NATIONAL ENERGY TECHNOLOGY LABORATORY

Research Portfolio Report

Unconventional Oil & Gas Resources:
Air, Wellbore Integrity & Induced Seismicity

U.S. DEPARTMENT OF ENERGY

Cover image: NETL's Mobile Air Monitoring Laboratory.

Research Portfolio Report

Unconventional Oil & Gas Resources: Air, Wellbore Integrity & Induced Seismicity

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The project data, photos, and graphics provided in the project summaries that follow the introduction come from available project documentation—including final reports, fact sheets, NETL project summaries, RPSEA monthly reports, and project websites—and through the generous assistance of Principal Investigators, industry partners, RPSEA, and NETL staff.

Executive Summary

Over the last four decades, ongoing research and development (R&D) programs sponsored by the U.S. Department of Energy's (DOE) Office of Fossil Energy (FE) have played an important role in advancing the development, demonstration, and commercialization of technologies that enhance the exploration and development of natural gas and oil from tight sands and shales. The R&D efforts of DOE, industry and others focused on unconventional oil and gas resources (UOG) have made the U.S. the number one natural gas and oil (including natural gas liquids) producer in the world.[1]

R&D efforts in unconventional oil and gas research—including in air, wellbore integrity and induced seismicity—have pushed the U.S. to the forefront in the production of natural gas from shale formations.

However, recovery of the abundant oil and gas resources from unconventional resources (primarily shales) has raised a number of growing concerns amongst the public including (1) significant use of fresh water (2) disposal of produced water (3) contamination of surface water and aquifers (4) air pollution and (5) induced seismicity. A primary concern with UOG development is potential impacts to both groundwater and air quality. While industry makes great efforts to isolate the production activity and its associated gases and fluids from the near-surface and surface environment (multiple casing strings, full reservoir to surface cementing, and other BMPs), challenges remain. While instances of such problems are not common, the sheer scale of the UOG development (the number and density of potential wells) mean that even infrequent and small-scale events can result in significant cumulative impacts, particularly over long time-scales.

The DOE's National Energy Technology Laboratory (NETL) began addressing these concerns in earnest around 2008. Early R&D focused primarily on produced water treatment and water management as outlined in the Research Portfolio Report for Produced Water Treatment and Water Management. The majority of research being conducted on air emissions, wellbore integrity and induced seismicity was initiated within the last 3-4 years; a large majority of these projects are still ongoing.

1 http://www.eia.gov/countries/index.cfm?view=production

These research efforts are funded through annual appropriations under the Environmentally Prudent Development Program, research initiated through Section 999 of the Energy Policy Act of 2005 (Section 999), aka the Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources Research Program, and research conducted through NETL's Office of Research and Development. The reduction of environmental impacts are key elements of these programs; thus, ongoing and future R&D will continue to focus on reducing the environmental footprint associated with developing unconventional resources and working to ensure sustainable development over time.

The Environmentally Prudent Development (EPD) Program focuses on advancing national research goals through science and technology development conducted in partnership with other federal agencies, national laboratories, and the private sector. The research program is aligned with the research priorities as described in "Federal Multi-agency Collaboration on Unconventional Oil and Gas Research" that was jointly released by the DOE, the USGS, and the EPA in July 2014. The goal of the EPD Program is to support the prudent development of the nation's shale gas, tight gas, and tight oil resources (collectively referred to as "Unconventional Oil and Gas ("UOG") resources") by 1) increasing our understanding of the varied nature of subsurface processes acting during development, 2) enabling the more efficient utilization of resources via technology that allows greater recovery from fewer, less impactful, wells, and 3) providing objective science and technological solutions that mitigate the environmental risks associated with UOG development.

To assist in achieving this goal, research done as part of the Unconventional Oil & Gas Resource: Air, Wellbore Integrity and Induced Seismicity portfolio must, among other things, be directed towards analyzing and improving wellbore integrity, understanding induced seismicity, characterizing well-site emissions, and improving air quality.

This report highlights many of the accomplishments achieved through partnerships among DOE, industry, and academia by projects within the Air, Wellbore Integrity and Induced Seismicity bin. For example:

- Cementing protocols for an integrated process to optimize zonal isolation were developed, based on field data collected from operators coupled with laboratory experiments. The results will improve operational safety and reduce the risk of environmental impact.
- An integrated software tool (geoWELL) helps researchers and industry identify location-specific subsurface geologic and wellbore (oil, gas, and underground injection) risks
- Initial recommendations for the monitoring and control of induced seismicity are made available through a University of Texas report.

Additional details on these and other accomplishments are provided in the following sections of the report.

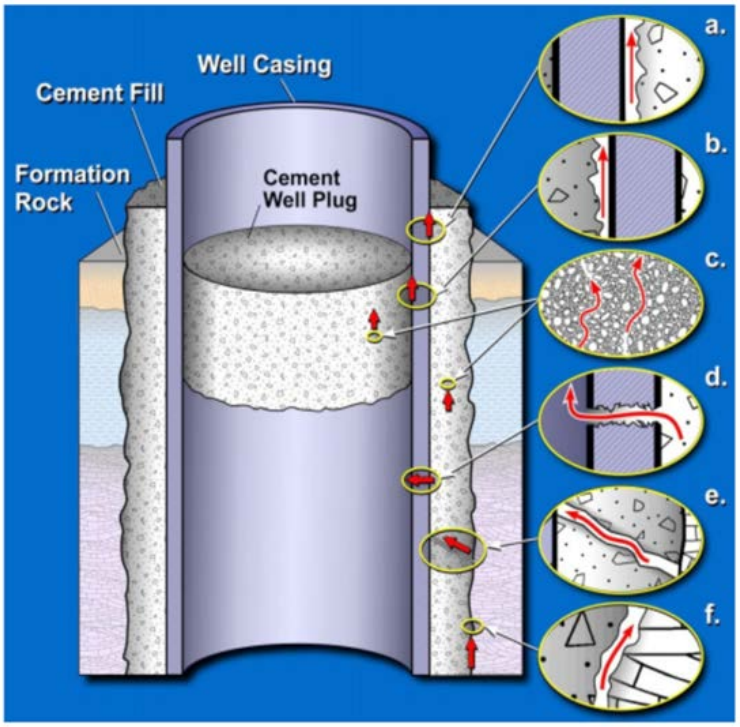

Image caption: *Poor cementing can lead to well integrity and performance failures.*

Introduction

The goal of the EPD Program is to support the prudent development of the nation's shale gas, tight gas, and tight oil resources by 1) increasing our understanding of the varied nature of subsurface processes acting during development, 2) enabling the more efficient utilization of resources via technology that allows greater recovery from fewer, less impactful, wells, and 3) providing objective science and technological solutions that mitigate the environmental risks associated with UOG development.

The research projects within the portfolio have been categorized into "bins" of projects focused on a common topic. This Research Portfolio Report provides a snapshot of results and accomplishments to-date for active and completed projects grouped into the Air, Wellbore Integrity and Induced Seismicity bin. The first section of this report provides an overview of the bin. Project summaries that include the objective, research conducted, results, and other pertinent information for each of the projects are provided in the pages that follow.

Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus and Haynesville Shales

Development of Methods to Prohibit and Remediate Loss of Annular Isolation in Shale Gas Wells: Prevention and Remediation of Sustained Casing Pressure and other Isolation Breaches

The two projects above will define best practices, including understanding of current cementing practices in the Marcellus and Haynesville Shales, the level of zonal isolation success, and issues resulting from incomplete zonal isolation. New cementing protocols and quantitative measurement of zonal isolation improvement resulting from new cementing protocols have been developed. A number of producing companies have been participating in the project and a cementing guideline software package has been developed.

Image caption: *Experimental pad used to detect flow. The large black cylinder is a high attenuation and relative high impedance material that improves the signal from the ceramic.*

Additional details about these projects are available on **p. 13** and **14**.

What is Air, Wellbore Integrity and Induced Seismicity research?

Cross-cutting research that brings together technical expertise in materials science, physics, chemistry, geology, engineering, computer modeling, and other oil and gas technologies to determine the characteristics of air emissions, the sealing effectiveness of cementing practices, the nature of induced seismicity, and the physics of fracturing. The technologies developed through this research must be available to operators and ultimately put into service in order to have a positive impact on the environment. Accordingly, technology demonstration and transfer efforts are important aspects of this research.

Why conduct this research?

Air

Rapidly-expanding UOG production and transmission produces a wide array of potential air quality impacts throughout the life-cycle of development. Effective impact mitigation requires accurate and consistent information on baseline (pre-development) conditions as well as reliable measurement and attribution of emissions to specific segments of the life cycle of UOG activities. Determining the true air quality impacts of UOG development requires a combination of regional studies as well as detailed investigations at specific sites. Studies also need to focus on a range of pollutants, including not only methane, but also carbon dioxide (CO_2), volatile organic compounds (VOCs), particulates, and others that are generated during site preparation, drilling, production, and gathering.

Wellbore Integrity

The long-term isolation of the production zone from overlying groundwater resources is largely dependent on the durability of well casings and cement, and the effective sealing of the well-bore annulus. These materials need to perform well over indefinitely long periods and under the unique settings of UOG development.

Induced Seismicity

Expanded UOG development has led to increased seismicity in several areas of the country, including certain areas in which seismicity was previously very uncommon. The primary cause of these events, which can reach magnitude 3.0 to 4.0 in some cases, has been identified as large-scale waste-water injection.

Accomplishments

The following selected examples of accomplishments recorded by completed projects in this portfolio illustrate the influence they have on unconventional gas recovery and production.

- **Approach for Assessing Spatial Trends and Potential Risks with UCR Systems** – This complementary research project carried out by NETL's Office of Research and Development resulted in an integrated software tool (geoWELL) that helps researchers and industry identify location-specific subsurface geologic and wellbore (oil, gas, and underground injection) risks.
- **Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact through Zonal Isolation Impacts** – Researchers at CSI Technologies created cementing protocols to optimize zonal isolation when completing Marcellus Shale wells. The decision matrix for cementing and drilling generated as a result of this project helps operators determine the most effective strategy for cementing, which in turn reduces potential environmental impacts and improves operational safety.
- **Relationship between Injection and Seismicity Varies by Region** – Researchers at University of Texas at Austin studied four geographic regions in Texas and discovered that the injection/seismicity relationship was different across the regions. This finding has implications for regulations and risk assessment/mitigation; local surveys need to be conducted to accurately determine the potential impact of injection and disposal.
- **The Environmentally Friendly Drilling (EFD) Systems Program** team at the Houston Advanced Research Center (HARC) has recorded multiple significant achievements, including:
    - **Eastern Mountain State Studies** – The EFD Team collaborated with the West Virginia University (WVU) to initiate an environmentally friendly E&P systems program. WVU published the white paper, "Challenges Facing Developers of the Marcellus Shale" that identifies issues associated with unconventional natural gas production in Appalachian Mountain states.
    - **Air Emissions Studies** – To help ensure that future air quality regulations are based on the best possible data, guidelines for the mitigation of oxides of nitrogen for a drilling site were published on the EFD website (www.efdsystems.org). A team led by The Center for Applied Technology at Texas A&M University collected air emissions data and developed a methodology for estimating and measuring emissions from a natural gas hydraulic fracturing operation in the Eagle Ford Shale Play. The emissions profiles developed as part of this study can be applied to similar sites.

