Radionuclide Migration at a Plowshare Program Site: the Gasbuggy Underground Nuclear Test Site, San Juan County, New Mexico—17019

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ABSTRACT

Project Gasbuggy in northwest New Mexico was the first of three subsurface nuclear tests the U.S. Atomic Energy Commission conducted to evaluate the potential to enhance the production of natural gas from low-permeability geologic formations. In 1967, a 29-kiloton nuclear device was detonated in the Lewis Shale (marine shale and siltstone), 1,292 m below the land surface. The detonation vaporized a cavity into which overlying rock collapsed, forming a 101-m high rubble-filled chimney with a radius of 25 m. Explosion-generated fractures extended between 120 m and 150 m from the working point (detonation location). Most of the radionuclides generated from the explosion remain in the cavity melt glass or have decayed to negligible amounts; tritium radioactivity, however, is still high enough and potentially mobile enough to be of concern. Tritium is able to exchange with stable hydrogen and form liquid water and water vapor; under two-phase (liquid and gas) reservoir conditions the majority of tritium is stored as liquid water and volatilizes only to restore equilibrium conditions as gas is removed. A numerical model was developed to examine the migration of tritium in both phases through the fractured shale and sandstone under present conditions. The results suggest that tritium has migrated only 110 m from the working point between 1967 and 2014. Although tritium is able to exchange between the gas and aqueous phases, the faster-diffusing gas phase is responsible for most of the tritium transport from the chimney. A hypothetical producing gas well located 340 m from the working point was added to the model to determine if tritiated water vapor (HTO) could migrate toward the well; results show that, because the low gas velocities could not compete with the high rate of radioactive decay, tritium would not reach the well.

INTRODUCTION

The Plowshare program, operated by the U.S. Atomic Energy Commission (AEC; a predecessor of today's Department of Energy, DOE), investigated peaceful uses of nuclear devices, such as their use in excavation of rock for construction projects

and stimulation of low-permeability natural gas formations. Of the twenty-seven projects in the by the program, three were conducted for formation permeability enhancement. These three projects were Projects Rulison (1969) and Rio Blanco (1973) in Colorado, and Project Gasbuggy (1967) in New Mexico (Table I). The DOE Office of Legacy Management is responsible for ensuring that DOE's stewardship responsibilities are met for the three gas stimulation sites and for providing effective and efficient long-term surveillance and maintenance to protect human health and the environment.

TABLE I. Date, yield (kilotons), depth below land surface of detonation (meters), and total tritium radioactivity released (Curies) at the time of detonation for three Plowshare gas stimulation projects.

Project	Date	[1]Yield, kt	Depth, m	[1]Total tritium radioactivity released, Ci
Gasbuggy	12/10/1967	29	1,292	40,000
Rulison	9/10/1969	40	2,568	10,000
Rio Blanco	5/17/1973	33 33 33	1,780 1,899 2,039	3,000 (total)

[1]U.S. DOE, 2015.

The overarching objective of developing a model for the Gasbuggy site is to support strategic planning for long-term surveillance and maintenance. Specifically, the purpose is to estimate the extent of radionuclide contamination in the subsurface at the present day, and to forecast radionuclide migration during possible future production of natural gas from nearby wells. A complete description of the explosion phenomenology, review of testing operations, conceptual model of flow and radionuclide transport, numerical model development and thorough explanation of all boundary and initial conditions, justification for all input parameters, and results are presented in Cooper and Chapman (2015).

DESCRIPTION OF METHODS

Physical Description of Site

The Gasbuggy site is located in northern New Mexico, approximately 100 miles northwest of Santa Fe. The device had a yield of 29 kilotons (DOE, 2015) and was detonated 1,292 meters (m) (4,240 feet) below ground surface on December 10, 1967. The site is located in Rio Arriba County within the Carson National Forest, Jicarilla Ranger District (Figure 1). The Jicarilla Apache Indian Nation lies one mile

to the east. The Gasbuggy site is generally considered to be the southwest ¼ of Section 36, Township 29 north, Range 4 west, New Mexico Principal Meridian, though there were at least five operational areas during site activities, and some of these were outside the quarter-section.

