# A White Paper Summarizing a Special Session on Induced Seismicity

February 2013

This special technology transfer session for seismologists, regulators, and other stakeholders entitled *"Assessing & Managing Risk of Induced Seismicity by Injection"* was a part of the GWREF Spotlight Series.

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The Ground Water Research & Education Foundation (GWREF) is a not-for-profit 501(c) 3 corporation dedicated to promoting research and education related to the protection of ground water.

Our mission is to promote and conduct research, education, and outreach, in the areas of development and application of technical systems, pollution prevention efforts related to ground water protection, underground injection technology, and watershed conservation and protection.

The foundation is comprised of a board made up of volunteers from government, institutes of higher education, and the public appointed through the Ground Water Protection Council.

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# White Paper Summarizing a Special Session on Induced Seismicity[1]

## Chapter 1 - Introduction

The Ground Water Protection Council (GWPC), held its 2013 Underground Injection Control Conference in Sarasota, Florida on January 22-24, 2013. On January 23, the conference included a special session entitled "Assessing & Managing Risk of Induced Seismicity by Underground Injection". The session was presented by the Ground Water Research & Education Foundation (GWREF), a not-for-profit corporation dedicated to promoting research and education related to the protection of ground water. The Foundation is associated with the GWPC.

### 1.1 The Special Session

The topic of induced seismicity, or earthquakes caused by human activities, has been raised increasingly by the media over the past several years. To help disseminate factual information on the subject, the GWPC and GWREF decided to include a session on induced seismicity in the January underground injection control conference. The session included 12 presentations separated into three groups. Lori Wrotenbery of the Oklahoma Corporation Commission chaired the first group of presentations with a theme of "Studies: Researchers Presenting Findings and Research Strategies". This was followed by a second group of presentations, chaired by Ed Steele of Swift Worldwide Resources, with a theme of "Industry: State of the Art Technology Used to Limit Risk". Wrotenbery presided over a third group of presentations on the theme of "Regulatory".

### 1.2 The White Paper

This white paper summarizes the information that was discussed during the special session. It is not intended to be a complete and detailed report on the subject, but is generally limited to the information actually presented during the twelve presentations and any associated discussion during the question and answer periods. Note that a detailed technical report on induced seismicity was released by the National Research Council of the National Academy of Sciences (NAS) in 2012. That report contains much broader and in-depth coverage of induced seismicity and was written collaboratively by experts in the field.

[1] The white paper was prepared for GWPC by John Veil of Veil Environmental, LLC.

Since the NAS report was discussed by several speakers, some information relating to cases briefly mentioned by the speakers was expanded by pulling more detailed information from the Council's report. Other information was drawn from the NAS report to provide better documentation for topics discussed by individual speakers. Chapter 3 of this white paper describes the NAS report and its main points.

Some of the material is highly technical and esoteric. That information is very useful to specialists and practitioners. But in order to explain the importance of induced seismicity and the issues surrounding it to a wider audience, this white paper is written in a style and at a level for a broader non-technical audience.

Rather than summarizing each presentation in the order in which speakers actually made their presentations, the white paper pulls material from different presentations into a more thematic narrative that covers the key topics in a coordinated way.

Most of the speakers in the session agreed to let the GWPC post copies of their presentations on the GWPC website. Where those presentations are available, they are directly linked to references in this white paper. For those other presentations whose authors did not authorize the GWPC to post the slides, relevant information is summarized, and reference is made to their names – readers can contact those authors directly for additional information.

The white paper also includes Appendix A, which shows the agenda for the special session.

# Chapter 2 –Seismicity

This chapter provides an overview of seismicity by drawing from different presentations.

### 2.1 What Is Seismicity?

Although several speakers offered their own definitions for induced seismicity, it makes sense to start with the description of seismicity used in the Summary section of the NAS report.

> *"Seismicity induced by human activity related to energy technologies is caused by change in pore pressure and/or change in stress taking place in the presence of (1) faults with specific properties and orientations, and (2) a critical state of stress in the rocks. In general, existing faults and fractures are stable (or are not sliding) under the natural horizontal and vertical stresses acting on subsurface rocks. However, the crustal stress in any given area is perpetually in a state in which any stress change, for example through a change in subsurface pore pressure due to injecting or extracting fluid from a well, may change the stress acting on a nearby fault. This change in stress may result in slip or movement along that fault creating a seismic event. Abrupt or nearly instantaneous slip along a fault releases energy in the form of energy waves ("seismic waves") that travel through the Earth and can be recorded and used to infer characteristics of energy release on the fault."*

That report further states: *"Earthquakes attributable to human activities are called 'induced seismic events' or 'induced earthquakes'*." This second quote includes two relevant points: a) "induced" means attributable to human activities, and b) the terms "seismic events" and "earthquakes" are comparable.

Jeff Bull, an oil and gas industry subject matter expert on induced seismicity, made a presentation on various aspects of induced seismicity. The presentation started with some basic introduction to seismicity – it is useful to include pieces of that introduction here.

Many earthquakes occur every day from natural causes. Most are far too small to be felt by humans at the surface. But seismic instruments can detect and document many of the small events. These frequent small earthquakes do not cause damage to man-made structures.

#### 2.1.1 Magnitude and Intensity of Seismic Events

Seismic events occur with varying degrees of intensity; there are many more small events than larger ones. If an earthquake is strong enough, the energy released during the event may reach the earth surface and cause noticeable shaking. Damage to structures, if any, depends on the

amount of energy reaching the surface, the characteristics of the soil, and the structural design and physical condition of the local structures.

The scientific community has developed various scales to characterize the strength of individual earthquakes. The most familiar scale to the public for characterizing the magnitude of earthquakes is the Richter scale, developed in the 1930s. A related scale, developed in the 1970s, that also measures the magnitude of earthquakes is called the Moment Magnitude scale. It is commonly used now by the scientific community, and was used throughout the NAS report. Both scales assign numbers to events of different sizes. The numbers run on a logarithmic scale (i.e., a 4.0 earthquake is ten times larger than a 3.0 earthquake) and represent the amplitude (height) of the seismic waves measured on a seismograph. Bull notes that although the increase in wave amplitude is ten times higher, the amount of energy released may be about 30 times higher.

The Richter scale has no theoretical upper or lower limits. The magnitude of recorded natural events typically ranges from -3 (the lower limit of microseismic sensor sensitivity) to 9+ (the most severe earthquake ever recorded).

Another scale that measures the intensity of earthquakes is called the Modified Mercalli Index (MMI). The MMI uses the perceived effects of a seismic event on the people and structures at the surface to determine its intensity at any given location, but does not provide a single number for any earthquake. The MMI includes 12 levels of seismic event severity, ranging from imperceptible to devastating. The numeric values of the magnitude scales (Richter and Moment Magnitude) as well as the MMI increase with the strength of an event, but do not match up in an exact linear manner. For measuring the impact of an earthquake on people and structures, the MMI level is more useful in describing actual local effects and has been used by the U.S. Geological Survey (USGS) in the development of educational materials for the general public.

The MMI value depends upon many factors including:

- Depth of the seismic event,
- Distance from the seismic event epicenter,
- Geomechanical characteristics, and
- Terrain.

Population density can contribute to reported MMI values because of the likelihood of more reports of shaking and damage when a higher population area experiences an earthquake.

Figure 1 is taken from Bull's presentation – Bull notes on his slide that the table was created by Wikipedia using USGS information. The figure shows the relationship between the Richter

scale and the MMI, and describes the types of surface effects that represent events of different magnitude. It also gives an indication of how many earthquakes occur each year within the different MMI ranges.

**Figure 1 – Comparison of Richter Magnitude Scale and MMI Values**

| Richter Magnitude | Description | MMI | Earthquake effect observations | World-wide occurrence |
|---|---|---|---|---|
| < 2.0 | Micro | | Micro earthquakes not felt by people and detected by sensitive instruments only. | Continual >8,000 per day |
| 2.0 – 2.9 | Minor | 1 | Imperceptible: Not felt except by a very few people under exceptionally favorable circumstances. | 1,300,000 per year (est.) |
| 3.0 – 3.9 | Minor | 2 | Scarcely felt: Felt by only a few people at rest in houses or on upper floors buildings. | 130,000 per year (est.) |
| | | 3 | Weak: Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognized as an earthquake. | |
| 4.0 – 4.9 | Light | 4 | Largely observed: Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic. Walls may creak; doors, windows, glassware and crockery rattle. | 13,000 per year (est.) |
| | | 5 | Strong: Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut. | |
| 5.0 – 5.9 | Moderate | 6 | Slightly damaging: Felt by all. People and animals alarmed. Many run outside. Walking steadily is difficult. Objects fall from shelves. Pictures fall from walls. Furniture may move on smooth floors. Glassware and crockery break. Slight non-structural damage to buildings may occur. | 1,319 per year |
| | | 7 | Damaging: General alarm. Difficulty experienced in standing. Furniture and appliances shift. Substantial damage to fragile or unsecured objects. A few weak buildings damaged. | |
| 6.0 – 6.9 | Strong | 8 | Heavily damaging: Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed. | 134 per year |
| 7.0 – 7.9 | Major | 9 | Destructive: Some buildings are damages and many weak buildings are destroyed. | 15 per year |
| 8.0 – 8.9 | Great | 10 | Very destructive: Many buildings are damaged and most weak buildings are destroyed. | 1 per year |
| | | 11 | Devastating: Most buildings are damaged and many buildings are destroyed. | |
| 9.0 – 9.9 | | 12 | Completely devastating: All buildings are damaged and most buildings are destroyed. | 1 per 10 years (est.) |
| 10.0+ | Massive | >12 | Never recorded, widespread devastation across very large areas. | Unknown |

Source: Presentation by Jeff Bull

### 2.1.2 Location of Seismic Events

Two related terms describe the location at which an earthquake is triggered. The "epicenter" is the location at the surface above the slip event. The "hypocenter" is the event's actual location in the subsurface.

