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# Gas Migration Project: Risk Assessment Tool and Computational Analyses to Investigate Wellbore/Mine Interactions, Secretary's Potash Area, Southeastern New Mexico

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**Abstract**

The Bureau of Land Management (BLM), US Department of the Interior has asked Sandia National Laboratories (SNL) to perform scientific studies relevant to technical issues that arise in the development of co-located resources of potash and petroleum in southeastern New Mexico in the Secretary's Potash Area. The BLM manages resource development, issues permits and interacts with the State of New Mexico in the process of developing regulations, in an environment where many issues are disputed by industry stakeholders. The present report is a deliverable of the study of the potential for gas migration from a wellbore to a mine opening in the event of wellbore leakage, a risk scenario about which there is disagreement among stakeholders and little previous site specific analysis. One goal of this study was to develop a framework that required collaboratively developed inputs and analytical approaches in order to encourage stakeholder participation and to employ ranges of data values and scenarios. SNL presents here a description of a basic risk assessment (RA) framework that will fulfill the initial steps of meeting that goal. SNL used 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.

The gas migration study described here was completed in 2013 and SNL does not present a definitive analysis of the problem. This work has significantly advanced understanding of what must be done to arrive at an analytical scope and focus agreed upon by participants. It has illuminated issues such as the need for agreed upon performance criteria for wellbore leakage and for unacceptable impact on mine safety margins. The progress represented here is development of a methodology to analyze the problem and presentation to BLM and stakeholders of options regarding the technical focus and level of detail of analysis they wish to see. Establishing an RA structure that requires collaboration has been a factor in initiating the first technical working group for stakeholders and this structure will provide them with a transparent, flexible, well-documented analytical tool they can develop and use to answer their technical questions using data they have provided. SNL's study of local wellbores through public records and wellbore re-entry will bring site-specific data to the analysis. The casing testing for the first time begins to answer the question of how stresses from geologic layers shifting affect casing behavior. It is expected that these steps are foundational for future work that will enable answering questions around gas migration potential and other technical issues related to development of these co-located resources in southeastern New Mexico.

The work described in this document was performed in 2011-2013. The results of this work were presented to BLM and the oil/gas and potash stakeholders through several cooperative meetings and through a draft version of this report. This final version, which has completed Sandia's Review and Approval process, is being published without official review comments from the BLM, who declined the option to review the report. In addition, a summary of this report has been published in engineering literature: Sobolik, Hadgu, Rechard, and Gaither, (2012), "Development of a Risk Assessment Tool to Investigate Gas Migration Interactions between Oil and Gas Wellbores and Potash Mines in Southeastern New Mexico", *Mechanical Behavior of Salt VII*, Editors Pierre Berest, Mehdi Ghoreychi, Faouzi Hadj-Hassen, Michel Tijani, CRC Press, Taylor and Francis Group, London, 2012, ISBN 978-0-415-62122-9.

## ACKNOWLEDGMENTS

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# CONTENTS

## FIGURES

## TABLES

Nomenclature

| | |
|---|---|
| 2D | two dimensional |
| 3D | three dimensional |
| API | American Petroleum Institute |
| bbl | Barrel |
| BLM | Bureau of Land Management (US Department of the Interior) |
| BOPCO | Bass Operating Company |
| BHP | Bottom Hole Pressure |
| CBL | cement bond log |
| FEPs | Features, Events and Processes |
| FTP | Flowing Tubing Pressure |
| KB | Kelly Bushing |
| MD | measured depth |
| MSHA | Mine Safety and Health Administration |
| NETL | National Energy Technology Laboratory (of the USDOE) |
| NMOCC | New Mexico Oil Conservation Commission |
| NMOCD | New Mexico Oil Conservation Division |
| PA | permanently abandoned |
| RA | Risk Assessment |
| SI | shut-in |
| SIP | shut-in pressure |
| SNL | Sandia National Laboratories |
| TA | temporarily abandoned |
| TD | total depth |
| TVD | true vertical depth |
| WIPP | Waste Isolation Pilot Plant |
| YMP | Yucca Mountain Project |

# 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 deposits are the best in the country, and as a strategic mineral, they 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 hired 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. With the present work BLM has chosen to build a risk assessment tool 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 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 document is the final report of 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. If RA development continues, this report documents an initial stage of RA development. Some data produced by the study such that hard copy delivery through this document is not practical, will be delivered to the BLM as files in digital format. An example of digital documentation includes input or output files from geomechanical or hydrological computational modeling.

## 1.1 Background of the Gas Migration Issue in Southeastern New Mexico

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 by US Mine, Safety and Health Administration (MSHA) standards because methane doesn't 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.

The potash ore zones are at ~ 1000 - 2000 feet depth in the Delaware Basin, which is also a prolific oil and natural gas source, producing from multiple zones at depth below the potash. The BLM controls the acquisition of permits to mine potash and to drill for petroleum and has the responsibility of ensuring responsible development of both of these resources. The specific issue for BLM that has initiated the work in the present study is "How close to potash mining can petroleum wellbores be without causing a hazard to mining from gas migration from a leaking wellbore?" At present standoff distances for new wells are, by regulation, ¼ mile for shallower Delaware wells, primarily oil wells, and ½ mile for deeper gas wells. There are many oil wells and three deep gas wells within the footprint of current and past mine works according to New Mexico Oil Conservation Division (NMOCD) public records (http://www.emnrd.state.nm.us/ocd/OCDOnline.htm). There are many wells within the Potash Area outside the footprint of mining and over 3,000 wells in the general area.

The BLM has to assess the potential for problems from existing wells and wants to work with industry to develop future wellbore designs that mitigate the risk of wellbore leakage. A tool such as RA, improved over time with significant site-specific data input, can be useful for analyzing many complex, interactive elements of many kinds of problems in a transparent and traceable manner. The RA tool provides a collection point for data and a record of analyses. The tool can be developed in collaboration with both industries and provide a common modeling site where conflicting scenarios and multiple data sets can be used to look at potential outcomes.

For decades both industries have been contesting various issues that arise from developing these co-located resources and BLM has selected SNL to provide neutral, scientific assessment of issues. The present work includes interaction at BLM meetings with stakeholders from both industries in order to hear feedback and to receive site-specific data, conceptual models and scenarios relevant to the problem. Encouraging industry collaboration and input is a goal of this work. As appropriate to the discussion, we include in this report stakeholder input relevant to the present analysis and relevant to the focus for potential future work by BLM.

## 1.2 Prior Study of Gas Migration Potential at Sandia and Focus of Present Work

This is the second study SNL has performed for BLM on the potential for gas migration from a petroleum wellbore to a potash mine (Arguello et al., 2009). The Arguello et al. (2009) study focused on how wellbore integrity might be compromised by stresses on steel casing and cement caused by shearing along bedding planes, especially as a result of geologic subsidence caused by mining. The analyses published in Arguello et al. (2009) comprised two separate geomechanical submodels: a two-dimensional (2D) global model that simulated the mechanics associated with mining and subsidence, and a three-dimensional (3D) wellbore model that examined the resulting impacts on wellbore casing. The 2D approximation of a potash mine using a plane strain idealization was considered reasonable given the large areal extent of the mines relative to mine depth. The 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 recommend standoff distances between a mine and well where mechanical effects would or would not be seen. The conclusions from Arguello et al. are more thoroughly discussed in Section 4.1, but the most important conclusions were the following:

- Depending on mine depth and mining direction, the distance from the mine boundaries to the points where maximum allowable slip occurs is between 600 m (~1970 ft) and 1100 m (~3610 ft) from the edge of the mine excavation.

- Large interbed slip magnitudes (greater than 0.5 m or ~20 in.) were predicted to occur on some interfaces over the mine excavation and would be expected to impact wells that have been mined around.

- For the single-casing situation, the casing first yields through its thickness with very little interbed slip, namely at 0.80 mm (~0.03 in.) of slip.

- Adding a second cemented casing to the wellbore model only doubles the amount of interbed slip needed for the inner casing to yield through its thickness, namely to 1.6 mm (~0.06 in.) of slip.

These conclusions were developed under the assumption that failure of the wellbore casing was defined as being when the entire casing thickness had achieved a stress state of plastic yield. From these simulations, Arguello et al. recommended standoff distances between the wells and the edge of the mine (between 810-830 m, or 2660-2720 feet) 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 in and of itself, is insufficient to determine the potential for 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 beds 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.

The present work uses output from the prior 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. This includes new work on the hydrology, geology and geomechanics of the problem and using data from 40 wellbores in the Potash Area.

Adopting an RA approach for studying this problem and other BLM resource development technical issues in the area is new. Though this report will discuss example outcomes from modeling and other investigations, they are presented only as examples of how the methodology works and what the products look like. They are not considered final "results" of calculations and are not meant as data that could support important decisions.

Part of this work was to perform field and laboratory studies designed to provide data to the RA and to test computer model outputs from a prior SNL study for BLM. Currently, a plan exists for re-entering wellbores in the area to study their condition after years of aging. As of the writing of this report no wellbores have yet been examined. The field investigation will examine wellbore sealing elements for potential aging effects, and for potential damage to wellbore structures due to mining-induced subsidence and related slip between bedding planes. The laboratory work developed a method and ran preliminary tests designed to show the effects of stresses on casing couplings. The tests are relevant to determining the failure behavior of a casing string under various conditions of stress, and they examine the effects on the threaded couplings, a type of test not often performed. Preliminary results of the laboratory testing were presented to BLM and stakeholders at a meeting in January 2011 (Dwyer, 2011). Based on the preliminary results, additional laboratory tests on casing joints are being considered. The final results of these parallel field and laboratory studies will be published in subsequent reports.

# 2 RISK ASSESSMENT FRAMEWORK FOR ANALYZING DEVELOPMENT OF CO-LOCATED RESOURCES OF POTASH AND HYDROCARBONS

## 2.1 Risk Assessment Overview

Over the last several decades, the concurrent development of potash and hydrocarbon resources on federal land managed by the BLM has caused controversy in southern New Mexico. Controversial topics have been dealt with through BLM rulings and in the courts, but this piecemeal approach has not resulted in satisfactory resolution of all issues. The present goal is to examine difficult topics that arise because of concurrent development of the potash and hydrocarbon resources through a more comprehensive approach based on risk assessment. 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.

### *2.1.1 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.

### *2.1.2 Benefits of Using 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. It is this benefit that we wish to exploit as much as possible initially. We are building a methodology to put existing and any new information collected through literature searches, testing, and modeling into context in order to provide an opportunity for dialog between participants. 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.

## 2.2 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 though 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. Figure 2-1 lists the seven tasks on the right and the left illustrates the iterative process in which steps are not always taken in a set order and some steps are re-assessed multiple times. In the list on the right the term "risk triplet" is a term summarizing the core, distinguishing operations of RA. System exposure model is a term used by the EPA that is similar to "consequence model" in other terminologies.

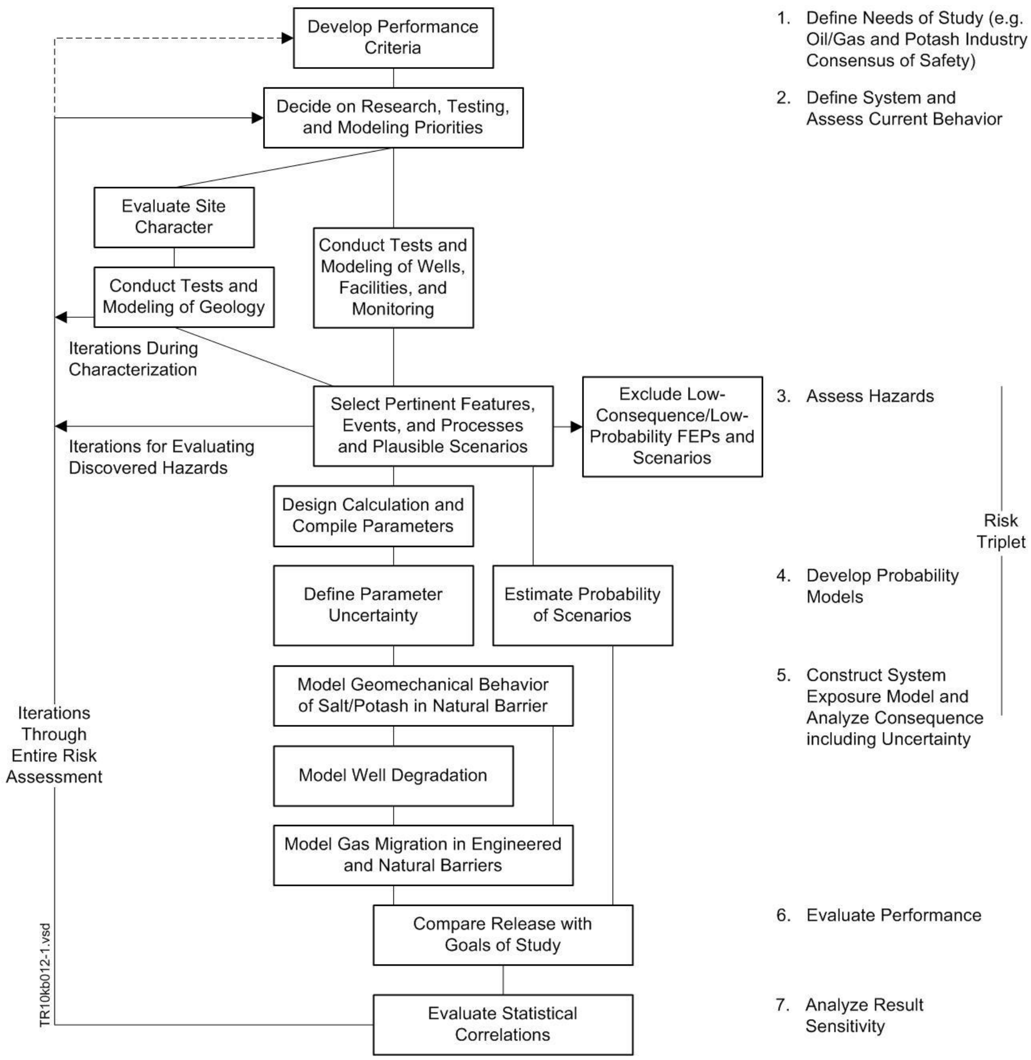



**Figure 2-1. Elements of a risk assessment, based on modeling, to assess gas migration (Rechard, McKenna, & Borns, 2010).**

## 2.3 Types of Risk Assessment

Various types of risk assessment can be defined based on how far one progresses through the risk assessment tasks and the method used for evaluating the probability and consequence. Frequently, risk assessments only progress through the first three tasks to identification of hazards before moving to risk management to eliminate or mitigate the hazard (Table 2-1). This use of FEPs analysis is somewhat similar to human behavior over the centuries where a hazard and its consequence was made known through experience and then an effort made to eliminate the hazard. The only distinction for risk assessment is that one is attempting to identify the hazard before severe consequences have occurred. Hence, the identification of potential hazards and the FEPs of those hazards needs to be systematic to help avoid missing FEPs (Savage, Maul, Benbow, & Walke, 2004) (Wildenborg, Leijnse, Kreft, Nepveu, & Obdam, 2004). A systematic approach might require cataloging 100 or so FEPs, but of these only several will likely remain after screening. A disadvantage of stopping at the third task of a risk assessment is that the probability and consequences are not estimated to determine the risk. From the risk, a ranking of hazards can be developed and, thereby, a means to select hazards to which the most resources should be devoted in order to find a means to eliminate or reduce them. Furthermore uncertainty in knowledge is not explicitly included in the evaluation. Finally, the fragmentation of the evaluation by examining the individual FEPs does not encourage looking at the system as a whole. However, this tendency can be countered by an effort to look at sequences of FEPs as scenarios.

A second type of risk assessment completes the fourth and fifths tasks, but in a qualitative manner through the use of expert opinion. By obtaining estimates of consequences and probability, various hazards can be ranked and more resources devoted to eliminating or mitigating those hazards of higher risk (Table 2-1). Methods and software have even been developed to qualitatively include estimates of uncertainty. Obtaining the necessary breadth of experts in the room at the same time can be difficult. Unless the experts rank all the hazards under study at the time, consistency of the expert review can become an issue. Hence, the evaluation must be systematic, with a well-defined process to evaluate the data and grade the risks in a consistent manner so that several groups of experts can work independently. The major shortcoming of this type of risk assessment is that there must be a base of experience with a similar system (or at least experience with many of the components that make up the system).

A third type of risk assessment evaluates the consequences quantitatively through modeling to develop knowledge on behavior or extrapolate to new situations in order to supplement knowledge based on experience (i.e., use modeling to expand the experience basis). The method, however, does not evaluate all the consequences exhaustively, but rather models only several simple situations (or uses a catalog of simple analysis) (Oldenburg, Bryant, & Nicot, 2009) (Table 2-1). The probability of events is estimated either qualitatively by expert opinion or quantitatively from information on local conditions on, for example, well leakage.

The fourth type of risk assessment completes all the tasks quantitatively. Hence, the experience base is greatly expanded. This approach can be important when several nonlinear effects are present in the system that cannot be accounted for through extrapolation from past experience or modeling of a few consequences by using extreme parameter values. Uncertainty is propagated through the system and a sensitivity analysis can determine the most important components and parameters that influence the variations in the results (Table 2-1). A full probabilistic risk assessment is useful for guiding the development of regulations or evaluating the risk of projects that generate large social concerns such as radioactive waste disposal. The disadvantage to this approach is the time and resources required to develop the underlying submodels of the system and define parameter distributions.

**Table 2-1. Types of Risk Assessment**

| RA Tasks | Methodology | Comments |
|---|---|---|
| FEP Analysis | Develop FEP databases and evaluate applicability of FEPs to site | Hazard identification with mitigation used for centuries |

| | | |
|---|---|---|
| Elicited Consequence and Probability | Pooled expert judgment and risk matrix | Requires experience basis; examples: URS RISQUE |
| Deterministic | Simulate aspects of the system that span possible ranges or use catalog of previous analysis | Expands experience base |
| Probabilistic Risk Assessment with Sensitivity Analysis and Iterations | Comprehensive propagation of uncertainty through pathway models | Used for setting technical risk criteria; used for radioactive waste disposal |

## 2.4 Components of the Issue

### *2.4.1 Task 1: Identify Performance Measures and Criteria*

In a general sense, requirements could be developed to capture safety, economic, social and other relevant issues. Here, we want to focus on safety, and at this early stage, the concept of safety can remain fairly general since in this early stage we will only progress through FEP analysis. Much of what might eventually occur for the gas migration study is selection of indicators for identified hazards, defining measures for those indicators, and finally, specifying appropriate limits on those measures. Another aspect could be identification of subsystem guidance that specifies desirable aspects of the system such as desirable (but not necessarily absolute minimum) distances.

### *2.4.2 Task 2: Characterize System*

The second task of a risk assessment is the characterization of the system. Currently, the system has been divided into three major components: (1) gas wells; (2) strata around a potash mine; and (3) the gas migration pathway. The characterization of the gas wells is discussed in Section 3 and includes evaluation of 40 gas wells around WIPP and potash mines in southern New Mexico. Another aspect of the characterization of the gas wells is the re-entry into oil or gas wells in the region that have been selected by BLM with input from the potash industry, and petroleum industry as discussed in Section 6. Along with this field work, well records on casing integrity in salt domes near the Gulf of Mexico are being examined. The characterization of the strata around a potash mine is discussed in Section 4. The characterization of the gas migration path is discussed in Section 5 and uses the same properties for marker beds as used for the WIPP when evaluating gas migration.

### *2.4.3 Task 3: Identify Hazards*

The third task is hazard identification based on characterization of the system. Any type of analysis must decide what features (such as fractures and faults in the host strata), events (short-term phenomena such as mining around a wellbore), and processes to model (long-term phenomena such as gas migration through marker beds into the mine fractures); however, the decisions are typically based on the experience of the modeler and somewhat ad hoc. Here, we want to be thorough to avoid missing FEPs and thus the task must eventually be systematic and formal. The comprehensive FEPs lists developed for the radioactive waste geologic disposal systems and generic lists specific to geologic $CO_2$ sequestration may provide useful starting points.

From the FEPs, sequences of events can be developed to form scenarios of behavior. The possibility of the FEPs and scenarios identified for each of three system components are discussed within Sections 3, 4, and 5.

Based on the first two tasks, a conceptual model of the system can be developed that is useful for dialog and for evaluating qualitatively the probability of FEPs and scenarios. Aspects of the conceptual model may eventually be developed into a mathematical formulation for numerical modeling of individual FEPs or scenarios for evaluating quantitatively the probability of FEPs or scenarios. The conceptual model will also form the basis of a mathematical formulation for examining the behavior of the system as a whole.

### 2.4.4 Task 4: Define Uncertainty in Model Parameters and Probability of Scenarios

The fourth task is evaluating the uncertainty associated with underlying parameters of the models and evaluating the probability of scenarios formed by sequences of FEPs. It is the explicit evaluation of uncertainty in parameters and scenarios that sets probabilistic risk assessments apart from other types of risk assessments. In controversial settings with non-linear systems, the inclusion of uncertainty in parameters can be beneficial in that not just the system behavior with worst case or mean parameters values or worst case or nominal scenarios are evaluated, but a whole range of system behavior is evaluated.

This advantage of an uncertainty evaluation can be introduced in later iterations of this risk assessment. For the FEP-like analysis conducted in this iteration, only worst case or nominal parameter values and scenarios were evaluated. However, the potential range of parameter values was noted in comments from the potash and petroleum industries.

In addition, basic information on leaking wells was evaluated from the literature as described in Section 3. For example, frequency of measureable leaking wells under usual conditions from the examination of wells in Alberta Canada is 6% (Bachu and Bennion, 2009). Collection of specific data on leaking wells in southern New Mexico and then an evaluation of causes could provide a basis for future risk assessments of the entire system and improve well performance and longevity in the region.

### 2.4.5 Task 5: Evaluating Consequences

The fifth task is evaluating the consequences of scenarios proposed such as the extent of leakage in the surrounding formation and migration to potash mines. As noted above, using expert elicitation is one approach to determining consequences. Provided the potash and petroleum industries can identify a group of experts, through consensus, for a controversial topic for which an experience base exists, perhaps this approach can be attempted in the future. For this initial iteration reported here, a modeling and experimental approach was taken to demonstrate the potential results that could be stitched together to form a risk assessment of the entire system. The influence of mining on slip along marker beds had been modeled previously in geomechanical analysis and these results were examined in more detail and some similar results with updated stratigraphy were repeated. Also, experiments were conducted to examine the behavior of casing and threaded connections under large shear stress.

The migration of natural gas from a leaking gas well to a potash mine via marker beds was evaluated. In this analysis, the source for the gas, the wellbore, was assumed to have failed. As mentioned under Task 4, future work could provide site-specific information on the types of failure and their probability in southern New Mexico (Figure 2-2). The driving force for the gas was assumed to be the flowing tubing pressure in an initially high pressure gas well. Future work would need to incorporate declining pressures over the life of the well (Figure 2-2). The pathways for the gas were marker beds that were near the horizon of the potash mine. The permeability/porosity of the marker beds was increased due to slippage caused by mining (as determined from the geomechanical analysis noted above). However, sufficient brine was assumed available to fill the additional pore space prior to introduction of the gas. The porosity and permeability of the marker bed could increase due to fracturing at high gas pressures. Future work would need to better define the stratigraphy, mining strategy and potential pathway of the gas around the wellbore and strata, not just the marker bed.

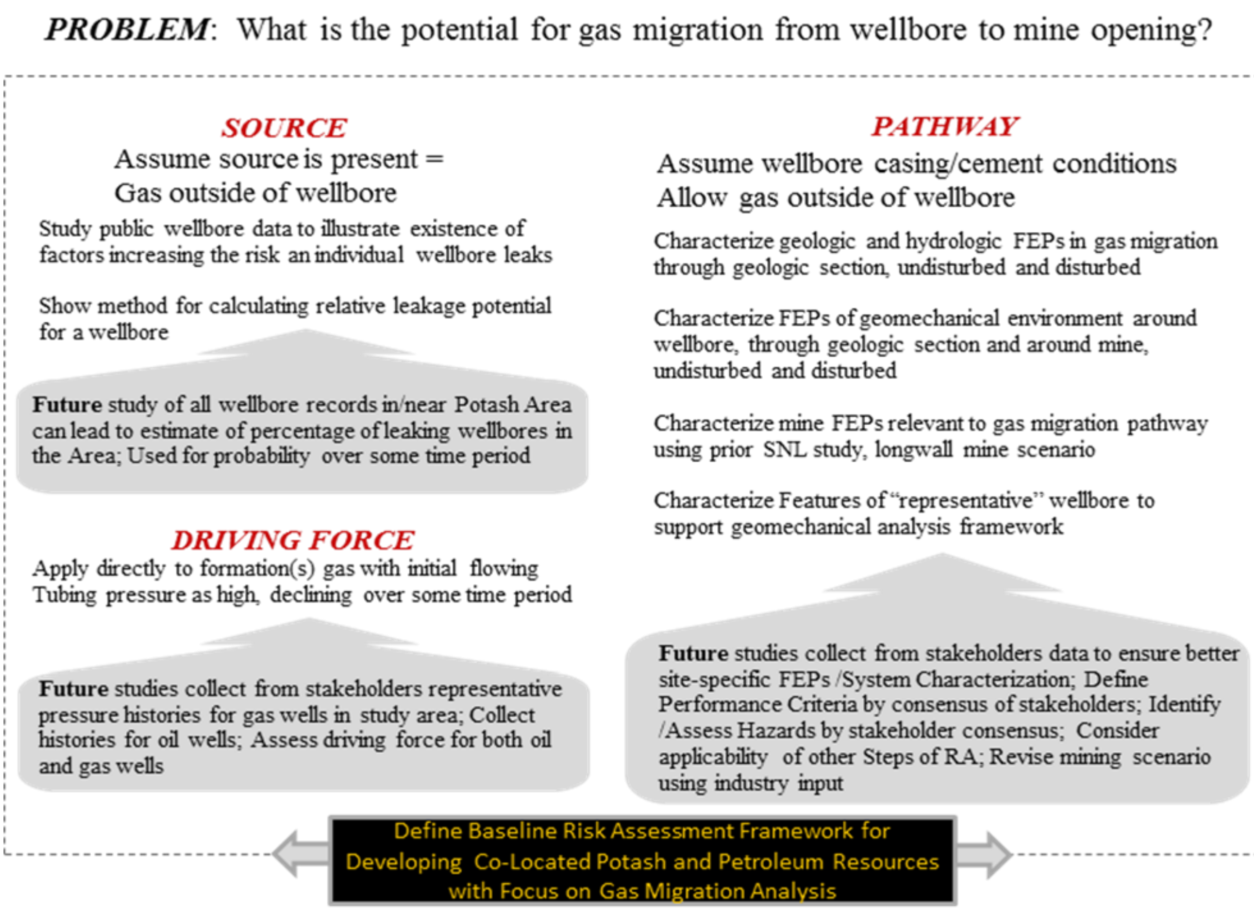



**Figure 2-2. Components of the problem, modeling approach in this demonstration study, and possible changes for future studies.**

### *2.4.6 Task 6: Evaluate Parameter Sensitivity*

The sixth task is a sensitivity analysis, which analyzes the effects of changes in parameters (or possibly the form of the mathematical model) on the change in system behavior. The four principal purposes of a sensitivity analysis are (Rechard 1996): (1) to gain understanding and insight about the system, (2) to help verify the correctness of the calculations, (3) to evaluate the influence of various options, and (4) to determine where more knowledge is required. The sensitivity analysis provides more details on system behavior and, thereby, help provide input on decisions to allocate resources on collecting more data and improving model forms to better refine the risk assessment in future iterations. It can also help in ranking hazards to mitigate first.

Several techniques can be used in sensitivity analysis In some cases, the number of parameters to examine is quite large. Also, parameters may interact within the model such that the influence in the change in one parameter depends upon the value of other parameters (where, as a simple example, the result depends upon two parameters which are multiplied together within the model) In these cases, statistical methods must also be applied such that the influence in the variation of a large number of parameters are efficiently evaluated and the interactions between parameters are correctly discerned. However, the simplest sensitivity method is where a limited number of parameters or model forms are varied one at time. This method is most appropriate for evaluating the influence of differences in options (such as well design and monitoring schemes) where the independence of the options can be reasonably assured.

### *2.4.7 Iterations Through Tasks*

An important aspect of risk assessments is to continue to iterate through the process. In early stages, much of the analysis can be qualitative to gain understanding of the system and identify the greatest unknowns about the system. As knowledge of the system improves, FEPs can be refined and scenarios analyzed individually. Later iterations can develop estimates of consequences and their probability through elicitation or modeling. With either approach mitigation plans can be developed on those aspects of the system that most affect results; however, with modeling, the influence of mitigation plans can be evaluated quantitatively. Also with modeling, sensitivity analysis can be conducted quantitatively to determine which models, FEPs, and parameters have the greatest impact on performance measures. From this information, activities can be initiated to gather more understanding concerning the parameters, models, and FEPs. For this demonstration study, the task is best represented by the comments on the study discussed in Sections 3, 4, and 5 that point to necessary improvements in a possible future iteration.

# 3 RISK ASSESSMENT SUB-MODEL FOR WELLBORE CONSTRUCTION AND PRESSURES AND HOW TO ESTIMATE LEAKAGE POTENTIAL

As introduced in section 2.4, this section begins characterization of the system with discussion of the wellbore sub-model and includes discussion of hazards and performance measures. Studies are presented that examined wellbore leakage issues and illustrate ways to evaluate uncertainty and probability of scenarios that could be applied in the Potash Area. Assessing uncertainty and probability involves examination of the FEPs and scenarios in a collaborative way that would clarify the discussion of risk and enhance the focus on the most important methods and engineered components for mitigation of risk.

## 3.1 Wellbore Sub-Model of the Risk Assessment

### *3.1.1 Introduction to Wellbore Sub-Model Development, Background and General Task Description*

Figure 3.1 is a diagram to help envision the conceptual model for study of the potential for gas migration from wellbore to mine. The diagram shows a wellbore within the mining subsidence zone and one outside of the subsidence zone and it represents one potential general configuration for mining. The diagram shows basic geomechanical zones (discussed later in Section 4) 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.

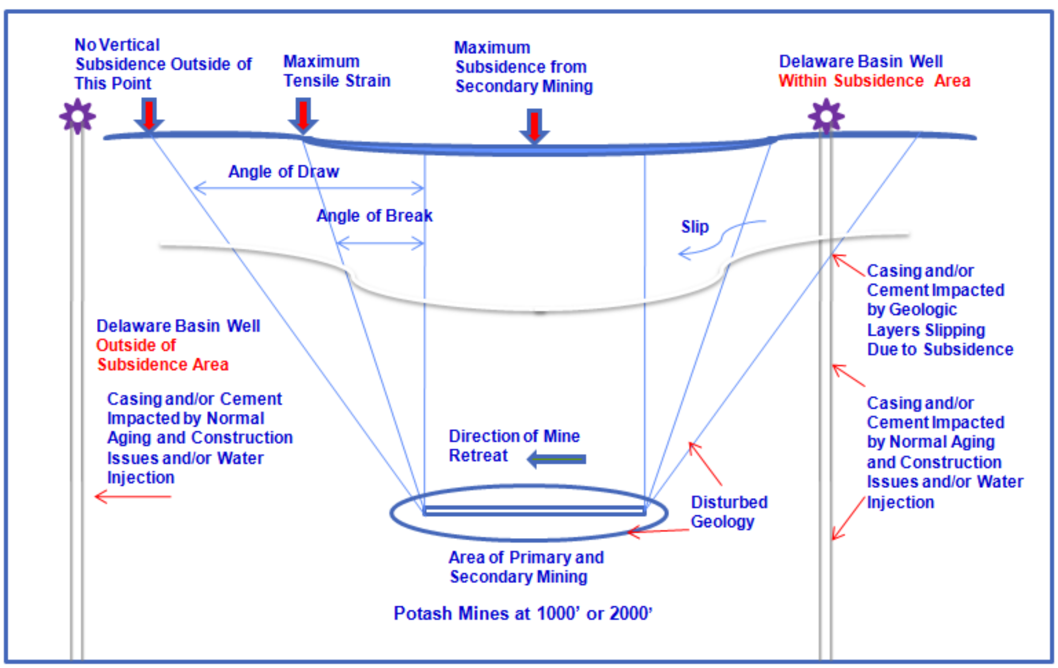



**Figure 3-1. Diagram showing representative Features and Events for discussion of gas migration potential between a wellbore and a mine.**

As shown in Figure 2-2 gas migration requires that the gas has a: 1) source; 2) driving force; and 3) pathway. The source and driving force come from the wellbore, and failure of the wellbore casing and cement are important to initiation of a pathway out of the wellbore. Features, Events, Processes and scenarios associated with wellbore construction, production, operations activities, aging and degradation of construction elements, eventual abandonment and post-abandonment history comprise the wellbore sub-model in a comprehensive RA framework. The most useful FEPs information can be found in publically available well records from the Potash Area.

The Delaware Basin section deposited from Ordovician through Permian time contains both potash and hydrocarbons. The Permian Salado Formation evaporite includes both salt and potash and lies above another evaporite, the Castile Formation. Below the Castile, several Permian sands, the Bell canyon, Cherry Canyon and Brushy Canyon Formations primarily produce oil. Much deeper in the section, the Pennsylvanian Morrow Formation primarily produces gas in the study area. The figure in Appendix A-1 presents the stratigraphy of the Delaware Basin, and compares it to other similar oil-and-gas-bearing formations in the southwestern United States. A study set of 40 gas wells was selected in the general vicinity of the Waste Isolation Pilot Plant (WIPP) which lies within the Potash Area. Appendix A-2 is a list of these wells and Appendix A-3 is a map showing their location in relation to WIPP. Wells near the WIPP site were selected because the geology, hydrology and geomechanics study uses WIPP data, and 40 wells produced a manageable data set that revealed FEPs patterns, though not a statistically significant data set. SNL suggests that the publically available wellbore data study should be expanded if BLM chooses to better support leakage probability development in the area of wellbore FEPs. The NMOCD records of these 40 wells, stakeholder feedback during SNL's prior study and wellbore data from WIPP studies led to development of a representative wellbore construction to be used in geomechanical modeling (Section 4) in this study. The representative wellbore is discussed in Section 3.2.1.

There is interest among stakeholders in the mechanical condition of wellbores that were drilled within an existing mine footprint or which were subsequently mined around. SNL was provided a list of these wells during the review process for our prior report (Arguello et al., 2009). We have included this list in Appendix A-4. There were only three deep gas wells in this compilation and they weren't in the vicinity of the WIPP site. This list is presented as a reference for future work which may want to examine one or more of these wellbores for mechanical effects from mining.

### 3.1.2 Narrowing the Wellbore Study Focus

### 3.1.1 3.1.2 Narrowing the Wellbore Study Focus

At the outset of the present study a literature survey was performed on cement, cement failure modes and wellbore failure causes. Appendix A-5 presents a brief discussion and annotated bibliography from that survey. It was determined that there was already a robust existing literature on cement, cement failure modes and other aspects of wellbore failure, like corrosion, that can be used as resource. Examining in detail all FEPs in wellbore failure in the present study would have been inappropriate in a situation where many of the basic issues such as the parties' concepts of risk and risk acceptance and data from local sources had not been explored and documented.

