Oil & Natural Gas Technology

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Clean and Secure Energy from Domestic Oil Shale and Oil Sands Resources

Quarterly Progress Report (January – March 2014)

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EXECUTIVE SUMMARY

The Clean and Secure Energy from Domestic Oil Shale and Oil Sands Resources program, part of the research agenda of the Institute for Clean and Secure Energy (ICSE) at the University of Utah, is focused on engineering, scientific, and legal research surrounding the development of these resources in Utah.

Outreach and education efforts in Task 2, focused on disseminating results from the various subtasks via publication of papers in peer-reviewed journals (Subtask 4.9) and participation in conferences (Subtask 7.3).The website has also been updated with links to all recent outreach efforts.

Task 3 focuses on utilization of oil shale and oil sands resources with CO_2 management. The Subtask 3.1 team continued gathering and compiling information about emission factors associated with natural gas production and processing. The team is also evaluating the Utah Division of Air Quality's emissions projections for 2012 from oil and gas sources in the Uinta and Piceance Basin for five criteria pollutants. The Subtask 3.2 research team is using a new reaction model, the LES Rate Constrained Chemistry Model, in their simulations and has decided that carbon monoxide (CO) emissions will be the quantity of interest for the remainder of the study. The Subtask 3.3 and 3.4 project teams focused on utilizing decline curve analysis to fit individual wells in the Uinta Basin and then using the resulting range of fitted coefficients in a Monte Carlo simulations of oil production in the Basin over the 1999–2013 period. The analysis has also been extended to include greenhouse gas (GHG) emissions for conventional oil and gas production based in emissions factors compiled by the Subtask 3.1 team.

Task 4 projects are related to liquid fuel production by in-situ thermal processing of oil shale. The Subtask 4.3 began examination of pyrolysis rates at low heating rates in February 2014. Bias errors relating to helium purity and mass flow were identified and fixed. The team has performed pyrolysis experiments at atmospheric pressure at low heating rates (0.5 and 1K/min). The 1 K/min pyrolysis experiments in pure helium agree very closely with the previous Brigham Young University (BYU) data.

Task 5 projects provide analyses of the environmental, legal, economic, and policy framework. A final topical report on policy and economic issues associated with using simulation to assess environmental impacts (Subtask 5.3) has not been submitted. All Task 6 projects (economic and policy assessment of a domestic unconventional fuels industry) are now complete.

Task 7 researchers are focused on research relevant to their industrial partner, American Shale Oil (AMSO). The Subtask 7.1 team continued its segmented linearization work and its development of constitutive modeling surfaces. They have performed preliminary permeability experiments on oil shale-type samples in a newly commissioned relative permeability apparatus. Subtask 7.3 researchers completed co-simulation of the second AMSO heater test for the fluid in the lower later well which houses the heater and for heat dissipation in the solid shale formation. They were able to match temperatures within 0.5 K over a period of 3 months as measured experimentally by AMSO in tomography wells at the site.

PROGRESS, RESULTS, AND DISCUSSION

Task 1.0 - Project Management and Planning

There were no schedule/cost variances or other situations requiring updating/amending of the Project Management Plan (PMP) in this quarter.

Task 2.0 -Technology Transfer and Outreach

Technology transfer and outreach efforts are focused on communicating project results through publication of papers and reports, through responses to requests for visits and interviews, and through updates of the Clean and Secure Energy from Domestic Oil Shale and Oil Sands Resources Program pages on the ICSE website. In this quarter, one paper was accepted for publication (Subtask 4.9) and research results for Subtask 7.3 (joint project with industrial partner AMSO) were presented at a conference in Austria.

Task 3.0 - Clean Oil Shale and Oil Sands Utilization with CO_2 Management

<u>Subtask 3.1 – Lifecycle Greenhouse Gas Analysis of Conventional Oil and Gas Development in the Uinta Basin (PI: Kerry Kelly, David Pershing)</u>

During this quarter, the project team worked on gathering and compiling information about emission factors associated with natural gas production and processing. Most fugitive emission estimates from the gas industry are based on comprehensive studies of methane leakage from gas production, processing, transportation and distribution of conventional and unconventional natural gas (this term is used for production using hydraulic fracturing, which is used widely in shale gas and tight gas production). A review of these studies was performed to better understand the potential scale of emissions, the main emission causing activities, and the reasons for any differences in the estimates. The compiled information includes the emissions from activities such as pre-production (site preparation, drilling, hydraulic fracturing, well completion and workovers); production (leakage and venting from well equipment and liquid unloading) and transmission and distribution. The source of estimates includes industry, government agencies and peer-reviewed publications.

In order to use the emission factors for this study, the team considered three types of scaling factors: well counts, spud counts and gas production. To present the emission factors, some conversions have been made in order to facilitate the comparison (see Tables 1 and 2). Sources listed in these tables are not included in the “References” list of this report but are available upon request.

Table 1. Emissions associated with site preparation and well completion in metric tons of CO_2e per well.

Activity	CO2 e (Metric tons/well)	source
Site preparation (Marcellus shale gas well pad)	299-354	Jiang et al (2011)[1]
Site preparation (Marcellus shale gas well pad)	143-143	Santoro et al (2011)[2]
Well completion		
unconventional (Shale gas wells)	483	O'Sullivan (2012)
unconventional (from tight oil wells)	1072	O'Sullivan (2012)
unconventional (from Shale gas wells)	762-1624	Jiang et al (2011)
unconventional (from Shale gas wells)	1294	Santoro et al (2011)
unconvetional (from Shale gas wells)	645	Stephenson et al (2011)
unconvetional (from Shale gas wells)	344-369	Broderick et al (2011)
unconvetional (from Shale gas wells)	656	NYSDEC (2011)
conventional	12	Canadian study
conventional	15	EPA revised emission factors
unconventional	3717	EPA revised emission factors
unconventional (from shale gas wells)	2058	EPA (2013)[3]

[1] includes emissions related to construction as well as fuel related impacts.

[2] Includes emissions from energy use.

[3] Flowback gas venting from shale gas wells. The average net emissions include a large number of wells not classified as shale wells (e.g., tight sands, etc).

Table 2. Emissions associated with well completion and workovers, processing, production and transmission and distribution in metric tons of CO_2e per billion cubic feet of total natural gas production.

Activity	CO2e (Metric tons/Billion cubic feet of total natural gas prod)	Source
Well completion and workovers (venting)		
conventional	12	Burnham (2011)[1]
unconventional	1841	Burnham (2011)[1]
unconventional (Marcellus shale)	2038	Jiang et al (2011)
Processing	600	Burnham (2011)[1]
Processing (Marcellus Shale gas)	1994	Jiang et al (2011)[2]
Processing (sweet)	533	Canadian study[3]
Processing (sour)	2267	Canadian study[3]
Production		
conventional		
Liquid unloading (venting)	4803	Burnham (2011)[1]
Well equipment (leakage and venting)	2922	Burnham (2011)[1]
total	7725	
unconventional		
Liquid unloading (venting)	0	Burnham (2011)[1]
Well equipment (leak)	2922	Burnham (2011)[1]
total	2922	
total production	7200	Jiang et al (2011)[2]
total production	1897	Canadian study[3]
total production	1481	Canadian study[4]
Transmission and distribution (leakage and venting)	1773	Jiang et al (2011)[1]
Transmission	1108	Jiang et al (2011)
distribution	665	Jiang et al (2011)
pipeline fugitive emissions	48	Emission Inventory Report (Chapter IV)[2]

[1] Author estimate as 10% of all vented -metric tons CH_4/well
[2] Production value estimated from Figure 4 of Jiang et al (2011)
[3] Canadian study based on Canadian data
[4] Canadian study based on US data

From the gathered information, the emissions from unconventional gas production completions were much higher than from the conventional gas completions, but losses from other components of the production chain were considered to be the same for both conventional and unconventional gas since much of the infrastructure is common to both. The studies indicate that flowback could cause the highest proportion of emissions from shale gas exploration and extraction. Emissions from well completions vary widely depending on the shale formation, the use of technology, and operating procedures. Well completion is expected to dominate potential pre-production emissions, followed by drilling and hydraulic fracturing activities.