## 2.2 What Is Induced Seismicity?

Consistent with the NAS report text shown in section 2.1, induced seismicity was defined by several of the speakers as seismic events that are caused by human activities (as opposed to natural geological events). Induced seismic activity has been attributed to a range of human activities including:

- Impoundment of large reservoirs behind dams,
- Controlled explosions related to construction,
- Mine cavity collapse,

- Underground nuclear tests, and
- Energy technologies that involve injection or withdrawal of fluids from the subsurface.

In recent years, many claims have been made that injection related to various forms of energy production have led to increased rates of earthquakes that can be felt by the public. Therefore, the special session focused on the fourth of these categories. Examples of energy technologies include the following, which are discussed in more detail in the next chapter:

- Enhanced geothermal energy,
- Hydraulic fracturing,
- Long-term injection and production associated with enhanced oil recovery (EOR) programs,
- Injection wells used for long-term disposal of produced water and other fluids, and
- Carbon capture and sequestration (CCS) programs.

**2.3 What Causes Induced Seismicity?**

Many of the speakers emphasized the point that induced seismicity is not caused by the injected fluids lubricating faults. Rather, the induced seismicity is triggered by the increased pore pressure in the rock that effectively reduces the natural friction on a fault. Water is an incompressible fluid such that pressure applied at a wellhead is transmitted to the bottom of the well and out into the formation. This allows the pressure to move over extended distances where it can cause already susceptible faults to slip. The overall physics involved in these processes is very complex; more research is needed to develop a better understanding.

Austin Holland of the Oklahoma Geological Survey (OKGS) reported that most of the Earth's upper crust is near failure. The increased pore pressure from fluid injection effectively reduces friction on faults.

In cases where injection continues over long periods of time, the injected fluids will cause a cumulative rise in formation pressure. An increased formation pressure by itself does not necessarily induce earthquakes, but if faults that are already near failure or susceptible to slippage are located near to the site of increased pressure, an earthquake may be triggered. In order for induced seismicity to take place there needs to be a critically stressed fault near the human activity. Not all faults are equally susceptible – the location, orientation, and properties of the fault play an important role too.

If a particular project involves injecting and removing fluids from the same formation, as in the case of an enhanced oil recovery project, it is the net fluid balance that is important, not just the injected volume.

Robin McGuire of Lettis Consultants International presented factors that affect the potential to generate felt seismic events:

- Rate of injection or extraction,
- Volume and temperature of injected or extracted fluids,
- Pore pressure,
- Permeability of the relevant geologic layers,
- Faults, fault properties, fault location,
- Crustal stress conditions,
- Distance from the injection point, and
- Length of time over which injection and/or withdrawal takes place.

# Chapter 3 - National Academy of Sciences Report

Injection of large volumes of fluids into underground formations can increase the potential for seismic events to occur under certain conditions. With the heightened level of U.S. oil and gas production, particularly with the rapid expansion of unconventional oil and gas resources that involve hydraulic fracturing and wastewater disposal through injection wells, Senator Jeff Bingaman of New Mexico, chair of the Senate Energy and Natural Resources Committee, wrote to Department of Energy Secretary Stephen Chu in 2010. Senator Bingaman requested the Secretary to engage the NAS's National Research Council to examine the scale, scope, and consequences of seismicity induced by energy technologies.

The NAS formed a Committee on Induced Seismicity Potential in Energy Technologies. Work began in 2011. A final report was released in June 2012[2].

This white paper does not include all the details of the NAS report. However, the presentation made by Robin McGuire of Lettis Consultants International (a member of the NAS committee that prepared the report) during the special session provides a summary of the report and its findings. Several others speakers made reference to the same report. Therefore, some of the key findings of that report are included here.

### 3.1 Focus of the NAS Report

According to McGuire's presentation, the NAS report:

- Summarized the current state-of-the-art knowledge on the possible scale, scope and consequences of seismicity induced during the injection of fluids related to energy production,
- Identified gaps in knowledge and the research needed to advance the understanding of induced seismicity, its causes, effects, and associated risks,
- Identified gaps and deficiencies in current hazard assessment methodologies for induced seismicity and research needed to close those gaps, and
- Identified and assessed options for interim steps toward best practices, pending resolution of key outstanding research questions.

[2] National Academy of Sciences, 2012, "Induced Seismicity Potential in Energy Technologies," prepared by an NAS Committee on Induced Seismicity Potential in Energy Technologies, published by the National Academies Press, Washington, DC, 300 pp. The report can be ordered in hard copy or downloaded in .pdf format at http://www.nap.edu/catalog.php?record_id=13355.

The report focused its attention on induced seismicity specifically associated with four energy technologies:

- Geothermal energy,
- Oil and gas production,
- Wastewater disposal in injection wells, and
- Carbon capture and storage (CCS).

Each of these is discussed in the following sections. The descriptions given below represent the level of detail provided in McGuire's presentation. The full NAS report contains far more detail and examples than are described here. Readers are encouraged to examine the report for additional information.

**3.2 Geothermal Energy**

Geothermal energy can be produced in at least three different ways. Some formations contain hot steam in the pores and fractures of the rock. These are called "vapor-dominated" systems. A well-known example of this type of production is the Geysers field located 75 miles north of San Francisco.

Others contain hot liquid water in the pores and fractures of the rock, and are referred to as "liquid–dominated" systems. Both of these systems require some water injection to maintain pressure and heated working fluids.

The third type of geothermal system is known as "enhanced geothermal systems (EGS)" or as "hot dry rock". In those formations, the hot formation does not contain abundant natural water or steam. To take advantage of the high temperature of the rock, extensive hydraulic fracturing must be done to promote water introduction into the rock and circulation of water within the rock formation. In addition, a water source must be injected into the rock as a heat-transfer fluid.

Geothermal systems employ both injection and withdrawal of water. Operators attempt to keep a balance between fluid volumes produced and the fluids replaced by injection to maintain reservoir pressure. Unlike the other forms of energy reviewed in the NAS report, geothermal energy has very high temperatures in the underground formation. The temperature difference between formation and injected water introduces an additional driving force for rock disturbance from thermal impacts.

### 3.2.1 Geothermal Influences on Induced Seismicity

The NAS report concludes that induced seismicity in geothermal systems appears related to both net fluid balance considerations and temperature changes produced in the subsurface. Different forms of geothermal resource development appear to have differing potential for producing felt seismic events:

- High-pressure hydraulic fracturing undertaken in some geothermal projects (EGS) has caused seismic events that are large enough to be felt.
- Temperature changes associated with geothermal development of hydrothermal resources has also induced felt seismicity (The Geysers).

### 3.3 Oil and Gas Production

Several aspects of the oil and gas production cycle involve injection and/or withdrawal of large volumes of fluids from underground formations. The NAS report focused on three of these. The first is oil and gas extraction. Typically this removes large volumes of fluids over decades. Operators attempt to balance the volume of fluids injected with the volume extracted as the fields mature. The relevant examples provided in the NAS report are all related to production from conventional oil and gas formations; most such cases are decades old.

The second aspect is enhanced recovery, in which fluids are injected to extract remaining oil and gas and maintain reservoir pressure. Often as fields grow more mature and the natural reservoir pressure diminishes, it is necessary to begin injection of fluids. The most common form is secondary recovery (injection of water for water flooding). When secondary recovery has reached its practical or economic limits, tertiary recovery (enhanced oil recovery using steam, $CO_2$, polymers, and other materials) may be employed. The key is maintaining pressure balance within the formation.

The third aspect is hydraulic fracturing. Although hydraulic fracturing has been performed on more than 1 million wells since the mid-1940s, the technique has become a household term in the past five years, as shale gas development has flourished in the United States. Hydraulic fracturing of horizontal shale gas wells often uses 5 million gallons of water injected under pressures high enough to fracture the shale rock.

### 3.3.1 Oil and Gas Extraction Influences on Induced Seismicity

Generally, oil and gas extraction from conventional wells has not caused significant seismic events. However, withdrawal of oil or gas from the subsurface can result in a net decrease in pore pressure in the reservoir over time, particularly if fluids are not reinjected to maintain or regain original pore pressure conditions.

There have been a limited number of earthquakes associated with oil and gas production. About half of these cases are from the United States. Two other well-documented cases were found in France and Uzbekistan.

### 3.3.2 Oil and Gas Enhanced Recovery Influences on Induced Seismicity

Intuitively, processes that withdraw fluids from a formation and reinject fluids back into the same formation are less likely to cause large increases in pore pressure. Enhanced recovery operations were found by the NAS committee to have minimal influence of induced seismicity. McGuire reported that relative to the large number of waterflood projects for secondary recovery, the small number of documented instances of felt induced seismicity suggests that those projects pose small risk for events that would be of concern to the public.

The committee did not identify any documented, felt induced seismic events associated with EOR (tertiary recovery). They concluded that the potential for induced seismicity is low.

### 3.3.3 Oil and Gas Hydraulic Fracturing Influences on Induced Seismicity

Although the rate of injection of fluids for hydraulic fracturing is quite high, the duration of a typical frac job is relatively short – typically just a few days, with any given frac stage subjected to elevated pressures for only a few hours.

