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Nevada National Security Site Underground Radionuclide Inventory, 1951-1992: Accounting for Radionuclide Decay through September 30, 2012

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ABSTRACT

This report is an update of report LA-13859-MS (Bowen et al., 2001). In that original report, the underground radionuclide inventory at the Nevada National Security Site (NNSS) was decay corrected to September 23, 1992, the date of the last underground nuclear test at the NNSS. In this report, the inventory is updated to account for the decay of radionuclides over two additional decades (1992-2012) and revised tritium, fission product and actinide inventory figures and tables are presented. The maximum contaminant levels for radionuclides were also updated to Safe Drinking Water Act Maximum Contaminant Levels (MCLs) (CFR, 2013). Also, a number of minor errata found in the original publication were corrected.

An inventory of radionuclides produced by 828 underground nuclear tests conducted at the NNSS by the Lawrence Livermore National Laboratory, the Los Alamos National Laboratory, and the Department of the Defense from 1951 to 1992 includes tritium, fission products, actinides, and activation products. The inventory presented in this report provides an estimate of radioactivity remaining underground at the NNSS after nuclear testing. The original test inventory is decayed to September 30, 2012, and predictions of inventory decay over the subsequent 1000 years are presented. For the purposes of summary and publication, the Los Alamos National Laboratory and Lawrence Livermore National Laboratory authors of this report subdivided the inventory into five areas corresponding to the principal geographic test centers at the NNSS. The five areas roughly correspond to Underground Test Area "Corrective Action Units" (CAUs) for remediation of groundwater. In addition, the inventory is further subdivided for the Yucca Flat region by tests where the working point depth is more than 328 feet (100 meters) above the water table and tests that were detonated below that level. Water levels used were those from the U. S. Department of Energy, Nevada Operations Office (1997), now called the Nevada Field Office. Curie activities and atoms are reported as of September 30, 2012. This inventory is strictly a compilation of the residual radiologic inventory remaining from the underground nuclear tests conducted by Lawrence Livermore National Laboratory, Los Alamos National Laboratory and the Department of the Defense from 1951 to 1992 and does not include radioactivity from other types of nuclear testing (e.g., atmospheric, reactors, rocket engines). A companion classified report (Miller *et al.*, 2002) contains test-specific data for each test performed at the NNSS. This work has been sponsored by the U. S. Department of Energy, National Nuclear Security Administration Nevada Field Office.

INTRODUCTION

This report is an update of the original report "Nevada Test Site Radionuclide Inventory, 1951-1992" published in September, 2001 (Bowen et al., 2001). The tables and figures have been updated to reflect the radionuclide inventory as of September 30, 2012 and several tables and figures have been added to give a clearer representation of radioactive decay over time.

This report provides an inventory of radionuclides from 828 underground nuclear tests conducted at the Nevada National Security Site (NNSS), formerly the Nevada Test Site (NTS), Nye County, Nevada. The radiologic inventory is part of a larger effort sponsored by the U. S. Department of Energy to comprehensively investigate the distribution and potential migration of these radionuclides in groundwater at the NNSS. Ultimately, the assessment of risk for receptors down-gradient from testing centers requires an accurate (as possible) quantitative measure of potential contaminant species.

Between 1951 and 1992, the United States government conducted 828 underground nuclear tests at the NNSS (U.S. Department of Energy, Nevada Operations Office, 2000) sponsored by the U. S. Department of Energy and its predecessors. These tests supported a program of strategic nuclear deterrence that served national defense policy during the four decades of underground nuclear testing. The Los Alamos National Laboratory (LANL), the Lawrence Livermore National Laboratory (LLNL), and the U. S. Department of Defense (DoD), with support from the national laboratories, conducted specific test series for the U. S. Government. In addition, a number of tests were conducted cooperatively on behalf of the United Kingdom by the national labs. Objectives of the nuclear test program included ensuring operational readiness of stockpiled nuclear weapons, executing proof-of-principle experiments driven by nuclear weapon design, and studying the effects of enhanced radiation fields produced during nuclear explosions. Individual test schedules varied year to year and are summarized in Figure 1. From 1958 to 1961, nuclear testing was suspended by a voluntary international moratorium; in October 1992 a second voluntary testing moratorium was adopted by the U. S. Government and has remained in effect to the present. In this report, we utilize data on the depths of burial and depths of the static water level in 1997 (U.S. Department of Energy, Nevada Operations Office, 1997) compiled in support of environmental activities at the NNSS.

THE NEVADA NATIONAL SECURITY SITE

The NNSS is situated approximately 65 miles (105 kilometers) northwest of Las Vegas and comprises approximately 1,375 square miles (3,561 square kilometers) of north–south tending mountain ranges and mesas separated by broad alluvial basins typical of the Basin and Range physiographic province throughout much of Nevada, Arizona, and Utah. On the basis of its remote setting, favorable year-round weather, restricted access and prevailing wind patterns, the Nevada Proving Grounds—forerunner to the NTS and now the NNSS—was established in the early 1950's as a continental proving ground for atmospheric nuclear tests. In 1951, the first underground nuclear test was fielded at the NNSS, and since late 1962, all U. S. nuclear tests at the NNSS have been conducted underground. In areas where underground nuclear tests were detonated, the NNSS is further characterized by deep groundwater (650 to 4088 feet (200 to 1250 meters) below the ground surface), and an extremely arid climate.

THE RADIONUCLIDE SOURCE TERM

The potential for the contamination of groundwater beneath the NNSS by nuclear testing has long been recognized (Batzel, 1959). Since the 1950s, studies of radiological contamination of soil and groundwater, notably those conducted by the Radionuclide Migration Program (later called the Hydrologic Resources Management Program), have complemented the nuclear test program. As a part of a Federal Facilities Agreement and Consent Order (1996) to address potential contamination at the NNSS, the U.S. Department of Energy National Nuclear Security Administration Nevada Field Office (NNSA/NV) designated the Underground Test Area (UGTA) project to manage technical studies of groundwater contamination associated with underground testing.

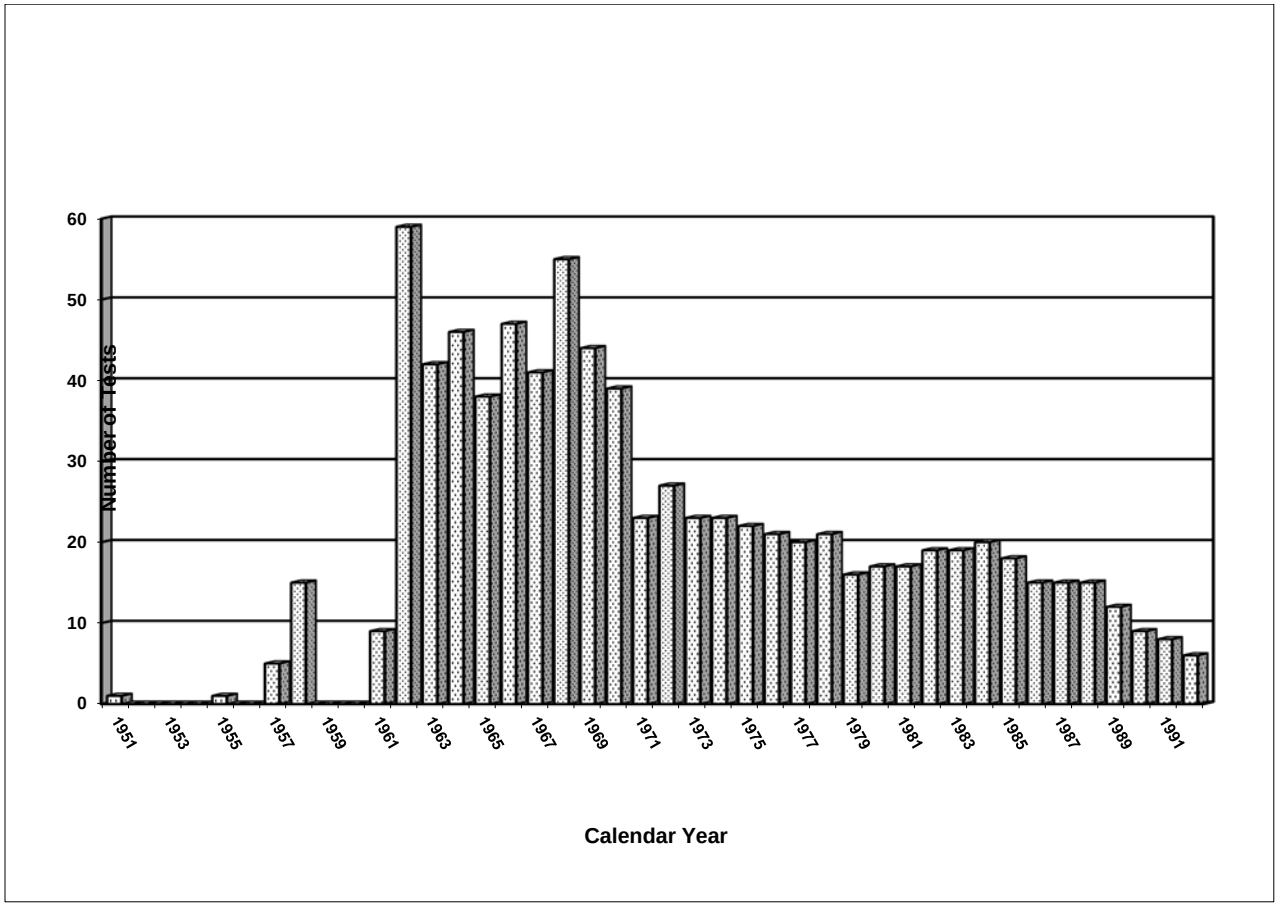


Figure 1: A histogram showing the number of underground nuclear tests conducted by year at the NNSS.

An early priority of the UGTA project included determining an accurate measure of the total radiological inventory present at the NNSS. The quantity of existing contaminants provides an upper bound on the contamination underground at the NNSS. This information is vital in the design of remediation strategies and effective resource management. Similarly, risk assessment

developed for human health and the environment requires a reliable measure of radionuclides available for potential transport by groundwater to down-gradient receptors. The radionuclide inventory includes long-lived radioactive species produced by or remaining after underground nuclear explosions at the NNSS during the period 1951 to 1992. The inventory represents a starting point for the estimation of radionuclides available for dispersal away from test centers. Not all radionuclides are equally available for transport in the time frame of hundreds to thousands of years. There is a necessary distinction between the radionuclide source term that includes all radioactive material remaining after a nuclear test and the hydrologic source term that includes only those radionuclides dissolved in and/or transported by groundwater. The radionuclide inventory reported here (the radiological source term) does not represent the amount of radioactivity that is or will be dissolved in groundwater at the NNSS (the hydrologic source term). The hydrologic source term is less than the total radiological source term in the time frame of hundreds to thousands of years. This report presents the radiological source term, which combines inventories compiled for the underground nuclear tests conducted by LANL and LLNL, as well as tests supporting the U. S. DOD.

UNDERGROUND NUCLEAR TESTING

As an aid to understanding the radiological source term, a review of the execution of underground nuclear tests and the phenomenology associated with nuclear explosions are presented. For the purposes of this report, underground nuclear tests may be considered as tests involving fissionable nuclear material placed underground, most of which were designed to produce a nuclear yield. The yield—or the amount of explosive energy released from a nuclear weapon—is typically measured in TNT equivalents released. Yields for NNSS underground nuclear experiments at the NNSS ranged from less than1 kiloton to greater than 1 megaton.

Underground nuclear testing practice has evolved considerably since the first underground test in 1951 was detonated in a shallow hole. The Rainier test of September 1957 was the first nuclear test contained completely underground and was designed to prevent the release of radioactivity as well as to determine whether diagnostic information could be obtained from an underground nuclear test. In 1963, the United States signed the Limited Test Ban Treaty prohibiting nuclear testing other than underground. Containment scenarios largely eliminated venting of radioactive debris to the atmosphere. Experience gained through 1992 was used to develop containment measures to minimize the accidental release of radioactive gas to the surface without compromising device performance or test diagnostics. Containment relies on the physical properties of surrounding geologic media including rock elastic strength and porosity, the device depth of burial, impermeable seals and backfill known as stemming, and cable gas blocks which prevent gas release out of the emplacement hole.

A brief introduction to underground testing is valuable to place the radiological source term in context. Interested readers are referred to a comprehensive discussion of the containment of underground nuclear explosions provided by the U. S. Congress, Office of Technology Assessment (1989) and Pawloski (1999). The majority of underground tests were either vertical shaft tests or horizontal tunnel tests. More than 90% of the underground tests were fired in vertical shafts a thousand feet or more below ground surface. Shaft tests were fielded primarily to test stockpile weapons or design features in new weapons systems. Vertical shaft tests at the

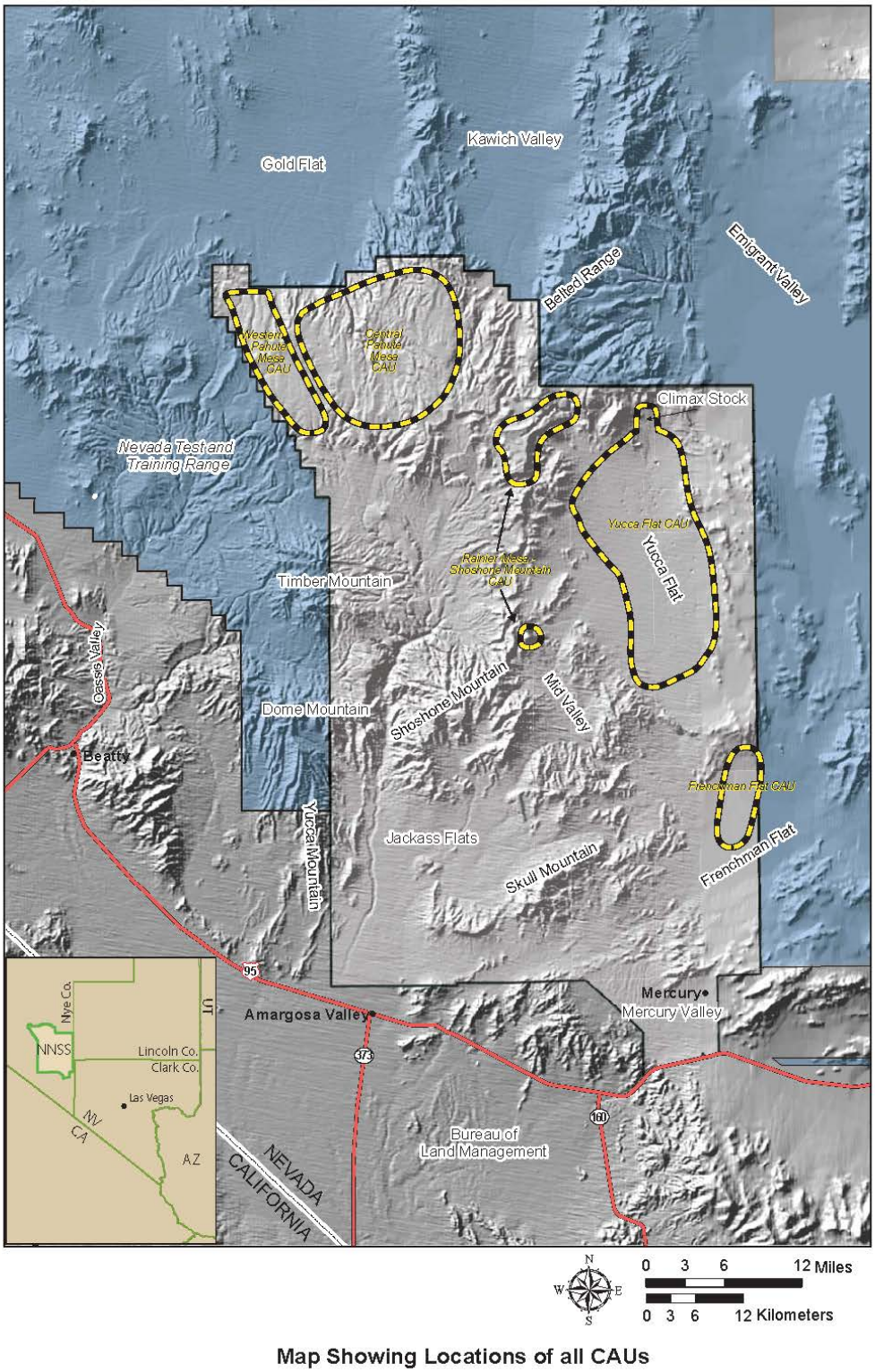
NNSS were conducted predominantly beneath Yucca Flat (Areas 1, 2, 3, 4, 6, 7, 8, 9, and 10) and Frenchman Flat (Area 5 and 11) for lower yield experiments and beneath Pahute Mesa (Areas 19 and 20) for higher yield experiments. Approximately 30% of the shaft tests were fired beneath the actual static water level (water table). Generally, tests conducted on Yucca Flat were buried at depths of approximately 2,000 feet (600 meters) or less. Some higher yield experiments were buried at depths exceeding 4,000 feet (1200 meters) on Pahute Mesa. Horizontal tunnel tests occurred within tunnel complexes excavated in Rainier and Aqueduct Mesas (Area 12), Oak Spring/Butte (Area 15), and Shoshone Mountain (Area 16). Most tunnel tests were fired within zones of discontinuously perched groundwater beneath the Rainier and Aqueduct Mesas. Figure 2 shows the CAU areas and the locations of underground nuclear tests at the NNSS.