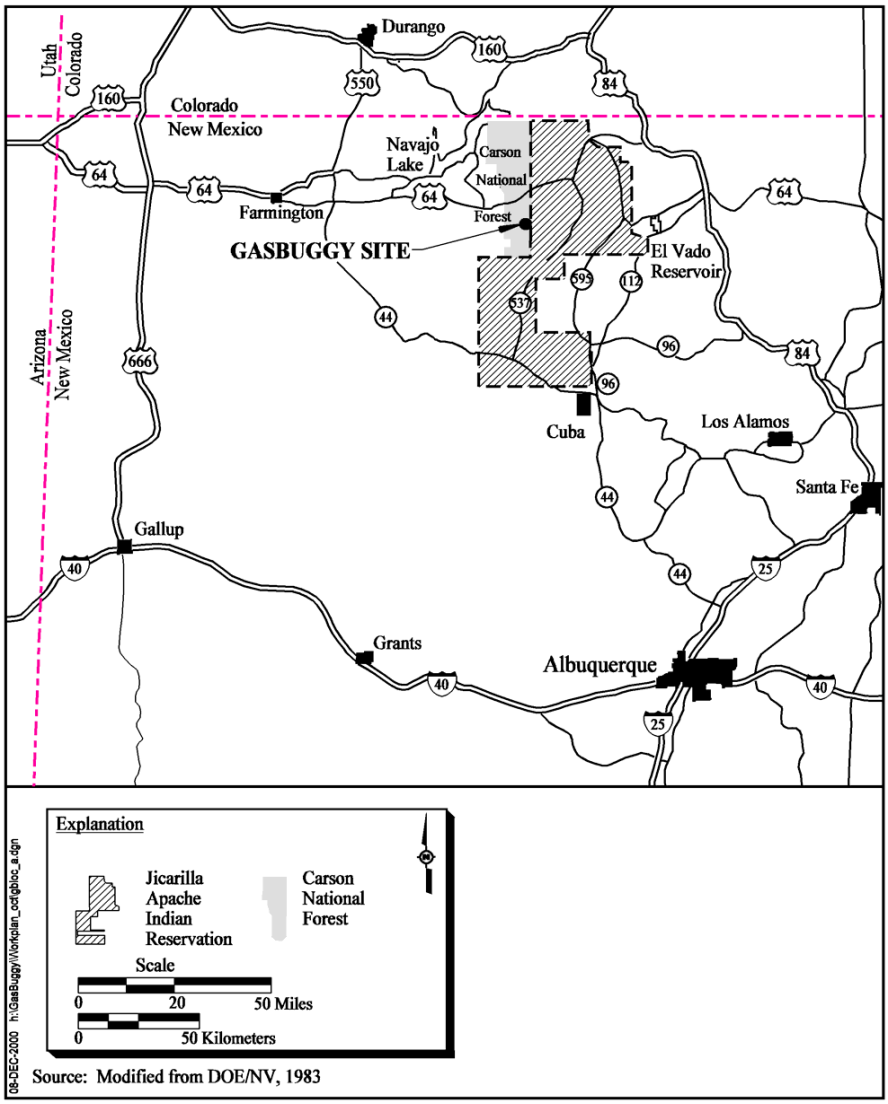

Figure 1. Location of the Gasbuggy, New Mexico, Site (from U.S. DOE, 2002).

Geologically, Gasbuggy is located in the San Juan Basin, a large structural basin containing approximately 3,700 m (12,000 ft) of Cretaceous and Tertiary sedimentary rocks. The nuclear test was detonated in the upper part of the Cretaceous Lewis Shale Formation, with the intention of fracturing the overlying Pictured Cliffs Sandstone Formation. The Lewis Shale extends another 450 m (1,500 ft) vertically below the test. The Pictured Cliffs is one of the San Juan Basin's major gas reservoirs; however, in the northeast part of the basin where Gasbuggy

is located, the Pictured Cliffs is a low-productivity, sparsely developed reservoir with a thickness of about 90 m (300 ft). Overlying the Pictured Cliffs is the 30-m-thick (100-ft) Fruitland Formation, composed of sandstone, shale, and siltstone. The Kirtland Shale overlies the Fruitland Formation. The Ojo Alamo Sandstone is above the Kirtland Shale and was identified as the closest water-bearing unit to the test horizon. The Ojo Alamo is a fine- to medium-grained, clayey sandstone containing minor shale beds (Mercer, 1967). Above the Ojo Alamo is the Nacimiento Formation, which is overlain by the San Jose Formation. The Nacimiento and San Jose are continental floodplain deposits with a combined thickness of approximately 1,050 m (3,500 ft). The fine- to medium-grained sandstone, interbedded with claystone and shale is water-bearing in many parts of the basin. Several tens of feet of alluvium (silty sand, poorly graded sand, and silt) occur at land surface in the immediate site vicinity.

Radionuclides of Potential Concern

Radionuclides associated with an underground nuclear test are present in three basic forms: gases, surface deposits, and volume deposits (Smith *et al*., 1995), the proportions of which change with time after the detonation. Immediately after the detonation, essentially all of the radionuclides are part of a superheated, expanding gas (Borg *et al*., 1976). When the temperature and pressure begin to drop, many of the gases condense in accordance with the properties of the nuclide. The refractory (high boiling point) radionuclides are primarily trapped in the solidifying melt glass (molten rock that has cooled quickly), much of which collects at the base of the cavity as “puddle glass.” These are the volume deposits, whose release from the solid phase is controlled by dissolution of the glass. Volatile (low boiling point) nuclides remain as gases longer, depending on the cooling rate of the cavity. Some portion of volatiles is embedded in the puddle glass, but a portion is also deposited as coatings on chimney rubble surfaces. These surface deposits are more susceptible to dissolution by groundwater than the puddle glass. Once dissolved in groundwater, surface and volume deposited radionuclides react with aquifer minerals, often exhibiting strong sorption properties that retard their movement.

The gaseous radionuclides produced from the detonation, such as tritium (T, or hydrogen-3), Kr-85, and C-14 are much more mobile in the Gasbuggy subsurface environment than the surface and volume deposited radionuclides. The total amount of tritium resulting from the nuclear test was estimated as about 40,000 Ci (Tewes, 1979). As of 2014, due to decay, offsite disposal, and well testing, there are approximately 2,830 Ci of tritium remaining in the subsurface. The present-day amounts of C-14 and Kr-85 are considered negligible and are not considered here. A more complete explanation of the radionuclide inventory is presented in Cooper and Chapman (2015).

