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MODELING OF FLOW AND TRANSPORT INDUCED BY PRODUCTION OF HYDROFRACTURE STIMULATED GAS WELLS NEAR THE RULISON NUCLEAR TEST

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ABSTRACT

The Project Rulison test in western Colorado, the second natural gas stimulation experiment in the Plowshare Program, was conducted in 1969 to determine if a nuclear device could be used to fracture low-permeability, gas-bearing rock to enhance natural gas production. Testing on the reentry well produced gas at rates significantly greater than those of conventional wells of the time; however, the presence of radionuclides (specifically tritium) in the produced gas persisted above acceptable levels, and the test was abandoned. Recent advances in hydrofracturing technology have made it feasible to extract natural gas from low-permeability reservoirs and have led to a significant increase of drilling in the area. However, drilling activity near the Rulison site has raised concerns that remnant radioactivity in the detonation zone could migrate to nearby producing wells and enter the natural gas distribution system.

The potential for tritium migration at Rulison was modeled with TOUGH2-EOS7R in 2007. The model has been revised to improve model defensibility and to reduce uncertainty by addressing reviewer suggestions and incorporating geologic and production data from the gas industry. Tritium is present as tritiated water, and since the gas permeability of the native formation is several orders of magnitude higher than the liquid permeability, any significant migration occurs with the gas phase. Tritium is introduced into the model as a fraction of the liquid mass in the detonation zone and partitions between the aqueous and vapor phases in relation to the Henry's law constant. The Henry’s constant for tritiated water vapor is simply the water vapor pressure. The code was modified to calculate a temperature-dependent Henry's law constant based on the vapor pressure. The code was also modified to substitute methane for air. Historical production and pressure data from the reentry well were used to calibrate model flow properties. The original and subsequent modeling with TOUGH2-EOS7R simulated the effects of production from an interval at the same depth as the detonation zone in a well positioned in the most vulnerable location (as near to the institutional control boundary as would be allowed, inline with the direction of highest formation permeability). More recently, the Rulison model domain has been expanded to include gas production wells installed in 2010 0.75 mile from the site. With over 1,000,000 elements, simulations required the use of the massively parallel version TOUGH2_MP-EOS7R. The new domain allows the simulation of production from the entire targeted gas-bearing section by multiple wells, each with multiple hydrofractured intervals. The model was calibrated to both the historical reentry well data and to data from the nearby gas wells. The large domain model has been used to simulate the effects of future wells that could potentially be installed nearer the Rulison site.

INTRODUCTION

The Piceance Basin in western Colorado contains significant reserves of natural gas in poorly connected, low-permeability (tight) sandstone lenses of the Mesaverde Group. The ability to enhance the production of natural gas in this area has long been a goal of the oil and gas industry. The U.S. Atomic Energy Commission, predecessor agency to the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission, participated in three tests using nuclear detonations to fracture tight formations in an effort to enhance gas production. The tests were conducted under