NUCLEAR EXPLOSION PHENOMENOLOGY

A brief discussion of phenomenology is warranted in the context of the evolution of the radiological source term. The following builds on the summaries provided by U. S. Congress, Office of Technology Assessment (1989) and those compiled by Glasstone and Dolan (1977). The sequence of events following a nuclear explosion is illustrated in Figure 3. At firing (zero) time, pressures within the weapons case can exceed several million pounds per square inch, and temperatures may be as high as 10^8 Kelvin. Milliseconds after detonation, the weapon's case, rack and geologic media immediately surrounding the device are vaporized and a cavity forms in response to gas pressure and the explosive energy imparted to the surrounding rock. The shock waves propagate outward away from the cavity forming a radius of fractured rock that extends approximately two to three times that of the spherical cavity. The shock wave loses energy until the surrounding rock is no longer crushed but is merely elastically compressed. Hydrodynamic calculations indicate that the shock wave vaporizes approximately 70 metric tons and melts approximately 700 metric tons of rock for each kiloton of explosive yield (Olsen, 1967). For tests fired at or below the water table, all standing water near the working point is vaporized. As the gas continues to expand adiabatically, the cavity grows (approximately) spherically for a few tenths of a second until the gas pressure drops below the ambient lithostatic pressure. At this point, the cavity has reached its maximum radius and volume. Scaling laws based on empirical studies relate cavity radius to explosive yield (see Glasstone and Dolan, 1977 and U. S. Congress, Office of Technology Assessment, 1989).

During the period of cavity growth, the vaporized material, consisting largely of volatilized silicate phases, condenses as it cools and mixes with molten rock that lines the circumference of the cavity. The melt flows down the walls and begins to coalesce in a puddle and solidify on the floor of the cavity. At this time, condensable gases change phase and cavity pressure drops. The gas pressure in the cavity diminishes to the point where the cavity normally can no longer support the weight of the overlying rock. The cavity collapses in on itself, often with blocks of rock chaotically incorporated in the still partially molten melt glass. As blocks of rock fill the cavity void, the process is perpetuated upward as the rubble continues to fall downward. This process creates a rubble chimney that propagates upward from the working point until the void volume in the chimney is completely filled with rubble debris and the strength of the overlying rocks can support the overburden, or until the chimney reaches the surface and creates a subsidence crater. Over half of underground nuclear tests result in surface subsidence craters. Typically the collapse and chimney formation occurs within a few hours of zero time, but it may

occur as late as a few days or months after the explosion. For tests fired at or below the water table, hydrologic heads immediately perturbed by the displacement of water during the explosion will begin to return to original preshot static water levels within days to years, depending on adjacent hydrologic conductivities.



Map Showing Locations of all CAUs

Figure 2: Map of the NNSS showing the locations of all Corrective Action Units (CAUs)

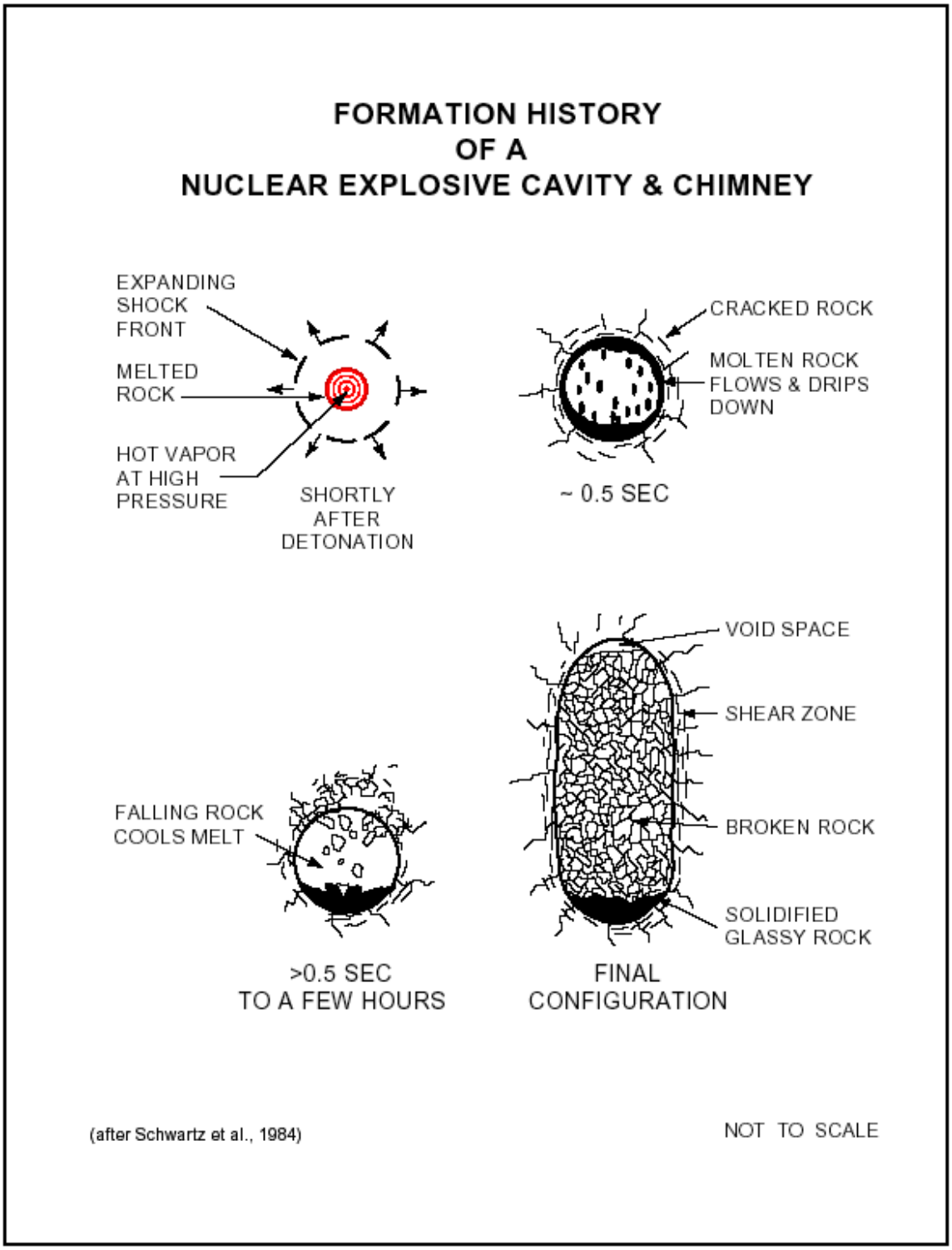


Figure 3: Idealized formation history of an underground nuclear explosion in siliceous rock. Stages are in elapsed time from detonation.

DISTRIBUTION OF RADIONUCLIDES

Temperature and pressure histories associated with the explosion strongly influence the distribution of radionuclides within the cavity-chimney complex (Borg *et al.*, 1976). Immediately after a nuclear explosion, all of the radioactive species exist as a plasma. As the cavity ceases to expand, heat is transferred to the wall rock and the cavity temperature and pressure begin to drop. The melt that flows to the floor of the cavity entrains the refractory radionuclides with higher boiling points (rare earth elements, alkaline earths, Zr, and Pu). Most of these refractory species are trapped in the cooling melt; a small proportion is incorporated with the collapsed chimney rubble as splash or fine droplets entrained with escaping cavity gases. Volatile species with lower boiling points (tritium, alkalis, Ru, U, Sb, Cl, I, CO_2) circulate up cracks in the rubble chimney. Activation products are concentrated around the working point and will be largely incorporated in the melt or debris that borders the cavity. Volatile species, particularly ^{90}Kr, ^{137}Xe, and $^{14}CO_2$ are transported as gases through the rubble and are concentrated higher in the cavity and in the chimney relative to the refractory radionuclides. Drillback samples systematically exhibit higher volatile to refractory radionuclide ratios (Cs/Eu) for returns collected higher in the cavity and chimney (Thompson, 1996). In addition, studies of nuclear tests fired both above and below the water table indicate that material may be transported by prompt injection through explosion induced fractures arranged radially away from ground zero (Smith et al., 1996). By this mechanism, gaseous species, particularly tritium and ^{137}Cs (^{137}Cs has a gaseous ^{137}Xe precursor with a 3.8 minute half-life), may be deposited several cavity radii away from the working point. There is some evidence that refractory species may be similarly transported by prompt injection (Nimz and Thompson, 1992). Ultimately, the amounts and types of radionuclides resulting from a specific nuclear explosion will depend on the amount of fissile material, the fission/fusion ratio, and the device yield. On a test-by-test basis, these data are classified. This report quantifies the abundance of these residual radionuclide species for five principal geographic test centers at the NNSS.

RADIONUCLIDE INCLUSION CRITERIA

Radionuclides to be considered for inclusion in the radionuclide inventory are: 1) residual and unburned fissile fuel and tracer materials, such as U isotopes, Pu isotopes, Am isotopes, and ^{244}Cm; 2) fission products such as ^{137}Cs and ^{90}Sr; 3) tritium (^{3}H); and 4) activities induced by neutrons in device parts, in external hardware, and in the surrounding geologic medium (such as ^{14}C, $^{36}C1$, and ^{41}Ca). Not all of the radionuclides produced during a nuclear test are included in the source term inventory. Many of the nuclides have half-lives so short (microseconds to hours) that they decay to undetectable levels soon after the test. Other nuclides are produced in such low initial abundance that they never exceed levels deemed unsafe or non-permissible by regulatory agencies.

In the original inventory analysis presented by Bowen et al. (2001), criteria were developed to exclude radionuclides with low abundance from the inventory; this permits the user to focus attention on the nuclides of interest from the perspective of risk assessment. Excluded were nuclides produced in such low amounts that if all of the amount produced during a nuclear test were dissolved into a volume of water equal to the volume of the detonation cavity for the test (assuming an open cavity with no geologic media), 100 years from 1992 (the year of the last

test), the resulting aqueous concentration (activity) in pCi/L (one pCi = 2.22 disintegrations per minute) would be less than one-tenth of the maximum contaminant levels (MCLs**).** The MCLs listed in the original report (Bowen et al., 2001) were obtained from the U. S. Federal Register, 1991, and are included in Appendix A for reference. The requirement of 100 years into the future eliminates many nuclides that are produced in great abundance in nuclear detonations but have half-lives sufficiently short that they will have decayed below the 0.1 MCL value by that time. However, if a radionuclide exceeded these criteria for at least one test, it was included for all other tests for which estimates are available, even if its concentration was below the 0.1 MCL criterion in the other tests. This comparison resulted in screening out radionuclides with half-lives < 10 years, except ^{154}Eu because of its abundance.

Table 1 lists the radionuclides with half-lives of >10 years (with the exception of ^{154}Eu at 8.6 years) that could be produced in nuclear detonations, and are retained in this inventory evaluation. Table 1 lists the current values of MCL's, which were obtained from *Radionuclides in Drinking Water: A Small Entity Compliance Guide* (EPA, 2002). For nuclides with no MCLs in the EPA 2002 document, values were calculated using RESRAD Version 6.5 (Yu et al., 2001). RESRAD is a computer model designed at Argonne National Laboratory to estimate radiation doses and risks from residual radioactive materials. The MCL calculated using RESRAD is that concentration in drinking water that will impart a dose of 4 mrem/year to a person drinking an average of 2 liters of water per day. We note that there are no MCLs listed in Table 1 for ^{39}Ar and ^{85}Kr since both of these radionuclides are gases. When the water is underground, high pressure keeps ^{39}Ar and ^{85}Kr in groundwater, but when water is brought to the surface, both radionuclides are released from the water to the atmosphere. These radionuclides are retained in the inventory, however, to be conservative. Table 1 also includes the principal radiochemical sources or production mechanisms of test-derived radionuclides. Where multiple sources are identified, each is listed. The list of radionuclides included in this inventory evaluation remains the same as in the previous analysis (Bowen et al., 2001).

TABLE 1

Radionuclides Included in the Source-Term Inventory
(MCL from EPA (2002) or calculated using RESRAD**)

Element	Nuclide	Half-life (y)*	MCL (pCi/L)	Main Source(s)
Hydrogen	^{3}H	12.32	2.0×10^{4}	device component; ^{6}Li (n,α) T
Carbon	^{14}C	5715	2.0×10^{3}	^{14}N (n,p); ^{13}C (n,γ); ^{17}O (n,α)
Aluminum	$^{26}A1$	7.1×10^{5}	$4.2 \times 10^{2**}$	$^{27}A1$ (n,2n)
Chlorine	$^{36}C1$	3.01×10^{5}	7.0×10^{2}	$^{35}C1$ (n,γ); ^{39}K (n,α)
Argon	^{39}Ar	269	----	^{39}K (n,p); ^{38}Ar(n,γ)
Potassium	^{40}K	1.27×10^{9}	$2.4 \times 10^{2**}$	Natural
Calcium	^{41}Ca	1.03×10^{5}	$7.8 \times 10^{3**}$	^{40}Ca (n,γ)
Nickel	^{59}Ni	7.6×10^{4}	3.0×10^{2}	^{58}Ni (n,γ)
	^{63}Ni	101	5.0×10^{1}	^{62}Ni (n,γ), ^{64}Ni (n,2n), ^{63}Cu (n,p)
Krypton	^{85}Kr	10.76	----	FP; ^{84}Kr (n,γ)
Strontium	^{90}Sr	28.78	8.0×10^{0}	FP
Zirconium	^{93}Zr	1.5×10^{6}	2.0×10^{3}	FP; ^{92}Zr (n,γ); ^{94}Zr (n,2n)
Niobium	^{93m}Nb	16.1	$1.2 \times 10^{4**}$	^{93}Nb (n,n′)
	^{94}Nb	2.0×10^{4}	$8.7 \times 10^{2**}$	FP; ^{93}Nb(n,γ)
Technetium	^{99}Tc	2.13×10^{5}	9.0×10^{2}	FP; ^{99}Ru (n,p)
Palladium	^{107}Pd	6.5×10^{6}	$4.0 \times 10^{4**}$	FP; ^{106}Pd (n,γ)
Cadmium	^{113m}Cd	14.1	$6.4 \times 10^{1**}$	FP
Tin	^{121m}Sn	44	$3.9 \times 10^{3**}$	FP; ^{120}Sn (n,γ)
	^{126}Sn	2.3×10^{5}	$3.2 \times 10^{2**}$	FP
Iodine	^{129}I	1.57×10^{7}	1.0×10^{0}	FP; ^{129}Xe (n,p)
Cesium	^{135}Cs	2.3×10^{6}	9.0×10^{2}	FP
	^{137}Cs	30.07	2.0×10^{2}	FP; ^{137}Ba (n,p)
Samarium	^{151}Sm	90	1.0×10^{3}	FP; ^{150}Sm (n,γ)
Europium	^{150}Eu	36	$1.1 \times 10^{3**}$	^{151}Eu (n,2n)
	^{152}Eu	13.54	2.0×10^{2}	FP, ^{151}Eu (n,γ); ^{153}Eu (n,2n)
	^{154}Eu	8.593	6.0×10^{1}	^{153}Eu (n,γ)
Holmium	^{166m}Ho	1.2×10^{3}	$7.4 \times 10^{2**}$	FP; ^{165}Ho (n,γ)
Thorium	^{232}Th	1.40×10^{10}	1.5×10^{1}	natural and device component
Uranium	^{232}U	69.8	6.7×10^{8}	device component; ^{233}U (n,2n)
	^{233}U	1.592×10^{5}	2.9×10^{5}	device component; radchem tracer
	^{234}U	2.46×10^{5}	1.9×10^{5}	natural and device component
	^{235}U	7.04×10^{8}	6.5×10^{1}	natural and device component
	^{236}U	2.342×10^{7}	1.9×10^{3}	device component; ^{235}U (n,γ); ^{238}U (n,2n)[2]
	^{238}U	4.47×10^{9}	1.0×10^{1}	natural and device component
Neptunium	^{237}Np	2.14×10^{6}	1.5×10^{1}	radchem tracer; decay of ^{237}U
Plutonium	^{238}Pu	87.7	1.5×10^{1}	device component; radchem tracer; ^{239}Pu (n,2n); ^{237}Np (n,γ)
	^{239}Pu	2.410×10^{4}	1.5×10^{1}	device component; decay of ^{239}U

