FINAL REPORT

JOINTLY SPONSORED RESEARCH PROGRAM ENERGY RELATED RESEARCH

Work Performed Under Cooperative Agreement
DE-FC26-98FT40323

For
U.S. Department of Energy, NETL

By
Western Research Institute

www.westernresearch.org

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Jointly Sponsored Research Program on Energy Related Research

Reporting Period: April 1998 – June 2009

September 2009

**Under Cooperative Agreement
DE-FC26-98FT40323**

**For
U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory
Morgantown, West Virginia**

**By
Western Research Institute
Laramie, Wyoming**

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ABSTRACT

Cooperative Agreement, DE-FC26-98FT40323, Jointly Sponsored Research (JSR) Program at Western Research Institute (WRI) began in 1998. Over the course of the Program, a total of seventy-seven tasks were proposed utilizing a total of \$23,202,579 in USDOE funds. Against this funding, cosponsors committed \$26,557,649 in private funds to produce a program valued at \$49,760,228.

The goal of the Jointly Sponsored Research Program was to develop or assist in the development of innovative technology solutions that will:

- Increase the production of United States energy resources – coal, natural gas, oil, and renewable energy resources;
- Enhance the competitiveness of United States energy technologies in international markets and assist in technology transfer;
- Reduce the nation's dependence on foreign energy supplies and strengthen both the United States and regional economies; and
- Minimize environmental impacts of energy production and utilization.

Under the JSR Program, energy-related tasks emphasized enhanced oil recovery, heavy oil upgrading and characterization, coal beneficiation and upgrading, coal combustion systems development including oxy-combustion, emissions monitoring and abatement, coal gasification technologies including gas clean-up and conditioning, hydrogen and liquid fuels production, coal-bed methane recovery, and the development of technologies for the utilization of renewable energy resources. Environmental-related activities emphasized cleaning contaminated soils and waters, processing of oily wastes, mitigating acid mine drainage, and demonstrating uses for solid waste from clean coal technologies, and other advanced coal-based systems. Technology enhancement activities included resource characterization studies, development of improved methods, monitors and sensors. In general the goals of the tasks proposed were to enhance competitiveness of U.S. technology, increase production of domestic resources, and reduce environmental impacts associated with energy production and utilization.

This report summarizes the accomplishments of the JSR Program.

EXECUTIVE SUMMARY

Cooperative Agreement, DE-FC26-98FT40323, Jointly Sponsored Research (JSR) Program at Western Research Institute (WRI) began in 1998. Over the course of the Program, a total of eighty two tasks were proposed for DOE approval. For various reasons beyond the task manager's control, on five of the eighty two tasks the work was never started and the tasks were later withdrawn. Over the ten year period of performance of the Cooperative Agreement, WRI has put in place projects utilizing a total of \$23,202,579 in USDOE funds. Against this funding, cosponsors have committed \$26,557,649 in private funds to produce a program valued at \$49,760,228. Tables 1 and 2 presented at the end of this section are a compilation of the funding for all the tasks conducted under the program. A breakdown of the funding in various program areas is graphically displayed in Figure 1.

Figure 1: Breakdown of Program Funding in Program Areas

The goal of the Jointly Sponsored Research Program was to through collaborative research with the industry, develop or assist in the development of innovative technology solutions that will:

- Increase the production of United States energy resources – coal, natural gas, oil, and renewable energy resources;
- Enhance the competitiveness of United States energy technologies in international markets and assist in technology transfer;
- Reduce the nation's dependence on foreign energy supplies and strengthen both the United States and regional economies; and
- Minimize environmental impacts of energy production and utilization.

Success of the Program can be measured by several criteria. Using the deployment of the federal funding with industrial participation, over the ten-year period of performance, the cosponsors contributed more dollars than the federal funds. Nearly 54% of the funding for the Program was derived from industrial partners. The industrial partners also enthusiastically supported the research and development activities with cash contribution. During the last five years of the agreement, industrial cash contribution averaged nearly 60% of the required cost share.

The ten-year Program ended on April 9, 2008. A no-cost extension was sought by WRI and granted through March 31, 2009. Work on all of the tasks has been completed. This report summarizes and highlights the results from the Program.

Under the JSR Program, energy-related tasks emphasized enhanced oil recovery, heavy oil upgrading and characterization, coal beneficiation and upgrading, coal combustion systems development including oxy-combustion, emissions monitoring and abatement, coal gasification technologies including gas clean-up and conditioning, hydrogen and liquid fuels production, coal-bed methane recovery, and the development of technologies for the utilization of renewable energy resources. Environmental-related activities emphasized cleaning contaminated soils and waters, processing of oily wastes, mitigating acid mine drainage, and demonstrating uses for solid waste from clean coal technologies, and other advanced coal-based systems. Technology enhancement activities included resource characterization studies, development of improved methods, monitors and sensors. In general the goals of the tasks proposed were to enhance competitiveness of U.S. technology, increase production of domestic resources, and reduce environmental impacts associated with energy production and utilization.

Technologies being brought to commercialization as a result of the funds provided by the Cooperative Agreement contribute to the overall goals of the USDOE and the nation. Each has broad applicability both within the United States and abroad, thereby helping to enhance the competitiveness of U.S. energy technologies in international markets and assisting in technology transfer.

Diesel Dog® has been used by the Wyoming Department of Environmental Quality (DEQ) to guide cleanup at a variety of sites throughout the state and the U.S. Army Corps of Engineers has used the technology at an abandoned FAA fuel-contaminated site in Alaska. TaBoRR (Tank Bottom Recovery and Remediation) was developed for cleaning up open pits in Wyoming, and will be utilized at used oil remediation sites and at motor oil remediation facilities. Similarly, WRITE (WRI's Thermal Enhancement) Process will be used to upgrade heavy oils in Canada. Working with our cosponsors, WRI is developing the design of a demonstration plant for a field upgrader based on the WRITE Processing concepts. The EnCore® sampler is the subject of ASTM Standard D-6418 and ASTM Standard D-4547. The Automated Flocculation Titrimeter (AFT) is a multipurpose instrument used to analyze asphalts and heavy oils and to acquire the data needed to employ WRI's patented Coking Index. Koehler Instrument Company of Bohemia, N.Y. manufactures and sells the AFTs. The instrument is used to perform ASTM D6703, Standard Test Method for Automated Heithaus Titrimetry. The units are being used by the petroleum refiners to assess the stability of oil blends. In scientific community, the units are being used to develop heavy oil and asphalt structural models. Working with KFx, Inc. and with Fuels Management Inc., WRI has assisted in the development of two different coal upgrading technologies. FMI technology is now being demonstrated at a nominal 100tpd size. Similarly, WRI's patented mercury removal technology developed and patented under the Base Program is being demonstrated with sponsorships from private industry and USDOE. A demonstration of this technology is also underway. Working with AeRock LLC, WRI has assisted in the

development of StoneDeck™ and other ash-based residential construction materials. In a related area, a flowable fill material (Ready-Fill™) is being marketed in conjunction with Montana-Dakota Utilities. Since September 2001, more than 300,000 gallons of liquids have been recovered from the Burnt Wagon Field in Wyoming and the cosponsor is devising methods to increase the gas rate from the remaining wells. In Egypt, WRI worked with TechLink and United Environmental to demonstrate technologies for the bioremediation of hydrocarbon contaminated sites. Bioremediation concepts developed at WRI being applied at several sites by well known remediation outfits such as Regensis and TetraTech. WRI entered into a development agreement with Novus Energy to demonstrate a synthesis technology to produce a mixture of alcohols from gaseous feedstock. Under the JSR program WRI has developed a patented catalyst formulation for the synthesis of mixed alcohols from syngas. WRI has similarly entered into a development agreement with several start-ups to demonstrate thermochemical biorefinery processes for ethanol production from cellulosic feedstock. If successful, similar technologies will someday convert coal into transportation-grade liquid fuels. Under the Cooperative Agreement, WRI developed gasification facilities that included three different gasifiers. A 7"-diameter fluidized bed gasifier has been used by several cosponsors to test sorbents and other gas-clean-up concepts. A unique, indirectly heated gasifier has been used to provide syngas for other systems testing. Working with USDA (ARS Corvallis), WRI developed and tested a unique gasification scheme for grass seed straw. The gasification facilities have also been used to support WRI's projects dealing with hydrogen production, development of water-gas shift catalysts and liquid-fuels synthesis technologies. A nominal 200 pph gasifier has been installed at a farm site near Spokane, WA for on-farm electricity production. Working with Pre-combustion Power Venture LLC, WRI acquired a Combustion Test Facility. The facility is now being used to support development of OxyCombustion technologies, to support development and testing of mercury capture technologies, to support development and testing of multi-pollutant control concepts, to test unique sorbents and sorbent injection configurations. Working with Mobotec, WRI demonstrated that Thief Carbon process WRI has developed unique devices for detecting halogenated hydrocarbons in soils and in water. One such device, X-Wand, was licensed to Bacharach Inc. WRI assembled a group of sub-bituminous coal producers, users, researchers and equipment manufacturers to monitor mercury emissions from coal-fired power plants. WRI is also working with EPRI and NIST to develop mercury calibration standards for emissions monitoring.

Table 1. DOE Funding for Tasks under Cooperative Agreement DE-FC26-98FT40323

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
00	Management Task			\$50,000								\$50,000
01	Koppelman "Series C" Process	\$800,000		\$600,000							\$3,631	\$1,403,631
02	Contained Recovery of Oily Wastes (CROW) Field Demonstration with Bell Lumber and Pole	\$27,864	\$23,000	\$32,400								\$83,264
03	Solid State NMR analysis of Mowry Formation Shale from Different Sedimentary Basins	\$20,000	\$15,000									\$35,000
04	The Use of TaBoRR as a Heavy Oil Upgrader		\$249,023									\$249,023
05	Validation of a New Soil VOC Sampler/Soil Samp	\$168,763	\$539,750	\$200,000	\$200,000	\$150,000	\$225,000	\$200,000	\$150,000	\$100,000	\$100,000	\$2,033,513
06	Market Assessment and Demonstration of Lignite FBC Ash Flowable Fill Applications	\$39,346	\$179,160									\$218,506
07	Fiddler Creek Polymer Augmentation Project	\$279,000	\$212,021								\$3,355	\$494,376
08	The Development of Synthetic Soil Materials for Successful Reclamation of Abandoned Mined Lands Sites	\$139,717	\$191,000	\$71,078		\$125,000						\$526,795
09	Fuels in Soil Test Kit		\$199,995	\$75,000	\$100,000							\$374,995
10	SYN-AG Process Demonstration and Product Acceptance Verification	\$232,928									\$2,411	\$235,339
11	Optimization of a Hydrocarbon Extraction Process for the Development of Utah Tar Sands	\$4,899										\$4,899
12	Value Added Products from Remote Natural Gas		\$108,216	\$450,000	\$182,034	\$211,653	\$53,851				\$1,099	\$1,006,853
13	Testing of FMI's Coal Upgrading Process		\$75,000		\$75,000		\$75,000		\$50,000	\$50,000		\$325,000
14	Ash-Based Grout Injection fro Subsidence Control at Shamrock Mine		\$83,329	\$125,999	\$140,895	(\$140,000)						\$210,223
15	The Use of Haz-Flote to Efficiently Remove Mercury from Contaminated Materials		\$60,000									\$60,000
16	Injection Profile Modification in a Hot, Dep Minnelusa Water Injection Project		\$153,000								\$12,805	\$165,805
17	PFBC Ash Management Evaluations and Demonstration		\$199,955									\$199,955
18	Fort Union Deep		\$173,237	\$171,763	\$80,000						\$5,918	\$430,918
19	The Potential of Reclaimed Lands to Sequester Carbon and Mitigate the Greenhouse Effect		\$200,000	\$137,953	\$159,115							\$497,068
20	Water Shut-Off Treatment in a Highly Fractured Sandstone Reservoir		\$111,690									\$111,690
21	Evaluation of Combined Biocatalytic and Hydrodesulfurization of Fuel Oils			\$92,000								\$92,000
22	Test of PEFI's Alcohol Process			\$200,000	\$345,000	\$147,000						\$692,000
23	SYN-AG Technology Applications			\$135,994	\$169,577	(\$112,000)						\$193,571
24	Ash-Based Panels Production According to AeRock Process				\$219,500	\$175,000						\$394,500

Table 1. DOE Funding for Tasks under Cooperative Agreement DE-FC26-98FT40323 (Contd.)

