# Oil & Natural Gas Technology

**DOE Award No.: DE-FE0001243**

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

# Quarterly Progress Report (October - December 2014)

Submitted by:
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Prepared for:
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National Energy Technology Laboratory

February 9, 2015

**Office of Fossil Energy**

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## Quarterly Progress Report

October 2014 to December 2014

Submitted by:
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155 S. 1452 E. Room 380
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Principal Investigator: Philip J. Smith
Project Period: October 1, 2010 to September 30, 2015

Prepared for:
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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 efforts in Task 2 included the presentation of two papers at the 34$^{th}$ Oil Shale Symposium in Golden, CO, in October 2014. Additional presentations will be made at various venues in Utah and in Alabama during January of 2015.

Task 3 focuses on utilization of oil shale and oil sands resources with $CO_2$ management. The Subtask 3.2 performed a simulation of the IFRF furnace that is stable after almost 8 seconds of simulation time. The Subtask 3.3 and 3.4 teams improved the decline curve analysis in their basin-scale conventional and unconventional fuel development model by automating a process that takes production curves with complicated production histories and divides the history into different production intervals.

Task 4 projects are related to liquid fuel production by in-situ thermal processing of oil shale. The Subtask 4.3 project, reservoir simulation of reactive transport processes, is submitting a topical report in early 2014. Subtask 4.1 and 4.7 researchers focused their efforts on related projects under Subtask 7 during this quarter.

Task 5 and 6 projects relate to environmental, legal, economic, and policy analysis. All Task 5 and 6 projects are now complete.

Task 7 projects have focused on in situ production processes at a commercially-relevant scale. The Subtask 7.1 team is using state-of-the-art testing to measure the permeability of pyrolyzed oil shale samples after first testing the validity of the procedure. They are also developing a comprehensive model of in situ oil shale pyrolysis to gain insight into the evolution of poroelasticity in oil shale and the practical consequences of this evolution. Subtask 7.3 researchers ran their simulations of oil shale retorting for time intervals of four and a half years. For the three well spacing/arrangement geometries tested, the net energy return was well below one. This result is attributed to the large heat losses which occur when heat supplied by the heaters goes into heating a large volume of oil shale to temperatures that never reach the temperature required for retorting.

## 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 visits and interviews, and through updates of the program website. In this quarter, researchers in two subtasks had papers that were accepted for presentation at the 34th Oil Shale Symposium, held in Golden, CO, in October 2014 (see **Recent and Upcoming Presentations/Publications**).

### 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 completed the milestone remaining project milestone:

- Complete modules in $CLEAR_{uff}$ for life-cycle $CO_2$ emissions from conventional oil and gas development in the Uinta Basin

To complete this milestone, they gathered, summarized and organized the life-cycle $CO_2$ emissions from conventional oil and gas operations in the Uinta Basin for use in the Monte-Carlo well attributes model, part of the basin-scale model developed for Subtasks 3.3 and 3.4. For each of the two categories - oil and gas - emissions were organized into the following process stages: site preparation, transportation of material, drilling and fracturing, well completion, production, processing and transport/distribution. A probability distribution for $CO_2$ emission factors was developed for each process stage, and the Monte-Carlo well attributes model was designed to randomly select an emission factor for each well from the probability distribution. When combined with oil and gas production volumes (also randomly generated from probability distributions), the model provides predictions for $CO_2$ emissions inventories in the Uinta Basin from conventional oil and gas development with uncertainty estimates.

In addition, the team focused on refining the emission factors associated with oil and natural gas production, transport and processing. This information will be used as part of the oil and gas production module to estimate greenhouse gas (GHG) emissions associated with oil and gas drilling operations in the Uinta Basin. The team also estimated the effect of EPA's New Source Performance Standards (NSPS) on new wells and considered the effect of new state regulations on existing oil and gas emissions.

For the same process, some emission factors vary by orders of magnitude. Figure 1 shows the range of methane emissions per well. Part of this uncertainty may be due to differences in the assumed well-head natural gas composition. There is also uncertainty introduced by unclear reporting of the species profile (wt%, vol%, or mol%).

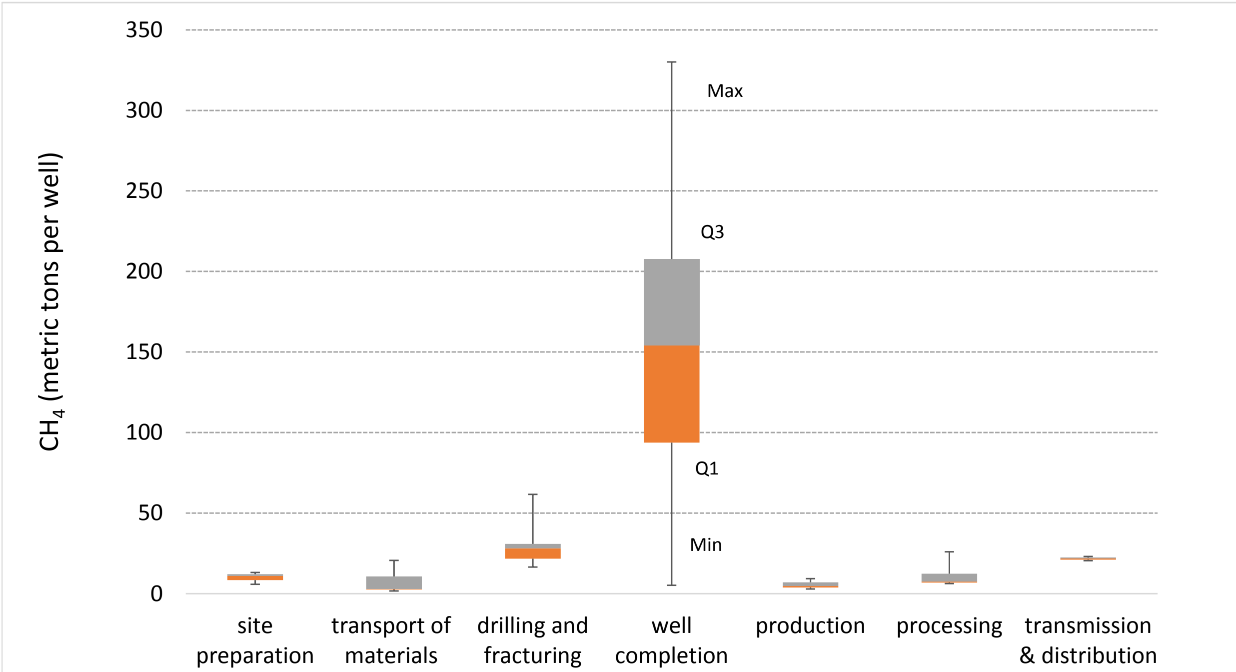



**Figure 1**. Median, 25th and 75th percentile, and minimum and maximum reported methane ($CH_4$) emissions per well. This includes all emissions identified in the literature, both controlled and uncontrolled.

Table 1 shows the current best estimates (mean and standard deviation) of emission factors for Uinta Basin gas production and processing. The project team is still investigating the ratios of VOCs to $CH_4$ and other species, and consequently the standard deviation for VOCs in not shown.

**Table 1**. Best estimates of emission factors for the Uinta Basin.

| Activity | $CO_2e$ | CH4 | VOCs | units |
|---|---|---|---|---|
| Site-preparation (excluding drill rig transportation) | 208±79 | 9.9±3.37 | 1.75E-03 | metric tons/well |
| Transportation of materials | | | | |
| *Drilling* | 0.40±0.56 | 8.6E-06±1.22E-05 | | metric tons/spud |
| *Completions* | 0.21±0.29 | 4.36E-06±6.16E-06 | | metric tons/spud |
| *Reworking* | 3.05±4.31 | 7.71E-05±1.01E-04 | | metric tons/spud |
| *Production* | 1.36±1.93 | 3.29E-05±4.65E-05 | | metric tons/well |
| Well drilling and fracturing | 569±326 | | | metric tons/well |
| Well completion | 1940±46 | 9.24E+01 | 1.63E-02 | metric tons/well completion |
| Production | 100±40 | 4.75±1.90 | 8.40E-04 | metric tons/year well |
| Processing | 901±46 | 5.58±3.91 | 9.87E-4 | metric tons/billion cubic feet of total natural gas production |
| Transmission & distribution | | 1.04±0.85 | 1.84E-4 | percentage of methane produced over the lifecycle of a well |

The EPA recently finalized NSPS for the oil and natural gas sector that will require a number of changes. After the NSPS implementation, the emission factors in Table 2 can be used to estimate the emissions for new wells.