The project team has started to gather emission inventories for oil and gas emissions in the Uinta and Piceance Basins (Bar-Ilan et al., 2012). Team members are also evaluating the Utah Division of Air Quality's emissions projections for 2012 (based on an original 2006 inventory) from oil and gas sources in the Uinta and Piceance Basin for five criteria pollutants (NO_x, VOCs, CO, SO_x and PM10). Five basic parameters are used for developing scaling factors: well counts, spud counts, gas production, oil production and condensate production. These scaling factors are applied to the 2006 baseline emissions for both basins. Well count projections for the Uinta Basin (Duchesne and Uintah counties) were developed by deriving an average ratio of annual spud counts to well counts for a number of historical years and then applying this ratio to the projected spud counts to estimate annual well counts for future years. For the Piceance Basin (Garfield, Rio Blanco, Mesa, Moffat, Routt, Chaffee, Eagle, and Lake Counties), the well counts were projected from historical data and spud counts were derived from the well counts (UDAQ, 2014).

For the Piceance Basin, the 2012 projected emissions showed that compressor engines are the main NO_x emission source, accounting for about 65% of the total basin-wide NO_x emissions, followed by the emissions from drill rigs, accounting for about 17% of the total. Emissions from pneumatic devices, venting from initial blowdowns and completions, and emissions from glycol dehydrators accounted for about 60% of the total VOC emissions in the Piceance Basin in 2012. For the Uinta Basin, the 2012 projected emissions for both tribal and non-tribal lands showed that drilling rigs and artificial lift engines were the predominant NO_x emissions source types, accounting for approximately 85-90 % of total basin-wide NO_x emissions. The main source of VOC emissions were emissions from pneumatic pumps, pneumatic devices and oil tanks, accounting for approximately 90-95 % of total basin-wide VOC emissions. Emissions from drill rigs were the main contributors to SO_x emissions with approximately 90 -95% of the total SO_x emissions, while artificial lift engines and drill rigs were the main sources contributing to CO emissions, with about 92-97 % of the total CO emissions of the total basin.

Starting in 2012, new EPA oil and gas regulations will reduce emissions from completions and other oil and gas operations, including:

- For storage tanks, operators must reduce VOC emissions by 95% for tanks that have a potential to emit more than 6 ton VOC/yr. These regulations have staggered phase-in requirements.
- For well completions, beginning October 15, 2012, operators must reduce VOC emissions either by flaring or by capturing produced gas using green completions. Beginning January 1, 2015, they must capture the gas and make it available for use or sale, which they can do through the use of green completions. A few exceptions exist to this regulation.
- For pneumatic control devices, operators must control reduce emissions by 95% from high-bleed, gas-driven controllers (with a gas bleed rate greater than 6

standard cubic feet per hour) that are located between the wellhead and the point where gas enters the transmission pipeline.

- For natural gas gathering and boosting stations, operators must reduce emissions by 95% from wet-seal compressors and perform certain maintenance on reciprocating compressors.
- For gas-processing plants, the rules require enhanced leak detection and repair requirements.

Subtask 3.2 - Flameless Oxy-gas Process Heaters for Efficient CO_2 Capture (PI: Jennifer Spinti)

This subtask was on hiatus during most of this quarter due to deadlines for other projects. Some work was done near the end of the quarter generating a new oxy-combustion reaction table. The reaction model for this table is the LES Rate Constrained Chemistry Model. It can be written as

$$C^* + O \xrightarrow{slow} C \xrightarrow{fast} P$$

where the slow step is determined by a global reaction rate computed from LES filtered quantities and the fast step is chemical equilibrium or flamelets occurring at the subgrid scale. There are three streams in this model:

1. C* (Initial fuel)
2. C (Fuel that can react to equilibrium - composition is that of natural gas used in IFRF experiment)
3. O (Oxidizer - O_2)

The reaction table is a function of three independent variables: two mass fractions that describe how much of each stream is present in the mixture and heat loss. When creating this table, researchers noted that very high levels of CO are present at equilibrium in mixtures of fuel and O_2, even in the presence of excess O_2. Given that equilibrium is not an adequate CO model (the slow CO to CO_2 reaction means that more CO_2 is present at equilibrium than will be present in a furnace given the relatively short residence time), actual CO levels in real combustions systems are even higher. Thus, a CO model needs to be implemented in the Arches simulation tool. A recent publication by Kühnemuth et al. (2014) on CO formation in oxy-fuel combustion indicates the reaction pathways that must be included in such a model. For the V/UQ study of the IFRF furnace data, the quantity will thus be CO and the remaining time in this project will be spent on developing a CO model, running a V/UQ test matrix of 3-6 simulations, and reporting on the results.

Subtask 3.3 - Development of Oil and Gas Production Modules for $CLEAR_{uff}$ (PI: Terry Ring)

Research during this quarter has focused on (1) utilizing decline curve analysis techniques to fit individual wells in the Uinta Basin, and (2) using the resulting range of fitted coefficients in a Monte Carlo simulation of oil production in the Basin over the 1999–2013 period.

As discussed in previous quarterly reports, oil and gas production rates are being modeled using the hyperbolic form of the Arps (Arps, 1945) decline curve equation:

$$q = q_1 \cdot (1 + b \cdot D_1 \cdot t)^{-\frac{1}{b}} \qquad (1)$$

where q is the production rate at time t, q_i is the initial production rate, D_i is the initial decline rate, and b is the decline exponent. The project team has developed a method to fit the hyperbolic form of the Arps decline curve equation to 94% of the individual oil and gas wells in the Basin for which production data has been reported to Utah's Division of Oil, Gas and Mining (DOGM). An example of the resulting fit for an individual oil well in Monument Buttes (Field 105) is shown below in Figure 1.

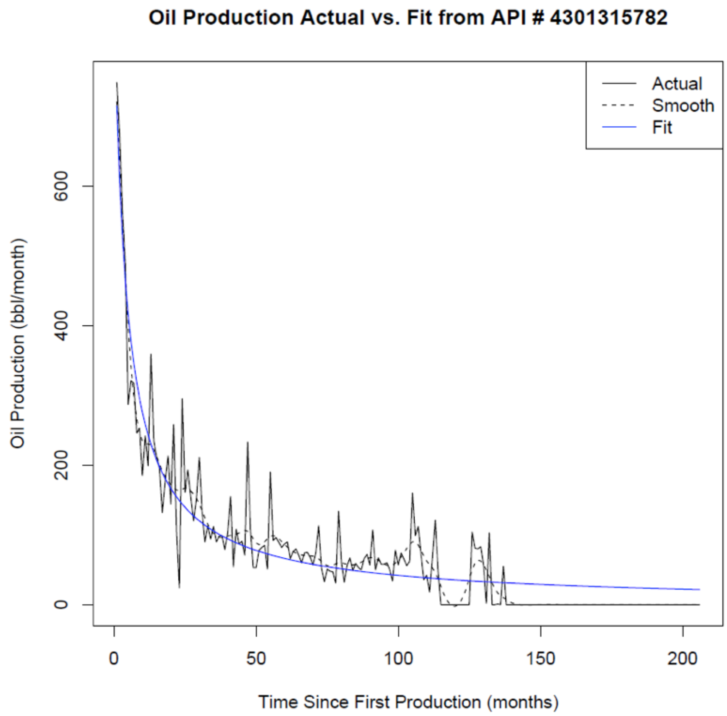

Figure 1. Hyperbolic decline curve fit for oil production from an oil well in Monument Buttes. Solid black line = actual production data, dotted line = actual data after smoothing with a spline function, blue line = resultant fit of the smoothed data.

After fitting each well in a given field, the coefficients from all of the converged well fits are collected and used to generate a cumulative distribution function (CDF) for each coefficient in Eq. [1] for that field. An example of these CDF's for the coefficient b for oil produced from oil wells is shown below in Figure 2.

These CDFs can be used in a Monte Carlo (MC) simulation to estimate the production from wells in the Basin and to show the confidence intervals of those predictions according to the following algorithm.

1. Pick a random number between 0 and 1 for each coefficient in Eq. [1].
2. Using the random number from step 1 and the CDF, generate a value for the coefficient.
3. Calculate the resulting production at each time step and store the values.
4. Repeat many times.
5. Review the range of outcomes and pick the 5th, 50th, and 95th percentile production values from all the simulated runs at each time step.