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
25	Bioremediation of Petroleum Hydrocarbon Contaminated Sites				\$431,791	\$207,000	\$250,000					\$888,791
26	Improved Fisher-Tropsch Slurry Reactions				\$160,000							\$160,000
27	Evaluation and Development of the PureVision Biorefining Technology				\$110,000	\$550,000	\$175,000					\$835,000
28	Preliminary Assessment of the TaBoRR Process and the Stability and Compatibility of Its Product				\$85,000							\$85,000
29	Management and Development of the Western Resources Project				\$50,000	\$65,000	\$15,000					\$130,000
30	Assessment of the Environmental Impacts of Coalbed Methane Development in the Powder River Basin					\$75,000	\$200,000	\$150,000			\$15,000	\$440,000
31	Emissions, Monitoring and Control of Mercury from Subbituminous Coal-Fired Power Plants					\$171,904			\$193,480		\$1,842	\$367,226
32	Combustion Characteristics of K-Fuel					\$200,000						\$200,000
33	Development of Enhanced Remedial Techniques for Petroleum Fuel and Related Contaminants in Soil and Groundwater						\$45,000					\$45,000
34	Removal of Mercury from Gaseous Streams Using Non-Thermal Plasmas					\$200,000	\$200,000					\$400,000
35	Bioremediation of Petroleum Hydrocarbon in Heterogeneous Soils -- Phase I -- Bench Studies and Base Model Establishment					\$60,000						\$60,000
36	Development of Solubility Product Visualization Tools					\$10,000						\$10,000
37	Combination Reforming of Methane/Carbon Dioxide Mixtures to Produce Synthesis Gas for Conversion to Fuels						\$100,000					\$100,000
38	Thermal Precombustion Mercury Removal Process for Low-Rank Coal-Fired Power Plants						\$492,182	\$35,930	\$40,000		\$13,681	\$581,793
39	Production of Substitute Natural Gas from Coal						\$200,000	\$50,000				\$250,000
40	Control and Treatment of Production Facilities VOC Emissions						\$175,000	\$22,000				\$197,000
41	Coal Cleaning Using Resonance Disintegration for Mercury and Sulfur Reduction Prior to Combustion						\$50,000					\$50,000
42	More Efficient, Clean Energy Generation for a Sugar Beet Processing Plant -- An Economic Evaluation						\$15,000					\$15,000
43	Evaluation of Nanoactive Sorbent Materials for the Treatment of Coal-Derived Synthesis Gas						\$28,470					\$28,470

Table 1. DOE Funding for Tasks under Cooperative Agreement DE-FC26-98FT40323 (Contd.)

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
44	In-situ Treatment of Acid Mine Drainage Using a Bio-Organic Oxygen Elimination Treatment						\$175,000	\$131,000		\$150,000	\$220,000	\$676,000
45	Photonic Measurements for Correlations to Traditional Coal Isotherms						\$100,000					\$100,000
46	Novel Low-Cost Process for the Gasification of Biomass and Low-Rank Coals						\$100,000	\$60,000			\$50,000	\$210,000
47	Development of Sodium Adsorption Ration Standards for Mine Soil Reconstruction						\$45,000	\$44,500	\$10,000			\$99,500
48	Evaluation of Raphite as a NOx Reduction Catalyst in a Coal-Fired Boiler							\$40,000				\$40,000
49	Reduction of Nox Emissions from coal Combustion Through Oxygen Enrichment							\$40,000				\$40,000
50	Development of Solubility Measurement Methodology							\$13,043				\$13,043
51	WRITE Process for Pipeline Ready Heavy Oil							\$393,817	\$275,515	\$280,766	\$228,500	\$1,178,598
52	Innovative Protocols for In-Situ MTBE Degradation by Using Molecular Probes -- An Enhanced Chemical-Bio Oxidation Technique							\$40,000	\$50,000			\$90,000
53	Optimization of Trona/Limestone Injection for SO2 Control in Coal-fired Boilers							\$40,000				\$40,000
54	Biodegradation of BTEX and Other Petroleum Hydrocarbons by Enhanced and Controlled Sulfate Reduction							\$75,000				\$75,000
55	Evaluation of Biomass and Coal Slurries as Fuel Lean Reburn Fuels							\$55,000				\$55,000
56	Development of a Novel Oxygen Supply Process and Its Integration with an Oxy-Fuel Coal-Fired Boiler							\$340,000	\$60,000			\$400,000
57	Production of Ethanol-Based Fuel from Natural Gas??							\$320,000	\$225,000	\$200,000	\$815,334	\$1,560,334
58	Mercury Calibration System							\$75,000				\$75,000
59	VOC Destruction by Catalytic Combustion Micro-Turbine							\$125,000				\$125,000
60	Advanced Oxidation Technologies in Treating MTBE and Gasoline Contaminants							\$61,000				\$61,000
61	Production of Lignin from Animal Bio-Wastes for Use as an Antioxidant in Asphalt Pavement											\$0
62	Mercury CEM Calibration							\$75,000		\$245,000	\$150,000	\$470,000
63	Elimination of Organic Contaminants in water by Separation/Oxidation											\$0
64	Novel Integrated Process to Produce Fuels from Coal and Other Carbonaceous Feedstocks								\$340,000			\$340,000

Table 1. DOE Funding for Tasks under Cooperative Agreement DE-FC26-98FT40323 (Contd.)

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
65	Evaluation of BOC's LOTOX Process for the Oxidation of Elemental Mercury in Flue Gas from a Coal-Fired Boiler								\$70,000			\$70,000
66	HVOC Field Screening								\$175,000			\$175,000
67	Installation of ROFA/ROTAMIX System and Chlorine Injection Testing in Combustion Test Facility								\$60,000	\$100,000		\$160,000
68	Co-Remediation of Petroleum Hydrocarbon, Metals and Elevated Sulfate/Sulfide in Groundwater											\$0
69	Enhanced Microbial Pathways for Methane Production from Oil Shale								\$100,000	\$70,000	(\$5,000)	\$165,000
70	Microbiological Study of Biodegradation of Petroleum Hydrocarbons and Pentachlorophenol in Groundwater								\$50,000		\$3,093	\$53,093
71	Assessments of Environmental Impacts and Beneficial Use of Coalbed Methane Produced Water in the Powder River Basin								\$55,000			\$55,000
72	Use of Advanced Oxidation and Aerobic Degradation for Remediation of Various Hydrocarbon Contaminants								\$200,000			\$200,000
73	Oil Reservoir Tracers Development									\$125,000	\$125,000	\$250,000
74	Corrosion Effects of Calcium Chloride Injection for Mercury Control on the Pollution Control Equipment									\$50,000		\$50,000
75	Novel Sorption/Desorption Process for Carbon Dioxide Capture (Feasibility Study)									\$50,000		\$50,000
76	Evaluation of Oil Shale's Multi-Pollutant Reduction Capabilities									\$150,000		\$150,000
77	Pilot-Scale Demonstration of Cowboy Coal Upgrading Process										\$550,000	\$550,000
78	Improving Asphalt Performance by the Addition of Lignin as an Antioxidant											
79	Pilot Testing of WRI's Novel Mercury Control Technology by Pre-Combustion Thermal Treatment of Coal										\$523,807	\$523,807
80	Novel Fixed-Bed Gasifier for Wyoming Coals											
81	Development of a Thermal Oxidizer for Distributed Micro Turbine-Based Generation										\$110,000	\$110,000
82	Evaluation of Membrane-Based Treatment Process for Desalination of Produced Water from Oil Production										\$60,000	\$60,000
	TOTAL	\$1,712,517	\$2,773,376	\$2,342,187	\$2,507,912	\$2,095,557	\$2,719,503	\$2,386,290	\$2,103,995	\$1,570,766	\$2,990,476	\$23,202,579

Table 2. Cosponsor Contributions for Tasks under Cooperative Agreement DE-FC26-98FT40323

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
00	Management Task											\$0
01	Koppelman "Series C" Process	\$1,350,000	\$0	\$787,300								\$2,137,300
02	Contained Recovery of Oily Wastes (CROW) Field Demonstration with Bell Lumber and Pole	\$27,864	\$32,727	\$32,727								\$93,318
03	Solid State NMR analysis of Mowry Formation Shale from Different Sedimentary Basins	\$20,000	\$15,000									\$35,000
04	The Use of TaBoRR as a Heavy Oil Upgrader		\$300,000									\$300,000
05	Validation of a New Soil VOC Sampler/Soil Samp	\$168,763	\$540,000	\$200,000	\$200,000	\$150,000	\$225,000	\$200,000	\$150,000	\$100,000	\$100,000	\$2,033,763
06	Market Assessment and Demonstration of Lignite FBC Ash Flowable Fill Applications	\$39,346	\$179,215									\$218,561
07	Fiddler Creek Polymer Augmentation Project	\$350,000	\$400,000									\$750,000
08	The Development of Synthetic Soil Materials for Successful Reclamation of Abandoned Mined Lands Sites	\$139,717	\$191,000	\$95,000		\$125,000						\$550,717
09	Fuels in Soil Test Kit		\$200,000	\$75,000	\$100,000							\$375,000
10	SYN-AG Process Demonstration and Product Acceptance Verification	\$232,928										\$232,928
11	Optimization of a Hydrocarbon Extraction Process for the Development of Utah Tar Sands											\$0
12	Value Added Products from Remote Natural Gas		\$125,000	\$450,000	\$208,000	\$250,000	\$60,000					\$1,093,000
13	Testing of FMI's Coal Upgrading Process		\$75,000		\$75,000		\$75,000		\$50,000	\$50,000		\$325,000
14	Ash-Based Grout Injection fro Subsidence Control at Shamrock Mine		\$83,420	\$126,000	\$141,000							\$350,420
15	The Use of Haz-Flote to Efficiently Remove Mercury from Contaminated Materials		\$81,995									\$81,995
16	Injection Profile Modification in a Hot, Dep Minnelusa Water Injection Project		\$405,500									\$405,500
17	PFBC Ash Management Evaluations and Demonstration		\$200,000									\$200,000
18	Fort Union Deep		\$267,000	\$264,728	\$80,000							\$611,728
19	The Potential of Reclaimed Lands to Sequester Carbon and Mitigate the Greenhouse Effect		\$200,000	\$137,953	\$160,000							\$497,953
20	Water Shut-Off Treatment in a Highly Fractured Sandstone Reservoir		\$118,400									\$118,400
21	Evaluation of Combined Biocatalytic and Hydrodesulfurization of Fuel Oils			\$92,000								\$92,000
22	Test of PEF's Alcohol Process			\$800,000	\$345,000	\$136,000						\$1,281,000
23	SYN-AG Technology Applications			\$135,994	\$170,000							\$305,994
24	Ash-Based Panels Production According to AeRock Process				\$219,500	\$175,000						\$394,500

Table 2. Cosponsor Contributions for Tasks under Cooperative Agreement DE-FC26-98FT40323 (contd.)

