LMS/RUL/S04617

Path Forward for Gas Drilling near the Rulison, Colorado, Site Revision 1

December 2019

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Abbreviations

COGCC	Colorado Oil and Gas Conservation Commission
DOE	U.S. Department of Energy
ft	feet
psi	pounds per square inch
R-E	emplacement hole
R-En	reentry well
R-EX	exploration well

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Executive Summary

The U.S. Department of Energy (DOE) Office of Legacy Management developed this report as a guide for discussions with the Colorado Oil and Gas Conservation Commission (COGCC) and other interested stakeholders in response to drilling for natural gas reserves near the underground nuclear test site at Rulison, Colorado. The Rulison site is located in the Piceance Basin of western Colorado, 40 miles northeast of Grand Junction. The Rulison underground nuclear test was the second natural gas reservoir stimulation experiment in the Plowshare Program, which was designed to develop peaceful uses for nuclear energy. On September 10, 1969, the U.S. Atomic Energy Commission, a predecessor agency of DOE, detonated a 40-kiloton nuclear device 8425 feet below the ground surface in an attempt to release commercially marketable quantities of natural gas. The blast vaporized surrounding rock and formed a cavity and collapse chimney. Although the contaminated materials from reentry drilling operations were subsequently removed from the surface of the site, remnant radioactive contamination remains in or around the detonation zone.

Drilling for natural gas is approaching the site and has raised concerns about the possibility of encountering radioactivity from the area of the detonation. DOE prohibits drilling in the 40-acre lot surrounding the site below a depth of 6000 feet. DOE does not believe contamination will migrate beyond the 40-acre institutional control boundary of Lot 11. This is based on geologic conditions that require wells to be stimulated by hydraulically fracturing the surrounding formation. The close spacing of the wells indicate that fluid migration is limited to the vicinity of the fracturing and the nuclear fractures surrounding the Rulison detonation are contained within Lot 11. Additionally, no test-related radionuclides have been observed at current producing wells 0.75 mile west of the site. The COGCC established two wider boundaries around the site. When a company applies for a permit to drill within a 2-mile radius of surface ground zero, COGCC notifies DOE and provides an opportunity to comment on the application. COGCC also established a 0.5-mile radius around surface ground zero. An application to drill within 0.5 mile requires a hearing before the commission.

This report outlines DOE’s recommendation that gas developers adopt a conservative, staged drilling approach allowing gas reserves near the Rulison site to be recovered in a manner that minimizes the likelihood of encountering contamination. This staged approach calls for collecting data from wells outside the 0.5 mile zone before drilling closer, and then drilling within the 0.5-mile zone in a sequential manner, first at locations with low contamination probability and then moving inward. DOE’s recommended approach for drilling will protect public safety while allowing the collection of additional data to confirm that contamination is contained within the 40-acre institutional control boundary of Lot 11.

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1.0 Introduction

The U.S. Department of Energy (DOE) Office of Legacy Management developed this report as a guide for discussions with the Colorado Oil and Gas Conservation Commission (COGCC) and other stakeholders in response to natural gas drilling near the Rulison, Colorado, Site. The Rulison site was the location of an underground nuclear test in 1969 that resulted in residual radionuclide contamination at the detonation depth of 8425 feet (ft). This Path Forward encourages gas developers to adopt a conservative, staged-drilling approach that allows gas reserves near the Rulison site to be recovered in a manner that minimizes the likelihood of encountering nuclear detonation-related contamination. This approach recommends drilling wells in the locations least likely to encounter contamination first and monitoring to confirm no contamination is present before proceeding to the next set of nearer locations.

This revision to the Path Forward provides an update to the original document completed in 2010 (DOE 2010) and includes the most recent available data for the site. Flow and transport modeling that simulates the implementation of the Path Forward indicates that contamination should remain within the Rulison site boundary, which is also the institutional control boundary and identified as Lot 11 (Figure 1). There is no evidence that leads DOE to suspect that contamination from the Rulison site detonation has migrated or will ever migrate beyond the site boundary. This approach to drilling new gas wells is suggested as a way to further enhance public safety while allowing additional data to be collected to confirm that the institutional controls are protective. Section 1.4 defines the institutional controls for the site. Figure 1 provides the location of the Rulison site.

1.1 Location and Background

The Rulison site is within the Piceance Basin of western Colorado, 40 miles northeast of Grand Junction in Garfield County (Figure 1). The site is identified as Lot 11, which is 40 acres of land situated in Section 25, T7S, R95W, of the 6th Principal Meridian. The Mesaverde Group formations within the Piceance Basin contain significant reserves of natural gas in poorly connected, low-permeability (tight) sandstone lenses. The Rulison test was designed and conducted to evaluate the use of a nuclear detonation to fracture the surrounding rock and enhance natural gas production in the Williams Fork Formation of the Mesaverde Group (Figure 2). Figure 2 provides a cross section showing the stratigraphic units of the Piceance Basin.

A 40-kiloton nuclear device was detonated in the emplacement hole (Hayward A 25-95 [R-E]) at a depth of 8425 ft on September 10, 1969 (DOE 2015). The detonation produced extremely high temperatures that vaporized a volume of rock, temporarily creating a cavity surrounded by a fractured area extending outward from the detonation point (AEC 1973). Shortly after the detonation, the overlying fractured rock collapsed into the void space, creating a rubble-filled collapse chimney that extends above the detonation point. The former cavity, now the lower part of the collapse chimney and the surrounding fractured rock are together referred to as the detonation zone. A reentry well (R-En) was drilled as a sidetrack hole off the exploration well (Hayward A 25-95 [R-EX]) into the collapse chimney and tested to evaluate the success of the detonation at improving gas production in the low-permeability sandstone reservoir. Four production tests conducted on the reentry well between October 1970 and August 1971 produced a total of 455 million standard cubic feet of natural gas. The estimated volume of gas extracted during the testing was approximately 10 times that of a conventionally stimulated well in the

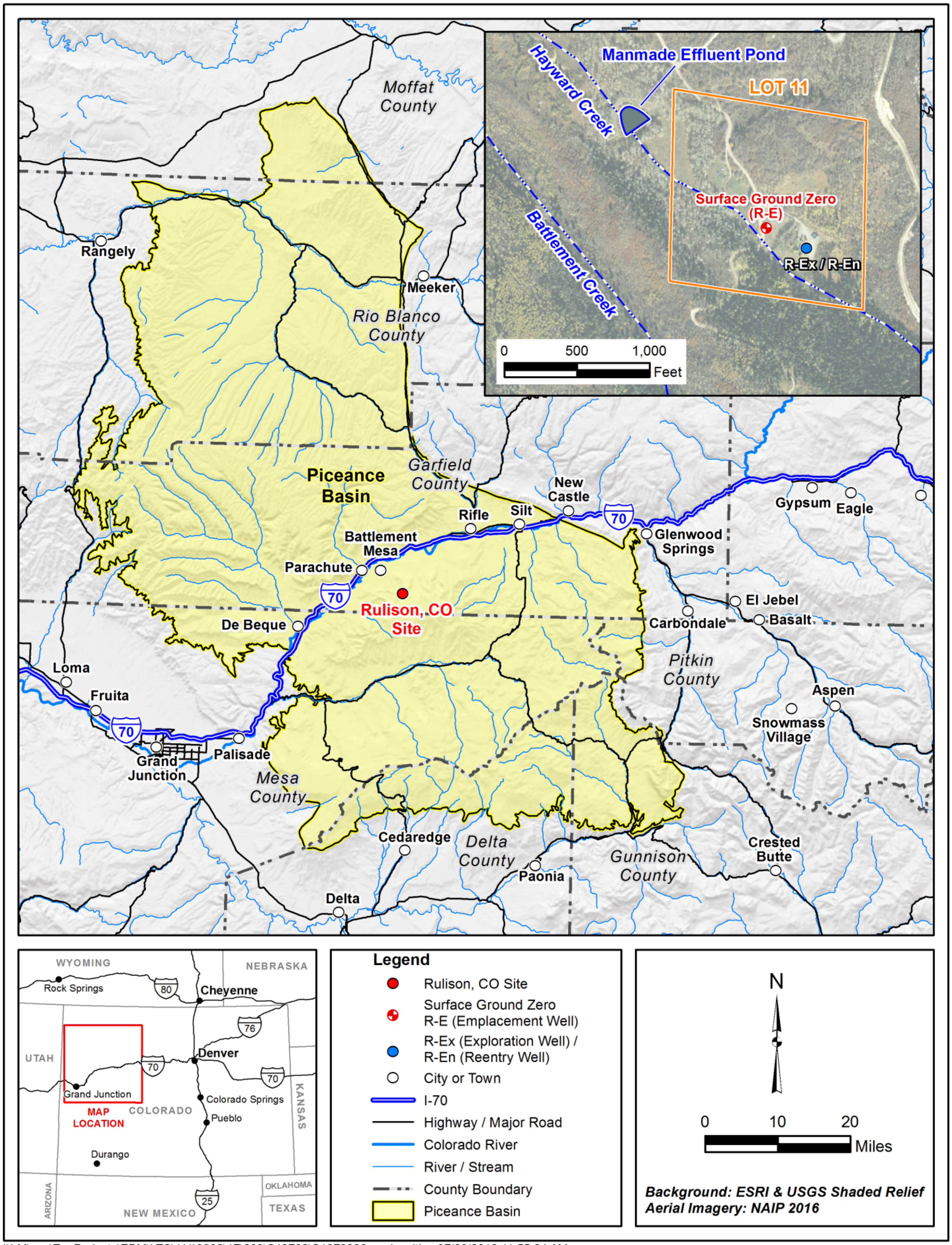

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Figure 1. Rulison site location map and institutional control boundary (Lot 11)

