APPENDIX H
UNDERGROUND NUCLEAR TESTING

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This appendix provides basic information regarding underground nuclear testing, including the general steps involved in conducting a test in a vertical shaft and the associated major long-term environmental impacts. The U.S. Department of Energy (DOE) and the National Nuclear Security Administration (NNSA) are not proposing to conduct an underground nuclear test as part of this *Site-Wide Environmental Impact Statement for the Continued Operation of the Department of Energy/National Nuclear Security Administration Nevada National Security Site and Off-Site Locations in the State of Nevada*. However, in accordance with Presidential Decision Directive 15 (November 1993), DOE/NNSA must be able to resume underground nuclear weapons tests within 24 to 36 months if so directed by the President. This capability is maintained by DOE/NNSA at the Nevada National Security Site (NNSS) (formerly the Nevada Test Site).

Because NNSA must maintain its readiness to conduct an underground nuclear test, this appendix provides general information regarding the activities and generalized potential environmental impacts associated with actually conducting such a test. In the event that NNSA is directed by the President to conduct an underground nuclear test, it would be conducted at Pahute Mesa, Rainier Mesa, or Yucca Flat within the Nuclear Test Zone (Areas 7, 8, 9, 10, and 20 and the northern portions of Areas 6 and 11) or at the Nuclear and High Explosives Test Zone (Areas 1, 2, 3, 4, 12, and 16) in the northern and northwestern portions of the NNSS (see Chapter 4, Section 4.1.6.2, Figure 4–13).

The NNSS became the United States' continental nuclear weapons testing site in December 1950, when a 680-square-mile area of land was withdrawn from the 5,000-square-mile Las Vegas Bombing and Gunnery Range (now the Nevada Test and Training Range). The initial nuclear weapon test took place on January 11, 1951, as part of Operation Ranger, and was code-named "Able." Able was an air-dropped test of a small-yield (about 1 kiloton) device (Johnson et al. 2000). Between December 1951 and July 1962, 100 atmospheric nuclear tests were conducted at the NNSS. The first of 828 underground nuclear tests conducted at the NNSS, code-named "Uncle," was detonated on November 29, 1951, in Area 10. The last underground nuclear test to be conducted at the NNSS, code-named "Divider," was on September 23, 1992, in Area 3 (DOE 2000).

The primary purpose of an underground nuclear test is to obtain information related to nuclear weapons. Two basic kinds of underground nuclear tests were conducted at the NNSS: weapon effects tests and weapons development tests. In addition, among the atmospheric and underground nuclear tests that were conducted at the NNSS, 23 were tests associated with the Plowshare Program. The Plowshare tests were part of an effort to develop peaceful uses of nuclear explosions for such purposes as canal and harbor excavation and making petroleum resources more accessible (OTA 1989). In general, underground nuclear tests were conducted in shallow boreholes, deep vertical shafts, and mined tunnels (DOE 1996). Most vertical drill hole tests were conducted for the purpose of developing new weapon systems. Tunnel tests were generally conducted to evaluate the effects (radiation, ground shock, etc.) of various weapons on military hardware and systems (OTA 1989). When the device was detonated at the bottom of a vertical drill hole, data from the test were transmitted through electrical and fiber-optic cables to trailers containing recording equipment placed on the surface near "ground zero." Performance information was also determined from samples of radioactive material recovered by drilling back into the solidified melt created by the explosion (i.e., drillback operations).

Conducting an underground nuclear test is a complex endeavor requiring significant long-term planning and commitment of resources, both natural and economic. A brief, generalized description of underground nuclear testing procedures for a test in a vertical drill hole is included in **Table H–1**.