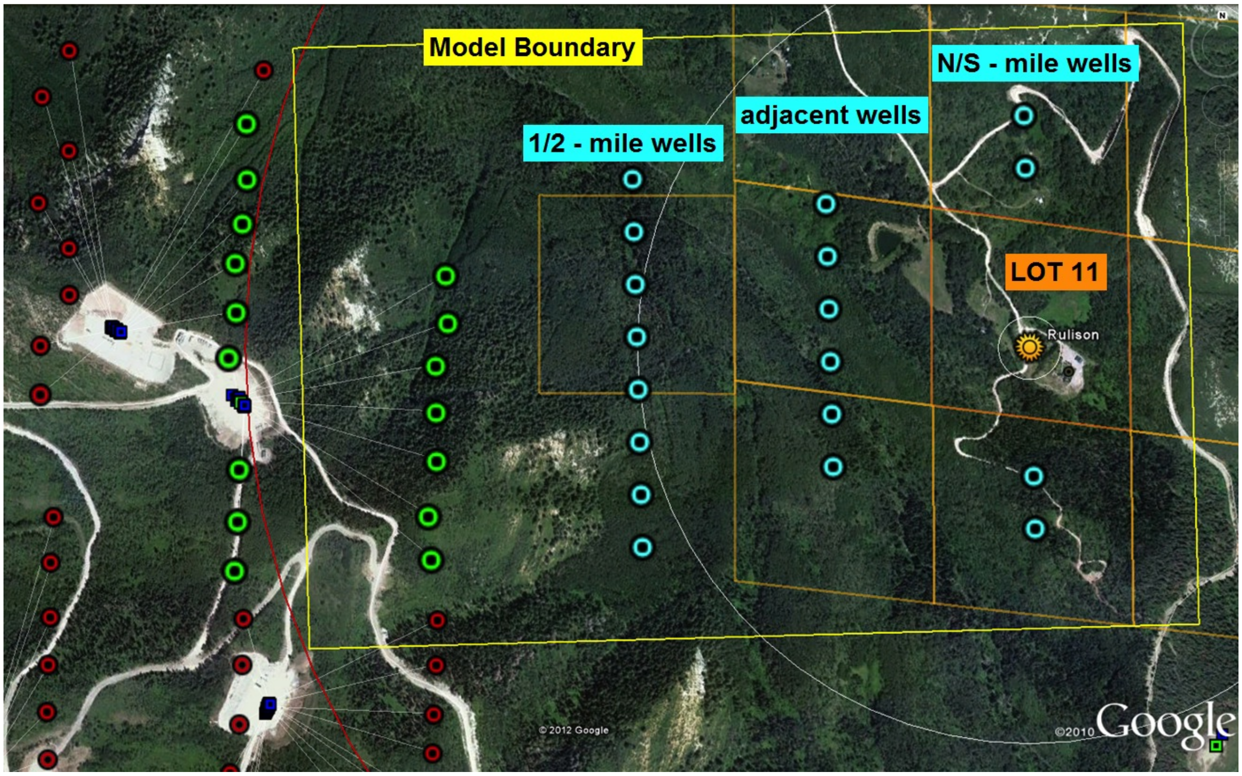

Figure 1. Model outline, institutional control (Lot 11), existing wells (red and green [sampled]), modeled future wells (blue).

Project Plowshare, a program designed to identify peaceful, beneficial uses for nuclear devices. The first, Project Gasbuggy, was conducted in 1967 in the San Juan Basin of New Mexico. The two subsequent tests, Project Rulison in 1969 and Project Rio Blanco in 1973, were in the Piceance Basin.

The ability to enhance natural gas production from tight sands has become practical through advances in hydrofracturing technology. This technology has led to an increase in drilling activity near the Rulison site, raising concerns that contamination currently contained in the subsurface could be released through a gas well drilled too close to the site. As wells are drilled nearer the site, the DOE Office of Legacy Management has taken the approach outlined in the June 2010 Rulison Path Forward document (DOE 2009), which recommends that drillers adopt a conservative, staged approach to gas development. They are encouraged to drill wells in areas with a low likelihood of encountering contamination (both distance and direction from the detonation zone are factors) and to collect data from these wells prior to drilling nearer the site's 40-acre institutional control boundary (Lot 11). Modeling results indicate that contamination has been contained within Lot 11 (Figure 1). The Path Forward document couples the model predictions with the monitoring of gas and produced water from the gas wells and the monitoring of shallow groundwater near the site.

Geologic Setting and Conceptual Model

Natural gas reserves in the Tertiary and Cretaceous strata of the Piceance Basin are estimated at 300 trillion cubic feet (http://oilshalegas.com/piceancebasin.html). The Williams Fork Formation, in which the Rulison blast occurred, is the primary producing interval near the Rulison site. It is composed of discontinuous, interbedded fluviodeltaic, low-permeability sandstones and shales (on the order of microdarcys for the sandstones and even less for the shales). The sandstones in the lower two-thirds of the Williams Fork can be stimulated by hydrofracturing to enhance production. Sandstones in the upper one-third of the Williams Fork are not production targets due to their higher water content, which lowers the relative permeability of the gas phase and causes water production to be excessive compared to the amount of gas that can be extracted.