Reducing the Environmental Impact of Gas Shale Development: Advanced Analytical Methods for Air and Stray Gas Emissions and Produced Brine Characterization

Determination of shallow gas in the Eastern region of the country where native shallow gas is present has been an important topic since the development activity in the Marcellus initiated. The project has defined careful procedures and analytics for sampling of shallow gas in fresh water aquifers. It has been shown that current practices are misleading in many circumstances. A best practices guide has been developed.

Additional details about this project are available on **p. 26**.

Image caption: *Pennsylvania Farmstead where a water well is instrumented to monitor and determine methane content.*

Lessons Learned

As with any type of research, environmental research into unconventional resources sometimes yields unexpected findings and uncovers challenges that need to be addressed through further research. The following high-level "lessons learned" have been identified during the course of work on these projects.

In the Marcellus Shale, near-surface casing annuli had the highest occurrence of sustained casing pressure of the wells researchers examined. One of the two major cement systems typically used for cementing that annulus was associated with more leakage and had demonstrated mechanical properties. An improvement in the system's mechanical properties should reduce the observed gas migration.

What are the benefits of air, wellbore integrity and induced seismicity research?

The technology developed and demonstrated under this program is vital in addressing the environmental risks associated with unconventional oil and gas development. Along with this environmental stewardship, other benefits of this research are clear and include the following:

- **Enabling the full development of unconventional resources**

  Significant hydrocarbon resources are found in the U.S., resources that can be extracted and used to provide economic benefits for all Americans. New technologies to mitigate environmental impacts are necessary order to ensure public acceptance of industry efforts to fully develop those unconventional oil and natural gas resources. Engaging industry and academia to perform research catalyzes the development and application of these new technologies.

- **Stabilizing the domestic energy portfolio**

  Ongoing environmentally-sound development of domestic petroleum resources, specifically research that advances the development of unconventional resources, can help provide a more robust and stable domestic energy portfolio and economic benefits. A diverse portfolio of domestic energy sources will ultimately be a cornerstone in building greater energy independence and national security. Successful research will advance the development of unconventional fossil resources and mitigate or prevent the unwanted environmental consequences of securing this energy supply.

- **Promoting technology transfer**

  The technology developed and demonstrated under this program will be shared, scaled-up when applicable, and drive future discovery and exploration as it is applied by operators to future hydrocarbon resources.

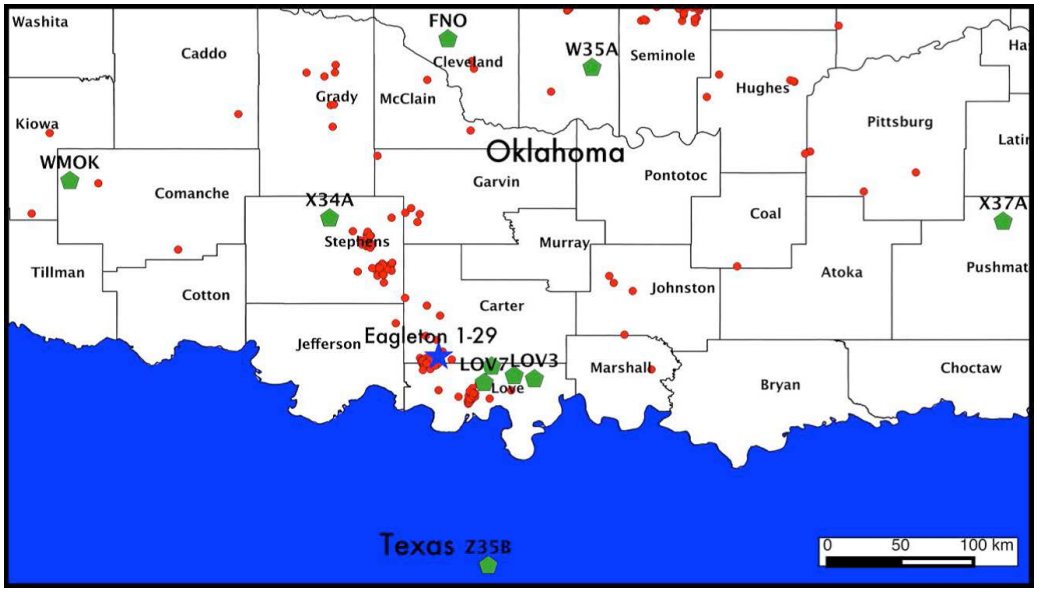

Image caption: *Regional seismic network*.

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Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus and Haynesville Shales

Objective: To comprehensively study the cementing processes used in drilling horizontal wells in the Marcellus Shale play and to examine the effects of zonal isolation problems on safety and the environment.

Research Conducted: A major challenge to drilling in the Marcellus Shale is maintaining adequate zonal isolation from the time cement is placed through well completion.

This study focused on analyzing zonal isolation technology to help develop best practices for cementing in the Marcellus Shale play. The project analyzed all aspects of wells drilled and cemented in the Marcellus Shale play between January 2012 and December 2012—from drilling to the well performance post-cementing.

After analyses, a field representative observed 60 cement jobs over a five-month period. Researchers tested a cement blend and water samples from the locations, initially conducting typical oilfield cement testing but expanding the analyses once baseline parameters were established. Data collected were used to determine if there were operational causes for potential zonal isolation problems and to develop a method of quantifying the potential for zonal isolation failure on a particular well.

Through analysis of each well, the team determined, within a certain confidence level, those wells that would continue to experience successful zonal isolation. They then created a decision matrix for cementing and drilling.

Results:

- Discovered potential issues with the cement systems being used and some cementing protocols.
- Discovered that intermediate (near surface) casing annulus had the highest occurrence of sustained casing pressure. One of the two major cement systems being used for that annulus was experiencing more leakage when compared to the other. Researchers found that zones with the higher percentage of leakage had poorer mechanical properties as compared to zones with better field results. An improvement in the system's mechanical properties should reduce the observed gas migration.
- A model developed by the University of Houston may help to predict failure in an annulus. It uses several dimensionless variables, but by targeting and improving these properties, the project team predicts fewer wells will experience gas migration.

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Lead Performer: CSI Technologies

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Project Number: 10122-19

Period of Performance: 4/2012-1/2015

Additional information about this project is available on the RPSEA website.

Prevention and Remediation of Sustained Casing Pressure and Other Isolation Breaches

Objective: To detect, diagnose, and stop unwanted gas flow resulting from sustained casing pressure (SCP). The project will also develop a protocol to assess gas flow potential and apply appropriate preventative methods.

Research Conducted: SCP is excessive pressure that develops in wells when formation fluid persistently rebuilds. SCP is usually the result of a well leak that permits the flow of gas through a cement sheath. This loss of integrity in the well due to SCP can lead to a release of reservoir fluids resulting in accidents and risks to personnel, assets, and the environment.

This study is researching and analyzing problems that lead to SCP to help illustrate the positive value and acceptable risk of gas shut-off and prevention concepts. Successful field trials will drive technology transfer of these concepts to shale gas drillers across the U.S. as well as other unconventional plays employing factory drilling methods for wells with a high potential of SCP.

Phase 1 of this project analyzed the issues related to SCP and focused on the development of methods to remediate or prevent gas communication in the Fayetteville Shale play. Initial work included an assessment of best practices, the current technology, and future trends. To identify, evaluate, and address SCP prevention best practices and area of improvement, current cement slurry designs and operational practices were evaluated. Other Phase 1 tasks focused on the development of an acoustic downhole tool to accurately locate gas flow behind a casing wall using both active and passive detection methods to address challenges related to remediation.

Researchers are developing an acoustic tool to use as a locator of downhole sources of gas migration that are occurring in wells. Field trials will be monitored and analyzed to determine success.

A passive listening tool will be used to obtain depth, type, and magnitude of flow. An active listening tool will help determine orientation.

Results:

- Application of the two detection methods (active and passive) in concert were found to be the most optimum method for flow detection. The passive tool is best suited to identify the depth range for remedial operation and the active tool to pinpoint flow path location and orientation.
- Statistical review of the historical data from operator reports in the Fayetteville Shale included casing information, cementing reports, directional surveys, sustained casing pressure information, and hydraulic fracturing job reports a remediation protocol has been developed. The protocol, which will be implemented during Phase 2 is designed to identify and locate a flow path behind casing, to access the flow path, to confirm the flow path has been intersected, and to inject a sealant into the path to stop SCP.
- Method to establish perforation location and orientation.

Ongoing Research: The project has entered Phase 2 and is in the process of applying the remediation protocol established in Phase 1. Working with Southwestern Energy, CSI Technologies will apply this protocol to wells in the Fayetteville Shale. New slurries designed by this project will be applied on wells drilled using the new protocol which calls for the top of cement in the production strings to be placed below surface.

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Lead Performer: CSI Technologies, LLC

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Project Number: 11122-42

Period of Performance: 5/2013-9/2016

Additional information about this project is available on the RPSEA website.

Nanite™ for Better Wellbore Integrity and Zonal Isolation

Objective: To demonstrate real-time sensing of wellbore integrity and zonal isolation in shale gas and applicable oil and gas operations using Nanite™, a nanotechnology application of cement.

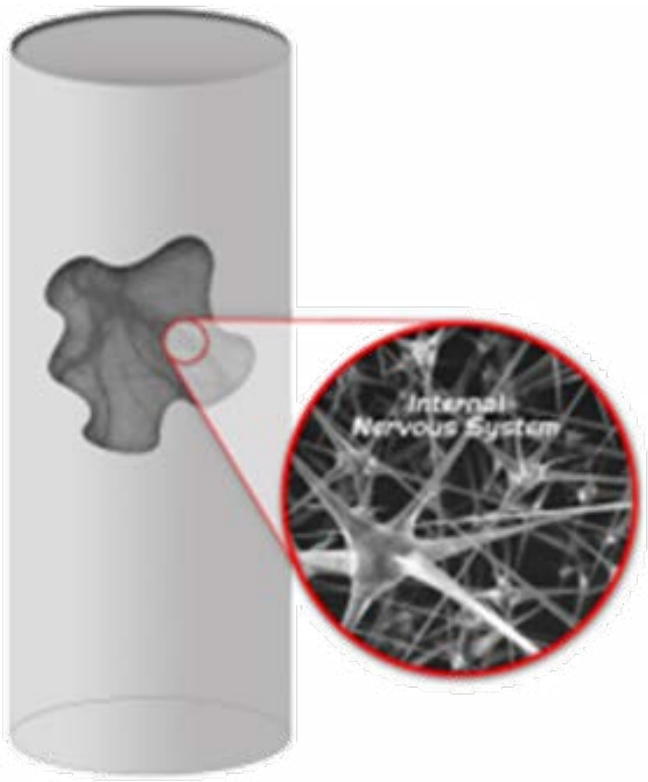
Research Conducted: Environmental protection regulations usually require cement to extend to 150 feet below the deepest water well in the Gulf of Mexico deepwater environment. Fracturing processes are not supposed to begin until the wellbore has been properly cased and cemented. Unfortunately, what may initially appear to be a good cement job or casing connection can be degraded by the pressure exerted during the actual fracking process. The resulting cracked cement or failed casing then leads to the aquifer or surface contamination with wellbore fluids.