Table H–1 Underground Nuclear Weapons Testing

Underground Nuclear Weapons Testing (Tests in Vertical Drill Holes)
Step 1 – Site Selection and Drilling. Two subsets of site selection would apply to nuclear tests: (1) selection of an existing drill hole for a specific test or (2) selection of a new drill site within the Nuclear Test Zone or Nuclear and High Explosives Test Zone (see Appendix A, Figure A–1) for a specific test if an existing inventory emplacement hole were not suitable. The goal of site selection would be to optimize the various parameters so that the operational feasibility and successful containment of yields could be attained at a suitably low cost. Many factors would be considered, including: (1) scheduling of field resources; (2) test schedules; (3) the shock sensitivity of a given experiment and possible interactions with other experiments; (4) the depth range required for a suitable device emplacement; (5) geologic structure; (6) geologic material properties; (7) the depth of the water table; (8) potential drilling problems; (9) adjacent expended sites, craters, chimneys, or subsurface collapses; (10) adjacent open emplacement holes or unplugged post-shot or exploratory holes; and (11) non-test program constraints such as groundwater concerns, roads, and power lines (Olsen 1993). If drilling is required after a test location were chosen by the sponsoring national laboratory, a drilling program outlining the requirements of the specific hole would be completed. The selected site would be surveyed, staked, and checked for cultural and biological resources. When these environmental studies are completed, the site would be graded and leveled, and mud pits and a reserve drilling-fluid sump would be constructed to contain drilling fluid and cuttings. A drill rig, usually with its own power source and utilities, would be moved onto the site. Water would be trucked or piped in and mixed with drilling compounds to fill the mud pits. The hole would be drilled using standard Nevada National Security Site (NNSS) big-hole drilling techniques. A normal hole would be from 48 to 120 inches in diameter and from 600 to 2,500 feet deep. During drilling, samples of drill cuttings would be collected at 10-foot intervals and rock cores would be taken as required. After drilling is complete, geophysical logs would be run in the hole to evaluate the condition of the hole and gain a more thorough understanding of the geology. The drill site would be secured by filling the sump and installing specially designed covers over the hole.
Step 2 – Test Site Engineering and Construction. When a hole is selected as a location for a nuclear test, the area around the hole would be surveyed and staked according to the criteria set forth by the sponsoring national laboratory. Cultural and biological surveys would be rerun to determine whether the status of the area has changed. The hole would also be uncovered, and selected geophysical logs rerun in the hole to confirm its condition. Once the environmental clearances are complete, an area would be cleared and leveled for the surface ground-zero equipment and another area close to the selected site would be cleared and leveled for the recording trailer park. This would be a typical earthmoving operation; native materials would be used to top the pads or, if the active native materials are unstable, suitable fill material (Type II base and/or gravel) would be used. Onsite construction would be temporary and would be abandoned after the test is complete. Concrete pads would be placed around the surface ground zero to provide a stable platform for downhole operations, as well as a base for the assembly towers. Equipment would be moved in to emplace the nuclear device in the hole, record the data produced, and provide radiological and seismic monitoring of the site. An extensive grounding system would be used to establish baseline instrumentation grounds, which might include a pit containing saltwater. The equipment to be left in position during the detonation would be protected with an aluminum foil, hex-cell-shaped, shock-mounting material or with dense foam. A circle of radiation detectors would be placed back from the surface ground zero to detect and assess any releases from the experiment. Finally, a perimeter fence would be erected, and access both into and out of the test location would be controlled.
Step 3 – Device Delivery and Assembly. The test article would be delivered to the Device Assembly Facility, any required assembly would be performed, and the test article would be delivered to the test location accompanied by armed convoy. It would then be attached to the diagnostics canister in preparation for emplacement in the hole. Checks would be run and alignment assured. A high state of security would be maintained during all operations involving the nuclear device.
Step 4 – Diagnostic Assembly. A diagnostic canister rack would be assembled off site and transported to the test site. The size of the diagnostic canister would depend on the diameter of the borehole and may be up to almost 12 feet in diameter and 120 feet long and contain all of the instrumentation required to receive data at the time of detonation (real time). The diagnostic canister may contain lead and other materials as shielding for the detectors. After its arrival at the test location, the diagnostic canister would be installed in the assembly tower to be mated with the device on site. Instrumentation cables would be connected to the experiments and the recording trailer park. Slack in the cables would allow the diagnostic canister to be lowered into the hole.