**Table 2**. Emission factors for $CO_{2e}$, methane ($CH_4$) and non-methane volatile organic carbons (NMVOCs) after the NSPS implementations (NETL, 2014).

| | $CO_{2e}$ emissions (metric tons $CO_{2e}$/billion cubic feet) | % reduction or increase (metric tons $CO_{2e}$/billion cubic feet) | $CH_4$ emissions (metric tons $CH_4$/billion cubic feet) | NMVOCs (metric tons NMVOCs/billion cubic feet) |
|---|---|---|---|---|
| Construction | 144 | *2* | | |
| Completion | 14[1] | 96 | 0.58 | 0.06 |
| Production | 721 | 66 | 18.2[2] | 1.8[2] |
| Processing | 3095 | 15 | 31.5[3] | 3.1[3] |
| Transport | 3183 | *0.5* | 102[4] | 10.2[4] |

*Italic font: % increase in the emissions after the NSPS implementation.*
[1] This completion emission factor was estimated as 40% of the emission factor for shale gas well completion as suggested in NETL (2014) for tight wells.
[2] Based on the NETL (2014) data. Methane emitted due to water delivery and water treatment activities was not included.
[3] Based on the NETL (2014) data. Value assumes that emissions from other point sources and valve fugitives are mainly due to methane.
[4] Based on the NETL (2014) data. Methane emitted due to pipeline construction was not included.

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

The project team performed simulations of the IFRF oxy-fuel furnace using a recently updated version of the ARCHES Large Eddy Simulation (LES) software. The inlet boundary conditions for the furnace were obtained from a simulation of the fluid flow through the complex burner geometry using the commercial software STAR-CCM+ as described in previous quarterly reports. A base case was run on 7098 processors on Vulcan, a Lawrence Livermore National Laboratory machine, for almost eight seconds of simulation time. This case was stable, so in the next quarter, an eight-case test matrix for the Validation/Uncertainty Quantification (V/UQ) study will be executed. Figure 2 shows a slice of the vorticity field through the mid plane of the furnace.

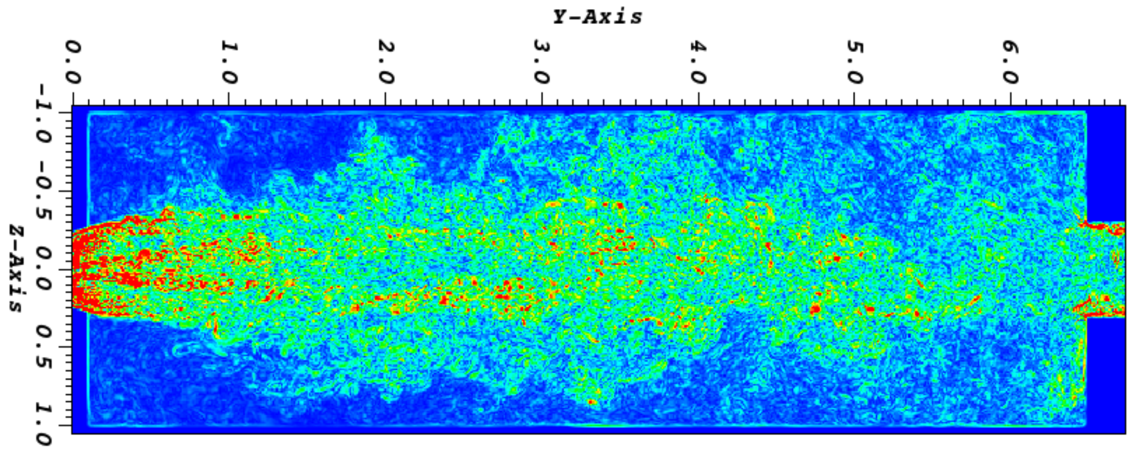



**Figure 2**. Slice through vorticity field of simulation of ox-fired IFRF furnace.

Because LES resolves both length and time scales, the question arises as to how to process simulation data to most closely match what was done experimentally. In the case of the IFRF furnace, experimental data were taken from the furnace wall to the centerline of the furnace at six axial locations (Coraggio and Laiola, 2009). These data represent some sort of time and spatial average although no indication is given as to the variability in the measurements.

Figure 3 shows the time-varying $CO_2$ mass fraction at a distance of 0.46 m from the burner face for a range of radial locations. In this figure, 10 indicates 10 cm from the furnace wall and 100 cm indicates the furnace centerline. Based on the data in Figure 3, a pseudo-steady state is reached around four seconds. Therefore, only the simulation data after four seconds will be averaged.

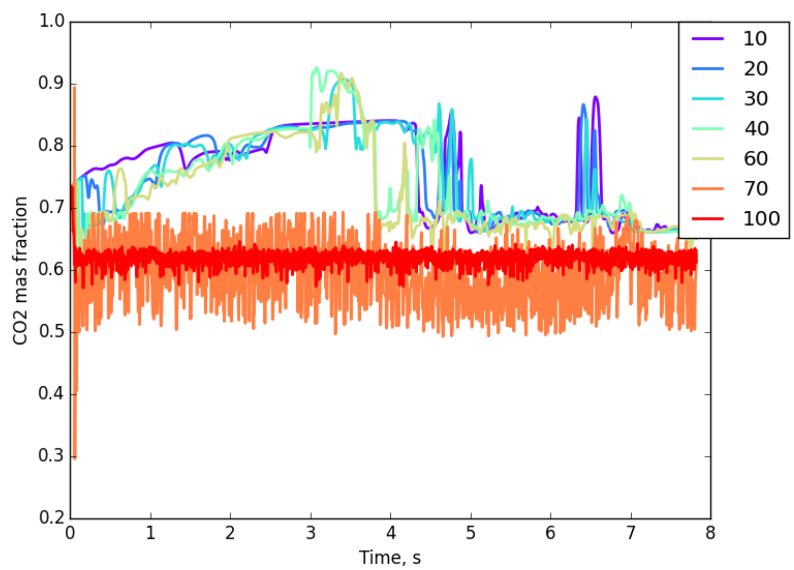



**Figure 3**. $CO_2$ mass fraction as a function of time at a distance of 0.46 m from the burner face for various distances from the side wall; 10 = 10 cm from side wall, 100 = centerline.

The simulation data in Figure 4 show the two $CO_2$ profiles across the furnace (left wall to right wall and bottom wall to top wall; see Figure 5) at a distance of 0.46 m from the burner face. Note that these data represent a single time slice taken at 5.72 s. Included in Figure 4 are the experimental data at the same location; $CO_2$ mass fractions from the simulation have been converted to volume percent $CO_2$ on a dry basis to match the experimental data. Figure 5 shows the time slice from which the data in Figure 4 were taken. There is a strong dependence of $CO_2$ mass fraction on the location of the sampling line. For the simulation, gravity acts in the x direction, so some of the spatial differences are buoyancy-related. Care must be taken to sample the simulation along the same line as the experiment, in this case line 2.

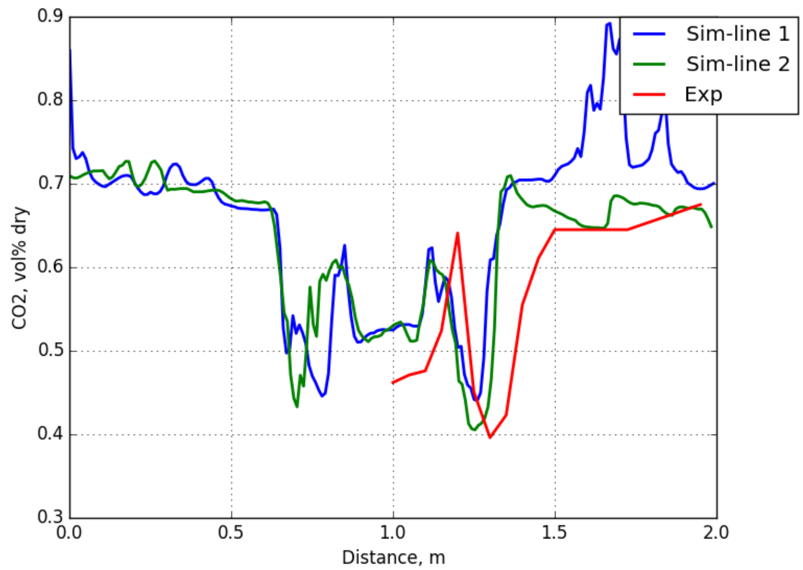



**Figure 4**. Experimental and simulation profiles of $CO_2$ across the width of the IFRF furnace. Measurements were taken 0.46 m from the burner face.

