Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches

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EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) Underground Injection Control (UIC) program regulates injection of fluids related to oil and gas production as Class II injection wells for the protection of underground sources of drinking water (USDW). Unconventional resources and new technologies, such as horizontal drilling and advanced completion techniques, have expanded the geographic area for oil and gas production activities resulting in a need for Class II disposal wells in some areas previously considered unproductive.

Recently, a number of low to moderate magnitude (M<5.0) earthquakes[1] were recorded in areas with Class II disposal wells related to shale hydrocarbon production. To address the concern that induced seismicity could interfere with containment of injected fluids and endanger drinking water sources, EPA's Drinking Water Protection Division requested the UIC National Technical Workgroup (NTW) develop a report with practical tools for UIC regulators to address injection-induced seismicity. This report used the existing Class II regulatory framework to provide possible strategies for managing and minimizing the potential for significant[2] injection-induced seismic events. The report focused on Class II disposal operations and not enhanced recovery wells or hydraulically fractured wells using diesel.

Unconventional production activities and associated larger wastewater volumes have resulted in an increased need for disposal capacity. Some disposal wells handling the increased volumes are located in new geographic areas. A few disposal wells, some of which are in these new geographic areas, have been suspected of inducing seismicity. Of the approximately 30,000 Class II disposal wells in the U.S., very few (<10) disposal well sites have produced seismic events with magnitudes greater than M4.0[3]. In formulating these strategies, the NTW conducted a technical literature search and review. Additionally, the NTW evaluated four case examples (Arkansas, Ohio, Texas, and West Virginia) and considered data availability, and variations in geology and reservoir characteristics. EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity.

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1 Information on earthquake terms is included under Glossary terms or http://earthquake.usgs.gov/earthquakes/glossary.php for terms used in USGS maps; http://earthquake.usgs.gov/learn/glossary/ for general earthquake terms

2 For the purposes of this report, the Induced Seismicity Working Group considers "significant" seismic events to be those of magnitude to potentially cause damage or endanger underground sources of drinking water.

3 Chapter 3, Table 3.4, page 104, and Chapter 7, Injection Wells for the Disposal of Water Associated with Energy Extraction Finding No. 1, pages 171-172; "Induced Seismicity Potential in Energy Technologies," 2013 NAS Publication.

Disposal wells are one of a number of historic causes of human activity-induced earthquakes. Others include construction and management of dams and water reservoirs, mining activities, oil and gas production, and geothermal energy production. Evaluation of induced seismicity is not new to the UIC program. This report is intended to describe for UIC program management the current understandings related to induced seismicity within the existing Class II regulatory framework for Class II disposal. The Class II UIC program does not have regulations specific to seismicity but rather includes discretionary authority that allows additional conditions to be added to the injection permit on a case-by-case basis as well as additional requirements for construction, corrective action, operation, monitoring, or reporting (including closure of the injection well) as necessary to protect USDWs.[4] Legal and policy considerations of Class II regulations, including regulatory revisions, are outside the scope of this technical report. This report is not a guidance document and does not provide specific procedures, but does provide the UIC Director with considerations for addressing induced seismicity on a site specific basis, using Director discretionary authority.

The NTW confirmed the following components are necessary for significant injection-induced seismicity: (1) pressure buildup from disposal activities, (2) Faults of Concern[5], and (3) a pathway for the increased pressure to communicate with the fault. The NTW noted that no single recommendation addresses all of the complexities related to injection-induced seismicity, which is dependent on a combination of site geology, geophysical and reservoir characteristics. An absence of historical seismic events in the vicinity of a disposal well does not provide complete assurance that induced seismicity will not occur; however, this historic absence may be an indicator of induced seismicity if events occur following activation of an injection well. A basic assumption is that an accurate history of seismic monitoring in the region of the injection well exists. Conclusive proof of induced seismicity is difficult to achieve, but is not a prerequisite for taking early prudent action to address the possibility of induced seismicity.

The NTW developed a decision model (Figure 1) to inform UIC regulators about site assessment strategies and practical approaches for assessing the three fundamental components. The model begins with considerations for a site assessment dependent on location specific conditions, because understanding the geologic characteristics of a site is an essential step in evaluating the potential for injection-induced seismicity. Monitoring, operational and

[4] 40 CFR §144.12(b); 40 CFR §144.52(a)(9) or (b)(1); or appropriate section of 40 CFR Part 147

[5] Fault of Concern as used in this report denotes a fault that is optimally oriented with the potential to cause a significant earthquake. Fault may refer to a single or a zone of multiple faults and fractures.

management approaches with useful practical tools for managing and minimizing injection-induced seismicity are recommended.

The NTW also found that the application of basic petroleum engineering practices coupled with geology and geophysical information can provide a better understanding of reservoir and fault characteristics. The multi-disciplinary approach offers many ways of analyzing injection-induced seismicity concerns, possibly identifying anomalies that warrant additional site assessment or monitoring. Such an approach would be enhanced by collaborative work between a wide variety of individuals in industry, government, and scientific and engineering research organizations. Consequently, the NTW recommends that future research consider a practical multi-disciplinary approach coupled with a holistic assessment addressing disposal well and reservoir behavior, geology, and area seismicity.

Introduction

The Environmental Protection Agency (EPA) Underground Injection Control (UIC) program, authorized by the Safe Drinking Water Act, regulates injection of fluids related to oil and gas production into Class II wells, for the protection of underground sources of drinking water (USDW). There are approximately 30,000 Class II active disposal wells in the U.S. used to dispose of oil and gas related wastes, many of which have operated for decades. EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity[6]. Very few (<10) of these disposal well sites have produced seismic events with magnitudes[7] greater than M4.0[8]. For example, there are approximately 5,000 active disposals wells in Kansas with no recent significant[9] seismic events occurring as a result of the disposal activities[10]. However, unconventional resources and new technologies, such as horizontal drilling and advanced completion techniques, have increased oil and gas production activities resulting in a need for additional new Class II disposal wells in expanded geographic areas.

Disposal wells are just one of a number of historic causes of human activity-induced earthquakes[11] Other causes may include construction and management of dams and water reservoirs, erection of skyscrapers, mining activities, oil and gas production, geothermal energy production, and geologic carbon sequestration.

Enhanced Recovery Injection Wells

Class II injection wells include injection for the purposes of enhanced recovery as well as those used for oil and gas production wastewater disposal. Injection for enhanced recovery projects generally poses less potential to induce seismicity than a wastewater disposal well because pressure increases resulting from injection for enhanced recovery are partially offset by nearby production wells. Disposal wells have no offsetting withdrawal and therefore, have a greater potential for pressure buildup. Given the recent seismic activity associated with Class II disposal wells, this WG effort focused on recommendations to manage or minimize induced seismicity associated with oil and gas related Class II disposal wells.

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[6] Seismic events resulting from human activities are referred to as induced, for this report.

[7] Magnitude will refer to the values reported by the USGS Advanced National Seismic System catalog

[8] Chapter 3, Table 3.4, page 104, and Chapter 7, Injection Wells for the Disposal of Water Associated with Energy Extraction Finding No. 1, pages 171-172; "Induced Seismicity Potential in Energy Technologies," 2013 NAS Publication.

[9] For the purposes of this report, "significant" seismic events are of a magnitude to potentially cause damage or endanger underground sources of drinking water or cause infrastructure damage.

[10] KCC active C2D well count was 4998 on September 10, 2013

[11] Earthquake terms are included under *Glossary Terms* or http://earthquake.usgs.gov/earthquakes/glossary.php for terms used in USGS maps; http://earthquake.usgs.gov/learn/glossary/ for general earthquake.

Hydraulic Fracturing

Although not the emphasis of this effort, seismicity associated with hydraulic fracturing (HF) was addressed by a review of selected literature sources. The Working Group agrees with the conclusions that HF has a low likelihood of inducing significant seismicity.

Unlike disposal wells that inject for an extended period of time, HF is a short-term event designed to create cracks or permeable avenues in lower permeability hydrocarbon-bearing formations. HF activity is followed by the extraction of reservoir fluids and a decrease in pressure within the formation. Therefore, the “pressure footprint” of a well that has been hydraulically fractured is typically limited to the fracture growth or fracture propagation area (Gidley et al., 1990). In comparison, the “pressure footprint” of an injection well is related to the injection rate, duration of the injection period and transmissibility of the reservoir (Lee et al., 2003). Class II disposal wells typically inject for months or years and generate large “pressure footprints” with no offset production of fluids.

HF is designed to crack the formation to enhance production. Several studies documented microseismicity (M<1) caused by HF (Das and Zoback, 2011; Phillips et al., 2002; Warpinski, 2009; and Warpinski et al., 2012). Studies also documented numerous examples of small faults encountered during the HF process with microseismicity magnitudes below M0 (Maxwell et al., 2011; Warpinski et al., 2008). Recording these very low magnitude seismic events (microseismicity) requires the use of downhole seismometers in nearby wells (Warpinski, 2009). Though rare, felt HF induced seismicity is possible if the HF encounters a Fault of Concern[12]. Documented cases list seismic events up to M3.8 due to HF communication with Faults of Concern (British Columbia Oil and Gas Commission, 2012; de Pater and Baisch, 2011; Holland, 2011 and 2013, Kanamori and Hauksson, 1992).

Geothermal Injection Wells

A number of informative references exist on induced seismicity and enhanced geothermal systems. These references cover a broad range of seismicity issues and outline many avenues of additional research needed (Hunt and Morelli, 2006; Majer et al., 2007 and 2011). These authors documented the combination of monitoring techniques with operational parameters to control seismicity. For example, thermal stress, in addition to pressure buildup, plays a key role

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[12] See Glossary: Fault of cConcern is a fault optimally oriented for movement and located in a critically stressed region. The fault would also be of sufficient length that movement has the potential to cause a significant earthquake. Fault may refer to a single or a zone of multiple faults and fractures.

in geothermal seismicity and may be applicable to wastewater disposal wells depending on the temperature of the injected fluids and receiving formation (Perkins and Gonzalez, 1984).

CO2 Geologic Sequestration

Geologic sequestration of CO2 requires a Class VI UIC permit. The Class VI permitting process includes assessment of potential induced seismicity. Class VI regulations require a detailed review on a site specific basis, consequently Class VI wells were not considered in this report. Some research pertaining to potential seismicity from CO2 geologic sequestration may be applicable to wastewater disposal.

Directive and Working Group

Revisions to Class II regulations are outside the scope of this technical report. This report is not a policy or guidance document and does not provide an exhaustive list of specific permitting procedures. It provides the UIC Director with considerations for minimizing and managing induced seismicity on a site specific basis, using Director discretionary authority.

To address the concern that injection-induced seismicity could breach the containment of injected fluids and endanger drinking water sources, EPA's Office of Ground Water and Drinking Water of the Drinking Water Protection Division requested the UIC National Technical Workgroup (NTW) develop recommendations for consideration by UIC regulators (Appendix A). The UIC NTW consists of UIC staff from each EPA Regional office, Headquarters, and six state UIC representatives. The Induced Seismicity Working Group (WG) of the NTW was formed in June 2011 to spearhead development of a report containing recommendations of possible strategies for managing or minimizing significant seismic events associated with induced seismicity in the context of Class II disposal well operations. The WG was comprised of a subset of NTW members and members outside the NTW included for their expertise on the subject matter. A list of the WG members is provided later in this report.

Regulatory Authorities

This report describes, for UIC regulators, the current understandings related to induced seismicity within the existing Class II regulatory framework for Class II disposal. Evaluation of induced seismicity is not new to the UIC program. Some UIC well classes address seismicity with specific regulatory requirements.[13] The Class II UIC program does not have regulations specific to seismicity but rather includes discretionary authority that allows additional conditions to be added to the UIC permit on a case-by-case basis. Examples of this

[13] 40 CFR §146.62(b)(1) and §146.68(f) for Class I hazardous; §146.82(a)(3)(v) for Class VI geologic sequestration

discretionary authority include additional requirements for construction, corrective action, operation, monitoring, or reporting (including well closure) as necessary to protect USDWs.[14] In the included case studies, the UIC Directors used discretionary authority to manage and minimize seismic events.

Potential USDW risks from seismic events could include loss of disposal well mechanical integrity, impact to various types of existing wells, changes in USDW water level or turbidity, USDW contamination from a direct communication with the fault inducing seismicity, or contamination from earthquake damaged surface sources. The EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity.

Report Purpose

The NTW's task was not to determine if there was a linkage between disposal and seismicity, but if a linkage was suspected, to identify practical approaches the UIC Director may use to minimize and manage injection-induced seismicity. A decision model was developed, which compiles and describes available options, and illustrates a process for applying them to manage or minimize possible injection-induced seismicity. The site assessment considerations included in the model were those identified as pertinent by the WG, though other factors may also be appropriate depending on site specific situations. The decision model also provides operational and monitoring options for managing injection-induced seismicity. It is supported by an extensive literature review and four case histories, which considered earthquake history, proximity of disposal well to these events, and disposal well behavior.

Many of the recommendations and approaches discussed in this report may be applicable to other well classes. For example, disposal activities also occur in Class I hazardous and non-hazardous wells, various Class V wells, and Class VI wells. The US Department of Energy and the International Energy Agency authored several publications dealing with specific Class V geothermal seismicity issues. The WG reviewed a number of publications as part of the literature survey for this report (Appendix K). Conclusions from some of these reports apply to this Class II injection-induced seismicity project and are referenced within the body of the report.

Injection-Induced Seismicity Project Objectives

The WG analyzed existing technical reports, data and other relevant information on case studies, site characterization, and reservoir behavior to answer the following questions:

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[14] 40 CFR §144.12(b); 40 CFR §144.52(a)(9) or (b)(1); or appropriate section of 40 CFR Part 147

1. What parameters are most relevant to screen for injection-induced seismicity?
2. Which siting, operating, or other technical parameters are collected under current regulations?
3. What measurement tools or databases are available that may screen existing or proposed Class II disposal well sites for possible injection-induced seismic activity?
4. What other information would be useful for enhancing a decision making model?
5. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection-induced seismicity?
6. What lessons have been learned from evaluating case histories?

Working Group Tasks

The UIC NTW was tasked by UIC management with developing a report including technical recommendations to manage or minimize significant levels of injection-induced seismicity.

The UIC NTW utilized the following approaches to address the objectives:

1. Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Preparation of a decision model
3. Applicability of pressure transient testing and/or pressure monitoring techniques
4. Summary of lessons learned from case studies
5. Recommendations for measurements or monitoring techniques for higher risk areas
6. Applicability of conclusions to other well classes
7. Recommendations for specific areas of research needed

Working Group Approach

The WG adopted the following strategy:

1. Summarize geoscience factors and applications
2. Apply petroleum engineering methods
3. Compile and review historical and current scientific literature including ongoing projects and material associated with upcoming reports on injection-induced seismicity
4. Select and study case examples of Class II brine disposal wells suspected of inducing seismicity and provide a summary of lessons learned for the following areas:
    a. North Texas
    b. Central Arkansas
    c. Braxton County, West Virginia
    d. Youngstown, Ohio

A study of disposal wells in areas with no seismic activity was not performed

5. Develop a Decision Model
6. Consult with the US Geological Survey (USGS) seismologists on the potential for deep stress field measurements and the USGS earthquake information as screening tools (Appendix M)
7. Compare data collected under existing UIC requirements to relevant information needed for assessment of injection-induced seismicity
8. Solicit review by EPA's UIC NTW and subject matter contributors from state agencies, academia, researchers, and industry.

Geoscience Factors Related to Injection-Induced Seismicity

The following paragraphs provide a general overview of the various geoscience aspects relevant to injection-induced seismicity. Appendix C describes these aspects in greater detail. The three key characteristics related to potential injection-induced seismicity that may lead to fault slippage and associated earthquakes are: (1) an increase in the formation pore pressure from disposal activities; (2) a fault optimally oriented for movement in a stress field, so that it is near its threshold of movement (Fault of Concern); and (3) a permeable avenue (matrix or fracture permeability) for the pore pressure increase to reach the fault.

Background

In general, continental oil and gas deposits occur in sedimentary rocks deposited by ancient seas over granitic basement rocks. Basement rocks have been and continue to be subjected to ongoing global tectonic forces. These forces result in fracturing and faulting (fracturing with lateral displacement) and are the origin of the constantly stressed condition of continental basement rocks. Practically all cases of suspected injection-induced seismicity felt by humans involved communication between disposal zones and basement faults. For these reasons, geologic site assessments related to potential injection-induced seismicity should include an analysis of both faults and stress conditions in basement rocks of the disposal well area. Since subsurface geologic stresses are transferred over great distances, fault and stress analyses should encompass a regional area around the disposal well.

Geologic Stress Considerations

Historic seismic activity is an indicator of critical stress in basement rocks. Subsurface stresses are typically not uniform in every direction. Instead, a principle stress direction exists, and the orientation of faults with respect to the principal stress direction is a fundamental indicator of which faults are subject to activation from pore pressure increases. Not all faults are Faults of Concern, only those optimally oriented in the subsurface stress field such that an increase in pore pressure can induce movement. Optimal orientation of faults is described in greater detail by Holland, 2013. Unfortunately, the principal stress direction may not be readily known to injection well permitting authorities. Some options to help determine the principal stress direction include data on borehole geometry, the World Stress Map (Appendix M, Task 2; Tingay et al., 2006), or consultation with experts, such as state geological surveys or universities. These experts may provide an estimate of the principal stress direction for a particular area as well as information on the location and orientation of known faults in the area.

An additional resource is the Quaternary Fold and Fault Map created by a USGS consortium (Appendix M, Task 1). This map shows all active faults with surface expression that are known to have created earthquakes over M6.0. These faults were defined from the geologic record for the Quaternary age (the last 1.6 million years).

Geophysical Data

Across the U.S., the USGS funds or maintains seismic arrays and associated databases that are excellent web based resources for seismic history assessments. A summary of available databases is provided in Appendix L. Seismometers in the permanent monitor grid in most of the central and eastern continental U.S. are spaced up to 200 miles (300 km) apart. With this spacing, the system is capable of measuring events down to approximately M3.0 or M3.5, although in some areas this may extend down to a M2.5. Epicenter location error for the permanent array averages up to six miles (10 km) horizontally and 10,000 to 16,500 feet (3-5 km) vertically. In tectonically active areas such as the continental western margin and New Madrid Seismic Zone, the seismometer spacing is closer, resulting in more accurate earthquake locations. Additionally, closer grid spacing generally measures seismic events of smaller magnitude. Despite the accuracy limitations, USGS or other seismicity databases (see Appendix L) are an excellent tool for initial site assessments. Event information included in databases is periodically updated over time as data are reprocessed. Relocated events are found in later publications and may not be in the catalogs.

Communication with Basement Rock

In almost all historic cases, felt injection-induced seismicity was the result of direct injection into basement rocks or injection into overlying formations with permeable avenues of communication with basement rocks. Therefore, the vertical distance between an injection formation and basement rocks, and the nature of confining strata below the injection zone are key components of any assessment of injection-induced seismicity. In areas of complex structural history, strata beneath the injection zone may have compromised vertical confining capability due to natural fracturing. Also, faulting in basement rock can extend into overlying sedimentary strata, thus providing direct communication between the disposal zone and the basement rock.

Importance of Porosity and Permeability of Injection Strata

Stratigraphic formations used as disposal zones can have a complex range of porosity types and permeability values. For this report, two fundamental types of porosity are considered; matrix porosity and fracture porosity. Matrix porosity refers to the rock pore spaces whether formed during deposition or alteration following deposition. Natural fractures in rocks create a second type of porosity referred to as fracture porosity. Fractures can provide preferential flow paths for fluid flow (permeability). Matrix porosity generally has smaller interconnections and is less permeable than fractures, but offers more storage space, potentially limiting the distance of pressure distribution. Pressure buildup is more difficult to predict in naturally fracture flow dominated disposal zones, and can extend much farther from the injection well. Most of the case study wells suspected of injection-induced seismicity in this report involved fractured disposal zones.

Petroleum Engineering Applications for Evaluating Induced Seismicity

Petroleum engineering applications have been used for decades in the oil and gas industry to evaluate wells and enhance hydrocarbon production. Petroleum engineering methodologies used in this document adhere to practices and equations commonly presented in petroleum engineering literature. The review of injection-induced seismicity literature revealed a lack of a multi-disciplinary approach inclusive of petroleum engineering techniques. Additionally, a typical Class II disposal permit review would not use many of the petroleum engineering analyses available, but such techniques could be useful in evaluating the potential for injection-induced seismicity.

Petroleum engineering methodologies provide practical tools for evaluating the three key components that must all be present for induced seismicity to occur: (1) pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway for increased pressure to communicate with the Fault of Concern. Different well and reservoir aspects can be evaluated depending on the methods used. Specifically, petroleum engineering methods typically focus on the potential for reservoir pressure buildup and the reservoir flow pathways present around a well and at a distance, and characterize reservoir behavior during the well's operation. Petroleum engineering approaches coupled with geologic and seismologic data may also provide area fault information. Some of the case study wells reviewed experienced specific Hall integral and derivative responses that corresponded to area seismic events. The Hall integral and derivative responses at these wells suggest hydraulic communication with a boundary (i.e. an offset well or fault) at some unknown distance from the well.

The petroleum engineering approach incorporates information collected typically from the permit application (well construction and completion data), and injection volumes and pressures during operation of the well. This information is presented in a graphical format. Well operations data is acquired through information reported for permit compliance. Plotting the operational data in graphical format illustrates behavior of the well over time. These graphs are compared to graphs of expected well behavior from various reservoir behavior models to identify anomalous patterns.

Review of operational data can provide a qualitative look at the well behavior. Operational analysis consists of plotting readily available data reported as part of the Class II disposal well permit compliance. These plots include:

- Injection volumes and wellhead pressures
- Bottomhole injection pressure gradient
- Hall Integral and derivative

Plotting injection volumes and pressures, along with pressure gradients may highlight significant changes in well behavior. For example, a decline in wellhead pressures coupled with an increase in volumes reflects enhanced injectivity, which could indicate operating pressures increased to a point that new reservoir pathways are created, e.g., fracturing of the formation at the well or entering a new stratigraphic zone in the well. The Hall integral and derivative plot is an operational assessment of injection rates and pressures to look for indication of a fault at a distance or enhanced injectivity during operations. The Hall integral plot provides a long time, long distance look at the disposal zone; including heterogeneities such as stratigraphic pinch outs or fault planes. Details for each petroleum engineering approach are included in Appendix D.

Supplemental evaluations may be performed, but use data or logs that may or may not be routine for Class II disposal permit activities. These evaluations quantitatively assess potential pathways and potential reservoir pressure buildup and may include:

- Step rate tests
- Pressure falloff tests
- Production logs
- Static reservoir pressure measurements

Step rate tests are used to determine the formation parting pressure. The quality of the data analyses is dependent on the amount of pressure data recorded during the test. Pressure falloff tests can provide the completion condition of the well (wellbore skin) and reservoir flow characteristics. Production logs typically include temperature logs, noise logs, radioactive tracer surveys, oxygen activation logs, or spinner surveys. These types of logs are used to evaluate the fluid emplacement at the well. Periodic static pressure measurements provide an assessment of reservoir pressure buildup. More details on supplemental testing and engineering evaluations are included in Appendix D.

Review of Scientific Literature

Literature Sources

Injection-induced seismicity has been documented in many reports from 1968 through 2013. The WG compiled and reviewed an extensive reference list included in Appendix K. Induced seismicity is a rapidly expanding area of research. This list is not a complete resource list. Inclusion of an article or website in this appendix does not reflect EPA's agreement with the conclusion of the article.

Earthquake Reporting

The USGS Advanced National Seismic System (ANSS) comprehensive catalog (Comcat), the largest U.S. database of earthquake events, includes earthquakes from the USGS National Earthquake Information Center (NEIC) and contributing networks. The real-time report and some of the catalogs include the location accuracy of the event. Catalogs may vary, but are an important consideration for induced seismicity analyses. Earthquake catalogs are discussed more fully in Appendices L and M. USGS, state geologic agencies, and universities may also collect and/or host earthquake information on their websites. There may be inconsistencies between databases, such as detection threshold, calculated epicenter, depth, magnitude determination or regional area covered. It should be noted that the expansion or development of regional seismometer networks may measure seismic activity at a lower magnitude threshold than previously recorded, creating the appearance of increased seismicity. Event interpretation is discussed more fully in Appendix D.

Possible Causes of Induced Seismicity

Seismicity induced by human activities has been extensively documented. Seismic events have been associated with mining, construction and management of dams and water reservoirs, geologic carbon sequestration, erection of skyscrapers, geothermal energy related injection, oil and gas production activities, and disposal wells. Davis and Frohlich (1993), Nicholson and Wesson (1990; 1992), and Suckale (2009, 2010) studied case histories of potential oil and gas related induced seismicity across the U.S. and Canada. Several waste disposal case studies were investigated including Rocky Mountain Arsenal, Colorado; and two locations in far northeastern Ohio (Ashtabula and Cleveland occurring from 1986 - 2001). Opposing conclusions were drawn on whether the Ohio seismicity was related to injection (Seeber and

Armbruster, 1993 and 2004; Gerrish and Nieto, 2003; Nicholson and Wesson, 1990). More recent publications concluded disposal activity induced seismicity in Central Arkansas and Youngstown, Ohio (Horton, 2012; Horton and Ausbrooks, 2011; Holtkamp, et al., 2013; Kim et al., 2012; Kim, 2013; ODNR, 2012). Disposal activities at the Rocky Mountain Arsenal and enhanced recovery the Rangely Field, both located in Colorado, have been associated with inducing seismicity. Operations at both Colorado facilities began prior to UIC regulations being in place. Production from the Rangely Field is still ongoing to date.

Several studies concluded that the Rocky Mountain Arsenal seismicity was caused by injection (Davis and Frohlich, 1993; Nicholson and Wesson, 1990; Nicholson and Wesson, 1992; Suckale, 2009 and 2010). At the Rocky Mountain Arsenal, the largest three earthquakes with magnitudes (M_L) between M5.0 and M5.5 occurred over one year after injection stopped. In March 1962, injection of waste fluids from chemical manufacturing operations at the Rocky Mountain Arsenal was initiated into a fractured crystalline basement rock beneath the facility. Initial injection exceeded the formation fracture pressure from March 1962 through September 1963 when the surface pump was removed leaving injection under hydrostatic pressure. Pumps were once again used for injection from April 1965 through February 1966 when injection ceased. Seismicity started five miles (8 km) from the well on April 24, 1962, ranging from M1.5 to M4.4 from 1962 through 1966, and three earthquakes ranging from M5.0 to M5.5 in 1967. Subsequent investigations identified a major fault near the well, and showed a direct correlation between increases in bottomhole pressure during injection and the number of earthquakes using Rank Difference Correlation (Healy et al., 1968; Hsieh and Bredehoeft, 1981; Raleigh, 1972).

From 1969 through 1974, the relationship between seismicity and Class II enhanced recovery injection operations at the Rangely Field in Colorado were studied (Raleigh, 1972; Raleigh et al., 1976). Reservoir pressures were controlled by varying injection into Class II wells and withdrawal from production wells within the Rangely Field to determine the relationship between pressure and induced seismicity. Fourteen seismometers deployed throughout the area recorded events ranging from M-0.5 to M3.1 in magnitude, which occurred in clusters in both time and space. Most of these events were below the threshold that is typically felt by humans[15]. Seismometer data and injection pressure and volume data coupled with modeling confirmed that earthquakes were induced through an increase in pore pressure. Frictional strength along the fault varied directly with the difference between total normal stress and fluid pressure (Raleigh et al., 1976). Unusual features in this case included measurable

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[15] Microseismic and small seismic events may occur but go undetected or unfelt and pose no significant risk to human health or USDWs.

response to fluid pressure along one part of the fault; recordable compartmentalization within the reservoir around the fault; and verification that maintaining the reservoir pressure below a calculated threshold stopped the seismicity (Raleigh, 1972; Raleigh et al., 1976). The Rangely Field example illustrates how operational changes were used to mitigate induced seismicity.

Numerous earthquakes were induced by Class V disposal operations in Paradox Valley, Colorado (Ake et al., 2002 and 2005; Block, 2011; and Mahrer et al., 2005). Seismicity is being managed using intermittent injection periods, injection rate control, and extensive seismic monitoring. Additionally a second Class V disposal well located several miles from the existing well is being evaluated by the U.S. Bureau of Reclamation in response to an expanding area of seismicity. The existing well is required for salinity control of the Delores River and operates above fracture pressure. More information is included in Appendix J.

Disposal wells have been suspected of inducing seismicity in a number of recent cases, (USGS, 2013). Verifying the presence of alternative causes, such as unusual changes in lake level (Holland et al., 2013; Klose, 2013; El Hariri, 2010), is a useful scientific approach.

Determinations of Injection-Induced Seismicity

Nicholson and Wesson (1990) stated that induced seismicity determinations rely on three primary characteristics of earthquake activity:

1. Geographic association between the injection zone and the location of the earthquake
2. Exceedance of theoretical friction threshold for fault slippage
3. Disparity between previous natural seismicity and subsequent earthquakes following disposal with elevated pressures

Davis and Frohlich (1993) developed a practical approach for evaluating whether seismic events were induced by injection based on similar characteristics stated by Nicholson and Wesson (1990) e.g., history of previous seismic events, proximity in time and space, and comparison of critical fluid pressures. The Davis and Frohlich approach utilizes a series of fundamental questions to evaluate the likelihood of induced seismicity. These questions are outlined below:

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicenters near wells (within 3 miles or 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?

7. Are changes in fluid pressure at hypocenter locations sufficient to encourage seismicity?

Although these approaches are qualitative and do not result in proof of injection-induced seismicity, they may be useful to UIC regulators. Proof of induced seismicity is difficult to achieve, but is not a prerequisite for taking early prudent action to address the possibility of induced seismicity.

Petroleum engineering techniques used in analysis of oil and gas development were not typically considered or used to evaluate reservoir characteristics potentially associated with induced seismicity in the scientific literature reviewed for this report.

CASE STUDY RESULTS

Our task was to provide practical tools that the UIC Director could use to assess site conditions to minimize and manage seismicity. Case study efforts were directed toward assessments of typical UIC program compliance data and its usability for characterization of injection well behavior and possible correlation with area seismicity. The case studies were not intended to focus on site problems or program administration issues, but rather to determine if practical assessment tools could be developed. The WG also found no indication that the injection wells associated with the case study areas injected outside of the operational boundaries or designated injection zones established by the permit parameters or endangered a USDW.

A total of four geographic areas of suspected injection-induced seismicity were selected by the WG for more detailed evaluation. These case studies were selected from areas where disposal wells were suspected causes for recent seismic events. Initially, the North Texas, Central Arkansas, and Braxton County, West Virginia areas were selected. The Youngstown, Ohio, area was included later in the project because a disposal well was the suspected cause of a series of seismic events in late 2011. No cases were evaluated where injection-induced seismicity was not suspected.

Initially, the WG identified disposal wells located in the vicinity of recent seismic events in the selected geographic areas. In order to compare well activities to seismic events, a radial area around the well was used to gather seismic data. Historic seismic events for the cases were derived from six different database catalogs. These external databases are discussed in more detail in Appendix L. A radius between five and twelve miles (8 to 19 km) around each case study well was selected based on the spacing density of the existing seismometers and location of the seismicity in the immediate area of the wells. Additionally, there is uncertainty with the depth to the hypocenter.

The specific strategies used by the WG for evaluating the cases included engaging researchers who had studied two of the cases, reviewing available geologic structure maps, acquiring specific injection well data from the four state regulatory agencies, and communicating with a well operator. A petroleum engineering analysis, based on the collected well data, was also performed on each case study well. Additional geoscience background and the results of EPA's petroleum engineering analysis on these cases are discussed in greater detail in the appendix specific to each case study (Appendices E, F, G, and H).

Each case is discussed below in terms of a background summary relating to the seismic activity and a description of how the case was evaluated by the WG. A summary of the common characteristics and lessons learned from the case studies is included following the case study summaries.

North Texas Area

Several small earthquakes occurred in the central part of the Dallas-Fort Worth metroplex near the Dallas-Fort Worth International Airport (DFW) on October 31, 2008, and near the town of Cleburne on June 2, 2009. Both areas are located in north central Texas, in the eastern portion of the Barnett Shale play. Prior to 2008, no earthquakes had been reported within 40 miles (64 km) of the locations of DFW and Cleburne case study areas. Although Barnett Shale hydrocarbon production was discovered in Wise County in 1981, extensive drilling into the Barnett Shale began in the late 1990s with the advancement of technologies. Disposal wells are the primary management approach to handle the wastewater associated with increased drilling activities. As of January 23, 2012, there are 195 UIC permits for commercial disposal wells in the 24-county area, only 2 of which were permitted in 2012, and not all of which are currently active.[16]

The Railroad Commission of Texas (RRC) standard UIC permit application package incorporated some site data and well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs[17] (Johnson, 2011). Site documentation reviewed by the WG included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion

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[16] RRC of TX website: http://www.rrc.state.tx.us/data/fielddata/barnettshale.pdf
http://www.rrc.state.tx.us/barnettshale/index.php updated 11/20/2013

[17] Doug O. Johnson, PE; Railroad Commission of Texas; Presentation to NAS – Committee on Induced Seismicity Potential In Energy Technologies; September 14, 2011; Dallas, TX

information) and disposal conditions (disposal zone, maximum allowable injection rate, and surface pressure). In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. WG review of the annual injection reports indicated that the well operated within the permitted pressure limits. One of the Cleburne area disposal wells was dually permitted as a Class II and Class I disposal well by different regulatory agencies. UIC Class I well requirements include conducting annual falloff tests. These tests provided reservoir characteristics and pressures for compliance with the Class I well permit and were not required in response to area seismicity. WG reviewed the available falloff tests that confirmed the Ellenburger disposal interval was naturally fractured.

Following the 2008 and 2009 events, the RRC identified active disposal wells in the area for further evaluation as to the possible cause of seismic events due to the wells' proximity to the epicenters of seismic events and the absence of seismicity prior to initiation of disposal. RRC opened a dialogue with the operators of the suspect disposal wells, resulting in the voluntary cessation of two wells, one in the DFW area and one in the Cleburne area, in August 2009 and July 2009 respectively. Since the two wells were shut-in the frequency of seismic events in the immediate focus area has substantially decreased. However, later seismic activity has appeared outside the DFW focus radius. This could be related to subsurface stresses shifting along the fault zone(s) to the north and to the east, as observed on the Guy-Greenbrier fault in Arkansas. The Cleburne case study incorporates more wells and is less well understood, as the seismic events continue to occur in new areas.

The RRC subsequently reviewed its permit actions for these wells and other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify there were no resulting public safety issues from these events. In follow-up, the RRC consulted with industry representatives, and researchers at the University of Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M University, and continues to monitor developments and research related to injection-induced seismicity.

More details on this case study are available in Appendix E.

Central Arkansas Area

From 2009 through 2011, a series of minor earthquakes occurred in the Fayetteville shale play near the towns of Guy and Greenbrier in Faulkner County, Arkansas. Regionally, the Enola area located approximately nine miles (14.5 km) southeast of Greenbrier experienced a swarm of earthquakes starting in 1982 (Ausbrooks and Doerr, 2007).

The Arkansas Oil and Gas Commission (Commission) standard UIC permit application package incorporated site assessment, well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs. Site assessment documentation included surface maps, location plats, disposal depths, and inventory of offset wells within the area of review. Several of the permit applications contained detailed geologic information, such as a narrative, structure map, type log and additional interpretive data. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and monitored disposal conditions (disposal zone and maximum allowable injection rate and surface pressure). In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. For one disposal well closest to the Enola area earthquakes, the Commission also required pressure falloff testing, additional seismic monitoring and intermittent injection during the permitting process. WG review of the annual injection reports indicated that the Enola area well operated within the permitted pressure limits.

In October 2009, three and a half months after injection was initiated, earthquake activity began in the immediate Greenbrier area. To investigate the earthquakes, the Commission worked with the Arkansas Geological Survey (AGS) and the University of Memphis Center of Earthquake Research and Information (CERI) and additional seismographs were deployed. In December 2010, following increased frequency and higher magnitude earthquakes, the Commission established a moratorium on the drilling of any new Class II disposal wells in an area surrounding and the immediate vicinity of the increased seismic activity. The Commission also required the operators of the seven existing Class II disposal wells operating in the moratorium area to provide hourly injection rates and pressures on a bi-weekly basis for a period of six months, through July 2011. During the moratorium period, the AGS and CERI analyzed the injection data and seismic activity to determine if there was a relationship.

In late February 2011, following a series of larger magnitude earthquakes, the operators of three disposal wells nearest to the seismic activity voluntarily terminated well operations prior to the issuance of the Commission cessation order issued on March 4, 2011. In July 2011, following the conclusion of the moratorium study, the Commission established a revised permanent moratorium area in which no additional Class II disposal wells would be drilled and required four of the original seven disposal wells to be plugged. The revised moratorium area was based on the trend of the Guy-Greenbrier fault, identified as the cause of the seismic activity. The operators of three of the wells voluntarily agreed to plug the subject disposal wells and were consequently not parties to the July 2011 Hearing heard by the Commissioners (appointed by the Governor of Arkansas). Following the July 2011 Commission Hearing, the Commission issued an order to the operator of the fourth disposal well to plug their well. The order of the Commission issued in July 2011 became a final administrative regulation on February 17, 2012.

Since July of 2011, the Commission, AGS and CERI continue to monitor disposal well operations and seismic activity. Additional seismic monitoring equipment has been purchased to facilitate the creation of an "early warning" system for emerging seismic activity thereby allowing more time to develop appropriate responses.

More details on this case study are available in Appendix F.

Braxton County, West Virginia

In April 2010, a series of earthquakes ranging in magnitude from M2.2 to M3.4 began in Braxton County, West Virginia. This area had previously experienced a 2.5 magnitude earthquake in 2000 prior to these events. Braxton County is located on the eastern edge of the Marcellus shale play and drilling in this area began in 2006. In March 2009, a nearby Class II disposal well began injecting Marcellus oil and gas production wastewater into the Marcellus formation.

The West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas standard UIC permit application package incorporated site assessment, well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs. The permit application contained detailed geologic information, such as an isopach and structure map. Site assessment documentation included surface maps, location plats, disposal depths, and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and disposal conditions (interval, rate, and pressure requested). A step rate test was also included with the permit information. In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. WG review of the annual injection reports indicated that the well operated within the permitted pressure limits. The data reported by the operator indicated that the well did not operate continuously.

In response to the seismic activity, the WVDEP reduced the maximum injection volume in September 2010. No additional earthquakes were recorded in the area since this restriction was enacted until a 2.8M earthquake occurred in January 2012. In response to the 2012 event, the WVDEP reduced the monthly disposal volume by half the permitted value and is currently researching the geologic structure of the area. The WVDEP and the WG found no conclusive evidence linking the cause of the seismicity to the disposal well.

In February 2012, WVDEP began requiring UIC permit applications to provide detailed geologic information specifically to identify subsurface faults, fractures or potential seismically active features. This additional information requirement includes at a minimum, public or privately available geologic information such as seismic survey lines, well records, published academic reports, government reports or publications, earthquake history, geologic maps, or other like information to access the potential that injection of fluids could lead to activation of fault features and increasing the likelihood of earthquakes.

More details on this case study are available in Appendix G.

Youngstown, Ohio

Starting on March 17, 2011, a series of 12 low magnitude seismic events occurred in Mahoning County in and around Youngstown, Ohio, culminating in a magnitude M4.0 event on December 31, 2011. Evidence suggested that a newly permitted, Northstar 1 Class II saltwater disposal well was the cause of the seismic activity and the injection well was voluntary shut down a day before the M4.0 event. The Northstar 1 injection well had been permitted as a deep stratigraphic test well and was drilled to a depth of 9184 feet into the Precambrian basement rocks in April of 2010. On July 12, 2010, the Northstar 1 was issued a Class II saltwater disposal permit and injection operations commenced on December 22, 2010.

The first Class II saltwater disposal well was permitted in Mahoning County in 1985 and eight more wells were converted to Class II injection between 1985 and 2004. These Class II injection wells utilized depleted oil and gas zones or were plug backed to shallower, non-oil and gas geologic formations for disposal. Injection was predominantly for disposal of production brine associated with conventional oil and gas operations. With the development of the unconventional shale plays in Pennsylvania and the lack of disposal in Pennsylvania, there was a need for additional disposal operations. To accommodate some of this need, five commercial disposal wells (Northstar 1 through 5) were permitted and drilled in Mahoning County, Ohio.

Historically, seismic monitoring in Ohio has been sporadic and seismic events have not been accurately determined. In 1999, the Ohio Seismic Network (OSN) was established with 6 stations and there were 24 seismic stations in operation in 2011. The seismometer at Youngstown State University was added to the OSN in 2003. Due to the continued seismic events occurring around the Youngstown area and near the Northstar 1 injection well, four portable seismic units, deployed on December 1, 2011, by Lamont-Doherty. This portable array allowed more accurate identification of seismic events. After the M4.0 event on December 31, 2011, the Governor of Ohio placed a moratorium on other deep injection wells within a seven-mile radius of the Northstar 1 and put a hold on the issuance of any new Class II saltwater injection well permits until new regulations could be developed.

There is a seismically active zone in western Ohio, and several episodically active faults 20 and 40 miles away from Youngstown, (Baranoski, 2002 and 2013). Prior to the earthquakes recorded in 2011, the only known deep-seated fault was mapped approximately 20 miles (32 km) away from the seismic activity based on a Pennsylvania Geological Survey report (Alexander et al., 2005). The vast majority of all historic and current seismic activity in Ohio occurs within the Precambrian basement rocks.

Due to the lack of deep geological information available for the Mahoning County area, a deep Precambrian basement fault in close proximity to the Northstar 1 well went undetected. This fault was confirmed through evaluation of geophysical logs from the offset deep disposal wells and an interpreted seismic line.