Wells near Rulison typically drain an area of roughly 1,200 ft by 300 ft (10 acres), with the long axis oriented east-west, along the natural fracture trend in the Williams Fork. In practice, this requires four wells per quarter-quarter section (centered east-west and aligned north-south) to drain each 40-acre parcel. The typical drainage pattern and area has been confirmed by over a hundred wells drilled near the Rulison site. Each well is expected to produce about a billion cubic feet (BCF) or more of gas on average over a 20- to 25-year life. It is evident that wells east and west of the detonation zone would be in the most susceptible transport direction, due to the increased permeability in that direction and the tendency of fractures to propagate in that direction.

The extremely high temperatures associated with a nuclear detonation vaporize a volume of rock and produce a roughly spherical cavity surrounding the blast point. A high-pressure shock wave spreads from the blast, fracturing the rock beyond the cavity wall. Within minutes to hours after the detonation, the fractured rock above the cavity collapses, forming a rubble-filled chimney. The Rulison detonation was at a depth of 8,425 ft below ground surface, and the top of the chimney was interpreted to be where the reentry well lost circulation 275 ft above the detonation.

Source and Potential Migration Pathway

Radionuclides that can exist in the gas phase, have a relatively long half-life, and were created in significant amounts by the detonations are of primary concern, because of their persistence in the subsurface and their potential mobility. The relative permeability of the gas phase is orders of magnitude greater than that of liquids in the natural-gas-producing reservoirs of the Williams Fork. Gas-phase radionuclides produced by the Rulison detonation (Reynolds 1971) in estimated order of abundance were tritium (approximately 10,000 curies), krypton-85, and minor amounts of argon isotopes and carbon-14.

A reentry well was drilled into the Rulison chimney and tested to determine the success of the detonation at improving gas production. The well produced 455 million cubic feet (MMCF) of gas in 107 days of testing that took place from October 1970 through April 1971 in four separate flow tests. The produced gas was flared to the atmosphere, and samples of the produced gas and produced water were collected and analyzed to determine the degree to which radioactivity levels changed as testing progressed. Radioactivity levels decreased throughout the testing as gas from the chimney region was produced, burned, and replenished by uncontaminated gas from the surrounding formation. Approximately 3,000 of the original 10,000 curies of tritium were removed by the production testing, leaving 7,000 curies of tritium that would have decayed to 600 curies by 2012. Radionuclides other than tritium were largely removed by production testing and radioactive decay. The depletion of tritiated methane by the production testing leaves tritiated water as the primary contaminant source for the Rulison site.

Modeling Objectives

A major limitation of the previous Rulison models was the computational constraints on the number of elements that nonisothermal EOS7R models could accommodate. With the advent of a massively parallel version of the modeling code (TOUGH2_MP), problems requiring several million elements can now be simulated. The modeling effort has been continued with an extended model domain that includes current gas production wells to the west and spans the entire productive interval. This new Rulison model was calibrated to not only the historical reentry well data, but also to production data from current producing wells. The extended domain made it possible to simulate the effects of the enactment of the Rulison Path Forward.

MODEL CONSTRUCTION

The model uses an equivalent porous media approach even though flow is predominantly through a fractured system. The approach is justified in that the fractures through which flow occurs are assumed to be frequent with limited extents. The mechanical forces that create the nuclear fractured and hydrofractured regions rubblize the formation to increase permeability.