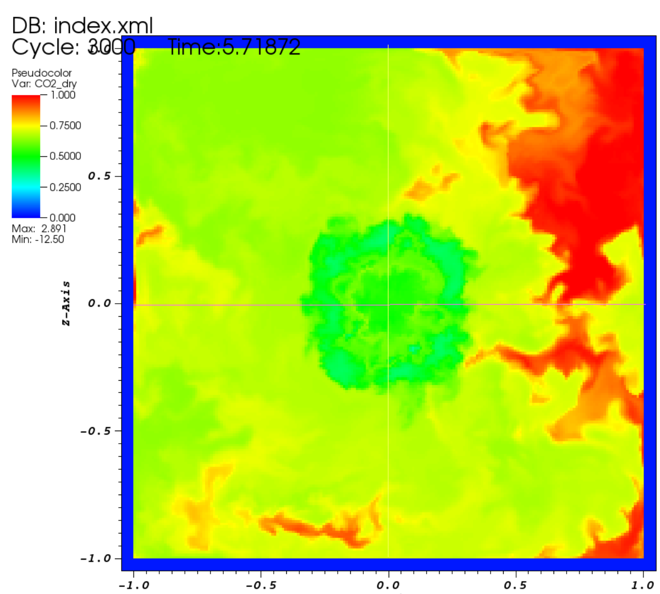
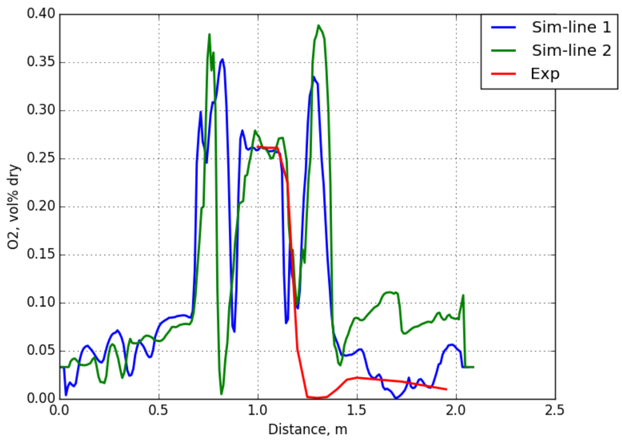



**Figure 5**. Slice through IFRF furnace simulation showing $CO_2$ mass fraction field at time=5.72 s.

Similar profiles across the furnace comparing simulation and experimental data for $O_2$ concentration and temperature at a distance of 0.46 m from the burner face are shown Figure 6. Even though the simulation data is from a single time slice and the experimental data is time-averaged, these preliminary results are encouraging with respect to the consistency of the species concentration and temperature data from the simulation and the experiment.



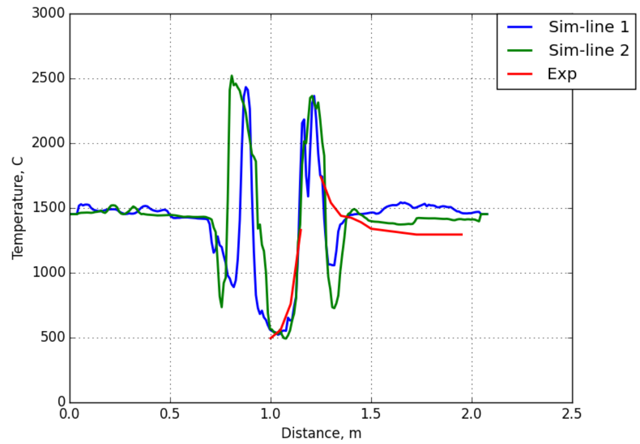




**Figure 6**. Experimental and simulation profiles of $O_2$ (left) and temperature (right) across the width of the IFRF furnace. Measurements were taken 0.46 m from the burner face.

Based on this analysis and additional insight from the experimentalists at IFRF regarding a sampling sphere of 2.5 cm radius around the sampling probe tip, the following procedure will be implemented for the V/UQ analysis:

1. Determine time when pseudo-steady state is reached by analyzing time traces of variables at various locations.
2. Average simulation data over a volume encompassing the experimental “sampling sphere” at each sampling location at each time step after pseudo-state state.
3. Compute time average at each sampling location using only time steps after pseudo-steady state is reached.
4. Given the potential effects of gravity in this furnace, make sure that correct furnace traverse is sampled from the simulation data.

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

Over the fourth quarter of 2014, research on this subtask has primarily focused on revising and improving the decline curve analysis (DCA) of individual oil and gas wells. Previously, the project team used the hyperbolic decline curve equation to fit all oil and gas well production data:

$$q(t) = q_o(1 + bD_i t)^{(-1/b)} \quad (1)$$

where $q$ is the oil or gas production rate at time $t$, $q_o$ is the initial production rate, $b$ is the decline exponent, and $D_i$ is the initial decline rate. Ideally Equation (1) can be applied to any well, but most wells have complicated production histories (shut-ins, workovers, water flooding, etc.) that prevent easy fitting. Examples of the ideal well for decline curve fitting and a more common complicated well are shown below in Figures 7 and 8.

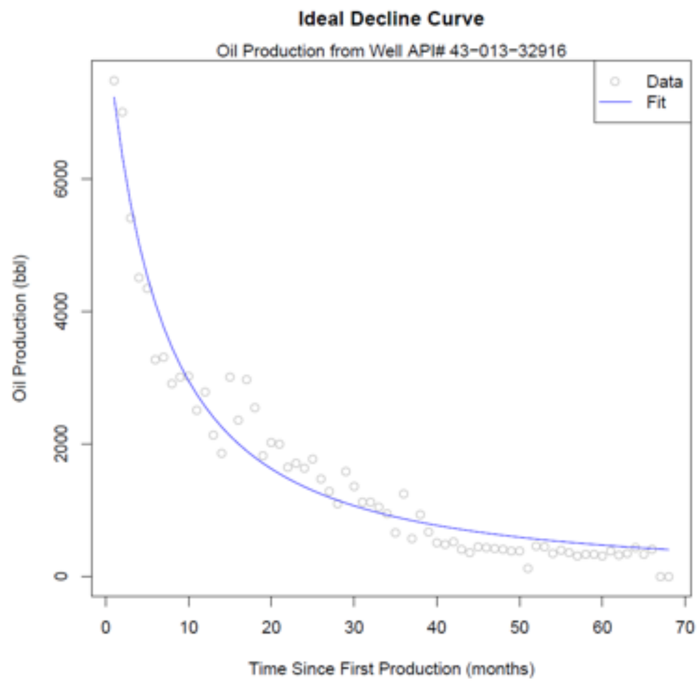



**Figure 7**. Production history for a well that is ideal candidate for DCA with Equation (1).

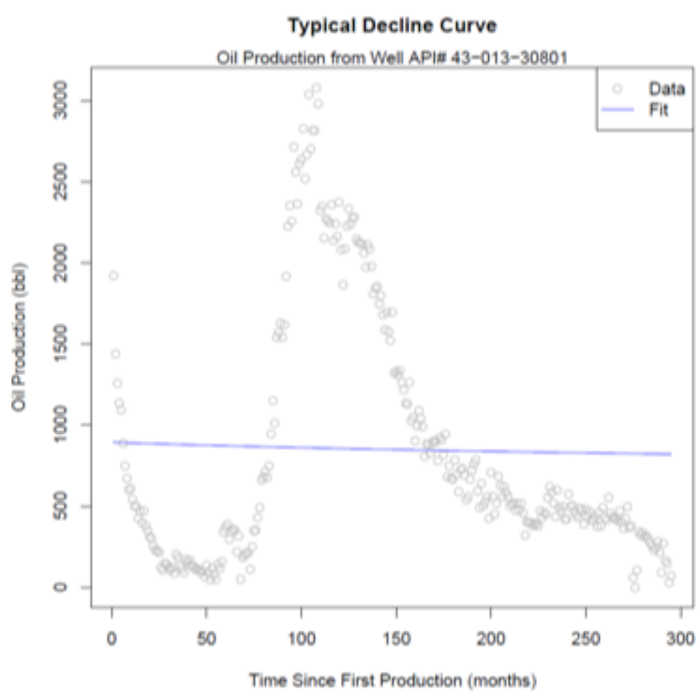



**Figure 8.** Production history for a more complicated well with a restart after approximately 100 months.

Performing nonlinear least-squares (NLS) on the production record shown in Figure 8 clearly fails when applied to the entire record, but it is also clear that there are two distinct decline curves that could be fit; the first between months 1–50 and the second between months 100–300. However, given the scale of the dataset (approximately 13,000 wells each with its own oil and gas production record), it would be impractical to analyze each plot individually and pick out the start and stop point of decline curve segments. Therefore, the team's challenge was to develop an algorithm that could reliably find these start/stop points.