According to the *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area* (Ohio Department of Natural Resources, March 2012), data suggests seismicity was related to Class II disposal. The Northstar 1 well was drilled 200 feet into the Precambrian basement rock. The ODNR report also suggests that pressure from disposal activities may have communicated with the Fault of Concern located in the Precambrian basement rock. The ODNR now prohibits the drilling of Class II injection wells into the Precambrian basement rock and has enhanced the standard UIC permit requirements[18] to facilitate better site assessment and collection of more comprehensive well information. The additional permit requirements includes the following options 'as deemed necessary' and are reviewed on a well-by-well basis: pressure fall-off testing; geologic investigation to identify faulting in the immediate vicinity of the well; a seismic monitoring plan or seismic survey; comprehensive suite of well logs; an initial bottomhole pressure measurement, and a radioactive tracer or spinner survey. Additional operational controls[19] consist of: daily injection volume and pressure monitoring; an automatic shut-off system; and monthly monitoring of annular pressure.

In late 2012, ODNR also implemented a proactive approach to seismic monitoring around deep, Class II disposal wells in Ohio and purchased nine portable seismic units to bolster earthquake monitoring capabilities. All nine portable seismic units are in operation and ODNR has been monitoring these seismic stations in real-time since late 2012. Additionally, two disposal well operators have installed their own portable seismic arrays around two new wells that ODNR is also monitoring in real-time.

More details on this case study are available in Appendix H.

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[18] http://codes.ohio.gov/oac/1501%3A9-3-06
[19] http://codes.ohio.gov/oac/1501%3A9-3-07

Common Characteristics, Observations, and Lessons Learned From Case Studies

The case studies highlighted in the report provided important lessons and observations as well as common characteristics for wells suspected of inducing seismicity. The lessons learned provided a basis for the decision model as well as the approaches to manage and minimize induced seismicity. The case study common characteristics and observations contributed to the site conditions component of the decision model. Common characteristics coupled with key case study observations and the lessons learned are summarized below:

Common Characteristics and Observations

The common characteristics and observations represent those aspects noted by the WG across multiple case studies.

- Petroleum engineering analysis indicated some correspondence between disposal well behavior and seismicity (all case study areas)
- The magnitude of the earthquakes may increase over time as observed in some case studies. (Central Arkansas, Ohio and West Virginia)
- Injection into fractured disposal zones overlying basement rock may be vulnerable to injection-induced seismicity. (all case study areas)
    - Deep disposal wells were in direct communication or suspected to be in hydraulic communication with basement rocks and Faults of Concern as in the Central Arkansas and Ohio case study examples.
- Disposal commonly occurred into disposal zones with naturally fractured reservoir characteristics as in the Central Arkansas and North Texas case study examples.
- Operational analysis of disposal rates and pressures exhibited enhanced injectivity responses in some wells. (all case study areas)
- Operating wells below fracture pressure avoids or minimizes fracture propagation. This may require actual testing, such as a step rate test, to measure the formation parting pressure or conducting an operational analysis for indication of enhanced injectivity.

Lessons Learned

The following key lessons were learned from the case study reviews:

- Initiating dialogue with operator can provide early voluntary action from operators, including well shut-in, or acquisition of additional site data.
    - Initiating dialogue between the operator and UIC regulator resulted in the voluntarily shut-in of some suspect disposal wells (North Texas, Central Arkansas and Ohio).

    - For example, an operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep seated fault (North Texas and Central Arkansas).
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone (all case study areas).
    - Hall integral and derivative plot may indicate no flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance.
    - Hall integral and derivative plot may illustrate enhanced injectivity.
- Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation or encountering an increased permeability zone at distance (all case study areas).
- Acquisition of additional data may provide an improved analysis.
    - Increased recording of operational parameters can improve the quality of the operational data analysis.
        - Increased frequency of permit parameters improved the operational analysis (Central Arkansas and Ohio).
- Conducting a falloff test can further refine the reservoir characterization.
    - Fractured flow behavior was confirmed from the falloff test analyses for the Ellenburger disposal zone in a Cleburne area well (North Texas).
- Engaging external geophysical expertise may bring a more accurate location (x,y,z) of the active fault and stress regime through reinterpretation or increased seismic monitoring.
    - Especially useful when earthquake event magnitudes increased over time (Central Arkansas, Ohio and West Virginia).
- Lack of historic seismic events may be a function of lack of seismic activity, seismic activity below recordable levels, or epicenters away from population centers.
- Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
    - Additional stations installed resulted in reliable identification of active fault locations (DFW airport area of North Texas and Central Arkansas).
    - Epicenters of recorded events are scattered, due to insufficient stations in proximity to the activity (West Virginia).
- Seismic event data is periodically updated
    - During preparation of this report the seismicity data were downloaded on different dates with many of the initial events later revised or deleted.
        - Deletions typically occur between the first event report and entry into the catalog (NEIC or Comcat).

            - Revisions cover 3D location as well as magnitudes.
                - Several of the catalogs have added a revision date to their entries, to help identify such changes.
- Seismic event data is reprocessed resulting in relocation of the event.
    - Fine tuned relocation is possible when a sufficiently detailed velocity model is developed.
    - Relocated events are found in later publications and may not be in the catalogs.
- Engage a multi-disciplinary combined approach to minimize and manage induced seismicity at a given location (all case study areas).
    - Working with state geological survey or university researchers provided expert consultation, resulted in installation of additional seismometers, and yielded a clearer understanding of the deep seated active faulting (North Texas and Central Arkansas).
- Director discretionary authority was used to solve individual site specific concerns:
    - Acquired additional site information, request action from operators, and prohibit disposal operations. Specific examples include:
        - Increased monitoring and reporting requirements for disposal well operators provided additional operational data for reservoir analysis (Central Arkansas).
        - Required one well to include a seismic monitoring array prior to disposal as an initial permit condition (Central Arkansas).
        - Plugged or temporarily shut-in suspect disposal wells linked to injection-induced seismicity while investigating or interpreting additional data (all case study areas).
        - Defined a moratorium area prohibiting Class II disposal wells in defined high risk area of seismic activity (Central Arkansas).
        - Decreased allowable injection rates and total monthly volumes in response to seismic activity (West Virginia).

DECISION MODEL

The primary objective of the WG was to develop a practical tool, the decision model, for the UIC Director to consider in minimizing and managing injection-induced seismicity potentially associated with new or existing Class II disposal wells. The decision model is specifically designed for Class II disposal wells. However, the UIC Director should also consider other causative factors, such as lake level changes or different types of area operations (mining, production activities, etc.). As mentioned previously, the three key components behind injection-induced seismicity are (1) pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway for the increased pressure to communicate from the disposal well to the fault. All three components must be present to induce seismicity. The decision model was designed to identify the presence of any of the three key components. Based on the historical successful implementation of the UIC program, the decision model would not be applicable to the vast majority of existing Class II disposal wells since most are not associated with seismic activity. Use of the decision model is predicated on the UIC Director discretionary authority. Federal UIC regulations do not specifically address risk consequences associated with seismicity, but allow the UIC Director discretion to ensure protection of USDWs.

The decision model incorporates a site assessment consideration process addressing reservoir and geologic characteristics related to the three key components. The decision model provides the UIC Director with specific site assessment considerations and approaches to identify and address seismicity criteria for both existing and new disposal wells. No one single question addresses all the considerations needed to evaluate a new or existing disposal well. If issues are identified, the decision model provides specific operational, monitoring, and management approaches as options for addressing the issues.

The diagram of the decision model, Figure 1, is followed by a discussion relating to the range of considerations for site assessment. The "area" referenced in the decision model is a geographic area with the extent being determined by the Director using expertise about the site circumstances. Issues identified through the site assessment consideration thought process are then addressed, as needed, by a combination of operational, monitoring, and management approaches. These options were identified by the WG from petroleum engineering methods, literature reviews, analyses of the case studies, and consultations with researchers, operators, and state regulators. A more detailed discussion of the decision model is included in Appendix B.

The decision model (Figure 1) contains three symbols that represent the following:

- Bubble – thought processes
- Diamond – decision point
- Rectangle – outcome

Existing or New Class II Disposal Well

The decision model was designed to address seismicity concerns related to new or existing disposal wells. Below are three different scenarios. Different site assessment considerations may be applicable to each scenario.

1) An existing disposal well operating in a zone with historical injection and lack of historical seismicity,

2) An existing disposal well in an area not experiencing seismicity, and requests a substantial increase to injection volumes or pressure, or
3) A new disposal well in a disposal zone or area where little or no disposal activity has previously occurred.

Scenario 1) may not warrant further site assessment based on successful historical operations, while scenarios 2) or 3) may warrant additional site characterization consideration, especially if the well was located in a region with possible Faults of Concern.

Have Any Concerns Related to Seismicity Been Identified?

If the UIC Director does not identify any injection-induced seismicity concerns, the well evaluation would exit the decision model and continue through the normal UIC regulatory process; otherwise, a continuation through the model for further site assessment considerations may be warranted.

Site Assessment Considerations

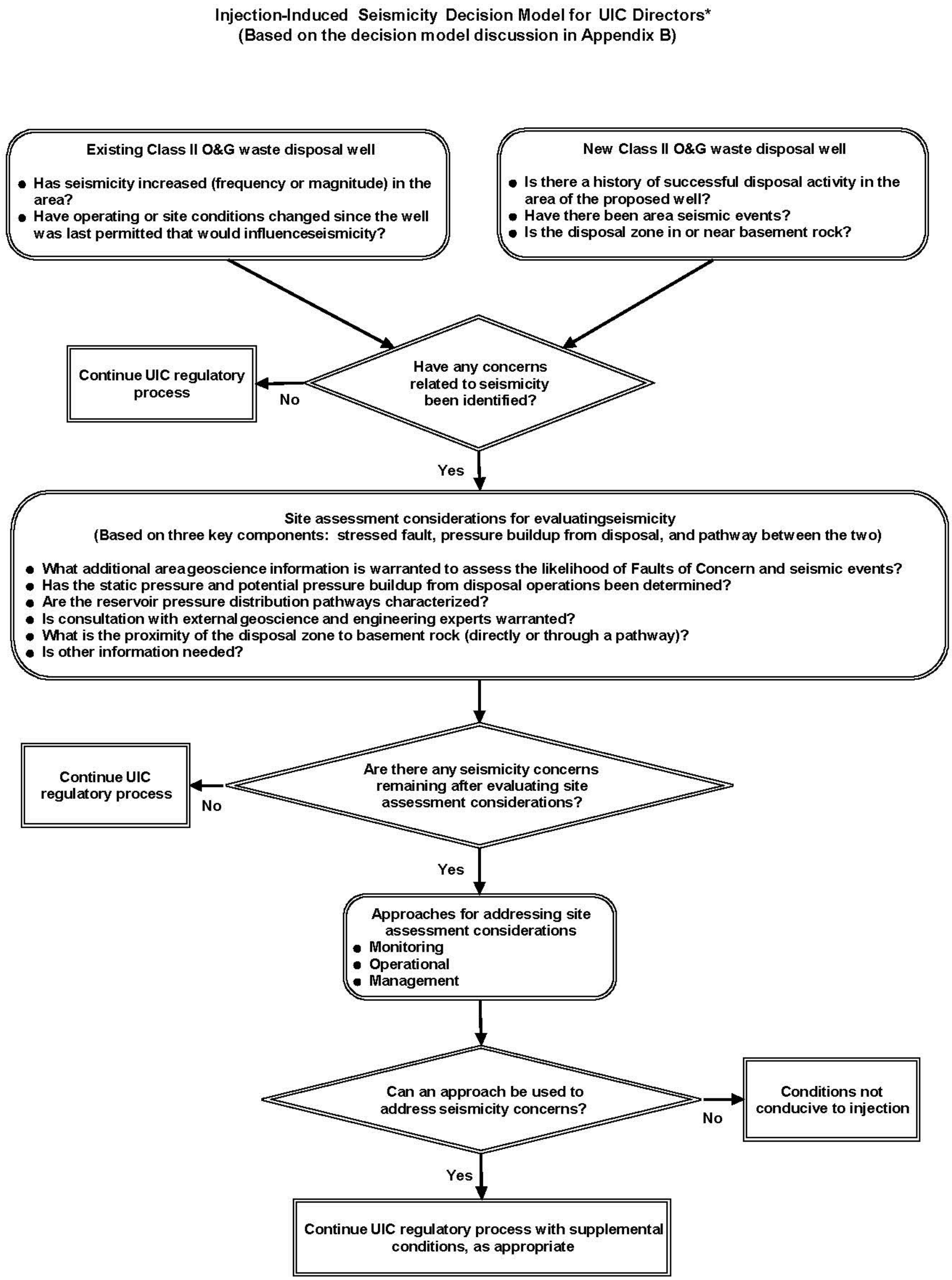
Site assessment considerations identify and evaluate any specific site characteristics that may represent potential issues for injection-induced seismicity. Uncertainties about any one of the three key components may warrant collection or review of additional data within the site assessment consideration process.

Site assessment considerations may pertain to information from permit applications or post approval permit monitoring data. Site assessment considerations may include aspects from both geosciences and petroleum engineering so a multi-disciplinary approach is advantageous. Details about the decision model diagram and its associated site assessment considerations are provided in Appendix B.

Site assessment considerations determined relevant for the decision model were the following:

- What additional area geoscience information is warranted to assess the likelihood of Faults of Concern and seismic events?
- Has the static pressure and potential pressure buildup from disposal operations been determined?
- Are the reservoir pressure distribution pathways characterized?
- Is consultation with external geoscience and engineering experts warranted?
- What is the proximity of the disposal zone to basement rock (directly or through a pathway)?
- Is other information needed?

FIGURE-1: INJECTION-INDUCED SEISMICITY DECISION MODEL



* Decision model is founded on Director discretionary authority

Are There Any Seismicity Concerns Remaining After Site Assessment?

If the UIC Director does not identify any injection-induced seismicity concerns following a more detailed site assessment, the well would exit the decision model and continue through the normal UIC regulatory process. When an injection-induced seismicity concern is identified, the Director may determine an approach to address the concern. The site assessment considerations are intended to guide the Director in selecting operational, monitoring, and management approaches that are appropriate to address induced seismicity issues.

Approaches for Addressing Site Assessment Issues

There are a number of approaches available to manage and minimize significant seismic events. These can be broadly categorized as operational, monitoring, and management approaches. An operational approach may include, for example, restricting the maximum allowable injection rate or pressure. A monitoring approach may necessitate collection of additional monitoring data, for example, operational pressures, additional seismic monitoring, or pressure transient well testing. A management approach supports a proactive approach for prompt action following seismic events and promotes agency, operator and public interaction. The Director determines which, if any, approaches are important depending on site specific considerations. Details about the approaches for addressing issues associated with the site assessment considerations are provided in Appendix B.

Can an Approach be Used to Successfully Address Seismicity Concerns?

If the UIC Director does not identify a suitable approach to address seismicity concerns, conditions may not be suitable for disposal operations at that location. If monitoring, operational or management approaches provide the required level of protection, the Director may condition the permit accordingly or use discretionary authority to require the desired approaches needed without revoking the permit.

Research Needs

The WG did not exhaust all avenues with respect to research on the value of petroleum engineering approaches. An abundance of research describing seismology and geomechanical behavior in the form of physical rock properties exists, although studies that combined petroleum engineering and geoscience approaches could not be found by the WG. The WG recommends future practical research using a multi-disciplinary approach and a holistic assessment addressing disposal well and reservoir behavior; geology; and area seismicity. Such an approach would benefit from combined expertise in geology, petroleum engineering, geophysics and seismology, which may not be available through one entity. For example, areas of expertise should include, but may not be limited to structural and stratigraphic geology; rock mechanics; seismology; reservoir characterization; reservoir fluid flow mechanisms; and disposal well construction, completion and performance.

The WG employed Hall plots for the petroleum engineering analysis because regulators may perform the analysis using widely available spreadsheet software; however, other petroleum engineering evaluations exist that may be applicable, if converted to injection conditions. The WG recommends a practically applied research project focused on assessment of injection well operating data to determine if there is a correlation between operating well behavior and seismicity. One of the key outcomes of the project would be a practical set of methodologies to assess operating data (templates) using injection well operating data acquired for existing UIC permits. The WG identified correspondence between injection well operational characteristics and seismic events in some of the case study wells.

Future research is needed to explore the correlation between disposal well operational behavior and earthquake events. The research should consider interaction between offset disposal wells on the operational plot characteristics along with area geology (flow geometry related to karstic vs. fractured carbonate). For example, evaluate the possible cause for the changes observed in both the Hall integral and derivative plots (offset wells volumes, fault effects, timing with earthquake activity).

There is also a need for research related to geologic siting criteria for disposal zones for areas with limited or no existing data. The geologic and geophysical study could focus on new stratigraphic horizons that could serve as disposal zones in these areas, the nature of subsurface stresses in basement rocks of these areas, and a more detailed regional geological assessment of basement faults. If sufficient earthquake catalog data are available, additional research to devise a statistical analysis to relate Class II disposal wells operating parameters with induced seismicity would be useful.

Recommendations to Minimize or Manage Injection-Induced Seismicity

The WG found no single recommendation addresses all the complexities related to managing or minimizing injection-induced seismicity where concerns have been identified. Recommendations included in this report were derived from a combination of WG expertise, case studies, consultations with outside experts, and data from literature reviews. Recommendations from the outcome of the decision model can be divided into three technical categories (site assessment considerations, operational, and monitoring) and a management component. An early step in the induced seismicity evaluation process is to conduct a site assessment. Based on the site assessment considerations, further operational, monitoring, and management approaches may be warranted. The complete discussion of the Decision Model is located in Appendix B.

Preliminary Assessment of Existing or New Oil and Gas Waste Disposal Wells

- Assess disposal history for correlation with area seismicity.
- Review area seismicity for increases in frequency or magnitude.
- Identify changes in disposal well operating conditions that may influence seismicity.
- Determine the depth to basement rock and the distance from the disposal zone.

Site Assessment Considerations

Site assessment considerations were developed to identify and evaluate specific site characteristics that may represent potential issues for injection-induced seismicity. Many geologic and petroleum engineering considerations for site characterization are not part of the typical permit application process. Additional data collection or review of additional data may be warranted. If needed, possible site assessment considerations are:

- Evaluate regional and local area geoscience information to assess the likelihood of activating faults and causing seismic events.
- Assess the initial static pressure and potential pressure buildup in the reservoir.
- Review the available data to characterize reservoir pathways that could allow pressure communication from disposal activities to a Fault of Concern.
- Consult with external geoscience or engineering experts as needed to acquire or evaluate additional site information.
- Determine the proximity of the disposal zone to basement rock.
- Consider collecting additional site assessment information in areas with no previous disposal activity and limited geoscience data or reservoir characterization prior to authorizing disposal.

Approaches

Possible operational, monitoring, and management approaches follow to address seismicity concerns that may arise from the site assessment evaluation. Several proactive practices were identified for managing or minimizing injection-induced seismicity. The applicability and use of any of these approaches should be determined by the Director.

Operational Approach

- Conduct a petroleum engineering analysis of operational data on wells in areas where seismicity has occurred to identify potential correlation.
- Conduct pressure transient testing in disposal wells suspected of causing seismic events to obtain information about injection zone characteristics near the well.

- Perform periodic static bottomhole pressure measurements to assess current reservoir pressures.
- Modify injection well permit operational parameters as needed to minimize or manage seismicity issues. This may require a trial and error process. Examples of modifications may include:
    - Reduced injection rates: This approach is likely a trial and error process, starting at lower rates and increasing gradually.
    - Inject intermittently to allow time for pressure dissipation, with the amount of shut-in time needed being site specific.
    - Separate multiple injection wells by a larger distance for pressure distribution since pressure buildup effects in the subsurface are additive.
    - Implement contingency measures in the event seismicity occurs over a specified level.
- Operate wells below fracture pressure to maintain the integrity of the disposal zone and confining layers.
- Perform annular pressure tests and production logging if mechanical integrity is a concern.

MONITORING APPROACH

- Increase monitoring frequency of injection parameters, such as formation pressure and rates, to increase the accuracy of analysis.
- Monitoring static reservoir pressure to evaluate pressure buildup in the formation over time.
- Install seismic monitoring instruments in areas of concern to allow more accurate location determination and increased sensitivity for seismic event magnitude.
- Increase monitoring of fluid specific gravities in commercial disposal wells with disposal fluids of variable density since the density impacts the bottomhole pressure in the well.

MANAGEMENT APPROACH

- Take action earlier to minimize the potential for additional injection-induced seismicity rather than requiring substantial proof of the causal relationship.
- Engage the operators early in the process, especially in areas that are determined to be vulnerable to injection-induced seismicity.
- Engage external multi-disciplinary experts from other agencies or institutions. For example, Directors may utilize geophysicists to interpret or refine data from seismic events for accuracy and stress direction.

- Provide training for UIC Directors on new reservoir operational analysis techniques to understand the spreadsheet parameters.
- Employ a multi-disciplinary team for future research to address possible links between disposal well and reservoir behavior; geology; and area seismicity.
- Include a seismic threshold as a condition of the permit describing action to be taken in the event of initiation or increase of seismic events. Thresholds could be based on the magnitude or frequency of events.
- Develop public outreach programs to explain the complexities of injection-induced seismicity.

Report Findings

The following major report findings are derived from the literature reviews, case study reviews, and the development of the decision model:

- The three key components behind injection-induced seismicity are (1) pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway for the increased pressure to communicate from the disposal well to the fault. Successful disposal occurs in areas with one or two characteristics present, but not all three.
- Take early prudent action to minimize the potential for injection-induced seismicity rather than requiring substantial proof of the causal relationship.
- The WG applied petroleum engineering techniques not identified in the injection-induced seismicity literature. These techniques have useful application for assessing flow path and fault presence. Basic petroleum engineering practices coupled with geology and geophysical information may provide a better assessment of well operational behavior in addition to improved understanding of reservoir and fault characteristics.
- A multi-disciplinary approach is important for the evaluation of the key three components. Understanding the geologic characteristics and reservoir flow behavior of a site involves methodologies from petroleum engineering, geology, and geophysics disciplines.
- The case studies were useful for identifying common characteristics for suspect wells and actions UIC Directors took through discretionary authority to manage and minimize seismic events in these areas.
- Future research is needed to explore the correlation between disposal well operational behavior and earthquake events.
- Future research should consider a practical multi-disciplinary approach and a holistic assessment addressing disposal well and reservoir behavior, geology, and area seismicity.

- The decision model, developed through this effort, is based on a thought process derived from a combination of case studies, literature reviews and understanding the conditions essential to cause seismicity. The WG selected a thought process versus a definitive framework to provide the Director with flexibility. The key questions of the decision model are:
    - Have any seismicity concerns been identified in new or existing wells?
    - Are there site considerations remaining following further review of data?
    - Can an approach be used to successfully address seismicity concerns?

Greater detail regarding these findings can be found in the respective report sections and associated appendices.

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Glossary of Acronyms and Terms

Acronyms

AAPG	American Association of Petroleum Geologists
AGS	Arkansas Geological Survey
ANSS	USGS Advanced National Seismic System
AOGC	Arkansas Oil and Gas Commission
BHP	Bottomhole Pressure
CERI	Center for Earthquake Research and Information
Comcat	Comprehensive catalog
EPA	US Environmental Protection Agency
HF	Hydraulic Fracturing
GIA	Geothermal Implementing Agreement
IEA	International Energy Agency
M4.0	Magnitude earthquake event; such as M4.0 means magnitude 4.0
MMbls	Million barrels
NCEER	Central and Eastern United States, CERI Earthquake database
NEIC	National Earthquake Information Center, US Geological Survey
NTW	National Technical Workgroup
ODNR	Ohio Department of Natural Resources
PDE	Preliminary Determination Earthquake, NEIC Earthquake database
RRC	Railroad Commission of Texas
SMU	Southern Methodist University
SPE	Society of Petroleum Engineers
SRA	Eastern, Central & Mountain States NEIC Earthquake database
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USGS	US Geological Survey
USHIS	Significant US quakes, NEIC Earthquake database
WG	Injection-induced Seismicity Working Group
WVDEP	West Virginia Department of Environmental Protection Office of Oil and Gas

Terms

Catalog aka earthquake catalog from USGS online Earthquake Search of the NEIC PDE catalog of earthquakes. http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

Class II injection wells inject fluids (1) which are brought to the surface in connection with conventional oil or natural gas production and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection, (2) for enhanced recovery of oil or natural gas; and (3) for storage of hydrocarbons which are liquid at standard temperature and pressure (40 CFR 146.5(b)).

Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth (USGS). Earthquakes resulting from human activities will be called induced earthquakes in this report.

Epicenter is the point on the earth's surface vertically above the hypocenter (or focus) point in the crust where a seismic rupture begins. NEIC coordinates are given in the WGS84 reference frame. The position uncertainly of the hypocenter location varies from about 100 m horizontally and 300 m vertically for the best located events, those in the middle of densely spaced seismograph networks; to tens of kilometers for events in large parts of the U.S.

Fault of Concern is a fault optimally oriented for movement and located in a critically stressed region. The fault would also be of sufficient length that movement has the potential to cause a significant earthquake. Fault may refer to a single or a zone of multiple faults and fractures.

Isopach is a contour map illustrating the variations of thickness of defined stratum.

Magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on the measurement of the maximum motion recorded by a seismograph or the energy released. Generally, damage is reported for magnitudes above 5[20]. Magnitude (M) will refer to the numbers reported by USGS or the NEIC, not separated between moment, body wave, or surface wave magnitudes.

Magnitude[21]	Earthquake Effects
2.5 or less	Usually not felt, but can be recorded by seismograph.
2.5 to 5.4	Often felt, but only causes minor damage.
5.5 to 6.0	Slight damage to buildings and other structures.
6.1 to 6.9	May cause a lot of damage in very populated areas.
7.0 to 7.9	Major earthquake. Serious damage.

[20] Building damage was reported following 2011 earthquakes near Trinidad, Colorado (5.3); near Greenbrier, Arkansas (4.7), and the Soultz France project (2.9).

[21] (Michigan Tech, 2011)

8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.

Microseismicity has no formal definition, but generally is an earthquake with a magnitude less than 2. (*The Severity of an Earthquake*, USGS website: http://earthquake.usgs.gov/learn/topics/richter.php)

Step rate test consists of a series of increasing injection rates as a series of rate steps and estimates the pressure necessary to fracture the formation.

Significant seismic events for use in this report are of a magnitude to cause damage or potentially endanger underground sources of drinking water.

Tectonic is the rock structure and external forms resulting from the deformation of the earth's crust. (Dictionary of Geological Terms, 1976).

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APPENDIX A: UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC #2011-3

UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC: #2011- 3

Technical Recommendations to Address the Risk of Class II Disposal Induced Seismicity

Background

Recent reports of injection-induced seismicity have served as a reminder that the UIC Program can and should implement requirements to protect against significant seismic events that could ultimately result in USDW contamination. The UIC Program's Class I hazardous and Class VI siting provisions require rigorous evaluations for seismicity risks. The other well classes, in contrast, allow the UIC Director the flexibility to decide if and when such evaluations are needed. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to inform and enhance strategies for avoiding significant seismicity events related to Class II disposal wells.

Project Objectives

The UIC NTW will analyze existing technical reports, data and other relevant information on case studies, site characterization and reservoir behavior to answer the following questions:

1. What parameters are most relevant to screen for injection induced seismicity? Which siting, operating, or other technical parameters are collected under current regulations? (Geologic siting criteria, locations and depths of area pressure sources and sinks, injection rates and pressures, cumulative injection or withdrawals of an area, evaluation of fracture pressure, stresses or Poisson's ratio, etc.)
2. What measurement tools or databases are available that may screen existing or proposed Class II disposal well sites for possible injection induced seismic activity? What other information would be useful for enhancing a decision making model? (Flow chart incorporating seismicity/hazard database resources, reservoir testing methods, area faulting, measuring or recording devices, reservoir pressure transient models, seismic models, other screening tools, etc)
3. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection induced seismicity?
4. What lessons have been learned from evaluating case histories?
    a. Did reviews of injection rate and pressure data sets reveal any concerns?
    b. Were any pressure transient tests conducted?
    c. How were the seismicity events attributed to Class II disposal activities?
    d. What levels of site characterization information were available?
    e. Which UIC regulations have regulators used to address the situation?
    f. Were there areas of concern identified that existing UIC regulations did not address?
    g. Any other lessons learned?

Output

The end-product of this analysis should be a report containing technical recommendations for avoiding significant levels of injection induced seismicity that EPA can share with UIC Directors. The UIC NTW will produce a report that includes the following elements:

1. Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Prepare a decision making model – conceptual flow chart
    a. Provide strategies for preventing or addressing significant induced seismicity
    b. Identify readily available applicable databases or other information
    c. Develop site characterization check list
    d. Explore applicability of pressure transient testing and/or pressure monitoring techniques
3. Summary of lessons learned from case studies
4. Recommended measurement or monitoring techniques for higher risk areas
5. Applicability of conclusions to other well classes
6. Define if specific areas of research are needed

Milestones

- July 2011 – Authorization from UIC managers for UIC NTW to proceed with injection induced seismic project proposal. Assemble UIC NTW project team and assign tasks to project members. Collect and distribute, to UIC NTW project team, information from published studies, peer-reviewed articles, and State and Federal UIC programs.
- August 2011 – Create project sub-teams. Collect and evaluate information from case histories. Review compilation of information and develop technical recommendations for addressing risks of significant injection induced seismicity. Create project teams.
- September 2011 - Consolidate input from project sub-teams
- October 2011 – Prepare and present preliminary technical recommendations and report to UIC NTW membership. Finalize technical recommendations and report with input from UIC NTW membership.
- November 2011 – Submit report for presentation to UIC management
- December 2011 – Finalize report and post to public accessible UIC NTW website

Project Focus Group

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Target Delivery Date: December 2011

Headquarters Approval

[signature] 7/20/11

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Date

SPECIFIC GUIDANCE TO WORKGROUP: (space unlimited)

APPENDIX B: DECISION MODEL

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INTRODUCTION

A key objective of this project was to develop a practical tool for UIC regulators to use in the evaluation of potential injection-induced seismicity or to manage and minimize suspected injection-induced seismicity. As a result, a decision model was developed for UIC Directors to consider based on site specific data from the Class II disposal well area in question. The decision model was designed in consideration of the three key components necessary for inducing seismicity, (1) pressure buildup from disposal activities, (2) a Fault of Concern, and (3) a pathway for the increased pressure to communicate from the disposal well to the Fault of Concern. Options for additional actions are included in this model.

The absence of recorded historical seismic events in the vicinity of a proposed Class II injection well does not mean there were not historic low-level seismic events below detection level. With the increased deployment of modern and more accurate portable seismic units or seismic arrays, many previously undetected low-level seismic events are now being documented in some areas of the United States. The increased deployment of these seismic instruments further enhances the ability to detect low-level seismic events, whether naturally occurring or induced. However, the occurrence of measurable seismicity after the initiation of disposal in areas with little or no historic seismicity supports the possibility of induced seismicity.

Class II disposal activities have existed for decades without inducing significant seismicity. This decision model may not be applicable to areas with historically demonstrated successful disposal activities. Because of complex variations in geology and reservoir characteristics across the country, it is neither practical nor appropriate to provide a detailed step by step decision model. Instead, the use of UIC Director discretionary authority will determine the applicability of this decision model to Class II disposal well activities and the need to address site specific conditions. The model presented in this report summarizes the various considerations and approaches identified by the Working Group (WG) from petroleum engineering methods, geosciences considerations, literature review, analysis of the case studies, consultations with researchers, operators, and state regulators, and feedback from subject matter experts. The decision model is included as Figure 1 in the report and the end of this appendix.

Areas for Review

Throughout the decision model discussion and Figure 1, the "area" referenced is a geographic area with the extent being determined by the Director based on usage, whether as a screening tool or a focused site specific basis. The geographic area can also vary based on geologic setting and the available seismic monitoring network. Therefore designating the term "area" with a specific areal extent was not practical for this report.

Options for a screening seismicity review include looking at the overall seismicity history of a broad area, statewide or by geologic province. A simple method is to use both a statewide historical seismicity map prepared by either USGS or another seismicity reporting service; and the Quaternary Fold and Fault Map created by a USGS consortium. Appendix M (Task 1) contains links and a more detailed discussion of these maps. This screening area could then be further subdivided by the level of seismic activity or quiescence.

In seismically active areas, the focused area of interest may center on the disposal well and related geologic structure of interest. For example, a more detailed, localized review may be recommended by the Director to further evaluate the potential for local geologic structure that could impact the injection well operations. In the determination of the size of the focused search area, the Director should consider geology and the density of seismometers, which impacts the accuracy of the recorded seismic events in both the lateral and vertical directions. Generally, because of reduced seismometer spacing, accuracy of hypocenter locations outside of active seismic zones is on average six miles (10 km) (Appendix M, Task 1). Vertical accuracy varies significantly depending on seismic processing assumptions and seismometer density, but the error range is typically 10,000 to 16,500 feet (3-5 km). The accuracy of seismic events can be further refined by the deployment of portable units around the disposal well.

Quiescent areas are less likely to be of concern for injection-induced seismicity. For seismically active areas, the Director may decide to continue through the decision model process and address potential induced events through other means.

Existing versus New Class II Disposal Well

Existing Class II Oil and Gas Waste Disposal Well

Two primary reasons the Director may find the decision model useful for existing wells are: 1) increased seismicity or 2) change in operating condition of a well located in areas susceptible to seismic events. On a case by case basis, the Director may elect to continue further into the decision model by utilizing site assessment considerations to address potential concern for or minimize and manage existing induced seismicity. If seismicity concerns arise during operation of the disposal well, the Director may revisit the decision model.

Increased seismicity can be determined from various means such as media reporting, available seismic databases, or USGS Earthquake Notification Service by area and magnitude. Appendix L lists available databases. A change in relevant operating or site conditions since the well was last permitted may prompt further review by the Director. Relevant parameters should relate to the key components for inducing seismicity (pressure buildup, reservoir pathway, or Fault of Concern).

New Class II Oil and Gas Waste Disposal Well

For new disposal well applications, the Director may consider if there is history of successful disposal activity in the area of the proposed well. Successful disposal activity would be years of historical disposal in the same geographic area and disposal zone. New wells located in such an area would not be of concern. Whereas, a new disposal well located in an area with no previous disposal activity in the proposed zone may require additional analysis. Uncertainties in reservoir characterization may exist in new areas with few or no existing wells, possibly justifying the need for additional site characterization information and analysis. Additionally, the location of the disposal zone relative to basement rock may be a consideration on a site by site basis. Again, the Director's knowledge of the area and historic disposal activity may determine the need for further site consideration process.

Have Any Concerns Related to Seismicity Been Identified?

If Director does not identify any injection-induced seismicity concerns, the well evaluation would exit the decision model and continue through the normal UIC regulatory process; otherwise, a continuation through the model for further site assessment considerations may be warranted. For a disposal well suspected of initiating seismic activity during its operational life, the Director determines the appropriateness of advancing the well further through the decision model. The Director may also determine a level of seismicity relevant for further evaluation.

Site Assessment Considerations for Evaluating Seismicity

Once the Director has identified potential concerns related to injection-induced seismicity, additional site assessment considerations may be justified. With few exceptions, injection-induced seismicity occurs in response to increased pore pressure from injection, transmitted through a pathway, to a fault plane of concern (Nicholson and Wesson, 1992). Therefore, the WG identified site specific assessment considerations for evaluating significant seismicity. These considerations may not all be applicable and are not listed in any order of importance. The Director determines which considerations may be applicable for an existing or proposed Class II disposal well based on site specific information. Ultimately, through discretionary authority, the Director may require additional site assessment information or monitoring for the protection of USDWs.

Site assessment considerations focus on identifying if any of the three key components of injection-induced seismicity are present. The considerations included in the decision model are discussed individually below, along with the positive and negative aspects for each.

- ### What additional area geoscience information is warranted to assess the likelihood of faults and seismic events?

With few exceptions, injection-induced earthquakes occur in response to increased pore pressure from injection, transmitted through a pathway to a Fault of Concern. Understanding the area geology through available geoscience information may clarify two of these induced seismicity components: the nature of the pathway transmitting the pore pressure response and identification of Faults of Concern subject to the pressure response. The lateral continuity and heterogeneity of the disposal zone influence both the pressure buildup from disposal operations and the distribution pathway. The effectiveness of overlying and underlying confining zones may influence the dispersion of pressure in all directions.

Accurate fault assessment, as part of the overall site characterization, is a critical aspect of managing injection-induced seismicity, including the orientation of faults with respect to the geologic stress field. Subsurface faults exist throughout most of the country; however, the presence of a fault itself may not be a concern. If a site is in an area with a history of seismic activity, Faults of Concern are likely present in the region. Consideration should be given to the possibility of deep seated faulting (basement faulting), as reported with the Rocky Mountain Arsenal (Hsieh and Bredehoeft, 1981) and Central Arkansas induced events (Ausbrooks, 2011a, 2011b, 2011c, 2011d; Horton and Ausbrooks, 2011).

There are a number of possible options for determining the presence or absence of faulting around a proposed or existing disposal well, including a review of published literature, state geological agency reports, commercial structure maps or evaluating seismic surveys[22]. While the latter are the most definitive, they are also the most expensive, time consuming to acquire, and may require access to land that cannot be readily obtained.

Well operators may have exploration seismic surveys to enhance fault analysis for the site characterization. For example, active faults in Central Arkansas and the Dallas-Fort Worth, Texas (DFW) area were identified first from seismic activity, and then verified on the operator's interpreted 3D seismic surveys, (Chesapeake Energy, personal communication, meeting September 16, 2011). If seismic surveys are available, a re-analysis may help identify any deep seated faults, and if present, the extent of the fault or associated fractures, although some faults, such as those that are near-vertical strike-slip, may be missed.

Correlations of geophysical logs or review of geologic cross-sections may indicate missing or faulted out rock sections. If a fault is present, information on the origin, displacement, and vertical extent of the fault may be a consideration. Geophysical logs may also identify the rock characteristic of the disposal zone and the reservoir pathways the pressure from disposal operations may encounter. If site specific geoscience information is limited or insufficient and regional studies indicate faults or subsurface stress in the broader area, additional information may be needed to evaluate the likelihood of inducing seismicity.

Geologic site characterization information on flow characteristics, fracture networks and stress fields may be available from: 1) regional and local geologic studies, or 2) information from geophysical logs, core analysis, and hydraulic fracturing results. Any published articles discussing the basin, reservoir rock or structural history of the area, may indicate if faulting, fracturing, or directional flow is present. Various publications provide information on determining optimal orientation of faults with respect to the stress field (Holland, 2013; Howe-Justinic et al., 2013).

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[22] Seismic survey lines are typically proprietary, but may be obtained commercially or viewed by special arrangement. If provided, the data may be submitted as confidential business information.

- **Has the static pressure and potential pressure buildup from disposal operations been determined?**

Reservoir pressure buildup, one of the three key components of induced seismicity, is influenced by reservoir flow behavior, disposal rate, and hydraulic characteristics of the disposal zone. To perform conventional reservoir pressure buildup calculations, knowledge of disposal zone hydraulic characteristics is required. Disposal zone hydraulic characteristics include static reservoir pressure, permeability, effective net thickness, porosity, fluid viscosity, and system compressibility. Details about these characteristics are generally determined from some combination of fluid level measurements, pressure transient testing results, logging and completion data, and fluid and rock property correlations. The static pressure provides a starting point for determining the pressure buildup during disposal activities. Once these values are obtained, the pressure buildup calculations can then be performed to access the magnitude of pressure increases throughout the disposal reservoir.

Typically an infinite acting homogeneous reservoir with radial flow is assumed for the pressure buildup calculation. In many Class II disposal applications, limited reservoir property measurements are available and actual pressure buildup calculations are done using assumed or accepted area formation characteristic values. Reservoir falloff tests can provide clarity as to whether the homogeneous reservoir behavior assumption is valid or pressure buildup projections should be calculated using a different set of fluid flow behavior assumptions. A static bottomhole pressure measurement, typically obtained at the end of a falloff test may also provide an assessment of reservoir pressure increase around the injection well, offering insight into the magnitude of pressure buildup to which the area fault may have been subjected.

Naturally fractured disposal formations involving induced seismicity may require more complex pressure buildup prediction methods to account for non-radial reservoir behavior. For example, several cases of suspected injection-induced earthquakes in the literature appear to be characterized by injection zones located within fractured formations (Belayneh et al., 2007; Healy et al., 1968; Horton and Ausbrooks, 2011).

- **Is the reservoir pressure distribution pathway characterized?**

The potential pathway or the ability of the reservoir to transmit pressure to a Fault of Concern is best characterized by a combination of geosciences and petroleum engineering information. Geologic information can help characterize the nature and continuity of the disposal zone. For example, a geologic isopach map or cross-section, may define the lateral continuity of the disposal zone and the area potentially impacted by the pressure response from disposal operations. Evaluation of the confining capability of formations overlying and underlying the disposal zone may indicate the potential for pressure dispersal outside the disposal zone. A type log from the disposal well or area offset well may illustrate if confining layers are present. Other useful aspects for consideration include the number of formations and thickness of permeable strata included within the disposal zone. Heterogeneities in the receiving formations will impact the pathway for pressure distribution away from the disposal well. This level of detailed information, while useful, is not typically required for Class II disposal well operations and therefore may not be available in all situations.

Review of daily drilling reports and open-hole geophysical logs may suggest characteristics of the disposal zone and overlying confining zones, helping to describe the reservoir pathway. For example, borehole washouts or elongated boreholes observed on a caliper log may suggest a higher stressed or fractured zone. Heavier mud weights used while drilling may suggest the presence of higher pressure zones. Core data are not typically acquired during the drilling of Class II disposal wells, but if available, could show natural fractures (open or sealed), karstic rock or fault gouging if present. Open-hole geophysical logs, such as a fracture finder log, multi-arm dipmeter, borehole televiewer, or variable-density log may also assist in identifying fractured zones.