Explosion Phenomenology and Conceptual Model of Flow and Transport

The nuclear device was detonated at a depth of 1,292 m (4,240 ft) below ground surface. The resulting heat vaporized rock and created a void (cavity) with a radius of 25 m (Rawson *et al*., 1968). The formation of the cavity meant that some overburden rock was no longer supported; within 30 seconds of the detonation geophones detected collapse of the overburden into the cavity, resulting in a

rubble-filled chimney (Smith, 1970). The pressure wave from the detonation exceeded lithostatic pressure radially 146 m from the working point, which fractured the surrounding rock. This distance is based primarily on the fact that a cable break in well GB-1, located 146 m radially from the shot point, was most likely caused by the detonation (the predicted fracturing radius was 130 m (425 ft). The chimney is thought to extend vertically from 28 m below the working point to 100 m above, to the top of the Pictured Cliffs Formation. While the bottom of the chimney is uncertain, post-shot drilling in well GB-ER strongly supports the elevation of the top of the chimney.

Pore fluids in the Lewis Shale, Pictured Cliffs, and Fruitland formations are about equally divided (by volume) between water and natural gas. The primary components of the gas phase are water vapor and methane, with progressively lesser amounts of higher-chained petroleum compounds (butane, ethane, pentane, etc.). The intrinsic permeability of the rock matrix (the pore space, excluding fractures) is so small that gas production is unfeasible without artificially fracturing the rock. Most of the gas flow, therefore, is through the slightly more permeable natural fractures, as well as fractures created during development of the reservoir. Each phase is assumed to be continuous throughout the reservoir and capable of flowing in response to its own potential energy gradient.

At Gasbuggy, the very low intrinsic permeability, coupled with approximately 50 percent gas-filled pore space, results in the liquid water phase being much less mobile than the gas phase. Additionally, radionuclides subject to the liquid phase are retarded in their movement by dissolution and solubility constraints and sorption processes. As a result, the focus of the radionuclide transport calculations is on the most abundant gas-phase radionuclide, tritium.

Tritiated liquid water (HTO_l) is always available for partitioning when in contact with an aqueous phase. At Gasbuggy, the aqueous phase is practically immobile and acts as a source/sink for tritium; in other words, a water vapor not containing tritium that comes in contact with tritiated liquid water will thermodynamically exchange tritiated water molecules from the aqueous to the vapor phase and vice versa. A complete explanation is given in Cooper and Chapman (2015). (Note that throughout the rest of this report, “tritium” refers to tritiated water (HTO), as either a liquid or gas.)

Both diffusive and advective transport are subject to processes that retard the migration of tritiated water. One of these processes is the exchange that occurs between tritiated water in the aqueous and gas phases. With aqueous-phase velocities much smaller than those in the gas phase, tritiated water exchanging into the aqueous phase encounters a significantly retarded flow velocity. As tritiated water vapor migrates downgradient, it encounters tritium-free liquid water and exchange occurs, removing tritiated water from the faster (gas phase) pathway. The second significant process is radioactive decay. The half-life of tritium is 12.32 years, decaying into nonradioactive helium. Thus, with time, the amount of tritium mass continually decreases. This accentuates the impact of exchange, because tritiated water transferred into the aqueous phase is essentially removed by decay. No other sorption or retarding processes are included in the transport model.

Formulation of the Numerical Model

The conceptual model includes flow and transport as fully coupled processes that must be solved simultaneously to get a realistic understanding of the spatial and temporal distribution of radionuclides within the reservoir. The Transport of Unsaturated Groundwater and Heat (TOUGH2) simulator (Pruess, 1991; Pruess *et al.*, 1999) was used to implement the flow and transport model. TOUGH2 is a DOE-sponsored code that has been used to study heat and mass flow in geothermal reservoirs, saturated/unsaturated groundwater environments, and oil and gas reservoirs. TOUGH2 can simulate fully coupled, transient, three-dimensional, multiphase and multicomponent nonisothermal (temperature dependent) flow. As implemented with the EOS7r equation of state module, TOUGH2 solves equations for two phases (gas and liquid) and five components: water, methane (replaces air), brine (not considered), radionuclide 1 (tritiated water), and radionuclide 2 (helium, the decay component of tritium, though it is not radioactive and is ignored). The gas phase is composed of methane, water vapor, tritiated water vapor, and helium. The liquid phase is composed of water, tritiated water, dissolved methane, and dissolved helium.

The model is 2000 m long in the *x*-direction, which is oriented N35E, N55W, or NS (Lorenz and Cooper, 2003) and is 340 m thick (Figure 2). The top of the model is located in the Fruitland Formation, 1,090 m below the land surface, and 100 m above the bottom contact with the Pictured Cliffs Sandstone. The domain is constructed such that the emplacement borehole GB-ER is centered in the rectangular solid comprising the chimney.