Model Domain and Discretization

The horizontal and lateral extents of the Rulison model domain were designed to include existing gas production wells 0.75 mile west of the site (Figure 1) and to include the entire gas-productive lower two-thirds of the Williams Fork Formation. The horizontal extent is 6,000 ft in the east-west direction and 4,000 ft in the north-south direction. The vertical extent of the model domain is 2,200 ft—the 2,000 ft thick lower two-thirds of the Williams Fork Formation and an additional 200 ft into the non-producing upper third of the Williams Fork. This allows data from the recently installed (2010) producing wells to be incorporated into the model to support historical data from the emplacement well and the re-entry well. The three-dimensional model is discretized into elements that are 50 ft (15.24 m) in the horizontal x and y directions and 20 ft (6.1 m) in the vertical z direction, for a total of 1,056,000 cells (120x, 80y, 110z).

Material Types

Geophysical and lithologic logs from the exploratory and emplacement wells, and gas wells in the domain, were used with published statistics on sand body sizes and correlation lengths to generate the sand-shale distributions. Data from Noble Energy, the primary operator in the area, indicate that about 42.5 percent of the targeted Williams Fork section near Rulison can be considered producing sandstones. The remaining 57.5 percent is considered shale for the purposes of the model. Figure 2 shows a vertical slice through a sandstone (yellow)-shale (olive) realization with the detonation zone (chimney [red], nuclear fractures [white]) and hydrofracture zones (red). Separate ROCK types were assigned to lower Williams Fork sandstones (LWFsd), upper Williams Fork sandstones (UWFsd), and shales.

The nuclear fractured region was defined as a truncated (at depth) ellipsoid with a longer east-west axis. Elements within the nuclear fracture and chimney ellipsoids were changed to ROCK types NFrac, chimn, or glass to allow for their own specified set of parameters. The melt glass provides a constant heat source at the base of the chimney.

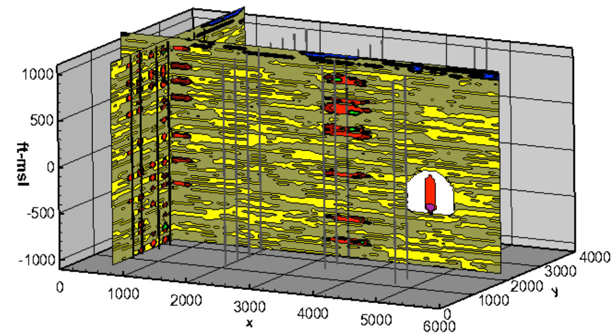

Figure 2. Sandstone/shale distribution.

Hydrofractured formation

At gas well locations, sandstones within the lower Williams Fork Formation that were 40 ft or more in thickness (model layers are 20 ft thick) were hydrofractured. Like an actual well, no information about how laterally extensive the sandstone was away from the wellbore was used to decide which interval would be hydrofractured. And, like an actual well, the horizontal distance that hydrofracturing extended from the wellbore was to a degree controlled by the lithology surrounding the wellbore. Hydrofractures were assumed to extend farther in sandstones than in shales, and it was assumed that hydrofracturing would be more effective in the sandstones. Figure 2 shows hydrofractures elongated in the east-west direction.

Model Parameters

Capillary pressure and relative permeability curves for each ROCK type were based on published information about the Mesaverde in Byrnes and Cluff (2009). The capillary pressure curves were based on the TRUST capillary function (Narasimhan et al. 1978), and the relative permeability curves were based on Corey (1954). A reasonable range of permeability and porosity values for the various ROCK types were determined by calibrating the Rulison model to production and pressure data from the reentry well and to gas wells within the domain.

Boundary Conditions

The size of the model domain in combination with the very low native permeabilities of the formations allows for no-flow boundaries on all sides without significantly altering the flow field, even for wells near boundaries. The majority of flow within the model domain is from regions that have been fractured to allow flow, the nuclear fractured region, or hydraulically fractured regions surrounding gas wells. These regions are separated from boundaries by the very low permeability formation, and any significant interaction with boundaries over the time frame of the simulations would in itself indicate that the model is not calibrated to observed real-world conditions.