Production logging data in an existing well may supplement geologic data by providing additional insight about out of interval fluid movement and vertical pressure dispersal. Production logs such as radioactive tracer surveys, temperature logs, noise logs, flowmeters (e.g., spinner surveys) and oxygen activation logs can show where fluid exits the wellbore and allow estimates of fluid volumes being emplaced into the intervals identified. Wellbore fill at the base of a well may reduce the interval thickness, alter the injection profile, and increase the pressure buildup during disposal operations. For example, wellbore fill may cover a large portion of the disposal zone in a well with a short perforated interval; resulting in a greater pressure buildup within the thinner interval receiving fluid. Production logs can also indicate if fluid is channeling upward or downward behind the casing to other intervals for potential hydraulic impact and show intervals impacted by cumulative long term injection.

Petroleum engineering approaches, such as a reservoir falloff test, can also provide clues about the pressure transmission pathway, by indicating whether the injection zone is behaving in a linear flow (possibly fractured) or homogeneous radial flow (non-fractured) manner. Falloff testing is not a requirement for Class II wells, but has been used as a lower cost alternative in some Class II operations to characterize the disposal reservoir flow parameters, reservoir pressure buildup, and well completion condition. Falloff testing is associated with the petroleum engineering approach which is discussed in further detail in Appendix D.

- **IS CONSULTATION WITH EXTERNAL GEOSCIENCE AND ENGINEERING EXPERTS WARRANTED?**

Site assessment considerations may require multi-disciplinary evaluations, necessitating consultations with geophysicists, geologists, and petroleum engineers. Consulting with seismologists and geophysicists at either state or federal geological surveys can provide additional information and may be necessary in situations based on existing site specific conditions. For example, in the Arkansas case study, the UIC Program coordinated with researchers from the University of Memphis and Arkansas Geological Survey to successfully acquire critical information on ongoing low level seismic activity. Data from this effort formed the basis for a disposal well moratorium in the area of disposal induced seismicity.

Seismic history for any area in the U.S. is readily available on the USGS website (see Appendix L) and/or state geological agencies websites at no cost. Where seismometers have recorded sufficient quality and quantity of data, seismologists may be able to refine the actual event location and depth data to identify the fault location and principal stress direction.

Geologists can provide insight on reservoir geologic data and identify the presence of faults or potential for faulting. Reservoir analysis by petroleum engineers may evaluate the completion condition of the disposal well, provide estimate of pressure buildup and characterize pressure distribution away from the disposal well. Other expertise may be available through academia, other agencies, or consultants.

- **WHAT IS THE PROXIMITY OF THE DISPOSAL ZONE TO BASEMENT ROCK?**

Most of the literature and case examples of alleged disposal induced seismicity described are related to faults in basement rocks. Therefore depth of the disposal zone to the basement rock or a flow pathway from the disposal zone to the basement rock may be a consideration. A comprehensive study of disposal in basement rock was not part of this study. Cases of successful disposal in basement rock may exist.

A lower confining layer between the disposal zone and basement rock may restrict pressure communication with underlying faults thereby minimizing the conditions for induced seismicity. Fault of Concern, as used in this report, denotes a fault that is optimally oriented with the potential to cause a significant earthquake. Fault may refer to a single or a zone of multiple faults and fractures.

- **IS OTHER INFORMATION NEEDED?**

Based on review of the available site characterization information, the Director may require additional information to respond to unique site specific circumstances.

Are There Any Seismicity Concerns Remaining After Site Assessment?

If the UIC Director does not identify any injection-induced seismicity concerns following a more detailed site assessment, the well would exit the decision model and continue through the normal UIC regulatory process. When an injection-induced seismicity concern is identified, the Director may determine an approach to address the concern.

Approaches to Address Site Assessment Consideration

The WG identified operational, monitoring, and management approaches to potentially address any significant seismicity concerns identified after evaluating site assessment considerations. Some of the approaches could overlap in classification.

Selecting the appropriate approaches depends on a number of factors. Key factors for addressing site assessment concerns are knowledge of the area and timing of seismic events relative to disposal activities. Characterizing the flow behavior in the injection zone, quantifying reservoir conditions and delineating fault characteristics is best accomplished using a multi-disciplinary team. The Director may elect to set up contingency measures in the event seismicity occurs or increases.

Operational Approaches

Operational approaches short of shutting in the well may be applicable, though some may involve modification to permit conditions or additional reservoir testing. Some of these approaches are discussed in the following paragraphs.

Reducing injection rates or implementing intermittent injection may decrease reservoir pressure buildup and allow time for pressure dissipation. Determining the reduction in pressure buildup needed to manage or minimize seismicity is likely a trial and error process. The resulting maximum allowable disposal rate or amount of shut-in time needed to remain below a determined reservoir pressure would be site specific. There would be no direct cost to implement, though the reduced disposal volume could impact facility operations and wastewater management.

Confirming site specific fracture pressure through testing defines a limiting operating pressure value. Operating below the fracture pressure maintains the integrity of the disposal zone and confining layers. Operating a well above fracture pressure could create new pathways by initiating or extending a fracture. Determining the site specific fracture pressure may require actual testing, such as a step rate test, to measure the actual formation parting pressure in lieu of a calculated fracture gradient. Additional cost would be associated with conducting a step rate test.

Conducting pressure transient tests in disposal wells suspected of causing seismic events may reveal the injection zone characteristics near the well, flow regimes that control the distribution of reservoir pressure, and completion condition of the well. A series of pressure transient tests may provide an indication that the reservoir characteristics and pathway remain consistent throughout the life of the well. Pressure transient testing would require some additional cost to the operator as well as specialized expertise to design and review the data.

Profiling where fluids are exiting the wellbore by running production logs, such as a flowmeter (spinner survey), radioactive tracer survey, or temperature log may be another useful testing technique for evaluating fluid emplacement. The thickness of the interval receiving fluid can impact the amount of pressure buildup in the reservoir. The location of fluid emplacement could provide insight on the reservoir pathway. Additional costs would be incurred by the operator to run the logs.

Verifying mechanical integrity following a seismic event may include performing tests to evaluate the well and bottomhole cement. Annulus pressure tests can evaluate the integrity of the tubing, packer and production casing. A temperature log, noise log, or radioactive tracer survey can confirm the location of fluid emplacement and verify no out of zone channeling of fluids.

Conducting a petroleum engineering analysis of available operational data (rate and pressure) on wells in areas where seismicity has occurred may provide a characterization of the flow behavior, such as enhanced injectivity, in the injection zone. Operational analysis can also quantify reservoir conditions and delineate fault characteristics. Operational analysis uses UIC compliance data so there is no additional cost to acquire data.

Pressure buildup effects in a formation are additive so separating multiple injection wells by a larger distance may reduce the amount of pressure buildup, but again the results would be site specific depending on the quality and size of the disposal zone and number of disposal wells completed in the same formation. Higher costs would likely be associated with drilling multiple wells and transferring wastewater to the additional wells.

Monitoring Approaches

Monitoring approaches focus on reservoir pressure and well condition during disposal operations along with levels of area seismic activity. In many cases, monitoring approaches would be conducted in conjunction with the other approaches.

Requiring more frequent operational data collection to assess site specific situations relevant to induced seismicity may be useful. The increased monitoring frequency adds improved data quality and quantity for use with operational approach analysis methods. More accurate data may require electronic measuring equipment to record and store data which may add cost. The frequency of data collection can influence the accuracy of the analysis. For example, in the Central Arkansas case study, hourly monitoring of injection pressure and volume yielded more data for analysis than the monthly data typically reported.

Monitoring static reservoir pressure provides an indication of the pressure buildup in the formation over time. Depending on the site specific conditions, static pressure can likely be obtained using a surface or downhole pressure gauge or fluid level measurement. A static reservoir pressure is easy and inexpensive to obtain, however it requires the well be shut-in for a period of time prior to the measurement.

Monitoring the specific gravity of the wastewater, especially in commercial disposal wells with variable disposal fluid density, allows conversion of surface pressures to bottomhole with no additional costs. The specific gravity impacts the hydrostatic pressure component of the bottomhole pressure calculation.

Monitoring for seismic events using a pre-existing seismic network may provide an early warning of seismic activity, if suitably configured and continuously evaluated. The monitoring program could use the existing USGS seismic monitoring network or include seismometers proactively installed prior to the injection operation. Tracking earthquake trends (magnitude and event frequency) for events in an area of possible induced seismicity can reveal possible increases in seismicity even before the events become significant. For example, in the Central Arkansas, Ohio, and West Virginia case studies, an upward trend in the magnitude of associated events is apparent.

Additional seismometers would result in more accurate locations of seismic events and greater sensitivity to detect smaller events. The USGS recommends configuring a monitoring network capable of detecting a minimum of M2.0 event. For example, in Central Arkansas, additional monitoring stations were deployed. The additional monitoring stations provided increased accuracy and resolution level of seismic events leading to identification of a previously unknown basement fault. Additional seismic monitoring stations and data analysis requires additional costs as well as geophysical expertise to process and review.

Management Approaches

A management approach addresses the human aspect including agency, operator and public interaction. As discussed below, these approaches provide proactive practices for managing or minimizing injection-induced seismicity.

Undertaking earlier action rather than requiring substantial proof prior to action by the Director to minimize and manage injection-induced seismicity is a prudent approach for a number of reasons. Early proactive action, such as reducing operating conditions to decrease pressure build-up may avoid escalation of event magnitudes and prevent complete shutdown of the well. Early discussions with surrounding operators may allow access to additional data, for example 3-D seismic data, or result in voluntary action. For example, in the DFW area, communication between the Director and operator resulted in the voluntary shut-in of a suspect disposal well. Early action may also increase public confidence in the regulatory agency.

Contacting external multi-disciplinary experts from other agencies or institutions to address site assessment concerns may result in improved quality of response to seismicity concerns. For example, geophysicists may be able to interpret the active fault from the seismic events along with stress directions; while geologists provide an overall picture of the setting; and engineers evaluate the well responses in conjunction with comments from the others. An initial cooperative effort may have minimal cost.

Providing technical training for UIC Directors, specific to petroleum engineering evaluations or geoscience techniques could benefit preparedness of the program and expand options for minimizing and managing seismicity. At a minimum, it would raise awareness of the advantages and disadvantages of the various techniques and disciplines. Some costs may be associated with the training.

Utilizing a multi-disciplinary team for practical research for links between disposal well and reservoir behavior; geology; and area seismicity allows all complex aspects of seismicity to be reviewed. It may be possible to utilize in-house personal from other disciplines to aid in the effort.

Establishing a contingency plan, e.g., based on a seismic magnitude and/or frequency threshold, can assure that specific expedited response actions by the injection well operator occur in response to surrounding area seismic events. For example, contingency conditions could be as simple as immediately notifying and working with the permitting agency to evaluate the situation. The use of existing seismic monitoring and reporting databases is inexpensive, but limited data accuracy may require additional expense to supplement the existing network. A contingency plan provides an alternative to approval or denial of a permit.

Developing public outreach programs to explain some of the complexities of injection-induced seismicity may have some value.

CAN AN APPROACH BE USED TO SUCCESSFULLY ADDRESS SEISMICITY CONCERNS?

The site assessment considerations are intended to guide the Director in selecting which operational, monitoring, and management approaches are appropriate to address induced seismicity issues. If the Director does not identify an acceptable approach to address seismicity concerns, conditions may not be suitable to disposal operations at that location. If monitoring, operational or management approaches provide the required level of protection, the Director may condition the permit accordingly or use discretionary authority to require the desired approaches needed without revoking the permit.

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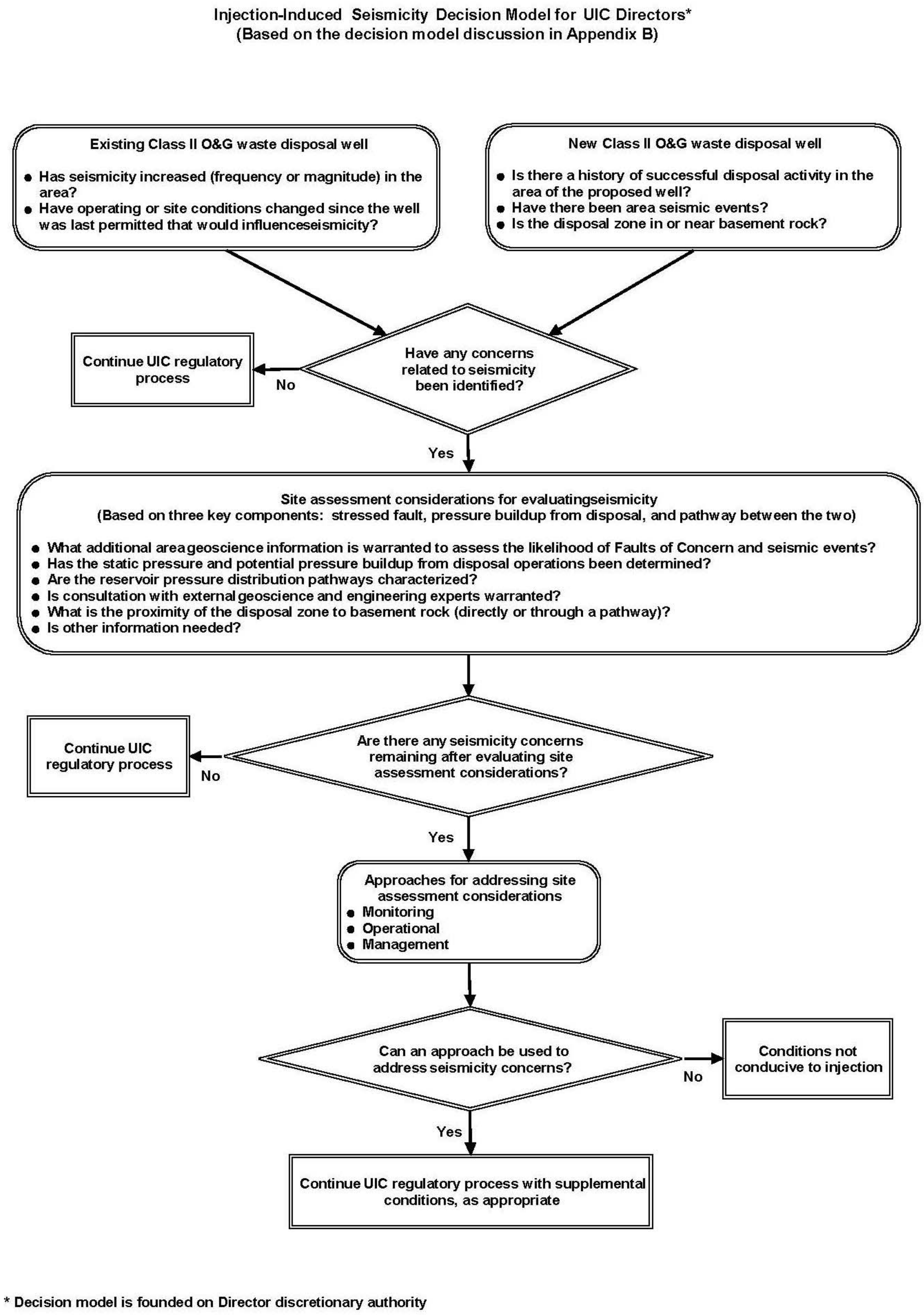
FIGURE 1 FROM THE REPORT:



APPENDIX C: GEOSCIENCES DISCUSSION AND INTRODUCTION TO INDUCED SEISMICITY RISK

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Basic Earth Science Concepts C-1
Basic Geologic Environment C-2
Geologic Interpretation Tools C-3
Rock Mechanics C-4
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Basic Seismology C-5
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Seismic Risk C-8
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INTRODUCTION

A basic understanding of the earth science concepts and natural processes through geology; rock mechanics; and seismology, including the science of seismic interpretation, is helpful in assessing the risks of inducing seismic events. A thorough discussion requires a working knowledge of tectonic processes and associated forces (physical stress and resulting strain, which change the shape of the earth's crust) as well as seismology—detailed topics outside the scope of this report. For any in-depth investigation (seismology, structural geology, reservoir characterization, etc.) consulting appropriate professionals is recommended, whether within your agency, a different agency (state or federal), professional society, academia, or private industry. As geologic conditions can vary widely depending on local conditions, no simplified approach to understanding fault movement and seismicity applies everywhere.

Information in this appendix was taken from Stein and Wysession, 2003; and Richard Sibson, 1994; along with a number of the websites cited at the end of this appendix and under 'Educational Websites' in the Subject Bibliography included as Appendix K.

BASIC EARTH SCIENCE CONCEPTS

The major earth layers are the core (inner and outer), mantle (inner and outer), and crust (oceanic and continental plates). Each layer has distinctly different characteristics and strengths. Oceanic plates are extremely dense and thin compared to the thick continental plates.

Over geologic time, convection currents within the mantle create complex movements beneath the earth's crust. The resulting forces cause sea floor spreading and plate collisions along crustal boundaries. Hot spots associated with volcanic areas extend down into the upper mantle. It is these processes that result in stressed conditions for crustal rocks below the ground surface and form the basis for the release of this energy along faults that are critically stressed.

Within the earth's crust, three-dimensional reactions to stress occur across every scale, from macro (plates) to micro (individual grains or crystals), with elastic, ductile and brittle response of the affected material depending on conditions. Examples of brittle deformation in rocks include all types of fracture systems with and without movement (faults and joints respectively). Faults in brittle formations are accompanied by fracture zones, with the frequency or density of fractures typically decreasing with distance away from the fault. The nature of faulting and associated fracture zones is an important consideration with respect to induced seismicity since these fracture zones can serve as avenues of communication for pore pressure buildup to the fault. Although stress histories can be inferred in some cases by analysis of fracture patterns (e.g., analysis of joint patterns), areas that have been subjected to multiple tectonic events may have extremely complex and extensive fracture systems.

Basic Geologic Environment

A particular geographic area can be described using approaches from three major geologic disciplines: stratigraphy (formation, sequence, and correlation of layered rock), petrology (rock origin through later alteration), and structure (structural features and their causes). Petrology uses three main rock classifications (igneous, metamorphic, and sedimentary) defined by rock origin, composition, and physical characteristics, among other details.

Stratigraphy primarily relates to geologic depositional processes and their order in time (law of superposition and identification of missing, repeated or overturned strata/sections). In the continental crust, the oldest (typically deepest) rock is called basement or crystalline basement if it is formed through igneous or metamorphic processes. Sedimentary rocks (carbonates, evaporites, and clastics), possibly with igneous intrusions (plutonic and volcanic), typically overlay the basement rocks. The contact between basement rocks and overlying younger strata is almost always an erosional surface (Narr et al., 2006). Basement rocks usually have no effective primary permeability (connectivity of pore space) or porosity (void space), but later weathering or movement can result in fractures or erosional features creating significant secondary porosity. Faulting of basement rocks can also result in fracture porosity and permeability along the fault zone. Basement faults that are active after deposition of overlying material can extend upward into overlying rock. Younger faults may also be present only in overlying sedimentary rocks.

Stratigraphic formations used as disposal zones can have a complex range of porosity types and permeability values. Sedimentary processes include precipitation (chemical and biological) and deposition of eroded rock particles that were transported by water or air and later buried and compacted into rock. The nature of fracture and matrix (bulk rock) porosities and permeabilities within the disposal zone is a critical aspect of pressure buildup from injection. Natural fractures can provide a permeable avenue for fluid flow while the matrix is generally being less permeable, but offers more pore space potentially limiting the distance of pressure distribution.

Petrology relates to the physical and chemical makeup of the rock, including how it is arranged (size and shape of pieces; void/pore space, cement overgrowths, dissolution, natural fractures, in-fill, etc.). Porosity provides the primary storage capacity of the reservoir, and permeability determines how effectively fluids and pressure are transmitted within the reservoir. Generally, deeper rocks have less permeability and porosity than shallower rocks. Deep basement rocks used for injection are usually either weathered (decomposed or altered), or fractured and faulted from tectonic forces. Wells injecting into, or connected with, fractured basement rock are more likely to induce seismicity.

The distribution and quality of porosity (both primary and secondary) and permeability within the disposal zone are critical for understanding how efficiently the formation will accept additional fluid. The area of increased pore pressure will be smaller in permeable and porous formations that allow fluids to move through the rock easily and quickly dissipate pore pressure, versus formations with restricted fluid movement and low porosity. Vertical and lateral variations in permeability and porosity are common in sedimentary rocks as are lateral variations in thickness of porous injection zones.

Geologic structure relates to the major physical changes in rock formations caused by three dimensional stresses. For example, earth stresses create fault and fracture zones; igneous intrusions; fold and thrust belts; wrench zones, and metamorphosed (changed by heat and pressure) rock. These stresses are directly related to the tectonic history of the region.

Geologic Interpretation Tools

Subsurface information on geologic structure can be inferred from surface geology, seismic data and information obtained from artificial penetrations (i.e. wells). Under the UIC program, developing sufficient geoscientific site data is the responsibility of the permit applicant. However, regulatory agency programs may elect to review publications, or consult with geoscience agencies (state geologic surveys, USGS) or universities with expertise in the geographic area for additional regional geologic information to address the areas of concern. Useful publications may include publicly or commercially available reports containing geologic information (geologic history, stratigraphy or structure) and rock characterization (flow characteristics, fracture networks and stress directions), and also geophysical well logs, core analysis, mine surveys, seismic surveys and geologic maps and cross-sections.

Geologic maps are designed to characterize the nature and continuity of the formations of interest (regional extent, depositional basin, major structural features, mineral deposits, petroleum reservoirs, etc.). For example, a geologic isopach (layer thickness) map or cross-section may define the lateral continuity of a disposal zone. An analysis of seismic reflection data may help identify any deep faults, and if present, the extent of the fault or associated fractures. Fault identification depends on the quality of available seismic data, though near-vertical strike-slip faults may be missed. Correlations of logs or a review of cross-sections may indicate missing or repeated sections, or potential faults. Information on the origin; direction and amount of movement; and vertical extent of the fault should be evaluated for any potential impact on the disposal project.

Gravity, magnetic, or resistivity surveys or heat flow data may aid in the assessment of the subsurface structures, although these additional techniques may not have the same resolution of scale as the tools discussed earlier. For example, gravity and magnetic surveys are typically conducted on a broad scale.

Rock Mechanics

Earth scientists and engineers have developed various theories to explain observed fault motion/rock failure, with accompanying seismicity.

- The Mohr-Coulomb failure criterion is a fundamental rock mechanics model used to describe fracturing or faulting. The Mohr-Coulomb criterion uses the tectonic stresses on a fault, the frictional resistance of the fault materials, and cohesion within the rock to determine whether or not movement along the fault will occur.
    - Fault movement occurs when shear stress along the fault exceeds the friction on the fault (Sibson, 1994).
    - The Mohr-Coulomb criterion is generally applicable to the upper most 15 kilometers of the crust (Davis et al., 2011).
- Research is ongoing in a number of areas to define criteria not covered by the Mohr-Coulomb criterion. Examples of a few of these areas include time-dependence, localization, material heterogeneity, and fracture propagation, also known as the Griffith Criteria (Sibson, 1994; Beeler et al., 2000; Pollard and Fletcher, 2005; Montési and Zuber, 2002).
- More information on deep stress fields and induced earthquakes provided by the USGS is available in Appendix M, Task 2.

Fault Motion

When sufficient deformation occurs in the subsurface with the accompanying buildup of in-situ stresses, a brittle rock will break, creating fractures. In contrast, a ductile rock has plasticity and will deform. Among the various sedimentary rock types, dolomite and limestone are brittle and shale is ductile (flexible). Brittle rock is more conducive to inducing seismicity in a disposal environment.

Unconsolidated sediments are also subject to faulting and overpressure. Areas with high sedimentation rates, such as the Gulf of Mexico, develop growth faults in response to active compaction and gravity load on unstable slopes. The movement on the growth fault is triggered by episodic periods of rapid sedimentation. Conversely, decreased pressure through pumping out ground water could also cause slip along the fault. Both causes effectively remove water from the sediment layer and increasing compaction of sediments, and hence increase the density and weight of the material triggering slip along the fault. Growth faults are also examples of shallow faulting unrelated to basement rocks.

Earth stress reactions will be accompanied by a level of seismicity that can be recorded with sufficiently sensitive and well placed monitoring devices. The USGS has compiled a map database of all faults in the U.S. believed to have caused earthquakes above magnitude 6 in the last 1.6 million years (USGS, 2004). The seismology community is actively studying the earth's structure, earthquake occurrence, and plate motion; in an effort to not only understand but to also forecast earthquakes. To grasp the difficulty in estimating seismicity potential, it is important to understand the basic aspects of seismicity, and how earthquakes are measured and interpreted.

Basic Seismology

An earthquake (seismic event) occurs when there is brittle failure along a fault at depth. The resulting brittle failure of the fault results in slip or displacement that generates elastic waves that propagate away from the fault. The event can be from a source in, on, or above ground that creates a wave motion in the earth. The movement (propagation) of the seismic wave is governed by laws of refraction and reflection within the geologic layering. Seismic exploration companies create seismic waves to identify structure, layering, and/or exploitable materials such as hydrocarbons in the subsurface. An earthquake (movement within the earth along a fault) gives rise to four types of seismic waves radiating away from the movement source (rupture zone or focus). These movements can be considered in two major wave categories, body waves and surface waves. Body waves travel through the earth, while surface waves are trapped near the surface of the earth. Body waves are faster than surface waves and are thus the first seismic waves to arrive; however, surface waves because they are trapped near the earth's surface decay more slowly with distance and can cause the most damage. As waves travel, their amplitude decays with increasing distance. Each of the four specific wave types has a characteristic motion (compressive, shear, or elliptical), frequency, wavelength, and velocity of propagation, with a corresponding wave equation. Travel velocities range from less than 1 to over 7 kilometers per second in the crust and upper mantle. For a specific location, there can be three to four arrival times of the different waves in quick succession whose difference in arrival time can be used to locate the source of the waves.

Large earthquakes are typically followed by smaller ones as stresses redistribute with the smaller earthquakes producing smaller waves. Crossing wave forms may create constructive or destructive interference. An earthquake series is a set of events related in space and time with similar characteristic wave signatures. In a series of earthquakes, the largest event is the main shock, with the rest classified based on whether they occur before (foreshock) or after (aftershock) the main shock. Detailed analysis of an earthquake series, with sufficiently detailed readings, can be used to map the causative fault location. Observation suggests that aftershocks occur across the fault plane of the main shock as stresses are shifted to new locations. The length of time encompassing the foreshocks and aftershocks is not uniformly defined, but the number of aftershocks decreases significantly over time (Richardson, 2013).

The size of an earthquake can be described with different magnitude scales based on the seismic waves generated: local or Richter (M_L), surface-wave (M_s), body-wave (m_b), or Moment magnitude (M_w). The first three (M_L, M_s and m_b) use formulas combining amplitude from seismometer recordings with a correction based on the distance the wave has traveled correcting for the spatial decay of the waves. Additionally, M_s and m_b incorporate the seismic wave period (peak to peak).

Moment magnitude (M_w or M) is proportional to the release of energy from large earthquakes (Seismic Moment, M_o). M_o is a physical measure of the size of the earthquake that is dependent on the area of the fault, the average displacement on the fault (slip), and shear modulus (rock rigidity). M_w is applicable to all sizes of earthquakes, giving similar results to either M_s or m_b for smaller earthquakes. In large earthquakes (M>5), the energy released is proportional to the amount of slip along the fault plane (Wells and Coppersmith, 1994; Båth, 1966). In preparation of this report, EPA used magnitude values reported in earthquake catalogs (see Appendix L), for the case study evaluations.

The Modified Mercalli Intensity scale is discussed under the Seismic Risk section since it relates to damage resulting from an earthquake.

SCIENCE OF SEISMIC INTERPRETATION

Technology used to record seismic waves has progressed from the original weighted spring or oscillating pendulum seismometers to complex seismographs that track motion in three perpendicular directions over broad frequency bands and record them digitally. In addition to faulting events, seismometers also record ground motions caused by a wide variety of natural and man-made sources, such as the motion of cars and trucks on the highway, building demolition, mining explosions, lake level changes, and ocean waves crashing on the beach. Instrumentation improvements have provided enhanced recording sensitivity. The difference in quality of earthquake data from today's seismometers to those from twenty or thirty years ago should be considered when viewing historic earthquake data. Knowing the details of the seismometer used to acquire the data is beneficial, noting that some older seismometers are still in service. Appendix L discusses the various earthquake databases.

The recordings of earthquakes must be analyzed to determine the origin (latitude, longitude and depth) of the faulting. At least three separate locations of seismograph readings are needed to locate the surface position (epicenter) of the earthquake. A model, with the major earth velocity layers, is used to separate the signals received into the different waves to determine the depth at which the earthquake occurred (hypocenter). Seismic wave velocity is a function of rock porosity, fluid saturation, compaction, and overburden pressure; or in rock mechanics terms, the elastic modulus, permeability, and density. For earthquake modeling, the Earth (surface through mantle) is divided into thick layers with uniform velocities. For exploration seismic modeling, a much more refined velocity model is needed to focus on the target interval.

Seismometers in the permanent monitor grid in most of the continental U.S. are spaced up to 200 miles (300 km) apart. With this spacing, the system is capable of identifying events down to approximately magnitude 3 or 3.5, although in some areas this may extend to 2.5. In tectonically active areas such as the continental western margin and New Madrid Seismic Zone, the seismometer spacing is closer, resulting in more accurate earthquake locations. Additionally, closer grid spacing generally measures events of smaller magnitude.

Beginning in 2007, the IRIS EarthScope Transportable Array has travelled systematically across the continental U.S. The deployment of this array has led to an increase in lower-level seismic event detection that was not previously possible. This array includes seismometers spaced every 70 km, and is capable of picking up events down to around magnitude 1. Subsequent research reports have concluded that the added modern seismometer density provided significant additional information, including improved seismicity rates for hazard analysis, and identification of earthquake swarms and clusters (Lockridge et al., 2012, Frohlich, 2012).

Consequently, the number of recorded seismic events over time is partly a function of the seismometer array density and instrument sensitivity.

The accuracy of earthquake focal depth determination is related to the seismometer grid density, seismometer quality, and the detail (quantity and accuracy) of the velocity model used to locate the event. Hypocenter depths are often reported using a default value for the geographic area model. On initial event notifications, default depths will have similar depth uncertainties. For example, a depth of 5 km (16,500 feet) may have a vertical uncertainty between three and five km (10,000 to 16,500 feet). Generally, accurate focal depths (within less than 300 m (1000 feet) vertically) are available only through special investigations, where the waves from the seismometers are individually analyzed with human assessment. The best depth estimates occur when a number of seismic instruments are within kilometers of the surface location of the earthquake.

According to the 2012 USGS glossary, the best located event has an uncertainty at the hypocenter of 100 m (300 feet) horizontally and 300 meters (1,000 feet) vertically. This small area of uncertainty may apply in California, but in the well constrained New Madrid Seismic Zone, Deshon (2013) noted, "Absolute earthquake location is a function of location algorithm, velocity model, event-station geometry and pick quality." Deshon (2013) found hypocenter locations moved up to seven km in depth and three km geographically, by incorporating different phases in the model.

Natural resource exploration firms have used various seismic reflection techniques for years to better image the subsurface in three dimensions. The additional quality gained by increased recording density from a regional two-dimensional (2D) survey to a tightly spaced three or four-dimensional survey is remarkable. Passive seismic recordings are now in use either in active seismic areas or producing hydrocarbon fields with microseismicity to further refine the subsurface structure (Shemeta et al., 2012; Verdon et al., 2010; Martakis et al., 2011).

There are a series of different seismic event reports available from the USGS Earthquake website that fit different needs. Initial seismic event reports, generated within hours of the event, are designed to help with emergency response, and are preliminary with a large location uncertainty. Later reports generally have increased accuracy (magnitude and location), as more information has been incorporated and the standard event modeling has been applied.

SEISMIC RISK

Seismic hazard represents the potential for serious seismic events, whereas risk is the potential damage to people and facilities that may result from the earthquake. Induced seismicity risk evaluates the potential for triggering an earthquake, by altering conditions and initiating movement along a preexisting, optimally oriented fault.

In 1977, Congress passed legislation to reduce the risks to life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program primarily designed to promote safe surface designs. As a result, USGS provides hazard maps used in risk assessments (Appendix M). Hazard typically relates to magnitude whereas risk is associated with intensity. The intensity scale describes how strongly the earthquake was either felt or the degree of damage it caused at a specific location. A strong earthquake yields different levels of intensity based on distance from the epicenter and local surface geology as well as the size of the earthquake. The USGS has instituted a 'Have you felt it?' campaign to increase the epicenter location accuracy and to better define the intensity according to the Modified Mercalli Intensity Scale[23]. The Modified Mercalli Intensity Scale is used to map surface effects for a given earthquake with scale increasing with amount of damage.

Surface and near-surface designs of structures are developed by engineers for projects ranging from water reservoirs, deep tunnel construction, or horizontal well drilling. These structures are designed to withstand existing and potential stress, including seismically created stress from strong ground motion (Pratt et al, 1978; Roberts, 1953; Schmitt et al., 2012; Coppersmith et al., 2012).

To understand how risk varies for surface versus subsurface structures, consider first the intensity difference. Seismic surface waves are the most likely to be felt, having the greatest amplitude and a motion similar to ocean waves. For the most damaging earthquakes, the earth moves very similar to the surface of the ocean in a storm. Consider the difference in motion on a ship at the top of the mast, main deck, and sea anchor. In simplistic terms, this would correspond to the top of a high-rise building, ground level structures, and deep structures such as a wellbore. Accordingly, a wellbore cemented through various layers of rock will undergo little motion.

Serious damage from large earthquakes occurs not from the primary fault motion, but from the secondary processes: landslides, subsidence, liquefaction, and surface fault displacements, combined with failure of engineered structures not designed for strong ground motion. High risk is also present along coastlines from submarine earthquakes, or on large bodies of water, in the form of large waves or erratic waves crashing on shorelines (tsunami and seiche, respectively).

[23] http://earthquake.usgs.gov/learn/topics/mercalli.php

Most reports cover damage at or above surface ground level. The USGS compiled a summary of earthquakes, over 4.5 magnitude, in the United States between 1568 and 1989 (Stover and Coffman, 1993), describing any damage that was observed including shallow and deep wells. The report covered tens of thousands of earthquakes. Forty-three wells were mentioned predominantly in connection with temporary turbidity or fluid level changes with fewer than ten damage reports. Most of these wells were shallow water wells. Damage was frequently minor, from a tile falling off to a crack in the surface casing. The most applicable report was for the May 2, 1983, earthquake in Fresno County, California: "In the oil fields near Coalinga, surface facilities such as pumping units, storage tanks, pipelines, and support buildings were all damaged to some degree. … Subsurface damage, including collapsed or parted well casing, was observed only on 14 of 1,725 active wells."

UIC programs require that operators run a mechanical integrity test after an injection well workover (repair casing or replace tubing and/or packer). The workover report typically lists the problem repaired, but does not identify the cause of the problem. UIC program directors also have discretionary authority, in cases of earthquakes, to require additional measures such as mechanical integrity testing, as necessary to protect USDWs.

Seismology and Rock Mechanics Glossary

Earthquake is a series of vibrations induced in the Earth's crust by the abrupt rupture and rebound of rocks in which elastic strain has been slowly accumulating (dictionary.com). The term describes both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth (USGS).

Earthquake hazard is anything associated with an earthquake that may affect the normal activities of people. This includes surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, tsunamis, and seiches. (http://earthquake.usgs.gov/learn/glossary/, downloaded 5/22/13)

Earthquake intensity is a number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Several scales exist, but the Modified Mercalli scale and the Rossi-Forel scale are most commonly used in the United States. There are many intensity values for an earthquake, depending on where you are, unlike the magnitude, which is a single value for each earthquake (USGS).

Earthquake magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph with an accompanying correction for the distance from the earthquake to the seismograph. Several scales have been defined, but the most commonly used are (1) local magnitude (M_L), commonly referred to as "Richter magnitude," (2) surface-wave magnitude (M_s), (3) body-wave magnitude (m_b), and (4) moment magnitude (M_w). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (M_w) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types.

Earthquake risk is the probable building damage, and number of people that are expected to be hurt or killed if a likely earthquake on a particular fault occurs. Earthquake risk and earthquake hazard are occasionally incorrectly used interchangeably. (http://earthquake.usgs.gov/learn/glossary/, downloaded 5/22/13)

Epicenter is the 2D location of the earthquake source on the earth's surface, directly above the source, i.e. latitude, longitude.

Hypocenter aka focus is the 3D location of the earthquake source, i.e. latitude, longitude, focal depth below ground.

Period is the inverse of frequency, or the time for one cycle of the wave shown in time units, versus wavelength in distance. It is equivalent to the wavelength divided by speed. This is the measure of time at the seismometer, peak to peak.

Radius of the earth is roughly 6,371 km (polar 6356.8 km and equatorial 6,378 km) (http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html, downloaded 5/22/13), with the core 3,485 km.

Rock mechanics is the study of the mechanical behavior of rocks, especially their strength, elasticity, permeability, porosity, density, and reaction to stress (dictionary.com).

Seiche is the sloshing of a closed body of water from earthquake shaking. Swimming pools often have seiches during earthquakes.

Shear is an action or stress, resulting from applied forces, which causes or tends to cause two contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact (Webster, 1946).

Shear Stress is the stress component acting tangentially to a plane, (Webster, 1995).

Shear Zone is a portion of rock mass traversed by closely spaced surfaces along which shearing has occurred and within which rock may be crushed and brecciated (Webster, 1995).

Stress is the physical pressure, pull, or other force exerted on one thing by another (dictionary.com), or the force of resistance within a solid body against alteration of form (Webster, 1995) such as:

a. The action on a body of any system of balanced forces whereby strain or deformation results.

b. The amount of stress, usually measured in pounds per square inch or in Pascal.

c. The load, force, or system of forces producing a strain.

d. The internal resistance or reaction of an elastic body to the external forces applied to the body.

e. The force acting on an area.

Strain is deformation of a body or structure as a result of an applied force (dictionary.com)

Torsion as used in mechanics (dictionary.com) is:

a. The twisting of a body by two equal and opposite torques.

b. The internal torque so produced.

Torsional Stress is a shear stress on a transverse (direction at right angles to each other) cross-section resulting from a twisting action (Webster, 1995)

Wavelength is one cycle of the wave shown in distance units. It is equivalent to speed times period, or speed divided by frequency. This is measured peak to peak at a single time.

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APPENDIX D: PETROLEUM ENGINEERING CONSIDERATIONS

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Petroleum engineering approaches offer many ways of assessing disposal well behavior and reservoir properties that may contribute to injection-induced seismicity. This appendix provides more details on the petroleum engineering analyses and methods used for this project and analyses of the case studies. Other petroleum engineering methods or applications may also be useful to operators and UIC Director in evaluating injection-induced seismicity. Collectively, petroleum engineering techniques may assist in a site-appropriate evaluation of the three key components for potential injection-induced seismicity.

Another aspect of the project included application of petroleum engineering techniques. Petroleum engineering methodologies provide core tools for evaluating the three key components of injection-induced seismicity as part of the site assessment process. A petroleum engineering based site assessment may provide important details by quantifying reservoir transmissibility, and by characterizing the flow pathways that together impact the amount and distribution of pressure buildup from disposal operations. Characterizing flow pathways helps determine if the pressure buildup is being dispersed radially or in a preferential direction from the disposal well. The Hall integral and derivative responses at some of the case study wells suggest hydraulic communication with a boundary (i.e. an offset well or fault) at some unknown distance from the well. An analysis of available operational data may not provide conclusive proof of induced seismicity, but may identify wells warranting additional investigation.

WHAT ARE PETROLEUM ENGINEERING CONSIDERATIONS?

Site assessment considerations in the decision model focus on three key components for the occurrence of injection-induced seismicity: a Fault of Concern, disposal interval pressure buildup and a reservoir flow pathway to transmit the pressure buildup from the disposal well to the fault. All three components are necessary to induce seismicity. Petroleum engineering methods address pressure buildup and the pathway present around the disposal well as well as characterizing reservoir behavior during the well's operation. Petroleum engineering approaches coupled with geologic and seismologic data may also provide area fault information. These methodologies can provide both quantitative and qualitative descriptions of the disposal wellbore and reservoir conditions. Some of the case study wells reviewed experienced specific Hall integral and derivative responses that correlated to area seismic events. The Hall integral and derivative responses at these wells suggest hydraulic communication with a boundary (i.e. an offset well or fault) at some unknown distance from the well.

Petroleum engineering methods encompass various well aspects including well construction, well completion, well operations, and reservoir characterization to evaluate and optimize well performance. In this report, these fundamental petroleum engineering methods were applied to evaluate disposal wells in the four case study areas using available data. The WG assessment process examined injection well operational and reservoir behavior in regard to seismic event activity.

Petroleum Engineering Information Collection

Information collection focuses on disposal wellbore details and how these parameters might contribute to injection-induced seismicity. Well construction and completion conditions, the well's injection profile (where the injected waste is emplaced), and injection rate determine bottomhole injection pressure and conditions that may impact the zonal isolation of the injected fluids. Applications of these aspects are detailed below.

UIC Class II disposal permits typically include disposal well construction and completion data such as the well completion date, casing and tubular dimensions and depths, cementing records, total well depth, packer depth and type, waste density, completion interval(s) and type (e.g., open-hole, screen and gravel pack, or perforations), and initial pressure prior to disposal. Detailed knowledge of the well layout is necessary for assessing the isolation of the disposal zone through cemented casing, geological confining layers, location of the disposal zone relative to basement rock, and if the disposal zone includes multiple intervals or is focused on a single interval.

Knowledge of the waste density and wellbore tubular dimensions coupled with the injection rate enables calculation of an operating bottomhole pressure by accounting for the hydrostatic pressure of the fluid column and friction pressure loss of the tubing. This calculation is particularly useful for converting surface pressure injection history to bottomhole conditions. The operational bottomhole pressure gradient trend can be compared against the estimated or measured fracture gradient for the disposal zone to assess if injection-induced fracturing is a concern. Static bottomhole pressures can be estimated from the static fluid level or surface pressure and fluid density.