Underground Nuclear Weapons Testing (Tests in Vertical Drill Holes)
Step 5 – Emplacement of the Experiment. The nuclear explosive and special measurement devices would be moved to the hole and lowered to the detonation position; all required diagnostic materials and instrumentation cables would also be lowered into the hole at this time. Downhole operations would be conducted according to a defined checklist and monitored by independent inspectors. The whole assembly would be placed on a set of fracture-safe beams that span the opening. Any auxiliary equipment would then be lowered into the hole, and the area would be secured. Emplacement equipment would be removed from the area, and test runs would be conducted on the downhole experiment. The hole would be stemmed (packed with material) to prevent radioactive materials from escaping during or after the experiment. Stemming materials used to backfill the hole would generally be placed in alternating layers, according to the containment design specification. Sand, gypsum, grout, cold tar, or epoxy plugs are some of the typical stemming materials that may be placed in the hole to provide impenetrable zones. The instrument cables within these zones would be sealed to prevent a radioactive gas path to the surface. Once completed, the area would be cleared of unnecessary equipment. A report would be compiled for the Containment Evaluation Panel to show that the as-built condition reflects the containment design plan.
Step 6 – Test Execution. After the Containment Evaluation Panel accepts the as-built design of the containment and all preliminary tests are successful, the nuclear device would be ready for detonation. Security operations would assure that all non-test-related personnel are evacuated prior to the detonation for security and safety reasons. The explosive would be armed. Radiation monitors would be activated, and aircraft with tracking capability would be prepared for flight in case gas and debris unexpectedly vent to the surface. Weather forecasts and fallout pattern predictions would be reviewed, after which the test device would be detonated. After the test is conducted, the test site would remain secure until it can be assured that the radiological products of the test have been contained. After a suitable time, a reentry crew would be dispatched to the site. Data would be retrieved and the condition of equipment noted. After all is assured to be secure, normal NNSS operations would resume. The site would be roped off, outlining an exclusion zone where there is danger of potential cratering.
Step 7 – Post-shot Operations. After the temperature of the cavity has cooled, a post-shot hole would be drilled into the point of the explosion to retrieve samples of the debris. These highly radioactive samples would provide important information on the test. The post-shot hole would be as small in diameter as possible and drilled at an angle to allow the drill rig to be positioned safely away from the surface ground zero. After drilling and sampling operations are complete, the drill rig and tools would be decontaminated. The site would be cleaned of residual radioactive contamination, and the hole would be plugged back to the surface. This generally completes the test operation.

Source: DOE 1996.

H.1 Disruption of the Physical Environment from Underground Nuclear Testing

Underground nuclear testing at the NNSS was conducted in six main areas: Pahute Mesa, Rainier Mesa, Yucca Flat, Frenchman Flat, Shoshone Mountain, and Buckboard Mesa (Areas 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 16, 18, 19, and 20 of the NNSS) (DOE 1996; DOE/NV 2010). These tests left their mark on the NNSS, both in terms of physical disruption and a subsurface inventory of remaining radioactive isotopes.

The major impacts of an underground nuclear test on the physical environment are ground motion, disruption of the geologic media, surface subsidence, and contamination of the subsurface geologic media and surface soils (DOE 1996). Ground motion is a temporary phenomenon that, with the exception of rockfalls and minor land displacements, has not resulted in permanent effects on the NNSS or offsite areas. Creation of subsidence craters, disruption of underground geologic media, and release of radioactivity into the environment are the most significant and enduring impacts on the physical environment resulting from underground nuclear testing. The following discussion is derived from *The Containment of Underground Nuclear Explosions* (OTA 1989), unless otherwise noted, and describes the events that occur after the moment a nuclear device is detonated.

Figure H–1 shows the sequence of events that occur after an underground detonation (Step 6 in Table H–1). Within a microsecond (one-millionth of a second) of detonation, the billions of atoms involved in a nuclear explosion release their energy. Pressures within the exploding nuclear device reach several million pounds per square inch and temperatures are as high as 100 million degrees Celsius

(over 180 million degrees Fahrenheit). A strong shock wave is created by the explosion and moves outward from the point of detonation.

