10 MMBtu/Hr AFBC Commercial Demonstration
Cedar Lane Farms – Wooster, OH

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Final Report

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Ohio Coal Devlopment Office of the Ohio Air Quality Development Authority

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Disclaimer

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OCDO Program Manager - Robert Brown

DOE-NETL Program Manager - Donald Bonk

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AUTHORS

This report was prepared by Harold M. Keener and Mary H. Wicks Ohio Agricultural Research and Development Center/The Ohio State University on behalf of AFBC Transitions, LLC.

Project history and design details were provided by Tom Machamer, Dave Hoecke, Don Bonk and Bob Brown

POINTS of CONTACT

For more information regarding the Atmospheric Fluidized-Bed Combustion (AFBC) at Cedar Lane Farms, please contact:

Bob Brown -- Ohio Coal Development Office, 50 West Broad Street, Columbus, Ohio 43215-5910, phone 614-466-3465, email bbrown@aqda.state.oh.us

Donald Bonk -- USDOE-NETL, 3610 Collins Ferry Road, P.O. Box 880, Morgantown, WV, 26507-0880, phone 304-285-4889, email donald.bonk@netl.doe.gov.

David Hoecke -- Enercon Systems, 300 Huron Street, Elyria, Ohio 44035, phone 440-323-7080, email enercon@earthlink.net.

Tom Machamer -- Cedar Lane Farms, 5713 Back Orrville Road, Wooster, Ohio 44691, phone 330-264-6200, email machamer@valkyrie.net

Anatol Kwartler, AFBC Transitions, 169 S. Main Street, P.O. Box 900, Orrville, Ohio 44667-0900, phone 330-684-5319, email akwartler@willburt.com

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EXECUTIVE SUMMARY

The objective of this project was to demonstrate and promote the commercialization of coal-fired atmospheric fluidized bed combustion (AFBC) systems, with limestone addition for SO_2 emissions control and a baghouse for particulate emissions control. This AFBC system was targeted for small scale industrial-commercial-institutional space and process heat applications in the 4-40 MMBtu/hr size range. A cost effective and environmentally acceptable AFBC technology in this size range could displace a considerable amount of heating gas and oil with coal, while resulting in significant total cost savings to the owner/operators.

Two project teams were assembled that provided state-of-the-art small AFBC technology and experience in engineering, manufacturing and marketing of small coal-fired equipment (stokers) for residential, commercial, and small industrial use. The first team (1987 to 1997) was the Ohio Agricultural Research and Development Center of Ohio State University (OARDC), Cedar Lane Farms (CLF) and the Energy and Environmental Research Corporation (EER). Their efforts involved three phases: Feasibility, Subsystem Development and Integration, and Proof-of-Concept (OCDO Project D-931-10). In the Feasibility Phase, the technical and economic feasibility of a 1 million Btu/hr (MMBtu/hr) coal-fired AFBC air heater was evaluated. In the Subsystem Development and Integration Phase, a small scale (1.5 MMBtu/hr) atmospheric fluidized bed combustion system was developed and tested. In the Proof-of-Concept Phase, a 2.2 MMBtu/hr unit was installed and successfully operated at Cedar Lane Farms (CLF), a commercial nursery in Ohio to heat hot water which was recirculated through greenhouses for cool weather heating. The U.S. Department of Energy (DOE) sponsored

the development effort through all phases. The Ohio Coal Development Office (OCDO) was the major funding sponsor for the Proof-of Concept Phase. The system was designed to be fully automated with minimal operator attention required. It incorporated flyash/sorbent reinjection and an under bed feed system to improve limestone utilization. Testing results showed the system lowered the Ca/S ratio from ~3.0 to ~2.0 while maintaining an SO_2 emissions level of 1.2 lb/MMBtu when burning the high sulfur Ohio coal with 3% sulfur (see Project D-931-10 Final Report, 1997).

The second team was Cedar Lane Farms; AFBC Transitions, LLC; DOE-National Energy and Technology Laboratory, Morgantown Enercon Systems and the Ohio Coal Development Office. This team used results from the earlier studies to design a larger commercial size AFBC, which would be more economical to build and operate. The new system design was an 8.5 MMBtu/hr combustor detailing all system components so AFBC Transitions, LLC could develop definitive fabrication costs for the combustor. This commercial phase of development was OCDO Project D-97-12.

The commercial AFBC was built using two pneumatic feed systems to transport the coal into the AFBC bed, instead of an under bed combined feed system of the earlier D-931-10 project. This new feed system also injected limestone with the recycled flyash and the fuel and sorbent was mixed by the motion of the fluidized bed. Recycled fly ash and spend sorbent, captured in a knockout box after the boiler, was pneumatically conveyed back into the bed by the limestone transport system. Use of pneumatic conveyance for the fuel and sorbent to the bed, instead of augers, prevented sand backflow into the feed transport line and eliminated the frequent occurrence of plugging of the feed pipes to the burner as occurred in the prototype design. The combustor design also included a new above-bed, natural gas startup heater rather then an induct air pre-heater ahead of the air plenum. This simplified the design and reduced capital costs.

In the 8.5 MMBtu/hr system, the hot water heater was a three pass horizontal fire tube, Kewanee 7L90 - Type C boiler which was thought to be typical of industrial boilers that might be retrofitted with the AFBC. Soot blowing was achieved by a blast of compressed air through the tubes. The tubes were divided into eight banks. One bank of tubes was cleaned every 15 minutes with two hours required to complete the cycle for all eight banks. This feature reduced the capital and operating cost.

The commercial AFBC is fully automated and cycles between a combustion mode and slumped bed mode depending on the amount of heat ~~is~~ required in the greenhouse. The control system monitors and controls fuel and limestone feed as required to maintain the bed temperature between 1550-1575^{o} F. The oxygen level at the combustor exit is monitored and maintained near 3% by controlling the fluidization fan speed. Numerous alarms and control circuits are incorporated to ensure safe unattended operation.

Environmental compliance testing was conducted by Air Compliance Testing, Inc. of Cleveland, Ohio. Three tests were run using an Ohio #6 coal with 3.71% sulfur and 13,809 Btu/lb on a dry weight basis. Sulfur was controlled using a dolomitic limestone. In a fully automated operational mode, the bed temperature was held steady from 1550-1575^{o} F. The oxygen set point was 3% at the stack. The average sulfur emission for the three runs was 0.65 lb SO_2 per MMBtu with a Ca/S molar ratio near 1. Opacity was zero. The study did not include optimization of NOx reduction. The enhanced efficiency of SO_2 capture per mole of Ca is emphasized and largely attributed to better distribution of limestone in the bed and operation of the bed at optimum temperature for SO_2 capture.

Thermal efficiency during the compliance testing was estimated at 87%. This estimate was based upon the heat and mass balances analysis of fuel and air into the system, combustion air and ash out of the system, carbon content of the fly ash, and heat losses typical for combustors with this type of construction.

A preliminary design was completed for the balance of plant equipment which included the receiving and storage equipment for fuel and lime, fuel preparation with a Gundlach, Accu-Grind roller mill to size the coal between 1/4" and under, and process controls. The lime and coal storage bins were sized to receive a 27-ton semi truck load with some excess capacity. Process controls were for a fully automated system with redundancy as needed for safe operations without an operator present through the night.

Price quotations were received on all major equipment items and total capital costs are presented in Table 1 for systems of 10 to 30 MMBtu/hr. Costs will vary depending on coal infrastructure already on site such as boilers to be heated with the AFBC, and the coal, limestone, and ash bins. Hopper-to-Stack equipment similar to the AFBC system demonstrated at Cedar Lane Farms is estimated at $750,000.

The economic advantage of an AFBC system versus a natural gas hot water system is presented in Table 2 based upon the current price of coal delivered at $53/ton and natural gas at $9/MMBTU plus a $5/MM BTU delivery charge for January-March 2006. With the current high price of natural gas, the AFBC capital costs could be recovered in as little as two heating seasons.

Table 1. 2005 Estimated budget costs for Hopper-to-Stack equipment similar to Cedar Lane Farms AFBC equipment

Size of AFBC Unit	**Estimated Cost**
10 MM Btu/hr coal input	$750,000
20 MM Btu/hr coal input	$1,300,000
30 MM Btu/hr coal input	$1,800,000
Not included in the above costs are financing, permitting and compliance stack testing. In addition, foundations and buildings, freight to site, and installation costs are dependent on site coal infrastructure and not included.	