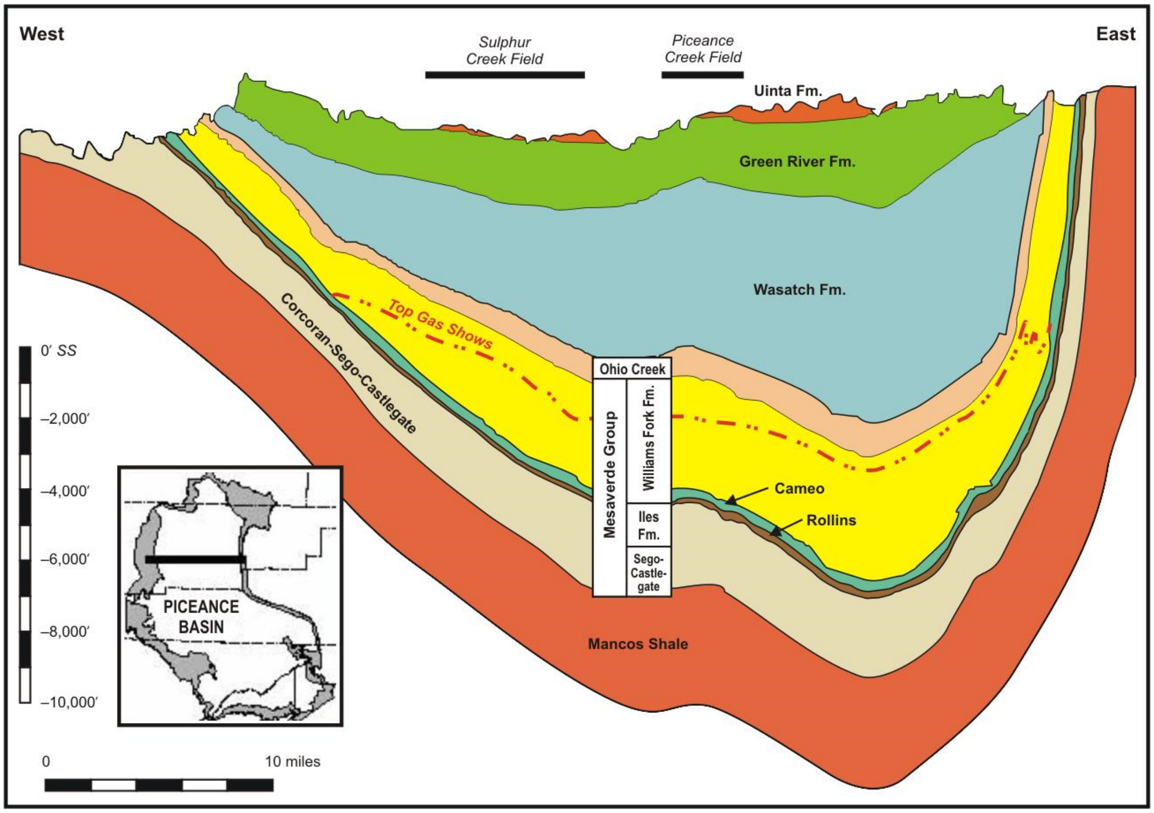

Figure 2. Piceance basin cross section (modified from Yurewicz 2003)

same production zone (AEC 1973). Radionuclide concentrations decreased throughout the production testing, but the remaining presence of radionuclides within the produced gas made it unmarketable. In 1976, the participating parties agreed that there would be no gas production in the future at the site, the R-En and R-Ex wells were abandoned, and a deed restriction was established for the site (Lot 11). The deed restriction prohibits penetration or withdrawal of any material below 6000 ft within the boundary of Lot 11 unless authorized by the U.S. government.

The COGCC has decision authority over applications for permits to drill oil and gas wells in Colorado and has imposed administrative controls on drilling in the vicinity of the Rulison site. The controls are necessary because the ability to enhance natural gas production from tight sands has become practical through advances in hydraulic fracturing technology (hydrofracturing). This technology has led to an increase in drilling activity near the site, raising concerns that nuclear detonation-related contamination currently contained in the subsurface could be released through a gas well drilled too close to the site (Lot 11). The COGCC requires that gas well operators adhere to a prescribed sampling and analysis plan (COGCC 2017) for approval of permits in this area (COGCC 2007). DOE has also implemented a monitoring program that emphasizes the sampling of gas wells near the site, specifically those with a bottom-hole location of 1 mile or less from the detonation, depending on the direction relative to the natural fracture trend of the producing formation (DOE 2018). The COGCC notifies DOE of any drilling permit activity within approximately 2 miles of the site. There are currently no active gas wells within a 0.5-mile radius of the site, and any future permits to drill wells in this area will require a hearing with COGCC and approval by the commission prior to installation (COGCC 2007). Figure 3 shows the active gas wells near the site with the planned (permitted) wells not yet installed.

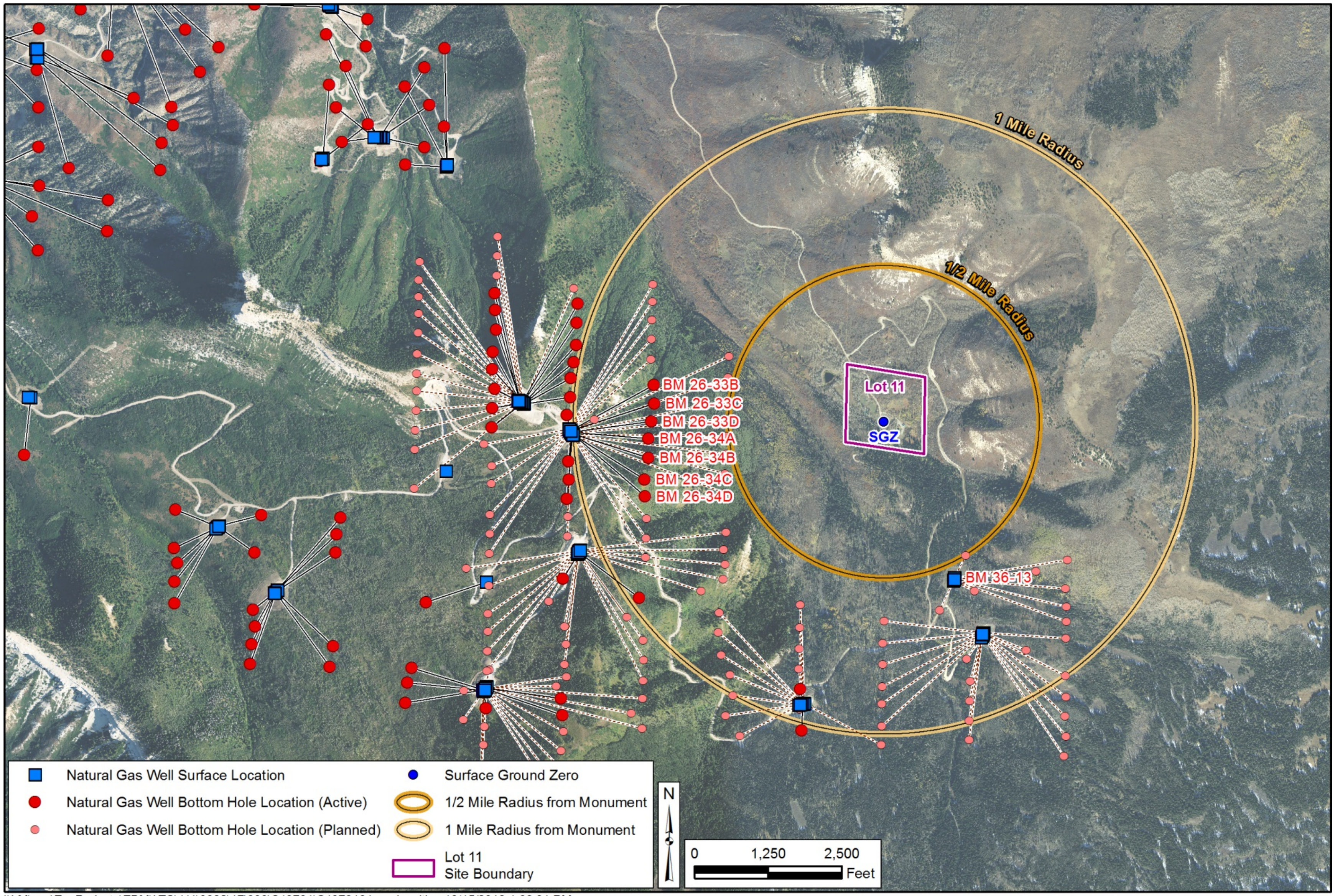

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Figure 3. Site and well location map of the Rulison, Colorado, site

1.2 Source of Contamination

Surface and subsurface contamination resulted from the underground nuclear test at Rulison. The surface contamination was excavated and removed in 1996, and the Colorado Department of Public Health and Environment approved closure of the surface with no further actions in 1998. Subsurface contamination remains in the detonation zone near the R-E emplacement hole. The detonation zone consists of a former cavity, collapse chimney that extends about 275 ft above the detonation level, and fractured rock that extends an estimated 209 ft radially from the detonation level (Figure 4). The extent of the surrounding fractured zone is based on analysis of data from the reentry well production testing that indicated a 33-fold increase in permeability to a distance of 2.75 cavity radii (Montan 1971; Rubin, Schwartz, and Montan 1972). The detonation level is approximately 650 ft from the east and west lot boundaries and approximately 450 ft from the southern lot boundary. Figure 4 is a schematic cross section that illustrates the detonation zone.