Nanite™, a cementitious material is being tailored to help prevent blowouts and gas leakage, thus helping to protect the environment and ease public concerns. Nanite™'s electrical, radiometric, and acoustic properties, combined with its improved durability, chemical composition, and physical properties have the potential to ensure long-term wellbore integrity and zonal isolation.

Project researchers performed chemical, thermal, and microscopic analysis to qualify nanomaterials. They assessed the properties of Nanite™ slurries and cements to determine the impact of Nanite™ admixtures on cement properties.

Project researchers successfully demonstrated the response of Nanite™, in the laboratory setting, to stress, temperature, fracture, and cement curing for one mode of interrogation (electrical). The dynamic electrical impedance spectra of Nanite™ were used to detect cement curing, loading, and fracture. A sub-scale demonstration of Nanite™ performance is planned before a field demonstration is complete.

Researchers are also developing a novel hybrid acoustic-electrical technique for monitoring Nanite™ and the electrical measurement form factor is being modified to accommodate concentric casings. Additionally, ongoing tasks, including *Optimization of Nanite™ for Acoustic Properties* and *Gamma Ray/Neutron Detection,* are part of the project's objectives.



Nanite™ is responsive to pressure (or stress), temperature, and any intrinsic changes in composition; as a result, Nanite™ can improve long-term wellbore integrity and zonal isolation in shale gas and applicable oil and gas operations.

Results:

- Developed the nanomaterial, cement compositions, electronic hardware, and the software for testing the Nanite™ response to stress, temperature, fracture, and curing of the cement for electrical interrogation. The response of Nanite™ was successfully observed at lab scale.
- Completed preliminary acoustic characterization of Nanite™. This characterization revealed distinguishing acoustic properties.
- Developed novel electronics hardware and software to analyze the Nanite™ condition for use in well cement monitoring.
- Developed a Nanite™ curing model to predict hydration rates and levels based on electrical impedance measurements.

Nanite™ for Better Wellbore Integrity and Zonal Isolation

- Designed, fabricated, and calibrated a next-generation Nanite™ electrical impedance analyzer module. This module has high sensitivity, a small form factor, and low energy requirement.
- Monitored and calibrated electrical impedance spectroscopy measurements to demonstrate the response of the cement composition in a cubed form for the proof of concept (stress, temperature, fracture, and curing) of the cement. Preliminary outputs from these tests are now being used to optimize hardware, software, and material formulations.
- Demonstrated enhanced sensitivity of Nanite™ to key intrinsic and environmental factors through informed selection of electrical impedance probe parameters. Advanced signal processing techniques proved essential to deconvolution of confounding effects. It was found that electrode geometry, cement configuration, and materials selection play a critical role in application of remote sensing techniques. The effort has benefited from end user (Joint Industry Partnership) involvement from the beginning, participating both financially and technically.

Ongoing Research: Ongoing research effort focuses on comprehensive characterization of Nanite slurries using API recommended practices for cementing slurries and potentially detecting (i) top-of-cement (TOC) and (ii) cement in an annular space between casing and formation using conventional and alternative non-traditional detection techniques. The goal is to complete material design and optimization, perform subscale proof testing and to identify currently utilized logging while drilling (LWD) tools for early development and easy adoption of Nanite. The techniques of interest are the electrical resistivity characteristics and background acoustics already researched during the phase I effort and also the gamma ray emission/neutron detection researched during the phase II effort.

As part of the project activities, performer is also coordinating efforts with industry partners to identify potential test wells and specific wellbore integrity issues to be addressed if a Joint Industrial Partnership (JIP) member or other Industry Partners would decide to work with the Recipient after the award has been completed on a field study of the Nanite Cement.

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Lead Performer: Oceanit

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Project Number: FE0014144

Period of Performance: 10/2013-9/2016

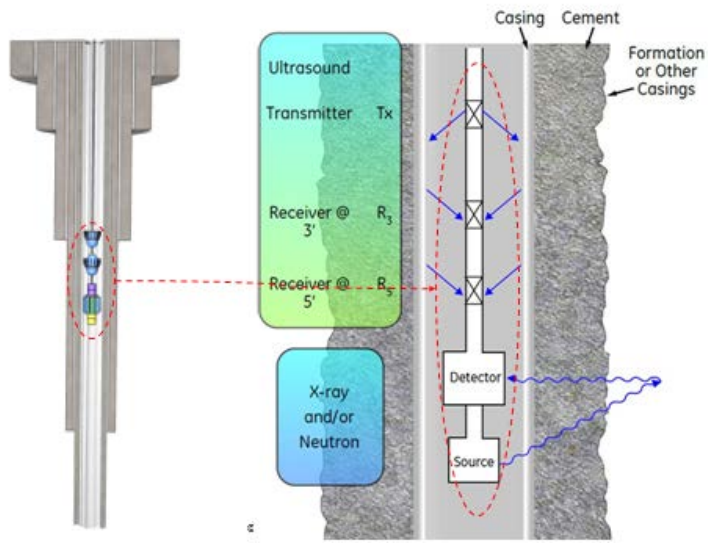
Additional information about this project is available on the NETL website.

nXis Well Integrity Inspection in Unconventional Wells

Objective: To develop a novel well-integrity inspection system based on nXis technology.

Research Conducted: nXis technology is founded on dual-particle imaging that combines information from X-ray and neutron backscatter to produce enhanced information about the flaw structure and topology of conventional and unconventional gas wells.

The benefits of using nXis technology include better data collection to ensure long-term borehole integrity and ultimately, better resource recovery. Cost savings will also be seen, as operators will be able to use the nXis inspection system to remedy well integrity flaws. Because environmental impacts related to construction and operations will be identified in both the aquifer depth region and lateral perforation zones, the technology will also enhance environmental safety, reducing environmental impacts on surface and groundwater sources.



nXis - Well Integrity Inspection System.

Results:

- Efforts to determine the entitlement for the high energy modalities of X-ray and neutron utilized Monte Carlo N-Particle (MCNP) modeling of transport properties. A basic modeling configuration of concentric cylinders of steel and cement was developed to represent concentric casings in the unconventional well and the soil field.
- Results show the penetrating capability of the X-ray photons of 80-450 keV energy through multiple casings and cement layers. These preliminary results demonstrate that the MCNP code is functioning and the neutron and photon transport properties can be used to examine the wellbore steel and cement structure

Ongoing Research:

- Testing of Xray and neutron sources continue with modeling defect detection tests utilizing a variety of emitting sources. Experiments are planned to confirm the modelled results.
- Researchers will carry out a down-selection of the neutron and gamma particle sources based on flux, energy, and borehole geometry requirements. The detection technologies for neutrons and gamma-rays will be selected based on compatibility with backscattering energy and resolution requirements as applied to the wellbore environment. This down-selection will include the determination of the design requirements of any combined detection methodology

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Lead Performer: GE Global Inc.

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Project Number: FE0024293

Period of Performance: 10/2014-9/2016

More information about this project is available on the NETL website.

Methods to Enhance Wellbore Cement Integrity with Microbially-Induced Calcite Precipitation (MICP)

Objective: To develop improved methods for sealing comprised wellbore cement in leaking natural gas and oil wells.

Research Conducted: The escape of hydrocarbons to the surface or into groundwater aquifers from poor cement placement, aging cement, or damage to the cement is a significant problem. Microbially induced calcite precipitation (MICP) has shown promise at the laboratory scale for sealing sandstone fractures. MICP offers a low viscosity solution that could possibly be injected further from the wellbore creating a larger and more permanent seal. Improved methods of sealing compromised wellbore cement will reduce the risk of unwanted upward gas migration and mediate potential damage to the environment, including the release of greenhouse gases and risks to overlying ground water supplies. The MICP technology could also open up other commercially-attractive applications.

Project researchers measured the cement contact of an existing well via cement bond logs which showed ~300 psi natural gas pressure in the annulus. Pressure response, logs of cement bonds, sidewall cores, gas flow rate reduction, and parallel laboratory experiments will be used to evaluate the MICP seal in that well. The team will collect and review relevant geology, well construction, and wellbore logging data from a representative well with known compromised wellbore cement. The information collected will guide the team in the design and operation of a wellbore cement analog testing systems to be used in the laboratory. Well characterization information will also be used to calibrate the MICP simulation model.

Results:

- Preliminary experiments showed that the elevated pH environment produced by cement enhances the MICP process.
- Construction of wellbore cement analog systems has been completed. These analogs are 1 inch (2.54 cm) core plugs designed with annular space between well casing steel and cement and cement and formation sandstone. Annuli will be varied in size to replicate fractures and various debonding spacing.
- Initial laboratory test to determine the effectiveness of MICP seals have been conducted. Preliminary results show that permeability of the annuli was reduced by seven orders of magnitude after inoculation with S. pasturii culture.

Ongoing Research: Based on laboratory results, the research team will establish a protocol to be used for an initial field test in an existing well with regions of poor cement contact. During that initial test, project scientists will evaluate the effectiveness of the MICP seal with ultrasonic imaging tools. Those tools will allow them to log the well, side wall coring, wellhead gas flow rate measurements, and pressure falloff data. The team will then conduct additional experiments and modeling to refine the MICP sealing technology. A second field test will then be performed.

NETL Contact: Robert Vagnetti, Robert.Vagnetti@netl.doe.gov

Lead Performer: Montana State University

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Project Number: FE0024296

Period of Performance: 10/2014-9/2017

Additional information about this project is available on the NETL website.

MICP Field Test Site at the Gorgas Power Plant near Jasper, Alabama.

Gas Flow from Shallow Gas Formations

Objective: The objective of this project is to gain a better understanding of how acid mine drainage water affects the integrity and structure of gas well cements.

Research Conducted: Half of the coal mines in Northern Appalachia are flooded with water with a low pH and high concentrations of dissolve iron and sulfates referred to as acid mine drainage (AMD). These acidic and corrosive waters have been known to degrade the cement used to line and protect shale gas wells that are drilled through coal mines or in the proximity of coal mines. With the large number of wells, both older conventional wells and newer unconventional natural gas wells, being drilled in Northern Appalachia, it is important to understand the effects that acid mine drainage might have on the integrity of gas well cements.

The Pennsylvania Department of Environmental Protection (PA DEP) recognizes this as a serious threat to wellbore integrity and zonal isolation with respect to modern Marcellus gas wells drilled through abandoned coal mines. The PA DEP has observed wells with complete cement degradation and the corrosion of the steel casing, creating a significant pathway for upward fluid migration.

To understand both the impact and rate alteration of acid mine drainage on cement, laboratory experiments were devised to observe how the fluid would affect a standard gas well cement in different conditions. The experiments seek to understand (1) how a set cement is affected by exposure to a stagnant, limited volume of acid mine drainage over a 4 week period, (2) how a set cement is affected by a continuous flow of acid mine drainage over a 3-day period and (3) how a cement slurry hydrates when the surrounding fluid is acid mine drainage water. These experiments focus on the effects of acid mine drainage on set cements and on hydrating cements as they set.

Results:

- Developed laboratory techniques to evaluate the impact of AMD fluid on set well cements and on hydrating cements.

