1.0 INTRODUCTION

The U.S. Department of Defense (DOD), through an Interagency Agreement with the U.S. Department of Energy (DOE), initiated a three-phase program with the Consortium for Coal-Water Slurry Fuel Technology, with the aim of decreasing DOD's reliance on imported oil by increasing its use of coal. The program was conducted as a cooperative agreement between the Consortium and DOE. The first two phases were previously reported (Miller et al., 1997; Miller et al., 2000) and the third and final phase is reported herein.

This introduction of the report discusses the overall project objectives, summarizes the results from the first two phases, and provides an outline of the third phase of the project.

1.1 DOD Project Objectives

The general objectives of the cost-shared cooperative agreement were to:

1. Establish a National Center of Excellence for Coal Utilization to decrease DOD dependence on foreign oil and increase its use of coal by pursuing a program of research and development and actively participating in technology transfer;
2. Promote both the public and private sector deployment of technologies for utilizing coal-based fuels in oil-designed combustion equipment; and
3. Provide a continuing environment for research and development of coal-based fuel technologies for small-scale applications at a time when market conditions in the U.S. were not favorable for the introduction of coal-fired equipment in the commercial and industrial capacity ranges.

To achieve the objectives of the project, a team of researchers was assembled and the members of the Consortium for the Phase III activities were Penn State (The Energy Institute, Department of Energy and Geo-Environmental Engineering, and Department of Energy, Environmental, and Mineral Economics), AMAX Research and Development Center, Corning Incorporated, and Foster Wheeler Development Corporation.

Phase I activities were focused on developing clean, coal-based combustion technologies for the utilization of both micronized coal-water mixtures (MCWMs) and dry, micronized coal (DMC) in fuel oil-designed industrial boilers. Phase II research and development activities continued to focus on industrial boiler retrofit technologies by addressing emissions control strategies for providing ultra-low emissions when firing coal-based fuels. Phase III activities expanded upon emissions reduction strategies through the use of deeply-cleaned coals as a means of reducing air toxics. Each phase included an engineering cost analysis and technology assessment.

1.2 Summary of Phase I Activities

Phase I activities were focused on developing clean, coal-based combustion technologies for the utilization of both MCWMs and DMC in fuel oil-designed industrial boilers. These technologies were identified by the U.S. Corps of Engineers, Construction Engineering Research Laboratory, as the two top priorities from a list of six topics for initial study (Schanche 1992). The specific objective in Phase I was to deliver fully engineered retrofit options for a fuel oil-designed watertube boiler located on a DOD installation to fire either MCWM or DMC. This was achieved through fundamental, pilot-scale, and demonstration-scale activities investigating coal beneficiation and preparation, and MCWM and DMC combustion performance. In addition, detailed engineering designs and an economic analysis were conducted for a boiler located at the Naval Surface Warfare Center, near Crane, Indiana.

1.2.1 Coal Beneficiation and Preparation Studies

Samples of six coals representing a range in the relative processing complexity required to meet sulfur and ash specifications for use in fuel oil-designed boilers were procured. Each of the samples was subjected to extensive characterization by float-sink analysis to determine the required level of cleaning. Some of these coals, and much of the potential reserve base, cannot be cleaned to the $<5\%$ ash, $<1\%$ sulfur specification by conventional means. Preliminary liberation models were developed in order to establish appropriate (conventional) cleaning strategies. Fine-coal cleaning processes including fine gravity separations and surface-based processes such as froth flotation and selective agglomeration were evaluated for their applicability to those coals which require fine grinding to achieve the necessary liberation. The factors that determine the size consist required for MCWM and the grinding/classification systems needed to obtain the desired size distribution were also investigated. A dry coal cleaning system based on tribolelectrostatic separation was evaluated particularly for DMC applications where dry cleaning would be preferred over wet cleaning.

1.2.2 MCWM and DMC Combustion Performance Evaluation

The combustion performance evaluation included conducting fundamental studies to determine the effect of the mineral matter on boiler tube erosion and deposition, identify the mechanism of atomizer wear (corrosion or erosion), and computationally model the burner and boiler. In addition, MCWMs and DMC produced from the candidate coals were fired in 1,000 and 15,000 lb steam/h watertube boilers. The fuels were fired in the 1,000 lb steam/h boiler in order to determine their relative performance, while one of the coals was used in two demonstrations firing DMC and MCWM in the 15,000 lb steam/h boiler (which is of similar size to the retrofit candidate at Crane). The accomplishments in this aspect of the project included: modifying and optimizing a full-scale boiler system to fire DMC and MCWM; integrating the coal storage, handling, and micronization with the burner (for DMC firing); achieving 95% combustion efficiency (DMC); determining that erosion is not significant in the convective pass; and meeting targeted NO_x, emissions of <0.6 lb/MM (million) Btu.