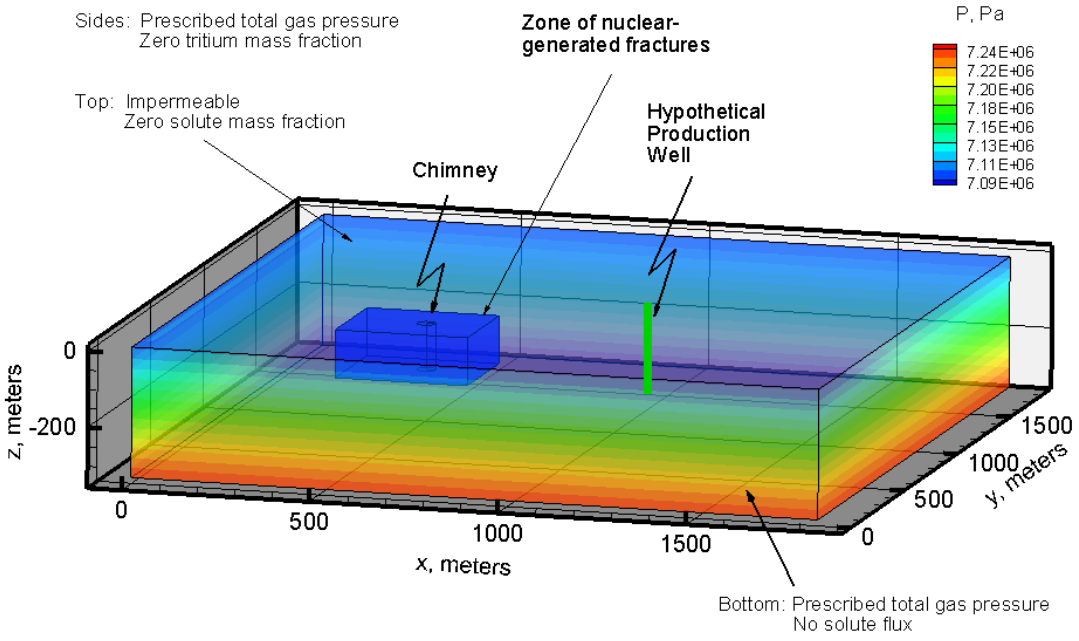

Figure 2. Computation domain showing boundary conditions on all six sides, location of chimney and hypothetical production well. The steady-state pressure field is shown in Pascals. The top of the model is 1,090 m below ground surface.

A vertical cross section of the model domain is shown in Figure 3. The nuclear chimney has a radius of 25 m, with detonation-caused fractures extending from 25 m to 150 m in the Lewis Shale and 25 m to 120 m in the Pictured Cliffs Sandstone. After achieving steady state flow for the time leading up to the nuclear detonation, the chimney was added to the model domain, along with the detonation-associated fractures to allow tritium to diffuse radially away from the chimney. After 47 years (i.e., 2014), the simulation was stopped, a hypothetical gas production well was placed in the domain, along with hypothetical fractures, and the model was allowed to run for an additional 100 years, until the tritium mass fraction was essentially reduced to zero everywhere in the model as a result of dilution and radioactive decay.

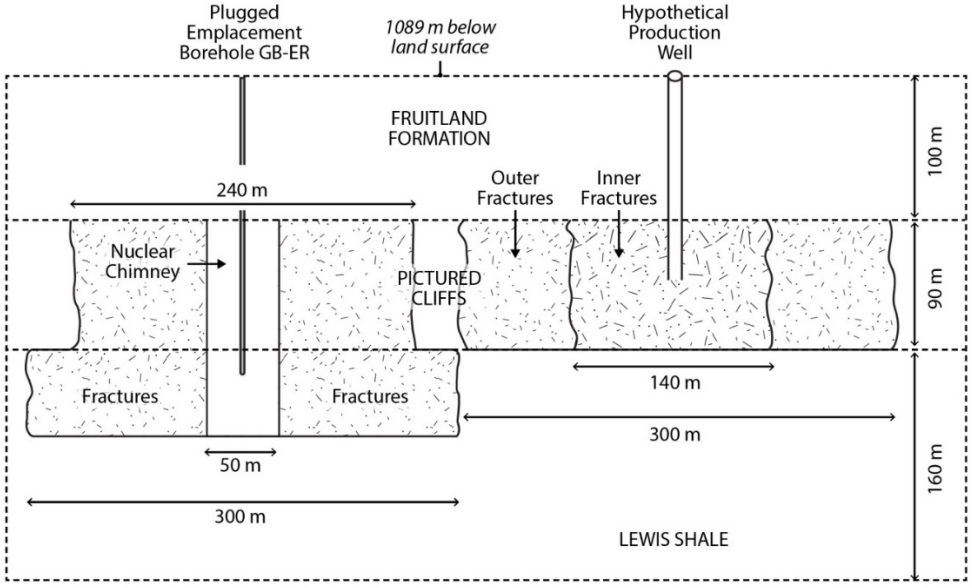

Figure 3. Cross section of model domain; the bottom 100 m of Ojo Alamo Sandstone, Kirtland Formation, and Fruitland Formation overlies the 90 m high Pictured Cliffs Sandstone, which overlies the top 160 m of the Lewis Shale. The detonation (1,292 m below the land surface) is 203 m below the top of the model domain. The lower part of the chimney occupies the upper 40 m of the Lewis Shale.