The studies listed in Appendix A-5 made it clear that gross Features of cement that can be easily studied, are key to sealing. Cement emplacement during installation (meaning getting it into the desired areas) and subsequent events impacting integrity are key indicators of whether the cement is likely to be effectively sealing. Cement Bond Logs (CBL) are run commonly upon installation and often during workover and are a good source of information. It is recommended that cement Features are a focus of future study as a means of qualitatively estimating likelihood of leakage. In addition, there is information in well records regarding general casing integrity and it is assessed and documented during workovers. The present study included collecting data that are indicative of cement and casing condition in the 40 well study set as a demonstration of important data that can be collected relatively inexpensively as shown in Appendix A-6.

The output of the tasks within this part of the research will be: 1) a representative wellbore construction for use in geomechanical modeling; 2) values for initial wellbore production pressures that are one set of inputs for the driving force in gas migration; 3) recommendations regarding which FEPs should be studied to begin to assign a value to the probability of wellbore leakage; 4) a limited parameter list for wellbore construction FEPs with some values for the wellbore sub-model; 5) a collection of wellbore data for 40 gas wells in the study area; 6) a compilation of stakeholder feedback on the wellbore sub-model acquired during the study; and 7) a literature search and discussion 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. For item 4 wellbore parameters such as cement geomechanical properties and steel casing properties will be presented in Section 4.

## 3.2 Wellbore Construction and Driving Force Pressures for Gas Migration Potential Analysis

The State of New Mexico 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 (http://.www.emnrd.state.nm.us/ocd/) and include documentation of daily activities during drilling, workovers, abandonment and other activities, well completion records, and testing data that provide well pressures. The 40 well study set includes only gas wells, since the study was gas migration potential. It is known that gas often accompanies oil production and gas can leak from oil wells, and these can be the subject of future study, but gas wells are the primary place to start a study of this type. To stay within time and resource limitations 40 wellbores were chosen, but there are hundreds of wellbores within the Potash Area and thousands counting those near the Potash Area. The list of 40 wellbores used in this study (Appendix A-2) is in approximate chronological order by spud (start of drilling) date to facilitate seeing changes in construction features over time. The attributes of wells of more recent vintage, approximately the second half of the list (reading the columns left to right) were given more weight when selecting wellbore construction features.

### *3.2.1 Representative Wellbore Features for Gas Migration Study*

At the detail of the present study, the Features of a representative wellbore are the casing and cement construction in relation to the geologic formations through which the well passes. Geomechanical model setups will use these Features which vary with depth.

The construction in the shallow portion of gas wellbores, from surface through the salt section, is likely to be more similar from well to well than is the deeper portion of the wellbore construction. This is, in part, because the current producing zones of greatest interest are below the salt section at varying depths, and operators may chose to have one intermediate casing or more and may run pipe as casing or a liner at different points. The internal well construction may vary with single or dual completions achieved through various methods; however, it is likely that all gas wells have tubing as part of their construction.

Figure 3.2 is a diagram of representative wellbore construction derived from the wellbore records of the 40 wells studied for this work. This diagram was presented at a BLM/stakeholders meeting January 10, 2011 and a version modified based on stakeholder feedback was presented at a similar meeting on February 8, 2011. At the February meeting a large spreadsheet documenting the wellbore components and initial flowing tubing pressures for the 40 well study set was given to stakeholders and BLM in hard copy form. That spreadsheet will be attached in digital form to this white paper because of its size (Attachment 1).

Shallow conductor casing holes are not used in model setups in this study. The surface casing hole is generally 17.5” in diameter and the surface casing is 13.375”, leaving an annulus for cement of 2.0625”. The salt string hole, which passes through the geologic section in which potash mining occurs, is generally 12.25” in diameter, the casing is 9.625” and the cement annulus is 1.3125”. The first intermediate hole varies between being 8.5” and 8.75” in diameter and the casing varies between being 7” and 7.625” making the largest cement annulus 0.875” and the smallest 0.4375”. From this point to total depth there is some variability within the 40 well set, though from the early 1980s onward the completion is with a 4.5” to 5.5” liner hung from the previous string. The tubing is 2.375” to 2.875”, sometimes two strings of tubing, through which the well is produced in varying constructions.

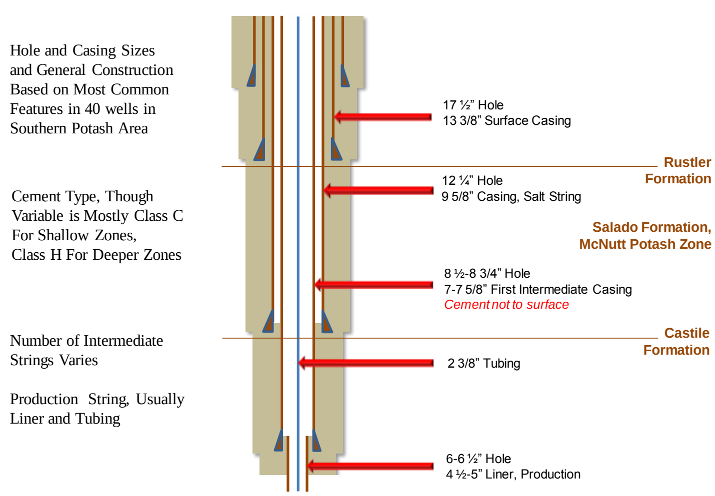



**Figure 3-2. Representative deep gas wellbore construction based on the 40 well study set, southern Potash Area.**

The focus of the present study of gas migration pathway is wellbore construction through the salt section with some attention given to the surface casing string. In general, the cement for the surface and salt strings was API Class C, or similar and for the first intermediate hole it varied with some Class C and some Class H, whereas the deeper strings were mostly cemented with Class H. Whether cement is emplaced to the surface for each string in the shallower section is a factor in shallow leakage potential as is the integrity of that cement emplacement (Watson and Bachu, 2008). Cement emplacement and general cement type was documented in the NMOCD records, but details of special additives, weight, etc were not features captured for the representative wellbore. Specifications for wellbore cement and casing for purposes of modeling will be presented in Section 4.

### *3.2.2 Discussion of FEPs and the Representative Wellbore*

There are several influences on the Features of gas wellbores as seen in the 40 well study set. The construction Features of gas wells in the study area tend to become similar during any time period spanning a few years, in response to successful practice over time. Gas well installation parameters in this area are constrained by the requirements of New Mexico Oil Conservation Commission (NMOCC) Order R-111-P, however, operators have asked for and received exceptions to these requirements. Studies in Canada were able to associate wellbore leakage with FEPs found a correlation between regulatory changes and changes in leakage potential for petroleum wells in their study area (Watson and Bachu, 2007). The scope of the present study did not include researching the regulatory history of the area, however regulations certainly impact wellbore Features and may be a factor in relative risk of leakage for existing wellbores of a given age group. Features are also influenced by changes in technology over time.

For this study the Feature “cement” is characterized by its American Petroleum Institute API Class with attributes derived from API standards (discussed in Section 4). In personal communications with local service companies we were told that there is no exactly “typical” cementing program because each well presents unique variations (personal communications Chris Faulkner, Halliburton, Houston, TX, 7/2/10; Dustin Guidry, BJ Services, Hobbs, NM, 7/27/10). The service companies may start with a baseline cementing program for an area, but they then vary the chemistry, water content, and weight and they change the variation in these attributes during different phases of the installation. For a baseline RA setup we suggest documenting the simplest aspects of the cement installation: 1) was the cement emplaced without incident, according to plan; and 2) was the cement brought to surface on all of the shallow section strings?

For this study the Feature “casing” is characterized by standard industry (API, etc.) material property parameters associated with the casing type (K 55, etc.). The thread type is not used in the geomechanical study. Tubing is not impacted in the geomechanical model, but can be characterized by industry standard material properties.

For wellbore FEPs analysis future work would involve the following.

- Establish the Features of representative wellbores in various configurations of interest (Oil, Gas, Active, permanently abandoned (PA), temporarily abandoned (TA), single, dual, etc.).
- Establish the Features of production.
- Define the Features and Processes of the geomechanical and geological/hydrological zones in which the wells exist.
- By consensus, develop a list of scenarios of interest that include likely Events and Processes acting on the wells, both human-caused and natural.

## 3.3 Risk Factors Associated with Construction, Workover and Aging of Wellbores

In its fullest expression a risk assessment framework has 7 general steps and is developed through months or years of iterations. The present work is focused on laying the foundation for risk assessment of the potential for gas migration through the first 3 RA steps: 1) Define performance criteria; 2) Characterize the system; and 3) Identify/Assess hazards. For the wellbore sub-model, SNL has researched the elements of these 3 steps and has researched an analogue for assigning relative risk of wellbore leakage based on study of wellbore records.

In a typical risk assessment, measures that are directly related to health, safety, or economic risk are evaluated for the system as a whole and compared to a. Performance Criteria. However, without previous experience, performance criteria have not been developed for the system as a whole under study here (i.e., well-degradation, well leak, gas fracture/gas migration system,). Hence, at this early stage of the risk assessment, subsystem performance criteria could be agreed upon, and appropriate measures defined. These measures may be conditional on certain events that have already occurred, that compromise the system. In this situation an absolute risk is not evaluated but rather a relative risk conditional on some events having occurred.

For gas migration, the wellbore scenarios involve whether the well leaks or not, which immediately requires a definition of "leak" that is meaningful in the setting of the problem, or stated differently, "What is the performance criteria for a leak?" Are all wellbore leaks potentially capable of resulting in the risk of interest, namely migration of methane through the geologic section and into a mine opening? The answer will require stakeholder input and consensus because the petroleum industry accepts that there can be "benign failure" of a wellbore sealing system that results in a gas source and driving force that cannot create a migration pathway to a mine. However, it has not been proven in a formal analysis framework for this site that, for some circumstances, gas released will have low volume and/or pressure or that it will have preferred pathways away from mine works and thus, be "benign" leakage with regard to mine works.

For the development of the RA model, the present study assumes that the Event labeled "gas is outside of the wellbore" has already occurred and that the leaking well exerts a driving force at a stratigraphic level where it represents a potential pathway to a mine opening. The approach here implicitly assumes that a leak from the wellbore and the presence of gas outside the wellbore is consequential to risk. The reason for that assumption is that it represents a step in the gas migration FEPs chain of events that has some percentage of probability of occurrence and so is reasonable to model as a possible Event. Under the RA model, further analysis would determine if that leak is a genuine concern, for example if it occurs at a stratigraphic location where significant quantities of gas can migrate out into the formation. If the BLM and stakeholders decide to model events prior to "gas outside of the wellbore," they could do that in the future, but at this point it is not clear how modeling the detailed failure modes for wellbores would be beneficial given the cost of doing so. Some other, less costly approaches could address the probability that any wellbore is leaking and could establish agreed upon Performance Criteria and thus, move the RA forward in a meaningful way.

The BLM and stakeholders would benefit by clarifying the Performance Criteria for "wellbore leaks" and can do so without costly studies to determine exactly how at a detailed level cement, casing and construction can fail. There are already many published studies by service companies and academics exploring topics in cement, casing and general construction failure. Though details remain to be explored, the general mechanisms and means of loss of wellbore sealing are known, and those FEPs are often recorded in wellbore records at NMOCD. If wellbores are not installed according to plan because of drilling and construction problems and if they degrade over time, as revealed in workover records, conclusions can be drawn regarding the relative risk that the wellbores may leak due to compromise of the sealing elements. These data can also reveal areas for focus for mitigation strategies going forward. Appendix A-6 contains information from NMOCD records that illustrate instances where wellbore installation was not performed according to plan or where workovers revealed degraded wellbore elements, resulting in either documented or reasonably likely increased chance of leakage due to compromise of sealing elements. These data can be used to begin a BLM and stakeholder discussion of the site-specific relative probability of wellbore leakage, eventually using data from all of the wells within the Potash Area.

## 3.4 Studies That Estimated Risk from Wellbore Leakage

The Alberta Canada regulatory agency, Alberta Energy and Utilities, oversees hundreds of thousands of wellbores and has initiated several studies on wellbore leakage. Researchers Theresa Watson and Stefan Bachu and their associates have published a series of papers on wellbore leakage, especially as it impacts considerations for $CO_2$ storage using former petroleum wellbores in Alberta, Canada (Gasda, et al., 2004; Watson and Bachu, 2007; Watson and Bachu, 2008; Bachu and Bennion, 2009; Bachu and Watson, 2009; Crow, et al., 2009). SNL has determined that these 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. The results of several of these papers are discussed here.

Watson and Bachu (2007) looked at records of 316,000+ wells in 2004, with a 500 well subset having substantial data and a 142 well subset having enough data for "full" evaluations. In 1995 the Canadian government required that wells have surface casing vent valves (SCVF) and soil gas migration (GM) studies performed when wells were completed and when they were abandoned. This provided a means to correlate actual data showing which wells were leaking with Features of the wellbore and its installation. They relied heavily on cement bond logs and casing integrity logs that were run upon installation and later in the life of the well and developed a system to rate well integrity based on these tools. They looked at many factors that could impact wellbore installation methods including existing regulations and the price of petroleum. Table 3-1 is a summary of their findings with regard to factors affecting wellbore leakage.

**Table 3-1. Bachu and Watson (2007) Factors Affecting Wellbore Leakage and Their Relative Impact**

| Factors with No Apparent Impact | Factors with Minor Impact | Factors with Major Impact |
|---|---|---|
| Well age | Licensee | Casing not covered by cement (as a result of the factors below) |
| Well operation mode (oil, gas or injection) | Surface casing depth | Wellbore deviation |
| Presence of $CO_2$ or $H_2S$ | Total depth | Well type (abandoned with no casing, versus cased and abandoned) |
| Completion interval | Well density | Abandonment method (cement plugs) |
| ----- | Topography (hydrostatic pressure) | Geographic area (study focused on an area prone to leakage and some other areas have different regulations) |

The implications for the present study are that cement emplacement is the most basic wellbore construction Feature affecting leakage potential. In this study "Low cement top or exposed casing was found to be the most important indicator for SCVF/GM…this wellbore condition has significant impact on external casing corrosion…" (Bachu and Watson, p. 6, 2008). Casing not covered by well-bonded cement is the most likely point of casing corrosion. This is relevant to discussions in the present study about whether cement should be emplaced to surface on casing below the salt string in order to protect the casing from corrosion. The study found that the best cement emplacement was found near the producing zones with the most likely place for poor or no cement emplacement being the shallower part of the wellbore. In the Canadian study regulations that dictated cement tops had an impact by requiring cement emplacement in shallower intervals. The price of oil at the time of well completion also had an effect with a strong correlation between the percentage of wells with leakage and those periods with a higher price of oil. The Bachu and Watson papers concluded that the intense drilling activity during periods of high oil prices led to improper completion of wells, resulting in a greater percentage of leaking wells.

Bachu, Watson and associates approached probability of leakage in two ways. In their 2007 paper (Watson and Bachu, 2007, Figure 17) they used their leakage risk factors to create a decision tree for assessing the potential for well leakage inside and outside of surface casing. At the farthest extent of the branches they were able to draw a line from left to right indicating increasing risk of leakage due to SCVF and/or GM. The present study could use an approach like this to determine relative risk.

The 2007 Watson and Bachu study focused on wellbore Features that impacted leakage potential in the shallow part of a wellbore. In their 2008 paper they focused on the Features that affect leakage potential in the deeper part of the wellbore with an emphasis on leakage pathways along a wellbore. In this paper (Watson and Bachu, 2008, Tables 1-4) they presented a numerical method to assign relative leak potential as a number from 1-8, calculated separately for shallow leakage factors and deep leakage factors; whereas in the 2007 publication they had presented the fault tree method to analyze leak potential that resulted in *relative* potential for leakage shown by a location along the fault tree's final tier. Their Tables 1 and 2 for shallow wellbore leakage factors are presented here to illustrate this method.

**Table 3-2. Shallow wellbore leakage factors with assigned relative values reflecting the influence of that factor on shallow wellbore leakage.**

| Factor | Criterion | Meets Criterion Value | Default Value |
|---|---|---|---|
| Spud date | 1965-1990 | 3 | 1 |
| Abandonment date | <1995 | 5 | 1 |
| Surface casing size | ≥244.5 | 1.5 | 1 |
| **Well type** | **Cased** | **8** | **1** |
| Geographic location | Special test area | 3 | 1 |
| Well total depth | >2500m | 1.5 | 1 |
| Well deviation | 1.2-1.8 | 1.5 | 1 |
| Cement to surface | No | 5 | 1 |
| Cement to surface | Unknown | 4 | 1 |
| Additional plug | No | 2 | 1 |
| Additional plug | Unknown | 1.5 | 1 |

**Table 3-3. Shallow leakage potential score derived from multiplication of values assigned in Table 3-2.**

| Shallow Leak Potential (SLP) | Score |
|---|---|
| Low | <50 |
| Medium | 50-200 |
| High | 200-400 |
| Extreme | >400 |

For estimating the value of factors in leakage engineering judgment can be used, developed in collaboration among participants. In these tables the factors that could readily be used for the present study purposes are spud date (relevant to the price of product), well deviation, cement to surface, and presence of plugs. These Features are found in publically available well records. The Bachu and Watson (2008) study also included deeper wellbore factors that are documented in NMOCD records, including the number of well treatments (fracture and acidizing) and the number of completions as well as abandonment type.

The conclusions of the Bachu, Watson and associates studies were that generally available well data can be used to predict which wells have a greater chance of leaking and most leaks occur due to mechanical factors during wellbore installation and abandonment. The implications for the present study are that a study of wellbore records in the Potash Area can yield enough information to determine which wellbores are more likely to leak than are others. These data can form the basis of *qualitative relative* probability estimations for wellbore leakage, especially when augmented by some field checks on wellbore annulus pressure conditions.

Nichol and Kariyawasam (2000) performed a risk assessment study for the US Department of Interior, Minerals Management Service (MMS) to determine the risk of leakage for temporarily abandoned or shut-in wells in the Gulf of Mexico Outer Continental Shelf Area. The object was to develop a methodology for assisting MMS in managing risk associated with having about 8,000 non-producing wells that could be hazardous to safety and the environment. For this study, risk was defined as the probability of a wellbore or wellhead leak to the environment multiplied by a measure of its subsequent adverse consequences. In their methodology they determined a well's risk level by (Nichol and Kariyawasam, 2000, p. 3): 1) defining a common well configuration for each well status (SI, TA, and PA); 2) identifying well attributes which influence the level of risk; 3) estimating the probability of a leak to the environment; and 4) determining the corresponding consequences of the leak. They used fault trees in their analysis (Nichol and Kariyawasam, 2000, Figures 3-5, 3-6) and developed reliability estimates for well components based on available data or engineering judgment and listed potential leak Events at each component (leak through production tubing, leak through packer, etc.).

Some of the methodology employed by Nichol and Kariyawasam (2000, Section 4.2-4.4) could be applied to the present study. For characterizing a release they looked at spill volume as leak rate multiplied by duration (which includes time to repair). The rate is the leak path size (theirs was in water) multiplied by the driving pressure. They knew the failure mechanisms were deterioration, corrosion and malfunction. They said that corrosion caused 85-90% of small leaks for estimation purposes. They cited a technical reference manual on estimating pipeline failure offshore to split the large/small leak percentage for wells into 10/90 and a large leak was defined qualitatively as a leak an order of magnitude larger than a small leak. This resulted in a size probability distribution of 0.9 for small leaks and 0.1 for large leaks

They looked at driving pressures for SI wells versus flowing wells, and flowing gas wells versus flowing oil wells. In a SI well the potential driving pressure was the pressure that can build up at the leak point being considered, and is related to the SIP of a given well. They noted that leaking oil wells can leak solution gas, but of course, more gas is released from a gas well which may also leak condensate. They established order of magnitude indices to assign relative magnitude of the case for these Events, and arrived at qualitative leak volume indices, e.g., gas and liquid volume indices. They used a base value of 10 for gas and fluid release from a flowing oil well, whereas the index for a flowing gas well was 100. Fluid releases from non-flowing wells were given indices 10 times lower than the flowing wells. Leak size comes from the leak volume index. These order of magnitude differences contrasted the Cases, not necessarily the effects of the release. For consequence analysis they calculated a life safety consequence and an environmental consequence.

Another study that applied RA methodology to the problem of achieving wellbore stability at a given mud weight is Moos et al. (2003). The figures in this study illustrate how they quantified the uncertainties in the input parameters need to compute mud weight limits and illustrated how output values can be presented in different forms including "minimum," "most likely," and "maximum." Stakeholder feedback at one meeting indicated concern about wellbore stability during drilling through the salt zone and concern about management of the mud parameters. This study shows how RA can be applied to study of that problem.

These studies are discussed here to support our contention that an RA using probability can be developed for the Potash Area to provide scientific analyses with outputs that can be used as site-specific information to support BLM in analyzing problems. SNL is not recommending that the BLM and stakeholders use the exact numbers developed by Bachu, Watson and associates or by Nichol and Kariyawasm (2000), but rather these studies are examples showing that risk assessment with probabilities can be done in a way suitable to the present work. Having actual, site-specific data on probability of Events would underpin risk discussions with a more scientific foundation.

## 3.5 Stakeholder Feedback on Present Work and Potential Future Work Related to Wellbores

There have been several stakeholder meetings as of the time of writing this report, though they occurred late in the process, and so are incorporated here as part of the dialog and data input for future work. It should be noted that the focus of the present study, gas migration pathway and the use of risk assessment, was chosen through reading stakeholder input on the previous SNL gas migration study. The stakeholder technical working groups established during the present study will be a continuing source of information for focusing future work.

All stakeholders are interested in improving Features of wellbores that will mitigate the risk of wellbore leakage. Yates Petroleum provided the wellbore diagram in Figure 3-3 at a stakeholder meeting February 8, 2011 as an example of wells they are currently constructing outside of the Potash Area. This construction could be considered as a baseline concept for discussion of improving wellbore designs in the future in the Potash Area.

Yates Petroleum provided the following text to accompany Figure 3-3 (E-mail communication sent through Craig Cranston, BLM, 2/11/11). "This is one possible well design with the purpose to mitigate any potential leak, independent of cause, by allowing pressure and fluid to divert to the surface, and to provide the opportunity for monitoring status of the open annuli. In this design the production tubing-production casing annulus is open to the atmosphere at the surface as is the production casing-intermediate casing annulus. The open annulus between the production casing and intermediate casing allows also for some shear and collapse in the case of subsidence before impacting the production casing or tubing as well as providing a direct path to the surface preventing pressure build up in the event of leak. The same applies to the annulus between the production casing and tubing if a packer is installed between tubing and casing. The type of equipment and monitoring would be a topic for future study."

For Figure 3-3 all depth measurements are relative to the Kelly Bushing (KB) on the drilling rig, and down is the positive direction. The green grass line represents ground level and the casing strings are cut off one foot below ground at 19’ (=19’ below KB). In the column on the right of the wellbore the first number after a hole or casing is the size in inches, the last two numbers are the depths in feet of the beginning and bottom of the hole or casing. Because of software issues the middle number is redundant of the “beginning” depth number in some cases. In the column on the left of the wellbore the numbers represent the depths of cement placement (top of cement and bottom of cement). MD means measured depth.

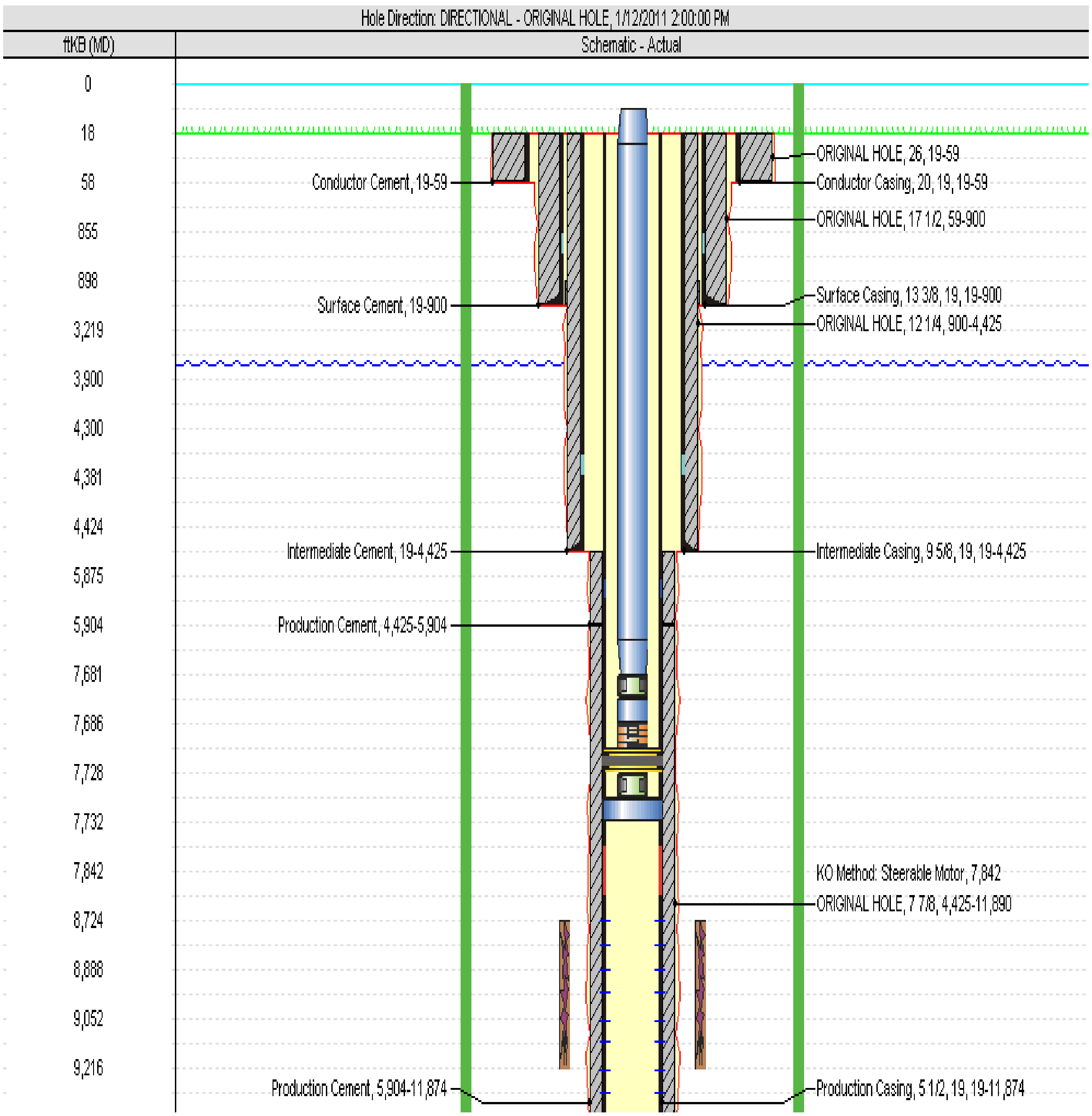



**Figure 3-3. Baseline concept from petroleum stakeholder for discussion of future wellbore design in Potash Area (provided by Yates Petroleum).**

Stakeholders have noted that many wells in the Potash Area are not deep gas wells, though they may form a component of the risk of gas migration. Oil wells (which have associated gas production) and shallower gas zones (as compared to the Morrow and other deep formations) may be components in the gas migration potential. They suggest investigation of: 1) Wellbore pressures for the entire suite of oil and gas reservoirs in the Potash Area; 2) Wellbore design changes that could mitigate risk; 3) Wellbore operational protocols that could mitigate risk; 4) Wellbore abandonment protocols that could mitigate risk; 5) Wellbore installation protocols that affect hole quality through the salt section, such as the mud chemistry; 6) Effects of time on the risk of mining close to existing wellbores; and 7) Mining operations methods that may mitigate risks from wellbores.

Stakeholders are concerned about using sustained, single gas pressures over very long modeling periods for gas migration study and have offered to provide actual gas pressure histories from the Area for future modeling. This will presumably, include both gas wells and oil wells with associated gas.

The general question of importance to both petroleum and mining stakeholders is "What is the minimal safe standoff distance between wellbores and mines?" An associated question is "Does a 'safe distance' change over time for any given wellbore?" Both industries have an economic stake in smaller standoff distances (personal communication, Dan Morehouse, Mosaic, 2/8/11 stakeholder meeting) given that there will be drilling within the Potash Area. Pillars of potash left around wellbores represent valuable volumes of asset. Potash mining has approached and mined around existing wellbores in the past and the plan is to continue to do so, if it can be done safely.

With regard to gas migration risk assessment the two stakeholder industries have differing views. The petroleum companies generally install wellbores with the understanding that their operation can be successful with some degree of "benign failure" of the overall wellbore construction (John Smitherman, BOPCO, 2/8/11 stakeholder meeting). For the most part the "failure" involves failure to seal the production within the engineered design of tubing, casing, packers and cement. An example of "benign failure," might be development of annular pressure from an internal tubing leak that does not reach the external environment. Another example might be gas leakage external to the well that is at a low volume and/or pressure such that it cannot migrate into the salt section. The petroleum stakeholders have suggested mitigation Features such as installation of surface casing vent valves that reveal and prevent annular pressure buildup.

In the gas migration risk assessment part of the process is establishing the performance criteria for an unacceptable level of methane entering a mine opening. The potash industry operates under a regulatory guideline from the Mine Safety and Health Administration (MSHA), Standard 30 CFR 57.21-1, that gives specific performance criteria for a mine being designated "gassy." Potash mines are not considered "gassy" as a default (unlike coal mines) and therefore, operate under much less costly conditions than do coal mines. The MSHA standard allows that a mine shall be deemed gassy if one or more of several conditions exist including "…a concentration of 0.25 percent or more, by air analysis, of flammable gas emanating only from the ore-body or the strata surrounding the ore-body has been detected not less than 12 inches from the back, face, or ribs in any open workings…" In discussions with the potash stakeholders (2/8/11 stakeholder meeting) it came out that regardless of the current chemistry of the air in a mine, they find the risk of *any* added methane unacceptable. They do not recognize "benign failure" in this area. They cite the potential high consequences (death) of the Event of any level of gas migration into a mine.

A challenge of risk assessment going forward will be to produce results acceptable to both stakeholder entities given the divergence of opinion as to what are acceptable risks. This sort of strong divergence of opinion has been successfully addressed in past risk assessments in which SNL has participated, with the WIPP site as an example. Continued stakeholder engagement and iteration of the RA elements will be required to make progress, but there is precedence for that happening when parties stay engaged.

# 4 GEOMECHANICAL COMPONENTS OF THE RISK ASSESSMENT TOOL PERTAINING TO GAS MIGRATION

The geomechanical component of the risk assessment tool examines the mechanical interaction between the potash mines and the oil and gas wells in the Secretary's Potash Area in southeastern New Mexico. Subsidence resulting from the removal of potash alters stresses and strains in the bedded layers of salt, potash, and anhydrite, resulting in 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. This section of the report discusses the geomechanical model used to evaluate the interaction between the mines and the wellbores. The following topics will be covered in this section:

1. A discussion of an earlier geomechanical analysis of the wellbore/mine interaction (Arguello et al., 2009). These analyses provide the basis for the development of the geomechanical model used for the risk assessment tool.
2. A discussion of the geomechanical conceptual model of the potash mine area. This will include an overview of the features, events, and processes related to geomechanical behavior, a description of the gas migration model and the three geomechanical submodels which comprise the model, and a discussion of relevant required parameters.
3. Illustrative examples based on site-specific data using the Arguello et al. calculations, to show how the geomechanical model will be used in the risk assessment tool and how the geomechanical model provides input to the hydrological model.

## 4.1 Background: 2009 Geomechanical Analyses of Wellbore/Mine Interactions

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 effect impacts 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 (Litt, 2009) and the oil and gas (Bogle, 2009) stakeholders, which included significant criticism regarding some of the assumptions of the model and conclusion 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). 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.

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 m (~1970 ft) and 1100 m (~3610 ft) from the edge of the mine excavation.
- Large interbed slip magnitudes (greater than 0.5 m or ~20 in.) 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 (~0.03 in.) 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 (~0.06 in.) 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 (0.33 in.). 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. For the double-casing simulation, the *entire* cross-section of the inner casing first yielded when the interbed slip reached a value of ~8.6 mm (0.34 in.). At this value of interbed slip the largest plastic strain in the inner casing is ~7.2%; similarly, the entire cross-section of the outer casing first yields when the interbed slip reaches a value of ~14.0 mm (0.55 in.) and 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, or 2660-2720 feet) 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. This new geomechanical model, which is described in detail in the succeeding sections, determines the effects of stresses, strains, and slips on the wellbore casings as well as the porosity and permeability of the numerous stratigraphic layers in the Salado Formation, and forwards relevant information to the hydrologic flow portion of the RA model described in Section 5.

## 4.2 Geomechanical 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. For this case of potential gas migration, the conceptual model is illustrated in Figure 3-1, which includes the three subsystems that are included in the conceptual model:

1. Geology of the Delaware Basin, in both undisturbed and disturbed conditions.
2. Wellbores used for extracting oil or gas (active, temporarily abandoned (TA), and permanently abandoned (PA)).
3. Mining for extraction of potash deposits.

The process of a risk assessment analysis is to examine all of the FEPs concerning the subsystems for a given model, determine their interconnections and relative effects toward a given scenario, and then develop physical models to evaluate the sensitivity to various FEPs to causing the scenario in question. For this RA model, the concern is gas migration from the wellbores to the mine. One of the first steps in assessing the potential for gas migration is to identify the relevant FEPs that may have some impact on gas migration. The risk assessment tool being developed for BLM has its roots in previous tools developed for the WIPP and Yucca Mountain radioactive waste disposal projects. These projects involve answering critical technological questions about a given scenario (e.g., what is the potential for radionuclides to migrate to a defined boundary of the accessible environment in 10,000 years), involving highly contentious issues, with a documentable and peer-reviewed scientific investigation resulting in the computation of the probability of occurrence of the question. It is with this previous experience that a similar risk assessment tool is being designed for BLM.

This section describes the FEPs associated with the gas migration scenario, particularly those related to geomechanics; then, the conceptual model that was developed is described in detail; and finally, the list of parameters required for the geomechanical submodel is discussed.

### *4.2.1 Geomechanical Components to FEPs*

Figure 3.1 presents a generalized conceptual model used for developing the risk assessment tool and specific geomechanical and hydrological submodels for evaluating potential gas migration. The three subsystems, geology, wells, and mine, coexist in the conceptualization. Table 4.1 represents an initial identification of the FEPs that are relevant to potential gas migration. The geological features in the Delaware Basin 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 4-1. 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 4-1. Features, Events and Processes (FEPs) for the gas migration scenario, with Geomechanical components highlighted in bold type.**

| Subsystem | Geology (Both Disturbed and Undisturbed | Gas-Transmitting Wellbores (Active, PA, TA) | 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** |

### *4.2.2 Gas Migration 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 source of gas; in this case, this is defined as a gas well that is leaking gas to the surrounding rock.
- A driving force, 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 (FTP) in NMOCD records. This assumption is probably true for a well casing that has suddenly failed; however, this assumption may be inaccurate for the case of gas leaking through degraded cement, for example, for which there may be a significant pressure drop. In addition, the FTP is generally not constant over the lifetime of a well. So knowledge of the expected FTP history is required.
- A pathway 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.

