

## **Pilot Scale Demonstration of MicGAS™ Coal Biotechnology for *in situ* Biological Gasification of Un-Minable Wyoming Sub-bituminous Coals**

ARCTECH Inc. 14100 Park Meadow Drive  
Chantilly, Virginia 20151  
703 222-0280, [www.arctech.com](http://www.arctech.com)

December 20, 2013

Submitted to:

### **School of Energy Resources**

ATTN.: Diana Hulme [dhulme@uwyo.edu](mailto:dhulme@uwyo.edu)

University of Wyoming

Department 3012

1000 E. University Avenue

Laramie Wyoming 82071

PHONE: 307-766-6639

FAX: 307-766-6701

WY SER Contract Numbers: 1001030/ CFDA # 15.250      1100-20268

## **EXECUTIVE SUMMARY**

Coalfields contain almost 10 times more unminable than minable coals, including “stranded” coal deposits simply too deep to extract. The *in situ* conversion of these vast coal masses into gas could turn deposits with little other potential into a bountiful source of clean fuels for the United States. Wyoming is the largest producer of coal in the USA: about 435 million tons per year of mostly low-sulfur sub-bituminous from open cast mining, or almost 50% of the total coal used today in the nation. Coal is also the second most important source of revenue for Wyoming’s state and local governments after natural gas; according to the Wyoming Mining Association (2010), coal’s estimated contribution in 2009 was over \$1.15 billion to state and local governments.

The Wyoming coalfields contain an estimated one trillion tons of deep un-minable coal based on USGS borehole data. This enormous quantity of coal is not accessible by open cast mining due to high seam-to-overburden ratio and safety issues prevent most underground mining of these deposits. These deep coals, however, have become an important source of coal bed methane

(CBM) that has remained adsorbed in the coal seams since their formation. In recent years industry has been recovering this gas by drilling wells into the seams and pumping huge volumes of water to depressurize, leading to the release of adsorbed gases that are pumped out. Based on gas-desorption studies of core samples, the deep seams in Wyoming contains on average 50-100 ft<sup>3</sup> ton<sup>-1</sup> of gas compared to 300-500 ft<sup>3</sup> ton<sup>-1</sup> in the San Juan basin (New Mexico), in the Ranton basin (Colorado), and in bituminous coals of the Eastern USA. While the Wyoming seams have lower gas production and more-rapid depletion times compared to natural gas wells, the coal seams are the thickest of any U.S. coalfields (up to 50 ft in some places), thereby allowing for more gas to be extracted per unit of land area than many parts of the country. Nonetheless, Wyoming CBM production increases from 133 billion ft<sup>3</sup> yr<sup>-1</sup> in 2000 to 535 Billion ft<sup>3</sup> yr<sup>-1</sup> in 2009 only account for some 2% of total annual gas use in the USA (EIA, 2010). Considering the steadily increasing demand for natural gas in the U.S. juxtaposed against the unrealized full potential of Wyoming's CBM resources, there is a great opportunity to increase the value of the state's natural energy resources through the enhancement of the Powder River Basin's CBM capacity.

New energy regulations also make the case for enhanced CBM in Wyoming. Since February 16, 2012, the USEPA has required the reduction of sulfur and many trace minerals emissions for existing power plants within 4 years. These regulations result in the loss of environmental advantage for low-sulfur Wyoming coals as the new limits on sulfur dioxide (SO<sub>2</sub>) emissions require the more-widespread use of expensive sulfur oxide (SO<sub>x</sub>) scrubbers. Moreover, new stringent requirements for trace mineral emissions will require additional scrubbers and expensive treatment processes to meet compliance standards. Table 1 presents the HAPs that will exceed the levels set by the USEPA regulations, based on the average contaminants of concern in Wyoming coals, including mercury (almost 10 fold), manganese (about 12 fold), and others (2 to 6 fold). Only nickel was calculated to be below the proposed USEPA limits. Therefore, cleaner-burning gas-utilizing plants will have a clear economic advantage over coal-fired plants.