Cased hole and production logs can also provide useful information on the wellbore condition to assess injection operation conditions. Production logging data may supplement geologic data by providing additional insight about out of interval fluid movement and vertical pressure dispersal. Cased hole logs such as a cement bond log can identify properly or poorly cemented portions of the injection casing. Production logs (radioactive tracer surveys, flowmeters, temperature, oxygen activation, and noise logs) provide information about injection profiles, zonal isolation, and upward and downward fluid channeling. The wellbore injection profile shows where fluid is going into the formation, which in turn controls the reservoir pressure buildup response. Annular pressure tests and production logging can also confirm well mechanical integrity if this is a concern following area seismic activity.

Temperature logs typically require the well be shut-in for 36 to 48 hours prior to running the log so the temperature differential between the injected fluid and reservoir temperature can be effectively measured. Radioactive tracer tests use slug chases or velocity shots to evaluate the injection profile in the well. The radioactive ejector tool has limited capacity and may require multiple trips in and out of the well to reload the ejector tool when profiling large disposal zones. Flowmeters, such as a spinner survey, are typically less effective in large diameter casing or open-hole intervals. Production logs are routinely used for Class I hazardous waste injection wells, but are not typically required for Class II disposal wells. Several of the case study wells had long vertical open-hole completions, but no assessment of the injection profile. In the Ohio case study, a production log was conducted to assess the portion of the disposal zone receiving fluid.

UIC operational compliance case history data generally included monthly injection volumes with maximum and/or average surface injection pressures. Using this data along with the well construction and completion information, the WG assessed well construction conditions and calculated operating bottomhole injection pressures for each case study well. The calculated bottomhole operating pressures were then used in the petroleum engineering approach analyses.

AVAILABLE CLASS II DATA

The most common data available for Class II disposal wells are injection rates/volumes and injection tubing pressures. Such data are routinely reported as part of both EPA direct implementation and state UIC Class II program requirements. Bottomhole pressures (BHP), more suitable for evaluating reservoir conditions, are not as readily available. The timeframe for reporting injection volumes and pressures varies between regulatory agencies and depends on site circumstances. Although less common, pressure transient test data are occasionally available.

The following data types may be available for Class II disposal wells:

Common UIC monitoring data reported:

- Injection rates or volumes
- Surface tubing pressures

Common data submitted in UIC permit applications:

- Well construction

  - Tubular (tubing/casing) dimensions and depth
  - Cementing information
  - Completion type and interval
- Reservoir information
  - Gross and net injection zone thickness
  - Porosity
  - Name and description of disposal zone and overlying confining zones
  - Bottomhole temperature
  - Initial static BHP
- Reservoir and injection fluids
  - Specific gravity
  - Fluid constituent analysis

Though less common, these pressure test measurements may also be available:

- Falloff/injectivity test: reservoir characterization and well completion condition
- Step rate test: fracture gradient
- Static pressures: initial pressure and pressure change during well operations

PETROLEUM ENGINEERING ANALYSIS OF OPERATIONAL DATA

The WG focused on petroleum engineering analysis of any available data sets for correlation with reservoir behavior and geologic environment. The petroleum engineering approach couples reservoir rock and fluid properties with time, pressure, and injection rate data from well operations to describe and predict reservoir behavior. Analysis of disposal well operating data and well testing, such as pressure transient tests, can provide details about the disposal zone reservoir pathway and the completion condition of the well. Operating injection rates and pressures are typically collected as part of the permitting compliance activity and consequently more readily available than pressure transient tests. Completion conditions reflect conditions at or near the wellbore while reservoir characteristics describe the disposal zone away from the well. For example, a well that has been fracture stimulated displays a different response than an unfractured well.

Reservoir characterization assesses the injection formation flow patterns, the formation's capacity to transfer pressure responses, and the completion condition of a disposal well. Identifying anomalous reservoir behavior through such analyses and then correlating the results with geoscience data may suggest relationships between injection well pressure response and induced seismic activity. The petroleum engineering approach was incorporated into the case study analyses.

Operational Data Plots and Analyses:

Both operating data and pressure transient data shown on appropriate plots represent "pictures" of mathematical responses that can be fit to reservoir models which qualitatively and, in some cases, quantitatively characterize well completion and performance conditions, reservoir flow geometry, and, in limited cases, reservoir geology. Graphs of typically reported injection volume and operational pressures reflect reservoir behavior over time. Longer periods of operational data (typically in months or years) results in a deeper, though less refined look into the reservoir than a shorter timeframe pressure transient test.

Graphical format for the petroleum engineering analytical plots varies, ranging from tandem linear axes to dual log axes depending on the type of analysis performed. The graphs may display certain patterns or quantitative values which inform the reservoir analyst as to what type of reservoir flow characteristics are present or identifies changes in reservoir behavior over time. Reservoir characteristics identify the type of disposal zone reservoir pathway present and indicate its tendency to dissipate pressure buildup, either radially or in a preferential direction. Hence, the data can be used to "describe" the reservoir pathway.

Operational data are analyzed using the steady state radial flow equation, in the form of the Hall integral and its derivative, while pressure transient tests are analyzed using solutions to the radial diffusivity equation. Operational data includes both injection rate and pressure information, but actual data reported can vary depending on the regulatory agency requirements. For example, injection volumes may be reported with daily, monthly, or quarterly frequency. Injection pressures may be reported a number of ways, such as a maximum value and a monthly average or as monthly minimum and maximum values.

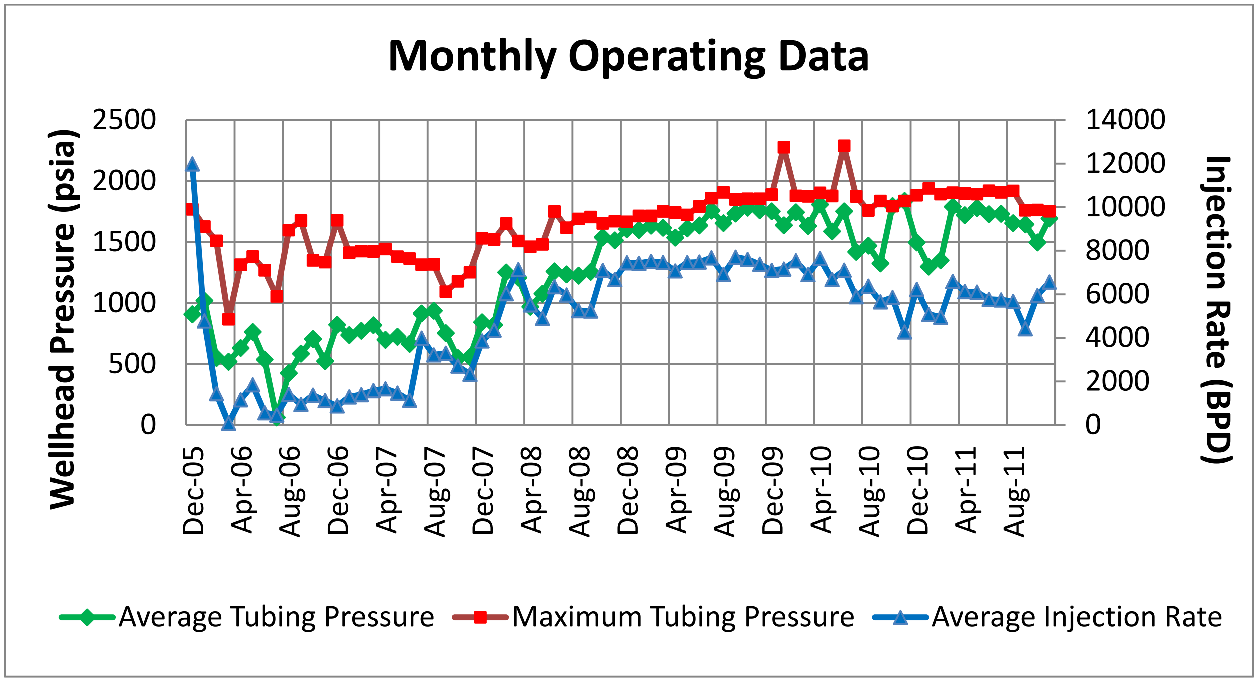
For best applicability, surface pressures should be converted to bottomhole conditions, prior to performing a Hall plot analysis. This conversion requires the analyst account for friction pressure loss with a correlation, such as Hazen-Williams (Westaway and Loomis, 1977; Lee and Lin, 1999), based on the tubing specifics and injection rates. The hydrostatic pressure from the fluid column must be added to the surface pressure as part of the bottomhole pressure calculation. The reporting frequency of injection rates can also impact the quality of the analysis. Plots, calculations, and analyses associated with operational data are summarized below:

Operating Rates and Pressures Overview Plot

- Overview of surface pressures and injection rate or volume plot (Figure D-1)
  - Cartesian (linear) plot of surface injection pressure and rate/volume versus date
    - y-axis primary: average and maximum wellhead (surface or tubing) pressure

- y-axis secondary: average injection rate (barrels per recording time period)
- x-axis: date (based on recording timeframe, e.g., daily, monthly, quarterly)

FIGURE D- 1: OVERVIEW PLOT OF MONTHLY OPERATING TUBING PRESSURES AND INJECTION RATES



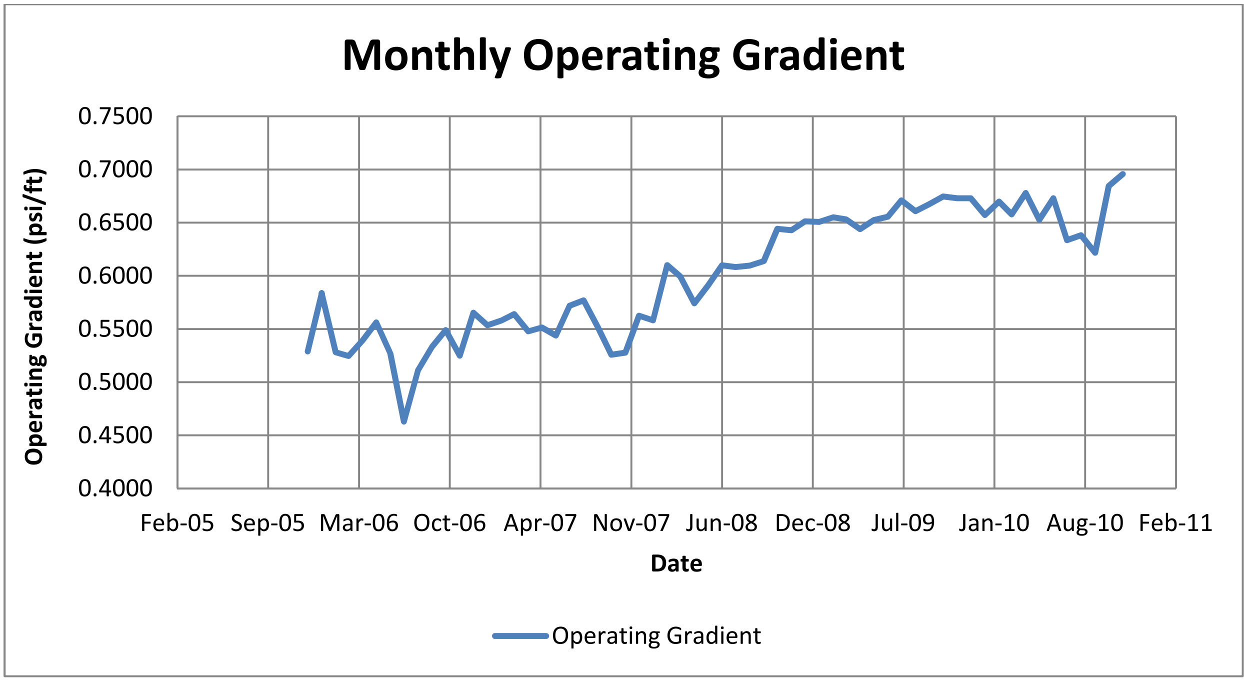
- Purpose
  - Identifies trends or large changes in pressure and/or injection rate/volume behavior
  - Provides a timeline of operational activity
- Challenges: Frequency of data reported, intermittent well use, quality of data
- Possible red flags
  - Maximum pressures nearing fracture pressure
  - Increased pressure with declining injection rates
  - Suspect data quality (e.g., repeating pressure value with varying rate)

OPERATING PRESSURE GRADIENT PLOT

- Cartesian plot of the operating bottomhole pressure (BHP) gradient (Figure D-2)
  - The operating BHP can be measured or calculated
  - Calculated values obtained by adding the hydrostatic fluid column, based on the fluid specific gravity, to the surface tubing pressure and subtracting friction pressure loss
    - Calculate hydrostatic pressure of the fluid column:
      - (disposal fluid specific gravity) x (fresh water gradient) x (depth)
    - Specific gravity is obtained from a fluid analysis or is estimated

- Friction loss estimated using tubing dimensions and Hazen-Williams friction loss correlation (Lee et al., 1999; Westaway et al., 1977)
  - Tubing friction factor, C, is based on tubing type
  - Frequency of rates data impact friction calculations
- Operating pressure gradient is operating BHP divided by depth (psi/ft)
  - Depth is the top of the completed interval or tubing depth
- Cartesian plot of bottomhole operating pressure gradient versus date
  - y-axis: operating pressure gradient, psi/ft
  - x-axis: date (based on recording timeframe, e.g., daily, monthly, quarterly)

FIGURE D- 2: MONTHLY OPERATING PRESSURE GRADIENT PLOT



- Purpose
  - Compare operating pressure gradient to calculated or measured area specific fracture gradients to confirm the disposal well is operating below fracture pressure
- Challenges
  - Conversion of surface pressure to BHP can be inaccurate
  - Varying injectate specific gravity introduces uncertainties in calculation of the hydrostatic fluid column
    - More of a concern in commercial disposal wells
  - Friction pressure estimates can be suspect, especially for wells with high injection rates through smaller diameter tubing
  - Frequency of rate data impacts friction calculations
- Possible red flags

- New or extension of fractures may occur if well is operating above the fracture gradient
- Tubing size and injection rates are not within the table range for calculating friction loss values

Hall Integral and Derivative Plot

The Hall integral has been used since 1963 (Hall, 1963; Jarrell et al., 1991). The Hall integral derivative evolved later after the derivative approach was developed for well testing techniques (Izgec and Kabir, 2009). The Hall plot uses readily available operational data coupled with an estimate or measurement of the average static reservoir pressure prior to injection. This operational data is routinely recorded as part of UIC permit compliance.

The Hall plot represents a graphical integration of the steady state radial flow equation which couples operating pressure and cumulative injection. Pressure values are calculated on a bottomhole (BHP) basis for use in the Hall Plot. The Hall Plot is a numerical integration between the operating BHP and static (reservoir) BHP. This numerical integration yields a straight line trend for radial flow (Figure D-3). The integral (summation) serves to "smooth out" noise commonly present in injection operating data. The derivative is the running slope of the Hall integral plot. The derivative magnifies any slope change and tends to be much noisier than the Hall integral. Adding the derivative trend to the integral plot helps to more readily identify significant changes in disposal well behavior.

The Hall integral is accepted petroleum engineering methodology that is easily calculated in a spreadsheet. The integral provides a much longer observation period of the injection zone than is generally obtained with a pressure transient test. The well's pressure response corresponds to a greater investigative distance into the reservoir the longer the well operates. The Hall integral is a function of the pressure difference between injection and shut-in conditions weighted by operating time increments.

- Cartesian (linear) plot of Hall Integral and Derivative curves (Figure D-4)
  - Hall integral is a numerical integration between the operating BHP and static (reservoir) BHP
    - Tracks the change in operating pressure with time, compared to the initial static conditions
    - Cumulative or running summation of ($\Delta P * \Delta t$) as well operates
      - Values will increase with cumulative operation time
    - ΔP: Injecting BHP-static BHP calculated for each measurement
    - Δt: Time increment for measurements matched to ΔP calculation

- y-axis: Hall integral (H_I) = Cumulative ($\Delta P*\Delta t$) function, psi - time period
- y-axis: Hall Integral Derivative: $D_{HI} = (H_{i2}-H_{i1})/(Wi_2-Wi_1)$
  - ($H_{i2}-H_{i1}$) represents difference between successive Hall integral values
  - (Wi_2-Wi_1) represents difference between successive cumulative injection values
- x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D- 3: STYLIZED EXAMPLE HALL INTEGRAL PLOT WITHOUT DERIVATIVE

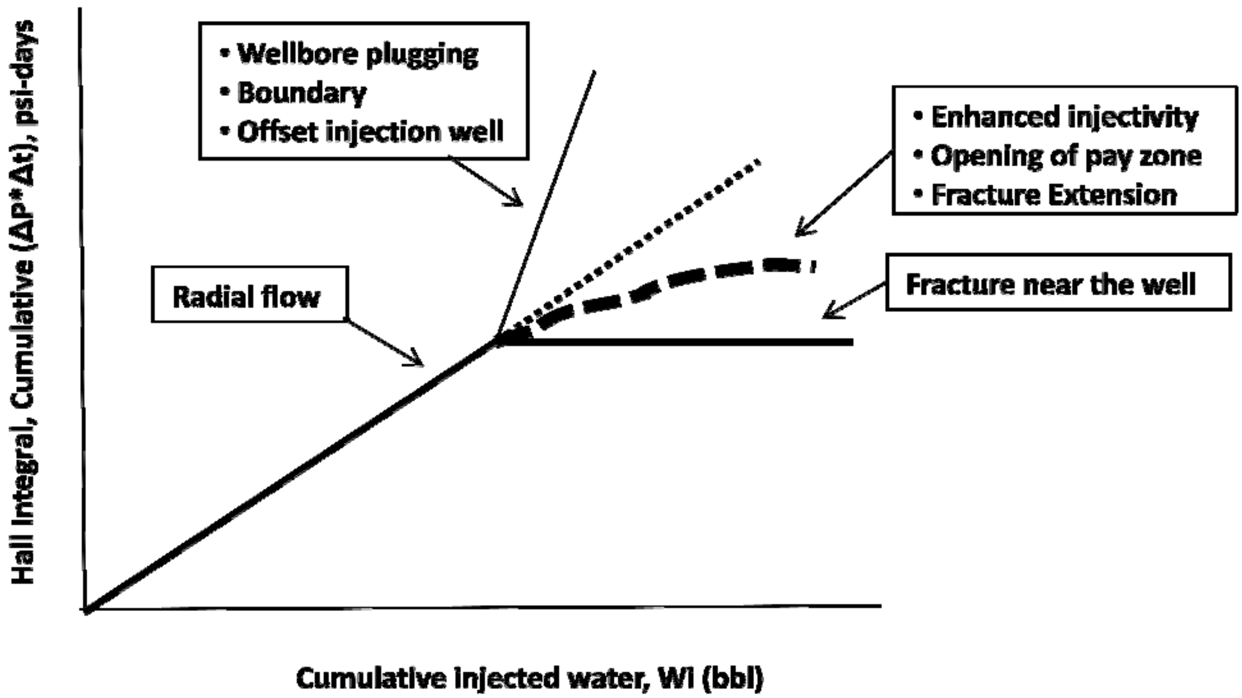
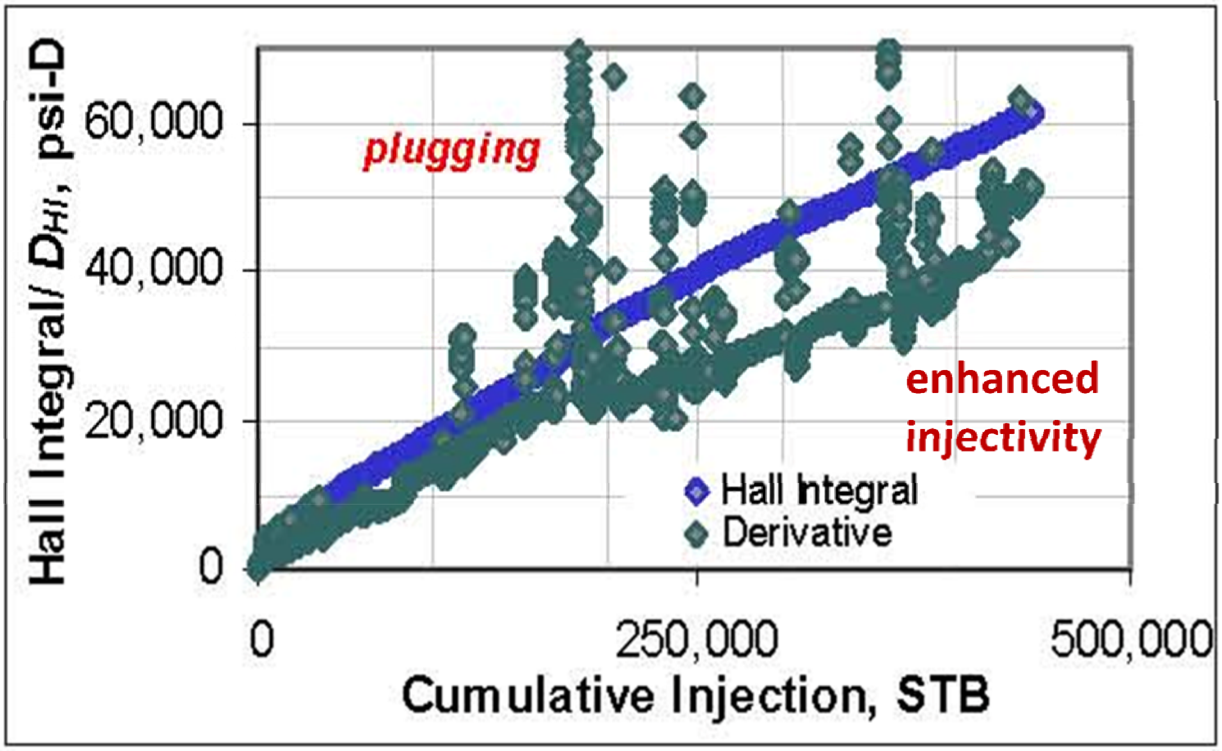


FIGURE D- 4: HALL INTEGRAL WITH DERIVATIVE (MODIFIED FIGURE 1 FROM YOSHIOKA ET AL., 2008, WITH PERMISSION)



- Purpose
  - Evaluates injection well performance and reservoir flow behavior or changes in behavior over time
    - Slope change on the Hall integral trend reflects the pressure response as fluid moves radially from the disposal well
      - Slope indicates a well's completion condition or injection efficiency
      - Negative slope break associated with enhancement of injectivity
      - Positive slope break indicates reduced injectivity
      - No slope break (straight line) represents radial flow
  - Location of derivative (D_{HI}) relative to the Hall integral (H_I) also indicates the completion condition of the well
    - Highlights well behavior patterns
      - D_{HI} located below H_I indicates enhanced injectivity
        - Examples: Opening of new pay zone, fracturing, extension of existing fracture
      - D_{HI} overlying H_I indicates radial flow
      - D_{HI} above H_I suggests a decrease of injectivity
        - Examples: Near wellbore plugging, boundary, offset injection well

        - Hall derivative (D_{HI}) should always be a positive value if Hall integral (H_I) is increasing
- Challenges:
    - Available time increment of pressure and injection reported data impacts quality of Hall derivative function and shape of plot
    - Requires an initial reservoir pressure
        - A measurement or estimate of the average initial static BHP is required
    - Conversion of surface pressure to BHP can be inaccurate
        - Friction pressure estimates can be suspect, especially for wells with high injection rates through smaller diameter tubing
    - Hall integral should increase as long as injection is occurring
        - Too high static reservoir pressure estimate can cause negative increments in the Hall integral calculation
    - Wells used intermittently require data manipulation to keep the Hall integral positive
- Possible red flags
    - Constant tubing pressure with varying injection volumes raises questions about data quality
    - Positive slope change may be associated with a plugging at the well, boundary or offset injection well
    - Negative slope break may be associated with the opening of a new pay zone, fracturing, or extension of existing fracture

Hall Integral Sensitivity Plots

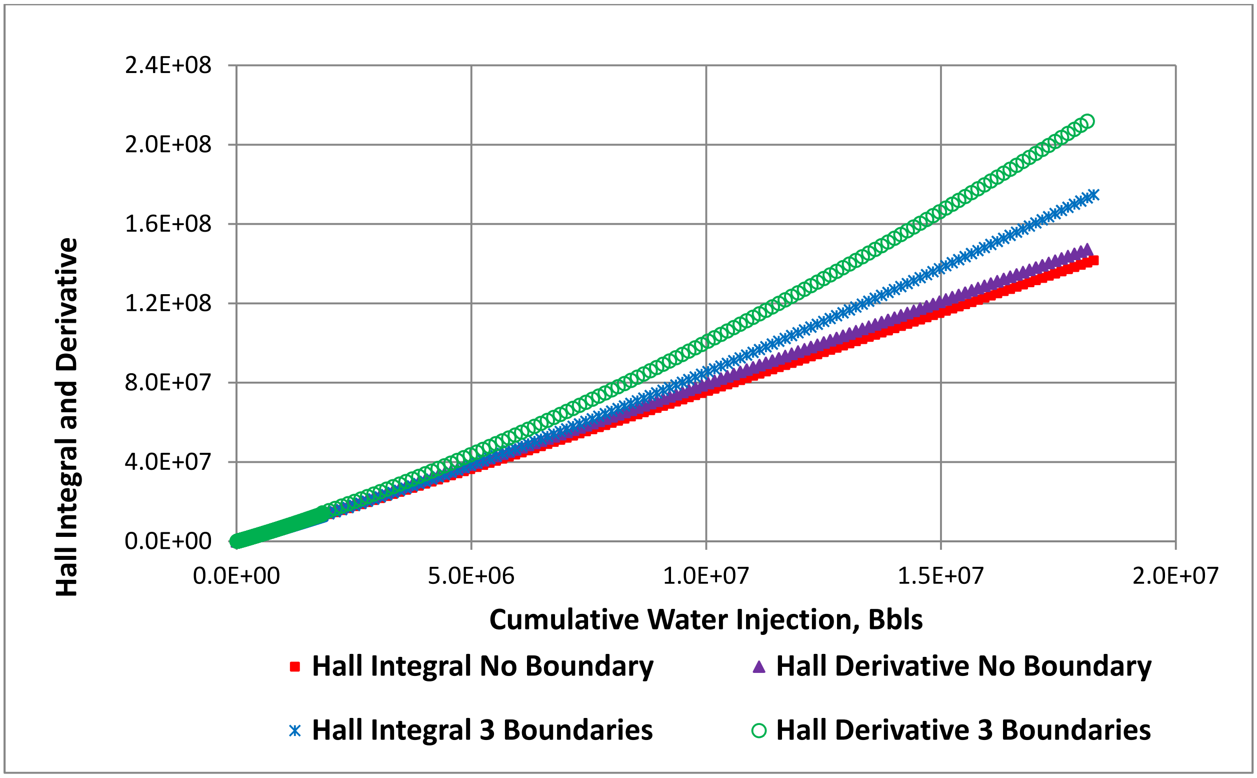
Three sensitivity analyses were conducted to determine the Hall integral and derivative responses. The three sensitivity cases included: 1) Hall integral response to a reservoir model containing boundaries, 2) the impact of the assumed initial pressure value used in the Hall integral calculation, and 3) the sensitivity of the Hall integral to the well operating timeframe.

Boundaries

Analytical models were set up using the PanSystem pressure transient software. One model included an infinite acting radial flow reservoir and the second model contained a U-shape fault configuring representing three no-flow boundaries, each 2 miles equidistant from the injection well. Each model included 5000 bpd continuous injection for 10 years (k=50 md, h=100 ft, μ=1 cp, r_w=.3 feet, c_t= $6x10^{-6}$ psi^{-1}, Φ= 20%, P_{init}=2000 psia). The modeled pressure responses represented bottomhole conditions and zero wellbore skin. The modeled pressures were then converted to Hall integral and derivative plots.

- Hall integral and derivative plot with and without boundaries (Figure D-5)
    - y-axis:
        - Hall integral (H_I) = Cumulative ($\Delta P * \Delta t$) function (psi- time period)
        - Hall Integral Derivative: $D_{HI} = (H_{i2}-H_{i1})/(Wi_2-Wi_1)$
    - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D- 5: HALL INTEGRAL AND DERIVATIVE RESPONSE FOR NO BOUNDARY AND 3 BOUNDARIES 2 MILES EQUIDISTANT FROM WELL



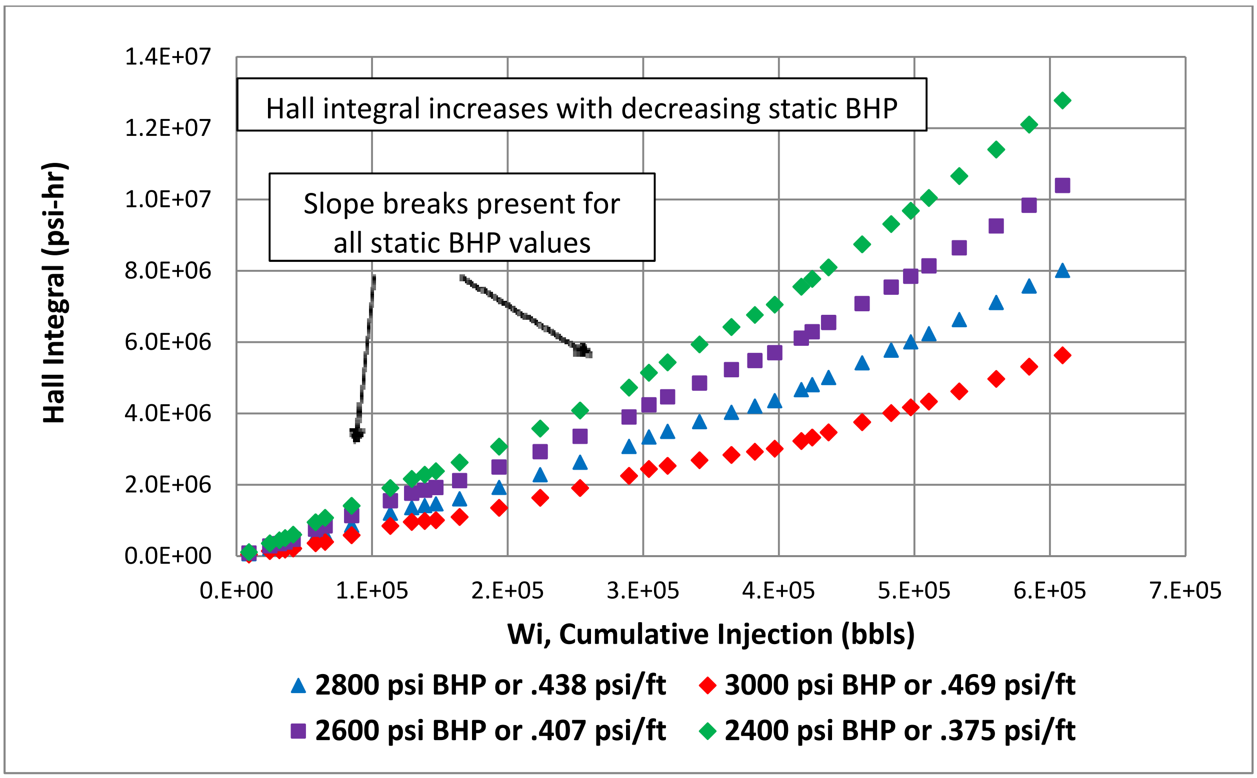
- Purpose:
    - Determine Hall integral and derivative responses to known boundary conditions
    - Compared radial flow to U-shaped boundary conditions
        - Bounded system response causes Hall integral and derivative curves to have positive slope breaks
            - Derivative response located above Hall integral
            - Separation between the Hall integral and derivative increases with number of boundaries encountered by injector pressures response
- Challenges:
    - Boundary conditions may be unknown due to limited geologic information
    - Upswing may be from offset disposal activity and not associated with a no-flow boundary or fault

Initial Pressure

Sensitivity calculations were performed on each of the case study wells using a range of assumed bottomhole static pressures to explore the impact of static pressure assumption on Hall plot behavior. Even with varied pressure assumptions, the overall slope change trend in each well was not impacted, but the degree of slope change did vary with the static pressure assumed. The WG concluded an incorrect static pressure may not critically alter the Hall plot qualitative meaning, though it would have a quantitative impact. For purposes of the case studies, the Hall plots were used for qualitative behavior assessment only.

- Linear plot of Hall Integral with varying initial pressures(Figure D-6)
  - Checks the sensitivity to a range of original reservoir static pressures
  - y-axis: Hall integral (H_I) = Cumulative ($\Delta P * \Delta t$) function (psi- time period)
  - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D- 6: HALL INTEGRAL INITIAL PRESSURE SENSITIVITY PLOT



  - Purpose:
    - Qualitative assessment of estimated static pressure estimate on character or shape of Hall integral trend

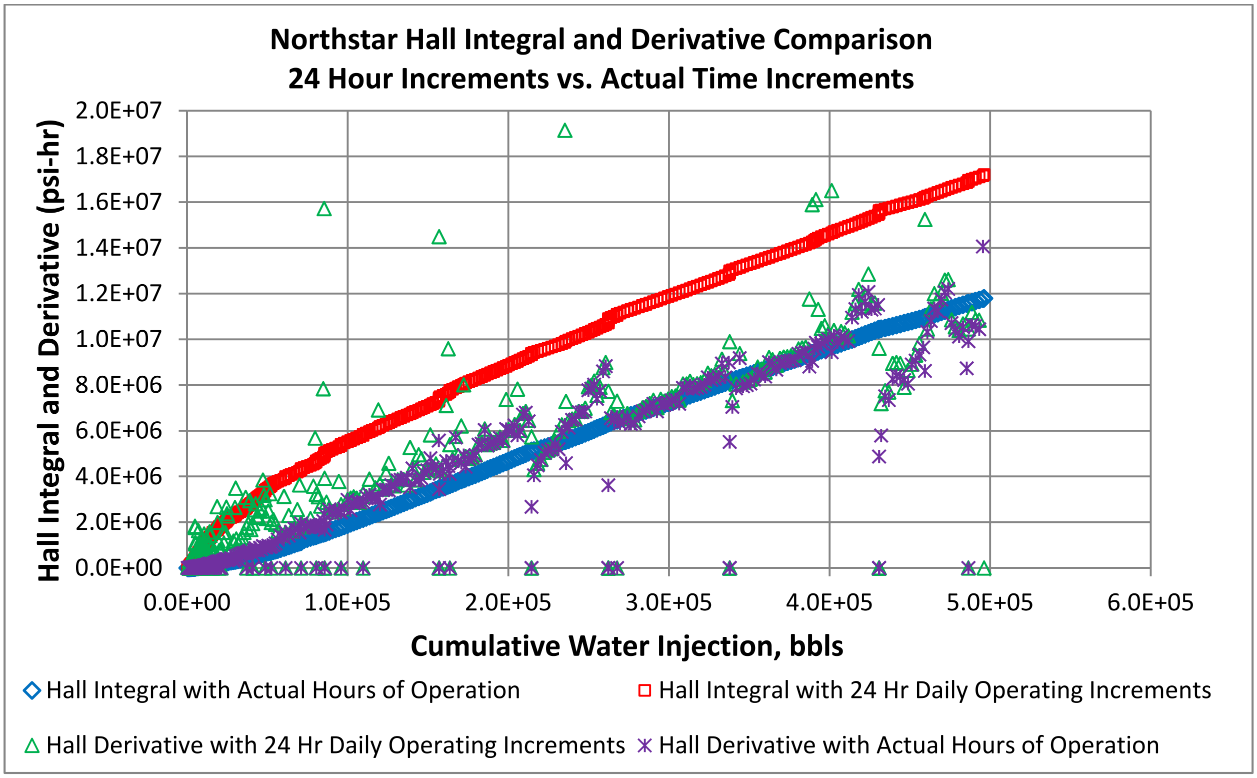
        - Hall integral becomes larger with decreasing initial static pressure due to increased pressure difference between injection and initial shut-in pressures
    - Challenges:
        - Negative increment in the Hall integral may occur if initial pressure assumption is too high
        - Degree of slope change in the Hall integral changes with the initial pressure assumption

<u>Hours of Operation</u>

Two different reviews were conducted for the Northstar case study well in OH. The initial review used quarterly reported volumes and assumed 24 hour continuous well operation. The second review was conducted for the refined data that included specific hours of well operation and daily reported volumes and pressure for the same operational period as the initial data set. The second review resulted in a different Hall integral response. This sensitivity analysis is included to illustrate the difference in the Hall integral response based on details of the well operational history. As illustrated in Figure D-7, the initial analysis using 24 hour well operation indicated enhanced injectivity while the actual time increment shows a combination of trends.

- Hall integral and derivative plot calculate using different hours of operation (Figure D-7)
    - Use different hours of well operation to calculate the Hall integral and derivative
        - 24 hours of operation daily
        - Actual reported hours of operation
    - y-axis:
        - Hall integral (H_I) = Cumulative ($\Delta P * \Delta t$) function (psi- time period)
        - Hall Integral Derivative: $D_{HI} = (H_{i2}-H_{i1})/(Wi_2-Wi_1)$
    - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE D- 7: IMPACT THE HOURS OF WELL OPERATION HAS ON HALL INTEGRAL AND DERIVATIVE CALCULATONS



- Purpose:
  - Determine the impact that the hours of well operation has on Hall integral and derivative calculation for wells that do not operate continuously
    - Hall integral and derivative magnitudes and trends are impacted by the time increment assumed for each injection volume reported
      - Too large a time increment value distorts the integral step size and corresponding derivative
      - Can present a misleading picture of shape of Hall integral and derivative response
- Challenges:
  - Actual hours of operation is not always reported

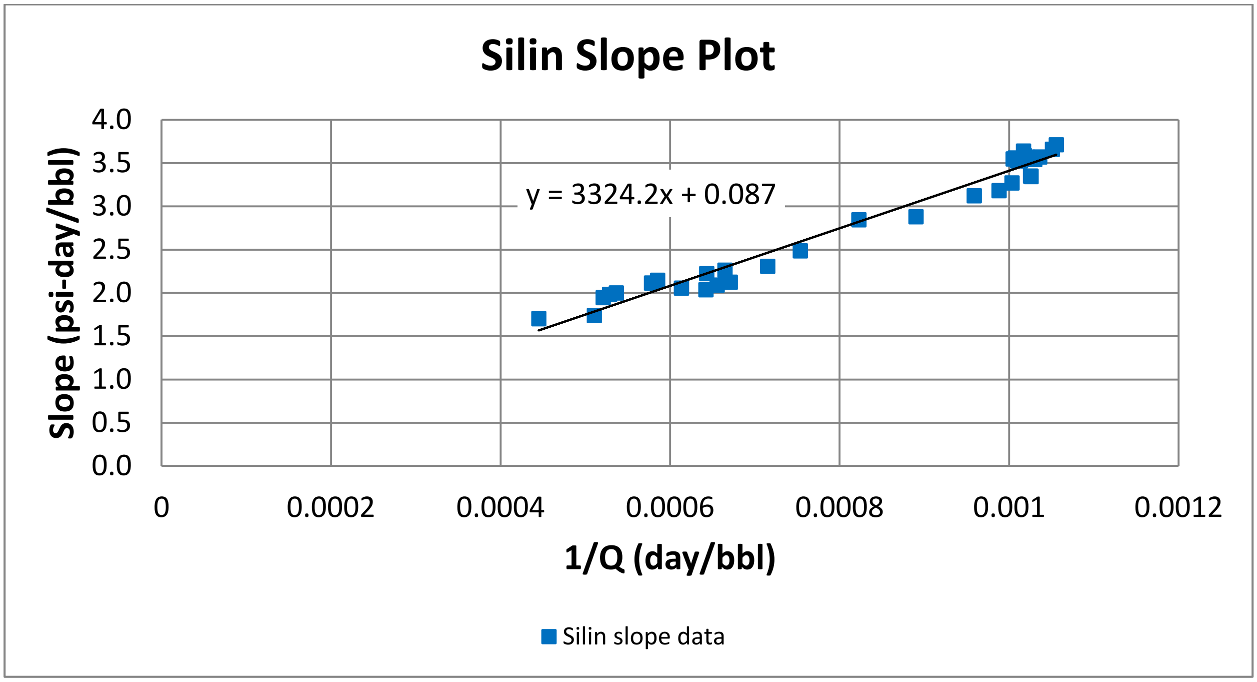
SILIN SLOPE PLOT

Silin Slope plot is used to determine average reservoir pressure around an injection well using injection pressures and rates. Operational injection data are plotted on a linear plot of wellhead pressure/injection rate versus reciprocal of injection rate. The resulting data points are fitted to a best fit straight line with the line's slope yielding a mean reservoir pressure around the disposal well. The resulting average reservoir pressure can then be used to develop a Hall plot. The Silin plot is designed as a method for monitoring reservoir pressure in active waterfloods and is only applicable to radial flow situations.

Silin Slope plots were performed on each of the case study wells. In some cases, an estimate of average disposal reservoir pressure was available from fluid level data. The results of the Silin plots were compared against available measured pressures and generally predicted too high a reservoir pressure. The high Silin Plot predicted pressures resulted in a negative Hall integral increment; consequently, the Silin plots were not included in the case study analyses.