Table 2. Estimated annual fuel cost savings with coal-fired AFBC at Cedar Lane Farms

Type Unit	**Capital Costs**	**Fuel Costs**	**Annual Capital and Operating Costs**	**Annual AFBC Savings**
AFBC	$750,000	$53/ ton	$355,800	-----
Natural Gas	$101,400	$8/ MMBtu	$618,500	$262,000
Natural Gas	$101,400	$10/ MMBtu	$766,200	$410,900
Natural Gas	$101,400	$14/ MMBtu	$1,062,000	$706,200
Based upon a 10 MMBtu/hr high sulfur coal-fired AFBC for hot water applications. Heating season set at 250 days per year at 100% capacity.				

The Ohio Long Term Forecast of Energy Requirements, 2003-2023, showed an annual energy consumption of 8.98 x 10^{14} Btu by the industrial/commercial market sector in Ohio in 2003 (PUCO). Based on a U.S. EPA study (as cited in EER, 1997), commercial /industrial boilers in the size range of 7.3 to 29.3 MMBtu/hr, firing mostly natural gas and fuel oil, make up about 25% of the total energy consumed by the industrial/commercial market sector. Applying this percentage of energy consumption to the State of Ohio, it was estimated that boilers in the above size range consumed approximately 2.2 x 10^{14} Btu/yr.

The AFBC developed under this program has applicability to boilers in the 4-40 MMBtu/hr size range. Assuming that coal fired in the AFBC units could increase coal consumption in this sector by 15% of the 1994 market share, by the year 2010 Ohio coal consumption would increase about 1.3 million tons/year.

The AFBC development has been very successful and widespread implementation of this AFBC system, could start to reverse the trend of decreasing coal use by the commercial, industrial, and institutional market sectors. With the widespread use of this technology, other benefits will arise in the form of increased business revenues from the sale of indigenous coal, and the possible sale of the flyash/sorbent by-product as a soil cement or soil conditioner. The AFBC will also provide a reduction in fuel costs for the users of the technology that will help make their products more cost competitive and maintain jobs in Ohio. The commercialization of the AFBC will result in a new technology that will be fabricated in Ohio and marketed throughout the United States and abroad.

1.0 INTRODUCTION

In the past, oil and gas have been the fuels of choice for the space and process heat requirements of commercial and small industrial applications. This was because of the convenience and cleanliness offered by these fuels compared to coal. Today however, the soaring prices of these fuels (Figure 1.0.1) make coal the lowest cost source of fossil energy. In addition, there are socioeconomic pressures in coal producing states, especially Ohio, to provide technologies which will enhance the acceptability of coal for these applications.

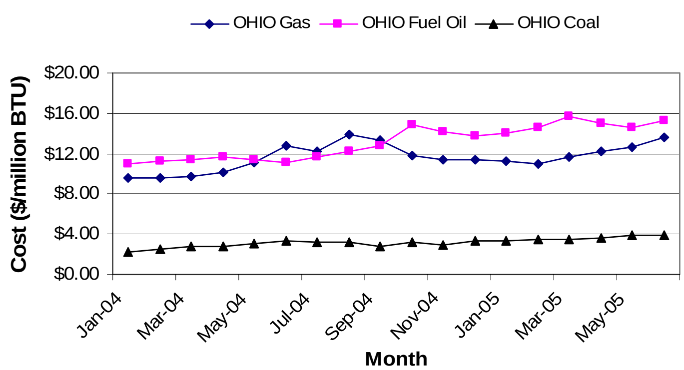

Figure 1.0.1. Cost comparison of energy provided by gas, fuel oil and coal in Ohio. Based on Natural Gas*-102,900 Btu/ccf (96% efficiency), Fuel Oil (No. 2) -138,690 Btu/gallon (87% eff), Coal - 24,916,000 Btu/ton (87% efficiency). Efficiencies reflect best possible designs

Commercial/small industrial boilers, i.e., those in the range of 7.3 to 29.3 MMBtu/hr, use mostly natural gas and oil and account for approximately 25% of the total gas and oil consumed. In the State of Ohio these boilers in 1994 consumed about 2.2×10^{14} Btu/year. It is estimated that if 25% of the oil- and gas-fired boilers/heaters in this size range were converted to coal, then Ohio coal consumption would be increased by some 1.3 million tons/year, or approximately 10% of the coal used in the commercial/industrial market sector in Ohio in 1994 (cited in EER, 1997).

Atmospheric fluidized bed combustion (AFBC) offers several potential advantages over conventional stoker-fired coal combustion systems for small scale market applications:

Minimal Fuel Processing. With the exception of high moisture and freezing of the coal under Ohio's winter conditions, which affects feed handling, the combustion process itself is not overly sensitive to the physical characteristics of the coal feed. Also, the AFBC system has a higher combustion efficiency than conventional stoker systems.

Low Temperature Combustion. Fluidized beds operate at low temperatures. This avoids problems such as clinker formation and slagging, which are major areas of concern with certain other coal-fired systems, and it can reduce nitrous oxide (NO_x) and carbon monoxide (CO) emissions.

SO_2 Emission Control. Limestone sorbent in the fluid bed reacts with the sulfur dioxide (SO_2) liberated during the combustion process to control SO_2 emissions. Emissions can be reduced in excess of 80 percent.

Potential small scale coal-fired, AFBC users include institutions (schools, hospitals, prisons, government), light industry (agriculture, food processing), commercial buildings (shopping centers), and large residential buildings (apartment complexes).

AFBC systems have been developed for several applications. However, at the start of this development program there was no commercial equipment available in the size range used by small scale market sectors. The overall goals of this program were:

- To demonstrate that an AFBC could satisfy the market and environmental requirements for small commercial and industrial heating systems.
- To provide the necessary background of operating experience to ensure the market acceptability of a small scale AFBC.
- To demonstrate that a reliable, automated computerized control system could minimize labor inputs.
- To actively promote the commercialization of the AFBC.

The first three goals have been met as indicated by the two years of successful operation of the system. AFBC Transitions, LLC, with support from Enercon is actively marketing the developed product.

2.0 SMALL SCALE AFBC DEVELOPMENT

A 1997 report (OCDO D-931-10 Final Report) outlined the development of small scale, less than 5 MMBtu/hr, AFBC systems. It reported on a study which demonstrated the economical and technical viability of a prototype commercial sized (2.2 x 10^6 Btu/hr) AFBC systems for use in the generation of hot water for greenhouse heating. The site for this demonstration was Cedar Lane Farms, Inc. (CLF), a nursery near Wooster, Ohio. Cedar Lane Farms grows and produces roses, perennials, flowering hanging baskets, potted flowering plants, vegetable flats and poinsettias. The greenhouse area under glass and heated by Cedar Lane Farms totals some 200,000 ft^2. The 2.2 MMBtu/hr AFBC provided heat to a portion of the greenhouse area and tied into an existing hot water distribution system that includes one coal-fired stoker and two natural gas-fired hot water heaters.

3.0 COMMERCIAL DEMONSTRATION

The proof of concept phase (commercial prototype application) began in November 1998. It involved demonstration of a 8.5 million Btu/hr AFBC with the goal to successfully develop an AFBC system to meet the needs of the small scale commercial and industrial markets. The demonstration of this commercial size unit was completed in three phases as follows:

Phase 1 -Engineering/Purchasing

Phase 2 -Construction and Startup

Phase 3 -Long Term Testing

3.1 Phase 1 - Engineering/Purchasing

The purpose of this phase of work was to complete the engineering design and purchase of additional equipment that was required for the commercial demonstration at CLF. Design activities included the development of mass and energy balances, process flow diagrams, piping and instrument diagrams, process control logic, specification of process equipment, piping specifications, and electrical equipment, equipment layout drawings, and structural and civil work. Following specification of equipment and process controls, items required for the construction phase of the project were purchased. The major tasks within Phase 1 were as follows:

Task 1 - Engineering

This task consisted of the development of piping and instrument diagrams, sizing of equipment, and conceptual control logic. Near the end of the process engineering work, a process design review meeting was held with the detail design group to discuss the design and determine what, if any, improvements might be made to provide a better design. The drawings from this phase are on file within the OCDO in Columbus, Ohio.

Task 2 - Detail Design Engineering

This task included all of the detail engineering activities required for purchasing and installing equipment. These activities included detailed specification and selection of process, control, piping and electrical equipment; the development of finalized piping, instrument and electrical diagrams; and structural and civil engineering.

Task 3 - Purchasing

This task included the purchase of all new equipment required for the installation of the AFBC system at CLF. AFBC Transitions used its standard procurement procedures for purchase of equipment items including purchase order preparation and approval, and receipt and inspection of equipment. Equipment was selected based on the following criteria; price, features, and services provided by vendor. The major equipment items purchased for the Cedar Lane Farms application are listed in Table 3.1.1.