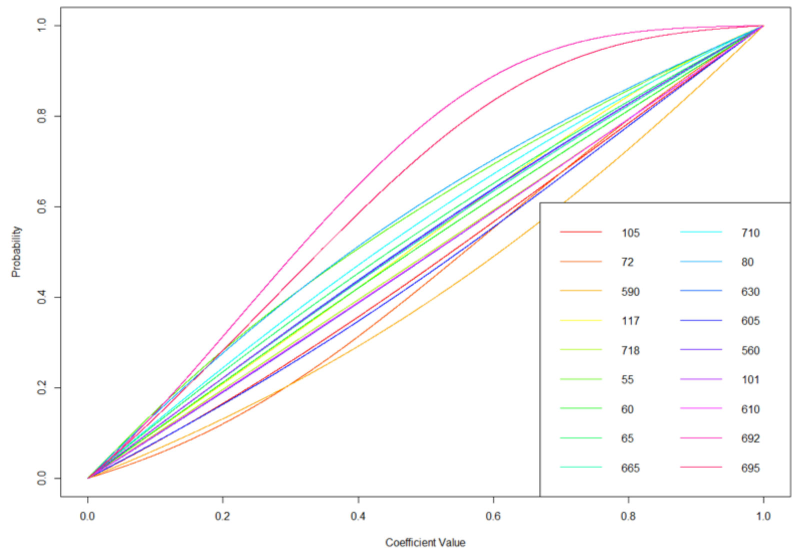

Figure 2. Comparison of CDF's for coefficient b for oil produced from oil wells from analysis of fitted decline curves for 3,947 wells.

An example of MC decline curve simulation results is shown in Figure 3 for wells in Monument Buttes (Field 105).

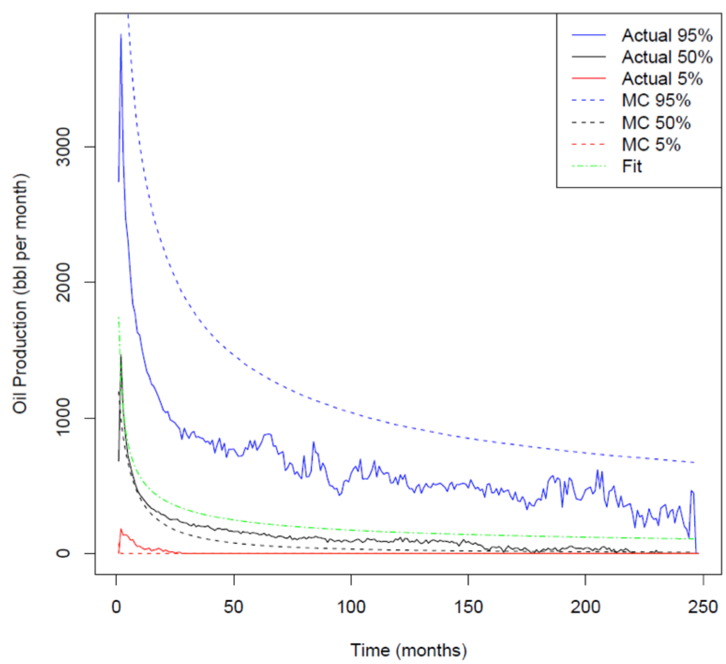

Figure 3. Comparison of 5th, 50th, and 95th percentiles of actual oil production data from Monument Buttes (Field 105) to the same percentiles of a MC simulation of decline curves from that field after 105 runs. The green line is a hyperbolic decline curve fitted to all of the production data in Field 105 using linear regression.

By combining MC simulations for individual decline curves with a given/assumed/ computed drilling growth rate, total production of oil and gas from the Basin can be calculated over time, and the resulting range of outcomes naturally lends itself to statistical analysis to show the confidence intervals of those predictions. An example of this final outcome is shown below in Figure 4 comparing actual oil production from oil wells in the Basin since 1999 to MC simulations of the same type of production.

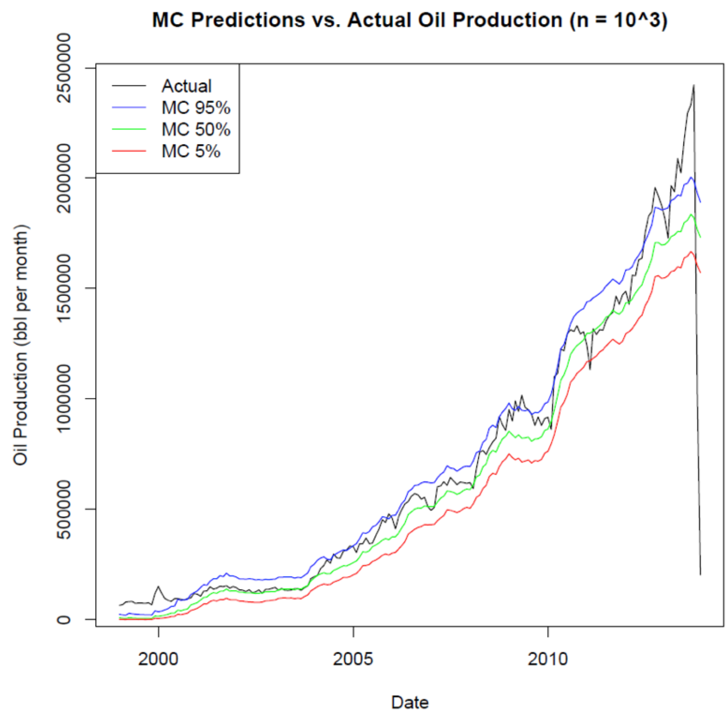

Figure 4. Comparison of the actual oil production from oil wells drilled since January 1, 1999 from all fields in the Uinta Basin vs. the 5th, 50th, and 95th percentiles of a MC simulation of oil production from the Basin after 10^3 runs. Note that the final data point shows a significant drop off because of partial reporting in the DOGM database during the last time step (December 2013).

Currently, the number of wells drilled in each time step of the simulation and the fields they are located in have been taken as a given in the MC simulation for the purposes of verifying simulation results against actual production data. Once the method is switched over to a predictive mode with an assumed or computed growth rate, a second random number generator can be used to determine what field a given well is assigned to (assuming that the proportion of wells drilled in each field remains constant in the future).

Subtask 3.4 - V/UQ Analysis of Basin Scale CLEAR$_{uff}$ Assessment Tool (PI: Jennifer Spinti)

The milestone to demonstrate full functionality of V/UQ methodology for conventional oil development in Uinta Basin was completed in this quarter. The methodology is outlined in the summary for Subtask 3.3 above for oil production from oil wells. The same methodology has also been applied to gas from oil well, gas from as wells, and oil from gas wells. There is still some question as to the choice of model for the individual well production data. Some of the hyperbolic decline curve fits are very poor, and the result is that the MC simulation results for certain fields show the 95% confidence limits far above the actual production levels. The project team is currently looking at ways to improve the decline curve model and to account for possible correlation between coefficients in the decline curve equation with a joint PDF from which the coefficients in the hyperbolic decline curve can be samples.

A further example of how this methodology is being applied is shown in Figure 5. This figure shows the computed GHG emissions from gas production in the Uinta Basin. To generate this range of outcomes, the maximum, mean, and minimum literature values of emission factors for various stages of oil and gas production were coupled to the drilling activity and production levels predicted by the model over time. The next step is to generate a probability distribution of emission factor values that can be sampled from in the Monte Carlo simulations. Figure 6 shows a probability density function and normal distirbution fit to literature values for well drilling/completion/workover.

