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Atmospheric Fluidized Bed Combustor Development Program

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APPENDIX

conf info available, cycled separately as M97004885.

"Small-Scale AFBC Hot Air Gas Turbine Power Cycle" (ASME Paper)

"Environmental Performance of Air Staged Combustor with Flue Gas Recirculation to Burn Coal/Biomass" (ASAE Paper)

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LIST OF ABBREVIATIONS

AFBC	Atmospheric Fluidized Bed Combustor
ASME	American Society of Mechanical Engineers
ASAE	American Society of Agricultural Engineers
CAAA	Clean Air Act Amendments
CEMS	Continuous Emissions Monitoring System
CFR	Code of Federal Regulations
CLF	Cedar Lane Farms, Inc.
DOE	United States Department of Energy
EER	Energy and Environmental Research Corporation
FGR	Flue Gas Recirculation
HAGT	Hot Air Gas Turbine
HHV	Higher Heating Value
LOI	Loss on Ignition
MDL	Method Detection Limit
NSPS	New Source Performance Standards
OARDC	Ohio Agricultural Research and Development Center
OCDO	Ohio Coal Development Office
U.S. EPA	United States Environmental Protection Agency
WB	Will-Burt

LIST OF UNITS

acf	Actual Cubic Foot
acfm	Actual Cubic Foot per Minute
Btu/kWhr	British Thermal Unit per Kilowatt-Hour
Btu/lb	British Thermal Unit per pound
Btu/scf	British Thermal Unit per Standard Cubic Foot
dscfm	Dry Standard Cubic Foot per Minute
°F	Degree Fahrenheit
ft	Foot
ft^2	Square Foot
ft^2/1000 acfm	Square Foot per Thousand Actual Cubic Feet per Minute
ft^3	Cubic Foot
ft/s	Foot per Second
gpm	Gallon per Minute
gr/dscf	Grain per Dry Standard Cubic Foot
HP	Horsepower
in	Inch
lb/ft^3	Pound per Cubic Foot
lb/hr	Pound per Hour
lb/min	Pound per Minute
lb/MMBtu	Pound per Million British Thermal Units
MW_e	Megawatt Electric
MMSCF	Million Standard Cubic Feet
ohm-cm	Ohm-Centimeter
psig	Pound per Square Inch (Gauge)
ppmv	Parts per Million Volume
ppmw	Parts per Million Weight
scfh	Standard Cubic Foot per Hour
scfm	Standard Cubic Foot per Minute
sfvg	Superficial Gas Velocity
%	Percent

GLOSSARY OF TERMS

Chemical Symbols:

Al_2O_3	Aluminum Oxide (Alumina)
BaO	Barium Oxide
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
Ca/S	Calcium (Sorbent) to Sulfur (Coal) Molar Ratio
$CaSO_3$	Calcium Sulfite
$CaSO_4$	Calcium Sulfate
Cl	Chlorine
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Fe_2O_3	Ferric Oxide
H_2	Hydrogen (Diatomic)
HCl	Hydrogen Chloride
H_2O	Water
K_2O	Potassium Oxide
$MgCO_3$	Magnesium Carbonate
MgO	Magnesium Oxide
MnO_2	Manganese Oxide
N_2	Nitrogen (Diatomic)
Na_2O	Sodium Oxide
NO_x	Nitrogen Oxides
NO	Nitric Oxide (Colorless Gas)
NO_2	Nitrogen Dioxide (Reddish Brown Gas)
N_2O	Nitrous Oxide (Colorless Gas)
P_2O_5	Phosphorous Pentoxide
O_2	Oxygen (Diatomic)
S	Sulfur
SiO_2	Silicon Dioxide (Silica)
SO_2	Sulfur Dioxide
SO_3	Sulfur Trioxide
SrO	Strontium Oxide
TiO_2	Titanium Oxide

EXECUTIVE SUMMARY

The objective of this project was to demonstrate and promote the commercialization of a coal-fired atmospheric fluidized bed combustion (AFBC) system, 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 1×10^6 to 10×10^6 Btu/hr capacity range. A cost effective and environmentally acceptable AFBC technology in this size range would displace a considerable amount of gas/oil with coal while resulting in significant total cost savings to the owner/operators.

The Energy and Environmental Research Corporation (EER) assembled a project team which provided both state-of-the-art small AFBC technology and experience in manufacturing and marketing small coal-fired equipment (stokers) for residential, commercial, and small industrial use. The original members of this team were, respectively, the Ohio Agricultural Research and Development Center of Ohio State University (OARDC) and the Will-Burt Company.

The project itself was separated into three levels: (1) Feasibility, (2-3) Subsystem Development and Integration, and (4) Proof-of-concept. In Level (1), the technical and economic feasibility of a 1 million Btu/hr coal-fired AFBC air heater was evaluated. In Level (2-3), the complete EER fluidized bed combustor (1.5 million Btu/hr) system was developed and tested. The goal of reducing SO_2 emissions to 1.2 lb/10^6 Btu, from high sulfur Ohio coal, was achieved by adding limestone with a Ca/S(coal) ratio of ~ 3.0. This testing was accomplished at OARDC facilities in Wooster, OH.

Finally , in Level (4), the proof-of-concept system, a 2.2 million Btu/hr unit was installed and successfully operated at Cedar Lane Farms, a commercial nursery in Ohio. In addition to the team members and the DOE, the Ohio Coal Development Office (OCDO) was a funding participant for the Level (4) proof-of concept phase.

The heat from the fluidized bed is being used for heating hot water which is then in turn recirculated through greenhouses for cool weather heating. The system is fully automated with little operator attention being required. This system was designed with flyash/sorbent reinjection and an underbed feed system to improve limestone utilization. With these additions it was possible to lower the Ca/S ratio from ~ 3.0 to 2.0, and still maintain an SO_2 emissions level of 1.2 lb/10^6 Btu when burning the same coal as tested at OARDC.

The project team has proposed to the OCDO, some additional funding for the AFBC project to correct some minor operational problems at Cedar Lane Farms and to complete the design of a 10×10^6 Btu/hr AFBC to provide for firm costs for a commercial size unit that can be marketed by the Will-Burt Company. The project team members will be sharing the cost of this added work without further funding assistance from the U.S. DOE.

1.0 INTRODUCTION

Currently, oil and gas are the fuels of choice for the space and process heat requirements of commercial and small industrial applications. This is because of the convenience and cleanliness offered by these fuels compared to coal. However, there are social and strategic pressures to provide technologies which will enhance the acceptability of coal for these applications.

Commercial/small industrial boilers, i.e., those in the range of 1.5 to 10 million Btu/hr size are large oil and gas users. For example, assuming a 50% capacity factor, these boilers consume about 3.5×10^{15} Btu/year. It is estimated that if only 25% of oil and gas-fired boilers in this size range were converted to coal, then coal consumption would be increased by some 35 million tons/year, an amount in 1995 of around twice the State of Ohio's annual coal production. Potential coal-fired AFBC users include institutions (schools, hospitals, prisons, government), light industry (agriculture, food processing), commercial users (shopping centers), and large residential users (apartment complexes).

Fluidized bed combustion offers several potential advantages over conventional coal combustion systems for small scale applications:

Minimal Fuel Processing The combustion process is not overly sensitive to the physical characteristics of the coal feed. There is no need to pulverize the fuel. This greatly simplifies the design and operation of the fuel supply system compared to conventional stoker systems.

Low Temperature Combustion. The fluidized bed operates at low temperatures. This avoids problems such as clinker formation and slagging which are major areas of concern with other coal fired systems.

