990

Nuclide	Geometric Mean Activity (MBq)						
	Unsurveyed (Area 4) 2.85E+06 m ²	S. Yucca (Area 6) 8.37E+07 m ²	QUAY (Area 7) 1.74E+07 m ²	Unsurveyed (Area 7) 3.26E+07 m ²	BANEBERRY 1.35E+07 m ²	SMOKY 8.55E+06 m ²	Unsurveyed (Area 8) 1.40E+07 m ²
²⁴¹ Am	1.50E+01	6.30E+01	5.60E+01	2.60E+01	3.30E+01	5.77E+02	1.50E+01
²³⁸ Pu	3.00E+01	1.22E+02	1.50E+01	7.00E+00	2.60E+01	2.59E+02	1.10E+01
^{239,240} Pu	9.30E+01	3.11E+02	4.14E+02	1.81E+02	1.33E+02	3.95E+03	8.50E+01
⁶⁰ Co	2.20E+01	1.50E+01	7.80E+01	1.10E+01	3.29E+02	7.80E+01	1.55E+02
¹³⁷ Cs	4.80E+01	1.22E+02	1.04E+02	1.22E+02	9.77E+02	4.96E+02	3.63E+02
⁹⁰ Sr	5.90E+01	1.85E+02	2.26E+02	2.66E+02	2.44E+02	6.33E+02	5.11E+02
¹⁵² Eu	0.00E+00	0.00E+00	1.11E+03	0.00E+00	0.00E+00	2.22E+02	0.00E+00
¹⁵⁴ Eu	0.00E+00	0.00E+00	8.90E+01	0.00E+00	0.00E+00	1.50E+01	0.00E+00
²³⁹ Pu	8.00E+01	3.00E+02	3.00E+02	1.00E+02	1.00E+02	3.00E+03	7.00E+01
²⁴⁰ Pu	2.00E+01	5.00E+01	7.00E+01	3.00E+01	2.00E+01	7.00E+02	1.00E+01
²⁴¹ Pu	9.00E+01	3.00E+02	4.00E+02	2.00E+02	1.00E+02	4.00E+03	8.00E+01
²⁴² Pu	2.00E-03	5.00E-03	7.00E-03	3.00E-03	2.00E-03	7.00E-02	1.00E-03

Table A3.6 (Cont.) Soil Site areas and geometric mean inventories on January 1, 1990

Nuclide	Geometric Mean Activity (MBq)							
	WILSON 1.94E+07 m ²	Unsurveyed (Area 9) 3.24E+07 m ²	SEDAN (Area 10) 1.99E+07 m ²	Unsurveyed (Area 10) 3.19E+07 m ²	Yucca Flat (Area 15) 1.11E+07 m ²	Yucca Flat (Area 17) 2.90E+07 m ²	Plutonium Valley 8.81E+06 m ²	PINSTRIFE 1.55E+06 m ²
²⁴¹ Am	1.33E+02	2.20E+01	6.81E+02	3.70E+01	9.30E+01	6.70E+01	1.22E+02	0.00E+00
²³⁸ Pu	7.00E+01	1.10E+01	6.81E+02	3.70E+01	7.80E+01	1.04E+02	1.90E+01	0.00E+00
^{239,240} Pu	2.80E+03	5.03E+02	3.74E+03	1.96E+02	7.88E+02	4.18E+02	1.07E+03	0.00E+00
⁶⁰ Co	5.60E+01	1.10E+01	9.14E+02	2.20E+01	1.10E+01	5.20E+01	0.00E+00	0.00E+00
¹³⁷ Cs	2.59E+02	1.18E+02	3.10E+03	5.92E+02	3.26E+02	3.40E+02	1.50E+01	7.00E+00
⁹⁰ Sr	4.92E+02	2.29E+02	2.53E+03	4.85E+02	4.48E+02	5.18E+02	7.00E+00	7.00E+00
¹⁵² Eu	1.15E+03	0.00E+00	1.11E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
¹⁵⁴ Eu	1.07E+02	0.00E+00	1.55E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
²³⁹ Pu	2.00E+03	4.00E+02	3.00E+03	2.00E+02	6.00E+02	3.00E+02	9.00E+02	0.00E+00
²⁴⁰ Pu	5.00E+02	9.00E+01	7.00E+02	3.00E+01	1.00E+02	7.00E+01	2.00E+02	0.00E+00
²⁴¹ Pu	3.00E+03	5.00E+02	3.00E+03	2.00E+02	7.00E+02	4.00E+02	1.00E+03	0.00E+00
²⁴² Pu	5.00E-02	9.00E-03	6.00E-02	3.00E-03	1.00E-02	7.00E-03	2.00E-02	0.00E+00

A3.3 References

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Appendix A4: Sensitivity Analysis

Sensitivity analysis is the process of quantifying how uncertainty in model input contributes to model output uncertainty. Understanding the relationship between input variation and model response is useful for understanding and interpreting model behavior, comparing model behavior with real system behavior, building model credibility, identifying model errors, and/or identifying strategies for reducing model output uncertainty.