Happily, the team was able to develop a suitable algorithm. The DCA start/stop point identification algorithm is summarized below.

1. Break the production record into evenly spaced time intervals.
2. Calculate the sum of the production records in each time interval, normalize the sums at each time interval by the largest sum, and then calculate the interval-to-interval difference in normalized production level.
3. If the difference in the production levels is ever positive and larger than some cutoff value, then the preceding interval contains a decline curve stop point. For example, if there were a 15% increase in production from interval A to interval B, than interval A contains a stop point.
4. Search the interval containing the stop point for its minimum non-zero production record. That production record is the stop point.
5. Search for the maximum production record in all points that proceed the identified stop point. That production record is the start point.

After tuning the algorithm parameters to pick the best values for interval length and cutoff values and tweaking the algorithm to handle common exceptions, the project team was able to fit the vast majority of wells in the Uinta Basin. The fitting success rate, skip rate (for wells that had too few production records), and failure rate (where the nonlinear solver failed to converge) for all oil and gas production records in the Basin are summarized in Table 3, followed by an example plot in Figure 9 of the results when the algorithm is applied to the production record previously shown in Figure 8.

**Table 3**. Results of decline curve analysis with start/stop algorithm.

| | Oil Production Records | Gas Production Records |
|---|---|---|
| **Fitted** | 10,500 | 11,035 |
| **Skipped** | 2,133 | 1,634 |
| **Failed** | 257 | 221 |
| **Total** | 12,890 | 12,890 |

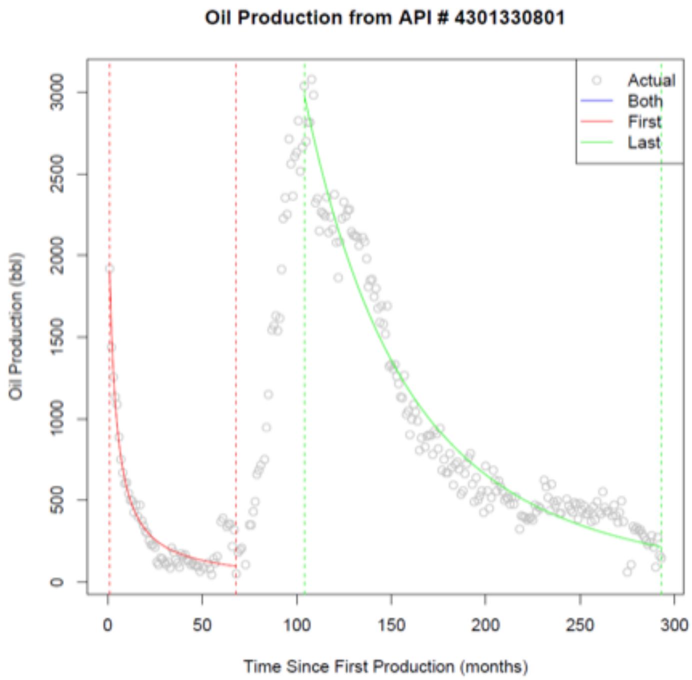



**Figure 9**. Results of applying start/stop point algorithm to complicated production record shown previously in Figure 8.

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

A summary of progress in this subtask is included with the Subtask 3.3 summary above.

**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)

In the past quarter researchers have continued to run simulations that represent the rubblized oil shale bed using the porous media approach. However, the majority of their efforts went to completing tasks associated with Subtask 7.3 and they were not able to complete their deliverables (listed below). They will be completing both deliverables by the end of the program.

- Distribute CFD-based simulation software over the web
- Topical Report on lessons learned from V/UQ study of thermal processing product yields as a function of operating conditions for indirectly heated, rubblized oil shale beds

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

The final deliverable for this project, a topical report, is being submitted with this report. This project is now completed.

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

One of two remaining deliverables for this project, a topical report, was completed and submitted in this quarter. The principal authors of the topical report were Dr. Fletcher and Dr. Pugmire. Dr. Fletcher gave an oil shale presentation to the BYU Chemistry Department and is scheduled to give a similar presentation to the College of Engineering at the University of Alabama, Huntsville. Work on the final deliverable, a paper describing the Chemical Percolation Devolatilization (CPD) model application to oil shale pyrolysis, has begun but progress has been slow because of illness and the start of school.

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)

This project has one remaining milestone and one deliverable. Both are listed below with their current status.

- (Milestone) Complete thermophysical and geomechanical property data analysis and validation–Data collection is complete. Numerical methods to allow interpolation of all in-house and public domain data continue and will be completed in the next quarter.
- (Deliverable) Topical Report assessing subsidence and compaction implications of in situ development of oil shale–This report is being compiled and the project team anticipates draft versions available in April.

The triaxial testing has been completed in this quarter. The apparatus is being used for pyrolyzing samples in advance of measuring their permeability for Subtask 7.1.

As part of his Ph.D. dissertation, Mr. Thang Tran is compiling all of the triaxial information, continuing with numerical simulations of mechanical performance, and developing guidelines for representing oil shale mechanical properties. This work encompasses previous information from SubTask 7.1.

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

The project team is working on a topical report.

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

This project has been completed.

**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)

This project has been completed. A final topical report was sent to Mr. Robert Vagnetti on November 6, 2014.

**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)

This project has three milestones remaining:

- Infer permeability-porosity-temperature relationships, develop model that can be used by other subtasks
- Basic reservoir simulations to account for thermal front propagation
- Evaluation of flow mechanics

The second milestone was complete in this quarter by Mr. Walter Glauser as part of his MS thesis. He has developed a computational methodology, described below, for simulation of subsidence and compaction associated with the in situ pyrolysis of oil shale. For the first and third milestones, laboratory measurements of pyrolyzed oil shale permeability continue. These milestones will be completed in the next quarter, during which time Mr. Tran will focus on measuring the permeability of a pyrolyzed Green River oil shale sample. That pyrolyzed sample was cored from a rich zone of the Skyline-16 well (50 gal/ton). He will also replicate the test with a lean sample (~25 gal/ton). From there, the goal is to see how porosity and permeability change with pyrolysis and to assess differences between a rich sample and a lean sample.

The research teams for Subtasks 4.7 and 7.1 have worked closely together and the work of both subtasks leverages the work of the other. Hence, a description of both the experimental and simulation work for Subtasks 4.7 and 7.1 will be included in a single topical report that will be submitted in April 2015.

*Numerical Simulation of In Situ Deformation During Pyrolysis*

The past two years have been spent developing a comprehensive model of in situ oil shale pyrolysis in order to gain insight into the evolution of poroelasticity in oil shale and the practical consequences. This work consisted of an exhaustive review of oil shale literature, followed by the development of robust algorithms to couple thermal, mechanical, fluid and poroelastic models into a cohesive whole. These were in turn implemented into Itasca Consulting Group's FLAC3D™ numerical package.

Results suggest that gas generated in isolated pores is causing fractures to open during pyrolysis. These fractures cannot be directly represented in the model because it is based on continuum mechanics. A module has been developed to relieve pressure by storing excess fluid in non-communicated fractures for each zone and allowing that fluid to be released should a negative pressure develop in the zone.

As debugging the code is an ongoing process, several validation models have been executed, demonstrating that the heat transfer and fluid models have been properly implemented. Two examples are provided. Figure 10 shows the thermal profile as a function of time.

*Porosity and Permeability Testing*

After completion of the Subtask 4.7 triaxial testing program, researchers had obtained the mechanical properties of oil shale at different temperatures and confining pressures for samples of oil shale from the Skyline-16 well. However, to understand how porosity and permeability change during pyrolysis, the in-vessel measurements were unsuccessful.

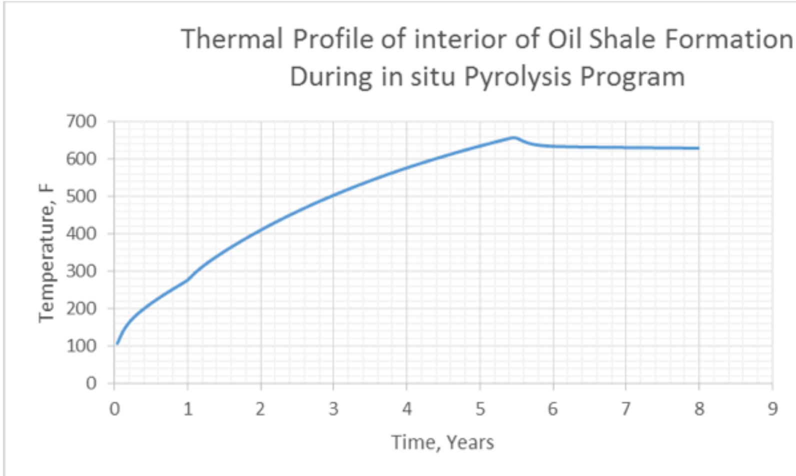



**Figure 10.** Thermal history for an interior element of oil shale close to a production well, emphasizing the long heat-up times that may be required.

