Oil & Natural Gas Technology

DOE Award No.: DE-FE0024297

Quarterly Research Performance Progress Report

(Period ending: 12/31/2016)

Marcellus Shale Energy and Environment Laboratory (MSEEL)

Project Period: October 1, 2014 – September 30, 2019

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NETL

Office of Fossil Energy

Quarterly Progress Report

October 1 – December 31, 2016

Executive Summary

The objective of the Marcellus Shale Energy and Environment Laboratory (MSEEL) is to provide a long-term field site to develop and validate new knowledge and technology to improve recovery efficiency and minimize environmental implications of unconventional resource development.

This quarter continued to be very active, as the team continued in-depth analysis of more than four terabytes of data collected during well drilling, completion and initial production. Production started on 15 December, 2015, but has been choked due to constrained demand, which has limited compete production documentation. Plans have been approved and are underway to perform production testing during 1QCY2017. As part of testing production has been choked back on all MSEEL-MIP wells except the MIP 3H, which is fully instrumented. The team held a program review meeting on November 1, 2016 to discuss project progress, plans for publications, and for team breakout sessions to discuss technical work plans and sample (rock, water, etc.) workflows to ensure that all project partners had access to needed materials. This meeting was attended by approximately 68 people, including representatives from WVU, OSU, national labs, and the US DOE. Monitoring of the wells continued through this quarter during the initial production phase with the fiber-optic DTS system.

Quarterly Progress Report

October 1 – December 31, 2016

Project Performance

This report summarizes the activities of Cooperative Agreement DE-FE0024297 (Marcellus Shale Energy and Environment Laboratory – MSEEL) with the West Virginia University Research Corporation (WVURC) during the fourth quarter of the FY2016 (July 1 through September 30, 2016).

This report outlines the approach taken, including specific actions by subtopic. If there was no identified activity during the reporting period, the appropriate section is included but without additional information.

A summary of major lessons learned through the end of CY2016 is provided as bullet points and expanded in this and previous reports. Plans call for a significant presentation and publication covering these aspects in the 2QCY2017.

1) Synthetic based drilling mud is ecofriendly as well as helps with friction which resulted in faster drilling and reduced costs while leading to drilling waste from both the vertical and horizontal portions of the wells that passed all toxicity standards.
2) Microseismic monitoring does not completely define propped fractures and the extent of stimulated reservoir volume from hydraulic fracture stimulation. Requires integration of data from core, logs and slow slip seismic monitoring.
3) Complex geology in laterals can lead to intercommunication between stages and reduced fracture stimulation efficiency. This can be mitigated with limited entry (engineered completions) that significantly improves fracture stimulation efficiency. NNE has continued the practice in subsequent wells. Planned production logging will help to define production efficiency.
4) The significant part of air emissions are in truck traffic not in drilling and fracture operations on the pad. Emissions from both the pad and trucking can be reduced with operational modifications such as reducing dust and truck traffic during fracture stimulation (e.g., Sandbox) and from bi-fuel (natural gas-diesel) engine operations.
5) Dual fuel engines demonstrated lower carbon monoxide (CO) emissions than diesel only operation. Dual fuel operations could reduce onsite diesel fuel consumption by 19 to 63% for drilling and 52% for hydraulic stimulation.
6) Biologic activity cannot be eliminated with biocides only delayed. The biologic activity results in a unique biota that may affect operations. There may be other methods to control/influence biologic activity.
7) Water production changes rapidly after fracture stimulation in terms of volume (500 bbl/day to less than 1 bbl/day) and total dissolved solids (TDS from freshwater to 100 to 150g/L). Radioactivity is associated with produced water not drill cuttings.

Topic 1 – Project Management and Planning

Subtopic 1.1. – Project Management

Approach

The project management team will work to generate timely and accurate reporting, and to maintain project operations, including contracting, reporting, meeting organization, and general oversight.

Results and Discussion

This quarter has continued to be very active, as the team has started in-depth analysis of the data collected during well development. The team held a program review meeting on November 1, 2016 to discuss project progress, plans for publications, and for team breakout sessions to discuss technical work plans and sample (rock, water, etc.) workflows to ensure that all project partners had access to needed materials. This meeting was attended by approximately 50 people, including representatives from WVU, OSU, and the US DOE.

The project team is tracking four milestones in this budget period.

1. Complete/Stimulate Production Wells (NNE 3H, 5H) – 12/31/2015 (Complete)
    a. Completed with successful gathering of subsurface data from the fiber-optic cable and from advanced logging.

2. Complete Preliminary Analysis of Surface and Subsurface Data – 3/31/2016
    a. Core was received, CT scanned and visually logged, an initial round of samples have been distributed to investigators. Preliminary examination from geomechanical logging and fracture analysis have been completed, but results have raised numerous questions that need to be addressed, including the effectiveness and the direction of fracture stimulation. Analysis of cuttings, produced water and air have been completed and are ongoing during production phase.

3. Complete SEM, XRD and PPAL imaging and Core Analysis – 9/30/2016 (was 12/31/2016)
    a. Initial results are coming in and will be available this summer. We have taken a very careful approach to calibrate results among labs, including WVU, OSU, NETL and Schlumberger. This has taken longer than expected, but should be completed well before 9/30/16

4. 3D Fracture Modeling Complete – 12/31/2016. (was 6/30/2016)
    a. This is advancing very quickly with the integration of microseismic and fracture logs (see write up for this quarter). Still need to integrate the sonic and temperature data from the fiber-optics. This should be well along by the end of summer.

Subtopic 1.2. – Database Development

Approach

We will use CKAN, open source data portal software (www.ckan.org). This platform is used by NETL-EDX and Data.gov among other organizations and agencies. We will use this platform to store, manage, publish and find datasets.

Results and Discussion

We have updated production data and will move to near-realtime posting of production data (gas and water) from all four wells at the MSEEL site. Example plots show daily and cumulative gas and water production from the MIP 3H and MIP 5H (Figures 1.1 and 1.2). As evidenced by the increase in gas and water production, the MIP 3H is moving to unconstrained production and will be subject to production testing in 1QCY2017 (Figure 1.3).

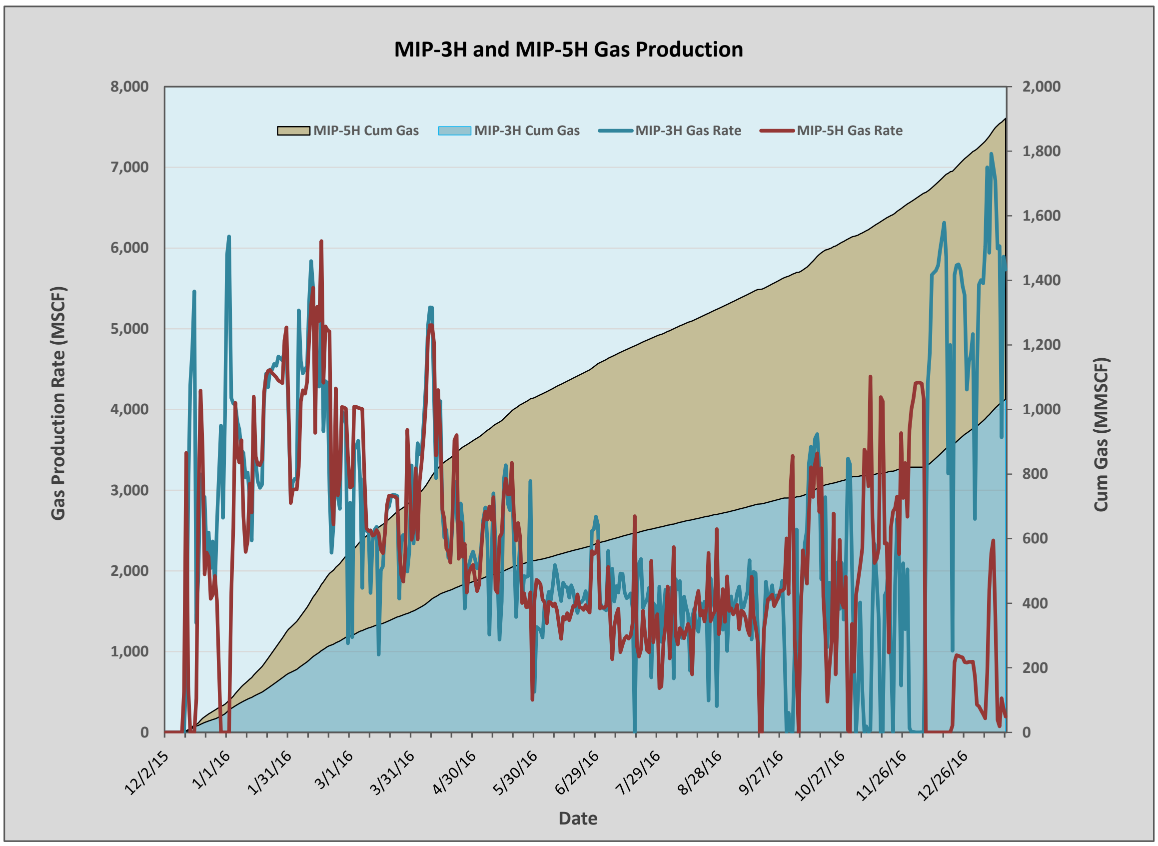


Figure 1.1 – Daily and cumulative gas production since initial production for the MIP-3H and MIP-5H at the MSEEL site. Note the increase in production in December, 2016 for the MIP-3H and the decrease in the MIP-5H. We are moving to produce the MIP-3H for production testing in 1QCY2017.

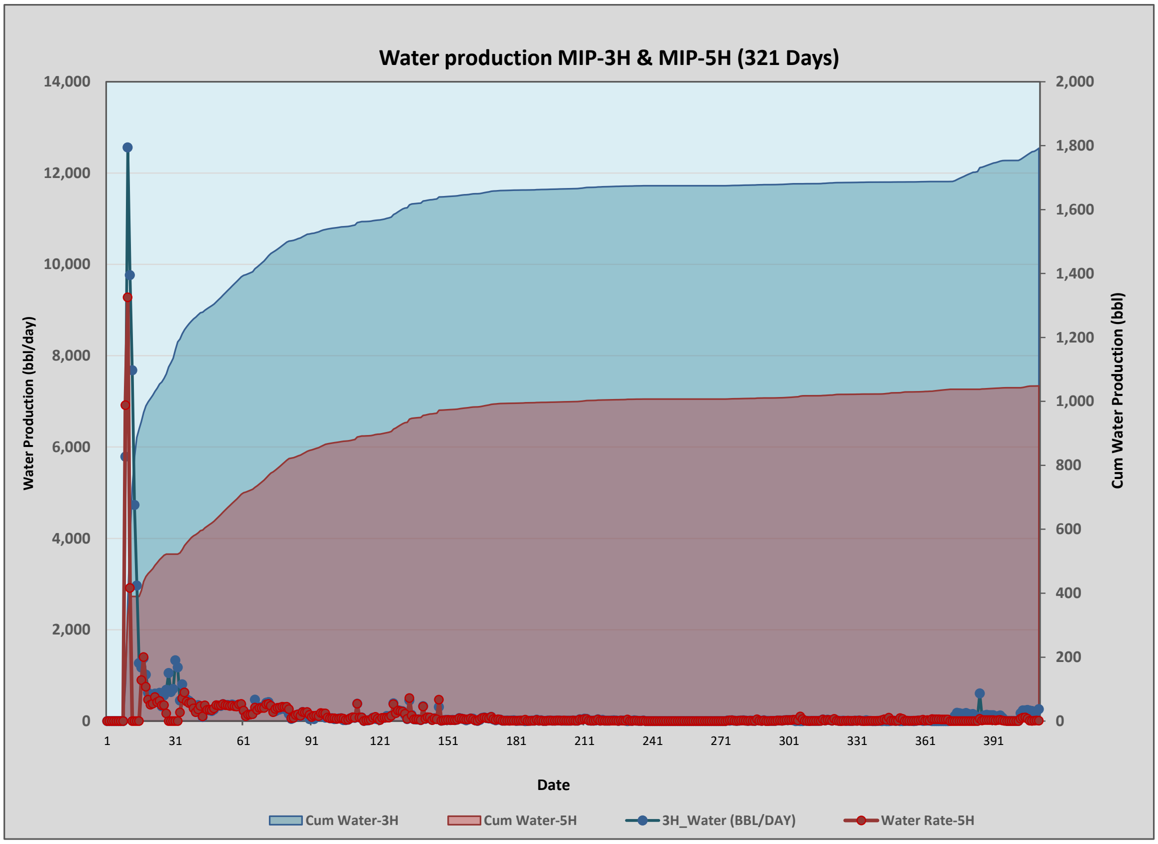


Figure 1.2 – Daily and cumulative water production since initial production for the MIP-3H and MIP-5H at the MSEEL site. Note the significant increase in water production in December, 2016 for the MIP-3H and the small decrease in the MIP-5H. We are moving to produce the MIP-3H for production testing in 1QCY2017.

Products

Updated production data for all four MIP wells at the MSEEL site. Updated DTS data for the MIP3H.

Plan for Next Quarter

Reorganize the portal and work to move some data (e.g., production) and results to the publically available website (www.mseel.org). Production testing of the MIP-3H during 1QCY2017.

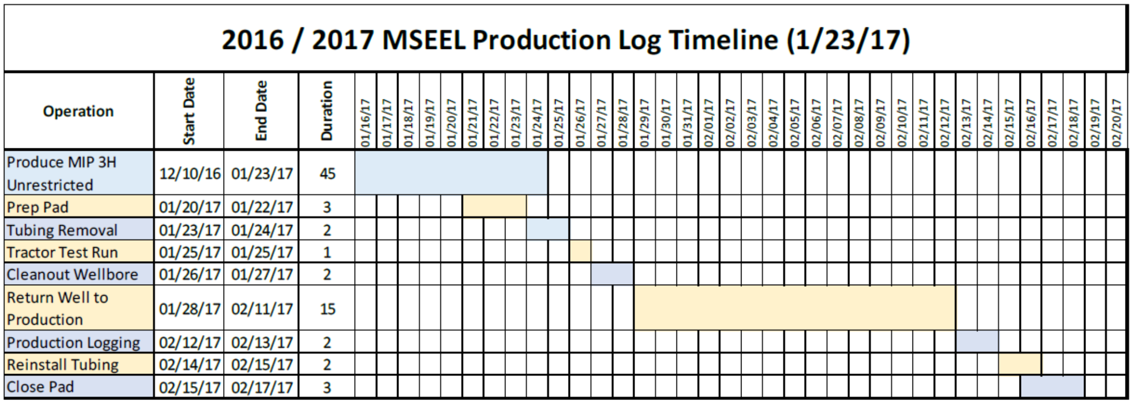


Figure 1.3 – Operational timeline for production testing of the MIP-3H during 1QCY2017.

Topic 2 – Geologic Engineering

Approach

The geologic engineering team will work to generate to improve the effectiveness of fracture stage design. Evaluating innovative stage spacing and cluster density practices to optimize recovery efficiency. The team will use a data driven approach to integrate geophysical, fluid flow and mechanical properties logs, microseismic and core data to better to characterize subsurface rock properties, faults and fracture systems to model and identify the best practices for field implementation, and assess potential methods that could enhance shale gas recovery through experimental and numerical studies integrated with the results of the production wells at the MSEEL site.