	^{240}Pu	6.56 x 10^3	1.5 x 10^1	device component; ^{239}Pu (n,γ); decay of ^{240}U
	^{241}Pu	14.4	3.0 x 10^2	device component; ^{240}Pu (n,γ); decay of ^{241}U
	^{242}Pu	3.75 x 10^5	1.5 x 10^1	device component; radchem tracer; ^{241}Pu (n,γ); decay of ^{242}U
Americium	^{241}Am	432.7	1.5 x 10^1	device component; radchem tracer; decay of ^{241}Pu
	^{243}Am	7.37 x 10^3	1.5 x 10^1	device component; radchem tracer
Curium	^{244}Cm	18.1	1.5 x 10^1	radchem tracer

* Half-lives obtained from GE Chart of the Nuclides, Sixteenth Edition (2002).
**MCL from RESRAD calculations

DATA STRUCTURE

The complete underground source-term inventory for the NNSS combines separate inventories compiled by LANL and LLNL. By agreement, LANL maintains the Microsoft® Access database and provides LLNL with any updated version of the database.

The database contains test-specific radionuclide amounts (reported in atoms and curies at test time) for 43 isotopes listed in Table 1. Several parent isotopes with shorter half-lives are also compiled in the database for decay calculations. Because the database compiles test-specific nuclear performance data including yield, residual nuclear fuels, and thermonuclear and fission products, by necessity it is classified as Secret Restricted Data. The database is accessible to investigators holding an active U. S. Department of Energy Q security clearance with a valid need-to-know.

For the purposes of summary and publication, LANL and LLNL subdivided the inventory into five areas corresponding to the principal geographic test centers at the NNSS (see Table 2). The five areas roughly correspond to UGTA CAUs. In addition, the inventory is further subdivided for the Yucca Flat region by tests where the working point depth is more than 328 feet (100 meters) above the water table and tests that were detonated below that level. This distinction for Yucca Flat differentiates (1) the inventory for those tests fully conducted in the unsaturated zone from (2) the inventory for tests that were either conducted below the water table or near enough to the water table that the cavity may have intercepted the water table and directly introduced radionuclides to groundwater. The 328-foot (100-meter) buffer accounts for those tests conducted close enough to the water table that radionuclides may have been introduced to groundwater immediately after detonation. Water levels used were those from U. S. Department of Energy, Nevada Operations Office (1997). Due to testing effects, the 1997 water levels are elevated in comparison to both pre-test water levels and more recent water levels measured at Yucca Flat. Therefore, the analysis is conservative for UGTA purposes in that more Yucca Flat tests are attributed to the saturated-zone inventory and less to the unsaturated-zone inventory than if long-term static water levels had been used.

TABLE 2

Combination of NNSS Areas into Principal Geographic Test Centers

Principal Geographic Test Centers	Areas Included
Yucca Flat/Climax Mines*	1, 2, 3, 4, 6, 7, 8, 9, 10, 15
Central Pahute Mesa – 19	19
Western Pahute Mesa – 20	20
Frenchman Flat	5, 11
Rainier Mesa/Shoshone Mt	12, 16, 18, 30

*Yucca Flat/Climax Mines was further subdivided into tests with the working point more than 328 feet (100 meters) above the water table and tests that were detonated below that level.

The summaries derived from this database and presented in this report list the aggregate activities in curies and atoms of radionuclides that meet the selection criteria. In the original report (Bowen et al., 2001), the values were decay corrected to September 23, 1992, the date of the last underground nuclear test at the NNSS, and designated as above or below the reference-point static water level (using U. S. Department of Energy, Nevada Operations Office, 1997) plus 328 feet (100 meters) for Yucca Flat. In this update, we have decay corrected the inventories to September 30, 2012, to account for the additional radioactive decay that took place over the last two decades. The 1997 reference-point static water level is retained in the calculations although water levels have changed and are currently generally lower because testing effects have diminished with time. These tables represent the long-lived radionuclide inventory for all tests conducted underground at the NNSS by LANL, LLNL, and the DoD between 1951 and 1992.

SOURCES OF RADIONUCLIDE DATA

Values for the total inventory of radionuclides were determined in two principal fashions for this compilation: measurements and calculations. Many nuclides were historically measured from small samples recovered from the underground environment as part of the radiochemical diagnostics effort. These nuclides were those most relevant for diagnostic purposes: fission products, residual fuel species, and radiochemical detector and tracer isotopes. These measurements have also served to establish an understanding of the processes occurring in the underground environment and were used in computer codes that predicted the production of nuclides in a test. These codes were used to stand in where measurements were not made at the time of the test or where interpretation of the data for total inventory was difficult.

Radiochemical diagnostics depend upon the recovery of a small portion of the debris from the underground nuclear test site. Both LANL and LLNL did this in a similar fashion, using slightly different methods to choose and collect samples. Only small portions of the residual materials were recovered. Recovered material was dissolved in strong acids to produce a solution of device material; analysis proceeded to determine atoms of particular nuclides per milliliter (or gram) of

this solution. These quantities can be converted into total inventory by dividing by the relative proportion of the device in the sample.

As part of the radiochemical diagnostics effort, knowledge of the pre-test inventory of materials going into the test device is required. Complete inventories of fissile isotopes (limited in early times by measurement techniques) were recorded for essentially all tests. Similarly, most tritium data are also available. Based upon complete suites of measurements, it is possible to establish mathematical relationships (implemented by computer codes) to mimic isotopic changes when measurements were not made. A large amount of the information required for this study was available in existing databases maintained by LLNL and LANL. Other information was derived from publications or databases from other organizations. Information collected in this study was entered into an Access database. These data have been collated for the summary described here, and are described in detail in a comprehensive classified report (Miller, et al., 2002).

METHODS OF ESTIMATING POSTSHOT RADIONUCLIDE CONTENT

Postshot radionuclides present underground at the NNSS can be grouped into four different categories: fission products, actinide elements, tritium, and activation products/natural materials. Each of these groups requires different methodologies for estimating the postshot quantities of the nuclides. In addition, historical differences in the radiochemical diagnostic approaches employed by LANL and LLNL lead to slightly different techniques for each laboratory. The following describes the methods used in this study.

FISSION PRODUCTS

Most of the fission products from nuclear tests are formed in such low amounts or have such long half-lives that they were not measured radiochemically following the tests. In addition, many of these isotopes experience chemical fractionation and are not representative of the bomb fractions. These volatile (gas-phase) radionuclides are of little or no diagnostic value, but are of importance to remedial investigations because of their potential mobility.

For a large number of tests, high-yield fission products were measured in order to determine the fission yield of the device. Other fission products were also measured to characterize the fission split or the distribution of fissions among the fissile materials. For the remaining tests, sufficient precedent or other diagnostic measurements were available to state the fission yield and split. Thus determined, the fission yields and splits have served as the basis for the calculation of the amounts of the various fission products given in this study.

We have chosen to calculate the postshot amounts from fission yields based on the type of fissile fuel and the neutron energy spectrum. In most cases, these characteristics were available in the documentation associated with each individual test. In other cases, we reasoned by analogy. The overall, effective yield of a fission product for each test is the weighted average of the yields from that test's mix of fissions from each fissile fuel and neutron energy spectrum. For the majority of fission products, the fission yields of England and Rider (1994) were used by both LANL and LLNL.

ACTINIDES

LANL and LLNL have chosen consistent paths in the manner in which they have treated their actinide data. This is in part driven by the available data and in part by the technical biases that developed in their individual histories of weapons radiochemical diagnostics.

For many isotopes, we based our determination of the residual amounts of radionuclides from the measurements on actual core samples. These measurements were made historically in the course of the underground test program. In most cases, the postshot amount of a particular isotope or suite of isotopes was known, based on device performance. This permitted the determination of the fraction of the device present in each particular sample (i.e., the bomb fractions). Through ratio measurements to other species, the absolute abundances of the isotopes could be calculated.

Different approaches were used when measurements were not available or were compromised by underground fractionation phenomena. Based on knowledge of the device, its performance, and production/destruction characteristics, we calculated the amounts of postshot isotopes, using algorithms implemented in the database structure. Some approximations were very simple: tracer isotopes were treated as unchanged from the ingoing amount loaded with the device. Other approximations were derived from many years of observations combined with explosion code information.

TRITIUM

For most U. S. nuclear tests, for times as long as 100 years following the detonation, tritium has the highest activity of any radionuclide with a half-life longer than ten years (see Figures 4a-d). However, tritium was not measured for most U. S. nuclear tests. Because of this, considerable effort was expended in estimating the residual tritium for the individual nuclear tests. We also sought to achieve agreement between LANL and LLNL for this isotope. Because of their earlier start on the underground inventory effort, LLNL provided most of the algorithms for tritium production and destruction. LANL confirmed these methods through independent explosion code calculations.

The amount of residual tritium from a nuclear test is the net result of the amount loaded on the device and the amounts produced and destroyed in the nuclear explosion. A wide variety of sources and reactions are involved in this production/destruction. Each unique material and device type was examined to provide methods consistent with the limited suite of tritium measurements and the results of explosion code calculations.

ACTIVATION PRODUCTS AND NATURAL ISOTOPES

Reactions of neutrons with parts of the device other than the fuel, such as the structural materials, the stemming, and the geologic medium, produce several nuclides with half-lives longer than 10 years. There are about 50 such nuclides, but many of them can be excluded using the source term inventory criteria, because of extremely short half-life of the nuclide or very small production rate. Several nuclides do meet the selection criteria, however. The contributions of these nuclides

to the source term were estimated using available data on other slow- and fast-neutron activation products, relevant cross section information, and neutron transport calculations.

For most of the nuclides of interest, activation of the geologic medium by reactions of slow neutrons is an important production mechanism. To estimate this, we made use of extensive data at both laboratories on the production of ^{160}Tb by ^{159}Tb (n,γ). Both LLNL and LANL have measured ^{160}Tb in debris samples from a large number of underground nuclear tests as an indicator of neutron activation of soil constituents. These measurements were used to correct other observations for such soil contributions. Empirical relationships were independently derived by the laboratories to estimate the ^{160}Tb production in cases where measurements were not made.

The amounts of other nuclides produced by the slow neutron reactions in the soil relative to ^{160}Tb were estimated using relationships derived at LLNL using neutron transport calculations. Monte Carlo neutron transport calculations were performed using the MCNP code (LANL, 1981); in addition, the Monte Carlo transport calculations by Lessler and Guy (1965) were also useful. Average trace element abundances (C.F. Smith, 1993) in the geologic media for several drill holes were used in these calculations (see Table 3). Adjustments were made for the different composition of the LANL magnetite stemming material. These approximations were considered adequate in view of the rather large uncertainties in the calculation of the activation products and the fact that the activation products in general are not major components of the radionuclide inventory.

The production of nuclides in device parts was, in some cases, calculated relative to other nuclides that were actually measured as part of the radiochemical diagnostics of the test. In addition, naturally-occurring radioactive isotopes (^{40}K, ^{232}Th, ^{234}U, ^{235}U, and ^{238}U) were included and represent the amount in the rock melted during a detonation (700 metric tons/kiloton of yield).

TABLE 3

Soil and Magnetite
Elemental Abundances

Element	Soil Abundance (wt%)	Magnetite Abundance (wt%)
Cl	0.011	<0.012
K	4.2	0.24
Ca	2.8	1.04
Ni	0.0094	0.0094
Nb	0.001	0.001
Eu	9.0×10^{-5}	2.3×10^{-4}
Tb	6.8×10^{-5}	2.2×10^{-4}

ACCURACY OF THE REPORTED INVENTORY

The accuracy quoted on the content of the inventory depends to a large part on the sources of the included nuclides. Clearly, nuclides whose abundances were measured directly are more accurately reported than those for which estimates had to be made based on device characteristics and performance. There are also tests in the inventory for which little or no post-shot information exists; estimates of radionuclide content for these tests are considerably more uncertain and increase the overall uncertainty for a given nuclide. In Table 4, we show the different groups into which the inventory nuclides have been combined, along with our ranges of the accuracies of the amounts we obtained for the nuclides in each group. The accuracies of fission product amounts from very low yield tests are not included in Table 4 because the contribution of such tests to the total fission product inventory is negligible.

TABLE 4

Estimated Accuracies for Individual Nuclides in
the Various Groups of Radionuclides in this Inventory

Fission products:	~ 10 to 30 % for most fission products
Unspent fuel materials:	~ 20 % or better
Fuel activation products:	~ 50 % or better
Residual tritium:	~ 300% or better
Activation products:	~ a factor of 10

FISSION PRODUCTS

For reported amounts of fission products, accuracy depends on the accuracy of the following for that test: 1) the fission yield (kilotons), 2) the fission split, and 3) the yields of the fission product (atoms per fission) from the various fissions for the test. Not counting some of the tests with very low yields (<0.1 ton), the fission yields of almost all the tests are known to within 5 to 30%. For those tests with radiochemical measurements, the fission splits among the fissionable nuclides usually are known accurately. The accuracies for the fission product yields we quote here are from England and Rider (1994). The least accurately known yields are those for the fission products ^{94}Nb, ^{113m}Cd, ^{121m}Sn, ^{152}Eu, and ^{166m}Ho. Fortunately, these are also the fission products with the lowest abundances, so they are very minor contributors to the radionuclide inventory. Furthermore, the total amounts of ^{94}Nb, ^{152}Eu, and ^{166m}Ho produced as activation products are at least 1000 times larger than the amounts from fission. The accuracies of the ^{126}Sn yields are 4 to 16%. The accuracies of the yields of all the other fission products in our inventory are 0.4 to 11%. For tests on which no radiochemical measurements were made, uncertainty for the fission products will be greater unless the test was known to be similar in design and performance to one measured.

ACTINIDES

Most of the tabulated amounts of unspent fission fuel and tracer materials are accurate to 1 to 10%. A few, including some of the values for tests for which the device performance is known only approximately, have uncertainties of up to 20%.

The tabulated amounts of minor isotopes and activation products of fission fuel, when derived from actual measurements, are accurate to 20% or better. However, when the amounts are estimates from approximate device performance information and estimated preshot compositions, the uncertainties for some of the isotopes may rise to 50%. The total ^{232}U inventory is good only to a factor of 2 or 3 because only about 15% of it is based on actual measurements.