- Linear plot of injection well operating data (Figure D-8)
  - Y-axis: Injection BHP divided by daily injection rate, P_{wf}/Q (psi-time period per barrel)
  - X-axis: Reciprocal of the injection rate, 1/Q (day per barrel)

FIGURE D- 8: SILIN SLOPE PLOT



- Purpose
  - Developed as a modification to Hall plot analysis to determine mean reservoir pressure around the injection well
- Challenges:
  - Rate fluctuations in operational data can cause data scatter
  - Method is applicable at very early times during the infinite-acting period
    - Faults or fractures may introduce error in assumptions for applicability
- Possible red flags

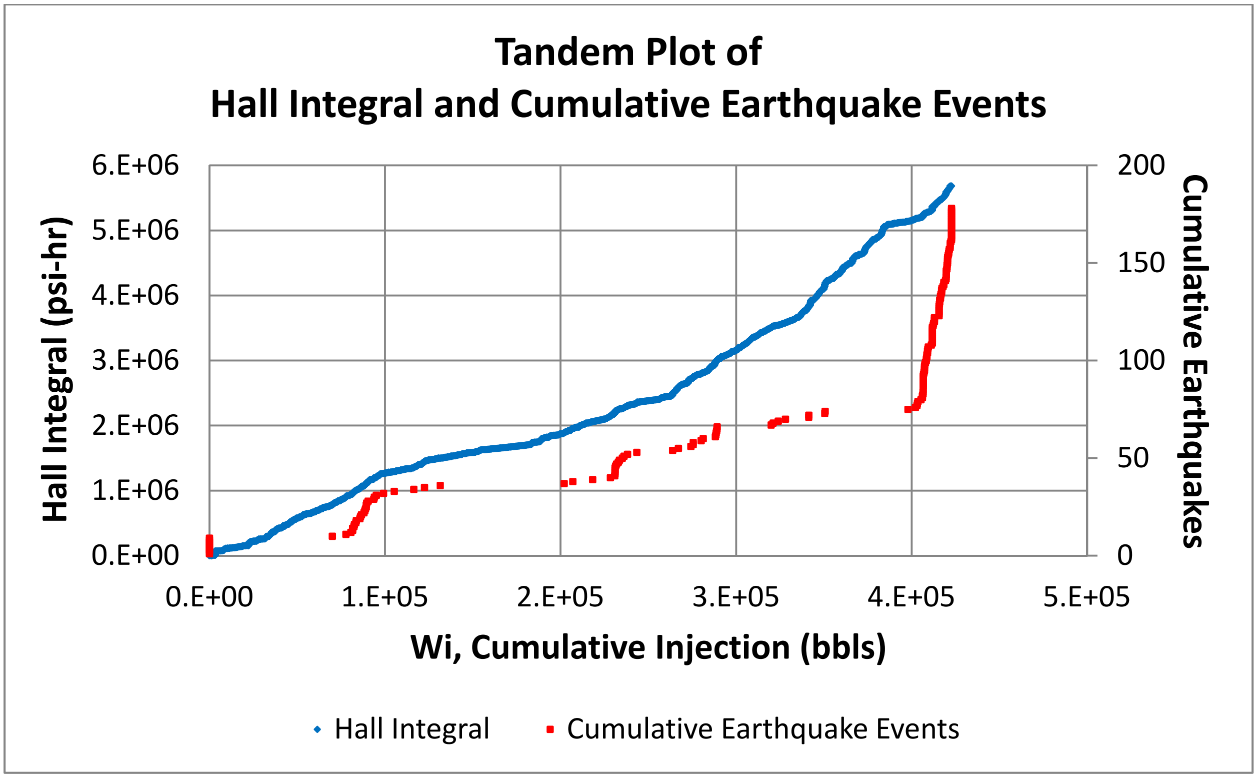
- Data quality may cause a scattered plot
- Unrealistically high static reservoir pressure

TANDEM PLOT COMBINING HALL INTEGRAL WITH SEISMIC EVENTS

The tandem plot is designed to graphically compare the Hall integral response to a cumulative count of seismic events within a selected radial search area.

- Cartesian (Linear) Tandem Plot (Figure D-9)
  - Plot Hall integral and cumulative earthquake events vs. cumulative injection
    - y-axis primary: Hall integral (H_I) = Cumulative ($\Delta P * \Delta t$) function (psi-time period)
    - y-axis secondary: Cumulative earthquake events (count)
    - X-axis: Cumulative injection volume, W_i (bbls)

FIGURE D- 9: TANDEM PLOT OF HALL INTEGRAL AND CUMULATIVE EARTHQUAKE EVENTS



- Purpose:
  - Plot provides a combined graphic of injection well behavior to number of seismic events
- Challenges:
  - Creating cumulative injection history for cumulative earthquake events
    - Selecting size of seismic monitoring area around disposal well

- Acquiring seismic data from various databases
- Linking earthquake events to cumulative injection based on event date
- Increase in events may be delayed owing to late deployment of additional seismometers
- Deciding what lower magnitude limit is needed for count of seismic events

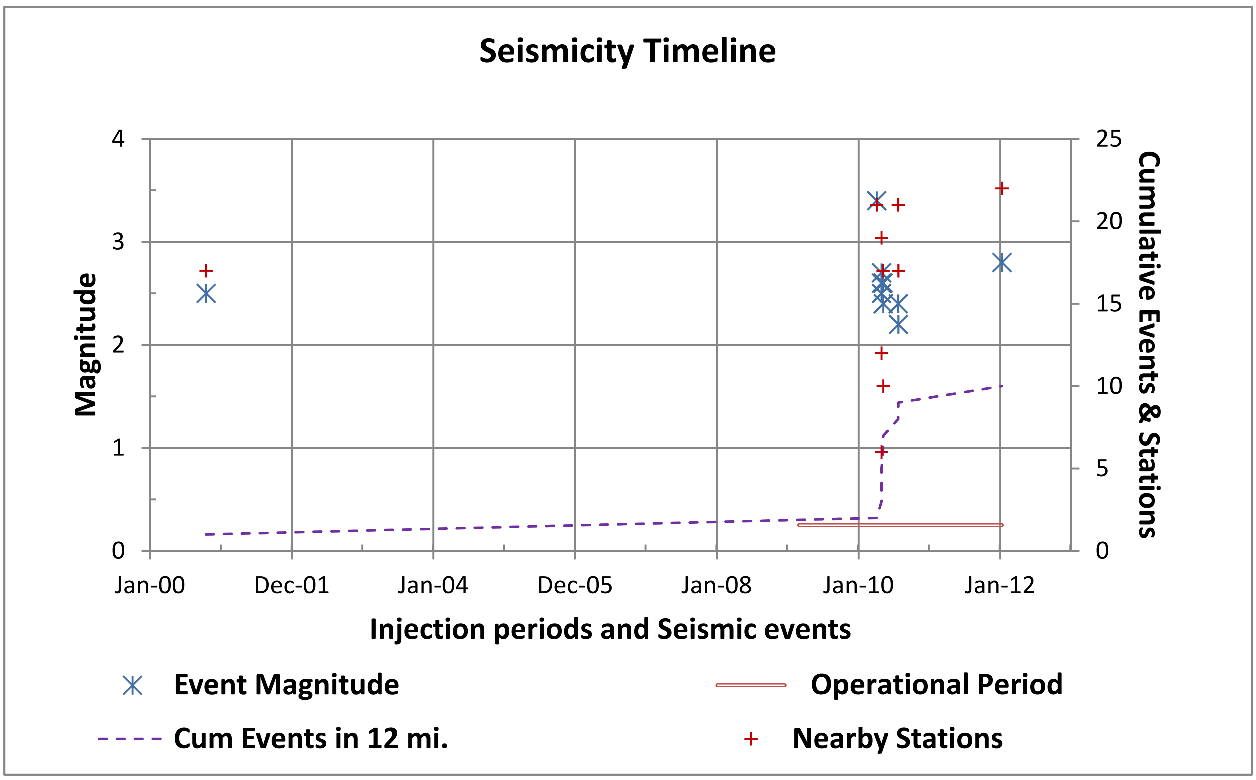
- Possible red flags
  - Correlation between injection well response (Hall integral slope change) and number of seismic events

SEISMICITY TIMELINE

Plot created to compare event magnitude, cumulative seismic events, number of seismometers, and disposal well operational period

- Seismicity Timeline Linear Plot (Figure D-10)
  - Plot of the earthquake magnitude and cumulative earthquake events versus the operational period of the disposal well
    - Primary Y-axis: Earthquake magnitude
    - Secondary Y-axis: Earthquake cumulative events and number of recording stations
    - X-axis: date and disposal well operational period

FIGURE D- 10: SEISMICITY TIMELINE PLOT



- Purpose:
  - Provide a common plot of seismic response and monitoring stations with disposal activity
- Challenges:
  - Selecting size of monitoring area around disposal well
  - Acquiring seismic data from various databases
  - Acquiring number of monitoring stations within the selected monitoring area
- Possible red flags
  - Correlation between operational period of disposal well and occurrence or number of seismic events
  - Seismic event background level prior to disposal well operations to determine if induced
  - Number of seismometers relative to number of seismic events

Overview of Pressure Transient Testing for Disposal Wells

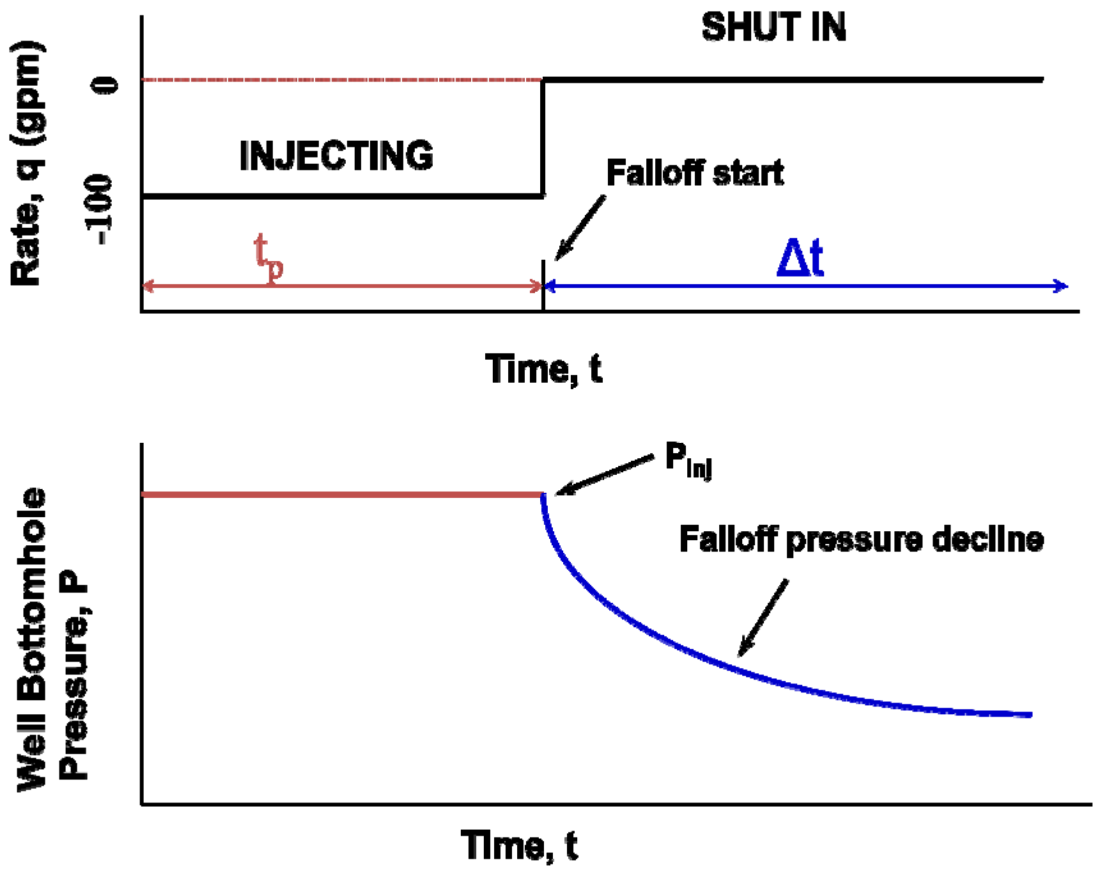
Pressure transient theory correlates pressures and rates as a function of time and is the basis for many types of well tests including both falloff and step rate tests. Pressure transient test analyses revolve around solutions to a partial differential equation, called the radial flow diffusivity equation. These solutions provide an injection well behavior model, a method for reservoir parameter evaluation, and allow calculation of pressure and rate as a function of distance.

The most common solution used applies only to radial flow. However, this solution is not applicable in all geologic or well completion situations. By solving the diffusivity equation for boundary conditions to address these geological or completion situations present at the wellbore or in the reservoir, mathematical solutions (type curves) specific to these situations are obtained. Since these reservoir model solutions are based on a differential equation, their "signature" is best presented in a log-log plot format.

Pressure transient tests provide a more refined look at the reservoir and well completion characteristics. Pressure transient tests run in disposal wells include falloff and step rate tests. Pressure transient tests are typically shorter in duration than the operational data analysis, but generally designed to provide a better reservoir description.

One type of pressure transient test commonly associated with a disposal well is a falloff test that measures the pressure decline by recording the well surface or bottomhole pressure (BHP) after the well is shut-in. Falloff tests are to a petroleum engineer as seismic surveys are to a geophysicist. Pressure transient tests provide short and intermediate distance mathematical "pictures" of the reservoir nature around the well when the data is analyzed against existing reservoir models and would be analogous to “a short term pinging of the reservoir with sonar” in the form of a pressure wave, whereas seismic surveys are acoustical “pinging” of the reservoir. Both use some type of energy wave to probe through the reservoir much like sonar “pings” the ocean or radar “pings” the airways. In both instances, the reservoir response to the associated “wave ping” is measured and analyzed. A falloff test sequence of events and pressure response is shown in Figure D-11.

FIGURE D- 11: FALLOFF TEST SEQUENCE OF EVENTS AND PRESSURE RESPONSES



Another type of pressure transient test commonly associated with a disposal well is a step rate test. Step rate tests are a direct method of estimating fracture pressure and fracture gradient (formation parting pressure) of the disposal zone. Step rate tests can be analyzed for both fracture gradient and reservoir characteristics. Step rate testing consists of a series of constant rate injection steps with each step being maintained for an equal duration of time as shown in Figure D-12 with corresponding pressure increases as illustrated in Figure D-13. Ideally, the injection pressure should be stabilized at the end of each rate step.

FIGURE D- 12: STEP RATE TEST RATE SEQUENCE

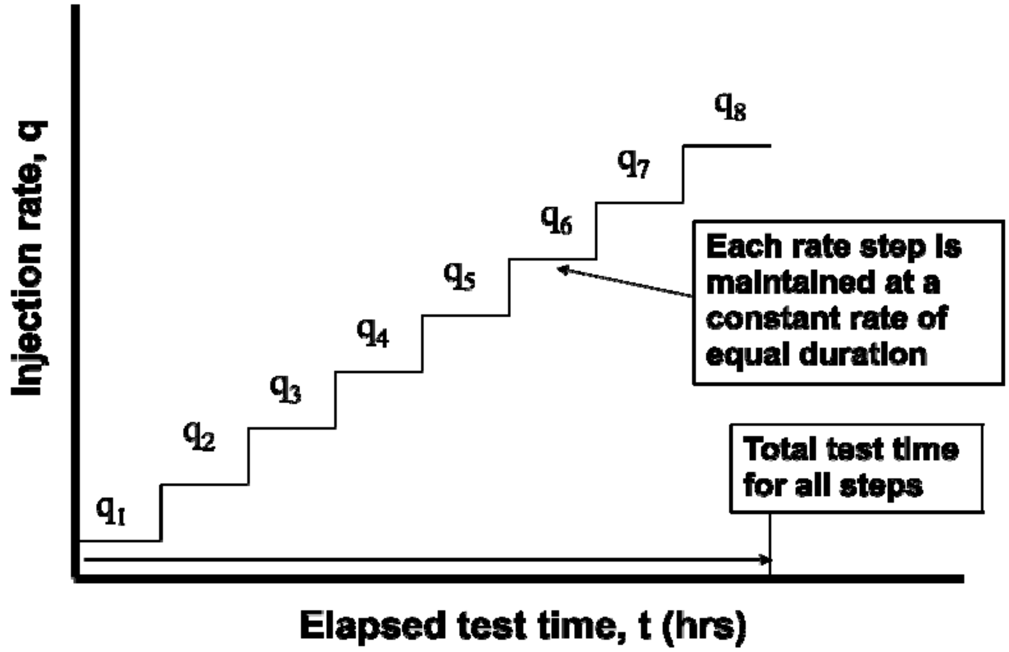
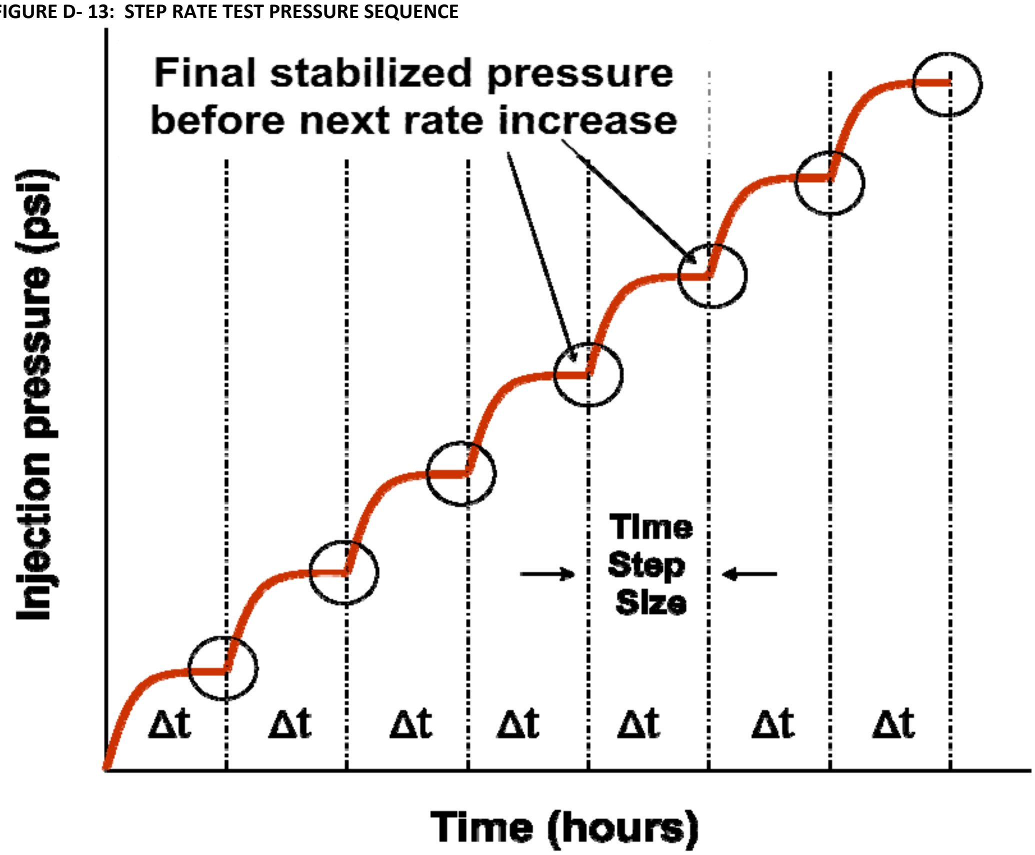


FIGURE D- 13: STEP RATE TEST PRESSURE SEQUENCE



ANALYSIS OF DISPOSAL WELL PRESSURE TRANSIENT TESTS

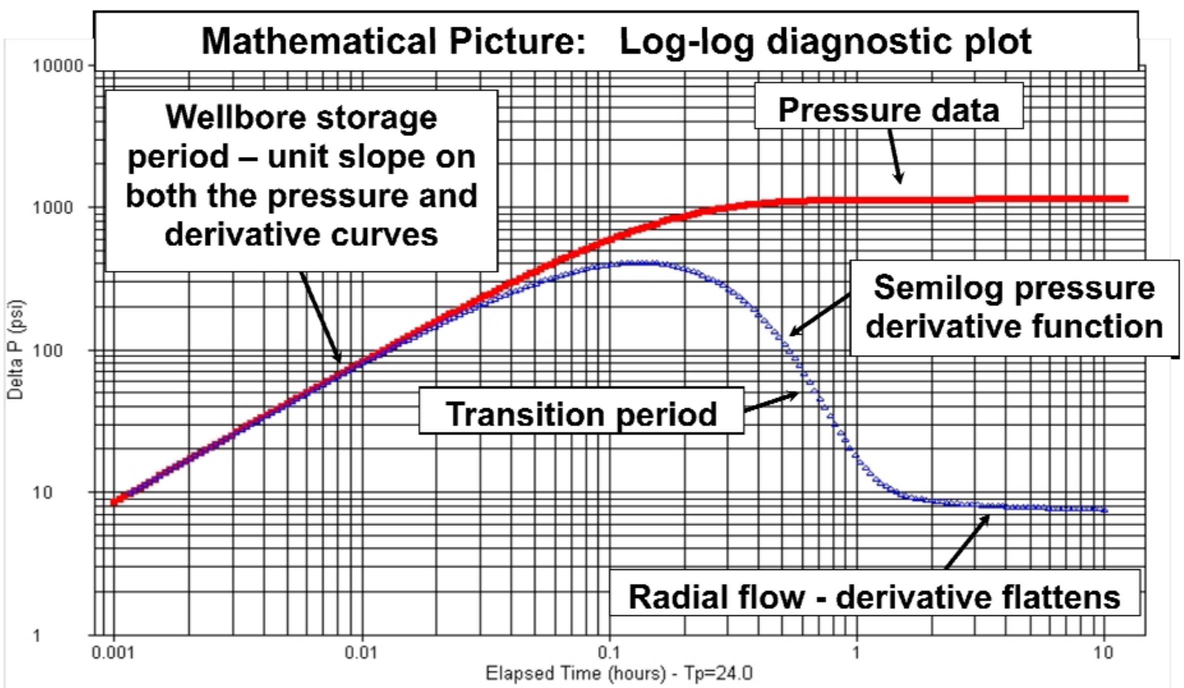
Analysis of both falloff and step rate tests involve pressure transient analysis techniques. Common methodology can be applied to each of these two tests. Falloff test analysis typically requires specialized software. Step rate tests can be analyzed using a spreadsheet, though a more detailed analysis may also necessitate the use of specialized software. Details relating to the analysis of each type of test are provided below.

FALLOFF TESTING

The first step to analyzing a falloff test is plotting the data in a format that allows for comparison against the known reservoir model solutions to the unsteady state radial diffusivity equation. To compare site specific test data to these solutions requires plotting the actual data in a log-log plot format, as shown in Figure D-14. Therefore the log-log plot becomes a useful diagnostic tool to see patterns of behavior at the well and into the reservoir. These patterns indicate the presence of different flow regimes.

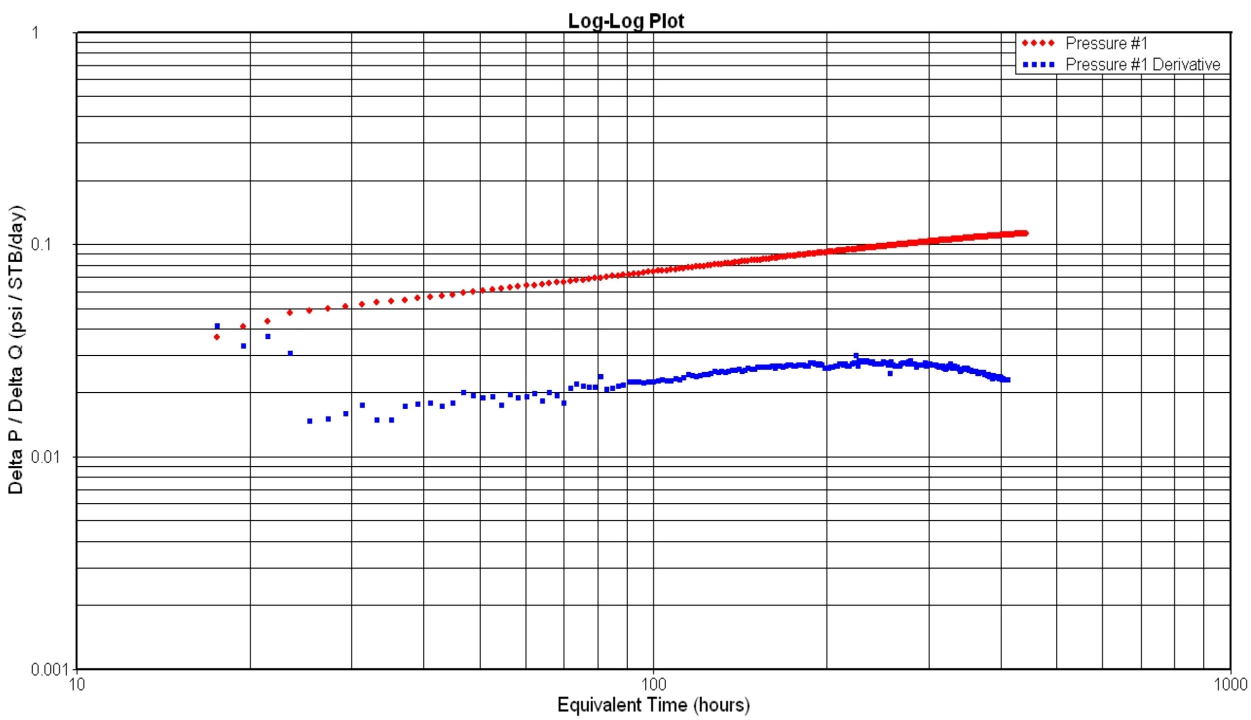
By identifying the flow regimes through a "mathematical picture" on the log-log plot, reservoir model solutions can then be matched to the test response to characterize the reservoir. The solutions to the reservoir flow models are plotted in the same log-log format, so finding the correct reservoir model becomes a picture matching process between the plotted test data and known reservoir responses.

FIGURE D- 14: LOG-LOG MASTER DIAGNOSTIC PLOT OF A FALLOFF TEST



- Log-log diagnostic plot (Figures D-14 and D-15)
  - Logarithmic y-axis:
    - Pressure change, ΔP
      - Subtract the final measured pressure at the end of injection period from each pressure value during the falloff period
      - ΔP increases as pressure declines during the falloff test
    - Pressure derivative, P’
      - Running slope calculated from a semilog plot of falloff pressure versus elapsed test time
  - Logarithmic x-axis:
    - Elapsed test time, Δt, starting from when well is shut-in
    - Time function is modified if the injection rate varied significantly prior to the falloff

FIGURE D- 15: LOG-LOG MASTER DIAGNOSTIC PLOT - WELL WITH FRACTURE FLOW CHARACTERISTIC



- Purpose
  - Final falloff pressure provides a static formation pressure measurement
  - Arranges test data in reservoir model format or mathematical “picture”
  - Derivative curve provides a “magnified” look at reservoir transient responses
    - Enhances identification of various flow regimes
    - Couples the log-log and semilog plot
      - Derivative curve is the running slope of the semilog plot

- Provides reservoir characteristics
    - Identify flow regimes
      - Derivative flattens during radial flow (See Figure D-14)
    - Identify reservoir boundaries, if located near the well
  - Measures the transmissibility of the injection zone or reservoir pathway
    - Transmissibility is the formation's ability to transmit pressure
    - Directly relates to the amount and lateral extent of pore pressure buildup
  - Indicates well completion condition
    - Spacing between the pressure and pressure derivative curves
    - Dimensionless wellbore skin factor describes the well completion condition
      - Negative skin: Enhanced completion
      - Positive skin: Damaged completion
      - Fractured wells exhibit very negative skin factors (-5 to -6)
- Challenges
  - Planning of test to obtain good quality data
  - Quality of recording devices to reduce data scatter
  - Duration of test sufficient to see beyond wellbore effects and identify reservoir characteristics
  - Special pressure transient software needed to analyze test
  - Handling of wastewater for duration of the test
- Possible red flags
  - Non-radial flow behavior may suggest pressure not dissipating radially from well
  - Lower permeable reservoirs may require longer test times
  - Unanalyzable test – planning or data collection issues

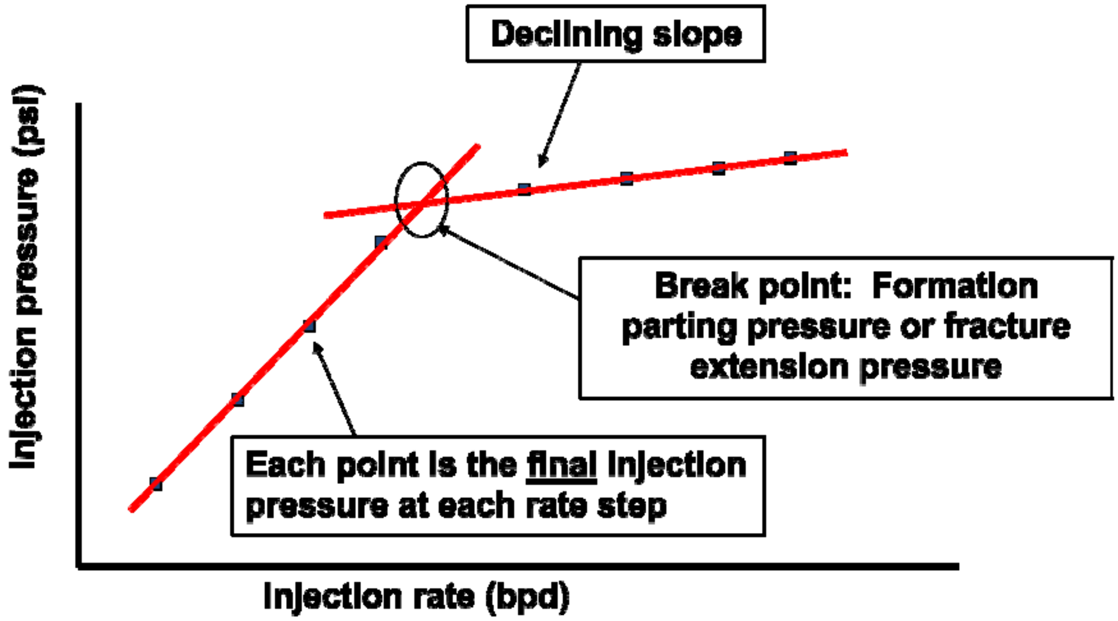
Step Rate Tests

Whereas falloff tests involve shutting in of the disposal well, a step rate test is conducted during operation of the well. Step rate test data can be analyzed either as a composite data set or through individual rate step analyses. Analysis of the composite approach involves a linear plot while injectivity analysis of individual rate steps involves a more complex log-log plot analysis of each rate step. If both methods are performed, the results can be compared for agreement. The injectivity analysis is similar to the falloff test analysis except pressures are increasing during each rate step instead of decreasing as in a falloff test. However, the limited duration of each rate step results in a shallower look into the reservoir. The goal of both analyses is to determine the reservoir formation parting (fracture) pressure.

Linear Plot

- Linear plot of injection pressure versus injection rate (Figure D-16)
  - y-axis: Final injection pressure of each rate step
    - Bottomhole pressure
  - x-axis: Constant injection rate of each rate step

FIGURE D- 16: STEP RATE TEST LINEAR PLOT



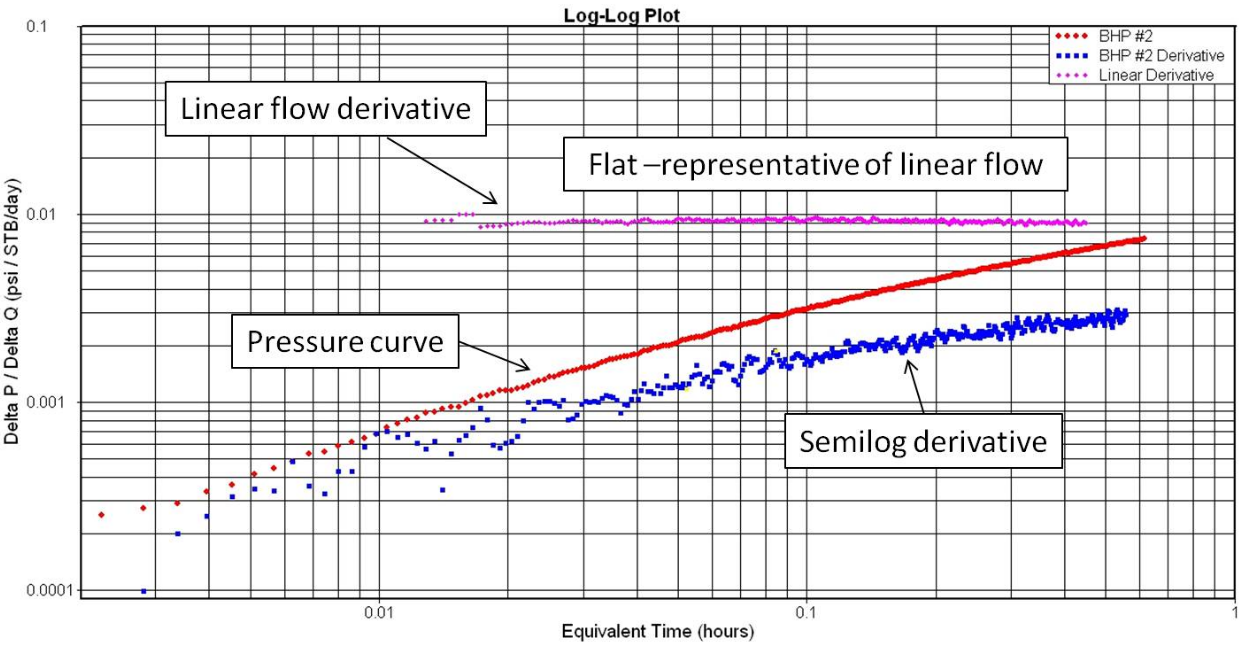
- Purpose
  - Identify formation parting pressure for use in determining maximum allowable operating pressure for disposal well
    - Review data for slope changes by drawing straight line(s) through data points
      - Negative slope break suggests enhanced injectivity or fracturing
      - No slope break
        - Fracture pressure not observed during test
        - Start pressure exceeded fracture pressure
  - Confirm well is operating below the fracture pressure gradient
- Challenges:
  - Surface pressure measurements may provide misleading results
    - Friction effects can mask the slope break
  - Conversion of surface pressures to bottomhole pressure
    - Must account for friction pressure
    - Friction calculation often in error for wells with high injection rates through smaller diameter tubing

- No break may be observed if disposal well is fractured prior to the first rate step
    - Starting injection rate too high
- Insufficient number of rate steps are included in the test to establish straight lines on the linear plot
- Stabilized pressures are not reached during each rate step
- Constant injection rates are not maintained during each rate step
    - Test typically requires a pump truck
    - Access to additional fluid volumes for continuous injection
- Use of continuous pressure and rate recording data throughout the test
    - Allows confirmation of pressure stabilization during each rate step
    - Allows each rate step to be analyzed as an injectivity test

Injectivity Plot

- Log-log injectivity plots of each rate step (Figure D-17)
    - Logarithmic y-axis:
        - Pressure change, ΔP
            - Subtract the pressures measured during injection period of each rate step from the final pressure from the preceding rate step or shut-in pressure for analysis of the first rate step
        - Pressure derivative, P’
            - Running slope of a semilog plot of test data
    - Logarithmic x-axis:
        - Superposition time function to account for changing injection rates during the test

FIGURE D- 17: INDIVIDUAL RATE STEP LOG-LOG INJECTIVITY PLOT



- Purpose
    - Identifies flow regime during each rate step
        - Review each step for fracture signature or fracture extension based on fracture half length
        - Fracture signature suggests formation parting pressure exceeded
- Challenges
    - Conversion of surface pressures to bottomhole pressure required for analysis
        - Must account for friction pressure
        - Requires continuously recorded downloadable electronic data
    - Data can be "noisier" since injection is occurring and passing by the pressure gauge
    - Requires pressure transient software for analysis

HOW CAN THE OPERATIONAL DATA AND PRESSURE TRANSIENT TEST ANALYSES BE USED?

Pressure change in the reservoir can induce seismicity in certain geologic settings. The petroleum engineering approaches may be useful for linking the pressure behavior of the injection well to seismicity and area geology for assessing if a reservoir is appropriate for a disposal zone. Pressure transient testing identifies flow behavior which indicates how the reservoir pathway pressure increases are distributed away from the disposal well and, in the case of a falloff, measures static pressure for assessing reservoir pressure buildup. For example, pressure increases from a disposal well exhibiting a fracture or linear flow characteristic may extend directionally over greater distances from the well than would be expected for radial flow.

One aspect of assessing induced seismicity concerns is the distance pressure buildup influence can be transmitted in the disposal reservoir. Two aseismic examples of large distance pressure influence are provided in Appendix I. One example highlights preferential pressure distribution over great distances in a formation suspected of containing a geologic anomaly and the second example illustrates the cumulative pressure buildup from multiple disposal wells injecting into the same formation.

For disposal wells identified as injecting into linear or fractured flow regimes, expanding the area reviewed may be useful to describe potential reservoir behavior. Typical pressure buildup calculations are based on the assumption that injection occurs into a radially, homogeneous, infinite acting reservoir. Naturally fractured reservoirs generally do not meet these assumptions. Therefore, pressure buildup distribution from a disposal well injecting into a fractured formation may require a more complex evaluation than for wells injecting into a formation exhibiting radial flow characteristics. In a homogeneous reservoir, the pressure dissipates equally in all directions away from the wellbore, however the cumulative pressure effects from multiple disposal wells injecting in the same formation may enlarge the area of pressure influence. Though the radial flow equations are applicable, modifications may be necessary to account for multiple pressure sources.

Analysis of the operating data coupled with any available pressure transient tests such as falloff and step rate tests for a disposal well may provide critical details, both geologically and hydraulically, about the nature and conditions on the injection reservoir. An attempt should be made to correlate anomalous test results to area seismic events to determine if additional data gathering, monitoring, or testing is warranted. Since operating data are readily available and require no additional monitoring, the petroleum engineering approach for analysis of such data provides an established technical methodology that may correlate existing well data to seismic events in the area.

How did the WG perform the case study petroleum engineering evaluations?

The detailed assessment for each case study is included in the respective case study appendices. While many of the methods used were highlighted during the preceding discussions, the software and tasks performed on the case study examples are outlined below. The software listed represents what was available to the WG, but other options are available.

- Software requirements

- Microsoft Excel® was used for the evaluation of operational data
    - Required assumptions to generate some parameters or functions used
- PanSystem® software was used to analyze pressure transient data
    - Other pressure transient test software could be used

- Tasks performed for all case study areas
  - Obtained injection pressure, rate, and time data for wells within the areas
  - Operational analysis plots generated:
    - Overview plot
    - Operating gradient plot
    - Hall integral plot with derivative
    - Tandem plot
      - Relates cumulative earthquakes to Hall integral
  - Pressure transient test (falloff and step rate) analysis plots generated when data available:
    - Cartesian overview plot
    - Log-log plot
    - Type curve match where applicable
    - Step rate test linear plot

CITATIONS

Hall, H.N., 1963, How to analyze waterflood injection well performance: World Oil, October 1963, p 128-130.

Izgec, B., and C. S. Kabir, 2009, Real-time performance analysis of water-injection wells: SPE Reservoir Evaluation & Engineering, v. 12, no. 1, p. 116-123, SPE-109876-PA..

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APPENDIX E: NORTH TEXAS CASE STUDY AREAS: DFW AND CLEBURNE

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All four case studies were considered in the development of the decision model. Consequently the UIC National Technical Working Group (WG) elected to apply the Decision Model framework to the case study events. Following the Decision Model framework, the wells in this case study fall under both the new and existing well categories. This case study covers a broad section of the Fort Worth Basin, with two focus areas. In both areas increased earthquake frequency and magnitude following the start of disposal operations raised concern. Future disposal wells may fall in the category of new wells in an existing area of seismic concern, depending on the level of seismicity selected as a cutoff.

North Texas Case Study Background

In late 2008, a series of small earthquakes occurred in north Texas near the Dallas - Fort Worth (DFW) international airport, followed by a separate group of small earthquakes starting in mid 2009 around Cleburne. Both areas are within the active Barnett Shale play (Figure E-1). Deployment of temporary seismic arrays was used to help identify the source of the earthquakes.

In order to better understand the various findings, a summary of the geologic setting, existing oil and gas activity, and seismic history will be described before focusing in on the two separate areas and nearby disposal operations.

Geologic Setting

The DFW and Cleburne focus areas are located within the Fort Worth Basin. The generalized east-west cross-section (Figure E-2) shows the relationship of the formations bounded on the east by the Ouachita thrust fault against basement rocks. The generalized north-south cross-section in Figure E-3 shows later Pennsylvanian age normal faulting (Bruner and Smosna, 2011). A third faulting episode appears in the basin, resulting from collapsed chimney structures above Ellenburger karst sink holes and caverns, (Bruner and Smosna, 2011; McDonnell, 2007; Montgomery et al., 2005; Steward, 2011; Sullivan et al., 2006), illustrated in Figure E-4 (Steward, 2011). The case study Class II disposal wells are completed in the Ellenburger formation.

The Barnett Shale lies below the Mississippian-Pennsylvanian unconformity, and unconformably over Ordovician carbonates (Viola, Simpson and Ellenburger formations). As shown in Figures E-2 and E-3, the Barnett Shale can lie directly on the Ellenburger. Therefore, there may be little or no confining strata between the Barnett and the underlying disposal zone.

During a meeting between EPA Region 6 and an area operator, the operator presented geologic data gathered in portions of the Fort Worth Basin, which indicated there are no obvious

Ellenburger karst features in the DFW airport area; however, the area around Cleburne showed significant karst features. The presentation displayed a major normal fault with approximately 600 feet of displacement, down to the east-southeast, in the DFW area. This same fault is also shown in literature (Figure E-5), and is located about a mile (1.6 km) west of the Ellenburger disposal well, DFW C1DE, (Ficker, 2012; Frohlich et al., 2011).

Oil and Gas Activity

The Barnett Shale production discovery took place in 1981 in Newark East field, in Wise County. Since 2002, most Barnett Shale wells are horizontally drilled with 1000 to 3500 foot lateral legs (Martineau, 2007). In Newark East, the top Barnett Shale depth ranges from 6900 to 7500 feet, with a thickness varying from 200 to over 700 feet near the Muenster Arch in the northeast (Montgomery et al., 2005).

History of Seismicity

Prior to October 2008, no earthquakes were reported in any of the six seismicity databases, (ANSS, SRA, NCEER, USHIS, CERI and PDE), within 40 miles (64 km) of the Dallas Fort Worth (DFW) international airport or the Cleburne area.

