Balancing Subsurface Restrictions and Resource Access under Conditions of Changing Land Use at the Rulison Underground Nuclear Test Site, Piceance Basin, Colorado, USA – 9440

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ABSTRACT

Site closure decisions often rely on institutional controls, and one of the requirements of long-term management is monitoring and responding to changes in land use. This challenge is particularly acute for underground nuclear tests, where contaminants occur in mobile fluids (groundwater or natural gas) subject to resource extraction. The Rulison underground nuclear test was conducted in Colorado in 1969 to evaluate the effectiveness of a nuclear detonation at stimulating natural gas production from the low-permeability Williams Fork Formation of the Mesaverde Group. After a period of production testing and surface cleanup, the site was deactivated in 1976, with a subsurface restriction on drilling intrusion within the 40-acre parcel surrounding the nuclear test well. Increasing natural gas exploration activities are causing the U.S. Department of Energy (DOE) to assess if the original site institutional controls remain effective at protecting the public. To support the assessment of institutional controls, a numerical model was developed to simulate the movement of nuclear-test-produced tritiated water in both gas and liquid phases through the subsurface. Uncertainty in geometry of geologic units and in flow and transport properties was included in the model in order to identify the likely system behavior, as well as low-probability but potentially high-consequence behavior. Generally, conservative assumptions were used for many parameter distributions, consistent with the uncertainties inherent in the problem and the desire to err on the side of caution. The Monte Carlo modeling approach allows transport predictions to be understood in a probabilistic context, so that the expected behavior is identified, as well as the unlikely outcomes captured by the tail of the distribution. Model results indicate that tritium migration is not currently expected beyond the existing land restriction, but the model's primary purpose is as a platform for hypothesis testing of the adequacy of the restrictions under various gas-production scenarios. Information on drilling strategies and development techniques (e.g., hydraulic fracturing) was gathered by consultation with gas exploration companies and the Colorado Oil and Gas Conservation Commission. Evaluation of hypothetical production scenarios indicates that tritium migration to production wells is expected in only a small number of realizations. The Monte Carlo results were examined to identify low-probability but high-consequence events, allowing additional evaluation to be focused on situations that may allow transport. In total, the model results allow DOE to provide recommendations for well placement, testing programs for new wells, and monitoring that does not unnecessarily restrict access to the resource but accounts for the possibility of unexpected conditions.

INTRODUCTION

In the 1960s and 1970s, both the United States and Soviet Union considered applying nuclear devices to the problem of enhancing hydrocarbon production from low-permeability reservoirs. Three field-scale feasibility tests were conducted in the United States, one at the Gasbuggy site in New Mexico, and two in Colorado at the Rulison and Rio Blanco sites. The Rulison test is located in west-central Colorado, approximately 40 miles from Grand Junction (Figure 1). It was conducted in the Piceance Basin, a large structural basin containing thousands of meters of sedimentary rocks, and specifically within the Williams Fork Formation of the Mesaverde Group. The Williams Fork is characterized by sandstone lenses within shale and siltstone. The very low permeability and discontinuous sandstone presents challenges for exploiting the natural gas accumulations. The intention of the Rulison test was to intersect multiple sandstone lenses with a large-diameter, high-permeability, rubble chimney created by the nuclear detonation when overlying rock collapsed into the cavity void.

A 40-kiloton nuclear device was detonated in the Williams Fork Formation on September 10, 1969 [1]. It was located 2,568 meters below ground surface in emplacement hole Hayward 25-95A. A site evaluation hole, Hayward 25-95, is located 95 meters to the southeast. Both boreholes are within Lot 11 of Section 25, T7S, R95W, 6th Principal Meridian. After waiting 7 months for short-lived radionuclides to decay, Hayward 25-95 was reentered, and directional drilling was used to intercept the nuclear chimney. A series of gas-production tests was conducted to evaluate the effects of the nuclear test on formation properties, gas production, and gas quality. The final flow test ended in April 1971, after which the well was shut in and the site was placed on standby status. General site cleanup operations began during the summer of 1972 and concluded when the two wells were plugged and abandoned in 1976.

The nuclear detonation cavity is protected by over 2,400 meters of overburden and a restriction on subsurface access. The restriction states that “no excavation, drilling, and/or removal of subsurface materials below a depth of 6,000 ft is permitted within Lot 11, NE ¼ SW ¼ of Section 25 Township 7 South, Range 95 West, 6th Principal Meridian, Garfield County, Colorado, without U.S. Government permission.”