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
25	Bioremediation of Petroleum Hydrocarbon Contaminated Sites				\$431,791	\$225,000	\$300,000					\$956,791
26	Improved Fisher-Tropsch Slurry Reactions				\$160,000							\$160,000
27	Evaluation and Development of the PureVision Biorefining Technology				\$110,000	\$631,000	\$375,000					\$1,116,000
28	Preliminary Assessment of the TaBoRR Process and the Stability and Compatibility of Its Product				\$92,324							\$92,324
29	Management and Development of the Western Resources Project				\$60,000	\$75,000	\$75,000					\$210,000
30	Assessment of the Environmental Impacts of Coalbed Methane Development in the Powder River Basin					\$75,000	\$200,000	\$150,000				\$425,000
31	Emissions, Monitoring and Control of Mercury from Subbituminous Coal-Fired Power Plants					\$171,904			\$193,480			\$365,384
32	Combustion Characteristics of K-Fuel					\$200,000						\$200,000
33	Development of Enhanced Remedial Techniques for Petroleum Fuel and Related Contaminants in Soil and Groundwater					\$0	\$80,000					\$80,000
34	Removal of Mercury from Gaseous Streams Using Non-Thermal Plasmas					\$200,000	\$200,000					\$400,000
35	Bioremediation of Petroleum Hydrocarbon in Heterogeneous Soils -- Phase I -- Bench Studies and Base Model Establishment					\$60,000						\$60,000
36	Development of Solubility Product Visualization Tools					\$13,043						\$13,043
37	Combination Reforming of Methane/Carbon Dioxide Mixtures to Produce Synthesis Gas for Conversion to Fuels						\$100,000					\$100,000
38	Thermal Precombustion Mercury Removal Process for Low-Rank Coal-Fired Power Plants						\$528,112		\$40,000			\$568,112
39	Production of Substitute Natural Gas from Coal						\$200,000	\$200,000				\$400,000
40	Control and Treatment of Production Facilities VOC Emissions						\$185,000	\$22,000				\$207,000
41	Coal Cleaning Using Resonance Disintegration for Mercury and Sulfur Reduction Prior to Combustion						\$50,000					\$50,000
42	More Efficient, Clean Energy Generation for a Sugar Beet Processing Plant -- An Economic Evaluation						\$15,000					\$15,000
43	Evaluation of Nanoactive Sorbent Materials for the Treatment of Coal-Derived Synthesis Gas						\$28,470					\$28,470

Table 2. Cosponsor Contributions for Tasks under Cooperative Agreement DE-FC26-98FT40323 (contd.)

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
44	In-situ Treatment of Acid Mine Drainage Using a Bio-Organic Oxygen Elimination Treatment						\$175,000	\$131,000		\$150,000	\$220,000	\$676,000
45	Photonic Measurements for Correlations to Traditional Coal Isotherms						\$100,000					\$100,000
46	Novel Low-Cost Process for the Gasification of Biomass and Low-Rank Coals						\$100,000	\$60,000			\$50,000	\$210,000
47	Development of Sodium Adsorption Ration Standards for Mine Soil Reconstruction						\$45,000	\$44,500	\$10,000			\$99,500
48	Evaluation of Raphite as a NOx Reduction Catalyst in a Coal-Fired Boiler							\$40,000				\$40,000
49	Reduction of Nox Emissions from coal Combustion Through Oxygen Enrichment							\$40,000				\$40,000
50	Development of Solubility Measurement Methodology							\$13,043				\$13,043
51	WRITE Process for Pipeline Ready Heavy Oil							\$309,529	\$165,000	\$715,579	(\$11,500)	\$1,178,608
52	Innovative Protocols for In-Situ MTBE Degradation by Using Molecular Probes -- An Enhanced Chemical-Bio Oxidation Technique							\$40,000	\$50,000			\$90,000
53	Optimization of Trona/Limestone Injection for SO2 Control in Coal-fired Boilers							\$40,000				\$40,000
54	Biodegradation of BTEX and Other Petroleum Hydrocarbons by Enhanced and Controlled Sulfate Reduction							\$75,000				\$75,000
55	Evaluation of Biomass and Coal Slurries as Fuel Lean Reburn Fuels							\$55,000				\$55,000
56	Development of a Novel Oxygen Supply Process and Its Integration with an Oxy-Fuel Coal-Fired Boiler							\$340,000	\$60,000			\$400,000
57	Production of Ethanol-Based Fuel from Natural Gas??							\$500,000	\$225,000	\$200,000	\$663,834	\$1,588,834
58	Mercury Calibration System							\$75,000				\$75,000
59	VOC Destruction by Catalytic Combustion Micro-Turbine							\$125,000				\$125,000
60	Advanced Oxidation Technologies in Treating MTBE and Gasoline Contaminants							\$61,000				\$61,000
61	Production of Lignin from Animal Bio-Wastes for Use as an Antioxidant in Asphalt Pavement											\$0
62	Mercury CEM Calibration							\$75,000		\$245,000	\$150,000	\$470,000
63	Elimination of Organic Contaminants in water by Separation/Oxidation											0
64	Novel Integrated Process to Produce Fuels from Coal and Other Carbonaceous Feedstocks								\$340,000			\$340,000

Table 2. Cosponsor Contributions for Tasks under Cooperative Agreement DE-FC26-98FT40323 (contd.)

Task	Title	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10	Total
65	Evaluation of BOC's LOTOX Process for the Oxidation of Elemental Mercury in Flue Gas from a Coal-Fired Boiler								\$70,000			\$70,000
66	HVOC Field Screening								\$175,000			\$175,000
67	Installation of ROFA/ROTAMIX System and Chlorine Injection Testing in Combustion Test Facility								\$60,000	\$100,000		\$160,000
68	Co-Remediation of Petroleum Hydrocarbon, Metals and Elevated Sulfate/Sulfide in Groundwater											\$0
69	Enhanced Microbial Pathways for Methane Production from Oil Shale								\$125,000	\$70,000	(\$5,000)	\$190,000
70	Microbiological Study of Biodegradation of Petroleum Hydrocarbons and Pentachlorophenol in Groundwater								\$50,000			\$50,000
71	Assessments of Environmental Impacts and Beneficial Use of Coalbed Methane Produced Water in the Powder River Basin								\$255,000			\$255,000
72	Use of Advanced Oxidation and Aerobic Degradation for Remediation of Various Hydrocarbon Contaminants								\$200,000			\$200,000
73	Oil Reservoir Tracers Development									\$125,000	\$125,000	\$250,000
74	Corrosion Effects of Calcium Chloride Injection for Mercury Control on the Pollution Control Equipment									\$152,268		\$152,268
75	Novel Sorption/Desorption Process for Carbon Dioxide Capture (Feasibility Study)									\$50,000		\$50,000
76	Evaluation of Oil Shale's Multi-Pollutant Reduction Capabilities									\$150,000		\$150,000
77	Pilot-Scale Demonstration of Cowboy Coal Upgrading Process										\$551,195	\$551,195
78	Improving Asphalt Performance by the Addition of Lignin as an Antioxidant											
79	Pilot Testing of WRI's Novel Mercury Control Technology by Pre-Combustion Thermal Treatment of Coal										\$526,000	\$526,000
80	Novel Fixed-Bed Gasifier for Wyoming Coals											
81	Development of a Thermal Oxidizer for Distributed Micro Turbine-Based Generation										\$110,000	\$110,000
82	Evaluation of Membrane-Based Treatment Process for Desalination of Produced Water from Oil Production										\$60,000	\$60,000
	Total	\$2,328,618	\$3,414,257	\$3,196,702	\$2,552,615	\$2,486,947	\$3,116,582	\$2,596,072	\$2,218,480	\$2,107,847	\$2,539,529	\$26,557,649

WRI JSR Program supported the development of energy and environment-related technologies consistent with DOE priorities. Individual tasks addressed the needs of coal, oil and gas, and biomass-based energy systems.

Under the Cooperative Agreement, WRI has built a modular, well-instrumented coal combustion test facility that mimics a coal-fired utility boiler in residence time and furnace temperature profile. This facility is being used for technology development and technology verification projects for national and international utilities, for coal technology companies, and for combustion and emissions control equipment manufacturers.

- working with our clients, we are testing new and cheaper methods for reducing NO_x emissions such as injection of coal and biomass-based slurries, injection of hydrogen and syngas, injection of ozone;
- working with our clients, we are testing cheaper sorbents and methods for capturing mercury. One such scheme reinjects the unburnt carbon recovered from the fireball of the boiler to capture mercury. This technology, thief carbon, can reduce the cost of mercury capture to a fraction of that for conventional activated carbon. Thanks to our cooperative agreement with the USDOE, the thief carbon WRI made in the CTF was recently injected by a utility in a 600MW unit to show that indeed thief carbon is nearly as effective as activated carbon;
- working with our clients we are testing advanced combustion concepts such as oxy-fuel combustion as a multi-pollutant control strategy for not only the sequestration-ready, power plants of the future but developing a technology that can benefit our existing fleet of power plants; and
- working with our clients, we are looking to the future and testing cheaper ways of making oxygen. Novel concepts for separating oxygen from air for use in the coal combustion processes are being tested at the combustion test facility.

Under the Cooperative Agreement, WRI has been developing synthesis technologies to produce transportation fuels. One such technology can convert any carbonaceous feedstock into a mixture of alcohols, and the mixture is ready for use as a gasoline blend.

- Imagine a confined animal feedlot. Animal waste is collected and processed in biogas digesters. Using the technology being demonstrated by WRI and partners, the digester gas becomes a mixture of alcohols for use in our cars, a transportation fuel.
- Imagine a remote abandoned natural gas field. Using the technology being demonstrated, this field can make transportation fuel that can be trucked to the markets.
- Imagine a biorefinery where forestry waste, animal waste, agricultural waste is processed using the technology developed at WRI to convert these renewable feedstock into transportation fuel.
- Imagine a power plant where Wyoming coal is the feed. Using the technology developed at WRI under the Cooperative Agreement, the plant not only produces electricity but also synthesizes a mixture of alcohols.

In conjunction with the appropriate gasification scheme this synthesis technology is a coal-to-liquids technology. In the same spirit, for remote natural gas fields this technology is a gas-to-liquid technology. As a biogas-based system, this technology is a means of capturing and converting green house gasses into a useful product.

Under the auspices of the Cooperative Agreement, WRI is developing and testing unique, low-cost biomass gasification technologies for smaller-scale, distributed power generation

applications. At WRI, we believe that our Nation's farmers and renewable energy are an essential part of our energy future. Technologies for distributed power generation and distributed production of synthetic fuels and chemicals from renewable resources have been an integral part of research under the Cooperative Agreement.

Under the auspices of the Cooperative Agreement, WRI addressed issues pertaining to upgrading of Western US low-rank coals. Technologies were developed to produce upgraded coals with some of the pollutants removed from the coal matrix before their use in the utility boilers.

- WRI developed and patented a process for upgrading PRB coal by thermally removing mercury prior to combustion at the power plant, thus eliminating the need for costly carbon injection to meet new mercury regulations. A recent economic study for the Electric Power Research Institute has shown this process to be one of the lowest-cost technologies for removing mercury from PRB coal-fired power plants.
- WRI assisted FMI with the development of its patented coal upgrading technology. This unique technology uses air-blown fluidized bed to dry and stabilize the coals whereby all the energy required comes from the coal itself. The technology is near-ready for commercialization and a 100 tpd pilot facility erected at the WRI's Advanced technology Center is being used to qualify the product for utilities.
- WRI's participation was key to the development of KFx technology for coal upgrading. Over the past eight years, the technology has been through three large-scale demonstrations.