Several small (M1.7 to M3.3) earthquakes occurred in the central part of the Dallas - Fort Worth metroplex near DFW international airport starting on October 31, 2008. The case study well in the DFW area began operations in June 2007 and March 2008. Seismic activity (M2.0 to M3.3) near the town of Cleburne started on June 2, 2009. The ten case study wells in the Cleburne area began operations between December 2005 and May 2008. Both focus areas are located in north central Texas and the eastern portion of the Barnett Shale play (Figure E-1).

North Texas Information Collected

Data for wells in the DFW and Cleburne focus areas were downloaded from the Texas Railroad Commission (RRC) website. Supplemental geosciences information was obtained from the deployment of additional seismometers. Operational monitoring reports provided monthly injection rates and wellhead pressures. Details for each focused area are included in the relevant Information Collected sections below.

Permitting and well documents provided details concerning completion depths, construction information, and permit conditions for the case study wells. Annual operation reports provided monthly injection volumes and average and maximum wellhead pressures. RRC disposal well database information available as of December 1, 2013, was used to update case study well pressures and volumes.

Locations and status of the Class II disposal wells in the areas were updated from the RRC website through mid August 2013. Locations of seismic events through 09/30/2013 were downloaded from the databases discussed for each of the particular focus areas.

Operational Details

For both the DFW Airport and Cleburne study areas, the individual well surface pressures were converted to approximate bottomhole pressure (BHP) at tubing seat depths. For this conversion, a fluid specific gravity of 1.05 (roughly equivalent to 45,000 ppm chlorides) was assumed. Tubing dimensions, length and inside diameter, were taken or estimated from permit documentation. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 100 for steel tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. Operating data-related plots were prepared for selected wells within the case study areas consisting of a seismicity timeline; an operational overview data plot; operating pressure gradient plot; and a tandem plot of Hall integral with derivative and seismic events. The tandem plot combines the Hall integral with cumulative area earthquake events against a common scale of cumulative disposal volume.

Focused Site Assessment for DFW Airport Area

Earthquake activity near DFW international airport occurred between October 31, 2008 and May 16, 2009, with episodic recurrence. An arbitrary five mile (8 km) radius was derived from the regional seismometer network and the earthquake activity. The selected composite focus area is shown in Figure E-6 and includes two disposal wells located within the airport property boundary. From the available databases there were no earthquakes around the northern well. However, in Figure E-7, some of the relocated events are within the focused radius of the northern well.

Information Collected

Disposal Well in DFW Airport Case Study Area

Data were gathered from the permit application and operational history for the two focus wells in Tables E-1, and E-2.

TABLE E- 1: DFW FOCUS WELL INJECTION PERMIT CONDITIONS AND COMPLETION DATA

	Injection Permit Conditions					Completion Data (feet Measured Depth)				
Disposal Wells (SWD)	UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation	Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
DFW C1DE	97642	No	5023	25,000	Ellenburger, open-hole	10,252'	13,729'	13729'	7" to 10253'	3 ½" to 10,181'
DFW North A1DM	98402	No	4400*	25,000	Ellenburger, open-hole	8,802'	13,165'	13190	7" to 8,800'; 4 ½" liner 13,166'	4 ½" to 8,800'

*** AMENDED FROM 4575**

DEPTHS ARE MEASURED DEPTHS IN FEET, NOT TVD

TABLE E- 2: DFW FOCUS WELL OPERATIONS

Disposal Wells (SWD)	Operations			Comments
	Initial Disposal	Final Disposal	Plugged and Abandoned	
DFW C1DE	Sep. 2008	Aug. 2009		Temporarily Abandoned
DFW North A1DM	Nov. 2007			Disposal continues; 4.5" liner run from 8722-13166' on 10/22/09

ADDITIONAL GEOSCIENCES INFORMATION

Additional seismometers (Figure E-8) included a temporary network by Southern Methodist University and two permanent stations by an area operator. The temporary network was deployed between November 2008 and early January 2009 (Frohlich et al., 2011). The two new stations were added October 2009 and April 2010 (Janská and Eisner, 2012).

The DFW airport area earthquakes recorded in the ANSS, COMCAT, and NEIC catalogs, supplemented with published SMU temporary array events (Frohlich et al., 2011), within the focus radius of the disposal well, are summarized in Table E-3 below and on a timeline illustrated in Figure E-9. Note that only events that included a magnitude value were incorporated into this report. Earthquakes from the other seismometers were not included in the table below as the specific data were not published.

TABLE E- 3: DFW AIRPORT AREA SEISMICITY THROUGH 9/30/2013

Year	Starting Event	Number of Events	Magnitude			Ending Event
			Min.	Avg.	Max.	
2008	10/31/2008	18	1.7	2.4	3.0	12/1/2008
2009	5/16/2009	3	2.6	3.0	3.3	5/16/2009
2010	11/23/2010	2	2.4	2.5	2.5	12/13/2010
2011	8/1/2011	2	2.2	2.4	2.6	8/7/2011
2012	9/30/2012	1		3.4		9/30/2012
2013	1/23/2013	1		3.0		1/23/2013

THE 2013 EVENT 10 MILES (16.1 KM) DEEP AND ONE 2009 EVENT 5/15/09 M3.3 EVENT 5.4 MILES (8.7 KM) DEEP WERE CONSIDERABLY DEEPER THAN ALL THE OTHER EVENTS, WHICH WERE REPORTED AT THE DEFAULT 5 KM VALUE. SMU'S RECALCULATED DEPTHS WERE BETWEEN 2.7 AND 2.8 MILES (4.34 AND 4.46 KM) FOR THE 2008 EVENTS.

Figure E-7 (Janská and Eisner, 2012), shows a clearly defined seismically active fault to the west and south of the disposal well location along with a scattered seismicity area to the north east. Published reports agree that the 2008 through 2009 seismicity occurred along the north-south trending fault to the west of the DFW C1DE well. The reports disagree on the actual focus depth and probable cause (Janská and Eisner, 2012; Reiter et al., 2012; Eisner, 2011; Frohlich et al., 2011).

PETROLEUM ENGINEERING REVIEW

OPERATIONAL ANALYSIS

Only operational data were available so no pressure transient test analyses were conducted in the DFW airport focus wells. Figures E-10 through E-13 provide an operational data overview and calculated operational pressure gradient plots for DFW C1DE and DFW A1DM. Figure E-14 is a tandem plot of the Hall integral with derivative and seismic events for C1DE and Figure E-15 is the Hall integral and derivative plot for A1DM.

Table E-4 summarizes the assumed reservoir pressure value used in the Hall integral calculation for the Hall plot.

TABLE E- 4: DFW AIRPORT FOCUS AREA HALL INTEGRAL ASSUMED INITIAL PRESSURE VALUE

Well	Hall Assumed Average Pressure (psi)
DFW C1DE	4545
DFW A1DM	3900

DFW C1DE

- Overview plot (Figure E-10)
    - Well was temporarily abandoned in August 2009
- Operating pressure gradient plot (Figure E-12)
- Tandem plot of Hall integral and derivative plot and seismic events (Figure E-14)
    - Showed no clear correlation between the Hall integral with derivative response and cumulative earthquake trend

DFW A1DM

- Overview plot (Figure E-11)
    - Injection volume declined during last half of the well operational history while injection pressure trend was generally unchanged
- Operating pressure gradient plot (Figure E-13)
- Hall integral and derivative plot (Figure E-15)
    - Hall integral with derivative responses showed multiple pronounced upswings
        - Upswing may represent a reservoir boundary effect
    - No seismic event locations available for correlation purposes

Actions taken by UIC regulatory agency in DFW airport study area

Following the 2008 seismic events, the RRC worked with the operator of the nearest disposal well, DFW C1DE. The operator voluntarily shut the well in. The RRC reviewed its permit actions for other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found from these reviews. RRC also inspected the area to verify no measurable harm or potential hazard related to the events. In follow-up, the RRC consulted with industry representatives, and researchers at the Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M University, and continues to monitor developments and research related to injection-induced seismicity.

Focused Site Assessment For Cleburne Area

Following the Cleburne area initial events on June 2, 2009, the earthquake activity areally expanded over time, as shown on Figure E-16. There are a number of active disposal wells in the area injecting into the Ellenburger below the Barnett Shale. Ten focus wells were selected based on their proximity to the initial seismic events. The focus study boundary, shown in Figure E-16, is derived from the regional seismometer network and the earthquake activity using a composite of an arbitrary five mile radius around each of the wells. The seismic events labeled '2011-J-A' in Figure E-16 are discussed in Frohlich, (2011), but located outside the focused area for this report.

Of the ten case study wells in the Cleburne study area, some of the wells were in close proximity to each other. Offset disposal should be considered when evaluating disposal well behavior.

Information Collected

Disposal Wells in Cleburne Case Study Area

Data were gathered from the permit application and operational history for all the focus wells in Tables E-5 and E-6

TABLE E- 5: CLEBURNE NORTH TEXAS FOCUS AREA WELLS PERMIT AND COMPLETION CONDITONS

	Injection Permit Conditions					Completion Data (feet Measured Depth)				
Disposal Wells (SWD)	UIC Permit	Com-mercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation	Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
Hanna 1	96321	yes	3800	20,000	Ellenburger	8,006	10,700	10,700	7" to 8006'	3 ½” to 7920’
Johnson Salty 3	96488	yes	3500	30,000	Ellenburger	7,850	10,000	12,000	7” at 9799’	4” at 7100’ Replaced w/ 4½” at 7750’ in Mar 2011
Rose 1	98425	yes	2500	30,000	Ellenburger	9,104	11,250	11,428	7” at 11,428’	4½” at 8,927’
Vortex 1	95462	yes	4300	37,000	Ellenburger	10430' 11094'	10644' 11235'	11,250	7” at 11,250’	4½” at 10,376’
S Mann 1	94931	yes	3708	20,000	Ellenburger	7,627	9,071	9,071	7” at 7627’	3 ½” at 7425’
Sparks Drive 1	93369	yes	2900	15,000	Ellenburger; open-hole	7,509	9,134	9,134	5 ½” at 7509’	3 ½” at 7421’
Johnson County 1	95581	no	3800	25,000	Ellenburger; open-hole	7,995	10,821	11,213	7” at 7994’	4 ½” at 7981’
South Cleburne 1	94930	yes-TA	3650	20,000	Ellenburger	10,422	10,755	10,952	7” at 10,903’	4½” at 10,349’
Cleburne Yard 1	97113	yes	2300	15,000	Ellenburger	7,650	11,500	10,128	7” at 7850’	4 ½” at 7765’
Johnson Salty 2	96487	yes	3500	30,000	Ellenburger	7,210	10,000	10,000	7” at 9808’	4” at 6950’ Replaced w/ 4½“ at 7080’ in Mar 2011

TABLE E- 6: CLEBURNE NORTH TEXAS FOCUS AREA WELLS OPERATING CONDITIONS

Disposal Wells (SWD)	Operations			Comments
	Initial Disposal	Final Disposal	Plugged and Abandoned	
Hanna 1	Apr 2007			Operating
Johnson Salty 3	Jan 2007			Operating
Rose 1	May 2008			Operating
Vortex 1	Dec 2006			Operating
S Mann 1	Oct 2006			Operating
Sparks Drive 1	Dec 2005			Operating
Johnson County 1	Apr 2007			Operating
South Cleburne 1	Oct 2006	Jul 2009		Temporarily abandoned
Cleburne Yard 1	Aug 2007			Operating
Johnson Salty 2	Jan 2007			Operating

ADDITIONAL GEOSCIENCES INFORMATION

The Cleburne area earthquakes were downloaded from the ANSS, COMCAT, and NEIC catalogs. Additional seismometers as shown in Figure E-17 were deployed between June 2009 and June 2010 by Southern Methodist University (Howe-Justinic et al., 2013).

A summary of the Cleburne area earthquakes is included in Table E-4, and in a timeline in Figure E-18.

TABLE E- 7: CLEBURNE FOCUS AREA SEISMICITY THROUGH 9/30/2013

Year	Starting Event	Number of Events	Magnitude			Ending Event
			Min.	Avg.	Max.	
2009	6/2/2009	9	2.0	2.4	2.8	10/1/2009
2010	11/8/2010	2	2.1	2.3	2.5	11/12/2010
2011	6/7/2011	1		2.2		6/7/2011
2012	1/18/2012	18	2.1	2.7	3.6	7/28/2012
2013		0				

Since 2009, Cleburne area events have been continuously reprocessed and relocated with significant changes to event locations. For example, one event was relocated a distance of 7 km on the surface and one km in depth. The published supplemental data from the additional seismometers provided the relocated events were not available in time to be incorporated into this report, but the locations are shown with a + symbol on the map (Figure E-17). The relocation report (Howe-Justinic et al., 2013), identified a total of fifty four events picked up by the temporary array in a well defined fault approximately two kilometers long oriented in a north-northeast direction, Figure E-17. The relocation places the fault hypocenters within the depth range of permitted injection by the closest two wells, (Cleburne Yard and South Cleburne).

ADDITIONAL DATA COLLECTED

The Sparks Drive SWD is dually permitted as a Class II commercial with the RRC and as the Class I disposal well with the Texas Commission on Environmental Quality (TCEQ). Class I wells are required to conduct annual falloff tests. EPA acquired the 2005, 2006, and 2008 through 2011 annual falloff pressure transient tests for the Sparks Drive SWD 1. Analyses of these pressure transient tests for Sparks Drive SWD 1 are included in this case study. No pressure transient tests were available for the other wells.

PETROLEUM ENGINEERING REVIEW

OPERATIONAL ANALYSIS

Operational data were reviewed and analyzed for all ten wells. The analysis plot for each well is included in the following list of figures:

- Operational data overview plots: Figures E-19 through E-28
- Operational pressure gradient plots: Figures E-29 through E-38
- Tandem plot of Hall integral with derivative cumulative earthquake events: Figures E-39 through E-48

Table E-8 summarizes the assumed reservoir pressure value used in the Hall integral calculation for each Hall plot. Hydrostatic pressures were used for all the wells.

TABLE E- 8: CLEBURNE AREA HALL INTEGRAL ASSUMED INITIAL PRESSURE AND ASSOCIATED FIGURES

Disposal Wells (SWD)	Figures E-	Hall Plot Assumed Initial Pressure (psia)
Hanna 1	19, 29 and 39	3432
Johnson Salty 3	20, 30, and 40	3160
Rose 1	21, 31, and 41	4059
Vortex 1	22, 32, and 42	3910
S. Mann 1	23, 33, and 43	3375
Sparks Drive 1	24, 34, and 44	3375
Johnson County 1	25, 35, and 45	3630
South Cleburne 1	26, 36, and 36	4705
Cleburne Yard 1	27, 37, and 47	3530
Johnson Salty 2	28, 38, and 48	3160

The operating pressure data analysis completed for each well is summarized below.

- Operational data overview plots (Figures E-19 through E-28)
  - Injection volume declined while injection pressure trend was generally unchanged (Figures 19 through 22)
  - South Cleburne was temporarily abandoned in August 2009
- Operating pressure gradient plots (Figures E-29 through E-38)
  - All wells had operating pressure gradients below 0.75 psi/ft
- Tandem plots of Hall integral with derivative and seismic events (Figures E39 through E48):
  - Hanna (Figure 39)
    - Multiple enhanced injectivity followed by earthquake events and positive upswing in Hall integral and derivative responses

        - Hall integral response similar to offset Johnson Salty III disposal well
    - Johnson Salty III (Figure E-40)
        - Multiple positive upswings in Hall integral and derivative responses with only one upswing corresponding with two earthquake events
        - Hall integral response similar to offset Hanna disposal well
    - Rose (Figure E-41)
        - Enhanced injectivity followed by a positive upswing in Hall integral and derivative responses and earthquake events
        - Hall integral response similar to offset Vortex disposal well
    - Vortex (Figure E-42)
        - Multiple positive upswings in Hall integral and derivative followed by earthquake events with the last upswing more pronounced and corresponding to earthquake events
        - Hall integral response similar to offset Rose disposal well
        - Cumulative injection volume only through November 2012 as more recent operational data was unavailable as of December 2013
    - S. Mann (Figure E-43)
        - Initial enhanced injectivity followed by positive upswings in Hall integral and derivative responses with earthquakes events occurring around the beginning of the second upswing
        - Similar response to offset Sparks Drive disposal well
    - Sparks Drive (Figure E-44)
        - Initial enhanced injectivity followed by positive upswings in Hall integral and derivative responses with earthquakes events occurring around the beginning of the second upswing
        - Similar response to offset Mann disposal well
    - Johnson County (Figure E-45)
        - Two positive upswings in Hall integral and derivative followed by earthquake events with the second upswing more pronounced
    - South Cleburne (Figure E-46)
        - Enhanced injectivity during operational period through July 2009
        - Last 4 earthquake events occur in 2012 with no injection occurring in well since July 2009
    - Cleburne Yard SWD 1 (Figure E-47)
        - Two positive upswings in Hall integral and derivative followed by enhanced injectivity periods, subsequently followed by a third more pronounced upswing in the Hall integral and derivative

        - Earthquakes correspond to the second and third upswings in the Hall integral and derivative plots
    - Johnson Salty II (Figure E-48)
        - Slight positive upswing in Hall integral and derivative corresponding with the two earthquake events in well focus area
        - Second positive upswing in Hall integral and derivative, but no corresponding earthquake events

PRESSURE TRANSIENT ANALYSIS

Annual falloff test data for Sparks SWD 1 was analyzed using PanSystem® well test software. Each test was plotted in a log-log format with the derivative response and then compared against various reservoir type curve models to identify flow regimes and reservoir and completion characteristics present. Data specific to each falloff test is summarized in Table E-7.

A summary of the Sparks Drive SWD 1 pressure transient test plot analyses are summarized in Table E-8 and additional discussion on select tests is included below:

- 2005 and 2006 falloff test
    - Overview plot (Figures E- 49 and E-50)
        - 2005 pressure declining measurably (1.33 psi/hr) at the end of the test (F-49)
        - 2006 pressure declining measurably (1.74 psi/hr) at the end of the test (F-50)
    - Log-log plot (Figures E-51 and E-52)
        - 2005 and 2006 plots suggest a highly stimulated completion followed by a pressure derivative decline (Figures E-51 and E-52 respectively)
        - 2006 – linear derivative added indicating linear flow during part of the test (Figure E-52)
    - Type curve match (Figures E-53 through E-55)
        - 2005 Infinite conductivity fracture type curve (Figure E-53)
            - Suggests high conductivity fracture
        - 2006 test could be matched using only the early (Figure E-54) or late time (Figure E-55) portions of the tests
            - Overall test did not fit a single type curve model
            - Both early and late responses fit a fracture type curve model with similar fracture half length dimensions
            - Early response kh result was roughly twice late response kh value
- 2008 Falloff test
    - Overview plot (Figure E-56)
        - Pressure declining measurably (1.26 psi/hr) at the end of the test

- Log-log plot (Figure E-57)
    - Linear flow behavior followed by late time derivative decline
- Type curve (Figures E-58 and E-59)
    - Radial homogeneous type curve (Figure E-58)
        - Suggests a stimulated completion
    - Infinite conductivity fracture type curve (Figure E-59)
        - Highly conductive fracture with results similar to 2005 and 2006 falloff tests

- 2009 Falloff test
    - Overview plot (Figure E-60)
        - Pressure declining measurably (0.82 psi/hr) at the end of the test
    - Log-log plot and dual permeability type curve (Figure E-61)
        - Late time data shows a derivative decline with a negative half slope
            - Possibly indicating spherical flow/layering
        - Late time portion of test fit a two layer model
- 2010 Falloff test
    - Overview plot (Figure E-62)
        - Pressure declining measurably (2.45 psi/hr) at the end of the test
    - Log-log plot and type curve matches (Figures E-63 and E-64)
        - Linear flow with late time derivative decline
        - Infinite conductivity fracture type curve (Figure E-63)
            - Highly conductive fracture similar to 2005, 2006 and 2009 falloff tests
        - Dual Permeability type match with late time data only (Figure E-64)
            - Late time portion of test fit a two layer model
- 2011 Falloff test
    - Overview plot (Figure E-65)
        - Pressure declining measurably (3.38 psi/hr) at the end of the test
    - Log-log plot and type curve match (Figure E-66)
        - Highly stimulated completion
        - Infinite conductivity fracture type curve
            - Marginal match with a highly conductive fracture similar to 2005, 2006, 2009, and 2010 tests

TABLE E- 9: SPARKS DRIVE SWD 1 (WDW 401) FALLOFF TEST CONDITIONS

Test Date	Injection Time (hrs)	Shut-in Time (hrs)	Gauge Depth (ft KB)	Final Injection Pressure (psia) and Rate (gpm)	Final Shut-in Pressure (psia) and Pressure Decline Rate (psi/hr)
8/29-30/2005	30.12	18.7	7620	4189.33/ 156	3851.12 / 1.33

9/21-22/2006	16	20.5	5500	3361.79/ 173	2921.68/ 1.74
8/25-26/2008	13.17	21.25	7500	4227.07/ 215	3859.42/ 1.26
8/27-28/2009	124.2	21.18	6334	3781.70/ 128	3281/ 0.82
8/4-5/2010	18.5	20	7620	4252.49/ 95.5	3876.98/ 2.45
8/1-2/2011	240	20.2	7620	4316.90/ 99	3973.69/ 3.38

SPARKS DRIVE SWD 1 FALLOFF TESTS SUMMARY

Tests generally indicated a fractured or highly stimulated completion signature, but entire test responses did not fit a simple model. Early time test responses were fitted to type curve models while the late time portions of the test deviated from the type curve response.

Late time test behaviors indicated pressure support/communication in the form of a declining pressure derivative response. This could reflect communication with a pressure support source, such as another layer and offset disposal well. Two of the late time test responses fit a dual permeability (two layer) type curve model.

Type curve matches were marginal, but all indicated a highly stimulated completion with matches obtained using both homogeneous reservoir and infinite conductivity fracture type curves to match the early portions of several falloffs. As the Ellenburger formation is naturally fractured, this type of response is consistent.

Matches also indicated a moderate transmissibility interval with transmissibilities in the 4,000-15,000 md-ft/cp range. Fracture characteristics from the type curve matches fit an unpropped fracture with fracture wing lengths on the order of 160 to 250 feet long.

The falloffs did not reach static pressure conditions at test end time as all the falloffs displayed noticeable pressure declines at their conclusions.

TABLE E- 10: CLEBURNE AREA FALL TEST ANALYSIS SUMMARY

Test	Type Curve Model	kh/u (md-ft/cp)	Skin Factor	x_f (ft)	Comments
2005	Homogeneous	3633	-5.3	---	
	Infinite Conductivity Fracture	3287	-5.7	200	
2006	Finite Conductivity Fracture	10,380	-4.5	190	
	Infinite Conductivity Fracture	10,380	-4.5	160	Early time data match
	Infinite Conductivity Fracture	4325	-5.6	170	Late time data match
2008	Homogeneous	13,107	-5.3		
	Infinite Conductivity	12,317	-5.4	176	

	Fracture				
2009	---	---	---	---	Not quantitatively analyzable
2010	Infinite Conductivity Fracture	2595	-5.6	175	
2011	Infinite Conductivity Fracture	4556	-5.5	254	

ACTIONS TAKEN BY UIC REGULATORY AGENCY IN THE NORTH TEXAS CLEBURNE AREA

Following the 2009 seismic events, the RRC worked with the operator of the nearest disposal well, *South Cleburne SWD 1*. The operator voluntarily shut the well in, though they do not consider the evidence to be conclusive. The RRC reviewed its permit actions for this wells, as well as other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify no measurable harm or potential hazard related to the events. In follow-up, the RRC consulted with industry representatives, and researchers at the University of Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M University, and continues to monitor developments and research related to injection-induced seismicity.

NORTH TEXAS AREA LESSONS LEARNED

- Publications (Howe-Justinic et al., 2013) indicate the optimal orientation for movement on a fault in the Barnett Shale play area is north to south. The majority of the regional faults shown on Figure E-1 are oriented more northeast to southwest.
- The ability to identify short (two to three kilometer length) faults is dependent on recording and relocating faults causing only small magnitude events. This is not possible using only the current seismometer network available in the north Texas area.
- Fine tuned relocation is possible when sufficient detail for the earth model in that specific area has been resolved.
    - Earthquake event relocation methodologies are undergoing development. The reviewed reports, Janská and Eisner, 2012; Reiter et al., 2012; Eisner, 2011; Frohlich et al., 2011, use different methods.
    - Several of the relocation methods require deploying a tightly spaced monitor network prior to the earthquake events.
    - Another of the relocation methods requires an existing network designed to record small, shallow seismic events. Recommended guidelines for this network configuration are available in Reiter et al., 2012.
- While many of these temporary networks are connected to one of the major seismic database catalogs, the reinterpretation is not typically uploaded. Therefore relocated

interpretation data is not available until after the associated publication has been released. This can be two to three years after the events.

  - Initiating dialogue with operator can provide early voluntary action from operators, including well shut-in, or acquisition of additional site data.
    - Initiating dialogue between the operator and UIC regulator resulted in the voluntarily shut-in of some suspect disposal wells.
    - For example, an operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep seated fault.
  - Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.
    - Hall integral and derivative plot may indicate no flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance or possible response from offset disposal wells.
    - Hall integral and derivative plot may illustrate enhanced injectivity.
  - Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation or encountering an increased permeability zone at distance.
  - Conducting a falloff test can further refine the reservoir characterization.
    - Fractured flow behavior was confirmed from the falloff test analyses for the Ellenburger disposal zone in a Cleburne area well.
  - Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
    - Additional stations installed resulted in reliable identification of active fault locations.
- Engage a multi-disciplinary combined approach to minimize and manage induced seismicity at a given location.
  - Working with state geological survey or university researchers provided expert consultation, resulted in installation of additional seismometers, and yielded a clearer understanding of the deep seated active faulting.
  - Director discretionary authority was used to solve individual site specific concerns:
    - Acquired additional site information and evaluated voluntary action of operators.

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APPENDIX F: CENTRAL ARKANSAS AREA CASE STUDY

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All four case studies were considered in the development of the decision model. The state agency's handling of these events was the basis for some of the approaches listed in the decision model described in Appendix B. Consequently the UIC National Technical Working Group (WG) elected to apply the Decision Model framework to the case study events. Following the Decision Model framework, the wells in this case study fall under both the new and existing well categories. Increased earthquake frequency and magnitude following the start of disposal operations raised concern.

CENTRAL ARKANSAS CASE STUDY BACKGROUND

From 2009 through 2011 a series of earthquakes occurred near the towns of Guy and Greenbrier in Faulkner County, Arkansas. The news media initially attributed these quakes to hydraulic fracturing in the Fayetteville Shale unconventional gas play illustrated on Figure F-1. Through deployment of additional seismographs, discussions with the various oil and gas operators, and coordination between the Arkansas Oil and Gas Commission (AOGC), Arkansas

Geologic Survey (AGS) and Center for Earthquake Research and information (CERI) at the University of Memphis, a more descriptive geologic picture emerged, clarifying the likely source of the activity was a previously unknown fault impacted by area disposal activity.

To understand area site conditions, a summary of the geologic setting, existing oil and gas activity and seismic history is provided, followed by focused site assessment including details related to the disposal well operations.

GEOLOGIC SETTING

The Greenbrier area is located in the Arkansas valley region of the eastern Arkoma basin. There are at least three phases of faulting as shown on the East Arkoma Basin structural cross-section in Figure F-2. (The location of the cross-section is shown in Figure F-1.) The most recent, normal listric[24] faults sole out on the Mississippian-Pennsylvanian unconformity. High-angle deeper normal faults extend into basement rock (Van Arsdale and Schweig, 1990). Not shown, is the recently discovered Guy-Greenbrier fault[25] (Figure F-3), a near vertical, normal fault that cuts from the basement up through the upper Mississippian-Pennsylvanian unconformity at its northern extent (Horton, 2012; Horton and Ausbrooks, 2011; Personal communication, September 16, 2011).

The Paleozoic section contains alternating carbonates, shales, and sandstones overlying crystalline basement rock. As illustrated in the stratigraphic column in Figure F-4, the Ozark confining unit separating the Boone and Hunton formations from the Ozark Aquifer[26] is thin or missing in the study area. The lower Ozark confining unit separating the Arbuckle from the Cambrian St. Francis Aquifer group and basement rock at the north end of the profile is also missing in this area. Thus there may be little vertical confinement between disposal intervals and basement rock.

OIL AND GAS ACTIVITY

The central portion of the Fayetteville Shale gas play started in 2004 and covers parts of Cleburne, Conway, Faulkner, Independence, Pope, Van Buren and White counties. Fayetteville shale production wells typically use horizontally completions with laterals from 4,000' to 7000' in length at depths between 2,000' and 6,000'. Disposal prior to 2009 was in the Atoka and

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[24] Listric faults can be defined as curved normal faults in which the fault surface in concave upwards; its dip decreases with depth.
(http://www.geosci.usyd.edu.au/users/prey/ACSGT/EReports/eR.2003/GroupD/Report2/web%20pages/Listric_Faults.html)

[25] Note that the precise location and upper elevation depend on the particular velocity model used, and vary between the two sources of information.

[26] The Ozark Aquifer is not a USDW in this area.

Hale formations above the Fayetteville shale. During the recent seismic activity, disposal was into the Boone through the Arbuckle formations. See Figure F-4 for the disposal zone formation sequence.

History of Seismicity

In 1811 and 1812, a series of magnitude 7 earthquakes rocked the New Madrid Seismic Zone (NMSZ), (USGS, 2011a). In 1982, Arkansas experienced the Enola swarm of earthquakes with the largest magnitude of 4.7 (USGS, 2011b) as illustrated on the timeline in Figure F-5. The more recent Greenbrier area earthquakes (2009-2011) were located nine miles from the edge of the Enola swarm and approximately 100 miles from the edge of the NMSZ as shown in Figure F-1.

Focused Site Assessment

The earthquake activity started in 2009 and continued prolifically into 2011. Five disposal wells injecting below the Fayetteville shale were active within the major area of seismic events. The boundary of this focus study is derived from the regional seismometer network and the earthquake activity using a composite of an arbitrary five mile radius around each of the five focus wells, Figure F-6. The focused site assessment includes all pertinent information applied to the petroleum engineering review and case study findings.

Information Collected

Data for these five wells were collected from the AOGC website and from the state regulatory hearing documentation associated with the disposal well moratorium discussed later. Permitting documents provided details concerning completion depths, construction information, and permit conditions. Supplemental geosciences information was obtained from the deployment of additional seismometers. Operational monitoring reports provided several months of injection rates and wellhead pressures with data being recorded as often as every hour in some wells.

Disposal Wells in Case Study Area

The five area disposal wells of interest are the Moore Estate 1-22, Edgmon 1, Trammel 7-13 1-8D, SRE 8-12 1-17, and Underwood 8-12 5-12. Data gathered from the permitting documents and operational reports for each well is summarized in Tables F-1 and F-2.

TABLE F- 1: CENTRAL ARKANSAS FOCUS AREA WELLS PERMIT AND COMPLETION CONDITIONS

	Injection Permit Conditions					Completion Data (feet)				
Disposal Wells (SWD)	UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation	Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
Moore Estate 1-22	39487	Yes	3,000	6,000	Boone through Arbuckle: open-hole below 8,087'	7,760	10,600	10,600	5 ½” to 8087’	2 7/8” to 8077'
SRE 8-12 1-17	43266		3,330	20,000	Boone & Hunton	6,044	6,312	6,500	7” to 6500’	4 ½” to 5925’
Trammel 7-13 1-8D	41079	No	2,300	12,000	Boone	6,836	6,918	7,160	5 ½” to 7126’	3 ½” to 6800’
Underwood 8-12 5-12	42981	No	2,669	7,500	Boone, Chattanooga, Penters, Hunton & Viola; open-hole from 5619 to 6320'; Recompleted to Orr on 09/23/2010.	5,426	6,320	6,320	4 ½” to 5521’	2 3/8” to 5978’
Edgmon 1	36380	Yes	8,454	20,000	Arbuckle	7,280	10,970	12,163	4 ½” to 12162’	2 7/8” to 7710’

TABLE F- 2: CENTRAL ARKANSAS FOCUS AREA WELLS OPERATING HISTORY

Disposal Wells (SWD)	Operations		
	Initial Disposal	Final Disposal	Plugged and Abandoned
Moore Estate 1-22	6/1/2009	7/15/2011	29-Sep-2011
SRE 8-12 1-17	7/8/2010	3/3/2011	30-Sep-2011
Trammel 7-13 1-8D	4/1/2009	6/20/2011	19-Oct-2011
Underwood 8-12 5-12	1/11/2010	6/27/2010	8-Mar-2011
Edgmon 1	8/18/2010	3/14/2011	

ADDITIONAL GEOSCIENCES INFORMATION

Additional seismometers, designated Q and X as illustrated in Figure F-7 were deployed in early September 2010 to investigate the Greenbrier area earthquakes through the combined efforts of Arkansas Geological Survey (AGS) and University of Memphis Center for Earthquake Research and Information (CERI). Figures F-3 and F-7 show the fault oriented N22°E identified through interpretation of the monitor network results, (Horton, 2012; AGS). This fault was confirmed on 3D seismic, courtesy of an area exploration company. Detailed information about the Greenbrier area earthquakes is available from the publications listed in Citations below, and in the Bibliography.

The more recent Greenbrier area earthquakes recorded in the ANSS, COMCAT, NEIC, and CERI catalogs, within the focus radius of the disposal wells of interest, are summarized in Table F-3 below and on a timeline illustrated in Figure F-8. A zoomed map area of the disposal well and earthquake activity is included on Figure F-6.

TABLE F- 3: GREENBRIAR AREA SEISMICITY THROUGH 9/30/2013

Year	Starting Date	Number of Events	Magnitude			Ending Date
			Min.	Avg.	Max.	
2001	5/4/2001	4	2.7	3.2	4.3	5/5/2001
2002		0				
2003	12/14/2003	2	2.7	2.8	2.8	12/15/2003
2004		0				
2005	1/27/2005	1	2.7	2.7	2.7	1/27/2005
2006	4/9/2006	2	2.8	2.8	2.8	10/17/2006
2007		0				
2008		0				
2009	10/15/2009	7	2.4	2.7	3.0	10/31/2009
2010	2/18/2010	677	0.2	1.8	4.4	12/31/2010
2011	1/1/2011	732	1.0	2.2	4.7	12/22/2011
2012	1/14/2012	2	2.0	2.1	2.2	1/14/2012
2013	9/11/2013	4	1.6	1.9	2.1	9/28/2013

OPERATIONAL DATA

Data were divided into two areas: operational and pressure transient testing. All five wells had operational data for analysis. A step rate test was available for the Edgmon. Surface pressure shut-in periods embedded in the monitored pressure data for the SRE, Trammel, SRE, and Edgmon wells were reviewed using pressure transient analysis techniques. Injection rates fluctuated significantly in all three wells prior to the shut-in periods. The shut-in pressures were recorded at the surface so no useful pressures were available after a well went on a vacuum, making the pressure falloff responses of limited duration.

Operational data consisted of monthly and hourly wellhead pressures and injection volumes. The high data recording rate yielded fairly noisy data sets for operational analysis from intermittent use, but the added recording frequency provided sufficient data for a limited falloff test analysis during some of the shut-in periods. The Underwood well had very limited injection.

Surface pressures were converted to approximate bottomhole pressures (BHP) at the tubing seat depth of each well. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A fluid specific gravity of 1.025 was used based on permitting documentation for the SRE well.

Petroleum Engineering Review

Operational Analysis

Operational data were reviewed and analyzed for each of the five wells. No Hall plot was generated for the Underwood well. The Underwood had intermittent operating data and the small diameter tubing caused the pressure conversion to bottomhole pressures to be suspect due to the friction loss calculation. The analysis plots are included in the following list of figures:

- Operational data overview plots: Figures F-9 through F-13
- Operational pressure gradient plots: Figures F-14 through F-18
- Tandem plot of Hall integral with derivative cumulative earthquake events: Figures F-19 through F-??

Table F-4 summarizes the assumed reservoir pressure value used in the Hall integral calculation for each Hall plot.

TABLE F- 4: HALL INTEGRAL INITIAL PRESSURE VALUES

Disposal Well (SWD)	Hall Plot Assumed Initial Pressure (psia)
Moore Estate 1-22	3500
SRE 8-12 1-17	2400
Trammel 7-13 1-8D	3800
Edgmon 1	3400
Underwood 1	n/a

The Arkansas case study had a large number of low to moderate level earthquake events recorded, making it possible to plot a well established cumulative event trend. To determine if the earthquake cumulative event trend followed the Hall integral trend, tandem plots of cumulative earthquake events and Hall integral response versus cumulative water injection were prepared for the Moore Estate, SRE, Trammel, and Edgmon wells and are shown in Figures F-26 through F-29.

The operating pressure data analysis completed for each well is summarized below. The results of the tandem plots are also included.

The operating pressure data analysis completed for each well is summarized below:

- Operational data overview plots (Figures F-9 through F-13)
  - Moore Estate 1-22 (Figure F-9)
    - Tubing pressures did not fluctuate with rate changes
  - SRE 8-12 1-17 (Figure F-10)
    - Operated intermittently with significant rate fluctuations
    - Short falloff test during final well shut-in prior to well going on a vacuum
  - Trammel 7-13 1-8D (Figure F-11)
    - Rates dipped between January and June 2010 with limited pressure decline
    - Short falloff test during final well shut-in
  - Underwood 8-12 5-12 (Figure F-12)
    - Operated intermittently
  - Edgmon 1 (Figure F-13)
    - Operated intermittently with significant rate fluctuations
    - Falloff test recorded during final well shut-in
- Operating pressure gradient plots (Figures F-14 through F-18)
  - Highest operating gradients in the Moore Estate well (Figure F-14)
- Tandem plots of cumulative earthquakes and Hall integral with or without derivative (Figures F-19 through F-26)
  - Moore Estate 1-22 (Figures F-19, F-20, and F-21)
    - Hall integral indicated some slope breaks
    - Derivative trend scattered
  - SRE 8-12 1-17 (Figures F-22 and 23)
    - SRE shut-in on March 4, 2011 with 2,471,012 bbls cumulative injection
    - Last 150 earthquake events occurred after well was shut-in
    - Hall integral with derivative show both positive and negative slope changes (Figure F-22)

        - Early slope breaks indicate possible enhanced injectivity (Figure F-23)
        - Gradual upward trend in Hall integral and derivative in last third of plot may suggest boundary, development of positive skin factor, or response to offset disposal
    - Trammel 7-13 1-8D (Figures F-24 and 25)
        - Hall integral contains multiple positive and negative slope changes (Figure F-25)
        - Last half of Hall integral and derivative plot contains significant upward trends separated by a slight downward trend, but the overall upward trend may suggest boundary, development of positive skin factor, or response to offset disposal (Figure F-24)
    - Underwood 8-12 5-12 (No Hall integral or tandem plot generated)
    - Edgmon 1 (Figure F-26, F-27, and F-28)
        - Hall derivative contains significant scatter from intermittent use, but trend remains below the Hall integral (Figure F-26)
        - Hall integral by itself shows multiple positive and negative slope changes, with some corresponding to earthquake events (Figure F-26 and F-27)

Pressure Transient Analysis

Edgmon 1 Step rate test (Figure F-29)

The WG reviewed the step rate test conducted in the Edgmon and found conflict between the reported data and field notes as summarized in Tables F-5 and F-6. The data from the recorded data and field notes in Table F-6 were used for preparation of the linear plot. A drastically reduced pressure response occurred during rate step 6. The small diameter tubing size in the well coupled with high injection rate values resulted in the calculated bottomhole pressures dropping below the actual measured surface pressures due to severe calculated friction loss. No slope breaks were observed in the surface pressure data. The test was not considered suitable for quantitative analysis.

TABLE F- 5: EDGMON STEP RATE TEST DATA FROM APRIL 10, 2010 TEST REPORT*

Step	Injection Rate (BPM)	Injection Rate (BWPD)	Surface Injection Pressure (psig)	Frictional Pressure (psig)	Estimated Hydrostatic Pressure (psig)	Estimated BHP Pressure (psig)
1	5.9	8500	760	710	3465	3515
2	7.0	10100	1204	1134	3465	3535

3	8.4	12100	1704	1584	3465	3585
4	9.9	14200	2380	2125	3465	3695
5	11.2	16100	3015	2715	3465	3765
6	14.4	20800	4960	4360	3465	4065
7	17.4	25000	6882	6097	3465	4250

*** EDGMON DATA SUMMARY TABLE IN REPORT LISTED INCONSISTENT TIME INCREMENTS AND INJECTION RATES COMPARED TO THE DATA FROM THE RECORDING INSTRUMENTS AND FIELD NOTES INCLUDED IN THE REPORT. TIME INCREMENTS = 15 MINUTES; WATER WEIGHT = 8.55 PPG; WATER SPECIFIC GRAVITY = 1.025; DEPTH TO TOP PERFORATION = 7806 FEET.**

TABLE F- 6: EDGMON 2010 STEP RATE TEST DATA FROM RECORDED DATA AND FIELD NOTES*

Step	Rate from data (bpm)	Rate (gpm)	Surface Pressure (psig)	Bottomhole Pressure (psig)	Friction Pressure (psi)	Bottomhole Pressure Corrected for Friction (psig)	Time Increments (min)
1	5.8	243.6	760	4182	1200	2982	60
2	6.9	289.8	1204	4626	1655	2971	60
3	8.3	348.6	1675	5097	2329	2768	60
4	9.9	415.8	2380	5802	2337	2575	60
5	11.1	466.2	3015	6437	3988	2449	60
6	11.2	470.4	1090	4512	4055	457	60
7	14.8	621.6	4997	8419	6791	1628	180

*** EDGMON SUMMARY TABLE COMPILED FROM RECORDED DATA AND FIELD NOTES. PRESSURE DROPPED DURING RATE STEP 6; REPORT PROVIDED NO EXPLANATION FOR PRESSURE DECREASE.**

Surface pressure falloff test data were also reviewed for the Trammel, SRE, and Edgmon wells using PanSystem® well test analysis software. The final falloff periods were analyzed and the reservoir characteristics are illustrated in Figures F-30 through F-32 for the three disposal wells located closest to the Guy-Greenbrier fault. The rate variations for each well were accounted for by the use of equivalent time on the log-log plot. The pressure transient analysis of the step rate test for the Edgmon and the final falloff tests for the Trammel, SRE, and Edgmon are summarized below:

- Edgmon 1 Step rate test (Figure F-29)
  - Linear plot of surface pressure test data converted to bottomhole
    - Anomalous behavior observed during step 6
      - At a constant injection rate of 11.2 bpm the surface injection pressure fluctuated greatly
        - Start at approximately 2860 psi for 5 min

        - Drop abruptly to approximately 960 psi
        - Climb gradually to approximately 1090 psi
    - Calculated BHPs declined with increasing injection rates
      - Friction factor of 140 resulted in a negative bottomhole pressure for the final rate step so used 150 friction factor used for step rate analysis only
- SRE 8-12 1-17 Final falloff test (Figure F-30)
  - Overview plot of shut-in periods and final falloff (Figure F-10)
  - Log-log plot indicated a fracture or highly stimulated completion signature
    - Matched using an infinite conductivity fracture model (Figure F-30)
    - Indicated a long fracture half length (> 500 feet) for this well's completion
    - Late test time derivative response declined
- Trammel 7-13 1-8D Final falloff test (Figure F-31)
  - Overview plot of shut-in periods and final falloff (Figure F-11)
  - Log-log plot indicated a fracture or highly stimulated completion (Figure F-31)
    - Completely dominated by linear flow
    - Could not be type curve matched
- Edgmon 1 Final falloff test (Figure F-32)
  - Overview plot of shut-in periods and final falloff (Figure F-13)
  - Log-log plot (Figure F-32)
    - Response was dominated by wellbore storage and unanalyzable

Actions taken by UIC regulatory agency in Central Arkansas area

Initial response was deployment of additional seismometers to better record the actual event epicenters (surface location) and focus location (depth). This was done through the combined efforts of Arkansas Geological Survey (AGS) and University of Memphis Center for Earthquake Research and Information (CERI), with some of the monitor stations directly linked into the USGS National Earthquake Information Center.