Ongoing Research:

- ***Design static bench top experiments.*** This experiment will use static vessels and a synthetic AMD fluid. Laboratory experiments were designed to simulate shallow subsurface AMD conditions. The synthetic AMD fluid was flushed with argon gas to limit the oxygen content and hold the dissolved iron in solution.
    - Completed preliminary 4-week long bench top experiments where cement cores were exposed to lab generated AMD in static vessels at 12°C.
    - Cement is being analyzed using Scanning Electron Microscopy (SEM). Effluent AMD is being analyzed using ICP-MS and IC.
- ***Design flow-through experiments.*** This experiment will observe the impact of AMD fluid on set cement as the fluid flows through a channel (simulated microannuli/gap). This experiment is designed to observe AMD fluid flow through set cement in NETL's Industrial CT Scanner.
    - Completed preliminary flow-through experiments in CT Scanner
    - Image analysis using ImageJ is currently being conducted.
- ***Design AMD/hydration experiments.*** The use of porous molds are being considered.

Lead Performer and NETL Contact: NETL ORD

Barbara Kutchko, Barbara.Kutchko@netl.doe.gov

Project Number: Task 12

Period of Performance: FY2012-2015

Approach for Assessing Spatial Trends and Potential Risks with UCR Systems

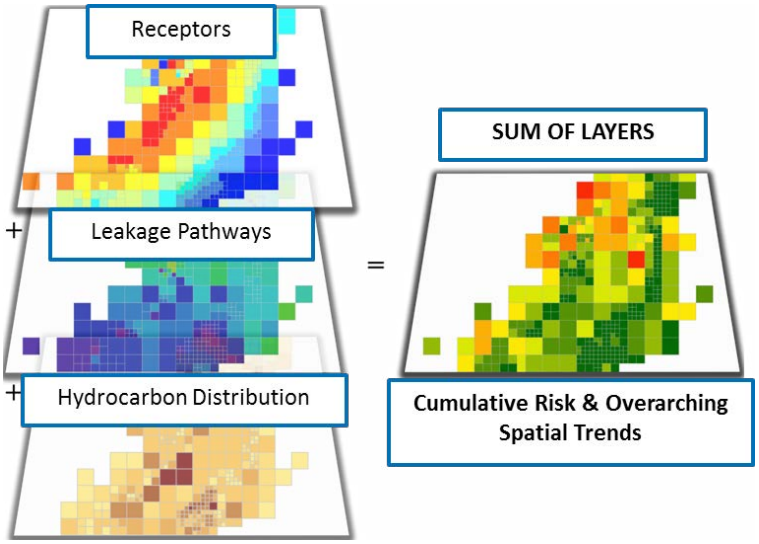
Objective: Unconventional resource development often coincides with areas where there is increased potential for impacts to near surface receptors (e.g. groundwater). In addition, uncertainty about the distribution of key subsurface elements, such as hydrocarbon distribution and leakage pathways can result inefficient development of unconventional resources. This project focused on developing and demonstrating how spatio-temporal tools and approaches can support uncertainty reduction and risk assessment for regions associated with unconventional resource development to improve decision making for a range of end-users such as researchers, industry, regulators, etc.

Research Conducted: Potential risks and impacts associated with shale gas development that are of concern to the general public include: potential contamination of underground sources of drinking water (USDWs); well blowouts during drilling; induced seismicity from hydraulic fracturing or associated wastewater disposal injection wells; inefficient development of unconventional resources, and surface water and soil contamination resulting from fracture fluid leakage. Public claims of impact are largely based on anecdotal evidence and are difficult to objectively evaluate. At the same time, industry experts assert that these risks are small and are managed effectively through operational best practices and engineered controls. The wide range of concerns, and the behavior of shale gas development during the evolution of a site results in the need for a rigorous science-based assessments and approaches that can provide an objective basis on which to evaluate potential risks.

This project worked to develop tools, data, and spatio-temporal analytical approaches that could be assembled and utilized to address questions about the efficacy and safety of developing unconventional resources. The study focused on demonstrating those approaches in relation to assessing the potential for liquids and gas to leak into near surface receptors (e.g. groundwater) via natural faults or fractures or via existing wellbores as a result of activities associated with drilling and producing natural gas from shale formations.

Project researchers focused on collecting data and developing methods to evaluate the distribution and interaction among three key subsurface systems: (1) hydrocarbon sources, 2) migration pathways, and (3) near surface receptors. The data and methodologies produced can be utilized independently or in combination to forecast the likelihood of impacts and risks on small-scale field areas to larger regional areas. The study utilized data from the Marcellus Shale region in Pennsylvania and West Virginia for demonstration of the approaches and tools developed by the study.

This project provided the geospatial framework and data needed to support integrated risk assessments and modeling. In addition to project specific technical products, available at https://edx.netl.doe.gov/ucr, the project also contributed to several knowledge transfer accomplishments including: (1) support for the development and release of NETL's Energy Data Exchange (EDX), (2) release of data-driven online applications that help support knowledge transfer of key unconventional resource datasets; this includes the North America Atlas of Unconventional Hydrocarbon Resources that continues to be updated and augmented based on the data compiled for this project, and (3) the development and release of geoWELL to help support access to key subsurface information and data utilized by researchers through the UCR portfolio as well as outside of NETL.



Approach for Assessing Spatial Trends and Potential Risks with UCR Systems

Results:

- All publically available results from the Unconventional Portfolio by ORD, including presentations, publications, tools/apps, and data are available from https://edx.netl.doe.gov/ucr. Please see the UCR Portfolio website for all products associated with Task 13.
- GIS boundaries for shale gas basins, U.S. and Worldwide, available for download from NETL's Energy Data eXchange. These boundaries were also utilized in the 2014 Global Shale Gas Development, Water Availability and Business Risks report produced by the World Resources Institute.
- NETL's Variable Grid Method (VGM), a geospatial analytical approach supporting simultaneous display of spatial data trends and uncertainty, was partially developed as part of this project. Provisional patent 61938862, full patent application submitted 1/2015
    - VGM approach was also selected for a special issue of Transactions in GIS slated for release in July 2015 coinciding with a special keynote presentation at the 2015 ESRI User Conference. Bauer, J., and Rose, K., in press, Variable Grid Method: an Intuitive Approach for Simultaneously Quantifying and Visualizing Spatial Data and Uncertainty, Transactions in GIS-ORA-1173
- Initiated development of NETL's Spatially Integrated Multivariate Probability Assessment (SIMPA) approach to identify risks and calculate the probability of impact related to well injection and production activities at meso-scales. Development of this approach and subsequent tool was discontinued in the UCR portfolio at the end of FY14 but continues through other work by ORD. Beta tool is anticipated out in 2016.
- Developed and released the geoWELL tool which is designed to assist users with finding and accessing information from state, federal and tribal agencies associated with subsurface systems including hydrocarbons, underground injection and water. Available at https://edx.netl.doe.gov/tools
- Released the Unconventional Energy Resources Atlas. This is an interactive web map application (UCR Atlas) that depicts geologic basin, oil and gas plays, and unconventional well locations in an online map environment with features connected to geospatial and bibliographic databases was updated to provide additional functionality and compatibility with DOE's Energy Data eXchange (EDX). EDX provides efficient access to key resources pertinent to energy related research. The UCR atlas is available at https://edx.netl.doe.gov/tools
- Collected and analyzed data that led to the mapping and interpretation of the base of groundwater for West Virginia and Pennsylvania. These data are important in evaluating the potential risk to aquifers, and for recommendations for casing depths.
- In-house datasets assembled for groundwater, hydrocarbon distribution from all subsurface sources, wellbores, as well as fault and fracture datasets for the Appalachian Basin region.
- Reviewed drilling records, allowing the team to reconstruct historical annual drilling activity in Pennsylvania. The historical records analysis provided a source of information on the temporal distribution of well completions, which can be used to assign completion years to wells from the database for which no completion year is reported.
- The reconstruction of historical annual drilling activity revealed that approximately 170,000 wells were not recorded in the Pennsylvania state databases for the years 1859-1974. The historical records analysis allowed the team to assign completion years to wells for which no completion year is reported.

Lead Performer and NETL Contact: NETL ORD

Kelly Rose, Geology & Geospatial Team Lead, kelly.rose @netl.doe.gov

Project Number: Task 13

Period of Performance: FY2014

Impacts of Shale Gas Development on Shallow Groundwater

Objective: To assess the vulnerability of shallow, drinking water aquifers to potential contamination or disturbance from gas or liquids released during the shale gas development process.

Research Conducted: The potential for liquids and gases to leak into drinking water aquifers is a concern associated with drilling and producing natural gas, including unconventional gas from shale formations. Cloudy and foul-tasting water has been reported from water wells in regions with shale gas development, and stray gas migration in aquifers has also been noted in these areas. The goal of the research is to determine the engineering risk for drilling/frac compounds to enter groundwater, and to identify transport mechanisms and migration pathways. This task is focused in three research areas: 1) field studies to monitor and assess aquifer impacts during tophole drilling and hydraulic fracturing operations, especially as shallow aquifers are penetrated by the borehole, 2) laboratory investigations of a) natural attenuation processes and rates, b) instrumentation response to drilling fluids and hydraulic fracturing chemicals, and c) conditions that result in mobilization of gas in fractured aquifers, and 3) hydrologic modeling to support these studies.

The impetus for this research was a drilling incident that occurred in 2012 in Sardis, West Virginia where drillers left an air compressor running while attempting to free a drill bit from an uncased, shallow borehole. Compressed air entered the fractured aquifer, and several hours later, water began flowing from a number of unused water supply wells a few hundred meters away. The hydraulic gradient imposed by the trapped, compressed air, the resulting groundwater flow surge, and the mobilization of groundwater through fractures in the aquifer that eventually cumulated in discharge from the unused water wells were modeled using the widely-available TOUGH-2 code, which provided reasonable and accurate results. The domestic wells and the gas well being drilled lined up along the direction of a set of prominent natural fractures, and the aquifer penetrated by the water wells is partially confined by an overlying shale near the gas well, trapping the compressed air. Laboratory-scale flow and transport experiments suggested that the entrainment and transport of methane gas in fractured aquifers can occur at relatively low flow velocities. The study concluded that pre-existing methane gas in shallow aquifers may be mobilized and transported by groundwater surges caused by compressed-air tophole drilling, which may explain some instances of methane migration in groundwater associated with the presence of nearby shale gas wells.

An electronic methane detector for groundwater monitoring was developed with the intent of deploying it in the field at a location upgradient of a shale gas drill site to determine if methane gas accumulates in the headspace of a monitoring well. (Headspace is the zone above the water level but below the cap of the well.) The intent is to field-test the idea of methane migration caused by tophole drilling. The device is based on a standard laboratory model laser-absorption methane detector, accurate from 10 ppm to the Lower Explosive Limit, incorporated into a field package that contains a power supply, data recorder, sampling pump, and membrane drying system. The unit is scheduled for operational field testing in the summer of 2015, followed by possible deployment at a drill site. A report of invention has been filed, and a patent application is in process.