SO$_2$ Emission Control. Limestone sorbent in the fluid bed reacts with SO_2 liberated during the combustion process to control SO_2 emissions. Emissions can be reduced in excess of 80 percent.

NO$_x$ Emissions. Low temperature combustion results in low NO_x emissions compared to other coal fired systems such as stokers or pulverized coal fired equipment.

Fluidized bed combustion systems have been developed for several applications. However, at present, no commercial equipment is available in the size range of interest or this project. The overall goals of this program are:

1. To demonstrate that an atmospheric fluidized bed combustor (AFBC) can satisfy all the market requirements for small commercial and industrial heating systems.

2. To provide such information as is necessary to ensure the market acceptability of the AFBC.

3. To actively promote the commercialization of the AFBC.

2.0 OVERALL DEVELOPMENT PROGRAM

The overall objective of this program was to develop commercial hardware which provided the primary incentive for team members participation in the program. The Will-Burt Company is a manufacturer of small scale coal fired under-feed stoker combustion equipment. While the market for this equipment has persisted for decades, the growth potential is limited. In most applications, under-feed stokers cannot compete with gas/oil fired equipment in terms of convenience, emissions and total cost.

The Will-Burt Company conducted an intensive review of alternate small scale coal-fired combustion technology and has identified AFBC technology as a prime candidate for market expansion. It was the intent of the Will-Burt Company to use this program to develop a commercial product for the small scale industrial-commercial-institutional markets. Commercialization agreements were established and are still in place between the three parties for the marketing of the system after Level 4 completion.

The project was separated into three levels: Feasibility, Subsystem Development and Integration, and Proof-of-Concept. A description of the work completed under those levels is provided in the following text.

3.0 LEVEL 1 - FEASIBILITY

This level of work centered on the evaluation of a small scale atmospheric fluidized bed combustion system, developed and tested by the Ohio Agricultural Research and Development Center (OARDC). The novelty of this system is that it incorporated a cooling annulus around the fluid bed (see Figure 3-1).

The objectives of Level 1 were to complete:

1) a scaleup design from the six-inch diameter, 150,000 Btu/hr externally cooled atmospheric fluidized bed combustor (AFBC), developed by the OARDC, to a 1 to 2 million Btu/hr unit,

2) to verify design and operational requirements for the AFBC,

3) to assess the small scale industrial/commercial/institutional market,

4) to compare the economics of a coal-fired AFBC boiler with conventional oil and gas boilers, and

5) to develop a plan for the next level of work, Level 2.

Following pilot plant testing, OARDC developed a small-scale fluidized bed with a six inch inside diameter. The technology included a unique air-cooled combustion chamber. It eliminated the need for in-bed heat transfer surfaces and was amenable to intermittent operation. It was successfully tested at 150 lb/hr steam equivalent (150,000 Btu/hr).

Several designs were considered for the scaleup of this pilot system. First of all a design that clustered four - eight inch diameter combustors was considered, that with the use of atmospheric air in the cooling annulus would yield a 1 million Btu/hr system.

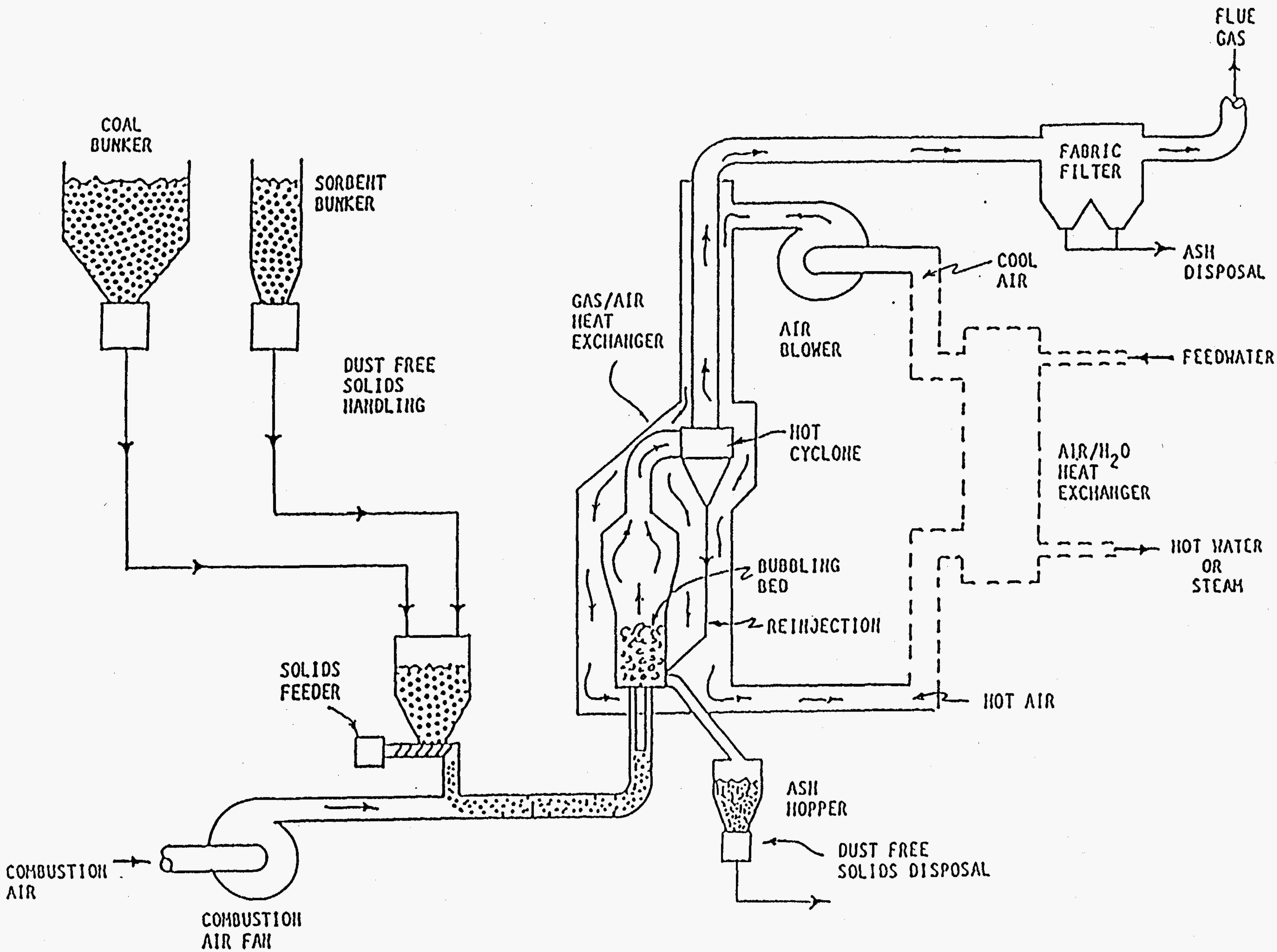


Figure 3-1. OARDC Air Cooled AFBC System

A second design was considered that with the use of one 16 inch diameter combustor, and helium or high pressure air at 8 atmospheres as the annular bed coolant, the bed could provide 1.6 million Btu/hr. A commercial scale AFBC boiler system based on the 16 inch diameter combustor was completed.