Following initial identification of the Guy-Greenbrier fault, the Arkansas Oil and Gas Commission (Commission) established a moratorium on the drilling of any new Class II disposal wells in an area surrounding and in the immediate vicinity of the seismic activity in December 2010; and also required the operators of the seven existing Class II disposal wells operating in the moratorium area to provide hourly injection rates and pressures on a bi-weekly basis for a period of six months, through July 2011. During the moratorium period AGS and CERI analyzed the injection data and seismic activity to determine if there was a relationship. The injection-induced seismicity project considered the five deeper wells closest to the Guy-Greenbrier fault selecting the three wells closest to the fault for further analysis.

Using (Wells and Coppersmith, 1994) equations, from the estimated fault rupture length and area, the potential maximum (moment) magnitude the fault in Figure F-5 could produce was estimated to be between 5.6 and 6.0. (Horton, 2011)

In February 2011, following a series of larger magnitude earthquakes, (4.7 with damage reported), the operators of the three disposal wells nearest the seismic activity voluntarily agreed to shut-in the subject disposal wells prior to the issuance of the Commission cessation order. The subsequent March 4, 2011 cessation order required the subject wells to cease disposal operations. In July 2011, following the conclusion of the moratorium study, the Commission established a revised permanent moratorium area in which no further Class II disposal wells could be drilled and that four of the original seven disposals wells included in the original moratorium area were required to be plugged. The revised moratorium area was based on the trend of the fault identified as the cause of the seismic activity. The operators of three of the wells (SRE, Trammel and Edgmon) voluntarily agreed to plug the subject disposal wells and plugging was complete. Following the July 2011 Commission Hearing, the Commission issued an order to the operator of the fourth disposal well to plug their well. The order of the Commission issued in July 2011 became a final administrative regulation on February 17, 2012. (Note: the operator of the Edgmon disposal well is in bankruptcy and the well will probably be plugged by the Commission under the Commission Abandoned and Orphaned Well Plugging Program).

Resulting Changes in Regulations or Methodology

The Commission finalized amendments to their Class II disposal well rules effective in February 2012. Since July of 2011, the Commission, AGS and CERI continue to monitor disposal well operations and seismic activity. Additional seismic monitoring equipment has been purchased to facilitate the creation of an "early warning" system for emerging seismic activity thereby allowing more time to develop appropriate responses.

Lessons Learned

- Initiating dialogue with operator can provide early voluntary action from operators, including well shut-in, or acquisition of additional site data.
    - Initiating dialogue between the operator and UIC regulator resulted in the voluntarily shut-in of some suspect disposal wells.
    - An operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep seated fault.
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.

    - Hall integral and derivative plot may indicate no flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance.
    - Hall integral and derivative plot may illustrate enhanced injectivity.
  - Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation or encountering an increased permeability zone at distance.
  - Acquisition of additional data may provide an improved analysis.
    - Increased recording of operational parameters can improve the quality of the operational data analysis.
      - Increased frequency of permit parameters improved the operational analysis.
  - Engaging external geophysical expertise may bring a more accurate location (x,y,z) of the active fault and stress regime through reinterpretation or increased seismic monitoring.
    - Especially important as earthquake event magnitudes increased over time.
- Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
  - Additional stations installed resulted in reliable identification of active fault locations.
- Engage a multi-disciplinary combined approach to minimize and manage induced seismicity at a given location.
  - Working with state geological survey or university researchers provided expert consultation, resulted in installation of additional seismometers, and yielded a clearer understanding of the deep seated active faulting.
  - Director discretionary authority was used to solve individual site specific concerns:
    - Acquired additional site information, request action from operators, and prohibit disposal operations. Specific examples include:
      - Increased monitoring and reporting requirements for disposal well operators provided additional operational data for reservoir analysis.
      - Required one well to include a seismic monitoring array prior to disposal as an initial permit condition.
      - Required plugging or temporary shut-in of suspect disposal wells linked to injection-induced seismicity while investigating or interpreting additional data.
      - Defined a moratorium area prohibiting Class II disposal wells in defined high risk area of seismic activity.

CITATIONS

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APPENDIX G: BRAXTON COUNTY, WEST VIRGINIA, CASE STUDY AREA

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All four case studies were considered in the development of the decision model. The state agency's handling of these events was the basis for some of the approaches listed in the decision model described in Appendix B. Consequently the UIC National Technical Working Group (WG) elected to apply the Decision Model framework to the case study events. Following the Decision Model framework, the well in this case study fall under the existing well category. Increased earthquake frequency following the start of disposal operations raised concern. The state agency's handling of these events was the basis for some of the approaches listed in the decision model described in Appendix B.

BRAXTON, WEST VIRGINIA CASE STUDY BACKGROUND

A series of minor earthquakes started in early 2010 around Braxton, West Virginia a little over a year after disposal operations started in a relatively nearby well, Figure G-1). The relationship between the earthquakes and the Class II disposal well was investigated by the West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas.

To understand area site conditions, a summary of the geologic setting, existing oil and gas activity and seismic history is provided, followed by focused site assessment including details related to the disposal well operations.

Geologic Setting

Braxton County is located in the Appalachian basin, on the eastern edge of the Paleozoic Marcellus shale and Devonian Trenton limestone gas plays, (Figure G-1). The Marcellus outcrops in eastern West Virginia, though this is not shown in Figure G-1 (Avary, 2011).

The Marcellus unconformably overlies the Onondaga Limestone (Figures G-2, Avary, 2011 and G-3, WVGES, 2011), which is an easily recognizable marker on logs and seismic surveys. The Marcellus is predominantly siliceous, with mixed muscovite and illite, and minor amounts of pyrite and kaolinite (Boyce and Carr, 2009).

Oil and Gas Activity

Gas production in the Marcellus Shale of West Virginia started in 2005, with Braxton County drilling starting in 2006. The Elk Valley (626407) Class II wastewater disposal well was initially completed in the Marcellus shale as a gas production well. The vertical well was later converted to disposal into the same interval.

History of Seismicity

West Virginia has a history of seismicity along the Ohio border and along the southeast border with Virginia. However, there was only one low level earthquake in 2000 recorded in the ANSS database, prior to the events starting in 2010. The seismicity search for this case study used a number of databases including ANSS, SRA, NCEER, USHIS, CERI and PDE.

Focuses Site Assessment

There is only one disposal well in the general vicinity of the earthquakes. Injection activities began in the Elk Valley disposal well in March 2009 about one year prior to the start of seismic events. A zoomed map area of the disposal well and earthquake activity in focus area is included on Figure G-4.

information Collected

Data for this case study well was collected from the WVDEP Office of Oil and Gas. Permitting documents provided details concerning completion depths, construction information, and permit conditions. Operational monitoring reports provided monthly injection volumes, maximum injecting tubing pressure, maximum shut-in tubing pressure, and hours operated during the month.

Disposal Well in Case Study

Permit, construction and completion information for the Elk Valley Well No. 626407 details are summarized below:

TABLE G- 1: ELK VALLEY DISPOSAL WELL PERMIT CONDITIONS

UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation
2D0072539	no	2100	N/A	Marcellus, fractured

TABLE G- 2: ELK VALLEY DISPOSAL WELL COMPLETION DATA

Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
6,472	6,524	6,556	5½ " at 6543'	2 7/8" at 6395'

DEPTHS ARE MEASURED DEPTH IN FEET, NOT TVD

TABLE G- 3: ELK VALLEY DISPOSAL WELL OPERATIONS

Initial Disposal	Final Disposal	Plugged and Abandoned	Comments
Mar 2009			operating

Permit information indicated that the vertical well was initially fractured with a total of 355,000 pounds of sand and 14,398 barrels of water prior to being converted to a disposal well.

The chlorides in the fluid analysis included in the permitting documentation ranged from 0-250,000 mg/L.

Additional Geosciences Information

A summary of the recent focus area earthquakes, within a twelve mile (19 km) radius[27] of the Braxton County case study well is provided in the Table G-4 below and a timeline of recent events is shown on Figure G-5. A zoomed map area of the disposal well and earthquake activity is included on Figure G-4.

[27] The search area was increased owing to the location uncertainty, occasioned by the poor density of seismometers.

TABLE G- 4: BRAXTON, WEST VIRGINIA FOCUS AREA SEISMICITY THROUGH 9/30/2013

Year	Starting Date	Number of Events	Magnitude			Ending Date
			Min.	Avg.	Max.	
2010	4/4/2010	8	2.2	2.6	3.4	7/25/2010
2011		0				
2012	1/10/2012	1		2.8		1/10/2012
2013	3/31/2013	3	2.6	2.9	3.4	8/16/2013

Operational Data

A single case study disposal well, Elk Valley disposal well, had monthly operating data available from the WVDEP. Monthly data included maximum and shut-in tubing pressures, total monthly injection volume, and hours operated that were used to convert the monthly injection volume to an average injection rate. The operating surface pressure was the average of the maximum injection and maximum shut-in pressures for each month. Surface pressures were converted to approximate bottomhole pressures (BHP) at 6395 feet. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 100 for steel tubing was used to limit the friction pressure loss. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A specific gravity of 1.125 was used to approximate 100,000 ppm chloride brine. The hydrostatic column of fluid was calculated at 3115 psia. Because the well went on a vacuum, an average static reservoir pressure of 2800 psia was assumed for the Hall integral calculation.

Petroleum Engineering Review

Operational Analysis

Three operating data-related plots were prepared including an operational data overview plot (Figure G-6), a monthly operating pressure gradient plot (Figure G-7), and Tandem plots of cumulative seismic events and the Hall integral with derivative, based on the calculated average tubing pressures, plotted against cumulative water injection(Figure G-8 and G-9).

The monthly hours reported indicated that the well did not operate continually throughout each month. The Hall integral and derivative functions were prepared as continuous functions from monthly data using and only the hours operated in month were used in the calculation of the Hall integral and derivative functions. To determine if the earthquake cumulative event trend followed the Hall integral trend, a tandem plot of both cumulative earthquake events and the Hall integral with derivative response versus cumulative water injection was prepared for the Elk Valley disposal well as shown in Figure G-8. Figure G-9 also shows an expanded view of the Tandem plot responses early in the operational life of the injection well.

- Operational Overview Plot (Figure G-6)
    - Last quarter 2010 had higher injection volumes with lower pressures
- Operating Pressure Gradient (Figure G-7)
- Tandem Plot of Hall Integral with Derivative and Cumulative Seismicity Events (Figures G-8 and G-8)
    - Hall integral with derivative upswing response during late portion of operational data with corresponding seismicity events
    - Zoomed Tandem Plot
        - Slight separation between Hall Integral and Derivative at seismic events early in operating life of the well

PRESSURE TRANSIENT ANALYSIS

A step rate test was performed on the Elk Valley disposal well in March 2008, prior to injection, and was also included with the permit information. The injection rate started at 0.5 and increased to 5.5 barrels per minute over eight rate steps. Individual steps were primarily 30 minute intervals, except for the last step held for 3 hours. A total of 1,410 barrels was injected into the well during 6.5 hours of step rate testing. A summary of the rate and tubing pressure measurements is included in Table G-5.

TABLE G- 5: MARCH 2008 STEP RATE TEST DATA

Injection Tubing Pressure at the End of Each Rate Step (psig)	Average Constant Injection Rate for Rate Step (bbls/min)
150	0.5
0	1.0
0	1.5
0	2.0
400	3.0
1160	4.0
1750	5.0
1900	5.5

A linear plot of the 2008 step rate test data were plotted and shown in Figure G-10. The linear plot is the final injection pressure at the end of each rate step versus the injection rate for the same rate step. Electronic data of the step rate test was not available to attempt a log-log plot analysis of each individual injectivity test. The well went on a vacuum following the first rate step. Pressures increased to nearly 2000 psi after positive pressures were reestablished during the 5th rate step.

Step Rate Test (Figure G-10)

- Linear plot indicated a slope break between the 6th and 7th rate steps of 4 and 5 barrels per minute
    - Suggested a fracture extension surface pressure of roughly 1650 psi
    - Value would suggest a fracture gradient of approximately 0.75 psi/foot

Although the Hall plot showed several slope breaks, the calculated operating gradient in Figure G-7 showed operating gradients under 0.75 psi/foot, below the fracture extension gradient indicated by the step rate test linear plot.

ACTIONS TAKEN BY UIC REGULATORY AGENCY IN BRAXTON COUNTY, WV AREA

In response to the seismic activity starting in April 2010, the West Virginia Department of Environmental Protection Office of Oil and Gas (WVDEP) reduced the injection volume in the Elk Valley disposal well.

LESSONS LEARNED

- Initiating dialogue with operator can provide early voluntary action from operators, including acquisition of additional site data**.**
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.
    - Upswing in Hall integral and derivative plot may indicate no flow boundary, such as a fault plane or stratigraphic pinch out, at a great distance.
- Engaging external geophysical expertise may bring a more accurate location (x,y,z) of the active fault and stress regime through reinterpretation or increased seismic monitoring.
- Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
    - Epicenters of recorded events are scattered, due to insufficient stations in proximity to the activity.
- Engage a multi-disciplinary approach to minimize and manage induced seismicity at a given location.
- Director discretionary authority was used to solve individual site specific concerns:
    - Acquired additional site information, requested action from operators.
        - Decreased allowable injection rates and total monthly volumes in response to seismic activity.

CITATIONS

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SRA and USHIS: http://earthquake.usgs.gov/regional/neic/

APPENDIX H: YOUNGSTOWN, OHIO CASE STUDY

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All four case studies were considered in the development of the decision model. The state agency's handling of these events was the basis for some of the approaches listed in the decision model described in Appendix B. Consequently the UIC National Technical Working Group (WG) elected to apply the Decision Model framework to the case study events. Following the Decision Model framework, the well in this case study fall under the new well category. Increased earthquake frequency and magnitude following the start of disposal operations raised concern. The state agency's handling of these events was the basis for some of the approaches listed in the decision model described in Appendix B.

YOUNGSTOWN OHIO CASE STUDY BACKGROUND

Starting on March 17, 2011, a series of 12 low magnitude seismic events occurred in Mahoning County in and around Youngstown, Ohio, culminating in a magnitude M4.0 event on December 31, 2011, Figure H-1. Evidence suggested that a newly permitted, Northstar 1 Class II saltwater disposal well was the cause of the seismic activity and the injection well was voluntary shut down a day before the M4.0 event. The Northstar 1 injection well had been permitted as a deep stratigraphic test well and was drilled to a depth of 9184 feet into the Precambrian basement rocks in April of 2010. On July 12, 2010, the Northstar 1 was issued a Class II saltwater disposal permit and injection operations commenced on December 22, 2010.

To understand area site conditions, a summary of the geologic setting, existing oil and gas activity and seismic history is provided, followed by focused site assessment including details related to the disposal well operations.

Geologic Setting

Youngstown is located in Mahoning County near the border of Pennsylvania, on the western flank of the Appalachian Basin. Figure H-2, (Baranoski, 2002; ODNR, 2012) illustrates the general structure across Ohio with deep Precambrian structures overlain by Paleozoic beds thickening to the east into the Appalachian Basin. Figure H-3, (ODNR, 2004) shows a regional stratigraphic column. The Utica and Marcellus shale plays are thin in eastern Ohio, thickening into the Appalachian basin to the east, (Figure H-4).

Very little control is available for the basement Precambrian structure, but regional maps based on well control combined with seismic lines have been compiled, (Baranoski, 2002, 2013; ODNR, Pennsylvania Geological Survey, OFGG-05). The 2013 Baranoski publication includes maps of all the Precambrian wells drilled since 2002. The Baranoski Precambrian maps do not show faulting in Mahoning County. The regional scale map (Figure H-1) shows the closest known fault to be about twenty miles away.

Oil and Gas Activity

Shallow oil and gas activity is plentiful in the area, with production from the upper Devonian Berea, and lower Silurian sandstones. The first Class II saltwater disposal well was permitted in Mahoning County in 1985 and eight more wells were converted to Class II injection between 1985 and 2004. These Class II injection wells utilized depleted oil and gas zones or were plug backed to shallower, non-oil and gas geologic formations for disposal. Injection was predominantly for disposal of production brine associated with conventional oil and gas operations.

With the development of the unconventional shale plays in Pennsylvania and the lack of disposal in Pennsylvania, there was a need for additional disposal operations. To accommodate some of this need, five commercial disposal wells (Northstar 1, 2, 3, 4, and 6) were permitted and drilled in Mahoning County, Ohio. The permitted disposal zones were the Knox through the Mount Simon Sandstone, but the disposal wells were drilled completely through the Mount Simon and into the Precambrian basement rock.

History of Seismicity

Prior to the March 2011 seismic events, there had been no prior seismicity epicenters recorded in Mahoning County. However, there is a seismically active zone in western Ohio, and several episodically active faults 20 miles (Smith Township fault) and 40 miles (Akron magnetic anomaly) away from Youngstown, (Figure H-1, Baranoski, 2002). The vast majority of all historic and current seismic activity in Ohio occurs within the Precambrian basement rocks.

Seismic monitoring in Ohio was sporadic until establishment of the Ohio Seismic Network[28] (OSN) in 1999. Prior to 1999, seismic monitoring was sporadic throughout the state, comprised of the USGS stations and other smaller monitoring networks. The earlier seismic network distribution made identifying events below a M3.0 difficult. In 1999, the Ohio Seismic Network (OSN) was established with 6 stations and there were 24 seismic stations in operation in 2011. The seismometer at Youngstown State University was added to the OSN in 2003.

The seismicity search for this case study used a number of databases including ANSS, OSN, SRA, NCEER, USHIS, CERI and PDE.

Focused Site Assessment

On March 17, 2011, a series of low magnitude earthquakes began in Mahoning County in and around Youngstown, Ohio, (Figure H-1). A nearby commercial Class II disposal well, Northstar 1, was shut-in by the Ohio Department of Natural Resources (ODNR) following a M4.3 (M3.9 refined value) magnitude earthquake on December 31, 2011. According to the *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area* published in March 2012 by the ODNR, the report suggests the seismicity was related to Class II disposal activites. The Northstar 1 was drilled 200 feet into the Precambrian basement rock. The ODNR report also concluded that pressure from disposal activities may have communicated with a fault located in the Precambrian basement rock.

Information Collected

The Ohio Department of Natural Resources (ODNR) standard UIC permit application package submitted prior to October 1, 2012, incorporated some site data, and well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs.

Data for the five Northstar wells were collected from the ODNR through the Oil and Gas Resources Division website and staff. Permitting documents provided details concerning

[28] OSN is coordinated by the Ohio Geological Survey of the ODNR

completion depths, construction information, and permit conditions. Supplemental geosciences information was obtained from the deployment of additional seismometers. Operational monitoring reports provided several months of injection rates and wellhead injection pressures, as well as fluid analysis, and a step rate test.

Disposal Well in Case Study

Six Northstar disposal wells were permitted for injection near the Youngstown area in 2011. According to the ODNR only one has injected, though all five were drilled and completed open-hole from the Knox into the Precambrian.

Injection activities began in the Northstar 1 in December 2010 about three months prior to the start of seismic events. A zoomed map area of the disposal well and earthquake activity in Mahoning County is included on Figure H-5. Two increases in the maximum allowable surface pressure were authorized by ODNR based on the actual specific gravity of the injectate. Permit, construction and completion information for the Northstar 1 disposal well are summarized below:

TABLE H- 1: NORTHSTAR 1 DISPOSAL WELL PERMIT CONDITIONS

UIC Permit	Commercial	Maximum Pressure (psig)	Maximum Rate (BPD)	Disposal Formation
3127	yes	2500	2000	top Knox through 200’ of Precambrian; open-hole completion

TABLE H- 2: NORTHSTAR 1 DISPOSAL WELL COMPLETION DATA)

Top Injection Zone	Base Injection Zone	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat
8,215’	9,180’	9,184’	5.5” at 8215’	3.5” at 8215’

DEPTHS ARE MEASURED DEPTHS IN FEET, NOT TVD

TABLE H- 3: NORTHSTAR 1 DISPOSAL WELL OPERATIONS

Initial Disposal	Final Disposal	Plugged and Abandoned
12/22/2010	12/31/11	

Additional Geoscience Information

The Cambrian Knox unconformity that was rarely penetrated in Mahoning County marks the top of the disposal zone permitted in the Youngstown area. The ODNR report indicates that the Northstar 1 penetrated the Precambrian and encountered primarily biotite, quartz, amphibole, and feldspar with undetermined trace minerals for the first 80 feet before reaching granite. The 2012 ODNR report stated there were indications of high angle fractures around the contact with the granite.

The Ohio Geologic Survey of ODNR collects and maintains information on geology, oil and gas well details, and the Ohio Seismic Network (OSN) data. The permanent seismometer network is tracked by the OSN.

Due to the continued seismic events occurring in and around the Youngstown area and near the Northstar 1 injection well, four highly sensitive, portable seismic units on loan from Lamont-Doherty, were deployed on December 1, 2011 (Tomastik, 2013; Kim et al., 2012). A later publication (Kim, 2013) provides relocated seismic events (horizontally and vertically relocated) for the twelve earthquakes carried on the OSN website, plus another nine events recorded on the temporary array. Table H-4 summarizes events located within a six mile (10 km) radius of the Northstar 1 case study well, as shown in timeline Figure H-6. The OSN catalog was used for the first twelve earthquakes in the focus study, and the nine small earthquakes picked up by the temporary network from the Kim publication. The relocated events are shown on Figure H-6 by the plus symbol, and in a closer view in Figure H-7.

TABLE H- 4: YOUNGSTOWN FOCUS AREA SEISMICITY THROUGH 9/30/2013 (OSN AND KIM, 2013*)

Year	Starting Date	Number of Events	Min.	Avg.	Max.	Ending Date
2011	3/17/2011	11	2.1	2.5	4.0	12/31/2011
2012	1/11/2012	10	0.1	0.6	2.1	2/11/2012
2013		0				

* OSN events 2011 through 1/11/2012; temporary network 1/12 through 2/11/2012

In Kim (2013, Figure 3a), the relocated events define a previously unknown Precambrian basement fault in close proximity to the Northstar 1 (Figure H-7). This fault was confirmed through evaluation of geophysical logs from the offset deep disposal wells and an interpreted seismic line.

Cross-correlation and wave-form matching were some of the techniques used by Kim (2013) to reanalyze the seismometer readings for the area, resulting in a total of 167 seismic events ($0<Mw<3.9$ between January 2011 through February 2012). Only the twenty one events listed above were accurately located seismic events. However, the first of the poorer located events occurred 13 days after the Northstar 1 started injection (Kim, 2013).

PETROLEUM ENGINEERING REVIEW

Data for the Northstar 1 disposal well were divided into two areas: operational data and pressure transient testing in the form of a step rate test.

OPERATIONAL DATA

Site documentation reviewed included surface maps, location plats, disposal depths, and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and disposal conditions (interval, rate, and pressure requested). A step rate test was also included with the permit information. In addition, an annual report filed by the operator provided injection volumes and pressure data.

Operational data consisted of quarterly and daily wellhead pressures and injection volumes with hours of well operation included in the daily report data. Surface pressures were converted to approximate bottomhole pressures (BHP) at the tubing seat depth. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A fluid specific gravity of 1.03 was used based on a fluid lab analysis included in the permit application. An initial bottomhole pressure of 3803 psi was used based on the initial pressure measured in the inactive offset Northstar 4.

The monthly hours reported indicated that the well did not operate continually throughout each month. The Hall integral and derivative functions were prepared as continuous functions from monthly data and only the hours operated in month were used in the calculation of the Hall integral and derivative functions. To determine if the earthquake cumulative event trend followed the Hall integral trend, a tandem plot of both cumulative earthquake events and the Hall integral with derivative response versus cumulative water injection was prepared for the Northstar 1 as shown in Figure H-8. Figure H-9 shows an expanded view of the Tandem plot responses early in the operational life of the injection well

- Operational Overview Plot (Figure H-8)
- Operating Pressure Gradient (Figure H-9)
- Tandem Plot of Hall Integral with Derivative and Cumulative Seismicity Events (Figure H-10 and H-11)

Overview Plot (Figure H-8)

- Higher injection rates followed acid stimulation on 8/2/2011

Operating Pressure Gradient (Figure H-9)

- Plateau at 0.75 psi/ft bottomhole operating gradient for extended time frame
  - 0.75 psi/ft was basis for determining maximum surface pressure limit in permit

Tandem Plot of Hall integral and derivative Plot (Figures H-10 and H-11)

- Multiple positive upswings in Hall integral and derivative responses with some corresponding with earthquake events

PRESSURE TRANSIENT ANALYSIS

The June 2010 step rate test conducted to evaluate the injectivity into the well was also reviewed (Figure H-12).

Step Rate Test (Figure H-12)

- Designed as an injectivity test to evaluate the formation's ability to accept fluid
- Test conducted through 5.5" production casing
- Pressure fluctuations measured during some of the rate steps
- Full range of pressure gauge (10,000 – 15,000 psi) excessive for measured pressure range (1800 psi maximum)
- Unable to determine from the step rate tests report if the pressure was stabilized during each rate step
- Slope breaks
  - Several different straight lines could be drawn suggesting breaks after steps 5 and 6
  - Final slope is nearly flat between steps 7 and 8

ACTIONS TAKEN BY UIC REGULATORY AGENCY IN THE YOUNGSTOWN, OHIO AREA

Evidence suggested that a newly permitted, Northstar 1 Class II saltwater disposal well was the cause of the seismic activity and the injection well was voluntary shut down a day before the M4.0 event. After the M4.0 event on December 31st, the Governor of Ohio placed a moratorium on the other three deep injection wells drilled within a seven-mile radius of the Northstar 1 and put a hold on the issuance of any new Class II saltwater injection well permits until new regulations could be developed.

The ODNR revised regulations prohibiting the drilling of Class II injection wells into the Precambrian basement rock and adopted additional standard permit requirements to facilitate better site assessment and collection of more comprehensive well information. ODNR can require supplemental permit application documentation, such as seismic monitoring or seismic surveys, more geologic data, and comprehensive well logs. On a well-by-well basis, additional requirements may include a plan of action should seismicity occur, step-rate test, falloff testing, and a determination of the initial bottomhole pressure. A series of operational controls may also be added, such as a continuous pressure monitoring system, an automatic shut-off system, and an electronic data recording system for tracking fluids.

In late 2012, ODNR purchased nine portable seismic stations and has hired a PhD seismologist for the UIC Section to maintain and monitor the seismic network. ODNR is proactively approaching the issue of induced seismicity by conducting seismic monitoring at several new Class II injection well permit locations prior to commencement of injection operations and monitoring the seismicity for up to six months after initiation of injection operations. If no seismicity occurs, then these portable units will be moved to the next location.

Lessons Learned

- Initiating dialogue with operator can provide early voluntary action from operators, including well shut-in, or acquisition of additional site data.
  - Initiating dialogue between the operator and UIC regulator resulted in the voluntarily shut-in of the Northstar 1 disposal well.
  - Acquisition of additional data provided an improved understanding of the area.
  - Increased recording of operational parameters improved the quality of the operational data analysis.
- Analysis of existing operational data may provide insight into the reservoir behavior of the disposal zone.
  - Upswings in the Hall integral and derivative plot may indicate no flow boundary, such as a fault plane or stratigraphic pinch out, a distance away from the well.
  - Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural fractures, higher pressures allowing fluid flow into lower permeability portions of the formation or encountering an increased permeability zone at distance.
- Engaging external geophysical expertise may bring a more accurate location (x,y,z) of the active fault and stress regime through reinterpretation or increased seismic monitoring.
- Lack of historic seismic events may be a function of lack of seismic activity, seismic activity below recordable levels, or epicenters away from population centers.
- Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events.
  - Deployment of the additional seismometers enabled accurate identification of the location and depths of the next two major seismic events that occurred on December 24th and December 31st.

- Engage a multi-disciplinary combined approach to minimize and manage induced seismicity at a given location.
- Director discretionary authority was used to solve individual site specific concerns:
    - Acquired additional site information, requested action from operators, and prohibited disposal operations.

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APPENDIX I: ASEISMIC EXAMPLES OF CLASS II DISPOSAL WELL ACTIVITY CAUSING LONG DISTANCE PRESSURE INFLUENCES

Introduction I-1
Example of Extended Directional Pressure Trend I-1
Example of Cumulative Pressure Effect from Multiple Class II Wells... I-4

INTRODUCTION

Since pressure buildup is one of the three key components to inducing seismicity associated with Class II disposal wells, this appendix provides two examples of pressure buildup occurrences that impacted long distances, though neither example induced seismicity. The examples are included to illustrate abnormal cases of pressure buildup observed from two different Class II disposal well activities. The examples illustrate reservoir pressure distribution from disposal activities is site specific and dependent on geology and reservoir characteristics. The first example illustrates pressure movement through a linear trend and the second illustrates the cumulative pressure effect from multiple Class II wells completed in the same formation. These two examples also demonstrate the benefits of reservoir pressure measurements and the applicability and usefulness of pressure transient techniques.

The area of review determination for Class II disposal wells in the federal UIC regulations includes options for the calculation of the pressure buildup using radial flow equations or alternately using a fixed quarter mile (.402 km) radius from the disposal well without calculations (40 CFR §146.6). Reservoir quality or reservoir flow characteristics may extend pressure influence from the disposal activity beyond a ¼ mile radius from the well. If the reservoir pressure does not dissipate radially from the disposal well, use of the radial flow equations in the regulations may not be applicable for calculating the zone of endangering pressure influence. Reservoir pressure buildup is also additive, so offset wells completed in the same disposal zone may need to be considered. The Director can use discretionary authority to assess the area of review for special site specific circumstances.

EXAMPLE OF EXTENDED DIRECTIONAL PRESSURE TREND

BACKGROUND

Three inactive wells, two located approximately one mile (1.6 km) from a Class II disposal well (5115' and 6006') and one just over ¼ mile (1584') (1559 m, 1830 m, 482 m respectively) from the disposal well experienced an increase in surface pressure. These three wells were located in an east-northeast directional trend from the disposal well. The disposal well was the only well operating at a pressure exceeding the highest surface pressure measured at one of the inactive wells. The disposal well started injection approximately five months prior to discovering the increased pressure in the three abandoned wells. Other inactive wells located closer to the disposal well showed no pressure increase.

After identification of the potential well of concern, an interference testing procedure was designed to evaluate if the disposal well was hydraulically communicating with the inactive wells. The test was designed to establish repeatability of pressure responses if communication was present. The test also required monitoring fluid levels in additional wells, located outside the suspected directional trend, for possible pressure responses. A falloff test concluded the testing of the disposal well.

Interference Test Summary

As illustrated in Figure I-1, the interference test consisted of a background period, a one week stabilization period with the disposal well shut-in, one week with injection, and a one week falloff (shut-in) period in the disposal well. During the injection period, the operator maintained as constant an injection rate as possible. No other active injection was present in the test area. During the background period, digital recording surface pressure gauges were installed on the disposal well and the three inactive wells experiencing surface pressures to monitor pressure responses during the test. The disposal well operator also installed an inline flowmeter on the disposal well. In addition to surface pressure readings, fluid level measurements were collected at the other well locations.

Measured Offset Well Pressure Responses

As shown in Figure I-2, the pressure response between the disposal well and three wells monitored with digital surface pressure gauges indicated direct communication. The repeatability of the pressure response was observed in all three wells. The lag time for the pressure response at each monitored well (Figure I-3) was much shorter than anticipated, and atypical of a radially homogeneous reservoir. The response times were not significantly different between the well located 1584’ from the disposal well and the two wells located 5115’ and 6006’ away. The magnitude of the pressure response varied, but a pressure response was still observed. The fluid levels monitored in other area wells plotted in Figure I-4 did not suggest any communication with the disposal well.

Analysis of Disposal Well Pressure Data

The disposal well pressure transient test data measurements, when reviewed and analyzed, indicated a strong linear flow signature. Pressure transient analysis provided an approach for identifying non-homogeneous, non-radial flow reservoir behavior at the disposal well. The elevated pressures from the disposal well exceeded the ¼ mile (402 m) area of review allowed for Class II underground injection control permits. The reservoir's linear flow behavior could not be explained based on a review of available geologic and reservoir information. The disposal well was shut-in and later plugged and abandoned.

The disposal well pressure responses were plotted in a log-log plot format as a diagnostic tool for identifying the flow regime signature away from the well. The log-log plots of the disposal well pressure response during the stabilization and falloff periods suggested bilinear (¼ slope) and linear (½ slope) reservoir flow characteristics (See Figures I-5 and I-6, respectively). A bilinear (¼ slope) trend was observed for the entire test period during the stabilization whereas the falloff test period exhibited bilinear flow (¼ slope) followed by a linear flow characteristic (½ slope).

Type curve matches were completed, using PanSystem® pressure transient software; on the disposal well pressure response during the stabilization and falloff periods. A single fracture model type curve match estimated a very low reservoir permeability and an unrealistically long fracture half length, nearly a mile (1.6 km) in length for both periods (See Figures I-7 and I-8). This fracture half length suggested the well was in communication with a linear fault system.

Monitoring Well Interference Tests

The pressure interference response recorded at the three inactive wells with surface transducers was also analyzed. The measured pressure response at all three wells located 1584', 5115', and 6006' in an east-northeast trend line from the disposal well was an easily measureable level with minimal lag time after a rate change at the disposal well. The repeatability of the results gave confirmation of the communication with the disposal well. The pressure transient test analyses of the interference data were marginal. The interference pressure responses measured at the three wells all demonstrated behavior outside the range of the Exponential Integral (Ei) type curve typically used for radial flow analysis, but did highlight the non-homogeneous nature of the disposal formation.

During the disposal well falloff period, the associated early time pressure response on the log-log plot for the well located 1584' east-northeast of the disposal well (See Figure I-9) exhibited a more rapid response than the typical Ei type curve, suggesting a naturally fractured reservoir characteristic or indication of directional permeability. The middle portion of the test matched to the Ei type curve estimated an unrealistically high (21 darcies) reservoir permeability before deviating off the type curve.

During the disposal well injection period, the pressure response from the well located 5115' east-northeast displayed two different Ei type curve responses on the log-log plot (See Figures I-10 and I-11). The Ei type curve results from the early portion of the test also estimated an unrealistically high (141 darcies) reservoir permeability, but a much lower permeability (28 md) was estimated from the Ei type curve match of the later portion of the test.

During the stabilization period, the pressure response for the well located 6006' from the disposal well also illustrated atypical pressure responses on the log-log plot (See Figure I-12). No match was attempted of the scattered early data. A type curve match in the middle portion of the test resulted in a permeability estimate of 488 md. The late time pressure response deviated off the Ei type curve.

The repeatable pressure response in the three abandoned wells confirmed that a linear pathway from the disposal well was present. Pressure transient testing at the disposal well also confirmed the presence of a linear flow environment. The interference test analyses also demonstrated a non-homogeneous reservoir. This example illustrates a long distance directional pressure influence through a linear pathway.

Example of Cumulative Pressure Effect from Multiple Class II Wells

This second example covers a facility with a long history of recorded bottomhole pressure with a substantial increase in static reservoir pressure with no corresponding increase in injection rate.

Background

Disposal well operations with regular bottomhole pressure monitoring began in 1981. Disposal volumes at the pressure monitored disposal well (monitored well) facility remained relatively constant until reservoir pressure began increasing substantially in 2006 (See Figure I-13). The disposal interval ranges from 15-50 feet in thickness with an average permeability of 70 md and 13% porosity. No cause for the approximately 500 psi pressure increase was identified within two miles (3 km) of the facility.

Expanded Review Area

A pressure transient analytical analysis was conducted using the above reservoir parameters along with a 35 ft (10 m) net thickness, 0.54 cp viscosity and an injection rate of 100 gpm (3430 bpd). A pressure increase of 31 psi was predicted 15 miles (24 km) away after 10 years of injection. The review area around the monitored well was expanded to 15 miles in an attempt to identify potential sources for the 500 psi reservoir pressure increase. Fourteen Class II disposal wells were identified as likely injecting into the same formation within a 15 mile radius of the monitored well (See Figure I-14). Additional Class II disposal wells exist beyond the 15 mile radius, but were not included for this demonstration.

EFFECTS OF OFFSET DISPOSAL ACTIVITY

Most of the offset disposal activity began in late 2005. One offset well has operated occasionally for an extended period of time, but the majority of the offset disposal activity is more recent. The monitored well is included in the cumulative well count shown on Figure I-15. Figure I-16 illustrates the disposal volumes of the monitored well and cumulative disposal volumes from the other fourteen wells located within the 15 mi radius. The cumulative pressure effects of from multiple disposal wells completed in the same zone may impact a large area as illustrated in this example.

APPENDIX J: PARADOX VALLEY, COLORADO

Figure J- 1: Injection-Induced Seismicity and Injection Rates J-2
Figure J- 2: Injection rates and Pressures..J-3
Figure J- 3: Earthquake Clusters...J-4

The U.S. Bureau of Reclamation runs a deep, high pressure, Class V disposal well in Paradox Valley, Colorado. This operation is part of the Colorado River Basin Salinity Control Project to remove near surface brine and limit saline flow into the Dolores River. Disposal is into the Mississippian carbonate and the upper Precambrian granite, e.g., basement rock. Prior to completion of the well, a ten station seismic network was installed in the area. Upgrades are made to the seismic network and the coverage area has been enlarged as necessary.

Figure J-1 contains two figures, the top shows the number and magnitude of events related to the distance from the disposal well. The lower figure adds the injection rate. Only one earthquake was recorded prior to injection starting in 1991. Numerous earthquakes followed the start-up of disposal operations, injection and stimulation tests (Phase I injection). Project reports highlight the apparent correlation between close earthquakes (near-well at ≤ 4 km from the injector) and initial tests. Relatively continuous injection (Phase II injection) did not begin until July 1996. A NW earthquake cluster (between 6 and eight km of the injector), accompanied this activity in addition to the near-well cluster. In response to a third Northern cluster of earthquakes (<13 km) developing along with near-well magnitude 3.5 and 4.3 events, the injection rate was reduced in 2000, (Phase III injection) including a biannual 20-day shutdown. This method was initially effective in reducing the earthquake frequency and magnitude.

In January 2002, (Phase IV injection) the injectate mix changed from 70% brine and 30% fresh Dolores River water to 100% brine. Figure J-1 shows a 3 to 3.5M earthquake occurring in the second distance cluster at about this time, followed by a greater than 3.5M nearby event around the end of 2003. Figure J-2 illustrates the injection rates with surface and bottomhole pressures, top, middle, and lower plots respectively. The lower plot shows an immediate increase in downhole pressure followed the conversion to all brine. The 3.5M higher magnitude event coincides with earlier 3.5M events when downhole pressure exceeded an apparent downhole pressure threshold. In 2004 a SE cluster of earthquakes (see Figure J-3) started, which increased in frequency in 2010.

More than 5,800 earthquake events have occurred since initial injection activities began in the area. There is minimal geosciences information along the northern edge of the valley. The Precambrian basement has not yet been modeled. The Precambrian earthquakes in the center of the valley are not well located. Currently a search for a second disposal well location is underway, (Block et al., 2012).