McGuire reports that the committee concluded that the process of hydraulic fracturing a shale gas well does not pose a high risk for inducing felt seismic events. They estimated that about 35,000 wells had been hydraulically fractured for shale gas development to date in the United States. Among all those frac jobs, only a few cases of felt induced seismicity from hydraulic fracturing for shale gas had been documented worldwide (examples from Oklahoma, the Horn River basin in Canada, and the United Kingdom).

### 3.4 Produced Water Disposal Wells

The Underground Injection Control (UIC) program regulates injection wells. The U.S. Environmental Protection Agency (EPA) and states that have received authority to administer the UIC program have permitted more than 150,000 injection wells for managing produced water from oil and gas operations. Many of these wells are used for injecting fluids for secondary or tertiary recovery as described in section 3.3. But an estimated 30,000 wells are used for disposal of wastewater to formations that do not produce oil and gas.

#### 3.4.1 Produced Water Disposal Well Influences on Induced Seismicity

Typically these disposal wells inject moderate volumes of fluids on a regular basis for many years. Given their ongoing injection and high cumulative volume, they may be thought to have some potential for inducing seismicity, if the local faults are susceptible. However, McGuire reports that the NAS committee found very few felt induced seismic events reported as either caused by or likely related to these wells.

A large percentage of disposal wells operate for years without creating any felt seismic events. But a small percentage of disposal wells do seem to be associated with clusters of earthquakes, typically small to moderate in strength. High injection volumes may increase pore pressure, and in proximity to existing faults could lead to an induced seismic event. Several examples of earthquake clusters linked to injection well activity are described in the next chapter.

Earthquakes associated with disposal wells are not necessarily limited in time and space to injection operations. The area of potential influence from injection wells may extend over several square miles, with earthquakes triggered more than 10 miles away. Induced seismicity may continue for months to years after injection ceases in some special cases, but the mechanisms that cause such effects are not well understood.

Evaluating the potential for induced seismicity in the location and design of injection wells is difficult because there are no cost-effective ways to locate faults and measure in situ stress. In a later chapter, several state regulators describe ways in which their agencies are trying to avoid locating new disposal wells in areas that are susceptible to induced seismicity.

### 3.5 CCS Operations

Over the past decade and a half, extensive research has been conducted on capturing $CO_2$ from large exhaust gas sources like power plants or gas processing plants. Once the $CO_2$ is captured,

it can be converted to a supercritical state and injected into an underground formation for permanent storage or sequestration. The volumes of $CO_2$ that would ultimately need to be sequestered to have a meaningful impact of atmospheric $CO_2$ levels will be extremely large. To the extent that full-scale CCS projects are implemented, they could represent very significant fluid injection programs.

### 3.5.1 CCS Influences on Induced Seismicity

According to McGuire's presentation, the only long-term (~14 years) commercial $CO_2$ sequestration project in the world is located at the Sleipner field offshore from Norway. That project injects $CO_2$ captured from an oil and gas production platform. The program is done at a small scale relative to the commercial projects proposed in the United States. Extensive seismic monitoring has not indicated any significant induced seismicity.

There is no experience with the proposed injection volumes of liquid $CO_2$ in large-scale sequestration projects (> 1 million metric tonnes per year). If the reservoirs behave in a similar manner to oil and gas fields, these large volumes have the potential to increase the pore pressure over large areas and may have the potential to cause significant seismic events.

One other consideration is that $CO_2$ has the potential to react with the host/adjacent rock and cause mineral precipitation or dissolution. The effects of these reactions on potential seismic events are not understood.

## 3.6 Comparative Impacts

McGuire's presentation included several charts taken from page 96 of the NAS report that show a side-by-side comparison of different energy activities and the amount of fluids injected on a daily and annual basis. That report is subject to copyright; therefore the figures are not reproduced here. The point of those charts is that some activities may have high daily injection volumes but have a short duration (e.g., hydraulic fracturing). When compared over an annual cycle, they have lower cumulative injection volumes than activities like CCS that have lower daily injection rates but continue throughout the entire year.

The charts also point out that some activities involve a relatively close balance of injection and withdrawal volumes (e.g., enhanced recovery) while CCS or disposal wells are presumed to incorporate injection only. Thus their cumulative impacts on pore pressure are likely to be more pronounced.

McGuire also showed a table that was adapted from Table S1 on page 6 of the NAS report. The table summarizes information for each of the energy activities regarding the number and strength of felt seismic events per year. The most prominent source of felt seismic events is vapor-dominated geothermal production at the Geysers, with an estimate 300-400 felt earthquakes per year since 2005. However, only one of those events had a magnitude greater than 4.0. The NAS report notes that the operators at the Geysers meet regularly with representatives of local communities, county government, federal and state regulatory agencies, the USGS, and national laboratory scientists in order to discuss the field operations and the recently observed seismicity.

Out of 30,000 water disposal wells surveyed, only 8 felt seismic events have been noted. However, 7 of those 8 events had a magnitude greater than 4.0.

**3.7 Government Involvement and Coordination**

McGuire noted that mechanisms are lacking for efficient coordination of government agency response to induced seismic events. He explained that responsibility for oversight of activities that can cause induced seismicity is dispersed among a number of federal and state agencies. Recently, potential induced seismic events in the United States have been addressed in a variety of manners involving local, state, and federal agencies, and research institutions. These agencies and research institutions may not have resources to address unexpected events; further, more events could stress this ad hoc system.

While EPA has overall regulatory responsibility for fluid injection under the Safe Drinking Water Act, and most states have delegated regulatory authority for the UIC program, neither the Code of Federal Regulations nor state regulations directly address induced seismicity. The USGS has the capability and expertise to address monitoring and research associated with induced seismic events. However, their mission does not focus on induced events. Significant new resources would be required if their mission is expanded to include comprehensive monitoring and research on induced seismicity.

Typically state agencies do not have the resources to undertake detailed seismic investigations. However, Tom Tomastik of the ODNR reported that his agency has undertaken its own seismic monitoring program. The agency hired two new geologists in 2012 to work in the UIC program (one of the new employees has a PhD in seismology).

Additionally, the ODNR began seismic monitoring for microseismic events around a few of the new Class II injection well sites. The ODNR purchased nine portable seismographs with the

capability of measuring movements in all three directional axes. Three of the new seismographs were deployed around a new disposal well. The ODNR is installing portable seismic units around some of the new Class II injection wells and will start monitoring prior to commencement of injection operations and will continue to monitor for a period of time after injection operations commence. They will continue to monitor for microseismic events up to approximately six months after initiation of injection operations. If no evidence of larger seismic events, the portable seismic stations will be moved to another new disposal well location.

This type of evaluation requires extensive resources and a great deal of time. Ohio's program is commendable, but may not be practical in other states. Chapter 6 discusses several approaches to evaluating risk on a case-by-case basis.

# Chapter 4 – Examples of Induced Seismicity

Many of the presenters described examples of specific cases in which injection activities caused detectable earthquake activity. Some were mentioned quickly as examples, while others were described in greater detail. This chapter provides summaries of some of those cases. The examples are organized by the four energy sectors used in the previous chapter.

## 4.1 Induced Seismicity from Geothermal Energy Production

### 4.1.1 Basel, Switzerland

Robin McGuire made brief reference to a magnitude 3.4 earthquake associated with injection of water for an enhanced geothermal project in the center of Basel, Switzerland in 2006. He did not offer any details. The NAS report provides a more detailed description of the case. During the hydraulic fracturing process for the system, many small seismic events were detected with several higher than magnitude 3.0. This caused the developers to discontinue the stimulation efforts and ultimately to abandon the project.

### 4.1.2 The Geysers

Robin McGuire made a few references to the Geysers geothermal project in California. A summary table in his presentation reported that there had been 300-400 felt seismic events per year since 2005. Between 1 and 3 of these had magnitude greater than 4.0. The NAS report offers much more information on the frequency and magnitude of the events.

## 4.2 Induced Seismicity from Oil and Gas Extraction

None of the presenters described examples in which extraction of oil and gas directly contributed to seismic events through removal of fluid leading to reduction of pore pressure in underground formations. However, the NAS report did provide two examples. These are the Lacq gas field in southwestern France and the Gazli gas field in Uzbekistan. Since these were not discussed in the special session, they are not mentioned further here. But interested readers can find more information in the NAS report.

### 4.3 Induced Seismicity from Enhanced Recovery Operations in Oil and Gas Fields

#### 4.3.1 Rangely, Colorado

Stuart Ellsworth of the Colorado Oil and Gas Conservation Commission (COGCC) provided some background on the Rangely field in northwestern Colorado. Oil production started many decades ago and was later augmented by water flooding operations beginning in 1957. Within a few years, the formation pore pressure rose to a level that triggered seismic events up to a magnitude 3.4. The area of injection was experiencing about 50 minor earthquakes per day.

The oil company operating the field agreed to let the USGS conduct an experiment to determine whether they could turn earthquakes off and on by injecting or withdrawing water from the formation. The researchers were successful in this experiment. When the injection ceased, the earthquakes dropped from more than 50 to fewer than 10 per day. When they began injection again, the daily number jumped back up to over 50. Over a two-year period, the USGS turned earthquake activity off, on, off, on, and off again.

Austin Holland of the OKGS included a figure from a 1976 scientific paper that shows how the number of earthquakes tracked the amount of water injected or withdrawn. The NAS report includes much more detail on the experiment.

#### 4.3.2 Other Cases

A summary table in McGuire's presentation reported that there had been felt seismic events at 18 water flooding sites around the world. Three of these had magnitude greater than 4.0. The NAS report offers more information on the frequency and magnitude of the events.