Another new USEPA environmental mandate of CSAPR: Cross State Air Pollution Rule is also resulting in shut down of almost 100+ coal plants. This new mandate requires increased reduction

of NO<sub>x</sub>, SO<sub>x</sub> and fine particles as small as 2.5 microns to reduce their impact on smog across state lines. US EPA has also announced drastic reduction of CO<sub>2</sub> emissions and limit CO<sub>2</sub> to less than 1100 pounds per MW from new plants and considering announcing similar level reduction from the existing plants. This requirement is almost 50% reduction from the today's coal plants.

Some attempts have been made to produce gas from the deep un-minable coals of Wyoming. For example, after the 1973 Energy Crisis a number of underground thermal coal gasification tests were conducted by pumping air and steam into the coal seam to affect partial oxidation and produce gas, which was converted on the surface into clean energy fuels. These tests were conducted in Wyoming from 1973-89 because of the extensive coal resources and favorable coal seam characteristics there. For example, Lawrence Livermore National Laboratory conducted three tests in 1976–1979 at the Hoe Creek test site in Campbell County, Wyoming, followed by 1979–1981 projects by Gulf Oil near Rawlins and then the Rocky Mountain project near Hanna in 1986-1988. These efforts were ultimately abandoned due to unfavorable economic and environmental concerns - the Hoe Creek test site is currently included in the U.S. DOE Legacy Program requiring ongoing treatment of benzene contamination in the groundwater.

Table 1. Expected Emission of HAPs Based on the Average Trace Metal Content of the Wyoming Coals

Hazardous Air Pollutants (HAP)	Wyoming Coal			d) Final EPA Emission Limits for Existing Coal Units, lb/GWh		Wyoming Coal Emission will be X times Higher than EPA Limits
	a) Concentration in Coal, ppm	b) Emission Factor for Coal-Fired Plants, % Emitted	c) Expected Emission, lb/GWh	Unit not low rank virgin coal	Unit designed low rank virgin coal	
Mercury (Hg)	0.13	89	0.130	0.013	0.12	<b>10/1.08</b>
Antimony (Sb)	0.49	2.4	0.013	0.008		<b>1.65</b>
Arsenic (As)	2.6	2.8	0.082	0.02		<b>4.09</b>
Beryllium (Be)	0.54	2	0.012	0.002		<b>6.07</b>
Cadmium (Cd)	0.21	2.7	0.006	0.003		<b>2.12</b>
Chromium (Cr)	6.1	1	0.069	0.03		<b>2.28</b>
Cobalt (Co)	1.9	1.2	0.026	0.008		<b>3.20</b>
Lead (Pb)	3	1.8	0.061	0.02		<b>3.03</b>
Manganese (Mn)	26	2	0.584	0.05		<b>11.69</b>
Nickel (Ni)	4.6	0.4	0.021	0.04		0.52
Selenium (Se)	1.1	14.4	0.178	0.06		<b>2.97</b>
Sulfur dioxide (SO <sub>2</sub> )	1.24 lbs/MMBtu			0.20 lb/MMBtu		

- a) G.D. Stricker and M.S. Ellis, Chapter PQ COAL QUALITY AND GEOCHEMISTRY, POWDER RIVER BASIN, WYOMING AND MONTANA in U.S. Geological Survey Professional Paper 1625-A, 1999.
- b) Carole B. Szpunar, PROJECTIONS OF AIR TOXIC EMISSIONS FROM COAL-FIRED UTILITY COMBUSTION: Input for Hazardous Air Pollutant Regulators", Second International Conference on Managing Hazardous Air Pollutants, Washington, D.C., U.S.A, 1993 (Assumption: Although somewhat simplistic, this set of considered to represent the best conservative estimates available for emissions from a new, emissivity factors can be modern, environmentally regulated, pulverized-coal-fired (PCF) power plant.)
- c) Assumptions: Heat rate = 9500 Btu/kWh, Heat Content = 8500 Btu/lb
- d) Federal Register / Vol. 77, No. 32 / Thursday, February 16, 2012 / Rules and Regulations; EPA, National Emission Standards for Hazardous Air Pollutants from Coal- and Oil-fired Electric Utility Steam Generating Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial-Institutional, and Small Industrial-Commercial-Institutional Steam Generating Units, 40 CFR Parts 60 and 63.