Boundary Conditions

The bottom horizontal boundary of the model is prescribed 7.24 MPa (1,050 psi; Ward and Lemon, 1968) total gas phase pressure, which remains fixed throughout each simulation. The aqueous-phase pressure is adjusted internally by TOUGH2 through the capillary pressure function. The upper boundary was prescribed zero fluid flux, to simulate a bed of low-permeability. The thickness of the domain was set large enough such that it would be less than the distance tritium would travel vertically (through diffusion or vertical pressure gradients possibly induced by gas production at a nearby well), and therefore not constrain vertical transport. After setting the bottom boundary pressure at 7.24 MPa, all four vertical (side)

boundaries bordering the computational domain were run in a separate simulation to steady state; these were then used as the initial conditions for the four vertical boundaries. The domain (2,000 m x 2,000 m x 340 m high) was made large so that the vertical boundaries would not affect flow and transport calculations around the chimney and gas production well.

At each boundary, the solute (i.e., tritium) transport boundary condition is equivalent to the respective hydraulic boundary condition. That is, zero solute concentration (as mass fraction) is prescribed in the aqueous phase on the bottom as well as each of the vertical boundaries. The reservoir was assumed to be isothermal with a temperature of 54°C.

Flow Model Parameters

All input data used in the model are presented in Table II. Data that are site specific, such as intrinsic permeability, porosity, and initial phase saturations, were gathered from reports specific to the nuclear test as well as from published literature.

The free-air (for gases) and molecular (for liquids) diffusion coefficients are multiplied by a tortuosity factor to account for the complicated paths in the porous medium and fractures that effectively lengthen the travel path. Tortuosity was modeled using the Millington and Quirk (1961) phase-dependent formulation. Since gas flow is assumed to occur primarily through fractures, tortuosity was made constant so that it would not vary with gas saturation, which was assumed to always be close to unity (Cooper *et al*., 2009). The tortuosity constants were developed for a porosity of 0.1 and gas phase saturation 0.4 and are 0.0219 for the gas phase and 0.0846 for the aqueous phase. These values are multiplied by the infinite-dilution diffusion coefficients in Table II to obtain the true diffusion coefficients used in the model.

Radioactive Source Values

As discussed above, the total amount of tritium at present day, due to decay, is approximately 2,830 Ci. All tritium is assumed to exist in the gas and aqueous phases, that is, none is assumed to be embedded in the melt glass. The tritium source is initiated in the model as mass fraction in the aqueous phase, which partitions thermodynamically (based on Henry's law) into the gas phase during the first time step. Mass fraction of tritium in a given phase is the ratio of tritium mass in the phase to the total mass of the phase. The initial mass fraction of tritiated water in the aqueous phase (X_l^{HTO}; mass of tritiated water in the aqueous phase per unit mass of liquid water) is 4.6×10^{-10}.

DISCUSSION OF RESULTS

The first step in the modeling sequence was to run a simulation without tritium to steady state in order to establish a dynamic steady state between gravity, pressure, and capillary forces throughout the solution domain. This steady state simulation is considered to approximate reservoir conditions prior to the Gasbuggy test. At the conclusion of the steady-state simulation, the resulting pressure and

TABLE II. Input data for the simulations. Justification for all parameters is given in Cooper and Chapman (2015).

Gas Reservoir Parameters		
Parameter	Value	Source
Intrinsic permeability, *x*-, *y*-, *z*-dir, Pictured Cliffs, m^2	10^{-16}	Ward and Lemon, 1968
Intrinsic perm., Fruitland Formation, m^2	10^{-17}	NM Oil & Gas
Intrinsic perm., Lewis Shale, m^2	1.5×10^{-17}	Dube *et al*., 2000
Intrinsic perm., nuclear chimney, m^2	10^{-13}	calibrated
Intrinsic perm., explosion-generated fracture EPM, m^2	10^{-14}	calibrated
Intrinsic perm., “inner” hydraulic fractures, m^2	5×10^{-14}	assumed 500*k* of PC
Intrinsic perm., “outer” hydraulic fractures, m^2	5×10^{-15}	assumed 500*k* of PC
Porosity, Pictured Cliffs Sandstone	0.10	Ward and Lemon, 1968
Porosity, Lewis Shale	0.05	Dube *et al*., 2000
Porosity, Fruitland Formation	0.09	NM Oil & Gas
Porosity, nuclear chimney	0.34	calibrated
Porosity, explosion-generated fractures	0.1	calibrated
Porosity, hydraulic fractured sandstone	0.1	best estimate
Capillary pressure, Pictured Cliffs	TRUST fit	Core Laboratories, 1971
Relative perm., PC, Lewis Shale, Fruitland Fm	van Genuchten	v.G., 1980; see text for parameters
Capillary pressure, Lewis Shale & Fruitland Fm	van Genuchten	v.G., 1980; see text for parameters
^3H radioactivity, liquid and gas, Ci	40,000	Smith, 1970
Diffusion coeff., HTO in methane, $m^2\ s^{-1}$	2.92×10^{-5}	Cussler, 1997
Diffusion coeff., HTO in liquid water, $m^2\ s^{-1}$	3.47×10^{-9}	Mills, 1973
Diffusion coeff., CH_4 in liquid water, $m^2\ s^{-1}$	1.49×10^{-9}	Reid *et al*., 1987
Tortuosity	const.	See text
^3H half-life, yr	12.32	Lucas and Unterweger, 2000
Initial Conditions		
Parameter	Value	Source
Formation pressure at base, MPa	7.24	Ward and Lemon, 1968
Gas saturation	0.6	Ward and Lemon, 1968
Reservoir temp., °C	54	Ward and Lemon, 1968
Mass fraction tritium in aqueous phase	4.6×10^{-10}	Calculated, see text