TRITIUM

The estimates of residual tritium have a wide range of uncertainties: from 1 - 300%. The 1 or 2% uncertainty applies to those tests on which there was no thermonuclear yield and negligible tritium production, in which case the post-shot amount of tritium equals the pre-shot amount. The 300% uncertainty applies to devices for a small number of tests with unusual designs and tests for which performance is only known approximately.

ACTIVATION PRODUCTS

Our activation product estimates are likely accurate only to a factor of 10 in most instances. This relatively large error is the result of the approximate nature of the methods we used to obtain the estimates described above, such as using data for nuclides from similar reactions and approximate Monte Carlo neutron transport models employing average elemental abundances for soil activation. The part of the europium isotope inventory that is based on direct measurements is more accurate, with uncertainties of 10 to 30%.

RADIONUCLIDE INVENTORY WITH TIME

Figures 4a-d and 5 illustrate the relative percentage and total activity (plotted on log scale) of residual tritium, fission product, and actinide activities remaining with time from underground nuclear tests conducted at the NNSS. The activities have been decay corrected to September 30, 2012, which is the new “zero time” for all of the tables and figures. Previously the data had been corrected to September 23, 1992, the date of the last underground test at the NNSS (Bowen et al., 2001). Figure 4 has been expanded to four figures (4a, 4b, 4c, 4d) to show in better detail the decay of the three radionuclide categories over time. As can now be clearly seen in Figures 4a-d, tritium initially dominates the radionuclide inventory for the first 80 years but is then replaced by fission products. After 1000 years, actinides (~90%) populate the majority of the remaining inventory. The total activity decreases approximately three orders of magnitude (Figure 5). Tables 5a and 5b contain the data that were used in Figures 4a-d, with Table 5a having the data as a percentage of the total and Table 5b presenting the data in total curies.

Ingrowth of Radionuclides

Since the nuclear tests at the NNSS were conducted over approximately a 40 year period and no tests have been conducted in the last two decades, a great deal of radioactive decay has taken place since the first tests in the 1950's.

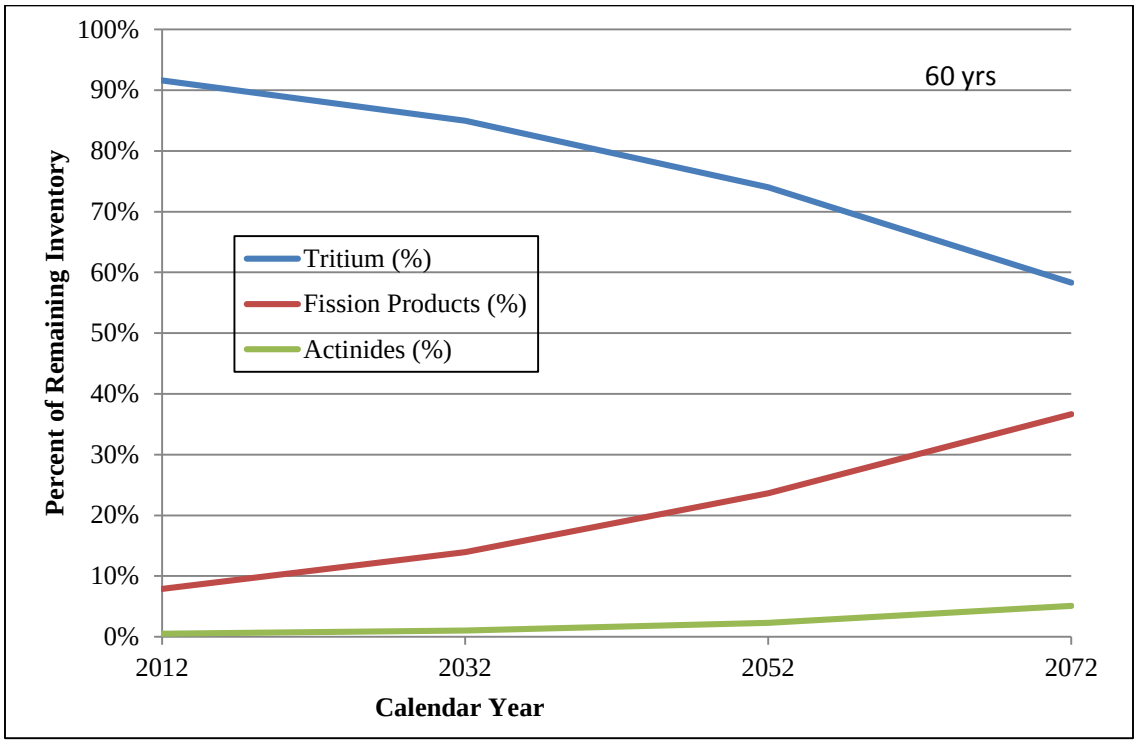


Figure 4a: Relative percentage of residual tritium, fission product, and actinide activities remaining with time. Decayed over 60 year time frame.

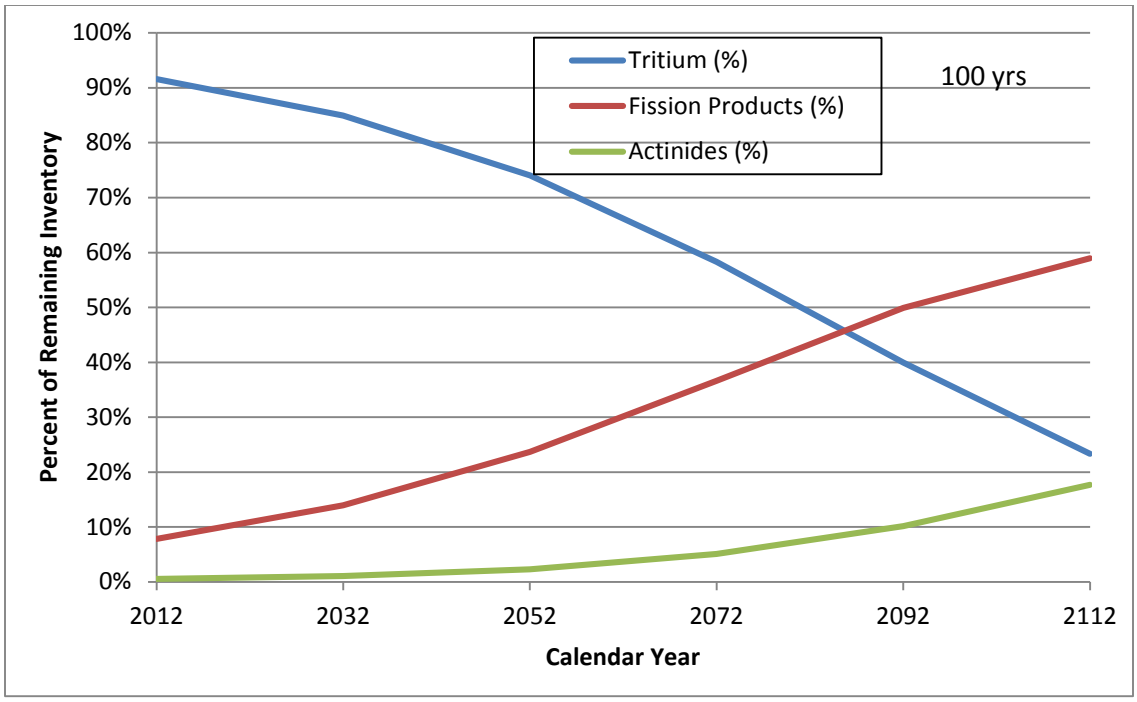


Figure 4b: Relative percentage of residual tritium, fission product, and actinide activities remaining with time. Decayed over 100 year time frame.

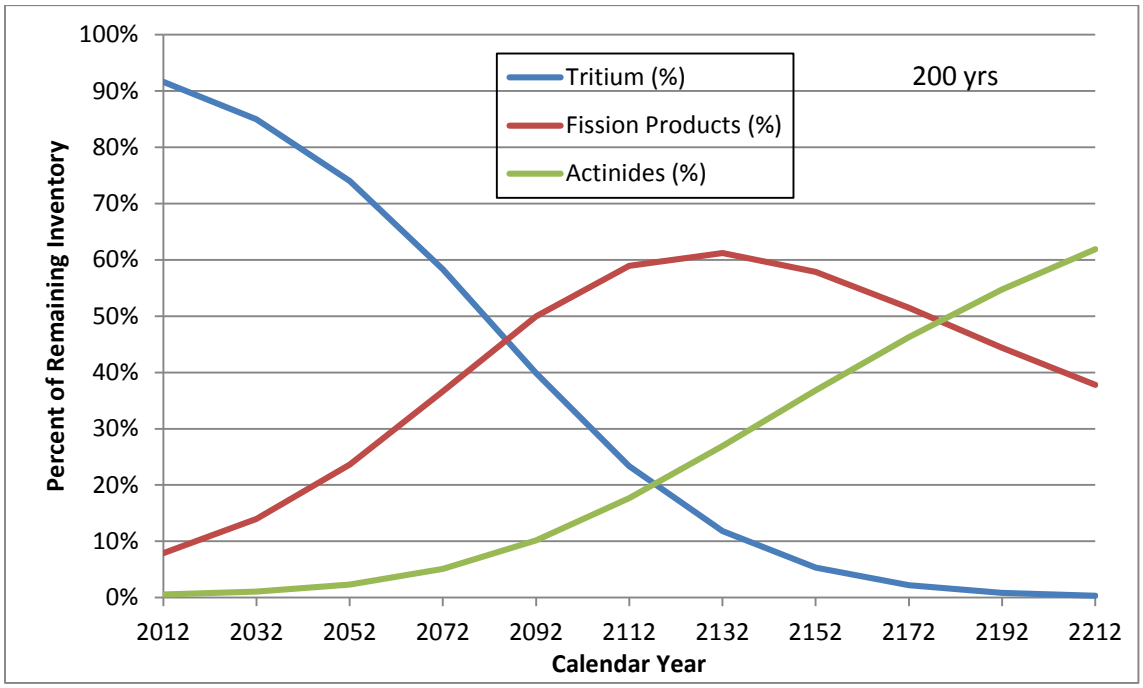


Figure 4c: Relative percentage of residual tritium, fission product, and actinide activities remaining with time. Decayed over 200 year time frame.

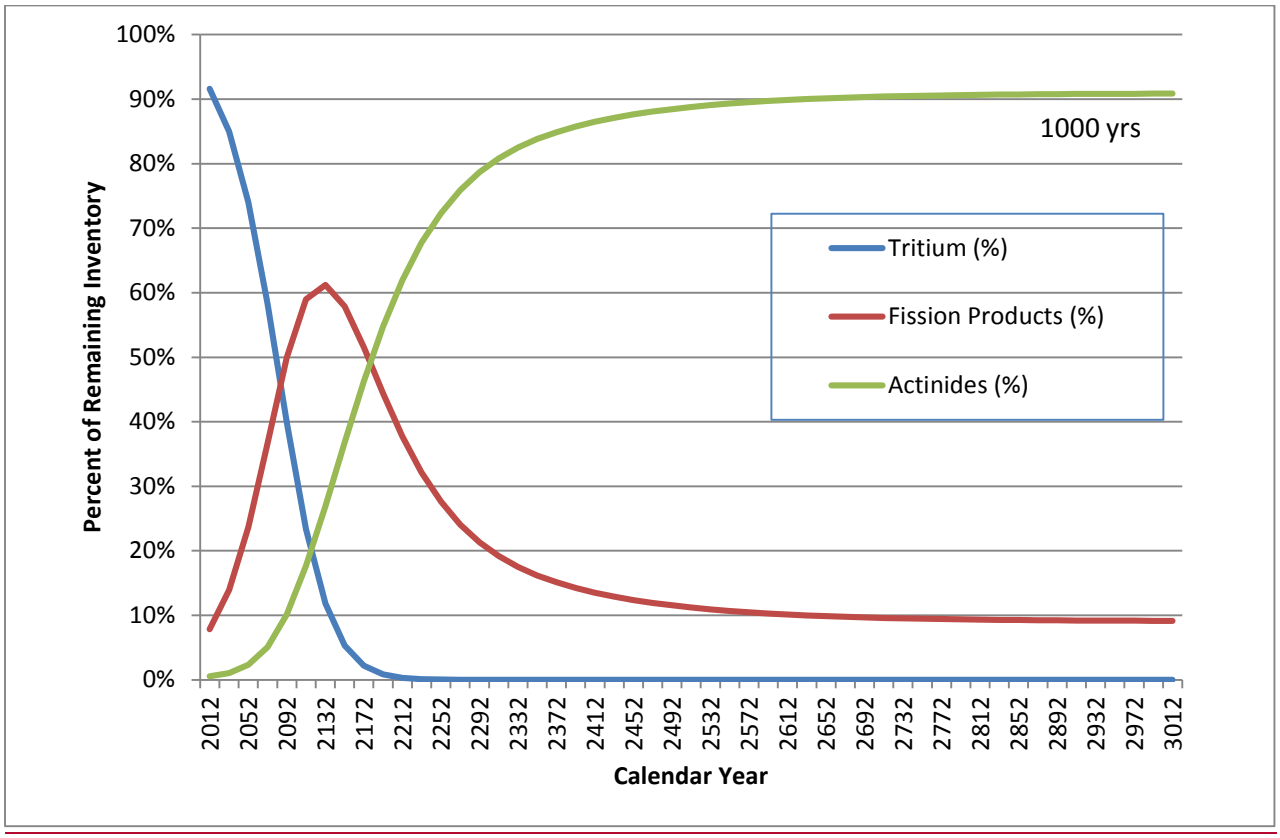


Figure 4d. The relative percentage of residual tritium, fission product, and actinide activities with time. Decayed over 1000 year time frame.

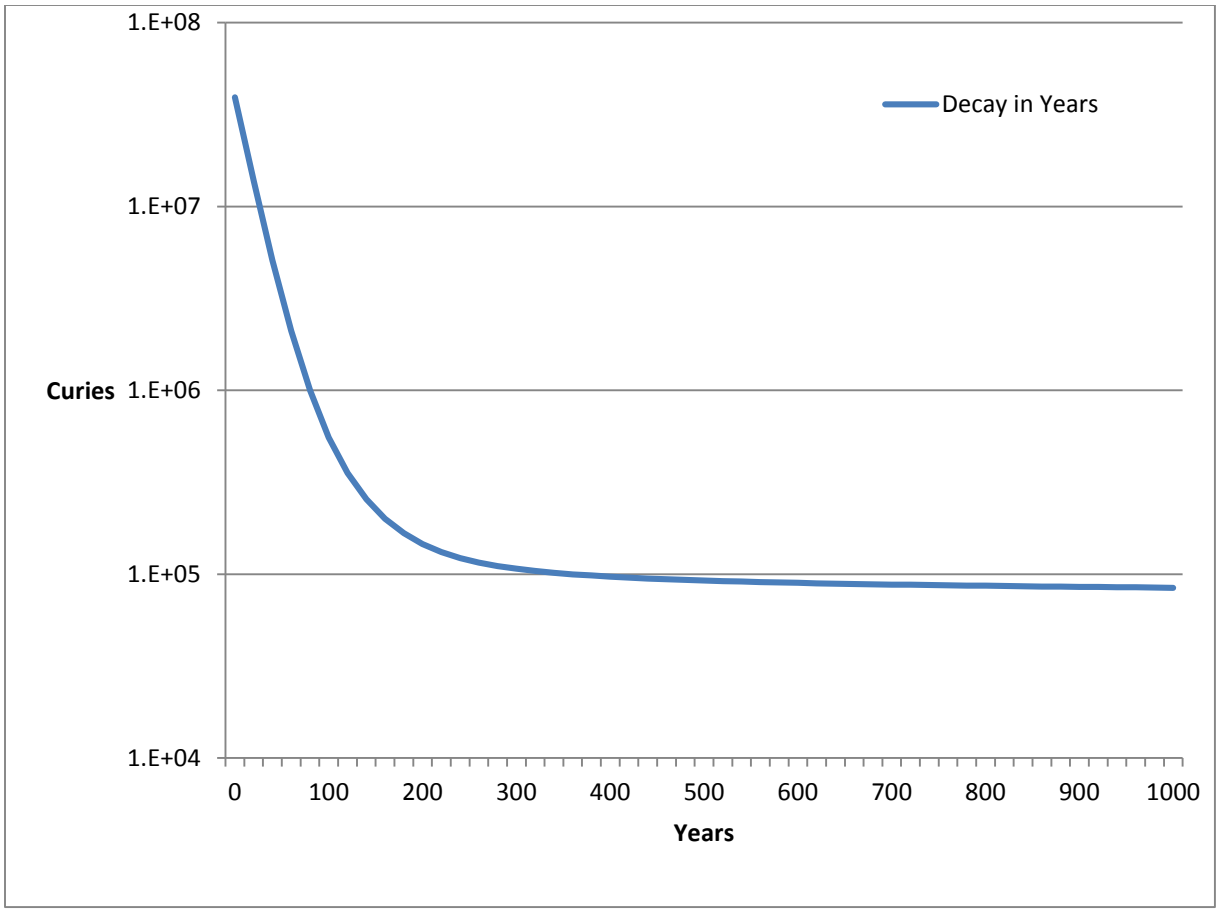


Figure 5: Total activity in curies decayed over 1000 years from September 30, 2012.