Table 3.1.1. Motors used in the commercial system at Cedar Lane Farms

Motor	Horsepower	Volts	Amps	Rpm	Hertz
Fly ash auger (unloader)	3	230/460	8.2/4.1	1725	60
Lime auger	3	230/460	10.2/5.1	1160	60
Lime and coal unloader	2	208,230-460	6-5.6/2.8	1740	60
Bucket elevator	5	208-230/460	13.8-13/4-6.7	1750	60
Twin screw	3	230/460	8.2-4.1	1750	60
Rotary coal feed valve 1	2	208-230/460	6.5-6.2/3.1	1725	60
Rotary coal feew valve 2	2	208-230/460	6.5-6.2/3.1	1725	60
Coal feeder fan (2)	4.2-4.5	200-230/460	12-11/5.5	CFM 206	
Crusher	7.5	230/460	12-10.5	1760	60?
Forced draft fan	75	230/460	166/83	3565	60
ID fan	20	230/460	51.4/25.7	1750	60
Baghouse rotary valve	0.75	208/320/460	32.-3/1.5	1725	60
Ash auger (inside)	3?	208-280/460	10.2-9.6/4-8	1144	60
Fly ash rotary valve	0.5	230-460	3.1/1.5	1750	60
Limit fly ash auger	0.75	230-460	3.8/1.5	1750	60
Stoke feed auger	1	208-230/460	3.8-1.9	1750	120?
Fly ash reinjection fan	4.2-4.5/4.5	200-230/460	12-4.1/5.5	CFM 206	50/60
Gas burner	3	208-230/460	8.1-7.2/460	3450	60
Sand auger (top by tubing)	1/4	115	4.6	30	60
Sand auger	1	208-230/460	3.7-3.4/1.7	1725	60
Air compressor	10	208-230/480	30-28/14	1725	60

The completion of the engineering design for the facility was an AFBC with a flue gas recirculation (FGR) system that provided for high thermal efficiency, reduced SO_2 emissions from the firing of high sulfur coal, reduced NO_x emissions, and resulted in a clean stack (very minimal particulate emissions as a result of the use of a bag house). This design, although applied to a hot water heating system, would also be viable, with minimal design modifications, for steam generation. The control system logic developed is applicable for hot water, steam and electric power generation.

3.2 Phase 2 - Construction and Startup

The construction activities included civil work at CLF; installation of process, instrumentation and electrical equipment; process piping; and hookup of other utilities required for operation of the unit. It also included building construction for equipment installation. Following construction, all of the process equipment, instruments and electrical wiring connections were checked out prior to start-up. The major tasks within Phase 2 were as follows:

Task 1 - Permits

AFBC Transitions, LLC, working with the Ohio EPA, obtained the permits required for the commercial demonstration project. It also obtained specific construction permits required from State, county and local governments.

The following limitations for emissions of SO_2, particulate matter and NO_x are specified in Ohio EPA Final Permit to Install 02-19776.

Standards for Sulfur Dioxide

For coal fired steam generating units with greater than 10 MMBtu/hr heat input capacities, but less than 75 MMBtu/hr heat input capacities, the standards limit SO_2 emissions to 1.2 lb/ MMBtu coal fired.

Standards for Particulate Matter

For coal fired steam generating units with heat input capacities greater than 30 MMBtu/hr, the standards limit particulate matter to 0.05 lb/ MMBtu of coal fired and limit the capacity to 20%.

Standards for Nitrogen Oxides

For coal fired steam generating units with heat input capacities of 100 MMBtu/hr and less, there are no standards promulgated for NO_x.

Water and Solid Waste

No significant water pollution impacts are projected, and the projected impacts on solid waste generation are small. In addition, the ash and flue gas desufurization materials produced by particulate matter control processes are non-hazardous and can possibly be used in concrete, as a soil amendment or disposed of using traditional techniques.

Task 2 - Construction

This task consisted of the delivery and installation of the AFBC equipment at CLF. It included the installation of equipment, piping, pumps, instrumentation electrical equipment, etc. to provide a complete installation. This task also included building civil and structural work.

Task 3 - Checkout of Equipment

Prior to start-up, Enercon Systems, DOE-NETL, and the CLF personnel checked out the equipment. Enercon Systems contacted the Ohio EPA to obtain approval to operate.

Task 4 - Startup and Operator Training

Following checkout of equipment, Don Bonk of DOE/NETL and Dave Hoecke of Enercon Systems initiated start-up of the unit and tested it under various conditions to assess the overall operability of the installed unit. During this time, Don Bonk trained the CLF operators in the safe operation of the atmospheric fluidized bed combustion/hot water production system.

3.3 Phase 3 - Long Term Testing

Following successful startup, the long term testing program was started on the AFBC system under normal operation load requirements of CLF. The heating load requirements determined coal feed rates to the unit. Limestone was added at the required rate to reduce SO_2 emissions to 1.2 lb/MMBtu of coal fired or less. A fully automated computer control system was developed by Northwest Controls for the AFBC with sufficient redundant circuits and safety circuits to ensure reliable and safe automated operation of the AFBC. Deliverables included a copy of the program in pfd format.

3.4 Phase 4 - Long Term Testing Continued

Task 1- System Modifications

Based upon the experiences of Phase 3, the following modifications to the AFBC system were completed to enhance the reliability of the system.

1. Replace the two fan system with one fan. The dual forced draft fan approach of the original design resulted in no improvements in fluidized bed operation. Because the gas pressure across the dual forced draft fans could not be controlled precisely, intermittent imbalances caused bed material to sift from the bed down into the wind-box. The dual fans were replaced by a single fan following conventional practice and is believed to be necessary for long term reliable operation and final commercialization of this technology.

2. Relocate limestone feed. While combustion efficiency met or exceeded expectations during the first long term operating period, sulfur capture was below acceptable levels. In the current design, limestone is injected with the recycled ash from the dust collector ahead of the unit's bag-house instead of with the coal feed as in previous work. This approach saves wear on the coal feed rotary seal valves. The air transport injection used for the limestone and recycled ash was similar to that used for the coal feed.

3. Upgrade ash removal system. The attempts to remove bed solids from the center of the bed via a screw feeder was proven to be unreliable. Because of auger’s length it is difficult to clear when plugged with over size bed solids. A short coupled pulse valve assembly was designed and installed on the front wall of the combustor to provide a more reliable system.

4. Additional items to enhance ease of operation and monitoring of the system. Based upon operation during the 2004 heating season, additional in-bed and above-bed temperature thermocouples were installed along with a set of non-plugging in-bed pressure taps and gauges. Also, an improved access to the wind-box along with an additional view-port was added to the AFBC.

Task 2 - Long Term Operation

To demonstrate the reliability of the AFBC system, it was operated continuously in automated mode during the 2003-2004 and 2004-2005 heating seasons under normal operation load requirements of CLF.

Task 3 - Environmental Testing

During the 2003-2004 testing period, a data logger monitored coal feed rate, limestone feed rate, and flue gas oxygen level. This data was used to complete a mass and energy balance of the system. Environmental testing on March 25, 2004 was conducted by a certified consultant to determine the limestone to coal feed ratio required to maintain SO_2 emissions less then 1.2 lb/MMBtu.

Task 4 -Marketing Plan

A marketing plan has been developed based upon successful operations during the 2003-2004 heating season. The marketing effort was kicked off with an open house on November 5, 2004. Among other results and data to be released, Enercon Systems discussed costs to potential customers for installation of a system on a turn-key basis. During the 2004 heating season to the present time, a number of parties have visited the site and discussed systems details with Tom Machamer, et. al.

4. TECHNICAL DISCUSSION

4.1 AFBC System

The commercial AFBC system is an 8.5 MM Btu/hr AFBC combustor designed to fire coal less than 1/4 inch top size and use flue gas recirculation. Bed temperature control is achieved by regulating fuel input, and air recirculation rate instead of using in-bed heat exchangers. Limestone is used with the coal to act as a sorbent for reduction of SO_2 emissions. Sand is used as the fluid bed media. Simple auger metering and pneumatic transport feed systems are used to feed coal and limestone separately into the combustor. The combustor is a refractory lined vessel with internal dimensions of a 5 x 8 foot rectangular base and a height of 6 feet. The nominal sand slumped bed depth is 12 inches. This type of AFBC could be amendable for retro-fitting existing small scale boilers and since there are no in-bed tubes to remove heat, the system may be banked for several hours under automated control of bed temperature. Thus, this AFBC is suited for cyclical service applications such as exist in greenhouse heating applications. Maintenance done on the AFBC involves periodic removal or replacement of sand to control bed depth and repair of refractory.