Results and Discussion

Task 2a – Rock Analysis

Results and Discussion

The permeability measurement experiments for 3 additional core plugs from the science well have been completed. Two of the plugs (Sample Numbers 99 from the depth of 7542.9 feet and Sample Number 102 from the depth of 7545.9) exhibited permeability values in micro darcy range which are high for the shale and as compared to our previous measurement results. After further inspection, it became evident that both plugs were fractured (visible fracture). It is believed that these fractures have been formed during the process of cutting the plugs. The third plug (Sample Number 80 from the depth of 7523.9 feet) exhibited similar permeability values as the previous samples. The permeability measurements were performed at higher pore pressures (600-1200 psia) with Helium. The purpose of these experiment was to investigate the flow regime in the shale.

The analysis of the production and stimulation data from the existing horizontal wells at the MIP site as well as other horizontal Marcellus shale wells in the region has been completed. The wireline data are in progress. The drilling and wireline logs data are based on different intervals and they are currently being evaluated to obtain a correct match in terms of depth and formation contacts prior to finalizing the correlations.

The analysis of the core plug permeability results indicated that for pore pressures below 900 psia, the flow regime is transition flow and modified Klinkenberg correction is necessary to determine the absolute permeability. For pore pressure above 1000 psia, the flow regime appears to be slip flow and Klinkenberg correction is sufficient to determine the absolute permeability.

Products

Plan for Next Quarter

The permeability and porosity measurements on additional core plugs will be undertaken.

Task 2b – Water Treatment

Our first research activity of produced water treatment focuses on developing an (bio)electrochemical method to remove scale-forming cations as a pre-treatment system for produced water treatment. A two-chamber bioelectrochemical system used in this study contained an anode and cathode chambers separated by a cation exchange membrane. Each chamber contained graphite woven felt electrodes. An electric current was used to create a pH unbalance between the anode and cathode. The high-pH cathlyte was then used to treat raw produced water to remove multi-valent cations as a softening process. Produced water sample was collected at the MSEEL site and used in the study. The treatment method was shown to be effective in removing scale-forming cations.

Results and Discussion

A two-chambered electrochemical system was designed for water softening of produced water treatment (Figure 2.b.1). It consisted of an anode and a cathode chambers separated by a cation exchange membrane (Membrane International Inc., Ringwood, USA). Anode and cathode chambers contained dimensionally stable anode (DSA) electrode (geometric dimension of $5.5 \times 5.5\ cm^2$, 0.1 cm thick, Edgetech Industries LLC., Medley, FL, USA) and stainless steel mesh electrode (geometric dimension of $5.5 \times 5.5\ cm^2$, 0.1 cm thick, McMaster-Carr., Elmhurst, IL, USA), respectively. The anode and cathode chamber each had a working volume of 170 mL. The synthetic wastewater contained 13.0 g/L (0.222 M) NaCl, 8.39 g/L (0.0573 M) $CaCl_2 \cdot 2H_2O$, 2.15 g/L (0.0226 M) $MgCl_2 \cdot 6H_2O$, pH 6.1 in cathode and pH 10.0 in anode.

Standard electrochemical methods (open circuit potential, electrochemical impedance spectroscopy, cyclic voltammetry) were performed using a potentiostat/galvanostat (Gamry Reference 3000). Open circuit potential (OCP) was 570 – 572 mV over 30 seconds (Figure 2.b.2). To check internal resistance of the reactor, electrochemical impedance spectroscopy (EIS) was examined. EIS showed a ohmic resistance 2.3 (Figure 2.b.3). Cyclic voltammetry (CV) scan was conducted from 0.57 to 1.07 V, then back to 0.57 V with a scanning rate 10 mV/S (Figure 2.b.4).

Figure 2.b.1. The two-chambered electrolysis system for generating high-pH catholyte.

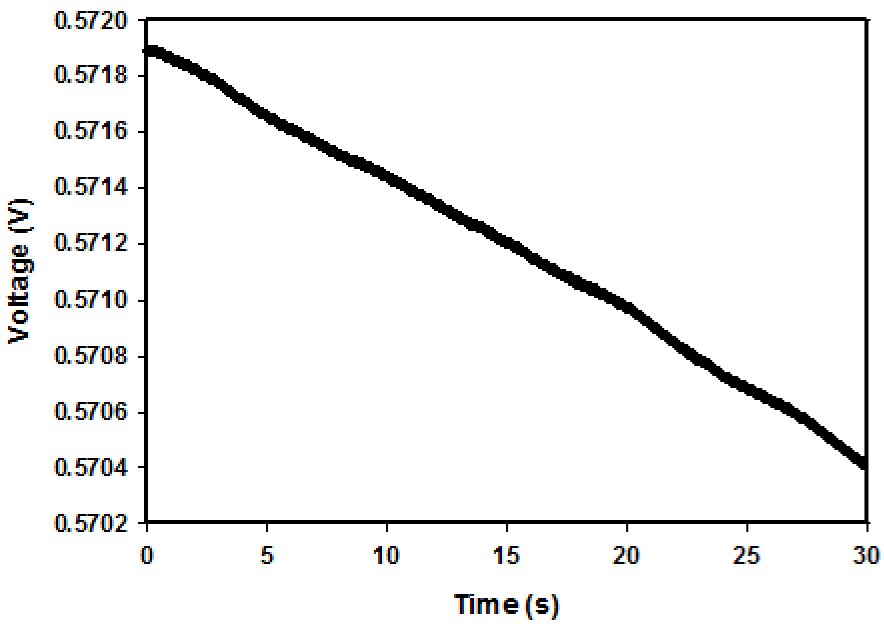


Figure 2.b.2. Open circuit potential in two-chambered electrochemical system.

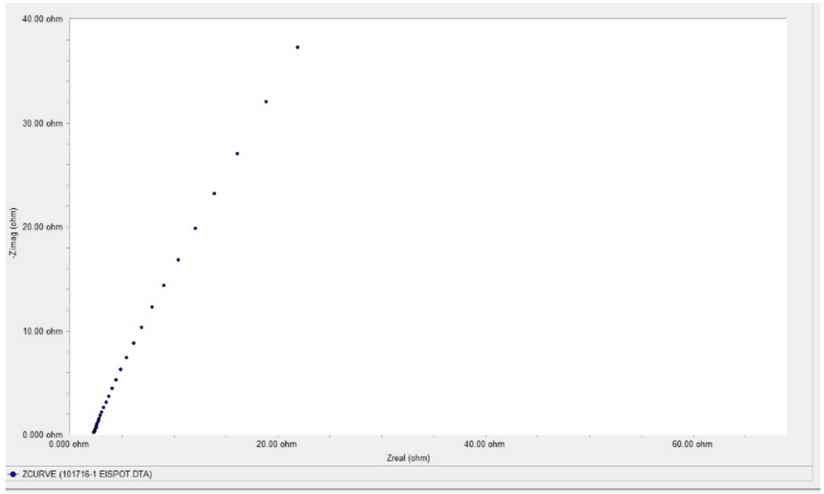


Figure 2.b.3. Electrochemical impedance spectroscopy (EIS) in two-chambered electrochemical system.

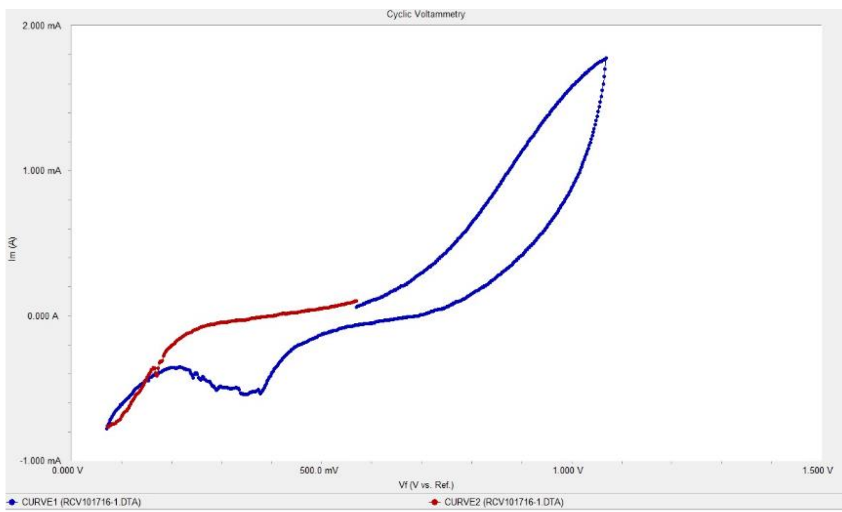


Figure 2.b.4. Cyclic voltammetry scan in two-chambered electrochemical system.

The two-chambered electrochemical system was driven by an electric current using a potentiostat/galvanostat (Gamry Reference 3000) to create a pH imbalance condition between the anode and cathode. The pH imbalance resulted in a low-pH anolyte and high-pH catholyte. In this study, 30, 50, 60, 100, and 300 mA currents were applied using a chronopotentiometry method. The catholyte pH was monitored during the experiments and the electrolysis conditions were found to generate catholyte solution with a pH 10 or above for most electrolytic conditions (Figure 2.b.5).

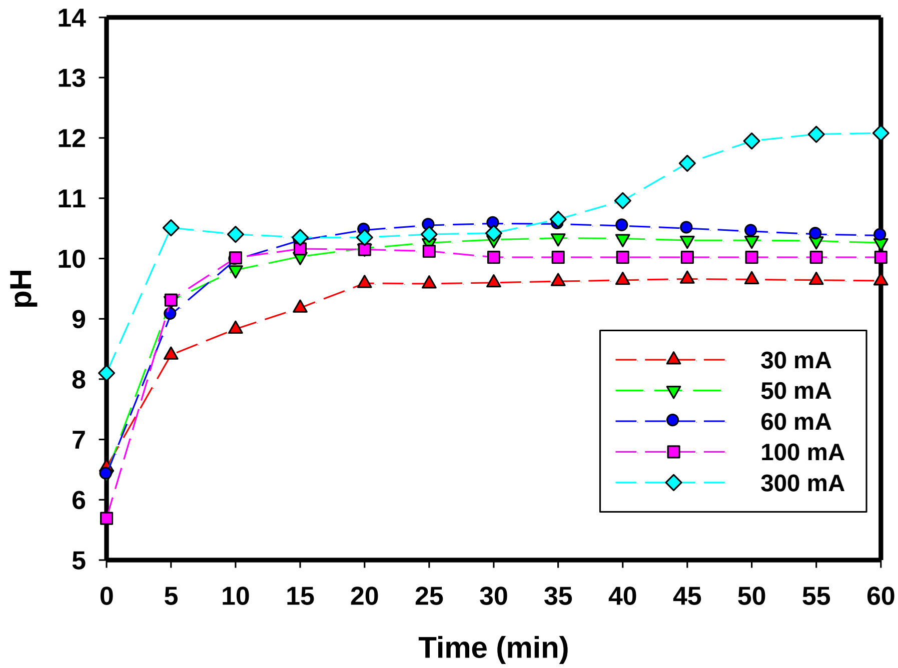


Figure 2.b.5. pH change at different applied currents.

Products

Plan for Next Quarter

1. Examine optimal condition for high-pH catholyte production and produced water softening.
2. Improve electric coulombic efficiency with new membrane (Nafion-117), modify electrolysis cell.

Topic 3 – Deep Subsurface Rock, Fluids, and Gas

Approach

The main focus of the subsurface team led by Sharma this quarter was to analyze core, fluid and gas samples collected from the MSEEL site. Members of Sharma's lab group (Dr. Warrier and Mr. Wilson) and Dr. Hanson from Mouser's lab group continue to coordinate and supervise all sample collection. Samples were also distributed to research team at OSU and NETL for analysis under different sub-tasks. Several talks and presentations were given at local and regional conferences /universities.

Results and Discussion

Progress on Sidewall Core, Vertical Core & Cutting Analysis

The side wall cores are curated at OSU and WVU. Based on the geophysical logs eight samples were selected from different lithologies i.e. zones where we expect to see maximum biogeochemical variations. Samples were homogenized and distributed among different PI's are currently being processed for biomarker, isotope analysis, elemental analysis, porosity/pore structure, and noble gas analysis. For whole core analysis cores were taken from 1foot interval through the 111 feet of whole vertical core. Samples were ground homogenized and distributed to different groups at WVU, OSU and NETL for different analysis.

In Sharma's research group PhD. student Vikas completed extraction and analysis of aliphatic biomarkers from pristine sidewall cores of 3H well from MSEEL site. The samples were from Tully, Mahantango, Marcellus Top, Upper Marcellus, and Middle Marcellus. Lower Marcellus, Marcellus-Onondaga transition and Onondaga formation was done. The analysis of the extracted biomarkers was done in Woods Hole Oceanographic Institute. The aliphatic biomarker analysis of the sidewall cores from 3H well from MSEEL site shows the presence of n-alkanes, pristine, phytane and hopanes in all the samples of Marcellus formation. Tully, Mahantango and Onondaga formation also shows the presence of n-alkanes and hopanes, but lacks pristane and phytane biomarkers. N-alkanes identified in all the samples ranged from n-16 to n-38, indicative of mixed (terrestrial and marine) sources of OM. Terrigenous to aquatic ratio (TAR) obtained from n-alkane distribution indicates that Lower Marcellus received the maximum input of marine organic matter whereas Tully received the maximum input of terrestrial organic matter. Pr/n-17 vs Py/n-18 cross plots indicates type II kerogen for all the samples of Marcellus formation. It also verifies that Marcellus formation received input from mixed sources of OM. The absence of shorter chain n-alkanes (n<16) and low concentration of n-16 to n-19 alkanes as compared to longer chain n-alkanes (n>19) indicate that microbes present in these formation might be utilizing shorter chain n-alkanes as their substrate. To study the effect of preservation on aliphatic biomarkers, aliphatic biomarkers were extracted from in pristine sidewall cores and vertical core plugs of the 2 similar formations. The variations in the biomarker result will be helpful in understanding the possible sources/substrates of microbes and the role of microbes in OM cycling and preservation. Source Rock Analysis (SRA) of 8 sidewall cores from MSEEL 3H well was done to determine the free, bound and residual hydrocarbons (HC). SRA results of 8 sidewall core of 3H well indicate that free HCs (S1) range from 0.02 to 0.35mg HC per gram of rock whereas bound HCs (S2) range from 0.02 to 0.46 mg of HC per gram of rock. Marcellus-Onondaga transition sample has the highest amount of free HC, Lower Marcellus has highest amount of bound HC whereas Tully has the lowest amount of free and bound HCs. Thermal maturity parameter Tmax determined from SRA results indicate that all the sample are over-mature (with Tmax > 560oC) and lies in dry gas window. Sharma's PhD. student Rawlings collected samples at selected intervals from the Mahantango, Marcellus top, and upper Marcellus Formations and the total yield and variety of the DGFA profiles were examined. The total biomass yield and variety of the DG-FAME profiles were higher in the Mahantango compared to the samples from the upper Marcellus formation and Marcellus/Mahantango interface (Marcellus top). The lipid fatty acids consisted of saturated, branched, monounsaturated, terminally branched, polyunsaturated, hydroxy, oxiranes, dimethyl esters, keto fatty acids, and their variations were presented in relative proportions (mol %) (Figure 3.1) The combination of the lipid fatty acids present in both cores showed indications of a potentially diverse assemblage of both gram (-), gram (+), aerobic, anaerobic, sulfate reducing bacteria, eukaryotes, stress, and toxicity related biomarkers. Some microbes indicating terrestrial and marine influence were also present (Figure 3.2).