This project focused on the 1 to 10 million Btu/hr industrial boiler market. When the market assessment was made, there were 209,000 (1.5 to 10 million Btu/hr size range) boilers installed and operating in the United States. In addition to the existing boilers some 5000 new boilers were installed per year. The total fuel consumption for the existing boilers was some 790,000 10^6 Btu/hr. Only a small fraction of these boilers at the time ($\sim 10\%$) were fired with coal. If coal fired equipment could be developed to compete with gas/oil fired boilers in the 1×10^6 Btu/hr to 10×10^6 Btu/hr sizes there could be a significant increase in coal production. For instance, if only 25% of the oil/gas boilers were converted to coal, coal consumption would be increased some 35 million TPY.

The success of a commercial AFBC system will depend primarily on its cost effectiveness compared to oil and gas fired boilers. The total installed cost for the 1.6 million Btu/hr AFBC (1991) was estimated at $63,000 compared to a conventional oil-fired boiler of approximately $27,000. Based on a cost of coal of $\$2/10^6$ Btu, and a #2 fuel oil cost of 80¢/gal or $\$5.80/10^6$ Btu. Based on the differential fuel cost of oil vs coal, for this size AFBC the payback on added capital required for coal would be less than two years.

Prior to entering the next level of work, because of the difficulty of scaling the externally cooled AFBC to the larger sizes and the inability to use this design for retrofit applications, a design change was made wherein the AFBC would be refractory lined with an external heat exchanger, the system to incorporate flue gas recycle to improve overall thermal efficiency. This design was recommended for development and the project proceeded into Level 2-3.

4.0 LEVEL 2-3 SUBSYSTEM DEVELOPMENT AND INTEGRATION

This level of the atmospheric fluidized bed combustor (AFBC) development program was carried out at the Ohio Agricultural Research and Development Center (OARDC), in Wooster, Ohio. The subsystem development and integration scope of work included the design, installation and testing of an AFBC coal combustion system designed for small scale industrial, commercial, and institutional applications. The combustion system was designed to be simple to operate and maintain.

The 1.5 MM Btu/hr atmospheric fluidized bed combustion test unit, designed by EER and OARDC, was installed at the OARDC facility in Wooster, Ohio and was started up in mid 1992. The coal combustion system was designed for small industrial, commercial and institutional applications. It is a simple to operate and maintain combustion system.

The fluid bed has no internal heat exchanger surfaces, the hot flue gases from the combustor pass through a waste heat boiler/exchanger generating steam and/or hot water for use in electric power generation and district heating. Flue gas from the heat exchanger enters a baghouse for removal of particulate prior to entering an induced draft fan. From the fan, the flue gases enter a stack and are emitted to the atmosphere. The combustion system includes the recycling of a portion of the flue gases exiting the baghouse, back to the inlet line that provides combustion air to the combustor. Flue gas is blended with fresh air prior to entering the fluid bed. This technique improves the overall thermal efficiency of the process. Limestone is added as a sorbent into the fluid bed to capture the sulfur dioxide produced when combusting coal, thus reducing sulfur dioxide emissions to the atmosphere.

The AFBC pilot unit was started up in mid-1992 and from startup through March 1993, some 108 operational runs were completed with data taken on 62 of these runs.

From a pollution perspective, small AFBC units with heat inputs greater than 10 MM Btu/hr will have to comply with the EPA 40 CFR Part 60, "Standards of Performance for New Stationary

Sources: Small Industrial-Commercial-Institutional Steam Generating Units; Final Rule (Federal Register, September 12, 1990)". Although the range of combustors being developed are 10 MM Btu/hr and less, the limitations under this regulation were used to set the pollutant limits for the combustor. The highlights of this regulation are as follows:

The affected facilities to which these standards apply is to each steam generating unit for which construction, modification, or reconstruction is commenced after June 9, 1989 and that has a maximum design heat input of 100 million Btu/hr or less, but greater than or equal to 10 million Btu/hr.

Standards for Sulfur Dioxide

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

Standards for Particulate Matter

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

Standards for Nitrogen Oxides

For coal fired steam generating units with heat input capacities of 100 MM Btu/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 wastes produced by particulate matter control processes are nonhazardous and can be disposed of using traditional treatment and disposal techniques.