Preferred sensitivity analysis methods should be global, quantitative, and model independent (Saltelli et al., 1999). A global sensitivity analysis investigates the model output response throughout the entire input sample space. Local sensitivity methods, in contrast, investigate the model response to variation in one input parameter at a time while all other inputs are conditioned at a single value, typically the mean or median. Local sensitivity analyses may miss interactions among input parameters.

A quantitative sensitivity analysis determines the quantitative fraction of the output variance that can be attributed to each input parameter. Quantitative sensitivity analysis allows quantitative predictions of the reduction in model output variance that can be achieved by reducing uncertainty in input parameters. These quantitative predictions are useful for guiding decisions about additional data collection.

Model independent methods require no assumptions regarding the relationship between inputs and outputs. Model dependent methods typically assume that a linear or monotonic relationship exists between the input variable and output. If the model dependent assumptions are correct, then model dependent sensitivity indices may be nearly quantitative. However, when model assumptions are violated, the sensitivity results will not be quantitative and can be misleading.

A4.1 Sensitivity Methods

The sensitivity analysis methods are applied to the Area 3 Radioactive Waste Management Site (RWMS) v2.102 model (or the Model). The Model includes all performance assessment (PA) and composite analysis (CA) calculations except for a few input parameters whose distributions are simulated by other methods and entered into the Model. Important PA input parameters developed by other methods include the Area 3 RWMS inventory, the subsidence settlement ratios, and the periods of institutional control (IC). CA input parameters developed by other methods include the HORNET ground zero (GZ) inventory and atmospheric dispersion coefficients for radionuclides resuspended from offsite contaminated Soil Sites.

Sensitivity analysis of the Model is difficult because the Model is non-linear, includes non-monotonic relationships, is highly dimensional, has long run times, and has limited built-in sensitivity analysis capabilities. The selected sensitivity analysis approach is to calculate Sobol's sensitivity indices (SIs) for a boosted regression tree model (Sobol', 2001; Elith et al., 2008). Boosted regression trees are an advanced regression algorithm using both machine learning and statistical techniques, which has been shown to provide accurate predictions and identify important variables and interactions. The first algorithm, regression trees, partitions the model input space into regions with homogenous output response and fits a mean response for each region. The second algorithm, boosting, iteratively fits regression tree models to improve model

accuracy. Each successive tree is fit to the residuals from all the previous trees. The final model is a linear combination of all the regression tree predictions.

Performing the sensitivity analysis on the boosted regression tree model rather than the GoldSim model overcomes two problems. First, most sensitivity analysis methods require input of manipulated data sets that are not simple Monte Carlo samples. The sensitivity analysis input data can be easily generated and input into a regression tree model, whereas the GoldSim model cannot read or generate the input data required for sensitivity analysis. Second, the regression tree model is computationally more efficient than the GoldSim model, which allows the large number of simulations required for sensitivity analysis. Performing sensitivity analysis on a model of a model is reliable to the extent that the boosted regression tree model fits the GoldSim model. As will be shown below, boosted regression tree models are well suited to this problem and can obtain excellent fits that account for interactions among parameters.

Sensitivity is measured by the Sobol's first-order and total effects SIs. Sobol's SIs are global and model independent SIs that allow decomposition of the variance into individual and interactive components among any combination of parameters. The first-order SI quantifies the fraction of the model prediction variance that is attributable to variance in the input factor in isolation. The total effect SI indicates the fraction of the model variance that is attributable to the model input and all of its higher order interactions with other parameters. If the main effect and total effect SI are significantly different, this indicates that higher order interactions are present.