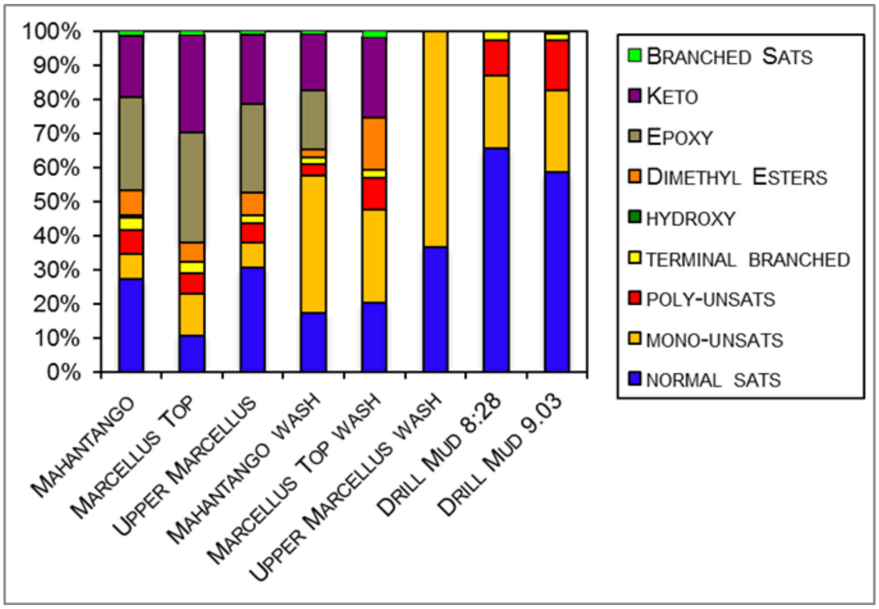
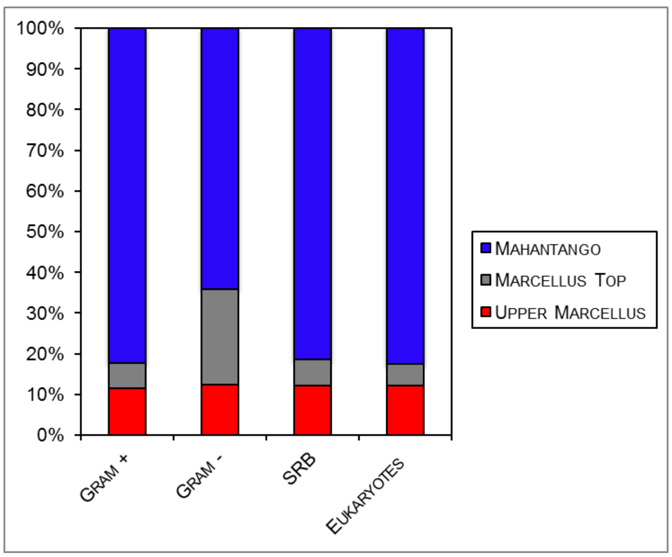


Figure 3.1. Relative abundance of lipid biomarkers for various core samples, core washes, and drill muds

Figure 3.2. Estimates of microbial community composition in Mahantango, Marcellus Top, and Upper



Marcellus formations.

In Mouser's group between September and December 2016, research associate Jenny Panescu developed salinity curves and characterized carbon metabolisms from *Arcobacter marinus* isolates collected from MSEEL wells. Jenny also extracted DNA from several isolates to be used for genome sequencing at JGI, coordinated/managed through the Wrighton lab. In October, Andrea Hanson traveled to Bremen, Germany to analyze archaeal and bacterial lipids in the remaining MSEEL sidewall cores, a subset of well fluids, and microbial isolates. Over a 5-week period, Andrea extracted lipids from approximately 15 samples and analyzed them on a series of high resolution liquid chromatography mass spectrometry instruments. She detected "ancient" archaeal lipids in many of the sidewall cores as well as many "intact" archaeal and bacterial lipids in later flowback fluids. Data analysis is currently underway. They hope to send Andrea back to Bremen to finalize her analysis in March, 2017 with a publication to follow.

Wrighton's research group submitted sequencing for 16S rRNA marker gene analyses for MIP3H and MIP5H drilling mud and produced water samples collected from project initiation through September 2016 (40 samples total). Data is currently being analyzed. Their group selected and submitted 10 samples from MIP3H and MIP5H for metagenomic sequencing, data expected March 2017. Completed DNA extractions from pristine sidewall core materials. We developed a new method of DNA extraction and low-input library preparation method for metagenomic sequencing. Submitted 10 libraries for sequencing, data is now being processed on Wrighton lab servers. This analysis will be complete by March, 2017. These data were paired to PLFA samples selected in the Mouser lab. Successfully isolated the dominant methane-producing microorganism from MIP3H, a member of the *Methanohalophilus*. The isolate has been submitted for genome sequencing, data expected March 2017. We are currently testing the *Methanohalophilus* isolate's salinity and pressure tolerance and plan to work with Sharma and Darrah labs to determine isotopic signature and quantify contribution of biogenic methane in MSEEL wells.

Cole's group performed large field BSE imagery for two polished thick sections of intact core samples, MT 25 (Marcellus Top, depth 7451.5') and ML 10 (Lower Marcellus, depth 7543.0'). From these organic matter-rich samples, more than 180 images with horizontal field widths (HFW) of approximately 1 mm were acquired for ML 10, and more than 100 images were acquired for MT 25. These data provide a large-area view of core cut perpendicular to bedding. Much of the secondary diagenetic mineralization associated with the large OM algal features in the deepest Marcellus sample (Figure 3.3) is quartz (informed by EDXS spot analysis). Elemental mapping of OM structures in MT 25 (Marcellus Top, depth 7451.5') reveals more complex mineralogy and diversity among the individual OM. An example elemental map superimposed on a BSE image of one algal OM feature is shown in Figure 3.4. The OM is approximately 150 μm in length and 30 micron thick in this cross sectional view. Secondary chlorite forms elongate, bladed crystals embedded in brown OM with elongation subparallel to bedding. A fragment of fine-grained rock matrix is also present in the center of the OM.

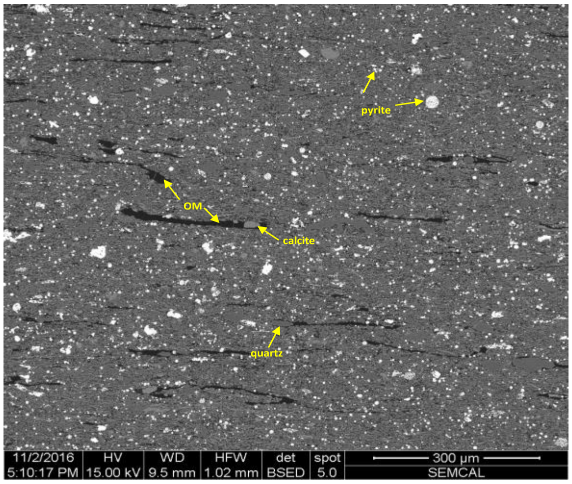


Figure 3.3. Example image of large field BSE scan for Lower Marcellus (depth 7543.0'). OM appears black, quartz and other siliclastics appear medium gray; carbonates and phosphates appear light gray, and the strongest BSE scattering minerals (mainly pyrite) appear white.

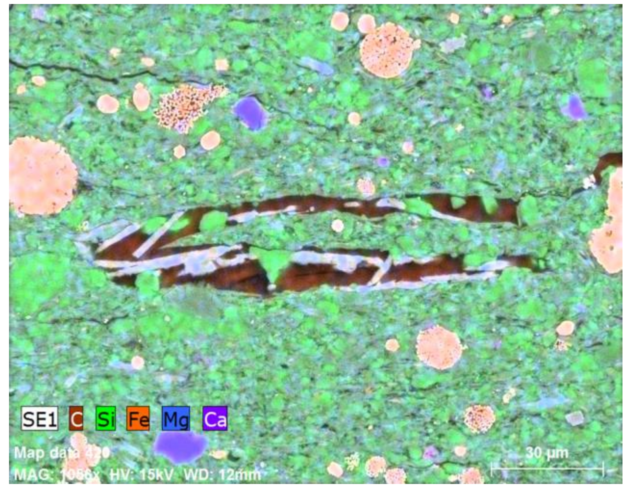


Figure 3.4. Elemental mapping of an OM structure in MT 25 (Marcellus Top, depth 7451.5').

N_2 gas sorption measurements of surface area (Figure 3.5) and connected pore size distribution (PSD) were conducted for MT 25 and TL 36 (Tully Limestone, depth 7200'). Data reduction are underway, but preliminary results suggest measurements of MT 25 are consistent with pore sizes measured with MICP analysis. For this sample, most connected pore volume originates from pores below 20 nm in length scale.

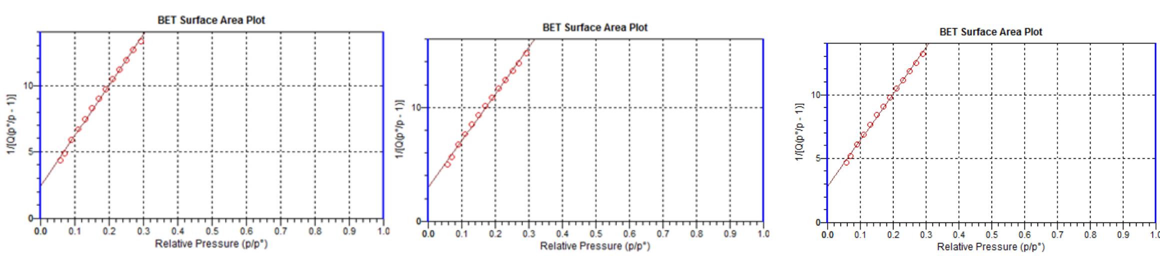


Figure 3.5. N_2 gas sorption analysis of mm-scale rock chips of MT 25. BET plots are shown from replicate runs #528 (upper left), #529 (upper right), and #530 (lower left)). These BET measurements suggest a surface areas for the runs of 2.2, 2.4, and 2.5 m^2/g, respectively. p/p^o is the relative pressure, referenced to 1 atm.; $[1/Q_{ads}(p/p^o\text{-}1)]$ is the normalized moles of adsorbed N_2/gram solid.

Progress on Produced Fluid and Gas Analysis

Produced water samples were collected in 5 gallon carboys every 6 weeks. The samples were the tranported, filtered and processed in Sharma Laboratory at WVU. All water samples were collected in different containers using different methods/ preservatives etc. specified for different kinds of analysis. All PI's at OSU and NETL and provided their detailed sampling instructions. Dr. Warrier, Wilson from WVU and Hanson from OSU were primarirly incharge of sample collection and distribution among different PI's at WVU, OSU and NETL. The collected fluids are curretly being processsed for biomass, reactive chemistry, organic acids, and noble gas and stable isotope analysis at different institutes.

Sharma Lab is continues to analyze the O,H,and C isotope composition of produced fluids and molecular and C/H isotope composition of produced gases collected from the sites. Produced water sampling at MSEEL has continued on a monthly schedule. Continual slow ^{13}C enrichment trend of DIC has been seen in both 3H and 5H since production began last year. The initial spike to highly enriched $\delta^{13}C_{DIC}$ during the initial three day flowback period is being investigated. Formation carbonate veins are being analyzed as possible sources of this. 11 samples of vertical core bedding parallel and perpendicular veins have been collected in and within one meter of the landing zone and will be analyzed for $\delta^{13}C_{DIC}$. Continued sampling of produced gas will also be analyzed, as well as major and minor geochemical constituents, and DNA analysis from collaborators to look for evidence of microbial activity that could potentially be responsible for the isotopic trends observed. Initial results were presented in GSA national meeting in Denver, CO in October.

In Wilkins Lab a total of 47 microbial isolates have been recovered from MSEEL produced fluids. These include 18 strains representing dominant Halanaerobium populations, 3 sulfide-producing Desulfovibrio strains, and a number of likely-fermentative microbes that can utilize input chemical compounds as a substrate. A subset of these isolates (likely ~ 10 strains) are currently being selected for whole genome sequencing at the Joint Genome Institute. In Wrighton's lab produced fluid samples (paired to metagenomic and PLFA samples) were sent to Pacific Northwest National Laboratory, Environmental Molecular Sciences Laboratory for NMR metabolite analysis. This provide chemical details on the compounds in the produced fluids. In Cole lab analysis of fluid samples from the MIP 3H and 5H wells continues. Data reduction from samples analyzed by IC, ICP-OES and ICP-MS continues. We have been reviewing the raw data, trying to identify and quantify trace species that are present in the flowback fluids. In December 2016, Hanson worked with Daly to prepare for MSEEL sampling from 3H, 4H, 5H and 6H wells. Additionally, materials were ordered to collect biomass (including lipids) from the liner pull expected to take place January 2017. In Darrah Lab molecular composition of hydrocarbons and isotope composition of noble gases in produced gas and fluids has been analyzed and initial results were presented in GSA national meeting in Denver, CO in October.

Products

Plan for Next Quarter

Topic 4 – Geophysical and Geomechanical

Approach

Team will conduct microseismic analyses during the frac jobs of the production wells and tie that data back to the geophysical logs obtained from the science well, providing a clearer picture of proppant placement through the establishment of a detailed rock velocity model. Some inferences toward fracture quantity and patterns will also be vetted.

Plan is to identify specific methodology to obtain the data that will provide most understanding of subsurface rock model

Results and Discussion

Task 4a - Geophysics:

The effort this past quarter concentrated on: 1) Presentations at the SEG convention in Dallas (16-21 Oct); 2) Paper submitted to the Journal Interpretation by November 1; 3) the main outgrowths from the integration of rock geophysical data with microseismic and well log data to develop multiscale reservoir simulation and fracture models were presented at SEG and in the paper submission. 4) Some continued efforts in this area were pursued this quarter and included development of hydraulic fracture simulations using a geomechanical model developed from well logs. These preliminary simulations consisted of multi-initiation point planar 3D models in models that did not include the stress gradients.

Project effort FY15 through December FY17: 4.2 FTE months.

Results and Discussion

1-2) The presentation was made at the annual SEG convention in Dallas (see http://library.seg.org/doi/pdf/10.1190/segam2016-13866107.1) and the paper was submitted to the Journal Interpretation.