A useful analogy to understand the three elements for gas migration is seen by looking at the three elements for fire. A fire has three elements – fuel, heat, and oxygen – and the removal of any one element puts out or prevents a fire. 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 are 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 well 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. Figure 4-1 illustrates several potential pathways from a leaky well to the surrounding rock. 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 4-2):

- Gas leakage due to normal well construction, operation, and aging issues (accounting for most of the potential pathways through cement). 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. As a placeholder, the current plan is to use an assumption based on the extensive studies of gas wells in Alberta, Canada documented in several papers (Bachu and Bennion (2009), Watson and Bachu (2008)). These papers 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.

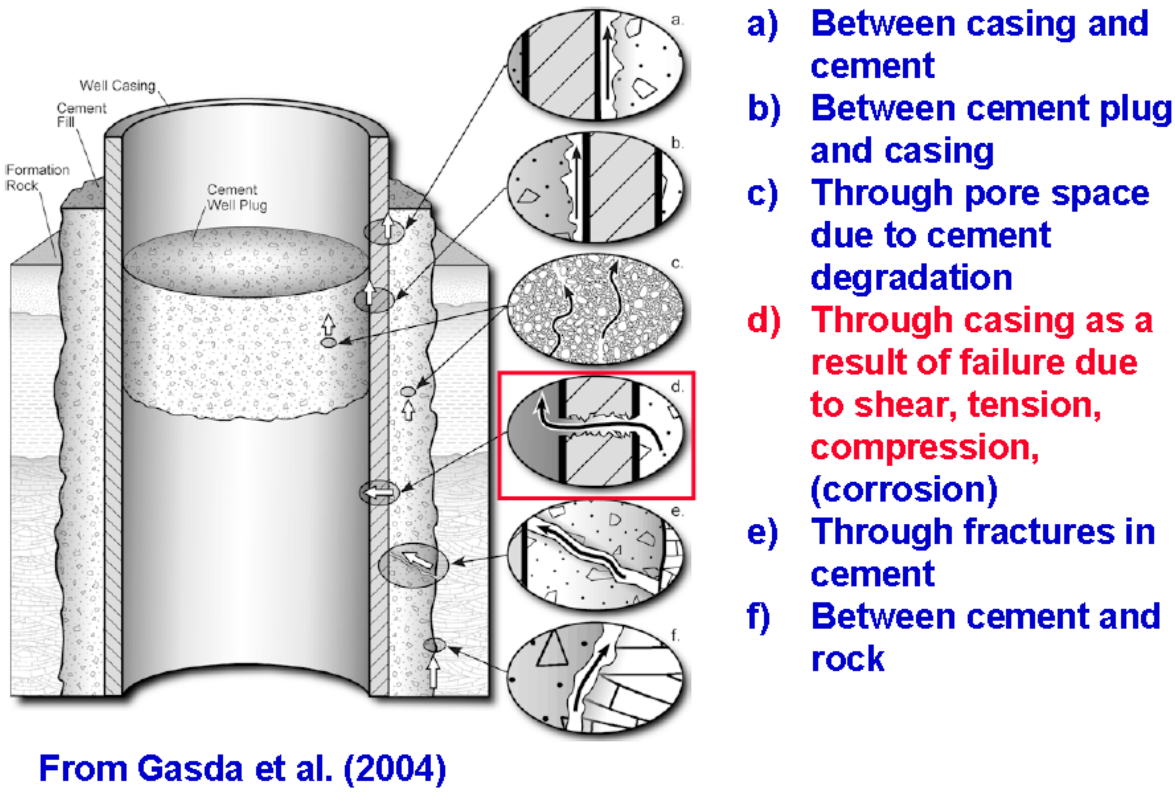



**Figure 4-1. Potential gas leak pathways from wellbore to surrounding rock.**

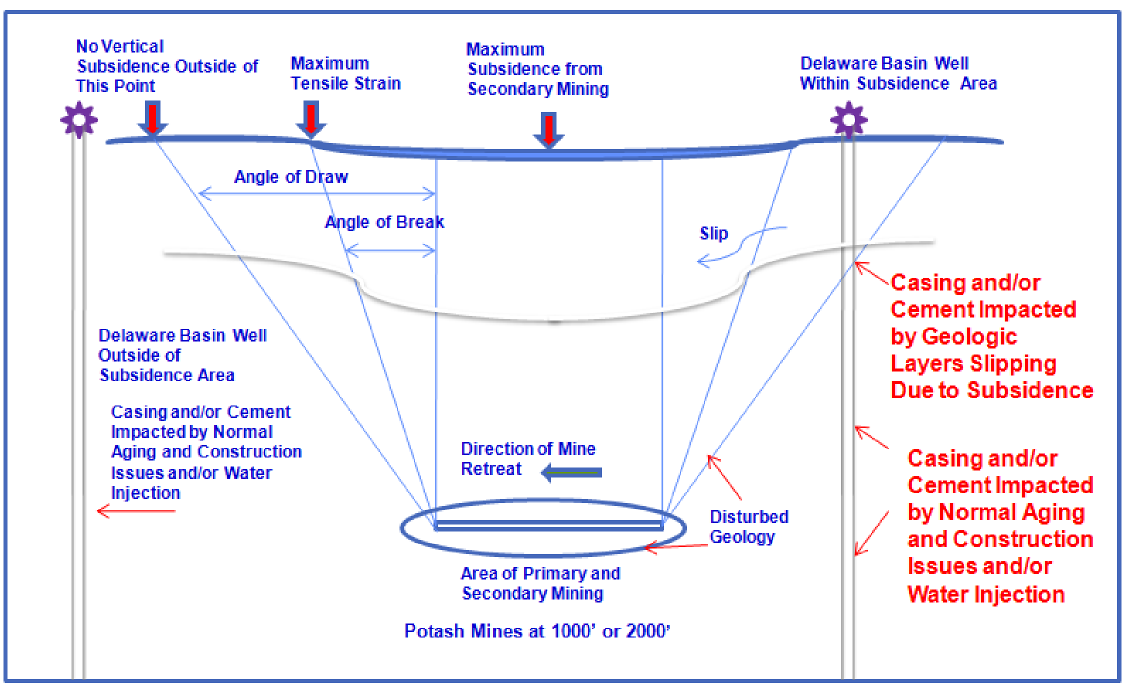



**Figure 4-2. Wellbore casing submodel.**

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 4-3 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 (Swift and Corbet, 2000), 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 process of hydrofracturing that might be caused by high-pressure fluids in the wellbores will not be modeled for this iteration of the RA model. 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.

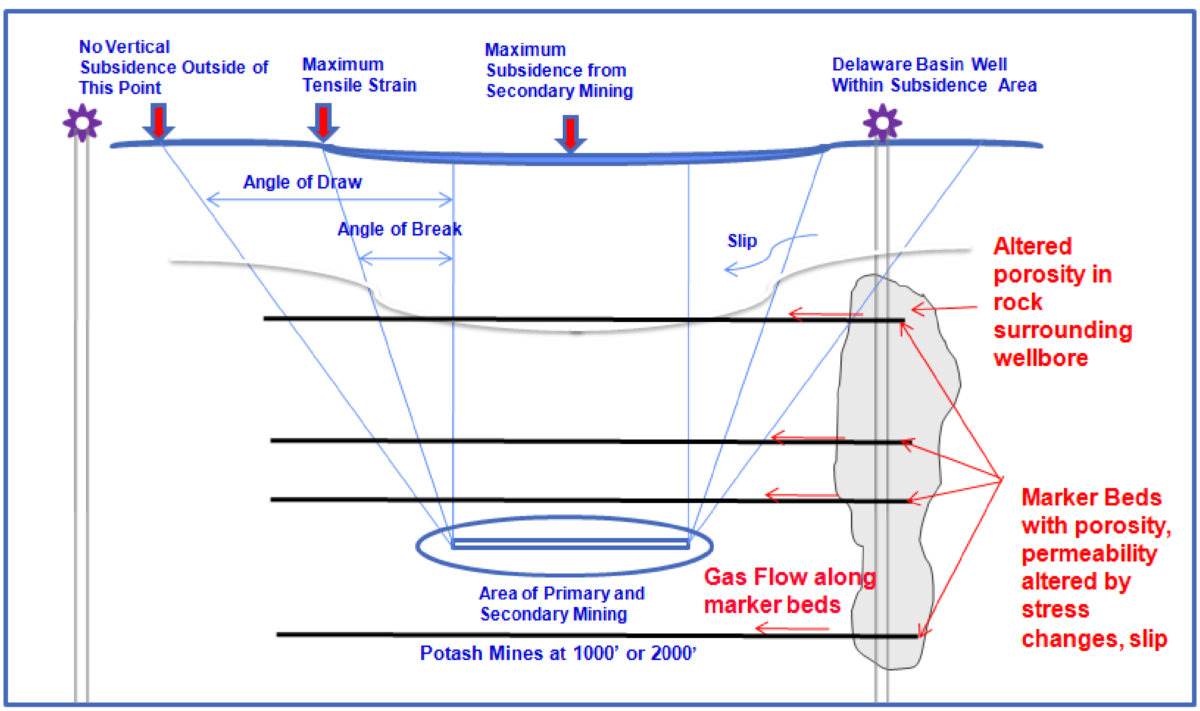



**Figure 4-3. Well-to-mine migration submodel.**

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 4-4: 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.

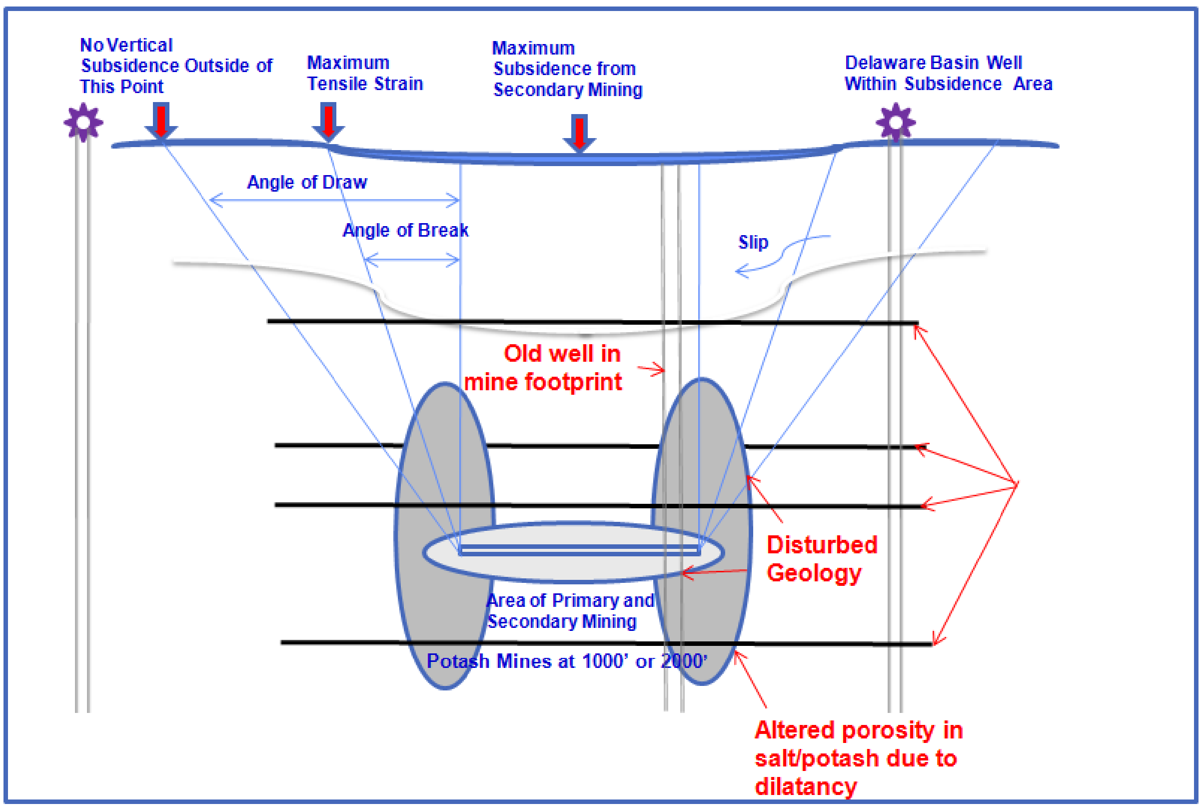



**Figure 4-4. Mine disturbed zone submodel.**

### 4.2.3 Description of Geomechanical Computational Model

The three geomechanical submodels are all components of the overall conceptual model, and must be integrated into the computational models that will simulate their physical behavior. There are many ways to convert the conceptual geomechanical model into one or more computational models that capture the physics described in the conceptual model. This section of the report will define the geomechanical model in three ways:

1. First, a definition of what features and processes any geomechanical model must include to contribute to evaluating potential gas migration.
2. A definition of the specific geomechanical model that will be used for this first iteration of the risk assessment model.
3. A description of possible enhancements to the geomechanical model in future iterations.

Figure 4-5 illustrates the basic requirements for the computational model. The requirements are listed as follows:

- Input features/processes – these are the parameters that define the problem geometry and physical setting. From these parameters, the conceptual model is built, the problem domain is defined (2D or 3D, thickness of layers, design of mine and/or well, etc.), the computational meshes are designed and built, and the problem is formulated.
- Input data required for the model – these include the in situ rock properties such as mechanical and creep properties, porosity and permeability, and friction coefficient along slip surfaces. They also include mechanical and strength properties for the casing and cement materials.
- Data required for model validation – these data help to give confidence in the results predicted by the model. Such data include measured subsidence at the surface above the mine, and measured slip between the bedded surfaces.
- A computational tool for conducting the analysis. The tool chosen for the analysis is JAS3D (Blanford et al., 2001).
- Analysis output data – these are the parameters directly obtained from the JAS3D calculations, or from post-processing those calculations. JAS3D directly calculates stresses, strains, displacements, and slip. Post-processing analysis determines if casing strengths were exceeded, if fracturing occurred in the marker beds, and any changes in porosity or permeability due to the changes in stress.
- Geomechanical input to the hydrological calculations – the results that directly apply to the gas flow calculations described in Section 5.

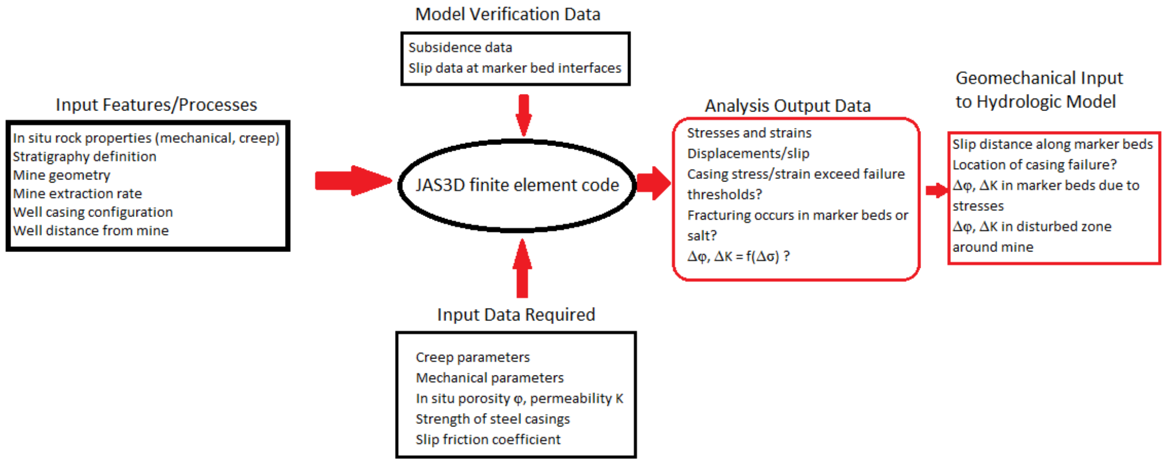



**Figure 4-5. Schematic of geomechanical computational model.**

The finite element code chosen for conducting the geomechanical computational analyses is JAS3D (Blanford et al., 2001), the same code used by Arguello et al. (2009). JAS3D is a three-dimensional iterative solid mechanics code developed at Sandia National Laboratories for analyzing the large deformation response of nonlinear materials subjected to a variety of loads. For quasistatic applications, as is the case here, this Lagrangian finite element program uses iterative algorithms to solve the equilibrium equations. A multi-level solver provides effective treatment of severe nonlinearities and frictional contact response. Eight-node uniform strain hexahedral elements are used in the finite element formulation for the application describe here. All constitutive models in JAS3D are cast in an unrotated configuration defined using the rotation determined from the polar decomposition of the deformation gradient. A robust contact algorithm allows for the interaction of deforming contact surfaces of quite general geometry (Blanford et al., 2001).

JAS3D is a mature production code. It represents approximately 30 plus years of research and development into explicit finite element code technology that has its genesis in the defense programs. Apart from its weapons usage, JAS3D has been used to support WIPP, YMP (Yucca Mountain Project), the DOE Strategic Petroleum Reserve, and various oil and gas applications. The technology embodied in JAS3D, through its predecessor codes Pronto (Taylor and Flanagan, 1989), JAC3D (Biffle, 1993), SANCHO (Stone et al., 1985), and SANTOS (Stone, 1997), has also been used for an even wider range of applications.

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 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 the inability to fully characterize the in situ response of the rock when subjected to events such as mining. Furthermore, certain geomechanical processes such as stress-induced creep and contact surface slip are computationally intensive. Furthermore, a robust risk assessment analysis requires multiple calculations of the same events using site-based variability in properties, to allow for a range of potential responses based on knowledge of the variability of the site. 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.

Except as noted below, all of the assumptions, material models, material properties, depths of layer contacts, and computational results from Arguello et al. (2009) are incorporated into this initial analysis. For the development of the risk assessment model, and in response to the stakeholder comments regarding the original analyses in Arguello et al. (2009), the following modifications or enhancements are being added to the geomechanical analyses:

Additional information will be extracted from the Arguello et al. (2009) calculations to use as input for gas migration calculations. This information included extent of slip along marker beds, the extent of the disturbed zone around the mine where shear stresses exceed dilatancy thresholds and gas migration may be enhanced, and estimation of changes in permeability in marker beds.

- The criteria for determining failure of a well casing will be redefined based on industry standards and from the recent testing of wellbore casings performed by SNL and the University of New Mexico (Dwyer, 2011).
- The computational model will be revised by replacing the contact surface ("knife-edge") rendering of the marker beds with anhydrite or polyhalite seams of finite thickness.

For the sake of completeness, an abridged description of the global mine excavation computational model and the wellbore model from Arguello et al. (2009) is re-printed here with a few revisions. The most important revisions are related to the inclusion of the marker beds as specific anhydrite or polyhalite layers (instead of just contact surfaces in the original analyses), in definitions of well casing failure, and in the future incorporation of a "typical" wellbore model, as discussed in Section 3. Other revisions are minor editing and formatting changes.

The finite element meshes developed for these analyses represent a region four miles in lateral dimension and extending vertically from the ground surface, considered to be the top of the Dewey Lake formation, down to the Salado-Castile boundary. In all cases the height of the mined region was assumed to be 3.048 m (10 ft). Modeling of simultaneous mining at multiple depths was initially considered but was not carried out in this work.

In Arguello et al. (2009), a set of mining scenarios was chosen that illustrated the potentially important effect of slip at bedding interfaces. By varying the depth of the mine, the length of the mine, and the mine excavation rate, a range of typical mining conditions was examined. The two mine depths evaluated were 304.8 m (1000 ft) and 609.6 m (2000 ft). The mine excavation lengths and mining rates were chosen to be 0.8 km (0.5 mile) and 1.6 km (1 mile), and 0.48 km/year (0.3 mile/year) and 1.6 km/year (1.0 mile/year), respectively. For this first iteration of the RA model, the only case to be considered is for the mine at 1000 feet deep, 1 mile in length, with an excavation rate of 1.0 mile/year.

The various formations (Dewey Lake, Rustler, and Salado) generally contain a number of layers of rock of various type and thicknesses. These layers within the formations were not explicitly represented in the numerical model but were assigned properties representative of the specific rock type. The individual potash ore zones, within the McNutt Member of the Salado Formation, were not included in the model but were assumed to behave similarly in terms of their mechanical (elastic and creep) response to Salado salt. The lack of data on the creep characteristics of potash material, which likely depends on the mineral types and ore grades, made this choice necessary.

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. (In the original 2009 analyses, these beds were represented as frictional planar interfaces; in the enhanced version for future analyses, they will be represented as anhydrite or polyhalite layers of thickness derived from Jones et al. (1954), in addition to having frictional planar interfaces.) 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 and DeVries, 1990; Munson et. al, 1990; Munson, 1997). For these analyses it was further assumed that the formations and marker beds were horizontally oriented.

The stratigraphy and material properties of the potash enclave that were defined in Arguello et al. (2009) for developing the computational mesh and problem definition are adopted for the current analysis. The potash zone where mining occurs can vary with depth from one location to another. In one location, it may be relatively shallow, but at a different location, it may be relatively deep. In the same way the thicknesses of the overburden layers, above the potash, may also vary. Table 4-2 summarizes the stratigraphy assumed for the numerical models used in the “shallow,” 304.8 m (1000 ft), and “deep,” 609.6 m (2000 ft), mine analyses, and Figure 4-6 illustrates the stratigraphy for the 1000-ft deep mine. Note that the thickness of the McNutt Potash zone was identical in the two models; however, the Dewey Lake, Rustler, and the upper Salado and lower Salado have different thicknesses in the two models. In the 304.8 m (1000 ft) model the Dewey Lake was 61 m (200 ft) thick and in the 609.6 m (2000 ft) model it was 152.4 m (500 ft) thick. In the 304.8 m (1000 ft) model, the Rustler was 91.4 m (300 ft) and in the 609.6

m (2000 ft) model it was 152.4 m (500 ft) thick. The upper Salado was 76.2 m (250 ft) thick in the 304.8 m (1000 ft) mine model and 228.6 m (750 ft) thick in the 609.6 m (2000 ft) model while the lower Salado was 259.1 m (850 ft) thick in the 304.8 m (1000 ft) mine model and 396.2 m (1300 ft) thick in the 609.6 m (2000 ft) model.

In these figures the Salado Formation appears to be divided into distinct regions, Upper Salado, McNutt Potash and Lower Salado. However, as previously noted, the material properties describing these regions were identical in the numerical model. The constitutive properties specified for all materials are discussed later. Figure 4-7 illustrates the locations of the 11 marker beds in the upper Salado and McNutt Potash zone for the 304.8 m (1000 ft) deep mine model.

**Table 4-2. Material layers specified in all mining simulations, including marker bed thickness**

| Formation / Member / Marker Bed (MB) | Distance from Ground Surface to bottom of bed[1] | |
|---|---|---|
| | 1000 ft mine | 2000 ft mine |
| Dewey Lake | 61.0 m (200 ft) | 152.4 m (500 ft) |
| Rustler =Top of Upper Salado | 152.4 m (500ft) | 304.8 m (1000 ft) |
| Upper Salado to MB 101 | 157.3 m (516 ft) | 321.9 m (1056 ft) |
| MB 101 (polyhalite) [2] | 158.5 m (520 ft) | 323.1 m (1060 ft) |
| Upper Salado to MB 102 | 168.9 m (554 ft) | 356.3 m (1169 ft) |
| MB 102 (polyhalite) | 169.2 m (555 ft) | 356.6 m (1170 ft) |
| Upper Salado to MB 103 | 178.3 m (585 ft) | 388.6 m (1275 ft) |
| MB 103 (anhydrite) | 181.4 m (595 ft) | 391.7 m (1285 ft) |
| Upper Salado to MB 109 | 192.6 m (632 ft) | 444.1 m (1457 ft) |
| MB 109 (anhydrite) | 201.2 m (660 ft) | 452.6 m (1485 ft) |
| Bottom of Upper Salado = Top of McNutt Potash | 228.6 m (750 ft) | 533.4 m (1750 ft) |
| MB 117 (polyhalite) Thickness 0.6 m (2 ft) | 249.9 m (820 ft) | 554.7 m (1820 ft) |
| MB 118 (polyhalite) Thickness 1 m (3 ft) | 259.1 m (850) | 563.9 m (1850 ft) |
| MB 119 (polyhalite) Thickness 0.6 m (2 ft) | 266.7 m (875 ft) | 571.5 m (1875 ft) |

| | | |
|---|---|---|
| MB 120 (polyhalite)<br>Thickness 0.6 m (2 ft) | 272.8 m<br>(895 ft) | 577.6 m<br>(1895 ft) |
| MB 121 (polyhalite)<br>Thickness 0.6 m (2 ft) | 277.4 m<br>(910 ft) | 582.2 m<br>(1910 ft) |
| MB 122 (polyhalite)<br>Thickness 0.6 m (2 ft) | 281.9 m<br>(925 ft) | 586.7 m<br>(1925 ft) |
| Bottom of Union member (anhydrite)<br>Thickness 3 m (10 ft) | 292.6 m<br>(960 ft) | 597.4 m<br>(1960 ft) |
| Top of Mine (roof) | 301.8 m<br>(990 ft) | 606.6 m<br>(1990 ft) |
| Bottom of Mine (floor) | 304.8 m<br>(1000 ft) | 609.6 m<br>(2000 ft) |
| MB 123 (anhydrite)<br>Thickness 1.8 m (6 ft) | 317.0 m<br>(1040 ft) | 621.8 m<br>(2040 ft) |
| Bottom of McNutt Potash = Top of Lower Salado | 335.3 m<br>(1100 ft) | 640.1 m<br>(2100 ft) |
| Bottom of Lower Salado = Top of Castile | 594.4 m<br>(1950 ft) | 1036.3 m<br>(3400 ft) |

Note: 1 The ground surface is considered to be the top of the Dewey Lake formation

2 For the current analysis, marker beds thickness are derived from site stratigraphic data listed in Jones et al. (1954).

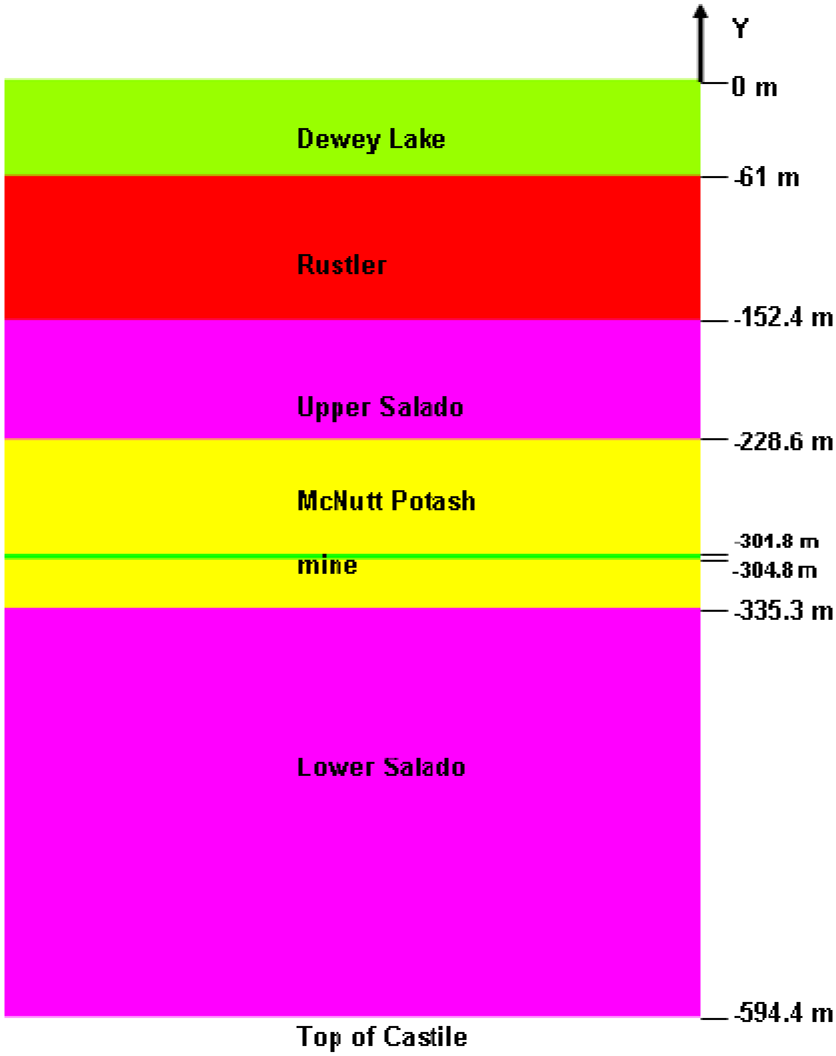



**Figure 4-6. Stratigraphy used in 304.8 m (1000 ft) deep mine (Arguallo et al., 2009).**

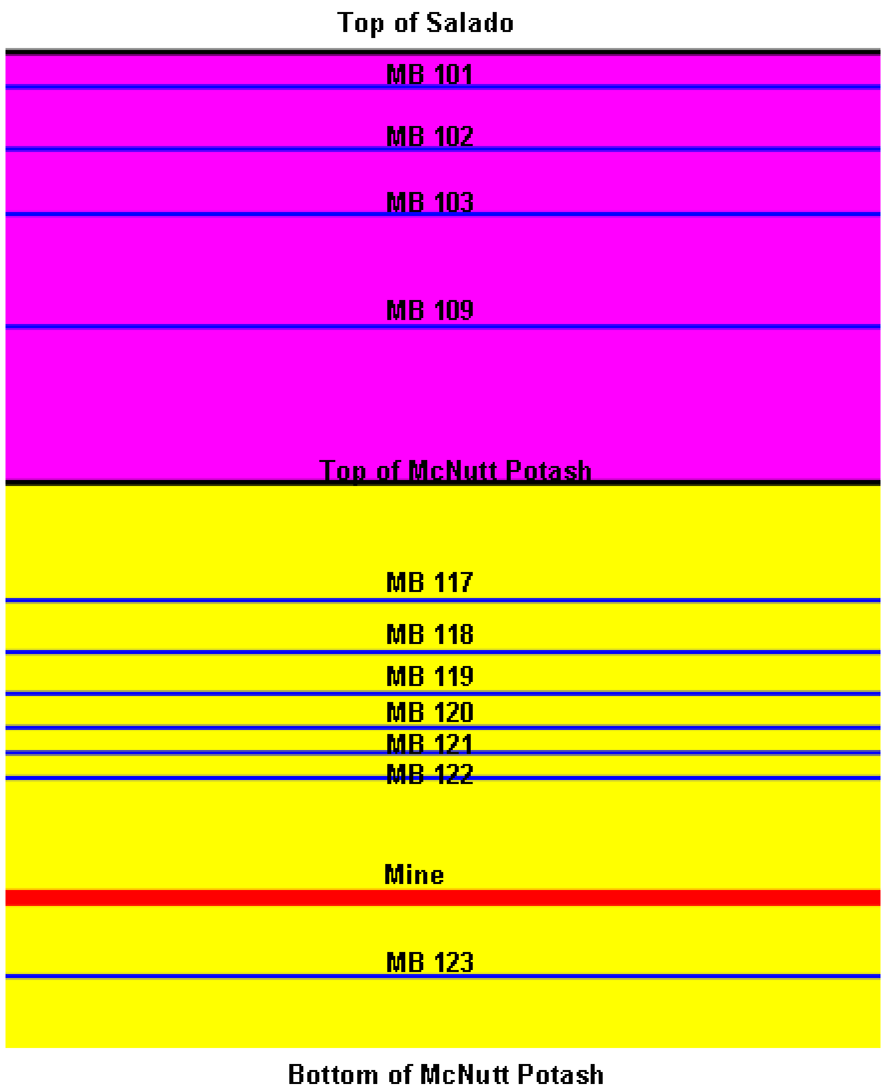



**Figure 4-7. Location of marker beds in 304.8 m (1000 ft) deep mine (Arguello et al, 2009).**

The non-salt materials located above the Salado Formation (Dewey Lake and Rustler Formations) were treated as isotropic linear elastic regions. The elastic constants, Young's Modulus and Poisson's ratio, and the mass density used in these regions are listed in Table 4-3.

**Table 4-3. Non-salt properties used in calculations.**

| Material | Young's Modulus | Poisson's Ratio | Density |
|---|---|---|---|
| Dewey Lake | 1.5 x $10^{10}$ Pa ($2.18 \times 10^6$ psi) | 0.25 | 2160 kg/$m^3$ (135 lb/$ft^3$) |
| Rustler | 2.0 x $10^{10}$ Pa ($2.90 \times 10^6$ psi) | 0.30 | 2160 kg/$m^3$ (135 lb/$ft^3$) |

The marker beds 103, 109, and 123, and the Union bedded layer, are described in Jones et al. (1954) as anhydrite layers. From the WIPP analyses, anhydrite has typically been modeled using the soil and foams model (Krieg, 1984). Table 4-4 lists the soil and foam properties used for the anhydrite layers.

**Table 4-4. Anhydrite properties used in calculations (Krieg, 1984).**

| Material | Bulk Modulus | Two*Mu | Coefficients | Density |
|---|---|---|---|---|
| Anhydrite | $8.34 \times 10^{10}$ Pa ($12.1 \times 10^6$ psi) | $5.56 \times 10^{10}$ Pa ($8.07 \times 10^6$ psi) | $A_0=2.338 \times 10^6$<br>$A_1=2.338$<br>$A_2=0$ | 2300 kg/m$^3$ (143.6 lb/ft$^3$) |

The Salado Formation, including the McNutt Potash zone, was modeled as rate-dependent material using a power law creep model. The components of the inelastic creep strain rate for the power law creep model can be described by the following equation:

$$\dot{\varepsilon}_{ij}^{c} = \dot{\varepsilon}_{eq}^{c} N_{ij}$$

where

$$\sigma_{eq} = \text{ von Mises equivalent stress } = \sqrt{3J_2} = \sqrt{\frac{3}{2} S_{ij} S_{ij}} \quad ,$$

$$S_{ij} = \text{ components of the deviatoric stress tensor } = S_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij} \quad ,.$$

$$\dot{\varepsilon}_{eq}^{c} = \text{ equivalent creep strain rate } = Ae^{-Q/RT}\sigma_{eq}^{N}$$

$$N_{ij} = \text{ gradient of creep potential } = \frac{\partial \sigma_{eq}}{\partial \sigma_{ij}} = \frac{3S_{ij}}{2\sigma_{eq}} \quad ,$$

$$\dot{\varepsilon}_{ij}^{c} = \text{ components of creep strain rate } = Ae^{-Q/RT}\sigma_{eq}^{N}\frac{3S_{ij}}{2\sigma_{eq}} \quad .$$

The mechanical properties used for the salt (and potash) material are shown in Tables 4-5 and 4-6. The salt mechanical and creep properties were also used for the marker beds designated as polyhalite. The creep model representing the salt also incorporates a temperature effect through the exponential term, $e^{-Q/RT}$. A linear thermal gradient of $T_{grad}$ along with a reference temperature of $T_{ref}$ and corresponding reference depth of $y_{ref}$ was employed to specify the temperature profile in the Salado Formation. The values of the thermal parameters are given in Table 4-7. The temperatures were treated as *time independent* variables in these analyses ($T = f(y)$).