### 4.4 Induced Seismicity from Hydraulic Fracturing of Oil and Gas Wells

Holland provided specific case examples from wells in Oklahoma for which he believed that hydraulic fracturing had possibly contributed to seismic events. He also mentioned other examples from the United Kingdom and Horn River basin in British Columbia, Canada.

The NAS report notes that the very low number of earthquakes relative to the large number of hydraulically fractured wells is likely due to the short duration of injection of fluids and the limited fluid volumes used in a small spatial area.

### 4.4.1 Oklahoma

Holland suggested that a small percentage of the hydraulically fractured wells in Oklahoma may have induced seismic events. He cited the fracturing in Eola Field in Garvin County as possibly contributing to about 100 earthquakes, with magnitudes as high as 2.9. He also suggested that fracturing activities in the Union City Field in Canadian County may have contributed to about 10 small earthquakes. However, these conclusions will require additional verification.

### 4.4.2 Blackpool, UK

Several of the presenters mentioned this case as a prominent example of earthquakes associated with hydraulic fracturing. However, none of the presenters provided details. The NAS report contains more detailed description. Cuadrilla Resources began drilling and completing some of the first shale gas wells in the UK in 2011. The hydraulic fracturing triggered earthquakes of 2.3 and 1.5 magnitude. The 2.3 earthquake was felt widely by residents, which created a great deal of media attention. Cuadrilla suspended drilling and fracturing while it undertook an extensive study.

## 4.5 Induced Seismicity from Produced Water Disposal Wells

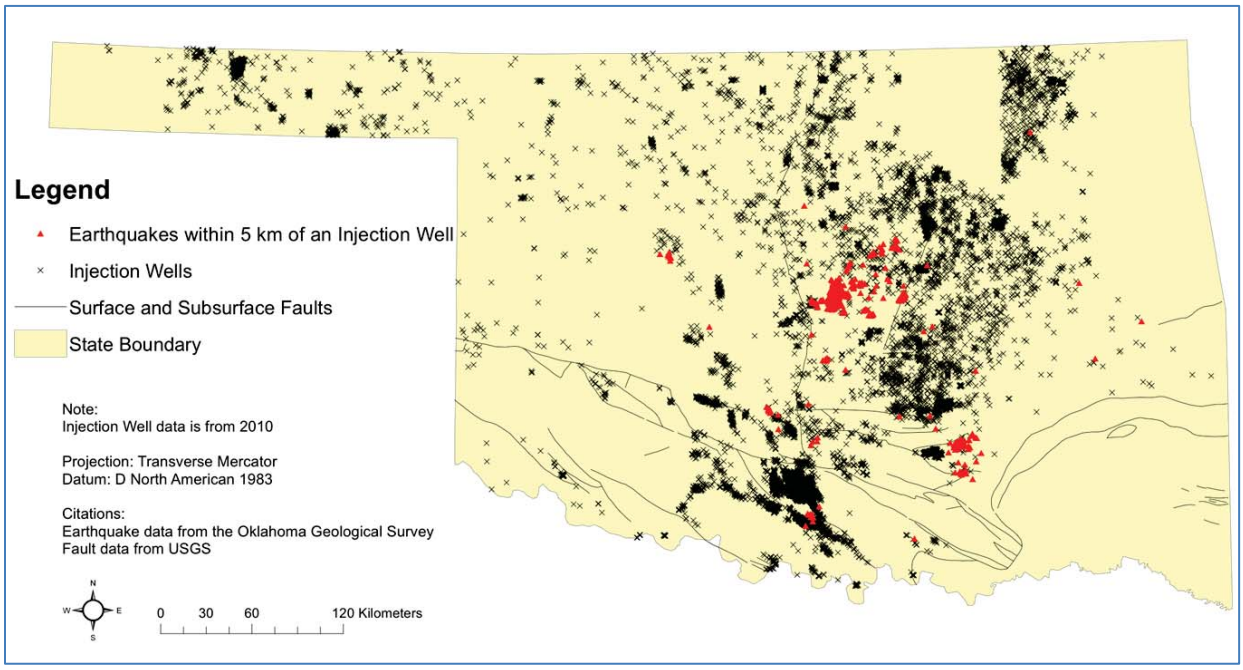
Compared to the other types of energy projects, disposal wells are more commonly linked to induced seismic events. This section describes examples relating to injection of oil and gas produced water. Two other examples of wells injecting other types of fluids are provided in section 4.6.

### 4.5.1 Oklahoma

Austin Holland reported on the relationship between earthquakes and injection wells in Oklahoma. Figure 2 plots the location of both of those categories on a map. Although some of the injection wells are located within 5 km of the earthquakes, there are many other injection wells throughout the state that clearly have not triggered earthquakes.

Holland described two cases in which injection of produced water into disposal wells was a potential cause for earthquakes. The first is an earthquake swarm of about 1,800 earthquakes located around Jones, OK, not far from Oklahoma City. The maximum magnitude of the events was 4.0 while the majority of them were of much smaller magnitude. Several large volume injection wells are located within 8-12 miles of the earthquake swarm. Prior to injection operations, the number of earthquakes in the area was small. Earthquake recurrence statistics

**Figure 2 – Location of Injection Wells, Faults, and Earthquakes in Oklahoma in 2010**




Source: Presentation by Austin Holland

in that area are not similar to those observed for the rest of Oklahoma. The data show a larger variation of active fault-plane orientations than expected. As a result, interpretation of the data is not as simple as anticipated. The Oklahoma Geological Survey continues to review the data and hopes to learn if the earthquake swarm was influenced by the disposal wells.

The second example described by Holland is a magnitude 5.7 earthquake near Prague, OK in November 2011. He noted that there are three UIC disposal wells within a mile of the earthquake location. Holland reported that other authors (in a manuscript currently under review for the journal Geology) propose the earthquakes were induced from injection from the 3 wells. Their hypothesis is based in part on the fact that the main shock occurred on a splay of the Wilzetta fault, which is consistent to be active in the regional stress-field. They also noted that the earthquakes have the characteristics typical of a natural aftershock sequence. Holland noted that as in the Jones swarm case, it is possible that these earthquakes were triggered by injection, but not certain. Where both natural and induced seismic events occur in the same area it can be very difficult to distinguish them from one another.

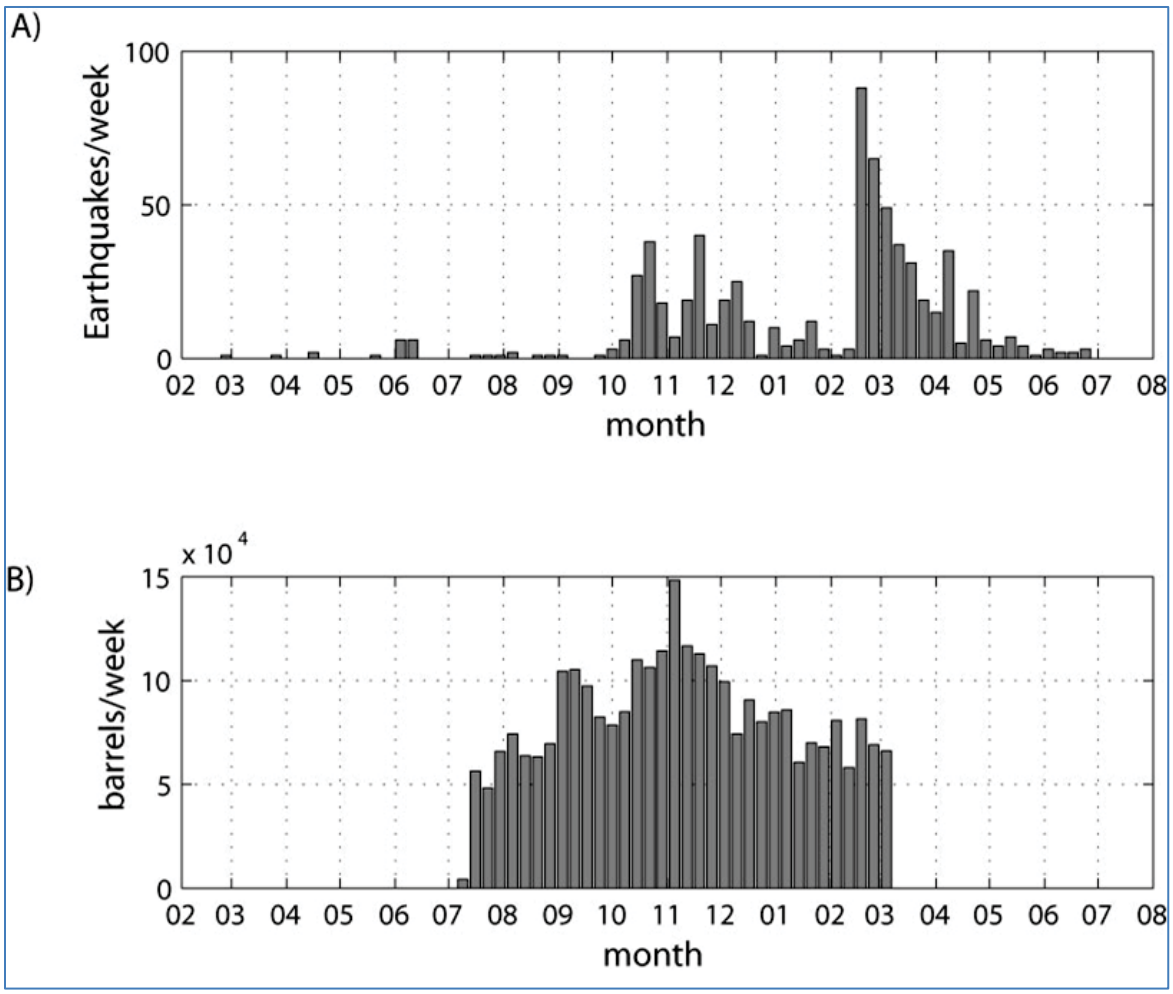
### 4.5.2 Arkansas

Scott Ausbrooks of the Arkansas Geological Survey reported on a cluster of earthquakes that occurred in the central portion of the state in the vicinity of several disposal wells. Following

injection of produced water and flowback water from shale gas production into several wells, a previously unknown fault, the Guy-Greenbrier fault, was illuminated by over 1,300 earthquakes with magnitudes up to 4.7 that occurred starting in September 2010. However, the vast majority of these events were relatively small in magnitude.

