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Development of a Risk Assessment Tool to Investigate Gas Migration Interactions between Oil and Gas Wellbores and Potash Mines in Southeastern New Mexico

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ABSTRACT: This report presents the development of a risk assessment tool developed to mediate technical issues arising from the co-location of potash, oil and natural gas resources in the Delaware Basin in the southwestern United States, and the competing industrial interests in those resources. The risk assessment model focuses on the issue of potential natural gas migration from a leaking gas wellbore, through the geologic section, and into a potash mine. The framework of the risk assessment model is described, and example geomechanical calculations are presented which examine the effect of subsidence from a potash mine on nearby gas wellbore casings.

1 INTRODUCTION

The Secretary's Potash Area in southeastern New Mexico is the location of three nationally important subsurface natural resources: potash, oil and natural gas. The potash ore zones occur at depths between 300 and 600 meters in the Delaware Basin, a region of bedded salt, polyhalite, and potash deposits that also includes the Waste Isolation Pilot Plant (WIPP), the United States' repository for transuranic waste in the deep salt formation. These potash deposits have been designated as a strategic mineral, and are directly controlled by the Secretary of the US Department of the Interior. Their development is overseen by the Bureau of Land Management (BLM), US Department of the Interior, with the Carlsbad Office being the day-to-day oversight group that also approves development permits. Sandia National Laboratories (SNL) has been asked by BLM to support their assessment of technical issues that arise during the development of these co-located resources with the focus for the present study being the potential for natural gas migration from a leaking gas wellbore, through the geologic section, and into a potash mine. The potential for gas migration from petroleum wellbores to potash mines is an important issue for several reasons. Potash mines currently operate as non-gassy mines because methane does not commonly occur at unsafe levels in potash mines. This saves the industry significant cost. Methane migration into a subsurface mine not set up for gassy-mine operation is a safety hazard which may be of high consequence. Associated issues such as the impacts of mine subsidence on wellbore assets (a factor in gas migration potential) represent potential financial loss to the petroleum industry. Both the potash mining industry and the petroleum development industry seek to maximize economic development of their leases, and time and resources spent during disagreement over key issues, such as gas migration, has been a costly business expense. For decades both industries have been contesting various issues that arise from developing these co-located resources. To mitigate the escalating legal costs arising from these issues, BLM offered the option of using SNL to provide neutral, scientific assessment of issues.

For this present work SNL has chosen to build a risk assessment tool for BLM with its underlying framework for encompassing conceptual models, data, and other elements, that provides a more centralized, traceable and transparent process for analysis of technical issues. This report summarizes the full risk assessment report sent to BLM (Sobolik et al., 2011), which presents the risk assessment (RA) framework and methodology SNL developed using the gas migration problem to set up example conceptual models, parameter sets and computer models and as a foundation for future development of RA to support BLM resource development. This RA framework is based on the SNL's previously successful development of such a methodology for WIPP. The framework is built upon a total systems approach encompassing the potash mines and oil and natural gas wellbores in the Delaware Basin, and utilizes site-specific geophysical data, as well as geomechanical and hydrological computational modeling. The tool described in this paper is in the first phase of RA development and shows the possibilities for development of a functioning RA tool that would grow to meet project needs over time.

This paper discusses the overall framework of the risk assessment tool, and provides example geomechanical computations for the gas migration problem. The geomechanical component examines the mechanical interaction between the potash mines and the oil and gas wells. This interaction occurs primarily from subsidence resulting from the removal of potash, which alters stresses and strains in the bedded layers of salt, potash, and anhydrite. These mechanical alterations induce slip between the bedded layers, stress-induced changes in porosity and permeability, and stresses and strains that can potentially affect the integrity of the wellbore casings structures. All of these processes can potentially develop conditions that may allow migration of gas from the wellbores to the mines.

2 RISK ASSESSMENT FRAMEWORK

Risk assessment provides a framework for placing information in context such that a system can be examined as a whole. For example, the United States has applied risk assessment to key decisions concerning radioactive waste disposal. During this same period, risk concepts have been applied to nuclear reactors, nuclear fuel storage and transportation systems, and critical infrastructure such as national treasures, dams, and water supplies. Risk assessment does not necessarily eliminate disagreements but the approach can clarify the nature of the disagreement for more productive dialog. In later iterations of the risk assessment, the approach can become much more detailed and used to illuminate further research that might develop more understanding. The risk assessment framework can also be used to evaluate the efficacy of proposed options to mitigate areas of concern.

2.1 *Risk assessment concepts*

Risk assessment is a type of policy analysis of what can go wrong in human affairs, in which the current state of scientific and technological knowledge is made accessible as input to risk management decisions. Although risk has several connotations inside and outside the profession of risk analysis, *risk* is generally used in this paper to express some measure that combines "the gravity of harm" to something valued by society and "the probability of the event." Frequently, within the risk profession, the measure of risk is the expected value of the consequence, e.g., probability times consequence based on average values, as used in simple annuity analysis. For financial investments, the measure is often the variance of the return on investment. For situations with large uncertainty, the measure of risk is the entire distribution of possible consequences.

2.2 *Benefits of a risk assessment framework*

In general, a risk assessment process provides a solid foundation and readily adaptable framework for evaluating the risks of gas migration. Using risk assessment as the hub for decisions has several benefits. First, a risk assessment provides a logical framework for organizing the information relevant to risks of gas migration. Second, the risk assessment provides a means to categorize various hazards and the evaluation of those hazards in order to provide input to future decisions on how to manage risk. A qualitative benefit of adopting a risk assessment framework is that it will help the BLM, potash industry, and petroleum industries develop sensible guidelines for future interaction.