Land use since 1976 facilitated site stewardship. Activities near the site were limited to recreation and scattered vacation homes in the surrounding area. Escalating energy costs in recent years have dramatically changed activities near the Rulison site. Over 4,900 wells are currently active in Garfield County; the most intensive development is within the tight gas sands of formations in the Mesaverde Group. Infill drilling is commonplace, and well densities are as close as 10-acre centers. DOE, as the steward of the Rulison site, recognized the need to reevaluate the drilling restrictions. When the original restrictions were developed, the current intensity of subsurface exploration was not foreseen, and advanced computer modeling capabilities had not yet been developed.

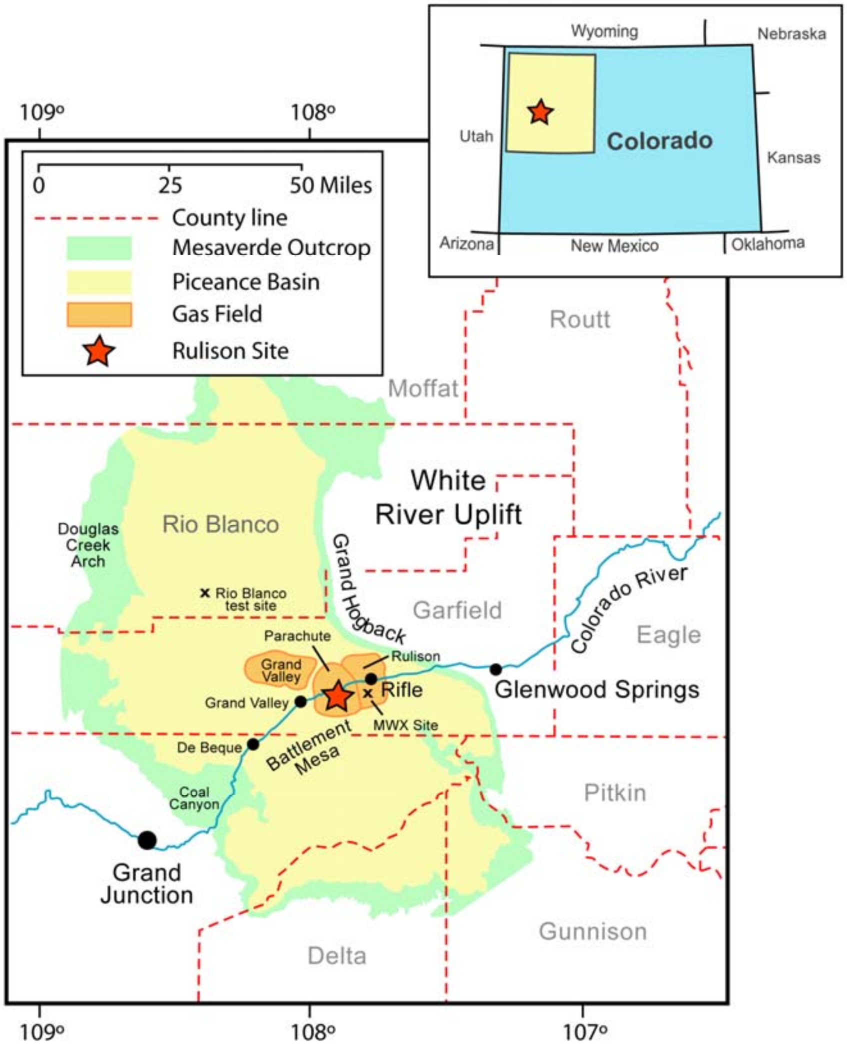

Fig. 1. Location map showing the Rulison site in the Piceance Basin of western Colorado.

ENVIRONMENTAL REMEDIATION ACTIVITIES

Annual sampling of wells, springs, and streams in the Rulison area has been conducted as part of a long-term radiological surveillance program of underground nuclear test sites [2]. No radionuclides have been detected above background. The DOE Environmental Management Program, designed to systematically evaluate and remediate DOE sites with contamination related to Cold War activities, became active at Rulison through a voluntary remediation of a surface mud pit in 1995. After the cleanup and closure of the surface mud pit, attention turned to evaluating the subsurface contamination [3]. There is no technically feasible method for removing the contamination in the nuclear cavity. Rather, the focus of the subsurface investigation is to evaluate if the existing subsurface restriction is adequately protective of human health and the environment, and if it is not, to determine how the restriction should be modified and managed to be protective. Responsibility for the Rulison site closure process was transferred from the Environmental Management Program to the Office of Legacy Management in 2007.

