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ABSTRACT

The Utah Heavy Oil Program (UHOP) was established in June 2006 to provide multidisciplinary research support to federal and state constituents for addressing the wide-ranging issues surrounding the creation of an industry for unconventional oil production in the United States. Additionally, UHOP was to serve as an on-going source of unbiased information to the nation surrounding technical, economic, legal and environmental aspects of developing heavy oil, oil sands, and oil shale resources. UHOP fulfilled its role by completing three tasks. First, in response to the Energy Policy Act of 2005 Section 369(p), UHOP published an update report to the 1987 technical and economic assessment of domestic heavy oil resources that was prepared by the Interstate Oil and Gas Compact Commission. The UHOP report, entitled “A Technical, Economic, and Legal Assessment of North American Heavy Oil, Oil Sands, and Oil Shale Resources” was published in electronic and hard copy form in October 2007. Second, UHOP developed of a comprehensive, publicly accessible online repository of unconventional oil resources in North America based on the DSpace software platform. An interactive map was also developed as a source of geospatial information and as a means to interact with the repository from a geospatial setting. All documents uploaded to the repository are fully searchable by author, title, and keywords. Third, UHOP sponsored five research projects related to unconventional fuels development. Two projects looked at issues associated with oil shale production, including oil shale pyrolysis kinetics, resource heterogeneity, and reservoir simulation. One project evaluated in situ production from Utah oil sands. Another project focused on water availability and produced water treatments. The last project considered commercial oil shale leasing from a policy, environmental, and economic perspective.
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EXECUTIVE SUMMARY

The Utah Heavy Oil Program (UHOP) was established in June 2006 to provide research support to federal and state constituents for addressing the wide-ranging issues surrounding the creation of an industry for unconventional oil production in the United States. The research sponsored by UHOP was to focus on clarifying issues and seeking solutions to challenges for managing and utilizing these natural resources. Additionally, UHOP was to serve as an on-going source of unbiased information to the nation surrounding technical, economic, legal and environmental aspects of developing heavy oil, oil sands, and oil shale resources. UHOP was to be multidisciplinary in nature, involving faculty and students from many departments and colleges at the University of Utah and elsewhere. In the work reported here, there was involvement from the following entities at the University of Utah: College of Law, Department of Chemical Engineering, Department of Civil and Environmental Engineering, Utah Bureau of Economic and Business Research, and the Energy and Geoscience Institute. There was also participation from the Utah Geological Survey.

UHOP fulfilled its role by completing the two primary tasks listed in the 2006 Statement of Project Objectives. Task 1 had two parts: to update the 1987 technical and economic assessment of domestic heavy oil resources that was prepared by the Interstate Oil and Gas Compact Commission and to develop an on-line repository for information, data, and software pertaining to heavy oil resources in North America. Task 2 was to perform UHOP-sponsored research related to the objectives in Section 369 of the Energy Policy Act of 2005 and report on the results of the research. In addition to these two tasks, UHOP has sponsored three conferences during the project period. These conferences, the Western U.S. Oil Sands Conference and the Western U.S. Oil Sands Technology Transfer Meeting, have included speakers from government, academic institutions, and industry presenting material relating to resource characterization, production/processing, legal and environmental issues, and economic analysis of western U.S and Canadian oil sands. Attendees at the conference have consistently numbered greater than 100 with representation from government, academia, and industry.

The UHOP update report was to include publicly available information and link to data already compiled by DOE NETL, as part of their Unconventional Oil Resources Project, and by the Canadian oil sands work in Alberta. It was also to include an analysis of available resources, a discussion of the state-of-the-art production and processing technologies, and an analysis of the economics of utilization and environmental impacts. In October 2007, UHOP provided to NETL for general release to the public “A Technical, Economic, and Legal Assessment of North American Heavy Oil, Oil Sands, and Oil Shale Resources.” The report included seven sections: Introduction, Utah Heavy Oil Program ArcIMS Map Server Interface, North American Unconventional Oil Resource, Production/Processing Technologies for Unconventional Oil Resources, Upgrading and Refining, Economic and Social Issues Related to Unconventional Oil Production, and Environmental, Legal and Policy Issues Related to Unconventional Fuel. The report represented the work of eight authors at the University of Utah. A PDF version of the report may be downloaded from http://ds.heavyoil.utah.edu/dspace/handle/123456789/4921. In addition to providing the electronic copy, UHOP printed 1000 copies of the report and distributed those copies to in-
interested individuals, companies, government officials, and universities. Prior to release, the report was reviewed by five individuals including two individuals at NETL, UHOP’s programmatic contact at DOE, a Canadian professor with expertise in oil sands processing, and an attorney who specializes in energy, natural resources, and the environment.