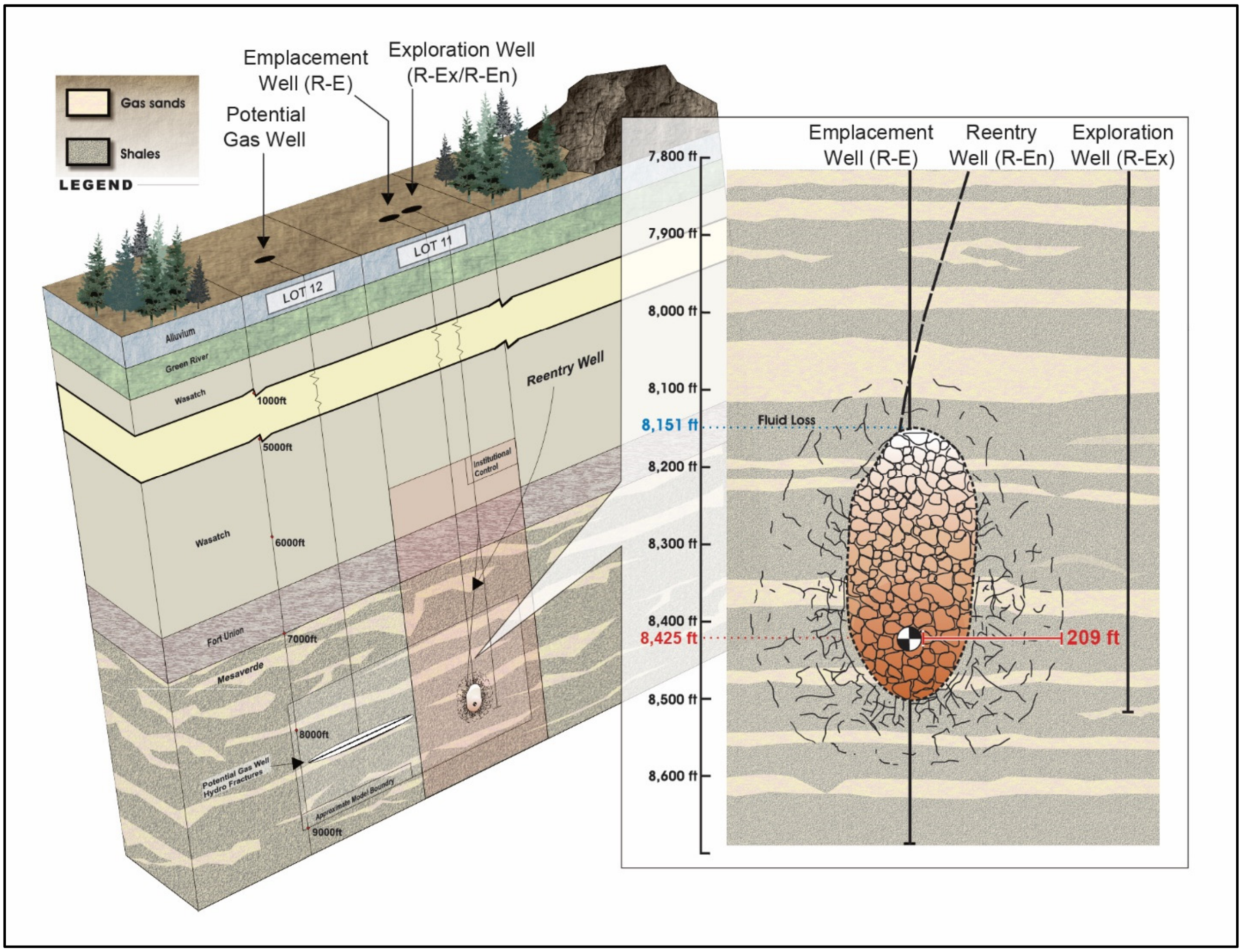


Figure 4. Schematic cross section of the Rulison site detonation zone

Most of the longer-lived radionuclides produced by the detonation are solid at relatively high temperatures and were incorporated within the molten rock as it cooled to form a melt glass at the bottom of the former cavity. When water-saturated rock is in contact with the melt glass, the solidified radionuclides can be subject to dissolution by and transport with passing groundwater. Studies of radionuclide releases to and transport within groundwater at underground tests on the Nevada National Security Site (formerly known as the Nevada Test Site) discuss the physical and chemical phenomena that influence the dissolution and transport processes (e.g., Tompson et al. 1999, Pawloski et al. 2001). These studies indicate that most of the radionuclides incorporated in the melt glass at the bottom of a detonation cavity are released to groundwater very slowly. Moreover, transport away from the cavity is typically impeded because the dissolved radionuclides either sorb to mineral grains or react chemically with the geologic media, and radionuclide movement is retarded with respect to groundwater movement.

The potential for contaminant migration from the detonation zone at the Rulison site is further reduced by the low native permeability of the surrounding formation. Additionally, the relative permeability of the liquids is several orders of magnitude lower than that of the gas. Though dissolution of radionuclides from melt glass at the bottom of a cavity can represent a long-term source of subsurface contamination at some sites, the potential for transport of dissolved radionuclides away from the former cavity area at the site is considered insignificant.

Several of the longer-lived radionuclides produced by the detonation in quantities great enough to potentially affect public health or the environment (tritium, krypton-85, and carbon-14) do not solidify at lower temperatures and can exist in either the liquid or gas phases. When present in the gas phase, these radionuclides are far more mobile than those bound in the solid phase or dissolved in the liquid phase. Tritium (an isotope of hydrogen) is primarily present as tritiated hydrogen gas (HT in place of H_2), tritiated methane (CH_3T in place of CH_4), or tritiated water (THO in place of H_2O). Carbon-14 is primarily present as part of the methane molecule or carbon dioxide molecule ($^{14}CH_4$ in place of $^{12}CH_4$ or $^{14}CO_2$ in place of $^{12}CO_2$), and krypton-85 is an inert gas. The flaring of gas during production testing on the reentry well removed almost all the carbon-14 and krypton-85 created by the detonation (AEC 1973), leaving tritium as the most mobile radionuclide that remains in quantities sufficient to pose a potential health concern. The 10,000 curies of tritium produced by the detonation were reduced to 7000 curies by production testing extraction and to a lesser degree by decay. By 2018, the quantity remaining after post-production testing has since decayed to less than 500 curies of activity. Tritiated water occurs both as liquid water and as water vapor, allowing it to readily migrate with either the liquid phase (less mobile formation water) or the more mobile gas phase. The gas phase is about 1000 times more mobile than liquid in the gas-bearing reservoirs and the only gas-phase radionuclide that remains in significant quantities after reentry well testing and decay is tritium, as tritiated water. Some tritium might also be incorporated in the solidified melt glass, though to be conservative in considering potential migration scenarios; it is assumed that all the remaining tritium is in the liquid or gas phases.

The upward migration of radionuclides to a depth at which they might affect public health or the environment solely via natural pathways (with fluids moving through pores and fractures) is extremely unlikely due to the depth of burial (more than 8000 ft) and the low permeability of the surrounding formations, which limit fluid movement. The detonation zone is in the lower part of the approximately 2500 ft thick Williams Fork Formation, more than 1000 ft below the overlying Ohio Creek Formation, and also below an unnamed formation and the Wasatch Formation

(Figure 2), which have a combined thickness of about 4400 ft at the Rulison site (Voegeli 1969). The pores of the tight, poorly connected sandstone reservoirs of the Williams Fork contain approximately 50% gas and 50% formation water (brine) and are isolated within lower-permeability shale. The need to use hydraulic fracturing methods to affect even small areas (each well drains roughly a 10-acre area) supports the concept that there is essentially no movement of fluids within any time frame of significance for tritium migration to be of concern. In the absence of wells that penetrate near the detonation zone, there is no realistic pathway for contamination to reach the surface or near-surface. Thus, the potential transport mechanism for tritium at the Rulison site is as tritiated water vapor migrating with natural gas to a nearby producing well.

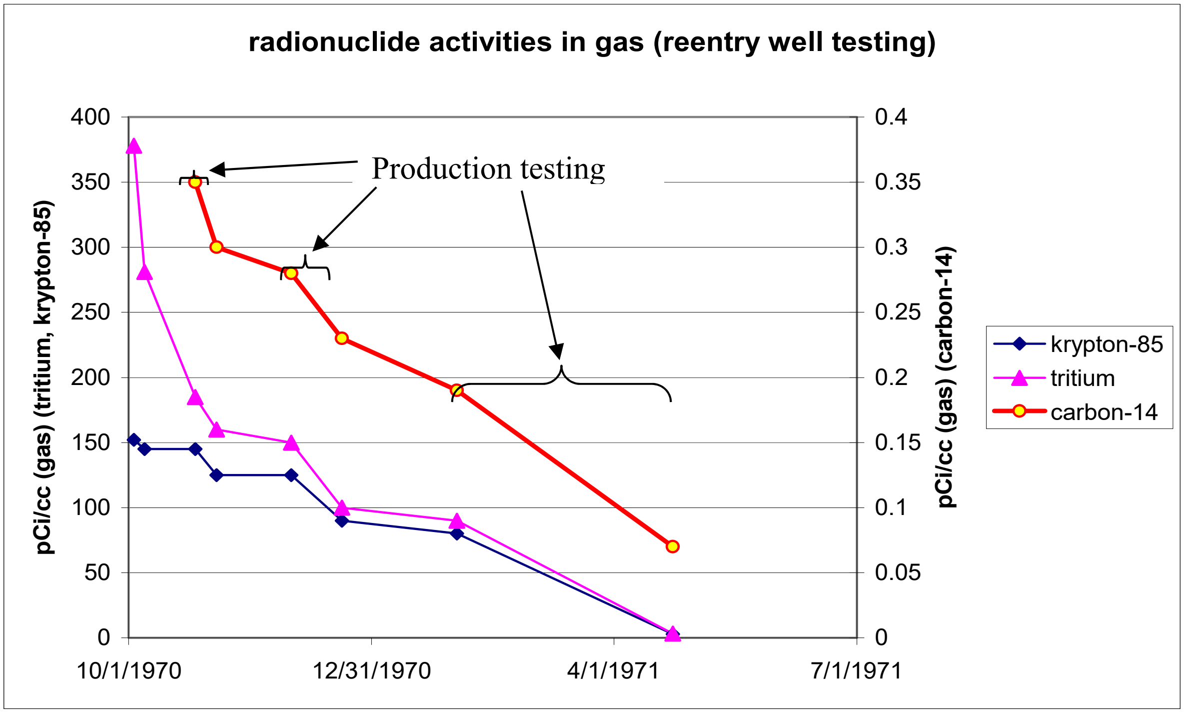
1.3 Selection of Tritium as the Contaminant of Concern

The selection of tritium as the only contaminant of concern for gas production is consistent with the gas testing results from the reentry well given in the Project Rulison Manager's Report (AEC 1973). The reentry well produced 455 million cubic feet of gas, and the only radionuclides detected were tritium, krypton-85, carbon-14, argon-37, argon-39, and mercury-203 (Table 1). Nonvolatile isotopes such as those of uranium and plutonium are not present in the gas phase and were not detected in samples produced from the reentry well. On the basis of estimated inventories of radionuclides produced by the detonation and the amounts removed by production testing, tritium is the only mobile radionuclide that remains in any significant quantity in the detonation zone. Table 1 provides the estimated radionuclide inventories derived from the Project Manager's Report (AEC 1973), Nork and Fenske (1970), Reynolds (1971), Smith (1971), and separate calculations.