TABLE 5a: Percentage of Total Activity for H-3, Fission Products (FP) and Actinides (AC), with Decay in Years

Decay in Years	H-3 (%)	FP (%)	Ac (%)
9/30/2012 (T = 0)	**92%**	**8%**	**1%**
20	85%	14%	1%
40	74%	24%	2%
60	58%	37%	5%
80	40%	50%	10%
100	23%	59%	18%
120	12%	61%	27%
140	5%	58%	37%
160	2%	52%	46%
180	1%	44%	55%
200	0%	38%	62%
220	0%	32%	68%
240	0%	28%	72%
260	0%	24%	76%
280	0%	21%	79%
300	0%	19%	81%
320	0%	18%	82%
340	0%	16%	84%
360	0%	15%	85%
380	0%	14%	86%
400	0%	14%	86%
420	0%	13%	87%
440	0%	12%	88%
460	0%	12%	88%
480	0%	12%	88%
500	0%	11%	89%
600	0%	10%	90%
700	0%	10%	90%
800	0%	9%	91%
900	0%	9%	91%
1000	0%	9%	91%

TABLE 5b: Total Activity (in Curies) for H-3, Fission Products (FP) and Actinides (AC), with Decay in Years

Decay in Years	H-3 (Ci)	FP Sum (Ci)	Ac Sum (Ci)
9/30/2012 (T = 0)	4.07E+07	3.08E+06	2.08E+05
20	1.32E+07	1.92E+06	1.44E+05
40	4.29E+06	1.21E+06	1.18E+05
60	1.39E+06	7.73E+05	1.07E+05
80	4.52E+05	5.00E+05	1.01E+05
100	1.47E+05	3.27E+05	9.80E+04
120	4.76E+04	2.18E+05	9.58E+04
140	1.55E+04	1.48E+05	9.41E+04
160	5.02E+03	1.03E+05	9.27E+04
180	1.63E+03	7.44E+04	9.15E+04
200	5.28E+02	5.53E+04	9.04E+04
220	1.72E+02	4.26E+04	8.95E+04
240	5.57E+01	3.39E+04	8.86E+04
260	1.81E+01	2.79E+04	8.78E+04
280	5.87E+00	2.37E+04	8.71E+04
300	1.90E+00	2.06E+04	8.65E+04
320	6.18E-01	1.83E+04	8.59E+04
340	2.01E-01	1.65E+04	8.54E+04
360	6.51E-02	1.51E+04	8.49E+04
380	2.11E-02	1.40E+04	8.44E+04
400	6.86E-03	1.31E+04	8.39E+04
420	2.23E-03	1.24E+04	8.35E+04
440	7.22E-04	1.17E+04	8.32E+04
460	2.34E-04	1.12E+04	8.28E+04
480	7.61E-05	1.08E+04	8.24E+04
500	2.47E-05	1.04E+04	8.21E+04
600	< 1E-07	9.10E+03	8.21E+04
700	< 1E-09	8.44E+03	8.21E+04
800	< 1E-11	8.07E+03	8.21E+04
900	< 1E-14	7.86E+03	8.21E+04
1000	< 1E-16	7.72E+03	8.21E+04

To give a general idea of the amount of decay that has taken place at the NNSS, a theoretical shot from each decade from 1950 to 1990 was chosen and decay corrected to 2012. 1992 was selected for the 90's because it was the year of the last underground nuclear test at the NNSS, and then 10 years were subtracted from it and subsequent dates to produce the shot years found in Table 6. Although there were no underground tests at the NNSS in 1952 (there were atmospheric tests), the table still gives the relative idea of the amount of decay for each radionuclide for the 1950's. As can be seen in the table, the majority of the ^{3}H, ^{85}Kr, ^{93m}Nb, ^{113m}Cd, ^{152}Eu, ^{154}Eu, ^{241}Pu and ^{244}Cm activities for all tests has already decayed away by 2012. For radionuclides with half-lives greater than several hundred years, very little decay has taken place by 2012.

TABLE 6. Percentage of Radionuclide Activity Remaining on September 30, 2012 for "Theoretical" Underground Tests by Decade.

Radio-nuclide	Year Shot Performed				
	1992	1982	1972	1962	1952
Yrs of Decay	20	30	40	50	60
H-3	32%	18%	11%	6%	3%
C-14	100%	100%	100%	99%	99%
Cl-36	100%	100%	100%	100%	100%
Ar-39	95%	93%	90%	88%	86%
K-40	100%	100%	100%	100%	100%
Ca-41	100%	100%	100%	100%	100%
Ni-59	100%	100%	100%	100%	100%
Ni-63	87%	81%	76%	71%	66%
Kr-85	28%	14%	8%	4%	2%
Sr-90	62%	49%	38%	30%	24%
Zr-93	100%	100%	100%	100%	100%
Nb-93m	42%	27%	18%	12%	8%
Nb-94	100%	100%	100%	100%	100%
Tc-99	100%	100%	100%	100%	100%
Cd-113m	37%	23%	14%	9%	5%
Sn-121m	78%	68%	60%	53%	47%
Sn-126	100%	100%	100%	100%	100%
I-129	100%	100%	100%	100%	100%
Cs-135	100%	100%	100%	100%	100%
Cs-137	63%	50%	40%	32%	25%
Sm-151	86%	79%	73%	68%	63%

Eu-150	68%	56%	46%	38%	31%
Eu-152	36%	22%	13%	8%	5%
Eu-154	20%	9%	4%	2%	1%
Ho-166m	99%	98%	98%	97%	97%
Th-232	100%	100%	100%	100%	100%
U-232	82%	74%	67%	61%	55%
U-233	100%	100%	100%	100%	100%
U-234	100%	100%	100%	100%	100%
U-235	100%	100%	100%	100%	100%
U-236	100%	100%	100%	100%	100%
U-238	100%	100%	100%	100%	100%
Np-237	100%	100%	100%	100%	100%
Pu-238	85%	79%	73%	67%	62%
Pu-239	100%	100%	100%	100%	100%
Pu-240	100%	100%	100%	99%	99%
Pu-241	38%	24%	15%	9%	6%
Pu-242	100%	100%	100%	100%	100%
Am-241	97%	95%	94%	92%	91%
Am-243	100%	100%	100%	100%	99%
Cm-244	46%	32%	22%	15%	10%

EXPLANATION OF RADIONUCLIDE INVENTORY TABLES

Table 7 contains the summary of radionuclide totals in Curies as of September 30, 2012. Table 8 contains the summary of the radionuclide totals in atoms as of September 30, 2012. These tables have been updated from Bowen et al. (2001) to account for the decay of radionuclides since the last underground nuclear test was conducted in 1992. The number of significant figures in the table has been reduced to three (there were four in the original report) to better reflect the precision of the data. These data are grouped according to five principal geographic test centers of the NNSS (with two sub-divisions in Yucca Flat). Radionuclides are arranged within each table according to their atomic number and atomic mass.

The data in Tables 7 and 8 were calculated using the data in the classified database, and they take into account decay for all of the radionuclides in the inventory. The ingrowth of radionuclides from decay of parent nuclides has been included for the following decay paths:

$^{238}Pu \rightarrow {}^{234}U$

$^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np$

$^{244}Cm \rightarrow {}^{240}Pu$

Note: There was an error in the data calculations for ^{234}U in Tables 5 and 6 in Bowen *et al.*, 2001. An explanation of the error and the correction can be found in appendix C.

TABLE 7 Radionuclide Summary in Curies for the Five Principal Geographic Test Centers; Decay Corrected to September 30, 2012

Radio-nuclide	French-man Flat	Pahute Mesa Area 19	Pahute Mesa Area 20	Rainer Mesa Shoshone Mt	Yucca Flat - Above	Yucca Flat - Below	Total
H-3	5.65E+04	5.76E+06	1.91E+07	2.48E+05	4.77E+06	1.07E+07	**4.07E+07**
C-14	6.64E+01	2.19E+02	4.68E+02	1.10E+02	1.13E+03	8.37E+02	**2.83E+03**
Al-26	7.03E-03	8.97E-04	8.373-03	4.548E-04	5.573E-02	3.59E-02	**1.08E-01**
Cl-36	8.91E+00	9.11E+01	1.57E+02	1.13E+01	1.16E+02	2.31E+02	**6.16E+02**
Ar-39	5.86E+00	6.08E+02	1.18E+03	3.48E+01	3.04E+02	9.07E+02	**3.04E+03**
K-40	1.65E+00	1.59E+02	3.17E+02	9.23E+00	8.22E+01	2.42E+02	**8.11E+02**
Ca-41	6.54E+01	5.05E+02	1.27E+03	7.06E+01	8.54E+02	1.66E+03	**4.43E+03**
Ni-59	1.63E+00	1.60E+01	2.98E+01	2.02E+00	2.14E+01	4.26E+01	**1.13E+02**
Ni-63	1.46E+02	1.50E+03	2.72E+03	1.84E+02	2.03E+03	4.55E+03	**1.11E+04**
Kr-85	3.54E+01	1.37E+04	1.57E+04	3.70E+02	3.13E+03	1.60E+04	**4.89E+04**
Sr-90	1.16E+03	3.58E+05	4.22E+05	9.83E+03	9.26E+04	4.62E+05	**1.35E+06**
Zr-93	1.12E-01	1.89E+01	2.37E+01	7.99E-01	6.85E+00	2.61E+01	**7.64E+01**
Nb-93m	0.00E+00	1.25E+03	2.15E+03	1.13E+00	2.64E+02	2.84E+03	**6.51E+03**
Nb-94	6.96E-01	7.93E+01	9.85E+01	9.24E-01	2.29E+01	1.97E+02	**4.00E+02**
Tc-99	1.17E+00	1.34E+02	1.78E+02	7.82E+00	6.15E+01	1.87E+02	**5.71E+02**
Pd-107	1.95E-02	5.96E-01	1.00E+00	1.16E-01	7.63E-01	8.22E-01	**3.32E+00**
Cd-113m	1.12E+00	1.87E+02	2.79E+02	9.51E+00	5.85E+01	1.87E+02	**7.22E+02**
Sn-121m	1.28E+01	1.38E+03	2.07E+03	8.40E+01	5.24E+02	1.49E+03	**5.57E+03**
Sn-126	8.19E-02	8.08E+00	1.19E+01	5.20E-01	3.40E+00	9.16E+00	**3.31E+01**
I-129	4.54E-03	4.15E-01	5.60E-01	2.92E-02	2.08E-01	5.42E-01	**1.76E+00**
Cs-135	1.36E-01	1.39E+01	1.84E+01	8.97E-01	6.93E+00	1.97E+01	**6.00E+01**
Cs-137	3.18E+03	4.39E+05	5.65E+05	2.38E+04	1.84E+05	5.86E+05	**1.80E+06**
Sm-151	2.53E+02	1.98E+04	3.06E+04	1.66E+03	1.19E+04	2.73E+04	**9.15E+04**
Eu-150	6.71E-03	5.31E+01	7.27E+02	1.40E-03	9.21E+03	7.47E+01	**1.01E+04**
Eu-152	2.72E+02	4.13E+03	1.07E+04	6.11E+02	1.30E+04	2.54E+04	**5.41E+04**
Eu-154	5.21E+01	1.41E+03	2.64E+03	1.81E+02	5.90E+03	1.09E+04	**2.11E+04**
Ho-166m	2.00E+00	3.05E+01	2.86E+01	3.32E+00	2.63E+01	5.45E+01	**1.45E+02**
Th-232	1.20E-01	1.15E+01	2.32E+01	6.76E-01	5.97E+00	1.75E+01	**5.89E+01**
U-232	8.42E-03	7.16E+01	1.42E+02	7.53E-01	7.38E+01	3.02E+02	**5.91E+02**
U-233	1.33E-03	6.51E+01	1.18E+02	1.11E+01	1.20E+02	1.52E+02	**4.66E+02**
U-234	2.91E-01	7.70E+01	7.03E+01	5.65E+00	8.62E+01	1.50E+02	**3.89E+02**
U-235	8.57E-03	1.29E+00	1.34E+00	1.72E-01	2.56E+00	3.22E+00	**8.59E+00**
U-236	2.99E-03	2.21E+00	2.65E+00	1.48E-01	9.12E-01	3.46E+00	**9.38E+00**

U-238	9.51E-02	6.83E+00	1.25E+01	6.92E-01	8.67E+00	1.57E+01	**4.45E+01**
Np-237	3.21E-02	1.21E+01	2.50E+01	2.40E-01	2.56E+00	1.11E+01	**5.11E+01**
Pu-238	2.76E+02	2.44E+03	4.07E+03	2.27E+03	1.51E+04	9.52E+03	**3.37E+04**
Pu-239	1.41E+03	7.68E+03	1.26E+04	1.08E+04	9.99E+04	2.74E+04	**1.60E+05**
Pu-240	3.48E+02	2.04E+03	4.40E+03	2.76E+03	2.53E+04	7.03E+03	**4.18E+04**
Pu-241	1.68E+03	1.12E+04	2.65E+04	1.65E+04	1.30E+05	3.94E+04	**2.26E+05**
Pu-242	2.88E-02	1.37E+00	2.28E+00	3.96E-01	7.48E+00	4.62E+00	**1.62E+01**
Am-241	5.75E+02	1.85E+03	4.86E+03	3.35E+03	2.93E+04	7.98E+03	**4.79E+04**
Am-243	0.00E+00	1.20E-02	1.77E-01	7.89E-01	2.68E+00	3.41E+00	**7.06E+00**
Cm-244	0.00E+00	5.53E+02	1.02E+03	2.30E+01	7.37E+02	1.16E+03	**3.50E+03**
Total	**6.60E+04**	**6.63E+06**	**2.02E+07**	**3.20E+05**	**5.39E+06**	**1.20E+07**	**4.46E+07**

TABLE 8 Radionuclide Summary in Atoms for the Five Principal Geographic Test Centers; Decay Corrected to September 30, 2012