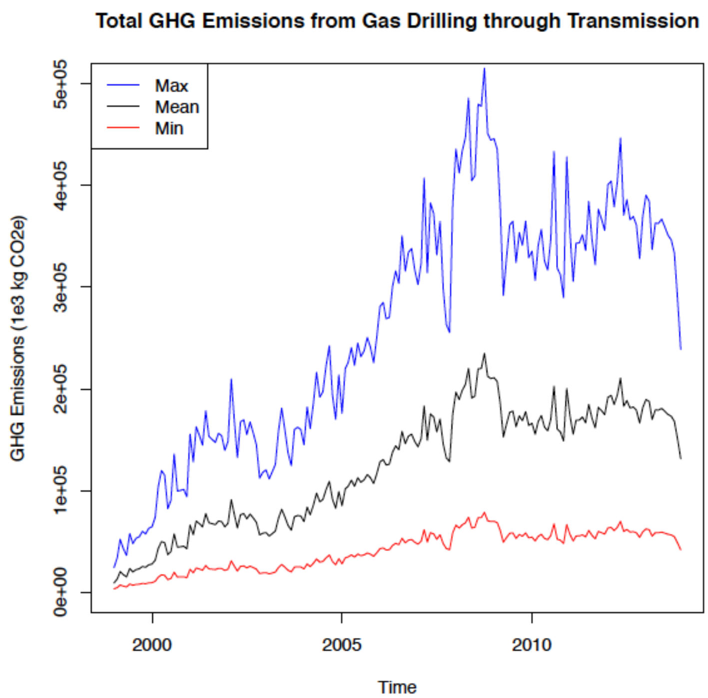

Figure 5. Total GHG emissions for natural gas production from gas wells in the Uinta Basin from 1999–2013 using maximum, mean, and minimum values for each type of emissions factor found in the literature (see Tables 1 and 2 in Subtask 3.1).

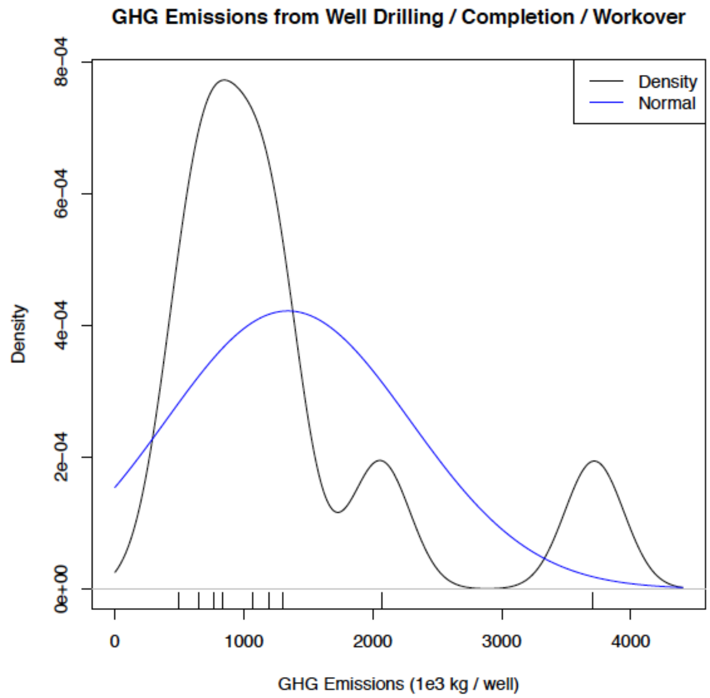

Figure 6. Probability density function and normal distribution fit to literature values for GHG emissions factors for well drilling/completion/workover. Literature values are hash mark above x-axis.

Task 4.0 - Liquid Fuel Production by In-situ Thermal Processing of Oil Shale/Sands

Subtask 4.1 (Phase II) - Development of CFD-based Simulation Tools for In-situ Thermal Processing of Oil Shale/Sands (PI: Philip Smith)

This project continued on hiatus the past quarter focusing. The project team has concentrated its efforts on completing simulations of the AMSO second heater test (Subtask 7.3). These results were presented at the STAR Global Conference in March 2014. As such, they have delayed completion of their topical report for this subtask. Its completion is anticipated in the next quarter.

Subtask 4.2 - Reservoir Simulation of Reactive Transport Processes (PI: Milind Deo)

No report received. A final report on this project is due.

Subtask 4.3 – Multiscale Thermal Processes (PI: Milind Deo, Eric Eddings)

The contract period was extended and additional funds were allocated to this project for the following two tasks:

1. Perform additional low heating rate oil shale pyrolysis experiments using a thermogravimetric analyzer (TGA) to explore the differences between the data at BYU and the University of Utah.

2. Expand the research on incorporating chemical structure features of oil shale into the CPD model.

However, this extension did not occur until early January 2014. There was a four-month period at the end of 2013 when this subtask was not funded at BYU while approval was being sought. Milestones and deliverables that remain are:

- M1 (07/2014): Perform experiments to resolve differences between Fletcher group & Deo group TGA data at 1 K/min
- M2 (07/2014): Extend CPD model for oil shale to include additional chemistry specific to oil shale
- D1 (08/2014): Topical Report describing CPD/shale & oil generation models including summary of their applications/limitations
- D2 (08/2014): Submit paper on combined kerogen/bitumen structures & CPD reaction model to a journal such as Energy & Fuels.

Comparison of Oil Shale Pyrolysis Models

With the additional time period and extended funding, the examination of pyrolysis rates at low heating rates began in February 2014. The initial data looked different than either the previous BYU or the University of Utah data. It was finally discovered that the "high purity" helium had been contaminated with oxygen, causing earlier reaction rates. Researchers also had to replace a problematic mass flow controller. They have performed TGA experiments at atmospheric pressure at low heating rates (2 runs at 0.5 K/min and many runs at 1K/min). The 1 K/min pyrolysis experiments in pure helium agreed very closely with the previous BYU data, as shown in Figure 7. Even though the instrument was calibrated previously for the 1 K/min experiments, researchers will recalibrate the TGA in order to ensure the accuracy of the temperatures, especially at the low heating rates (0.5 and 1 K/min).

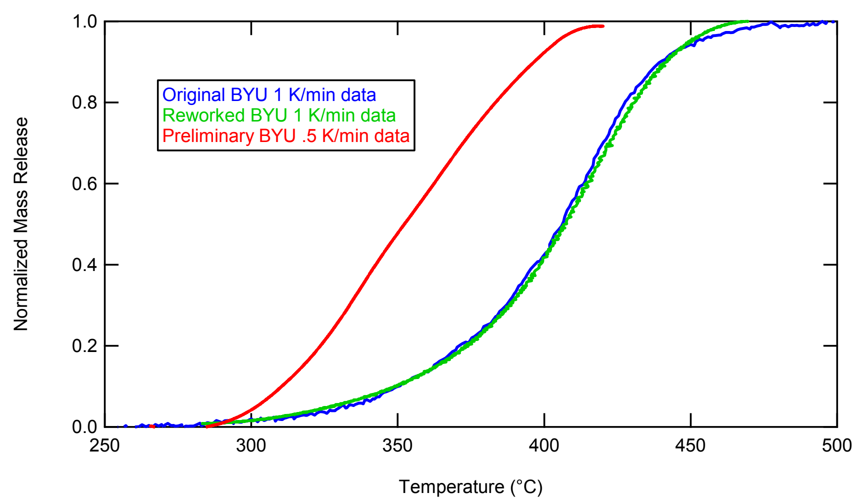

Figure 7. Normalized mass release during pyrolysis of demineralized kerogen (GR2.9) in helium at 1 atm.

Subtask 4.4 - Effect of Oil Shale Processing on Water Compositions (PI: Milind Deo)

This project has been completed.

Subtask 4.5 - In Situ Pore Physics (PI: Jan Miller, Chen-Luh Lin)

This project has been completed.

Subtask 4.6 - Atomistic Modeling of Oil Shale Kerogens and Oil Sand Asphaltenes (PI: Julio Facelli)

This project has been completed.

Subtask 4.7 - Geomechanical Reservoir State (PI: John McLennan)

The milestone to complete the experimental was not completed in this quarter. Currently the testing apparatus is being used by other parties (it was a shared expenditure) and will be available mid-May. The Subtask 4.7 team has redesigned the heating element and anticipates an improved heat distribution. Experimentation will resume and the milestone will be completed once the apparatus is available.

Subtask 4.8 - Developing a Predictive Geologic Model of the Green River Oil Shale, Uinta Basin (PI: Lauren Birgenheier)

The project team will finish the final report on this project in June 2014.