There are a number of challenging aspects to evaluating the Rulison underground nuclear test and managing the site in an environmentally responsible manner. Some of these challenges are pragmatic. The cost benefit of characterization data is not favorable for field investigations; at a depth of over 2,500 meters, drilling and testing are expensive, yet only a very small portion of the subsurface is interrogated by a borehole. Intrusion into the site by drilling would also create potential pathways where none currently exist. Abundant data are available for the general subsurface conditions in the area as a result of intensive government-sponsored research, such as the Multiwell Experiment Site (MWX) [4], and an oil and gas industry approach in the Piceance Basin that favors the open exchange of information through scientific publications and workshops [5]. Conversely, an evaluation that relies on numerical modeling faces significant challenges from the fundamentally incomplete understanding of fluid flow in partially saturated fracture systems. Neither the physics nor the data can support flow and transport calculations using a discrete fracture network approach for Rulison. An equivalent porous-medium approach is the practical alternative, though it has the drawback of approximating true subsurface conditions.

These technical challenges are rivaled in importance by the challenges presented by the conceptual site model in terms of risk and risk-management options. The current site conditions preclude an exposure pathway for radionuclides to reach people. Rather, the concern relates to future land use that could result in a pathway via a drilling operation. Although the intensity of drilling in the Piceance Basin renders a drilling scenario well-founded, the specifics of where wells will be drilled, the manner of their completion in 3-dimensional space, their operation, and the relative timing of these actions are speculative, resulting in infinite combinations of conditions for future scenario analysis. This type of problem is not unique to Rulison, and a common approach is to be conservative in terms of protecting human health by considering the most adverse combination of conditions. While this conservatism may be easy to tolerate in some situations, the cost at Rulison could be extraordinarily high: the value of the natural gas resource is equal to many millions of dollars for local landowners, energy-exploration and production companies operating leases, and investors in those companies. Conservative assumptions cannot be casually applied simply to ease the analysis, yet stakeholders without a financial stake in the gas resource understandably view the uncertainties as demanding conservatism.

The approach to meet these challenges seeks to strike a balance between realism and conservatism, but with the paramount objective being protection of human health and the environment. Access to the natural gas resource is not promoted by this approach, but neither is it unnecessarily prohibited. Land use restrictions and monitoring are the measures planned for long-term stewardship. A numerical model of flow and transport is a tool to support the land-use and monitoring plans, and a mechanism for understanding and updating those plans as new information becomes available. The remainder of this paper focuses on the approaches used to develop a model that reflects the desired balance and is scientifically defensible. First, a general description of the dual-phase model and simulator is provided, highlighting aspects relatively unique to the Rulison problem. Second, the approach to uncertainty is presented, and its relationship to conservatism is discussed. Third, the involvement of stakeholders in developing future scenarios is described. Finally, observations regarding reaction to the model are presented, along with opportunities for using it to continue providing information for site stewards.

THE FLOW AND TRANSPORT MODEL

The conceptual model for the deep subsurface at the Rulison site describes flow and transport through the unconventional natural gas reservoir found in the Williams Fork Formation. This reservoir is characterized by very low-permeability sandstone lenses surrounded by even lower-permeability shale and siltstone (Figure 2). Liquid water and gas coexist; neither phase is dominant. Successful gas production relies on the presence of natural fractures in the sandstone, but even with these fractures, the reservoir is considered very “tight.” The fractures trend in an east–west direction, leading to higher permeability, and more gas drainage to a well, along that direction. Natural gas producers drill a borehole to intercept many of the individual sandstone lenses and hydrofracture them to create viable gas-production wells.

The nuclear test created a rubble-filled chimney with very high permeability and porosity. Surrounding this chimney is a zone of fractures caused by the pressure wave from the test, similar to hydrofractures.

The majority of radionuclides produced by the nuclear device are incorporated into immobile nuclear melt glass. Some do occur in the gas phase, but to a large extent, these were removed during production testing in the 1970s and released to the atmosphere during the flaring (burning) of the natural gas on site. Tritium is the current constituent of concern at the Rulison site for the following three reasons: (1) it occurs in the gas phase and, thus, is mobile in this partially saturated subsurface environment; (2) it has significant mass remaining in the subsurface after gas-production testing at the site; and (3) separate risk analyses determined that it was the only radionuclide of concern from nuclear-stimulated gas wells [6].