Initial Concentration and Partitioning of Tritiated Water (THO)

The Henry's law constant is used to describe the partitioning of a compound between the gas and aqueous phases. This partitioning provides a method to calculate the mass fraction of THO in the gas phase using the vapor pressure of water, assuming that THO is in molecular equilibrium with the gas and liquid phases. The Henry's law constant used to calculate the partitioning of THO between the two phases is simply the water vapor pressure. The water vapor pressure is directly related to temperature (Figure 3), and the code was modified to calculate a spatially variable temperature-dependent Henry's law constant based on the vapor pressure. The inverse pressure form of the Henry's law constant is developed below and was used to reproduce published values (Smiles et al. 1995) for confirmation.

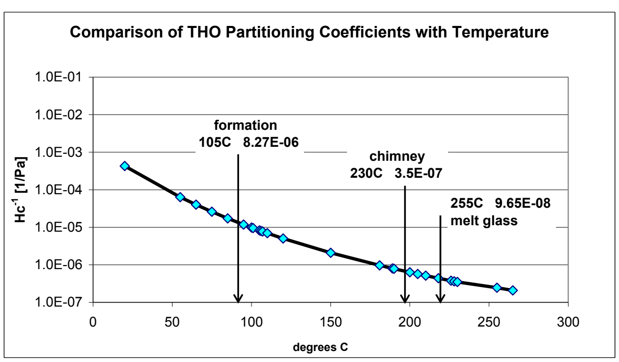

Figure 3. Inverse vapor pressure of water relative to temperature

The initial concentration was assigned to chimney elements (1.0×10^{-9} for Rulison) as a mass fraction of THO in the aqueous phase (a primary variable). The gas-phase mass fraction of THO (a secondary variable) is calculated (partitioned) with the first time step of the simulations based on the initial thermophysical properties for the chimney elements. The code was also modified to replace air (not in the gas reservoirs) with methane. This was necessary to get the initial partitioning correct, because the molecular weight of air (29 g/mol) is greater than that of methane (16 g/mol). The mass fraction of THO in the gas phase will be higher if it partitions into a less-dense gas phase (methane rather than air).

Inverse Henry's Law constant (*HCRN1*):

$$HCRN1 = \frac{\chi_l^{THO}}{P_g^{THO}}$$

Gas and aqueous phases should have same ratio of molecules:

$$\frac{P_g^{THO}}{P_g^{H_2O}} = \chi_g^{THO} = \chi_l^{THO}$$

Substitute to get HCRN1, same pressure units (pascals [Pa]) as TOUGH2 EOS7R (1/Pa)

$$HCRN1 = \frac{\chi_l^{THO}}{P_g^{THO}} = \frac{\dfrac{P_g^{THO}}{P_g^{H_2O}}}{P_g^{THO}} = \frac{1}{P_g^{H_2O}}$$

where:

χ_l^{THO} = mole fraction of tritiated water in the aqueous phase

P_g^{THO} = partial pressure of tritiated water vapor in the gas phase

Initial Conditions

The initial pressures ranged of 19.7 to 22 MPa (about 2,850 to 3,190 psi) from the top to the bottom of the domain. Shut-in pressures through the productive interval from drill-stem tests in the pre-shot exploratory well ranged from 2,250 to 3,050 psi (Nork and Fenske 1970). Water saturations are about 0.5 in the sandstones and about 0.65 in the shales, with the variation due to the capillary pressure curve used for each and some variation with depth. Formation temperatures were initialized to 105°C (220°F) (from Montan, 1971). The temperature of the chimney was assigned an initial value of 230°C (445°F) (from DeGolyer and MacNaughton 1971). The melt glass elements at the base of the chimney were assigned a temperature of 255°C to act as a constant heat source.

Well Treatment

Production from the reentry well was simulated using a MASS extraction (Pruess et al. 1999) of combined gas and water based on the historical data that recorded both the amount of gas and water extracted over time and the resulting pressure decline. A total of 455 MMCF of gas (430 MMCF dry gas) was produced along with 20,244 barrels of water during the testing.