The sensitivity analysis is implemented in scripts written in the R statistical language (R Development Core Team, 2011). The boosted regression tree model is fit using the generalized boosted model (GBM) package distributed with R (Ridgeway, 2010). The GBM package returns a boosted regression tree model with a prediction method, a plot of the residual sum of squares versus the number of trees, the relative influence, and the marginal dependence of the explanatory parameters. The relative influence is an SI calculated as the Type III sum of squares normalized to sum to 100. The Type III sum of squares measures the reduction in the residual sum of squares due to adding the parameter to the model with all other parameters included. The marginal dependence graphically represents the relationship between a single model input and the model prediction. The marginal dependence indicates the range over which a parameter is sensitive, the form of the relationship, and indicates where thresholds may occur. The script reads the Monte Carlo input vectors obtained from the Model and manipulates the vectors to produce vector sets required for the Monte Carlo estimate of Sobol's SIs (Sobol', 2001). The new data sets are input to the boosted regression tree model to obtain the Model response, and the SIs are calculated.

Sensitivity is evaluated for three PA model results (or end points): the resident air pathway annual total effective dose (TED), the resident all-pathways annual TED, and the radon-222 (^{222}Rn) flux density at 1,000 years (y). CA sensitivity is evaluated for the resident annual TED at 1,000 y.

A4.1.1 Method Verification

The sensitivity analysis method was tested on a model with known sensitivity. The Sobol' g function was developed for testing sensitivity analysis methods. The function is non-linear, non-monotonic, and allows tuning of parameter sensitivity. Exact analytical solutions for the

Sobol's SIs can be obtained for comparison with the method's results. The Sobol' g function is (Sobol', 2001):

$$g = \prod_{i=1}^n \frac{|4x_i - 2| + a_i}{1 + a_i}$$

where

$n = 8$

a_i = tuning parameters (99, 0, 9, 0, 99, 4.5, 1, 99)

x_i = explanatory variables $\sim U(0, 1)$

The sequence of a_i values is selected to tune sensitivity. Parameters with equal a_i values will have equal sensitivity. Parameters with equal sensitivity are generally the most difficult for sensitivity methods to identify and quantify. An a_i value of zero causes the highest sensitivity, while values of 99 or greater have negligible sensitivity.

The GBM provided an excellent fit to the Sobol' g function with an adjusted r-squared of 0.99 (Figure A4.1). No large outliers are observed.

Figure A4.1 Calculated versus GBM predicted value of the Sobol' g function ($n = 20,000$)

The GBM first-order SIs were found to be in good agreement with the analytical value for the most sensitive parameters (Table A4.1). For the less sensitive parameters, $a_i > 1$, the first-order SIs tend to be negative. Analysis of Sobol' g function directly yields similar results, indicating that the negative values are not a consequence of the GBM, but are likely an artifact of the Monte Carlo estimate of Sobol's SIs. The total effects SIs are also in good agreement with the analytical values for the most sensitive parameters. The total effects SI is able to correctly assess the sensitivity to an a_i value of at least 4.5. Parameters with minimal sensitivity, $a_i > 4.5$, did not produce negative SIs but were overestimated.

Table A4.1 Comparison of Sobol's SIs for the GBM with exact SIs for the Sobol' g function

Parameter	a_i	First-Order Sobol's SI		Total Effects Sobol's SI	
		Analytical Value	GBM Prediction	Analytical Value	GBM Prediction
x_1	99	0.00003	-0.02531	0.000068	0.00078
x_2	0	0.3495	0.3484	0.5121	0.5340
x_3	9	0.00349	-0.02361	0.006805	0.005044
x_4	0	0.3495	0.3349	0.5121	0.5069
x_5	99	0.00003	-0.02546	0.000068	0.00069
x_6	4.5	0.01155	-0.01547	0.02233	0.02234
x_7	1	0.08737	0.07031	0.1576	0.1545
x_8	99	0.00003	-0.02549	0.000068	0.00063

A4.2 Results

A4.2.1 Performance Assessment Results

Air-Pathway

A GBM for the air pathway annual TED at 1,000 y was fit using 20,000 realizations of 336 independent variables and results. A good fit was obtained with an adjusted r-squared of 0.93 (Figure A4.2). The fit is good except for a single large outlier, underestimated by the GBM.

Figure A4.2 GBM predicted air pathway annual TED versus A3 RWMS v2.102 results (n = 20,000)

The air pathway annual TED at 1,000 y was found to be weakly sensitive to a comparatively large number of parameters. Although all of the parameters are weakly sensitive, five parameters appear to be significantly more sensitive (Table A4.2). Three of the five most sensitive parameters are directly related (i.e., U-3ah/at radium-226 [^{226}Ra] inventory, the U-3ah/at radon emanation coefficient, and U-3bh thorium-230 [^{230}Th] inventory) and indirectly related (i.e., depth of the no-liquid-flux boundary [NLFB]) to the ^{222}Rn source term. The radon emanation coefficient is the fraction of generated radon that is released to the air-filled pore space. The depth of the NLFB affects the ^{222}Rn source term by increasing or decreasing the transport of radon parents into the cover where the diffusion length to the atmosphere is less. The fourth most sensitive parameter is the length of the active IC period. Parameters ranked below the top five most sensitive parameters are very weakly sensitive, but also appear to be related to ^{222}Rn parent transport into the cover.