Under the auspices of the Cooperative Agreement, WRI has developed a patented Thermal Enhancement (WRITE) process for heavy oil upgrading. The process a variant of the TaBoRR technology developed under the Base Program, converts bitumen (e.g. heavy oil, oil sands) into residuum-free oil whose density and viscosity meets pipeline specifications. With the co sponsorship of a Canadian company, the WRITE technology and is being readied for a commercial-scale demonstration plant. When deployed, the technology will reduce our dependence on oil shipments from unstable parts of the world.

In Wyoming, CBM produced water-related environmental issues are paramount in developing this resource. Under the Cooperative Agreement, WRI worked with producers to demonstrate beneficial agricultural and related uses for this precious water.

WRI has taken a lead role in policy support for air quality regulations by creating and facilitating the Subbituminous Energy Coalition (SEC). The organization's approximately 50 members represent the major coal companies in the Powder River Basin, utilities burning PRB coal, railroads serving the PRB, and other interested parties. The SEC provides a forum for industry discussions on environmental control issues and provides a collective voice for PRB coal producers and users. The SEC has orchestrated a detailed review of proposed EPA mercury rules to ensure that subbituminous coal remains an environmentally acceptable and competitive fuel source. Looking to the future, SEC is poised to tackle CO₂ emissions and related issues.

Under the Cooperative Agreement, WRI has developed value-added uses for power plant coal combustion by-products. Use of these materials for applications such as mine-site subsidence control, soil amendment, acid mine drainage mitigation, and construction were developed and tested.

Environmental consequences of energy and fuels production are paramount in our research programs. Under the auspices of the Cooperative Agreement, WRI scientists are developing and testing site-specific bio-remediation technologies for restoring contaminated soils and water.

WRI has developed or made significant contributions to several environmental testing and sampling instruments currently (or soon to be) commercially available. Examples include Soil Test Kit for in-the-field quantitative analysis of hydrocarbon contaminants in soil, integrated storing field soil samples for volatile analysis, and the X-Wand, an instrument for measuring halogenated volatile organic compounds, a common but difficult to measure class of contaminants. All three are commercially available.

Researchers at NETL developed the Thief Process that extracts partially burned coal from a pulverized coal-fired combustor using a suction pipe, or "thief," and injects the resulting sorbent into the flue gas to capture the mercury. The process greatly reduces the costs of removing mercury by using already existing coal rather than expensive activated carbon. The process can prevent 90 percent of the mercury from reaching the atmosphere, thereby making the air safer for people and generating clean energy from domestic coal. When NETL licensed the technology to Nalco Mobotec of Orinda, Calif., WRI assisted Nalco Mobotec with the independent evaluation not only in the WRI's Combustion Test Facility but by making sufficient quantities of "thief" carbon for testing at a utility boiler.

Looking to the future, WRI is continuing to implement an ambitious research and technology demonstration agenda under the new five-year Cooperative Agreement. With the establishment of the state-supported University of Wyoming School of Energy Resources, there is an opportunity for collaborative research between the University faculty and WRI staff. Collaborative research will also allow us to add an education and training component to our Cooperative Agreement projects thereby meeting our demand for trained energy professionals.

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BACKGROUND

Cooperative Agreement, DE-FC26-98FT40323, Jointly Sponsored Research (JSR) Program at Western Research Institute (WRI) began in 1998. The objective of the JSR Program was to conduct both fundamental and applied research that will assist industry in developing, deploying, and commercializing efficient, nonpolluting fossil energy technologies that can compete effectively in meeting requirements for clean fuels, chemical feedstocks, electricity, and water resources in the 21st century. WRI is located in Wyoming, the Btu capitol of the United States. For almost 25 years, WRI's proximity to the energy resources in the Western United States has given its management and staff a heightened sense of responsibility and purpose in how it conducts business and sets direction. WRI remains closely aligned with DOE objectives of secure and reliable energy; clean power generation; development of hydrogen resources; energy efficiency and development of innovative fuels from low and no-cost sources.

The Program supports and contributes to the energy science and technology mission of DOE/Fossil Energy:

- Increase the production of U.S. energy resources
- Enhance the competitiveness of U.S. technologies
- Reduce dependence on foreign energy supplies and strengthen National and regional economies, and
- Minimize environmental impacts of energy production and utilization processes.

The goal of the Program has been to develop, commercialize, and deploy technologies of value to the nation's fossil energy industry. To ensure relevancy and early commercialization, the involvement of an industrial partner was encouraged, requiring at least 50% non-Federal cost-share.

The projects propose under the JSR Program covered three major areas:

1. *Energy Program* - Activities under this program emphasized energy independence through increased production and use of domestic energy resources and include enhanced oil recovery; heavy oil upgrading; recovery of value-added products from abandoned gas fields; development of gas-to-liquid technologies; coal beneficiation, upgrading and use; enhanced coalbed methane recovery; development of technologies for the production of hydrogen and other alternative fuels from fossil fuels; development and verification of technologies for the development of unconventional resources; and the development of renewable energy resources, primarily based on biomass.
2. *Environmental Program* - Activities under this program were designed to minimize the impact of energy production and enhance the use of U.S. and subbituminous western coals, oil and gas, and coalbed methane resources. Efforts will focus on technologies and technical services for mitigation of hazardous air pollutants (HAPs) emission such as mercury, arsenic, selenium from coal-fired power plants; use of coal combustion and

conversion by-products in novel applications; mitigation of the impact of produced waters from the coalbed methane development; re-vegetation of abandoned mine lands through the development of synthetic soils; bioremediation of oil contaminated materials; assessment of environmental issues relative to unconventional and renewable resources development.

3. *Technology Enhancement and Technology Transfer* - Activities under this area were meant to refine or add to the current technologies to minimize the environmental impacts and/or improve the efficiency of energy production processes. Efforts were devoted to the development and improvement of environmental monitors and sensors, resource and predictive models, and process controls.

Over the course of the Program, a total of eighty two tasks were proposed for DOE approval. For various reasons beyond the task manager's control, on five of the eighty two tasks (Tasks 11, 61, 63, 68, and 78 in Tables 1 and 2 displayed earlier in this report) the work was never started and the tasks were later withdrawn. Over the ten year period of performance of the Cooperative Agreement, WRI has put in place projects utilizing a total of \$23,202,579 in USDOE funds. Against this funding, cosponsors committed \$26,557,649 in private funds to produce a program valued at \$49,760,228. Figure 2 shows the year-by-year expenditures of the USDOE funds over the course of the program. The figure also includes a red bar representing the total cost share over the term of the Cooperative Agreement. As we prepare to close this Cooperative Agreement, the financial records show that actual cosponsor contributions exceeded the commitments by nearly five million dollar, a testament to the success of the Program.

Figure 2: Cumulative Funding over the course of the JSR Cooperative Agreement

This report summarizes the accomplishments of the overall JSR Program. This document represents a stand-alone Final Report for the entire Program. It should be noted that topical reports describing the work concluded under individual tasks were prepared and submitted on a task-by-task basis as warranted.

In order to portray a cohesive picture of the work performed under this Program, in this report we have combined the discussion of various tasks. This approach also preserves the confidentiality of our cosponsors yet allowing us to disseminate as much information as possible.

RESEARCH HIGHLIGHTS

CROW™ Technology Demonstration at Bell Lumber and Pole

Task 02 – CROW Field Demonstration

Under previous Cooperative Agreements, WRI developed an in-situ remediation technology, Contained Recovery of Oily Wastes, CROW™. The patented process is an in-situ thermal flushing process that reduces concentrations of oily wastes in subsurface soils, aquifers, and underlying bedrock to residual saturations, thereby immobilizing them.

Because it uses steam and hot water to extract contaminants, such as coal tar, creosote, and petroleum products, directly from the ground, the CROW™ process eliminates the need for excavation, minimizing disturbance to the site and reducing costs. Further economy is achieved when recovered organic stock is reused or sold. The technology had been successfully applied at two former manufactured gas plants (MGPs). Under Task 02, the technology demonstration was conducted at a large wood treatment site. The actual work on this site began in 1995 under a previous Cooperative Agreement and continued through 2001. During the demonstration, 25,502,902 gallons of hot water was injected and 83,155 gallons of organics was recovered from the contaminated area. A large of the material recovered was reused to partially offset the cost of remediation.

CROW Facilities at Bell Lumber and Pole

Coal Upgrading Technology Developments

Task 01 – Koppelman “Series C” Process

Tasks 13 & 77 – Testing of FMI’s (Cowboy) Coal Upgrading Process

Tasks 38 & 79 – Thermal Pre-Combustion Mercury Removal Process

There are four primary types of coal. Anthracite, bituminous, subbituminous, and lignite, all four types of these coals principally contain carbon, hydrogen, nitrogen, oxygen, and sulfur, as well as moisture. However, actual concentrations of these elements and moisture vary widely from rank-to-rank. For example, anthracite, the highest ranking coals contain about 98 % carbon, while lignite, the lowest ranking coals may only contain about 30 % carbon. The amount of moisture in anthracite and bituminous coals can be less than 1%, but for subbituminous and lignite coals the moisture content can be in the 25 – 40%, range. The high-moisture subbituminous and lignite coals have lower heating values and their high moisture content adversely affects coal-fired power plant performance and emissions. High moisture content results in significantly lower boiler efficiencies and higher unit heat rates. The high moisture content of the coal can also raise fuel handling, transportation and fuel preparation issues.

Eighty-nine percent of the coal mined in the US is used for electricity production. Bituminous coals have been the most widely used rank of coal because of their abundance and relatively high heating value. However, these coals contain high levels of sulfur. Low-rank coals account for about 50% of coal reserves and their use is limited due to low heating value and concerns regarding spontaneous combustion. Many of the low-rank coals, however, contain lower sulfur and lower ash than the bituminous coals. So if these coals could be efficiently and economically processed to yield a higher-grade, high-heating value product, there will be a beneficial impact not only on the energy supply side but also on the environmental side as well. A successful coal upgrading process has to be economical and address the issues of spontaneous combustion, decrepitation, and equilibrium moisture.

The most recent challenge for low-rank coal use is mercury emissions. These coals are comparatively high in their mercury content and are threatened to lose their market share. Under the auspices of the JSR Cooperative agreement WRI worked on the development and testing of three different coal upgrading technologies. All three technologies involve thermal processing to produce an upgraded product which is higher in Btu content than the parent coal and concomitantly reduced in the mercury and other volatile contaminant content. Reductions achieved are obviously determined by the detailed processing parameters.

Under the Cooperative Agreement Programs, WRI’s support for the development of Koppelman process began in the late 1980s. Under previous cooperative agreements, WRI staff worked with Mr. Koppelman to perform bench and pilot-scale development of the coal drying technology. K-Fuel technology uses heat and pressure to dry and clean up raw coal so that the product has fewer emissions when burned in power plants. Under the JSR Program, in collaboration with the staff

from Rio Tinto, WRI supported the development and successful testing of a semi-continuous batch reactor. Testing performed demonstrated that processing at lower pressures and lower temperatures yield less dusty and stronger product.

Development of the FMI coal upgrading technology was partially supported by the Cooperative Agreement. The FMI technology involves coal-drying in an air-blown bubbling fluidized bed. Over a period of nearly seven years with the JSR funding support the technology has been brought to a near-commercial scale. A nominal 100-tons per day test facility has been constructed and operational at the WRI's Advanced Technology Center. Coals received from several Western US mines in the Powder River Basin and from Alaska and Indonesia have been run through the FMI facilities at WRI to demonstrate universal applicability of the process. The facility is presently being used to produce large quantities of processed coal to demonstrate product stability and pyrophobicity. Large batches of product are also being shipped to utilities and industrial coal users to establish handling and combustion characteristics of the product.