**Table 4-5. Salt/Potash properties used in calculations.**

| Material | Young's Modulus | Poisson's Ratio | Density |
|---|---|---|---|
| Salt/Potash | $3.1 \times 10^{10}$ Pa ($4.50 \times 10^6$ psi) | 0.25 | 2160 kg/m$^3$ (135 lb/ft$^3$) |

**Table 4-6. Secondary creep properties used in calculations.**

| Material | Structure Factor (A) | Stress Exponent (N) |
|---|---|---|
| Salt/Potash | $4.48 \times 10^{-38}$ $(Pa^N \cdot sec)^{-1}$ | 5.0 |

**Table 4-7. Thermal input used in calculations.**

| Material | Reference Depth( $y_{ref}$) | Reference Temperature ($T_{ref}$) | Gradient($T_{grad}$) | Q/R |
|---|---|---|---|---|
| Salt/Potash | -650 m (-2132.6 ft) | 300.15 K (27C) | 0.01 K/ m | 5033 K |

Note: R is the universal gas constant = 1.987 cal/K-mole and Q is an experimental constant = 10000 cal/mole

Slip is defined as the relative displacement between points on opposite sides of a contact interface between bedding layers. For computational analyses, slip is defined as the relative displacement between slave nodes on the lower surface relative to master nodes on the upper surface. In the numerical models, the slip interfaces or contact surfaces were defined by an upper and lower surface. The regions were discretized such that the master and slave nodes have the same coordinates at the beginning of the simulation. Positive slip occurs when a slave node on the lower surface moves to the right relative to the master node on the top surface. Negative slip occurs when a slave node on the lower surface moves to the left relative to the corresponding master node on the top surface. According to the Coulomb friction model used in these simulations, the maximum allowable shear stress is linearly dependent on the normal stress acting at the point. Slip occurs when the shear stress on the interface equals the allowable shear stress. JAS3D uses an iterative procedure to ensure that all interface nodes satisfy the frictional constraints of the Coulomb model as well as satisfying the equilibrium conditions for the internal and external forces at the end of a load step. Since gravity stresses are included in these calculations the normal stresses acting on the interfaces are greater on the lower marker beds than the upper ones. Beyond the boundaries of the mined region the amount of slip that would be expected would be lower on the deeper marker beds because of the increased normal stresses at those locations.

In the numerical models developed by Arguello et al., eleven slip interfaces, corresponding to the locations of the marker beds, were included in these analyses. All slip interfaces were modeled with a constant coefficient of friction of 0.2. This value of friction coefficient is, again, consistent with that used in the treatment of marker beds in the numerical models that were used for validation against experimental room data for the WIPP (Munson and DeVries, 1990; Munson et. al, 1990; Munson, 1997). The interfaces were not allowed to separate. For future analyses, the computational mesh has been modified to include the marker beds as distinct layers of anhydrite or polyhalite with finite thickness to allow for calculation of stress changes which may affect porosity. The marker bed interfaces still include contact surfaces to allow for frictional slip.

The 3D wellbore model, examines the resulting impacts from the global mine excavation model on a wellbore casing (or casings). A vertical slice through a representative wellbore is shown schematically in Figure 4-8. The model includes steel casing(s); cement surrounding the casing(s); and formation rock around everything. Displacement boundary conditions arising from slippage along the interbeds in the global mine excavation model are imposed on the boundaries of the Wellbore Model to simulate shearing and parting along a bedding plane cutting through the well axis. The bedding is treated as a "slip surface" at the top or bottom of a layer. The results of this model are used to evaluate the potential for casing and cement damage, and to assess the state of stress in the surrounding formation rock. The improved model will use the wellbore configuration shown in Figure 3-3 for model development.

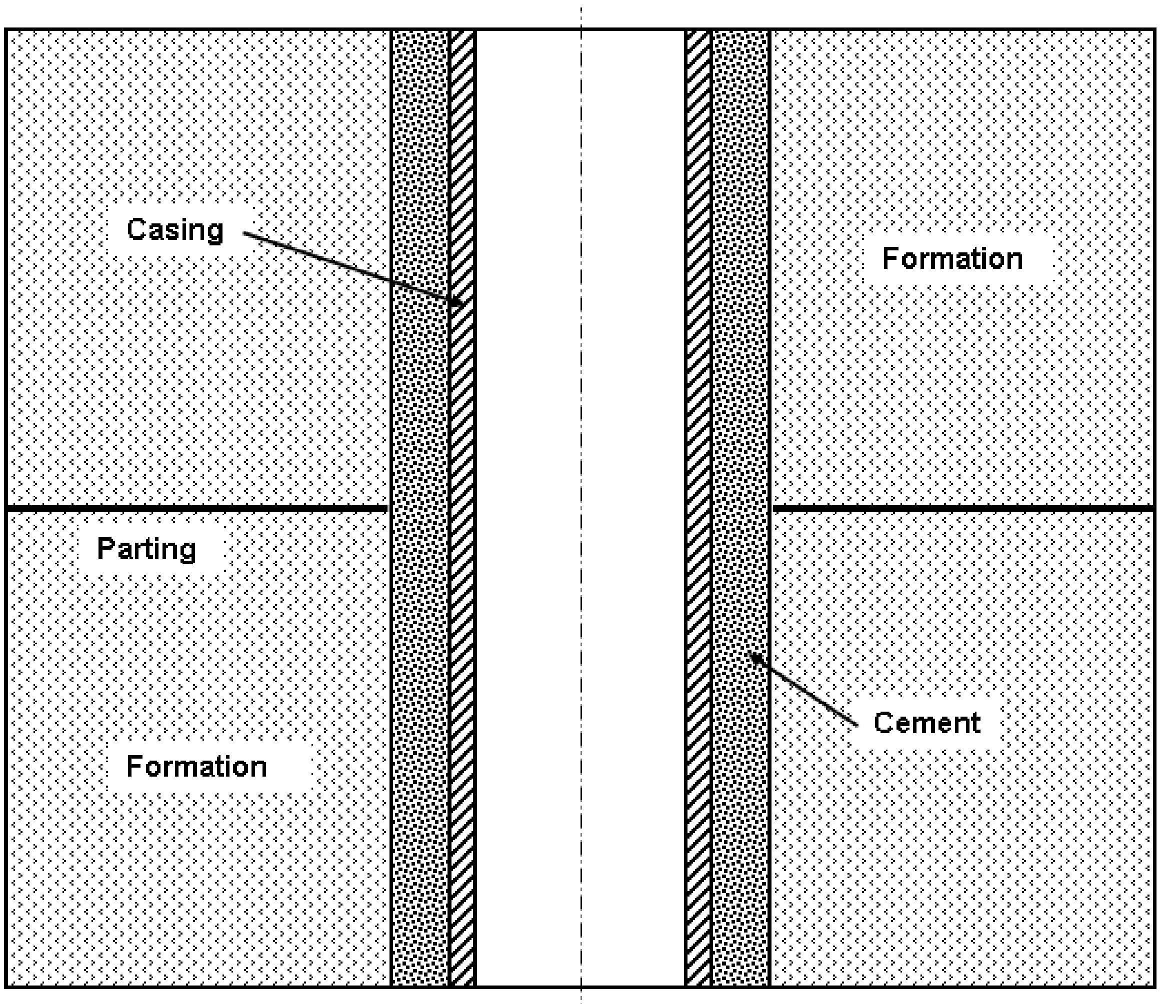



**Figure 4-8. Schematic of wellbore model (Arguello et al., 2009).**

The three materials comprising the wellbore configuration, namely the steel, cement, and surrounding rock were modeled numerically in Arguello et al. (2009) using three different constitutive models. The K55 steel was modeled with an elastic-plastic constitutive model. The cement was modeled with the Sandia Geomodel, a generalized cap-plasticity model. The surrounding formation was modeled as an elastic material. The elastic-plastic model used here is based on a standard von Mises type yield condition and uses combined kinematic and isotropic hardening, in the most general case. For purposes of the calculations herein, hardening was not allowed, thereby rendering the model to be elastic perfectly-plastic. Table 4-8 shows the K55 steel material parameters used in the calculations for the elastic-plastic model.

**Table 4-8. Elastic-Plastic Material Model parameters used for K55 Steel**

| Young's Modulus, E | Poisson's Ratio, ν | Yield Stress | β (Isotropic/Kinematic Hardening Parameter) | Hardening Modulus |
|---|---|---|---|---|
| $1.999 \times 10^{11}$ Pa ($29.0 \times 10^{6}$ psi) | 0.33 | $4.277 \times 10^{8}$ Pa (62,000 psi) | 0.5 | 0.0 |

The overarching goal of the Sandia Geomodel developed by Fossum and Brannon is to provide a unified general-purpose constitutive model that can be used for any geological or rock-like material that is predictive over a wide range of porosities and strain rates. The details of the Sandia Geomodel, which is implemented in JAS3D, are provided in Fossum and Brannon (2004). As it is a unified theory, the Sandia Geomodel can simultaneously model multiple failure mechanisms or it can duplicate simpler idealized yield models such as classic Von Mises plasticity and Mohr-Coulomb failure (by using only a small subset of the available parameters). For natural geomaterials, as well as for some engineered materials (e.g., ceramics and concretes), common features are the presence of microscale flaws, such as porosity, and networks of microcracks. The former (microscale flaws) permit inelasticity even in purely hydrostatic loading. The latter (networks of microcracks) lead to low strength in the absence of confining pressure and to noticeable nonlinear elasticity, rate-sensitivity, and differences in material deformation under triaxial extension when compared to triaxial compression. Simpler models that do not include this phenomenology are incapable of accurately predicting the response of rock-like materials such as the cement.

Because of lack of actual data on Lite/Class C cement to generate the appropriate parameters for the Sandia Geomodel, the cement material response in the calculations was modeled using the parameters given in Fossum and Brannon (2004), Appendix B for "Conventional Strength Portland Concrete." Table 4-9 shows the material parameters for the Sandia Geomodel used in the calculations to simulate the cement. The parameters B0 and G0 given in the table correspond to the elastic bulk and shear modulus, respectively. These values convert to a corresponding Young's modulus, E, of 18.405 GPa ($2.67 \times 10^{6}$ psi) and Poisson's ratio, ν, of 0.22, which is on the order of the elastic properties for a Lite/Class C cement ($E=3.8 \times 10^{6}$ psi and $\nu=0.19$). While it is recognized that the simulant contains aggregate and is a different material than Lite/Class C cement, from a purely elastic response point-of-view, the Sandia Geomodel and parameters used should adequately simulate the cement. The post-yield response of this representation for the cement is dictated by the remaining parameters below as determined for a Conventional Strength Portland Concrete with an initial porosity of ~6.5%. The unconfined compressive strength for this concrete is 27.6 MPa (4,000 psi). Cement mechanical properties have been identified as one of the more important sets of parameters, and further discussion of this issue in Sections 4.2.4 and 4.4.

The surrounding material was assumed to be within the Salado Formation; hence the material was modeled as salt. Because the slippage at the interbeds in the global mine excavation model occurs over a relatively short time-frame (less than a year), the material was modeled as a time-independent elastic material. The elastic parameters used for the salt were E=31.0 GPa ($4.495 \times 10^6$ psi) and $\nu$=0.25, as recommended in Krieg (1984).

**Table 4-9. Sandia Geomodel parameters used for Class C cement.**

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| B0 | $1.0954 \times 10^{10}$ Pa ($1.59 \times 10^6$ psi) | A1 | $4.26455 \times 10^8$ Pa (61,900 psi) | CTPS | $1.0 \times 10^6$ Pa (145 psi) |
| B1 | 0.0 Pa | A2 | $7.51 \times 10^{-10}$ $Pa^{-1}$ ($5.18 \times 10^{-6}$ $psi^{-1}$) | T1 | 0.0 s |
| B2 | 0.0 Pa | A3 | $4.19116 \times 10^8$ Pa (60,800 psi) | T2 | 0.0 $s^{-1}$ |
| B3 | 0.0 Pa | A4 | $1.0 \times 10^{-10}$ Radians | T3 | 0.0 |
| B4 | 0.0 | P0 | $-1.95520 \times 10^8$ Pa (-28,400 psi) | T4 | 0.0 $s^{-1}$ |
| G0 | $7.5434 \times 10^9$ Pa ($1.09 \times 10^6$ psi) | P1 | $1.2354 \times 10^{-9}$ $Pa^{-1}$ ($8.52 \times 10^{-6}$ $psi^{-1}$) | T5 | 0.0 Pa |
| G1 | 0.0 | P2 | 0.0 $Pa^{-2}$ | T6 | 0.0 s |
| G2 | 0.0 $Pa^{-1}$ | P3 | 0.065714 | T7 | 0.0 $Pa^{-1}$ |
| G3 | 0.0 Pa | CR | 12.0 | J3TYPE | 3 |
| G4 | 0.0 | RK | 1.0 | A2PF | 0.0 $Pa^{-1}$ |
| RJS | 0.0 m | RN | 0.0 Pa | A4PF | 0.0 Rads |

| | | | | | |
|---|---|---|---|---|---|
| RKS | 0.0 Pa/m | HC | 0.0 Pa | CRPF | 0.0 |
| RKN | 0.0 Pa/m | CTI1 | $3.0 \times 10^6$ Pa (435 psi) | RKPF | 0.0 |
| | | | | SUBX | 0.0 |

One of the important aspects of a risk assessment model is the opportunity to enhance the computational model with greater complexity as more is learned about the site. Several potential features have been identified that may be included in future iterations of the geomechanical model. Some of these features are natural extensions of the existing model, such as a 3D rendering of the mine, and inclusion of cased boreholes in the global mine excavation model. Other features have been suggested by the stakeholders in response to the Arguello study or in stakeholder meeting moderated by BLM. The list of potential future enhancements to the geomechanical model includes, and is not limited to, the following:

- Create a 3D computational model with the mine, marker beds, and full rendering of wellbore construction.
- Include failure criteria for both threaded and welded joints in casings.
- Include additional marker beds below the mine depth.
- Include known natural features such as faults, fractures, voids, etc.
- Include modeling of fracturing due to high gas pressures (Wawersik and Stone, 1989).
- Include modeling to consider recommendations for mitigation (e.g., regarding mining toward open holes, placement of pipe couples, etc.).
- Casing design evaluation.

### *4.2.4 Required Geomechanical Parameters*

Many types of parameters are required to conduct a full-scale risk assessment analysis. The parameters take many forms: properties values (both single values and ranges of values), operation and design specifications, geological material information, and specific safety and failure threshold values. These types of parameters generally fall into three categories which define how they will be used:

1. Model parameters – These are the data and parameters that will be used to build the computational mesh and model. They include geological/lithological data (including stratigraphic designations and thicknesses), hydrological and mechanical material properties for the geological media, well design and operation data (casing arrangement,

operational pressures, date of construction, etc.), and mine design and operations data (dimensions, date of construction, etc.).

2. Threshold parameters – These parameters are used to define stress, strain, or flow states that result in a failure or safety criterion being exceeded. Such parameters include failure strength in tension, shear, or bending of casing as a function of diameter (for continuous and jointed sections), designated safety standards for methane concentration in a mine environment, and hydrofracture pressure of salt as a function of depth.

3. Verification parameters – These field data are used to verify the results of the model calculations, to provide confidence in their results. Measured surface subsidence in the mined region, and measured slip in boreholes between bedded planes are two examples of these data.

Table 4-10 presents an extensive list of parameters required to analyze the geomechanical influences on potential gas migration. The parameters are grouped by the expected source from which the data will be obtained. Many of these data require direct input from the oil/gas and potash stakeholders, to use values or ranges of values that represent established industry standards. To illustrate how parameters such as these will be used in the geomechanical calculations, two examples have been chosen. These examples include gas pressure histories in active wells, and the data required to validate the effective friction coefficient between the interfaces of marker beds and salt/potash strata.

**Table 4-10. Required parameters for geomechanical computational analyses.**

| Parameter | Expected data source (as of Feb. 2011) |
|---|---|
| Cement strength (tension, shear, etc.) | Industry standards |
| Qualitative probability of leak of individual wells or percentage of wellbores in Potash Area based on analysis of well records and engineering judgment consensus | NMOCD records, oil/gas stakeholders |
| Post-installation deformation of well string due to geologic stress regime or other factors | Petroleum stakeholders |
| Constructed deviation of well string (typical, extremes) | Petroleum stakeholders |
| Frequency of threaded vs. welded casing connections | Petroleum stakeholders |
| Gas pressure history (typical, extreme) for wells in all producing reservoirs (also an input to hydrological analysis) | Petroleum stakeholders |
| Hydrofracture pressure of rock in marker beds (and other lithologies) | Petroleum stakeholders |
| Location and characteristics of oil bearing zones in Potash Area; determine potential effect on gas migration pathways | Petroleum stakeholders |

| | |
|---|---|
| Pressure used for injection wells | Petroleum stakeholders |
| Well abandonment method (plug locations, cement and/or CIBPs, casing cut, presence of open space or annuli) | Petroleum stakeholders |
| Representative well configurations for various production types (oil, gas, dual, single, etc) with casing and cement specifications | Petroleum stakeholders |
| Well pressure (FTP and SIP) histories (operation histories; typical, extreme) | Petroleum stakeholders |
| Cement strength (tension, shear, etc.) | Industry standards |
| Performance criteria for acceptable level of methane gas entering mine | Potash stakeholders |
| Mining excavation rate | Potash stakeholders |
| Mining methods (long wall v. room-pillar, mined height) | Potash stakeholders |
| Elastic collapse pressure of steel casing (function of diameter) | SNL lab data, API standards (API, 2008; Lyons and Plisga, 2005; others) |
| Failure bending stress of K55 steel casing (function of diameter) | SNL lab data, API standards |
| Failure bending stress of threaded coupling of K55 steel casing (function of diameter) | SNL lab data, API standards |
| Failure bending stress of welded coupling of K55 steel casing (function of diameter) | SNL lab data, API standards |
| Failure shear stress of K55 steel casing (function of diameter) | SNL lab data, API standards |
| Failure shear stress of threaded coupling of K55 steel casing (function of diameter) | SNL lab data, API standards |
| Failure shear stress of welded coupling of K55 steel casing (function of diameter) | SNL lab data, API standards |
| Failure threshold, longitudinal strain in casings | SNL lab data, API standards |
| Plastic collapse pressure of steel casing (function of diameter) | SNL lab data, API standards |
| FEPs - specific to scenarios and issues for BLM RA modeling | SNL, Petroleum, Potash |
| FEPs - WIPP FEPs to use as framework for developing gas migration FEPs | WIPP records |
| Friction coefficient (effective) along marker beds | WIPP records |
| Geologic heterogeneities (damaged regions, reef, etc.) | WIPP records |
| Marker bed composition, for material mechanical properties (each one) | WIPP records |
| Marker bed permeability, including fractures (each one) | WIPP records |
| Marker bed porosity (each one) | WIPP records |

| | |
|---|---|
| Marker bed thickness (each one) | WIPP records |
| Pore pressure of geologic layers | WIPP records |
| Porosity of geologic layers | WIPP records |
| Potash creep properties (use salt properties) | WIPP records |
| Potash mech. properties (E, ν, strength) (use salt properties) | WIPP records |
| Potash permeability (use salt properties) | WIPP records |
| Potash porosity (use salt properties) | WIPP records |
| Salt creep properties | WIPP records |
| Salt mechanical properties (E, ν, strength) | WIPP records |
| Salt permeability | WIPP records |
| Salt porosity | WIPP records |
| Well drilling data in WIPP footprint | WIPP records (Dave Hughes, WTS) |
| Slip displacement data along marker beds (use to validate model assumptions) | WIPP records, field data |
| Relationship, dilatant stress to porosity/perm changes, salt and potash | WIPP records, geomechanics literature |
| Relationship, stress change to porosity/perm change, clay and anhydrite in marker beds | WIPP records, geomechanics literature |
| Surface subsidence data in vicinity of mine | WIPP records, potash stakeholders |

The pressure inside a well casing provides two important boundary conditions for the analysis of potential gas migration:

- for the calculation of stresses in a well casing,
- as an interior pressure to counteract the external stresses on the casing due to subsidence, slip and creep; and
- in the event of a gas leak, as the source pressure that could drive the gas into the surrounding formation (depending on the pore pressure/gas pressure ratio), or through the open uncemented annuli to other horizontal flow pathways or to the surface.

Figure 4-9 presents data from five oil wells constructed in the Delaware Basin since 2008; these wells produce a combination of oil, gas, and water. The FTP is measured at the wellhead, whereas the bottom hole pressure (BHP) is measured by a pump located at the bottom of the hole. These particular wells are vertical wells until they reach the oil-bearing formation, and then are kicked off to a near-horizontal orientation. Because these well produce a mixture of gas, oil, and water, the pressure difference between the bottom of the hole and the wellhead is probably greater than would be the case for a gas-only well. Using curves such as these, the fluid pressure at a given location within the wellbore can be estimated as a function of both depth and time, and that function can be used as a boundary condition for one of two types of calculations described above.

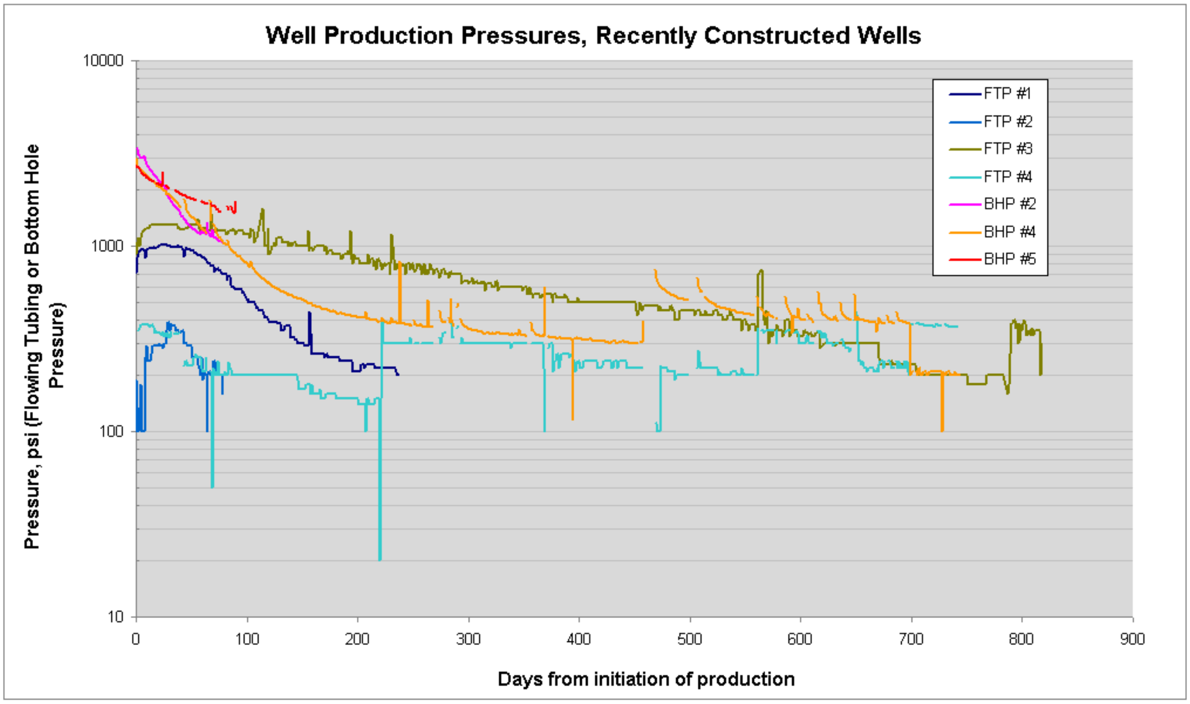



**Figure 4-9. Well pressure histories of recently constructed wells in the Delaware Basin.**

A second set of parameters includes measured subsidence and slip behavior, which will be used to compare to predicted results and either provide validation of the model or suggest necessary changes to the model. Subsidence, tilt, horizontal displacement, curvature and strain are the subsidence parameters normally used to define the extent of the surface movements that will occur as mining proceeds and generally form the basis for the assessment of the impacts of subsidence on surface infrastructure (Mine Subsidence Engineering Consultants, 2007). Measured slip in boreholes provides additional information used to calculate an effective friction coefficient between bedded planes. To emphasize the importance of obtaining such data, Figures 4-10 and 4-11 are re-printed from Arguello et al. (2009), showing the effect of friction coefficient on maximum interface slip as a function of distance from the mine face, and on mine closure as a function of time, respectively. The effect of slip on the shear stresses in wellbore casings has been identified as one of the most important processes for gas migration. This fact emphasizes the need for subsidence and slip data for model development and validation. There are existing WIPP subsidence data available, and other data from local mining would improve the relevance and applicability of the outputs.

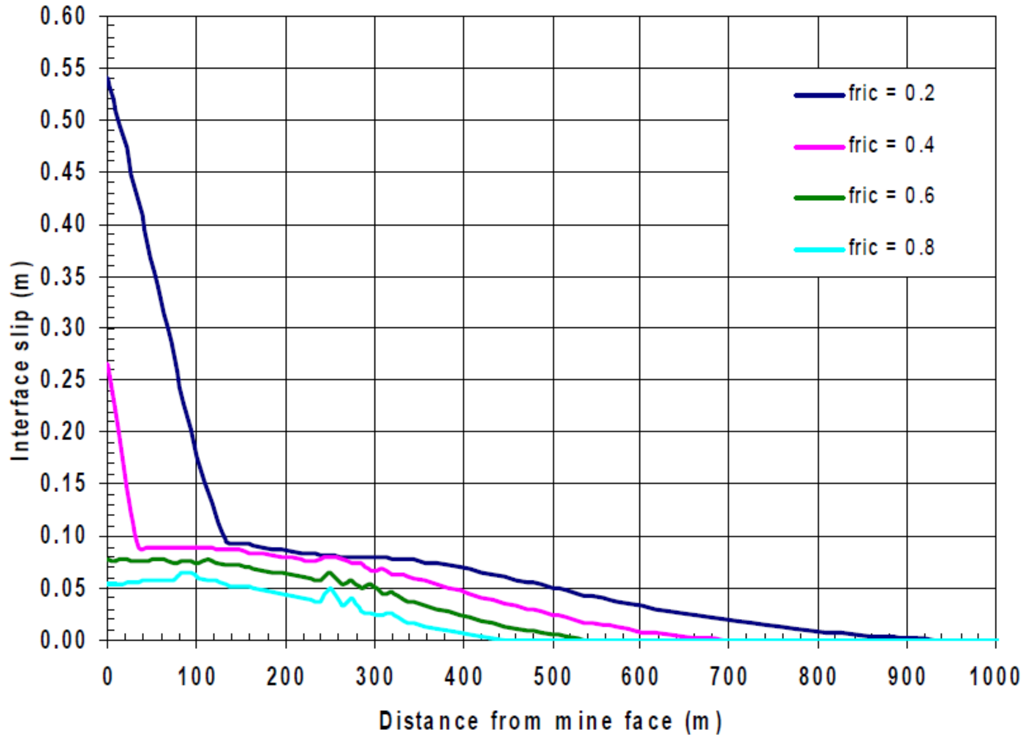



**Figure 4-10. Effect of friction coefficient on slip envelope: mining towards well (1000 ft deep mine; 1 mile, excavation; 1 mile/year, excavation rate; from Arguello et al., 2009).**

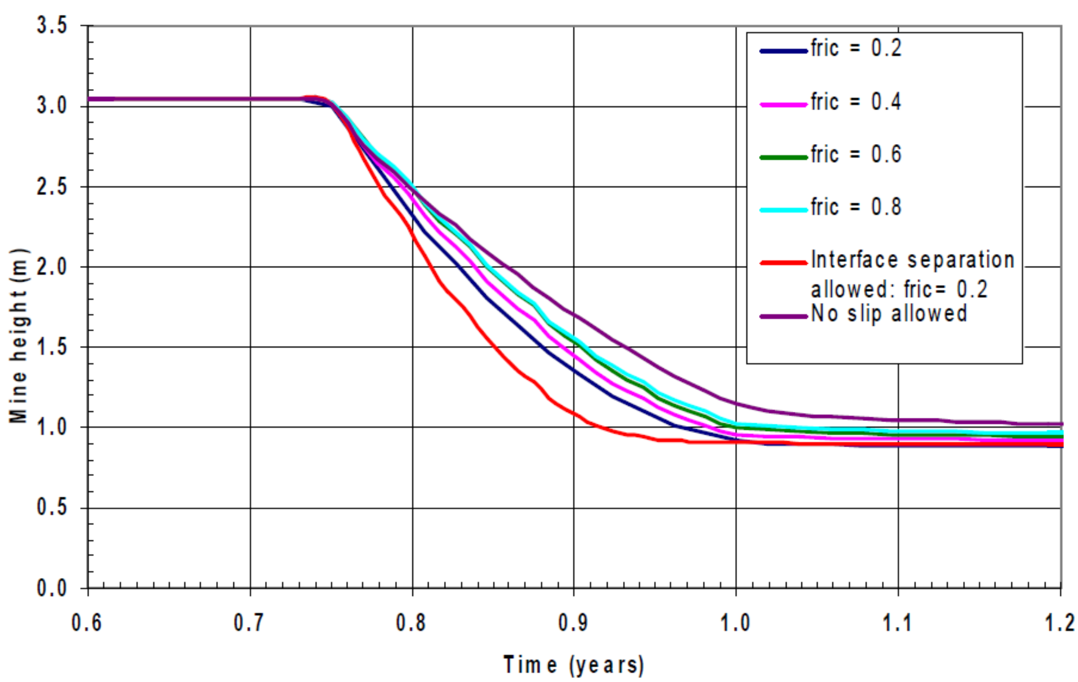



**Figure 4-11. Effect of interface properties on mine closure for 304.8 m (1000 ft) mine (Arguello et al., 2009).**

## 4.3 Geomechanical Model Outputs

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). By convention, tensile normal stresses are positive, and compressive normal stresses are negative, hence the sign nomenclature in the following equations. The dilatant criterion chosen here is the equation typically used from Van Sambeek et al. (1993),

$$\sqrt{J_2} = -0.27 I_1$$

The Van Sambeek damage criterion defines a linear relationship between $I_1$ and $\sqrt{J_2}$, and such linear relationships have been established from many suites of laboratory tests on WIPP, Strategic Petroleum Reserve (SPR), and other salt samples. This criterion was applied during post-processing of the analyses. A damage factor (safety factor) index was created ($SF_{VS}$) by normalizing $I_1$ by the given criterion:

$$SF_{VS} = \frac{-0.27 I_1}{\sqrt{J_2}}$$

Several earlier publications define that the Van Sambeek damage factor $SF_{VS}$ indicates damage when $SF_{VS}$<1. In previous studies, values of $SF_{VS}$<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 4-12 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 eight times, from 0.25 to 25 years after initiation of mine excavation. Damage factor values less than 1.0 (onset of microfracturing) are plotted in red, and values less than 1.5 are in yellow. 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. Over time, as the stresses in the salt and potash equilibrate toward hydrostatic values, the damage factor increases, indicating a retreat from potential microfracturing, and perhaps the onset of fracture healing. Compare Figure 4-12 to Figure 4-4, 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 intuitively 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 4-13 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.

There are currently sparse available data that relate the change in porosity or permeability in salt or potash to a change in stress conditions. Permeability changes in potash would first require the attainment of deviatoric stresses that exceed the dilatant condition. There should also be a time component to the function; greater time at high deviatoric stresses may allow for larger permeabilities or larger regions of enhanced permeability. 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 (Stormont et al., 1991; Domski et al., 1996). 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.