Table A4.2 Sensitivity analysis results for the air pathway annual TED at 1,000 y

Rank	Parameter	GBM Relative Influence	Sobol's SIs	
			First-Order	Total Effects
1	U-3ah/at ^{226}Ra Inventory	12.7	0.19	0.23
2	U-3ah/at Emanation Coefficient	11.1	0.18	0.24
3	U-3bh ^{230}Th Inventory	7.63	0.10	0.12
4	Period of Active Institutional Control	7.28	0.11	0.12
5	Depth of NLFB	6.61	0.06	0.21
6	U-3ah/at ^{234}U Inventory	2.50	0.02	0.02
7	Rodent Burrow Shape Parameter b	2.41	0.03	0.06
8	Uranium Solubility (K_{sp})	2.00	0.02	0.03

The weakness of the sensitivity is in part due to there being two source terms, U-3ah/at and U-3bh and multiple ^{222}Rn parents in the source term. The five most sensitive parameters account for only 45% of model variability. The weak sensitivity of individual parameters and low percentage of the variability explained suggests that interactions among parameters are occurring. The differences between the total and first-order Sobol' SIs confirm that interactions are significant for the depth of the NLFB. Using the total effects SI, the depth of the NLFB would move up in rank to the third most sensitive parameter. Small interactions are observed for the inventories and emanation coefficients. The length of the active IC period appears to have little interaction.

The marginal dependency indicates how the model output changes as a single parameter is varied over its range. The radon source term should have a positive linear relationship with the lead-210 (^{210}Pb) release and the air pathway annual TED. Parameters directly related to the ^{222}Rn source term (parameter ranks 1, 2, 3, and 6) display such a relationship over the range of the input parameter where there are sufficient realizations to determine a relationship (Figure A4.3). The length of the active IC period shows a decreasing non-linear relationship with the air pathway annual TED with a strong threshold at 1,000 y. The marginal dependence of the total length of the active IC period should be a step function, stepping down from the mean annual TED of 6E-6 mSv to zero at 1,000 y. Because the total length of IC is the sum of the active and passive periods, a sharp step function is not expected for the length of the active IC period alone.

Figure A4.3 Histogram of input parameter values (grey) and marginal dependence (blue) of most sensitive parameters for the air pathway annual TED at 1,000 y

The marginal dependency of the NLFB shows a threshold at approximately 1.9 meters (m) (6.2 feet [ft]) above which there is no sensitivity. At shallower depths there is a decreasing non-linear relationship with the air pathway annual TED. This sensitivity probably indicates an

interaction between upward liquid advection and biotic transport. The depth of 1.9 m (6.2 ft) most closely corresponds with the maximum depth of rodent burrowing, 2.0 m (6.6 ft). The sensitivity of the rodent burrow shape parameter also suggests sensitivity to rodent burrowing. The rodent burrow shape parameter, b , has a threshold at approximately $b = 5$. Shape parameter values of 4 and above are concave cones with minimal burrow volume at depth.

The sensitivity analysis results are consistent with how the conceptual and mathematical models are expected to behave. This supports a conclusion that the conceptual and mathematical models have been correctly implemented in GoldSim. The air pathway annual TED is expected to be dominated by gaseous species if present in sufficient quantities. Gaseous radionuclides have the greatest potential to be released from the site. With its long-lived uranium-238 (^{238}U) chain parents, ^{222}Rn is the only gaseous radionuclide likely to be present at 1,000 y. Model results at 1,000 y indicate that the highest concentration radionuclide in air is ^{222}Rn , followed by ^{210}Pb , a progeny of ^{222}Rn , and technetium-99 (^{99}Tc). The relationship between ^{222}Rn source term and dose is linear as expected.