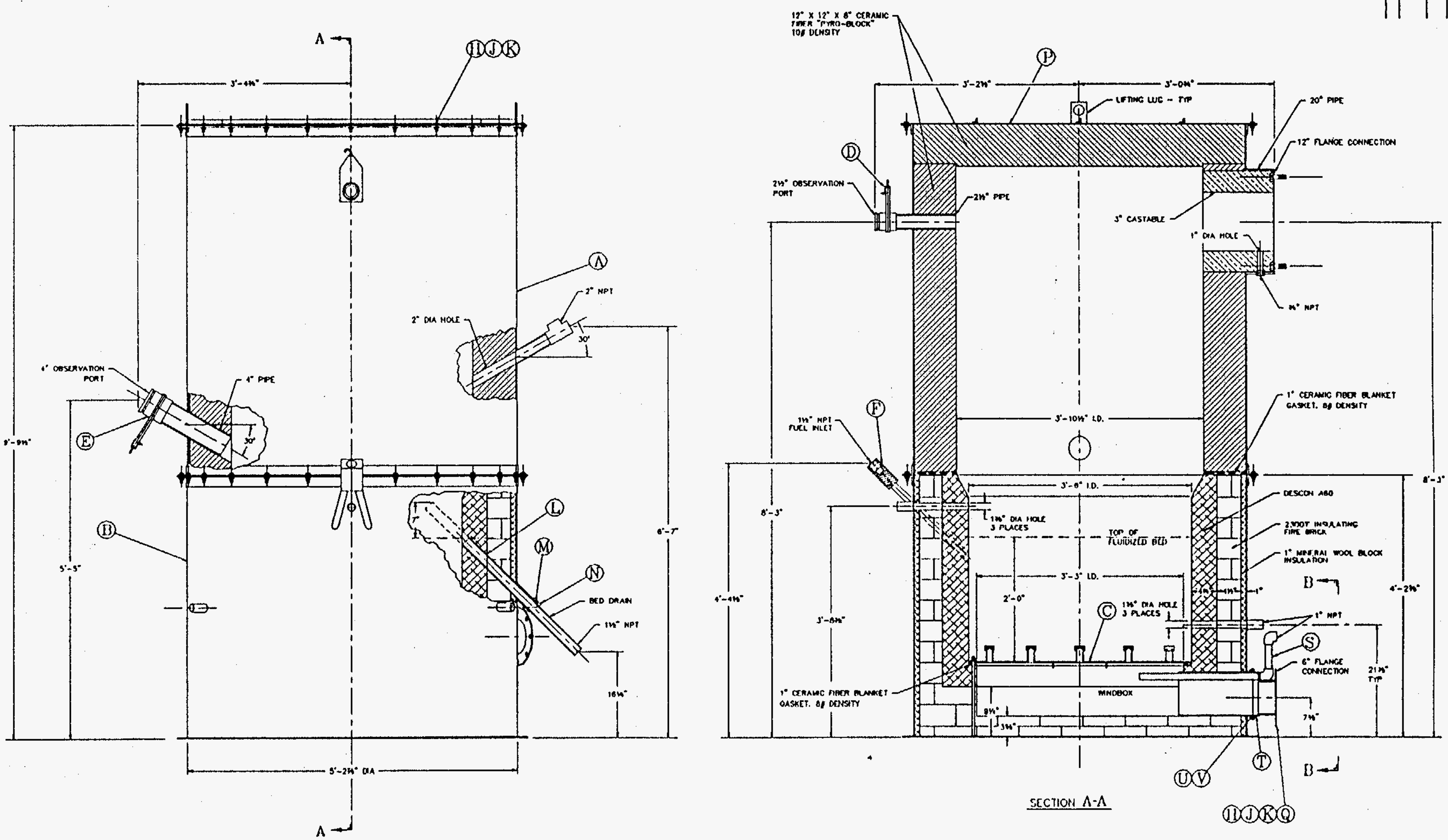
4.1 AFBC Process Description

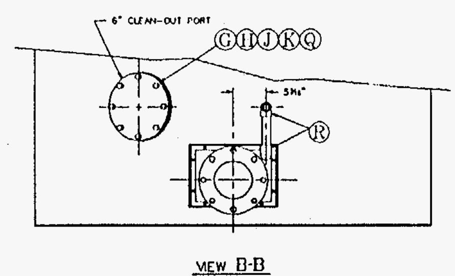
The 1.5 MM Btu/hr (nominal coal heat input) Atmospheric Fluidized Bed Combustor (AFBC) was designed for the OARDC pilot demonstration. For the demonstration the fluidized bed combustor was designed to burn Ohio coal to produce hot flue gas for the generation of hot water in a waste heat recovery heat exchanger. The AFBC was designed to meet current and expected future air emission standards. The cooled flue gas from the heat exchanger is drawn through a bag house for particulate removal, via an induced draft fan which discharges to a stack vented to the atmosphere.

The combustion system fired coal, with a particle size of -¼"x 0". Slack coal was purchased and screened to provide coal for the tests. Coal and limestone were weighed and dumped into bins. Coal and limestone augers were used to meter fuel and sorbent into a pneumatic line which fed into an air eductor which blew the coal and limestone into the AFBC (bubbling) bed slightly under the expanded bed, see Figure 2-2. The combustor was designed to operate at 1500 - 1600°F. Coal combustion and sulfur dioxide capture take place within the fluidized bed. The coal rate was set to yield the energy release required. The limestone sorbent rate was set to meet the desired reduction in sulfur dioxide emissions.

The flue gas, at nominally 1550°F, entered a waste heat recovery hot water heater, heating recirculated hot water. Heat was extracted from the circulated water by means of an air cooled heat exchanger. Flue gas exited the heat exchanger at a temperature in the range of 250 - 350°F and then flowed through a bag house for removal of particulate.

An induced draft fan, on the exit of the bag house, provided the motive force to draw the flue gas through the system. The fan was designed and controlled to maintain a slight negative pressure at the outlet of the combustor (~-0.2" WC).





ITEM	QTY	DESCRIPTION
A	1	UPPER SHELL - SEE DWG D8620E-008 SHEET 2
B	1	LOWER SHELL - SEE DWG D8620E-008 SHEET 1
C	1	S.S. DISTRIBUTION PLATE - SEE DWG D8620E-009 SHEET 1
D	1	"TATE-JONES" BLAST GATE OBSERVATION PORT - 2½" NPT (QUARTZ LENS)
E	1	"TATE-JONES" BLAST GATE OBSERVATION PORT - 4" NPT (QUARTZ LENS)
F	1	FUEL INLET MANIFOLD - SEE DWG D8620E-010
G	1	FLANGE COVER - SEE DWG D8620E-011
H	58	½" HEX HD BOLT X 1" LG (CARBON STEEL)
J	58	½" HEX NUT (CARBON STEEL)
K	58	½" LOCKWASHER (CARBON STEEL)
L	1	BED DRAIN TUBE - SEE DWG D8620E-011
M	1	¼" PACKING - ROUND OR SQUARE X 20" LG.
N	1	PACKING CAP - SEE DWG D8620E-011
P	1	TOP PLATE - SEE DWG D8620E-012
Q	1	⅛" THK CERAMIC FIBER GASKET - SEE DWG. D8620E-011
R	2	1" NPT S.S.(304) 90° ELBOW
S	1	1" NPT X 6" LG S.S.(304) NIPPLE
T	1	WINDBOX INLET - SEE DWG. D8620E-009 SHT 2
U	12	½" HEX HD BOLT X ½" LG (STAINLESS STEEL)
V	12	½" LOCKWASHER (STAINLESS STEEL)

Figure 4-1.

CUSTOMER NAME:	O.A.R.D.C.
CUSTOMER ORDER NUMBER	Energy and Environmental Research Corporation
DRAWN	RVV
CHECKED	
ENGINEER	FLUIDIZED BED COMBUSTOR
PROJ MGR	
DATE	22 JUL 91
SCALE	⅛" = 1"
JOB No	8620
DWG	A8620E-005
REV	0

The AFBC incorporated a flue gas recycle system. A portion of the flue gas from the induced draft fan was mixed with fresh combustion air and then discharged into the fluid bed windbox plenum. The mixture provided the oxygen for combustion of coal in the fluid bed. As the flue gas recycle rate is increased, the fresh air rate is reduced and the oxygen content of the gas entering the wind box decreases. This flue gas recycle technique increases the overall thermal efficiency of the unit some 4 - 5%, compared to an air only combustion system.

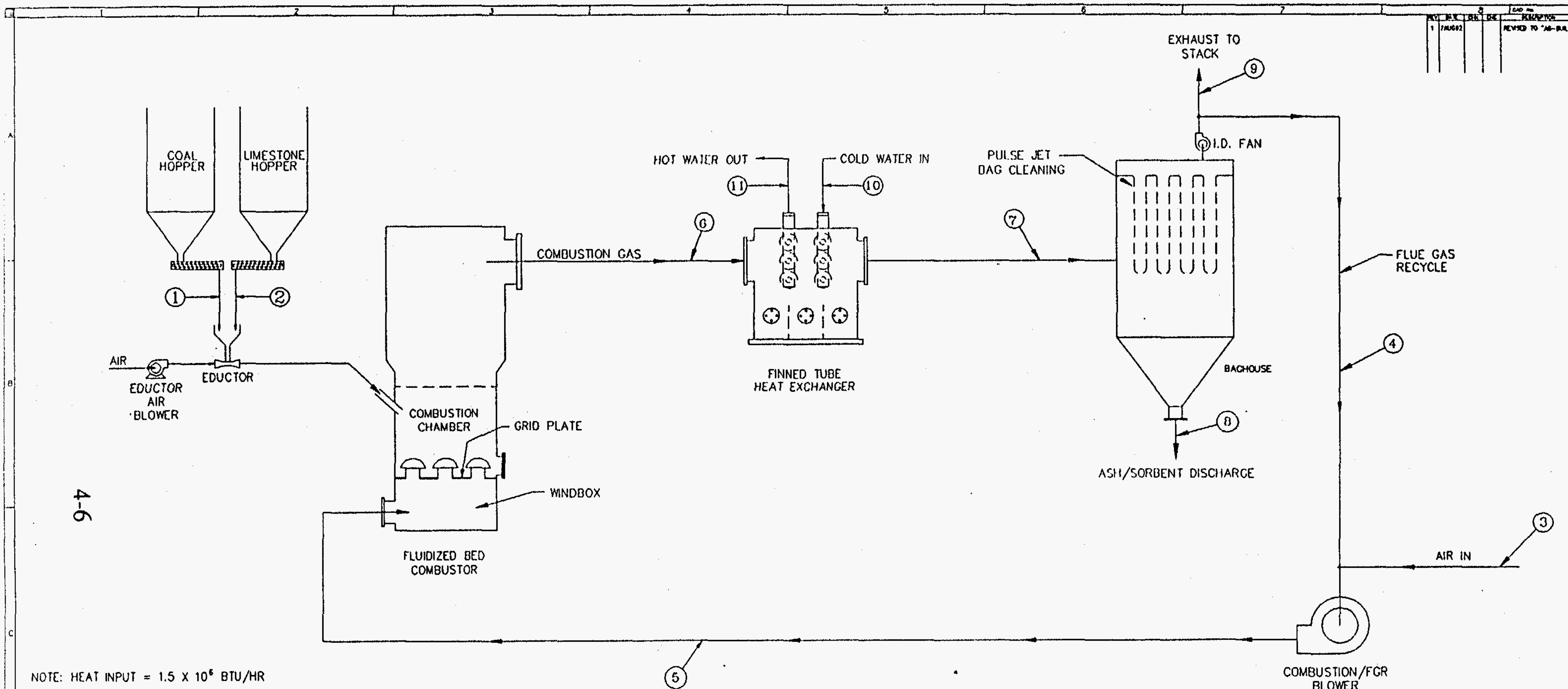
The recycled hot flue gas-air mixture exited the wind box through grid plate air distributor caps, to provide air for combustion and the proper velocity to fluidize the bed. The flue gas recycle control also provides a means to reduce NO_x emissions.