The second part of Task 1, the development of a comprehensive, publicly accessible online repository of unconventional oil resources in North America, began with the selection of the DSpace software platform for UHOP’s digital archiving needs. DSpace, jointly developed by MIT Libraries and Hewlett-Packard Labs, is a digital repository system that captures, stores, indexes, preserves, and redistributes an organization’s research data. DSpace accepts all forms of digital materials including text, images, video, and audio files. Additionally, DSpace is freely available as open source software. These characteristics made DSpace ideal for the UHOP repository, which was to be populated and sourced by all constituencies in the unconventional oil community. The DSpace repository has two portals: a text-based interface that can be accessed at http://repository.icse.utah.edu/dspace/index.jsp and an interactive map-based interface accessed at http://map.icse.utah.edu/website/uhop_ims/viewer.htm. All documents uploaded to the repository are fully searchable by author, title, and keywords through the text-based interface. To make this full text search possible, older documents that were scanned in have been processed through optical character recognition software. The interactive map interface allows users to access data in a geospatial setting. A user can search in a certain geographical location, highlight an unconventional fuel resource in that area (heavy oil, oil shale, or oil sands), and then query the repository for information related to the geographically-referenced resource. The UHOP repository was initially populated with over 1000 documents on unconventional fuels collected by the Utah Geological Survey. Additional resources were obtained from various UHOP researchers. Where possible, the repository contains the actual digital material. However, due to copyright issues, some information in the repository is only available in abstract form.

Task 2 in the UHOP Statement of Project Objectives, to develop potential research area ideas for UHOP-sponsored projects and then to perform and report on the research, was accomplished in several phases. First, each member of the UHOP Directorate (Ray Levey, Energy and Geoscience Institute; Robert Keiter, College of Law; Michael Lemmon, College of Business; Milind Deo, College of Engineering; and Philip Smith, College of Engineering) provided a list of research topics in his field of expertise that complemented other work in industry, academia, and government. This list of potential research topics was presented to NETL at the project kick-off meeting on October 26, 2006, in Tulsa, Oklahoma. After incorporating input from NETL, the list of research topics was finalized and included in a section of the internal request for proposals (RFP) that was released in October 2006. Eleven proposals were submitted by the December 2008 deadline, requesting in excess of $1.6 million in research money. A proposal review panel convened on February 15, 2007 to select projects for funding. The review panel included Philip Smith, Director of UHOP; Jennifer Spinti, Research Associate in UHOP; Brandon Lloyd, Millenium Synfuels, LLC; and Olayinka Ogunsola, DOE. The review panel was impressed with the quality and breadth of the proposals that covered the wide range of issues associated with unconventional fuel development, including technical, geological, legal, and economic issues. Five of the projects were selected

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for funding for a total of $600,000 in research from the solicitation. The five selected projects are listed in Table 1.

Table 1 UHOP Research Projects Selected for Funding

<table>
<thead>
<tr>
<th>Title of Proposal</th>
<th>Principal Investigator</th>
<th>Affiliation</th>
<th>Funding Level</th>
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<tbody>
<tr>
<td></td>
<td>Michael Hogue</td>
<td>Bureau of Economic and Business Research</td>
<td></td>
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<tr>
<td>Depositional Heterogeneity and Fluid Flow Modeling of the Oil Shale Interval of the Upper Green River Formation, Eastern Uinta Basin, Utah</td>
<td>Md. Royhan Gani Milind Deo</td>
<td>Energy and Geoscience Institute</td>
<td>$110,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>In Situ Production of Utah Oil Sands</td>
<td>Milind Deo</td>
<td>Chemical Engineering</td>
<td>$100,000</td>
</tr>
<tr>
<td>Quantifying Water Availability Impacts and Protecting Water Quality while Developing Utah Oil Shale and Sands</td>
<td>Steven Burian Ramesh Goel Andy Hong</td>
<td>Civil and Environmental Engineering</td>
<td>$130,000</td>
</tr>
<tr>
<td></td>
<td>Milind Deo Eric Eddings Terry Ring</td>
<td>Chemical Engineering</td>
<td>$150,000</td>
</tr>
</tbody>
</table>

Following is a summary of the research results obtained from the five projects listed in Table 1. Detailed final reports for all five projects are presented as appendices to this document.