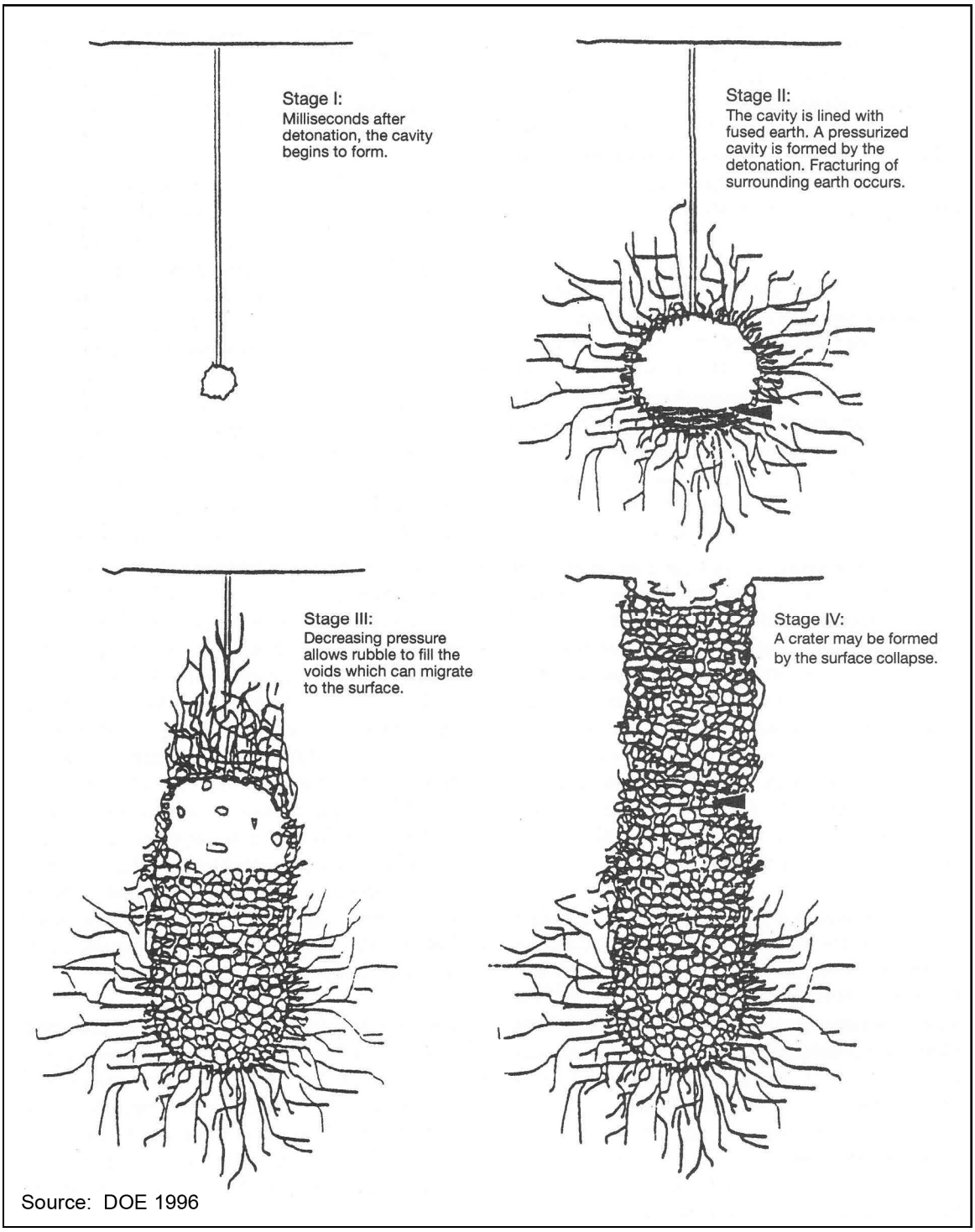

Figure H–1 Formation of an Underground Nuclear Explosive Test Cavity, Rubble Chimney, and Surface Subsidence Crater

Within tens of milliseconds (thousandths of a second) following the detonation, the nuclear device and surrounding rock are vaporized, creating a "bubble" of high-pressure steam and gas. An underground spherical cavity is formed by the pressure of this gas bubble, and the explosive momentum is imparted to the host rock.