Should the risk assessment move to a modeling phase, the risk assessment provides a means to analyze how different components (reservoir, production wells, abandoned wells, and migration pathways) of the system behave in conjunction with each other (e.g. evaluate ability of various well designs to mitigate risk). A risk assessment can readily identify components of the system that contribute most to the risks and identify areas of research that should be conducted to reduce these risks. Therefore, the results of a risk assessment provide a means to prioritize future data, modeling, and monitoring needs to aid in decisions on research and data collection priorities. The risk assessment framework can also be used to evaluate monitoring schemes. An ancillary benefit of a risk framework is that the analysis process and any decisions based on the analysis are more transparent and traceable and thus more readily scrutinized by peers.

2.3 *Risk assessment tasks*

In general, a probabilistic risk assessment comprises up to seven tasks that form a framework for organizing information (Rechard, McKenna, & Borns, 2010): (1) identify needs of study (such as develop appropriate measures of risk and identify risk limits); (2) define and characterize the system (such as wellbore and geologic barrier and agents acting on the system); (3) identify sources of hazards through selection of features, events, and processes (FEPs) and form scenarios of alternative behavior from these FEPs (such as marker bed feature, failure event of wellbore, fracturing and migration of gas in marker bed); (4) quantify uncertainty in consequence estimates (such as definition of uncertainty in modeling parameters using probability distributions) and evaluate probability of scenarios (such as through expert elicitation); (5) evaluate the consequences (such as qualitatively through expert elicitation or quantitatively through construction of a system of physical models); (6) combine the evaluated consequences and probabilities and rank relative risk guidelines; and (7) perform sensitivity analyses to identify the parameters and model form whose uncertainty most explains the variance in the performance measure to gain further understanding, if the risk assessment is quantitative. These seven tasks are part of an iterative process in which steps are not always taken in a set order and some steps are re-assessed multiple times. Steps 3, 4, and 5 form a "risk triplet," a term summarizing the core, distinguishing operations of RA.

3 GAS MIGRATION CONCEPTUAL MODEL

In the development of a risk assessment model for a large system, one of the first steps is to develop a conceptual model of the problem domain. Figure 1 is a diagram that illustrates the conceptual model for study of the potential for gas migration from wellbore to mine. There are three subsystems represented by this conceptual model: 1) the geology of the Delaware Basin; 2) Wellbores used for extracting oil or gas (active, temporarily abandoned, and permanently abandoned); and 3) mining for extraction of potash deposits. The diagram shows a wellbore within the mining subsidence zone and another outside of the subsidence zone and it represents one potential general configuration for mining. The diagram shows basic geomechanical zones and represents the presence of geology/hydrology in the problem. It is understood that the real world setting is three-dimensional with stresses from various directions, and elements such as the angle of draw are not crisp, straight-lines, but are probably zones with irregular boundaries. Still, this diagram is adequate for visualizing the Features and Events of gas migration in a general discussion.

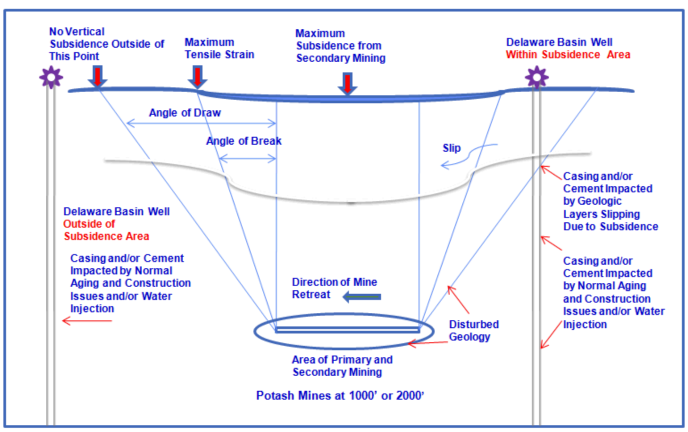

Figure 1. Diagram showing representative Features and Events for discussion of gas migration potential between a wellbore and a mine.

Figure 1 presents a generalized conceptual model used for specific geomechanical and hydrological submodels for evaluating potential gas migration. The three subsystems, geology, wells, and mine, co-exist in the conceptualization. Table 1 represents an initial identification of the FEPs that are relevant to potential gas migration. The geological features are listed – rock types, structure, presence of potash, oil, gas, water, and so on – as are relevant events (fracturing) and processes (creep, subsidence, change to permeability) that may affect gas flow in the region. Similar lists were developed for the wellbores and the mine. The FEPs that have a specific geomechanical component are listed in bold type in Table 1. The geomechanical model developed for this initial iteration of the RA tool evaluates selected FEPs, and uses the output from the calculations as input to the hydrological flow calculations.

Table 1. Features, Events and Processes (FEPs) for the gas migration scenario.

Subsystem	Geology (Both Disturbed and Undisturbed	Gas-Transmitting Wellbores	Mine/Methods Primary, Secondary
Features	**Rock Types (Salt, Potash, Anhydrite, etc.), Contact Between Layers, Fractures, Permeability, Pore Pressure,** Geochemistry, Aquifers/Breeched Water, Oil/gas reservoirs	**Cement Type & Sealing, Extent of Cement Fill (Completion), Casing and Joints, Pressure, Perforations,** Geochemistry between cement, casing, salt/potash	**Mine dimensions, depth, width (effect on wellbores), long wall vs. room-and-pillar,** gases
Events	**Fracturing around newly mined opening, fracturing along marker beds or salt/potash, oil/gas drilling in vicinity of mines,** resource exploitation, abandoned boreholes	**Sudden casing breach, cement crushing, cement fracturing during wellbore events like drilling or pressure changes, loss of bonding due to stress,** loss of cement bonding during setup	**Gas intrusion (sudden burst, gradual diffusion) into mine from potash layers, other accidents or unplanned events**
Processes	**Creep, shifting of beds over years of subsidence, alteration of porosity/ permeability**	Pressure changes over lifetime of wellbore; corrosion over time.	**Subsidence of mine over years following mine closure**