All-Pathways TED

A GBM with 20,000 realizations of 335 independent variables was fit for the all-pathways annual TED at 1,000 y. The fit was very good with an adjusted r-squared of 0.97 (Figure A4.4). A few outliers out of 20,000 realizations are under-predicted by the GBM and some GoldSim zero values are predicted to have small non-zero values. This latter group of outliers likely corresponds to realizations with total IC periods that slightly exceed 1,000 y. The Model dose is zero when IC exceeds 1,000 y, but the GBM is unable to fit this sharp boundary.

Figure A4.4 GBM predicted all-pathways annual TED versus A3 RWMS v2.102 results (n = 20,000)

The all-pathways annual TED at 1,000 y was found to be weakly sensitive to a comparatively large number of parameters. Five parameters appear to be significantly more sensitive (Table A4.3). Three of the five most sensitive parameters (i.e., the U-3ah/at ^{226}Ra inventory, the U-3ah/at emanation coefficient, and the U-3bh ^{230}Th inventory) are related directly to the ^{222}Rn source term. The third most sensitive parameter is the length of the active IC period. The fifth most sensitive parameter, the inadvertent soil ingestion rate, suggests the importance of inadvertent ingestion of ^{210}Pb in soil as an exposure pathway. Parameters ranked below the top five most sensitive parameters are very weakly sensitive, but also appear to be related to ^{222}Rn parent transport into the cover and the length of IC. The Sobol' SIs indicate significant higher order interactions for the five most sensitive parameters.

Table A4.3 Sensitivity analysis results for the all-pathways annual TED at 1,000 y

Rank	Description	GBM Relative Influence	Sobol's SIs	
			First-Order	Total Effects
1	U-3ah/at ^{226}Ra Inventory	22.3	0.20	0.30
2	U-3ah/at Emanation Coefficient	17.2	0.18	0.30
3	Period of Active Institutional Control	12.7	0.10	0.15
4	U-3bh ^{230}Th Inventory	12.1	0.09	0.14
5	Inadvertent Soil Ingestion Rate	11.4	0.10	0.17
6	U-3bh Emanation Coefficient	3.00	0.01	0.05
7	Depth of NLFB	2.81	0.02	0.04
8	Period of Passive Institutional Control	1.63	0.01	0.01

The marginal dependence of the all-pathways annual TED sensitive parameters show the same trends as observed for the air pathway (Figure A4.5). The marginal dependence of the length of the passive IC is not stair stepped, reflecting that the IC period is the sum of the active and passive periods.

Figure A4.5 Histogram of input parameter values (grey) and marginal dependence (blue) of most sensitive parameters for the all-pathways annual TED at 1,000 y

The results of the all-pathways annual TED sensitivity analysis are consistent with the mathematical model, but suggest an area for improvement in the implementation of the conceptual model. ^{222}Rn is expected to migrate through the disposal unit covers and deposit ^{210}Pb in cover soil. The mathematical model makes a simplifying assumption that ^{210}Pb is instantaneously transported without dilution to the 100-m (330-ft) site boundary. Once ^{210}Pb is transported to the boundary, it will be separated from its gaseous parent ^{222}Rn and will decay with its 22-y half-life. Depending on the kinetics of these transport process, the soil ^{210}Pb concentration at the site boundary may be much less than in disposal unit covers. Simplifying assumptions may be causing an overestimate of the contribution of ^{210}Pb to the all-pathways TED.

^{222}Rn Flux Density

A GBM for the ^{222}Rn flux density at 1,000 y was fit using 20,000 realizations of 340 independent variables and results. An excellent fit was obtained with an adjusted r-squared of 0.99 (Figure A4.6). A few of the higher flux density realizations are underestimated by the GBM.

Figure A4.6 GBM predicted ^{222}Rn flux density versus A3 RWMS v2.102 results (n = 20,000)

Based on the sensitivity results for the air pathway, the ^{222}Rn flux density is expected to be dominated by factors related to the radon source term. The sensitivity of the ^{222}Rn flux density shows a moderate sensitivity to the radon source term, especially the U-3ah/at source term (Table A4.4). Although the sensitivity is moderate, it is stronger than observed for the air and all-pathways TED. The moderate sensitivity again is due in part to the interaction of multiple parameters (i.e., radon parent inventories and emanation coefficient) and two disposal units

(i.e., U-3ah/at and U-3bh). A weak but significant sensitivity is observed for two more parameters related to the U-3bh ^{222}Rn source term. The remaining parameters show a very weak sensitivity. Interactions among parameters are important for the four most sensitive parameters.