The conceptual flow and transport model considers tritium migration from the nuclear chimney as the tritiated water molecule (THO) in both the gas and liquid phases. Transport occurs radially from the nuclear chimney under a chemical concentration gradient (diffusion) for the 38 years from the time of the nuclear test to 2007. At that time, a hypothetical gas-production well is assumed to begin gas production adjacent to Lot 11. The production is assumed to continue for 30 years, during which time the transport of tritium is enhanced by the pressure gradient induced by the well.

The conceptual model is implemented in the numerical simulator TOUGH2 [7], which solves for two-phase flow of gas and liquid, as well as transport of a compound in both phases. An equivalent porous-medium (EPM) approximation is used to simulate the fractured environment, meaning that discrete fractures are not modeled but are instead represented by adjusting porous-media properties to account for fracture flow behavior. Concerns about representing flow in individual fractures by using relatively large grid blocks (in this case, 20 × 20 × 5 meters) can be at least partially addressed by considering spatially variable hydraulic properties that replicate the preferred fracture orientation and the effect on the permeability field. The Rulison problem introduces another issue regarding the EPM: with a fracture aperture typically larger than the characteristic pore diameter, fractures will tend to be filled with the gas phase, whereas the pore spaces will contain gas and liquid. This can affect the relative permeability assigned through Corey's function [8], the tortuosity calculated in the model using the Millington-Quirk model [9], and the partitioning of tritium between gas and liquid phases. If many fractures are gas-filled ("dry"), the relative permeability and tortuosity could allow faster velocity than simulated using an EPM. The partitioning is an important "sink" during transport, as tritium may migrate quickly in the gas phase but then exchange into the immobile adjacent liquid phase. Again, if fractures are dry, the EPM may overestimate this transfer because more contact between liquid and gas is allowed in the model than may occur in the fractures.

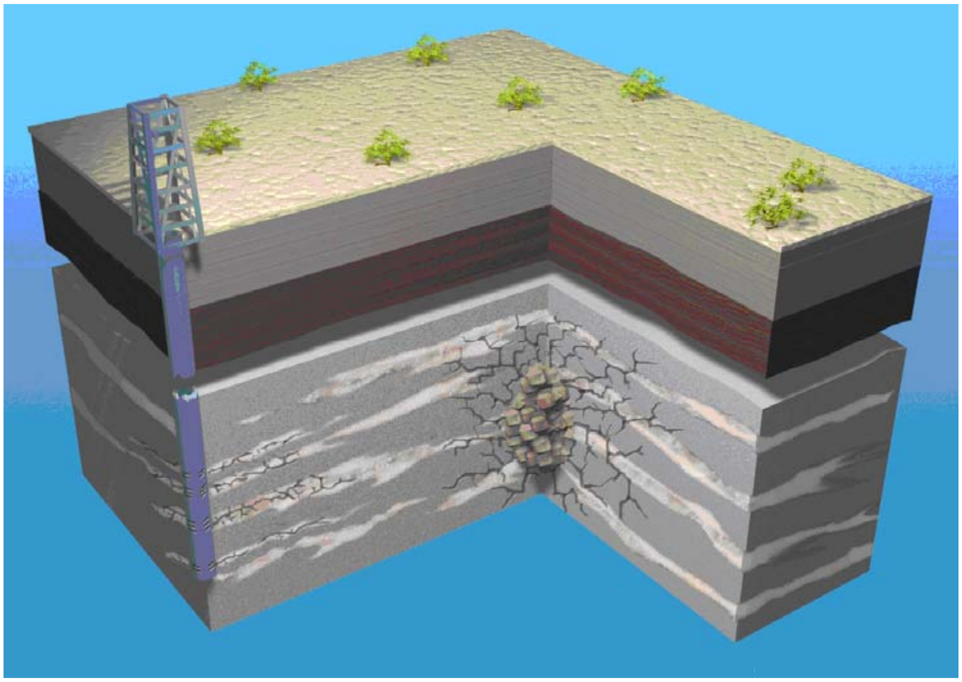

Fig. 2. Conceptual model of the Rulison flow and transport numerical model. The high-porosity and high-permeability nuclear chimney is depicted, as well as a hypothetical gas-production well with hydrofractures into the light-tan sandstone lenses. The darker gray represents shale or siltstone.