An *in situ* biological conversion of the vast coal resources can greatly expand the domestic natural gas supply where traditional CBM has failed. On February 18, 2011, Governor Mead signed a Biogenic Gas Bill (Senate Bill 116) into law, establishing a permitting system in Wyoming for well and reservoir injections to restore or enhance the microbial conversion of hydrocarbon substrates (coal and oil) to methane gas. This change of policy has allowed the attempted biogasification of coal through nutrient amendments by several American companies. For instance, LUCA, a Colorado company, undertook renovation of almost 400 depleted CBM wells by recharging with water and nutrients to stimulate the activity of the indigenous microbes in the coal seam. This resulted in proving the concept but did not result in producing sufficient, commercially feasible gas; LUCA has since abandoned these operations in Wyoming (Press Reports 2013 ). CIRIS Energy, also from Colorado, has for a second time attempted a similar approach of injecting nutrient solutions alone to stimulate indigenous microbes and produce gas. However, CIRIS Energy has yet to release a detailed, independently-verifiable account of their projects.

ARCTECH's approach is based on injecting MicAN into the coal seam, especially after adaptation of the proprietary microbes to the particular coals in the lab. This pilot project's main objective was to establish the gas production potential in a pilot unit under simulated *in situ* seam conditions by using core coal samples from the target formation. The Wyoming Department of Environmental Quality (WY DEQ) was also contacted to seek understanding of permit requirements for injecting microbes in the coal seam. The WY DEQ currently has no limits on

"microbes" per se, other than that any injectate must be free of disease-causing organisms like *Vibrio cholerae* and certain types of non-pathogenic bacteria like iron or sulfur-reducing species to prevent operational problems. Thus, depending on the microbes to be injected, the WY DEQ may require disinfection prior to re-injection. WY DEQ representative also communicated to ARCTECH that based on the CBM experience, most CBM operators in Wyoming have targeted aquifer formations that are susceptible to bacterial contamination of drinking water supplies. MicAN microbes are free of any pathogens and iron and sulfur reducing bacteria. An independent laboratory report on analysis of MicAN is included in Attachment #2.

Microbes have been extensively applied to soils and groundwater in both environmental and agricultural applications. *In situ* anaerobic bioremediation has been used as an effective means of degrading various forms of chlorinated compounds dissolved in groundwater. When anaerobic degradation of chlorinated compounds occurs without the participation of microbial populations, which are frequently incapable of performing the function with available nutrients, it is considered a component of natural attenuation and not bioremediation per se. Therefore, a variety of organic substrates have been applied to the subsurface to promote anaerobic degradation of undesired organic substrates to innocuous end-products by resident microbes. In some cases, microorganisms may themselves be added for "bioaugmentation."

Regulatory approval for the injection of commercial microbial cultures for bioaugmentation (e.g. KB-1, Bachman Road, Pinellas) has been granted by the governments of Alaska, California, Delaware, Florida, Massachusetts, Michigan, Nebraska, New Jersey, Pennsylvania, South Carolina, and Texas. Large-scale anaerobic bioremediation projects have already been initiated. For example, the mixed culture "Bachman Road" Enrichment from the Bachman Road aquifer in Oscoda, Michigan has been commercially field-tested (Lendvay *et al.*, 2003). Additionally, Dybas *et al.* (2002) describe the use of bioaugmentation with *Pseudomonas stutzeri* strain KC to degrade CT in a full-scale biocurtain at the Schoolcraft site in Michigan. In this case, the dechlorinating microorganism was isolated from another site where CT transformation was observed and then grown onsite to sufficient quantities prior to use.