To enhance overall thermal efficiency, a unique design feature of this AFBC, is the use of flue gas recycle plus fresh air for bed temperature and air/fuel ratio control. Approximately 50% of the cleaned flue gas was recycled to the combustor system by the clean air fan (CAF). The recycled gas was combined with fresh air, which provides the oxygen for combustion of coal, to achieve adequate airflow for fluidization of the sand.

During operation, the coal feed rate was controlled to maintain the desired bed temperature, the recycle flue gas to fresh air ratio was held steady and total flow delivered by the CAF was varied to maintain combustion oxygen at about 3%. Using flue gas in place of excess fresh air improves the overall thermal efficiency of this AFBC system by approximately 3.5% to 5% (D-931-10 Final Report). Overall thermal efficiency was estimated at approximately 87% based upon the heat and mass balances analysis of fuel and air into the system, combustion air and ash out of the system, carbon content of the fly ash, and heat losses typical for combustors with this type of construction.

Hot combustion gases along with entrained particulate traveled upward and out of the fluid bed into the boiler located above the fluidized bed. The boiler/hot water heater (Figure 4.1.1) used to transfer heat from the burner to the greenhouse was a three pass horizontal fire tube boiler, Kewanee 7L90 - Type C, which was thought to be typical of industrial boilers that might be retrofitted with the AFBC. Soot blowing was achieved by a blast of compressed air through the tubes. The tubes were divided into eight banks. One bank of tubes would be cleaned every 15 minutes with two hours required to complete the cycle for all eight banks. This feature reduced the capital and operating cost.

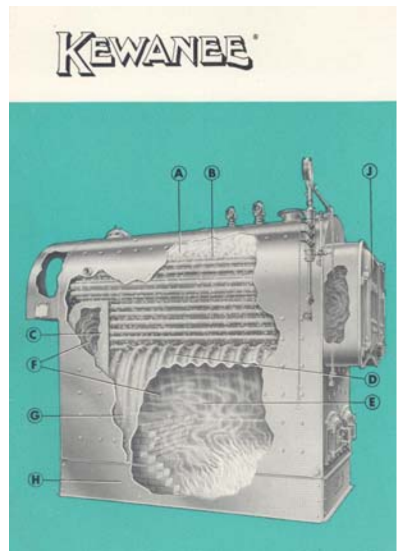

Figure 4.1.1. Example of boiler at Cedar Lane Farms

The system uses pneumatic sorbent re-injection into the fluidized bed to improve calcium utilization. A knockout hopper at the exit of the heat exchanger allows removal, captured and re-injection of large particles of sorbent and un-combusted char. This enables more efficient use of the sorbent for sulfur capture and reduces the limestone/coal ratio required to meet Ohio EPA standards.

From the knockout hopper the exhaust gas flows to the baghouse where particulate matter is removed. The baghouse was equipped with a reverse jet, air pulse system to periodically remove particulate matter (i.e., spent sorbent and fly ash) collected on the bags. Particulate collected in the baghouse drops into a hopper equipped with an ash discharge auger, which transports the material to an ash storage bin. An induced draft fan provides a portion of the motive force to overcome pressure drops beyond the fluid bed and transport a portion of the cleaned flue gas to the chimney for exhausting to the atmosphere. Fly ash and spent sorbent removal from the boiler tubes, mechanical collector, and baghouse was automated.

Coal from the outside bin is delivered to a Gundlach Accu-Grinder roller mill crusher by a twin screw auger. The mill produces coal particles with a top size of ¼ inch. The ground coal is collected in two surge hoppers beneath the grinder. Control of the twin augers and grinder is on/off as required to maintain the level in the surge hoppers between a high and low set point. Coal from the surge hopper passes through a variable speed airlock and then drops through a tube to a pneumatic line which injects (blows) the coal into the combustion zone of the bed. Injection occurs at two locations, each just two inches above the in bed fluidization nozzles and centered along one side of the combustor. The system can be operated on one coal injection system while the other is repaired.

In parallel to the coal feed, limestone from a separate feed bin is metered from its storage bin using a variable speed screw auger that discharges into a rotary airlock. Simultaneously, sorbent and char collected in the hopper from the knockout box flows into the rotary airlock. These materials fall from the airlock into a drop tube then are pneumatically transported and injected into the fluidized bed. The variable speed screw auger is coupled with the coal feed rate control to ensure the appropriate ratio of limestone to coal feed rates.

Pure kiln dried silica sand is used as the fluidization media. Construction grade sand was found to contain too many impurities to be used in this application.

Coal combustion and sulfur dioxide capture take place in the fluid bed. The coal rate is set to provide the energy release to maintain the fluid bed temperature and the limestone: coal ratio is set to yield the SO_2 capture desired. The hot flue gas from the combustor flows through the fire tubes of the boiler (heating the water in the boiler) and exits at a temperature of approximately 300° F. It then flows through a knockout box where large particles of coke and sorbent are removed and pneumatically recycled back into the fluid bed as described above. The purpose of this re-injection technique for sorbent was to yield better calcium (limestone) utilization for SO_2 capture and combustion of coal. In previous studies a 2.5:1 Ca/S molar ratio was used to drop sulfur emissions by about 67%. For this operation, the Ca/ S molar ratio near 1:1 reduced sulfur emissions by 88%.

The flue gas from the knockout box next enters a cartridge dust collector for particulate removal. An induced draft (ID) fan on the exit of the dust collector provides the motive force to draw flue gas from the combustor, maintaining a slight negative pressure at the combustor flue gas outlet. The ID fan discharges into an atmospheric stack.

The flue gas from the dust collector, not expelled to the stack, is also recycled back to the windbox of the combustor for temperature control. Manually set dampers maintain control of the ratio of fresh air to recycled air entering the suction side of clean air fluidization blower. Combustion oxygen level is monitored and controlled near 3% by controlling the speed of the motor on the clean air fluidization fan. This recycled flue gas-fresh air mix enters the windbox of the fluidized bed combustor and flows up through air distributor caps on the grid plate that supports the inert sand bed, providing the proper velocity to fluidize the sand bed.

The control system was designed by Northwest Controls, under direction by Don Bonk, and fully automates the AFBC. It allows the system to cycle between a combustion mode and slumped bed mode as heat is required in the greenhouse. It monitors and controls fuel and limestone feed to maintain the bed temperature between 1550-1575^{o} F. It monitors oxygen level at the combustor exit and maintains oxygen level near 3% by controlling speed of the fluidization fan. It also incorporates numerous alarms and control circuits to ensure safe unattended operation. More details are presented in the Operations Assessment section.

4.2 Operations Assessment

The operation of the AFBC has proven successful in meeting the cyclical heating demand loads of the greenhouse. Over the past 18 months, the reliability of the AFBC has been very good, especially taking into consideration that it takes 24 motors to operate the system. Ease of operation is a big advantage with the AFBC. Other than two hours per day and seasonal startup and shutdown, the system runs itself. CLF intends to use the AFBC as a first on last off unit, in lieu of running their natural gas fired hot water heater.

AFBC Control System

The AFBC operation at CLF was monitored using a control program written by Northwest Controls. The controller was designed to be simple and intuitive to operate, require low maintenance, be easy to install and provide a number of alarms for safe operation. It utilized an open network design, had automated reporting, and could be assessed remotely. One reason for fully automating the AFBC system was the fact CLF did not have personnel who could be dedicated to watch the system throughout the day. Since the demand for hot water varied throughout the day, the AFBC needed to shutdown and start back up automatically with little to no operator attention. As an example, operation during the spring months showed on-off cycling could occur five or six times in a 24-hour period because of the cyclical nature of the heat load. Another reason for automating the system was to control the fuel, sorbent and airflow rates to insure the highest combustion efficiency while minimizing emissions of SO_2 and NO_x.

The control program written by Northwest Control used a programmable logic control (PLC) system. It not only monitored various variables in the system to turn motors on and off or move dampers, but it provided visual display (Fig. 4.2.1) of alarm status and averages of a number of the systems variables. Below is a description of the variables monitored and how they were used for control.

Figure 4.2.1. Control monitor (a) showing output screen of AFBC system and control panel (b) showing gauges measuring pressures in AFBC system at Cedar Lane Farms

Ambient Air Temperature - Ambient air temperature is measured using a thermocouple located outside on the west side of the structure housing the combustor. The temperature signal was used to adjust coal feed rate.