Subtask 4.9 - Experimental Characterization of Oil Shales and Kerogens (PI: Julio Facelli)

Professors Ron Pugmire and Tom Fletcher spent this quarter working on the paper on the analysis of the pyrolysis products from kerogen, including NMR analyses of the char and tar samples obtained at different temperatures, GC/MS analyses of the tar samples, and FTIR analysis of the light gases. This paper was submitted to *Energy & Fuels* as Part 2; Part 1 was accepted for publication in January 2014. Part 2 was reviewed with quite a few comments. A revised paper was developed, the paper was re-reviewed, and a response to the second set of comments was written and resubmitted. The associate editor then made some additional comments and these were addressed. The paper, entitled "Characterization of Macromolecular Structure Elements from a Green River Oil Shale, II. Characterization of Pyrolysis Products by ^{13}C NMR, GC/MS, and FTIR," was recently accepted for publication and is included in the Publications list of this report.

Task 5.0 - Environmental, Legal, Economic and Policy Framework

Subtask 5.1 – Models for Addressing Cross-Jurisdictional Resource Management (PI: Robert Keiter, John Ruple)

This project has been completed.

Subtask 5.2 - Conjunctive Management of Surface and Groundwater Resources (PI: Robert Keiter, John Ruple)

This project has been completed.

Subtask 5.3 - Policy and Economic Issues Associated with Using Simulation to Assess Environmental Impacts (PI: Robert Keiter, Kirsten Uchitel)

No report received. A final report on this project is due.

6.0 – Economic and Policy Assessment of Domestic Unconventional Fuels Industry

Subtask 6.1 Engineering Process Models for Economic Impact Analysis (PI: Terry Ring)

This project has been completed.

Subtask 6.2 - Policy analysis of the Canadian oil sands experience (PI: Kirsten Uchitel)

This project has been completed

Subtask 6.3 – Market Assessment Report (PI: Jennifer Spinti)

This project has been completed

7.0 – Strategic Alliance Reserve

Subtask 7.1 – Geomechanical Model (PI: John McLennan)

The milestone to infer permeability-porosity-temperature relationships and to develop a model that can be used by other subtasks was not completed in this quarter. As mentioned previously, the project team has added triaxial testing (on an AMSO sample, CT scanned last quarter along with the Skyline samples) from the work being done for SubTask 4.7 to increase the mechanical properties data available. Subsidence and compaction are also being evaluated to meet this milestone. The testing in SubTask 4.7 will provide some basis for inferring permeability and porosity relationships with temperature.

With respect to the development of a geomechanical model, segmented linearization and development of constitutive modeling surfaces are proceeding with the help of an undergraduate working with a Ph.D. candidate. The project team has also performed preliminary permeability experiments on a Skyline 16 sample in a newly commissioned (& groundbreaking) relative permeability apparatus at the Energy & Geoscience Institute (EGI) at the University of Utah. Numerical simulations have been initiated.

Measuring Oil Shale Permeability

During the first quarter of 2014, the project team gained access to a relative permeability apparatus that had been acquired by funding outside of this program (through the College of Engineering and EGI). This acquisition was fortuitous because measuring the ultra-low permeability of pristine or pyrolyzed oil shale has been difficult. Team members have done some preliminary permeability experimentation on low permeability analog samples – low permeability

Nugget sandstone – to develop measurement techniques before testing their valuable oil shale samples. They can ideally measure permeability of core rock sample in the nanodarcy range. The apparatus, shown in Figure 8, can apply a confining pressure of up to 10,000 psi and temperatures of 200°C on the sample. It includes one syringe pump for confining pressure, one oven for temperature, a core holder (shown in Figure 8) sitting inside the oven and two other syringe pumps that are capable of flowing two different fluids through the core holder. All of the components of the machine can be controlled by one computer.

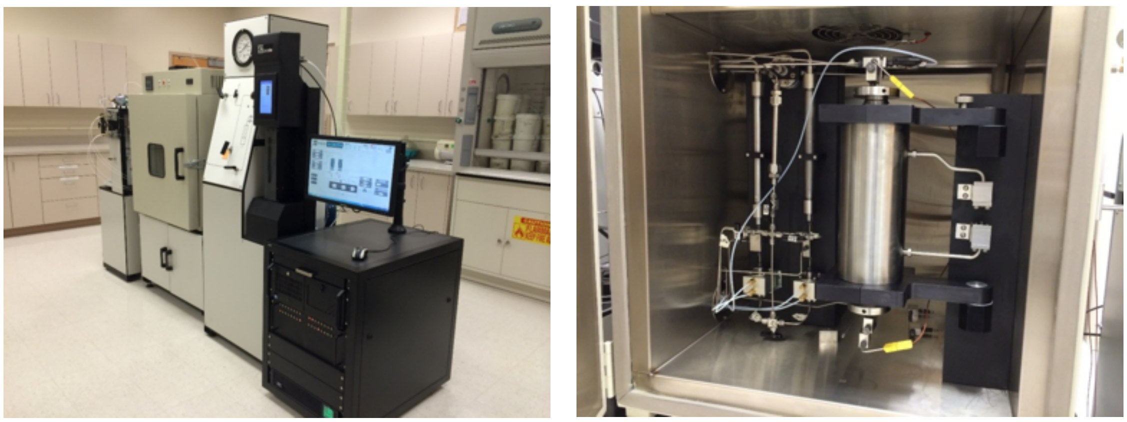

Figure 8. (Left) Low permeability apparatus. (Right) Core holder.

The project team began testing the apparatus with a White River oil shale sample. Its dimensions were 1.5 inches diameter and 3 inches long, a standard length of sample for permeability measurements on higher permeability samples. They could not flow water through the sample because of the very low permeability and the sample length.

In order to make sure that the apparatus was working properly, a new test was done using a microdarcy range sample. A Nugget sandstone sample (1.5 inches in diameter and 1 inch long) was obtained for this purpose. The sample was tested under two different confining pressures: 3,000 psi and 5,000 psi with a back pressure of 1,000 psi. The absolute permeability of the Nugget sandstone was 0.5 microdarcy at 3,000 psi confining pressure and 0.3 microdarcy at 5000 psi confining pressure as shown in Figures 9 and 10.

These results allowed team members to establish that the machine was performing correctly. This permeability is probably an order of magnitude larger than oil shale. Hence, they will test permeability measurement on disks of shale. They will initially test thin oil shale disks (1.5 inches in diameter and ¼ inch to ½ inch in length). There are potential issues with sample length and end effects that will need to be resolved. The project team will then move to Skyline 16 samples (pristine and pyrolized).

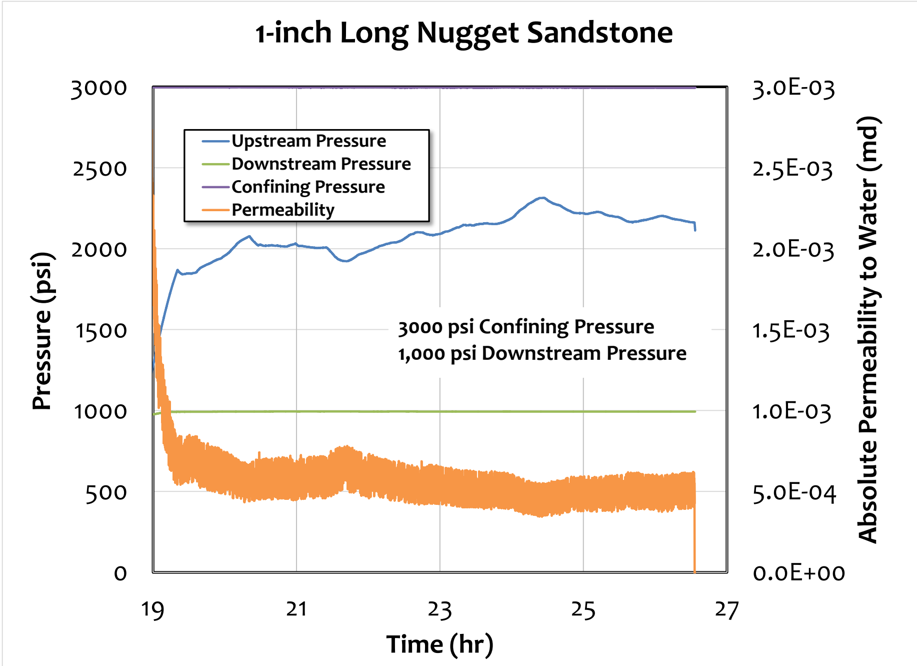

Figure 9. Absolute permeability of Nugget sandstone at 3,000 psi confining pressure.