Table 1. Radionuclides in Reentry Well Gas

Radionuclide	Estimated from Detonation (curies)	Estimated Removed by Production Testing (curies)	Half-Life	Estimated Remaining 2012 (curies)	Estimated Remaining 2053 (curies)
Tritium	10,000	2824	12.32 years	700	70
Krypton-85	1,100	1,064	10.8 years	<10	<1
Carbon-14	2.2	2.4	5730 years	<1	<1
Argon-37	10–100	Not available	35 days	Not available	Not available
Argon-39	2–20	Not available	269 years	Not available	Not available
Mercury-203	Not available	0.0001	47 days	Not available	Not available

The small amounts of mercury-203 (0.00004, 0.00003, and 0.00003 curie) removed in the first, second, and third production tests are consistent with the amount found naturally in the formation (Reynolds 1971). The original estimate of 2.2 curies of carbon-14 produced by the detonation (Smith 1971) is slightly less than the amount observed to be removed during production testing. The declining activities of the radionuclides produced in the gas are shown in Figure 5. The tritium concentrations in the extracted gas declined similarly to those of the other volatile radionuclides, even though approximately 7000 curies of tritium remained. This is primarily attributed to the likelihood that after the tritiated hydrogen gas and tritiated water vapor were removed during the gas-flow testing, the remaining tritium was present as tritiated liquid water. The relatively immobile tritiated liquid water remains as a long-term source that will continually exchange into the more mobile gas phase.



pCi/cc = picocuries per cubic centimeter

Figure 5. Activity of radionuclides in gas from the production tests on the reentry well (Note that the scale for carbon-14 is on the right side of the graph)

1.4 Institutional Controls and Nearby Drilling

The Rulison site (Lot 11) is 40 acres of privately owned land, and the deed restriction associated with the site was signed by the property owner in 1976. It prohibits drilling below a depth of 6000 ft in Lot 11 and is an institutional control that is legally enforceable. It is designed to minimize the potential exposure to any residual detonation-related contamination at the site. Detonation-related contamination is likely restricted to the vicinity of the detonation zone within the Lot 11 boundary. This conclusion is based on results from modeling studies (Cooper et al. 2007, Cooper et al. 2009, Cooper et al. 2010, and DOE 2013) that estimate potential tritium migration distances with the inclusion of nearby gas development.

Wells drilled near the Rulison site are hydrofractured to increase the permeability around the well, effectively extending the area that a well can drain. Past development in the area has shown that a typically developed well drains an east–west elongated area of about 10 acres. The elongated drainage pattern results from hydrofractures preferentially propagating along the direction of the formation's natural fracture trend (east–west in the Rulison area). Typically, four wells are drilled centered within each 40-acre lot and equally spaced north–south. Each lot is about 1310 ft wide, indicating that hydrofracturing increases the permeability of developed wells by about 600 ft east and west, and less than 200 ft north to south. The extent of the nuclear fractures is known from analysis of reentry-well drilling (encountered fractures 275 ft above the detonation point) and production test data that indicate formation permeability was increased out to a distance of approximately 209 ft from the detonation level. This would indicate that the extent of nuclear fracturing is contained within Lot 11 (Figure 4) since the detonation depth in the emplacement hole is approximately 650 ft from the east and west lot boundaries and approximately 450 ft from the southern lot boundary.

2.0 Modeling of Potential Contaminant Transport

Modeling was performed to estimate how far contamination has migrated since the detonation and how close wells can be drilled and produced without encountering contamination. There have been several iterations of transport modeling for the Rulison site, each using the TOUGH2 modeling code from the Lawrence Berkeley National Laboratory. TOUGH2 can simulate radionuclide transport under multiphase, multicomponent, and nonisothermal conditions. The following sections summarize the results of these modeling efforts.

2.1 Modeling (2007, 2009, 2010)

The original model was configured to estimate the nearest distance, in the direction of greatest permeability from the detonation, at which a hypothetical gas-producing well could be located with no reasonable expected risk of encountering contamination (Cooper et al. 2007). The results of the modeling suggested that it would likely be safe to place a production well near the minimum legal distance (200 ft prior to year 2005) from the Lot 11 boundary (within Lot 12) along the trend of natural fracturing. Restrictions that prevent the removal of material from Lot 11 make it unlikely that a well would be drilled this close to the lot boundary. The model was revised in an addendum (Cooper et al. 2009) to address concerns that were identified in the review process, and to locate the simulated well in the center of the adjacent Lot 12 (1310 ft from the detonation) where it would most likely be drilled. The model was again revised in an update (Cooper et al. 2010) to include sandstone and shale ratios from recently drilled nearby wells (0.75 mile west of the detonation) and to calibrate the model to the production test data collected from the reentry well in 1970 and 1971. No significant amount of tritium reached the hypothetical gas well for any of multiple realizations with varying sandstone–shale configurations. Due to computational demands that limited the model domain to just over 100,000 elements, these models simulated only one hydrofractured sandstone lens at the detonation level, rather than the entire 2000 ft producing section with multiple hydrofractured stages.

2.2 Most Recent Modeling (2013)

The release of the massively parallel version of TOUGH2 made it possible to extend the model domain vertically to include the entire producing section and horizontally to include recently drilled wells 0.75 mile from the detonation and simulate the recommended staged-drilling approach to gas development in the vicinity of the Rulison detonation (Figure 6). The model domain was composed of over 1 million elements, and the model incorporates the effects of the nuclear detonation on the surrounding rock, the production testing from the reentry well, and the hydrofracturing and production from nearby gas wells (DOE 2013). Figure 6 shows the horizontal extent of the model domain with the active wells that began production in 2010 (located 0.75 mile west of the detonation dated 2010), planned wells that have been permitted but not yet installed, and projected model wells (blue) that simulate the staged drilling approach (2015, 2020, and 2025). The simulated installation dates (2015, 2020, and 2025) of the projected model wells did not anticipate the current market conditions and decline in natural gas prices that have delayed gas development throughout the region.

A fence diagram (Figure 7) oriented west to east (*x* direction) with a north–south slice through the existing wells that began production in 2010 shows the rock type distribution within the model domain. The yellow represents lower Williams Fork sandstone gas reservoirs interbedded with shale (olive). The white area is the nuclear fractured region, which extends 209 ft from the former cavity and collapse chimney shown in red. The hydrofractured sandstone lenses of the lower Williams Fork are also shown in red, with hydrofractured shale (restricted to shale near the wells) shown in green. The elongation of the hydrofractured areas in the west–east direction (natural fracture trend) relative to the south–north direction is consistent with drainage patterns and well spacing seen near the site.

The simulation results indicate that tritium extends somewhat beyond the nuclear fractured region but remains well inside the lot boundary and within the 2900 pounds per square inch (psi) pressure contour that indicates a slight pressure low is still present from the production testing within the detonation zone. The 2010 simulated extent of tritiated water vapor (THO_v) around the detonation is shown in Figure 8. The concentration is expressed as a mass fraction (X) of THO in the gas phase (XthoGAS). As a result of production testing and decay, tritium concentration in the collapse chimney is about an order of magnitude lower than that just after the detonation. Tritium has a half-life of 12.3 years, which is equivalent to a decline by an order of magnitude every 40.9 years.

The simulated pressure distribution in 2015, 5 years into production of the existing wells 0.75 mile west of the detonation, is shown in Figure 9. Production from wells in the model occurs by assigning a downhole pressure (600 psi based on conversations with operators, light blue in the figure) to model elements at the perforated intervals. This allows fluids in the formation (pressure of about 2900 psi) to flow to the well due to the 2300 psi pressure difference (2900 – 600). Pressures in the formation surrounding the wells decline as fluids are removed. Pressure declines below 1000 psi are limited to the hydrofractured elements at early times due to the low permeability of the formation. The area around the detonation zone still has not fully recovered from the production testing (based on simulation results), though the remaining difference is within observed natural pressure variations in the formation. Replacing the 2900 psi contour with a 2850 psi contour would mask the area of slightly depressed pressures.

The simulated pressure distribution 10 years into production (2020) of the existing active wells 0.75 mile west of the detonation and 5 years into production of potential path forward wells completed just outside the 0.5-mile radius (0.5-mile wells) is shown in Figure 10. The simulation indicates that the drawdown areas around the wells are beginning to interact, though the increased pressure drop at a well due to production from an adjacent well would likely be too small to detect for most wells at this early stage of production. The difference between yellow and orange on these plots is within the natural pressure variations of a few hundred psi.

The simulated pressure distribution after all wells in the simulated staged approach have completed their productive life (2045) indicates a possible compounding effect of drawdown areas between wells but no additive drawdown towards the detonation zone (Figure 11). To illustrate the small difference in pressures between the well to the west in Lot 12 and the chimney, the 2900 psi contour was changed to 2850 psi, removing the remnant effects of the reentry well production testing. This shows that the extent of the pressure gradient that develops from producing wells in adjacent Lot 12 would be insufficient to induce migration (Figure 12).