Radio-nuclide	French-man Flat	Pahute Mesa 19	Pahute Mesa 20	Rainer Mesa/ Shoshone Mt	Yucca Flat Above	Yucca Flat Below	Total
H-3	1.17E+24	1.20E+26	3.97E+26	5.14E+24	9.90E+25	2.23E+26	**8.45E+26**
C-14	6.39E+23	2.11E+24	4.51E+24	1.06E+24	1.09E+25	8.06E+24	**2.73E+25**
Cl-36	4.52E+24	4.62E+25	7.97E+25	5.73E+24	5.90E+25	1.17E+26	**3.12E+26**
Ar-39	2.65E+21	2.75E+23	5.37E+23	1.58E+22	1.38E+23	4.11E+23	**1.38E+24**
K-40	3.53E+27	3.40E+29	6.78E+29	1.97E+28	1.76E+29	5.18E+29	**1.74E+30**
Ca-41	1.13E+25	8.76E+25	2.21E+26	1.22E+25	1.48E+26	2.88E+26	**7.68E+26**
Ni-59	2.09E+23	2.04E+24	3.81E+24	2.59E+23	2.74E+24	5.46E+24	**1.45E+25**
Ni-63	2.46E+22	2.53E+23	4.58E+23	3.11E+22	3.42E+23	7.67E+23	**1.88E+24**
Kr-85	6.41E+20	2.49E+23	2.85E+23	6.71E+21	5.67E+22	2.90E+23	**8.87E+23**
Sr-90	5.62E+22	1.74E+25	2.05E+25	4.76E+23	4.49E+24	2.24E+25	**6.52E+25**
Zr-93	2.82E+23	4.77E+25	5.99E+25	2.02E+24	1.73E+25	6.59E+25	**1.93E+26**
Nb-93m	0.00E+00	3.40E+22	5.84E+22	3.06E+19	7.15E+21	7.71E+22	**1.77E+23**
Nb-94	2.35E+22	2.67E+24	3.32E+24	3.11E+22	7.73E+23	6.65E+24	**1.35E+25**
Tc-99	4.19E+23	4.82E+25	6.39E+25	2.80E+24	2.21E+25	6.73E+25	**2.05E+26**
Cd-113m	2.65E+19	4.45E+21	6.63E+21	2.26E+20	1.39E+21	4.43E+21	**1.72E+22**
Sn-121m	1.18E+21	1.28E+23	1.92E+23	7.78E+21	4.85E+22	1.38E+23	**5.16E+23**
Sn-126	3.45E+22	3.40E+24	5.00E+24	2.19E+23	1.43E+24	3.86E+24	**1.40E+25**
I-129	1.20E+23	1.10E+25	1.48E+25	7.72E+23	5.50E+24	1.43E+25	**4.65E+25**
Cs-135	5.28E+23	5.40E+25	7.12E+25	3.47E+24	2.68E+25	7.63E+25	**2.32E+26**
Cs-137	1.61E+23	2.23E+25	2.86E+25	1.20E+24	9.32E+24	2.97E+25	**9.12E+25**
Sm-151	3.83E+22	3.00E+24	4.64E+24	2.52E+23	1.80E+24	4.14E+24	**1.39E+25**
Eu-150	4.07E+17	3.22E+21	4.41E+22	8.48E+16	5.58E+23	4.53E+21	**6.10E+23**
Eu-152	6.19E+21	9.42E+22	2.43E+23	1.39E+22	2.97E+23	5.79E+23	**1.23E+24**
Eu-154	7.55E+20	2.04E+22	3.82E+22	2.62E+21	8.55E+22	1.58E+23	**3.05E+23**
Ho-166m	4.04E+21	6.16E+22	5.78E+22	6.70E+21	5.33E+22	1.10E+23	**2.94E+23**
Th-232	2.82E+27	2.71E+29	5.47E+29	1.59E+28	1.41E+29	4.13E+29	**1.39E+30**
U-232	9.90E+17	8.41E+21	1.68E+22	8.85E+19	8.68E+21	3.56E+22	**6.95E+22**
U-233	3.58E+20	1.74E+25	3.15E+25	2.97E+24	3.22E+25	4.09E+25	**1.25E+26**
U-234	1.21E+23	3.19E+25	2.92E+25	2.34E+24	3.57E+25	6.22E+25	**1.61E+26**
U-235	1.02E+25	1.53E+27	1.59E+27	2.04E+26	3.03E+27	3.82E+27	**1.02E+28**
U-236	1.18E+23	8.73E+25	1.04E+26	5.85E+24	3.60E+25	1.36E+26	**3.70E+26**
U-238	7.16E+26	5.14E+28	9.41E+28	5.21E+27	6.53E+28	1.18E+29	**3.35E+29**
Np-237	1.16E+23	4.35E+25	9.03E+25	8.65E+23	9.23E+24	4.02E+25	**1.84E+26**
Pu-238	4.08E+22	3.60E+23	6.01E+23	3.35E+23	2.24E+24	1.41E+24	**4.98E+24**

Pu-239	5.74E+25	3.12E+26	5.12E+26	4.40E+26	4.06E+27	1.11E+27	**6.49E+27**
Pu-240	3.85E+24	2.25E+25	4.86E+25	3.05E+25	2.79E+26	7.77E+25	**4.62E+26**
Pu-241	4.08E+22	2.73E+23	6.43E+23	3.99E+23	3.16E+24	9.57E+23	**5.47E+24**
Pu-242	1.82E+22	8.64E+23	1.44E+24	2.50E+23	4.73E+24	2.92E+24	**1.02E+25**
Am-241	4.19E+23	1.35E+24	3.54E+24	2.44E+24	2.13E+25	5.82E+24	**3.49E+25**
Am-243	0.00E+00	1.49E+20	2.20E+21	9.79E+21	3.32E+22	4.23E+22	**8.77E+22**
Cm-244	0.00E+00	1.69E+22	3.11E+22	7.03E+20	2.25E+22	3.55E+22	**1.07E+23**
Total	**7.16E+27**	**6.64E+29**	**1.32E+30**	**4.16E+28**	**3.90E+29**	**1.06E+30**	**3.48E+30**

DISCUSSION

The total underground radionuclide inventory for the NNSS provides a reasonable estimate of residual radioactive products present after nearly four decades of nuclear testing and two additional decades following the last nuclear test. The radionuclide inventory is unique for three reasons. First, this compilation provides a quantified radiological source term specifically derived from individual test data. Second, the radionuclide inventory includes longer-lived radionuclides, which were less important for test diagnostics but may be important to the contaminant boundary calculations. Third, the inventory incorporates a significant portion of radionuclides introduced from natural sources in addition to those expected from anthropogenic sources.

As mentioned earlier, these radionuclide totals represent an upper limit of radionuclides potentially available for transport. The radiological source term will never be transported in its entirety due to its relative insolubility; the hydrologic source term comprises those species that are dissolved in or transportable by groundwater. The mobility of radionuclides is moderated both by chemical kinetics and hydrology. Numerous experimental and field studies accompanying the nuclear test program (see Borg *et al.*, 1976, Nimz and Thompson, 1992, and Smith, 1998) indicate, in general, long-lived radionuclides (actinides, fission products) are relatively insoluble in the local groundwater. Furthermore, these are attenuated during transport by ion-exchange and surface reactions with sorptive minerals—particularly zeolites—characteristic of the NNSS volcanic stratigraphy. With the exception of tritium, which is efficiently dispersed in groundwater as molecular HTO, the hydrologic source term will always be less than or equal to the radiological source term. Finally, the hydrology of the NNSS consists of a complex and variably transmissive stratigraphy of regional Paleozoic carbonate (transmissivities up to 10^5 gallons/day/foot) and overlying Tertiary volcanic (transmissivities of up to 10^4 gallons/day/foot) aquifers divided by prevailing flow directions and by discharge areas into three groundwater subbasins. While a comprehensive description of radionuclide migration and NNSS hydrology is outside the scope of this report, radionuclide transport likely will not occur uniformly away from the testing centers at the NNSS. Different geologic and hydrologic properties will greatly affect potential radionuclide transport.

The source term was summed over 828 underground nuclear tests to provide radionuclide totals for five principal geographic test centers. By summing radionuclide totals for individual tests into regional areas, radionuclide production from an individual test is integrated into the sum for that region. Because the radiological source term is device dependent, local contributions will be disproportionately skewed toward the regional average.

The radionuclide inventory is dominated by residual radioactivity introduced by nuclear testing, but also includes a significant proportion of natural radioactivity. Volcanic tuffs and rhyolites erupted from volcanic centers over the past 15 million years are highly evolved rocks that contain oxides of uranium, thorium, and potassium—all of which are naturally radioactive. Past studies (Olsen, 1967) on core samples from underground nuclear tests indicate that approximately 700 metric tons of geologic media are melted per kiloton of nuclear explosive yield. This value was confirmed by examining the radiochemical diagnostic data for the most

device-debris-rich core sample from each of 18 LLNL tests between 1970 and 1988. Therefore, natural ^{40}K, natural ^{232}Th, and natural uranium activities are mixed into the melt created by all the tests in each of the five principal geographic test centers. The average potassium, thorium, and uranium concentrations of NNSS working point media are 4%, 22 ppm, and 3.7 ppm by weight, respectively. Using these values, we calculate that 0.0229 Ci of naturally occurring ^{40}K, 0.00169 Ci of naturally occurring ^{232}Th, and 0.00177 Ci of naturally occurring uranium are incorporated into the melt per kiloton of yield. We include this contribution in our totals for each of the five principal geographic test centers defined for the inventory. Background radioactivity from naturally occurring radionuclides constitutes an effective lower limit for monitoring or remedial levels proposed for the NNSS.

NOTES ON CALCULATIONS

We give below several basic equations useful in relating activities and numbers of radioactive atoms at specified times. It should be noted that activities (A) and decay constants (λ) must be in the same time units in these equations. In Tables 5b and 7 activities are given in curies (disintegrations/second) and half-lives in years, so time conversions are required. We assumed 1 year = 365.24 days = 3.156E+7 seconds.

- Activity $\Leftrightarrow$ atoms

$A = \lambda N$

A = activity in disintegrations/unit time

λ = ln(2)/half-life

N = number of atoms

- Activity or atoms at various times

$A(t) = A(0)e^{-\lambda t}$

$N(t) = N(0)e^{-\lambda t}$

A(0), N(0) are at reference time

A(t), N(t) are at time-of-interest

λ = ln(2)/half-life

t = difference between reference time and time-of-interest

FUTURE WORK

It should be recognized that the database represented by this work is an evolving entity, subject to improvements and corrections as more sophisticated interpretations evolve and additional information is gleaned from the historic record. We expect, with continued support, that the values of the underground nuclide inventory will improve, but large-scale changes in the sums are not expected.

LANL expects to actively maintain the database, commensurate with the resources available. Improvements to the database structure and implementation are envisioned to facilitate greater utility and quality assurance.

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Appendix A: Abstract and selected tables and figures from the original report of Bowen et al., 2001

This appendix contains the abstract, Tables 1, 5 and 6, and Figures 4 and 5 from the original report "Nevada Test Site Radionuclide Inventory, 1951-1992," Los Alamos National Laboratory manuscript LA-13859-MS (Bowen et al., 2001). These tables and figures are included to allow the reader to easily check the changes in the updated report.

Nevada Test Site Radionuclide Inventory, 1951-1992

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ABSTRACT

An inventory of radionuclides produced by 828 underground nuclear tests conducted at the Nevada Test Site by the Lawrence Livermore National Laboratory and the Los Alamos National Laboratory from 1951 to 1992 includes tritium, fission products, actinides, and activation products. This inventory provides an estimate of radioactivity remaining underground at the Nevada Test Site after nuclear testing. For the purposes of summary and publication, Los Alamos National Laboratory and Lawrence Livermore National Laboratory subdivided the inventory into five areas corresponding to the principal geographic test centers at the Nevada Test Site. The five areas roughly correspond to Underground Test Area "Corrective Action Units" for remediation of groundwaters. In addition, the inventory is further subdivided for the Yucca Flat region by tests where the working point depth is more than 328 feet (100 meters) above the water table and tests that were detonated below that level. Curie activities and atoms are reported as of September 23, 1992, the date of the last underground nuclear test at the Nevada Test Site. This inventory does not represent the total radioactivity dissolved in the groundwater beneath the Nevada Test Site, but is strictly a compilation of the residual radionuclide inventory remaining from those underground nuclear tests conducted by Lawrence Livermore National Laboratory and Los Alamos National Laboratory from 1951 to 1992. The written report is a companion to a personal computer-based database resident in the Analytical and Nuclear Chemistry Division of the Lawrence Livermore National Laboratory and the Chemistry Division of the Los Alamos National Laboratory. This computer database tabulates radionuclide totals, cavity radius, working point lithology, static water level, hole name, and firing data for each test. A companion classified report contains test-specific data from this computer database. This work has been sponsored by the Environmental Restoration Division at the U. S. Department of Energy, National Nuclear Security Administration Nevada Operations Office.

TABLE I

Candidate Radionuclides for Inclusion into Source-Term Inventory
(Maximum Permissible Concentration (MPC) values from Federal Register, 1991)

Element	Nuclide	Half-life (y)*	MPC (μCi/mL)	Main Source(s) (FP=fission product)
Hydrogen	^{3}H	12.32	6.1×10^{-5}	device component; ^{6}Li (n,α) T
Carbon	^{14}C	5715	3.2×10^{-6}	^{14}N (n,p); ^{13}C (n,γ); ^{17}O (n,α)
Aluminum	$^{26}A1$	7.1×10^{5}	----	$^{27}A1$ (n,2n)
Chlorine	$^{36}C1$	3.01×10^{5}	1.8×10^{-6}	$^{35}C1$ (n,γ); ^{39}K (n,α)
Argon	^{39}Ar	269	----	^{39}K (n,p); ^{38}Ar(n,γ)
Potassium	^{40}K	1.27×10^{9}	----	natural
Calcium	^{41}Ca	1.03×10^{5}	----	^{40}Ca (n,γ)
Nickel	^{59}Ni	7.6×10^{4}	2.7×10^{-5}	^{58}Ni (n,γ)
	^{63}Ni	100	9.9×10^{-6}	^{62}Ni (n,γ), ^{64}Ni (n,2n), ^{63}Cu (n,p)
Krypton	^{85}Kr	10.76	----	FP; ^{84}Kr (n,γ)
Strontium	^{90}Sr	28.78	4.2×10^{-8}	FP
Zirconium	^{93}Zr	1.5×10^{6}	5.1×10^{-6}	FP; ^{92}Zr (n,γ); ^{94}Zr (n,2n)
Niobium	^{93m}Nb	16.1	1.0×10^{-5}	^{93}Nb (n,n′)
	^{94}Nb	2.0×10^{4}	7.1×10^{-7}	FP; ^{93}Nb(n,γ)
Technetium	^{99}Tc	2.13×10^{5}	3.8×10^{-6}	FP; ^{99}Ru (n,p)
Palladium	^{107}Pd	6.5×10^{6}	3.7×10^{-5}	FP; ^{106}Pd (n,γ)
Cadmium	^{113m}Cd	14.1	----	FP
Tin	^{121m}Sn	~55	2.3×10^{-6}	FP; ^{120}Sn (n,γ)
	^{126}Sn	2.5×10^{5}	2.9×10^{-7}	FP
Iodine	^{129}I	1.57×10^{7}	2.1×10^{-8}	FP; ^{129}Xe (n,p)
Cesium	^{135}Cs	2.3×10^{6}	7.9×10^{-7}	FP
	^{137}Cs	30.07	1.2×10^{-7}	FP; ^{137}Ba (n,p)
Samarium	^{151}Sm	90	1.4×10^{-5}	FP; ^{150}Sm (n,γ)
Europium	^{150}Eu	36	----	^{151}Eu (n,2n)
	^{152}Eu	13.54	8.4×10^{-7}	^{151}Eu (n,γ); ^{153}Eu (n,2n)
	^{154}Eu	8.593	6.7×10^{-7}	^{153}Eu (n,γ)
Holmium	^{166}Ho	1.2×10^{3}	----	FP; ^{165}Ho (n,γ)
Thorium	^{232}Th	1.40×10^{10}	9.2×10^{-8}	natural and device component
Uranium	^{232}U	69.8	1.0×10^{-8}	device component; ^{233}U (n,2n)
	^{233}U	1.592×10^{5}	2.6×10^{-8}	device component; radiochemical tracer
	^{234}U	2.46×10^{5}	2.6×10^{-8}	natural and device component
	^{235}U	7.04×10^{8}	2.6×10^{-8}	natural and device component
	^{236}U	2.342×10^{7}	2.7×10^{-8}	device component; ^{235}U (n,γ); ^{238}U (n,2n)[2]
	^{238}U	4.47×10^{9}	2.6×10^{-8}	natural and device component

Element	Nuclide	Half-life (y)*	MPC (μCi/mL)	Main Source(s) (FP=fission product)
Neptunium	^{237}Np	2.14 x 10^{6}	7.2 x 10^{-9}	radiochemical tracer; decay of ^{237}U
Plutonium	^{238}Pu	87.7	7.2 x 10^{-9}	device component; radiochemical tracer; ^{239}Pu (n,2n); ^{237}Np (n,γ)
	^{239}Pu	2.410 x 10^{4}	6.5 x 10^{-8}	device component; decay of ^{239}U
	^{240}Pu	6.56 x 10^{3}	6.5 x 10^{-8}	device component; ^{239}Pu (n,γ); decay of ^{240}U
	^{241}Pu	14.4	----	device component; ^{240}Pu (n,γ); decay of ^{241}U
	^{242}Pu	3.75 x 10^{5}	6.8 x 10^{-8}	device component; radiochemical tracer; ^{241}Pu (n,γ); decay of ^{242}U
Americium	^{241}Am	432.7	6.4 x 10^{-9}	device component; radiochemical tracer; decay of ^{241}Pu
	^{243}Am	7.37 x 10^{3}	6.5 x 10^{-9}	device component; radiochemical tracer
Curium	^{244}Cm	18.1	1.0 x 10^{-8}	radiochemical tracer

* Half-lives obtained from GE Chart of the Nuclides, Fifteenth Edition (1996).