Bed Temperatures - Temperatures in the bed are measured using thermocouples (type k, located in thermowells) at four locations: southwest, southeast, northeast and northwest sides of the combustor at approximately 6 inches above the plenum. At least two thermocouples must be recording for the combustor to operate.

For control purposes a bed temperature between 1550-1575^o F is the desired temperature range. Temperature is maintained by regulating feed rate (proportional control) depending on bed temperature. A set point of 1250^o F is used to trigger the low set point alarm and 1025^o F is used to shut the bed down. The low set point alarm of 1250^o F was chosen because below this temperature incomplete combustion is most likely to occur. A bed temperature set point of 1750^o F triggers a high bed temperature alarm.

Above Bed Temperature - Temperature above the bed is measured in two locations and at the entry to the hot water boiler. It is used as an alarm control.

Boiler Outlet, Hot Water Supply Temperature - Boiler water temperature (BT) controls and alarms are:

- High-High Alarm if BT > 220^o F,
- High Alarm and Control if BT >215^o F, Resets at 210^o F
- Control-off if BT>185^o F
- Control-on if BT <160^o F.

Under normal operation, the bed will slump and fuel feed will stop at BT temperatures of 185 ^{o} F or above and conversely, the bed will be fluidized and fuel feed start if BT drops to 160^o F or below. If the BT rises to 215^o F a redundant circuit sounds an alarm and again the bed should slump and coal feed should stop. If BT rises to 220^{o}F or more an alarm sounds and a signal is sent to the greenhouse operator's home.

Boiler Inlet, Hot Water Return Temperature - If boiler water inlet temperature drops below 165^o F the system is turned on.

Bag House Temperature - Bag house temperature is critical to prevent the burning/melting of the bags used for dust collection. If temperature rises above the set point, the AFBC system will set off an alarm.

Flue Gas Recirculation Temperature - Flue gas recirculation temperature is recorded for operational analysis (stored data), but is not used for control.

Flue Gas Recirculation Damper Position – The damper position is manually adjusted to balance the proportion of fresh air to recirculating combustion gas.

Clean Air Fan Damper Position - Position of the clean air damper is controlled manually to balance the proportion of fresh air to recirculating gas.

Mixing Valve - Controlled by the greenhouse temperature, this valve proportions amount of water sent (zero if greenhouse temperature is above setpoint) to the boiler or returned directly back to the greenhouse radiators.

Coal Feeder Rate - The range between maximum and minimum coal feed rates varies with the outside temperature. At an outside temperature of 5^o F or lower, the coal feed rate is regulated between 4.6 and 5.8 lbs/minute per feeder. At an outside temperature of 39^o F or higher, the coal feed rate is regulated between 2.5 and 4.1 lbs/minute per feeder. These rates are also dependent upon operation at an average bed temperature of 1575^o F and oxygen levels maintained within their control setting.

Theoretical Combustion Airflow - Combustion airflow is calculated based on coal feed rate and air flow rate (pitot tube measurement).

Oxygen Level - Oxygen level is measured in the flue gas stream as it leaves the boiler. If oxygen drops below the setpoint of 3% v/v, the coal feed rate is reduced and/or stopped. The oxygen level is also controlled by the variable speed clean air fluidization fan which increases speed as oxygen level drops and decreases it as oxygen level rises.

Coal Feeder Blower 1 - It is monitored as on or off.

Coal Feeder Blower 2 - It is monitored as on or off.

Lime Transport Auger – The lime transport auger operates at a **v**ariable rate which is determined by-the coal feed rate.

Lime Blower - It is monitored as on or off.

Sand Auger – The auger is manually operated on an as needed basis.

Grit Injector Auger - It is monitored as on or off. It is on if coal feeder is on, otherwise it is off.

Fly Ash Auger - It is monitored as on or off. It is on if combustor air is on, otherwise it is off.

Bed drain – The drain is manually operated on an as needed basis.

Bed Air Pressure - Bed air pressure is measured 6 inches above the diffuser plates' bubble caps.

Over Bed Pressure - The combustor over bed pressure is measured 6 feet above the diffuser plates bubble caps. It is used for induced draft (ID) fan control.

Bed Differential Pressure - The bed differential pressure is measured between the windbox and the freeboard space above the bed. It has a high set point of 31 inches H_2O and a low set point of 8 inches H_2O. If bed pressure differential rises above 31 inches, a high alarm is activated. If it drops below 8 inches, a low alarm is activated.

AFBC Bed Media

This particular AFBC uses a washed and dried silica sand as the fluidizing media. The sand size ranged from over 20 to under 40 mesh size. With this AFBC there have been no ash-calcium agglomerates formed in the bed.

AFBC Electrical Service

Main service to the AFBC system is 600 amps at 230 volts, 3-phase. This system provided ample power for all areas of the complex and supplied the requirements of the AFBC installation. A list of the motors and dampers used in the system, along with a description of power requirements is given in Table 3.1.

Coal Handling

The commercial AFBC uses a new coal handling/preparation system, compared to the prototype, to improve receiving, storing and preparing the coal for feeding into the burner. The use of a bucket elevator simplifies the receiving of coal as it is delivered by a semi truck, dumped easily, and conveyed with minimal power requirements (compared to an auger) to storage. Dust can be an issue during receiving of the coal, and control needs to be provided. The hopper bottom storage is capable of holding 54 tons of coal, which allows for receiving coal by the semi-truck load (approximately 27 tons/load). When full, total storage capacity provides enough fuel to operate the burner for 166 hours (6.9 days) when operated at maximum capacity (650 lbs/hr).

Coal Preparation/ Feed System

The commercial AFBC at CLF relies on a roller miller crusher to size the coal and fill a surge hopper above a rotary air lock used to prevent airflow from escaping through the coal bin from the high pressure side of the feed system. The crusher is turned on/off, depending on the level of coal in the surge bin.

Rotational speed of the rotary air lock (powered by a variable speed motor) sets the coal feed rate. Coal from the rotary air lock is dropped into a pneumatic feed system with its own blower to deliver the coal to the combustion zone. During operation, the crusher has been found to operate with no blockage and produces a coal with a top size of 1/4". A clean out port was added to allow easier cleaning without completely shutting down the system. Based on operational performance during the 2+ years of use, the current design of the coal feeding system is reliable and easy to operate.

Boiler Ash Removal

During the engineering design phase, it was known that if a heat exchanger with horizontal tube passes was selected for the system the ash/sorbent plugging might be a problem due to the high particulate loading associated with the addition of limestone to the AFBC system. However, a horizontal tube standard hot water "boiler" was the least costly alternative, and with the addition of automatic soot blowers, it appears that the particulate problem is minor.

Fly Ash/Spent Sorbent from Knockout Box

Unspent sorbent, bed material and large particulate flyash accumulates in the knockout box for re-injection into the bed. Based on observation of the system, the collected material is successfully collected and re-introduced back into the combustor.

Fly Ash/Spent Sorbent Bag House

Fly ash and spent sorbent is captured in a pulse jet bag house containing 96 8-foot long Nomex bags. The fly ash removal system includes an auger that transports the ash/spent sorbent from the hopper to an outside storage bin. The auger starts and stops with operation of the combustor fluidizing air and has been trouble free in operation.

Induced Draft Fan

The induced draft (ID) fan is operated to maintain -0.7 inches H2O (negative pressure) as monitored six feet above the fluidized bed. It provides a nominal airflow of 4000 acfm when operating at 2/3 of its rated speed. Speed control of the ID fan is regulated by over bed pressure.

Startup of the Burner

Startup of the burner is speeded up by introducing wood pellets into the burner which ignite at a lower temperature than coal and burn to add additional heat to that of the gas burner. The following procedure has allowed startup to occur and transfer to automatic controls in 7-8 hours:

- Turn on the ID fan - manual control.
- Turn on the gas burner which heats top of bed - manual control.
- Turn on feeder blowers, augers and rotary valves - manual control.
- Turn on fluidizing fan to move sand as it heats - manual control.
- At bed temperature of 500-600 ^{o}F (between 3-4 hours of heat cycle) introduce wood pellets into bed. Continue introducing wood pellets as temperature builds up - manual control.

- At 900 ^oF (approximately 1 more hour) begin introducing small quantities of coal at a time - manual control.
- After average bed temperature reaches 1400 ^oF-1550 ^oF, switch to all automatic controls.

Operation of AFBC

The AFBC system requires very little operator attention as it runs primarily on automatic control. The only operator function normally required is the daily monitoring of equipment, dumping bed material and cleaning pressure taps as well as loading coal and lime and dumping ash once a day. These procedures require less than two hour per day. To date, combustor operation has been successful. Upgrades were implemented during the long term test program to make it more commercially acceptable.