MODEL UNCERTAINTY

The significant uncertainties inherent in models of subsurface processes render deterministic approaches inadequate and potentially misleading. In response, a variety of approaches have been developed for groundwater models to incorporate uncertainty into the calculation process. This produces results with more information and intellectual honesty, and in the case of the Rulison problem, it also provides a mechanism for evaluating both the expected system behavior and the low-probability, high-consequence tail of the distribution.

A Monte Carlo method is the workhorse of the Rulison uncertainty approach. Three types of uncertainty were addressed. First is the uncertainty in the geometric configuration of sandstone and shale in the subsurface. Experience in the Williams Fork Formation of the Piceance Basin has identified that gas production occurs from the numerous and relatively thin sandstone lenses and that the intervening shale is a barrier to flow. As a result, the configuration of sandstone lenses is a primary control on the potential for migration from the nuclear cavity to a production well. Because the spatial distribution of sandstone and shale cannot be known precisely between boreholes, the geologic units are treated as random variables. Conditional random realizations of the sandstone and shale geometry were generated using a transition-probability/Markov-chain approach that ultimately developed from observations of sandstone occurrence in boreholes and outcrop. Five hundred realizations of sandstone and shale geometry were simulated for the model domain, conditioned on the observations at the two site wells (Figure 3). These are carried forward as the geologic framework for the subsequent TOUGH2 simulations.

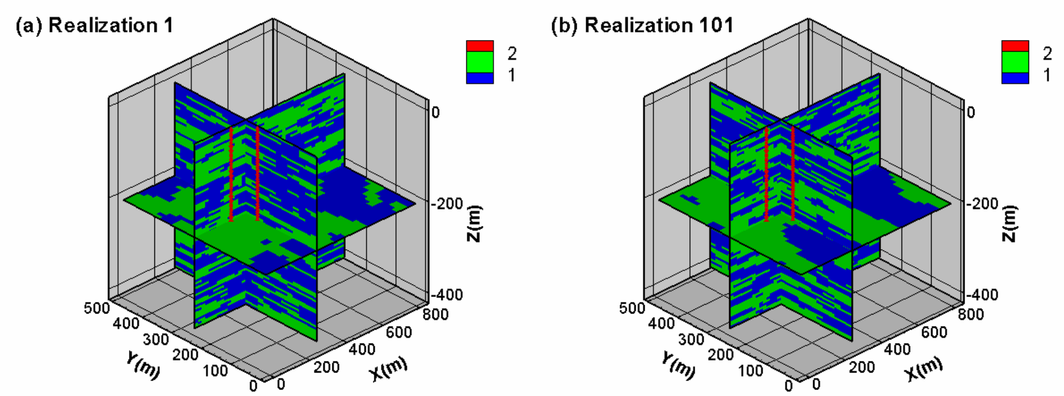

Fig. 3. Two conditional random realizations of sandstone (denoted as 1, in blue) and shale (denoted as 2, in green). Conditioning data at the boreholes are marked in red.

The second type of uncertainty is parametric uncertainty regarding flow and transport properties. Although values are available for parameters such as permeability and porosity, uncertainty results from spatial variability, measurement errors, and sampling bias or inadequacy. Distributions for the uncertain parameters are built from the available information, with a conscious bias toward values that promote flow and transport. Parameters treated stochastically include the intrinsic permeability of sandstone in the *y*- and *z*-directions (developed from core measurements of permeability), the anisotropy ratio for permeability in the *x*-direction relative to that in the *y*- and *z*-directions (developed based on the greater permeability measured for the reservoir in field tests relative to the core measurements), the intrinsic permeability of sandstone in the *x*-direction (by virtue of the anisotropy ratio), and sandstone porosity. Uncertainty exists in other model parameters, but they were treated deterministically either because the model was insensitive to the possible range of values, or because there was no information on which to base a distribution around the one best estimate.

The third type of uncertainty is also parametric, but it is highlighted separately because these parameters pertain to properties of hypothetical model elements that do not currently exist near the site. These are specific to hydraulic fracturing assumed to occur in the hypothetical gas-production well, and their uncertainty stems not only from the same tangible reasons as the previous parametric aspects but also from the speculative nature of future anthropogenic activities. The length of a hydraulic fractured zone outward from the hypothetical well is treated stochastically, as is the intrinsic permeability in the *x*-, *y*-, and *z*- directions of the hydraulically fractured zone. In this case, the permeability for each direction is calculated by multiplying the values for *x*, *y*, and *z* in the native fractured sandstone in that realization by 100.