Production from current and future gas wells was simulated as production against a specified wellbore pressure (well on deliverability, Pruess et al. 1999). An estimated down-hole pressure of 600 psi (based on discussions with operators of gas wells within the model domain) was assigned to perforated well elements using the DELV option in the model (pressure differential of about 2,300 psi; 2,900−600). The resulting production rate declined over time as fluids were depleted. The simulated production rate was compared to the actual production rate from existing producing wells within the model domain to determine how well the model simulated actual production.

MODEL CALIBRATION

Reentry Well Calibration

The primary calibration of the model was based on the historical reentry well data. Parameters adjusted during the calibration process were the permeability and porosity of the chimney, nuclear fractured region, and the lower Williams Fork sandstone. The fit parameters are given in Table 1, and the best fit is shown in Figure 4. The permeability of the lower Williams Fork sandstone in the horizontal direction of the natural fracture trend (kx) was assumed to be 10 times that of the permeability normal to the trend (ky) and that of the vertical permeability (kz). This anisotropy ratio was constant for all simulations.

Table 1. Reentry well calibrated parameters.

ROCK	kx [m^2]	Porosity
chimn	0.4×10^{-11}	0.33
NFrac	0.6×10^{-15}	0.06
LWFsd	0.5×10^{-17}	0.05
shale	0.1×10^{-19}	0.06

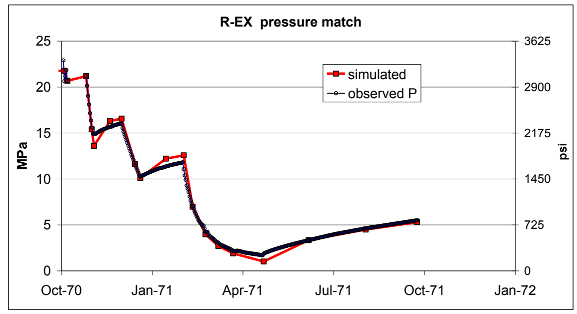

Figure 4. Observed and simulated pressures

Gas Well Calibration

Parameters adjusted during the calibration process were the permeability and porosity of the LWFsd, the hydrofractured sandstone near the well (HFnsd), the hydrofractured sandstone far from the well (HFfsd), and the hydrofractured shale near the well (HFshl). Three wells, two with many sand layers perforated (26-33B, 26-34C) and one with few sand layers perforated (26-34D), were chosen for the calibration. The best fit (solid lines) plus two other simulation results are shown on Figure 5. The best fit parameters are given in Table 2.

Table 2. Gas well calibrated parameters.

ROCK	kx [m^2]	k increase [a]	Porosity
LWFsd	0.4×10^{-11}		0.06
HFnsd	0.6×10^{-15}	40	0.06
HFfsd	0.8×10^{-17}	4	0.06
HFshl	0.1×10^{-19}	4 (800x shale)	0.06

[a] k increase is permeability multiplier over LWFsd

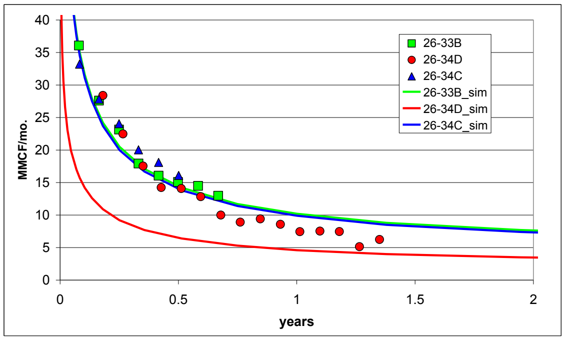

Figure 5. Observed and simulated production.

Because of the limited production history, a better method than matching simulated and actual production rates for these wells is to compare the simulated and industry-expected total production over the life of a well. With a simulated production life of 25 years, wells 26-33B and 26-34C would produce about 1.44 and 1.34 BCF, respectively, given the parameters of the calibrated model. The low simulated-production rate well 26-34D would produce about 0.66 BCF.