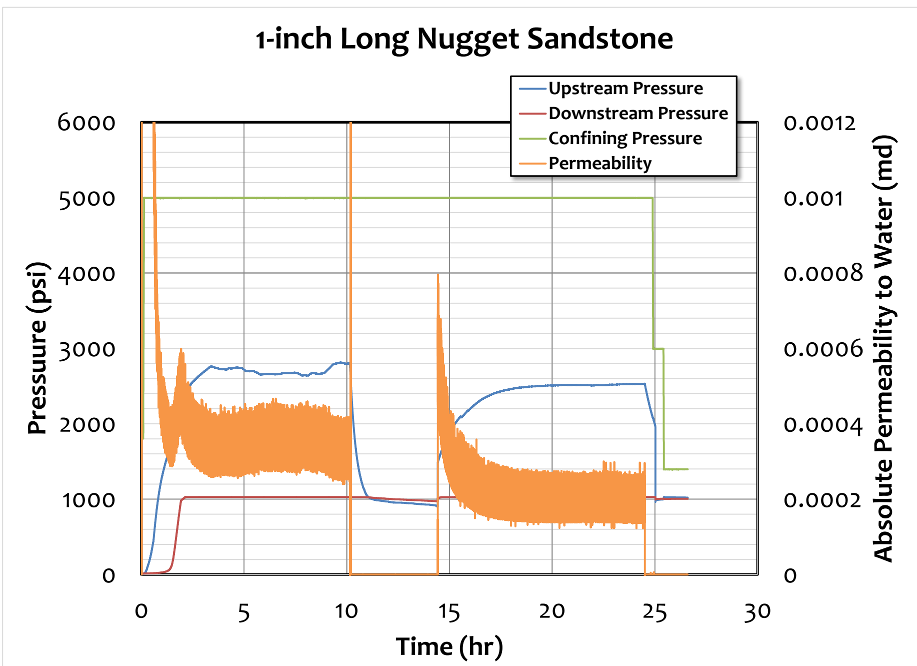

Figure 10. Absolute permeability of Nugget sandstone at 5,000 psi confining pressure.

Subtask 7.2 – Kinetic Compositional Models and Thermal Reservoir Simulators (PI: Milind Deo)

Project has been terminated.

Subtask 7.3 – Rubblized Bed High Performance Computing Simulations (PI: Philip Smith)

During this quarter, researchers have continued to develop high performance simulations of the AMSO process for in-situ thermal treatment of oil shale. They completed the co-simulation created in the previous quarter and presented the results at the STAR Global Conference in March 2014. With the co-simulation, they were able to capture the small fluid time scales occurring in the fluid around the heater inside the lower lateral and the larger solid time scales occurring in the solid shale formation.

The co-simulation was run using two separate simulations. The first simulation, the solid shale formation, contained 2.4 million computational cells. The mesh was refined in the vicinity of the heater and of the tomography wells and was much coarser farther away from the area of interest. To step this simulation through time, the initial time step was set to 600 seconds and then gradually increased to 3,600 seconds as the simulation progressed. The solid simulation was run on 480 cores. The second simulation, the fluid domain, was much more computationally intensive in order to resolve the unsteady convective currents occurring around the heater. This simulation contained about 17 million cells at 1 cm resolution and was run on 720 computational cores. Researchers used Large Eddy Simulation with 10-second time steps to resolve the unsteady convective currents.

To enable co-simulation, the fluid and solid simulations are run at the same time. Initially, both simulations are set up to exchange heat transfer information across the common boundary. The co-simulation was used to simulate the first two weeks of the AMSO second heater test, over which the heater was enabled. In the AMSO experiment, the heater was turned off after two weeks. Therefore, after simulating two weeks of heating, fluid and solid simulations were decoupled and only the solid simulation was continued to simulate 3 months of heat dissipation inside the shale formation.

The heat dissipation profile throughout the formation was tracked for three months and then compared with the experimental tomography well data. Simulation results match experimental results at various tomography wells to within 0.5 K over the three-month period. This close agreement of simulation and experimental data was not previously possible with any other simulation strategies. These results were presented at the STAR Global Conference in March 2014.

CONCLUSIONS

In outreach efforts, the paper submitted as the final deliverable for Subtask 4.9 was accepted for publication during this quarter and research work with industrial partner AMSO under Subtask 7.3 was presented at the STAR Global Conference in March 2014. Development of a conventional oil and gas model for the Uinta Basin under Task 3 continued with decline curve fits to field-specific production data and GHG emissions factors applied to the various stages of oil and gas production. The Subtask 4.3 team discovered and fixed several bias errors in their experiments and began the examination of pyrolysis rates at low heating rates. Subtask 4.7 and 7.1 researchers have redesigned the heating element in their testing apparatus for improved distribution of heat and have done preliminary permeability experimentation on a Skyline sample in a newly commissioned relative permeability apparatus. In Subtask 7.3, researchers completed co-simulation of the second AMSO heater test for both the fluid time scales occurring in the lower later well which houses the heater and the time scales of heat dissipation throughout the solid shale formation. Two projects scheduled for completion this quarter, Subtasks 4.3 and 4.8, have been delayed until the next quarter due to academic schedule of the PIs.

COST PLAN/STATUS

Baseline Reporting Quarter - PHASE II	Yr. 4								Yr. 5			
	Q13		Q14		Q15		Q16 - REVISED		**Q17**		Q18	
	10/01/12 - 12/31/12		01/01/13 - 03/31/13		04/01/13 - 06/30/13		07/01/13 - 09/30/13		**10/01/13 - 12/31/13**		01/01/14 - 03/31/14	
	Q13	**Total**	Q14	**Total**	Q15	**Total**	Q16	**Total**	Q17	**Total**	Q18	**Total**
Baseline Cost Plan												
Federal Share	146,824	**5,235,073**	146,824	**5,381,897**	146,824	**5,528,721**	-471,238	**5,057,483**	157,250	**5,214,733**	157,250	**5,371,983**
Non-Federal Share	36,705	**1,306,563**	36,705	**1,343,268**	36,705	**1,379,973**	-211,982	**1,167,991**	53,484	**1,221,475**	53,484	**1,274,959**
Total Planned	183,529	**6,541,636**	183,529	**6,725,165**	183,529	**6,908,694**	-683,220	**6,225,474**	210,734	**6,436,208**	210,734	**6,646,942**
Actual Incurred Cost												
Federal Share	128,349	**4,485,377**	180,613	**4,665,990**	233,732	**4,899,722**	157,761	**5,057,483**	113,187	**5,170,670**	148,251	**5,318,921**
Non-Federal Share	79,871	**1,051,976**	62,354	**1,114,330**	51,708	**1,166,038**	1,953	**1,167,991**	66,131	**1,234,122**	48,378	**1,282,500**
Total Incurred Costs	208,220	**5,537,353**	242,967	**5,780,320**	285,440	**6,065,760**	159,714	**6,225,474**	179,318	**6,404,792**	196,629	**6,601,421**
Variance												
Federal Share	18,475	**749,696**	-33,789	**715,907**	-86,908	**628,999**	-628,999	**0**	44,063	**44,063**	8,999	**53,062**
Non-Federal Share	-43,166	**254,587**	-25,649	**228,938**	-15,003	**213,935**	-213,935	**0**	-12,647	**-12,647**	5,106	**-7,541**
Total Variance	-24,691	**1,004,283**	-59,438	**944,845**	-101,911	**842,934**	-842,934	**0**	31,416	**31,416**	14,105	**45,521**

Note: Baseline Cost Plan adjusted in Q16 to reflect NCE projections.