As the cavity continues to expand, the pressure decreases and, usually within a few tenths of a second of detonation, equalizes with the pressure from the overlying rock. At this point the cavity reaches its greatest dimensions. Concurrent with this pressure decrease, the shock wave from the detonation travels outward, crushing and fracturing the rock in the near-test environment. Eventually, the shock wave weakens and the rock is no longer crushed, but is merely compressed; it then returns to its original state. This compression and relaxation phase becomes seismic waves that travel through the ground in the same manner as seismic waves formed by an earthquake.

After a few seconds, as the hot gases cool, the molten rock begins to collect and solidify on the cavity sidewalls and in a puddle at the bottom of the cavity. Most of the radioactive products of the explosion would be confined in the solidified rock in this puddle.

When the gases cool, the pressure decreases to the point where it no longer can support the overlying rock and soil and the cavity may collapse, forming a chimney upward from the cavity. The collapse occurs as the overlying rock breaks into rubble and falls into the cavity void. This process continues until either the cavity completely fills with rubble, the chimney reaches a level where the strength of the rock can support the overburden, or, as usually happens, the chimney reaches land surface. When the chimney reaches the surface, the ground sinks, forming a saucer-like subsidence crater. The crater usually forms within a few hours after the detonation, but may take months to form.

Radioactive material produced by a nuclear explosion would remain underground due to the combined effects of the sealing nature of the compressed rock around the cavity, the porosity of the rock, the depth of burial strength of the rock, and the stemming of the emplacement hole.

Stemming consists of the placement of impenetrable plugs, located at various distances within the emplacement hole, to prevent the emplacement hole from being the path of least resistance for the flow of radioactive materials. It is also designed to prevent gases from traveling up the emplacement hole by forcing them into the surrounding rock, where they are absorbed into the pore spaces.

As noted above, the explosion creates a pressurized cavity filled with gas that is mostly steam. As the cavity pushes outward, the surrounding rock is compressed. Because there is essentially a fixed quantity of gas within the cavity, the pressure decreases as the cavity expands. Eventually, the pressure drops below the level required to deform the surrounding material. Meanwhile, the shock wave imparts outward motion to the material around the cavity. Once the shock wave passes, the material tries to return (rebound) to its original position. The rebound creates a large compressive stress field, called a "stress containment cage," around the cavity. The physics of the stress containment cage are somewhat analogous to how stone archways support themselves. In the case of a stone archway, the weight of each stone pushes against the others and supports the archway. In the case of an underground nuclear detonation, the rebounded rock locks around the cavity, forming a stress field that is stronger than the pressure inside the cavity. The stress containment cage closes any fractures that may have begun and prevents new fractures from forming.

The predominantly steam-filled cavity eventually collapses, forming a chimney. When this collapse occurs, the steam in the cavity is condensed through contact with the cold rock falling into the cavity. The noncondensable gases remain within the lower chimney at low pressure. After the collapse, high-pressure steam is no longer present to drive gases from the cavity region to the surface.

If the test is conducted in porous material, such as alluvium or tuff, the porosity of the medium provides volume to absorb the gases produced by the explosion. For example, all of the steam generated by a 150-kiloton explosion beneath the water table could be contained in a condensed state within the volume of pore space that exists in a hemispherical pile of alluvium 200 to 300 feet high. Although most steam condenses before leaving the cavity region, the porosity of the geologic media helps contain noncondensable gases, such as carbon dioxide and hydrogen. The noncondensable gases diffuse into the interconnected pore space, and the pressure is reduced to a level that is too low to drive the fractures. The deep water table and high porosity of rocks at the NNSS would facilitate this aspect of containment.