1.2.3 Engineering Design

Two engineering studies were performed for the complete retrofit of a DOD boiler to fire either DMC or MCWM. Each design package includes a fuel preparation system (for the DMC option only; two conceptual MCWM processing circuits were prepared but not engineered), fuel delivery and handling systems, low-NO_x burner, baghouse, forced-draft fan, combustion air preheaters, induced-draft fan, ash silo, stack, and control system. The retrofit designs conform to accepted engineering practices and site requirements. The designs were based on the system in place at Penn State and the information that was learned from operating it. The design packages are intended to be used for soliciting bids from engineering/construction firms for completion of the detailed design, construction, and start-up of the candidate DOD boiler.

1.2.4 Cost/ Economic Analysis

With respect to direct capital and operating cost considerations, retrofit DMC and MCWM technology boilers are not economically viable over a broad range of parameters for the Crane Site. For boiler retrofits to become economically viable, capital cost must be reduced, transportation costs of MCWM must be reduced, higher performance must be attained, and demand for slurry fuel in any given local area must be increased. Improving these parameters would increase the price differential of the DMC and MCWM with respect to fuel oil and natural gas.

With respect to direct capital and operating cost considerations, new DMC and MCWM technology boilers are not economically viable over a broad range of parameters for the Crane Site. There does not exist a sufficient critical mass of military boilers in one location to transform this into a viable option. For new DMC and MCWM technology boilers to become economically viable, capital costs and boiler derating must be reduced, higher performance must be attained, or fuel costs must be lowered.

Retrofit capital costs, followed by transportation costs, are the major inhibiting factors to the economic viability of MCWM technology at the Crane site. DMC delivered fuel costs are insensitive to fuel demand level. Transportation costs can be improved by developing a lower cost system of transportation dedicated solely to coal. With respect to environmental regulations, DMC and MCWM technologies are economically viable under a broad range of circumstances. Given the small size of industrial boilers, existing pollution control devices will adequately meet environmental regulations. The regional multiplier effects of DMC and MCWM technologies are not significant for cases of less than 10 and 15 Crane size-equivalent installations, respectively, in a substate area. Regional multiplier effects can be significantly enhanced by purchasing more inputs from local vendors, though the sites where this is possible are limited.

1.3 Summary of Phase II Activities

As the project progressed, Phase II was modified to incorporate results from Phase I and reflect programmatic changes by DOD. The original objectives of Phase II were to: (a) extend the Phase I boiler retrofit options by including designs to achieve further reductions in gaseous and particulate emissions, (b) prepare and characterize fuels compatible with coal precombustors, and (c) investigate precombustion as a means of using high ash, high sulfur coals. Upon investigating precombustion options for installing a system on either the demonstration boiler (15,000 lb steam/h) or research boiler (1,000 lb steam/h), it became apparent that there were limited viable options and that the complexity of the systems would likely preclude their use on small-scale, industrial boilers. A similar conclusion was presented by the U.S. Corps of Engineers regarding the use of slagging combustors in the Army (Davidson et al., 1991). Consequently, the Phase II work was revised by eliminating the precombustion studies and focusing on emissions reduction strategies.

1.3.1 Emissions Reduction

Strategies were developed to provide for ultra-low emissions when firing coal-based fuels in industrial boilers. Emissions that were addressed were SO_2, NO_x, fine particulate matter ($PM_{2.5}$), and air toxics (trace elements and volatile organic compounds). To accomplish the overall objective, emissions reduction strategies were reviewed, fundamental and pilot-scale studies were conducted, and selected emissions reduction techniques were demonstrated.