The characterization of the individual FEPs regarding wellbores relied upon a significant amount of research into characteristic wellbore construction parameters, public records of existing oil and gas wellbores in the Delaware Basin region, and a literature search to form the foundation for assigning risk of leakage to wellbores based on the condition of the cement and other factors described in publically available well records. In addition, these steps include continuous interaction with the oil, gas, and potash stakeholders to develop agreement on appropriate data to use in the RA model. The State of New Mexico Oil Conservation Division (NMOCD) requires that petroleum producers provide them with certain data when a wellbore is permitted, installed, operated and abandoned. These data are available at the NMOCD website and include documentation of daily activities during drilling, workovers, abandonment and other activities, well completion records, and testing data that provide well pressures. Several studies in Alberta, Canada of thousands of wellbores and wellbore leakage, especially as it impacts considerations for CO_2 storage using former petroleum wellbores in Alberta, Canada (Watson and Bachu, 2008; Bachu and Bennion, 2009), were able to associate leakage with FEPs and found a correlation between regulatory changes and changes in leakage potential for petroleum wells in their study area. SNL has determined that these types of studies provide insight into how BLM might use publically available records, in combination with stakeholder input, to assess wellbore leakage potential in the Potash Area. Determining the actual likelihood of wellbore leakage in the Potash Area would be a key step in a comprehensive risk analysis of the potential for gas migration into a mine.

4 GEOMECHANICAL SUBSYSTEMS ANALYSIS

4.1 *Prior geomechanical analysis*

In 2007, BLM asked Sandia to provide technical guidance to help them mitigate the divergent concerns regarding the development of potash and oil/gas resources near Carlsbad. To this end, BLM tasked Sandia to perform a geomechanical analysis of the potential effects of subsidence caused by potash mining on wellbore casings in nearby oil and gas wells, and how that affects gas migration potential from a well to a mine. The results were published and sent to BLM (Arguello et al., 2009). Comments on that analysis were received from the mining and the oil and gas stakeholders, which included significant criticism regarding some of the assumptions of the model and conclusions of the analysis.

The analyses published in Arguello et al. (2009) comprised two separate submodels: a global model that simulated the mechanics associated with mining and subsidence, and a wellbore model that examined the resulting impacts on wellbore casing. The first model was a two-dimensional (2D) approximation of a potash mine using a plane strain idealization for mine depths of 304.8 and 609.6 m (1000 and 2000 ft). Figure 2 illustrates the stratigraphy for the 304.8-m (1000-ft) deep mine. A 2D model was considered reasonable given the large areal extent of the mines relative to mine depth. The three-dimensional (3D) wellbore model considered the impact of bedding plane slippage across single- and double-cased wells cemented through the Salado Formation. The Arguello wellbore model established allowable slippage to prevent casing yield and failure. The predicted slippage across bedding planes in the global mine model were then compared to the allowable wellbore slippages to determine "safe standoff distances" (defined in the report as the distance such that mechanical effects on wellbores would not exceed the failure criteria) between a mine and well.

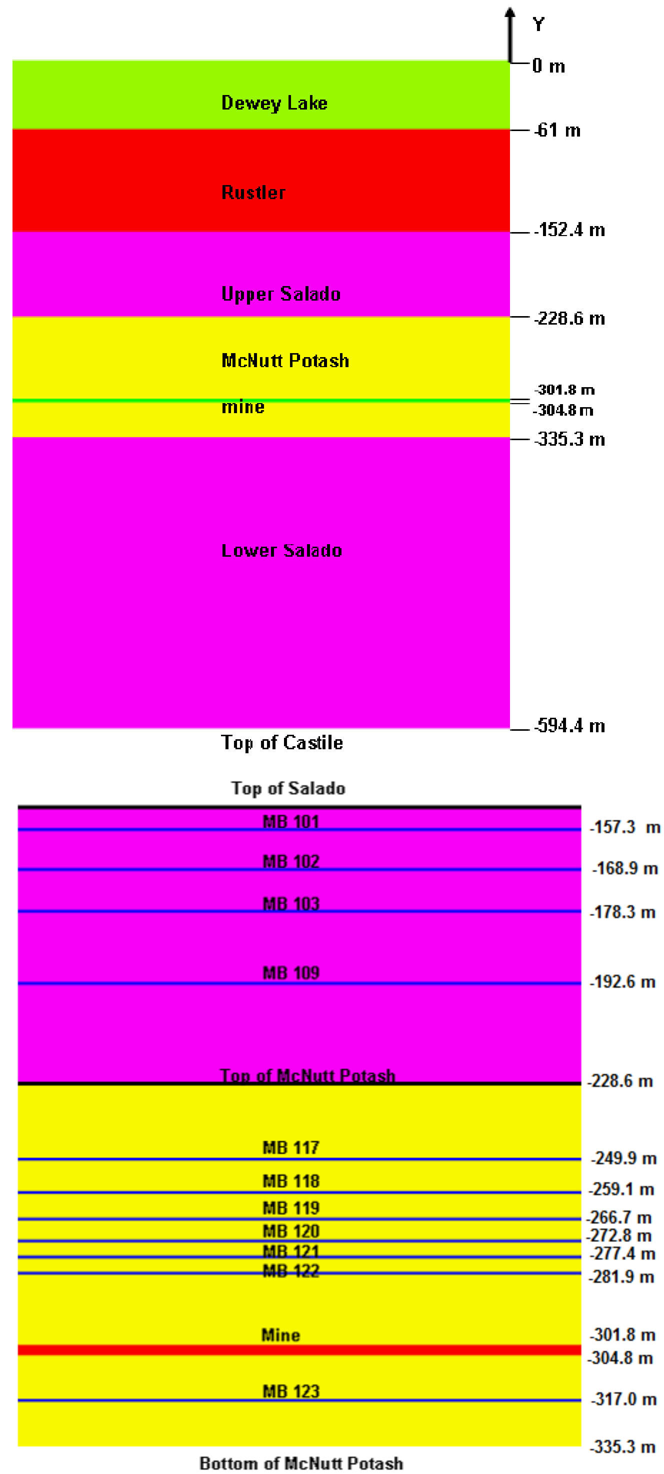

Figure 2. Stratigraphy and marker bed locations used in 304.8 m (1000 ft) deep mine (Arguello et al., 2009).