Containment also occurs because of the pressure of the overlying rock. The depth of burial provides a stress that limits fracture growth. For example, as a fracture initiated from the cavity grows, gas seeps from the fracture into the surrounding material. Eventually, the pressure within the fracture decreases below the level needed to extend the fracture. At this point, growth of the fracture stops, and the gas simply leaks into the surrounding material.

Rock strength is another important aspect of containment, but only in the sense that an extremely weak rock (such as water-saturated clay) cannot support a stress containment cage. As a result, sites at the NNSS containing large amounts of water-saturated clay would be avoided for any test conducted in the future.

The final aspect of containment is placement of the stemming material into a vertical hole after the nuclear device has been emplaced and before detonation.

How the various containment features perform depends on many variables, including the size of the explosion, the depth of burial, the water content of the rock, and the geologic structure. Problems may occur when the containment cage does not form completely and gas from the cavity flows either through the emplacement hole or the overburden material. When the cavity collapses, the steam condenses and only noncondensable gases, such as carbon dioxide and hydrogen, remain in the cavity. Carbon dioxide forms from the vaporization of carbonate material in the rock; hydrogen forms when water reacts with the iron in the nuclear device and the diagnostics equipment. The carbon dioxide and hydrogen remain in the chimney if there is available pore space. If the quantity of noncondensable gases is large, however, they can act as a driving force to transport radioactivity through the chimney or the overlying rock. Consequently, the amount of carbonate material and water in the rock near the explosion and the amount of iron available for reaction are important considerations when evaluating containment for a particular test.

Historic deep vertical underground testing resulted in the formation of hundreds of craters at the NNSS (DOE 1996). This resulted in the "pockmarked" appearance of Yucca Flat, the location of the majority of underground nuclear tests on the NNSS, as shown in **Figure H–2**. These subsidence craters generally range from 200 to 2,000 feet in diameter and from a few feet to 200 feet deep. The size of the crater is primarily related to the depth of emplacement and the explosive energy of the device that was detonated. Crater formation occurred less frequently with tests conducted on Pahute Mesa because of the greater competency of the rocks in that area and the depths of most tests. The development of craters has been the principal consequence of underground nuclear testing on the terrain of the NNSS.

In addition to the cavity, chimney, and subsidence crater, pressure ridges and small displacement faults occurred at the surface in some cases. Surface fracturing and faulting are the result of the sudden uplift of the earth at the time of detonation and the collapse during the formation of the chimney and crater. Another permanent consequence of testing is vertical displacement along existing geologic faults, particularly along the Yucca and Carpetbagger Faults in Yucca Flat. Vertical displacement of as much as

8 feet occurred along portions of the Carpetbagger Fault (DOE 1996). Fracturing occurred on the top of Rainier Mesa due to the loss of strength in the rocks in that area (DOE 1996).

Figure H–2 Aerial View of a Portion of Yucca Flat, Nevada National Security Site

Although underground nuclear testing had long-term physical consequences on the environment, the effects of the tests were additive, rather than synergistic. That is, the sum of the effects of multiple tests did not produce unexpected consequences or consequences that were greater than the sum of the individual tests (DOE 1996).

Fracturing of the rock in the near-test environment may have resulted in some alteration of the natural permeability of the rocks underlying parts of the NNSS. The shock wave and compressive forces from a test could have increased the permeability of the rock by creating more fractures near the test or may have actually decreased permeability by widening and then closing fractures at greater distances from the test. Post-test measurements of rock samples taken from tunnel complexes generally show that the properties of the host rock are unchanged at a greater distance than three cavity radii from the point of detonation. Beyond that distance, no fracturing occurs from the detonation, but preexisting fractures are widened as the shock wave propagates through the host rock and then are closed after the shock wave has passed. In some instances, the closing of the fractures may reduce the fracture aperture and may result in some permanent reduction in the gross permeability of the rock mass. The implications of the permeability changes in the rock due to underground nuclear testing are discussed in the next section.