4.3 Data Analyses

During the long term operation of the AFBC at CLF, data were collected and analyzed under normal operating conditions.

Coal and Sorbent

Over the testing period one type of coal and one type of limestone were used. The coal was an Ohio bituminous coal with an average high heating value (HHV) of 12,640 Btu/lb and a sulfur content of 2.93 (Table 4.3.1.). The permissible upper limit for sulfur content of the coal, as set by the operating permit, was 3.8% by dry weight. The limestone used was a dolomitic limestone supplied by National Lime and Stone, Bucyrus, Ohio. The limestone was classified as a #18 and it had a calcium carbonate ($CaCO_3$) content of 80% (Table 4.3.2).

Table 4.3.1. Typical ultimate and ash analysis of unwashed Wayne mine Ohio bituminous, size 2" x 0" coal fueling AFBC at Cedar Lane Farms.

Ultimate Analysis	Wt %	Ash Analysis	Wt %
Date	(Average)		(Average)
Carbon	71.15	SiO_2	41.46
Hydrogen	4.44	AI_2O_3	24.26
Oxygen	8.13	TiO_2	1.08
Nitrogen	1.24	Fe_2O_3	26.95
Sulfur	2.93	CaO	2.00
Moisture	5.68	MgO	0.82
Ash	5.68	Na_2O	0.46
		K_2O	1.80
Total	100.00	P_2O_5	0.28
		SrO	0.06
Higher Heating Value (HHV) Btu/lb	12,640	BaO	0.00
Coal Sulfur = 4.63 lb SO_2/million Btu		MnO_2	0.13
		Other	0.36
Calculated Ca/S ratio of ash = 0.04			
where, Ca = Ca + Na_2 + K_2		Total	99.66

Table 4.3.2. Typical dolomitic limestone[1] chemical and physical analyses

Chemical		Physical (U.S. Standard Sieve Size)	% Retained	
	%w/w	Mesh Size	#18	#70
Calcium carbonate ($CaCO_3$)	80.00	16	Trace	
Magnesium carbonate ($MgCO_3$)	17.00	20	9	
Insolubles	2.50	30	25	
Iron oxide (Fe_2O_3)	0.20	40	24	Trace
Sulfur as SO_3	0.25	50	19	9
Total	100.00	70	14	4
		100	5	13
		140	2.5	15
Loss on Ignition	44 wt%	200	0.5	5
Bulk Density	95 Ib/cu.ft.	-200	1.0	

[1]National Lime and Stone, Bucyrus , Ohio ($11.50 ton + $150 freight = 11.50+ 3 = 14.50/ton)

Combustion tests were conducted by Air Compliance Testing, Inc., Cleveland, Ohio. On March 25, 2004 three tests were run on the AFBC during operation in a fully automated mode using an Ohio #6 coal as fuel and dolomitic limestone as the sulfur dioxide (SO_2) sorbent. The coal feed rate was set to a level that would maintain the temperature of the fluidized bed in the combustor at 1550° F temperature. The coal feed rate was 695 lbs coal/hr (8.96 MMBtu/hr) and the limestone feed rate was 83.5 lbs/hr of limestone (0.12 lb lime/lb coal). The calculated Ca/S ratios were approximately 1. Table 4.3.3 summarizes those results.

Table 4.3.3. Compliance stack emission test results for atmospheric fluidized bed combustor burning coal[1,2,3] at Cedar Lane Farms Corp., March 25, 2004. Measurements taken at the B009 Fabric Filter Exhaust Stack.

	Run 1	**Run 2**	**Run 3**	**Average**
Sulfur Dioxide Mass Emision Rate (lb/MMBtu)	0.64	0.58	0.73	0.65
Sulfur Dioxide Concentration (ppmvd)	328	309	382	340
Oxygen Concentration (%-dry)	3.402	2.830	3.134	3.122
Published F-Factor for Bituminous Coal at 0% Oxygen and 68°F (Fd) dscf/MMBtu)	9,780	9,780	9,780	9,780
CRT Readout (Sorbent to Sulfur Ratio)	10/18	10/18	10/20	-

1 Ohio Coal: #6. 6.57% moisture, dry basis → 13809 Btu/lb, and 3.71% sulfur

2. Lime: Bucyrus #18 (dolomitic), 80% calcium.

3. Coal feed rate 695 lbs/hr (wet basis), limestone 83.5 #/hr (wet basis), Ca/S = 1.0.

Sulfur Dioxide Capture

The Ohio coal being fired during the testing of the CLF system was slightly different from the coal analysis shown in Table 4.3.1. On a dry basis the coal had a sulfur content of 3.71 wt% and a higher heating value of 13,809 Btu/1b which translates to 5.37 lbs SO_2/MMBtu. The burner operating temperature was 1550^o F, which is the optimum temperature range for SO_2 capture when using dolomitic limestone as a sorbent and is based on the earlier studies done on the prototype AFBC (see Appendix A). Oxygen concentration averaged 3.122% (Figure. 4.3.1). Results on SO_2 capture at a Ca/S ratio of 1.0 yielded flue gas emission rates of 0.65 lb/MMBtu (Figure 4.3.2). This compares with emission rates of about 0.98 lb of SO_2 per MMBtu of coal fired with dolomitic limestone added at a Ca/S ratio of 2.5 during the prototype testing at CLF. These results show the newer design for the commercial AFBC is meeting Ohio's required sulfur release rate of 1.3 lb/MMBtu, even when using 1/2 the amount of limestone indicated by earlier studies. This higher efficiency of absorption of SO_2 by the limestone is attributed to fly ash and sorbent re-injection along with maintaining optimum combustion temperature for SO_2 capture.

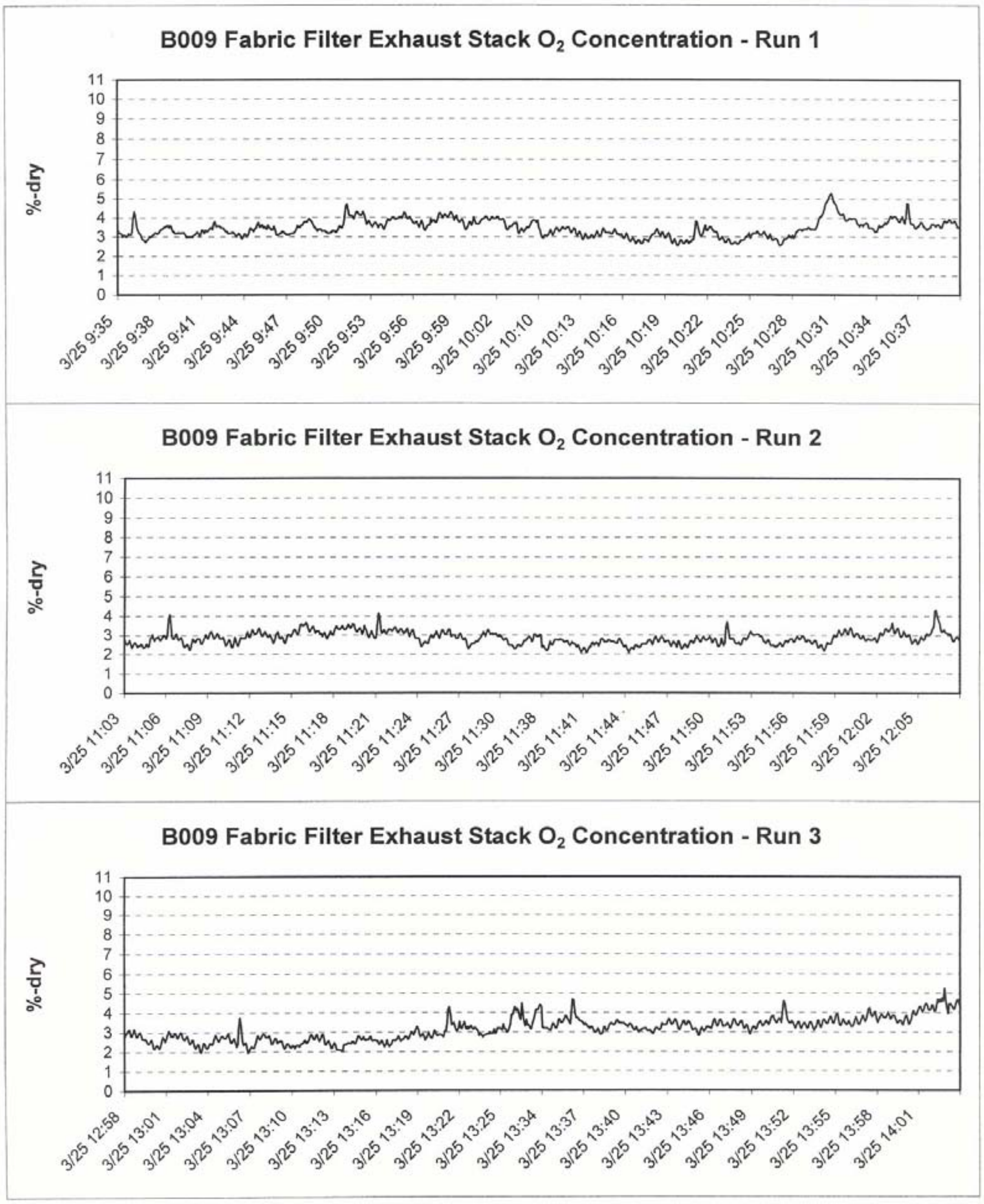

Figure 4.3.1. Exhaust stack O_2 concentrations during compliance testing on March 25, 2004.