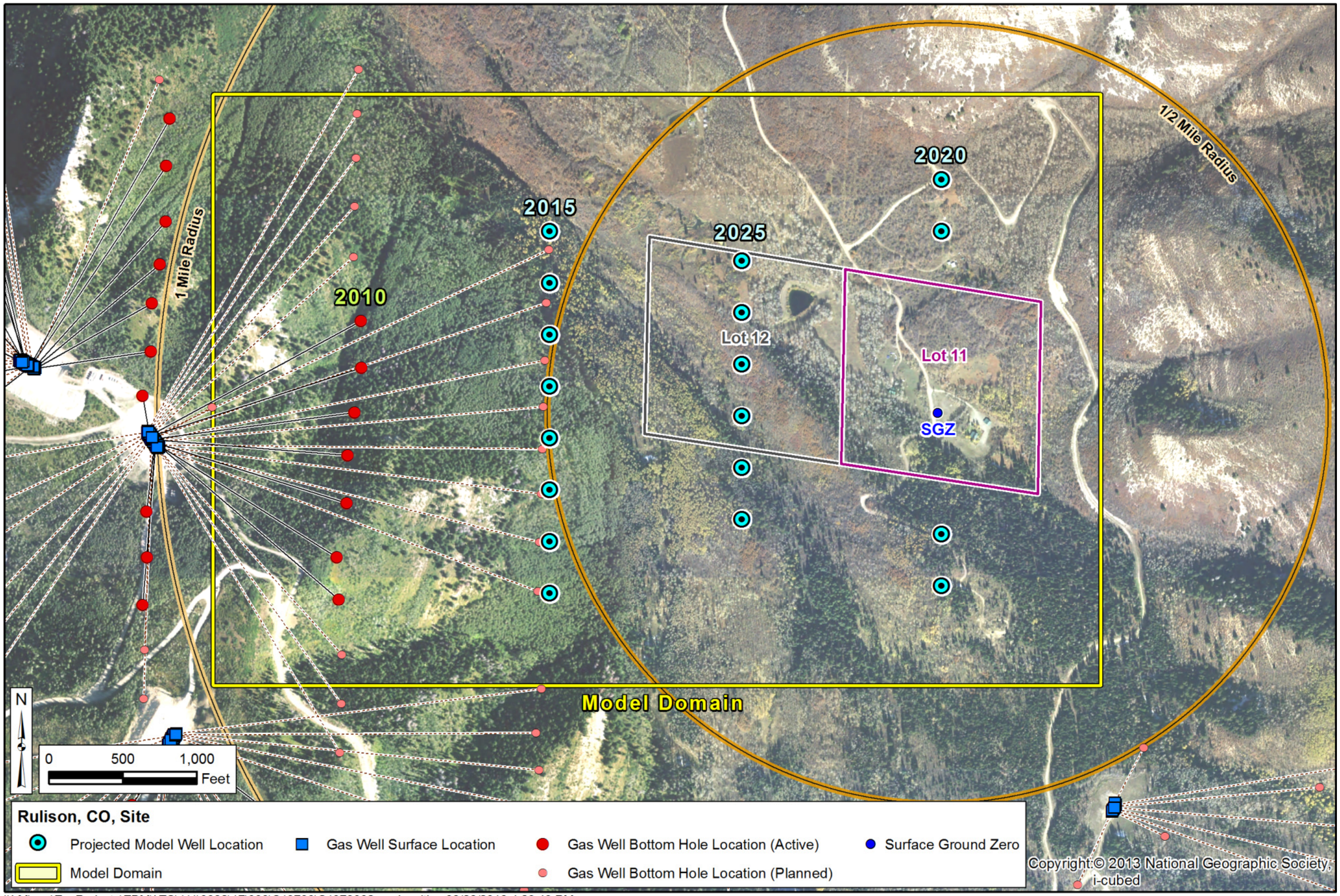


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Figure 6. Map of the model domain and simulated wells

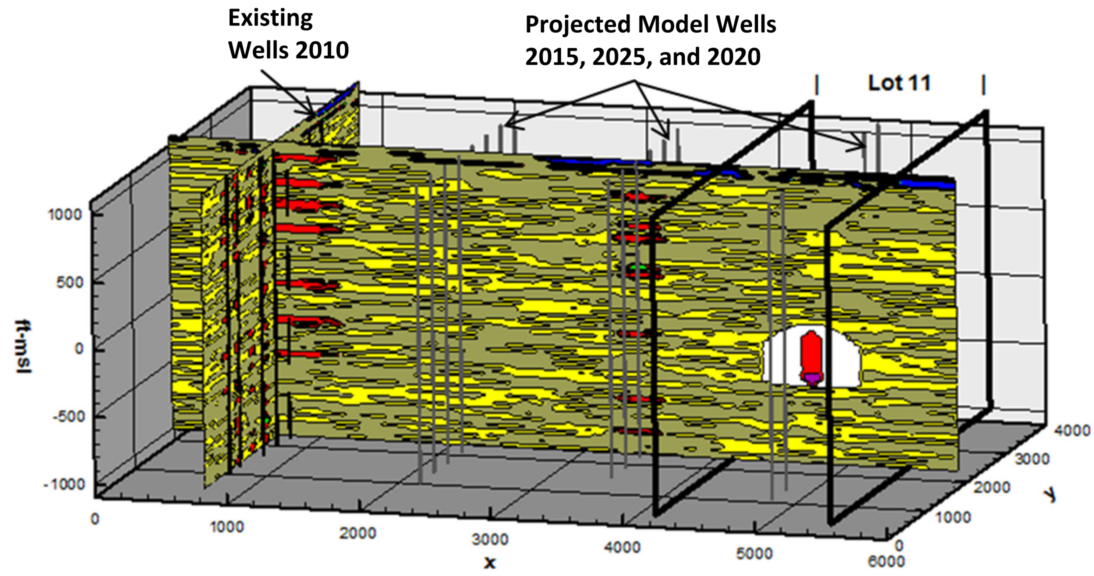

Figure 7. Fence diagram of the model domain showing the distribution of rock types yellow (lower Williams Fork sandstone gas reservoirs), olive (shale), white (nuclear fractures), red (hydrofractured sandstone, chimney), blue (upper Williams Fork sandstone), green (hydrofractured shale)

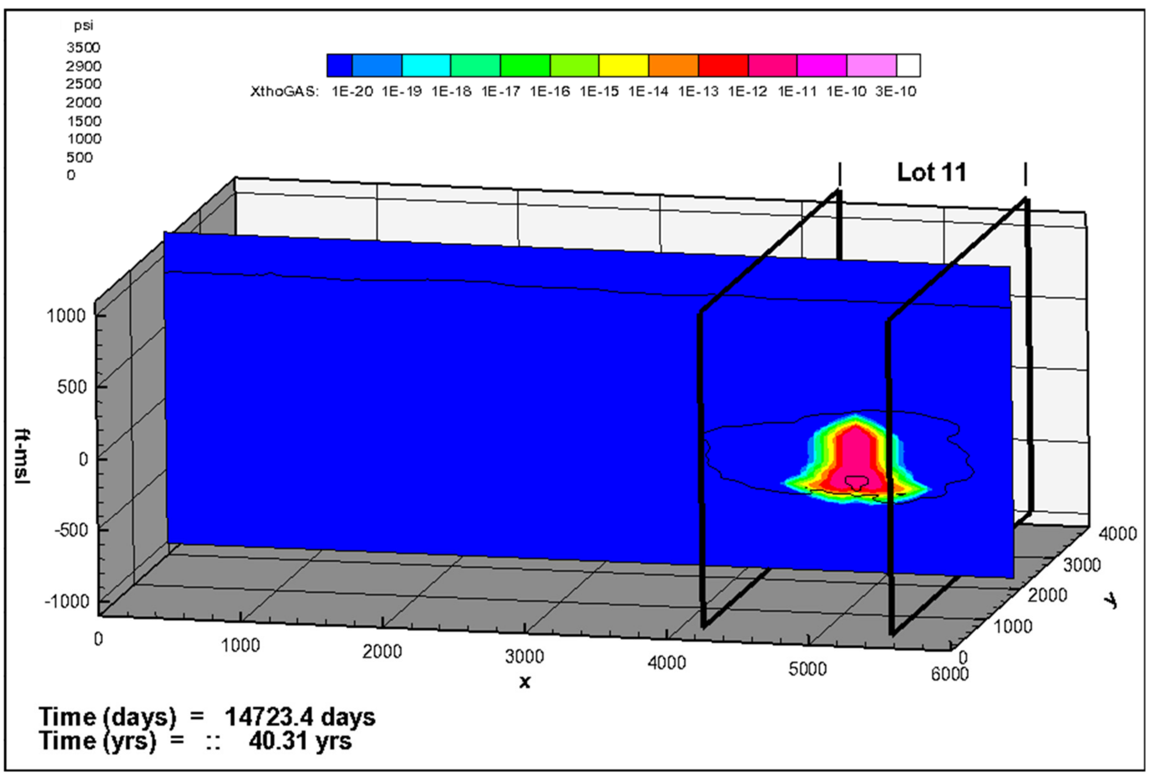

Figure 8. 2010 Distribution of tritiated water vapor

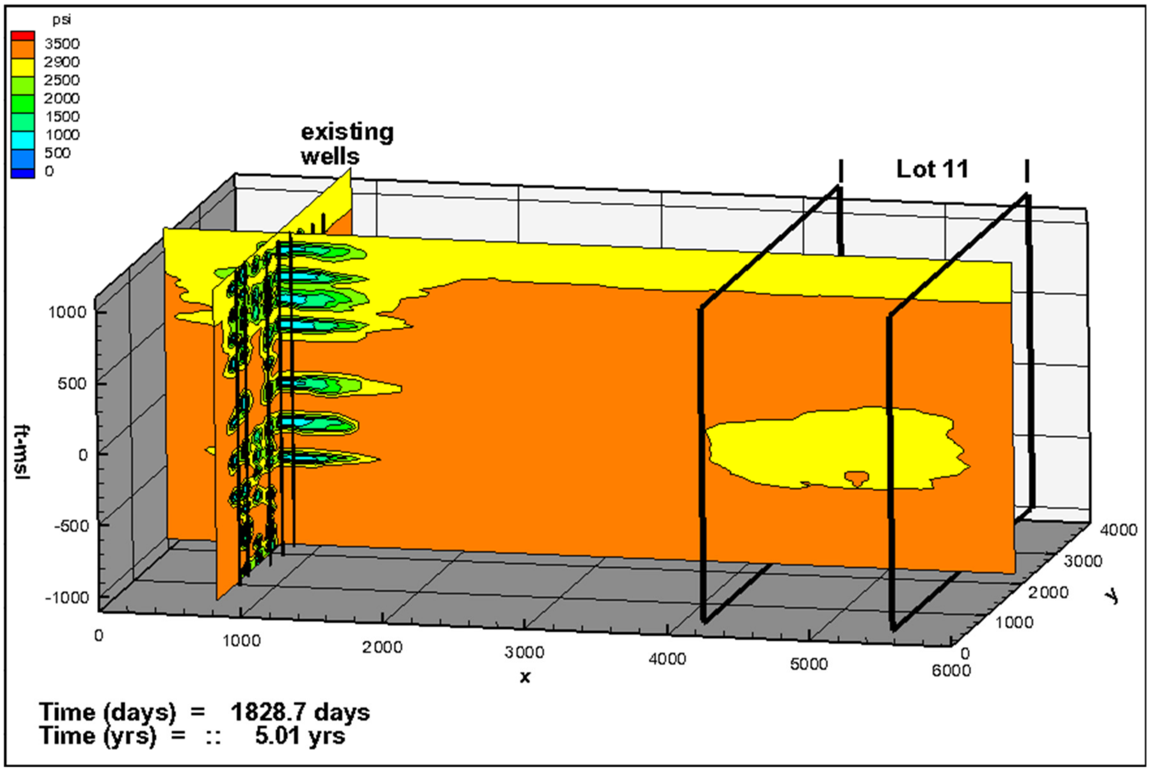

Figure 9. Simulated pressure distribution after 5 years of production from the existing active wells 0.75 mile from the detonation (year 2015)