The following conclusions were drawn from the 2D global model:

- The slip magnitude was generally largest on the uppermost marker bed (in the Upper Salado, closest to the Rustler formation).
- Depending on mine depth and mining direction, the distance from the mine boundaries to the

points where no slip occurs is between 600 and 1100 m from the edge of the mine excavation.

- Large interbed slip magnitudes (greater than 0.5 m) were predicted to occur on some interfaces over the mine excavation and would be expected to impact wells that have been mined around.

The following conclusions were drawn from the 3D wellbore model:

- For the single-casing situation, the casing first yields through its thickness with very little interbed slip, namely at 0.80 mm of slip.
- Adding a second cemented casing around it only doubles the amount of interbed slip needed for the inner casing to yield through its thickness, namely to 1.6 mm of slip.

These conclusions were developed under the assumption that failure of the wellbore casing was determined when the entire casing thickness had achieved a stress state of plastic yield. For the single-casing simulation, the *entire* cross-section of the casing first yielded when the interbed slip reached a value of ~8.4 mm. At this value of interbed slip the largest plastic strain in the casing is approaching ~11.0% (close to the maximum uniform strain from uniaxial test data observed for this material); beyond this value of slip any additional interbed slip results in unimpeded movement of the top of the model relative to the bottom at the interbed. From these simulations, Arguello et al. recommended standoff distances between the wells and the edge of the mine (between 810-830 m) to prevent first yielding of the casing.

The potash and oil/gas stakeholders responded to these reports with several critical comments. Some of the most important comments included the following:

- The analytical procedure used by Arguello et al. did not include modeling of gas flow from a possible well casing failure toward the mine. This comment correctly suggested that a failure of a well casing, just of itself, is insufficient to determine the potential impact on gas flow into the mine.
- The criterion used for failure of a casing (plastic yield achieved through the entire thickness of casing) was too conservative for an unjointed casing. Casings are known to undergo significant bending in the field without losing gas containment.
- The technique of modeling the marker bed layers as contact surfaces capable only of slip did not allow for deformation of the beds themselves, which may decrease the transmission of shear stresses to the well casings.

On the basis of these and additional comments, BLM and Sandia considered developing the risk assessment tool described in previous sections, with the geomechanical model as an important subset to that model. The present work uses output from the Arguello study on the effects on wellbores and expands to studying other elements of the problem, with particular focus on the migration pathway from wellbore to mine, and forwards relevant information to the hydrologic flow portion of the RA model described in Sobolik et al. (2011).

4.2 *Geomechanical model*

The geomechanical model developed for this project must analyze the effect of changing stresses and strains on the three subsystems in the problem domain. For the conceptual model, gas migration comprises three elements, and those elements must be defined precisely. Those elements are:

- A <u>source of gas</u>; in this case, this is defined as a gas well that is leaking gas to the surrounding rock.
- A <u>driving force</u>, which is the pressure of the gas at the source location. For the purposes of developing the geomechanical model, the driving force is assumed to be within a range of pressures represented by the flowing tubing pressures in NMOCD records.
- A <u>pathway</u> from the source of the leak to the mine. This pathway will involve migration through pores and fractures in the salt, potash, and bedded layers of anhydrite, and also via existing wells within the mine footprint.

The three elements for gas migration – source, driving force, and pathway – must all be present, and in the right combination, for migration to the mine to be possible. Each of these three elements is represented by a submodel in the geomechanical conceptual model, so it is important to examine each element individually. The gas source specifically relates to the integrity of the well, so the well constitutes one geomechanical submodel. The driving force is a function of the gas pressure and the mode of leakage; for this first iteration of the RA model, there will be no geomechanical analysis of the driving force. The pathway is more easily understood by dividing it into two components: migration from the wells to close proximity with the mine; and then from there, migration into the mine itself. Therefore, the geomechanical model of the gas migration scenario has been divided into three submodels, which evaluate the gas migration elements most affected by geomechanics:

- Geomechanics on wellbore casings.
- Geomechanics related to gas migration from a well to the mine area (primarily along marker beds).
- Geomechanics related to the disturbed zone around the mine.