Table A4.4 Sensitivity analysis results for the ^{222}Rn flux density at 1,000 y

Rank	Parameter	GBM Relative Influence	Sobol' SIs	
			First-Order	Total Effects
1	U-3ah/at ^{226}Ra Inventory	36.5	0.31	0.41
2	U-3ah/at Emanation Coefficient	31.2	0.30	0.43
3	U-3bh ^{230}Th Inventory	17.4	0.14	0.20
4	U-3bh Emanation Coefficient	5.01	0.02	0.07
5	U-3ah/at Settlement Ratio	2.77	0.01	0.03
6	U-3ah/at ^{230}Th Inventory	2.47	0.02	0.03
7	U-3ah/at ^{234}U Inventory	1.26	0.01	0.02
8	U-3ah/at Settlement Acceleration Factor	0.35	0.01	0.004

As observed for the other endpoints, there is an increasing linear relationship between factors related to the radon source term and the flux density (Figure A4.7).

Figure A4.7 Histogram of input parameter values (grey) and marginal dependence (blue) of most sensitive parameters for the ^{222}Rn flux density at 1,000 y

Two new parameters appear in the ^{222}Rn flux density sensitivity related to subsidence. The marginal dependence of the settlement ratio displays a decreasing relationship between the settlement ratio and flux density. The results are consistent with conceptual expectations as increasing settlement (or subsidence) should lead to a thicker cover by repair and reduced ^{222}Rn flux. The sensitivity of the acceleration ratio is weak but consistent with conceptual expectations. An acceleration factor greater than one will positively accelerate subsidence, causing more subsidence during the maintenance period. This will increase cover thickness and reduce ^{222}Rn flux density. The expected negative relationship is observed for acceleration factors greater than 1.5.

A4.2.2 Composite Analysis Results

A GBM for the composite analysis annual TED at 1,000 y was fit using 5,000 realizations of 464 independent variables and results. The total TED was calculated using the 50th percentile TED for the offsite Soil Sites. The TED from offsite soil sources is only available at the 50th and 95th percentile in the Model. A very good fit was obtained with an adjusted r-squared of 0.97 (Figure A4.8). The fit is good except for some zero dose results that the GBM predicts to have a low dose. These are realizations that likely have total IC periods slightly greater than 1,000 y.

Figure A4.8 GBM predicted CA TED at 1,000 y versus A3 RWMS v2.102 results (n = 5,000)

The CA TED is predominantly from the HORNET GZ contaminated Soil Site. Dose from the HORNET GZ is predominantly from inhalation of resuspended transuranic radionuclides. Model sensitivity is consistent with this conceptual understanding. Model variability is accounted for by factors related to the HORNET GZ source term, the length of IC, and the inhalation exposure

pathway (Table A4.5). Approximately 84% of Model variability is explained by the HORNET GZ enrichment factor, the HORNET GZ plutonium-239 (^{239}Pu) inventory, and length of the active IC period. The enrichment factor is the ratio of radionuclide concentration in resuspended particulates to the concentration in bulk soil. The enrichment factor is affected by the concentration of the radionuclide in different particle size fractions of the soil. If the radionuclide is uniformly distributed among all size fractions, the enrichment factor will be 1.0. If the radionuclide is concentrated in large and difficult to resuspend particles, the enrichment factor will be less than 1.0. It can be greater than one if the radionuclide is associated mostly with the smallest size fraction.

Table A4.5 Sensitivity analysis results for the CA annual TED at 1,000 y

Rank	Parameter	GBM Relative Influence	Sobol's SIs	
			First-Order	Total Effects
1	HORNET GZ Enrichment Factor	32.9	0.36	0.47
2	HORNET GZ ^{239}Pu Inventory	29.1	0.22	0.30
3	Length of Active Institutional Control Period	21.7	0.20	0.27
4	Length of Passive Institutional Control Period	3.19	0.03	0.02
5	Outdoor Mass Loading	2.22	0.04	0.04
6	Indoor Mass Loading	1.64	0.02	0.02
7	HORNET GZ ^{240}Pu Inventory	1.36	0.03	0.02
8	Inadvertent Soil Ingestion Factor	0.71	0.02	0.01

The marginal dependencies are consistent with the conceptual understanding of the system (Figure A4.9). Source term related factors (i.e., HORNET GZ enrichment factors and inventories) show an increasing linear relationship between the factor and the CA annual TED. The IC periods show a step function-like relationship shifting from the mean CA annual TED, 0.02 mSv, to zero at 1,000 y.

Figure A4.9 Histogram of input parameter values (grey) and marginal dependence (blue) of most sensitive parameters for the CA annual TED 1,000 y

A4.4 References

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