Under a previous Cooperative Agreement, WRI developed and patented a thermal precombustion mercury removal technology (WRItc Coal). Under the auspices of this cooperative agreement a pilot facility was constructed to optimize the subsystems for the process. The mercury removal technology processes the coal in two distinct steps to first remove the water from coal and then through further heating, mercury and other coal-based contaminants are removed. The technology was one of the twelve selected by DOE under Phase III Mercury Control Technology Field Testing and Related Mercury Control Research and Development.

Combustion tests have been performed using all three upgraded products to confirm the beneficial environmental impact on mercury emissions reduction. Tests performed with WRI upgraded product

showed that coal upgrading in conjunction with powder activated carbon injection can achieve up to 90 % mercury emissions reduction.

Contaminant Sampling and Methods Development

Task 05 – Soil Samplers

Task 09 – Fuels in Soil Test Kit

Task 66 – HVOC Field Screening

Hydrocarbon contaminated soils and waters are an important environmental issue. Clean-up standards are typically site-specific, and are based on health considerations but more often arbitrary. At WRI, our efforts concentrated on the development of methods and devices for precise measurement of the contaminants. Under the auspices of the Cooperative Agreement, WRI developed sampling methods, sample storage containers to preserve the integrity of the samples such that volatile organic contaminants are not lost during the shipment of the samples, sampling devices and field deployable kits for sample screening and site surveillance.

Sampling techniques for volatile organic analysis must be designed to minimize loss of volatile organic compounds (VOCs) from the sample. Preventing VOC loss from for example soil cores that are collected from the subsurface and brought to the surface for sub-sampling is difficult. Existing technique used to subsample cores for VOC analysis exposes the soil core to the atmosphere and therefore prone to losses.

WRI developed three alternative techniques for screening and collecting soil samples from subsurface soil cores for VOC analysis and field testing. These techniques provide easy soil screening without violating the integrity of the soil that will be sampled. They also maintain the integrity of the soil during sample collection and provide very short exposure time of the soil to the atmosphere

during sampling. Based on the results of the field testing performed under the Cooperative Agreement, ASTM D4547, Standard Guide for Sampling Waste and Soils for Volatile Organic Compounds, was revised to include the information about the new techniques.

A portable soil test kit, *Diesel Dog*[®] was developed for performing field analysis of fuel-contaminated soils. The technology is based on WRI patented methods (US Patents 5,561,065 and 5,976,883). The hardware developed for

commercial use is based on spectrophotometry that allows the methods to be performed in the field and does not require the use of highly toxic reagents. The method is designated as ASTM Method D 5831-96, Standard Test Method for Screening Fuels in Soils. The Diesel dog technology was awarded the American Chemical Society's Regional Industrial Innovation Award in 2001.

A new screening technology was developed for field measuring halogenated volatile organic compounds. The new device called the X-Wand screening tool is based on a heated diode refrigerant leak detector sensor. The sensor is selective to halogens and does not respond to fuel hydrocarbons or water vapors. Laboratory and field validation of the X-Wand was conducted with TCE-contaminated soils. A new ASTM method, D 7203-05, Standard Test method for Screening Trichloroethylene (TCE) Contaminated Soil using a Heated Diode Sensor, was developed. The technology can also be used for screening TCE contamination in waters. An ASTM Method D 7203-06, Standard Test Method for Screening TCE-Contaminated Media Using Heated Diode Sensor is pending with an ASTM Committee.

Development and Testing of TaBoRR®/WRITE™ Technologies

Task 04 – The Use of TaBoRR® as a Heavy Oil Upgrader

Task 28 – Assessment of the TaBoRR® Process and Stability/Compatibility of Products

Task 51 – Development of the WRITE™ Process for Pipeline Ready Heavy Oil

Under a previous Cooperative Agreement, WRI developed and patented TaBoRR® (Tank Bottoms Recovery and Remediation) technology for the remediation of tank bottom wastes while recovering salable oil. The concept involved three distinct steps, 1) flash to remove water, 2) strip to recover salable oil, and 3) pyrolysis to render solids and heavy hydrocarbons to a benign, land-fillable state. Flash involves heating the tank bottoms under pressure to a temperature commensurate with the desired water removal, followed by a sudden release of pressure. As soon as the pressure is released, water and some light hydrocarbons are vaporized and sent to the flare. The flash bottoms contain hydrocarbons and solids, and are stripped. The stripping operation is a distillation step that involves heating the material to a temperature commensurate with the desired recovery, yet low enough to prevent cracking. The vaporized hydrocarbons from the stripping operation are condensed as salable product and the remaining liquid consisting of heavy hydrocarbon fractions and solids are pyrolyzed. The pyrolysis step involves heating the material to considerably higher temperatures to recover more light hydrocarbons and to convert the material to a solid residue. Some of the light hydrocarbons produced during pyrolysis are condensable and can be recovered as liquid product and sold, and some are gases that can be used as fuel for the process.

During the course of this Cooperative Agreement, a series of tasks were undertaken to support various aspects of the TaBoRR® technology for use as a heavy oil upgrader, the WRITE™ (WRI Thermal Enhancement) technology.

Cold lake bitumen was tested in WRI's bench-scale equipment to evaluate the potential use of TaBoRR® technology for heavy oil upgrading to produce a stable, partially (or fully) upgraded product that will either reduce or eliminate the need for diluent for transportation of bitumen or ultra-heavy crudes to market. Approximately 70 to 75 wt% of bitumen feed was converted to a partially upgraded overhead product that could be transported directly by pipeline or blended with the parent bitumen to produce transportable crude.

Stability and compatibility of TaBoRR® products was evaluated on samples produced in the bench-scale equipment. Storage stability tests were performed for periods up to four weeks that showed that the viscosity of the products did not change with time. Chemical analyses of the overhead product blends met pipeline specifications for viscosity and density; however the bromine number does not, indicating the need for mild hydrotreating. Storage stability tests showed the blends to be stable. The blends were also soluble and compatible with most other Alberta crudes.

Based on the bench-scale test data and preliminary economic analysis, Task 51 was formulated to develop WRITE™ technology as a variant of TaBoRR® to address heavy oil upgrading. WRITE™ technology is a field-deployable heavy oil and bitumen upgrading process that produces residuum-free, pipeline ready oil from heavy material with undiluted density and viscosity that exceed prevailing pipeline specifications. WRITE™ technology uses two processing stages to achieve low and high temperature conversion of heavy oil or bitumen. The first stage, distillate recovery unit (DRU), operates at mild thermal cracking conditions, yielding a light overhead product and a heavy residuum or bottoms. These bottoms flow to the second stage, a continuous coker that operates at severe pyrolysis conditions, yielding light pyrolyzate and coke. The combined product from these two stages forms WRITE™ technology's synthetic crude oil (SCO) production.

Economic analysis concluded that WRITE™ process is a technically feasible method for upgrading bitumen and that it produces an SCO that meets pipeline specifications for density. When compared to delayed coking, the industry benchmark for thermal upgrading of bitumen, WRITE™ technology produced more SCO, less coke, less CO₂ per barrel of bitumen fed, and had lower capital and operating costs.

The development of the WRITE™ technology is being continued under the sponsorship of a commercial client. The positive indicators for WRITE™ notwithstanding, a comprehensive test program is being conducted to provide additional information for more detailed process evaluations and associated economics. These evaluations must be completed before WRITE™ is

deployed as a field-scale pilot. The test program includes operating a nominal 5-bpd engineering-scale plant with bitumen produced from commercial sponsor's production facilities.

A petroleum analysis laboratory has also been established and staffed to support heavy oil upgrading activities at WRI. The laboratory currently supports the operation of the 5-bpd engineering-scale reactor. Analyses performed by the laboratory include bromine number, atmospheric distillation of petroleum products, shear and kinematic viscosity, density, micro carbon residue, determination of asphaltene concentration, simulated distillation, volatile matter in petroleum coke, elemental analysis (excluding oxygen), and hydrocarbon types.

ASTM Analyses Performed in the Petroleum Analysis Laboratory

ASTM Method	Method Title
D1159	Bromine Number
D86	Atmospheric Distillation of Petroleum Products
D5018	Shear viscosity
D445	Kinematic Viscosity
D2320	Relative Density of Solid Pitch (Pycnometer Method)
D 4052	Density by Digital Density Meter
D1298	Density by the Hydrometer Method
D4530	Micro Carbon Residue (equivalent to Conradson Carbon Residue)
D6560	Determination of Asphaltene Concentration
D2887 & D5307	Simulated Distillation
D6374	Volatile Matter in Green Petroleum Coke
D5291 & D1552	Carbon, Hydrogen, Nitrogen and Sulfur
D2207	Hydrocarbon Types

Bioremediation Technologies

Task 25 – Bioremediation of Petroleum hydrocarbon Contaminated sites

Task 33 – Development of Remedial Techniques for Contaminants in Soil and Groundwater

Task 35 – Bioremediation of Petroleum Hydrocarbons in Heterogeneous Soils

Task 60 – Advanced Oxidation Technologies in Treating MTBE and gasoline

Task 70 – Microbiological Study of Biodegradation of Hydrocarbons in Groundwater

Task 72 –Advanced Oxidation and Aerobic Degradation for Remediation of Hydrocarbons

Bioremediation exploits the ability of certain microorganisms, usually heterotrophic bacteria and fungi, to degrade organic materials to innocuous materials such as carbon dioxide, methane, water, inorganic salts, and biomass. Microorganisms may derive the carbon and energy required

for growth through the biodegradation of organic contaminants or transforms more complex organics through fortuitous co-metabolism. Bioremediation has been widely applied in the restoration of petroleum hydrocarbon-contaminated soils. Petroleum hydrocarbons in excess of 20,000 ppm can be tolerated without inhibition to microbial growth. The complexity of the bioremediation process can be great at many sites due to large number of interacting factors that impact the microbial populations and their abilities to degrade the contaminants present. This complexity has shown the remediation industry the need to carry out detailed laboratory testing before the biological process can be successfully applied in the field. Effort in the laboratory most often translates into successful field applications of bioremediation technology.

Contaminated sites are complex in nature, and often several techniques are required for complete remediation. A range of factors is known to influence the biological transformation and degradation of contaminants. Parameters that may affect the rate and efficiency of biodegradation include temperature, moisture, salinity, nutrient availability, microbial species, and type and concentration of contaminants. Nutrient availability, such as nitrogen and phosphorus, is often limited in petroleum-contaminated soils due to the excessive carbon input from the hydrocarbons. Therefore, nitrogen and phosphorus are usually identified as the limiting factors for biodegradation in soils. Other factors can also affect the success of the bioremediation treatment of contaminants, such as climatic conditions, soil type, soil permeability, contaminant distribution and concentration, and drainage.

WRI collaborated with several commercial remediation companies and area universities such as University of Wyoming, Colorado State University to develop a viable support program that proposed, developed and participated in the field testing and deployment of site-specific remediation schemes for specific contaminants under prevailing indigenous conditions. In Egypt, several contaminated sites around (Ras Shukheir facility) were studied by collecting laboratory samples and then evaluating microbial activities to devise appropriate land-farming remediation program. These investigations lead to the development of a bench-scale biotreatment cell (solid-phase bioreactor) which then led to the design of a field-scale system. Similar studies were undertaken for several contaminated sites in California's Simi Valley neighborhoods.