The wellbore casings submodel specifically examines the gas source element. The source for gas migration is defined as a wellbore that is leaking gas to the surrounding rock. There are numerous ways for gas to leak from an established well. Most of these pathways involve migration through cement, either through fractures in the cement, via incomplete bonding or gaps between the cement and the casing or rock, from porous flow through the cement, or due to the cement's mechanical or chemical degradation. One pathway involves a failure of the casing; this may occur due to stresses or strains applied through tension, bending, shear, or collapse, or by corrosion via interaction with the salt and cement. Most of the issues involving leaking through the cement are related to normal construction, operation, and aging issues experienced by wells in any oil or gas production setting. Therefore, it was decided to evaluate the geomechanical effect on the casing in the gas source submodel. There are two components of the source for this study (illustrated in Figure 3):

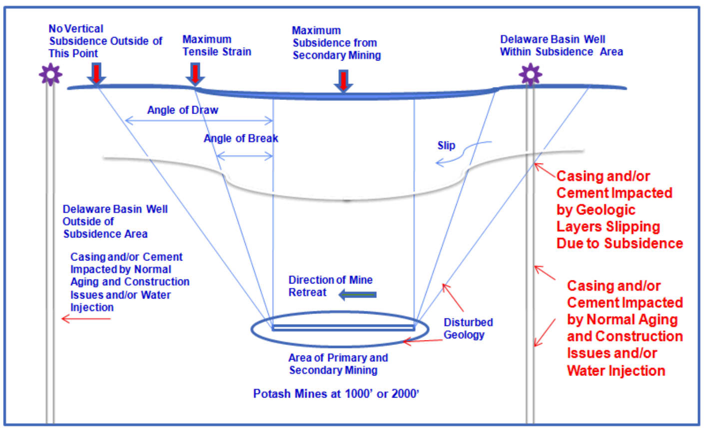

Figure 3. Wellbore casing submodel.

- Gas leakage due to normal well construction, operation, and aging issues. This component requires knowledge of the percentage of wells that have documented leaks, and also knowledge of where those leaks occur along the wellbore. The NMOCD records contain some instances of documented leaks in wells in the Delaware Basin region, but the data there are incomplete and need to be better studied and verified. The extensive studies of gas wells in Alberta, Canada documented in several papers (e.g. Bachu and Bennion (2009), Watson and Bachu (2008)) report that 6% of the wells in Alberta have documented gas leakage. This number will be used as part of the hydrology model and the overall risk assessment tool to develop probabilities of gas migration or multiple sets of geomechanical and hydrological parameters.
- Gas leakage from wells in which casing failure occurs. Casings will be subject to additional geomechanical stresses and strains caused by the effect of subsidence induced by the mining of potash. This subsidence will transmit stresses and strains laterally from the mine footprint, and will possibly also induce slip between marker beds and adjoining salt or potash layers. The geomechanical analysis will evaluate the effect of the induced slip and changes in stresses/strains on the well casings.

The second geomechanical submodel evaluates gas migration from a well to the mine area. Typically, wells will be located hundreds to thousands of feet away from the edge of the mine. Because of the long standoff distances, there must be either naturally-occurring or stress-created pathways to allow gas transmission to the region immediately surrounding the mine. Figure 4 illustrates the well-to-mine migration submodel. The most likely location for these preferential pathways are in the marker beds, which consist of more porous anhydrite and polyhalite, and which may be altered by slip along bedding planes, by fracturing, or by altered porosity. In addition, a disturbed zone around the well created during well drilling/installation may aid in the transmission of gas into the surrounding formation. The well-to-mine migration submodel will evaluate the following geomechanical features and processes, and their effect on gas flow:

- In situ porosity and fractures in potash, salt, marker beds.
- Slip, stress changes in marker beds induced by subsidence of mine and overlying layers.
- Creation of fractures in marker beds due to slip.
- Alteration of porosity in marker beds due to slip, stress changes.
- Alteration of porosity in salt or potash due to stress changes.
- Changes in permeability determined from geomechanics, given as input to hydrologic calculations.

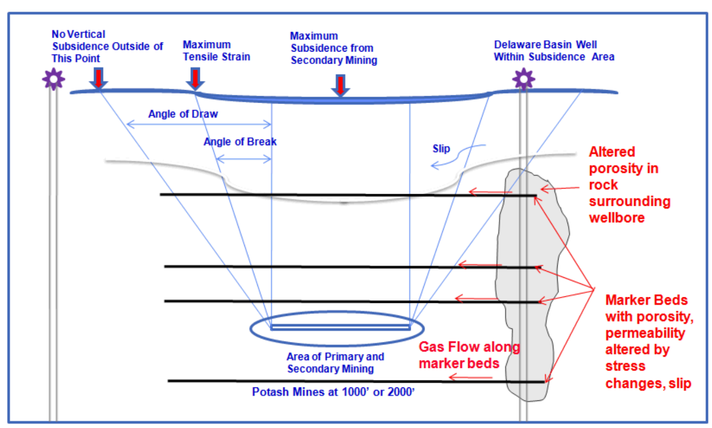

Figure 4. Well-to-mine migration submodel.

The third geomechanical submodel evaluates the disturbed zone around the mine. If gas has migrated from the wells to the mine vicinity, the next step is to find a path into the mine itself. There are two primary ways for gas to get into the mine, as illustrated in Figure 5 through the disturbed salt and potash surrounding the mine, and through pre-existing wells and mine shafts within the mine footprint. The disturbed zone around the mine may create sufficiently high shear stresses to induce dilatancy, in which microfractures are created which increase the permeability of the salt or potash and may eventually lead to significant fracturing. The mine disturbed zone submodel will evaluate the following geomechanical features and processes, and their effect on gas flow:

- Creation of fractures in the salt and potash due to stress changes.
- Alteration of porosity in the salt and potash due to high shear stresses (dilatancy).
- Presence of old wellbores within the mine footprint, which may provide preferential pathways.

The resulting changes in permeability are determined from geomechanics, and then given as input to hydrologic calculations.