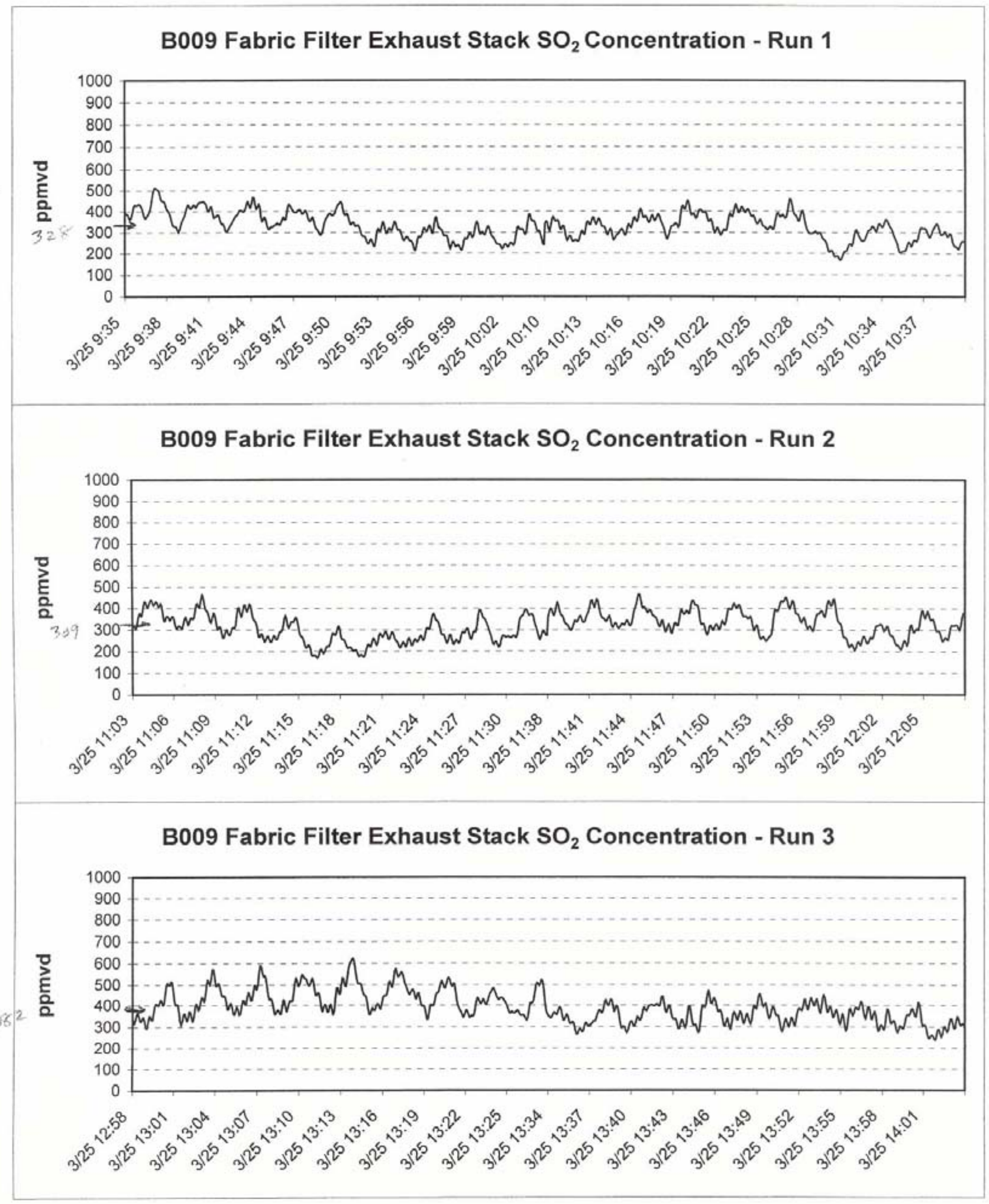

Figure 4.3.2. Exhaust stack SO_2 concentrations during compliance testing on March 25, 2004.

NO_x Reduction

The nitrogen oxide (NO_x) emission for the CLF AFBC was not measured during the March 25, 2004 testing program, but would be expected to be quite low with O_2 levels in the combustion air being controlled at less than 5% v/v (see earlier studies reported by EER et al., 1997 on effect of O_2, CO levels on NO_x).

Thermal Efficiency

The thermal efficiency of hot water out to fuel in for the various run periods examined was calculated to be about 87%. This is based on a heat and mass balance of the fuel and air into the system, combustion air and ash out of the system, carbon content of fly ash, and heat losses typical for combustors with this type of construction.

Fly Ash/Sorbent Use

Flyash removed from the baghouse for the March 11, 2004 test were analyzed by Hazen Research, Inc., Golden Colorado. Total carbon in the fly ash was 13.74%, with 1.19% listed as a carbonate (CO_2) form and 12.55% listed as organic carbon. This implies the fuel was not being fully consumed. A goal of the combustion process would be less than 5% organic carbon in the ash.

The mineral analysis of the ash is given in Table 4.3.4 and parallels the chemical analysis of the coal ash before combustion, as would be expected. Earlier studies on using fly ash from the prototype burners by the Ohio Agricultural Research and Development Center (OARDC) found the flyash/sorbent mixture could be used as a soil cement and also as a soil conditioner (lime substitute) for acid soils. In the tests for use as a soil conditioner, it was determined that with normal application, trace elements in the ash were within acceptable limits so as not to produce any soil contamination problems.

Table 4.3.4. Elemental analysis of fly ash from Cedar Lane Farms AFBC on March 11, 2004.

Oxide/Element	%	Oxide/Element	%	Oxide/Element	%
$Si0_2$	10.00	CaO	27.30	$P20_5$	0.56
Al_20_3	5.29	MgO	12.10	$S0_3$	18.90
$Ti0_2$	0.17	Na_20	0.12	Cl	0.32
Fe_20_3	6.97	K_20	0.40	$C0_2$	4.38

5.0 COMMERCIALIZATION AND MARKETS

he United States has substantial coal reserves (10^9 tons), currently estimated at 27% of the world's recoverable coal (EIA, IEO2005). In 2002 the United States consumed 1,066 million tons of coal. By 2025 consumption is projected to rise to 1,505 million tons as the United States relies more heavily on coal for generating electricity. (EIA, 2005).

However, environmental constraints imposed to curb air pollution associated with burning high sulfur content coal has resulted in a significant decline in the industrial and commercial use of coal. According to the 1994 State Energy Data Report, from 1970 to 1994, the annual coal use in Ohio by commercial and industrial entities dropped from 30.9 million tons in 1970 to 7.2 million tons in 1994, a 77% decrease. To reverse this trend, and in light of rapidly rising natural gas prices, the industrial and commercial sectors of the economy are ready to consider low cost, environmentally acceptable technologies that are adequate to address the pollution issues associated with burning high sulfur content coal.

The AFBC system that was developed under sponsorship by the U.S. DOE and OCDO is a system that has the potential to solve the cited pollution problems, and has the potential to reverse the trend toward ever increasing use of natural gas at the expense of the coal industry .The AFBC is a simple design and easy to operate system that lends itself to modular construction, allowing for lower cost shop fabrication as opposed to field (onsite) fabrication. This AFBC system is amenable for use with all types of coal independent of ash, moisture or sulfur content. It uses low cost limestone, which is abundant in the State of Ohio, as a sorbent to meet the regulatory limits on SO_2 emissions. Also, the AFBC incorporates a flue gas recycle technique which can be used to reduce NO_x emissions and increases the overall thermal efficiency of the system.