The journal submission is titled Marcellus Shale model stimulation tests and microseismic response yield insights into mechanical properties and the reservoir DFN with several co-authors involved in various aspects of this multidisciplinary study. The authors included:

Thomas H. Wilson[1], Malcolm Yates[3], Keith MacPhail[3], Ian Costello[2], Tim Carr[1], B. J. Carney[2], Jay Hewitt[2], Emily Jordon[2], Natalie Uschner[3], Mandy Thomas[3], Si Akin[3], Oluwaseun, Magbagbeola[3], Adrian Morales[3], Asbjoern Johansen[3], Leah Hogarth[3], Olatunbosun Anifowoshe[3], Kashif Naseem[3]

[1]West Virginia University, [2]Northeast Natural Energy, LLC, [3]Schlumberger

3) The outgrowths of integrated rock geophysical data, microseismic and well log data in multiscale reservoir simulation and fracture model development included: stimulation tests of a model discrete fracture networks (DFN) designed using log data, including fracture image logs from vertical pilot and horizontal wells. The data provided geomechanical properties, fracture trend and intensity and stress orientation. Microseismic cluster trends provided additional constraints on geomechanical model development. Results from stimulations tests have been used to modify the reservoir DFN and geomechanical model.

Induced fractures observed in the vertical pilot well indicate an SHmax orientation of N57oE. Shmin in the reservoir is approximately 42MPa (6100psi) with horizontal stress anisotropy of approximately 2.76MPa (400psi). The vertical stress (Sv) is approximately 60.7MPa (8800psi). Northeast asymmetry in the microseismicity associated with hydraulic fracture treatment is interpreted to result from a horizontal drop of Shmin toward a previously drilled well. The asymmetry is interpreted to result from stress reduction associated with treatment of an earlier parallel well, presence of a cross-strike structure parallel to the well or a combination of the two.

Two fracture sets were required in the model DFN to reproduce the stimulation trend inferred from the microseismic data. Mohr-Coulomb failure criteria indicate fractures with average trend of N83oE in the area are likely to fail through shear. The N57oE set of open and healed fractures parallels SHmax and is expected to facilitate development of the hydraulic fractures through channeling of fluids into the east-northeast oriented fracture set. Limited downward growth, inferred from the microseismic response, required an increase of minimum stress in model strata underlying the Marcellus.

4) The 4.2 month FTE project effort was extended to include multi-initiation point planar 3D hydraulic fracture stimulation tests. The tests were conducted using an earlier version of the geomechanical model that does not include stress gradients noted in 3). Hydraulic fractures from each perforation have half-lengths of approximately 1500ft (Figure 4.a.1A). The initial models suggest that upward hydraulic fracture growth is limited to about 200 ft Figure 1B). The hydraulic fracture forms slowly and normally does not produce high frequency microseismic activity. However, it will be a major source of low frequency energy release as fluid and proppant flow progress through the hydraulic fracture. We would be curious to know if the low frequency recordings at the site, similar to those presented by Kumar et al. (2016) in Greene Co. PA, can help locate the extent of low frequency activity. Unless the depth errors of 0.6 miles, noted by (Kumar et al., 2016) in Greene Co., are reduced significantly, this may not be possible, but we would be very interested to know if they are able to constrain locations with higher accuracy.

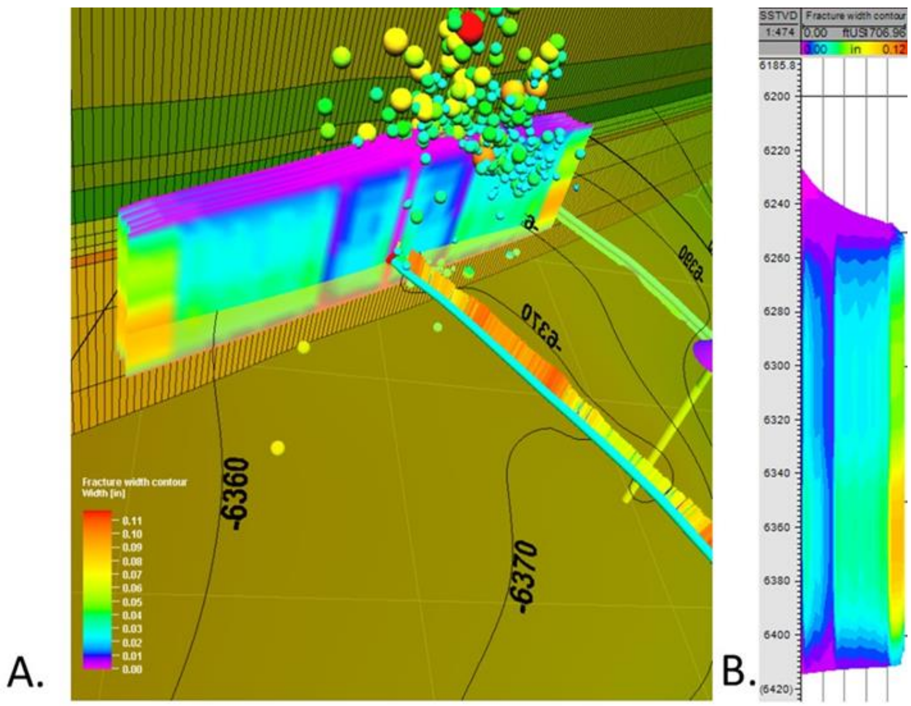


Figure 4.a.1: A) Simulated hydraulic fracture model shown in 3D perspective view. Color bar represents fracture width. Microseismic activity in this stage is included for reference. B) Display of fracture width and height.

Note that hydraulic fracture width (Figure 4.a.1) varies laterally away from the injection point with variations in proppant concentration (Figure 4.a.2).

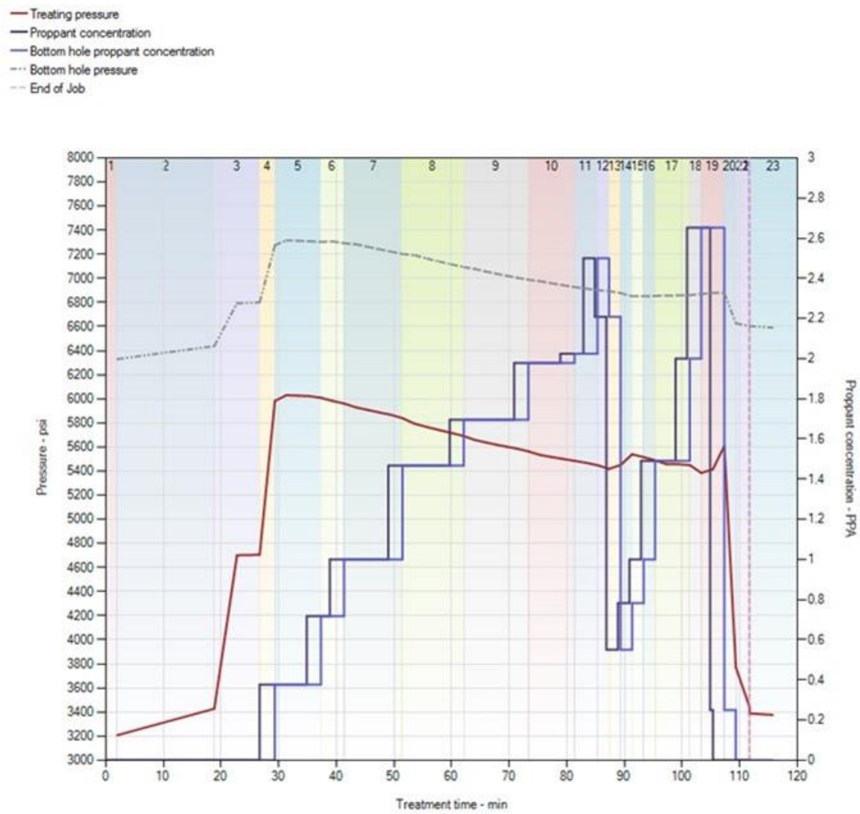


Figure 4.a.2: pressure and proppant data used in the simulation.

Step name	Treatment type	Pump rate (bbl/min)	Fluid name	Fluid volu (gal)	Proppant	Prop. conc. (PPA)	Prop. mass (lb)	Slurry volu (bbl)	Pump time (min)	Step type
Pad	Propped Fracture	5.98	SAPPHIRE VF...	502.04		0.00	0.00	11.95	2.00	Pad
Pad	Propped Fracture	15.05	SAPPHIRE VF...	10643.81		0.00	0.00	253.42	16.83	Pad
Pad	Propped Fracture	63.41	SAPPHIRE VF...	20949.78		0.00	0.00	498.80	7.87	Pad
Pad	Propped Fracture	98.73	SAPPHIRE VF...	10988.67		0.00	0.00	261.64	2.65	Pad
5	Propped Fracture	100.28	SAPPHIRE VF...	33127.77	-80 + 100 Mesh...	0.38	12464.36	802.23	8.00	Slurry
6	Propped Fracture	100.33	SAPPHIRE VF...	16310.64	-80 + 100 Mesh...	0.72	11702.92	401.32	4.00	Slurry
7	Propped Fracture	100.33	SAPPHIRE VF...	40913.43	-80 + 100 Mesh...	1.00	40913.73	1018.34	10.15	Slurry
8	Propped Fracture	100.32	SAPPHIRE VF...	42072.85	-80 + 100 Mesh...	1.47	61740.02	1068.46	10.65	Slurry
9	Propped Fracture	100.32	SAPPHIRE VF...	43816.19	-80 + 100 Mesh...	1.70	74291.45	1123.53	11.20	Slurry
10	Propped Fracture	100.32	SAPPHIRE VF...	30929.83	-80 + 100 Mesh...	1.98	61209.17	802.57	8.00	Slurry
11	Propped Fracture	100.33	SAPPHIRE VF...	15429.59	-80 + 100 Mesh...	2.02	31232.05	401.32	4.00	Slurry
12	Propped Fracture	100.31	SAPPHIRE VF...	7567.55	-80 + 100 Mesh...	2.50	18918.88	200.63	2.00	Slurry
13	Propped Fracture	100.33	SAPPHIRE VF...	7666.72	-80 + 100 Mesh...	2.21	16930.70	200.84	2.00	Slurry
14	Propped Fracture	100.33	SAPPHIRE VF...	8222.38	-80 + 100 Mesh...	0.55	4522.31	200.66	2.00	Slurry
15	Propped Fracture	100.32	SAPPHIRE VF...	8138.40	-80 + 100 Mesh...	0.78	6368.29	200.65	2.00	Slurry
16	Propped Fracture	100.32	SAPPHIRE VF...	8060.93	-80 + 100 Mesh...	1.00	8060.93	200.64	2.00	Slurry
17	Propped Fracture	100.32	SAPPHIRE VF...	23683.05	-80 + 100 Mesh...	1.49	35307.42	602.04	6.00	Slurry
18	Propped Fracture	100.34	SAPPHIRE VF...	7726.73	-80 + 100 Mesh...	2.00	15453.46	200.67	2.00	Slurry
19	Propped Fracture	100.32	SAPPHIRE VF...	15046.62	-80 + 100 Mesh...	2.65	39904.92	401.38	4.00	Slurry
20	Propped Fracture	25.18	SAPPHIRE VF...	2031.10	-80 + 100 Mesh...	0.25	507.77	48.91	2.00	Slurry
Pad	Propped Fracture	5.00	SAPPHIRE VF...	500.50		0.00	0.00	11.92	2.38	Pad
Flush	Propped Fracture	5.00	SAPPHIRE VF...	10733.05		0.00	0.00	255.55	51.11	Flush

Figure 4.a.3: Data table for showing variables for each treatment step.

Products

Plan for Next Quarter

During the next quarter the research focus will be expanded to incorporate stress gradients inferred from the unconventional fracture model stimulation tests (Wilson et al., 2016 [see http://library.seg.org/doi/pdf/10.1190/segam2016-13866107.1] and Wilson et al., submitted). We will be interested to see how the hydraulic fractures behave across the interpreted zone of mechanical weakness between the 3H and 5H wells.

The limited height growth observed in the hydraulic fracture simulations will also be examined. Variations in model geomechanical properties will be explored to determine their effect on height growth and half length.

Task 4b - Geomechanical:

Results and Discussion

During this quarterly period, the influence of a natural discrete fracture network on the growth of hydraulic fractures was investigated through the use of numerical modeling simulations. The previous hydraulic fracture model was updated to include an assumed natural discrete fracture network.

Natural fractures are pervasive in shale formations, and their inclusion in the numerical modeling to simulate field conditions could provide a more realistic assessment of hydraulic fracture growth. The assumed discrete fracture network includes vertical and horizontal natural fractures which are interconnected to the primary induced hydraulic fractures. These natural fractures receive injected fluid from the primary stimulated hydraulic fractures and are capable of extending beyond the dimensions of the primary hydraulic fracture. Figure 4.b.1 shows the fracture geometry for one of the primary induced hydraulic fractures in stage 1 of well MIP-3H discussed in the previous quarter. Figure 4.b.2 shows the fracture geometry of one of the primary induced hydraulic fractures in stage 1 of well MIP-3H with the inclusion of the discrete fracture network in the updated numerical modeling. The height growth is much higher with the inclusion of a discrete fracture network, as can be seen from these figures. Figure 4.b. 1 shows a comparison of the fracture dimensions of stage 1 of well MIP-3H in the previous and the current quarters. In general, the microseismic measured data has shown seismic activity at greater vertical distances from the injection point. The numerical model shows that with the inclusion of a discrete fracture network, the computed fracture height is greater than the values calculated from conventional single fracture models.

A parametric study was then performed on available discrete fracture network parameters. The following discrete fracture network parameters were modified to determine their influence on primary fracture geometry: spacing along the major axis, spacing along the minor axis, aperture ratio of minor vertical fractures, aperture ratio of major vertical fractures, and the aspect ratio. These parameters were varied to find their influences on fracture geometry and the results are shown in Figure 4.b. 2.