Simi Valley News

The Simi Valley City Council presented two Certificates of Commendation for Environmental Stewardship at its April 20, 2009, meeting. One of the Certificates was presented to the Western Research Institute (WRI) of Laramie, Wyoming, in the field of Groundwater Remediation. WRI initiated a partnership with the City of Simi Valley to conduct research and development focused on a groundwater contamination problem. The Institute managed a jointly sponsored research program under an agreement with the U. S. Department of Energy that provided funding of over \$48,000 to the City. The research facilitated the development of a microbiological based cleanup technology coupled with a chemical oxidation technology that has proven to be an effective groundwater remediation method. WRI has presented the research results to the international environmental community at the prestigious Battelle Memorial Institute Conference at Monterey, California, the East Coast Association for Environmental Health and Sciences at the University of Massachusetts, and the West Coast Contaminated Soil, Sediments and Groundwater Conference in San Diego, California.

Heavy Oil Processing and Petroleum Refining Efficiency Improvements

Task 36 – Development of Solubility Product Visualization Tools

Task 50 – Development of Petroleum Residua Solubility Measurement Methodology

Several Base Program Tasks

Under a series of tasks, the development of a predictive model for petroleum residua coke formation was proposed with the expressed intent that rapid laboratory diagnostic analyses or on-line analytical concepts will lead to refining efficiency improvements.

Under the tasks carried out in this area, WRI developed two Coking Indexes as a diagnostic method of how near a residuum is to coke formation when heated to pyrolysis temperatures. This allows refiners to optimize cracking and distillate yields, resulting in overall improved energy efficiency in the refining processes. The indexes act as a predictor as when to stop heating a residuum to prevent fouling of heat exchangers and pipes due to coke formation. The Coking Indexes as determined from flocculation titrations or the cyclohexane-soluble portions of asphaltenes were found to apply universally to every residua material evaluated, for materials with distillate removed, and for whole visbroken oils.

Research concluded under these tasks generated additional insight into a common problem in the petroleum industry related to the fouling of pipes, heat exchangers, and pumping systems in both upstream and downstream operations when heavy oils are heated or blended. The research resulted in the development of new technologies (WRI Coking Indexes US Patent 6,773,921, Automated Flocculation Titrimeter, ASTM D 6703). The AFT technology was licensed to Koehler Instruments for manufacture and sales in November 2003.

In an AFT (shown here) samples of asphalt or heavy oil, or residuum are dissolved in toluene at various concentrations and titrated with iso-octane or n-heptane at controlled temperatures to determine the point of flocculation (asphaltene precipitation) and calculate the Heithaus compatibility parameters. These results are intended primarily as a laboratory diagnostic tool for estimating the colloidal stability or compatibility of asphalt, asphalt cross blends, aged asphalt, pyrolyzed asphalt and crudes, and heavy oil, or residuum. Compatibility influences important physical properties of these materials as well as the formation of coke which causes fouling in refining processes.

The AFT is a highly automated, computerized instrument that acquires oil stability and compatibility parameters directly. The AFT can be used to perform ASTM D 6703 test method for Automated Heithaus Titrimetry. The AFT operates as a closed system with accurately controlled temperatures between 20-100°C, important for properly determining Heithaus compatibility parameters. The flocculation point is determined spectroscopically and the results are analyzed by the data acquisition system, virtually eliminating operator error in the interpretation of endpoints. The automated method is fast, accurate and very reproducible. The utility of the original Heithaus method has been expanded by developing multiple titration schemes. The software uses the data from the expanded method to predict the proximity to coke formation during heavy oil distillation. Many refiners stop distillation short of coke formation to avoid fouling in distillation equipment, tanks and transfer lines. The expanded AFT methodology allows the refiner to recover additional distillate without the fear of fouling.

The continuing effort in this area has recently lead to the development of a new separation technique and new characterization methods for upstream oil recovery improvement and downstream process monitoring for refinery efficiency improvement. A better, more rapid method to measure asphaltene solubility uses a novel on-column asphaltene precipitation and re-dissolution technique. The separations are performed using a column packed with ground polytetrafluoroethylene (PTFE). Although high performance liquid chromatography (HPLC) equipment is used, the separation does not involve adsorption or chromatographic mechanism. It is strictly solubility based.

Coal Power Mercury Emissions

Task 31 – Emissions Monitoring and Control of Hg from Subbituminous Coal-Fired Plants

Tasks 58 & 62 – Mercury CEM Calibration

Clean Air Act Amendments and EPA review of hazardous air pollutants has prompted the development of technologies to capture mercury from the flue gases of coal-fired utilities. In support of developing emission regulatory guidelines, the U.S. EPA collected information on the mercury capture across the post combustion Air Pollution Control Devices (APCD). These data were then used to propose regulation of mercury emissions from coal-fired utilities.

The basis for the mercury emissions regulations were the data collected from eighty one coal-fired plants. Due to the feedstock, processes and combustion equipment design variables on the speciation and native capture of mercury, the data were mostly qualitative in nature. For most cases, any quantification of the trends was not possible. Specifically, the distribution of mercury species in the flue gas stream varied considerably between the bituminous and subbituminous/lignite coal types. About 40% of the plants showed negative mercury removals across the plant and/or across the air pollution control devices. The variations were more pronounced in units firing low-rank coals.

In order to resolve the ambiguities in the data, specifically for the low-rank coals, WRI and its cosponsors re-tested stack gas emissions from power plants burning subbituminous coals. In Phase I of the project, mercury emissions from ten subbituminous coal-fired plants were measured. In Phase II the project focused on obtaining a mass balance of total mercury and speciated mercury across the Western Farmers Electric Cooperative (WFEC) Hugo Station subbituminous coal-fired power plant. Project also dealt with a comparison of Hg source sampling methods, investigation into the variability of Hg emissions, and the long-term performance of continuous emission monitoring strategies for mercury. Among many, the main conclusion reached was that mercury emissions monitoring equipment and techniques need to be improved. Improvements are warranted both in the performance and in the maintenance/calibration of the equipment. Tasks 58 and 62 addressed the issues.

Calibrator Evaluation Setup

Whereas the mercury emissions from coal-fired power plants are comprised of both elemental and oxidized mercury, current CEM analyzers are designed to measure elemental mercury only. Therefore, the oxidized mercury present in the flue gas must first be converted to elemental mercury. A viable CEM system must demonstrate the ability to measure both elemental and oxidized mercury with equal reliability and certainty. As a part of JSR Cooperative Agreement, WRI evaluated the performance of commercially

available mercury monitors. Working very closely with NIST, considerable effort was devoted to the efficacy of calibration methodologies based on gas cylinders, and on elemental and oxidized mercury vapor generators. Results of WRI work with gas cylinders were consistent with the previous work suggesting that calibration gas cylinders can be used to verify the output of a calibrator in certain control settings. The use of mercury vapor generator as calibrators requires the use of oxidized mercury generators followed by an efficient conversion of the oxidized mercury to elemental mercury. There are currently two basic types of mercuric chloride (HgCl_2) generators used for this purpose. One is an evaporative HgCl_2 generator, which produces gas standards of known concentration by vaporization of aqueous HgCl_2 solutions and quantitative mixing with a diluent carrier gas. The other is a device that converts the output from an elemental Hg generator to HgCl_2 by means of a chemical reaction with chlorine gas. The work concluded by WRI with different calibrators formed the basis of a new QC procedure for verifying proper elemental calibrator performance. The

procedure involves output concentration ratios, and it does not require comparison with another calibrator. This procedure is now included as a mandatory QC check in the draft EPA traceability protocol as Section 7.2.2.

Results for a commercially available calibrator are summarized below.

1. The elemental mercury output is highly linear.
2. The effect of back pressure that can be encountered due to long stack umbilical, up to 9 psi, is insignificant.
3. The effect of changes in ambient pressure is insignificant.
4. The effect of ambient temperature can be significant. Components of the calibrators such as Peltier coolers and mass flow controllers can be adversely affected by temperatures ranging from 10 – 30 °C. Therefore the units should be operated in environments as close to 20 °C as possible.
5. The effect of line voltage between 105 – 125 V is insignificant.

Combustion Test Facility

Task 32 – Combustion Characteristics of K-Fuels

Task 41 – Coal Cleaning using Resonance Disintegration for Hg and S Reduction

Task 48 – Evaluation of Raphite as a NO_x Reduction Catalyst

Task 49 – Reduction of NO_x through Oxygen Enrichment

Task 53 – Optimization of Trona/Limestone Injection for SO₂ Control

Task 55 – Evaluation of Biomass and Coal Slurries as Reburn Fuels

Task 56 – Development of a Novel Oxygen Supply Process...

Task 65 – Evaluation of BOC's LoTO_x Process for Hg Control

Task 67 – Installation of ROFA/ROTAMIX ...Hg Control Technologies...Thief C...

Task 76 – Evaluation of Oil Shale for Multi-Pollutant Control

Tasks 13 & 77 – Combustion Testing of Cowboy Coal

Coal combustion technologies that make coal combustion cleaner and more environmentally efficient are receiving a great deal of attention in the industry. Under Task 32, WRI acquired a 250000 Btu/h Combustion Test Facility. A pilot-scale coal combustion facility that simulates a pulverized coal-fired utility boiler is set up to simulate a tangential-fired boiler. The facility can easily be adapted to wall-fired or other configurations. The facility is equipped with appropriately sized heat-recovery surfaces (water-cooled waterwall section, and air-cooled superheater, reheater, and economizer simulators). There are provisions for preheating the combustion air to mimic a utility air preheater. Several over-fire air injection ports are incorporated in the design to allow for combustion staging. Base particulate clean-up device is a two-bag two compartment bag filter

that allows isolation and collection of flyash samples from different plant operations. Stack gas analysis system includes on-line analyzers for the monitoring of O₂, NO_x, SO₂, CO, CO₂, as well as elemental and oxidized vapor-phase mercury.

The Combustion Test facility has been extensively used during the course of the JSR Cooperative Agreement Program. Over a six year period, twelve JSR tasks and thirteen commercial projects were supported by the facility. List of recent clients includes Nalco-Mobotec, KFx Inc./EverGreen Fuels, FMI/Cowboy Coal/NuCoal, Idaho National Laboratories, Breen Energy, BOC-Linde, Headwaters, PulseWave, University of Wyoming, Jupiter Oxygen, BHP Billiton, Hydrogen Technology Applications, MR&E, Afton Chemicals Inc., PreCombustion Power Venture and SaskPower.

Gasification of Western U.S. Coals

Task 39 – Production of Substitute Natural Gas from Coal

Task 43 – Nanoactive Sorbent Materials for the Treatment of Coal-Derived Synthesis Gas

Task 46 – Novel Low-Cost Process for the Gasification of Biomass and Low-Rank Coals

Task 80 – Novel Fixed-Bed Gasifier for Wyoming Coals

A series of tasks proposed under the JSR Cooperative Agreement addressed the specialized processing needs of the direct utilization and conversion of western U.S. coals in advanced power systems. The utilization schemes being developed and tested rely on the fact that western U.S. coals can be "partially" gasified at relatively low temperatures, and that the concomitant char produced is reactive. These characteristics afford western U.S. coals a significant advantage over bituminous coals and solid waste fuels such as petroleum coke. Several two-stage gasification schemes can be designed to exploit the special characteristics of these coals. However, one of the major issues facing such utilization of coal is the arrival of vapor-phase ash constituents and other contaminants which can cause compatibility issues with downstream components and or are otherwise an emissions issue.

As part of this project, WRI constructed and tested a fuel-flexible gasifiers and gas cleanup options. Advanced concepts were tested that did not require the use of expensive oxygen plants yet produced a medium-Btu syngas stream for potential use as a feedstock for liquid fuels synthesis.