Figure 3, taken from Ausbrooks' presentation, shows the relationship between the number of earthquakes in that region and the volume of water injected. The data show a strong correlation between cumulative volume of water injected and the number of earthquakes, but as displayed in the bottom chart, there is a lag time of several months between the commencement of injection and the uptick in earthquakes. A similar relationship can be seen after injection is stopped – the earthquakes continue for another few months.

**Figure 3 – Relationship between Volume of Water Injected and Number of Earthquakes**




Source: Presentation by Scott Ausbrooks; the co-author is Stephen Horton of CERI.

Ausbrooks reported that the Guy-Greenbrier fault was already critically stressed prior to the start of injection. The earthquakes along the Guy-Greenbrier fault began after the start of injection at well #1 with intense seismic activity following the start of injection at well #5. The injection of fluids increased pore pressure in the Ozark aquifer. Because of the hydraulic connection between the Ozark aquifer and the Guy-Greenbrier fault, pore pressure could also have increased in the fault zone.

Ausbrooks concluded that given the spatial and temporal correlation between the disposal wells and activity on the fault, it would be an extraordinary coincidence if the earthquakes were not triggered by fluid injection. As discussed below in section 6.3, the AOGC placed a permanent moratorium on permitting any new or additional Class II disposal wells in a large area surrounding the Guy-Greenbrier and Enola seismically active areas.

### 4.5.3 Ohio

Tom Tomastik of the ODNR described the series of earthquakes that occurred near Youngstown, OH. The Northstar #1 injection well is located in an industrial district in Youngstown in the northeastern portion of the state. The lower portion of the well was originally drilled as a stratigraphic test well to 9,184 feet in April 2010. The DNR issued a permit to convert the wells to a Class II injection well in July 2010. Injection commenced on December 22, 2010.

The first two seismic events happened on March 17, 2011. Ten additional events followed through the end of 2011. Figure 4 shows the seismic events and their magnitudes.

**Figure 4 – Seismic Events in Youngstown, OH**

| DATE | ORIG. TIME UTC | EPICENTER | MAGNITUDE | FELT |
|---|---|---|---|---|
| Mar. 17, 2011 | 10:42:20.22 | 41.11, -80.70 | 2.1 | Not Felt |
| Mar. 17, 2011 | 10:53:09.51 | 41.11, -80.68 | 2.6 | Felt (27 reports) |
| Aug. 22, 2011 | 08:00:31.50 | 41.12, -80.73 | 2.2 | Not Felt |
| Aug. 25, 2011 | 19:44:20.99 | 41.10, -80.71 | 2.4 | Not Felt |
| Sept. 02, 2011 | 21:03:26.20 | 41.12, -80.69 | 2.2 | Felt (few) |
| Sept. 26, 2011 | 01:06:09.82 | 41.11, -80.69 | 2.6 | Felt |
| Sept. 30, 2011 | 00:52:37.58 | 41.11, -80.69 | 2.7 | Felt (300 reports) |
| Oct. 20, 2011 | 22:41:09.54 | 41.11, -80.68 | 2.3 | Not Felt |
| Nov. 25, 2011 | 06:47:26.58 | 41.10, -80.69 | 2.2 | Not Felt |
| Dec. 24, 2011 | 06:24:57.98 | 41.119, -80.694 | 2.7 | Felt (90 reports) |
| Dec. 31, 2011 | 20:04:59.03 | 41.118, -80.693 | 4.0 | Felt (more than 4,000) |
| Jan. 13, 2012 | 22:29:33.45 | 41.11, -80.69 | 2.1 | Not Felt |

Source: Presentation by Tom Tomastik

After the September seismic events, downhole testing was performed on the Northstar #1 injection well. In October, a tracer survey was conducted and indicated that injection fluids were entering 26 multiple injection zones from 8,215 to 8,940 feet. On December 30th, at the request of the Director of ODNR, the well operator shut down the Northstar #1 well. As described in some of the previous examples, often the seismic events continue after the injection has ceased. On the following day, the largest event to date occurred, with a magnitude of 4.0. In response, the Governor placed an indefinite moratorium on the other three drilled Northstar injection wells and one outstanding Northstar injection permit within a seven mile radius around the Northstar #1 injection well.

Tomastik reported that studies done by Lamont-Doherty Earth Observatory on the seismic data indicate there may be an unknown fault within the Precambrian rocks near the Northstar #1 injection well. Injection from the Northstar #1 well may have communicated with this potential fault and caused the seismic activity. Data continues to be collected and evaluated.

**4.5.4 West Virginia**

Tom Bass of the West Virginia Department of Environmental Protection (WVDEP) reported on multiple seismic events in central West Virginia during 2010 near a disposal well. West Virginia has 52 active non-commercial and 14 active commercial UIC disposal wells. These wells are important for the disposal of fluids associated with oil and natural gas development, particularly from the Marcellus Shale.

A commercial UIC well located in Braxton County, WV began experiencing small earthquakes in the range of magnitude 2.2 to 3.4 in April 2010. The same area had experienced one seismic event of 2.5 magnitude in 2000 prior to the injection well being drilled.

The well was originally drilled for production but was not economical. Therefore the operator elected to convert it to a disposal well. The well passed a mechanical integrity test making sure casing, tubing, and packer were tight prior to injection. All reports submitted by the operator prior to the earthquakes indicated that the well operated within permitted pressure limits. In response to the seismic activity, the Office of Oil and Gas placed a limit on the volume that could be injected within a 30 day period (15,000 bbl). No conclusive evidence was linked between the disposal well and the seismic activity.

#### 4.5.5 Texas

McGuire briefly mentioned a series of earthquakes that occurred near the Dallas-Ft. Worth airport during 2008-2009. The proposed cause was injection of produced water from shale gas operations into a disposal well. He provided no details.

Adel Younan of ExxonMobil briefly mentioned another example in the same section of Texas. Although he provided no details, a speaker at a previous GWPC conference (Cliff Frohlich of the University of Texas) had described a series of earthquakes near Cleburne, Texas to the southwest of Fort Worth. Frohlich's investigation suggested that the earthquakes had been caused by a disposal well nearby.

### 4.6 Induced Seismicity from Other Types of Disposal Wells

Several presenters mentioned two well-known cases of disposal wells injecting fluids other than produced water that contributed to induced earthquakes. Both of these examples are found in Colorado.

#### 4.6.1 Rocky Mountain Arsenal

Stuart Ellsworth of the COGCC provided some background on injection activities at the Rocky Mountain Arsenal near Denver. In the late 1950s, liquid waste was stored in ponds at the U.S. Army's Rocky Mountain Arsenal. The Army decided to inject the liquid into a 12,045-foot deep well drilled into deep, pre-Cambrian crystalline rock.

Injection began in March 1962. Less than a year after injection began, earthquakes began occurring in the vicinity. Thousands of small earthquakes were recorded near the Arsenal. In 1967, two earthquakes occurred with magnitude of 5.0. In 1968 injection stopped, and the Army began removing fluid from the Arsenal well at a very slow rate in an effort to reduce earthquake activity.

Ellsworth noted several features of this example that contributed to the observed earthquakes. These same factors also apply to the next example – Paradox Valley.

- Large injection volumes,
- High injection rate, and
- Low porosity and low permeability reservoir.

Holland included a figure from a 1968 scientific paper that shows the strong correlation between the volume of waste injected at the Rocky Mountain Arsenal and the earthquake frequency.

**4.6.2 Paradox Valley**

Hal Macartney of Pioneer Resources presented a detailed review of injection at Paradox Valley in southwestern Colorado. Although he gave the presentation, the listed authors of the presentation are Lisa Block and Chris Wood of the U.S. Department of Interior – Bureau of Reclamation. Macartney's presentation is not included on the GWPC website. Additional information relating to this project is taken from the presentation by Stuart Ellsworth and from the NAS report.

The Bureau of Reclamation operates the Colorado River Basin Salinity Control Project in the Paradox Valley to reduce the amount of salt entering the Dolores River and ultimately the Colorado River. They collect naturally occurring seepage of salt brine before it can contaminate the Dolores River. The intercepted salty water is disposed of by a combination of evaporation ponds and injection to a deep limestone formation at a depth of approximately 14,100 to 15,750 feet. The Bureau's scientists expected that this process might trigger earthquakes and thus deployed a network of local seismometers to monitor any activity.