H.2 Radioactive Contamination of the Geologic Media and Groundwater

The second major effect of underground nuclear testing, in addition to the impacts on the physical environment, is the formation of pockets of radioactive contamination surrounding each underground test and injection of radionuclides and other contaminants into the groundwater. The total amount of radioactivity released into the underground environment during a test is called the "radionuclide source term." The source term includes numerous isotopes that are both short- and long-lived. For instance, in a 1-kiloton atmospheric detonation, an initial release of about 41 billion curies of radioactivity decays to about 10 million curies in just 12 hours (OTA 1989). All radioactive isotopes decay at specific rates. The decay process is measured in terms of "half-life." The radioactive half-life for a given radioisotope is the time for half the radioactive nuclei in any sample to undergo radioactive decay. The half-lives of radioisotopes vary tremendously. For example, polonium-216 has a half-life of about 0.15 seconds and plutonium-239, a half-life of over 24,000 years; other isotopes may have shorter or longer half-lives. As a simplified example of radioactive decay, the half-life of tritium (radioactive hydrogen) is about 12.3 years. So, beginning with an initial sample of 100 atoms of tritium, after 12.3 years there would be 50 atoms, and after another 12.3 years, about 25 atoms. This decay process continues until there are no radioactive isotopes remaining from the original sample.

In a 2001 report, scientists from Los Alamos National Laboratory and Lawrence Livermore National Laboratory calculated the underground inventory of radionuclides resulting from underground nuclear testing at the NNSS between 1951 and 1992 (Bowen et al. 2001). The radionuclide inventory was divided into six principal geographic test areas where underground nuclear testing was conducted at the NNSS: Frenchman Flat, Pahute Mesa in Area 19, Pahute Mesa in Area 20, Rainier Mesa/Shoshone Mountain, Yucca Flat (above the water table), and Yucca Flat (below the water table). Not all radionuclides produced in an underground nuclear test were included in this inventory. Radionuclides included in the inventory were: (1) residual and unburned fissile fuel and tracer materials, such as isotopes of uranium, plutonium, americium, and curium-244; (2) fission products such as cesium-137 and strontium-90; (3) tritium (a radioactive isotope of hydrogen); and (4) neutron-induced radioisotopes in device parts, external hardware, and the surrounding geologic medium (such as carbon-14, chlorine-36, and calcium-41). Radionuclides that were excluded from the inventory are (1) those with half-lives that are so short (microseconds to hours) that they decay to undetectable levels soon after the test and (2) those that are produced in such low initial abundance that they never exceed levels deemed unsafe or nonpermissible by regulatory agencies. Because no underground nuclear tests have been conducted since 1992, the radionuclide inventory has been decreasing due to the natural decay of radioactive particles.

Table H–2 provides the calculated total radionuclide source terms for the six geographic test areas and for the NNSS overall.

Table H–2 Underground Radionuclide Inventory in the Six Principal Geographic Test Areas at the Nevada National Security Site (in curies; decay corrected to September 23, 1992)

Geographic Test Areas at the NNSS	*Frenchman Flat*	*Pahute Mesa, Area 19*	*Pahute Mesa, Area 20*	*Rainier Mesa/ Shoshone Mountain*	*Yucca Flat (more than 328 feet above the water table)*	*Yucca Flat (less than 328 feet above the water table)*	*Total Inventory*
Radionuclide Inventory	190,000	19,200,000	60,900,000	887,000	15, 800,000	35,200,000	132,000,000

NNSS = Nevada National Security Site.
Note: Numbers are rounded to three significant figures.
Source: Bowen et al. 2001.

The inventory in Table H–2 represents an upper limit of the radionuclides that are potentially available for transport in the groundwater. The portion of the source term that is considered available to the groundwater regime at the NNSS is the radioactive inventory under or within 328 feet of the water table. About 30 percent of underground nuclear tests at the NNSS were conducted beneath the water table (Bowen et al. 2001). In 1996, DOE estimated, based on work by Bryant and Fabryka-Martin (1991) that about 38 percent of the underground nuclear tests at the NNSS were conducted within about 246 feet (75 meters) of the water table. Using that estimate as the basis, a conservative estimate of the potential hydrologic source term for radionuclides underground at the NNSS as of September 1992 is just over 50,000,000 curies. As noted in Bowen et al. 2001, the radionuclide source term will never be transported in its entirety; the hydrologic source term comprises only those radionuclides that are dissolved in or transportable by groundwater. Further, within the hydrologic source term, the mobility of radionuclides is moderated both by chemical kinetics and hydrology.