Since permeability was still an essential component for process simulation, the following methodology has been used to evaluate the porosity and permeability of processed oil shale in a different apparatus.

1. The first step is to measure the porosity and permeability of virgin oil shale samples using a 0.5 inch-thick disk.
   1.1. Porosity of the oil shale is measured using an Ultra-Pore 300 porosimeter, available in the laboratories of the Department of Chemical Engineering.
   1.2. Permeability is then measured using the Core Flood system, available at the Energy & Geoscience Institute. The disk is used because the permeability is extremely low and reliable measurements would require too long, even using state-of-the-art equipment.
2. The second step is measuring the porosity and permeability of the pyrolyzed oil shale using a 3 inch-long sample. The sample is previously pyrolyzed at 500°C for 4 hours using confining pressure in the high temperature/high pressure vessel to prevent delamination during heatup.

Before measuring the permeability of the pyrolyzed oil shale sample, it was necessary to assure the validity of this state-of-the-art testing. Therefore, researchers have been validating the testing protocols by running permeability tests on different ultra-low permeability samples using the system. For example, an absolute permeability measurement was made on a low-permeability, organic shale using water as the flowing fluid. Due to the low permeability of this organic shale, it was necessary to flow for almost 300 hours to reach steady-state (see Figure 11).

The next two validation tests were performed on a chalk sample. Two different lengths from the same sample were evaluated. This experiment had two purposes.

1. Assess the ability of the machinery to measure relative permeabilities of water and decane mutually occupying the sample. This is one of the very few relative permeability measurements that have been carried out on a low-permeability oil shale analog.

2. Confirm if the length of the sample affected the result. To test virgin oil shale, shorter sample lengths (not commonly used) are essential. The time required for reaching steady state conditions is directly proportional to the length of the sample. To ensure nominally parallel streamlines and to avoid end effects, conventional wisdom has been to use a two times length to diameter ratio. This ratio is not acceptable from the perspective of time required. By testing two sample lengths, the validity of testing sample disks as opposed to cylinders could be assessed.

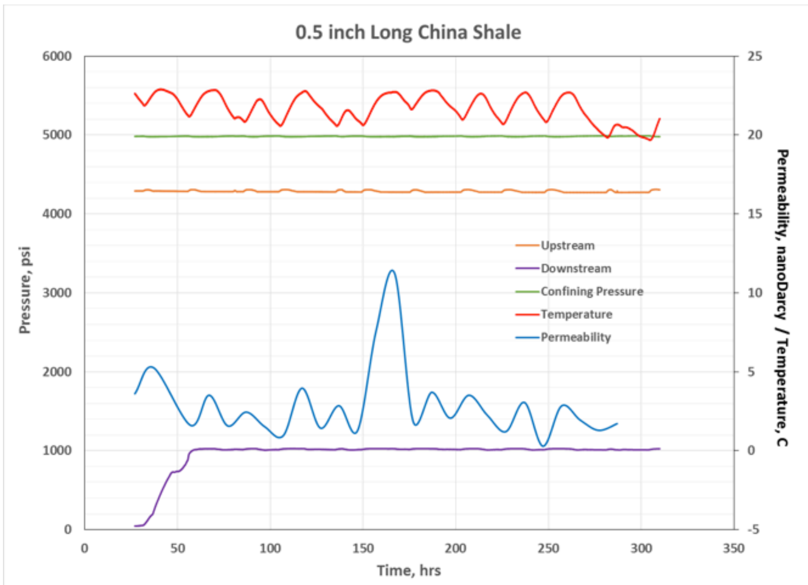
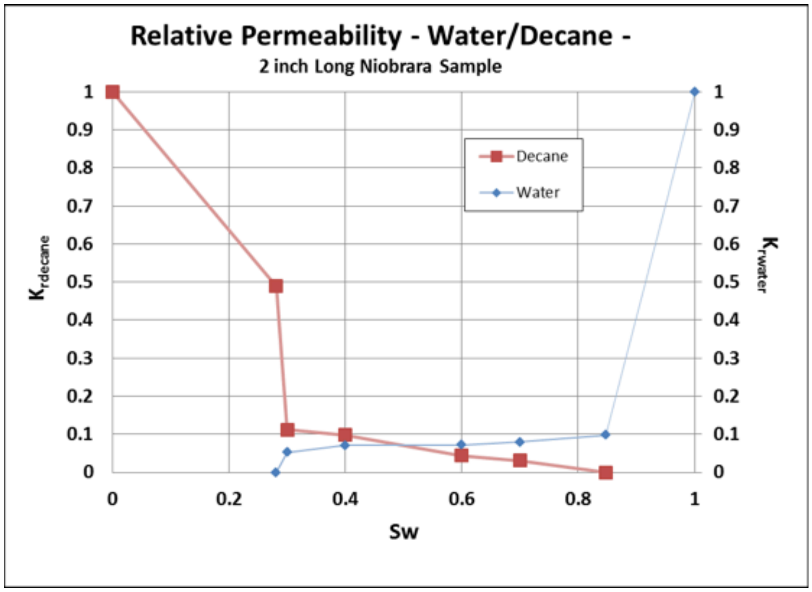



**Figure 11**. Absolute permeability to water of 0.5-inch long organic shale sample. The permeability is in nanodarcies.

Figure 12 shows the results of these validation tests. Slightly different relative permeability curves were generated for the two samples. While favorable, it is too early to conclude that the raw measured permeabilities on short samples can be used without some length correction. Researchers are planning additional tests with even shorter samples.



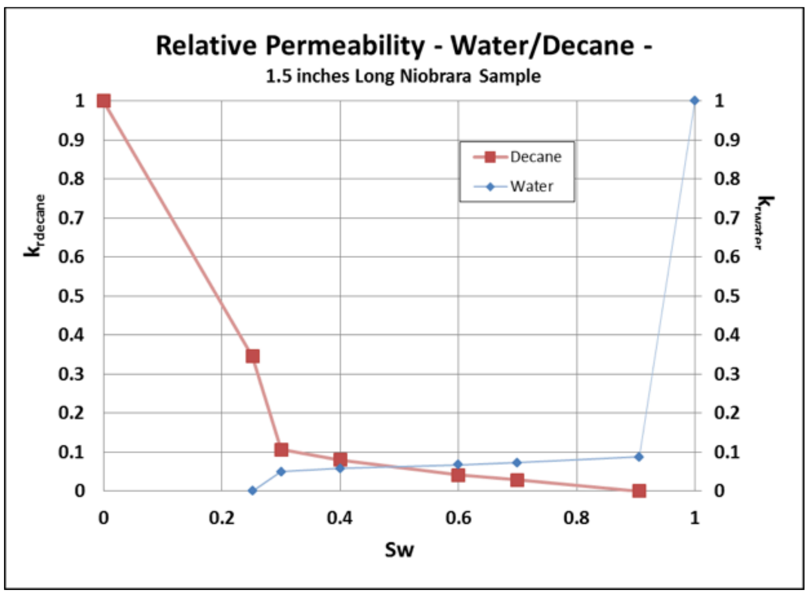




**Figure 12.** Relative permeability of water/decane on (top) 2-inch-long and (bottom) 1.5 inch-long Niobrara samples.

## 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)

In this quarter, researchers continued to run their High Performance Computing simulations of in-situ thermal treatment of oil shale. Their simulations now capture about four years of underground heating. Using heat transfer results from the simulation, they are able to compute the net energy return (NER) for the simulated scenarios.

In the last quarterly report, researchers detailed their simulation approach as well as the three test scenarios located in the Uinta Basin. They are using the test scenarios to study underground thermal retorting of oil shale and to analyze energy requirements for heating the shale formation to retorting temperatures.

The overall size of the simulated retorting region was the same for all three test scenarios: 0.125 km x 0.25 km x 0.45 km. The heating domain contained horizontal wells, each with a 300 m long heating section. The temperature boundary was held constant at 675 K for the entire course of all simulations. The simulation domain represents only a small region of an actual in-situ process. Therefore, researchers used lateral periodic boundary conditions so that the simulation results are a representative subset of an actual in-situ process. This choice of boundary conditions also allows the results to be scaled up to represent a retorting region containing hundreds of horizontal wells.