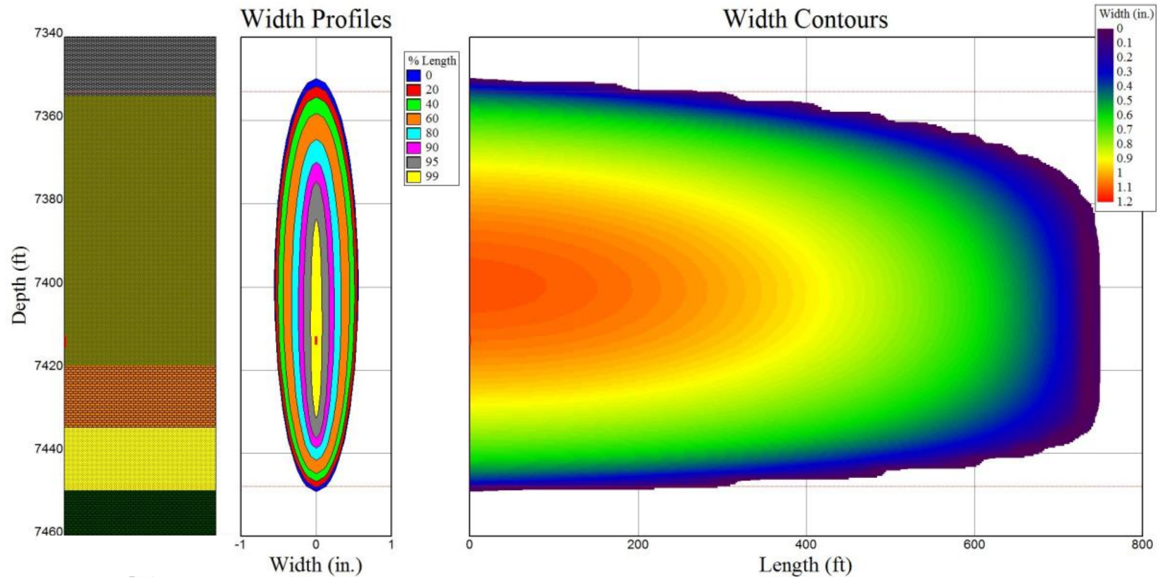


Figure 4.b.1: Fracture Geometry for Stage 1 - MIP 3H – Without Discrete Fracture Network

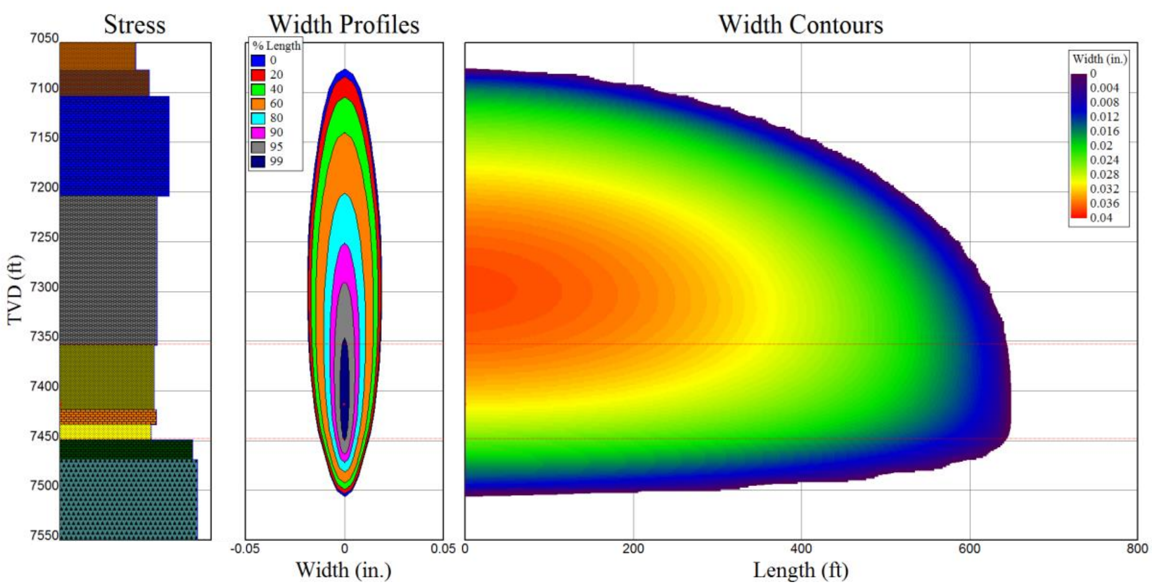


Figure 4.b.2: Fracture Geometry for Stage 1 - MIP 3H – With Discrete Fracture Network

Table 4.b. 1: Comparison of Stages 1 Fracture Dimensions from the Previous and Current Quarters

MIP 3-H Stage # 1			
Discrete Fracture Network Used?	Maximum Fracture Length (ft)	Maximum Fracture Height (ft)	Average Fracture Width (in)
No	749.5	100.7	0.7041
Yes	649.2	435.7	0.0233

Table 4.b. 2: Influence of Discrete Fracture Network Parameters on Fracture Geometry

Parameter - Change	Maximum Fracture Length (ft)	Maximum Fracture Height (ft)	Average Fracture Width (in)	Average Discrete Fracture Network Width (in)
Base Case - No Change	649.4	435.7	0.021313	0.0019899
Spacing along the Major Axis Decreased	610.7	403.4	0.020736	0.0018976
Spacing along the Major Axis Increased	660.9	452.1	0.0225	0.0021326
Spacing along the Minor Axis Decreased	442.8	414.9	0.029622	0.0027079
Spacing along the Minor Axis Increased	759.9	359.7	0.02871	0.0027631
Aperture Ratio of Minor Vertical Fractures Increased	617.1	406.6	0.020667	0.0024914
Aperture Ratio of Minor Vertical Fractures Decreased	660.9	452.1	0.0225	0.0017964
Aperture Ratio of Major Vertical Fractures Increased	570.4	387.8	0.021175	0.0032142
Aperture Ratio of Major Vertical Fractures Decreased	673.1	478.4	0.024321	0.0015661
Aspect Ratio Decreased	791.5	378.1	0.029576	0.0029198
Aspect Ratio Increased	528.6	415.2	0.24995	0.0022956

Products

Plan for Next Quarter

Topic 5 – Surface Environmental

Task 5a – Surface Environmental – Water

Approach

The Marcellus Shale Energy and Environment Laboratory (MSEEL) is the first comprehensive field study coupling same site environmental baseline, completion and production monitoring with environmental outcomes. One year into the post completion part of the program, the water and solid waste component of MSEEL has systematically sampled flowback and produced water volumes, hydraulic fracturing fluid, flowback, produced water, drilling muds, drill cuttings and characterized their inorganic, organic and radio chemistries. In addition, surface water in the nearby Monongahela River was monitored upstream and downstream of the MSEEL drill pad. Toxicity testing per EPA method 1311 (TCLP) was conducted on drill cuttings in both the vertical and horizontal (Marcellus) sections to evaluate their toxicity potential.

Surface water baseline sampling was conducted in June at the three points selected along the Monongahela River. Based on the timeline for gas well development being shortened and activities moved up, two separate sampling events were conducted. Figure 5.1 shows the locations of sampling points MR-1, MR-2, and MR-3 in red with the Northeast Energy site indicated in purple.

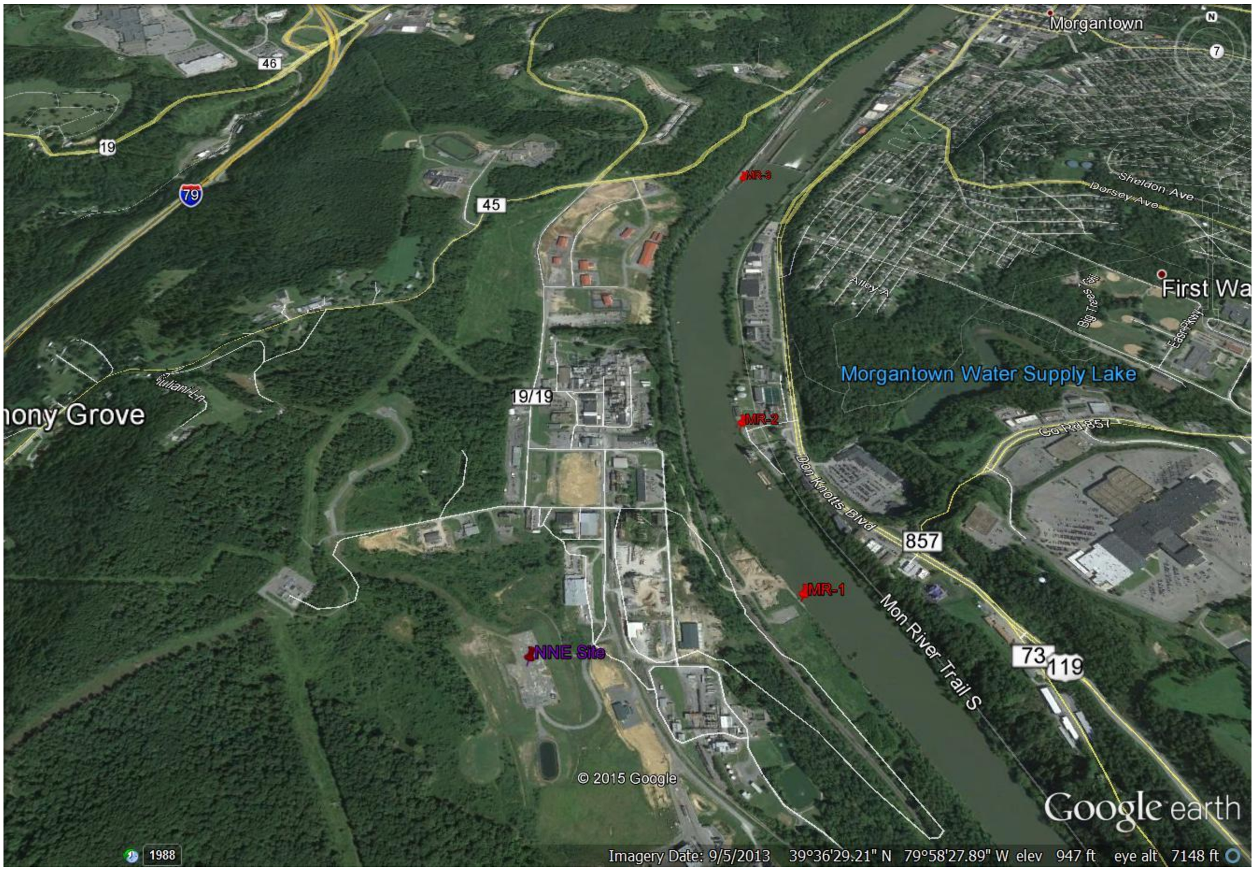


Figure 5.a.1: MSEEL surface water sampling locations

Previous findings

The MSEEL wells used green completion strategy including a synthetic based drilling fluid (Bio-Base 365). All drill cutting samples fell below TCLP thresholds for organic and inorganic components indicating that they are non-hazardous per the Resource Conservation and Recovery Act. Maximum specific isotopic activity in drill cuttings was recorded for 40 K which was 28.32 pCi/g. Gross alpha accounted for the highest reading at 60 pCi/g. The maximum combined radium isotope values was 10.85 pCi/g. These radioactivity levels are within the background range for the region.

The composition of the hydraulic fracturing (HF) fluids in both wells was similar to the makeup water which was drawn from the Monongahela River. Its chemistry was typical of Monongahela River water. This is true of inorganics, organics and radio chemicals. Organic surrogate recoveries were in the range of 90 to 104% indicating good quality control at the analytical laboratory. There was no evidence that Monongahela River quality was influenced by well development, completion or production at the MSEEL site.

Produced water is severely contaminated indicating care in handling. Concentrations of all parameters increased through the flowback/produced water cycle. 226+228 Ra reached 20,000 pCi/L at post completion day 251 indicating an important trend that will be carefully assessed in ongoing monitoring.

Methods

Sampling schedule

Table 5.a.1 summarizes the produced water sampling schedule for the quarter. Makeup water was pumped from the Monongahela River and mixed with the hydraulic fracturing fluids. Produced water samples were taken at the upstream end of each well's separator.

Table 5.a.2 Sampling schedule for the quarter.

	Freshwater		Aqueous/Solids: drilling/completion/production								
	Mon River	Ground water	HF fluid makeup	HF fluids	flowback/ produced	drilling fluids	drilling cuttings/ muds	total aqueous	total solids	Sampling Dates	Sampling Notes
Flowback @ 45 weeks - 3H					1			1		10/19/2016	one sample 3H
Flowback @ 45 weeks - 5H					1			1		10/26/2016	one sample 5H
Flowback @ 49 weeks - 3H					0			0		11/16/2016	3H not producing
Flowback @ 49 weeks - 4H					1			1		11/16/2016	one sample 4H
Flowback @ 49 weeks - 5H					1			1		11/16/2016	one sample 5H
Flowback @ 49 weeks - 6H					1			1		11/16/2016	one sample 6H
Flowback @ 53 weeks - 3H					1			1		12/14/2016	one sample 3H
Flowback @ 53 weeks - 4H					1			1		12/14/2016	one sample 4H
Flowback @ 53 weeks - 5H					0			0		12/14/2016	5H off-line
Flowback @ 53 weeks - 6H					1			1		12/14/2016	one sample 6H

Analytical parameters

Analytical parameters are listed in tables 5.a.2 and 5.a.3.

Table 5.a.3 Aqueous analytical parameters

Aqueous chemistry parameters - HF fluids and PW						
Inorganics					Organics	Radionuclides
	Anions	Cations*				
pH	Br	Ag	Mg		Benzene	α
TDS	Cl	Al	Mn		Toluene	β
TSS	SO_4	As	Na		Ethylbenzene	^{40}K
Conductance	sulfides	Ba	Ni		Total xylene	^{226}Ra
Alkalinity	nitrate	Ca	Pb		m,p-xylene	^{228}Ra
Bicarbonate	nitrite	Cr	Se		o-xylene	
Carbonate		Fe	Sr		MBAS	
TP		K	Zn		O&G	

* total and dissolved

Table 5.a.4 Analytical parameters drill cuttings and mud.

Solids chemistry parameters - Cuttings & Muds								
Inorganics				Organics	Radionuclides	TCLPs		
	Anions	Cations*		Propane				
alkalinity**	Br	Ag	Mg	DRO	α	Arsenic	1,4-Dichlorobenzene	Methly ethyl ketone
conductance	Cl	Al	Mn	ORO	β	Barium	1,2-Dichloroethane	Nitrobenzene
pH	SO_4	As	Na	GRO	^{40}K	Benzene	1,1-Dichloroethylene	Pentrachlorophenol
bicarbonate**	sulfide	Ba	Ni	Ethylbenzene	^{226}Ra	Cadmium	2,4-Dinitrotoluene	Pyridine
carbonate**	nitrate	Ca	Pb	m,p-xylene	^{228}Ra	Carbon tetrachloride	Endrin	Selenium
TP	nitrite	Cr	Se	o-xylene		Chlordane	Heptachlor	Silver
		Fe	Sr	Styrene		Chlorobenzene	Heptachlor epoxide	Tetrachloroethene
		K	Zn	Toluene		Chloroform	Hexachlorobenzene	Toxaphene
				Total xylenes		Chromium	Hexachlorobutadiene	Trichloroethylene
				TOC		o-Cresol	Hexachlororethane	2,4,5-Trichlorophenol
				COD		m-Cresol	Lead	2,4,6-Trichlorophenol
				O&G		p-Cresol	Lindane	2,4,5-TP (Silvex)
						Cresol	Mercury	Vinyl chloride
						2,4-D	Methoxychlor	

Results and Discussion

Produced water volume trends in wells MIP 3,5H and MIP 4,6H

NNE's water production logs were used to estimate produced water volumes. While water production rates were similar in the first two months post completion, cumulative water production rates soon diverged yielding very different curves for each well (figure 5.a.1). It is noted that the older wells (4H, 6H) were shut in between 12 Dec 15 and 17 Oct 16, an interval of 315 days.

The proportion of hydrofrac fluid returned as produced water, even after 1844 days (5 years) was only 12% at MIP 4H and 7.5% at MIP 6H (table 5.a.4). The reason for the variation among wells both respect to cumulative and proportional produced water returns remains an unanswered question.