A seven-inch diameter, fluidized-bed gasifier was designed to be operated as an air-blown, enriched air-blown, oxygen-blown, or as a steam pyrolysis unit. A series of cold-flow fluidization tests was performed with a bed of Wyodak coal in the

1/16"-1/8" size range. Observation of the bed allowed the fluidization regime to be determined for ambient pressure, ambient temperature operation. Hot-flow tests were performed at 1200 to 1450°F range, to assess the fluidization behavior at temperature. Analysis of the syngas product allowed an optimum air/coal ratio to be identified.

The fluidized-bed gasification unit then became a test bed for several additional projects under the scope of this and other Cooperative Agreements as well as for commercial projects requiring coal-derived syngas.

- The gasifier facility was used to test carbon-based sorbents for mercury removal from syngas. The results showed that acidified carbon was more effective than activated carbon for elemental mercury removal from syngas.
- The gasification system was used to test hydrogen separation membranes and water gas shift catalysts.
- The gasifier facility was used for the development of a real-time on-line alkali monitor. The underlying principle for the on-line probe was the determination of the dew point of the vapor phase compounds. Once the dew point had been established the concentration could be deduced from the available thermodynamic equilibrium data.
- The gasifier facility was used to test NanoActive® materials for cool- and warm-gas scrubbing of H₂S, ammonia, HCN, Hg and other contaminants from syngas.

Advanced concepts for small-scale gasifiers proposed under the Cooperative Agreement in broad terms required four steps: (1) separating the fixed carbon from the volatile matter (pyrolysis or devolatilization), (2) converting the volatile fraction into syngas (reforming), and (3) generating process heat by combusting residual char (combustion). A key advantage of such an approach is that no oxygen plant is needed for char combustion. In addition, highly efficient counter-current heat-recovery methods are used to direct heat from the char combustion section to the endothermic gasification and reforming stages of the process.

One such gasifier was assembled at WRI, tested and then transported to a farm cooperative in Spokane, WA. Another version of such a gasifier is routinely used at WRI for providing syngas stream for other projects involving gas clean-up technology development and testing and other similar uses to support coal and biomass gasification technology development.

Two-stage Gasifier

Synthesis of Liquid Fuels

Task 22 – Testing of PEFI's Alcohol Process

Task 26 – Improved F-T Slurry Reactors

Task 37 – Combination Reforming of CH₄/CO₂ Mixtures...

Task 57 – Production of Ethanol-Based Fuels from Natural Gas

Task 64 – Novel Integrated Process to Produce Fuels from Coal and Other...

Under the auspices of the Cooperative Agreement, WRI began the development of synthesis technologies to convert syngas to a mixture of alcohols. Consistent with the DOE interest in furthering the technologies for the production of transportation fuels from alternate sources such as natural gas, biomass and coal, mixed alcohols represented a way to replace MTBE as the oxygenate gasoline blend. The first step of these processes is the production of synthesis gas; the second step of these processes is a catalytic conversion of synthesis gas to alcohols or other fuels. WRI's gasification program and associated facilities are described elsewhere in this report.

Under Task 22 of the JSR Cooperative Agreement and additional tasks funded by the Base Cooperative Agreement, development of a catalyst with selectivity for ethanol and higher alcohols was undertaken. Catalyst production and testing facilities were developed including fixed-bed, slurry-bed and fluidized-bed synthesis reactors. Early catalyst work concentrated on MoS₂-based formulations to extend the early catalyst development work from DOW. The MoS₂-based catalyst produces predominately straight-chain terminal C1-C6 alcohols, a similar product to the DOW catalyst discovered in the mid 1980's. However, a key disadvantage of the MoS₂-based catalyst is that sulfur containing byproducts are produced, a potentially serious issue for the end-use of the product. Under the auspices of the Cooperative Agreement then undertook a catalyst development program with the goal of matching or exceeding the performance of the MoS₂-based catalyst while eliminating the sulfur issues. As a result a Mo₂C-based catalyst formulation was developed and is now patented awaiting a licensing agreement. Further refinements of the catalyst in various supported pelletized and raw powder forms are in various stages of development.

The process for the synthesis of mixed alcohols is an outgrowth of a long-term development project in Fischer-Tropsch (FT)

chemistry. However, the mixed alcohol synthesis has an advantage over the conventional synthesis in that a fungible product is produced which after dewatering is ready for the consumer. Previous data also indicate that the overall conversion yield can be nearly two times that of the conventional Fischer-Tropsch synthesis. The principal use foreseen for the alcohol mixtures is as a high-octane blending stock (10% or higher) for gasoline. It is expected that the mixed alcohol product, essentially denatured ethanol, will also make a high powered, clean burning fuel, either neat or in an 85% blend with gasoline. The availability of the co-product, higher alcohols, may offer chemical producers and refiners an attractive way to use synthesis gas particularly that produced from isolated natural gas sources. Through the use of proper front-end gasification technology and appropriate gas cleaning, synthesis gas from various waste materials, such as biomass from municipal solid waste (MSW) or refuse-derived fuel (RDF), and coal can become chemical feedstock for the synthesis technology.

Under the JSR Program Cooperative Agreement, the mixed alcohol synthesis technology was scaled-up to 50 gallons per day pilot facility. Anticipating that the pilot plant will require as much as fifty pounds of catalyst, catalyst development and testing activities under this task were designed to scale-up WRI catalyst production capabilities and facilities. Early catalyst development work employed a fluidized bed catalyst preparation set-up. The set-up could produce no more than 10 g batches of catalyst. Further scale-up of the fluidized bed configuration was deemed not possible because of the large quantities of process gases required for fluidization. Instead, a small rotary kiln based set-up was developed to allow production of up to 100 g batches. Once the small rotary kiln facility was debugged and began producing consistent batches, another scale-up to a larger rotary kiln was attempted. This allowed manufacture of up to 5,000 g batches of WRI catalyst.

Development of a supported catalyst was also undertaken. The catalyst support selected was activated carbon, and several batches of supported catalyst were produced. Bench-scale testing showed that supported catalyst was not as selective to ethanol and higher alcohols as its unsupported counterpart. Similarly, bench-scale data showed that a substantial amount of carbon was converted into

alkanes. The supported catalyst formulation was optimized to reduce the production of alkanes and methanol.

Plant construction has been completed and nearly all of the pilot plant equipment have now been shaken down and upgraded, as warranted.

The mixed alcohol synthesis process offers several advantages over conventional FT synthesis. Sulfur poisoning of the catalyst is a major problem in a number of other processes and usually requires a reduction in the sulfur levels in the synthesis gas before it can be admitted to the reactor. The catalyst formulation for this process is sulfur tolerant and hence such a conditioning step is not critical. The product from this catalyst requires very little treatment to be used as a motor fuel, probably only dewatering. FT processes require the equivalent of a mini refinery to convert the product to a usable motor fuel.

Ash Management/Use Activities

Task 06 – Market Assessment and Demonstration of Lignite FBC Ash Flowable Fill Applications

Task 10 – SYNAG Process Demonstration and Product Acceptance Verification

Task 14 – Ash-based Grout Injection for Subsidence Control at Shamrock Mine

Task 17 – PFBC Ash Management Evaluations and Demonstrations

Task 23 – SYNAG Technology Applications

Task 24 – Ash-based Building panels Production According to AeRock Process

Under the JSR Cooperative Agreement Program WRI teamed with several commercial entities to develop value added uses and products for coal combustion byproducts.

A trade-marked product Ready-Fill™ was developed with lignite FBC fly ash and waste sand. The geotechnical properties of the product could be modified to meet the needs of a range of applications from structural fill requiring compressive strengths in the 750 to 1500 psi to excavatable fill requiring compressive strengths only in the 75 to 200 psi range. The environmental properties of the product are such that its use does not pose any threat to the adjacent groundwater or soils. Several field applications of the product were demonstrated as a part of the JSR Program.

A trade-marked process SYNAG™ is a method for the production of normal-weight and lightweight aggregate from coal combustion ashes. The process involves cold-bonding of ash to produce a hardened form which can then be crushed and sized if needed to the desired particle size distribution for use as construction aggregate. The SYNAG process is cost competitive with other synthetic aggregate production technologies. SYNAG process can use off-spec ashes and yet produce an aggregate that meets AASHTO specifications. As a part of the JSR Program,

laboratory-scale demonstration of the SYNAG technology involving mixing, compaction and product quality were conducted in Gurnee, Illinois.

Coal ash-based grouts have been commonly used in underground mines for acid mine drainage mitigation and subsidence control. Working with commercial partners, WRI evaluated the environmental and geotechnical issues associated with the use of an ash-based grout for a Colorado flooded underground mine to control subsidence. A series of pumpable grout mixes were designed and prepared. Mine emulation studies were completed with an overall conclusion that such a grout injection did not represent any environmental or geotechnical issues. However, the field trials were not conducted because of permitting issues.

PFBC ashes were evaluated for their potential use (a) in construction applications, and (b) as an amendment for acidic soils and spoils in agricultural and reclamation applications. Work completed demonstrated that if there were to be a wide-spread use of the PFB technology, the ash from these installations would be a viable material in established applications for conventional coal combustion ashes.

Working with a commercial partner, WRI supported the development of rapid-setting, ash-based, fiber-incorporated green building products. A formulation composed primarily of recycle materials, principally ash, ash-based cement and fiber can be used for producing alternative building products to wood. The product is not only attractive, durable, resistant to moisture and UV damage, fire resistant and will not crack, split or warp; it is environmentally friendly in that materials are recycled saving landfill space.

Reclamation/AMD Mitigation

Task 08 – Development of Synthetic Soil Materials for Reclamation of AML Sites

Task 19 – Potential of Reclaimed lands to Sequester Carbon...

Task 44 – In-situ Treatment of AMD using Bio-Organic Oxygen Elimination Treatment

Abandoned mine sites associated with coal and hard-rock mining across the western United States have been left as unproductive wastelands. Many are covered with spoil materials that are very acidic and high in toxic constituents. They represent an environmental hazard for contamination of surface and groundwater. WRI staff have been working with local agencies to

develop site-specific amendments to reclaim the sites and mitigate the acid mine drainage impact on local watershed.

At a mine site in Montana, several synthetic soil amendments were used to reclaim an abandoned mine site. Growth of vegetation was monitored to show that indeed the treatment was successful in promoting plant germination and biomass growth. Continued monitoring also established that reclamation also represents sequestered carbon.

AMD often results from mining operations from the oxidation of pyrite (FeS_2) in water that yields ferric hydroxide and sulfuric acid. Ferric iron then further oxidizes pyrite to release more acidity, and continued reactions result in AMD. The AMD mitigation scheme developed by WRI is based on depletion of oxygen such that the oxidizing sequence of pyrite and associated generation of acid can be shut down. The unique metabolic mechanisms of sulfate-reducing bacteria (SRB), is an alternative technique for eliminating AMD formation. The sulfate-reducing process consumes protons, resulting in the rise of pH to the neutral range. A secondary benefit was also expected from the biofilm produced from the SRB in that the process coats the pyrite surface, preventing it from further oxidation. The precipitates also consume the dissolved oxygen on the surface of pyrite, providing a galvanic protection of pyrite being oxidized; therefore the pH in a mining site may be maintained within the neutral range for a long period of time.

Laboratory experiments involved AMD water collected from a site in Montana with pyrite added to each treatment microcosm. Corresponding treatments were inoculated with SRB from sediments collected from a lake bottom and different substrates (carbon sources) were compared for their enhancement of SRB. The substrates included sodium lactate, glucose, and corn starch over a range of pH. The results confirmed that AMD can be treated with SRB and pH can be maintained in neutral levels by the formation of a biofilm retarding further conversion of AMD-producing material. Based on the success of the laboratory experiments, a JSR project with Rio Tinto Energy America (formerly Kennecott Energy) is demonstrating the SRB treatment at a coal mine in Tennessee (Sequatchie Valley Coal).