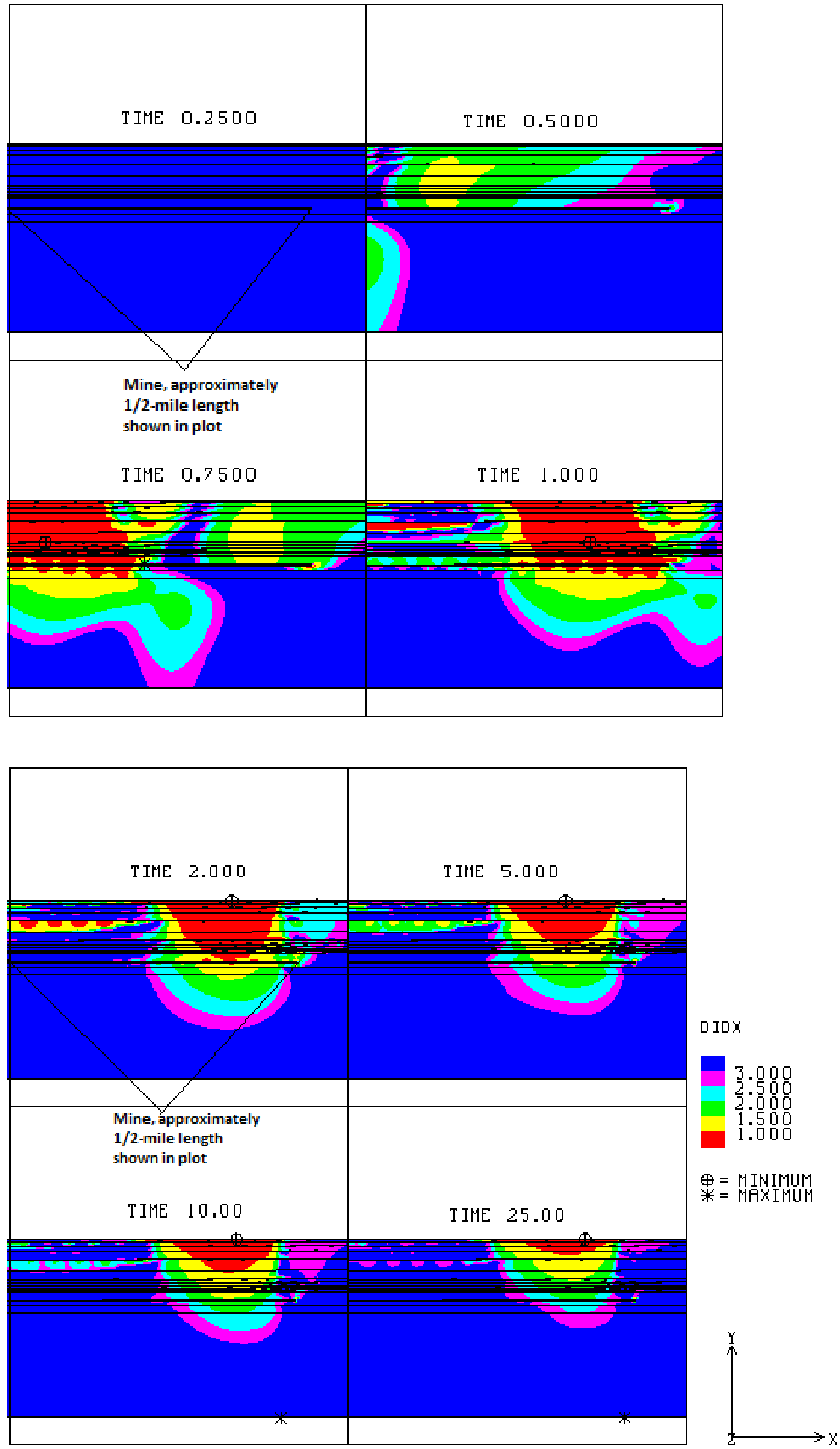
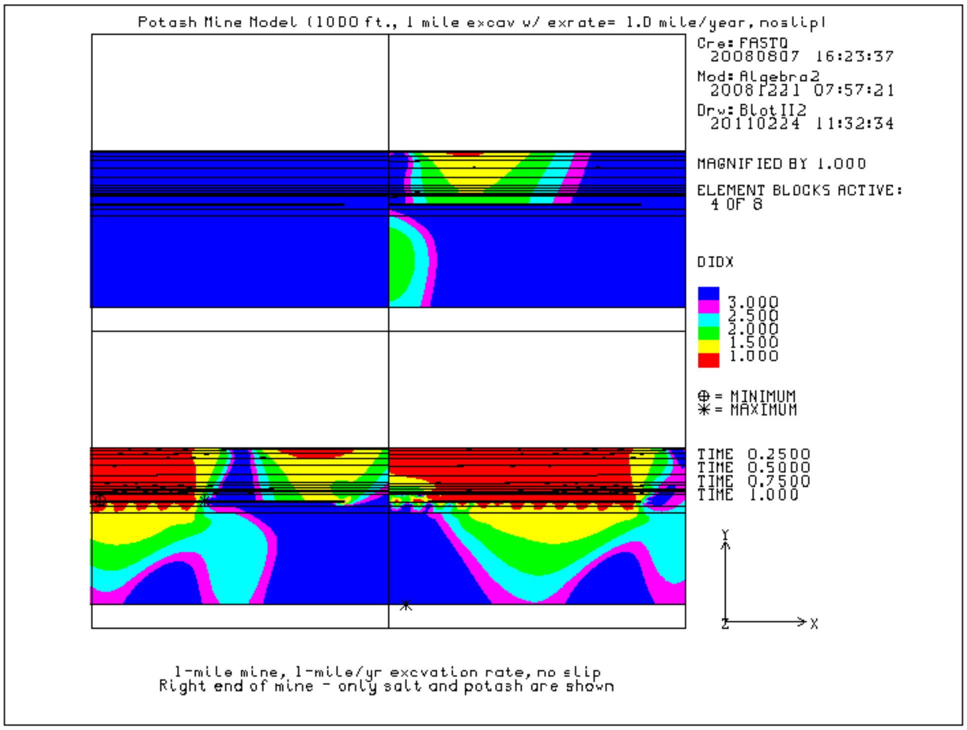



**Figure 4-12. Dilatant damage factor for mine 1000-ft deep, 1-mile wide, 1 mile/year excavation rate, marker bed friction coefficient = 0.2 (Times from 0.25 through 25 years).**



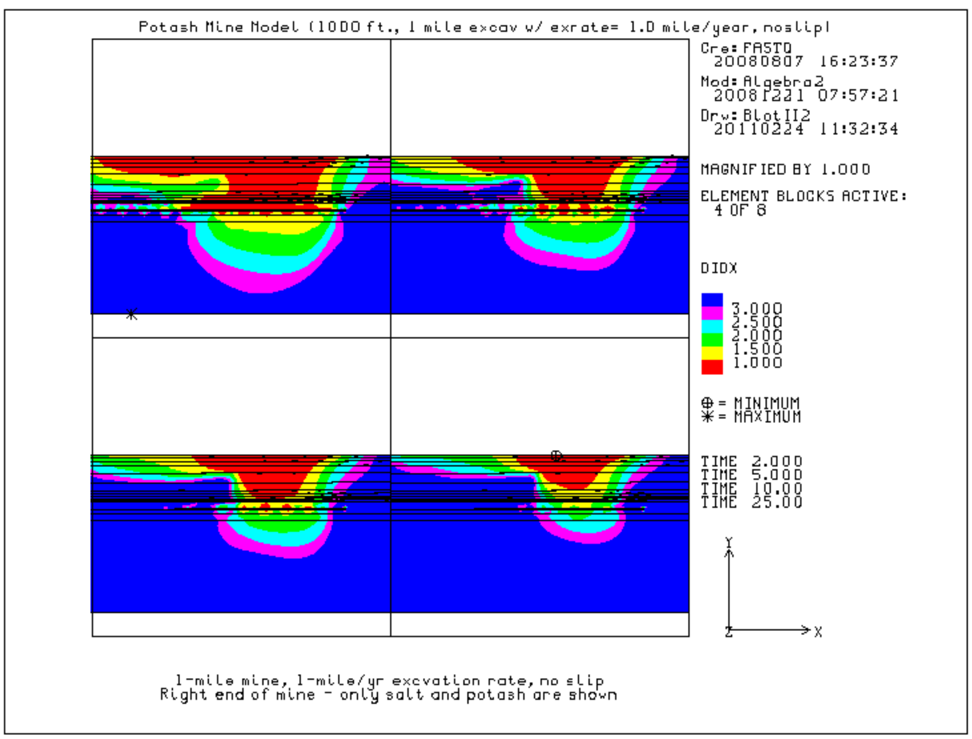




**Figure 4-13. Dilatant damage factor for mine 1000-ft deep, 1-mile wide, 1 mile/year excavation rate, no slip between marker beds (Times 0.25 through 25 years).**

Earlier, Figures 4-10 presented predictions of a slip envelope as a function of interface friction coefficient. For all the curves on that plot, 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. Figures 4-14 and 4-15 plot the horizontal extent of 1-mm and 5-mm slip, respectively, 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 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.

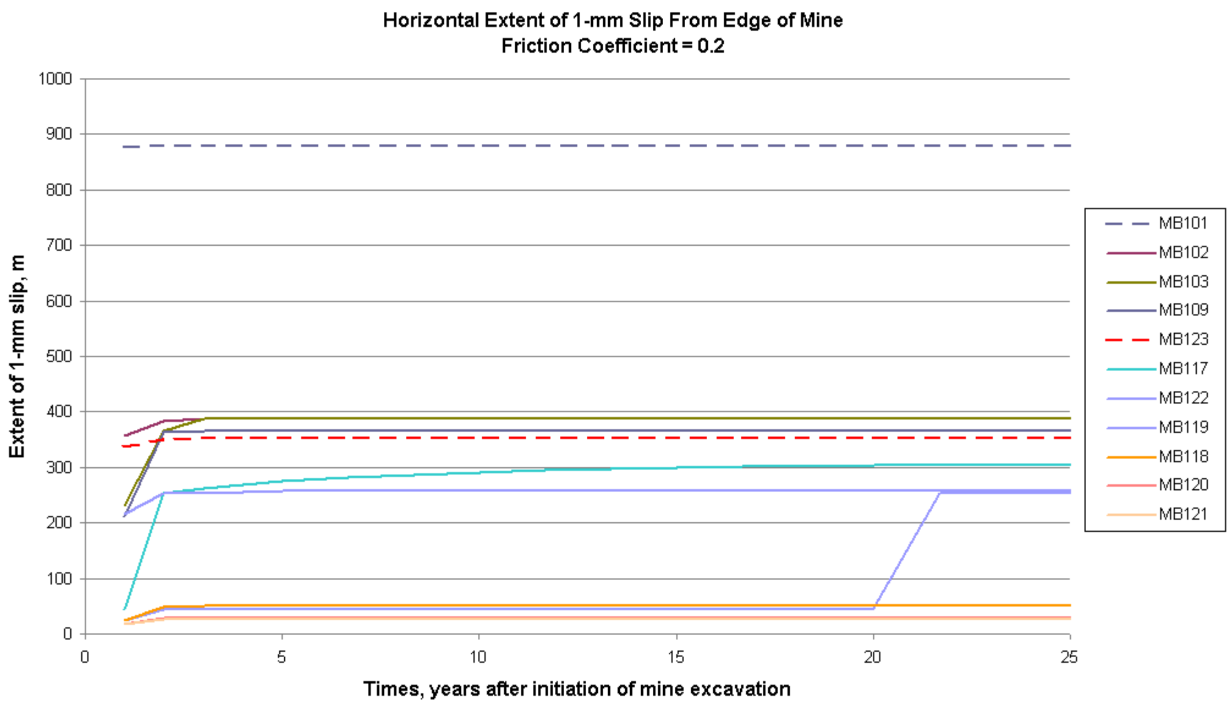



**Figure 4-14. Horizontal extent of 1-mm slip from edge of the mine, friction coefficient = 0.2 (Derived from calculations in Arguello et al., 2009).**

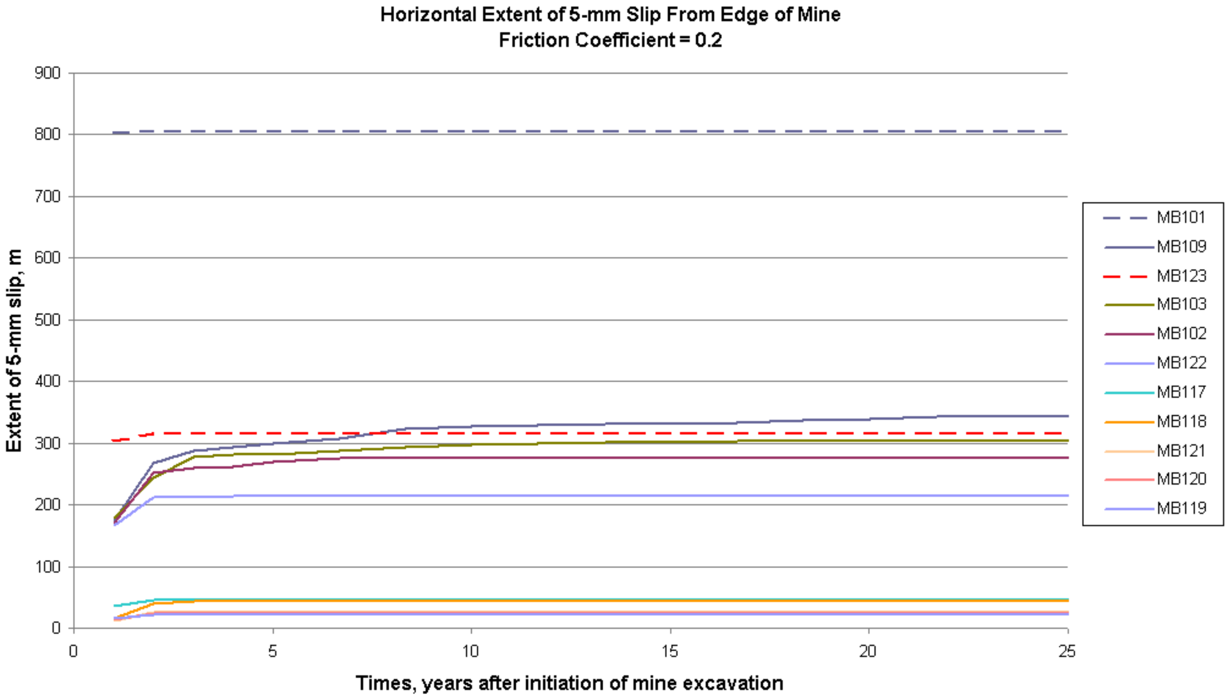



**Figure 4-15. Horizontal extent of 5-mm slip from edge of the mine, friction coefficient = 0.2 (Derived from calculations in Arguello et al., 2009).**

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, resulting in loss of product. 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 2500 to 5000 psi (Thorton and Lew, 1983). 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 and Ehgartner, 2009). This threshold for steel casings has been used to identify casing failure at specific wells with reasonable accuracy.

Figure 4-16 shows the development of axial strains along wellbores within the mined region (again, using the base case calculations from Arguello et al.). 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 ("red" values between 1.2 to 1.6, "white" value greater than 1.6 millistrains). 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.

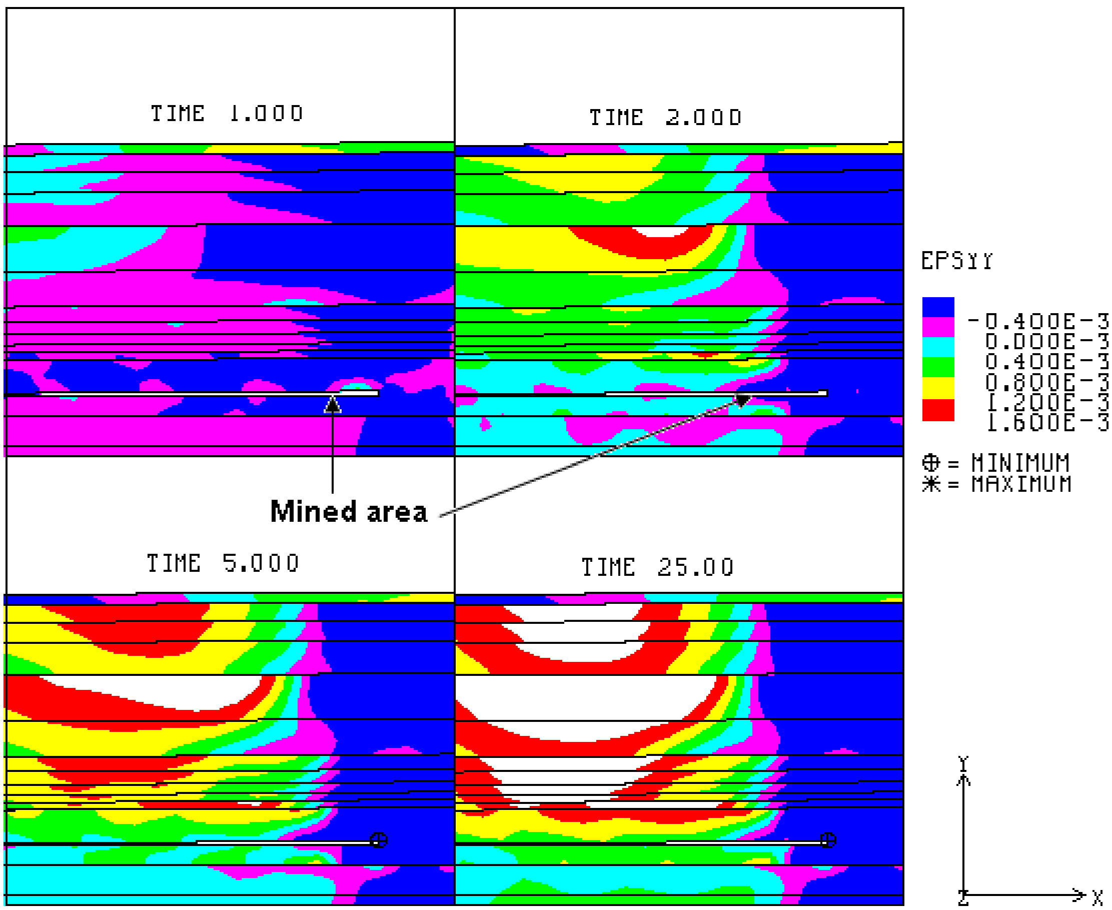



**Figure 4-16. Vertical strain over the edge of the mine; casing yield threshold at 1.6 millistrains (Derived from calculations in Arguello et al., 2009).**

## 4.4 Other Geomechanical Model Topics

In the development of the geomechanical portion of this RA model, the authors researched the existing literature and found numerous published reports of processes and studies relevant to the study of the Secretary's Potash Area. These reports include analyses of relevant geologic processes such as hydrofracturing of salt/potash, mechanical properties of potash, mechanical properties of cement used in wellbores, analysis of wellbore leakage, and other risk assessment analyses performed for analog sites. There is a wealth of information in these reports, and they will be useful for the further development of the current model. The reports are summarized below as an annotated bibliography.

**Hydrofracturing in salt/potash**

Bedded salt formations generally include non-salt interbeds and clay partings. For this reason, experiments on interbed fracturing in the WIPP may be of interest. Concerns about gas-driven fracturing in salt and potash formations prompted several sets of analyses in the past. Several of these studies were conducted in conjunction for WIPP. Wawersik and Stone (1989) characterized in situ stress conditions using hydraulic fracturing and modeling. Wawersik et al. (1995) estimated the conditions under which gas pressure in the WIPP disposal rooms would initiate and advance fracturing in nearby anhydrite interbeds MB 139 and 140. Weatherby et al. (1991) studied the structural response of a WIPP disposal room to internal gas generation from the embedded waste, and Arguello et al. (1991) investigated the corresponding effect on pre-existing fractures. In addition to the WIPP studies, a field experiment tested a proposal for solution mining of potash in the Secretary's Potash Area (Davis and Shock, 1970). Field testers used four boreholes in a triangle/centroid arrangement, and discovered that water at pressures of 300 psi over lithostatic pressure created fractures which propagated to distance of 200 feet in 5-10 minutes. This study confirms the need to investigate hydraulic fracture propagation from a well experiencing casing fracture.

**Cement properties**

Construction and mechanical properties of cement were discussed to some extent in Section 3. For the initial analyses to be performed under the RA model, the Class C cement properties used in Arguello et al. (2009) will be used. However, there exists extensive literature on the range and variability of mechanical properties for cements used in a salt environment. Heathman and Vargo (2006) provide an informative summary of the differences between salt and non-salt cements. Bhatty and Tennis (2008) is a great general reference on all things related to Portland cement. Jo (2008) and Gray et al. (2009) performed extensive analytical and numerical analyses on the behavior of casings and cements in the wellbore environment. Finally, Melvin Harris performed a survey study of the mechanical, chemical, and engineering properties of the cements that have been used in the Delaware Basin wellbores. His work, performed during his undergraduate summer student internship at SNL, is included in Appendix B.

**Wellbore leakage**

Wellbore leakage has also been discussed in some detail in Section 3. There are several factors affecting wellbore leakage that are not necessarily geomechanical phenomena, such as cement degradation, corrosion of the casings, incomplete emplacement or setting of the cement, and so on. The numerous Bachu and Watson papers in the references address leakage in oil and gas well in Alberta, Canada, and provide a model for statistical consideration of well leakage rates under normal operating conditions. Furthermore, as illustrated in Figure 4-1, Gasda et al. (2004) further examine the processes affecting wellbore integrity and provide a methodology for spatial characterization of these phenomena.

Among other papers investigating wellbore leakage, Bourgoyne et al. (2000) performed an extensive summary and analysis of failure due to sustained casing pressure in the Outer Continental Shelf. Huerta (2009) continued with an investigation of sustained casing pressure damage as affected by geomechanics and chemistry. An SPE publication from the University of Texas also investigates wellbore pathway permeability and additional modeling approaches in relation to carbon sequestration (Tao et al., 2010).

**Analog studies**

The problem of gas migration from wells to mines in the Secretary's Potash Area has been investigated before in Hazlett and Teufel (2000); they concluded that there would be no migration of gas into the active mines. A review of this study presented in Van Sambeek (2005) listed several technical arguments suggesting that gas migration was a significant possibility. These reports provide a background for the current RA work.

Sites similar to the Secretary's Potash Area have been investigated using similar risk assessment methodologies. Recently a series of risk assessment analyses of Trona mining in the Green River Basin, Wyoming (Fugro-McClelland Marine Geosciences, Inc., 1997 and 2002) have been performed. Similar studies look at modeling reservoir compaction, which is similar to the mine collapse model problem (Dusseault and Rothenburg 2002). The methodologies for geomechanical and risk assessment analyses in these studies were very detailed, and provide an excellent example of how to build a site-specific RA model for a similar location like the Secretary's Potash Area.

# 5 RISK ASSESSMENT GEOLOGY/HYDROLOGY ANALYSIS

This section describes the geology/hydrology of the WIPP repository area and Secretary's Potash area, and its relevance to the gas migration study. The section also details numerical modeling of gas flow from a leaky gas well towards the potash mines. Because of the proximity of the mine area to the WIPP site, WIPP literature and software were adopted for this study.

## 5.1 Objectives of Geology/Hydrology Study

The geology/hydrology study investigates the potential for gas to migrate from a damaged gas well in the vicinity of the Carlsbad potash mines to mine openings through transmissive formations. The objectives are to:

- Study the geology/hydrology of the area, and investigate potential pathways for gas migration.
- Study pressure and rate history of gas wells in the area.
- Set up a preliminary numerical brine-gas flow model.
- Implement outputs of the geomechanical model in the hydrology (flow) model.
- Identify areas for further study, based on the findings of the preliminary flow model.

## 5.2 FEPs Relevant to the Geology/Hydrology Study

A preliminary identification and categorization of features, events and processes relevant to the geology/hydrology section of the gas migration study has been carried out. The FEPs analysis will provide guidance for the identification of potential FEPs that could impact flow and transport of hydrocarbon fluids from a well towards potash mines. The identification of relevant FEPs helps to prioritize data collection and modeling work. Table 5-1 provides a preliminary listing of FEPs relevant to geology/hydrology.

## 5.3 Geology/Hydrology of the Area and Its Relevance to Gas Migration

Geology/hydrology of the Delaware Basin in southeastern New Mexico has been the subject of numerous petroleum- and WIPP-related studies. An example is the study of the geology of southeastern New Mexico and west Texas by Hills (1984). Swift and Corbet (2000) also provided a complete summary of the geology, hydrology and resources of the area. The Delaware Basin extends from north of Carlsbad, New Mexico, southward into Texas. Most of the economically important sedimentary rocks in the area, including the Salado Formation, were deposited during and after the Permian period (286-245 million years ago). The area is semiarid and sparsely inhabited.

Five rock units were studied for WIPP performance assessment: Castile, Salado, Rustler Formations, Dewey Lake Red Beds and near-surface rocks (see Figure 5-1). These formations are also relevant to the potash, and oil and gas resource areas. At the WIPP site, the Castile

Formation is about 385 m (1263 ft) thick and contains three thick anhydrite units separated by halite layers. The Castile Formation has very low permeability, and well data show that it contains pressurized brine reservoirs. Geochemical studies showed that the most likely source of the brine is ancient (Permian-age) seawater (Popielak et al., 1983).

The Salado Formation is about 600 m (1968 ft) thick at the WIPP site and is divided into three members: lower, McNutt Potash, and upper (Figure 5-1). The McNutt Potash Zone includes 10 ore zones with high concentrations of potassium salts. The lower and upper members remain unnamed. Forty-four anhydrite and marker beds in the Salado have been identified and numbered (Jones, et al., 1960). Hydraulic testing in the Salado in boreholes in the WIPP underground, and laboratory tests on core samples provided quantitative estimates of the hydraulic properties of the Salado halite and anhydrite.

The Rustler Formation is 95 m (312 ft) thick at the WIPP site, and is composed of anhydrite, halite, siltstone and sandstone, and dolomite. The formation is divided into four formally named members and a lower unnamed member (Vine, 1963). These five units are, from bottom to top, the unnamed lower member, the Culebra Dolomite, the Tamarisk, the Magenta Dolomite, and the Forty-niner member. The unnamed lower member is directly above the upper Salado member. The lower portion of the unit contains claystones and sandstones, while the upper part of the unit includes halitic and sulfatic beds within clastics.

The Culebra is a microcrystalline dolomite or dolomitic limestone that ranges in thickness in the WIPP region from 4 to 11.6 m (13 to 38 ft). Extensive testing in the Culebra has provided ample hydraulic data. The Tamarisk is about 36 m (118 ft) thick at the WIPP site, and consists of mostly anhydrite or gypsum with interbedded claystone and siltstone. The thickness of the Tamarisk varies in the region from about 8 m to 84 m (26 to 276 ft). The Tamarisk has extremely low hydraulic conductivity. The Magenta is about 8 m (26 ft) thick at the WIPP site and consists of a fine-grained gypsiferous dolomite. Although, less permeable than the Culebra, the Magenta does produce water in wells. In most locations, the hydraulic conductivity of the Magenta is one to two orders of magnitude less than that of the Culebra. The Forty-niner is about 20 m (66 ft) thick throughout the WIPP area and consists of low-permeability anhydrite and siltstone.

The Dewey Lake consists predominantly of reddish-brown fine sandstone, siltstone, and silty claystone, and is approximately 150 m (49 ft) thick in the center of the WIPP site (Holt and Powers, 1990). The formation is thicker to the east of the WIPP site, in part because western areas were eroded before the overlying Triassic rocks were deposited. The Dewey Lake contains a saturated and permeable zone in the southwestern to south-central portion of the WIPP site and south of the site. Elevation of the water table at the WIPP site is estimated to be 980 m (3214 ft) above mean sea level, approximately 60 m (197 ft) below the land surface (USDOE, 1996).

**Table 5-1 . Preliminary List of FEPs relevant to Geology/Hydrology**

| |
|---|
| 1. Lithology |
| 2. Petrophysical properties (permeability, porosity, rock compressibility, etc. |
| 3. Formation pressure |
| 4. Structural Features (faults, fractures, voids and other natural features) |
| 5. Hydrological response to geologic changes |
| 6. Formation damage (subsidence) |
| 7. Fluid composition (gas, oil, brine, multiphase flow) |
| 8. Effects of pressurization on rocks |
| 9. Sorption and desorption of gas |
| 10. Advection and diffusion of gas |
| 11. Displacement of formation fluids |
| 12. Dissolution in formation fluids |
| 13. Contamination of groundwater from wellbore fluids |
| 14. Injection of water into geologic formations |
| 15. Vertical geothermal gradient |

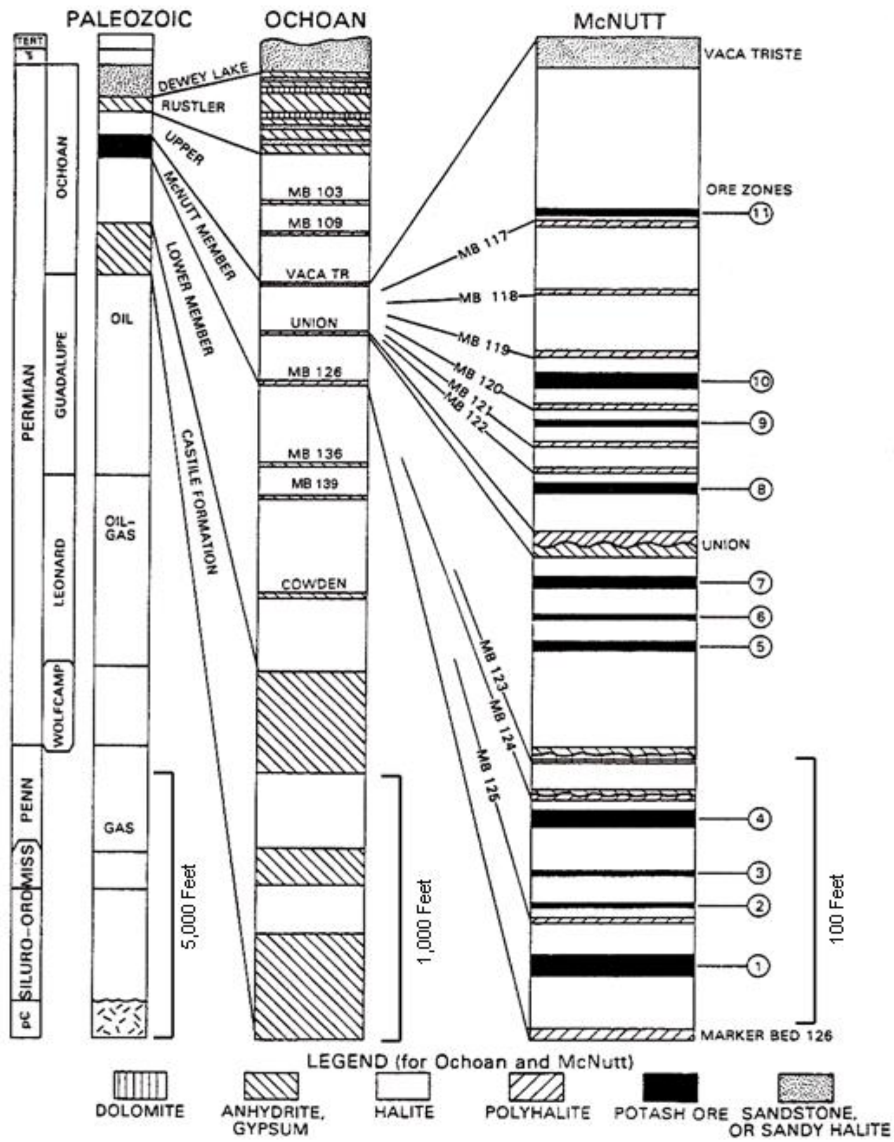



**Figure 5-1. General stratigraphic column of the Potash Area of southeastern New Mexico, featuring the McNutt Potash member. After Barker and Austin, 1999.**

### *5.3.1 Fluid Flow and Potential Pathways for Gas Migration*

The region contains important natural resources such as hydrocarbons and potash (potassium salts used for industrial and agricultural purposes). As such, oil and gas wells and potash mines co-exist in the area. There is thus the potential for gas to migrate from active gas wells or abandoned wells to open mines. Such possibility could arise whenever gas leaks due to damage to a gas well. However, the gas pressure would have to be sufficiently higher than in situ formation pressure for migration to occur. The damaged area could be at any depth along the length of the well. The gas could travel through breaches through the well or cemented annuli towards ore zones or adjacent formations. Flow through well breaches or cemented annuli is not the subject of this study. This study concentrates on gas pressure outside the well, exerted on the formation.

Thus, for gas to migrate to potash mines, the following conditions would need to be met:

- A sufficiently high and sustained gas pressure (driving force)
- A transmissive pathway

To quantify the driving force, sufficient local well pressure history for all reservoirs would be needed. Qualitative studies could also be conducted using information from literature on well production and declining pressures. To identify the pathway for gas migration there is a need to study formation parameter values and the effect of subsidence as a result of mine openings.

The mechanisms for gas migration through the stratigraphic layers are advection and diffusion. Diffusion of hydrocarbon gas through salt would be very slow due to the low diffusion coefficient. Advection would also be slow in salt due to low permeabilities. However, advection could be faster through relatively higher permeability formations (e.g., nonsalt interbeds) and as a result of fracturing. WIPP literature provides information on transmissivity of the major formations. WIPP performance assessment studies have shown that the bedded salt of the Salado Formation is the primary geologic barrier to migration of contaminants from the WIPP repository. Performance assessment results indicated that due to the extremely low permeability of the halite layers no contaminants will migrate vertically through the salt to overlaying strata if wells do not intersect the repository. Lateral flow within the somewhat more permeable anhydrite interbeds will be slow. Field studies indicate that subsurface transport is more likely to occur in the Culebra dolomite, where physical and chemical retardation processes will reduce migration.

For the gas migration study the scenario of interest is potash mining at depths of about 305 m (1000 ft). This corresponds to the depths of the McNutt Formation around Ore Zones 5 to 7 (Figure 5-1), and the marker beds near the mine. For this initial study we have selected the $7^{th}$ Ore Zone as representative. In this study the ore zones are considered to be intact halite. We have also concentrated on the two major marker beds near the $7^{th}$ Ore Zone: the Union anhydrite and MB123. The marker beds are important to the hydrology study because of their relatively higher permeability compared to the intact halite. They are also modeled as subject to pressure induced fracturing. For this study we have adopted the WIPP fracture model to be applied to the marker beds and disturbed rock zones. For future studies, the potential for gas migration in shallower marker beds and/or more permeable beds in the overlying Rustler Formation toward mine shafts may also be considered. Gas flow rates presumably would be higher at shallower depths because of the lower hydrostatic pressure in the formation opposing the inflow and because of greater potential for hydrofracturing. Following is a description of the fracture model (Vaughn et al,, 2000).

### *5.3.2 WIPP Pressure–Induced Fracture Treatment*

The fracture treatment used for anhydrite marker beds allows for pressure-induced alterations to the porosity by introducing a pressure-dependent porosity. Fracturing is assumed to occur at pore pressures slightly below lithostatic pressure. The WIPP fracture model and data have been used here to demonstrate the approach employed in the RA model; if available, other relevant models and data may be used instead. The WIPP fracture model is based on the following assumptions:

- Fracturing of the marker beds begins at a pressure, $P_i$, of:

$$P_i = P_0 + \Delta P_i \tag{5.1}$$

where $P_0$ = initial formation pressure,

$\Delta P_i = 2 \times 10^5$ Pa (29 psi)

- Fracturing of marker beds ceases at a pressure, $P_a$, and at a fully altered porosity of $\phi_a$. $P_a$ is defined by:

$$P_a = P_i + \Delta P_a \tag{5.2}$$

where $\Delta P_a = 3.8 \times 10^6$ Pa (551 psi).

In order to calculate the altered porosity as a result of pressure induced fracturing, BRAGFLO requires the following input parameters:

- Initial rock compressibility ($C_i$)
- Porosity of intact material ($\varphi_i$)
- Pressure increment above initial formation pressure ($\Delta P_i$)
- Pressure increment above fracture initiation pressure at which the fracture is fully developed ($\Delta P_a$)
- Maximum allowable fracture porosity ($\varphi_a$)

The altered porosity is calculated as a function of rock compressibility and induced pressure. The fully altered compressibility is defined by Equation 5.3. The altered porosity is calculated using Equation 5.4. For induced pressures above Pa, the porosity is calculated using Equation 5.5.

for $P_i \leq P < P_a$

$$C_a = C_i\left[1 - 2\frac{(P_a - P_o)}{P_a - P_i}\right] + \frac{2}{(P_a - P_i)} ln\left(\frac{\varphi_a}{\varphi_i}\right) \quad (5.3)$$

$$\varphi = \varphi_i exp\left\{C_i(P - P_o) + \frac{(C_a - C_i)(P - P_i)^2}{2(P_a - P_i)}\right\} \quad (5.4)$$

for $P \geq P_a$

$$\varphi = \varphi_a \quad (5.5)$$

The marker bed fracture treatment further allows for change in the fracture material permeability. Permeability is calculated using the parallel plate analogy for flow in fractured rock in the form:

$$\frac{k}{k_i} = \left[\frac{\varphi}{\varphi_i}\right]^n \quad (5.6)$$

| | | | |
|---|---|---|---|
| where | $k$ | = | permeability of altered material, |
| | $k_i$ | = | permeability of intact material, |
| | $\varphi$ | = | porosity of altered material, |
| | $n$ | = | an empirical parameter. |

The altered permeability model requires the exponent $n$ as an input. A schematic representation of the pressure-dependent porosity and permeability in the marker bed fracture model is shown in Figure 5-2. Parameter values of materials relevant to the gas migration model are given in Table 5-2. Again, data based on WIPP measurements and modeling have been selected, but other data and models maybe used instead.