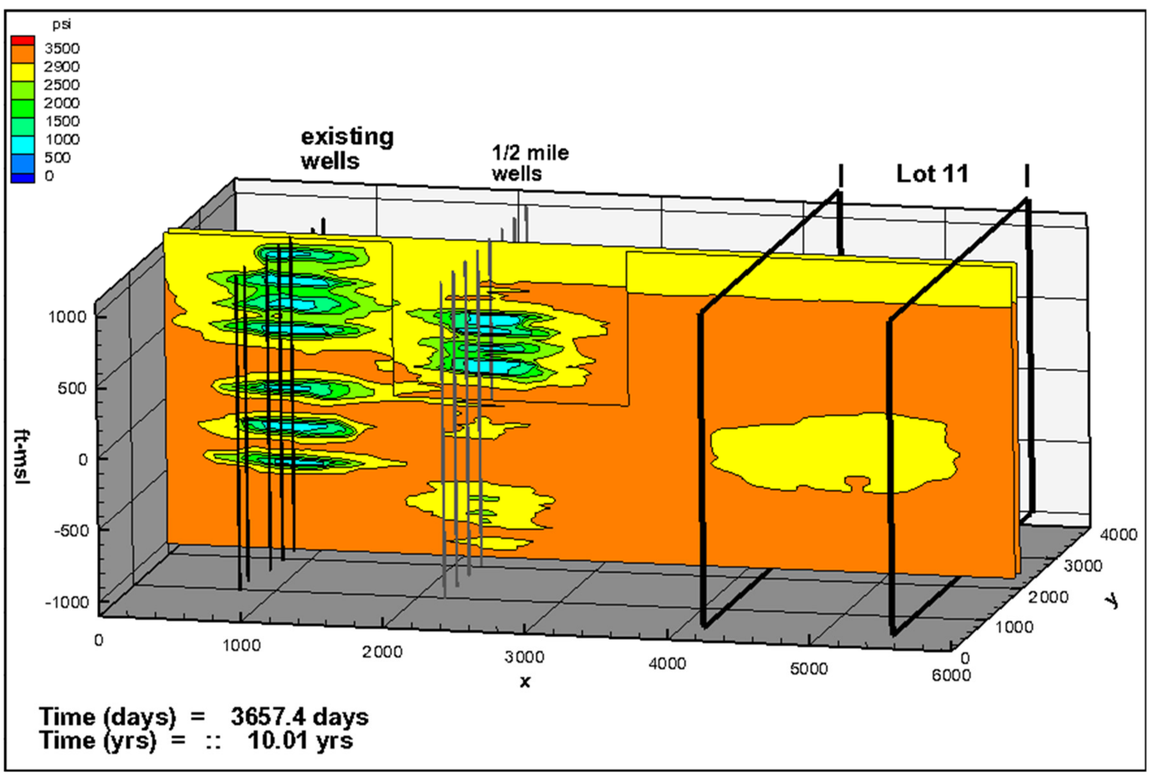

Figure 10. Simulated pressure distribution after 10 years of production from existing wells 0.75 mile and 5 years of production from potential path forward wells 0.5 mile from the detonation (year 2020)

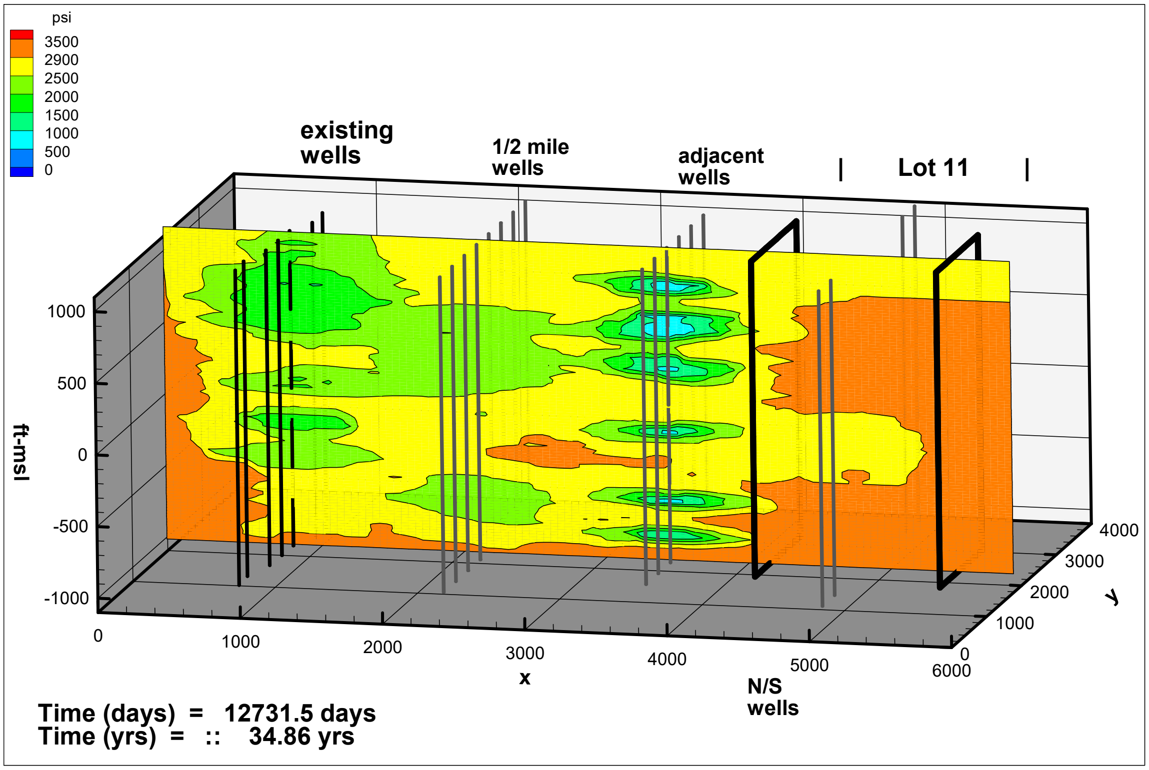

Figure 11. Simulated pressure distribution in 2045 after simulating the producing life of staged approach wells west, south, and north of the site within the 0.5-mile radius

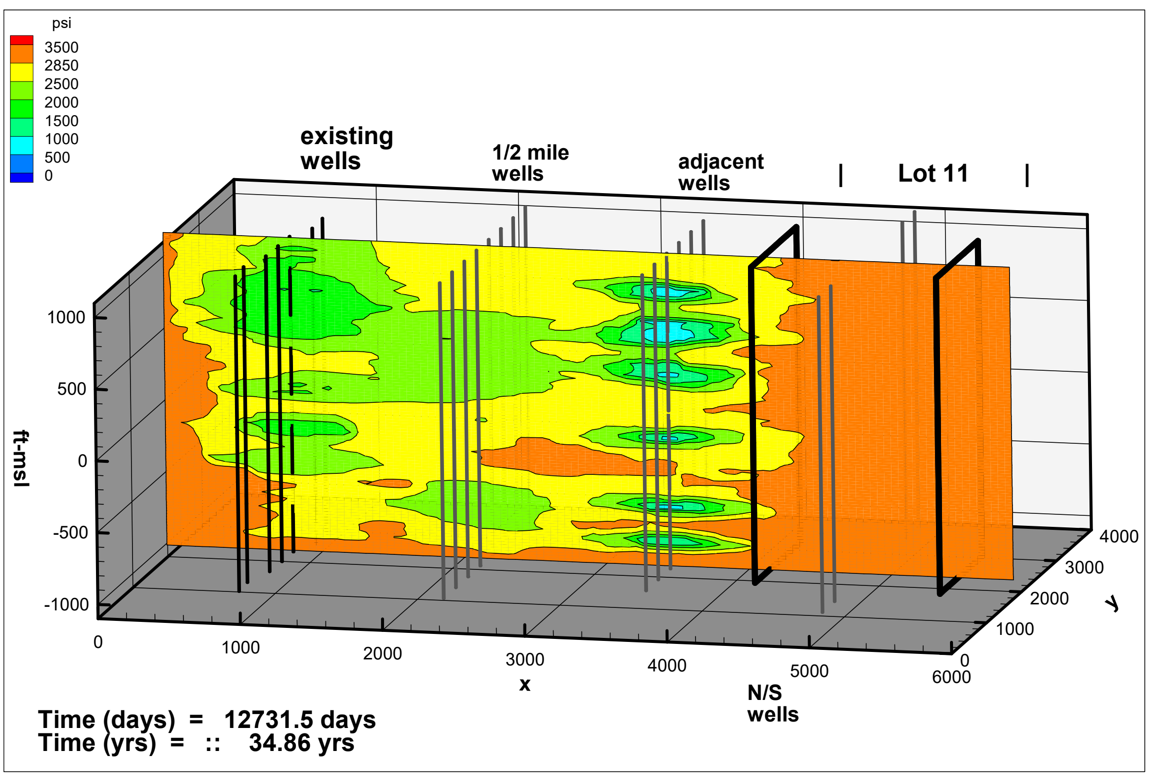

Figure 12. Simulated pressure distribution in 2045 with 2900 psi contour changed to 2850 psi