The simulation process begins by selecting one of the realizations of sandstone-shale geometry and assigning parameter values selected from the distributions for sandstone porosity, intrinsic permeability in the *y*- and *z*-directions, anisotropy ratio, and hydrofracture length. Permeabilities for the sandstone *x*-direction and for the hydrofracture are then calculated, and the simulation proceeds to calculate tritium migration for the 500 years following the nuclear test. The process is then repeated until 500 realizations are completed, each time selecting values for the uncertain parameters from their respective distributions. The stability of the mean and standard deviation indicate that 500 realizations are sufficient to achieve convergence in the sample statistics.

STAKEHOLDERS AND SCENARIO DEVELOPMENT

During the first 38 years of the simulation (from the time of the nuclear test until 2007), the numerical model is replicating the natural conditions in the deep subsurface, as best understood from available information. No nearby drilling or reservoir-production activities have occurred subsequent to the pressure tests associated with Rulison, so tritium migration has been by diffusion during this period. The primary concern for site stewardship focuses on hypothetical future scenarios. The intensity of natural gas resource development from the Williams Fork Formation in the Piceance Basin strongly suggests that such development will occur near the Rulison site; however, although the general scenario may be likely, the exact nature and conditions of such development are highly speculative. This provides an opportunity to involve stakeholders in the modeling process. In contrast to most model input, where parameters and boundary conditions must be grounded in data to the fullest extent possible, scenario development can readily be tailored to address stakeholder concerns.

Communication from some local residents and other stakeholders indicated great concern that the existing restrictions on subsurface intrusion may be inadequate. Some of this concern may have been generated by confusion between a 3-mile notification region, within which the Colorado Oil and Gas Conservation Commission (COGCC) notifies DOE of drilling applications, and the actual DOE drilling restriction for Lot 11. In addition, the COGCC instituted a half-mile region in 2007, within which permits require a hearing before the COGCC. The result is heightened concern on the part of some stakeholders that the Lot 11 boundary does not provide sufficient protection to prevent new wells from intercepting radionuclides from the Rulison test.

In response, the scenario selected for the model focuses on a hypothetical gas-production well placed at the most vulnerable location outside the DOE restriction in Lot 11. This location is 258 meters due west of the nuclear cavity. Permeability is enhanced in the east–west direction due to natural fracture trends, and the nuclear chimney is closer to the western lot boundary than to the east. The distance from the chimney to the lot line is 185 meters, with the remainder representing the set-back distance for drilling adjacent to a unit boundary. Not only are the most vulnerable map coordinates for scenario evaluation selected, but the most vulnerable vertical production horizon is identified. Because the geometry of sandstone and shale lenses is different in each realization, the exact vertical location of the hypothetical production interval also differs. It occurs either at the same elevation as the nuclear detonation point, or if that elevation is shale in a given realization, it is placed in the closest model cell that represents sandstone. Placing the producing interval at the same, or nearly the same, interval as the radionuclide source ensures that the shortest possible flow path is considered in the analysis.

It is also important that the gas-production scenario is a realistic depiction of current practices, otherwise, the production companies and leaseholders could find the analysis biased and uninformative. With the production location selected to be most vulnerable, the production characteristics attempted to replicate current experience in the Piceance Basin. To that end, the operator at that time for leases near Rulison (Presco, Inc.) was consulted to determine the typical vertical extent of perforated intervals, the characteristics of hydraulic fractures in stimulated wells (length and permeability), and the general producing histories of their wells in fields near the Rulison test (production decline curve and years of production). In the case of hydraulic fracture length, the Presco, Inc., experience was important in determining the distribution from which fracture length was selected, and it was augmented by detailed hydraulic fracturing research at the MWX site. It is possible, though not necessarily routine, to estimate the length of hydraulically generated fractures using microseismic techniques, but this length does not necessarily reflect conductive, connected flow paths. Generally, effective fracture lengths are those that are propped open by injected sand, and they tend to be significantly shorter than designed or predicted fracture lengths. Though the bulk of the distribution of hydraulic fracture length is consistent with industry and research experience, the upper end of the distribution was extended to include longer fractures that could directly connect the production well and the nuclear fracture zone. This conservative decision is justified by the overall uncertainty in subsurface fracturing and the desire to err on the side of caution.

The COGCC and the Colorado Department of Public Health and Environment (CDPHE) are the active state oversight agencies for the Rulison site. The CDHPE was closely involved in the remediation of the site surface, with the COGCC more heavily involved in the subsurface investigation. The location and production characteristics for the Rulison scenario were discussed with COGCC personnel during model development to confirm that the scenario was a reasonable representation of current gas industry practices and rules. Both the COGCC and CDPHE conducted reviews of the model report [10] and provided detailed technical comments.