See Figures 4-2 and 4-3, process flow diagram and piping and instrumentation diagram for the AFBC system. A typical unit mass and energy balances for the system operated at OARDC is shown in Table 4-1.

4.2 Operations Assessment

The AFBC system installed was easy to operate. Operational control of the system was very stable and adjustments could be easily made without upsetting the system. The auxiliary burner, flue gas recycle system, fans, coal and limestone feeder all performed satisfactorily.

Initially, the Acrison coal feeder created some problems due to its inability to maintain a controlled coal feed rate. OARDC maintenance personnel modified the feeder by installing a baffle above the screw feeder, and coal flow control was much more reliable. Operationally, problems were very minor; however, a bottleneck to the throughput capacity of the system existed because of the design of the installed heat exchanger.



NOTE: HEAT INPUT = 1.5 X 10^6 BTU/HR

STREAM NUMBER	1	2	3	4	5	6	7	8	9	10	11
STREAM NAME	COAL FEED	LIMESTONE FEED	COMBUSTION AIR	FLUE GAS RECIRC.	COMBUSTION AIR + FGR	AFBC FLUE GAS	B.H. INLET FLUE GAS	B.H. ASH	STACK GAS	C.W. INLET	C.W. OUTLET
UNITS	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr
C	82.0				0.0	0.2	0.2	0.2	0.0		
H	6.1										
O	9.9										
N	1.7										
S	3.5										
ASH	8.3					8.3	8.3	8.2	0.0		
H2O(l)	5.1									11432	11432
CH4											
O2			774.2		774.2	512.4	512.4		512.4		
N2			2556.9		2556.9	2558.4	2558.4		2558.4		
H2O(v)			43.3		43.3	102.6	102.6		102.6		
CO2						314.0	314.0		314.0		
SO2						0.7	0.7		0.7		
HCl						0.0	0.0		0.0		
NOx AS NO2						0.7	0.7		0.7		
CO						0.1	0.1		0.1		
CaCO3		32.5									
CaSO4						13.2	13.2	13.2			
CaO						12.7	12.7	12.7			
TOTAL	116.5	32.5	3374.4	0.0	3374.4	3523.4	3523.4	34.4	3489.0	11432	11432
FLOW RATE, GPM										22.9	22.9
PRESSURE, PSIA.	14.7	14.7	14.7						14.7	49.7	47.7
PRESSURE, in. H2O					30	-0.1	-0.2	-4			
TEMPERATURE, F	80	80	80		80	1600	350	347	347	140	245

Coal HHV (12876 Btu/lb)   Fuel to Hot Water Thermal Efficiency = 80.0%

Figure 4-2.

CUSTOMER NAME: O.A.R.D.C.

CUSTOMER ORDER NUMBER

Energy and Environmental Research Corporation

PROCESS FLOW DIAGRAM
HIGH EXCESS AIR FOR COMBUSTOR TEMPERATURE CONTROL

DATE 1 NOV 89

JOB No. 8620 DWG P8620D-005 REV 1

REV 1 REVISED TO "AS-BUILT"