MODEL RESULTS

The first step after model construction was to simulate the post-detonation events up until the gas wells in the model domain were installed (2010). The second step simulated production from the existing gas wells and staged additions of future gas wells for 25 years as suggested in the Rulison Path Forward document.

Post-detonation to 2010 Simulations

The post-detonation simulations show conditions after the detonation through the reentry well testing to just before recent gas development in the area. Figure 6 and Figure 7 show the conditions after the fourth and last production test. The low pressures caused by the production testing enhanced the evolution of THO from the aqueous phase into the gas phase, increasing the concentration in the gas phase in the lower chimney. The pressure drop in the chimney extended through the nuclear fractured region into adjacent sandstones. Diffusion of THO did not extend much beyond the nuclear fractured region, and the pressure in the chimney recovered to near pre-detonation levels.

Path Forward Simulations

The Rulison Path Forward recommends that wells encroaching on the site be drilled in a staged approach to minimize the risk of encountering contamination. The path forward simulations begin with the onset of production from wells installed in 2010. The plots of simulated results in 2015 show the pressure drop extending from the existing wells and the remnant pressure effect from the reentry well (Figure 8), and the unaffected concentration distribution (Figure 9). Production from the 0.5-mile wells begins at this time.

Figure 10 shows the pressure distribution in 2030, 5 years after the closest simulated wells (adjacent) started producing.

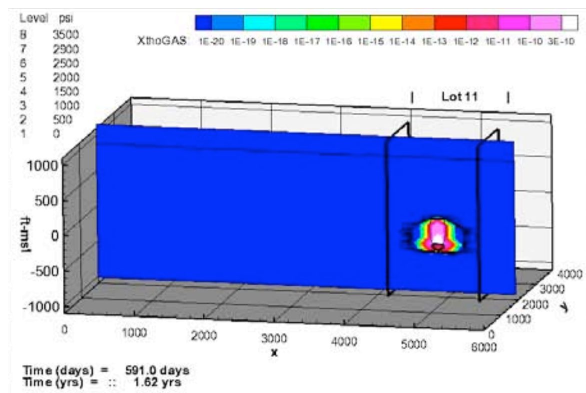

Figure 6. Concentration distribution after testing.

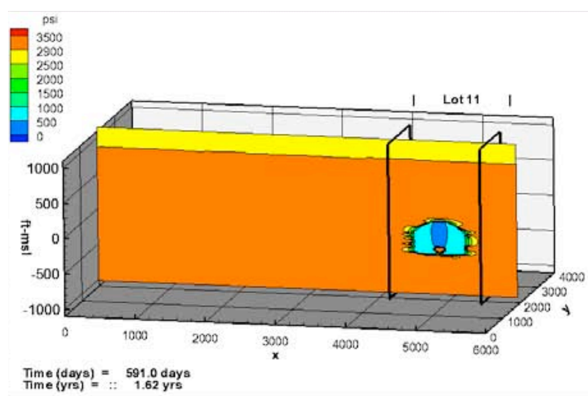

Figure 7. Pressure distribution after testing.

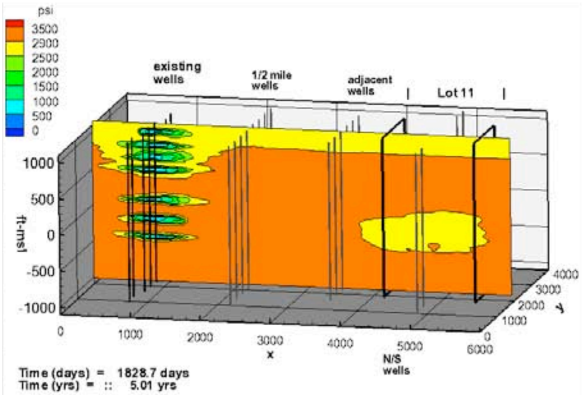

Figure 8. Simulated pressure distribution in 2015.