Most investigators have concluded that, exclusive of tritium, much of the radioactivity released during an underground nuclear test remains confined in the melted and fused rock in the detonation cavity, particularly the refractory isotope species, such as plutonium, rare earth elements, zirconium, and alkaline earth elements. The more volatile nuclides, such as alkali metals, ruthenium, uranium, antimony, tellurium, and iodine, tend to condense on the chimney rubble. The most mobile isotopes are the gaseous species, including argon, krypton, and xenon, that tend to rise through the chimney and may ultimately seep out to the surface (DOE 1996).

The mechanisms by which radionuclides can enter the groundwater include leaching from the melt glass and condensation in the cavity and chimney; injection into fractures outside the cavity during the first milliseconds after the test; and interactions between gaseous species and the groundwater.

Leaching from the rubble chimney is probably an important pathway to the groundwater for radionuclides from tests that were conducted under the water table or in or under perched aquifers. Groundwater within the cavity area was vaporized at detonation of the device, and some portion of that vapor was forced by the shock wave out of the cavity and into the surrounding host rock. With time, groundwater gradually flowed back into the cavity and chimney and came into direct contact with the radionuclides that were condensed onto the chimney rubble. Depending on the solubility of the radionuclides, the groundwater would dissolve the residues until chemical equilibrium was achieved. Once dissolved, the radionuclides would be available for migration through groundwater flow. The impacts of past underground nuclear testing are discussed in Chapter 4, Section 4.1.6.2, and Chapter 6, Section 6.3.6.2.

Leaching of radionuclides from the melt glass and cavity rubble probably has occurred to some degree. According to Borg et al. (1976), studies asserted that (1) less than 1 percent of the radionuclides in the melt glass near the bottom of the chimney would be distributed onto the chimney rubble, and (2) most of the tritium would be mixed with the water in the chimney and cavity at times for about 1 year, while some tritium may be trapped in the melt glass. Leaching of radionuclides from the melt glass probably would occur over extended periods of time, and the leachate would be available for transport through groundwater flow.

Fracture injection is the final pathway for the introduction of radionuclides into the groundwater regime. Water vapor discharged from the cavity immediately following a detonation was seismically “pumped” into the fractures formed by the test and through other fractures that were widened by the shock wave. Following the achievement of equilibrium conditions, radionuclides injected into fractures under the water table became available for transport through groundwater flow.

Tritium is one of the most mobile of the radionuclides resulting from underground nuclear testing present in the subsurface environment surrounding the detonation cavity following an underground nuclear test.

It is also present at higher concentrations (comprising about 95 percent of the total radiological source term as of September 1992 [Bowen et al. 2001]) than other radionuclides for a period of 100 to 200 years following a test, and is generally believed to be present principally as part of a free water molecule, rather than being bound in the puddle glass that contains the large majority of the radionuclides remaining after a test. Tritium is known to migrate when induced by pumping at nearby wells, while many other radionuclides remain in or near the detonation cavity (Bryant 1992). Therefore, tritium represents the radionuclide of greatest concern to users of groundwater for at least the next 100 years because of its mobility and high concentration. For these reasons, in the assessment of impacts from the groundwater pathway, tritium is the primary radionuclide used in the models that have been and are being developed to improve our understanding of the potential movement and risk associated with groundwater beneath the NNSS (see Chapter 6, Section 6.3.6.2). Bowen et al. (2001) calculated the amount of tritium in the overall NNSS radiological source term to be about 125,560,000 curies. Using the 38 percent ratio noted above, it is estimated that about 48,000,000 curies of tritium could be considered to be part of the hydrologic source term, as of September 23, 1992. Based on the radioactive decay rate (half-life) for tritium, the amount of tritium currently available as part of the hydrologic source term is considerably less than 48,000,000 curies.

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