The difference between the three test scenarios was in the well spacing and well arrangement. The first test scenario (Case 1) contained five horizontal wells spaced 25 m apart. The second test scenario (Case 2) contained ten horizontal wells spaced 12.5 m apart. The third test scenario (Case 3) also featured 12.5 m lateral well spacing between wells, but every other well was offset vertically 12.5 m, essentially forming a triangular pattern. Previously, researchers showed results after two years of heating. In the latest quarter, the simulations have been extended to approximately 1,600 days of heating, which is almost four and half years.

Figure 13 shows a plot of cumulative energy requirements as function of time for all three cases. Initially, as the formation heats up, power requirements are the greatest. After a few months of heating, the cumulative power requirements increase at a constant rate. As expected, power requirements are greater for the two scenarios with ten heating wells, Cases 2 and 3, in comparison to Case 1, which only contains 5 heating wells. The rate of power required to continuously heat the formation can be obtained from the daily power requirements as shown in Figure 14. The daily power requirements decrease as a function of time as the formation continues to be heated.

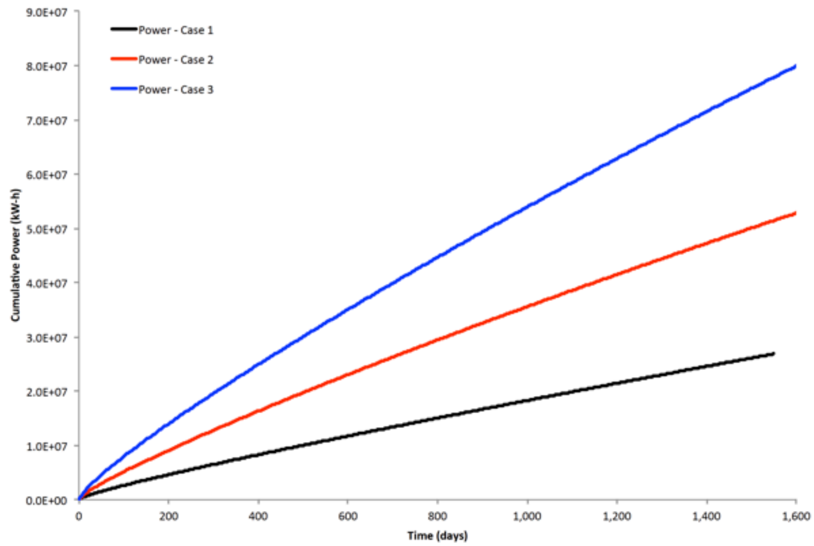



**Figure 13**. Cumulative power requirements for the three test scenarios.

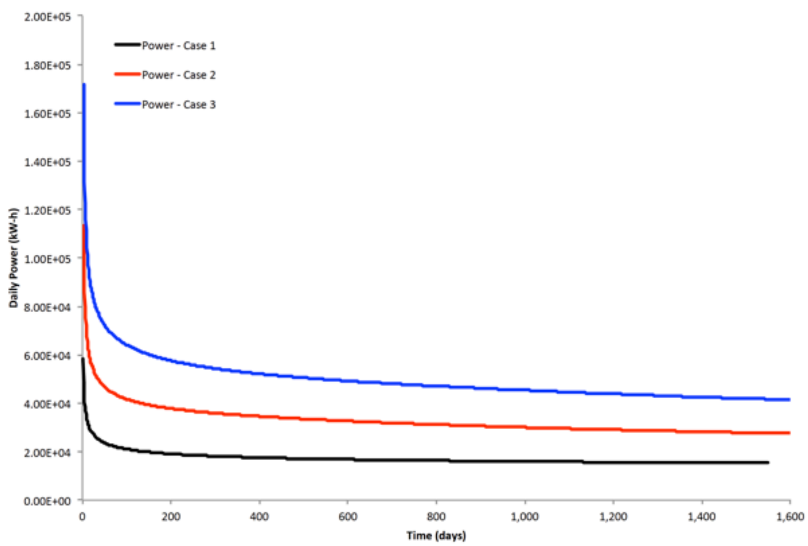



**Figure 14**. Daily power requirements for the three test scenarios.

Also computed in the simulations is the oil production as a function of time. The cumulative production as well as the daily production are shown in Figures 15 and 16. The cumulative production continuously increases for all three cases, with Case 2 having the largest oil yield. The difference in oil production between Case 2 and Case 3, which both contain ten horizontal heating wells, is attributed to the different well arrangement and thus the location of the heater with respect to the oil shale grade distribution.

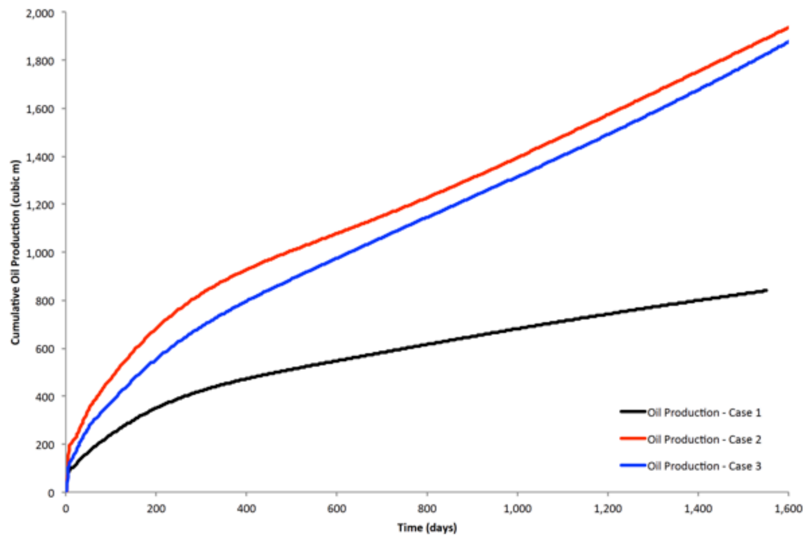



**Figure 15**. Cumulative oil production in cubic meters for the three test scenarios.

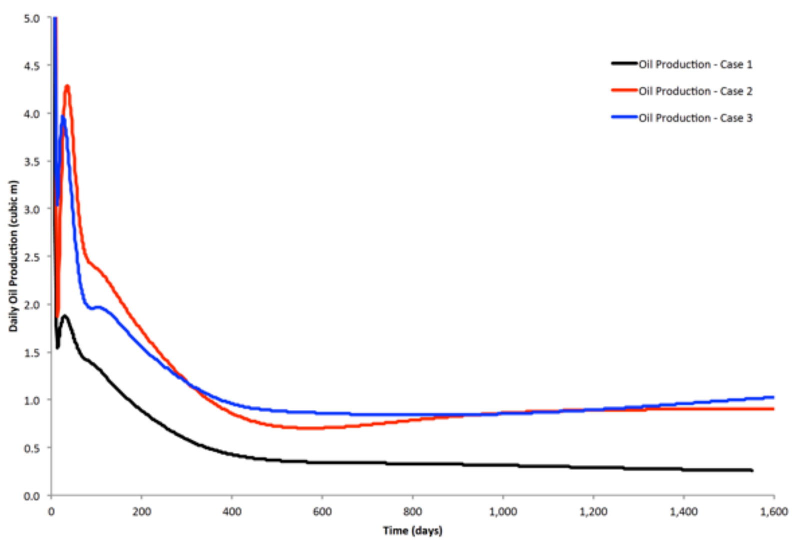



**Figure 16**. Daily oil production in cubic meters for the three test scenarios.

Given power requirements as well as oil production results, researchers computed the NERs for all three scenarios. The cumulative as well as daily NERs are shown in Figures 17 and 18. The cumulative NER continues to decrease even after the formation is heated for more than four years. However, the daily NER varies during the four year heating interval. Fluctuations in the daily NER results capture the daily heat transfer and the different richness of the oil shale layers which are retorted as the heat moves away from the heating well. However, the most notable result is that neither the cumulative or the daily NERs are above one. Therefore, even on daily basis, it takes more energy to heat the formation than the energy equivalent stored in the produced oil. This result is mostly because the majority of the heat supplied by the heaters goes into heating parts of the oil shale formation that do not reach retorting temperatures after four years. Heat losses for these scenarios greatly contribute to the low NERs.