liquid saturation fields (i.e., P and S_l at each grid block) were used as the initial condition for a 47-year tritium transport simulation, from late 1967 through 2014. The rock conditions were then changed—their permeability, porosity, capillary pressure and relative permeability functions—for the grid blocks which become the chimney and surrounding nuclear-generated fractures. The model was restarted to simulate tritium transport for the 47-year period. Figure 2 shows the initial conditions in 1968. Although gas production testing of GB-ER occurred through November, 1969, the gas production tests were not included in the model in order to maximize transport away from the chimney. If included, production testing would act to confine radionuclides to the chimney and nearby fractures and limit their diffusion away from it during the testing period. Although gas production during testing was not modeled, tritium removed from the subsurface during production testing was accounted for in the tritium balance, as discussed previously.

The total pressure at the bottom of the chimney increased due to drainage of water through the (now) highly permeable rocks comprising the chimney, and its ponding at the base. This created a slight outward pressure gradient of both phases, which along with gas-phase diffusion, contributed to tritium migration away from the chimney in all directions. Figure 4 shows tritium concentration (as mass fraction of tritiated water) in the gas phase (X_g^{HTO}) at the start of the 47-year period. Aqueous-phase tritiated water is uniformly applied to all chimney grid blocks at X_l^{HTO} = 4.6 x 10^{-10}, and partitioned after the first time step (1 second) into the aqueous and gas phases. As dictated by Henry's law, the bulk of tritium stays in the aqueous phase, such that the mass fraction in the aqueous phase is essentially unchanged, while a small amount partitions into the much less-dense gas phase (initial X_g^{HTO} = 7.6 x 10^{-12}).

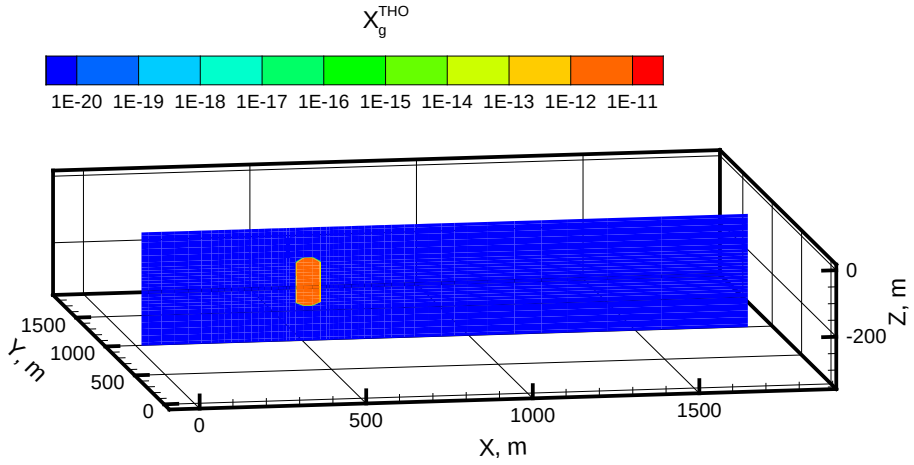

Figure 4. Initial mass fraction of tritium in the *gas* phase (X_g^{HTO}, or tritiated water vapor) in December, 1967, at the start of the simulation. This and subsequent figures display a two-dimensional slice through the three-dimensional model domain. The colors represent tritium concentration in the gas phase, as mass fraction.

By 1993, 26 years after the detonation, tritium has spread as far as 110 m from the detonation point in the upper part of the Lewis Shale (Figure 5). By 2014 (Figure 6), diffusion in both phases has slowed to a point where it is balanced by radioactive decay, and the leading edge of the tritium is still at 110 m, so it appears that tritium has stopped diffusing (although it actually has not), and that the tritium mass fraction is diminishing solely by radioactive decay. Tritium in the aqueous phase (not shown) has a similar appearance to tritium in the gas phase, though the values are different. The reason that the tritium extent is matched in the two phases is that tritium travels in the higher diffusivity and permeability gas phase, but continually dissolves into the aqueous phase (thermodynamically, not kinetically) where it is able to achieve a mass fraction several orders of magnitude greater than the gas phase.