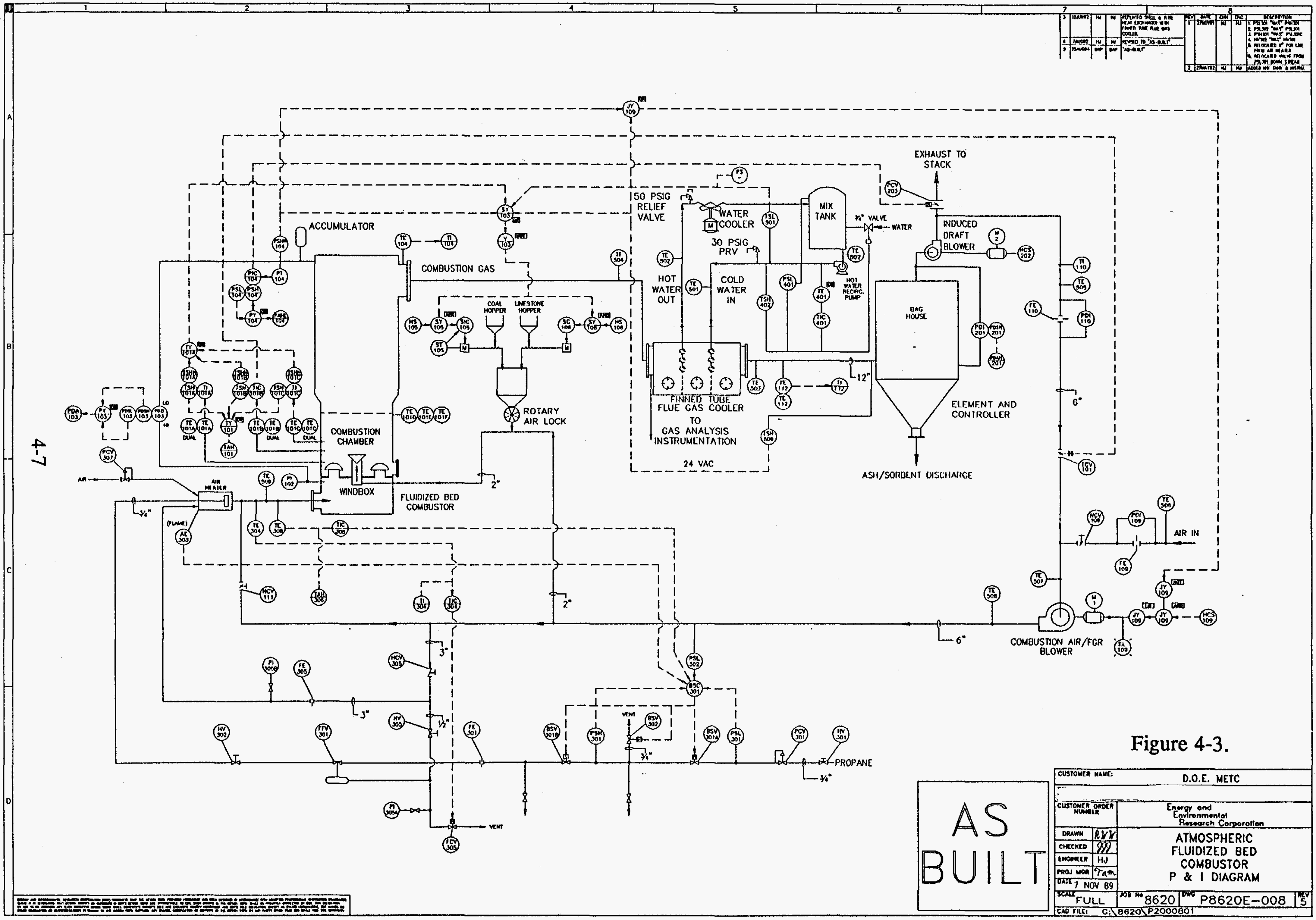

ACCUMULATOR
COMBUSTION GAS
COAL HOPPER
LIMESTONE HOPPER
ROTARY AIR LOCK
COMBUSTION CHAMBER
WINDBOX
FLUIDIZED BED COMBUSTOR
AIR HEATER
AIR
50 PSIG RELIEF VALVE
WATER COOLER
30 PSIG PRV
HOT WATER OUT
COLD WATER IN
MIX TANK
¾" VALVE
WATER
HOT WATER RECIRC. PUMP
FINNED TUBE FLUE GAS COOLER
TO GAS ANALYSIS INSTRUMENTATION
24 VAC
EXHAUST TO STACK
INDUCED DRAFT BLOWER
BAG HOUSE
ELEMENT AND CONTROLLER
ASH/SORBENT DISCHARGE
AIR IN
COMBUSTION AIR/FGR BLOWER
PROPANE
VENT
AS BUILT
CUSTOMER NAME: D.O.E. METC
CUSTOMER ORDER NUMBER
Energy and Environmental Research Corporation
ATMOSPHERIC FLUIDIZED BED COMBUSTOR P & I DIAGRAM
DRAWN
CHECKED
ENGINEER HJ
PROJ MGR
DATE 7 NOV 89
SCALE FULL
JOB No 8620
DWG P8620E-008
REV 5
CAD FILE: G:\8620\P2000801

Figure 4-3.

TABLE 4-1
OHIO BITUMINOUS COAL
1.5 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{COMBUSTION ZONE}

Basis: 60F & H_2O(l)		TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:					
FEED		80			
12,640	Btu/lb actual				
Comp.	wt%				
C	71.15		84.4		
H	4.44		5.3		
O	8.13		9.7		
N	1.24		1.5		
S	3.28		3.9		
Cl	0.00		0.0		
Ash	6.08		7.2		
H_2O(l)	5.68		6.7		
total	100.00				
Subtotal			118.7	9.6	1142
NATURAL GAS (CH_4)		80	0.0	11.2	0
23861	Btu/lb, HHV				
AIR	wt%	95			
O_2	22.94		404.1	7.4	3003
N_2	75.77		1334.8	8.4	11172
H_2O(v)	1.28		22.6	1074.8	24309
(MW =	28.797)				
Subtotal	387 scfm		1761.6		38483
F.G. REC.	vol%	267			
O_2	7.04		138.0	45.7	6308
N_2	74.83		1283.7	51.0	65426
H_2O(v)	6.65		73.4	1152.1	84586
CO_2	11.47		309.2	44.7	13823
SO_2,ppmv	441		1.7	32.5	56
HCl,ppmv	0		0.0	41.6	0
NO_x,ppmv	230		0.6	44.7	29
CO,ppmv	187		0.3	53.3	17
Ash			0.0	45.6	1
Carbon			0.0	33.2	0
$CaSO_4$	Gas MW =	29.506	0.0	41.5	1
CaO	387 scfm		0.0	37.3	1
			======		======
Total	100.00		1807.1		170248
	Mol. Wt.				
$CaCO_3$	100.09	80	36.4		
Ash			9.1		
			======		======
Subtotal			45.5	4.4	200
Heat of Combustion					1488132
			======		======
TOTAL			3732.8		1698207
OUTPUT:					
FLUE GAS	vol%	1550			
O_2	7.04		281.6	363.7	102443
N_2	74.83		2619.8	392.5	1028142
H_2O(v)	6.65		149.8	1806.5	270664
CO_2	11.47		631.0	392.7	247768
SO_2,ppmv	441		3.5	276.6	976
HCl,ppmv	0		0.0	274.1	0
NO_x,ppmv	230		1.3	392.7	520
CO,ppmv	187		0.7	399.1	261
Ash		sfgv =	16.3	327.8	5357
Carbon		5.36	0.8	238.4	202
$CaSO_4$		fps	12.7	298.0	3788
CaO	Gas MW =	29.506	15.2	268.2	4073
	800 scfm				
Subtotal	100.00		3732.8		1664193
Heat Loss	2.00%				33964
			======		======
TOTAL			3732.8		1698157

Mass Closure = 100.00% Energy Closure = 100.00%

TABLE 4-1
OHIO BITUMINOUS COAL
1.5 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{HOT WATER HEATER}

Air Leakage = 0.00% Ctrl. Air
Cooling Water = 85.0 gpm

Basis: 60F & H2O(l)		TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:					
FLUE GAS	vol%	1550			
O2	7.04	7.54	281.6	363.7	102443
N2	74.83	dry	2619.8	392.5	1028142
H2O(v)	6.65		149.8	1806.5	270664
CO2	11.47		631.0	392.7	247768
SO2,ppmv	441		3.5	276.6	976
HCl,ppmv	0		0.0	342.8	0
NOx,ppmv	230		1.3	392.7	520
CO,ppmv	187		0.7	399.1	261
Ash			16.3	327.8	5357
Carbon			0.8	238.4	202
CaSO4			12.7	298.0	3788
CaO			15.2	268.2	4073
(MW =	29.506)		----------------		----------------
Subtotal	100.00		3732.8		1664193
COOLING WATER		150			
H2O(l)			42484.4	90.0	3823597
AIR LEAK.	wt%	95			
O2	22.94		0.0	7.4	0
N2	75.77		0.0	8.4	0
H2O(v)	1.28		0.0	1074.8	0
(MW =	28.797)		----------------		----------------
Subtotal	0 scfm		0.0		0
			======		======
TOTAL			46217.2		5487790
OUTPUT:					
FLUE GAS	vol%	275			
O2	7.04		281.6	47.4	13357
N2	74.83		2619.8	52.9	138491
H2O(v)	6.65		149.8	1155.6	173145
CO2	11.47		631.0	46.4	29293
SO2,ppmv	441		3.5	33.7	119
HCl,ppmv	0		0.0	43.1	0
NOx,ppmv	230		1.3	46.4	61
CO,ppmv	187		0.7	55.2	36
Ash			16.3	47.3	773
Carbon			0.8	34.4	29
CaSO4			12.7	43.0	547
CaO			15.2	38.7	588
(MW =	29.506)		----------------		----------------
Subtotal	100.00		3732.8		356439
HOT WATER		180			
H2O(l)			42483.9	120.0	5098066
Blowdown @ 0.0%		180	0.0	120.0	0
Heat Loss	2.00%				33284
			======		======
TOTAL			46216.7		5487788

Mass Closure = 100.00% Energy Closure = 100.00%

TABLE 4-1
OHIO BITUMINOUS COAL
1.5 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{BAG HOUSE}