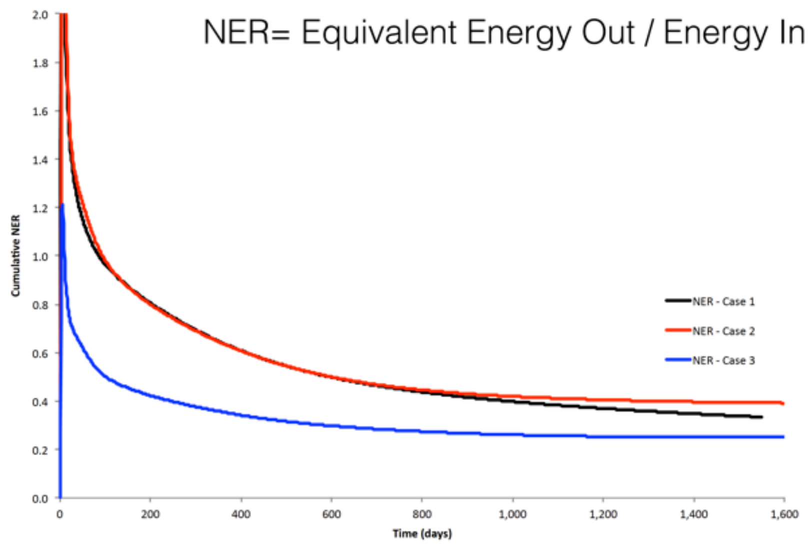



**Figure 17.** Cumulative net energy return for the three test scenarios.

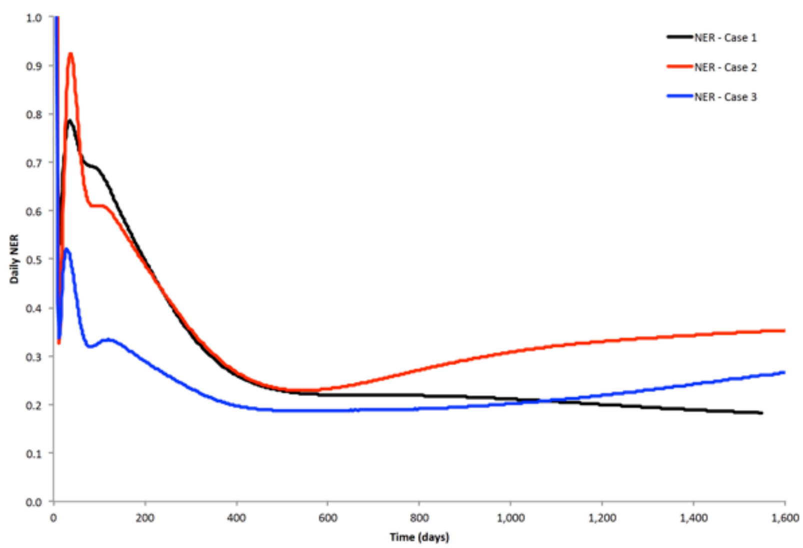



**Figure 18**. Daily net energy return for the three test scenarios.

However, it is important to note that these results apply only to the three well arrangements/spacing chosen for this study. Different well arrangements, spacing, heating rates or heating times could results in different conclusions. Furthermore, due to the specificity of formation characteristics as a function of depth, results cannot be generalized for all formations. Lastly, simulation assumptions could have a great effect on the overall heat transfer and therefore NERs. For example, only conductive heat transfer was considered. While this is a great simplification, it serves as a starting point for understanding heat transfer during oil shale retorting.

## CONCLUSIONS

The Subtask 4.2 topical report, “Validation Results for Core-scale Oil Shale Pyrolysis” was completed in January 2015 and will be submitted with this report. The Subtask 5.3 topical report, Policy and Economic Issues Associated with Using Simulation to Assess Environmental Impacts, was submitted to Mr. Robert Vagnetti on November 6, 2014. Subtask 3 research focused on improving the approach to decline curve fitting of gas and oil well production. In addition, simulations of the IFRF oxy-fired furnace are now stable and a V/UQ analysis will be completed in the next quarter. Two graduate students in Subtasks 4.7 and 7.1 are wrapping up both experimental and modeling work associated with a geomechanics study of oil shale and will submit their final report in April 2015. Researchers in Subtask 7.3 ran their simulations of oil shale retorting for a time period of four and a half years. Even for these longer heating times, the NER remains below one.

# COST PLAN/STATUS

| Baseline Reporting Quarter - PHASE I | Yr. 1 | | | | | | | | Yr. 2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | Q2 | | Q3 | | Q4 | | Q5 | | Q6 | |
| | 7/1/09 - 12/31/09 | | 1/1/10 - 3/31/10 | | 4/1/10 - 6/30/10 | | 7/1/10 - 9/30/10 | | 10/1/10 - 12/31/10 | | 1/1/11 - 3/31/11 | |
| | Q1 | **Total** | Q2 | **Total** | Q3 | **Total** | Q4 | **Total** | Q5 | **Total** | Q6 | **Total** |
| **Baseline Cost Plan** | | | | | | | | | | | | |
| Federal Share | 484,728 | **484,728** | 484,728 | **969,456** | 484,728 | **1,454,184** | 484,726 | **1,938,910** | 323,403 | **2,262,313** | 798,328 | **3,060,641** |
| Non-Federal Share | 121,252 | **121,252** | 121,252 | **242,504** | 121,252 | **363,756** | 121,254 | **485,010** | 80,835 | **565,845** | 199,564 | **765,409** |
| Total Planned | 605,980 | **605,980** | 605,980 | **1,211,960** | 605,980 | **1,817,940** | 605,980 | **2,423,920** | 404,238 | **2,828,158** | 997,892 | **3,826,050** |
| **Actual Incurred Cost** | | | | | | | | | | | | |
| Federal Share | 420,153 | **420,153** | 331,481 | **751,634** | 547,545 | **1,299,179** | 428,937 | **1,728,116** | 593,386 | **2,321,502** | 307,768 | **2,629,270** |
| Non-Federal Share | 29,456 | **29,456** | 131,875 | **161,332** | 151,972 | **313,304** | 100,629 | **413,933** | 191,601 | **605,534** | 45,101 | **650,635** |
| Total Incurred Costs | 449,609 | **449,609** | 463,356 | **912,966** | 699,517 | **1,612,483** | 529,566 | **2,142,049** | 784,987 | **2,927,036** | 352,869 | **3,279,905** |
| **Variance** | | | | | | | | | | | | |
| Federal Share | 64,575 | **64,575** | 153,247 | **217,822** | -62,817 | **155,005** | 55,789 | **210,794** | -269,983 | **-59,189** | 490,560 | **431,371** |
| Non-Federal Share | 91,796 | **91,796** | -10,623 | **81,172** | -30,720 | **50,452** | 20,625 | **71,077** | -110,766 | **-39,689** | 154,463 | **114,774** |
| Total Variance | 156,371 | **156,371** | 142,624 | **298,994** | -93,537 | **205,457** | 76,414 | **281,871** | -380,749 | **-98,878** | 645,023 | **546,145** |

*Note: Q5 and Q6 reflect both CDP 2009 and CDP 2010 SF424a projections as the award periods overlap.*

| Baseline Reporting Quarter - PHASE II | Yr. 2 | | | | Yr. 3 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q7 | | Q8 | | Q9 | | Q10 | | Q11 | | Q12 | |
| | 04/01/11 - 06/30/11 | | 07/01/11 - 09/30/11 | | 10/01/11 - 12/31/11 | | 01/1/12 - 03/31/12 | | 04/01/12 - 06/30/12 | | 07/01/12 - 09/30/12 | |
| | Q7 | **Total** | Q8 | **Total** | Q9 | **Total** | Q10 | **Total** | Q11 | **Total** | Q12 | **Total** |
| **Baseline Cost Plan** | | | | | | | | | | | | |
| Federal Share | 712,385 | **3,773,026** | 627,423 | **4,400,449** | 147,451 | **4,547,900** | 147,451 | **4,695,351** | 147,451 | **4,842,802** | 245,447 | **5,088,249** |
| Non-Federal Share | 178,100 | **943,509** | 156,854 | **1,100,363** | 36,863 | **1,137,226** | 36,863 | **1,174,089** | 36,863 | **1,210,952** | 58,906 | **1,269,858** |
| Total Planned | 890,485 | **4,716,535** | 784,277 | **5,500,812** | 184,314 | **5,685,126** | 184,314 | **5,869,440** | 184,314 | **6,053,754** | 304,353 | **6,358,107** |
| **Actual Incurred Cost** | | | | | | | | | | | | |
| Federal Share | 449,459 | **3,078,729** | 314,813 | **3,393,542** | 271,897 | **3,665,439** | 267,784 | **3,933,223** | 191,438 | **4,124,661** | 232,367 | **4,357,028** |
| Non-Federal Share | 48,902 | **699,537** | 48,835 | **748,372** | 105,695 | **854,067** | 40,652 | **894,719** | 33,092 | **927,811** | 44,294 | **972,105** |
| Total Incurred Costs | 498,361 | **3,778,266** | 363,648 | **4,141,914** | 377,592 | **4,519,506** | 308,436 | **4,827,942** | 224,530 | **5,052,472** | 276,661 | **5,329,133** |
| **Variance** | | | | | | | | | | | | |
| Federal Share | 262,926 | **694,297** | 312,610 | **1,006,907** | -124,446 | **882,461** | -120,333 | **762,128** | -43,987 | **718,141** | 13,080 | **731,221** |
| Non-Federal Share | 129,198 | **243,972** | 108,019 | **351,991** | -68,832 | **283,159** | -3,789 | **279,370** | 3,771 | **283,141** | 14,612 | **297,753** |
| Total Variance | 392,124 | **938,269** | 420,629 | **1,358,898** | -193,278 | **1,165,620** | -124,122 | **1,041,498** | -40,216 | **1,001,282** | 27,692 | **1,028,974** |