It was the intent of this activity to reduce the emissions levels of SO_2, NO_x, and particulate matter from that obtained in Phase I of the project. The Phase I emissions levels were 1.2 lb SO_2/MM (million) Btu (using low-sulfur coals), 0.6 lb NO_x/MM Btu (using low-NO_x burners), and <0.1 lb particulate matter/MM Btu (Penn State's demonstration boiler's permitted level from the Department of Environmental Protection) and >99.5% collection efficiency using a fabric filter baghouse. The Phase II targets, which are those from the U.S. Department of Energy's (DOE) High Performance Power Systems program, were: SO_2 <0.1 lb/MM Btu; NO_x <0.1 lb/MM Btu; and particulate matter <0.003 lb/MM Btu. The SO_2 and NO_x targets were met; however, the particulate matter emissions were slightly greater than the target and were ≈0.005 lb/MM Btu. In addition to achieving the SO_2, NO_x, and particulate matter emissions, a detailed characterization of air toxics from coal-fired industrial boilers was conducted to assist DOE in determining the levels and composition of air toxic emissions to identify control strategies.

1.3.2 Coal Preparation/ Utilization

Research was carried out on the design of coal grinding/classification systems for the efficient production of optimally formulated MCWM, and on the development of advanced processes for beneficiating high ash/sulfur coals. Detailed investigations of the rheology and stability of bimodal (coarse/fine) slurries demonstrated that these can be used to achieve high solids loading at acceptably low viscosity provided the appropriate composition range (coarse:fine) is maintained. This constraint was especially critical as the solids loading is increased. Investigation of a two-stage grinding/classification scheme demonstrated that this approach could be used both to permit grinding under reasonably optimum conditions and to provide considerable flexibility in product composition. General criteria for slurry formulation and for the design and operation of the grinding circuit were established. Simulations of dense-medium separations were performed to examine the effects of design and operating conditions on the separation efficiency for 28x100 mesh coal. Dense-medium separations were carried out using a solid-bowl centrifuge to process 100x150 mesh coal. Magnetic fluids were tested as an alternative medium in float-sink separations. Studies of the use of froth flotation for deep-cleaning high ash/sulfur coals revealed that single-stage separations are often inadequate. Several different grinding-flotation circuits were investigated in order to establish the role of circuit configuration in the efficiency of coal cleaning. The results indicated that the most effective circuit depends strongly on coal type. Fundamental studies of flotation kinetics were conducted in order to establish the basis for process/circuit design and control. Emphasis was on the development of procedures for evaluating the distributions of flotation rate constants for the various floatable components. These kinetics parameters represented the key to the role of coal characteristics in flotation circuit performance. Column flotation is an attractive alternative to conventional flotation for deep cleaning of coal, particularly because of the froth-washing capability. Laboratory studies were used to establish column operating conditions for the production of clean coal from different feed sources. Process simulations were used to evaluate the performance of three-stage (rougher/cleaner/scavenger) circuits for producing clean coal at <5 wt.% ash with maximum combustibles recovery. The classification and cleaning steps in slurry production must generally be carried out at relatively low solids concentration. A preliminary analysis of the use of gravity sedimentation methods for slurry density control following these steps was also performed. Studies of dry cleaning included testing of a batch triboelectrostatic separator to examine the effects of surface moisture, humidity, and particle size on the separation of Upper Freeport, Pittsburgh and Indiana seam coals. A laser-sheet generator was fabricated for use in examining particle charge after tribocharging.

1.3.3 Engineering Design and Cost; and Economic Analysis

The widespread adoption of new coal-fired boilers has economic impacts beyond initial capital expenditures and the subsequent increased demand for coal. Results indicated that modest, but far from insignificant, gains would be transmitted throughout the surrounding regional economy via multiplier effects. In addition, despite improved combustion efficiency, which leads to a relative decrease in most pollutants, a relative increase in CO_2 emissions may ensue.

Research found the market potential for private sector retrofits of industrial boilers to MCWM to be rather modest in Pennsylvania at the energy prices in effect in the mid-1990s (note, the prospects are much better if coal refuse is utilized but much worse if the current lower price of oil is considered). The shift away from oil to coal, however, generates relatively more business in Pennsylvania, especially if it displaces foreign oil, and could translate into as many as 10,000 new jobs on a sustained basis.

Public attitudes toward new coal-fired boiler adoption were examined and it was found that such concerns were a rather low priority among a long slate of environmental issues. Finally, it was noted that the increased energy conversion efficiency and pollution reduction capability of MCWM technology relative to oil-fired units reduced all pollutants but would likely lead to a relative increase in CO_2 emissions, though of a trivial total amount.

Finally, the economic impact of a carbon tax on the Pennsylvania economy was examined and found a minimal overall economic impact, though a sizeable negative impact on the State's coal industry.