Contacts were made with nearly a dozen different shale gas production companies in an attempt to obtain permission for groundwater monitoring during gas well drilling. NETL was refused access in every instance, even for sites that were approved for air monitoring, microseismic and other studies. Reasons included concerns that groundwater studies would lead to more regulations, a feeling that such investigations would find no impacts and therefore were a waste of time, worries by landowners that scientific research would delay royalty payments or discover contaminants for which the landowner could be held responsible, and assertions by operators that their pre-drilling, domestic water-well testing program already constituted "hydrologic monitoring."

In 2014, an agreement was reached with the Pennsylvania Department of Conservation and Natural Resources (DCNR) to monitor groundwater adjacent to an existing, undeveloped gas lease in Moshannon State Forest in north central PA. Current low gas prices have resulted in a great deal of uncertainty on the part of the leaseholder as to when or even if any gas wells will be drilled. As such, the Moshannon-based fieldwork portion of this project has been suspended, although other options for field site access are still under consideration. In lieu of field work, research has been focused on instrumentation response assessments and natural attenuation investigations in the laboratory, and developing groundwater models to test different contaminant transport and gas migration scenarios.

Impacts of Shale Gas Development on Shallow Groundwater

Results:

- A numerical model was developed using TOUGH-2 in collaboration with faculty in the Civil and Environmental Engineering Department at the New Jersey Institute of Technology in Newark, which provided reasonable results that closely reproduced the observed scenario at Sardis. (Geng, X., Davatzes, N., Soeder, D., Torlapati, J., Rodriguez, R., and Boufadel, M., 2013, Migration of high-pressure air during gas well drilling in the Appalachian Basin: *Journal of Environmental Engineering*, 10.1061 (ASCE) EE.1943-7870.0000769, B4014002. 46 p.)
- Additional modeling at NETL by an ORISE post-doc has provided further details about the Sardis incident, more clearly defining the mechanisms involved in potential gas transport from groundwater flow surges. (Zhang, Liwei and Soeder, D.J., 2015, Modeling of methane migration in shallow aquifers from shale gas well drilling, *Groundwater*, in press, 19 p.)
- Laboratory-scale flow and transport experiments were used to study the entrainment and transport of contaminants in fractured aquifers. Results showed that the water flow velocity needed to entrain and transport gas bubbles clinging to the sides of fractures was surprisingly low. (Giri, Poonam, 2013, Shale Gas Production and Methane Migration through Aquifers, Mickey Leland Energy Fellowship final report, 22 p.)
- Vertical flow-through sand columns have been constructed in the lab for natural attenuation studies in five different mineralized substrates plus a control; these studies are underway.
- Laboratory assessment of the response characteristics and detection limits of standard, electronic water monitoring instrumentation has been completed for pH, eH, conductivity, turbidity, temperature and other parameters. (Aubrey E. Harris, 2015, MS thesis for West Virginia University, Department of Civil and Environmental Engineering)

Lead Performer and NETL Contact: NETL ORD

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Project Number: Task 14

Period of Performance: FY2015

The Environmentally Friendly Drilling Systems Program

Objective: To identify, develop and transfer critical, cost effective, new technologies that can provide policy makers and industry with the ability to accelerate development of US domestic reserves in a safe and environmentally friendly manner.

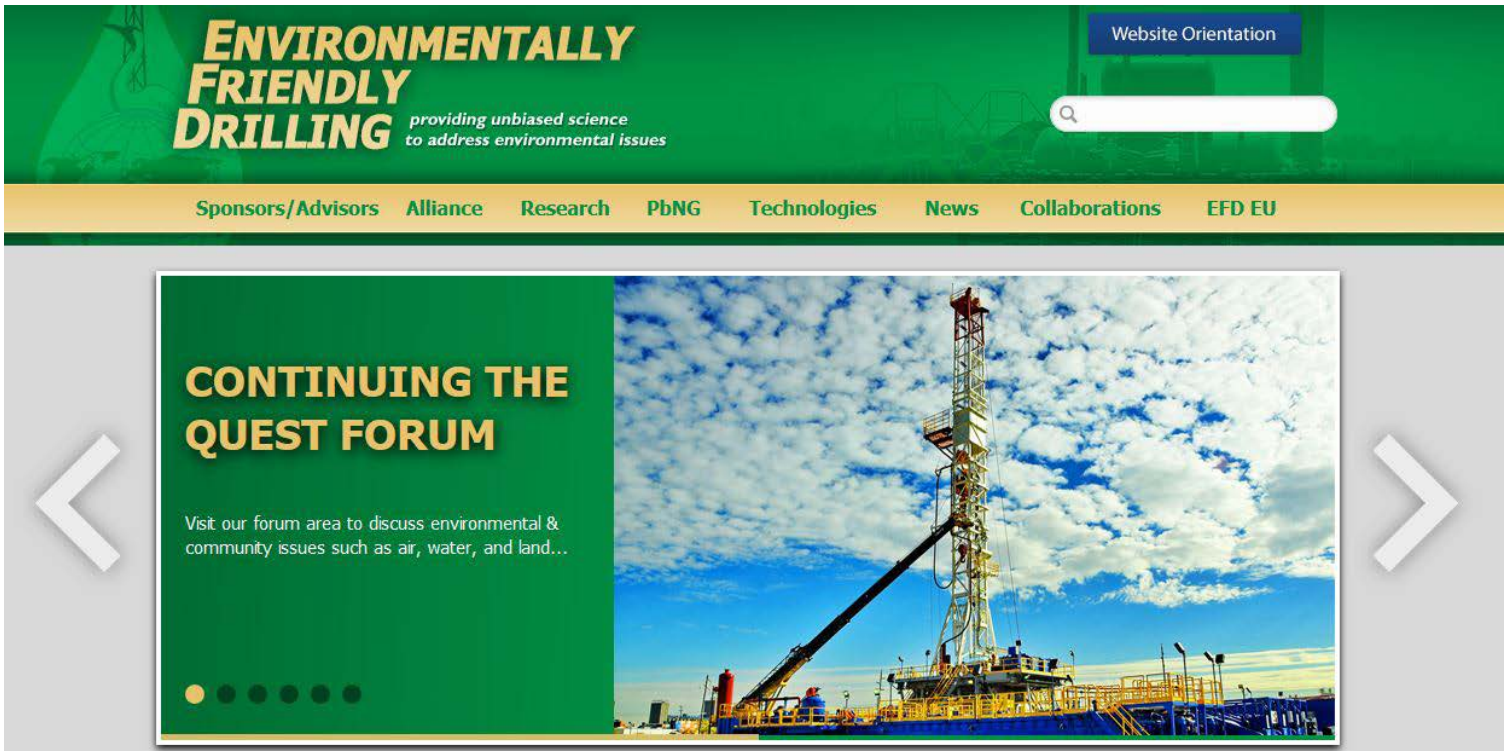
Research Conducted: Though industry has made great strides in protecting the environment while increasing natural gas production in the U.S., producers face continual challenges to effectively produce more natural gas in environmentally sensitive areas. Houston Advanced Research Center (HARC) and its partners offer options to address environmental issues of oil and gas operations in environmentally sensitive ecosystems.

The Environmentally Friendly Drilling (EFD) program, a collaborative project led by HARC, combines new low-impact technologies that reduce the footprint of drilling activities, integrates light weight drilling rigs with reduced emission engine packages, addresses on-site waste management, optimizes the systems to fit the needs of specific development sites, and provides tools to enhance industry's stewardship of the environment.

The program leveraged on-going research in order to move technologies closer to field application and subsequent commercialization. The research team focused on technologies for developing unconventional energy resources that can be used in environmentally sensitive areas to maintain a good standard of living and preserve quality of life. The program included participants from environmental organizations, academia, state and federal agencies, government laboratories, and industry.

Results:

- Created an information site that enables users to learn about natural gas resources available in Arkansas and explains the steps followed by natural gas development companies, from gaining access to land through sending gas to marketplace. For each step in the process, the site provides information about state and federal regulatory requirements that developers must follow.
- Collected air emissions data and used it to develop a methodology for estimating/ measuring emissions from a natural gas hydraulic fracturing operation. The information can be



Environmentally Friendly Drilling project website, http://www.efdsystems.org/.

The Environmentally Friendly Drilling Systems Program

applied to other similar sites and used to help ensure that future air quality regulations are based on the best possible data.

- Developed a computer based model to select complementary environmentally friendly technologies for energy and petroleum (E&P) operations along with an EFD scorecard to measure performance. The scorecard concept engages all stakeholders including industry, academia, and environmental organizations in identifying technologies and systems that can be used to recover unconventional natural gas reserves with the lowest possible environmental footprint.
- Conducted a series of studies aimed at measuring the effectiveness of an EFD program. Focus groups, interviews, and household surveys were used to collect data around the U.S. where energy development is an integral part of the local society. The findings revealed that over 8 in 10 individuals believed that natural gas operators must adopt and use more environmentally friendly drilling practices.
- Commercialized technologies that treats and reuses produced water. Developed alternate rig power to reduce operating costs and emissions. Identified and tested technologies and equipment to reduce access road and well pad footprints, and to optimize EFD technologies in E&P activities. All of these technologies are at the tipping point of profitability and acceptance by the industry. If the costs of their processes can be reduced, and their benefit to low impact drilling realized by the public and policy makers, then many unconventional natural gas developments that are uneconomic today could become economically viable in the future.
- Tested new types of disappearing roads in a desert like environment to measure their effectiveness and ability to protect sensitive environments from conventional road construction and usage damage. The program developed a layered mat, roll-out road system design using composite building materials to minimize the environmental impacts of well pad access roads.

Ongoing Research: A follow-on project to this work—10122-06—is helping to dentify, develop, and transfer critical, cost effective, new technologies. A project summary for 10122-06 is available on p. 49 of the UCR Bin #2 Research Portfolio Report.

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Lead Performer: Houston Advanced Research Center

Richard Haut, Houston Advanced Research Center, (281) 364-6097, rhaut@hard.edu

Project Number: 08122-35

Period of Performance: 7/2009-11/2012

Read/download the final report.

Reducing the Environmental Impact of Gas Shale Development: Advanced Analytical Methods for Air and Stray Gas Emissions and Produced Brine Characterization

Objective: Accurate and consistent practices for characterizing potential impacts and/or waste streams associated with shale gas development assist in the evaluation of environmental aspects associated with shale gas extraction. The objective of this project is to evaluate current sampling and testing technologies and develop practical guidance for:

Baseline Sampling & Stray Gas Investigation: development of a practical protocol for baseline water quality programs based on an improved understanding of the variability associated with sampling methodology and temporal factors. Understanding the key drivers for variability in dissolved methane concentrations is an important step to improving baseline sampling programs and stray gas identification.

Advanced Analytical Air Monitoring: development of a protocol for measurement of air emissions from drilling operations, frac spread equipment, and storage units using Open Path Fourier Transform Infrared (OP-FTIR) instrumentation, integrated weather sensors, and backward Lagrangian stochastic (bLS) techniques. Producers will benefit from real-time data collection, improved delineation of air emissions, and quantification of emission rates.

Produced Water Characterization: evaluation of tools and techniques for on-site analysis of key chemical and microbial constituents in flowback/produced water to facilitate cost-effective reuse, treatment, and/or disposal. Documentation of new "field ready" products will enable rapid analysis of produced water and improved decision making for water treatment.