The results of no nuclear detonation-related contamination extending beyond Lot 11 from earlier modeling did not change, even when simulating a fully developed production network near the site (Figure 6). The only material difference between the tritium distribution around the detonation in 2010 (Figure 9) and 2045 (Figure 13) is the decay of nearly an order of magnitude in concentrations in the collapse chimney (pinkish red to red). The results of limited migration are further supported in that no significant gradient (beyond observed natural variations within the formation) develops between the detonation and the nearest production well west of the detonation. This is significant in that the model assumes that partitioning of tritiated water between the gas and liquid phases is in molecular equilibrium (the same temperature-dependent ratio of tritiated water molecules to non-tritiated water molecules in the gas and liquid phases). This mechanism effectively retards the migration of tritiated water away from the detonation zone by progressively transferring tritiated water molecules from the more mobile gas phase into the less mobile liquid phase as gas migrates. Under reservoir conditions, the liquid phase has about 10 times more molecules per unit volume than the gas phase, thereby accentuating this effect. The model is based on porous media, so there is no possibility of simulating “dry” fractures to allow migration without the retardation effects of tritiated water vapor encountering non-tritiated liquid water. Another model shortcoming is that there are no simulated high-permeability short circuits, such as an extensive fault or a laterally continuous coal seam that would be more susceptible to fracturing than sandstone.

Even if tritium were to reach a gas well, the risk is low, in that there is no reasonable exposure scenario that would endanger public health (Daniels and Chapman 2011). Almost all of the tritium (migrating as THO_v with the methane gas) would be captured at the wellhead where the water vapor condenses and is removed from the gas prior to entering the gas distribution system. Despite the low risk, a cautious approach to gas development near the Rulison site is recommended and is described in the following sections.

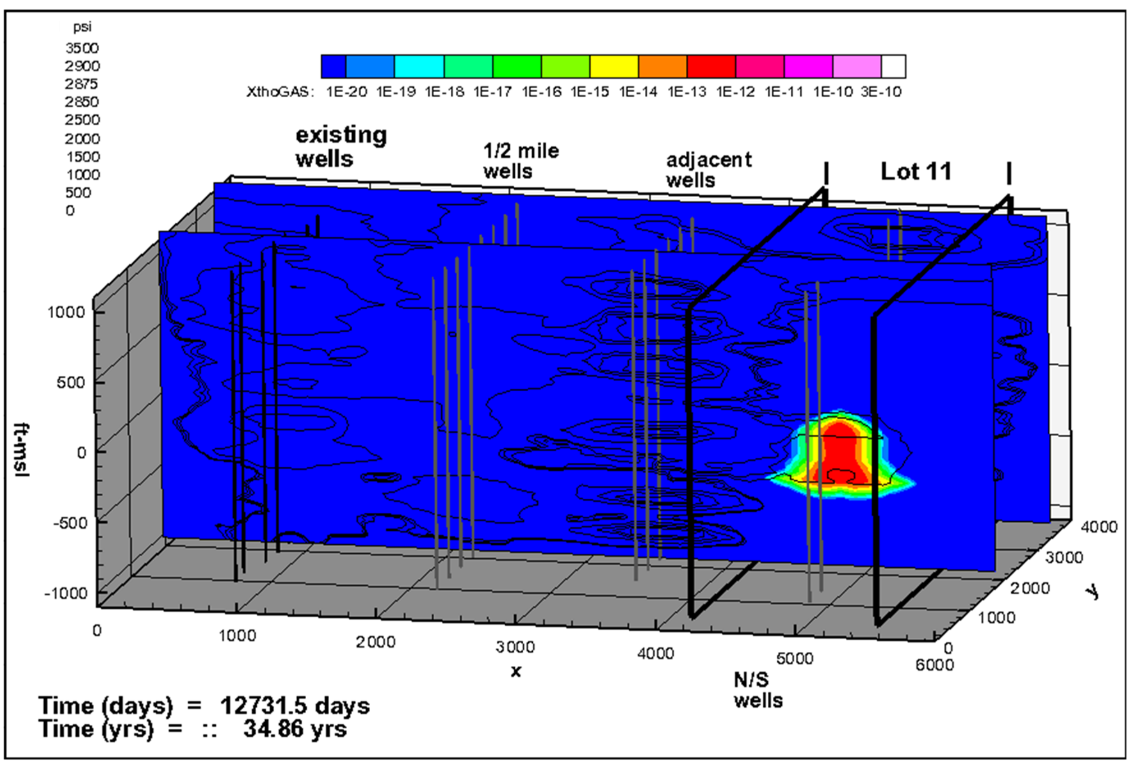

Figure 13. Year 2045 simulated distribution of tritiated water vapor

3.0 Gas Development near Rulison

The recommended staged approach uses conservative modeling but primarily relies on the collection of data to confirm that drilling near the Rulison site is safe. The results of model simulations that apply conservative transport parameters indicate that gas-production wells can be located in the lots west and east of the Rulison site so long as the hydrofractures emplaced during well completion remain outside of the institutional control of Lot 11. The simulated tritium concentration at a hypothetical well located west of the site, in the center of Lot 12, is at or below background for all simulations during the life of the well.

The first stage of the proposed approach calls for confirming that existing wells completed west of the Rulison detonation, along the natural fracture trend, do not encounter detonation-related contamination. Sampling and analysis results since 2010 from the 0.75-mile wells confirm the lack of detonation-related contamination at this distance. Wells just outside the 0.5-mile hearing radius have been permitted and can be drilled, though no firm date has been set. A condition of the permitting was that DOE be allowed to collect microseismic data to monitor the propagation of the hydrofractures during the completion of at least one of the 0.5-mile wells (discussed in more detail in the following section). There are currently no wells within the 0.5-mile radius, so this will allow for confirmation of the natural fracture trend near the site.

Once installed and completed, the wells surrounding the 0.5-mile radius will act as a focused monitoring network, with sampling and analysis of fluids from the wells to confirm that tritium has not migrated beyond the 0.5-mile radius. Because of the difficult topography to the east, gas development has been approaching the site primarily from the west. One well, Battlement Mesa 36-13 (Figure 3), has already been drilled near the 0.5-mile radius south-southeast of the site, and no detonation-related contamination has been detected in this well. Planned well locations just outside the 0.5-mile radius are shown along with ovals depicting theoretical drainage areas in Figure 14. DOE recommends staging the wells within the 0.5-mile radius on the basis of sampling results from wells just outside the 0.5-mile radius and on the orientation of the natural fracture trend as determined by dipole sonic logs and microseismic mapping of one or more 0.5-mile wells. The initial wells inside the 0.5-mile radius (darker lined oval in Figure 14) should be located north and south of the detonation to minimize the possibility of encountering detonation-related contamination. Drilling wells in line with the predominant fracture trend and the detonation within the 0.5-mile radius (Lot 12 to the west and Lot 10 to the east) can be considered after locations to the north and south are drilled and monitored.

The COGCC notifies DOE when it receives applications for drilling permits within 2 miles of the Rulison site and considers comments from DOE in the approval process. For well permit applications inside a 0.5-mile radius of the site, a hearing before the commission is required (COGCC 2007). DOE discourages placing wells within the 0.5-mile radius until data have been collected from wells just outside the 0.5-mile radius. The data to be collected include not only information about the orientation of the natural fracture trend near the site but more importantly, laboratory data from fluid samples at these wells. DOE does not believe that detonation-related contamination has migrated or will migrate beyond Lot 11. The support for drilling wells inside the 0.5-mile radius would be more convincing to both the public and regulators if data confirm the lack of detonation-related radionuclides at wells just outside the 0.5-mile radius. As in the case of wells just outside this radius, it is recommended that the first wells installed within the 0.5-mile radius be located north and south of the detonation zone (Figure 14), in the least likely transport