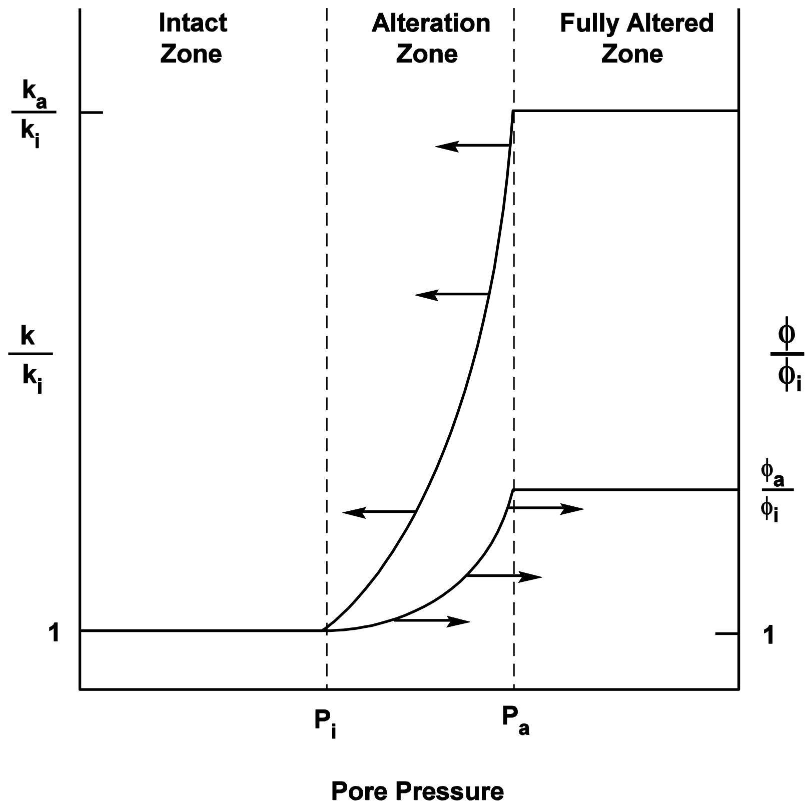



**Figure 5-1. Pressure dependent porosity and permeability in the marker bed fracture model.**

**Table 5-2. Rock Material Properties of Major Lithologic Units**

| **Intact Halite** | | |
|---|---|---|
| | **Permeability ($m^2$)** | **Porosity** |
| Distribution | Uniform | Piecewise Uniform |
| Range | $10^{-24}$ to $10^{-21}$ | 0.001 to 0.031 |
| Mean, Median | $3.16 \times 10^{-23}$ | 0.018, 0.01 |
| **Anhydrite Marker beds** | | |
| | **Permeability ($m^2$)** | **Porosity** |
| Distribution | Student with 5 degrees of freedom | |
| Range | $10^{-21}$ to $10^{-17.1}$ | |
| Mean, Median | $1.26 \times 10^{-19}$ | 0.01 |
| **Disturbed Rock Zone** | | |
| | **Permeability ($m^2$)** | **Porosity** |
| Distribution | None - deterministic | |
| Range | | |
| Mean, Median | $1.0 \times 10^{-17}$ | halite porosity + 0.0029 |

## 5.4 Hydrology Modeling

The hydrology conceptual model for the gas migration study was developed based on the conceptual model illustrated by Figure 3-1. To generate the hydrology conceptual model, relevant geology and hydrology of the area and some possible pathways were added to the generalized conceptual model. Also, geomechanics model results, such as slippage along marker beds and disturbed rock zones around excavated regions will be included.

To make computations manageable, modeling simplifications were made. For the present study the hydrology is represented with a two-dimensional grid. The 2D model is a simplification which allows for shorter computational times and thus the simulation of multiple scenarios, but likely will overestimate the extent of gas migration relative to the actual 3D system of radial flow from a leaking well. The grid is a vertical cross-section of the stratigraphy. Figure 5-3 shows a schematic diagram of the stratigraphy used in hydrology modeling for the McNutt Potash. The figure shows relevant formations in the McNutt Potash, and overlying and underlying layers. The Union member and MB123 are included as they are the marker beds closest to the 7th Ore Zone.

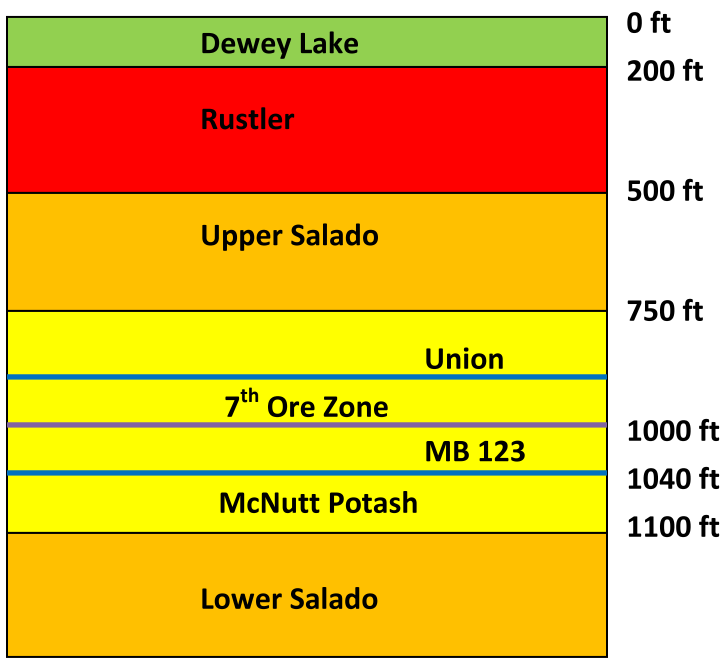



**Figure 5-3. Schematic diagram showing stratigraphy of the mine area for 1000 ft mine. (Not to scale.)**

Because of symmetry only one side of the mine opening is modeled. Also, the current grid does not include near surface formations such as the Dewey Lake, and formations much lower than the McNutt Potash. It was decided that those formations are not as relevant to the gas migration study because of their distance from the mine. The Rustler was subdivided into its component members (Layers 16-20, Table 5.4). The current mesh includes 1800 grid blocks (90 horizontal by 20 vertical). Figure 5-4 shows thicknesses of the vertical layers. The baseline model uses mean parameter values from the WIPP database. Table 5-3 shows modeled materials and mean material properties used in simulations. For Unnamed and Forty-niner layers very low permeability values are used to indicate that they are modeled as impermeable, because the numerical code BRAGFLO, WIPP PA (1996) does not accept zero permeability.

WIPP software and databases were used for the simulations. For two-phase brine-gas flow the WIPP numerical code BRAGFLO (Version 6.0) was used. BRAGFLO incorporates various models including interbed fracturing in response to fluid pressure (Vaughn et al, 2000). Mesh generation, initial conditions set-up, and pre- and post-processing were also done using WIPP software.

| Layer | Thickness (m) | Member | WIPP Material |
|---|---|---|---|
| 20 | 21 | FORTY-NINER | FORTYNIN |
| 19 | 7 | MAGENTA | MAGENTA |
| 18 | 24 | TAMARISK | TAMARISK |
| 17 | 7 | CULEBRA | CULEBRA |
| 16 | 35 | UNNAMED | UNNAMED |
| 15 | 56 | UPPER SALADO | S_HALITE |
| 14 | 21 | UPPER SALADO | S_HALITE |
| 13 | 42 | MCNUTT POTASH | S_HALITE |
| 12 | 7 | MCNUTT POTASH | S_HALITE |
| 11 | 5 | MCNUTT POTASH | S_HALITE |
| 10 | 4.5 | UNION ANHYDRITE | MB |
| 9 | 2 | MCNUTT POTASH | S_HALITE |
| 8 | 1.5 | 7th Ore Zone | S_HALITE |
| 7 | 5 | MCNUTT POTASH | S_HALITE |
| 6 | 7 | MCNUTT POTASH | S_HALITE |
| 5 | 5 | MCNUTT POTASH | S_HALITE |
| 4 | 2.3 | MB123 | MB |
| 3 | 7 | MCNUTT POTASH | S_HALITE |
| 2 | 11 | MCNUTT POTASH | S_HALITE |
| 1 | 7 | LOWER SALADO | S_HALITE |
| Total | 277.3 | | |

**Figure 5-4. Thicknesses of vertical layers of hydrology simulation mesh**

**Table 5-3. Mean Porosity and Permeability Values of Rock Units**

| Rock Material | Permeability ($m^2$) | Porosity | Compressibility (1/Pa) |
|---|---|---|---|
| Halite | $3.16 \times 10^{-23}$ | 0.0100 | $9.75 \times 10^{-9}$ |
| Disturbed Rock Zone | $1.00 \times 10^{-17}$ | 0.0129 | $5.74 \times 10^{-8}$ |
| Marker Beds | $1.29 \times 10^{-19}$ | 0.0110 | $2.03 \times 10^{-9}$ |
| Unnamed Member | $1.00 \times 10^{-35}$ | 0.1810 | 0 |
| Culebra | $9.59 \times 10^{-15}$ | 0.1510 | $6.62 \times 10^{-10}$ |
| Tamarisk | $1.00 \times 10^{-35}$ | 0.0640 | 0 |
| Magenta | $2.10 \times 10^{-15}$ | 0.1380 | $1.92 \times 10^{-9}$ |

| | | | |
|---|---|---|---|
| Fortyniner | $1.00 \times 10^{-35}$ | 0.0820 | 0 |

### 5.4.1 Initial Conditions:

The system is modeled to be initially at saturated conditions. Initial formation pressures were evaluated based on assigned pressures at specified locations. For this study WIPP practices were adopted, for which the initial conditions for the entire stratigraphy were developed based on assigned pressure conditions in MB139, which lies underneath both the WIPP and potash zone horizons. Using this technique, the following are imposed as initial formation pressures:

- Far field pressure at the depth of MB139 – mean: 12.47 MPa (1808 psi)
- Pressure at Culebra – mean: 0.933 MPa (135.5 psi)
- Pressure at Magenta – mean: 0.963 MPa (139.7 psi)

### 5.4.2 Boundary conditions:

The mine opening is assumed to be at atmospheric conditions. Alternatively, formation pressure boundary conditions were imposed at the ore zone next to the mine opening. To calculate the quantity of any flow of fluid into the mine opening, a well model that is part of the BRAGFLO numerical code was used. In BRAGFLO output from a well with an imposed flowing wellbore pressure is described by an inflow performance relation given in Equation 5.7. The equation would be used to calculate the mass rate for each phase entering the mine opening, if any.

$$q_l = -\frac{(PI)\rho_l k_{rl}}{\mu_l}\left(P_l - P_{wf}\right), \tag{5.7}$$

where
$l$ = phase index ($l$ = *brine*,*gas*)
$q_l$ = phase mass flow rate
$P_l$ = phase pressure
$P_{wf}$ = flowing wellbore pressure
$PI$ = well productivity index
$\rho_l$ = phase density
$\mu_l$ = phase viscosity
$k_{rl}$ = phase relative permeability.

To calculate any gas or brine flow into the mine opening, either atmospheric or formation pressure was used as flowing borehole pressure in Equation 5.7. For steady radial flow the productivity index, PI, can be calculated from (Coats, 1977):

$$PI = \frac{2\pi\,(k\Delta Z)}{ln(r_e/r_w)+s-1/2} \tag{5.8}$$

Where $\Delta Z$ is layer thickness, k is permeability, $r_e$ is grid block radius, $r_w$ is well radius, and s is skin factor. For a rectangular grid block, $r_e$ , the grid block radius, can be approximated using:

$$r_e = \sqrt{A/\pi} \tag{5.9}$$

where A is the grid block area. For a horizontal grid,

$$A = \Delta x \cdot \Delta y \tag{5.10}$$

A driving pressure was also imposed at the location of the gas well. The user can specify the location of the well. Collected well data show flowing tubing pressures of up to 5000 psi. Thus, 5000 psi and 2500 psi were used as preliminary boundary driving gas pressures. These pressures and the gas rate decline with time. Pressure decline history would be required to accurately model gas migration as a result of the imposed gas pressure. Section 4.2.4 provides some recent pressure history data from oil wells in the area. These data and others collected from oil and gas wells will be used in future gas migration simulations. Figure 5-5 illustrates the boundary conditions used in the model. Driving gas pressure was imposed at the well, at the selected three layers. The gas pressure is imposed in all directions, although only gas migration towards the mine opening is tracked.

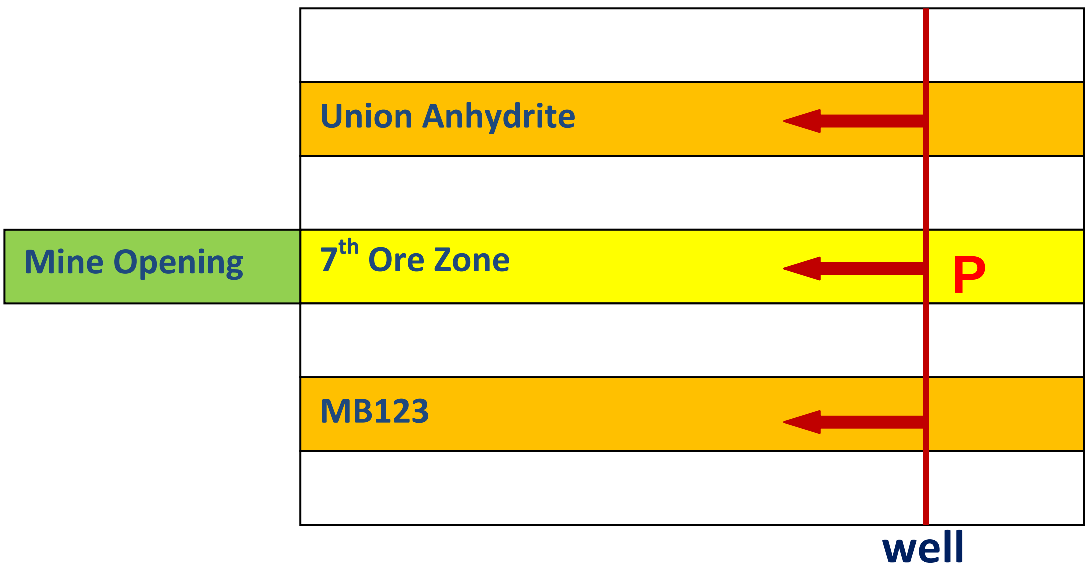



**Figure 5-5. Schematic diagram representing boundary conditions. (Not to scale.)**

### *5.4.1 BRAGFLO Simulation Runs*

As part of the RA model, hydrological calculations will evaluate several specific events or processes that may impact potential gas migration from a well to the mine. Two example simulations are presented here to illustrate how these gas flow processes will be examined under the RA model. The basic scenario for the present modeling study includes gas migrating from a leaky well towards a potash mine through an ore zone and surrounding marker beds. The scenario also includes fracturing of marker beds as a result of induced pressure overcoming formation pressure. The location of the well can be considered uncertain. The gas is represented with methane properties. The in-situ liquid is represented as brine. The ore zone is modeled as intact halite. The WIPP fracture model is applied to MB 123 and Union Anhydrite marker beds, and to disturbed rock zones around mine openings.

A test run (Test 1) was made with BRAGFLO exerting 34.5 MPa (5000 psi) gas pressure at MB123, 7$^{th}$ Ore Zone and Union Anhydrite layers, at a selected distance from the mine opening. The pressure represents a gas well leaking at the specified layers simultaneously. On the mine opening side, calculated initial formation pressure (see Section 5.4.1) at the level of the 7th Ore Zone was imposed, as the flowing wellbore pressure. A productivity index of 7.66 x $10^{-17}$ $m^3$ was calculated assuming the well is in a disturbed zone with permeability of 1 x $10^{-17}$ $m^2$, and using 1.5 m as the thickness of the 7th Ore Zone. The simulation was run for a total time of one year. Figure 5.6 shows a pressure buildup plot in the Union Anhydrite, indicating the distance from the borehole subject to pressurization. The results show that at the end of the one year simulation time gas traveled a negligible distance along the 7th Ore Zone layer. This is because of the very low permeability of the 7th Ore Zone, represented by intact halite (see Table 5-3 for permeability of halite). The results also show that the gas travel distance in the Union Anhydrite for one year of simulation was about 30 m (98 ft). The gas travels further in the marker beds because of the higher initial permeability of the marker beds and due to increased permeability as a result of fracturing, as well as increased relative permeability after the gas saturation increases in the flow path. The travel distance would also increase in the disturbed rock zone with its higher initial permeability and possible fracturing under pressure.

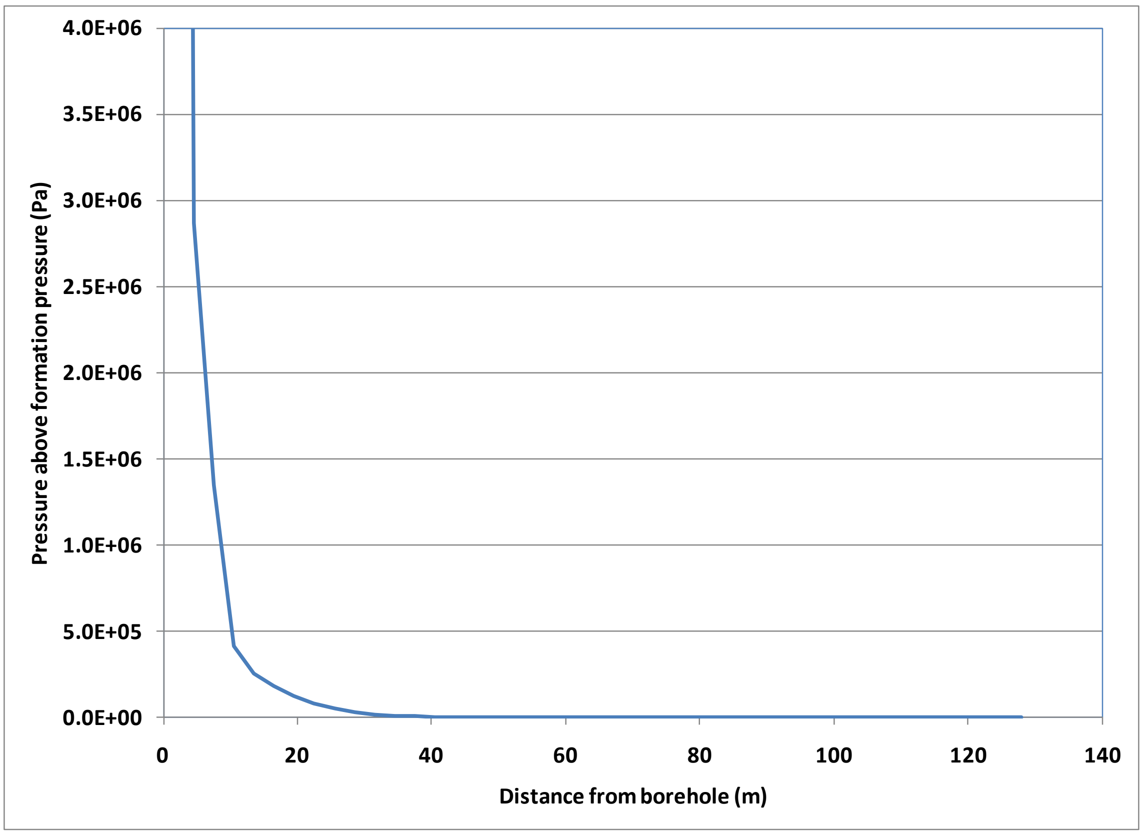



**Figure 5-6. Pressure buildup vs. distance from borehole at Union Anhydrite after one year simulation (Test 1).**

A second test run (Test 2) was carried out to illustrate the use of geomechanical data in the hydrology simulations. Geomechanics simulations provided slippage information in marker beds. The information was given in terms of distances from mine opening affected by the slippage. For the base case geomechanical simulations reported by Arguello et al. (2009) (1000-

ft deep, 1-mile wide mine with friction coefficient along marker beds = 0.2), the predicted subsidence of the mine caused slip (i.e., relative motion between opposite points on either side of a marker bed interface) between the marker beds. An assumption was made that a slip of magnitude 0.5 mm would be sufficient to create a significantly more permeable flowpath (fracture or fracture-like) for gas in the vicinity of the mine. From the base case calculations, a slip of magnitude 0.5 mm along MB 123 was predicted to extend to 325.5 m beyond the edge of the mine. In order to model the affected area in the hydrology simulations, there is a need for representative parameter values. These data are not available at this time. Thus, the assumption was made to represent the affected area using disturbed zone properties given in Table 5.3. In addition, the disturbed zone is also subject to fracturing as with the marker beds. The rest of the BRAGFLO input was the same as in Test 1. Pressure buildup results for MB123 are shown in Figure 5.7. The results of Test 2 show that gas travel distance in MB123 of about 200 m (656 ft) for one year simulation. In this case the gas traveled further than in Test 1 because the initial disturbed rock permeability is about two orders of magnitude higher than marker bed permeability (Table 5.3). As shown in Figure 5.4 MB123 is located about 17 m (56 ft) below the $7^{th}$ Ore Zone, with intact halite between them. Thus, gas migration in MB123 did not have any measurable effect on the $7^{th}$ Ore Zone.

Modeling for longer times would require well pressure decline history data from actual wells. If gas pressures decline to that of the in situ formation pressures, the driving force for gas migration is assumed to stop. Other scenarios will be included when geomechanics results are available, and also in the risk assessment study.

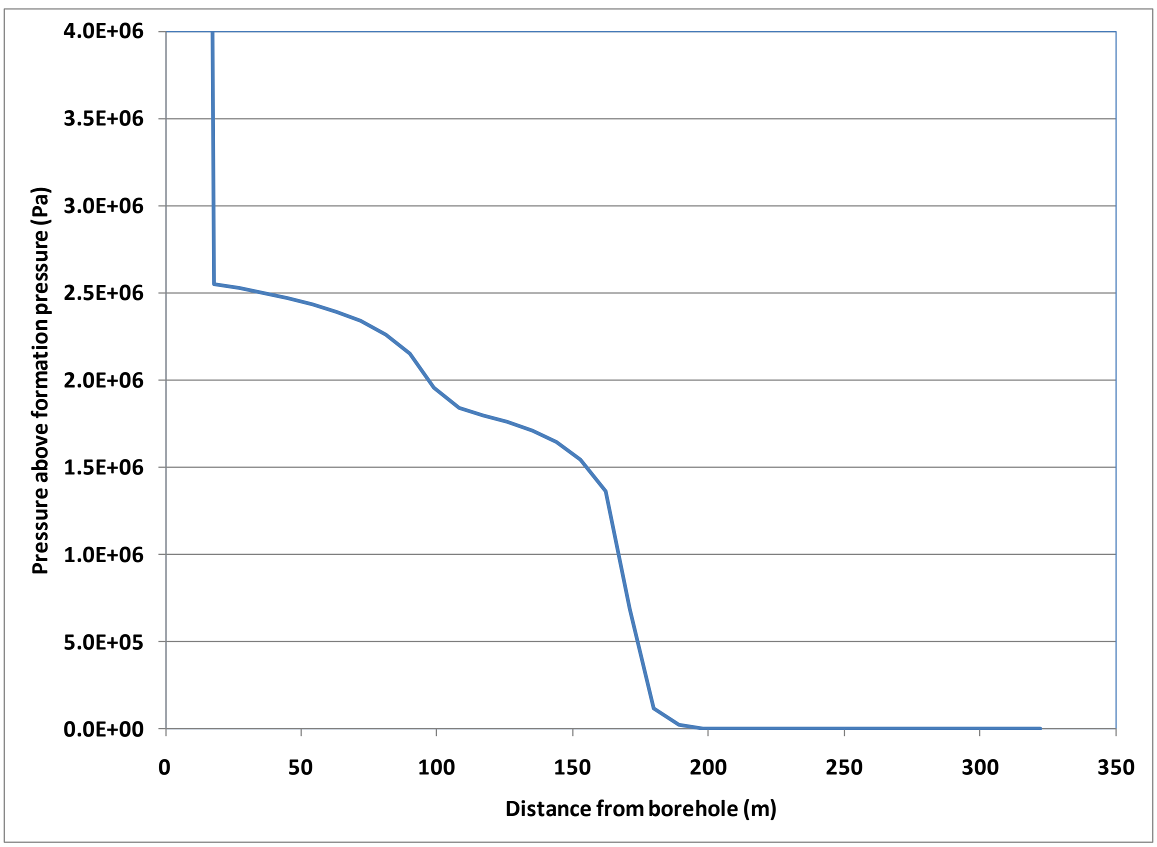


**Figure 5-7. Pressure buildup vs. distance from borehole at MB123 after one year simulation (Test 2).**

## 5.5 Stakeholder Feedback and Future Work

At the two stakeholder meetings that were held the suggestions for the geology/hydrology modeling were to use:

- Pressure histories of local oil and gas wells with declining pressure.
- Initial pressures relevant to the oil and gas and potash resource areas.

Future work would thus address the above issues. Additionally, future work would attempt to do the following:

- Incorporate results of the geomechanical model.
- Conduct a sensitivity study by varying parameter values.
- Revisit pressure-induced fracturing of rocks.
- Study natural features (faults, folds, voids, etc.).
- Study the possibility of using 3-dimensional modeling.

# 6 SUMMARY

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.

The present work has begun bringing in site-specific data relevant to gas migration study through examination of a 40 well study set of deep gas wells in the vicinity of the WIPP site. Just this small sample has shown that there is significant publically available data that can improve gas migration analysis. There has been new work on the hydrology, geology and geomechanics of the problem, particularly focused on parameters and concepts that characterize the gas migration pathway. The geomechanical zones of importance have been described along with issues that impact gas migration potential. The combined hydrological and geological analytical work has, similarly, brought in site specific data and developed parameter lists and concepts important for gas migration pathway analysis. The result has been to better define the analytical issues and parameter needs for gas migration study and to show the participants that they have collaborative work to do to set up and define the problem, collect data and define performance measures before a useful analytical outcome can be achieved. In all of the technical areas mentioned this work has produced exemplars of how analyses are performed in the RA framework. Appendix C is a table summarizing FEPs examples that were discussed.

SNL will provide BLM with a description of next steps in RA development and a path forward if they choose to continue RA development. The present work has served the purpose of catalyzing change in the way contentious technical issues, such as the potential for gas migration, are framed for discussion and has shown that there is a tried and proven methodology that can be developed through future work to sustain this type of more productive stakeholder interaction.

At a high level, next steps in RA involve developing the first three tasks in the seven tasks of RA listed in Section 2.2 and diagrammed in Figure 2-1. Assuming a continued desire to assess gas migration potential while building a framework that can be used for other studies, next steps would be as follows. The first step would be to identify the needs of the gas migration potential (or other) study, meaning more clearly defining which elements of the problem are important and clarifying the risk of concern. Examples of this first step include identifying the performance measures of importance and measures of risk as well as risk limits. Step two is to define and characterize the system, which means to collect more site-specific data on wellbores, wellbore production histories, mining parameters and how mining impacts geology/hydrology, and features of the geology/hydrology that affect migration potential. Step three is to identify sources of hazards through selection of FEPs, and to form scenarios of alternative behavior from these FEPs. The current work has just started that process, and it should be much more fully developed through collaborative input and decisions on relevant FEPs. As the participants become more comfortable with RA as a tool, the discussion of using engineering judgment to either qualitatively or quantitatively assign probabilities to FEPs and scenarios would comprise the next phase of the work. The probability of gas migrating from a wellbore to a mine is the critical issue being sought through this analysis.

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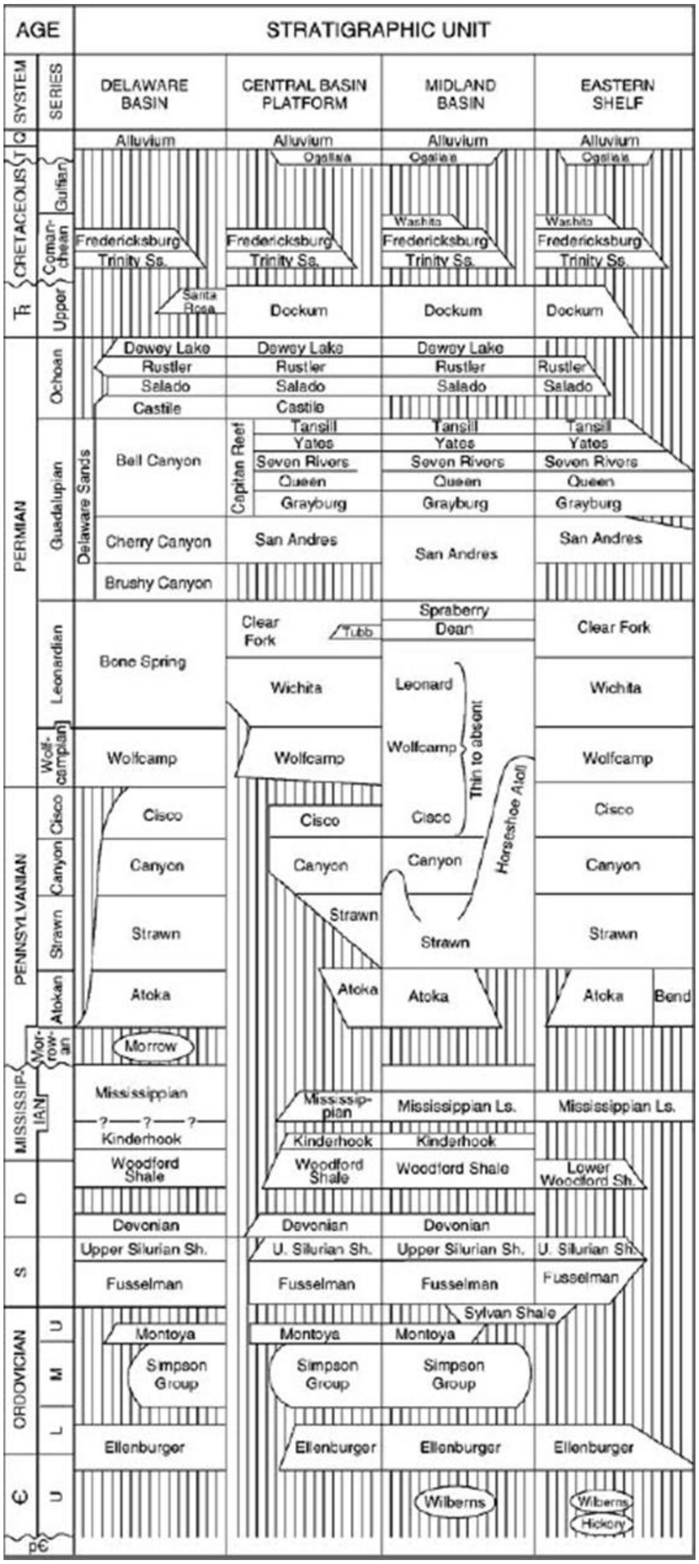
# APPENDIX A-1: PERMIAN BASIN STRATIGRAPH COLUMN

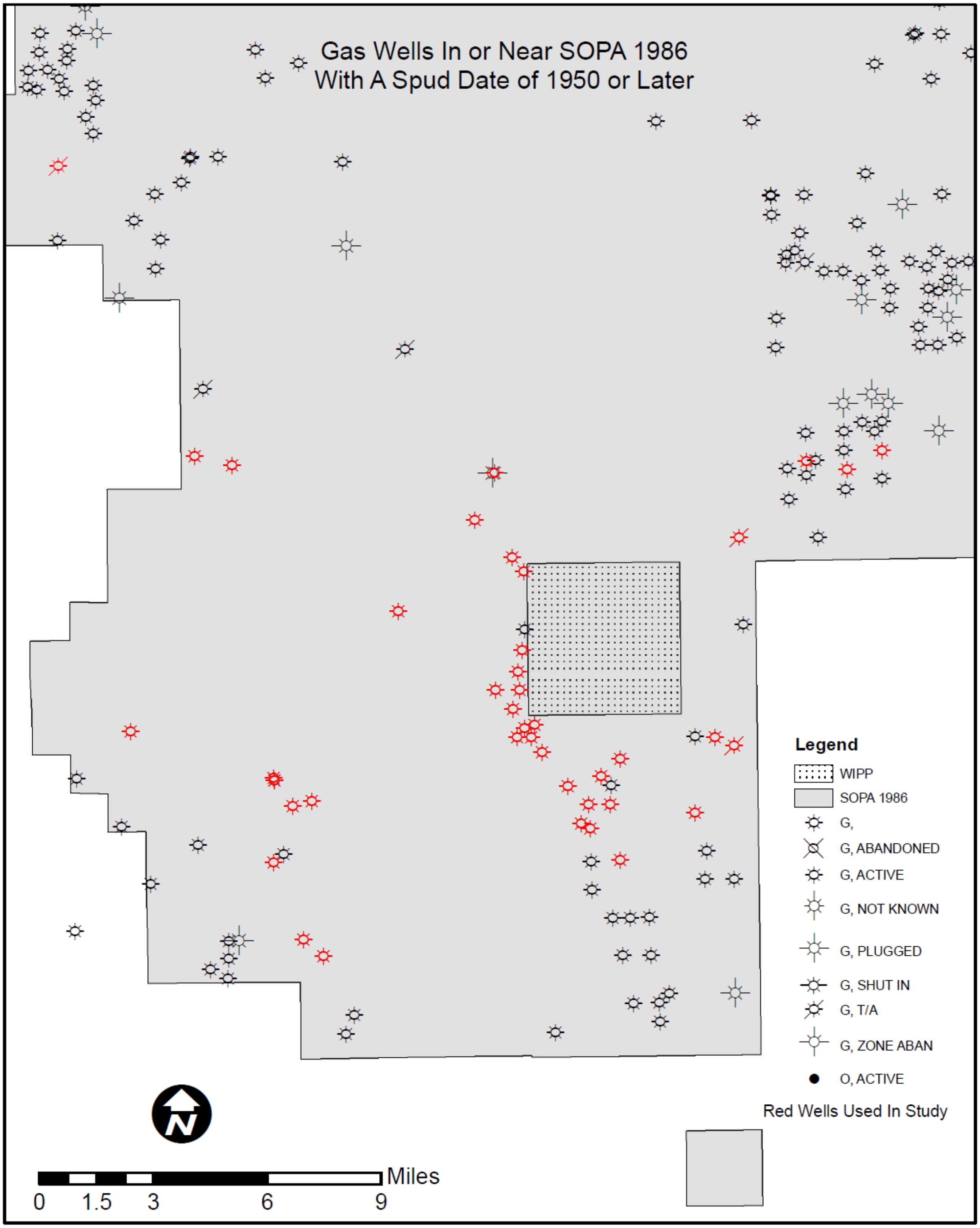
From geogateways.com



# APPENDIX A-2: LIST OF 40 WELLS IN THE WIPP AREA USED AS A STUDY SET FOR WELLBORE CONSTRUCTION, PRESSURES AND LEAKAGE FACTORS

| Spud 1960's | Spud 1970's | Spud 1980's | Spud 1990's | Spud 2000's |
|---|---|---|---|---|
| **30-015-04735**<br>James Ranch Unit #001<br>BOPCO | **30-015-20232**<br>James Ranch Unit #003<br>BOPCO | **30-015-22162**<br>James Ranch Unit #012<br>BOPCO | **30-015-26296**<br>North Pure Gold 8 Federal #002<br>Devon | **30-015-31412**<br>Poker Lane Unit #153<br>BOPCO |
| **30-015-10806**<br>James A Com #001<br>ConocoPhillips | **30-015-20298**<br>Todd 14 K Federal No. 001<br>Devon | **30-015-23075**<br>James Ranch Unit #010<br>BOPCO | **30-015-26382**<br>Medano VA State #002<br>Yates | **30-015-31511**<br>Remuda Basin 24 State #001<br>XTO Energy |
| | **30-015-20803**<br>James Ranch Unit #004<br>BOPCO | **30-015-23175**<br>Pure Gold A Federal #001<br>Kaiser-Francis | **30-015-26509**<br>PG 4 Federal #001<br>Devon | **30-015-31774**<br>Remuda Basin 31 State Com #001<br>BOPCO |
| | **30-015-20940**<br>Big Eddy Unit #038<br>BOPCO | **30-015-23377**<br>James Ranch Unit #011<br>BOPCO | **30-015-27208**<br>James Ranch Unit #018<br>BOPCO | **30-015-32548**<br>Nash Unit #053<br>Murchison O&G |
| | **30-015-21277**<br>Nash Unit #001<br>XTO Energy | **30-015-23389**<br>Carthell Federal Com #002<br>COG Operating | **30-015-27270**<br>Pure Gold B Federal #002<br>EOG Resources | |
| | **30-015-21501**<br>Livingston Ridge Unit, #001Y<br>COG Operating | **30-015-23992**<br>Pure Gold C Federal #001<br>Devon | **30-015-27410**<br>Apache 25 Federal #001<br>Devon | |
| | **30-015-21672**<br>Nash Unit #002<br>Murchison O&G | **30-015-24062**<br>James Ranch Unit #013<br>BOPCO | **30-015-27434**<br>Apache 13 Federal #001<br>Devon | |
| | **30-015-21781**<br>Nash Unit #003<br>Murchison O&G | **30-015-24138**<br>Big Eddy Unit #097<br>BOPCO | **30-015-27478**<br>Apache 25 Federal #002<br>Devon | |
| | | **30-015-24232**<br>SCL Federal #002<br>OXY USA | **30-015-28012**<br>James Ranch Unit #070<br>BOPCO | |
| | | **30-015-24420**<br>James Ranch Unit #014<br>BOPCO | **30-025-30886**<br>Bilbrey 32 State Com #001<br>ConocoPhillips | |
| | | **30-015-24780**<br>James Ranch Unit #015<br>BOPCO | **30-025-31120**<br>Bilbrey 34, Federal No. 001<br>COG Operating | |
| | | **30-015-24954**<br>Barclay Federal #001<br>Linn Operating | **30-025-32383**<br>Bilbrey 33, Federal No. 002<br>ConocoPhillips | |
| | | **30-015-25534**<br>Barclay State #001<br>Linn Operating | | |
| | | **30-015-26021**<br>Pure Gold C-17 Federal #002<br>Devon | | |

## APPENDIX A-3: GAS WELLS IN OR NEAR THE SECRETARY'S POTASH AREA




Red symbols used to identify wells listed in Appendix A-2.