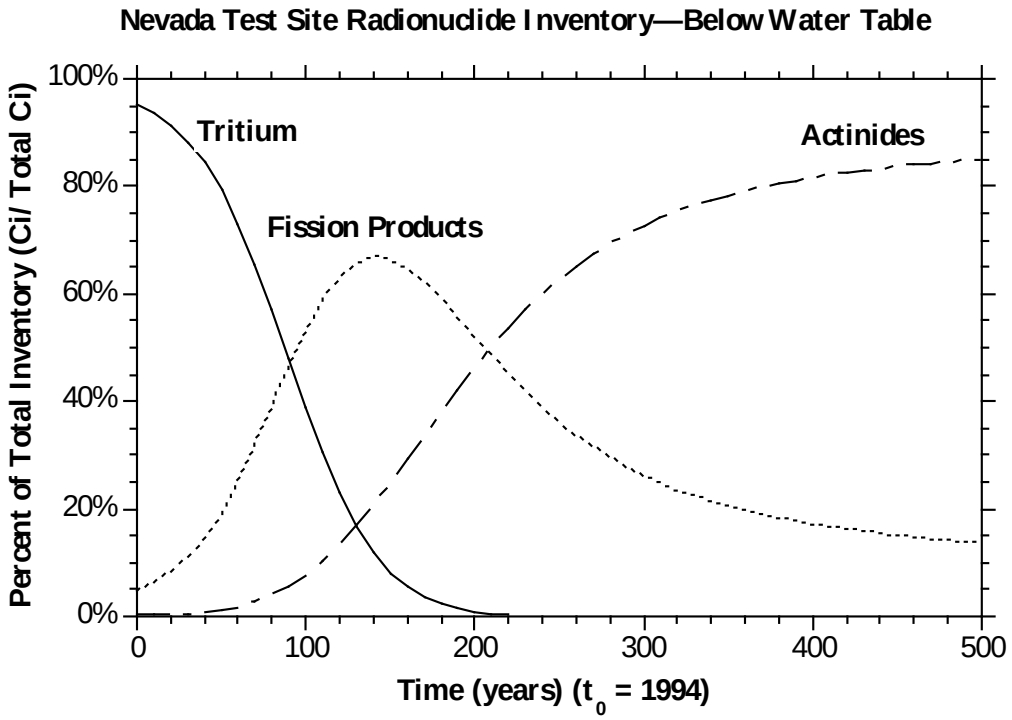

Figure 4: Relative percentage of residual tritium, fission product, and actinide activities below water table remaining with time.

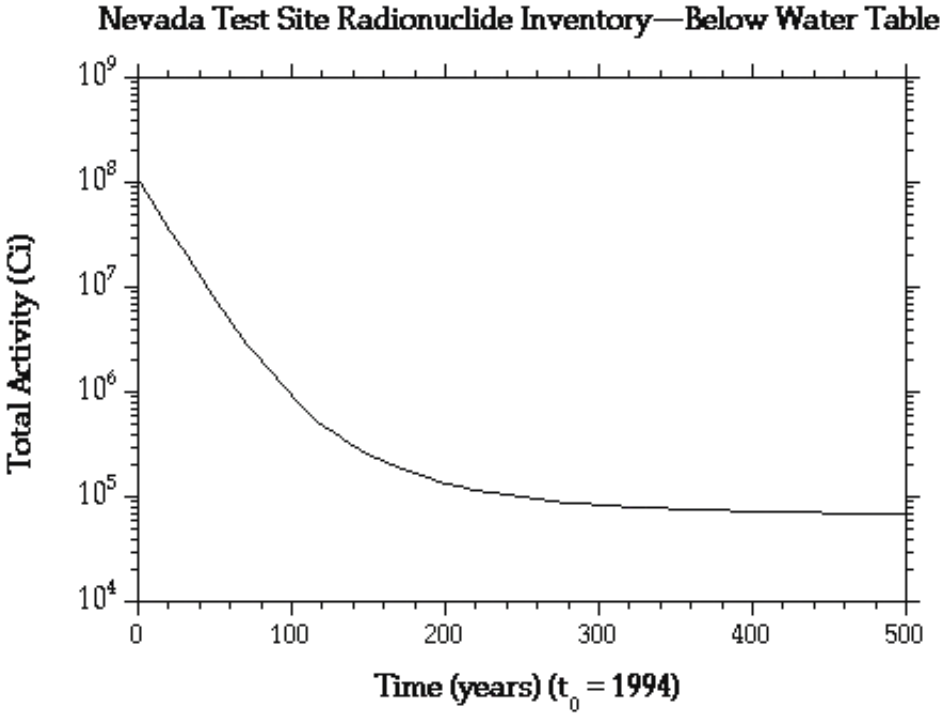

Figure 5: Total activity in curies below water table decayed over 500 years.

TABLE V

Radionuclide Summary in **Curies** Decay Corrected to September 23, 1992
for the Six Principal Geographic Test Centers

Radio-nuclide	Frenchman Flat	Pahute Mesa-19	Pahute Mesa-20	Rainer Mesa Shoshone Mt	Yucca Flat - Above	Yucca Flat - Below	**Total**
H-3	1.744E+05	1.778E+07	5.903E+07	7.645E+05	1.472E+07	3.316E+07	**1.256E+08**
C-14	6.653E+01	2.193E+02	4.693E+02	1.102E+02	1.137E+03	8.389E+02	**2.841E+03**
Al-26	7.035E-03	8.975E-04	8.370E-03	4.548E-04	5.573E-02	3.595E-02	**1.084E-01**
Cl-36	8.907E+00	9.108E+01	1.573E+02	1.130E+01	1.163E+02	2.309E+02	**6.158E+02**
Ar-39	6.166E+00	6.398E+02	1.247E+03	3.663E+01	3.204E+02	9.551E+02	**3.205E+03**
K-40	1.649E+00	1.588E+02	3.171E+02	9.233E+00	8.219E+01	2.422E+02	**8.112E+02**
Ca-41	6.542E+01	5.050E+02	1.273E+03	7.063E+01	8.545E+02	1.661E+03	**4.429E+03**
Ni-59	1.634E+00	1.596E+01	2.976E+01	2.021E+00	2.139E+01	4.265E+01	**1.134E+02**
Ni-63	1.679E+02	1.724E+03	3.126E+03	2.118E+02	2.334E+03	5.229E+03	**1.279E+04**
Kr-85	1.285E+02	4.981E+04	5.706E+04	1.344E+03	1.137E+04	5.805E+04	**1.778E+05**
Sr-90	1.879E+03	5.804E+05	6.835E+05	1.592E+04	1.499E+05	7.479E+05	**2.179E+06**
Zr-93	1.118E-01	1.887E+01	2.372E+01	7.990E-01	6.852E+00	2.607E+01	**7.641E+01**
Nb-93m	0.000E+00	2.969E+03	5. I00E+03	2.667E+00	6.246E+02	6.730E+03	**1.543E+04**
Nb-94	6.968E-01	7.938E+01	9.852E+01	9.248E-01	2.296E+01	1.975E+02	**3.999E+02**
Tc-99	1.167E+00	1.344E+02	1.782E+02	7.817E+00	6.153E+01	1.875E+02	**5.706E+02**
Pd-107	1.949E-02	5.957E-01	1.002E+00	1.164E-01	7.634E-01	9.226E-01	**3.420E+00**
Cd-113m	2.991E+00	5.017E+02	7.469E+02	2.545E+01	1.566E+02	4.994E+02	**1.933E+03**
Sn-121m	1.646E+01	1.782E+03	2.667E+03	1.081E+02	6.738E+02	1.918E+03	**7.165E+03**
Sn-126	8.193E-02	8.085E+00	1.188E+01	5.200E-01	3.402E+00	9.161E+00	**3.313E+01**
I-129	4.542E-03	4.153E-01	5.596E-01	2.920E-02	2.079E-01	5.422E-01	**1.759E+00**
Cs-135	1.362E-01	1.393E+01	1.838E+01	8.966E-01	6.926E+00	1.970E+01	**5.997E+01**
Cs-137	5.045E+03	6.971E+05	8.957E+05	3.773E+04	2.919E+05	9.299E+05	**2.857E+06**
Sm-151	2.949E+02	2.307E+04	3.568E+04	1.939E-i-03	1.388E+04	3.189E+04	**1.068E+05**
Eu-150	9.859E-03	7.805E+01	1.069E+03	2.057E-03	1.354E+04	1.099E+02	**1.479E+04**
Eu-152	7.569E+02	l.151E+04	2.970E+04	1.703E+03	3.634E+04	7.083E+04	**1.508E+05**
Eu-154	2.622E+02	7.099E+03	1.327E+04	9.090E+02	2.968E+04	5.480E+04	**1.060E+05**
Ho-166m	2.024E+00	3.083E+01	2.892E+01	3.354E+00	2.665E+01	5.514E+01	**1.469E+02**
Th-232	1.196E-01	1.147E+0l	2.319E+01	6.757E-01	5.969E+00	1.752E+01	**5.895E+01**
U-232	l.027E-02	8.730E+01	1.738E+02	9.188E-01	9.004E+01	3.690E+02	**7.211E+02**
U-233	1.334E-03	6.508E+01	1.176E+02	1.107E+01	1.202E+02	1.525E+02	**4.664E+02**
U-234	4.316E-01	1.421E+02	1. 179E+02	1 .037E+01	1 .648E+02	2.8 14E+02	**7. 169E+02**
U-235	8.570E-03	1.293E+00	l.343E+00	1.717E-01	2.557E+00	3.220E+00	**8.593E+00**
U-236	2.995E-03	2.213E+00	2.647E+00	1.483E-01	9.123E-01	3.458E+00	**9.381E+00**
U-238	9.507E-02	6.826E+00	1.250E+01	6.919E-0l	8.674E+00	1.570E+01	**4.449E+01**
Np-237	1.379E-02	1.196E+0l	2.476E+01	6.027E-02	1.140E+00	1.072E+01	**4.865E+01**
Pu-238	3.232E+02	2.857E+03	4.768E+03	2.659E+03	1.774E+04	1.115E+04	**3.950E+04**
Pu-239	1.415E+03	7.684E+03	1.262E+04	1.085E+04	9.997E+04	2.746E+04	**1.600E+05**
Pu-240	3.489E+02	2.041E+03	4.405E+03	2.763E+03	2.532E+04	7.045E+03	**4.193E+04**
Pu-241	4.408E+03	2.946E+04	6.952E+04	4.315E+04	3.415E+05	1.034E+05	**5.914E+05**
Pu-242	2.882E-02	1.367E+00	2.279E+00	3.962E-01	7.485E+00	4.621E+00	**1.618E+01**
Am-241	5.022E+02	1.299E+03	3.567E+03	2.555E+03	2.309E+04	6.088E+03	**3.710E+04**
Am-243	0.000E+00	1.203E-02	1.772E-01	7.900E-01	2.682E+00	3.416E+00	**7.078E+00**
Cm-244	0.000E+00	1.190E+03	2.197E+03	4.961E+01	1.586E+03	2.506E+03	**7.529E+03**
Total	**1.901E+05**	**1.920E+07**	**6.086E+07**	**8.867E+05**	**1.578E+07**	**3.523E+07**	**1.321E+08**

TABLE VI

Radionuclide Summary in **Atoms** Decay Corrected to September 23, 1992
for the Six Principal Geographic Test Centers

Radio-nuclide	Frenchman Flat	Pahute Mesa-19	Pahute Mesa-20	Rainer Mesa Shoshone Mt	Yucca Flat - Above	Yucca Flat - Below	**Total**
H-3	3.620E+24	3.689E+26	1.225E+27	1.586E+25	3.055E+26	6.881E+26	**2.607E+27**
C-14	6.405E+23	2.111E+24	4.518E+24	1.061E+24	1.094E+25	8.076E+24	**2.735E+25**
Al-26	8.413E+21	1.073E+21	1.001E+22	5.439E+20	6.665E+22	4.300E+22	**1.297E+23**
Cl-36	4.516E+24	4.618E+25	7.973E+25	5.730E+24	5.899E+25	1.171E+26	**3.122E+26**
Ar-39	2.794E+21	2.899E+23	5.652E+23	1.660E+22	1.452E+23	4.328E+23	**1.452E+24**
K-40	3.527E+27	3.398E+29	6.783E+29	1.975E+28	1.758E+29	5.181E+29	**1.735E+30**
Ca-41	1. 135E+25	8.763E+25	2.208E+26	1.225E+25	1.483E+26	2.882E+26	**7.685E+26**
Ni-59	2.092E+23	2.043E+24	3.810E+24	2.587E+23	2.738E+24	5.460E+24	**1.452E+25**
Ni-63	2.828E+22	2.904E+23	5.266E+23	3.568E+22	3.932E+23	8.808E+23	**2.155E+24**
Kr-85	2.329E+21	9.028E+23	1.034E+24	2.437E+22	2.060E+23	1.052E+24	**3.222E+24**
Sr-90	9. 109E+22	2.8 14E+25	3.3 14E+25	7.7 17E+23	7.265E+24	3.626E+25	**1 .057E+26**
Zr-93	2.825E+23	4.767E+25	5.993E+25	2.019E+24	1.731E+25	6.587E+25	**1.931E+26**
Nb-93m	0.000E+00	8.053E+22	1.383E+23	7.234E+19	1.694E+22	1.825E+23	**4.184E+23**
Nb-94	2.347E+22	2.674E+24	3.3 19E+24	3.1 16E+22	7.734E+23	6.652E+24	**1.347E+25**
Tc-99	4.189E+23	4.821E+25	6.394E+25	2.805E+24	2.208E+25	6.727E+25	**2.047E+26**
Pd-107	2.135E+23	6.523E+24	1.097E+25	1.274E+24	8.359E+24	1.010E+25	**3.744E+25**
Cd-113m	7.104E+19	1.192E+22	1.774E+22	6.044E+20	3.719E+21	1.186E+22	**4.591E+22**
Sn-121m	1.525E+21	1.651E+23	2.470E+23	1.001E+22	6.243E+22	1.777E+23	**6.638E+23**
Sn-126	3.450E+22	3.405E+24	5.002E+24	2.190E+23	1.433E+24	3.858E+24	**1.395E+25**
I-129	1.201E+23	1.098E+25	1.480E+25	7.723E+23	5.498E+24	1.434E+25	**4.65 IE+25**
Cs-135	5.277E+23	5.397E+25	7.120E+25	3.474E+24	2.683E+25	7.633E+25	**2.323E+26**
Cs-137	2.555E+23	3.53 1E+25	4.537E+25	1.91 1E+24	1.478E+25	4.7 10E+25	**1.447E+26**
Sm-151	4.471E+22	3.498E+24	5.409E+24	2.940E+23	2.105E+24	4.835E+24	**1.619E+25**
Eu-150	5.979E+17	4.733E+21	6.483E+22	1.247E+17	8.209E+23	6.664E+21	**8.972E+23**
Eu-152	1.726E+22	2.626E+23	6.774E+23	3.885E+22	8.288E+23	1.615E+24	**3.440E+24**
Eu-154	3.796E+21	1.028E+23	1.921E+23	1.316E+22	4.297E+23	7.932E+23	**1.535E+24**
Ho-166m	4.092E+21	6.231E+22	5.846E+22	6.781E+21	5.387E+22	1.1 15E+23	**2.970E+23**
Th-232	2.821E+27	2.706E+29	5.468E+29	1.594E+28	1.408E+29	4.133E+29	**1.390E+30**
U-232	1.208E+18	1.026E+22	2.044E+22	1.080E+20	1.059E+22	4.338E+22	**8.478E+22**
U-233	3.578E+20	1.745E+25	3.154E+25	2.969E+24	3.223E+25	4.090E+25	**1.251E+26**
U-234	1.788E+23	5.888E+25	4.885E+25	4.298E+24	6.828E+25	1.166E+26	**2.971E+26**
U-235	1.016E+25	1.533E+27	1.592E+27	2.036E+26	3.032E+27	3.819E+27	**1.019E+28**
U-236	1.181E+23	8.730E+25	1.044E+26	5.851E+24	3.599E+25	1.364E+26	**3.701E+26**
U-238	7.159E+26	5.140E+28	9.41 1E+28	5.210E+27	6.531E+28	1.182E+29	**3.350E+29**
Np-237	4.969E+22	4.310E+25	8.923E+25	2.172E+23	4.108E+24	3.863E+25	**1.753E+26**
Pu-238	4.775E+22	4.220E+23	7.043E+23	3.929E+23	2.621E+24	1.647E+24	**5.835E+24**
Pu-239	5.744E+25	3.1 19E+26	5. 123E+26	4.406E+26	4.058E+27	1.1 15E+27	**6.495E+27**
Pu-240	3.855E+24	2.256E+25	4.867E+25	3.053E+25	2.798E+26	7.785E+25	**4.633E+26**
Pu-241	1.069E+23	7.145E+23	1.686E+24	1.047E+24	8.284E+24	2.508E+24	**1.435E+25**
Pu-242	1.821E+22	8.637E+23	1.440E+24	2.503E+23	4.728E+24	2.919E+24	**1.022E+25**
Am-241	3.661E+23	9.468E+23	2.600E+24	1.863E+24	1.683E+25	4.437E+24	**2.704E+25**
Am-243	0.000E+00	1.493E+20	2.200E+21	9.807E+21	3.330E+22	4.241E+22	**8.787E+22**
Cm-244	0.000E+00	3.629E+22	6.700E+22	1.513E+21	4.836E+22	7.641E+22	**2.296E+23**
Total	**7.158E+27**	**6.646E+29**	**1.324E+30**	**4.164E+28**	**3.901E+29**	**1.057E+30**	**3.483E+30**