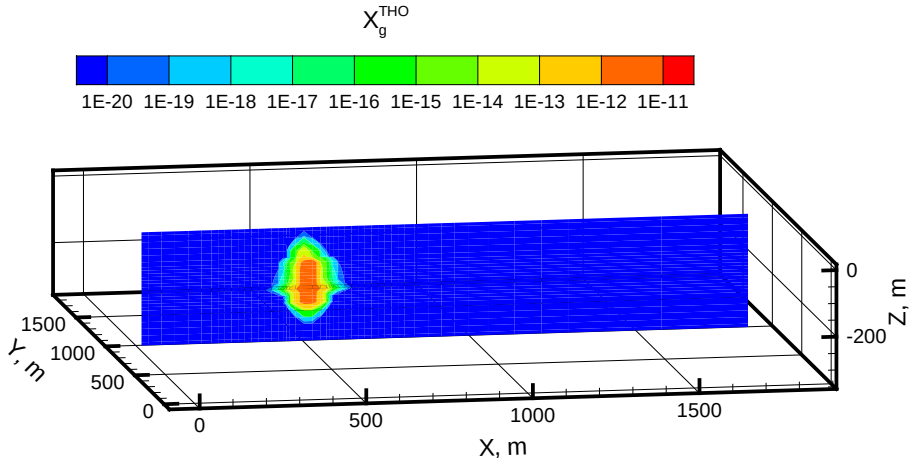

Figure 5. Mass fraction of tritiated water vapor in 1993, 26 years after the detonation.

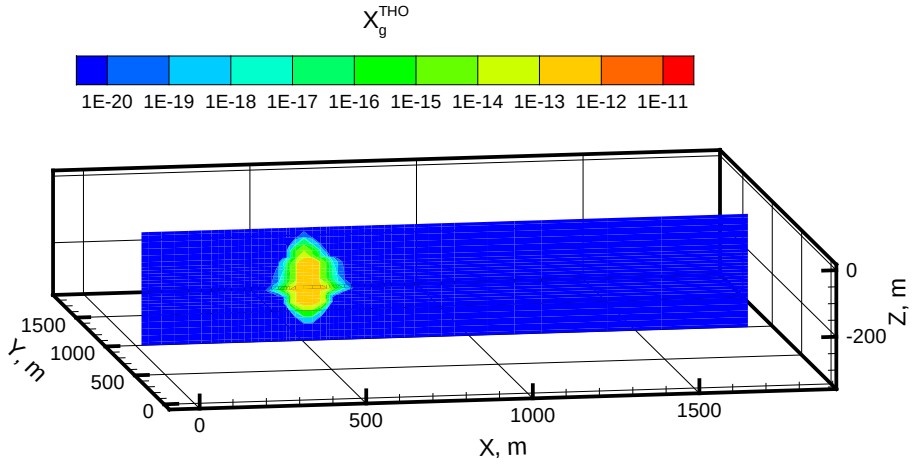

Figure 6. Mass fraction of tritiated water vapor in 2014, 47 years after the detonation.

Tritium Migration During Gas Production

The model of unstressed (i.e., no gas production from wells) conditions was run for 47 years to present day, at which time the simulation was stopped and a producing gas well was added to the domain. The well is located 340-m distant along the principal axis, producing from a 10-m interval located in the middle of the Pictured Cliffs Sandstone. The choice of well location was guided by the desire to find the minimum distance that a well could be placed from the working point and produce gas for 30 years without capturing tritium from the detonation. The well was assumed to operate on deliverability against a 2.75 MPa (400 psi) wellhead pressure. The mass fraction field of tritiated water vapor eight years after the start of production (year 2022) shows the definite influence that gas production has on the flow of tritium through the Pictured Cliffs, while almost no effect on flow through the unfractured Lewis Shale is observed (Figure 7). At this time, the leading edge of the tritium plume has migrated 130 m from the working point and the mass fraction of HTO in the gas phase at the leading edge is X_g^{HTO} = 3 x 10^{-18}. After 30 years of production (year 2044), the leading edge of the plume is 230 m from the detonation, and 90 m from the gas well (Figure 8). No tritium has reached the well at that time.

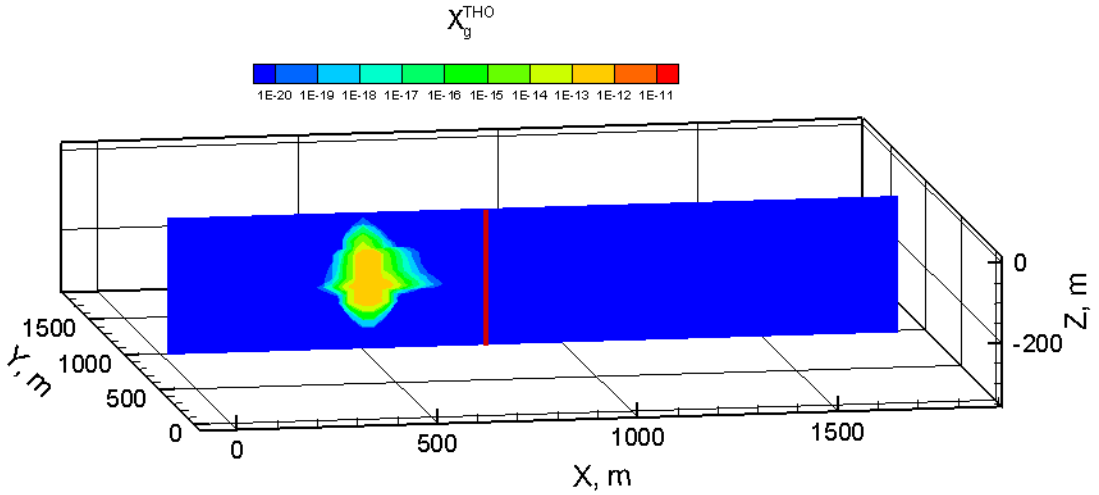

Figure 7. Mass fraction of tritiated water vapor in 2022, 55 years after the detonation and 8 years after the start of gas production from a hypothetical well (red vertical line) located 340 m from the detonation. Gas production is from a 10-m interval located at the center of the Pictured Cliffs Sandstone.