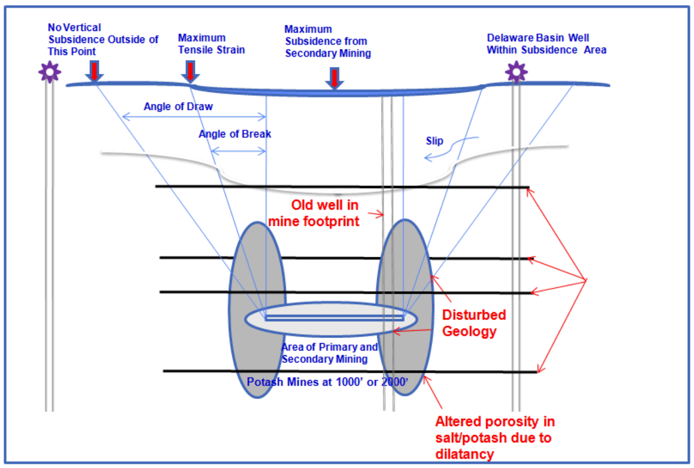

Figure 5. Mine disturbed zone submodel.

The finite element code chosen for conducting the geomechanical computational analyses is JAS3D, (Blanford et al., 2001), a three-dimensional finite element program developed by Sandia National Laboratories, and designed to solve large quasi-static nonlinear mechanics problems. Several constitutive material models are incorporated into the program, including models that account for elasticity, viscoelasticity, several types of hardening plasticity, strain rate dependent behavior, damage, internal state variables, deviatoric creep, and incompressibility. A robust contact algorithm allows for the interaction of deforming contact surfaces of quite general geometry (Blanford et al., 2001).

The geomechanical model for this first iteration of the RA model is nearly identical to that implemented by Arguello et al. (2009): a global 2D model of the mine and surrounding formations to calculate subsidence and bedding slip induced by the mining activities, and a 3D representation of a wellbore casing at the slip plane between two bedded layers. (The 3D wellbore model is discussed in detail in Sobolik et al. (2011), but is not covered in this paper.) The global 2D model allows for a physically realistic representation of a mine to be modeled with a minimal number of elements for numerical stability. As stated in Arguello et al. (2009), analyses involving geologic materials are well known to be very challenging due to the extreme variability of rock quality (e.g. degree of fracturing), and certain geomechanical processes such as stress-induced creep and contact surface slip are computationally intensive. Therefore, it is important to include only as much complexity in the model as is necessary. The 2D description of the mine assumes that the mining process takes place over a sufficiently large areal region such that plane strain conditions can be reasonably assumed. Furthermore, while room and pillar mining has not been explicitly considered, the effects of secondary mining, which reduces the pillar size, may be similar to those of long wall mining conditions once the secondary mining operation is initiated. Similarly, the 3D wellbore model examines the resulting stresses and displacements from the global mine excavation model on a wellbore casing structure. Displacement boundary conditions resulting from slippage along the interbeds in the global model are imposed on the boundaries of the wellbore model to simulate shearing and parting along a bedding plane cutting through the well axis.

Within the Salado Formation a number of marker beds (designated here as MB) exist. These marker beds were assumed to be the locations of potential relative displacement between the layers of salt. A total of eleven marker beds were included in these simulations as potential planes of slip. Of the eleven marker beds four were located in the upper Salado and seven were located in the McNutt potash zone. One marker bed, MB 123, was located below the floor of the mine. By using frictional slip planes in the model it has been implicitly assumed that the tangential slip deformations will be localized to a very thin region (usually on the order of a few centimeters). This assumption was chosen to be consistent with the noted presence of thin clay seams at the bottom of the marker beds. Furthermore, this assumption is consistent with the treatment of marker beds in the numerical models that were used for validation against experimental room data for the WIPP (Munson et. al, 1990; Munson, 1997).

4.3 *Geomechanical model results*

The analyses presented in Arguello et al. (2009) concentrated on the effect of slip-induced shear strain on the wellbore casing structure and the potential for that shear to cause casing failure. This is one important process to consider in the geomechanical calculations; however, as detailed in the descriptions of the geomechanical submodels, there are other important features, events, and processes that may contribute to gas migration. To demonstrate other applications of the geomechanical analyses, three additional processes that contribute to an understanding of gas migration are presented here. These processes are analyzed using the computational results of Arguello et al. (2009). The three processes presented here are: 1) dilatancy around the mine and its effect of permeability; 2) a more detailed look at slip along the marker beds; and 3) axial well strain in tension, particularly as it may affect wells within the mine footprint.

The salt damage factor (analogous to a safety factor) has been developed from a dilatant damage criterion based on a linear function of the hydrostatic pressure (Van Sambeek et al., 1993). Dilatancy is considered as the onset of damage to rock resulting in significant increases in permeability. Dilatant damage in salt typically occurs at a stress state where a rock reaches its minimum volume, or dilation limit, at which point microfracturing increases the volume. Dilatant criteria typically relate two stress invariants: the mean stress invariant I_1 (equal to three times the average normal stress) and the square root of the stress deviator invariant J_2, or $\sqrt{J_2}$ (a measure of the overall deviatoric or dilatant shear stress). A damage factor index was defined for this criterion (*DF*) by normalizing $\sqrt{J_2}$ yielding:

$$DF = \frac{0.27 I_1}{\sqrt{J_2}}, \qquad (1)$$

Several earlier publications define that the damage factor *DF* indicates damage when $DF<1$. In previous studies, values of $DF<1.5$ have been categorized as cautionary because of unknown localized heterogeneities in the salt that cannot be captured in these finite element calculations. This report will use these damage thresholds to indicate stress levels at which dilatancy of the salt and potash may be occurring.