The successful commercialization of this system could start to reverse the trend of decreasing coal use by the commercial, industrial, and institutional market sectors. With the widespread use of this technology, other benefits will arise in the form of increased business revenues from the sale of indigenous coal and limestone, the reduction in fuel costs for the end user which will make its products more cost competitive, and the development of a new technology that will be fabricated and marketed in the United States, creating new jobs.

The Ohio Long Term Forecast of Energy Requirements, 2003-2023, showed an annual energy consumption of 8.98×10^{14} Btu by the industrial/commercial market sector in Ohio in 2003 (PUCO, 2005). Based on a U.S. EPA study (as cited in EER, 1997), commercial and industrial boilers in the size range of 7.3 to 29.3 MMBtu/hr, firing mostly natural gas and fuel oil, make up about 25% of the total energy consumed by the industrial and commercial market sectors. Applying this percentage of energy consumption to the State of Ohio, it is estimated that boilers in the above size range consume about 2.2 x 10^{14} Btu/yr.

The AFBC developed under this program can be suitably applied to boilers in this size range. Assuming that coal fired AFBC units could replace15% of the oil and natural gas energy needs by the year 2010, Ohio coal consumption would increase about 1.3 million tons/year. To accomplish this increase in market share would require the installation of approximately 753 10-MMBtu/hr AFBC units (@ 50% capacity factors).

A marketing strategy for the technology is in place. AFBC Transitions, LLC (a subsidiary of Will-Burt Company, Orville, Ohio) is the team member who will fabricate and market the technology. The Will-Burt Company is currently marketing and fabricating small scale coal fired stokers for industrial, commercial, and institutional use. The AFBC system will be added to its market line as a replacement for the stoker technology. This technology will readily comply with all facets of the Federal Clean Air Act Amendments of 1990. The development team is very enthusiastic about the potential of this technology and is looking forward to the successful commercialization of the AFBC system.

6.0 BUDGET SUMMATION

Total expenditures were slightly above the budget as non OCDO cost share was more then the required 67% of total expenditures. The percentage of the total expenditures paid by each collaborator were as follows: OCDO, 31.2%; AFBC Transitions, LLC, 38.7%; US DOE, 10.6 %; CLF, 17.8%; Enercon, 1.7% (Table 6.0.2)

Table 6.0.1. Expenditure of OCDO Funds by Line Item

Budget Category	Amount Budgeted	Funds Expended
Personnel	$ 125,904.00	$ 73,267.92
Travel	$ 1,980.00	$ 498.64
Equipment	$ 197,604.00	$ 261,612.45
Supplies	$ 6,534.00	$ 9,130.58
Contractural	$ 164,543.00	$ 150,346.95
Total Direct	**$ 496,565.00**	**$ 494,856.54**
Indirect	$ 34,185.00	$ 35,853.57
Total	**$ 530,750.00**	**$ 530,710.11**

Table 6.0.2. Total Expenditures of OCDO and Collaborator Funds by Line Item

Budget Category	Total Project Budget	Project Funds Expended OCDO	AFBC	DOE	CLF	Enercon
Personnel	$ 496,706.00	$ 73,267.92	$ 130,207.66	$ 56,725.41	$ 184,786.00	$ 25,466.85
Travel	$ 5,999.00	$ 498.64	$ 365.11	$ 663.74	$ 644.60	$ -
Equipment	$ 490,214.00	$ 261,612.45	$ 313,808.79	$ 78,273.76	$ 8,942.98	$ 2,825.00
Supplies	$ 49,150.00	$ 9,130.58	$ 6,944.14	$ 1,760.87	$ 33,921.00	$ -
Contractual	$ 483,691.00	$ 150,346.95	$ 127,096.27	$ 28,425.86	$ 74,017.00	$ -
Total Direct	**$ 1,525,760.00**	**$ 494,856.54**	**$ 578,421.97**	**$ 165,849.64**	**$ 302,311.58**	**$ 28,291.85**
Indirect	$ 130,810.00	$ 35,853.57	$ 78,984.51	$ 14,558.73	$ -	$ -
Total	**$ 1,656,570.00**	**$ 530,710.11**	**$ 657,406.48**	**$ 180,408.37**	**$ 302,311.58**	**$ 28,291.85**

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PUCO. 2003. http://www.puco.ohio.gov/emplibrary/files/util/UtilitiesDeptReports/ OhioLTFEnergyReq 2003-2023final.pdf, Tables 4.0.1; 4.2.1; 4.31.; 4.4.1

APPENDIX A.

Effect of bed temperature in an atmospheric fluidized bed combustor on SO_2 capture using a Ca/S ratio of 2.5 (Reference EER, 1997).

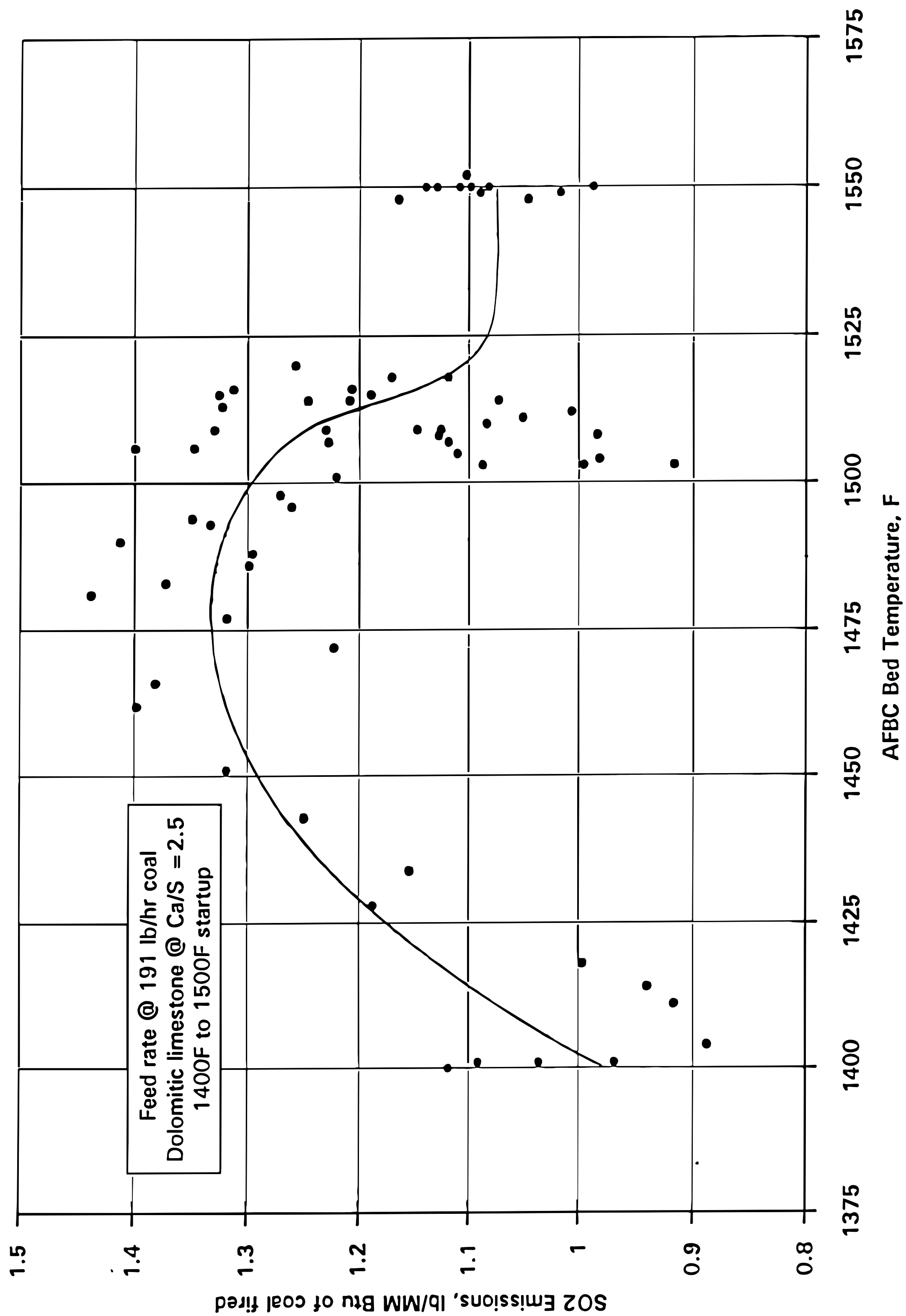

Figure 3-4. SO2 emissions versus fluid bed temperature