| 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** |

| Baseline Reporting Quarter - PHASE II | Yr. 5 | | | | Yr. 6 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q19 | | Q20 - REVISED BUDGET | | **Q21** | | Q22 | | Q23 | | Q24 | |
| | 04/01/14 - 06/30/14 | | 07/01/14 - 09/30/14 | | **10/01/14 - 12/31/14** | | 01/01/14 - 03/31/15 | | 04/01/15 - 06/30/15 | | 07/01/15 - 09/30/15 | |
| | Q19 | **Total** | Q20 | Total | **Q19** | **Total** | Q20 | **Total** | Q19 | **Total** | Q20 | **Total** |
| **Baseline Cost Plan** | | | | | | | | | | | | |
| Federal Share | 157,250 | **5,529,233** | 80,000 | **5,609,233** | 35,000 | **5,644,233** | 10,000 | **5,654,233** | 4,000 | **5,658,233** | 4,282 | **5,662,515** |
| Non-Federal Share | 53,484 | **1,328,443** | 44,136 | **1,372,579** | 30,000 | **1,402,579** | 8,000 | **1,410,579** | 3,000 | **1,413,579** | 2,300 | **1,415,879** |
| Total Planned | 210,734 | **6,857,676** | 124,136 | **6,981,812** | 65,000 | **7,046,812** | 18,000 | **7,064,812** | 7,000 | **7,071,812** | 1,700 | **7,078,394** |
| **Actual Incurred Cost** | | | | | | | | | | | | |
| Federal Share | 147,582 | **5,466,503** | 86,384 | **5,552,887** | 70,197 | **5,623,084** | | **5,623,084** | | **5,623,084** | | **5,623,084** |
| Non-Federal Share | 46,472 | **1,328,971** | 38,582 | **1,367,554** | 29,038 | **1,396,592** | | **1,396,592** | | **1,396,592** | | **1,396,592** |
| Total Incurred Costs | 194,053 | **6,795,474** | 124,966 | **6,920,441** | 99,235 | **7,019,676** | 0 | **7,019,676** | 0 | **7,019,676** | 0 | **7,019,676** |
| **Variance** | | | | | | | | | | | | |
| Federal Share | 9,668 | **62,730** | -6,384 | **56,346** | -35,197 | **21,149** | 10,000 | **31,149** | 4,000 | **35,149** | 4,282 | **39,431** |
| Non-Federal Share | 7,012 | **-528** | 5,554 | **5,025** | 962 | **5,987** | 8,000 | **13,987** | 3,000 | **16,987** | 2,300 | **19,287** |
| Total Variance | 16,681 | **62,202** | -830 | **61,371** | -34,235 | **27,136** | 18,000 | **45,136** | 7,000 | **52,136** | 1,700 | **58,718** |

## 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 2015 |
| 3 | 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 $CLEAR_{uff}$ for life-cycle CO2 emissions from conventional oil & gas development in the Uinta Basin | Nov-14 | Dec-14 | Discussed in this quarterly report |
| 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 $CLEAR_{uff}$ | | | |
| | Develop preliminary modules in $CLEAR_{uff}$ 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 $CLEAR_{uff}$ 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 | Discussed in Apr. 2014 quarterly report |
| | Demonstrate full functionality for conventional & unconventional oil development in Uinta Basin | Mar-14 | Jun-14 | Discussed in July 2014 quarterly report |

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| 4 | Liquid fuel processing by in-situ thermal production of oil shale/sands | | | |
| 4.1 | Development of CFD-based simulation tool for in-situ thermal processing of oil shale/sands | | | |
| | 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 |
| | Perform experiments to resolve differences between Fletcher group & Deo group TGA data at 1 K/min | Jul-14 | Sep-14 | Discussed Oct. 2014 quarterly report |
| | Extend CPD model for oil shale to include additional chemical structure features specific to oil shale | Jul-14 | Sep-14 | Discussed in Oct. 2014 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 |

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| 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 | May-14 | Report sent to R. Vagnetti on 27 May 2014 |
| | Complete thermophysical & geomechanical property data analysis & validation | Dec-14 | | Delayed until first quarter of 2025 |
| 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 Apr. 2012 quarterly report |
| | Development of a structural model of kerogen & bitumen | Jun-12 | Jun-12 | Discussed in July 2012 quarterly report |

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| 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 |
| 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 |

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| 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 | Dec-14 | | Due date has been revised to reflect status of expts. |
| | Basic reservoir simulations to account for thermal front propagation | Mar-15 | Dec-14 | Discussed in this quarterly report |
| | Evaluation of flow mechanics | Mar-15 | | 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 | Sep-14 | Sep-14 | Discussed in Oct. 2014 quarterly report |

## NOTEWORTHY ACCOMPLISHMENTS

Researchers from Subtasks 4.7 and 7.1 are performing permeability measurements on material with such low native transport ability that there are no existing data in the literature. With this work, there is cross-disciplinary application to assessing $CO_2$ enhanced oil recovery permeability relationships and deliverability from shale oil reservoirs. Additionally, the numerical simulations of subsidence have taken on the most complex geomechanical material that one can consider. The mechanical properties change as a function of temperature and phase evolution.

## PROBLEMS OR DELAYS

Nothing to report.

## RECENT AND UPCOMING PRESENTATIONS/PUBLICATIONS

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 33rd 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 33rd 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 macromolecular structure elements from a Green River oil shale, II. Characterization of pyrolysis products from a Utah Green River oil shale by $^{13}C$ NMR, GC/MS, and FTIR. *Energy and Fuels, 28,* 2959-2970. dx.doi.org/10.1021/ef500095j

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.

Barfuss, D. C., Fletcher, T. H. Fletcher and Pugmire, R. J. (2014, October). Modeling oil shale pyrolysis using the Chemical Percolation Devolatilization model. Presented at the 34$^{th}$ Oil Shale Symposium, Golden, CO, October 13-15, 2014.

Hardisky, M. and Smith, P. J. (2014, October). Evaluation of well spacing and arrangement for in-situ thermal treatment of oil shale using HPC simulation tools. Presented at the 34$^{th}$ Oil Shale Symposium, Golden, CO, October 13-15, 2014.

Wilkey, J., Ring, T., Spinti, J., Pasqualini, D., Kelly, K., Hogue, M., & Jaramillo, I. (2015, January). Predicting emissions from oil and gas operations in the Uinta Basin. Presented at the *Air Quality in Utah: Science for Solutions Workshop,* Salt Lake City, UT, January 13, 2015.

Fletcher, T. H., Hillier, J., Gillis, R., Adams, J., Barfuss, D., Mayne, C. L., Solum, M. S. and Pugmire, R. J. (2015, January). Oil shale: Structure and reactions. Invited seminar, BYU Chemistry Department, Provo, UT, January 13, 2015.

Fletcher, T. H., Hillier, J., Gillis, R., Adams, J., Barfuss, D., Mayne, C. L., Solum, M.S. and Pugmire, R. J. (2015, January). Oil shale: Structure and reactions. Invited seminar, College of Engineering, University of Alabama Huntsville, Huntsville, AL, January 29, 2015.

Tran, T. and McLennan, J. (2014, November). Evaluation of transport properties of in-situ processed oil shale. Presented at *USTAR Confluence: Where Research Meets Commercialization*, Salt Lake City, UT, November 3-4, 2014.

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