During 6 years of pre-injection seismic measurement, the Bureau recorded only one earthquake. However, once injection began in July 1996, earthquakes were recorded almost immediately. Minor earthquakes continued through mid-1999, and two magnitude 3.5 events occurred in June and July of 1999. In response to the higher magnitude earthquakes, the Bureau of Reclamation initiated a program to cease injection for 20 days every six months. After experiencing a magnitude 4.3 earthquake in May 2000, they reduced injection to every other month. The result has been no more earthquakes over magnitude 4.0.

After monitoring injection into the Paradox Valley Unit injection well for almost 15 years, the Bureau of Reclamation has recorded over 4,600 induced seismic events. The largest seismic event occurred on May 27, 2000 and had a magnitude of 4.3. Macartney reports that about 1.92 billion gallons have been injected to date.

Macartney concluded that injection has induced earthquakes up to 16 km from the injection well, including on the far side of Paradox Valley. Decreasing the injection flow rate reduced the rate of induced seismicity and caused a region around the well to become aseismic. However,

it did not prevent the occurrence of felt earthquakes, nor did it stop the geographical expansion of the induced seismicity.

The largest induced earthquakes with magnitudes of 3.0 and above occur in a narrow band about 2 km from the well, on the side away from the salt valley. The occurrence of larger-magnitude earthquakes appears to correlate with high long-term average injection pressures. The response time of the seismicity to injection is increasing.

# Chapter 5 – Evaluating the Risk of Induced Seismicity

There are numerous injection wells and production wells in the United States. Hydraulic fracturing is conducted on thousands of wells each year. If felt seismicity were induced equally by all of those activities, there would be thousands of reports of earthquakes in many states each week. Yet the relatively small number of felt earthquakes associated with energy production activities suggests that not all individual injection activities pose the same degree of risk. This chapter discusses some of the factors that relate to the risk and severity of induced seismicity and describes two separate risk evaluation systems developed by the oil and gas industry. It also describes risk models developed under DOE's research programs.

## 5.1 NAS Report Recommendations on Assessing Risks of Induced Seismicity

Robin McGuire summarized the finding made by the NAS committee regarding assessment of risks. The committee believes that methods do not exist currently to evaluate the hazards posed by individual projects. The types of information and data required to provide a robust hazard assessment include:

- Net pore pressures,
- In situ stresses,
- information on faults,
- Background seismicity, and
- Gross statistics of induced seismicity and fluid injection for the proposed site activity.

The committee recommended that a detailed methodology should be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. The methodology would involve making assessments before operations begin in areas with a known history of felt seismicity, then following up with subsequent assessments in response to any observed induced seismicity.

This type of effort was recently begun in Ohio. Tom Tomastik reported on the ODNR's new seismic evaluation program. Some of the new Class II injection wells are being selected for pre-injection seismic monitoring based upon the geology and the proximity of the injection zone in relation to the Precambrian basement rocks, where most of the seismic activity occurs in Ohio. Monitoring would continue for six months after injection begins. If no significant induced seismicity is detected, the monitors will be moved to another location.

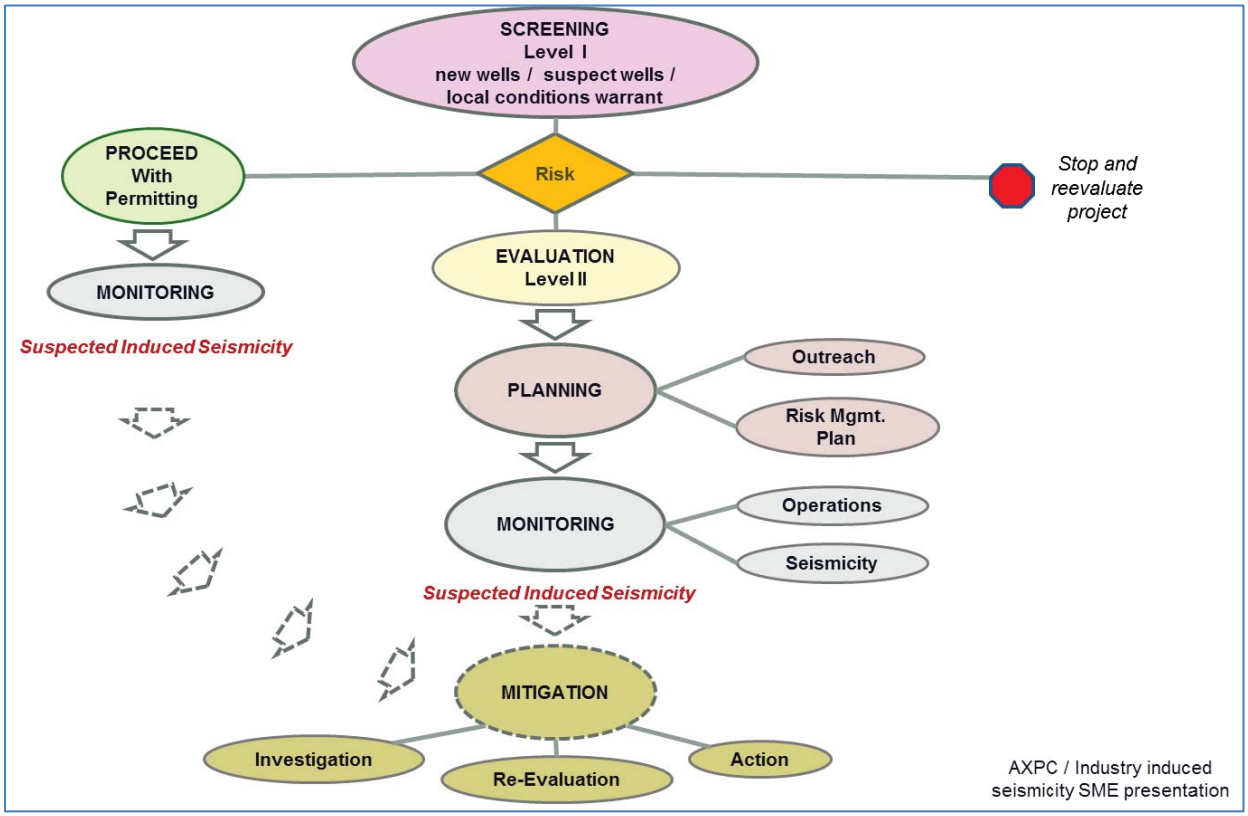
McGuire reported that the NAS committee further recommends that data related to fluid injection (e.g., well locations, injection depths, injection volumes and pressures, time frames)

should be collected by state and federal regulatory authorities in a common format and made accessible to the public (through a coordinating body such as the USGS). In addition, in areas of high-density of structures and population, regulatory agencies should consider requiring that data on fault identification for hazard and risk analysis be collected and analyzed before energy operations are initiated.

### 5.2 Risk Management Protocol Proposed by Industry Subject Matter Experts

Jeff Bull , an oil and gas industry subject matter expert on induced seismicity, shared a framework for screening, evaluation, planning, monitoring, and mitigation focused on wastewater injection wells. The framework was proposed by members of an industry working group representing companies from the American Exploration and Production Council and other industry participants. Bull noted that the framework is intended to be a "fit for purpose framework to manage the risk of induced seismicity and that it is scalable, allowing the operator to define the potential risk/impact at hand and then 'right size' any evaluation by selecting the appropriate tools to perform the evaluation". A flowchart of the framework is shown in Figure 5.

**Figure 5 – Framework for Evaluating Risks of Induced Seismicity**




Source: Presentation by Jeff Bull

Readers are referred to Bull's presentation for all the details. Some of the main points are summarized below. The first level of screening looks at new wells, any existing wells suspected of induced seismicity, and at other places where local conditions warrant. Depending on the evaluation, three possible outcomes can be reached:

- Proceed with permitting,
- Stop and reevaluate the project, or
- Proceed to additional evaluation.

If additional evaluation is the chosen outcome, the next step involves assessing the possibility of seismic events and ground motion occurring as a result of fluid disposal and estimating the impact on local population, property, or environment, including distress, damage, or loss. Some of the items that would be reviewed include:

- Key geologic horizons and features,
- Regional stress assessment,
- Surface features,
- Ground conditions,
- Ground response,
- Local seismic events,
- Reservoir characterization,
- Reservoir properties, and
- Disposal conditions.

The next step involves planning and communication/outreach. Figure 6 shows the "traffic light" planning protocol for assessing risks.

Figure 6 is a hypothetical example that includes ratings of six factors (the blue rows). The actual threshold values of a traffic light system would be based on specific local conditions. Depending on the ratings given for each factor at a particular location, the project is assigned to a green, amber, or red category that helps to determine the next steps.

If a project receives a green rating, it could move ahead. At this point a variety of monitoring would be implemented. Some of the monitoring would measure the injected fluid itself while other monitoring would focus on the reservoir and any local or regional seismic activity that is observed. If the project receives an amber or red rating, risk mitigation would be considered and implemented as appropriate before continuing activities.