Appendix B: Evaluation of the Interaction of Yucca Flat Underground Nuclear Tests with Groundwater Using the Predevelopment Carbonate and Alluvial-Volcanic Aquifer Potentiometric Surfaces published in Fenelon et al. (2012)

Authors: Tim Vogt, Joe Fenelon, Irene Farnham, and Kay Birdsell

Background

For the Yucca Flat Corrective Action Unit, the underground radionuclide inventory is distributed between tests located above and below the water table. This distribution was based on information from U. S. Department of Energy (DOE), Nevada Operations Office (1997), also known as the "Pickus Report." The report provides a working point elevation and water table elevation estimate for each detonation. If the elevation of the working point was 328 feet (100 meters) above the regional water table or deeper, then the detonation was categorized in DOE (1997) as having a potential to interact with the regional ground water system. The inventory for these tests were then included in the "Yucca Flat – Below" inventory by Bowen et al. (2001). Tests located greater than 328 feet (100 meters) above the water table were included in the "Yucca Flat – Above" inventory, indicating that they were conducted wholly in the unsaturated zone. Figure B-1 illustrates the Yucca Flat underground nuclear tests indicating (1) potential for groundwater interaction (DOE 1997) in green, and (2) no potential for groundwater interaction (above the water table) in red.

Due to testing effects, the water levels reported in DOE (1997) were elevated at some locations in comparison to pre-test (predevelopment) water levels measured at Yucca Flat. Subsequent to that report, additional data compilation and analyses of water levels within Yucca Flat have been performed. This appendix includes a comparison of the working point elevations for the Yucca Flat tests to updated water-level information to determine whether any of the Yucca Flat tests might be re-categorized with respect to their potential to interact with regional groundwater. The most current interpretations of water-level surfaces for Yucca Flat are the predevelopment carbonate and alluvial-volcanic aquifer potentiometric surfaces published in Fenelon et al. (2012). These surfaces represent predevelopment (pre-testing) water levels and may be a measure of more natural water table elevations toward which the site will presumably return. The alluvial-volcanic aquifer is generally shallower than the carbonate aquifer; its areal extent is smaller in size than and lies entirely within the footprint of the carbonate surface, as illustrated in Figure B-1. For the comparison, a single combined water table surface was generated, called here the "USGS Volcanic-Alluvial/Carbonate Combined Surface," where the two surfaces are combined giving precedence to the higher elevation between the two water table surfaces defined by Fenelon et al. (2012). Outside the alluvial-volcanic aquifer surface, the carbonate aquifer defines the surface where it is present (Figure B-1). This combined surface provides the most appropriate water table and forms most of the basis for determining the relationship between the Yucca Flat tests and their relative position to the water table for the comparison presented here. Most of the Yucca Flat tests fall within the combined surface although 25 tests fall outside the boundary of the surface (Figure B-1). Those 25 tests are not included in the comparison presented here.

Process

The process used to compare the pre-development water levels of Fenelon et al. (2012) was to prepare surfaces representing each of the two water-table data sets (Carbonate and Alluvial-Volcanic Aquifer), combine those according to the process described above, interpolate the elevation of the water table at the location of each Yucca Flat test, and compare the results with the original determination of groundwater interaction published in DOE (1997) and used for distributing the Yucca flat inventory in Bowen et al. (2001).

Data used as input for the Predevelopment Carbonate Aquifer System in Yucca Flat consist of the contour lines and some of the data points shown on Plate 4 of Fenelon et al. (2012). Data used as input for the Predevelopment Alluvial-Volcanic Aquifer System in Yucca Flat consist of the contour lines and some of the data points shown on Plate 3 of Fenelon et al. (2012). For both surfaces, additional control points were added to make the surfaces consistent with the interpretations given in Plates 3 and 4 respectively. EarthVision software was used to produce and process the surfaces. Excel was used to compare the interpolated values for each test / water table surface elevation with the original elevations in the Pickus report. A data package fully describing the process was developed and documents the building of these surfaces and the full comparison.

Results

The comparison was performed to determine whether the classifications of Yucca Flat tests with respect to potential interaction with the regional water table would change if predevelopment water-level information was considered. The results of the comparison are that four tests changed relative to potential interaction with the regional water table, as indicated in Figure B-1 and Table B-1. The classification of all four tests changed based on their inclusion/exclusion in the 328-foot (100-meter) buffer zone.

Table B-1: Yucca Flat tests for which the potential groundwater interaction changed based on a comparison of DOE (1997) water levels and the predevelopment "USGS Volcanic-Alluvial/Carbonate Combined Surface"

Test and Announced Yield	**Change**	**Initial Classification and Distance**	**Changed Classification With Predevelopment Water-Level Information and Distance**
BONARDA 20 to 150 kt	Changed to Potential Interaction	No Potential Interaction; 358 feet (109 meters) above 1997 water table	Potential Interaction; 299 feet (91 meters) above the predevelopment Volcanic-Alluvial/Carbonate combined water table surface
CREPE 20 to 200 kt	Changed to No Potential Interaction	Potential Interaction; 306 feet (93.4 meters) above 1997 water table	No Potential Interaction; 352 feet (107.2 meters) above the predevelopment Volcanic-Alluvial/Carbonate combined water table surface
REDMUD < 20 kt	Changed to Potential Interaction	No Potential Interaction; 351 feet (107 meters) above 1997 water table	Potential Interaction; 318 feet (97 meters) above the predevelopment Volcanic-Alluvial/Carbonate combined water table surface
TOPMAST < 20 kt	Changed to Potential Interaction	No Potential Interaction; 387 feet (118 meters) above 1997 water table	Potential Interaction; 304 feet (92.6 meters) above the predevelopment Volcanic-Alluvial/Carbonate combined water table surface

In summary:
(1) Three tests (BONARDA, REDMUD, and TOPMAST) changed from being categorized as having no potential interaction with the regional water table, based on the 1997 water levels, to having potential for interaction with the regional water table based on predevelopment water levels. In each case, the elevation of the test went from being just above (23 to 59 feet [7 to 18 meters]) the 328-foot (100-meter) buffer zone based on the 1997 water levels to being within and very near the top (10 to 29 feet [3 to 9 meters] from the top) of the buffer zone based on the predevelopment water levels.
(2) One test (CREPE) changed from being categorized as having the potential for interaction with the regional water table to having no potential for interaction with the

regional water table based on the predevelopment water levels. The elevation of the test went from being within but very near the top (22 feet [7 meters]) of the 328-foot (100-meter) buffer zone based on the 1997 water levels to being just above (24 feet [7 meters] from the top) the buffer zone based on the predevelopment water levels.
Based on this comparison, it was decided that the two Yucca Flat inventory estimates would not be updated based on these four tests changing their relative elevations with respect to the water table because of three reasons. First, the inventory developed in the main body of this report is based on actual yields, not announced maximum yields, but sum totals for a given corrective unit are reported and no classified source-term information is reported. However, because so few tests were found to differ with respect to their location relative to the water table, classified source-term information might be compromised if the true inventories for these 4 Yucca Flat tests were reallocated. Second, the maximum announced yields for the tests listed above are nearly equivalent (i.e., sum of 190 kt vs. 200 kt) and reallocating the test inventories based on their relative location to the updated water table surface would have almost no impact on the two Yucca Flat inventory estimates. Finally, the elevations of the four tests are all relatively close to the top of the 328-foot (100-meter) buffer zone used to define the potential for interacting with the water table based on a generic cavity radius, which is an uncertain measure. Therefore, the use of the 1997 water levels was retained for categorizing the Yucca Flat sources as being in the "Yucca Flat – Above" and the "Yucca Flat – Below" inventories, and no changes from the original Bowen et al. (2001) inventory allocation are recommended for the update provided by this report.

References:

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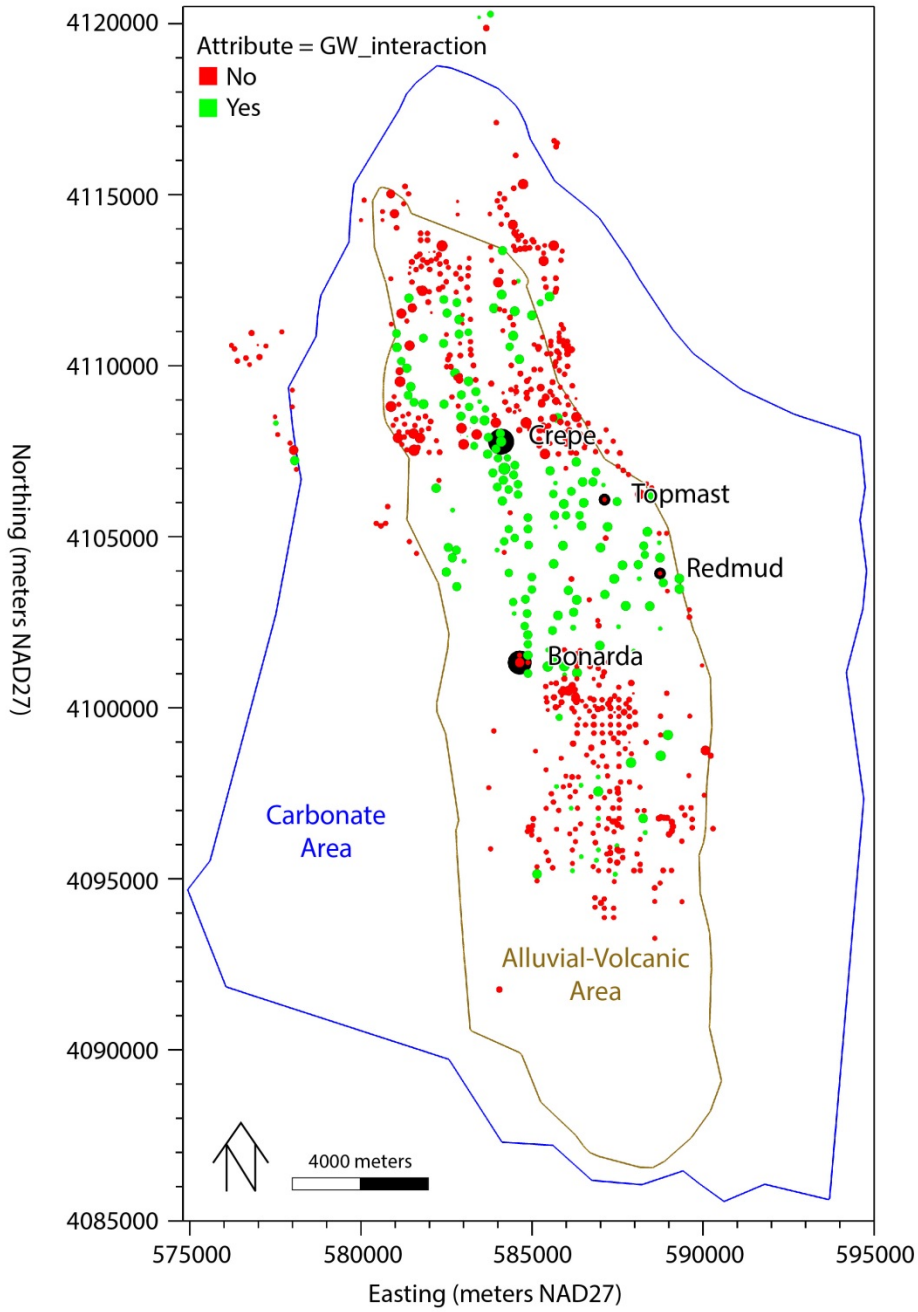

Figure B-1. Yucca Flat underground nuclear tests indicating (1) potential groundwater interaction (DOE 1997) (below the water table) in green, and (2) no potential groundwater interaction (above the water table) in red, Alluvial-Volcanic footprint with brown line, and Carbonate footprint with blue line. The blue line also indicates the footprint of the "USGS Volcanic-Alluvial/Carbonate Combined Surface." Black circles indicate detonations for which the groundwater interaction status changed based on the "USGS Volcanic-Alluvial/Carbonate Combined Surface."

Appendix C: Explanation of U-234 error and Correction in Bowen (2001)

There was an error in the data for ^{234}U in Tables 5 and 6 in the original Bowen report (Bowen *et al.,* 2001). The problem was found in the Access database while working with the uranium isotopes. The problem was as follows: The uranium isotopes have two sources: the test device and the soil. The uranium content of the soil and device for each test was calculated. Total uranium was defined as the sum of ^{234}U from the soil and ^{234}U from the test device. In the summation of the ^{234}U in the Access database, the sum was inadvertently defined as ^{234}U from the device plus ^{234}U from the device. This led to incorrect values for both atoms and curies of ^{234}U in all of the principal geographic test centers. It also caused very small errors (in the third decimal place) for the total atoms in Pahute Mesa (Area19) and Yucca Flat-above water table. The formula in the database was corrected for ^{234}U and is now equal to ^{234}U from test device plus ^{234}U from soil. The tables have been updated to reflect the correct values.