EFFICIENCY = 99.7 %

Basis: 60F & H2O(l)		TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:					
FLUE GAS	vol%	275			
O2	7.04		281.6	47.4	13357
N2	74.83		2619.8	52.9	138491
H2O(v)	6.65		149.8	1155.6	173145
CO2	11.47		631.0	46.4	29293
SO2,ppmv	441		3.5	33.7	119
HCl,ppmv	0		0.0	43.1	0
NOx,ppmv	230		1.3	46.4	61
CO,ppmv	187		0.7	55.2	36
Ash			16.3	47.3	773
Carbon			0.8	34.4	29
CaSO4			12.7	43.0	547
CaO			15.2	38.7	588
(MW =	29.506)		=======		=======
TOTAL	100.00		3732.8		356439
OUTPUT:					
FLUE GAS	vol%	267			
O2	7.04	7.54%	281.6	45.7	12873
N2	74.83	dry	2619.8	51.0	133520
H2O(v)	6.65		149.8	1152.1	172624
CO2	11.47		631.0	44.7	28210
SO2,ppmv	441		3.5	32.5	115
HCl,ppmv	0		0.0	41.6	0
NOx,ppmv	230		1.3	44.7	59
CO,ppmv	187		0.7	53.3	35
Ash			0.0	45.6	2
Carbon			0.0	33.2	0
CaSO4			0.0	41.5	2
CaO			0.0	37.3	2
(MW =	29.506)		----------		----------
Subtotal	100.00		3687.8		347441
B.H. SOLIDS		267			
Ash			16.3	45.6	743
Carbon			0.8	33.2	28
CaSO4			12.7	41.5	526
CaO			15.1	37.3	565
			----------		----------
Subtotal			45.0		1862
Heat Loss	2.00%				7129
			=======		=======
TOTAL			3732.8		356432

Mass Closure = 100.00% Energy Closure = 100.00%

TABLE 4-1
OHIO BITUMINOUS COAL
1.5 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{FLUE GAS RECYCLE}

Flue Gas Recycle @ 49.0%

Basis: 60F & H2O(l)		TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:					
FLUE GAS	vol%	267			
O2	7.04	7.54%	281.6	45.7	12873
N2	74.83	dry	2619.8	51.0	133520
H2O(v)	6.65		149.8	1152.1	172624
CO2	11.47		631.0	44.7	28210
SO2,ppmv	441		3.5	32.5	115
HCl,ppmv	0		0.0	41.6	0
NOx,ppmv	230		1.3	44.7	59
CO,ppmv	187		0.7	53.3	35
Ash			0.0	45.6	2
Carbon			0.0	33.2	0
CaSO4			0.0	41.5	2
CaO			0.0	37.3	2
(MW =	29.506)				
	791	scfm	======		======
TOTAL			3687.8		347441
F.G. REC.	vol%	267			
O2	7.04		138.0	45.7	6308
N2	74.83		1283.7	51.0	65425
H2O(v)	6.65		73.4	1152.1	84586
CO2	11.47		309.2	44.7	13823
SO2,ppmv	441		1.7	32.5	56
HCl,ppmv	0		0.0	41.6	0
NOx,ppmv	230		0.6	44.7	29
CO,ppmv	187		0.3	53.3	17
Ash			0.0	45.6	1
Carbon			0.0	33.2	0
CaSO4			0.0	41.5	1
CaO			0.0	37.3	1
(MW =	29.506)				
	387	scfm	----------------		----------------
Subtotal			1807.0		170246
STACK	vol%	267			
O2	7.04	7.54%	143.6	45.7	6565
N2	74.83	dry	1336.1	51.0	68095
H2O(v)	6.65		76.4	1152.1	88038
CO2	11.47		321.8	44.7	14387
SO2,ppmv	441		1.8	32.5	58
HCl,ppmv	0		0.0	41.6	0
NOx,ppmv	230	0.45	0.7	44.7	30
CO,ppmv	187	lb/MM Btu	0.3	53.3	18
Ash			0.0	45.6	1
Carbon			0.0	33.2	0
CaSO4			0.0	41.5	1
CaO			0.0	37.3	1
(MW =	29.506)				
	403	scfm	----------------		----------------
Subtotal			1880.8		177195
			======		======
TOTAL			3687.8		347441

Mass Closure = 100.00% Energy Closure = 100.00%

OPERATIONS SUMMARY

Sulfur In	5.18	lb SO2/MM Btu	SO2 Removal	=	76.8%
Sulfur Out	1.20	lb SO2/MM Btu	Ca/S Ratio Estimat	=	3.0
NOx	0.45	lb NO2/MM Btu	Thermal Efficienc	=	85.0%
Particulate	0.04	lb/MM Btu	Flue Gas Recycle	=	49.0%

4.3 Data Analysis

Data was taken for sixty-two operational run periods; of those, 29 runs have yielded complete sets of data for analysis. Tables 4-2 and 4-3 show the test results for the Ohio coal. Table 4-4 shows the Ohio coal and ash analyses, and the analyses of the limestones fed into the fluid bed to capture sulfur dioxide. Table 4-5 shows the results of the testing of 1000 lbs of Alaska coal; also shown are the coal and ash analyses.

4.3.1 Coal and Sorbent

The coal throughput was limited by the heat exchanger performance. After the heat exchanger had been cleaned, a coal feed rate of 1.1 to 1.2 MM Btu/hr was possible. After running for sometime the heat exchanger performance would drop off and rates generally leveled out at 0.9 to 1.0×10^6 Btu/hr. The combustor design coal feed rate was 1.5×10^6 Btu/hr.

Over the testing program two coals and two limestones were tested in the combustor. The coals and limestones tested were as follows:

Coal:

- Wayne Mine Coal - High Sulfur Bituminous Ohio Coal
- Little Tonzana Coal - Low Sulfur Sub-Bituminous Alaska Coal

Limestone:

- National Lime and Stone Limestone - 80 wt% $CaCO_3$ Calcitic Limestone
- Ohio Lime Company - 54.5 wt% $CaCO_3$ Dolomitic Limestone

TABLE 4-2.
Atmospheric Fluidized Bed Combustion Tests @ OARDC
Pilot Runs using Calcitic Limestone as Sorbent