The field demonstration of the concept has been successfully demonstrated at a mine site in Tennessee. The field trials also showed that electromagnetic induction equipment typically used to measure ground conductivity is an effective tool for identifying AMD source material and for monitoring the progress of the treatment.

EM Surveillance Setup

Technical Assistance and Technology Transfer Programs

As a part of the JSR Cooperative Agreement, WRI supported local communities with their energy- and environmental-related issues. For the City of Torrington WRI staff evaluated various power generation options to mitigate the impact of lost generation capacity. For the city of Worland the staff evaluated coal- vs. natural gas-fired steam generation for a sugar mill. Similarly, when Encampment lumber mill was facing levies and fines for fugitive emissions WRI staff assisted the regulators and city government with the evaluation of various mitigation options.

Under the Cooperative Agreement Program WRI unsuccessfully attempted to develop a consortium of oil and gas producers. A mass mailing was conducted to independent operators along the Front Range seeking input on the need for a consortium to define R&D needs. The mailing also introduced them to WRI and our ongoing DOE-sponsored programs in the Oil and Gas extraction area. From the feedback, it was realized that need for such services was quite sparse. Further efforts to organize the independent producers were abandoned.

Based on WRI's long-standing presence in the subbituminous coal industry, a coalition of the coal producers and users was successfully formed, Subbituminous Energy Coalition (SEC). At the time SEC was formed, Environmental Protection Agency (EPA) had promulgated mercury control regulations on coal-fired power plants which then brought out the specialized problems and needs of the subbituminous coal industry. Like the lignite coal industry, the subbituminous coal-fired power plants have the vast majority of their mercury in the flue gas in the form of elemental mercury, while the eastern bituminous coal-fired power plants have the vast majority of their mercury in the flue gas in the oxidized form. Working with SEC members, this task addressed the coal industry's need of technical support and assistance. Information exchange forums and sessions were organized. From its modest beginnings, the SEC now has over 50 members. On the mercury issue, the SEC was an effective voice for the subbituminous coal industry in commenting on the proposed regulatory actions by EPA. Recently, the SEC has included the issues and challenges of the climate change / greenhouse gas emissions / CO₂ capture and storage in its working agenda. Outreach efforts under the Cooperative Agreement have been very successful in providing forums for the industry to share information, technology transfer, organize a consensus of the industry for regulatory comments, and jointly developing future plans for industry.

As a part of the technology transfer activities, WRI collaborated with NCUT to cosponsor the 3rd and the 4th Upgrading and Refining Conference in Edmonton, Alberta, Canada. Working with NETL, WRI was responsible for providing a Keynote Speaker for the Conference. Nearly 300 delegates attended the 4th Conference where 32 papers

technical were presented. In addition, WRI organized a workshop on Corrosion and Fouling in the refinery equipment. The workshop was also well attended.

IN CONCLUSION

Over the course of the Program, a total of eighty two tasks were proposed for DOE approval. For various reasons beyond the task manager's control, on four of the eighty two tasks the work was never started and the tasks were later withdrawn. Over the ten year period of performance of the Cooperative Agreement, WRI has put in place projects utilizing a total of \$23,202,579 in USDOE funds. Against this funding, cosponsors have committed \$26,557,649 in private funds to produce a program valued at \$49,760,228.

Success of the Program can be measured by several criteria. Using the deployment of the federal funding with industrial participation, over the ten-year period of performance, the cosponsors contributed more dollars than the federal funds. Nearly 54% of the funding for the Program was derived from industrial partners. The industrial partners also enthusiastically supported the research and development activities with cash contribution. During the last five years of the Agreement, industrial cash contribution averaged nearly 60% of the required cost share.

Under the Program, energy-related tasks emphasized enhanced oil recovery, heavy oil upgrading and characterization, coal beneficiation and upgrading, coal combustion systems development including oxy-combustion, emissions monitoring and abatement, coal gasification technologies including gas clean-up and conditioning, hydrogen and liquid fuels production, coal-bed methane recovery, and the development of technologies for the utilization of renewable energy resources. Environmental-related activities emphasized cleaning contaminated soils and waters, processing of oily wastes, mitigating acid mine drainage, and demonstrating uses for solid waste from clean coal technologies, and other advanced coal-based systems. Technology enhancement activities included resource characterization studies, development of improved methods, monitors and sensors. In general the goals of the tasks proposed were to enhance competitiveness of U.S. technology, increase production of domestic resources, and reduce environmental impacts associated with energy production and utilization.

Technologies being brought to commercialization as a result of the funds provided by the Cooperative Agreement contribute to the overall goals of the USDOE and the nation. Each has broad applicability both within the United States and abroad, thereby helping to enhance the competitiveness of U.S. energy technologies in international markets and assisting in technology transfer.

For the most part, the WRI Program supported the development of energy and environment-related technologies consistent with DOE priorities. Individual tasks addressed the needs of coal, oil and gas, and biomass-based energy systems.

As envisioned during the establishment of the Program, the Cooperative Agreement funded high-risk research in areas based on several factors:

- Our Nation's need for cheap electricity underscored the need to research, develop and demonstrate technologies for cleaning the stacks of existing coal-burning power plants.
- Our Nation's need for cheap electricity in the carbon constrained future, underscored the need for research, development and demonstration of enabling technologies toward zero emissions power plants of the future.
- Our Nation's appetite for transportation fuels and our desire to maintain our way and quality of life underscored the need for research, development and demonstration of technologies for the production of clean-burning liquid fuels.
- Our Nation's desire for energy independence underscored the need for technologies to upgrade and convert North American resources, unconventional resources such as oil shale.
- Our Nation's desire to curtail and reduce carbon emissions means cost-effective, sustainable renewable resources need to be integrated in our future energy mix. Technologies that co-develop renewable options within the fossil systems are likely to be more cost effective and efficient than stand-alone.
- Wyoming is the Btu capital of the Nation. There is a need for research activities dedicated to developing value-added energy products and associated economic benefits for the state and the region.

Under the Cooperative Agreement, WRI is responding to the energy research needs of our Nation and the region. The program has contributed significant benefits over the years for industry.

- Under the Cooperative Agreement, WRI has built a modular, well-instrumented coal combustion test facility that mimics a coal-fired utility boiler in residence time and furnace temperature profile. This facility is being used for technology development and technology verification projects for national and international utilities, for coal technology companies, and for combustion and emissions control equipment manufacturers.
 - working with our clients, we are testing new and cheaper methods for reducing NO_x emissions such as injection of coal and biomass-based slurries, injection of hydrogen and syngas, injection of ozone;
 - working with our clients, we are testing cheaper sorbents and methods for capturing mercury. One such scheme reinjects the unburnt carbon recovered from the fireball of the boiler to capture mercury. This technology, thief carbon, can reduce the cost of mercury capture to a fraction of that for conventional activated carbon. Thanks to our cooperative agreement with the USDOE, the thief carbon WRI made in the CTF was recently injected by a utility in a 600MW unit to show that indeed thief carbon is nearly as effective as activated carbon;

- working with our clients we are testing advanced combustion concepts such as oxy-fuel combustion as a multi-pollutant control strategy for not only the sequestration-ready, power plants of the future but developing a technology that can benefit our existing fleet of power plants; and
 - working with our clients, we are looking to the future and testing cheaper ways of making oxygen. Novel concepts for separating oxygen from air for use in the coal combustion processes are being tested at the combustion test facility.
- WRI has been developing synthesis technologies to produce transportation fuels. One such technology can convert any carbonaceous feedstock into a mixture of alcohols, and the mixture is ready for use as a gasoline blend.
 - Imagine a confined animal feedlot. Animal waste is collected and processed in bio-digesters. Using the technology being demonstrated by WRI and partners, the digester gas becomes a mixture of alcohols for use in our cars, a transportation fuel.
 - Imagine a remote abandoned natural gas field. Using the technology being demonstrated, this field can make transportation fuel that can be trucked to the markets.
 - Imagine a biorefinery where forestry waste, animal waste, agricultural waste is processed using the technology developed at WRI to convert these renewable feedstocks into transportation fuel.
 - Imagine a power plant where Wyoming coal is the feed. Using the technology developed at WRI under the Cooperative Agreement, the plant not only produces electricity but also synthesizes mixture of alcohols.

In conjunction with the appropriate gasification scheme this synthesis technology is a coal-to-liquids technology. In the same spirit, for remote natural gas fields this technology is a gas-to-liquid technology. As a biogas-based system, this technology is a means of capturing and converting green house gasses into a useful product.

- Under the auspices of the Cooperative Agreement, WRI is developing and testing unique, low-cost biomass gasification technologies for smaller-scale, distributed power generation applications. At WRI, we believe that our Nation's farmers and renewable energy are an essential part of our energy future. Technologies for distributed power generation and distributed production of synthetic fuels and chemicals from renewable resources have been an integral part of research under the Cooperative Agreement.
- Under the auspices of the Cooperative Agreement, WRI has developed and patented a process for upgrading PRB coal by thermally removing mercury prior to combustion at the power plant, thus eliminating the need for costly carbon injection to meet new mercury regulations. A recent economic study for the Electric Power Research Institute has shown this process to be one of the lowest-cost technologies for removing mercury from PRB coal-fired power plants.

- Under the auspices of the Cooperative Agreement, WRI has developed a patented Thermal Enhancement (WRITE) process for heavy oil upgrading. The process a variant of the TaBoRR technology developed under the Base Program, converts bitumen (e.g. heavy oil, oil sands) into residuum-free oil whose density and viscosity meet pipeline specifications. A Canadian company has acquired the rights to the WRITE technology and is cosponsoring the development of a commercial-scale demonstration plant. When deployed, the technology will reduce our dependence on oil shipments from unstable parts of the world.
- In Wyoming, CBM produced water-related environmental issues are paramount in developing this resource. Under the Cooperative Agreement, WRI worked with producers to demonstrate beneficial agricultural and related uses for this precious water. At the same time, under the Base Program several new concepts were tested for water purification and reuse.
- WRI has taken a lead role in policy support for air quality regulations by creating and facilitating the Subbituminous Energy Coalition (SEC). The organization's approximately 50 members represent the major coal companies in the Powder River Basin, utilities burning PRB coal, railroads serving the PRB, and other interested parties. The SEC provides a forum for industry discussions on environmental control issues and provides a collective voice for PRB coal producers and users. The SEC has orchestrated a detailed review of proposed EPA mercury rules to ensure that subbituminous coal remains an environmentally acceptable and competitive fuel source. Looking to the future, SEC is poised to tackle CO₂ emissions and related issues.
- Under the Cooperative Agreement, WRI has developed value-added uses for power plant coal combustion by-products. Use of these materials for applications such as mine-site subsidence control, soil amendment, acid mine drainage mitigation, and construction were developed and tested.
- Environmental consequences of energy and fuels production are paramount in our research programs. Under the auspices of the Cooperative Agreement, WRI scientists developed and tested site-specific bio-remediation technologies for restoring contaminated soils and water.
- WRI has developed or made significant contributions to several environmental testing and sampling instruments currently (or soon to be) commercially available. Examples include Soil Test Kit for in-the-field quantitative analysis of hydrocarbon contaminants in soil, integrated storing field soil samples for volatile analysis, and the X-Wand, an instrument for measuring halogenated volatile organic compounds, a common but difficult to measure class of contaminants. All three are commercially available.

Looking to the future, WRI is continuing to implement an ambitious research and technology demonstration agenda under the new five-year Cooperative Agreement. With the establishment

of the state-supported University of Wyoming School of Energy Resources, there is an opportunity for collaborative research between the University faculty and WRI staff. Collaborative research will also allow us to add an education and training component to our Cooperative Agreement projects thereby meeting our demand for trained energy professionals.