This report seeks to identify the salient environmental, policy, economic and socioeconomic issues that are relevant to determining when and how a federal commercial oil shale program might be implemented. Where appropriate, this report offers conclusions and recommendations as to potential paths forward on oil shale policymaking.

If commercial oil shale development occurs on the public lands, it will be subject to a comprehensive and complex legal framework. Additionally, the Bureau of Land Management, the largest single manager of oil shale-bearing lands, operates under a"multiple use--sustained yield" mandate that requires the BLM to weigh and balance current and future needs for the various resources and resource values found on the public lands. Many of the BLM’s discretionary decisions as to the proper resource balance meet with legal challenge, and this is currently the case for recent BLM decisions affecting the potential scope of oil shale development. Programmatic BLM management plan amendments have identified lands available for application for commercial leasing, but these plans also remain encumbered by legal challenges. New policies announced by the Obama Administration favor more detailed and environmentally informed decisions, which in turn may foster enhanced certainty for prospective energy developers and the public alike. In addition to federal lands, state, private and tribal interests overlie extensive and valuable oil shale resources. The public interest, the interests of the various oil shale resource owners, national energy needs and environmental impacts will all influence the course of commercial oil shale leasing and development on the public lands.

Presently, analysts and policymakers must guess at the number, size, location and technologies employed by what is as yet only a prospective oil shale industry. While much is anticipated about the tradeoffs of commercial oil shale development on the public lands, important gaps in information remain. And these tradeoffs are not solely environmental; for example, development of conventional oil and gas may be at odds with commercial oil shale development.

Making water available for a commercial oil shale industry raises several policy issues. In a region where water resources are fully allocated, potentially water intensive oil shale development will require reallocation of existing water supplies. While in theory existing water law is well suited to facilitating water right transfers, it is hampered by large unresolved claims and is of little help in answering the more basic question of what competing water uses society is willing to forego in favor of oil shale development.
The intrinsic energy demand and related air quality issues associated with producing shale oil raises policy questions as to the energy balance of oil shale development. Similarly, absent proven carbon management technologies, anticipated regulation of greenhouse gases has the potential to significantly constrain the scale and economics of commercial oil shale development.

Development of a sustainable commercial oil shale industry also faces a number of economic challenges. Will a commercial oil shale industry be likely to generate a return on investment sufficient to retain or attract capital? Can a future commercial oil shale industry effectively compete with conventional petroleum sources and emerging alternatives to liquid transportation fuels? Would commercial oil shale development provide a sufficiently broad public benefit --whether energy security or economic -- to warrant government support?

Finally, unbalanced growth is a salient feature of past episodes of rapid mineral development, including the oil shale development efforts that occurred in western Colorado in the late 1970s and early 1980s. The problems associated with "boom-town growth" are central to evaluating when and how a federal commercial oil shale leasing program might be implemented.

2. Depositional Heterogeneity and Fluid Flow Modeling of the Oil Shale Interval of the Upper Green River Formation, Eastern Uinta Basin, Utah

A detailed geological analysis was performed followed by a reservoir modeling exercise. For the geological analysis, ~300 m of cores were correlated to gamma and density logs in well P4 in the lower to middle Eocene (49.5–48.0 million years ago (Ma)), upper Green River Formation of the eastern Uinta Basin, Uintah County, Utah. In well P4, three distinct facies associations were identified that represent three phases of deposition linked to the hydrologic evolution of Lake Uinta: 1) an overfilled, periodically holomictic lake system with deposition of primarily clastic mudstones, followed by 2) a balanced-filled, uniformly meromictic lake system with deposition of primarily calcareous and dolomitic mudstones, followed by 3) an underfilled, evaporative lake system with nahcolite precipitation. The richest oil shale zones were deposited during the second depositional phase. While the studied interval is popularly known as oil "shale", this bed-by-bed investigation revealed that lithologically, thus chemically, the interval is quite heterogeneous. This complexity has significant impact on modeling strategies for oil shale exploitation.