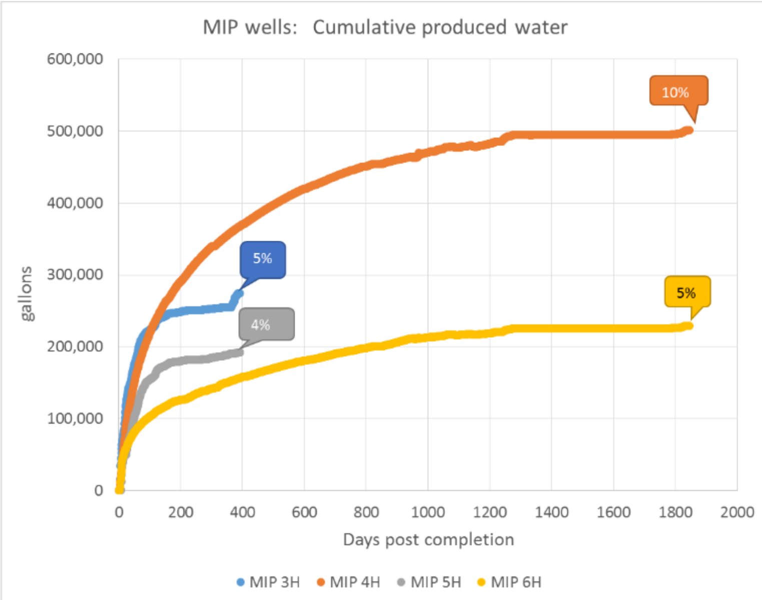


Figure 5.a.2. Cumulative water production at the four MSEEL wells. The estimated proportion of produced water to HF fluids are shown in the callouts.

Table 5.a.5. Produced water volumes relative to injected HF fluid for each MSEEL well.

	days post completion	cumulative produced water gal	cumulative produced water % injected	HF injected gal
MIP 3H	392	274,102	2.6%	10,404,198
MIP 5H	392	192,134	2.0%	9,687,888
MIP 4H	1844	501,396	12.0%	4,160,982
MIP 6H	1844	229,183	7.5%	3,042,396

Trends in produced water chemistry

Major ions

While makeup water was characterized by low TDS (total dissolved solids) and a dominance of calcium and sulfate ions, produced water from initial flowback is essentially a sodium/calcium chloride water (figure 5.a.2). Other than slight increases in the proportion of barium and strontium, the ionic composition of produced changed very little through 314 days post completion.

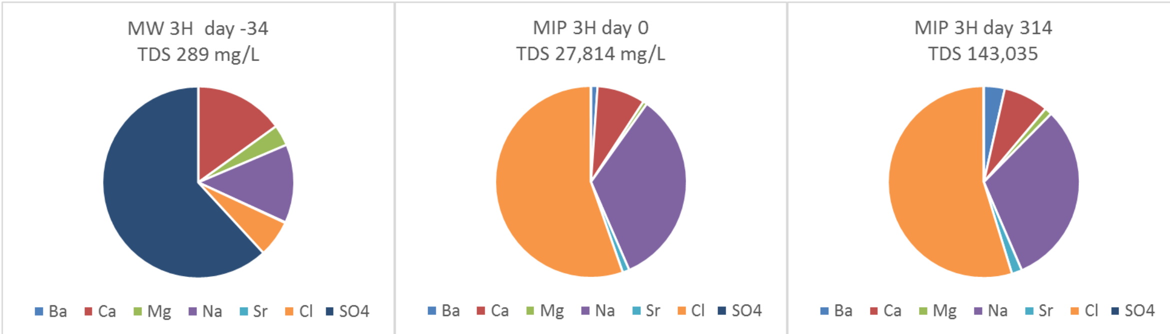


Figure 5.a.3 Changes in major ion concentrations in produced water from well MIP 3H. From left to right the charts represent makeup water from the Monongahela River, produced water on the first day of flowback and produced water on the 314th day post completion.

In fact, after 1858 days ionic composition remained nearly identical to the initial produced water (figure 5.a.3).

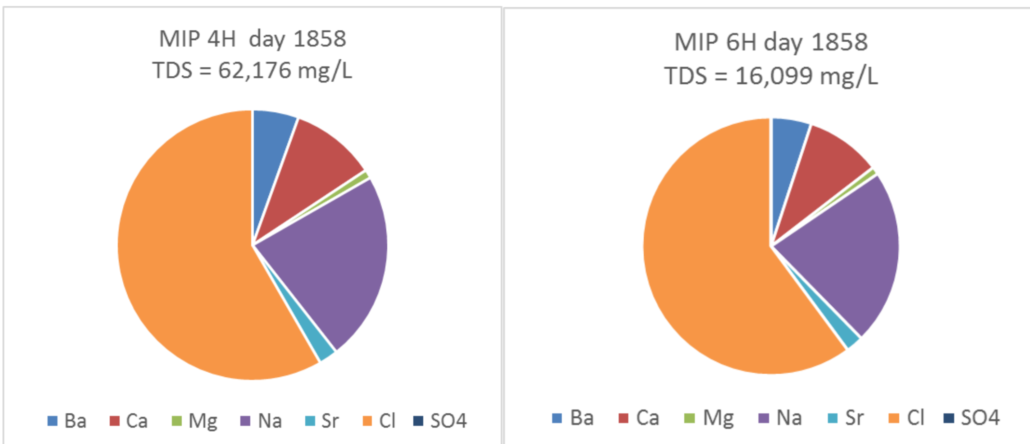


Figure 5.a.4 Major ion composition of wells MIP 4H and 6H 1858 days after completion.

While TDS increased rapidly over the initial 90 days post completion, it appears to have levelled off between 100,000 and 150,000 mg/L (figure 5.a.4). The older 4H and 6H wells offer insight into the longer term TDS trend. Those wells only came back on line during this quarter after a shut in period of 315 days and those results vary but they are much lower than the current values for wells MIP 3H and 5H. Thus far, results are only available for two sampling dates: 16 Nov 16 and 14 Dec 16. TDS varied between 62,176 mg/L at well MIP 4H and 16,099 mg/L at MIP 6H. If these trends continue, it would suggest that available salt is being exhausted.

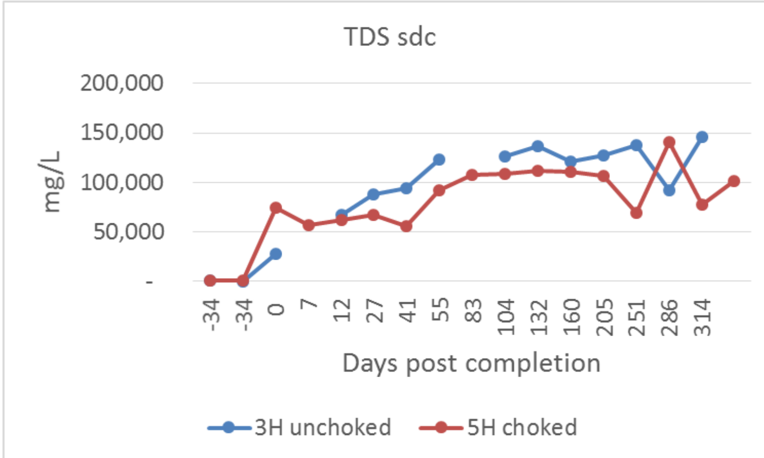


Figure 5.a.5 Changes in produced water TDS sdc (sum of dissolved constituents) through the first 340 days post completion.

Water soluble organics

The water soluble aromatic compounds in produced water: benzene, toluene, ethylbenzene and xylene were never high. With one exception at post completion day 321, benzene has remained below 30 µg/L (figure 5.a.5). This seems to be a characteristic of dry gas geologic units. After five years, benzene has declined below the drinking water standard of 5 µg/L.

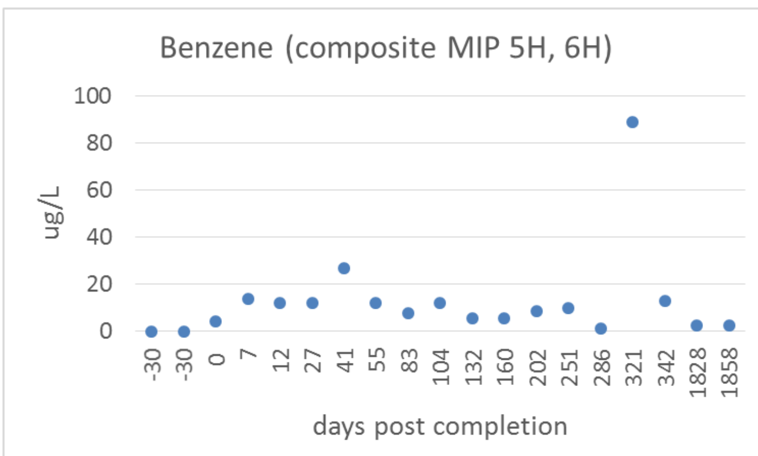


Figure 5.a.6 Changes in benzene concentration. The figure shows data from well 5H through the first 342 days post completion, followed by results from well 6H.

Radium isotopes

Radioactivity in produced water

Radium concentrations generally increased over the 314 days post completion at wells MIP 3H and 5H. Maximum levels of the radium isotopes reached about 20,000 pCi/L at the unchoked 3H well and about half that amount at 5H.

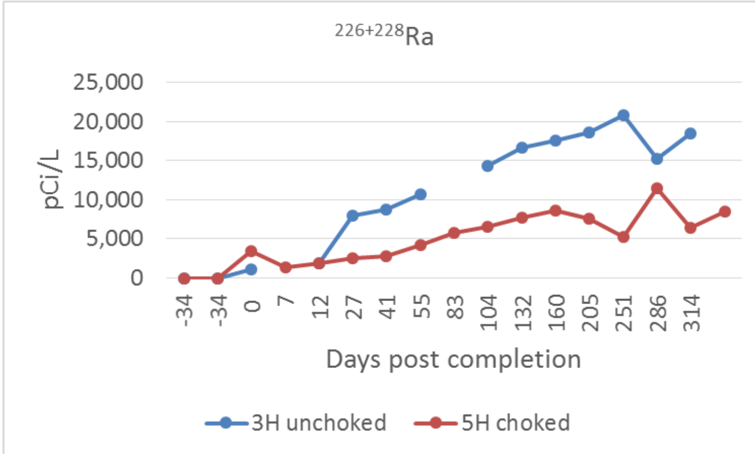


Figure 5.a.7 The radium isotopes are plotted against days post well completion. Well 5H was choked periodically. It produced less water and lower concentrations of radium.

At the older wells MIP 4H and 6H, all isotope concentrations declined to low levels, often below the MDC (minimum detectable concentration) (table 5.a. 5). This, like the apparent decline in TDS at the older wells is an interesting result and, if sustained by future sampling, would suggest exhaustion of contaminant reserves within the fracture field.

Table 5.a.6 Radiochemistry of the older wells 4H and 6H at 1828 (5 years) days post completion.

		16-Nov-16 MIP 4H days post completion: 1828			16-Nov-16 MIP 6H days post completion: 1828		
		act[1]	unc[2]	mdc[3]	act[1]	unc[2]	mdc[3]
α	pCi/L	228.0	53.6	27.2	57.7	10.9	1.6
β	pCi/L	48.7	20.1	29.2	7.4	1.6	0.8
^{226}Ra	pCi/L	353.3	260.6	309.2	199.3	333.5	390.3
^{228}Ra	pCi/L	31.1	31.9	48.6	0.0	20.9	54.6
^{40}K	pCi/L	49.7	95.5	102.7	0.0	21.9	151.4

[1] activity

[2] +/- uncertainty

[3] minimum detectable concentration

Solid waste

The TCLP (toxicity characteristics leaching procedure) or USEPA method 1311is prescribed under the Resources Conservation and Recovery Act (RCRA) to identify hazardous solid waste. TCLP was applied to thirteen drill cutting samples, twelve from MIP 3H and 5H and one from another well in western Monongalia County. All three wells had been developed using green, synthetic drilling fluid. All samples fell below the TCLP criteria for hazardous waste and would be classified under RCRA subtitle D. Bio-Base 365 drilling fluid (Shrieve Chemical Products, Inc.) had been used at the MSEEL wells and ABS 40 (AES Drilling Fluids Inc.) was used at the other well.

Products

Presentations of MSEEL results during the quarter included:

Date	Location	Event	Presentation
1-Nov-16	Morgantown WV	MSEEL Review: USDOE HQ/NETL	MSEEL Liquid and solid waste findings
9-Nov-16	Morgantown WV	WVU Shale Gas Network	MSEEL Liquid and solid waste findings
14-Nov-16	Morgantown WV	RSA National/State O&G Regulators	MSEEL Liquid and solid waste findings
18-Nov-16	Morgantown WV	USDOE/NETL UOG Webinar	MSEEL Liquid and solid waste findings

Plan for Next Quarter

We will continue to sample and analyze flowback/produced water (FPW) from wells MIP 3H, 4H, 5H and 6H. With the older wells (4H, 6H) back on line we will use their produced water to extent the prediction range of the newer wells (3H, 5H). This will allow us to focus on long term trends, geochemical analysis and generation of journal publications.

Task 5b – Surface Environmental – Air and Vehicular

The approach to the CAFEE portion of Topic 5 has been focused on methane and other emissions associated with unconventional well development. As data analyses are completed, our approach will transition to quantify methane emissions from typical site operation. These audits will be completed with the use of WVU's Full Flow Sampling System (FFS). Results of the first complete site audit is presented below.

Results and Discussion

Introduction

The first Marcellus Shale Energy and Environment Laboratory (MSEEL) site assessment through West Virginia University (WVU) was carried out on November 22, 2016. The goal of this assessment was to measure the emissions of methane (CH4) emitted leaking from the wells, tanks, heaters, and other onsite equipment. Additional measurements were performed on December 7, 2016. These measurements included an assessment of the natural gas burner stacks on site and were conducted to estimate the carbon dioxide (CO2), carbon monoxide (CO), and oxides of nitrogen (NOx) emissions, and methane emissions from these larger combustion sources. The findings from these assessments are summarized below.

Methodology

Leak Detection and Measurement

In order to conduct the site audit, all equipment on site was checked for potential leaks using an Eagle 2 from RKI Instruments. This instrument uses a pump with a sample rate of 2 SCFH. The lower range can detect methane between 0 and 50,000 ppm with an accuracy of ±25ppm and a resolution of 5ppm [1]. Leak checking involved scanning components of the wellheads, dehydrators, and water retainment tank to determine location of leaks. Detected leaks were marked and quantified with the WVU Full Flow Sampling (FFS) system. The FFS system consists of a hose that feeds an explosive-proof blower, which exhausts the collected leak sample and excess dilution air through a mass airflow sensor (MAF) and sample probe. The setup of the system is shown in Figure 5.b.1.

Figure 5.b.1: WVU's Full Flow Sampling System

To accurately quantify methane, CO2, and water vapor (H2O) the system utilizes laser spectroscopy in the form of an Ultraportable Greenhouse Gas Analyzer (UGGA) from Los Gatos Research (LGR). The UGGA uses off-axis integrated cavity output spectroscopy (OA-ICOS). The operation principle for the UGGA is described in literature. The UGGA records measurements of methane, CO¬2, and H2O. The precision (1 σ, 5 sec / 100 sec) for the three species are as follows: methane (2 ppb / 0.6 ppb), CO2 (300 ppb / 100 ppb), and H2O (200 ppm / 60 ppm) [2].

Well Head Flux

It was determined that direct quantification of the well head components with the conventionally used methods would be difficult and could risk underestimating emissions due to difficult to reach areas with potential leaks. In order to compensate for this, all wellheads were temporarily covered with a tent and a hose fixed to the tent to measure a methane flux from each individual wellhead. The FFS was again used to measure concentrations pulled through the hose and explosive proof blower to determine a methane concentration. A setup of the system is shown in Figure 5.b.2. Each well was sampled for a period of at least 60 minutes to ensure that periodic events such as relief of pneumatic devices were captured in the flux. In addition to each well being measured, a baseline sample was also recorded on site to ensure that elevated levels were distinguishable from the background. The background included tenting of an open area free of components and sampling natural soil flux to ensure the values reported from the wells were indicative of natural gas emissions.