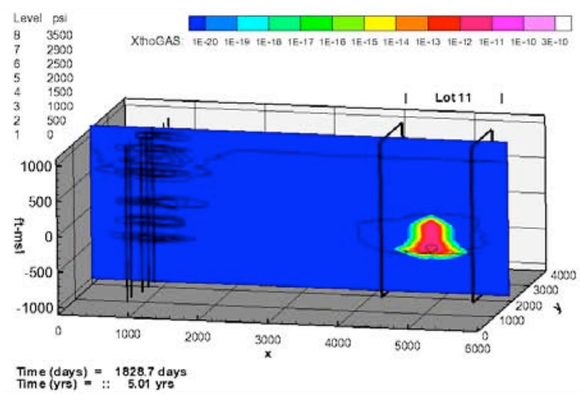

Figure 9. Simulated THO distribution in 2015.

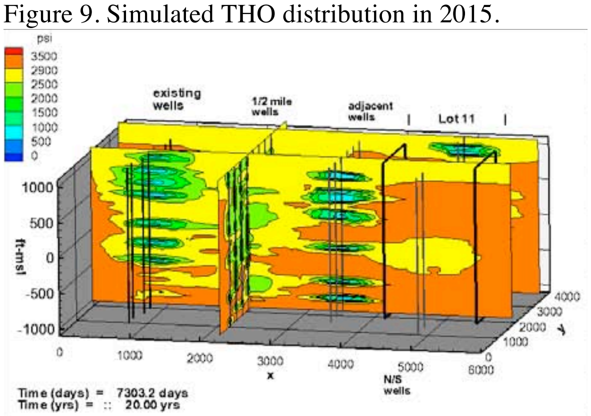

Figure 10. Simulated pressure distribution in 2030.

Figure 11 shows the pressure distribution in 2045, at the end of the adjacent wells' production life. An additional contour (2875 psi) was added to see the pressure effects extending into the chimney region. Note that this pressure gradient is insufficient to induce migration of THO from the detonation zone (Figure 12).

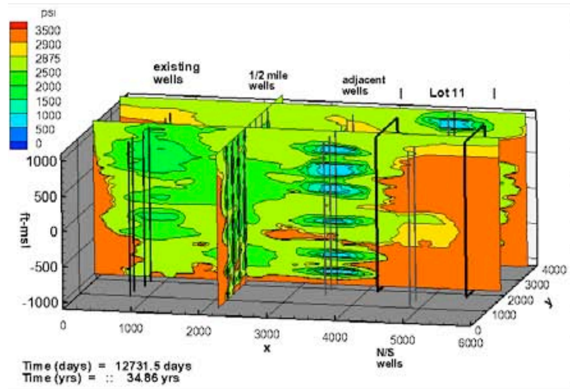

Figure 11. Simulated pressure distribution in 2045.

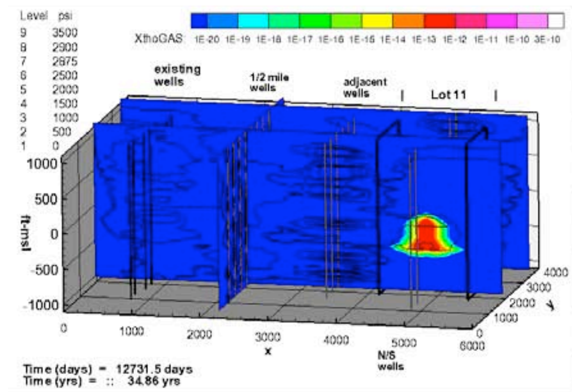

Figure 12. Simulated THO distribution in 2045.

CONCLUSIONS

The finding that THO did not migrate from the detonation zone was fully expected, considering the retarding effects of THO vapor coming into contact with liquid water. In addition, the possibility that production from nearby gas wells could reduce pressure in the formation enough to make a connection with the detonation zone was demonstrated for a few perforated intervals in a simulated well in the most vulnerable location. However, the induced pressure gradient was less than observed natural pressure variations in different sandstones in the same well and was not sufficient to induce contaminant migration.

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