A critical component of this project is participation from our Technical Advisory Steering Committees (TASC), consisting of representatives from industry, government organizations, regulatory agencies, non-governmental organizations, and academia. TASC members provide recommendations and feedback on workplans, field programs, and results.

Research Conducted: Phase I (2013-2014) and ongoing Phase II (2014-2016) activities for the three principal components of the project are described below.

Baseline Sampling & Stray Gas Investigation: in Phase I, the study evaluated the effect of three common sampling methods on the variability of dissolved gas, isotopic composition, and groundwater chemistry at a series of private water supply wells in northeastern Pennsylvania. In addition, a complete review of current regulations and guidance for baseline sampling programs was completed. The Phase II field program is currently underway to i) quantify temporal variability in dissolved methane concentrations, ii) determine the impact of the pressure tank on dissolved gas concentrations at residential wells, and iii) assess whether water use has a discernible effect on analytical results.

Advanced Analytical Air Monitoring: In Phase I, several preliminary trials were conducted using a controlled release of methane to determine the OP-FTIR instrumentation's ability to pinpoint a source. Ambient measurements were taken downwind of construction activities as a means to test the equipment's capability to detect and delineate air emissions under a field setting. In Phase II, the OP-FTIR, integrated weather sensors, and bLS will be deployed for emission assessment of upstream oil and gas operations Field sites have been identified and are awaiting approval from participating oil and gas operators.

Produced Water Characterization: In Phase I, analytical instrumentation to measure total organic carbon; benzene, toluene, ethylbenzene, and xylenes (BTEX); and biologicals in brine were evaluated using actual produced water. Treatment technologies, such as hollow tube microfiltration, ceramic filters, and membranes, were tested to evaluate the removal efficiencies for total suspended solids. Work proposed for Phase II includes the addition of biological monitors, new field sites in a diversity of shale plays and development of technology summaries to support produced water analyses.

Results: Key findings and recommendations from the Phase I program are as follows:

- Baseline regulations and guidance vary considerably between state agencies, national/ regional organizations, and international agencies, making compliance with baseline sampling requirements challenging for operators in multiple locations.
- Sampling method can impact observed dissolved methane concentrations, particularly at wells with methane concentrations approaching or exceeding solubility. A closed-system sampling device that minimizes loss of gases to the atmosphere is better suited for collection of effervescing or near-saturation water samples from residential water wells.

Reducing the Environmental Impact of Gas Shale Development: Advanced Analytical Methods for Air and Stray Gas Emissions and Produced Brine Characterization

- Preliminary trials were successfully performed to i) select optimal geometric and equipment positioning configurations for the OP-FTIR and ii) optimize collection of chemical concentration and meteorological data. The OP-FTIR and integrated weather sensors successfully delineated the source of methane at preliminary field trials.
- Preliminary trials of treatment and analytical technologies yielded promising results. Approximately 16,000 gallons of brine were passed through coated and uncoated membranes without any change in the throughput rate and pressure. No significant fouling was noted with either of the filters. Turbidity was reduced from 140 NTU to values between 2 and 11 NTU. Real-time measurement of organic components in produced water was successfully achieved using a portable GC/MS.

Ongoing Research: GSI began the Phase II field program in northeast Pennsylvania on April 27, 2015. Sampling was conducted at eight residential water wells using a closed system sampling device (tested in Phase I). Quarterly sampling events will be conducted to quantify temporal variability in dissolved gas concentrations, isotopic composition, and general water quality.

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Lead Performer: GSI Environmental Inc.; John Connor, 713-522-6300, jaconnor@gsi-net.com

Project Number: 11122-45

Period of Performance: 6/2013-6/2016

Additional information about this project is available on the RPSEA website.

Measurement of Hydrocarbon and Greenhouse Gas Emissions from Uncharacterized Area Sources

Objective: To develop and apply a sensitive, cost-effective method to measure carbon dioxide, methane, and non-methane hydrocarbon emissions from sources, including produced water ponds, land farms, natural (and human-enhanced) geological formation seepage areas, and soils near wells in Utah's Uintah Basin.

Research Planned: These sources have never been quantified before, but likely contribute significantly to overall ozone-forming hydrocarbon and greenhouse gas emissions.

Project researchers will modify a U.S. Environmental Protection Agency Surface Emission Isolation Flux Chamber and use the enhanced version to measure emissions from five produced water disposal facilities, three land farm facilities, soil in the vicinity of at least 20 wells, and soil seeps distant from wells at 30 or more strategic locations around the Uintah Basin. A flux chamber measures emissions as the difference in concentrations inside and outside the chamber.

Researchers will compare the flux chamber with a plume characterization/inverse modeling measurement approach and characterize additional facilities as well.

Collected data from the experiments will be used to develop computational models that use hydrocarbon concentrations, meteorological conditions, and other parameters to predict emissions from oil and gas waste facilities, including facilities in the Uintah Basin.

This project will provide cost-effective tools and methods for identifying various emissions from uncharacterized sources in the Uintah Basin and other areas.

Results:

- Finished all the lab methods with the exception of the method for speciated VOC in water.
- Characterized three produced water facilities with the flux chamber method. The third facility was also measured with plume characterization which will be used with inverse modeling in order to compare results to the flux chamber method.

Ongoing Research:

- A fourth produced water facility will be measured in spring 2015.
- Researchers will begin emissions measurements from soils. These measurements will occur on oil and gas well pads (to quantify subsurface leaks) and on other surfaces, including exposed oil shale and oil sand, near a fault zone, and in pressurized and unpressurized oil and gas fields. Measurement sites are being selected for the study which will begin summer 2015.

NETL Contact: Sandra McSurdy, Sandra.McSurdy@netl.doe.gov

Lead Performer: Utah State University

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Project Number: 12122-15

Period of Performance: 05/2014-05/2016

Additional information about this project is available on the RPSEA website.

Reconciling Basin-scale Top-down and Bottom-up Methane Emission Measurements for Onshore Oil and Gas Development

Objective: This study aims to develop independent estimates of methane emissions using top-down and bottom-up measurement approaches and then to compare the estimates, including consideration of uncertainty. Such approaches will be applied at two scales: basin and facility. The relative comparison of the bottom-up and top-down estimates made at both scales will help improve understanding of the accuracy of the tested measurement and modeling approaches.

Research Conducted: This study is being conducted to enable a greater understanding of the variance between different emissions estimates, allow for reconciliation, and will enable more accurate estimations. Accurate estimations are important for meeting environmental regulations and for developing methods for mediating potential environmental risk.

At facility scale, multiple methods will be used to measure methane emissions of the whole facility (controlled dual tracer and single tracer releases, aircraft-based mass balance and Gaussian back-trajectory), which are considered top-down approaches. The bottom-up approach will sum emissions from identified point sources measured using appropriate source-level measurement techniques (e.g., high-flow meters). At basin scale, the top-down estimate will come from boundary layer airborne measurements upwind and downwind of the basin, using a regional mass balance model plus approaches to separate atmospheric methane emissions attributed to the oil and gas sector. The bottom-up estimate will result from statistical modeling (also known as scaling up) of measurements made at selected facilities, with gaps filled through measurements and other estimates based on other studies.

Results:

- The top-down team analyzed the data collected in the Denver Julesberg Basin in the Fall 2014 and finalized emission estimates for 14 well sites, 1 compressor stations and 1 pipe switch yard. Estimated emissions normalized by monthly average production are quite variable and do not seem to correlate with production statistics or the age of the well. The geometric mean for the normalized emissions at well pads is 1.6%.
- The magnitude of emission estimates is first driven by the type of facility, with larger operations such as processing plants showing higher emissions. One multiwell pad with a malfunction exhibited very high emissions mostly due to flashing vapors from tanks being released directly to the air. The emissions anomaly at that site had been detected by the NOAA Mobile Lab.

Ongoing Research:

- The mobile lab team has been working on improving the data QA/QC for the Picarro isotopic methane analyzer. Two night time drives on the same roads during different seasons suggest a strong seasonality of the contribution from agricultural methane sources.
- A first-pass sampling plan, detailing sources excluded and included, was developed including an estimate of the facility count for the fall 2015 campaign. An analysis was performed to identify that the eastern half of the chosen second basin, an 8 county area, was the preferred location for the project.
- The Fall campaign will include basin scale, top-down estimates that include boundary layer airborne measurements upwind and downwind of the basin, using a regional mass balance model plus approaches to separate atmospheric methane emissions attributed to the oil and gas sector. The bottom-up estimate will result from statistical modeling of measurements made at selected facilities, with gaps filled through measurements and other estimates based on other studies.
    - An approximate target range for number of facilities includes:
        - Well pads – 35 to 60
        - Compressor stations – 11 to 20
        - Other small oil & gas facilities (not distribution) – 8 to 14
        - Non-oil and gas sources (e.g., landfills, livestock facilities, etc) – 1

NETL Contact: Sandra McSurdy, Sandra.McSurdy@netl.doe.gov

Lead Performer: Colorado School of Mines

Dag Nummedal, Colorado School of Mines, 303-384-2506, nummedal@mines.edu

Project Number: 12122-95

Period of Performance: 8/2014-9/2016

Additional information about this project is available on the RPSEA website.

Continuous, Regional Methane Emission Estimates in Northern Pennsylvania Gas Fields Using Atmospheric Inversions

Objective: To measure emissions over large areas to account for regional trends. Researchers will quantify both fugitive and total methane emissions from the Marcellus gas production region in north-central Pennsylvania.

Research Conducted: Previous fugitive emissions were based on individual component measurements, which led to the creation of emissions factors. Existing emissions estimates are based on those factors, activity data, and field measurements. Because emissions vary over time and by production facility and operators, current estimates are error-prone. Accurate, comprehensive, and continuous monitoring of the rate of leakage from shale gas production must occur to help document the impact of greenhouse gases and evaluate efforts to reduce emissions.

This study is focused on detecting changes in emissions caused by changes in gas production activity over time. The project, when completed, will provide the most comprehensive shale gas production emission measurements to date, from any location. The technology created through this work can lead to effective measures for minimizing fugitive emissions once leakage rates are quantified and the locations of the leakage are determined.

The team completed mobile emission sampling campaigns in three Pennsylvania counties, analyzed the resulting data, and categorized thermogenic and biogenic emissions sources. The team also configured a Weather Research and Forecasting - Four Dimensional Data Assimilation (WRF-FDDA) atmospheric modeling system for network design.

A geographic information systems (GIS) database is being developed with information about wells, landfills, wetlands, and other methane sources in Pennsylvania and New York. The team is constructing spatially-resolved methane emission estimates from livestock farming based on agricultural data provided by Penn State's College of Agriculture. If the information can be located, the team will include gas pipeline GIS data in the database as well. The team is also documenting shale gas well locations. To generate emission maps at 3 km resolution, researchers will incorporate EPA emission factors with the spatially distributed activity data.

Results:

- Created an initial inventory of methane emissions and coupled it to the WRF-FDDA system. Using that modeling system, the locations of four tower-based methane sensors were optimized.
- Mobile sampling experiments conducted in 2014 show that emissions from unconventional gas wells are most likely intermittent and levels are dependent on the stage of the well development. WRF results agree with observed contributions from unconventional wells.
- Based on four drive-around mobile campaigns in PA and NY, first estimates of methane emissions near gas wells is approximately 2% of production.