# APPENDIX A-4: WELLS WITHIN MINES

## WELLS WITHIN EDDY POTASH MINED AREA



| UNIT | SECTION | TOWNSHIP | RANGE | OPERATOR | LEASE | WELL # | SPUD DATE | COMP. DATE | TOTAL DEPTH | FORMATION(AT T.D.) | RESULTS I. P. | COMP. INTERVAL | CUM. PROD. | STATUS | LAST PROD. | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | BARBER FIELD | | | | | |
| B | 20 | 20S | 30E | SHACKELFORD OIL CO | COLGLAZIER | 1 | 1/18/1937 | 2/11/1937 | 1443 | YATES | 132 BOPD | 1438-1443 OH | 130,831 BO | ACT. | 1/08(60 BO & 1082 BW) | |
| E | 20 | 20S | 30E | BARBER OIL | MORRIS & HOOVER | 1 | 5/16/1937 | 6/12/1937 | 1461 | YATES | 200 BOPD | 1451-1461 OH | | P & A | | P&A 1947, REPLUGGED 9/22/93 BY P.C. |
| D | 20 | 20S | 30E | BARBER OIL | STATE | 1 | 6/19/1937 | 8/3/1937 | 1477 | YATES | 132 BOPD | 1467-1477 OH | | P & A | | P&A 10/23/52, WITNESSED BY P.C. |
| H | 19 | 20S | 30E | BARBER OIL | STATE "A" | 2 | 3/1/1938 | 10/7/1938 | 1650 | YATES | | | | P& A | | REPLUGGED 10/4/93 BY P.C. |
| N | 20 | 20S | 30E | BARBER OIL | STATE | A-3 | 4/12/1938 | 5/27/1938 | 1531 | YATES | 300 BOPD | 1195-1531 OH | | P & A | | P&A 12/11/52, WITNESSED BY P.C. |
| G | 20 | 20S | 30E | SHACKELFORD OIL CO | COLGLAZIER | 2 | 8/19/1938 | 9/18/1938 | 1436 | YATES | 8 BOPD | 1418-1436 OH | 105,355 BO | ACT. | 1/08(15 BO & 97 BW) | |
| F | 20 | 20S | 30E | SHACKELFORD OIL CO | STOVALL WOOD | 2 | 1/1/1941 | 1/1/1941 | 1473 | YATES | 96 BOPD | 1254-1473 OH | 195,606 BO | ACT. | 1/08(58 BO & 361 BW) | |
| L | 20 | 20S | 30E | BARBER OIL | MORRIS & HOOVER | 2 | 2/25/1941 | 3/26/1941 | 1507 | YATES | 72 BOPD | 1397-1507 OH | | P & A | | P&A 3/8/62 |
| K | 20 | 20S | 30E | BARBER OIL | STATE | 1-B | 4/5/1941 | 5/4/1941 | 1548 | YATES | 60 BO & 6 BW | 1447-1548 OH | | P & A | | P&A 12/22/52, WITNESSED BY P.C. |
| O | 17 | 20S | 30E | SHACKELFORD OIL CO | STATE "A" | 1 | 12/27/1941 | 1/2/1942 | 1575 | YATES | 120 BOPD | 1442-1575 | 130,165 BO | ACT. | 1/08(53 BO & 715 BW) | |
| C | 20 | 20S | 30E | SHACKELFORD OIL CO | STOVALL WOOD | 1 | 1/16/1942 | 2/4/1942 | 1540 | YATES | 103 BOPD | 1406-1540 | 235,591 BO | ACT. | 1/08(52 BO & 1189 BW) | |
| J | 17 | 20S | 30E | SHACKELFORD OIL CO | STATE "A" | 4 | 6/14/1942 | 7/13/1942 | 1539 | YATES | 240 BOPD | 1478-1539 | 91,731 BO | ACT | 1/08(15 BO & 10 BW) | |
| N | 17 | 20S | 30E | SHACKELFORD OIL CO | STATE | 2 | 7/20/1942 | 8/13/1942 | 1520 | YATES | 240 BOPD | 1143-1520 | 181,034 BO | ACT. | 12/03(57 BO) | NOW SWD/INJECTION |
| C | 20 | 20S | 30E | BARBER OIL | STATE | 5 | 1/1/1943 | | 207 | RUSTER | | 195-207 | | P & A | | P&A 2/2/94, INJECTED WITHOUT AUTH. # |
| J | 20 | 20S | 30E | EASTHAM HARRIS | COLGLAZIER | 1 | 5/9/1943 | 9/27/1943 | 1600 | YATES | 26 BOPD | 1502-1600 OH | 31,991 BO | P & A | | IN SECOND MINED AREA |
| F | 20 | 20S | 30E | SHACKELFORD OIL CO | STOVALL WOOD | 3 | 11/5/1953 | 12/23/1953 | 1470 | YATES | 125 BO+375 BW | 1306-1470 OH | 104,689 BO | ACT. | 1/08(21 BO) | |
| G | 20 | 20S | 30E | SHACKELFORD OIL CO | COLGLAZIER | 3-C | 12/28/1953 | 2/6/1954 | 1553 | YATES | 120 BOPD | 1315-1553 OH | 43,586 BO | ACT. | 1/08(23 BO & 121 BW) | |
| G | 19 | 20S | 30E | W.C. WILLS | STATE | 1 | | | | | | | | P & A | | |
| | | | | | | | | | | | PCA FIELD | | | | | |
| D | 22 | 20S | 30E | CONTINENTAL | BARRETT | 1 | 4/9/1937 | 6/5/1937 | 1953 | YATES | DRY | | | P & A | | REPLUGGED 1/26/65 BY P.C. |
| P | 14 | 20S | 30E | CONTINENTAL | BARETT A-14 | 1 | 8/1/1937 | 9/26/1937 | 2283 | YATES | | | | P & A | | REPLUGGED 3/30/65, SECOND MINED AREA |
| F | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 1 | 11/10/1939 | 12/19/1939 | 1587 | YATES | 77 BO/11HR | 1550-1587 OH | 211,464 BO | ACT. | 2/08(14 BO & 36 BW) | |
| G | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 2 | 10/4/1940 | 11/25/1940 | 1661 | YATES | 138 BOPD | 1624-1661 OH | 177,401 BO | ACT. | 2/08(3 BO) | |
| J | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 3-A | 11/30/1940 | 1/21/1941 | 1639 | YATES | | | 161,939 BO | ACT. | 2/08(7 BO) | |
| K | 15 | 20S | 30E | BARBER OIL EXPL | KEYES 'C' | 4 | 5/11/1941 | 6/20/1941 | 1642 | YATES | 77 BO/11HR | 1489-1642 OH | 40,110 BO | P & A | | P&A 4/3/54 |
| N | 15 | 20S | 30E | KEYES ATWOOD | KEYES 'A' | 1 | 8/29/1941 | 10/10/1941 | 1636 | YATES | 100 BO/10HR | 1500-1636 OH | 8218 BO | P & A | | P&A 5/58 |
| D | 15 | 20S | 30E | PAN AM | HARGRAVE FED. | 2 | 12/21/1941 | 1/23/1942 | 1633 | YATES | 192 BOPD | 1568-1633 OH | 71,088 BO | P & A | | P&A 6/16/65 |
| E | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 5 | 5/6/1942 | 6/9/1942 | 1641 | YATES | | 1552-1641 OH | 135,011 BO | ACT. | 2/08(3 BO) | |
| M | 10 | 20S | 30E | EASTHAM HARRIS | HARGRAVE FED. | 3 | 7/6/1943 | 8/20/1943 | 1733 | YATES | P. 91 BO & 460 BW | 1688-1733 OH | 10,568 BO | P & A | | P&A 6/27/65, WITNESSED BY P.C. |
| C | 15 | 20S | 30E | PAN AM | HARGRAVE FED. | 3 | 7/6/1943 | 8/20/1943 | 1733 | YATES | 210 BOPD | 1576-1615 OH | 96,498 BO | P & A | | P&A 6/2/65, WITNESSED BY P.C. |
| B | 15 | 20S | 30E | NEIL WILLS | KEYES 'C' | 6 | 2/28/1944 | 3/30/1944 | 1674 | YATES | | 1607-1670 | | P & A | | P&A 5/1/54, IN SECOND MINED AREA |
| D | 23 | 20S | 30E | MAC ANDERSON | HALE | 1 | 8/28/1944 | 12/31/1944 | 1954 | YATES | DRY | | | P & A | | REPLUGGED 3/30/65, SECOND MINED AREA |
| N | 10 | 20S | 30E | EASTHAM HARRIS | HARGRAVE FED. | 4 | 9/18/1947 | 1/18/1948 | 1595 | YATES | P. 50 BO & 50 BW | 1580-1595 OH | 167 BO | P & A | | P&A 6/29/65, WITNESSED BY P.C. |
| F | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 7 | 10/16/1947 | 11/20/1947 | 1633 | YATES | 116 BOPD | 1531-1633 OH | 24,701 BO | ACT. | 2/08(7 BO) | |
| C | 15 | 20S | 30E | AMOCO | HARGRAVE FED. | 5 | 10/19/1947 | 4/27/1948 | 1614 | YATES | P. 5 BO & 5 BW | 1552-1614 OH | 2561 BO | P & A | | P&A 6/22/65, WITNESSED BY P.C. |
| | | | | | | | | | | | GETTY MORROW FIELD | | | | | |
| M | 24 | 20S | 29E | ODESSA NAT. GAS | DOOLEY FED | 1 | 5/18/1963 | 10/18/1963 | 13415 | SILURIAN | 16,700 MCFPD | P.12,102-12,229 | 514,335 MCFG | P & A | | P&A 9/20/67 |
| | | | | | | | | | | | GETTY YATES FIELD | | | | | |
| P | 14 | 20S | 29E | GETTY OIL | RAWSON | 2 | 6/4/1927 | 9/21/1927 | 1670 | YATES | | | | P & A | | P&A 6/19/39 |
| A | 23 | 20S | 29E | TIDEWATER | DOOLEY 'A' | 2 | 10/3/1927 | 11/11/1927 | 1374 | YATES | | 1325-1368 OH | 89,561 BO | P & A | | P&A 2/4/66, APP. 3/15/67 BY USGS |
| D | 25 | 20S | 29E | GETTY | NICHOLAS | 1 | 12/27/1927 | 2/8/1928 | 1384 | YATES | 35 BOPD | 1359-1383 OH | | P & A | | P&A 11/21/65, IN SECOND MINED AREA |
| D | 24 | 20S | 29E | TIDEWATER | DOOLEY | 3 | 2/12/1928 | 3/28/1928 | 1378 | YATES | 422 BOPD | 1288-1378 OH | 26,365 BO | P & A | | P&A 10/20/54, APP. & WITTNESSED BY PCA |
| N | 13 | 20S | 29E | SKELLY | RAWSON 'A' | 3 | 7/23/1928 | 9/13/1928 | 1397 | YATES | 430 BOPD | 1353-1397 OH | 943 BO | P & A | | P&A 3/26/66, APP. 10/2/66 BY USGS |
| H | 23 | 20S | 29E | GETTY OIL | DOOLEY | 4 | 2/18/1929 | 4/8/1929 | 1356 | YATES | | 1332-1356 OH | 88,537 BO | P & A | | P&A 2/2/66 |

## WELLS WITHIN EDDY POTASH MINED AREA

| UNIT | SECTION | TOWNSHIP | RANGE | OPERATOR | LEASE | WELL # | SPUD DATE | COMP. DATE | TOTAL DEPTH | FORMATION(AT T.D.) | RESULTS I. P. | COMP. INTERVAL | CUM. PROD. | STATUS | LAST PROD. | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K | 23 | 20S | 29E | GETTY | DOOLEY | 5 | 7/14/1930 | 8/26/1930 | 1554 | YATES | DRY | | | P & A | | P&A 9/17/39, APP. 10/20/39 BY USGS |
| L | 24 | 20S | 29E | SKELLY(GETTY) | DOOLEY 'A' | 6 | 10/3/1930 | 12/11/1930 | 1353 | YATES | 760 BF (79% OIL) | 1337-1353 | 89,781 BO | P & A | | P&A 3/4/66, APP. 3/15/67 BY USGS |
| E | 24 | 20S | 29E | TIDEWATER | DOOLEY 'A' | 7 | 1/7/1935 | 11/25/1935 | 6683 | DELAWARE | | P. 1335-1401 | 1,078,327 BO | P & A | | P&A 12/2/65, APP. 3/15/67 BY USGS |
| I | 23 | 20S | 29E | TIDEWATER | DOOLEY 'A' | 8 | 7/16/1943 | 8/12/1943 | 1370 | YATES | P. 55 BOPD | 1334-1370 OH | 140,169 BO | P & A | | P&A 11/27/65, APP. 3/15/67 BY USGS |
| P | 23 | 20S | 29E | TIDEWATER | DOOLEY 'A' | 9 | 9/26/1943 | 11/16/1943 | 1394 | YATES | P. 78 BOPD | 1340-1394 OH | 127,222 BO | P & A | | P&A 12/65, APP. 3/15/67 BY USGS |
| M | 24 | 20S | 29E | TIDEWATER | DOOLEY 'A' | 10 | 12/1/1943 | 3/15/1944 | 1394 | YATES | P. 20 BOPD | 1340- 1360 OH | 51,430 BO | P & A | | P&A 11/27/65, APP. 3/15/67 BY USGS |
| D | 24 | 20S | 29E | TIDEWATER | DOOLEY 'A' | 11 | 11/1/1954 | 11/8/1954 | 1375 | YATES | 12 BO & 12 BW | 1340-1375 OH | 85,280 BO | P & A | | P&A 12/7/65, APP. 3/15/67 BY USGS |
| J | 14 | 20S | 29E | NIX & CURTIS | TEXACO | 1 | 6/29/1960 | 7/20/1960 | 1381 | YATES | DRY | | | P & A | | P&A 7/20/60 |
| RED HILLS FIELD | | | | | | | | | | | | | | | | |
| B | 33 | 19S | 30E | COMPTON | VANDERGRIFF | 1 | 4/26/1929 | 2/13/1930 | 2002 | YATES | DRY | | | P & A | | INTENT TO REPLUG 2/2/66, NO FINAL P&A REP. |
| M | 28 | 19S | 30E | MIDWEST | LANE | 1 | 5/2/1929 | 7/6/1934 | 2001 | YATES | | | | P & A | | REPLUGGED BY P.C. 1/2/66, SEC. MINED AREA |
| A | 32 | 19S | 30E | HEN. BLACK | LOWEST | 1 | 1/16/1956 | 2/20/1956 | 1832 | YATES | 155 BOPD | P. 1666-1674 | 9767 BO | P & A | | P&A 1958, REPLUGGED 5/3/61 BY P.C. |
| M | 28 | 19S | 30E | W.H. BLACK | YATES 'A' | 1 | 2/24/1956 | 3/13/1956 | 1697 | YATES | 49 BOPD | P. 1654-1680 | 52,780 BO | P & A | | P&A 10/5/61, P.C. NOT NOTIFIED, SEC. MINED A |
| P | 29 | 19S | 30E | YATES DRILLING | LANE | 3 | 8/13/1956 | 9/18/1956 | 1724 | YATES | 126 BOPD | 1606-1724 OH | 20,205 BO | ACT. | 3/08(13 BO & 307 BW) | |
| P | 29 | 19S | 30E | YATES DRILLING | LANE | 4 | 4/19/1958 | 5/9/1958 | 1720 | YATES | 9 BOPD | P. 1656-1702 | 3928 BO | P & A | | P&A 4/12/89 |
| P & A WELLS OUTSIDE BARBER, GETTY, PCA, AND RED HILLS FIELDS | | | | | | | | | | | | | | | | |
| D | 35 | 20S | 29E | SNOWD &MCSWEEN. | LAWRENCE | 1 | 3/5/1928 | 5/4/1928 | 1728 | YATES | DRY | | | P & A | | IN SECOND MINED AREA |
| H | 8 | 20S | 30E | MARLAND | CUNNINGHAM | 1 | 6/22/1929 | 10/2/1929 | 1944 | YATES | DRY | | | P & A | | |
| A | 7 | 20S | 30E | BROWN&MCNALLEY | RIGGS | 1 | 4/14/1940 | 7/3/1941 | 1591 | YATES | DRY | | | P & A | | REPLUG. BY P.C. 4/20/67 FAILED |
| N | 12 | 20S | 30E | WILLS&ABELL | HALE | 1 | 8/28/1940 | 11/6/1940 | 1848 | YATES | DRY | | | P & A | | REPLUG 530' TO SURFACE, SECOND MINED A |
| B | 29 | 20S | 30E | PENMAN&HOOVER | STATE | 1 | 7/31/1943 | 8/28/1943 | 1820 | YATES | DRY | | | P & A | | P&A 8/28/43 |
| L | 12 | 20S | 30E | WILLS | HALE | 2 | 10/8/1944 | 12/10/1944 | 1860 | YATES | DRY | | | P & A | | REPLUG 6/21/61, IN SECOND MINED AREA |
| I | 7 | 20S | 30E | HARDENDORF | RIGGS | 1 | 10/24/1944 | 12/22/1944 | 1605 | YATES | DRY | | | P & A | | REPLUG 9/30/65, APP. 10/4/65, SEC. MINED A. |
| E | 21 | 20S | 30E | HARRIS EASTHAM | COLGLAZIER | 1 | 12/30/1945 | 2/18/1946 | 1750 | YATES | DRY | | | P & A | | |
| M | 12 | 20S | 30E | WILLS | HALE | 3 | 4/15/1946 | 5/13/1946 | 1800 | YATES | DRY | | | P & A | | REPLUG 530' TO SURFACE, SECOND MINED A |

# WELLS WITHIN HORIZON (AMAX) MINED AREA

| UNIT | SECTION | TOWNSHIP | RANGE | OPERATOR | LEASE | WELL # | SPUD DATE | COMP. DATE | TOTAL DEPTH | FORMATION(AT T.D.) | RESULTS I. P. | COMP. INTERVAL | CUM. PROD. | STATUS | LAST PROD. | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BENSON YATES FIELD | | | | | | | | | | | | | | | | |
| F | 16 | 19S | 30E | HARVEY E. YATES | SNOWD&MCSWEEN | 1 | 4/16/1943 | 6/1/1943 | 1836 | YATES | 120 BO & 460 BW | 1726-1836 OH | 72,685 BO | P & A | | P&A 3/18/65, IN SECOND MINED AREA |
| G | 16 | 19S | 30E | HARVEY E. YATES | SNOWD&MCSWEEN | 2 | 8/27/1943 | 10/6/1943 | 1795 | YATES | 500 BF | 1750-1795 | 74,007 BO | P & A | | P&A 4/1/66, IN SECOND MINED AREA |
| H | 16 | 19S | 30E | HARVEY E. YATES | WHELAN ST. | 1 | 8/30/1952 | 3/4/1953 | 2920 | 7 RIV. | | | | P & A | | P&A 3/14/53, WITNESSED BY P.C., IN SEC MINED |
| I | 16 | 19S | 30E | HARVEY E. YATES | SNOWD&MCSWEEN | 3 | 1/11/1945 | 3/31/1945 | 1856 | YATES | P. 60BO & 20BW | 1843-1856 OH | 12,564 BO | P & A | | P&A 6/20/53, WITNESSED BY P.C., IN SEC MINED |
| J | 16 | 19S | 30E | HARVEY E. YATES | SNOWD&MCSWEEN | 2 | 10/1/1943 | 11/7/1943 | 1899 | YATES | 150 BO & 450 BW | 1751-1899 OH | 74,687 BO | P & A | | P&A 3/29/67, WITNESSED BY P.C., IN SEC MINED |
| K | 16 | 19S | 30E | HARVEY E. YATES | STATE B9646 | 4 | 5/8/1952 | 7/9/1952 | 1836 | YATES | P. 20 BOPD | 1730-1836 OH | 10,432 BO | P & A | | P&A 4/12/67, IN SECOND MINED AREA |
| E | 16 | 19S | 30E | YATES & STROUP | STATE | 1 | 9/15/1942 | 5/3/1946 | 1890 | YATES | DRY | | | P & A | | REPLUGGED 9/1/65 BY P.C., IN SEC MINED AREA |
| B | 16 | 19S | 30E | HARVEY E. YATES | STATE | 1 | 7/20/1943 | 8/30/1943 | 1960 | YATES | DRY | | | P & A | | P&A 4/12/62, ATTEMPTED SWD, IN SEC MINED A |
| K | 16 | 19S | 30E | YATES & STROUP | STATE | 3 | 7/16/1944 | 8/22/1944 | 1904 | YATES | DRY | | | P & A | | P&A 3/30/46, REPLUG. 8/10/70, IN SEC MINED A |
| TURKEY TRACK MORROW | | | | | | | | | | | | | | | | |
| L | 24 | 19S | 29E | YATES PETROLEUM | SOUTHLAND ROYALTY APM STATE #1 | 1 | 1/5/1979 | 2/15/1979 | 11,880 | MORROW | 1260 MCFGPD | 11,422-11,562 | 671,959 MCFG | ACT | 5/08(817 MCF & 12 BW) | |
| L | 23 | 19S | 29E | CHI OPERATING | STATE 23-A | 1 | 2/20/1979 | 5/14/1979 | 11,775 | MORROW | 1925 MCFGPD | P. 11,278-11,465 | 1,013,651 MCFG | INA | | PLUGGED BACK TO BONE SPRINGS |
| TURKEY TRACK BONE SPRING | | | | | | | | | | | | | | | | |
| L | 23 | 19S | 29E | CHI OPERATING | STATE 23-A | 1 | RE-COMP | 12/3/1993 | 8170 | BONE SPRING | | 7936-8022 | 162,992 MCFG | ACT. | 4/07(108BO 0 MCF) | |
| RED HILLS YATES FIELD | | | | | | | | | | | | | | | | |
| N | 20 | 19S | 30E | WAYNE SPEARS | KELLY | 1 | 10/10/1960 | 11/27/1960 | 1785 | YATES | P. 30 BO & 20 BW | P. 1672-1727 | 1385 BO | P & A | | P&A 2/27/68, IN SECOND MINED AREA |
| K | 20 | 19S | 30E | WAYNE SPEARS | KELLY | 4 | 12/3/1960 | 1/19/1961 | 2850 | GREY. | 1 BOPD | P. 1789-1797 | | P & A | | P&A 8/22/61, WITNESSED BY P. C. |
| EAST BENSON YATES FIELD | | | | | | | | | | | | | | | | |
| E | 13 | 19S | 30E | TOM R. CONE | FEDERAL 13 | 1 | 10/25/1960 | 12/26/1960 | 2216 | YATES | P. 70 BOPD | 2100-2120 | 40,196 BO | ACT. | 12/07(5 BO) | IN SECOND MINED AREA |
| F | 13 | 19S | 30E | TOM R. CONE | FEDERAL 13 | 2 | 2/2/1961 | 2/13/1961 | 2321 | YATES | P. 11 BOPD | 2180-2207 | 3,819 BO | ACT. | 5/08(1 BO) | IN SECOND MINED AREA |
| H | 14 | 19S | 30E | TOM R. CONE | SO. CAL | 1 | 5/16/1960 | 6/11/1960 | 2136 | YATES | P. 47 BOPD | 2098-2130 | 52,593 BO | ACT. | 5/08(54 BO) | IN SECOND MINED AREA |
| WELLS OUTSIDE OF BENSON & TURKEY TRACK FIELDS | | | | | | | | | | | | | | | | |
| P | 12 | 19S | 29E | KELLY STOUT | DUNNIGAN ST. | 1 | 10/25/1950 | 10/31/1951 | 2643 | QUEEN | | | | P & A | | WIT. & APP. 4/4/52 BY P.C., IN SECOND MINED A |
| O | 4 | 19S | 30E | ELLILOT | CANNON | 1 | 7/19/1939 | 4/17/1940 | 2355 | 7 RIVERS | | | | P & A | | REPLUGGED 4/12/56, APP 4/4/52, IN SEC MINED A |
| M | 10 | 19S | 30S | HARVEY E. YATES | FOARD | 1 | 10/19/1943 | 12/31/1943 | 2988 | QUEEN | DRY | | | P & A | | APP. 2/24/45 |
| H | 17 | 19S | 30E | HARVER E. YATES | PERKINS | 1 | 6/28/1946 | 11/20/1946 | 2703 | 7 RIVERS | DRY | | | P & A | | REPLUGGED 8/20/65, IN SECOND MINED AREA |

# WELLS WITHIN OTHER MINED AREAS

| UNIT | SECTION | TOWNSHIP | RANGE | OPERATOR | LEASE | WELL # | SPUD DATE | COMP. DATE | TOTAL DEPTH | FORMATION(AT T.D.) | RESULTS I. P. | COMP. INTERVAL | CUM. PROD. | STATUS | LAST PROD. | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WELLS WITHIN INTREPID POTASH EAST MINE'S (NEW MEXICO POTASH/KERR MCGEE) MINED AREA | | | | | | | | | | | | | | | | |
| N | 8 | 21S | 31E | BOSWORTH | CARPER BOSWORTH | 1 | 8/10/1949 | 10/1/1949 | 4505 | DELAWARE | DRY | | | P & A | | P&A 10/1/49, IN SECOND MINED AREA |
| D | 10 | 21S | 31E | BRYANT | WILLIAMSON | 1 | 1/28/1944 | 5/14/1945 | 4287 | DELAWARE | DRY | | | P & A | | P&A 5/14/45, IN SECOND MINED AREA |
| C | 35 | 20S | 32E | RYAN | ACREE | 1 | 12/28/1934 | 3/14/1935 | 3410 | YATES | DRY | | | P & A | | APP. 3/27/35, IN SECOND MINED AREA |
| WELLS WITHIN MOSIAC (IMC/IMC KALIUM) MINED AREA | | | | | | | | | | | | | | | | |
| P | 9 | 22S | 29E | H&W DRILLING | DANFORD | 1 | 5/18/1937 | 7/27/1937 | 3322 | DELAWARE | DRY | | | P & A | | IN SECOND MINED AREA |
| WELLS WITHIN INTREPID POTASH WEST'S (MISSISSIPPI CHEMICAL) MINED AREA | | | | | | | | | | | | | | | | |
| F | 18 | 20S | 32E | TEXAS PRODUCING | HUMPHREY | 1 | 4/26/1929 | 7/15/1929 | 3105 | YATES | DRY | | | P & A | | APP. 8/29/29 |

## ACTIVE WELLS WITHIN POTASH MINED AREAS

| UNIT | SECTION | TOWNSHIP | RANGE | OPERATOR | LEASE | WELL # | SPUD DATE | COMP. DATE | TOTAL DEPTH | FORMATION(AT T.D.) | RESULTS I. P. | COMP. INTERVAL | CUM. PROD. | STATUS | LAST PROD. | REMARKS | API NUMBER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WELLS WITHIN HB POTASH (INTREPID) (PCA/EDDY) MINE | | | | | | | | | | | | | | | | | |
| BARBER FIELD | | | | | | | | | | | | | | | | | |
| B | 20 | 20S | 30E | SHACKELFORD OIL CO | COLGLAZIER | 1 | 1/18/1937 | 2/11/1937 | 1443 | YATES | 132 BOPD | 1438-1443 OH | 130,831 BO | ACT. | 1/08(60 BO & 1082 BW) | | 3001504693 |
| G | 20 | 20S | 30E | SHACKELFORD OIL CO | COLGLAZIER | 2 | 8/19/1938 | 9/18/1938 | 1436 | YATES | 8 BOPD | 1418-1436 OH | 105,355 BO | ACT. | 1/08(15 BO & 97 BW) | | 3001504694 |
| F | 20 | 20S | 30E | SHACKELFORD OIL CO | STOVALL WOOD | 2 | 1/1/1941 | 1/1/1941 | 1473 | YATES | 96 BOPD | 1254-1473 OH | 195,606 BO | ACT. | 1/08(58 BO & 361 BW) | | 3001504701 |
| O | 17 | 20S | 30E | SHACKELFORD OIL CO | STATE "A" | 1 | 12/27/1941 | 1/2/1942 | 1575 | YATES | 120 BOPD | 1442-1575 | 130,165 BO | ACT. | 1/08(53 BO & 715 BW) | | 3001504685 |
| C | 20 | 20S | 30E | SHACKELFORD OIL CO | STOVALL WOOD | 1 | 1/16/1942 | 2/4/1942 | 1540 | YATES | 103 BOPD | 1406-1540 | 235,591 BO | ACT. | 1/08(52 BO & 1189 BW) | | 3001504700 |
| J | 17 | 20S | 30E | SHACKELFORD OIL CO | STATE "A" | 4 | 6/14/1942 | 7/13/1942 | 1539 | YATES | 240 BOPD | 1478-1539 | 91,731 BO | ACT. | 1/08(15 BO & 10 BW) | | 3001504687 |
| N | 17 | 20S | 30E | SHACKELFORD OIL CO | STATE | 2 | 7/20/1942 | 8/13/1942 | 1520 | YATES | 240 BOPD | 1143-1520 | 181,034 BO | ACT. | 12/03(57 BO) | NOW SWD/INJECTION | 3001504686 |
| F | 20 | 20S | 30E | SHACKELFORD OIL CO | STOVALL WOOD | 3 | 11/5/1953 | 12/23/1953 | 1470 | YATES | 125 BO+375 BW | 1306-1470 OH | 104,689 BO | ACT. | 1/08(21 BO) | | 3001504703 |
| G | 20 | 20S | 30E | SHACKELFORD OIL CO | COLGLAZIER | 3-C | 12/28/1953 | 2/6/1954 | 1553 | YATES | 120 BOPD | 1315-1553 OH | 43,586 BO | ACT. | 1/08(23 BO & 121 BW) | | 3001504695 |
| PCA FIELD | | | | | | | | | | | | | | | | | |
| F | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 1 | 11/10/1939 | 12/19/1939 | 1587 | YATES | 77 BO/11HR | 1550-1587 OH | 211,464 BO | ACT. | 2/08(14 BO & 36 BW) | | 3001504674 |
| G | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 2 | 10/4/1940 | 11/25/1940 | 1661 | YATES | 138 BOPD | 1624-1661 OH | 177,401 BO | ACT. | 2/08(3 BO) | | 3001504675 |
| J | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 3-A | 11/30/1940 | 1/21/1941 | 1639 | YATES | | | 161,939 BO | ACT. | 2/08(7 BO) | | 3001504676 |
| E | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 5 | 5/6/1942 | 6/9/1942 | 1641 | YATES | | 1552-1641 OH | 135,011 BO | ACT. | 2/08(3 BO) | | 3001504678 |
| F | 15 | 20S | 30E | SHACKELFORD OIL CO | KEYES | 7 | 10/16/1947 | 11/20/1947 | 1633 | YATES | 116 BOPD | 1531-1633 OH | 24,701 BO | ACT. | 2/08(7 BO) | | 3001504680 |
| RED HILLS FIELD | | | | | | | | | | | | | | | | | |
| P | 29 | 19S | 30E | YATES DRILLING | LANE | 3 | 8/13/1956 | 9/18/1956 | 1724 | YATES | 126 BOPD | 1606-1724 OH | 20,205 BO | ACT. | 3/08(13 BO & 307 BW) | | 3001504645 |
| WELLS WITHIN HB POTASH (INTREPID) (HORIZON/AMAX/SOUTHWEST) MINED AREA | | | | | | | | | | | | | | | | | |
| TURKEY TRACK MORROW | | | | | | | | | | | | | | | | | |
| L | 24 | 19S | 29E | YATES PETROLEUM | SOUTHLAND ROYALTY APM STATE #1 | 1 | 1/5/1979 | 2/15/1979 | 11,880 | MORROW | 1260 MCFGPD | 11,422-11,562 | 671,959 MCFG | ACT | 5/08(817 MCF & 12 BW) | | 3001522679 |
| L | 23 | 19S | 29E | CHI OPERATING | STATE 23-A | 1 | 2/20/1979 | 5/14/1979 | 11,775 | MORROW | 1925 MCFGPD | P. 11,278-11,465 | 1,010,651 MCF | INA | PLUGGED BACK TO BONE SPRINGS | | 3001522814 |
| TURKEY TRACK BONE SPRING | | | | | | | | | | | | | | | | | |
| | | | | | | | RE-COMP | 12/3/1993 | 8170 | BONE SPRING | | 7936-8022 | 162,992 MCFG | ACT. | 4/07(108BO ) | | |
| EAST BENSON YATES FIELD | | | | | | | | | | | | | | | | | |
| E | 13 | 19S | 30E | TOM R. CONE | FEDERAL 13 | 1 | 10/25/1960 | 12/26/1960 | 2216 | YATES | P. 70 BOPD | 2100-2120 | 40,196 BO | ACT. | 12/07(5 BO) | N SECOND MINED AREA | 3001504597 |
| F | 13 | 19S | 30E | TOM R. CONE | FEDERAL 13 | 2 | 2/2/1961 | 2/13/1961 | 2321 | YATES | P. 11 BOPD | 2180-2207 | 3,819 BO | ACT. | 5/08(1 BO) | N SECOND MINED AREA | 3001504599 |
| H | 14 | 19S | 30E | TOM R. CONE | SO. CAL | 1 | 5/16/1960 | 6/11/1960 | 2136 | YATES | P. 47 BOPD | 2098-2130 | 52,593 BO | ACT. | 5/08(54 BO) | N SECOND MINED AREA | 3001504600 |

# APPENDIX A-5: BACKGROUND STUDY ANNOTATED BIBLIOGRAPHY WELLBORE CEMENT AND WELLBORE LEAKAGE

The purpose of this Appendix is to provide a list of references we examined in our initial research while we were formulating how to approach the present study. It serves as an annotated bibliography. This Appendix includes a brief discussion of how we started out and why we chose not to focus on details of how cement and other wellbore construction elements fail when sealing fails. It was through reading the references cited here that we were guided to narrow the focus of the present study to the migration pathway and gas driving force because the scope of detailed study of wellbore failure is beyond the bounds of the current budget and timeframe and it is well covered in the existing literature.