CITATIONS FOR PARADOX VALLEY (CLASS V) DISPOSAL WELL

Block, L., W. Yeck, V. King, S. Derouin, and C. Wood, 2012, Review of Geologic Investigations and Injection Well Site Selection, Paradox Valley Unit, Colorado; Technical Memorandum No. 86-68330-2012-27, Bureau of Reclamation, Denver, Colorado, 62 p., http://www.coloradoriversalinity.org/docs/CRB_TM_final_reduced.pdf

FIGURE J- 1: INJECTION-INDUCED SEISMICITY AND INJECTION RATES

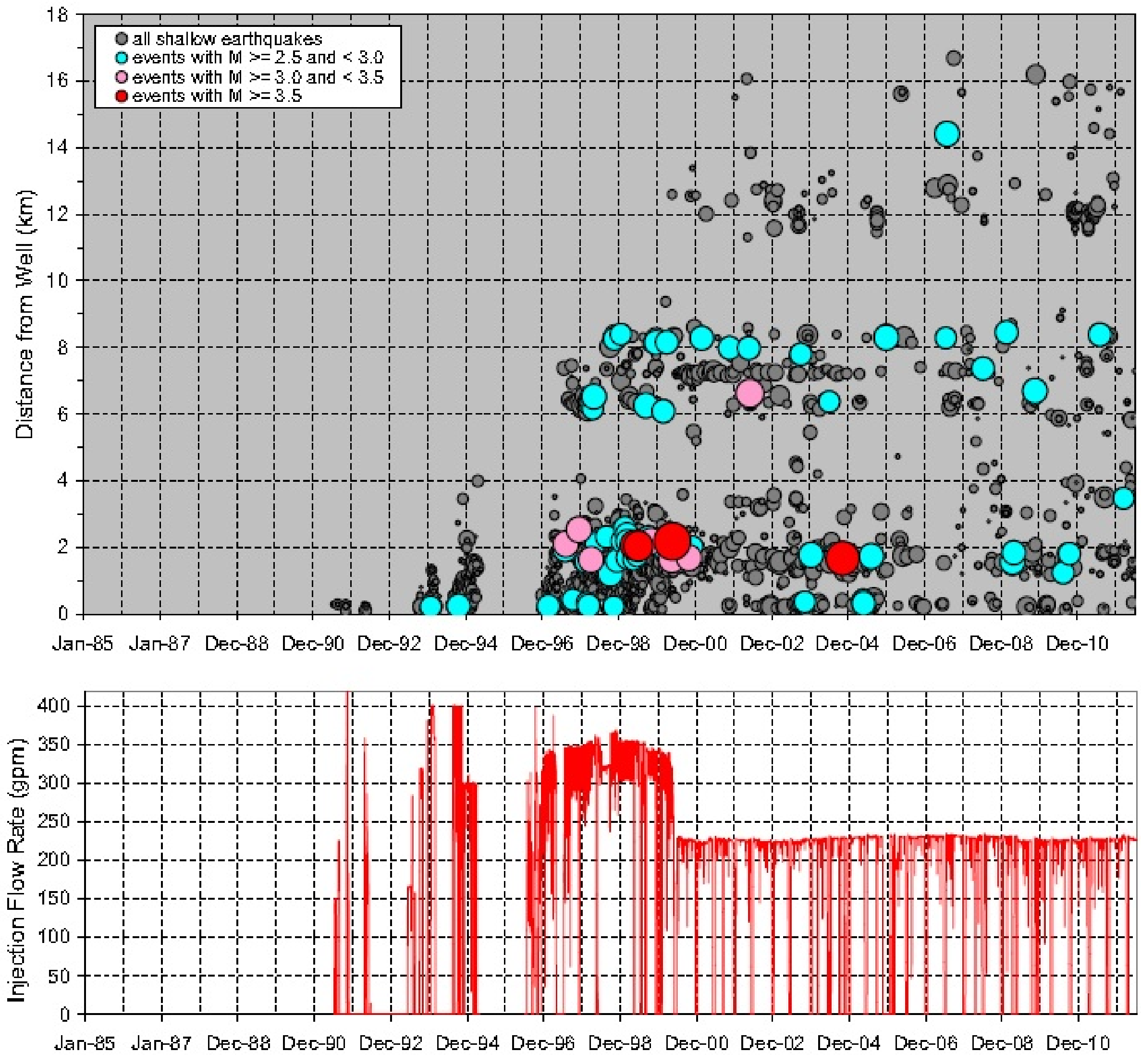

FIGURE J- 2: INJECTION RATES AND PRESSURES

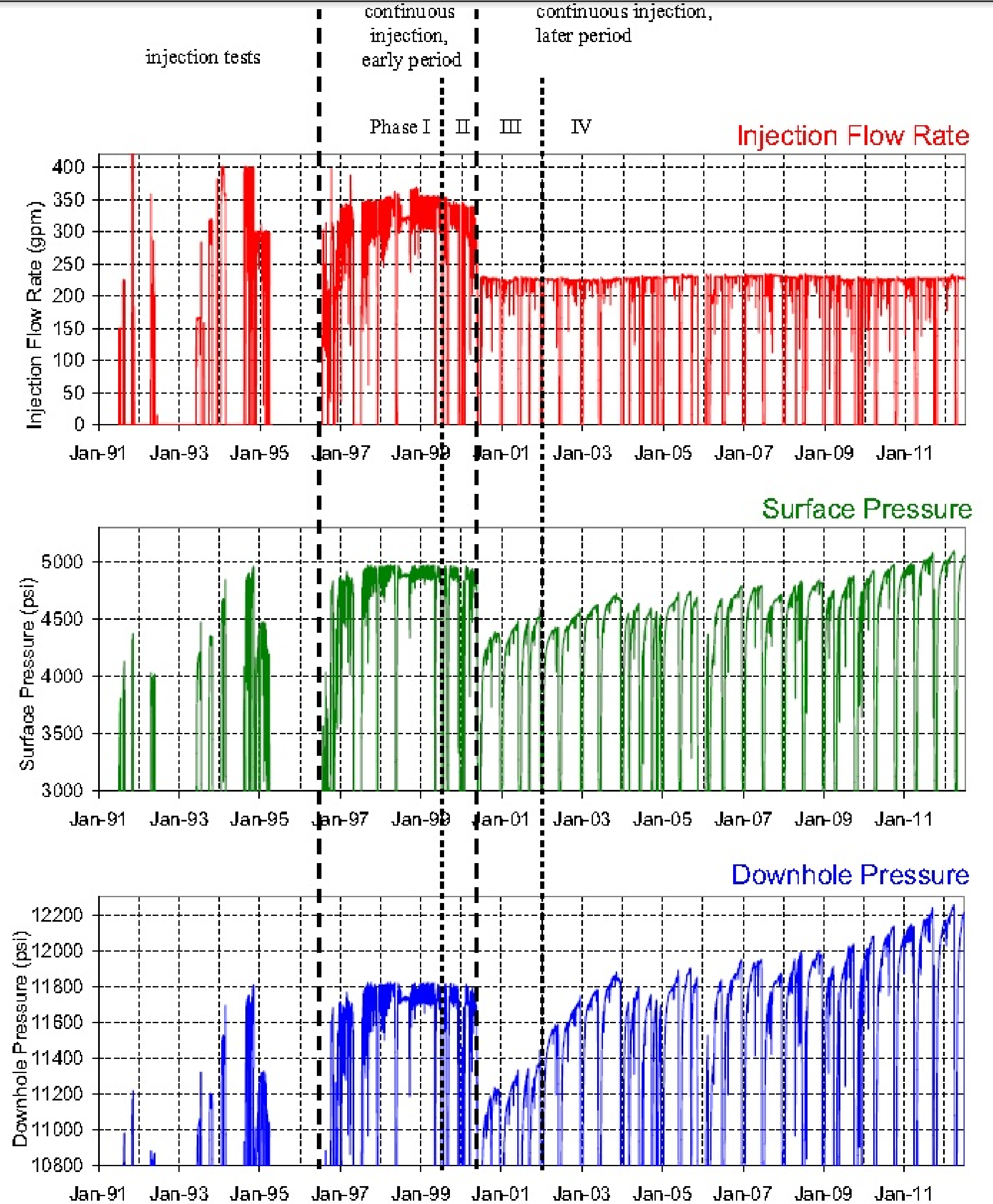

FIGURE J- 3: EARTHQUAKE CLUSTERS

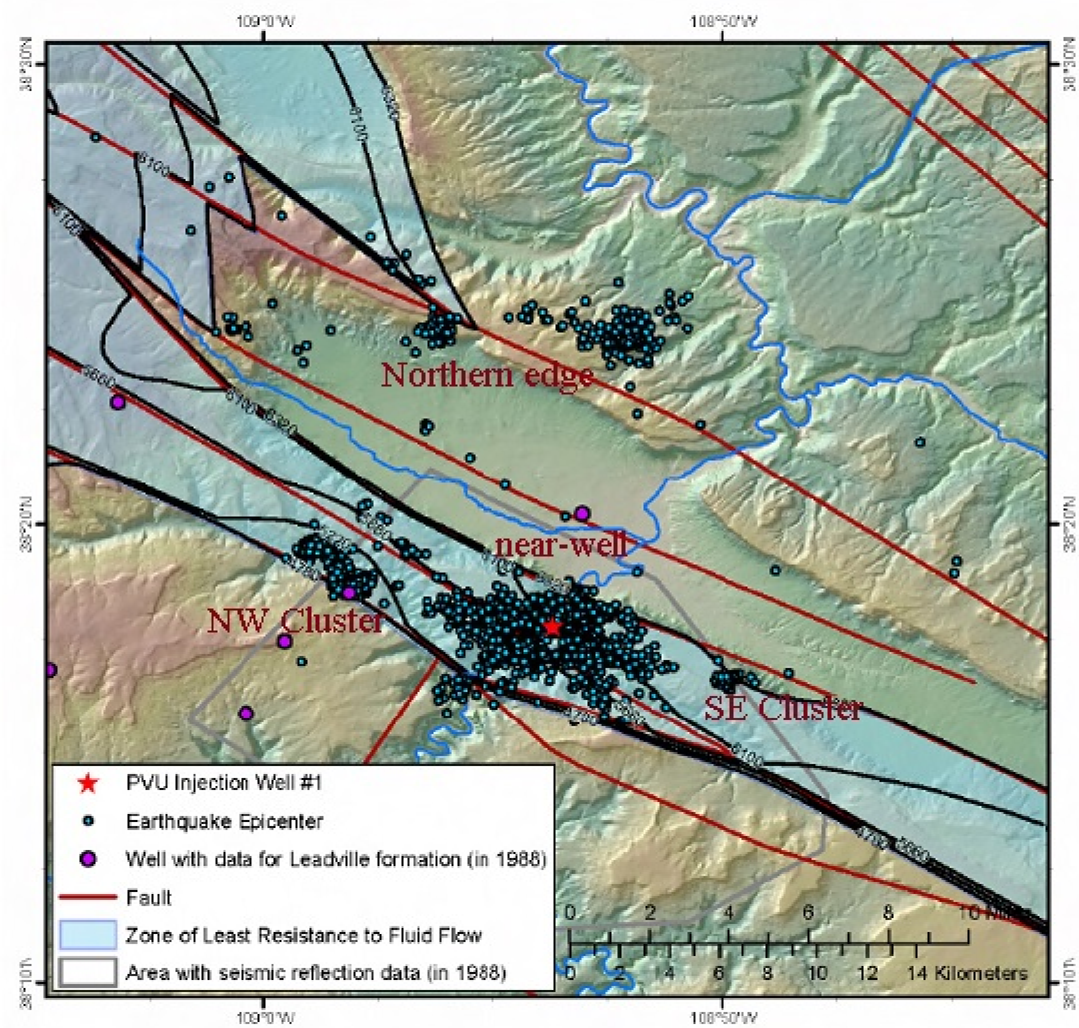

Figure 25: Contour map of hydrostatic pressure within the Leadville formation and predicted area of least resistance to fluid movement and pressure rise from injection into PVU Injection Well #1, from Bremkamp and Harr (1988) (drawing no. 2), and epicenters of shallow earthquakes interpreted to be induced by fluid injection into PVU Injection Well #1. (Fault traces were digitized from drawing no. 1, Bremkamp and Harr, 1988).

APPENDIX K: SUBJECT BIBLIOGRAPHY

Injection-induced seismicity is a rapidly expanding area of research. This list is not intended to serve as a complete resource list. Additionally, websites frequently shift links so that some may become inactive.

Disclaimer K-1
Helpful Links K-2
  Associations & Surveys: Professional Scientific and Engineering K-2
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DISCLAIMER

Inclusion of an article or website in this appendix does not represent EPA's agreement with the conclusion of the article.

Helpful Links

Associations & Surveys: Professional Scientific and Engineering

American Association of Petroleum Geologists, http://www.aapg.org/

Canadian Association of Petroleum Producers, http://www.capp.ca/aboutUs/mediaCentre/NewsReleases/Pages/Seismicitynaturalgasproducerstakestepstoensurecontinuedsafehydraulicfracturingoperations.aspx

Canadian Society of Exploration Geophysicists: Microseismic User Group (MUG), http://cseg.ca/technical/category/mug/

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APPENDIX L: DATABASE INFORMATION

CATALOGS OF EARTHQUAKE EVENTS

The largest U.S. database of earthquake events is maintained by the Advanced National Seismic System (ANSS). The National Earthquake Information Center (NEIC) maintains several other data catalogs. Both ANSS and NEIC programs are under the USGS. There is limited consistency between the various groups on coverage areas, detection thresholds, or magnitude determinations. Table L-2 provides a reference to the primary earthquake catalogs. State Geologic Agencies and universities may also collect and/or host earthquake information on their website. The catalogs generally include an indication of the event location reliability. The main ANSS composite catalog, hosted by the Northern California Earthquake Center at Berkeley, contains events from multiple sources and time periods, but strips duplicate listings.

As an example of catalog coverage, the following table shows the number of events recorded in the search area of the Central Arkansas Area Case Study (discussed in detail elsewhere in this report). Care must be taken to avoid duplication when using multiple sources of data. Not all matching events have the same calculated epicenter and depth. It is also noted that depth refinements to preliminary NEIC data, have been incorporated in the ANSS catalog, but not in the NEIC PDE catalog.

TABLE L-1: EARTHQUAKE CATALOG EVENTS FOR CENTRAL ARKANSAS CASE STUDY

Catalog	Common Events with ANSS	Unique Catalog Events	Total Events
ANSS: Central and Eastern US	-	1533	1533
NEIC: SRA[31]	0	0	0
National Center for Earthquake Engineering Research (NCEER)	15	1	16
NEIC: USHIS[32]	1	0	1
Center for Earthquake Research and Information (CERI)	1523	4	1527
NEIC: PDE & PDE-Q	267	12	279
Total unique AR events		1549	

[31] Eastern, Central and Mountain States of U.S. (1350-1986)

[32] Significant U.S. Earthquakes (1568-1989)

TABLE L-2: EARTHQUAKE CATALOGS

Source	Coverage (Years)	Area	Comments/Caveats
International Seismological Centre[33]	1904- present	The official world catalog	
ANSS Catalog[34][35] (hosted by NCEDC)	1898 - present	Composite across the USA	M1.0 and greater
ANSS Comprehensive Catalog (ComCat)	Combined from 2/2/2013	Composite of US contributing networks	Includes moment tensors, plus (see Appendix M, Task 1)
CERI Catalog AKA New Madrid Earthquake Catalog[36]	1974 - present	New Madrid Seismic Zone and surrounding regions	
NEIC (USGS) Catalog[37]	SRA: 1350-1986	Eastern, Central & Mountain States	Very few magnitudes given
	USHIS: 1568-1989	Significant US quakes	Felt or M4.5 and greater
	PDE: 1973- present	USA	Updated file from PDE-Q
	PDE-Q: 1973- present	USA (most recent)	Very preliminary locations
	Real Time: Last 7 days	USA	≥ M1.0; interactive map locations ; with accuracy range
	Alert: current	USA and World	E-mail notification available
NCEER Catalog[38]	1627 - 1985	Central and Eastern United States	Used in national hazard map creation
ANF/ANFR[39]	2009 - present	US Array Network	Contains many surface induced events
IRIS[40] SeismiQuery	1960 - present	US & world	USGS and other networks
Harvard CMT Catalog	1976 - present	Global	Tensor calculations for > M5
Northern California Earthquake Data Center (NCEDC)[41]	1910 - 2003 1967 - present	Northern and Central CA; some all of CA or Western USA	
Southern California Earthquake Data Center (SCEDC)[42]	1977 - present	Southern CA	

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[33] ISC: http://www.isc.ac.uk/iscbulletin/search/bulletin/interactive/

[34] Comcat: http://earthquake.usgs.gov/earthquakes/search/

[35] ANSS: http://quake.geo.berkeley.edu/cnss/

[36] CERI/New Madrid Catalog: http://www.ceri.memphis.edu/seismic/catalogs/cat_nm.html

[37] NEIC: http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

[38] NCEER: http://www.ceri.memphis.edu/seismic/catalogs/cat_nceer.html

[39] IRIS EarthScope Data: http://www.iris.edu/earthscope/usarray/

[40] IRIS: http://www.iris.edu/SeismiQuery/sq-events.htm & http://www.iris.edu/dms/wilber.htm

[41] NCEDC: http://www.ncedc.org/ncedc/catalog-search.html

[42] NCEDC: http://www.data.scec.org/

APPENDIX M: USGS COLLABORATION

Through an interagency agreement, EPA was able to employ the expertise of USGS staff for this project as outlined in the scope of work[43] below. The USGS prepared a report titled, *Evaluate Potential Risks of Seismic Events due to Injection-Well Activities.* The report included a guide on the USGS earthquake hazards and seismic activity maps aimed at non-geophysicists (UIC scientists and engineers). The report also provided USGS insight on the relationship between subsurface stress fields and the likelihood of induced seismicity.

The USGS Task 4 was to update the *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001*[44] publication, but the draft update was not finalized and therefore not included.

[43] Task 3 was dropped from the scope of work. The timeframe for Task 4 has been extended.

[44] Meremonte, M. E., J. C. Lahr, A. D. Frankel, J. W. Dewey, A. J. Crone, D. E. Overturf, D. L. Carver, and W.T. Bice, 2002, Investigation of an Earthquake Swarm near Trinidad, Colorado, August-October 2001: US Geological Survey Open-File Report 02-0073 [http://pubs.usgs.gov/of/2002/ofr-02-0073/ofr-02-0073.html], accessed December 5, 2011.

Scope of Work for USGS and EPA Project on Induced Seismic Activity for Class II Disposal Wells

Objective: Provide support data for EPA's UIC National Technical work group project on induced seismicity from Class II brine disposal well operations.

Background: Numerous publications exist that study the relationship between induced or triggered earthquakes and injection activity. The factors that might influence the occurrence of large damaging earthquakes near Class II disposal wells include (1) large-scale nearby fault(s), (2) high differential stresses at depth, and (3) changes in fluid pressure or stress due to fluid injection. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to enhance strategies for avoiding damaging seismicity events related to Class II disposal wells.

Scope of Work: Through available expertise, complete the following specific work tasks that support the UIC NTW induced seismicity project. USGS and/or procured data will be used and referenced in the UIC NTW final work product. The tasks will necessitate cooperation between EPA and USGS, including incorporating the expertise and experience from EPA UIC geologists and engineers and USGS staff.

Work Tasks

1. Prepare a practical guide on the USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers (non-geophysicists). The document should cover topics such as background information relevant to the two maps, confidence levels and sensitivity of the mapped data. For example:
    a. Describe the epicenter location and hypocentral depth with respect to accuracy of the data. This should include accuracy within both map and depth locations.
    b. Describe the relevance of the earthquake hazard maps for subsurface use.
2. Using technical expertise what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?
3. Incrementally evaluate commercial structure maps on the deepest available horizon for one of the following areas to determine if this type of data can be used as a screening tool. EPA will provide USGS with the structure maps. The evaluation may include, but is not limited to, correlating seismic events and available injection well locations with structural maps. During coordination between EPA and USGS, specific location information will be provided. The following are the generic areas of interest, though EPA may change the priorities.
    a. North Texas Ouachita Thrust front
    b. Arkansas Fayetteville Shale play
    c. West Virginia Braxton County
    d. Colorado Trinidad area
    e. Ashtabula Ohio area

    Depending on the results of the initial pilot study, additional analyses may be performed on more of these areas at a later date.

4. Review *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001* and submit a progress report and final report on updates to this study including identifiers that could have predicted the recent 5.3 earthquake.
5. Provide interim data, final report of conclusions and all work completed.

Milestones

Provide monthly updates

Timeframe

Work and accompanying reports for tasks 1-3 should be completed by December 16, 2011.

A progress report for task 4 should be completed by December 31, 2011, with work on task 4 continuing into 2012. The final report for task 4 should be completed no later than April 30, 2012.

Underground Injection Control Interagency Agreement
EPA IA DW-14-95809701-0

EVALUATE POTENTIAL RISKS OF SEISMIC EVENTS DUE TO INJECTION-WELL ACTIVITIES

A. McGarr, W. Ellsworth, J. Rubinstein, S. Hickman, E. Roeloffs, and D. Oppenheimer

United States Geological Survey

The Scope of Work for the USGS and EPA project on induced seismic activity for Class II disposal wells includes two tasks:

Task 1: Prepare a practical guide on USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers.

Task 2: Using technical expertise, what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?

The results of USGS work on these two tasks are described in this report.

TASK 1. USGS DATA PRODUCTS FOR EARTHQUAKE HAZARDS

EARTHQUAKE CATALOG—ANSS EARTHQUAKE CATALOG

http://www.quake.geo.berkeley.edu/anss/

This is the authoritative earthquake catalog for the United States. It contains the most current information from all of the participating regional networks and the U.S. National Network in the Advanced National Seismic System (ANSS). This catalog can be searched for a given geometric area, over a given time and a given magnitude range. Quarry blasts and earthquakes can also be selected/deselected. Earthquake time, location, magnitude, magnitude type, and parameters relating to how the earthquake location and magnitude were computed (number of stations, travel time error, and source network) are contained in the output of this search. This catalog contains all earthquakes that were detected by the local and regional networks within the United States, including both natural and induced earthquakes—if quarry blasts are not turned off, they will be included as well. This catalog reflects historical seismicity, which may be used as a guide to where we expect future seismicity, but there is always a possibility that earthquakes will occur where previous earthquakes have not. The catalog can be searched for earthquake-specific areas using the search tools at http://www.ncedc.org/anss/catalog-search.html. This catalog is updated in near-real time.

CAVEATS

- This earthquake catalog is not uniform. In some regions, the catalog begins much earlier than in others, because seismometers were deployed earlier.
- Detection capabilities are not uniform. As a seismic network becomes denser with time, it is able to record smaller earthquakes. This also means that regions with dense networks will see smaller earthquakes than regions with more sparse seismic networks.
- Earthquake locations and magnitudes are of varying quality. As the number of instruments close to the earthquakes increases, location and magnitude estimates become more accurate. This means that location and magnitude quality vary from region to region. Location and magnitude quality also vary over time within a region as the number of instruments increase.
- Earthquake magnitudes are computed a number of different ways depending on the earthquake size and number of nearby stations. These magnitudes are often similar, but not always the same.
- ANSS also maintains a webpage with caveats about their catalog: http://www.ncedc.org/anss/anss-caveats.html

An example of how increasing station density improves earthquake detection is found at the end of this document in the **USArray** section.

Earthquake Databases

http://earthquake.usgs.gov/earthquakes/search/

A variety of additional earthquake catalogs covering the U.S. are available online and can be used to search for both recent and historical earthquakes. An introduction to earthquake databases and catalog sources is available at http://earthquake.usgs.gov/earthquakes/map/doc_aboutdata.php. Special attention should be paid to the explanation of differences between the various catalogs.

Online search tools that can be customized to select earthquakes in different geographic regions and over different time and magnitude ranges are available at http://earthquake.usgs.gov/earthquakes/search/.

Caveats

- These earthquake catalogs are not uniform in either space or time. In some regions, the catalog begins much earlier than in others because seismometers were deployed earlier.
- Earthquake smaller than magnitude 1 are not included in these catalogs.
- In most areas, the catalog is complete since 1973 for earthquakes of magnitude 3 or larger.
- The accuracy of the earthquake locations varies considerably. In most areas outside of California, Nevada, Oregon, Washington, and Utah, earthquake epicenters may be in error by as much as 6 miles, on average. Exceptions apply where there are local networks, such as in the New Madrid Seismic Zone.

National Seismic Hazard Map

http://earthquake.usgs.gov/hazards/products/

The National Seismic Hazard Map delineates the probability of strong shaking across the United States from natural earthquakes. These maps do not assess the risk of shaking owing to induced earthquakes. These are probabilistic maps and do not refer to specific earthquakes. Instead, the maps provide information on the strength of earthquake shaking that is unlikely to be exceeded over a given period of time.

A guide to the hazard maps can be found at: http://earthquake.usgs.gov/hazards/about/basics.php

FREQUENTLY ASKED QUESTIONS ABOUT HAZARD MAPS:

http://www.usgs.gov/faq/?q=taxonomy/term/9843

The maps are derived from knowledge of active faults, past earthquakes, and information on how seismic waves travel through the Earth. As indicated above, our knowledge of past earthquakes and faults is incomplete, which means that strong shaking due to earthquakes may still occur in regions with low probabilities. It is less likely to occur in these regions, but it still can happen.

The ground motions reported in these maps are estimated for the surface. Ground motions decrease with depth below the surface. Shaking is strongest in the area immediately surrounding an earthquake.

EARTHQUAKE PROBABILITY CALCULATOR
https://geohazards.usgs.gov/eqprob/2009/index.php

This tool allows you to compute the probability of an earthquake occurring within a specific radius of a specified location. The probabilities are derived from the National Seismic Hazard Map described above. The tool produces two products:

1. A map surrounding the location specified, with color contours giving the probabilities of an earthquake larger than or equal to the magnitude specified by the user (minimum magnitude 5.0)

2. An optional text report describing the annual rates of earthquakes of different sizes.

It is important to note that, where the probability on the maps is shown to be 0.00, this does not mean that there will not be an earthquake there. When a region falls into the 0.00 category, it means that the probability of an earthquake is less than 1% during the time period specified.

By selecting the Text Report, it is possible to change the radius from the default value of 50 km. The Text Report gives information for earthquakes that fall within magnitude bins (for example, between 7.35 and 7.45): the annual rate at which an earthquake in that bin is expected to occur, the annual rate at which an earthquake within that bin or larger will occur, and probabilities of an event within that magnitude bin and within that bin or larger occurring in the time period specified by the user. The last two quantities can be inverted to determine the average number of years between earthquakes.

Limitations of the Probability Mapping Calculation

The probability is only calculated for events of M5.0 and larger. It is advisable to consider the rates of smaller earthquakes that may be the first evidence that an area is sensitive to injection-induced earthquakes. Such a calculation can be done using catalog searches but is not currently available as an online tool.

There are no confidence intervals on the probabilities. The values given are annual averages and earthquake rates naturally fluctuate in time. Therefore, as presently written, this application cannot help decide whether the seismicity in the last year, for example, is within the normal range of variation for this site.

The Quaternary Fault and Fold Database of the United States

http://earthquake.usgs.gov/hazards/qfaults/

This database contains information on known faults and associated folds in the United States that are believed to have been sources of M>6 earthquakes during the Quaternary (the past 1,600,000 years). The website includes both static and interactive maps of these geologic structures, with links to detailed references.

This database does not include faults that show no evidence of Quaternary movement. Faults that have had M>6 earthquakes but that do not extend to the surface and/or that have not been recognized at the surface may not be in the database. Only faults believed capable of hosting M>6 earthquakes are included, but earthquakes as small as M5.0 are potentially damaging, especially in the Central and Eastern U.S.

These considerations mean that, if the site is near a fault in the Quaternary Fault and Fold Database, then the necessary geologic structure exists to host an earthquake of M>6. However, if no fault in the database is near the site, it does not necessarily mean that no such fault is present.

New faults are continually being discovered, often as they reveal themselves by earthquake activity. Several years or more may pass between initial recognition that a fault is present, documentation in peer-reviewed literature that the fault is aerially extensive enough to produce a significant earthquake, and incorporation of the fault into the database. Changes to the Quaternary fault database are incorporated into the updates to the National Seismic Hazard Maps that occur every 6 years.

USArray—An Example of Improved Detection Capabilities From Increased Station Density

http://www.usarray.org/

As of this writing, a large seismic array of 400 instruments is moving across the conterminous U.S. This array, called USArray, is operated by the Incorporated Research Institutions for Seismology (IRIS) and is funded by the National Science Foundation as part of the EarthScope Program. During the 18 months that it takes for the USArray to pass by any particular location, the density of seismic stations is temporarily increased to one station approximately every 70 km, placing a seismometer within about 35 km of every point within the footprint of the array. This higher station density makes it possible to detect and locate earthquakes with M≥2 in most areas and provides data that can be used to reduce the location uncertainty.

When USArray was passing through eastern Colorado and New Mexico from late 2008 to early 2010, several hundred events were detected that were not initially identified by the USGS. Many of these earthquakes lie within or near the coal-bed methane field west of Trinidad, CO.

The Oklahoma Geological Survey has recently used data from USArray to study earthquakes in Garvin County, Oklahoma, and their possible association with shale gas stimulation activities in the Eola Field (Holland, 2011). This report illustrates the potential of improved seismic monitoring for answering basic questions about the association between earthquakes and fluid injection activities. It also draws attention to the challenges of drawing firm conclusions when the historical context of the activity is poorly known and poorly resolved. The same general conclusions can be drawn from the study of earthquakes near Dallas-Fort Worth Airport (Frohlich, C., and others, 2011).

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The online tools described here are products of the U.S. Geological Survey, but no warranty, expressed or implied, can be provided for the accuracy or completeness of the data contained therein. These tools were not developed for the specific purpose of assessing the potential for induced seismicity and are not substitutes for the technical subject-matter knowledge.

TASK 2. DEEP STRESS FIELDS AND EARTHQUAKES INDUCED BY FLUID INJECTION

EXECUTIVE SUMMARY

The purpose here is to explain what we know about deep stress fields and how this might influence the likelihood of earthquakes induced by injection well activities. The available evidence indicates that whether the tectonic setting is active (for example, near the San Andreas Fault in California) or inactive (for example, central or eastern United States), activities that entail injection of fluid at depth have some potential to induce earthquakes. This does not imply, however, that all injection-well activities induce earthquakes or that all earthquakes induced by injection activities are large enough to be of concern. Indeed, most injection wells do not appear to cause earthquakes of any consequence. The differences between the small percentage of wells that induce noticeable earthquakes and those that cause negligible seismicity are poorly understood. Thus, it is necessary to measure the response of the rock mass to injection to estimate the likelihood that a particular injection well will contribute to the local seismicity. An effective way to do this is seismic monitoring, using local networks that are capable of recording small-magnitude events. Furthermore, to evaluate the likelihood of inducing damaging earthquakes on large-scale, pre-existing faults, information is also needed on the geometry of potentially active faults in relation to the orientations and magnitudes of stresses at depth. This information can be obtained from network observations of ongoing micro-seismicity (if present), borehole stress measurements, and geophysical and geological investigations of fault geometry and fault-slip history.

Even in the absence of detailed information on stresses and fault geometry for a particular site, some useful generalizations can be made on the deep stress field. These generalizations are based on borehole stress measurements made around the world at depths of as much as 8 km, in conjunction with earthquake, geologic, and laboratory studies:

1. The stress field can be described in terms of three principal stresses that are oriented perpendicular to one another. To a good approximation, one of these principal stresses is vertical and the other two are horizontal.
2. The vertical principal stress is readily estimated because, at a given depth, it is due to the weight of the overlying rock mass.
3. The state of stress falls into three categories, depending on the relative magnitudes of the three principal stress regimes: normal, strike-slip, and reverse faulting, for which the vertical principal stress is the maximum, intermediate, or minimum principal stress, respectively. Studies of earthquake focal mechanisms, borehole stress indicators, and active faults have revealed the orientation of the principal crustal stresses at a broad, regional scale over most of the United States.

4. Stress measurements made in boreholes indicate that the horizontal principal stresses generally increase linearly with depth, similarly to the vertical principal stress, but sometimes with significant local perturbations.
5. For a given state of stress and depth, borehole stress measurements are generally consistent with laboratory friction experiments, which suggest that stresses are limited by the strength of the crust.
6. Observations that earthquakes, natural or man-made, may be induced by relatively small stress changes support the idea that the crust is commonly close to a state of failure.

INTRODUCTION

Of the approximately 144,000 Class II injection wells in the United States that inject large quantities of brine into the crust, only a small fraction of these wells induce earthquakes that are large enough to be of any consequence. In spite of their small numbers, these few cases raise concerns about the potential for significant damage resulting from larger induced earthquakes. Accordingly, it would be useful to have some guidelines concerning the likelihood that a particular well will cause significant earthquakes. The intent of Task 2 is to investigate the possibility that the deep stress field can be estimated from surface data. If so, then the next question is whether this stress information can be used to estimate the likelihood of substantial induced seismicity.

STATE OF STRESS

From information already available, we know the deep stress field to some extent. The stress field can be described as three principal stress components orthogonal to one another, with one component oriented vertically, perpendicular to the earth's surface, and the other two oriented horizontally. Factors including topography and geologic structure can alter these principal stress directions somewhat, but not on a large scale. The vertical principal stress at a given depth is, to a good approximation, the product of depth, gravity, and the average density between the surface and the point of interest. Because the approximate density structure of the crust is known nearly everywhere, the vertical principal stress can be readily estimated. Estimating the horizontal principal stress magnitudes requires more information, including knowledge of the local tectonic stress regime.

Surface data from seismograph stations or from observations of active faults and other stress indicators can reveal the tectonic stress regime, at least on a regional scale. This stress regime falls into three categories: normal faulting (vertical principal stress is maximum), strike-slip faulting (vertical principal stress is intermediate), or reverse faulting (vertical principal stress is minimum) (fig. 1). Earthquake focal mechanisms determined from ground motion recorded at seismograph stations indicate the stress regime wherever earthquakes occur, and, if properly analyzed, can provide valuable information on stress orientations (for example, Hardebeck and Michael, 2006). Geologic investigations of active faults, as well as geodetic measurements of crustal strain accumulation, provide similar information. Accordingly, from these sorts of investigations, which can be made from the surface, we know the regional tectonic stress

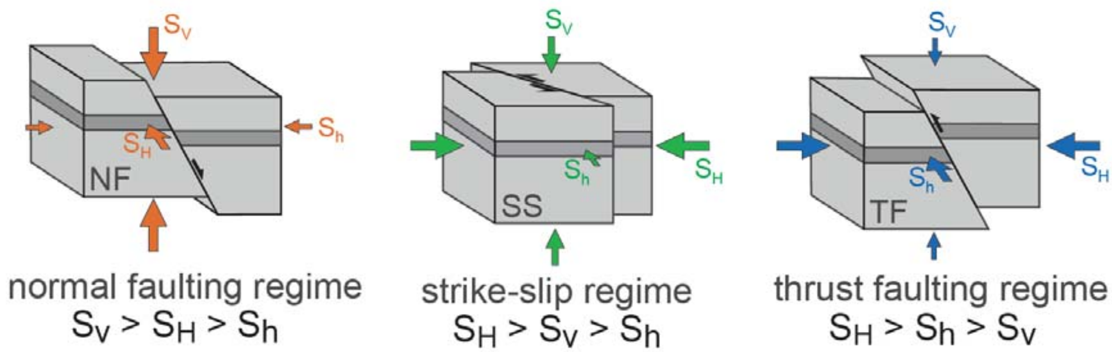

FIGURE 1. SCHEMATIC DIAGRAM SHOWING TECTONIC STRESS REGIMES AND SENSE OF FAULT OFFSET IN RELATION TO THE VERTICAL PRINCIPAL STRESS (S_V), THE MAXIMUM HORIZONTAL PRINCIPAL STRESS (S_H), AND THE MINIMUM HORIZONTAL PRINCIPAL STRESS (S_H) (FROM WORLD STRESS MAP, CITED BELOW).

regime nearly everywhere in the United States and for much of the world (see World Stress Map, cited below). However, these observations only tell us the orientations and relative magnitudes of the horizontal principal stresses, and, hence, indicate whether we are in a normal, strike-slip, or reverse faulting stress regime. They do not tell us the absolute magnitudes of the horizontal stresses, which, together with information on stress orientations, determine proximity to failure on optimally oriented pre-existing faults.

MAGNITUDES OF HORIZONTAL STRESSES

The question of the magnitudes of the horizontal stresses is more challenging. Most of our information about horizontal stress magnitudes comes from deep boreholes, using the hydraulic fracturing technique and observations of borehole failure (breakouts and tensile cracks; see Zoback and others, 2003). Additional stress data come from stress relaxation measurements made in deep mines. The deepest measurements were made in the KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) scientific borehole, eastern Bavaria, Germany, and extend to a depth of about 8 km (Brudy and others, 1997). Stress measurements worldwide indicate that the two horizontal principal stresses increase approximately linearly with depth, as is the case for the vertical stress. Moreover, in-situ stress magnitudes have been compared to laboratory experimental friction results (for example, Brace and Kohlstedt, 1980; Townend and Zoback, 2000) to find that the crust appears to be close to a failure state nearly everywhere. This experimental observation is consistent with the idea that the Earth's crust is extensively faulted and can deform by frictional sliding. Moreover, the crust is continually undergoing strain accumulation, at quite a slow rate in tectonically stable regions and at higher rates in tectonically active regions. The result of this long-term strain accumulation is that the crust is always near a failure state and releases strain whenever the yield stress is reached. In a seismogenic region of the crust (much of the uppermost ~15 km), this strain release appears as an earthquake sequence (mainshock and aftershocks). Other evidence in support of the hypothesis that the crust is near a state of failure nearly everywhere includes the observation that earthquakes can be triggered by remarkably small stress changes imposed on faults (for example, Reasenberg and Simpson, 1992).

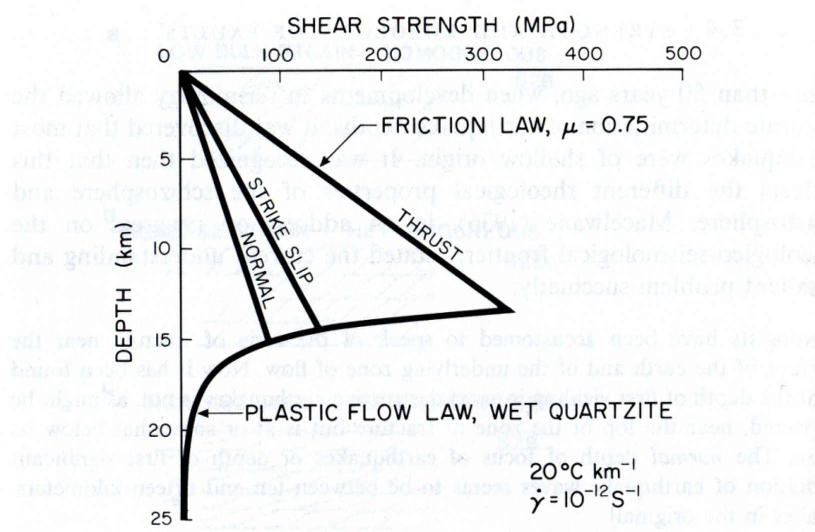

FIGURE 2. SHEAR STRENGTH OF THE CRUST BASED ON LABORATORY FRICTION EXPERIMENTS FOR THE UPPER CRUST (UPPER 14 TO 15 KM) AND EXPERIMENTS AT HIGH TEMPERATURES AND PRESSURES FOR THE LOWER CRUST WHERE DEFORMATION IS DUCTILE. THE STRENGTH FOR STRIKE-SLIP FAULTING CAN BE ANYWHERE BETWEEN THE REVERSE- AND NORMAL-FAULTING REGIMES. IN THIS FIGURE, SHEAR STRENGTH IS DEFINED AS THE DIFFERENCE BETWEEN THE MAXIMUM AND MINIMUM PRINCIPAL STRESSES (FROM SCHOLZ, 2002).

The laboratory friction results shown in figure 2 provide some information about the horizontal stress magnitudes. The line for a normal-faulting regime (labeled "normal") indicates the difference between the vertical principal stress and the minimum horizontal principal stress. For a reverse-faulting regime, the line shows the difference between the maximum horizontal principal stress and the vertical principal stress. Because the vertical stress can be readily estimated for any depth, as noted before, it is easy, from the information in the figure, to estimate the minimum principal stress for the normal-faulting regime and the maximum principal stress for the reverse-faulting regime. For a strike-slip regime, neither horizontal principal stress can be inferred because the line labeled "strike slip" can fall anywhere between those for normal and reverse regimes. Although generalizations can be drawn about proximity of the crust to failure from this type of analysis, it is important to note that for a particular fault to be activated in response to fluid injection requires that it be well oriented for frictional failure in the local tectonic stress field.

In brief summary, we know that the vertical principal stress can be calculated for any depth, and we also know that laboratory friction experiments (fig. 1) are reasonably consistent with in-situ stress measurements in deep boreholes. These deep borehole measurements, in concert with the observation that earthquakes can be triggered at low applied stresses, indicates that the crust is near a failure state nearly everywhere. Taken together, this information can be used to estimate, at least approximately, the magnitudes of the maximum and minimum principal stresses at depth that are valid for most rock types for normal- and reverse-faulting regimes; for strike-slip regimes, the maximum and minimum principal stresses fall somewhere in the range between the normal and reverse results. If direct information on stress orientations is lacking for a particular area, then the orientations of the horizontal principal stresses can be estimated by comparison with nearby data that might be available through the World Stress Map Project (http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction_frame.html).

CONCLUSIONS

Because the state of stress in much of the Earth's crust appears to be close to failure, the safest assumption is that any amount of fluid injection could produce some earthquakes. Knowing that it may be possible to induce some earthquakes, however, is not enough to estimate earthquake hazard. It is also important to be able to estimate the maximum likely earthquake that might be induced by a particular injection operation and measure the seismic response of the rock mass to injection. That is, one needs to be able to estimate the distribution of earthquake magnitudes, including the maximum magnitude, likely to result from a given injection activity. To accomplish this goal, it is first recommended to determine the in-situ stress field in relation to the orientation and extent of potentially active faults (fig. 1). Of particular interest would belarge faults capable of producing damaging earthquakes. Then, in order to monitor the injection disposal operation, a local seismic network should be installed before commencement of injection that is capable of recording and locating earthquakes over a wide magnitude range. Monitoring induced earthquakes in this way will allow comparison with the injection-time history, as well as with background seismicity. Monitoring seismicity will also help define the subsurface geometry of large-scale active faults that comprise the greatest hazard. With information provided by a seismic network, the contribution of the induced earthquakes to the ambient seismic hazard can be assessed.

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