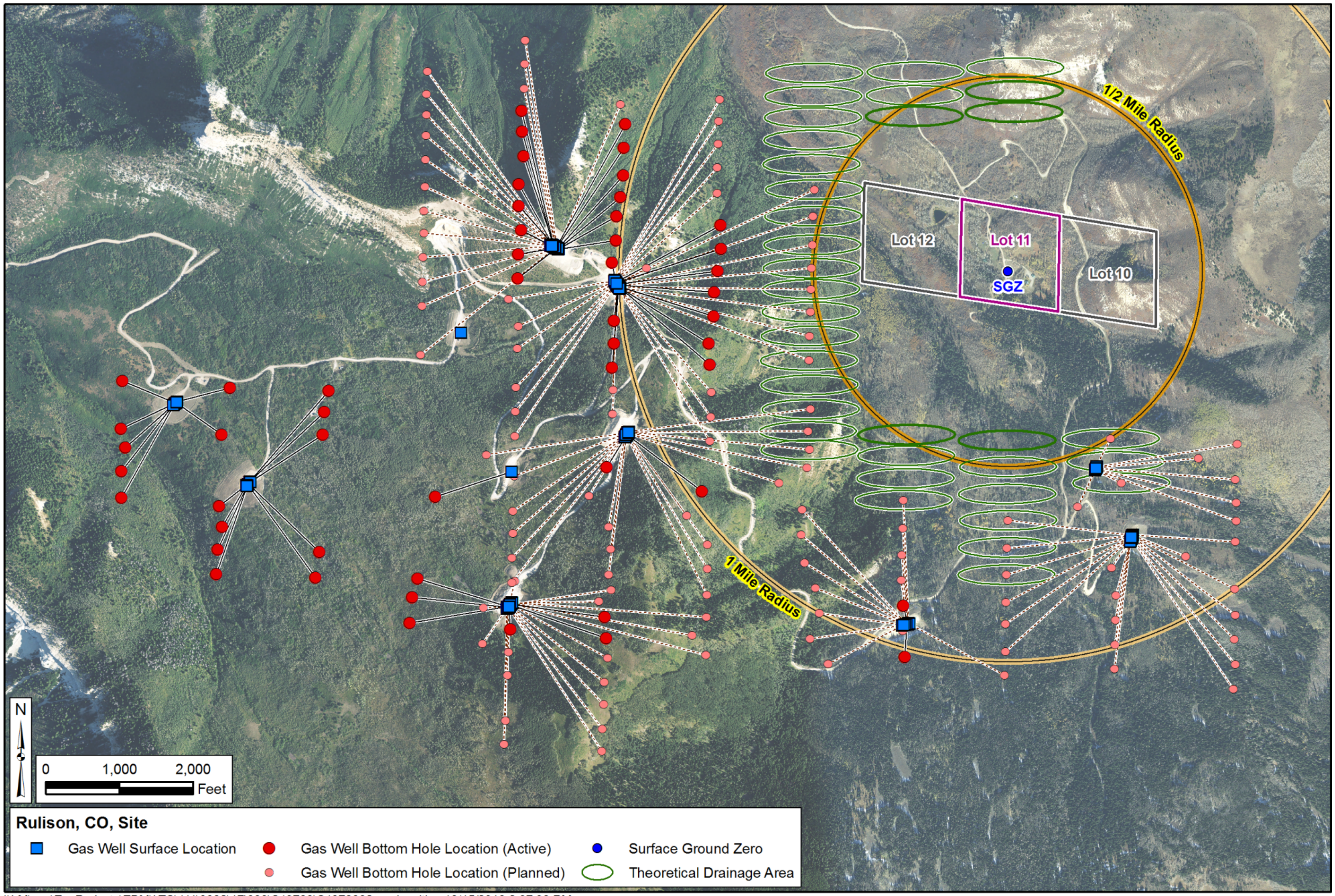

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Figure 14. Map of the Rulison area showing potential well locations for production and monitoring outside the 0.5-mile hearing radius (ovals indicate the extent of influence of potential 0.5-mile well locations)

direction. Subsequent wells could then be installed in a sequence that gradually approaches the higher-risk transport direction, currently believed to be in a roughly east–west orientation relative to the nuclear detonation.

If testing confirms that the natural fracture trend is oriented east–west, the areas of greatest risk will be Lot 12, west of the site, and Lot 10, east of the site. Drilling and producing from these two lots is not recommended until the lack of detonation-related contamination is confirmed by data from producing wells located in safer directions within the 0.5-mile radius.

No well will be located such that encroachment into or removal of materials from Lot 11 might occur. This includes all hydrofractures and flow-inducing gradients by way of production near Lot 11 that could cause tritium to migrate from the detonation zone. To ensure that encroachment into Lot 11 does not occur, it is recommended that microseismic mapping be conducted during the hydrofracturing of wells completed within Lot 10 or Lot 12. It is also recommended that, if a microseismic survey conducted during the hydrofracturing of a well indicates fracture penetration into Lot 11, the well should not be put into production without written approval from DOE.

3.1 Confirmation of Natural Fracture Trends near the Site

The Williams Fork Formation of the Piceance Basin has a natural fracture field that generally trends east to west, though the orientation can vary somewhat depending on location within the basin. The permeability of the formation is greater in the direction of the natural fracture trend, and hydrofractures used to further increase permeability during well development tend to elongate in this direction. The orientation of the fracture trend in a given area can be measured using several methods. A dipole sonic log can be used to determine the minimum and maximum principal stress directions within the formation, which can then be used to infer the stress field orientation. Microseismic mapping uses geophones placed in one or more wells near a well being completed to monitor hydrofracture propagation.

Microseismic mapping was used to detect average fracture orientation in a portion of the Rulison Field, a gas-producing area located approximately 6–8 miles northeast of the Rulison site. Results from the microseismic testing illustrated in Figure 15 identified a fracture orientation of N 75° W, with a local range of ±10 degrees (Wohlart et al. 2005). In the Grand Valley Field (approximately 8 miles northwest of the test site), the average fracture orientation was determined to be N 84° W, with a local range of ±5 degrees (Wohlart et al. 2005). A dipole sonic log from Noble Energy well BM 26-34A, 0.75 mile west of the site, supports an east–west orientation of the natural fracture trend near the Rulison site.

The results of dipole sonic logs and the microseismic mapping can be used to guide and perhaps modify the drilling sequence of future wells recommended in this document.

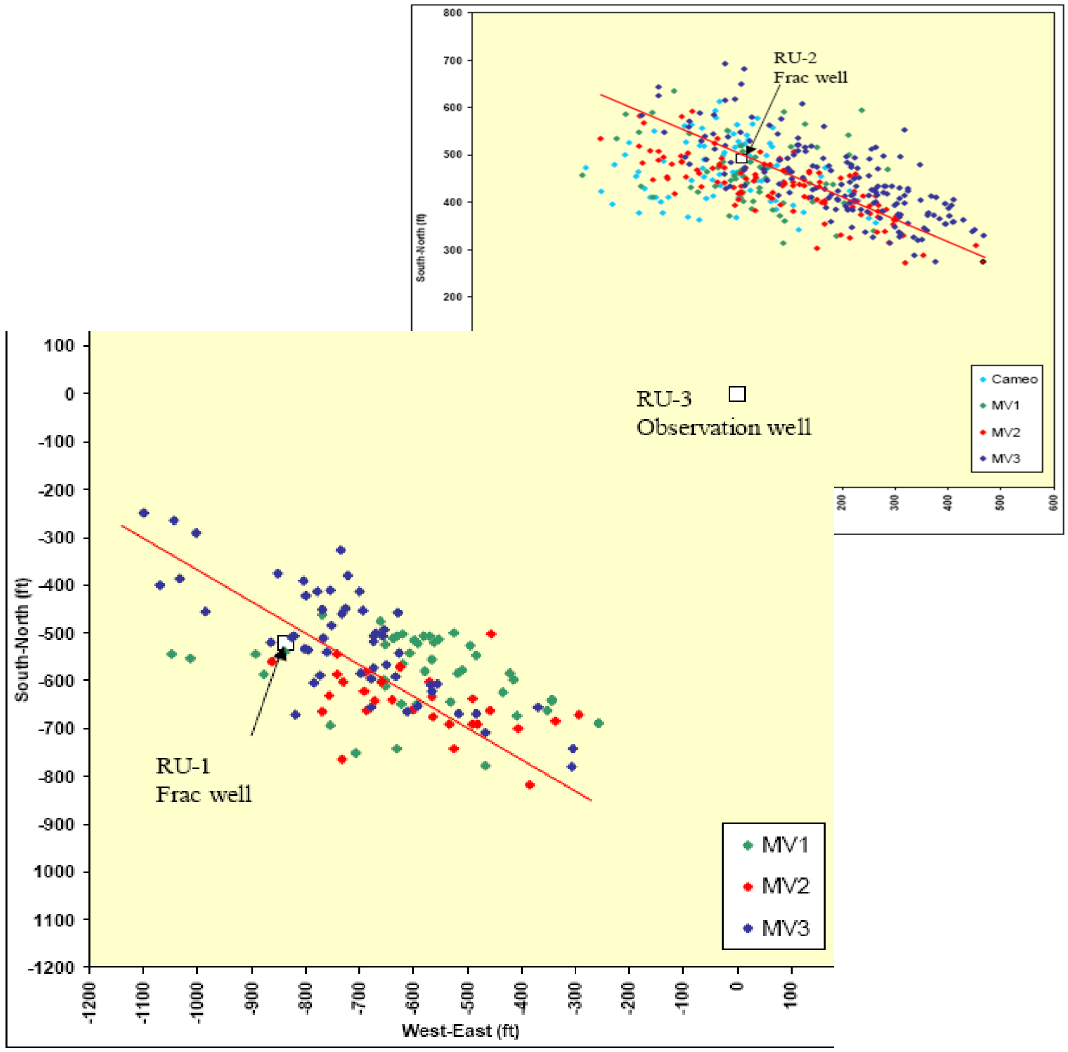

Figure 15. Microseismic mapping of the hydrofracturing of two wells

Mapping was conducted at different times during the winter of 2001–2002 using the same observation well (RU-3) in the Rulison Field (modified from Wolhart et al. 2005). The points are microseisms, small seismic events associated with hydrofracture propagation. The point colors represent different hydrofracture stages (sandstone reservoirs fractured as a group within a given depth range; Cameo is the deepest and Mesaverde-3 is the shallowest). Note that the hydrofracture wing nearest the observation well has an apparent length greater than the opposite wing. This is interpreted as an artifact of detection distance from the observation well, not the actual asymmetry of hydrofracturing extent.

4.0 Summary and Conclusions

DOE does not believe detonation-related contamination poses a threat to nearby gas-producing wells. The fracturing caused by the detonation is contained within the 40-acre institutional control boundary, Lot 11. The flow of fluids (gas or liquid) that could transport contamination is limited in the low-permeability formation in the absence of stimulation (such as nuclear or hydraulic fracturing) that increases permeability. The gas phase is about 1000 times more mobile than liquid in the gas-bearing reservoirs and the only gas-phase radionuclide that remains in significant quantities after reentry well testing and decay is tritium, as tritiated water. The potential for tritium migration is also retarded by partitioning of tritiated water between the gas phase and less mobile liquid phase.

A numerical model was constructed to simulate a staged drilling approach near the Rulison site. DOE recommends that wells drilled near Rulison be installed in a sequential manner, allowing data to be collected at wells a similar distance from the site before drilling nearer wells. The model simulated this approach by adding model projected wells 5, 10, and 15 years after production began at existing wells in the model domain. No contaminant migration was induced in the simulations even after wells were located as close as would be feasible given current well-spacing constraints in the area. Even though contaminant migration is believed to be highly unlikely based on current data and numerical modeling, DOE recognizes the potential for uncertainties that have not been identified and were not included in the model. For instance, no high-permeability short circuits were simulated, such as a permeable fault zone or a laterally continuous coal seam that would be more susceptible to extensive fracturing than sandstone. DOE continues to recommend that gas development near Rulison follow the staged drilling approach to minimize the likelihood of encountering detonation-related contamination.

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