Modeled project data has been made publicly available on the project webpage.

Communication tower used for deployment. The Cavity Ring-Down Spectroscopy (CRDS) analyzers are installed at the facility near the tower and a tube is deployed on the structure.

Continuous, Regional Methane Emission Estimates in Northern Pennsylvania Gas Fields Using Atmospheric Inversions

Ongoing Research:

- PI is coordinating the National Oceanic and Atmospheric Adminstration (NOAA) aircraft flights with the tower installations in May. Megacores will also be collected in the region. Two counties in central PA will be the focus of the sampling.
- Team members have been preparing for the month-long deployment of the NOAA aircraft in May 2015 which will be instrumented with a continuous CRDS $CO_2/CH_4/CO/H_2O$ analyzer and an ethane analyzer. Flask samples will also be collected aboard the aircraft and measured for the same species as the tower samples, including C^{13}-CH_4.
- The research team has designed and built a system for collecting samples of air in bags in addition to the flasks. These measurements will give spatial context and scalability to the C^{13}-CH_4 measurements being made continuously by the Penn State team at the towers and on the ground during driving campaigns.
- Methane inventory data is being gathered and includes fugitive emission estimates from natural gas activity during transmission and distribution and emissions from natural seeps and wetlands. Researchers will perform simulations of wetland CH_4 emissions using a high resolution vegetation model.

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Project Number: FE0013590

Period of Performance: 10/2013-9/2016

Additional information about this project is available on the NETL Website.

Assessing Fugitive Methane Emissions Impact Using Natural Gas Engines in Unconventional Resource Development

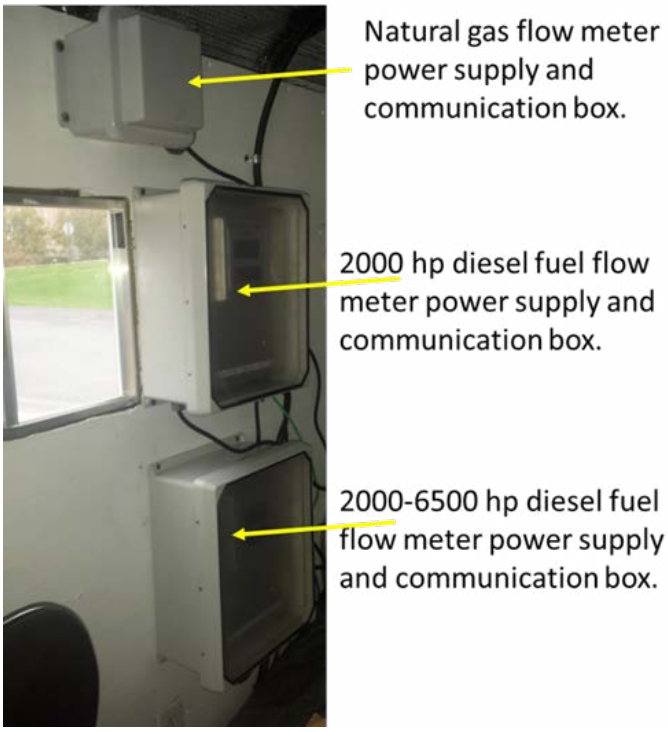
Objective: To characterize the effects of fugitive methane emissions from dual-fuel and dedicated natural gas engines employed on well sites.

Research Conducted: The collaborative team will identify and characterize the impacts of fugitive methane emissions from engines using natural gas and engines using a dual fuel of natural gas and diesel at unconventional gas drilling sites. These engines are beginning to replace diesel-powered units currently in use in well site operations. Specifically, the team will measure the fugitive methane emissions at well site locations focused on the main contributors – unburned exhaust methane and crankcase vent emissions, along with methane emissions from onsite fuel equipment.

Through the characterization of engine-duty cycles of candidate dual-fuel engines and the measurement of fugitive methane and diesel-engine emissions in conventional and dual-fuel operation, the project will provide the natural gas industry with information needed to implement low-cost, robust technologies that will mitigate risks to the public, oil and gas personnel, and the environment.

Researchers reviewed the currently available dual fuel and dedicated natural gas equipment being implemented into unconventional well development. Research showed that the prime movers associated with unconventional well development were the hydraulic fracturing engines, drill rig engines, and the on-road vehicles servicing well development – mainly water and sand hauling. Researchers developed a data collection system for fracturing, drilling, and on-road equipment to obtain in-use engine-activity data. A methodology for cycle development has been created. The processed activity data is combined with a Markov Chain Monte Carlo method and genetic algorithm to produce representative test cycles. Scaled engines both dual fuel and dedicated natural gas, will be operated over these cycles under controlled laboratory conditions.

They have also obtained non-disclosure agreements from multiple oil and gas companies, as well as, water and sand hauling companies. Data collection for on-road vehicles is completed and represents both Marcellus and Utica activity. In-field data collection for hydraulic fracturing and drilling equipment is ongoing. The team recently completed emissions and fuel efficiency testing with Baker-Hughes at their staging facility in Searcy, AR. This effort focused on a hydraulic fracturing pump unit that was recently commissioned to operate as dual fuel. Emissions data were collected at six points across the engine-operating map. Baker-Hughes and West Virginia University (WVU) also assessed the efficiency of two diesel oxidations catalysts and their ability to mitigate methane emissions. A report is forth coming.



Part of the field test instrumentation.

Assessing Fugitive Methane Emissions Impact Using Natural Gas Engines in Unconventional Resource Development

Results:

- Performed a comprehensive literature review of available dual-fuel and natural gas technologies, well site fueling infrastructure, diesel fuel consumption rates of the prime movers, and emissions regulations.
- The comprehensive review was summarized in a journal article published in a special edition of energy technology.
- The interim report currently being developed for the Baker-Hughes testing will likely be restructured and submitted as a formal publication.
- Updated multiple miniature stand-alone data loggers. These loggers were implemented in on-road prime movers and are collecting activity data for cycle development. On-road data collection has been completed, while off-road continues.
- A scaled dedicated natural gas engine (Cummins-Westport ISL-G 8.9L) has been obtained and installed in the WVU test cell. On-road cycles are currently being operated to establish regressions statistics for selection of the final on-road cycle.
- A Cummins ISX 15L engine is currently being outfitted with a dual fuel system.

Ongoing Research: Researchers continue to work with industry to collect off-road activity data. They are working with Baker-Hughes and other industry leaders in horizontal drilling and well stimulation to obtain additional activity data and in-use emissions and fuel consumption data. They are proactively engaged in the Marcellus Shale Energy and Environment Laboratory (MSEEL) project and will collect additional data at this site - operated by Northeast Natural Energy and the main subcontractor, Schlumberger.

Researchers are currently working with catalyst manufacturers to develop a methane oxidation catalyst for laboratory testing. The laboratory portion of the program will also examine the effects of various gas blends – pure methane (liquified natural gas or LNG), pipeline gas (compressed natural gas or CNG) and two to three additional shale plays. WVU has recently obtained a CNG compressor to blend all gases in their laboratory. Gas blends will contain higher levels of ethane and propane which are typical in shale plays and which could alter the performance of these new technologies.

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Project Number: FE0013689

Period of Performance: 10/2013-3/2016

Additional information about this project is available on the NETL website.

Measurements and Modeling to Quantify Emissions of Methane and VOCs from Shale Gas Operations

Objective: To determine the leakage rates of methane and ozone-forming volatile organic compounds (VOCs) and the emission rates of air toxics from Marcellus shale gas activities at a process level.

Research Conducted: By analyzing and understanding direct emission rates, researchers and industry will have a better understanding of how shale gas development affects air quality. Analyzing methane, VOCs, and other air emissions will improve the characterization of emissions for the technologies and processes used in the Marcellus Shale region and may provide a basis for insight in other regions. This study is being conducted to help explain how fugitive emissions vary depending on technologies in use and the age of a facility. The ultimate dataset of emission rates will be useful in lifecycle analyses, chemical transport models, and policy decision-making.

Project researchers have performed a literature search and compiled existing data on methane emissions from traditional natural gas sources and unconventional operations (shale gas sources). The team also conducted tracer flux experiments at shale and non-shale sites and calibration experiments of the tracer release technique to determine uncertainty bounds for field measurements. The team gathered measurements and compiled data from non-gas sources of methane, such as landfills and agricultural sources.

Initially, seven producing wells and three wells in the flowback stage were sampled in Pennsylvania. In West Virginia, five conventional gas wells were initially sampled. Once researchers honed a method to determine the fractional leakage of methane, they sampled other sites. In 2014, samples were obtained from 30 sites and analyzed. The team continues to perform field sampling and is identifying abandoned wells for further sampling. Field sampling is scheduled to continue until October 2015.

Results:

- Fostered relationships with industry partners and through those relationships, was able to identify specific unit operations at various stages of shale gas development. They arranged access and conducted direct measurements of methane emissions and performed tracer release experiments.
- Sampled ten wells in Pennsylvania. Methane emissions were higher at flowback sites than at producing wells sites. The team determined that the methane emissions rates needed to be normalized to total natural gas production at each site in order to determine the fractional leakage of methane.
- Researchers have performed sampling at 31 facilities with tracer testing. Methane emissions at producing wells were estimated at 1% of production levels.

Ongoing Research:

- The team will be combining emission data with well population data in order to estimate emission contributions from shale and non-shale sources.
- In the spring of 2015, the team will sample at sites in Pennsylvania and study the results based on well age and seasonality. The latter will be tested by identifying 5 wells that will be sampled quarterly over the next year.

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Project Number: FE0014055

Period of Performance: 10/2013-9/2016

Additional information on this project is available on the NETL website.

Fugitive Air Emissions Field Data

Objective: To understand air quality impacts from both short-term emissions and life-cycle greenhouse gas emissions associated with unconventional oil and gas development and production, and to evaluate how these effects can be mitigated.

Research Conducted: A scientifically-based evaluation of air pollutant impacts requires improved quantitative evaluations of emissions, as air pollutants and their emission rates from unconventional reservoirs and the technologies associated with the development of these reservoirs remain insufficiently characterized. Efforts have focused on collecting field-based data sets representative of current operator practices to evaluate both ambient (regional effects) and point-source (specific process component) air emissions. The current efforts focus on the Appalachian Basin.

Researchers collected information about methane and other pollutant emissions from unconventional shale gas operations through monitoring conducted with the mobile air monitoring laboratory and with point source measurements taken using an acetylene tracer technique. The mobile air monitoring laboratory, a trailer that was developed through prior EPAct-driven research efforts, includes a suite of instruments to measure concentrations of pollutants associated with oil and gas development: methane, oxides of nitrogen, particulate matter, volatile organic compounds, ozone, and carbon dioxide. The mobile lab was used to evaluate air quality at a number of on- and off-well pad Marcellus shale drilling sites in various stages of operation, including vertical drilling, horizontal drilling, hydraulic fracturing, flowback, and flaring.

The Maryland Department of the Environment requested that NETL perform baseline air monitoring in northwestern Maryland using the mobile air monitoring laboratory. Collection of ambient air quality measurements are being made pre-development, in anticipation of the lifting of the moratorium on Marcellus Shale development in Maryland. The team conducted spring/summer and fall/winter monitoring campaigns in 2014-2015 and plan to perform follow-up monitoring if or when development occurs for during- or post-development comparisons.