REACTION TO THE MODEL

The numerical modeling investigation found a very low probability that tritium will migrate from the Rulison nuclear test to the simulated production well at concentrations above background. Migration in the absence of nearby production is driven by diffusion. Though diffusion is rapid in the region fractured by the nuclear test, it is slow through the surrounding area, such that no migration beyond Lot 11 is predicted. A hypothetical gas-production well impacts the migration of tritium from the nuclear chimney in many model realizations, significantly enhancing migration in the direction of the pumping well. Although westward migration is promoted, concentrations above background do not arrive at the well in over 95 percent of the model realizations, and the peak mass fraction of tritium at the 99^{th} percentile is only slightly above background (Figure 4).

By including uncertainty in critical parameters, the model output must be described in statistical terms. The major advantage to this is that more information is available to decision makers: they are able to assess the likely behavior and the low-probability tails of the distribution. The major disadvantage is that the results can be less readily understandable in a deterministic context. Expressing the model results in statistical terms is more intellectually correct in reflecting the limits of knowledge, but it can be unsatisfying for people seeking certainty in an answer.

Rigorous technical review of the Rulison model generally accepted the technical approach while commenting on issues introduced by the EPM approximation and related features described previously. With the model results indicating very limited tritium transport, there was an understandable interest in reevaluating assumptions relevant to the upper tail of the distribution. Hand in hand with this, interest in quantification of overall uncertainty decreased. Additional simulations were performed with the model, focusing on a limited number of realizations that allowed the most transport, to test features such as tortuosity and fracture porosity. This analysis provides DOE with additional information regarding events that are highly improbable but possibly consequential if they occurred. The difficulty is that the likely system behavior expressed by the bulk of the realizations can be overlooked when stakeholders consider the results. In this case, the outcome of these tests did not significantly affect conclusions derived from the previous model results. Modifying tortuosity did promote greater diffusion, with concentrations above background approaching the Lot 11 boundary prior to the onset of pumping at the hypothetical well. However, dilution as a result of the diffusive spreading of mass in all directions from the nuclear chimney minimizes the impact in terms of the production well.