After 30 years of gas production, the mass fraction of tritium in the aqueous phase, X_l^{HTO}, at the leading edge of the plume is 2 x 10^{-18}. Tritium above background never reaches the well not only because the gas velocities are small, but also because the gas is diluted due to radial flow. In addition, the 12.32-year half-life of tritium means that 3.8 half-lives have passed since the detonation through 2014.

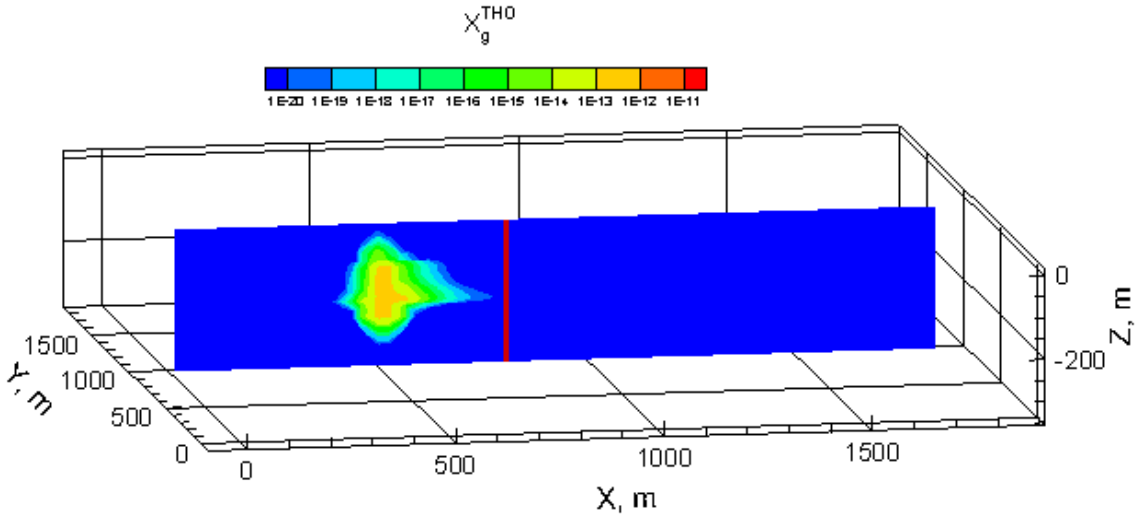

Figure 8. Mass fraction of tritiated water vapor after 30 years of gas production, in the year 2044.

CONCLUSIONS

The Gasbuggy dual-phase model provides information to support strategic planning for long-term surveillance and maintenance of the Gasbuggy site. Based on the model, the extent of tritium migration (as tritiated water, HTO) from the nuclear detonation as of 2014 is expected to be approximately 110 m from the working point, with most of this transport through the chimney and surrounding rock fractured by the detonation. The main transport process is diffusion in the gas phase. Aqueous phase diffusion (i.e., through liquid water) also occurs, but is a much slower process—typically two orders of magnitude slower owing to the difference in diffusion coefficients for HTO in gases and liquids. However, diffusion in each phase is not an isolated process; the phases are coupled by the ability of HTO to transfer from the gas phase into the aqueous phase in a proportion such that at any time, over 100 times more tritiated water exists in the aqueous phase as in the gas phase. The important point is that although tritium *migrates* primarily as gas HTO, it is primarily *stored* as liquid water. Tritium migration is primarily a function of porosity and tortuosity. Since the tortuosity of fractures is unknown, the conservative approach was taken that they are straight, resulting in faster (and farther) migration than would occur through more tortuous pores in the rocks. Other gaseous radionuclides, C-14 and Kr-85, were largely removed from the chimney during production tests that followed the detonation.

The model was also used to explore possible future scenarios and assess their impact on contaminant migration. A scenario in which a hypothetical production well was assumed to produce gas for 30 years from a ten-meter interval in the middle (vertically) of the Pictured Cliffs Sandstone investigated the impact of nearby production on tritium migration. A gas well located 340 m from the working point was placed in the domain. Gas was produced on deliverability at a pressure of 400 psi (2.75 MPa) from an assumed hydraulically fractured region with a

permeability greater than the native permeability. The drainage radius reached the chimney within three years of gas production, and clearly induced tritium migration toward the well, though tritium did not ever reach it. HTO above background concentration came to within 90 m of the well, but the combination of low permeability to gas, low pressure gradient, radioactive decay, and dilution with uncontaminated gas resulted in no HTO above background reaching the well. The well was located directly in line with the principal direction of the hydraulic fractures; wells located off of this trend could theoretically be located closer to the chimney without inducing significant transport, since the permeabilities would be lower when not aligned with the principal stress direction. Conceptual and numerical modeling are not only valuable for evaluating past activities, but can also be powerful tools for site managers to assess the impact of proposed activities that may be disruptive to the subsurface.

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