Examples of use of microbes and regulatory approvals in remediation of contaminated underground water, in agriculture as bio-control and biofertilizers and in enhanced oil recovery in USA and abroad are included in the report.

Stranded coal deposits in Wyoming alone are estimated by the USGS to exceed one trillion tons. This project, utilizing the patented and proprietary MicGAS™ technology, established the feasibility of biologically converting Powder River Basin coals into methane-rich biogas. The MicGAS™ *in situ* technology is based on a two-stage approach: the MicAN microbes and their nutrients are injected into the formation for bioconversion of coal into acetate in Stage 1, and then the acetate-enriched water is pumped into aboveground bioreactors for conversion to gas by Mic-Methanogen microbes in Stage 2. The water is then reinjected and a circulation loop allows the proliferation of MicAN and the maintenance of hydraulic control in and around the treatment wells.

The overall objective of the current project was to demonstrate the bench-scale and pilot-scale applicability of the MicGAS™ *in situ* approach to bioconvert coals from the Powder River Basin to methane-rich gas and to thereby enable the next step of bringing the technology to the field. Three key goals to this end were: (1) to increase the rate and yield of coal biogasification by testing the productivity of MicAN with four coal samples as substrates and selecting the best-performing coal for larger-scale *in situ* simulated laboratory testing; (2) to create cost-competitive gas from coal in the process; and (3) to evaluate the effect of injecting MicAN and proprietary nutrients on the integrity of underground formation waters consistent with conditions in Wyoming coal seams.

This project entailed drilling to collect core coal and formation water samples from near the Tongue River in Rosebud County, Montana, in a collaborative effort between ARCTECH and USGS researchers. The drilling occurred approximately 30 miles north of the Wyoming border (N 45° 26' 6.3", W106° 23' 31.6") and two core samples were collected from each of four coal beds: Knobloch (145.9ft – 160.1ft), Calvert (167.1ft – 172.0ft), Nance (204.1ft - 205.1ft), and Flowers-Goodale (370.7ft -380ft). Data showed that the core coal samples were amenable to degradation by MicAN microbes at 5% coal solids and substantial biogas was produced. To

better-model *in situ* conditions in the biogas productivity tests, microbioreactor cultures were also setup with high coal loading of 2:1 coal-to-medium ratio (67% coal solids). After more than 209 days of incubation, Knobloch coal produced the highest biogas volume of 693.5 mL containing 546.354 mL methane. Based on the results obtained from the microbioreactor tests, Knobloch coal was selected for an *in situ*, large-scale simulated horizontal bioreactor test, which generated a total of 1,262 mL biogas containing 680 mL methane over a mere 73 days. The gas yields of both the high loading microbioreactor and *in situ* simulated horizontal bioreactor tests were extrapolated to 648.8 scf/ton and 414 scf/ton of Knobloch coal per year, respectively.

Techno-economic analysis was conducted based on data obtained from the *in situ* simulated laboratory tests on the bioconversion of Knobloch coal. The data was extrapolated and productivity of biogas was calculated as 414 scf/ton of Knobloch coal per year. The cost of gas production was estimated based on the production rate while varying efficiency from 50% to 75% in field projects on a 40 acre site with 50-foot thick coal seam. Based on calculated % of coal carbon consumed for average scf of gas produced per ton per year, lifespan of gas production in field projects was estimated. The following assumptions were taking into consideration:

- Net Coal Seam Thickness: 50 feet
- Project Area: 240 acre
- Coal Seam Density, Tons/Acre-foot: 1800
- Net Coal Volume, Tons: 20 Million Tons
- Gas per Ton: 414.5 SCF
- Capital cost (\$8 million):
  - 100 wells each 1000 ft. deep = 100,000 linear feet @ \$25 per linear feet = \$2.5 million
  - Surface facilities (pump, transfer pipes, compressor) = \$1.5 million
  - MicGAS™ Microbes/Nutrient production Unit, Stage 2 Bioreactor and startup MicAN microbes and Nutrients = \$4 million