Baseline Reporting Quarter - PHASE II	Yr. 5			
	Q19		Q20	
	04/01/14 - 06/30/14		07/01/14 - 09/30/14	
	Q19	**Total**	Q20	**Total**
Baseline Cost Plan				
Federal Share	157,250	**5,529,233**	133,282	**5,662,515**
Non-Federal Share	53,484	**1,328,443**	87,436	**1,415,879**
Total Planned	210,734	**6,857,676**	220,718	**7,078,394**
Actual Incurred Cost				
Federal Share		**5,318,921**		**5,318,921**
Non-Federal Share		**1,282,500**		**1,282,500**
Total Incurred Costs	0	**6,601,421**	0	**6,601,421**
Variance				
Federal Share	157,250	**210,312**	133,282	**343,594**
Non-Federal Share	53,484	**45,943**	87,436	**133,379**
Total Variance	210,734	**256,255**	220,718	**476,973**

MILESTONE STATUS

ID	Title/Description	Planned Completion Date	Actual Completion Date	Milestone Status
1.0	Project Management			
2.0	Technology Transfer and Outreach			
	Advisory board meeting	Jun-13	N/A	Decision has been made to disband EAB
	Hold final project review meeting	Jun-13		NCE will delay this meeting until 2014
3.0	Clean Oil Shale & Oil Sands Utilization with CO2 Management			
3.1	Lifecycle greenhouse gas analysis of conventional oil & gas development in the Uinta Basin			
	Complete modules in CLEAR CO2 emissions from conventional oil & gas development in the Uinta Basin	Mar-14		Milestone date has been changed to reflect new project timelines
3.2	Flameless oxy-gas process heaters for efficient CO2 capture			
	Preliminary report detailing results of skeletal validation/uncertainty quantification analysis of oxy-gas combustion system	Sep-12	Oct-12	Report attached as appendix to Oct. 2012 quarterly report
3.3	Development of oil & gas production modules for CLEAR			
	Develop preliminary modules in CLEAR for conventional oil & gas development & produced water management in Uinta Basin	Oct-11	Dec-11	Discussed in Jan. 2012 quarterly report
3.4	V/UQ analysis of basin scale CLEAR assessment tool			
	Develop a first generation methodology for doing V/UQ analysis	Oct-11	Nov-11	Discussed in Jan. 2012 quarterly report
	Demonstrate full functionality of V/UQ methodology for conventional oil development in Uinta Basin	Nov-13	Apr-14	Demonstration delayed until first quarter of 2014
	Demonstrate full functionality for conventional & unconventional oil development in Uinta Basin	Mar-14		
4.0	Liquid Fuel Production by In-Situ Thermal Processing of Oil Shale/Sands			
4.1	Development of CFD-based simulation tool for in-situ thermal processing of oil shale/ sands			

ID	Title/Description	Planned Completion Date	Actual Completion Date	Milestone Status
	Expand modeling to include reaction chemistry & study product yield as a function of operating conditions	Feb-12	Mar-12	Discussed in April 2012 quarterly report
4.2	Reservoir simulation of reactive transport processes			
	Incorporate kinetic & composition models into both commercial & new reactive transport models	Dec-11	Dec-11	Discussed in Jan. & July 2012 quarterly reports
	Complete examination of pore-level change models & their impact on production processes in both commercial & new reactive transport models	Jun-12	Jun-12	Discussed in July 2012 quarterly report
4.3	Multiscale thermal processes			
	Complete thermogravimetric analyses experiments of oil shale utilizing fresh “standard” core	Sep-11	Sep-11	Discussed in Oct. 2011 quarterly report
	Complete core sample pyrolysis at various pressures & analyze product bulk properties & composition	Dec-11	Sep-12	Discussed in Oct. 2012 quarterly report
	Collection & chemical analysis of condensable pyrolysis products from demineralized kerogen	May-12	Sep-12	Discussed in Oct. 2012 quarterly report
	Complete model to account for heat & mass transfer effects in predicting product yields & compositions	Jun-12	Jun-12	Discussed in July 2012 quarterly report
4.5	In situ pore physics			
	Complete pore network structures & permeability calculations of Skyline 16 core (directional/anisotropic, mineral zones) for various loading conditions, pyrolysis temperatures, & heating rates	Mar-12	Mar-12	Discussed in April 2012 quarterly report; PI dropped loading condition as variable
4.6	Atomistic modeling of oil shale kerogens & oil sand asphaltenes			
	Complete web-based repository of 3D models of Uinta Basin kerogens, asphaltenes, & complete systems (organic & inorganic materials)	Dec-11	Dec-11	Discussed in Jan. 2012 quarterly report
4.7	Geomechanical reservoir state			
	Complete high-pressure, high-temperature vessel & ancillary flow system design & fabrication	Sep-11	Sep-11	Discussed in Oct. 2011 quarterly report
	Complete experimental matrix	Mar-14		Due date revised to reflect status of expts.
	Complete thermophysical & geomechanical property data analysis & validation	Apr-14		Due date has been revised to reflect status of expts.

ID	Title/Description	Planned Completion Date	Actual Completion Date	Milestone Status
4.8	Developing a predictive geologic model of the Green River oil shale, Uinta Basin			
	Detailed sedimentologic & stratigraphic analysis of three cores &, if time permits, a fourth core	Dec-12	Dec-12	Discussed Jan. 2013 quarterly report
	Detailed mineralogic & geochemical analysis of same cores	Dec-12	Dec-12	Discussed Jan. 2013 quarterly report
4.9	Experimental characterization of oil shales & kerogens			
	Characterization of bitumen and kerogen samples from standard core	Jan-12	Feb-12	Email sent to R. Vagnetti on Feb. 6, 2012 & discussed in April 2012 quarterly report
	Development of a structural model of kerogen & bitumen	Jun-12	Jun-12	Discussed in July 2012 quarterly report
5	Environmental, legal, economic, & policy framework			
5.1	Models for addressing cross-jurisdictional resource management			
	Identify case studies for assessment of multi-jurisdictional resource management models & evaluation of utility of models in context of oil shale & sands development	Jun-11	Jul-11	Discussed in Oct. 2011 quarterly report
5.2	Conjunctive management of surface & groundwater resources			
	Complete research on conjunctive surface water & groundwater management in Utah, gaps in its regulation, & lessons that can be learned from existing conjunctive water management programs in other states	Aug-11	Aug-11	Discussed in Oct. 2011 quarterly report
5.3	Policy & economic issues associated with using simulation to assess environmental impacts			
	White paper describing existing judicial & agency approaches for estimating error in simulation methodologies used in context of environmental risk assessment and impacts analysis	Dec-12	Dec-12	Submitted with Jan. 2103 quarterly report
6	Economic & policy assessment of domestic unconventional fuels industry			
6.1	Engineering process models for economic impact analysis			
	Upload all models used & data collected to repository	Oct-12	Aug-13	All models/data have been uploaded to the ICSE website

ID	Title/Description	Planned Completion Date	Actual Completion Date	Milestone Status
7	Strategic Alliance Reserve			
	Conduct initial screening of proposed Strategic Alliance applications	Mar-11	Mar-11	
	Complete review and selection of Strategic Alliance applications	Jun-11	Jul-11	Discussed in Oct. 2011 quarterly report
	Implement new Strategic Alliance research tasks	Sep-11	Sep-11	Discussed in Oct. 2011 quarterly report
7.1	Geomechanical model			
	Make experimental recommendations	Aug-13	Aug-13	Discussed in this quarterly report
	Infer permeability-porosity-temperature relationships, develop model that can be used by other subtasks	Jan-14		Due date has been revised to reflect status of expts.
	Basic reservoir simulations to account for thermal front propagation	Aug-14		Due date has been revised to reflect status of expts.
	Evaluation of flow mechanics	Aug-14		Due date has been revised to reflect status of expts.
7.2	Kinetic compositional models & thermal reservoir simulators			Project has been terminated
	Incorporate chemical kinetics into thermal reservoir simulators	Jun-12	Jun-12	Discussed in July 2012 quarterly report
7.3	Rubblized bed HPC simulations			
	Collect background knowledge from AMSO about characteristics & operation of heated wells	Jun-12	Jun-12	Discussed in July 2102 quarterly report
	Perform generation 1 simulation - DEM, CFD & thermal analysis of characteristic section of AMSO rubblized bed	Sep-12	Sep-12	Discussed in Oct. 2012 quarterly report
	Perform generation 2 simulation that incorporates kinetic compositional models from subtask 7.2 and/or AMSO	Jun-13	Jan-14	Delayed due to priorities of AMSO

NOTEWORTHY ACCOMPLISHMENTS

Subtask 4.7 and 7.1 researchers are have developed a material response curve enfranchising temperature, confining pressure and grade. They believe the new permeability measurement capability will greatly enhance their analysis.