In-situ methods are expected to have a lessened environmental impact and are likely to have lower costs than mining and surface processing. Heat transfer pathways, chemical kinetics, geomechanics, multiphase fluid flow, and process strategies add complexity to any in-situ oil shale production strategy. Understanding each of these phenomena as well as appropriate model coupling is necessary to accurately model in-situ oil shale production.
processes. For the reservoir modeling exercise, various in-situ oil shale production methods for this heterogeneous resource were explored using the geologic information from U059 (core P4). The core information was converted to wt% hydrocarbon (organic matter or kerogen) and used directly in the reservoir simulation model. Results from in-situ oil shale modeling with the STARS simulator show that oil production from the Green River Formation is feasible. Challenges to achieving economic rates of recovery include porosity-permeability creation and the establishment of contiguous pathways between injectors and producers. Idealized energy efficiency and carbon footprint for an electrical conduction-type process were estimated as 3:1 net energy gain and 36 kg CO₂/barrel (bbl) oil produced respectively.

3. In Situ Production of Utah Oil Sands

The objective of this project was to evaluate and rank a variety of in-situ heavy oil production method for the production of bitumen from a representative Utah oil sand formation within the Uinta Basin. Two oil sand reservoirs located in Utah’s Uinta Basin were considered for analysis: Whiterocks, a small, steeply dipping, contained reservoir containing about 100 million barrels, and Sunnyside, a giant reservoir containing over four billion barrels of oil in place. Cyclic steam stimulation, steam assisted gravity drainage, and in-situ combustion processes were considered for the production of oil from these reservoirs. Different well configurations and patterns were examined. It was found that the application of steam-based in-situ processes would be feasible but challenging for Utah oil sands. For most configurations, the steam to oil ratios were higher than five, indicating marginal economic viability. Additionally, the water production rates were high. The in-situ combustion process was simulated with and without the presence of a hydraulic fracture for a homogeneous reservoir. The nature of the combustion front was radial without the fracture and linear with the fracture. Even though the process appears feasible, rigorous evaluation with an appropriate geologic model will be necessary to determine technical and economic viability.

4. Quantifying Water Availability Impacts and Protecting Water Quality While Developing Utah Oil Shale and Sands

When project proposals were reviewed, there were three related to water availability and water quality. However, there was not enough money to fully fund all three projects. Instead, the principal investigators were asked to reduce the scope of their proposals and work in a synergistic manner to maximize their efforts within the available budget. As a result, three subparts were created for this project. The results from each of these subparts is summarized here.

**Water Resources Sustainability:** The goal of this project was to mitigate water resources impacts from oil shale development in the U.S. by compiling geospatial data and
water use estimates to assess water availability impacts. A brief literature search was conducted to acquire publications and fact sheets on oil shale and water resources. Water resources geospatial datasets for the Uinta and Piceance Basins in Utah and Colorado were also collected to support the development of the water management model. The 50 documents obtained in the literature review were uploaded to the UHOP repository and the geospatial datasets collected and created have been incorporated into the UHOP interactive map. To update water requirements estimates, projections for urban growth, estimates of available oil shale resources, and the quantification of water requirements for the urban growth, oil shale industry, and energy generation sectors were needed. The Eastern Utah urban growth projection was based on a retrospective analysis of growth in Fort McMurray, Canada, in response to their oil sands development growth. The retrospective analysis provided a model to follow that was fine-tuned in discussions with Vernal planning department officials to arrive at a reasonable estimate of future urban growth and to generalize key characteristics of the urban demographic and growth pattern likely to influence water demand. The in-place oil shale resource estimates were based on a geostatistical analysis. Water demand estimates were made using a range of possible oil shale production rates, technologies, and urban and energy water demands. A methodology to determine water availability was also conceived. The conceptual approach identified the need to develop a water management model for the White River (a tributary to the Green River in the Colorado River Basin), to acquire and incorporate hydrologic information, and to accurately account for the current water users in the region.