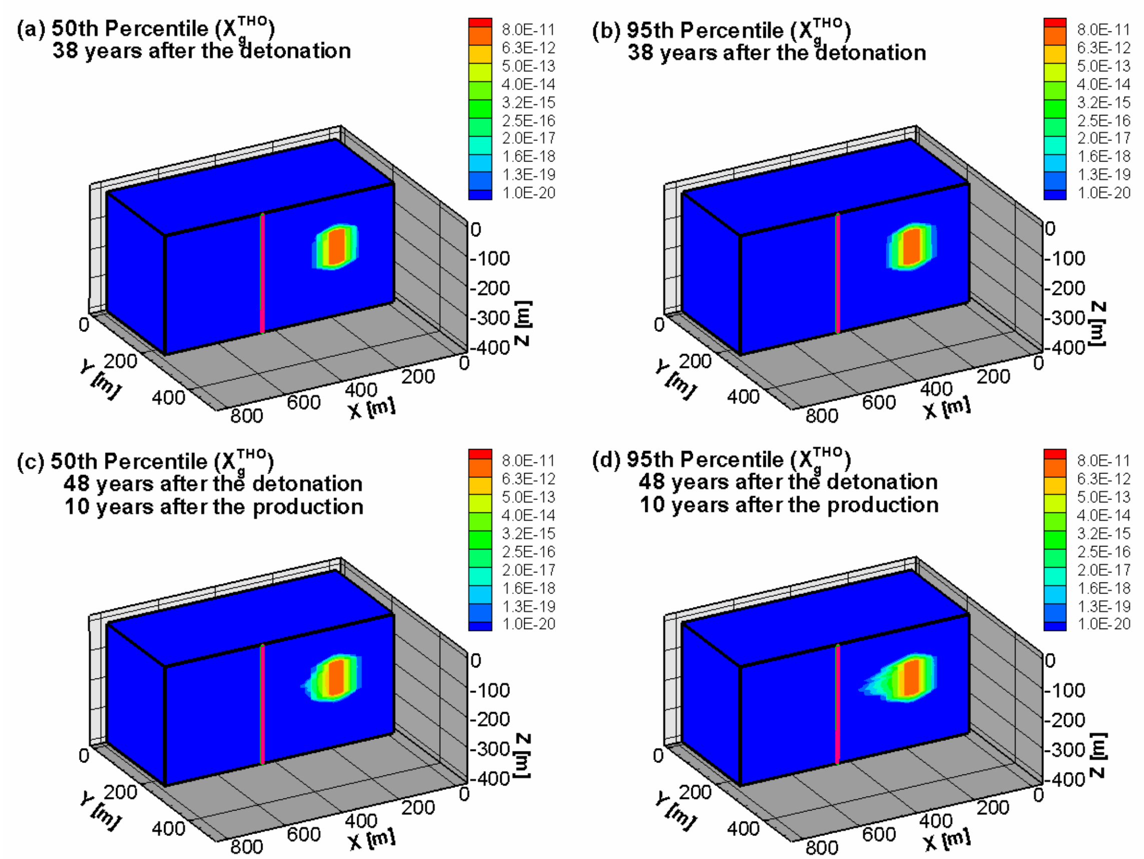

Fig. 4. The 50th and 95th percentiles of tritium mass fraction in the gas phase (X_g^{THO}) (a and b) after 38 years from the detonation (before the gas production starts) and (c and d) after 48 years from the detonation (10 years after the start of gas production).

Review by stakeholders from the gas industry also generally supported the geologic formulation of the model and formation properties, but a new operator in the area indicated that the production-well scenario did not match its development plans for the area around Rulison. The new company's plans call for the closest possible production well to actually be over 120 meters farther than the analyzed scenario. The operator also indicated that the decline curve used was overly optimistic in predicting more gas production than expected through the years. The revised well location was evaluated with the more conservative tortuosity and porosity assumptions, for the subset of the upper 28 of the original 500 realizations. Tritium above background levels did not reach the revised production well location in any of the realizations.

CONCLUSIONS

Institutional controls are a critically important tool to safeguard closure of underground nuclear test sites, sites where contamination occurs in mobile fluids with resource value (groundwater and natural gas). A major challenge for site stewardship is evaluating changes in land use that can impact the effectiveness of institutional controls and potentially threaten closure conditions. When the Rulison underground nuclear test site was deactivated in the 1970s, land use in the area was limited to recreational uses and sparsely distributed residences and vacation homes. Now the region is the center of a booming gas exploration and development industry with an intensity of drilling unforeseen by earlier site stewards. Some stakeholders are concerned that the existing institutional controls are inadequate for this change in land use. Other stakeholders have valuable property or resource holdings that could be affected by changes in controls.

Monitoring and other forms of data collection are invaluable approaches for ensuring public safety. Their drawback is that they do not provide predictive information in and of themselves. Models of subsurface flow and transport provide a vehicle for combining data and scenarios with physics to predict future behavior. These predictions come with substantial uncertainties, but nonetheless provide our only ability to foresee the consequences of potential land use actions. As a result, the numerical model of the Rulison site is a valuable tool for site land managers to navigate through the changing resource landscape in the Piceance Basin.

The Rulison model provides a mechanism for maintaining balance between subsurface restrictions and resource access in stewardship decisions. By including uncertainty in geologic conditions and parameter distributions, the likely system behavior can be identified while also examining the tail of the distribution describing low-probability, but potentially high-consequence, events. The severity of the low-probability events can then guide the approach to instituting restrictions to avoid those events.

In the case of Rulison, the model results indicate a low probability of tritium transport to a hypothesized gas-production well, and a low consequence if it did occur. With these results from a relatively comprehensive uncertainty analysis, DOE was able to determine that the existing institutional controls (i.e., Lot 11 drilling restriction and COGCC hearing requirement within ½ mile of Surface Ground Zero) were generally acceptable, even for the new land use conditions, and able to rule out an urgent need for increased restrictions. Attention is now focused on developing a comprehensive monitoring strategy in cooperation with the energy industry, compliant with regulatory requirements, and satisfying to stakeholders. The model remains a tool in this process. The upper tail of the transport distribution continues to be investigated to identify failure scenarios that the monitoring must guard against, and the production-well scenario is updated as new information comes to light.

For the long term, the model provides a platform for incorporating data acquired by subsurface activities and for improving predictions as the understanding of the physics of flow and transport in partially saturated, fractured environments improves. Additionally, the model scenarios can be updated as drilling and production proceeds in the region. This active management approach takes considerably more effort than many types of site closures, but it will allow resource development near the Rulison site as conditions are carefully monitored and new data are fed back to test the closure assumptions.

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