Figure 5.b.2: Tented Well (Left) and FFS System on rear of Research Vehicle (Right)

Stack Emission Rates

The stacks of the burners on site were also evaluated for emission rates. The burners are 750M BTYU/hr enclosed gas production units. The burners and other connected components evaluated for leaks are shown in Figure 5.b.3.

Figure 5.b.3: Natural Gas Burners and Other On-site Equipment

At the time of the initial audit both burners were operating, however, when stack emissions were taken, only one burner was operational. Estimation of an emission rate was performed by measuring the stack gas flow rate and concentration. The gas flow rate was determined by using an S-type pitot tube, which was calibrated against a NIST traceable laminar flow element (LFE). The calibration is shown in Figure 5.b.4.

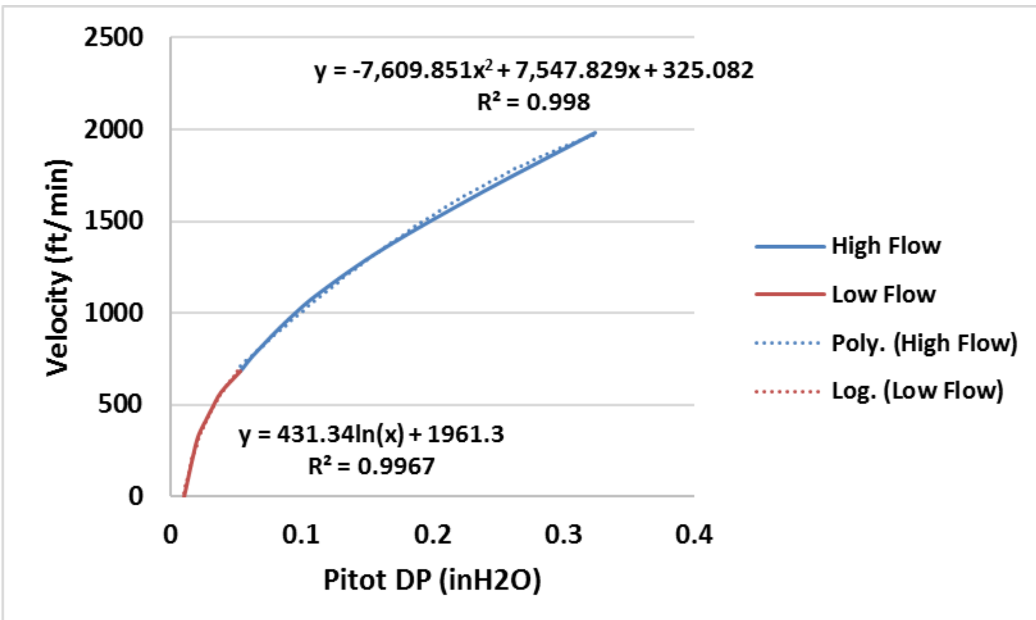


Figure 5.b.4: S-Type Pitot Tube Calibration for Low and High Range Differential Pressures

The use of an S-type pitot tube allowed for a determination of the average stack velocity. Stack geometry then allowed for an estimated flow rate in cubic feet per minute. The temperature of the stack flow was measured using a standard K-type thermocouple during sampling of velocity and emissions. A sample was collected from the stack using a pump and probe and was captured in a sealed Teflon bag. Bag samples were later evaluated using a MKS Multigas™ 2030 FTIR Continuous Gas Analyzer for concentration measurements [3]. This allowed for determination of up to 20 different gas species including CH4, CO2, CO, and NOx.

Results

Methane fluxes were measured from all four well heads on site. Leak rates were also measured from seven different identified leaks. Emissions from the water tank were measured from both the vent and hatch at the top of the tank. Emissions from the natural gas burner used for power on site was also measured. Background CH4 concentration on site was determined to be 2.46

parts per million (ppm). The average methane lost from each well head is presented in Table 5.b.1.

Table 5.b.1: Methane Loss Rate from Well Heads

Test	CH_4 Concentration above Background	CH_4 Loss Rate	CH_4 Loss Rate
	ppm	g/hr	kg/yr
Well #1	0.74	0.17	1.46
Well #2	0.68	0.16	1.42
Well #3	0.59	0.14	1.20
Well #4	1.66	0.39	3.37
Total		0.85	7.45

The CH4¬ losses from the burner and water tank were evaluated separately from the leaks since these emissions are a product of system design and represented as methane losses. The results from the small natural gas burner for power generation and the water tank are shown in Table 5.b.2.

Table 5.b.2: Methane Losses from Burner and Water Retainment Tank

Test	CH_4 Concentration above Background	CH_4 Loss Rate	CH_4 Loss Rate
	ppm	g/hr	kg/yr
Burner Exhaust	0.86	0.12	1.04
Burner Vent	5.07	0.70	6.11
Burner Total		0.82	7.15
Tank Hatch	300.27	64.05	561.11
Tank Vent	93.09	19.93	174.56
Tank Total		83.98	735.66

All identified leaks on site were quantified using the FFS. A summary of the emission rates due to leaks around the dehydration units and other equipment are shown in Table 5.b.3. Pictures of leak locations can be found in Appendix A.

Table 5.b.3: Methane Losses from On-site Leaks

Test	CH_4 Concentration above Background	CH_4 Loss Rate	CH_4 Loss Rate

	ppm	g/hr	kg/yr
Leak #1	181.77	38.71	339.11
Leak #2	437.13	87.43	765.91
Leak #3	97.83	20.70	181.33
Leak #4	144.59	31.27	273.91
Leak #5	46.47	10.59	92.73
Leak #6	130.56	30.68	268.72
Leak #7	33.81	8.02	70.27
Total		227.40	1991.99

Another identified source of methane emissions were the housings on the Exterran stacks located on site. Multiple leaks were located within the housing using a FLIR GF-320 oil and gas-imaging camera. In order to measure all combined leaks, the hose to the FFS was placed on the inside and the doors were closed as much as possible. The opened areas were sealed with a plastic tarp to ensure that the entire leak was captured. The emissions from the two housings are shown in Table 5.b.4.

Table 5.b.4: Methane Losses from Exterran Unit Housings

Test	**CH_4 Concentration above Background**	**CH_4 Loss Rate**	**CH_4 Loss Rate**
	ppm	**g/hr**	**kg/yr**
Stack #1	1428.98	334.21	2927.67
Stack #2	97.83	22.30	195.31
Total		356.50	3122.98

Emissions from the stacks of the Exterran units contained minimal CH4. The levels were below those of the local background, however, the stacks were evaluated for CO2, CO¬, and NO¬x emissions. Only one stack could be evaluated at the time of the audit because the other was offline. The stack velocity was measured with a pitot tube and the average velocity was determined to be 290.4 ft/min giving a flow rate of 228 standard cubic feet per minute (SCFM). Stack emissions were estimated by multiplying the concentration measured from the bag sample by the estimated flow rate are shown in Table 5.b.5.

Table 5.b.5: Emissions from Exterran Stacks

Emissions	**ppm**	**g/hr**	**kg/hr**	**kg/yr**
CO_2	74896.78	17880.09	17.88	156629.61
CO	24.95	3.79	0.00	33.20
NO_x	25.38	4.78	0.00	41.89

Conclusions

Methane losses were measured from a variety of site components including: well heads, water retainment tank, natural gas burner, stack housings, and leaking devices. The total estimated methane emissions are shown in Table 5.b.6. The contribution of each component is shown in Figure 5.b.5. The Exterran stack emissions were also analyzed and showed emissions of CO2, CO, and NOx. These emissions contribute to the total greenhouse gas (GHG) emissions of the site and can be taken into account in estimating a total GHG emission rate on a CO2-equivalent basis. The total CO2-equivalent GHG emissions from the methane and CO2 are shown in Table 5.b.7.

Measuring the methane emissions from new unconventional well pads of is interest in order for the EPA and other agencies to develop accurate emissions factors for new equipment and technologies. A recent study by Rella, et al., used mobile flux techniques to estimate the total site emissions from well pads in the Barnett Shale region of Texas [4]. In total 193 sites were audited and 122 were found to have measureable emissions rates. Other sites may or may not have had emissions rates due to the measurement technique. Of the sites that had measureable fluxes, the geometric mean was 0.63 ± 0.09 kg/hr with an arithmetic mean of 1.74 ± 0.35 kg/hr. As shown in Table 6 the site wide emissions of the MSEEL well pad was 0.67 kg/hr, which is nearly identical to the geometric mean of Rella et al, and only about 1/3rd of their arithmetic mean. Therefore, the MSEEL continuous methane emissions seem similar to expected emissions from well pads.

Table 5.b.6: Total Methane Losses

Category	**CH_4 Loss Rate**	**CH_4 Loss Rate**	**Percent of Total Site Emissions**
	g/hr	**kg/yr**	**%**
Leaks	227.40	1991.99	33.96%
Burner	0.82	7.15	0.12%
Water Tank	83.98	735.66	12.54%
Stack Housing	356.50	3122.98	53.25%
Well Heads	0.85	7.45	0.13%
Total	**669.55**	**5865.23**	100.00%

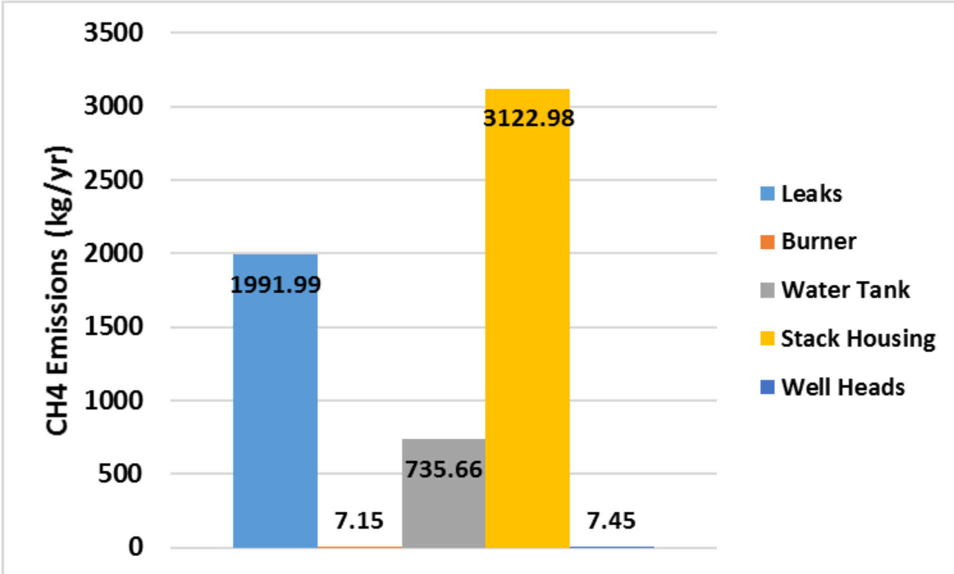


Figure 5.b.5: Methane Emissions Rate Each Component (kg/year)

Table 5.b.7: CO2-Equivalent Greenhouse Gas Emissions (Both Stacks Online)

GHG Emissions	CO2-equivalent	
	kg/yr	%
CO_2	313259.23	68%
CH_4	146630.8	32%
Total	459890.04	100%

References

[1] RKI Instruments, "Eagle 2 Model," 16 August 2000. [Online]. Available: http://www.rkiinstruments.com/pdf/eagle2.pdf. [Accessed 19 September 2016].

[2] Los Gatos Research, "Ultraportable Greenhouse Gas Analyzer (CH4, CO2, H2O)," 2016. [Online]. Available: http://www.lgrinc.com/analyzers/ultraportable-greenhouse-gas-analyzer/. [Accessed 19 September 2016].

[3] MKS Instruments, "Multigas 2030 FTIR Continuous Gas Analyzer," 15 March 2007. [Online]. Available: http://www.mksinst.com/docs/UR/onlinemultigas2030ds.pdf. [Accessed 16 October 2015].

[4] C. W. Rella, T. R. Tsai, C. G. Botkin, E. R. Crosson and D. Steele, "Measuring Emissions from Oil and Natural Gas Well Pads Using the Mobile Flux Plane Technique," Environmental Science and Technology, vol. 49, no. 7, pp. 4742-4748, 25 March 2015.

Appendix A: Leak Location Images

Leak #1

Leak #2

Leak #3

Leak #4

Leak #5

Leak #6

Leak #7

Products

CAFEE are currently in working with Dr. Gil Bohrer of the Ohio State University and NNE to conduct additional research on the effects of hydraulic well stimulation on methane fluxes at, on, or near, fracture well sites. This will likely occur at a non MSEEL site location but is directly a product of the MSEEL collaborations and in lieu of the OSU site.

CAFEE researchers have collaborated with LI-COR Biosciences in developing a proposal just submitted to the National Science Foundation's Environmental Engineering Program. This project would build upon current site audits and also utilize eddy-covariance flux techniques. The goal of this program is to assess the validity of employing these techniques to highly heterogeneous emissions sources such as wells sites.

Plan for Next Quarter

- Obtain additional funding to purchase LI-COR 7700 high frequency methane analyzer and integrate into a mobile platform for short term audits.
- Complete the quarter two audit.

Task 5c. – Surface Environmental – Air

Approach

Previously we had reported on the association between distance from the MSEEL well pad and the concentration of trace elements for the time period 10/28 – 10/30 of 2015 during the hydraulic fracturing activity on the well pad. Samples were collected at the well pad and each of the three operational sampling sites (approximately 1 km, 2 km and 7 km) downwind of drilling activity). This trace element analysis should allow for characterization of the effect of contaminant dispersion throughout the area.

Simultaneous direct-reading 1 min $PM_{2.5}$ mass measurements were performed at each site (n=10,000 readings/site). Mass readings from the gas well pad during hydraulic fracturing were as high as 300 $\mu g/m^3$, with 1 min averages over one week of 12 $\mu g/m^3$. The total average of the other three sampling sites was 6 $\mu g/m^3$. Our study found mixed results for correlation between direct mass measurements and spikes in emissions resulting primarily from stationary pumps and generators burning diesel fuel on the well pad.

Results and Discussion

Using a model for trace metal analysis (e.g. V, Fe), we were able to determine that the emitted plume traveled downwind as far as our 7 km sampling station. Although these data suggest that mass measurements return to background at a 1 km distance from the well pad, exposure to emitted dust from the fracture-stimulation process occurs much further out. These data appear to draw a parallel finding to epidemiological studies showing effects of UNGD as far as 15 km out. We observed what appeared to be a plume profile diminishing exponentially with distance from the pad for the trace element magnesium (Mg). We were able to fit an exponential equation to the results with a correlation coefficient of > 0.7 (Figure 5.c.1).