Figure 6 shows the predicted salt damage factor over the right half of the mine in the 2D global excavation model, for the case where the marker bed slip coefficient is 0.2 (this was established as the "base case" in Arguello et al.). The damage factor is plotted for four times, from 0.25 to 5 years after initiation of mine excavation. Damage factor values less than 1.0 (onset of microfracturing) are plotted in white. Note that the regions of low damage factor (i.e., high dilatancy potential) tend to be closer to the edge of the mined region instead of over the middle; however, because the mine face is constantly moving, nearly all the regions above the mine will at some time experience deviatoric stresses that exceed damage conditions, with the region above the current edge of the mine experiencing the most severe conditions. Over time, as the stresses in the salt and potash equilibrate toward hydrostatic values, the damage safety factor increases, indicating a retreat from potential microfracturing, and perhaps the onset of fracture healing. Compare Figure 6 to Figure 5, which illustrates the damage zone geomechanical submodel; the regions near the edge of the mine may have a greater potential for gaseous flow pathways in the event that gas enters these zones from the well locations. It is obvious that for a longer period of time a region experiences dilatant stress conditions, there is greater opportunity for the creation of microfractures which would increase permeability.

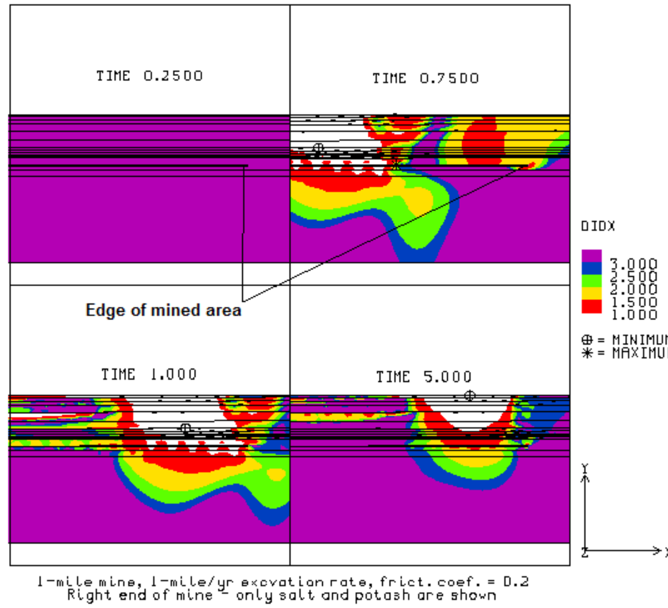

Figure 6. Dilatant damage factor for mine 1000-ft deep, 1 mile/year excavation rate, marker bed friction coefficient = 0.2.

Figure 7 shows the same plots of damage factor, but for the case of no slip along the marker beds. Note that the no-slip condition results in both a larger region of dilatant stresses, and that they exist for a longer period of time near the mine horizon. The condition with low-friction slip allows for more stress relief than the no-slip condition, allowing for a greater relaxation of the dilatant shear stresses. This difference in results illustrates the need to better understand slip between bedded layers and, the need for data to compare predictions with measured results.

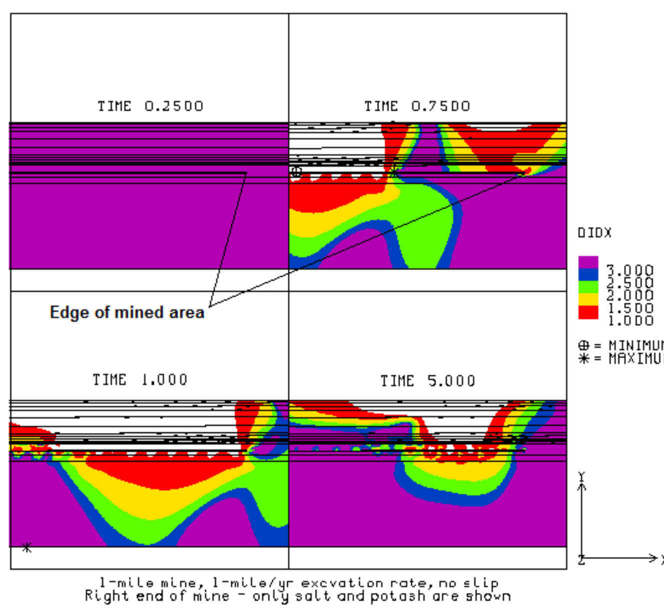

Figure 7. Dilatant damage factor for mine 1000-ft deep, 1 mile/year excavation rate, no slip between marker beds.

There are currently sparse available data that relate the change in porosity or permeability in salt or potash to a change in stress conditions. There are existing WIPP data that evaluate the depth of a damaged zone around the WIPP mine and the effect of dilatant stress on salt. Other laboratory and field data may exist in the engineering literature. These sources will be explored to find a way to convert dilatant stress conditions to permeability changes that can be used in the hydrological calculations.

Arguello et al (2009) presented predictions of a slip envelope as a function of interface friction coefficient. The largest slip by far was predicted to occur along MB 101, which is near the top of the Salado Formation. It is instructive to examine the predicted slip along the individual marker beds in Arguello calculations as well. Figure 8 plots the horizontal extent of 1-mm slip for each marker bed for the base case calculations (friction coefficient = 0.2). The predicted slip along MB 101 has the furthest extent. After that, the other marker beds within the Upper Salado, and the marker beds closest to the mine (MB 122 and 123) are also among the highest in the plots. The other marker beds within the McNutt potash zone have the least extent of slip. The slip along MB 123 is particularly instructive. When the mine closes due to creep, both the ceiling and the floor deform into the mined region. Because of the upward movement of the floor, significant slip may be induced in marker beds below the mine horizon. These marker beds may be more significant potential pathways for gas flow than those above the mine, because of the tendency of gas to move upward in the absence of a combination of pressure and impedance to force downward flow. Therefore, one possible future enhancement of the geomechanical model is the implementation of several marker beds below the mine horizon.