**Figure 6 – Risk Assessment Plan Using Traffic Lights**

Green — Continue operations – no seismicity felt at surface (MMI I-II)*

Amber — Modify operations – seismicity felt at surface (MMI II-III+)*

Red — Suspend operations – seismicity felt at surface with distress and/or damage (MMI V+)*

| Perceived Shaking | Not Felt | Weak | Light | Moderate | Strong | Very Strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| Potential Damage | none | none | none | Very Light | Light | Moderate | Moderate Heavy | Heavy | Very Heavy |
| Peak Acceleration (%g) | <0.17 | 0.17 to 1.4 | 1.4 to 3.9 | 3.9 to 9.2 | 9.2 to 18 | 18 to 34 | 34 to 65 | 65 to 124 | >124 |
| Peak Velocity (cm/s) | <0.1 | 0.1 to 1.1 | 1.1 to 3.4 | 3.4 to 8.1 | 8.1 to 16 | 13 to 31 | 31 to 60 | 60 to 116 | >116 |
| Magnitude | 1 – 2.9 | 3 – 3.9 | 4 – 4.4 | 4.5 – 4.9 | 5 – 5.4 | 5.5 – 5.9 | 6 – 6.4 | 6.5 – 6.9 | 7.0+ |
| Modified Mercalli | I | II to III | IV | V | VI | VII | VIII | IX | X+ |
| Traffic Lights * | | | | | | | | | |

Source: Presentation by Jeff Bull

### 5.3 Risk Management Framework Proposed by ExxonMobil

Adel Younan of ExxonMobil described a possible risk management framework based on various technical considerations that were developed by a multi-disciplinary in-house team. This approach uses a "Risk Matrix" to assess risk level by a qualitative assessment of potential probabilities and consequences of an induced seismic event. After the risk level is identified, possible risk mitigation approaches can be evaluated (effectiveness/cost) and considered for implementation based on local conditions. The approach considers four levels of risk, with the following assigned categories:

- White – very low risk → continue operations
- Grey – very low risk → continue operation
- Yellow – medium risk → adjust operations; consider steps to mitigate risk
- Red – high risk →consider suspending operations; mitigate to reduce risk

The ExxonMobil protocol uses a matrix with probability on one axis and consequences on the other axis. Figure 7 shows the matrix. On the probability axis, A is highly likely, and E is very highly unlikely. On the consequence axis, 1 is MMI > VIII, and 5 is MMI of I to IV. The presentation includes details on the criteria that are used to rank the project.

**Figure 7 – Risk Matrix Approach for Assessing Potential Induced Seismicity in Wastewater Disposal Wells and Hydraulically Fractured Wells**

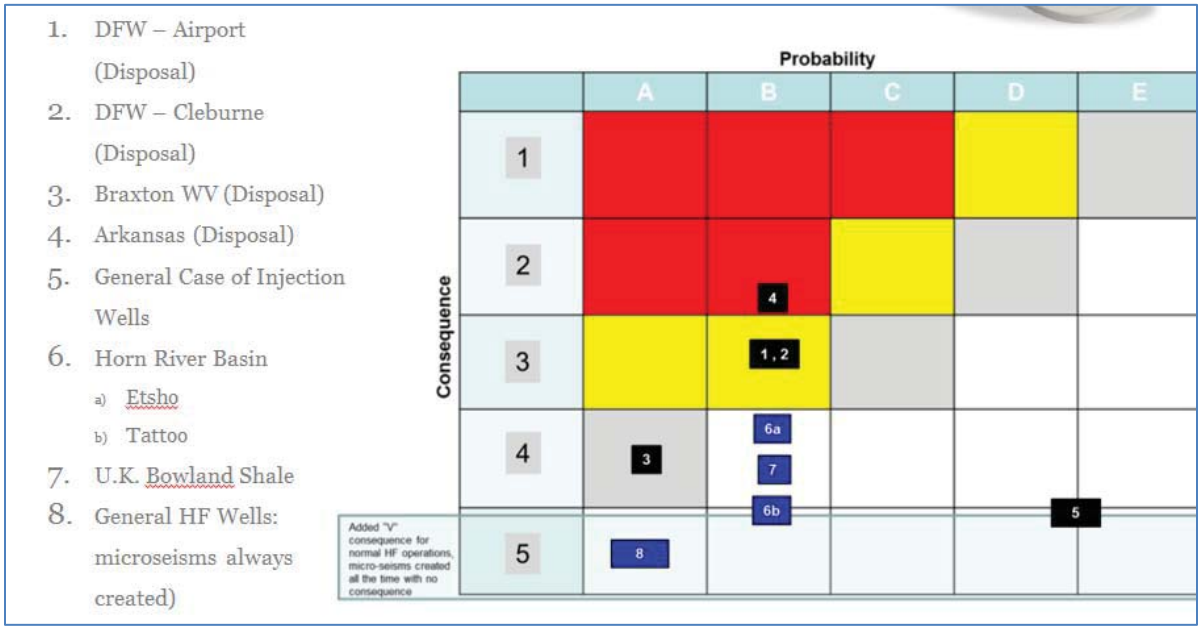
| Consequence \ Probability | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | HIGH | HIGH | HIGH | MEDIUM | LOW |
| 2 | HIGH | HIGH | MEDIUM | LOW | VERY LOW |
| 3 | MEDIUM | MEDIUM | LOW | VERY LOW | VERY LOW |
| 4 | LOW | VERY LOW | VERY LOW | VERY LOW | VERY LOW |
| 5 (Added "V" consequence for normal HF operations, micro-seisms created all the time with no consequence) | VERY LOW | VERY LOW | VERY LOW | VERY LOW | VERY LOW |

Source: Presentation by Adel Younan

To illustrate how the risk assessment methodology could be applied, Younan gave examples using four specific injection wells and two specific cases of hydraulic fracturing, as well as the general examples of normal injection well operations and hydraulic fracturing operations (where microseisms are routinely created as part of the stimulation process).

Figure 8 shows these examples plotted on the induced seismicity risk matrix. For example, two disposal wells in Texas that were linked to induced seismicity (Dallas/Fort Worth airport and Cleburn) were placed in box B3. The Braxton disposal well in West Virginia was placed in box A4. The Arkansas disposal wells were placed in box B2. Younan rated injection wells in general as falling at the intersection of rows 4 and 5 and columns D and E (i.e., very low consequence and probability of occurrence). He rated three specific hydraulic fracturing projects (two Canadian projects and the Blackpool site in the United Kingdom) in box B4. He indicated that hydraulic fracturing in general always creates microseisms but that the risk would fall into box A5 (i.e., high probability, but low consequence).

**Figure 8 – Application of Risk Assessment to Example Wells**




Source: Presentation by Adel Younan

Younan concluded that approaches to assess and manage seismicity risk should:

- Be encouraged,
- Be based on sound science,
- Take into account the local conditions, operational scope, geological setting, historical baseline seismicity levels, and
- Reflect reasonable and prudent consideration of engineering standards and codes related to seismicity structural health.

Seismicity monitoring and mitigation should be considered in local areas where induced seismicity is of significant risk. In such areas, appropriate monitoring and mitigation should include:

- A mechanism to alert the operator quickly to the occurrence of seismicity significantly above local historical baseline levels, and
- A procedure to modify and/or suspend operations if seismicity levels increase above threshold values for maintaining local structural health integrity and minimizing secondary damage.

Younan also emphasized that any specific methods and/or approaches selected for monitoring and mitigation should be fit for purpose and based on local conditions and the risk level, working collaboratively.

### 5.4 DOE Risk Models Relevant to Induced Seismicity

Grant Bromhal of DOE's National Energy Technology Laboratory reported on some of the DOE research efforts currently underway that deal with induced seismicity. DOE's National Risk Assessment Partnership (NRAP), with a team that includes 5 national labs (Lawrence Berkeley National Lab, Lawrence Livermore National Lab, Los Alamos National Lab, National Energy Technology Laboratory, and Pacific Northwest National Lab), is focused around quantifying risks associated with carbon storage in underground formations. One such area is the potential for induced seismic events resulting from large-scale CCS projects. Additionally, DOE and other federal agencies have research programs targeting induced seismicity around other energy-related areas such as geothermal resources, unconventional oil and gas recovery, and wastewater disposal.

NRAP has developed an Integrated Assessment Model with three components:

- RSQSim1—simulates tectonic earthquakes and slow slip events on faults, adapted to use time-dependent pore pressure changes,
- EMPSYN—calculates ground accelerations and velocities, and
- SIMRISK—calculates a frequency-magnitude distribution.

Bromhal reported that Generation 1 of the IAM for Probabilistic Seismic Hazards Assessment of single faults was released in July 2012. DOE expects that Generation 2 will be available in the spring of 2013. It will incorporate multiple faults and time periods, a calculation of the nuisance risk, and the ability to included parameter sensitivity. DOE plans a Generation 3 version of the IAM. It will incorporate higher frequencies in ground motion, full risk, and ties to fault leakage risk.

Regarding cooperation between federal agencies, Bromhal noted that DOE, USGS, and EPA have had a recent discussion on unconventional resource research. They included induced seismicity as an area for future collaboration. DOE and USGS have ongoing efforts in natural and induced seismic hazards analysis. The agencies proposed holding annual collaborative meetings between agencies and with other players to assess gaps/needs.

# Chapter 6 – Regulatory Considerations

The final portion of the special session included remarks from EPA and several states describing the efforts that had been made to establish regulations relating to induced seismicity.

## 6.1 EPA

Keara Moore of EPA's Office of Ground Water and Drinking Water spoke in the special session but did not use any presentation slides. She stated that the subject of induced seismicity does concern EPA, particularly if the seismicity creates conditions that would harm any underground source of drinking water (USDW). At this time, EPA has no national rulemaking directly focused on induced seismicity under development. However, EPA's UIC National Technical Workgroup, with representatives from the regional EPA UIC program offices, is developing a report on the subject. The report would not carry the weight of regulations but could help to explain EPA's perspective on the subject. Moore reported that a draft of the workgroup's report is now being reviewed.

## 6.2 Ohio

Tom Tomastik of the ODNR made two presentations in the special session. His presentation on the Northstar #1 well and the seismic events associated with it was covered in Chapter 4. In this section, Tomastik's other presentation that reviewed Ohio's response to the Northstar #1 incident and the state's subsequent rulemaking is discussed.