At the outset when SNL began research on FEPS relevant to wellbore leakage we surveyed the literature of wellbore cement characteristics and performance and looked for studies on wellbore sealing integrity. It was quickly seen that the wellbore service companies (Schlumberger, Halliburton, Dowell and others), petroleum professional associations (Society of Petroleum Engineers and others) and universities have developed many studies on wellbore cement properties, failure modes, mitigating cement chemistry and installation practices and other aspects of cement technology and how well construction elements seal or fail to seal. We also saw that the recent interest in $CO_2$ sequestration in geologic formations that formerly produced petroleum had led to a quickly burgeoning literature on wellbore sealing and $CO_2$ migration pathways in poorly sealed wellbores. These resources provide scientific studies at a level of sufficient detail for understanding the means by which wellbores fail to seal in the present gas migration study. The entities specializing in this problem continue to study the details and work on mitigation studies but, for the present study it was decided that we would assume that gas is outside of the wellbore, creating a source for gas migration. We decided that for the present study the higher level site-specific conceptual model could be advanced by better understanding of the driving force and pathway, whereas the current budget and timeframe was insufficient to significantly advance the study of how wellbores fail to seal.

When an RA framework includes the step of “Develop Probability Models” the probability of wellbore leakage is one Event that can be estimated. One part of the current study is to describe how this might be done. In the body of the paper we discuss this in some detail with a focus on a couple of representative studies. In this section we list a few other papers on wellbore leakage. The purpose of this background study was to find prior studies that show how the probability assessment piece might be approached in future study.

**Cement Properties and Cement Failure in Wellbore Sealing**

A group at the University of Texas at Austin is currently developing detailed models of FEPs in the near-wellbore region during cementing (Gray, et al., 2007). Their finite element models look in detail at the near-wellbore geomechanical environment and material models for cement, casing and formations in a series of studies. A thesis in this area is Huerta (2009) which presents a study of fluid leakage along a cemented wellbore and looks at the effects of sustained casing pressure and geomechanics.

A good basic reference on cement properties comes from the Portland Cement Association (Bhatty and Tennis, 2008). In the body of the geomechanics section of the paper both ASTM and API standards are also cited.

Morris, et al. (2003) performed tests on cement toughness when additives are used and provided cement mechanical properties. They noted that well completion operations (perforating and fracturing) and mechanical stress from formation displacements can severely damage cement's ability to seal.

Gas migration into the cement sheath/annulus is a problem that affects zonal isolation as is discussed in Bonett and Pafitis (1996). This occurs when pressure is lower in the annulus than at the formation face, a common problem. It discusses how stress imbalances at cement interfaces create microannuli that allow migration.

Papers that discuss cement properties include Benge (2009) which looked at injection wells and observed that a current problem in stress modeling of the wellbore environment is the need for good data on cement mechanical properties including Young's Modulus for which they say there are no consistent test methods. The change in boundary conditions as the wells change is also a problem noted by Benge. This paper also discusses Portland and non-Portland and specialty cements and the use of swell packers in well annuli. Other papers looking at cement properties and mechanical behavior include Mueller and Eid (2006), Rogers, et al., (2006),

McCulloch, et al. (2003), present cement properties and analysis of failure modes in geothermal wells. They include conventional and thermal resistant cements and discuss the role of life-cycle modeling in selecting appropriate cements.

Kulakofsky, et al (2006) discussed ultra lightweight cement technology to improve cement circulation and seal. They noted that standard density for oilfield cement is 15.6-16.4 lb/gal and how cement that is too heavy can breakdown and be lost in weak or depleted zones. They also noted that remedial cementing, trying to repair a poor primary job, is often "hit or miss." They described the problems of creating lightweight cement through dilution that led to using lightweight microspheres or stable foam for density reduction. Cement that is too dense won't circulate properly in the annulus and could fail to seal in production zones allowing formation water a migration pathway.

**Wellbore Leakage**

In the body of the paper we have discussed the Canadian studies by Watson and Bachu and others whose studies led us to focus on cement as a sealing Feature the condition of which can be directly linked to probability of wellbore leakage. Their studies and those that followed used publically available well records to compare cement bonding conditions to wellbore leakage as detected through surface casing vent valves and gas migration studies required by Canadian regulations since 1995. Example papers from these studies are Gasda, Bachu and Celia (2004), Watson and Bachu (2007) and Bachu and Bennion (2009).

The 2008 Watson and Bachu study presented factors associated with a likelihood of wellbore leakage and they included degradation of cement in plugs temporarily or permanently placed in wells. Another Canadian study authored by Nygaard (2010) discusses leakage factors and cites several other studies of wellbore leakage that give percentages of leaking wells as well as containing a good summary Table 2 (p. 10-11) of cement types citing Schlumberger and Halliburton sources. Wakeley et al. (1981) characterized samples of a cement-borehole plug in evaporates in SE New Mexico that had been in place in the Salado for 18 years. A joint industry group studying wellbore plug failure as an element in leak potential has published papers including Mainguy, et al., (2007) which discusses the effects of pressure and thermal stresses after abandonment. From the various Watson, Bachu and associates studies it can be concluded that coverage of the casing by cement is important in preventing corrosion, a conclusion supported in Crow, et al., (2009) which found good casing condition in a 30 year old well exposed to natural $CO_2$ because it had good cement coverage that limited circulation of formation fluids at cement-casing interfaces.

They looked at other aspects of $CO_2$ sequestration that are also relevant to the BLM gas migration study including looking at failures in injection wells in Bachu and Watson (2009).

Several papers address modeling issues and the physics of the problem of gas migration from wellbores including Tao, et al. (2010) which discusses the connection between sustained surface casing pressure and the transport properties of the wellbore leakage pathway. Viswanathan et al., (2008) at Los Alamos have also developed models that attempt to capture the physics of the wellbore leakage problem and discuss the role of cement in the problem and how difficult it is to characterize some key parameters such as effective wellbore cement permeability.

Potash industry stakeholders have expressed interest in the possibility of water migration through wellbore pathways. Though their concern is primarily with downward migration, groundwater salination from migrating oil field waters has been studied by Jeffery G. Paine of the Texas Bureau of Economic Geology who has shown that this phenomenon can be detected using airborne geophysics.

M.B. Dusseault, SPE, Porous Media Research Institute, University of Waterloo, Waterloo, Ontario has published on why wells leak and cites the mechanisms of channeling, poor cake removal, shrinkage and high cement permeability (Dusseault, et al., 2000). This paper notes that issues of cement emplacement and behavior are complex and that some problems arise from shrinkage that leads to "…circumferential fractures that are propagated upward by the slow accumulation of gas under pressure behind the casing." (p. 1). The paper discusses issues in salt sections where high concentration formation brines dewater cement slurries which shrink during setting while also stating that “Cement will not bond to salt…” (p. 3). According to the study if effective radial stress is not maintained in a cement sheath, a circumferential fracture can open, seen as a lack of “bond” on cement bond logs and hydraulic fracturing conditions can exist at this interface (p. 3). These fractures are seen to develop over time and with service (p.3).

Stringent well integrity operations occur in some large fields with large resources to dedicate to this area. Anders, et al., (2006) describes a wellbore integrity monitoring system at Prudhoe Bay and mentions some guidelines that may be applicable to the present study. Their wellbore evaluations look for two levels of protection for wellbore integrity and examine where product might go if one barrier leaks and how the newly pressured components will react. They’ve also tried to address questions like how much tubing can leak and still be an effective barrier. They present other useful starting points for discussion relevant to the present study in the area of leakage potential.

The USDOE National Energy Technology Laboratory (NETL) is funding study of wellbore leakage factors and in October of 2009 started a study called “Quantification of Wellbore Leakage Risk Using Non-Destructive Borehole Logging Techniques.” Ongoing work can be followed at www.netl.doe.gov.

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# APPENDIX A-6: LIST OF WELLS FROM THE NMOCD SITE OF POSSIBLE ISSUES – PG. 1

| API | Spud Date | First intermediate string top of cement (TOC) | Well installation issues | Well workover issues |
|---|---|---|---|---|
| 30-015-04735 | 11/29/1956 | TOC 5270', bottom of salt casing 3848' | First intermediate string lost circulation, no returns while cementing, lost 500 bbls mud, then 180 bbls | 12/93 Sundry Notice of Intention: Pull tubing, replace bad joints |
| 30-015-10806 | 6/13/1966 | TOC 4865', bottom salt casing 3657 | Had problems cementing and discovered first intermediate string collapsed (8551-8597') while perforating and appear to have re-run liner | 1/03 Workover found tubing thin, holes, and collars in very poor condition, also parted casing 12152-12154', holes at 11870-11880' and 2750-2752' and noted "casing shows wear throughout" |
| 30-015-20232 | 9/24/1971 | TOC 3550', bottom salt casing 3890' | | 5/73 Reported communication between tubing and annulus at 12847', annulus producing from another zone, internal leak; 1/76 Removing tubing, left 24 joints and equipment in hole, fished and cleaned hole |
| 30-015-20298 | 6/9/1970 | TOC 3140', bottom salt casing 4454' | 8/70 to 10/70 First attempt to cement top of liner left no cement on top of liner, squeezed 100 sacks | 6/92 Replaced all tubing, deteriorated, and fished for a stuck packer; 11/98 Pushed fish (ESP pump, cable, tubing) to bottom, recovered some equipment, reamed and milled |
| 30-015-20803 | 5/21/1973 | TOC 3900, bottom salt casing 3890' | 10/73 Atoka frac 12912-12920' went out of zone into Morrow (top at 13764') | |
| 30-015-21277 | 7/25/1974 | TOC 3920', bottom salt casing 3325' | | 6/75 Found hole eroded in tubing opposite Strawn perforations due to abrasives from Strawn; 6/75 Found saltwater percolating from cellar, bradenhead open; 4/09 Perforated 3874' and cemented to 700' from surface; 5/09 Cement Bond Log (CBL) 50% bond 2500-1700' and 0% 810' to surface |

| API | Spud Date | First intermediate string top of cement (TOC) | Well installation issues | Well workover issues |
|---|---|---|---|---|
| 30-015-21501 | 3/29/1975 | TOC 3542', bottom salt casing 3698' | | 12/00-3/01 Workover found 8 joints tubing corkscrewed with bottom joint split, partially collapsed casing, 13.375" parted at 2401', logging tool lost outside of casing |
| 30-015-21672 | 11/6/1975 | TOC 3325', bottom salt casing 3300' | 6/76 Lost returns while cementing first intermediate casing 7.625", ran 3/4" tubing to 1167' between 7.625" and 10.75" and cemented annulus; Did not tag cement with bit when returning to 5" liner after cementing, set retainer and squeezed | 7/81 Proposed workover to retrieve stuck BHP bomb (stuck since 1/80 during unsuccessful packer leakage test) at Atoka and "repair leak in Morrow string" (dual); 11/81 Found tight spots; perforated at 10653', pumped in 60 bbls KCL, recovered 1.5 bbls, lost returns; found channel behind pipe from 12680' to Atoka perforations 12432-12441', cemented across perforations, CBL good 12422-12558', poor 12558-12700' |
| 30-015-21781 | 5/9/1976 | TOC 3100', bottom salt casing 3123' | 6/76 Had problems cementing 20" casing, shoe didn't hold, bradenhead squeezed; lost returns cementing 9.625" and didn't circulate cement to surface between 9.625" and 13.375" then after completion cemented this annulus with 1" coiled tubing | 11/91 Sundry Notice of Intention: "Swabbing indicates tubing has a leak" |
| 30-015-22162 | 9/4/1980 | TOC 9590', bottom salt string 3726.59' | Didn't circulate cement and installed part of cement with 1" for 17.5" hole | 8/09 Workover found "tubing leak on 175th joint of 2.875 tubing... split 5" above pin, top of fish at 5494' "; 9/09 "Tag bad spot in 5.5" casing" cut, milled and washed hole until 5.5" came free |
| 30-015-23175 | 8/12/1980 | TOC 7850', bottom salt string 4206' | | 3/95 Sundry Notice of Intent: "Repair behind pipe", fishing Vann guns at 14243'; 2/01 sundry Notice of Intent: "Repair a tubing leak" |

| API | Spud Date | First intermediate string top of cement (TOC) | Well installation issues | Well workover issues |
|---|---|---|---|---|
| 30-015-23377 | 9/18/1980 | TOC 6040', bottom salt string 3839' | Stuck 5" liner in deviated hole (13881') due to doglegs, ran tubing to TD (14600') through liner (requested exception to tubing setting rules), perforated 13044-48' | |
| 30-015-23389 | 6/17/1981 | No TOC | Cement didn't circulate for 20" casing, used 1" to bring to surface | |
| 30-015-23992 | 1/31/1982 | No TOC | Cementing 9.625" bullheaded second stage down backside and used 1" to cement 747' to 409' (bottom 20" casing at 604'); Cementing 7.625" liner (second intermediate) no cement between float collar (14203') and float shoe (14245') none below shoe, had to squeeze shoe | |
| 30-015-24780 | 4/10/1984 | TOC 6936', bottom salt string 4012' | Fished stuck drill pipe 3 times 13118-13699', left fish in hole, put in cement plug 13353-12875', not solid, re-cemented, kicked off around fish at ~13278' | |
| 30-015-26509 | 10/29/1990 | TOC 4240', bottom salt string 4122' | | 7/07-11/07 Workover found hole in casing at 5066-98' when going in to perforate Bone Spring |
| 30-015-27410 | 5/5/1993 | No TOC | Cementing 7" casing, lost circulation during last 40 bbls displacement mud after second stage cement and valve wouldn't close with 4 tries | |

| API | Spud Date | First intermediate string top of cement (TOC) | Well installation issues | Well workover issues |
|---|---|---|---|---|
| 30-025-30886 | 5/23/1990 | TOC 1400', bottom salt string 4600' | 5/90 17.5" surface hole, didn't circulate cement and used 1" tubing to fill from 100' to surface;7/14/90 Stuck drill pipe 14277' and recovered fish 8/2/90; Workover 11/19/1994-4/9/1995 was lengthy due to "tool and fishing complications" | |
| 30-025-32383 | 1/20/1994 | TOC 2500', bottom salt string 4640' | | Completion and workover data on well diagram sheet notes 1/99 suspected tubing leak, 5/99 suspected casing leak; 11/02 drilled cast iron bridge plug and left pieces in hole |
| 30-015-31511 | 5/26/2001 | TOC 1800' bottom salt string 3148' | 6/3/01-7/14/01 12.25" hole to 3148' did not circulate cement, TOC at 440', used 1" to fill in, then on 8.5" hole when running 7" casing after second stage cement, lost circulation after 70 bbl displacement, pumped 160 bbl with no circulation, TOC 1800', tried to run 1", then 3/4" down back of 7" casing and couldn't get past 90', received permission to leave as was | |

# APPENDIX B: STANDARD AND SPECIALIZED WELLBORE CEMENTS IN DELAWARE BASIN EVAPORITE GEOLOGY

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Standard Specialized Wellbore Cements in Delaware Basin Evaporite Geology

**Introduction**
Sandia National Laboratories is performing a risk assessment for the Bureau of Land Management(BLM) to examine scenarios of possible gas migration from old, degraded or poorly cemented wellbores into active potash mines in the Delaware Basin in Southeast New Mexico. The components of the entire system consist of the geological system, the wellbore and its construction and the mining operation. Wellbore cement is important to prevent gas migration because the cement acts as a sealant. The engineering and chemical properties of the cements, standard and special, are important in creating the sealing capability. The study will survey wellbore cements used in the Delaware Basin, special and standard, to provide data for decision makers. The study will also collect data for both, standard and special, cements on their applications, chemical composition, and engineering properties. In addition, it will catalogue performance claims of the service companies for special cements. This study will examine the wellbore cement degradation factors including: geochemical and mechanical effects along with the initial wellbore installation

**Background**
The Delaware Basin, part of the Permian Basin, is a 300 million year old structural depression covering approximately 23,000 km$^2$ from north of Carlsbad, New Mexico going south into Texas. This survey will briefly discus the stratigraphy and geology of relevance to the BLM gas migration study. The geology of the area is comprised of the following (shallowest to deepest): the Dewey Lake, Rustler, Salado, and Castile as well as the Bell, Cherry and Brushy Canyons.

Oil and gas production in the area goes to the Morrow (between 11,000' and 14,000'), while the potash mines are in the Salado formation (approximately 850'-2830'). The Salado in the Potash Horizon consists of about 60% halite, 30%sylvite, 5% langbeinite, while the other 5% is polyhalite and insoluble minerals. The Salado is rich in salt and ground waters and re-injected production waters are often brines. This survey will mention the effect of brines on cement as a geochemical degrading factor. With petroleum and potash resources being in the same area the government placed the Department of the Interior in charge of resource development. The Bureau of Land Management is the agent for making the decisions. There are also regulatory requirements from the state of New Mexico that control wellbore construction.

The BLM is concerned with standoff distances between the mining and drilling operations because of the safety considerations and because both industries want to maximize their production. The safety concern is that the oil and gas wells have to go through the potash zones in order to get to the oil reservoirs. Gas migration from well bores is one of the safety aspects that BLM is looking into. Cement is used in the wellbore as a sealant to prevent gas migration. This survey will show the mechanical properties of some of the cements available, along with the composition of the cement. This study will also look at the following factors of cement degradation: geochemical effects, pressure and temperature effects, mechanical stresses and installation factors.

**Research**

The research for this study examines properties of cements used in Delaware Basin wellbores. This survey examines both standard and specialized cements that are available. Standard cements are considered the bare minimum needed for a cement to be used in a wellbore. The cements that were determined to be standard are the different mixes of API and Portland cement mixes. The industry declared these the standards because they are both functionally capable and cost effective. Although considered standard the cements varies in use by depth and location (personal communication Dustin Guidry BJ's Services). The most commonly used standard cements in the study area are API Class C, from surface to 6,000', and Class H, below 6,000'. (Faulkner, Jones, Guidry)

Over time, the Delaware Basin has been home to many well bores and it should be noted that the standard cement has varied between each well. Even the wells that were constructed in the same time period vary between each company. Also, the variability of a well could change from the top of the well to the bottom due to each need. The standard cements examined in this survey are all of the classes regulated by the American Petroleum Institute (API) and four of the five classes set by the Portland Cement Association (PCA). The Portland Cements also follow ASTM standards.

Cements are described by their chemical composition and this changes for each cements needs and depth to be used at. Also, cements are described by the different components that API and ASTM have made optional chemistry (i.e. fly ash). They also vary in the type and size of aggregate that the cement uses (personal communication J. Krumhansl). Standard cements can also be defensive against common degrading factors. For example certain API cements are made to mitigate the effects of sulfate. Specialty cements use a basic mixture of the standard cement needed for the depth in the well bore then which ever specific additive is needed for the geology. They can be tailored to help make the geology and cement combination work better together. An element that is important to the cement's ability to seal to the casing is the cement's mechanical properties. The mechanical properties viewed in this study are: strength, Young's modulus, Poisson's ratio, density, porosity percent, permeability and the chemical composition of the cements. Tables 1 and 2 show the properties of API and Portland Cements. The API cements, shown in Table 1, are different because they have standards for ordinary cement, medium sulfate resistance cement and a high sulfate resistance. The need for sulfate resistant cements is to help prevent the cement from having the aluminum sulfate reaction which will degrade the cement.

Table 2 displays the chemistry of the Portland Cement as well as the mechanical properties. The information that is missing from Table 1 and Table 2 was not available because of the lack of research done on the cements. (Ehgartner 2010)

| | API | Cements | | | |
|---|---|---|---|---|---|
| **Cement Class→** | A | B | C | G | H |
| **Cement Composition ↓** | | | | | |
| **Ordinary Type (O)*** | | | | | |
| Magnesium oxide, maximum % | 6 | : | 6 | : | : |
| Sulfur trioxide, maximum % | 3.5 | : | 4.5 | : | : |
| Tricalcium aluminate, maximum % | : | : | 15 | : | : |
| **Moderate Sulfate-Resistance Type (MSR)*** | | | | | |
| Magnesium oxide, maximum % | : | 6 | 6 | 6 | 6 |
| Sulfur trioxide, maximum % | : | 3 | 3.5 | 3 | 3 |
| Tricalcium silicate, maximum % | : | : | : | 58 | 58 |
| Tricalcium silicate, minimum % | : | : | : | 48 | 48 |
| Tricalcium aluminate, maximum % | : | 8 | 8 | 8 | 8 |
| Total alkali content expressed as sodium oxide equivalent maximum % | : | : | : | 0.75 | 0.75 |
| **High Sulfate-Resistance Type (HSR)*** | | | | | |
| Magnesium oxide, maximum % | : | 6 | 6 | 6 | 6 |
| Sulfur trioxide, maximum % | ; | 3 | 3.5 | 3 | 3 |
| Tricalcium silicate, maximum % | : | : | | 65 | 65 |
| Tricalcium silicate, minimum % | : | : | | 48 | 48 |
| Tricalcium aluminate, maximum % | | 3 | 3 | 3 | 3 |
| Tetracalcium aluminoferrite plus 2 times tricalcium aluminate, maximum % | : | 24 | 24 | 24 | 24 |
| Total alkali content expressed as sodium oxide equivalent maximum % | : | : | : | 0.75 | 0.75 |
| **Mechanical Properties** | | | | | |
| Minimum Compressive strength (24 hrs.) (Psi/MPa)* | 1800/12.4 | 1500/10.3 | 2000/13.8 | 1588/10.95 | 1588/10.95 |
| Tensile Strength (psi)** | N/A | N/A | 217.5 | 270.6 | 467 |
| Young's Modulus** | N/A | N/A | 3.8x10^6psi | 5.48 | 1.91 |
| Poisson's ratio** | N/A | N/A | 0.19 | 0.015 | 0.193 |
| Porosity %** | N/A | N/A | 6.5 | 33.84 | 21 |
| Permeability** | N/A | N/A | N/A | 1.116x10^19 | 5.63x10^-6 |
| Density (pounds per gallon)** | 15.6 | 15.6 | 14.8 | 15.8 | 16.5 |

Table 1. API Cements (1. American Petroleum Institution, **Properties were found through multiple sources.)

Table 2. Portland Cements (*American Society for Testing and Materials, 1979, **Rogers et al., 2006).

| | Portland | Cements | | |
|---|---|---|---|---|
| **Cement Type→** | I | II | III | V |
| **Cement Composition ↓** | | | | |
| **Portland Cement***[*]** | | | | |
| Silicon Dioxide, minimum % | : | 21 | : | : |
| Aluminum oxide, maximum % | : | 6 | : | : |
| Ferric oxide, maximum % | : | 6 | : | : |
| Magnesium oxide, maximum % | 6 | 6 | 6 | 6 |
| Sulfur trioxide, maximum % | 3 | 3 | 3.5 | 2.3 |
| Tricalcium silicate, maximum % | : | : | : | : |
| Dicalcium silicate minimum% | : | : | : | : |
| Tricalcium aluminate, maximum % | : | 8 | 15 | 5 |
| Tetracalcium aluminoferrite plus 2 times tricalcium aluminate, maximum % | : | : | : | 20e |
| **Mechanical Properties** | | | | |
| Minimum Compressive strength (24 hrs.) (Psi/MPa) | 1260/8.7 | 1100/7.6 | 2350/16.2 | 1070/7.4 |
| Tensile Strength** | 191 | 191 | 169 | 149 |
| Young's Modulus[**] | 0.764 | 0.764 | 0.621 | 0.621 |
| Poisson's ratio[**] | 0.107 | 0.107 | 0.142 | 0.142 |
| Porosity %[**] | N/A | N/A | N/A | N/A |
| Permeability[**] | N/A | N/A | N/A | N/A |
| Density (pounds per gallon)[**] | 15 | 15 | 14 | 14 |

Table 3. lists some specialty cements offered from Halliburton and Schlumberger, information from Hallibrutron.com and Schlumberger.com.

| Specialty | Cements |
|---|---|
| Halliburton | Schlumberger |
| **CorrosaCem™ Cement**<br>Designed to survive under a wide variety of corrosive wellbore environments | **ISOBLOK**<br>Latex particle and liquid polymer synergy for gas migration control for temperatures ranging from 38 to 177 degC (100 to 350 degF). |
| **ExtendaCem™ Cements**<br>Designed to create a lower cost cementing solution | **D400 EasyBLOK**<br>Solid, water-activated, low-molecular-weight polymer additive for temperatures ranging from 20 to 110 degC (68 to 212 degF). |
| **ElastiCem® Cement**<br>Designed for wells where a more elastic or resilient cement is required | **CemCRETE**<br>Increases the solid content of the slurry using particle-size distribution technology. |
| **ReverSeal™ Cement**<br>Designed to effectively circulate down the annulus forming an annular seal even when pumped backwards | **FUTUR Self-Healing Cement System**<br>Active Set-Cement Technology for Long-Term Zonal Isolation |

**Factors that Degrade Cements**

Cement performs at its best if it provides a seal between the casing and the geology preventing fluids to flow into undesirable pathways. Factors that contribute to the degradation of wellbore cement include geochemistry, mechanical stresses (which in this study includes the effects of pressure) and poor cement installation. The degradation of the cement due to any of these factors can jeopardize the integrity of the seal created by the cement in the original installation. Each of these aforementioned factors have been written about in depth and the purpose of this survey is to introduce the factors while summarizing their effects on the wellbore cement and if it has the potential to allow gas migration.

Degradation of cement in this survey means that the properties needed to create a seal between the cement and the casing has been degraded. If the cement's ability to seal has been degraded then that opens up possibilities for gas migration out of the well. Sealing is degraded when the cement begins to have faults like vugs, cracks, loss of strength and density or has an increase in permeability or porosity.

To discuss all of the possible scenarios that would result in geochemical, mechanical or installation factors degradation of cement is beyond the scope of this survey. This survey will consider just a few examples. Companies tailor specialty cements to help mitigate factors that degrade cement.

The geochemical factors that can degrade the wellbore cement are the hydrogen sulfide and the brine which is present in the Salado and formations beneath the Salado. The effect of hydrogen sulfide on the cement comes from the aluminum sulfate reaction and leads to deterioration of the cement. Therefore, bacterial action is first needed to oxidize the $H_2S$ to $H_2SO_4$ at which point both the development of sulfuric acid and the pressure of sulfate are destructive to cement integrity. (Personal Communication Krumhansl 2010). The brine of the Delaware Basin and the cement reaction is discussed in depth by Krumhansl 2010, and in a summary, we find that the brine an however, independent of this most Salado brines inherently contain large amounts of sulfate concentrations. While those that originate from

underlying strata are poorer in sulfate, but richer in $H_2S$. It is this combination of features that conclude that weakened and degraded cement could occur within a few, months, or more time, decades, depending on the amount of brine that comes into contact with the cement.
The mechanical stresses discussed in this survey have been further elaborated and discussed in other reports (Arguello et al., 2009). The main stress discussed in the Arguello report is interbed slippage, either naturally caused or from an external force. This has an effect on the cement due to the pressure applied in opposite directions, and if the elasticity and strength aren't high enough the cement would likely begin to crack and eventually crumble. Arguello further discusses the effects of slip occurring away from the potash mines and notes that the cement acts as a barrier to prevent the casing from being severely damaged.

The source of the external pressure can possibly come from the salt. The Salado of the Delaware Basin is a salt zone, which has been characterized to creep. If the salt were to creep and form around the cement, the cement will face a large amount of exerted pressure. Pressure inside of the casing from the production pressure can put mechanical stress on the cement. The data for pressures in well bores in the potash area will be examined in a later study. Sandia National Laboratories will be asking for these data from the petroleum companies and will study the effect pressure has on the cement and casing from leaking wellbores.

Initial wellbore installation is a factor of degradation to cement. If the cement is not installed correctly then the cement will be more likely to have faults and fail. Bachu and Bennion (2008) cover the effects of a poor seal between the casing and cement in detail. If the cement and casing bond is not perfect then that leaves voids for the gas to flow out of it, and naturally the larger the void the more gas that is able to escape from the well. Also if the cement is installed before the drilling mud is removed then the cement will not be able to function at a maximum level and is less effective because it would have shrunk (Krumhansl 2010).

**Results**

This survey examined wellbore cement as a factor in the potential for gas migration from the petroleum wells into the potash mines for BLM. In this report the properties of standard cements were given and according to Bachu and Bennion (2008) a good seal between the cement and casing will be a reliable barrier to prevent gas migration. Also if the cement is not installed correctly this will jeopardize the cement's ability to bond with the casing and seal the gas inside. This shows that if used correctly standard cement would be able to seal the gas inside the well and help to prevent gas migration.
The research also suggests that the specialty cements improve the performance of cement. (Morris et al, 2003) If the right additive is used the cement could be made much stronger and have a much better ability to bind the cement to the casing. If the cement is installed correctly and the amount of contact with factors of degradation is limited the cement has a better chance at sealing with the casing and has less potential to allow gas migration.

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# APPENDIX C: FEATURES, EVENTS, AND PROCESSES CONSIDERED FOR INITIAL RISK ASSESSMENT EXERCISE FOR POTENTIAL GAS MIGRATION: EXAMPLE 1

| Wellbore Sub-System | Features | Events/Processes |
|---|---|---|
| **See Figure 3-1** | | |
| Cement | Cement material properties (strength, density, etc.) both initial and degraded by time and wellbore environment or enhanced by workover; cement emplacement zones; see Table 4-9 | Cement fracture, chemical degradation, absence of cement during emplacement, processes causing cement bond to fail, adding cement during workover |
| Casing, Liners, tubing | Material properties, thread types, size, weight and set points; configuration of casing/ liner/tubing (overlaps, etc) | Installation, degradation by aging, degradation by drilling and workover; sudden casing collapse or breech |
| Wellbore configurations (oil, gas, dual, single, active, TA, PA, type and location of plugs, injection, completion intervals, deviation, annuli, vent valves) | Configuration of wellbore elements, casing, cement, tubing, packers, plugs, etc. including new and as changed or degraded over time | Workover changes, degradational processes from aging or workover processes |
| Production<br>(oil, gas, condensate) | Source and driving force properties, nature of the fluid, pressure of driving force at any given time | Source changes (nature of fluid) over time; Driving force pressure changes over time; Change in location of source/ driving force by workover |

# APPENDIX C: FEATURES, EVENTS, AND PROCESSES CONSIDERED FOR INITIAL RISK ASSESSMENT EXERCISE FOR POTENTIAL GAS MIGRATION: EXAMPLE 2

| Geomechanical Sub-System | Features | Events/Processes |
|---|---|---|
| **See Table 4-1, Table 4-10, Figure 4-1, Figure 4-2, Figure 4-3, Figure 4-4** | | |
| Undisturbed geology/hydrology | Lithologic parameters (composition, density, permeability, porosity, etc) | Very slow natural geologic processes unlikely to impact features over time periods of interest to production |
| Disturbed geology/hydrology around wellbore | Permeability, porosity, fractures, changed fluid composition | Installation of wellbore, perforation and stimulation |
| Disturbed geology/hydrology subsidence-impacted | Permeability, porosity, fractures, compaction, dilation, etc. | Geologic layer slip caused by subsidence, changed hydrologic flow conditions; Slip, stress changes in marker beds due to subsidence with possible fracturing and change in porosity in marker beds; Stress changes in salt or potash changing porosity |
| Disturbed geology/hydrology, mined area | Permeability, porosity, fractures changed by mining activities | Primary and secondary excavation, blasting, drilling, collapse of rooms/walls; creation of fractures due to stress changes; alteration of porosity due to shear stresses (dilatancy) |
| Disturbed geology/hydrology from existing boreholes, coreholes wellbores | Cased or uncased holes; configuration of cased holes; see wellbore features; geometry of distribution of all boreholes | Creation of potential preferential pathways for fluid flow |
| Wellbores impacted by disturbed geology, drilling and workover activities | Casing, cement, geology/hydrology permeability, fracturing, compaction, etc. | Geologic layer slip caused by subsidence, pressure impacts on casing and cement from drilling and workover activities |

# APPENDIX C: FEATURES, EVENTS, AND PROCESSES CONSIDERED FOR INITIAL RISK ASSESSMENT EXERCISE FOR POTENTIAL GAS MIGRATION: EXAMPLE 3

| Geological/Hydrological Sub-System | Features | Events/Processes |
|---|---|---|
| **See Table 5-1** | | |
| Lithology | Composition (halite, sylvite, potash, etc.); see descriptions Section 5.3 | Very slow natural geologic processes unlikely to impact lithology over time periods of interest to production |
| Rock petrophysical, geomechanical properties | Density, mechanical and strength properties, permeability, friction coefficient along slip surfaces, etc.; see Tables 4-3 through 4-8 | Human-caused resource development activities change geomechanical properties in affected zones by changing stresses, adding or subtracting fluids, etc.; effects of pressurization on rocks |
| Stratigraphy | Layering sequence, nature of contacts between lithologies; see descriptions Section 5.3 | Mining subsidence impacting contacts between lithologic layers |
| Geochemistry | Fluid composition (gas, oil, brine, multiphase); sorption, desorption of gas; geochemistry of rocks and minerals | Impacts from resource development; intentionally add or remove fluids; unintentional leakage of natural or man-made fluids |
| Water-bearing zones (aquifers and non-potable) | Composition, especially salts and dissolved solids | Wellbore fluids leak into groundwater; fluids injected into geologic formations; displacement of formation fluids |
| Potash-bearing zones | Location, geometry, lithology, etc. | See mining events/processes |
| Petroleum-production zones | Location, geometry, lithology, production characteristics etc. | See wellbore events/processes |
| Vertical geothermal gradient | Temperature of rocks at varying depths | Very slow natural geologic processes unlikely to impact gradient over time periods of interest to production |

# APPENDIX C: FEATURES, EVENTS, AND PROCESSES CONSIDERED FOR INITIAL RISK ASSESSMENT EXERCISE FOR POTENTIAL GAS MIGRATION: EXAMPLE 4

| **Mine Sub-system** | **Features** | **Events/Processes** |
|---|---|---|
| | **See Figure 4-3** | |
| Mining type (longwall, room and pillar) | Geometry and configuration changes over time; dimensions of mined areas (height, room size, extraction ratios, etc.); equipment used and timing; 3D stresses associated with mining methods | Primary mining activities; secondary mining activities |
| Depth of mine | 1000' or 2000' depth used for general cases | Depth can change over time as mining follows resource zones |
| Nature of resource (salt or potash) | Lithology, stratigraphy, geometry, depth, features impacting economics (grade, thickness, etc.) | Very slow geologic processes unlikely to impact resources; see mining events/processes; |

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