Magnesium was also found to be proportional to eight other elements at sampling sites 7 km downwind of the Morgantown UNGD well site with a correlation coefficient > 0.7 (n=8; Ba, Fe, La, Mn, Rb, Sr, Ti, V). Magnesium was correlated most strongly at an R2 > 0.9 (n=4) with Sr (R2=0.9876), V (R2=0.9413), La (R2=0.9396), and Fe (R2=0.9202). It was associated with Rb (R2=0.8659) at an R2 >0.8 (n=1), and Ti (R2=0.7551), Mn (R2=0.7546) and Ba (R2=0.7241) at a correlation of R2 > 0.7 (n=3). Chromium is consistently proportional to six other elements at sampling sites 7 km downwind of the Morgantown UNGD well site with a R2 correlation between 0.7 to 0.8 (n=6); V (R2=0.7841), Ti (R2=0.7794), Ba (R2= 0.7528), (R2=0.7459), Mn (R2=0.7441), Sr (R2=0.7319). That trace element composition was not unlike those reported in the literature for diesel exhaust particulate, although sand, introduced as proppant in the fracturing process, could not be entirely ruled out as a contributing factor.

More recently we have begun examining the other periods in which the hydraulic fracturing occurred. The results are not strongly consistent with the initial analyses (figures 5.c.2 and 5.c.3), however, there is still more analyses to be done, including examining the effects of meteorology which was also recorded for the sampling period.

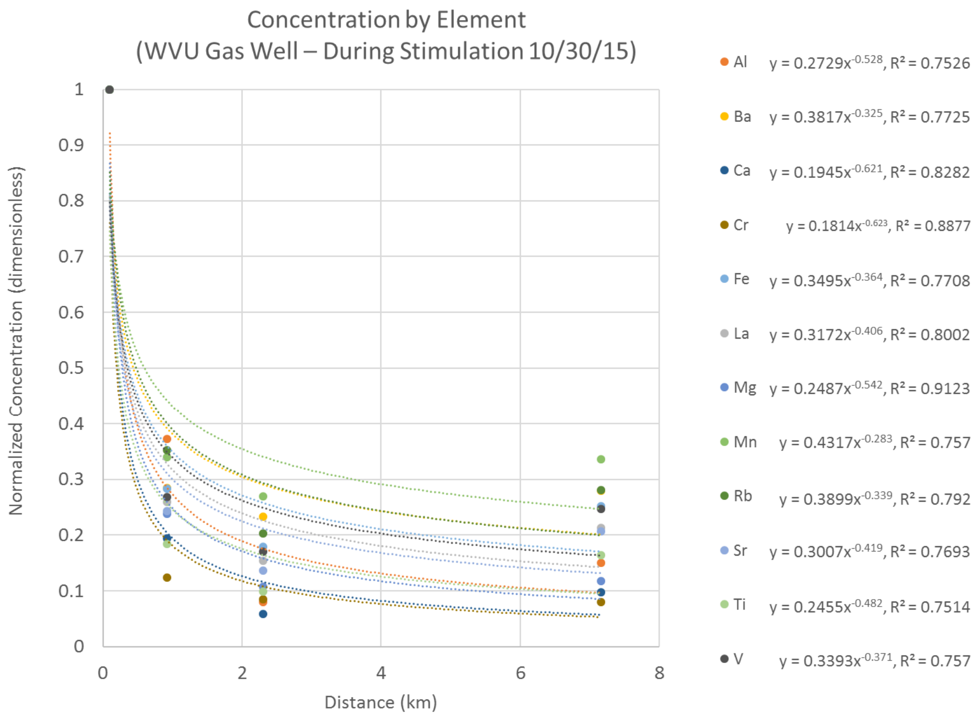


Figure 5.c.1. Previously reported correlation between distance from the well pad (denoted as distance = 0) and 12 trace element concentrations (normalized to the concentration at the well pad) sampled during the initial phases of the hydraulic fracturing for the period 10/28-30/2015. Magnesium stood out as the strongest tracer correlating with a majority of the other trace elements.

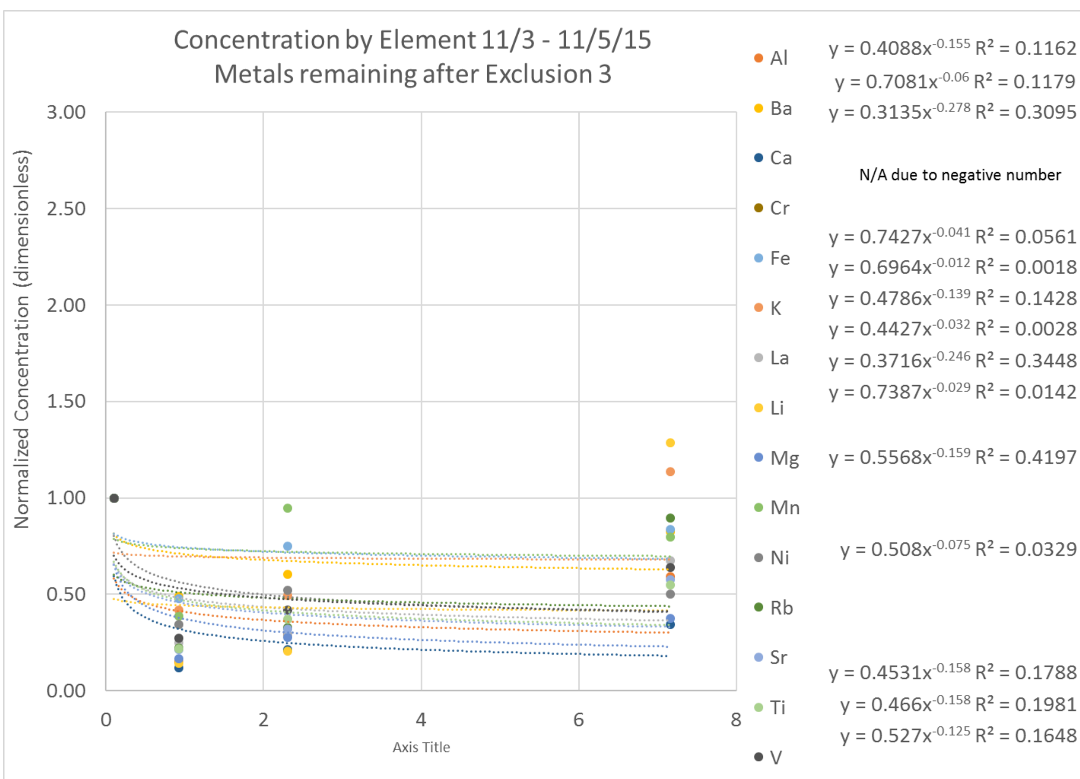


Figure 5.c.2. Correlation between distance from the well pad (designated as 0 km) and trace element concentration (normalized to the concentration at the well pad) for samples collected 11/1-3/2015. Fit of the exponential function to the data was not as high as for the period 10/28-30/2015.

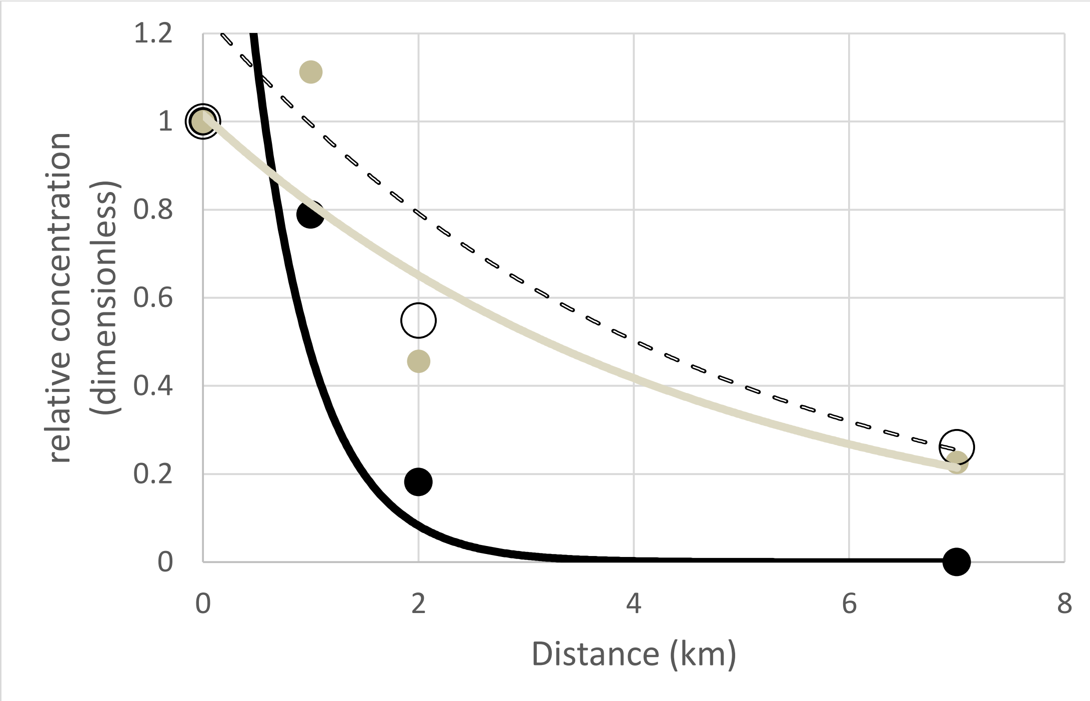


Figure 5.c.3. PM2.5 dust concentration (normalized to the concentration at the well pad) as a function of distance from the well pad (denoted as distance = 0) measured using a direct-reading photometer. The black line and dot are for the period 10/28-30/2015, the gray line and dot are for 11/1-3/2015 and the open dot and dashed line are for the period 11/4-5/2015. Correlation coefficients for all three curves are greater than 0.7.

Products

Plan for Next Quarter

Continue analyses of trace elements to determine the sources of the elements that appear to indicate plume dispersion from the well pad.

Topic 6 – Economic and Societal

Approach

The lead on the political and societal project will work to identify and evaluate the factors shaping the policymaking response of local political actors. Included in this assessment will be an accounting, past and present, of the actions of public and private individuals and groups acting in favor of or opposed to shale gas drilling at the MSEEL site.

First year activity includes developing, distributing, collecting and compiling the responses from a worker survey and a vendor survey. The worker survey will address job characteristics and offsite expenditures. The vendor survey will help to identify per-well cost structures.

Results and Discussion

The team completed work this quarter documenting the state of the region at the initiation of the Marcellus shale experimental well-drilling project. The document, entitled "MSEEL Project Context: State of the Region (2001-2014)", is published as an on-line report accessible from the WVU Regional Research Institute website at http://rri.wvu.edu/resource-documents/. The report, which describes the socioeconomic context for the MSEEL well, provides socioeconomic trends leading up to the project, and includes data on gas drilling and production trends.

The second activity draws on collaboration with NNE on a model for providing generalizable costs for future shale gas development impacts assessments. A technical document describing this model is in progress and should be completed and posted to the RRI website by summer 2017.

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Stair, CA, S Ghosh, and R Jackson (2017) “MSEEL Project Context: State of the Region (2001-2014),” RRI Resource Doc 2017-01, WVU Regional Research Institute: Morgantown WV. January 17, 2017.

Abstract. The Marcellus Shale Energy and Environmental Laboratory, or MSEEL, is the nation's first integrated research initiative on shale gas drilling. An experimental hydraulic fracturing gas well is the centerpiece of the MSEEL project, “which West Virginia University launched in fall 2014 in partnership with Northeast Natural Energy, the National Energy Technology Laboratory of the U.S. Department of Energy and Ohio State University. The five-year, $11 million project is the first-ever long-term, comprehensive field study of shale gas resources in which scientists will study the process from beginning-to-end.” Because one dimension of the MSEEL analysis is the economic impacts and implications of well-drilling activity, this report has been prepared to provide a statistical overview and description of the local and regional economies leading up to the initiation of the MSEEL project, and to set the stage generally for subsequent socioeconomic analyses. The report includes various graphs and tables that describe the local economy during the 2001 to 2014 period, providing a context within which to view the role of gas extraction activities in the economy.

Products

Plan for Next Quarter

Cost Status

Year 1

Start: 10/01/2014 End: 09/30/2017

Baseline Reporting Quarter

	Q1 (12/31/14)	Q2 (3/30/15)	Q3 (6/30/15)	Q4 (9/30/15)
Baseline Cost Plan	(From 424A, Sec. D)			
(from SF-424A)				
Federal Share	$549,000		$3,549,000	
Non-Federal Share	$0.00		$0.00	
Total Planned (Federal and Non-Federal)	$549,000		$3,549,000	
Cumulative Baseline Costs				
Actual Incurred Costs				
Federal Share	$0.00	$14,760.39	$237,451.36	$300,925.66
Non-Federal Share	$0.00	$0.00	$0.00	$0.00
Total Incurred Costs - Quarterly (Federal and Non-Federal)	$0.00	$14,760.39	$237,451.36	$300,925.66
Cumulative Incurred Costs	$0.00	$14,760.39	$252,211.75	$553,137.41
Uncosted				
Federal Share	$549,000	$534,239.61	$3,296,788.25	$2,995,862.59
Non-Federal Share	$0.00	$0.00	$2,814,930.00	$2,814,930.00
Total Uncosted - Quarterly (Federal and Non-Federal)	$549,000	$534,239.61	$6,111,718.25	$5,810,792.59

Start: 10/01/2014 End:
09/30/2017

Baseline Reporting Quarter

	Q5 (12/31/15)	Q6 (3/30/16)	Q7 (6/30/16)	Q8 (9/30/16)
Baseline Cost Plan	(From 424A, Sec. D)			
(from SF-424A)				
Federal Share	$6,247,367		$7,297,926	
Non-Federal Share	2,814,930		$4,342,480	
Total Planned (Federal and Non-Federal)	$9,062,297	$9,062,297.00	$11,640,406	
Cumulative Baseline Costs				
Actual Incurred Costs				
Federal Share	$577,065.91	$4,480,939.42	$845,967.23	$556,511.68
Non-Federal Share	$0.00	$2,189,863.30	$2,154,120.23	$0.00
Total Incurred Costs - Quarterly (Federal and Non-Federal)	$577,065.91	$6,670,802.72	$3,000,087.46	$556,551.68
Cumulative Incurred Costs	$1,130,203.32	$7,801,006.04	$10,637,732.23	$11,194,243.91
Uncosted				
Federal Share	$5,117,163.68	$636,224.26	$1,004,177.30	$447,665.62
Non-Federal Share	$2,814,930.00	$625,066.70	($1,503.53)	($1,503.53)
Total Uncosted - Quarterly (Federal and Non-Federal)	$2,418,796.68	$1,261,290.96	$1,002,673.77	$446,162.09

Start: 10/01/2014 End: 09/30/2017

Baseline Reporting Quarter

	Q9 (12/31/16)	Q10 (3/30/17)	Q11 (6/30/17)	Q12 (9/30/17)
Baseline Cost Plan	(From 424A, Sec. D)			
(from SF-424A)				
Federal Share				
Non-Federal Share				
Total Planned (Federal and Non-Federal)				
Cumulative Baseline Costs				
Actual Incurred Costs				
Federal Share	$11,223.71			
Non-Federal Share	$0			
Total Incurred Costs - Quarterly (Federal and Non-Federal)	$113,223.71			
Cumulative Incurred Costs	$11,307,467.62			
Uncosted				
Federal Share	$334,441.91			
Non-Federal Share	($1,503.53)			
Total Uncosted - Quarterly (Federal and Non-Federal)	$332,938.38			

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