The Northstar #1 well was closed in December 2011. The ODNR immediately made changes to its Class II saltwater injection well program. Three other Class II wells nearby were shut down. The ODNR put a hold on the issuance of any new permits.

The ODNR initiated drafting of new regulations to help prevent larger magnitude induced seismicity associated with Class II injection in late spring of 2012. By July of that year, the Governor issued Executive Order 2012-09K as an emergency amendment of UIC Rules 1501:9-3-06 and 1501:9-3-07 of the Ohio Administrative Code. This Executive Order allowed for the implementation of new draft UIC rules into the legislative process.

The new UIC Class II saltwater injection well rules proceeded through the legislative process, were passed and went into effect in October 2012. The ODNR started to issue new Class II saltwater injection well permits again in November 2012. The new permits incorporated the

requirements from the new regulations. The chief of the division issuing the permits could include various new monitoring on a case-by-case basis:

- Pressure fall-off testing,
- Geological investigation of potential faulting within the immediate vicinity of the proposed injection,
- Submittal of a seismic monitoring plan,
- Testing and recording of original bottomhole injection interval pressure,
- Minimum geophysical logging suite, such as gamma ray, compensated density-neutron, and resistivity logs,
- Radioactive tracer or spinner survey, and
- Any such other tests the chief deems necessary.

In addition the new permits would not allow drilling and completion of the wells into the Precambrian basement rock. No injection would be allowed until the results of the monitoring are evaluated. Upon review of the data, the chief can withhold injection authority, require plugging of the well, or allow injection to commence. The chief has the authority to implement a graduated maximum allowable injection pressure. All new Class II injection wells must continuously monitor the injection and annulus pressures to maintain mechanical integrity. They must include a shut-off device installed on the injection pump set to the maximum allowable injection pressure.

To supplement the new permitting requirements, the ODNR established a new state seismic monitoring program. This was described previously in section 3.7.

**6.3 Colorado**

Stuart Ellsworth of the COGCC described the ways in which Colorado evaluates injection projects in relation to their potential for induced seismicity. The COGCC's permit process considers:

- Injection volume,
- Pressure below the fracture gradient, and,
- Input from the Colorado Division of Water Resources and Colorado Geological Survey to reduce the potential for induced seismicity related to UIC Class II wells.

The COGCC permit writer calculates a maximum injection volume, based on thickness and porosity from geophysical logging data. By COGCC policy, the injection volume is restricted to a one-quarter mile radial volume and the height of the injection formation.

COGCC's policy is to keep injection pressures below the fracture gradient, which is defined uniquely for each injection well, minimizing the potential for seismic events related to fluid injection. Some injection wells do not need to inject under pressure because the formation will take water on a vacuum. Maximum surface injection pressure is calculated based on a default fracture pressure gradient of 0.6 psi per foot of depth or other data provided by the applicant.

Beginning in September 2011, the COGCC UIC permit review process was expanded to include a review for seismicity potential by the Colorado Geological Survey. If historical seismicity has been identified in the vicinity of a proposed Class II UIC well, COGCC requires an operator to define the seismicity potential and the proximity to faults through geologic and geophysical data prior to any permit approval.

**6.3 Arkansas**

Scott Ausbrooks of the Arkansas Geological Survey described the earthquake swarm around the Guy-Greenbrier fault beginning in 2010. He did not discuss the regulatory changes introduced by the Arkansas Oil and Gas Commission (AOGC) following those seismic events. But the NAS report did include some information on those regulations.

In January 2011, the AOGC placed a permanent moratorium on permitting any new or additional Class II disposal in a 1,150-square-mile area surrounding the Guy-Greenbrier and Enola seismically active areas. Operators with existing Class II wells were required to report daily injection pressures and volumes to the AOGC Director. In the surrounding Fayetteville Shale development area, the AOGC Director may propose additional requirements for any new disposal wells.

**6.4 West Virginia**

During his presentation, Tom Bass mentioned that the West Virginia Department of Environmental Protection had no plans to develop regulations specifically focused on induced seismicity. He did note that injection permits would be issued on a case-by-case basis.

# Chapter 7 - Review of Major Issues and Findings

This chapter lists a few of the major issues and findings discussed during the special session.

1. Natural seismic events (earthquakes) occur regularly in many locations, but most of them are very small in magnitude and are not felt by humans at the surface, nor do they cause damage to surface structures. The Richter scale measures the size of the wave on a seismograph, whereas the Modified Mercalli Index measures the extent of impact occurring at the surface to people and structures.

2. Many of the seismic events are naturally occurring, but some can be caused by human activities. These are referred to as “induced seismicity”.

3. The special session and this white paper focus on induced seismicity resulting from energy activities, including geothermal production, oil and gas extraction, enhanced recovery, and hydraulic fracturing, disposal wells used to inject produced water or other wastewaters, and carbon capture and storage projects. The information presented over several hours and summarized here served to enlighten a wider audience and provide some factual information concerning the risks associated with activities that can cause induced seismicity. The NAS report provides a greater body of historical information on this subject and is referenced frequently throughout the white paper.

4. In general, the hazards posed by geothermal operations are not significant because project operators both inject and withdraw water from the formations, thereby keeping the formation pore pressures from climbing dramatically, although constant minor tremors are often associated with such activities. In one noteworthy enhanced geothermal project located at Basel, Switzerland, a large water injection effort to open pathways in the hot rock caused felt earthquakes of sufficient concern to residents in that city that the project was subsequently cancelled.

5. Induced seismicity may occur occasionally in association with oil and gas extraction, but the number of documented cases is extremely small.

6. Induced seismicity rarely occurs during enhanced recovery operations. During such operations, fluids are injected into a formation while oil and gas are withdrawn from the same formation, thereby keeping formation pore pressures from rising dramatically.

7. Hydraulic fracturing involves injection of fluids at high rate for a short period of time. In nearly all cases, the potential for felt seismicity is very low, although a few cases have been observed where unique conditions were present. However, these have not led to any significant surface damage. The NAS report concluded that hydraulic fracturing does not pose a high risk for induced seismicity.

8. Tens of thousands of disposal wells are employed each day to inject produced water and other wastewaters into formations that are not hydrocarbon bearing. Most of these pose low risk of induced seismicity, but given the ongoing injection and cumulative formation pressure build up over time, there is some potential that disposal wells can contribute to induced seismicity. Most wells are completed in areas and geological formations that are not likely to lead to induced seismicity, but several well-documented examples are described in this white paper where seismic activity was linked to disposal wells (e.g., Ohio, Arkansas, Oklahoma, and Texas). These are typically due to some geological anomalies or faults in those locations.

9. The relatively new concept of large-scale injection of $CO_2$ into underground formations as part of carbon capture and storage projects could lead to induced seismicity. The ongoing, long-term injection of $CO_2$ could lead to increased formation pore pressure.

10. The oil and gas industry is aware of the potential for its activities to induce seismic events in certain circumstances. Two different frameworks for assessing the risk for individual injection projects were described during the special session.

11. Most state regulatory agencies do not have regulations that focus specifically on induced seismicity. The white paper describes some regulatory initiatives put into play in Colorado, Ohio, and Arkansas. EPA does not have regulations specifically focused on induced seismicity, but its UIC National Technical Workgroup is currently developing a position paper on the subject.

# Appendix A – Agenda for Special Session

## *Assessing & Managing Risk of Induced Seismicity by Underground Injection: A Special session for seismologists, regulators, and other stakeholders*

**January 23, 2013**

**Moderator: Lori Wrotenbery, Oklahoma Corporation Commission**
*Part 1 - Studies: Researchers presenting findings and research strategies*

- Abstract 22: Potential for Induced Seismicity within Oklahoma - **Austin Holland**, OK Geological Survey
- Abstract 23: Preliminary Report on the Northstar #1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area – **Tom Tomastik**, Ohio DNR
- Abstract 7: Induced Seismicity Potential and Energy Technologies - **Robin McGuire**, Lettis Consultants International, Inc.
- Abstract 19: Disposal of Hydraulic Fracturing Flowback Fluid by Injection into Subsurface Aquifers Triggers Guy-Greenbrier Earthquake Swarm in Central Arkansas - **Scott Ausbrooks**, Arkansas Geological Survey
- Abstract 29: Research in the Area of Induced Seismicity – **Grant Bromhal**, USDOE-NETL

**Moderator: Edward Steele, Swift Worldwide Resources**
*Part 2 - Industry: State of the art technology used to limit risk*

- Abstract 35: Induced Seismicity and the Oil and Gas Industry Oil and Gas Industry – **Jeff Bull**, oil and gas industry subject matter expert on induced seismicity
- Lessons Learned at Paradox Valley - **Hal Macartney**, Pioneer Resources
- Abstract 27: Technical Elements to Consider in a Risk Management Framework for Induced Seismicity - **Adel Younan**, ExxonMobil Upstream Research Company

**Moderator: Lori Wrotenbery, Oklahoma Corporation Commission**
*Part 3 - Regulatory*

- Abstract 36: EPA Overview - **Keara Moore**, EPA Office of Ground Water & Drinking Water
- Abstract 24: Ohio's New Class II Regulations and Its Proactive Approach to Seismic Monitoring and Induced Seismicity – **Tom Tomastik**, Ohio DNR
- Abstract 28: **Tom Bass,** West Virginia DEP, Office of Oil & Gas
- Abstract 30: **Stuart Ellsworth**, Colorado Oil & Gas Conservation Commission

*Induced Seismicity Session Wrap up discussion*