1.4 Phase III Project Outline

As the project progressed, Phase III was modified to reflect results from Phase II and programmatic changes by DOD and DOE. The original objectives of Phase III were to: (a) develop coal-based fuel/waste cofiring technologies, and (b) assist DOD in improving the combustion performance and reducing emissions from existing stoker-fired boilers. Since the initial development of the program's statements of work (Phases I through III), there has been a change in military boiler plant operating philosophy. This, coupled with recent developments in cofiring technologies and DOE coal preparation programs, necessitated the revision of the Phase III statement of work. Consequently, the Phase III work was revised by eliminating coal-based fuel/waste cofiring and stoker combustion performance analysis and evaluation, and focusing these efforts toward evaluating deeply-cleaned coals as industrial boiler fuels, and investigating fundamental, pilot-scale, and demonstration-scale emissions reduction strategies. The revised Phase III consisted of five tasks as outlined below:

Task 1. Coal Preparation/Utilization

- Subtask 1.1 Particle Size Control
- Subtask 1.2 Physical Separations
- Subtask 1.3 Surface-Based Separation Process
- Subtask 1.4 Dry Processing
- Subtask 1.5 Stabilization of Coal-Water Mixtures

Task 2. Emissions Reduction

- Subtask 2.1 SO_2 Reduction
- Subtask 2.2 NO_x Reduction
- Subtask 2.3 Study VOC and Trace Element Production, Reduction, and Capture

Task 3. Economic Evaluation

- Subtask 3.1 Cost and Market Penetration of Coal-Based Fuel Technologies
- Subtask 3.2 Selection of Incentives for Commercialization of the Coal-Using Technology
- Subtask 3.3 Community Sensitivity to Coal Fuel Usage
- Subtask 3.4 Regional Economic Impacts of New Coal Utilization Technologies
- Subtask 3.5 Economic Analysis of the Defense Department's Fuel Mix
- Subtask 3.6 Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects
- Subtask 3.7 Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies
- Subtask 3.8 Integrate the Analysis

Task 4. Evaluation of Deeply-Cleaned Coals as Boiler Fuels

- Subtask 4.1 Modify MCWM Preparation Circuit
- Subtask 4.2 Fuels Characterization
- Subtask 4.3 Pilot-Scale Combustion Tests
- Subtask 4.4 Demonstration-Scale Combustion Tests

Task 5. Final Report

1.5 References

Davidson, J.E., Hartsock, D.K., Conley, A.D., Hein, R.L. and Schanche, G.W., 1991, "Overview of Slagging Coal Combustion Systems as Applied to Army Central Heat Plants," Technical Report, USA CERL, E-91/04.

Miller, B.G., Morrison, J.L., Pisupati, S.V., Poe, R.L., Sharifi, R., Shepard, J.F., Walsh, P.M., Xie, J., Scaroni, A.W., Hogg, R., Chander, S., Cho, H., Ityokumbul, M.T., Klima, M.S., Luckie, P.T., Rose, A., Addy, S., Considine, T.J., Gordon, R.L., Lazo, J., McClain, K., Schaal, A.M., Painter, P.C., Veytsman, B., Morrison, D., Englehardt, D. and Sommer, T.M., January 31, 1997, "The Developent of Coal-Based Technologies for Department of Defense Facilities Phase I Final Report," U.S. Department of Energy, Federal Energy Technology Center, Cooperative Agreement No. DE-FC22-92PC92162, 590 pages.

Miller, B.G., Boehman, A.L., Falcone Miller, S., Hatcher, P., Knicker, H., Krishnan, A., McConnie, J., Moulton, B., Pisupati, S.V., Shepard, J.F., Vittal, M. Wincek, R.T., Scaroni, A.W., Hogg, R., Chander, S., Cho, H., Ityokumbul, M.T., Klima, M.S., Luckie, P.T., Rose, A., Addy, S., Crombie, D.R., Gordon, R.L., Harley, K., Jung, G., Lazo, J., Li. P.C., McClain, K., Schaal, A.M., Smead, J., Strellac, K., Mansour, A., Humphrey, W., and Chigier, N., July 31, 2001, "The Developent of Coal-Based Technologies for Department of Defense Facilities Phase II Final Report," U.S. Department of Energy, National Energy Technology Laboratory, Cooperative Agreement No. DE-FC22-92PC92162, 784 pages.

Schanche, G.W., October 23, 1992, Personal communication, DOD/DOE Coal Utilization Project Meeting No. 1, Pittsburgh, Pennsylvania.