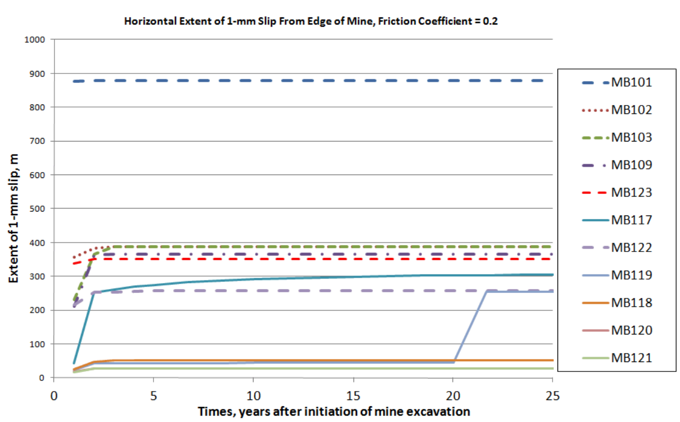

Figure 8. Horizontal extent of 1-mm slip from edge of the mine, friction coefficient=0.2.

A third process to examine with the geomechanical model is tensile axial well strain along casings within the mine footprint. The physical presence of wells and surface structures is not included in the global excavation finite element model, but the potential for ground deformation to damage these structures can be conservatively estimated by assuming that they will deform according to the predicted ground strains. At well locations within the mined region, subsidence will primarily induce elongation of the axis of the well. (For wells at significant standoff from the mine face, shear and bending stresses are the primary processes of concern, whereas tensile strain is the primary concern for wellbores within the mined region.) Tensile strengths of cements are very poor, and are a much more significant indicator of failure potential than compressive strength of cements. Under tensile conditions, the cemented annulus of the wells may crack, forming a horizontal tensile fracture that may extend around the wellbore. More extensive damage could heavily fracture the cement radially and vertically, which could result in a loss of well integrity producing a gas pathway along the outside of the casing. Such leakage could result in flow to the surrounding environment. The allowable axial strain for cement (i.e., the threshold value at which cement failure is expected to occur) for purposes of this report is assumed to be 0.2 millistrains in tension. This would be typical of cement with a compressive strength in the range from 17 to 34 MPa. It should also be noted that vertical well strain reduces the collapse resistance of the steel casings. A typical threshold for negligible resistance to casing collapse and tensile failure used for the SPR is 1.6 millistrains (Sobolik et al., 2011). This threshold for steel casings has been used to identify casing failure at specific wells with reasonable accuracy.

Figure 9 shows the development of axial strains along wellbores within the mined region. Note that during the first two years after mine excavation begins, nearly all of the area above the mine experiences predicted strains well over the cement threshold of 0.2 millistrains. Furthermore, as subsidence continues over 25 years, over half the region over the mine experiences predicted strains well over the steel casing threshold of 1.6 millistrains ("white" values). These results indicate that when potash is mined around existing wells, there is a significant potential for the creation of cement fractures and steel casing failure above the mine, possibly creating fast pathways. Also, note that vertical strains below the mine eventually exceed the 0.2 millistrain threshold. It is also important to note that large pillars are usually left around existing wells, so the amount of subsidence in the vicinity of the well may be less than predicted by the model. These calculations indicate an area of concern that is a strong candidate for further analysis.

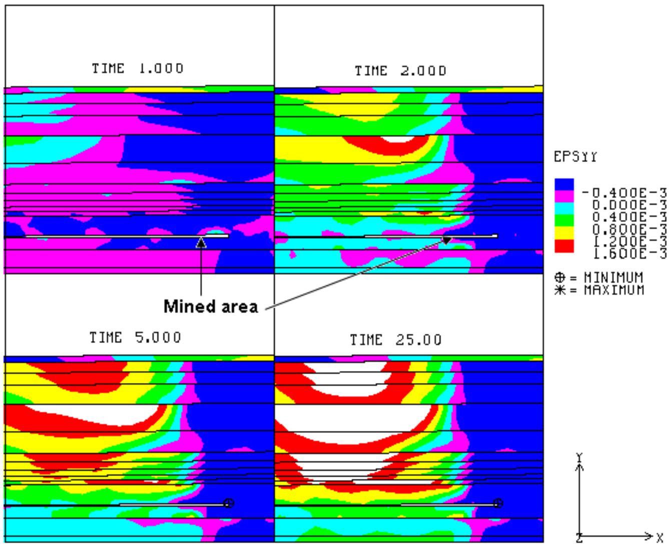

Figure 9. Vertical strain over the edge of the mine; casing yield threshold at 1.6 millistrains.

5 CONCLUSIONS

This document summarizes the progress in the first stage of developing an RA framework for BLM which may be employed to make informed decisions based on technical issues that arise during development of co-located potash and petroleum resources in southeastern New Mexico. Through meetings attended by SNL and stakeholders BLM has achieved the early stages of changing the way disputed issues are discussed and framed for analysis through using SNL's proposed RA approach. Industry and BLM have seen the benefits of using RA as a logical framework for organizing the information relevant to examining the risks of gas migration. This work has begun building a methodology for putting existing and any new information collected through literature searches, testing and modeling into context in order to provide an opportunity for dialog between participants. In addition, this work has shown that going forward RA can provide further advantages through developing the means to categorize various hazards and the evaluation of those hazards. Building the RA framework and using site-specific data will give the BLM and industry a firm technical base that examines the range of possibilities in a collaboratively developed tool that can be used for better supported decisions on how to manage or mitigate gas migration and other risks in the future.

In the development of the geomechanical portion of this RA model, the authors identified specific Features, Events, and Processes that require data-based validation of the conceptual and computational models. SNL will work cooperatively with the oil/gas and potash stakeholders to identify existing field data, and to develop new data, to answer the questions developed by the RA model components. Among the issues identified in this initial iteration of the RA model include the development of an appropriate model for slip along bedded surfaces, a correlation between dilatant stress in the potash and its effect on porosity and permeability, and realistic stress and strain threshold values for failure of wellbore casing components.

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