Wyoming has large un-minable coalfields containing about one trillion tons of coal that currently generate relatively low value from CBM gas. By installing ARCTECH's MicGAS™ Coal Biotechnology, these coal beds will be rendered as true value-added resources. An economic analysis of *in situ* MicGAS™ biogas production projects that gas production costs will be about \$1 per million Btu (Mcf) before government taxes and levies. If this gas is competitively priced at \$3 per million Btu (Mcf) for wholesale at the wellheads, then a 20% tax on \$2 per million Btu

(Mcf) of income will result in revenues of \$0.4 per million Btu (Mcf). If this technology is applied to only 1% of the un-minable reserves, the royalty fee to the Government, will result in yearly revenues to the State of almost \$1.6 billion out of \$11.4 billion in revenues generated by industry. This analysis supports the MicGAS™ *in situ* approach as offering very high profitable business opportunities for industry and very high potential revenues for the Government.

### **Conclusions–Recommendations, Business Plan Approach for Applicability to Wyoming**

- The MicGAS™ approach for biogasification of un-minable deep coal seams has real potential for the creation of a new paradigm for the production of lower cost and higher volume gas than the current approach to CBM. To this end, data obtained from *in situ* simulated tests on bioconversion of Tongue River coal with formation water to methane-rich gas will be useful for the implantation of the MicGAS™ coal biotechnology to the un-minable coals of Wyoming.
- Presently there is growing controversy about the use of chemicals for hydro-fracking to increase gas production from the tight oil sand and shale formations. However, the recently enacted Biogenic Gas Law paves the way for establishing controls so that the local environment is protected. This project developed specific data from field tests for comparison with the regulatory limits to answer these concerns.
- The time-course data obtained at 37°C supported the following conclusions: (1) no gas was produced from control samples lacking MicAN microbes; (2) at the high coal loading (2:1 coal-to-media), Knobloch coal produced a substantial 648.8 scf biogas/ton/year; (3) in the 1200 mL horizontal bioreactor, Knobloch coal produced a lesser but still significant 414 scf biogas /ton/year.
- ARCTECH's analysis of the nutrients contained in the proprietary growth media for MicAN compared with the Wyoming Department of Environmental Quality limits for hazardous substances in groundwater suggested that, while dilution in formation water was only one of various significant factors, a ten-fold or greater dilution of the injected media would allow



all nutrients to remain below regulatory limits. In such a case, the formation water composition would change minimally after injection of MicAN microbes and their media.

- **Progress Toward Commercialization:** In recent years the operation of gas wells in Wyoming, especially the CBM wells, has become commercially challenging due to the decrease in natural gas prices resulting from the “shale gas boom” now underway. Also the gas produced in Wyoming coal fields is remote and lack adequate transportation to the end users. Recently on December 11, 2013, Gov. Matt Mead of Wyoming announced a plan to plug more than 1,200 orphaned oil and gas wells within the next four years, in a dramatic expansion of the state's efforts to close abandoned wells. So industry is reluctant to take up any project now to expand only the gas production.

MicGAS™ Coal Biotechnology approach was selected by the SER for conducting its Techno-Economic Analysis for moving the Wyoming Coals up the value chain based on producing both clean fuels and organic humic products. This analysis included commercial potential of this in situ approach integrated with the applicability to mined coals for both production of biogas and organic humic products for use in agriculture and environmental sectors. This study considered that the biogas from both mined and from deep stranded coals will be further converted to aviation fuel, which is both higher value and can be transported by the existing infrastructure to the markets. It lends itself to a business model of “carbon and energy economics,” whereby clean fuels remain competitive even during falling gas and oil prices and the use of humic products yields a negative carbon footprint by distributing the technology costs and carbon utilization for both energy and non-energy products. ARCTECH is seeking to pursue advance this integrated technology approach of offering value generation approach of utilizing vast resources of coal in Wyoming and comply with increased mandates on coal use.