**Biological and Chemical Treatment of Produced Water:** Produced water is composed of dispersed oil, dissolved organic compounds, production chemicals, heavy metals, naturally occurring radioactive minerals and other inorganic compounds. Every year, larger quantities of produced water go through underground injection or discharge into natural water bodies, which do not meet the requirement of sustainable development and also present a potential threat to the aquatic ecosystem. Produced water has been treated by physical (deep bed filter, gas flotation, sand filtration, activated carbon, etc.), chemical (ozonation, ion exchange, UV treatment, etc.) and biological methods respectively. However, none of those methods alone gives a substantive treatment. The long-term objective of this work is to develop an integrated treatment scheme which will employ a combination of physical, chemical and biological treatment methods to treat produced water for sustainable production in oil/gas fields. The objective in this first phase of the project was to test and refine each of the steps in the combined treatment approach. Real produced water samples (6 samples in triplicate) from ConocoPhillips were characterized using ICP-MS to identify elements present and the HACH method to identify ammonia, nitrite, nitrate, phosphorus, and COD. The identified constituents were used to simulate the composition of the synthetic produced water in the integrated treatment scheme. Naphthalene and BTEX were used as the model refractory compounds to test the treatment efficiency of advanced oxidation and biological methods. While the rate of degradation of naphthalene and BTEX in electrolytic experiments was slow and not all the contaminants were degraded, the electro-Fenton method was able to oxidize and remove the bulk of the organic compounds. The results show that up to 60 weight percent of the naphthalene and more than 99 weight percent of BTEX were removed after 8 hours of electrolysis. Furthermore, biomass from municipal
sewage removed more than 95 weight percent of the naphthalene and BTEX. The bacteria responsible for the biodegradation were identified through the 16S rDNA-based cloning and sequencing technique. Both oxidation and biological treatment results are affected by volatilization as indicated by tests conducted with blanks.

**Ozonation of Produced Water:** Produced water from gas and crude oil production is voluminous, requiring extensive treatment before it can be safely discharged or reused. The project objectives were: 1) to treat oily wastewater such as produced water that contains dissolved and suspended oil, 2) to remove the potential for sheen formation on the water surface, 3) to render the water amenable to reuse and safe environmental release, and 4) to demonstrate bitumen extraction from oil sands. To complete these tasks, the project used a newly developed pressure-assisted ozonation technology for removing oil from water and to prevent oil sheen at the water surface. The new process is based on heightened reactions of ozone and hydrocarbon molecules occurring at the gas-liquid interface of the microbubbles. Ozonation in pressure cycles combines the advantages of microbubbles for flotation and heightened reactivity of ozone for the removal of oil from water. Ozone converts small hydrocarbons in the aqueous phase into hydrophilic organics in a short time (< 20 min). The dissolved organic acid products exhibited good biodegradability. Because the treated water contains biodegradable end products at low concentrations, safe discharge to the environment or for various reuses is possible. The new process is especially valuable for coastal discharge, as well as for energy development and water use in arid regions. Finally, the pressure-assisted HOSE process rapidly accomplished bitumen extraction from oil sands using little energy and requiring no chemical additives, demonstrating its potential as an effective oil sands process.

5. **Oil Shale Pyrolysis & In Situ Modeling**

When modeling in situ extraction of oil shale, the chemical reactions that detail the conversion of kerogen to oil have a first order effect on predicted oil production rates. Accordingly, the two subparts of this project focused on (1) obtaining a better understanding of oil shale pyrolysis and (2) employing a pyrolysis mechanism in a multi-physics model of in situ extraction using DC and RF heating of the deposit.

**Detailed Study of Shale Pyrolysis for Oil Production:** Good kinetic data are essential for accurate mathematical modeling of various ex-situ and in-situ oil shale processes. The purpose of this project was to develop a more detailed kinetic understanding of the pyrolysis of oil shale. Studies significant to the kinetic analyses of oil shale are compiled and discussed. Then, methods and experiments relating to the pyrolysis and combustion of Green River oil shale samples from Utah are presented. Kinetic analysis of both pyrolysis data from thermogravimetric analysis (TGA) and combustion data was performed using conventional and isoconversion (Friedman) methods. A reasonable match of the data was obtained by considering activation energy as a function of heating rate. For decomposition of complex materials such
as kerogen, isoconversion methods are recommended. Based on the data collected, a distribution of activation energies (with conversion) was established.