The acetylene tracer technique for point source measurements was recently developed and involves releasing a tracer (acetylene) at or near the emission source and concurrently measuring atmospheric concentration of the tracer and methane downwind of the source, resulting in a calculated methane emission rate from the source. This approach was used at well pads to estimate methane emission rate during well completion, and will be used at natural gas pipeline leaks to estimate leakage rate.

Results of monitoring efforts at various sites are currently being processed into a format that will be useful for calculating new emissions factors using a Bayesian statistical technique. Use of updated emissions factors in atmospheric chemistry and transport models and/or greenhouse gas life-cycle assessment models informs decision makers and allows the assessment of emissions performance for alternative operational scenarios. The updated DOE methodology, combined with field data from Appalachian Basin monitoring, will reduce uncertainties in NETL's shale gas greenhouse gas life-cycle assessment.

Results:

- Refined statistical methods to represent the air quality impact from Marcellus Shale drilling and fracking activities based on the field data.
- Compiled data obtained from the mobile air quality monitoring laboratory during a monitoring campaign designed in collaboration with the West Virginia Department of Environmental Protection (WV DEP). The report was published on the WV DEP's website and is also available as a technical report series (TRS) document and in multiple peer-reviewed publications and conference presentations.
- Conducted a monitoring campaign in Pennsylvania's Allegheny National Forest (ANF) to evaluate regional impact of oil and gas exploration and production activity. Three monitoring sites were chosen with one representative of background air quality. Concentrations of most measured pollutants did not vary significantly between the three sites, suggesting that the monitoring laboratory was far enough downwind of active areas of development and/or production to allow for sufficient dispersion. Ethane was found to be useful as a tracer species for oil and natural gas activity; elevated values are evidence of impact from nearby ethane sources and an indication that production emissions may be significant. Measurements may serve as baseline, or pre-development, conditions for consideration of impacts from future development of Marcellus or Utica shale gas reserves within the ANF.

Fugitive Air Emissions Field Data

- Measurements were collected a short distance from a well pad in Washington County, Pennsylvania from pre-development until the wells were in production. Results are being evaluated for impacts specific to phases of operation.
- Conducted methane/acetylene surveys on public roads, well pad, and well pad access road during flowback at one of the Greene County, Pennsylvania sites. Although researchers were able to detect low concentrations of acetylene downwind of the well pad during some of the surveys, there were no coincident methane peaks. It is possible that during flowback, emissions were episodic and not measurable when the surveys were conducted.

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Project Number: Task 7

Period of Performance: FY2011-2015

NETL's air quality monitoring trailer collecting measurements during active hydraulic fracturing.

Relationships between Induced Seismicity and Fluid Injection: Development of Strategies to Manage Fluid Disposal in Shale Hydrocarbon Plays

Objective: (1) To determine the relationships between fluid injection practices, regional geology and stress regime, and the occurrence of earthquakes and (2) to identify waste disposal strategies for injection that reduce and minimize the triggering of seismic activity, or that ensure that seismic activity is confined to low-magnitude, harmless events.

Research Conducted: The University of Texas at Austin completed two year surveys of earthquake activity in the Fort Worth Basin of Texas, the Eagle Ford of Texas, the Bakken/Williston Basin of North Dakota and Montana and the Haynesville of Texas and Louisiana.

In the Fort Worth Basin, the project identified 67earthquakes occurring during the 2009-2011 survey period, of which only eight were reported by the U.S. Geological Survey. Of these 67 earthquakes, all the reliably-located events occurred in eight clusters, and each of these clusters was situated within 3.2 km of one or more high-volume injection disposal wells, i.e., wells having maximum monthly injection rates exceeding 150,000 barrels/month. This suggests that higher-volume injection wells in the Fort Worth Basin did trigger earthquakes; however, there were numerous such high-volume wells that did not have earthquakes nearby. It is unclear why earthquakes occurred near some high-volume wells and not others.

In the Eagle Ford, the project identified 62 earthquakes occurring during the 2009-2011 survey period, of which only four were reported by the U.S. Geological Survey. Of these 62 earthquakes, the majority (47 events) occurred following increases of fluid extraction (not injection) at nearby wells. The most reasonable conclusion is that most earthquakes identified in the Eagle Ford are triggered by petroleum operations—mostly by production/extraction of petroleum and water. But the triggering mechanism is clearly different than in the Fort Worth Basin, where earthquakes are associated with injection wells.

In the Bakken/Williston Basin, the project identified only nine earthquakes occurring during the 2008-2011 study period. Of these, only three were near injection wells. Thus earthquakes in general and possibly-triggered earthquakes in particular were far rarer in the Bakken/Williston Basin region than in the Fort Worth Basin or the Eagle Ford regions of Texas.

In the Haynesville of Texas and Louisiana, the project identified 50 earthquakes from the February 2010 through 2012 study period. The project identified a cluster of activity near Bienville Parish, LA that had not been previously reported. This included 16 earthquakes between magnitudes 1.2-2.7 occurring over just a few months (August-October 2011). These smaller magnitude earthquakes without a preceding larger event for the Bienville Parish activity are most consistent with classification as a seismic swarm.

The project results indicate that the relationship between seismicity and injection is not similar in the four geographic regions studied. Injection disposal triggered nearby earthquakes in the Fort Worth Basin; fluid extraction triggered earthquakes in the Eagle Ford; earthquakes were virtually non-existent in the Bakken; and two earthquake sequences occurred within the Haynesville including a magnitude 4.8 triggered event, but otherwise there was little apparent triggered activity. The observation that injection/seismicity relationship is significantly different in different geographic regions is important and has implications for managing injection waste disposal operations. It implies that before crafting regulations or implementing hazard-reduction actions in any particular local, surveys should be undertaken to access the relationship between injection and seismicity within that local. The project highlights the continued need for investments in monitoring seismicity in areas of active oil and gas activities.

Results:

- The relationship between earthquake activity and injection/extraction varies greatly among different geographic environments.
- When triggered earthquakes occur in environments where there is adequate seismic monitoring, knowledge of injection volumes at nearby locations, and sufficient information about subsurface structure, the earthquakes tend to occur approximately at depths at or beneath the depths of injection (often apparently in the basement), injection volumes tend to be relatively high (100,000 barrels/month or more), and there is likely to be a fault situated within a few km of the epicenters and the injection wells.

Relationships between Induced Seismicity and Fluid Injection: Development of Strategies to Manage Fluid Disposal in Shale Hydrocarbon Plays

- Where there is adequate information available concerning subsurface rock properties, structure and injection/extraction history including volumes and pressures, geomechanical modeling to evaluate Coulomb stresses provides a valuable tool for assessing whether past seismicity may have been triggered or whether future seismicity is likely to be triggered.
- The most significant still unresolved research question concerning injection-triggered seismicity is why earthquakes occur near some injection wells and not near other wells having similar injection volumes.

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Project Number: 11122-27

Period of Performance: 3/2013-3/2015

Additional information on this project is available on the RPSEA website.

4D Integrated Study Using Geology, Geophysics, Reservoir Modeling, and Rock Mechanics to Develop Assessment Models for Potential Induced Seismicity Risks

Objective: The objectives of this project are to understand the conditions in central Oklahoma that have increased the seismicity and potentially generated induced seismicity, via an innovative and highly integrated study of the geology, geophysics, reservoir and geo-mechanical conditions in the target area. The lessons learned in study are intended to be transferable to other areas where the possibility of induced seismicity is an issue. A specific issue is developing a list of "best practices and methods" standards to address the likelihood and risk of induced seismicity. This study will integrate a variety of methods and data at different scales to evaluate what properties may be most helpful in rigorously identifying both induced seismicity and the potential for induced seismicity, based on modeling and physical measurements.

Research Conducted: This study will provide lessons learned that can be transferred to other locations in which the possibility of induced seismicity is an issue. Best practices, methods, and standards will be developed to guide the assessment of the likelihood and risk of induced seismicity. Additionally, through the integration of methods and data at different scales, researchers will be able to evaluate the properties that allow for the identification of both induced seismicity and the potential for induced seismicity, using modeling and physical measurements.

Gravity surveying, expansions and improvements to the team's seismograph network, seismic monitoring, and 3-D modeling efforts were started. The seismic monitoring portion of the research, entitled OKRaH, for Oklahoma Risk and Hazard, includes the deployment of temporary seismic stations (see the accompanying figure). Each seismic station has a seismometer, recording device, batteries and solar panels. Data from some of the stations is collected immediately through the Oklahoma Geological Survey (OGS) monitoring system, while other data is recorded locally and collected regularly.

In total, 12 temporary seismic stations will be deployed in central Oklahoma as part of the existing seismic monitoring network operated by the OGS. The data from these stations will be incorporated into routine earthquake analysis. The data will also be archived at the IRIS data management center (www.iris.edu).

The research team will analyze the data to better understand active faults, subsurface rocks and their properties, ground motion, and any changes that may be causing seismic activity in Oklahoma. They will build, test and update a causal multivariate and volumetric geologic interpretation, with data from existing well and well-log databases, rock-mechanics, rock properties, and seismic imaging. This interpretation will be tested against acquired gravity data and the OKRaH data and any variance in observed data and modeled geophysical data will be evaluated.

Results:

- Built a multidisciplinary research group, including members from the Mewbourne College of Earth and Energy at the University of Oklahoma, the OGS, and industry. Seismic monitoring has begun.
- Developed and successfully tested a key algorithm.
- Modeling of injection continues with analysis of the Wilzetta North oil field to study the effect of wastewater injection in two disposal wells.
- Gravity surveying and precision GPS data continues with over 1679 data points completed.
- Seismogragh Network: Earthquakes continue in Oklahoma at an increased rate and are continuing to be recorded on the OKRaH network and the Oklahoma regional network. One new permanent station was installed in April 2015 in south-central Oklahoma near Marietta, Oklahoma.
- The software development for the 3-D modeling effort continues to progress very well. Tests use two approaches to the calculation of gravity effects of vertical prisms in the model, and in each case, the basic software for the calculating the mass of its elements is much faster than in previous versions while maintaining very high precision.
- The fault database continues to grow as more faults from published literature are being identified and added to the database. A preliminary compilation of the fault database was made available as on OGS Open File Report OF3-2015 titled "Preliminary Fault Map of Oklahoma" with digital files and references available on the OGS website – www.ogs.ou.edu.

4D Integrated Study Using Geology, Geophysics, Reservoir Modeling, and Rock Mechanics to Develop Assessment Models for Potential Induced Seismicity Risks

Ongoing Research: The University of Oklahoma will continue gravity surveying and data reduction efforts. They will continue their investigations of target areas for detailed modeling of fluid flow and geomechanics. They will continue exploring more sophisticated data assimilation schemes for challenging datasets. This is going to be largely based on a literature review. They will also implement a support-vector-machine based data assimilation scheme to test on small-scale datasets. They will continue to install the upgraded seismic equipment in their network. The development of the 3-D model of the study area and the software required to make the geophysical calculations will be a continuing effort.

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Project Number: 12122-91

Period of Performance: 6/2014-6/2016

Additional information about this project is available on the RPSEA website.

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