PROBLEMS OR DELAYS

There are delayed milestones for Subtasks 3.1, 3.4, 4.7, and 7.1. The Subtask 3.1 and 3.4 delays are due to the graduate student focusing on the preparation of a research proposal during this quarter. The research proposal will be presented to the student's committee on May 2, 2014. Delays in Subtask 4.7 and 7.1 were mainly due to the availability of the experimental apparatus and the arrival of new equipment for measuring permeability. Two topical reports (Subtasks 4.3 and 4.8) have been delayed due to availability of the PIs.

RECENT AND UPCOMING PRESENTATIONS/PUBLICATIONS

Vanden Berg, M. D., Birgenheier, L. P. & Rosenberg M. J. (2012, September). Core-based sedimentologic, stratigraphic, and geochemical analysis of the lacustrine upper Green River Formation, Uinta Basin, Utah: Implications for conventional and unconventional petroleum development. Paper presented at the 2012 American Association of Petroleum Geologists - Rocky Mountain Section Meeting, Grand Junction, CO.

Rosenberg, M.J., Birgenheier, L.P, & Vanden Berg, M.D. (2012, October). Sedimentology and sequence stratigraphy of the Green River Formation, eastern Uinta Basin, Utah. Paper presented at the 32^{nd} Oil Shale Symposium, Golden, CO, October 15-19, 2013.

Burnham, A., Day, R., Switzer, L., McConaghy, J., Hradisky, M., Coates, D., Smith, P., Foulkes, J., La Brecque, D., Allix, P., Wallman, H. (2012, October). Initial results of the AMSO RD&D pilot test program. Paper presented at the 32^{nd} Oil Shale Symposium, Golden, CO, October 15-19, 2013.

Deo, M. (2012, October). *Oil shale liquefaction: Modeling and reservoir simulation*. Short course presentation to Statoil, Trondheim, Norway.

Deo, M. (2012, October). *Oil shale conversion to liquids: Experimental aspect*. Short course presentation to Statoil, Trondheim, Norway.

Fletcher, T. H. (2012, October). *Oil shale 1: Chemical structure and pyrolysis*. Short course presentation to Statoil, Trondheim, Norway.

McLennan, J. (2012, October). *Legacy and new geomechanical measurements of oil shale*. Short course presentation to Statoil, Trondheim, Norway.

Smith, P. J. (2012, October). *Multiscale simulation*. Short course presentation to Statoil, Trondheim, Norway.

Smith, P. J. (2012, October). *A description of a UQ-predictive validation framework for application to difficult engineering problems*. Short course presentation to Statoil, Trondheim, Norway.

Tiwari, P., Deo, M., Lin C. L. & Miller, J.D. (2012, October). Characterization of the oil shale core pore structure before and after pyrolysis. Paper presented at the 2012 AICHE Annual Meeting, Pittsburgh, PA, October 28-November 2, 2012.

Orendt, A. , Pimienta, I. S. O., Badu, S., Solum, M., Pugmire, R. J., Facelli, J. C., Locke, D. R., Winans, R. E., Chapman, K. W. & Chupas, P. J. (2012). Three-dimensional structure of the Siskin Green River oil shale kerogen model: A comparison between calculated and observed properties. *Energy and Fuels, 27*, 702-710.

Spinti, J. (2013, January 10). Presenter/panelist - *The real impact of oil shale and oil sands development in Utah.* 2013 Governor's Energy Development Summit, Salt Lake City, UT.

Hradisky, M., Smith, P. J. & Burnham, A. (2013, March). *STAR-CCM+ simulations of in-situ thermal treatment of oil shale*. Paper presented at the STAR Global Conference, Orlando, FL, March 18-20, 2013.

Orendt, A. M., Solum, M. S., Facelli, J. C., Pugmire, R. J., Chapman, K. W., Winans, R. E. & Chupas, P. (2013, April). Characterization of shale and kerogen from a Green River oil shale core, ENFL-535. Paper presented at the 245th American Chemical Society National Meeting, New Orleans, LA, April 7-11, 2013.

Birgenheier, L. P. (2013, May 7). Presenter/panelist - *Constructing a basin-wide geologic model*. University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Smith, P. J. (2013, May 7). Presenter/panelist - *Simulation of in situ production process using computational fluid dynamics*. University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Spinti, J. P. (2013, May 7). Presenter/panelist - *Assessment of unconventional fuels development costs*. University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Birgenheier, L.P., Plink-Bjorklund, P., Vanden Berg, M.D., Rosenberg, M., Toms, L. & Golab, J. (2013). *A genetic stratigraphic framework of the Green River Formation, Uinta Basin, Utah: The impact of climatic controls on lake evolution*. Paper presented at the American Association of Petroleum Geologists Annual Meeting, Pittsburgh, PA, May 22-25, 2013.

Vanden Berg, M. D., Eby, D. E., Chidsey, T. C. & Laine, M.D. (2013). *Microbial carbonates in cores from the Tertiary (Eocene) Green River Formation, Uinta Basin, Utah, U.S.A.: Analogues for non-marine microbialite oil reservoirs worldwide*. Paper presented at Microbial Carbonates in Space and Time: Implications for Global Exploration and Production, The Geological Society, London, United Kingdom, June 19-20, 2013.

Rosenberg, M. J. (2013). Facies, stratigraphic architecture, and lake evolution of the oil shale bearing Green River Formations, eastern Uinta Basin, Utah. M.S. thesis, Department of Geology and Geophysics, University of Utah.

Tiwari, P., Deo, M., Lin, C. L. & Miller, J.D. (2013, May). Characterization of oil shale pore structure before and after pyrolysis by using X-ray micro CT. *Fuel*, *107*, 547–554.

Pugmire, R. J., Fletcher, T. H., Hillier, J., Solum, M., Mayne, C. & Orendt, A. (2013, October). Detailed characterization and pyrolysis of shale, kerogen, kerogen chars, bitumen, and light gases from a Green River oil shale core. Paper presented at the 33rd Oil Shale Symposium, Golden, CO, October 14-16, 2013.

Fletcher, T. H., Gillis, R., Adams, J., Hall, T., Mayne, C. L., Solum, M.S. & Pugmire, R. J. (2013, October). Characterization of pyrolysis products from a Utah Green River oil shale by ^{13}C NMR, GC/MS, and FTIR. Paper presented at the 33^{rd} Oil Shale Symposium, Golden, CO, October 14-16, 2013.

Wilkey, J., Spinti, J., Ring, T., Hogue, M. & Kelly, K. (2013, October). Economic assessment of oil shale development scenarios in the Uinta Basin. Paper presented at the 33^{rd} Oil Shale Symposium, Golden, CO, October 14-16, 2013.

Hillier, J. L., Fletcher, T. H., Solum, M. S. & Pugmire, R. J. (2013, October). Characterization of macromolecular structure of pyrolysis products from a Colorado Green River oil shale. Accepted, *Industrial and Engineering Chemistry Research*. dx.doi.org/10.1021/ie402070s

Birgenheier, L. & Vanden Berg, M. (n.d.). Facies, stratigraphic architecture, and lake evolution of the oil shale bearing Green River Formation, eastern Uinta Basin, Utah. To be published in Smith, M. and Gierlowski-Kordesch, E. (Eds.). *Stratigraphy and limnogeology of the Eocene Green River Formation*, Springer.

Solum, M. S., Mayne, C. L., Orendt, A. M., Pugmire, R. J., Hall, T., Fletcher, T. H. (2014). Characterization of macromolecular structure elements from a Green River oil shale-(I. Extracts). Submitted to *Energy and Fuels, 28*, 453-465. dx.doi.org/10.1021/ef401918u,

Kelly, K.E., Wilkey, J. E. Spinti, J. P., Ring, T. A. & Pershing, D. W. (2014, March). Oxyfiring with CO_2 capture to meet low-carbon fuel standards for unconventional fuels from Utah. *International Journal of Greenhouse Gas Control, 22,* 189–199.

Fletcher, T. H., Gillis, R., Adams, J., Hall, T., Mayne, C. L., Solum, M.S., and Pugmire, R. J. (2013, January). Characterization of pyrolysis products from a Utah Green River oil shale by ^{13}C NMR, GC/MS, and FTIR. *Energy and Fuels*. In press.

Hradisky, M., Smith, P. J., Burnham, A. K. (2014, March). STAR-CCM+ high performance computing simulations of oil shale retorting system using co-simulation. Presented at the STAR Global Conference, Vienna, Austria. March 2014.

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