While obtaining comprehensive combustion kinetic information was not one of the original project objectives, other research activities indicated that in situ combustion could be one of the processes used to generate sufficient energy for the pyrolysis process. Pyrolysis yield information was generated using ¼ inch core samples. Yields generally increased slightly with temperature in the narrow temperature window examined in this work. The highest yield was obtained in the experiment with a slow heating rate. Compositional information of the samples revealed that higher temperature processes yielded oil with higher residue. No significant difference in yield or composition was observed in experiments performed by soaking cores in water for short durations (1-10 days). Selected GC-MS analyses of the products revealed the alkene-alkane pairs typical of shale oils. Significant amounts of aromatics were also present in the oils. In general, these compounds have higher water solubilities than the paraffinic and naphthenic species in the oil. The GC-MS analyses revealed the necessity of detailed compositional analyses.

**Modeling In situ Oil Shale Recovery Extraction:** In situ production processes are being vigorously pursued by all the major energy companies. However, fundamental issues related to the kinetics of kerogen conversion to natural gas and light oil products and the production of the resulting oil require further multi-physics analysis to aid in situ extraction. Additionally, in situ processing is a highly energy-intensive process. Better energy utilization and efficiency is necessary to make the extraction of this resource cost effective. A multi-physics model of in situ extraction of oil shale was developed which couples kerogen pyrolysis, fluid flow, mass transfer of multiple species, heat transfer and AC (RF) and DC heating of the deposit. All physical properties used in these model equations were functions of the local chemistry of the deposit and of local temperature. A 2D slice consisting of a heating and a production well located 25 feet (7.62 m) apart, was simulated for up to 5 years. The 2D slice is a right triangle consisting of the smallest repeating unit of a hexagonal drill pattern. The model calculated the concentrations of kerogen, bitumen, oil and gas at all locations in the deposit; physical properties such as viscosity, permeability, heat capacity, thermal conductivity, electrical conductivity, dielectric constant, and loss tangent; and pressure, temperature, and thermal and pressure stresses in the deposit. The results showed that a pusher fluid, a gas in this work, was necessary to move the oil to the production well; that thermally-induced stresses did not induce fracture of the deposit; and that more uniform heating of the deposit by RF heating was beneficial to oil extraction.

**FUTURE WORK**

The Utah Heavy Oil Program was terminated at the end of the project period. However, the work conducted by UHOP was phased into new programs within the Institute for Clean and Secure Energy (ICSE) in 2008. For example, the repository and interactive map are continu-
ing to evolve as online resources for unconventional fuels, especially in Utah and the western U.S., and are supporting the work of ICSE researchers in coal, oil sands, and oil shale. Policy work continues in the areas of produced water and water availability, land use impacts, and the potential to learn from the Canadian oil sands experience as a model for development in the U.S., particularly in Utah. Another assessment is also being prepared on the supply costs and economic impact of oil shale, oil sands, and heavy oil industries where development does not currently exist. Projects related to oil shale pyrolysis, geologic characterization, and reservoir simulation have been continued, and new projects studying atomistic modeling of kerogen and porosity/permeability in pyrolyzed oil shale samples have been added. Both technical and legal projects have two overarching objects. In the area of clean oil shale & oil sands utilization with efficient CO₂ capture, the objective is to produce the research and simulation tools needed to provide efficient CO₂ capture for process equipment for production and upgrading of oil shale and oil sands and specifically to produce predictive capability with quantified uncertainty bounds for a pilot-scale, oxy-gas process heater using flameless technologies. In the area of secure liquid fuel production by in-situ thermal processing of oil shale & oil sands, the objective is to apply science, engineering, technology and economics research tools developed within ICSE to a wide variety of in-situ processes and to explore the environmental, legal and policy framework for implementation of such technologies on public and private lands.