Run:	Run #22	Run #23	Run #24	Run #26	Run #28	Run #29	Run #30	Run #31	Run #32	Run #33	Run #35
Date:	9/14/92	9/14/92	9/15/92	9/15/92	9/16/92	9/16/92	9/16/92	9/16/92	9/16/92	9/16/92	9/28/92
Time:	16:40	17:20	15:15	16:30	11:30	11:56	13:46	14:56	15:50	17:00	17:16
Category:											
Bed Material	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand
Limestone Supplier	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime	Nat'l Lime
Particle Size	12x100 mesh	12x100 mesh	12x100 mesh	12x100 mesh	12x100 mesh	12x100 mesh	12x100 mesh	12x100 mesh	12x100 mesh	12x100 mesh	6x16 mesh
Lime Rate, lb/hr	7.4	15.2	15.2	25.2	25.2	25.2	25.2	25.2	39.6	39.6	39.6
Coal	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.
Coal Feed, lb/hr	52.4	45.1	74.2	64.8	93.2	93.2	64.8	74.2	74.2	97.9	83.7
Coal Feed, MM Btu/hr	0.66	0.57	0.94	0.82	1.18	1.18	0.82	0.94	0.94	1.24	1.06
Ca/S Ratio, Limestone only	1.10	2.64	1.61	3.04	2.12	2.12	3.04	2.66	4.17	3.16	3.70
Ca/S Ratio*, Coal Ash only	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Overall Ca/S Ratio	1.14	2.68	1.65	3.08	2.16	2.16	3.08	2.70	4.21	3.20	3.74
Fl. Bed FG Outlet Temp., F	1634	1649	1703	1671	1589	1597	1647	1657	1664	1613	1593
H. Ex. FG Outlet Temp., F	464	477	526	521	461	462	439	445	447	466	466
Heat Removed (HE), MM Btu/hr	0.468	0.407	0.673	0.586	0.860	0.842	0.642	0.745	0.743	0.996	0.846
Flue Gas Recirculation, %	0	0	0	5.3	0	0	28.2	33.3	33.4	48.3	48.2
SO2-Coal, lb/MM Btu	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18
SO2-Flue Gas, lb/MM Btu	3.46	2.76	2.61	2.52	1.51	1.87	1.65	2.13	1.52	1.25	1.76
Sulfur Capture, %	33.1	46.9	49.7	51.4	70.8	63.8	68.1	58.9	70.7	75.8	66.1
Calcium Utilization, %	30.0	17.7	30.9	16.9	33.5	30.2	22.4	22.2	16.9	24.0	17.9
NOx**-Flue Gas, lb/MM Btu	0.99	0.99	0.92	1.00	0.92	0.96	0.95	0.97	0.98	0.87	0.37
Fuel Bound N to NOx**, %	30.6	30.8	28.6	31.2	28.5	29.9	29.6	30.1	30.6	27.0	11.4
N2O-Flue Gas, lb/MM Btu	-	-	-	-	-	-	-	-	-	-	0.082
Fuel Bound N to N2O, %	-	-	-	-	-	-	-	-	-	-	2.5
CO-Flue Gas, lb/MM Btu	0.245	0.235	0.174	0.157	0.166	0.161	0.194	0.184	0.192	0.316	0.452
O2 dry (calc), vol% dry	13.5	13.5	13.5	13.2	14.0	13.8	11.0	10.3	10.1	7.8	8.0
O2 dry (meas), vol% dry	13.5	13.5	13.5	13.2	14.0	13.8	11.0	10.3	10.1	7.8	8.0
CO2 dry (calc), vol% dry	6.7	6.8	6.7	7.1	6.3	6.5	9.1	9.7	10.1	12.1	12.0
CO2 dry (meas), vol% dry***	6.1	6.1	5.7	6.2	5.4	5.6	8.2	9.1	9.3	11.6	11.3
SO2 dry (calc), ppmvd	758	599	569	569	307	391	479	662	479	479	662
SO2 dry (meas), ppmvd	758	599	569	569	307	391	479	662	479	479	662
NOx** dry (calc), ppmvd	300	300	280	300	260	280	276	280	288	240	100
NOx** dry (meas), ppmvd	300	300	280	300	260	280	276	280	288	240	100
N2O dry (meas), ppmvd	-	-	-	-	-	-	-	-	-	-	17.0
CO dry (calc), ppmvd	122	117	87	77	77	77	92	87	92	143	202
CO dry (meas), ppmvd	122	117	87	77	77	77	92	87	92	143	202

* Coal Ca (includes Ca, Na2 and K2)

** NOx is total nitrogen oxides reported as NO2

*** Following runs found instrument calibration off in mid range

TABLE 4-3.
Atmospheric Fluidized Bed Combustion Tests @ OARDC
Pilot Runs using Dolomitic Limestone as Sorbent

Run:	Run #37	Run #38	Run #39	Run #40	Run #51	Run #52	Run #53	Run #54	Run #55	Run #56	Run #57	Run #58	Run #59	Run #60	Run #61	Run #62
Date:	9/29/92	9/29/92	9/29/92	9/29/92	1/14/93	1/14/93	1/14/93	1/14/93	1/18/93	1/18/93	1/18/93	1/18/93	1/18/93	1/18/93	1/18/93	1/18/93
Time:	10:36	11:06	14:06	15:15	21:30	22:10	22:51	23:42	16:05	16:50	17:35	18:58	19:34	21:00	21:15	21:45
Category:																
Bed Material	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand
Limestone Supplier	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime	Ohio Lime
Particle Size	6x16 mesh	20x80 mesh	-325 mesh	10x30 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh	20x80 mesh
Lime Rate, lb/hr	39.0	39.0	60.0	60.0	0.0	10.4	20.8	31.3	0.0	10.8	17.0	33.5	33.5	17.0	10.8	0.0
Coal	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.	OH, Bitum.
Coal Feed, lb/hr	81.5	76.5	76.5	76.5	69	69	69	70	72	75	75	75	75	75	75	75
Coal Feed, MM Btu/hr	1.03	0.97	0.97	0.97	0.87	0.87	0.87	0.88	0.91	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Ca/S Ratio, Limestone only	2.58	2.74	4.22	4.22	0.00	0.81	1.62	2.41	0.00	0.77	1.27	2.40	2.40	1.22	0.77	0.00
Ca/S Ratio*, Coal Ash only	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Overall Ca/S Ratio	2.62	2.78	4.26	4.26	0.04	0.84	1.65	2.44	0.04	0.81	1.31	2.44	2.44	1.26	0.81	0.04
Fl. Bed FG Outlet Temp., F	1634	1641	1580	1572	1598	1627	1580	1590	1596	1599	1604	1599	1608	1597	1603	1602
H. Ex. FG Outlet Temp., F	458	456	447	461	495	502	495	507	520	519	518	523	529	528	525	523
Heat Removed (HE), MM Btu/hr	0.832	0.778	0.771	0.772	0.628	0.630	0.635	0.642	0.651	0.687	0.669	0.687	0.675	0.673	0.679	0.680
Flue Gas Recirculation, %	47.4	44.0	42.5	46.9	41.2	35.8	34.2	43.3	44.5	35.9	40.7	43.0	41.1	41.0	40.6	39.2
SO2-Coal, lb/MM Btu	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18	5.18
SO2-Flue Gas, lb/MM Btu	2.06	0.92	0.59	0.77	4.42	3.68	2.05	1.61	3.78	3.17	2.76	1.70	1.74	2.45	2.76	3.95
Sulfur Capture, %	60.3	82.2	88.6	85.1	14.6	29.0	60.3	69.0	27.0	38.8	46.7	67.3	66.4	52.6	46.8	23.8
Calcium Utilization, %	23.6	30.3	21.2	20.4	0.0	36.0	37.6	28.9	0.0	50.6	38.6	28.3	27.9	43.6	60.9	0.0
*NOx**-Flue Gas, lb/MM Btu*	*0.65*	*0.83*	0.92	*0.93*	1.05	*0.98*	1.08	*1.00*	1.01	*0.93*	*0.98*	*0.98*	*0.97*	*0.98*	*0.93*	1.01
Fuel Bound N to NOx**, %	20.3	25.9	28.7	29.0	32.7	30.4	33.6	30.9	31.2	28.8	30.3	30.3	30.1	30.5	29.0	31.4
N2O-Flue Gas, lb/MM Btu	0.081	0.067	0.113	0.107	-	-	-	-	-	-	-	-	-	-	-	-
Fuel Bound N to N2O, %	2.5	2.1	3.5	3.3	-	-	-	-	-	-	-	-	-	-	-	-
CO-Flue Gas, lb/MM Btu	0.344	0.296	0.263	0.338	0.198	0.212	0.173	0.220	0.237	0.217	0.219	0.220	0.242	0.252	0.244	0.245
O2 dry (calc), vol% dry	7.8	8.5	9.3	8.5	10.0	10.5	11.0	9.5	9.5	10.7	10.0	9.5	9.8	10.0	10.0	10.3
O2 dry (meas), vol% dry	7.8	8.5	9.3	8.5	10.0	10.5	11.0	9.5	9.5	10.7	10.0	9.5	9.8	10.0	10.0	10.3
CO2 dry (calc), vol% dry	12.0	11.4	10.9	11.6	9.7	9.3	9.0	10.4	10.1	9.1	9.8	10.4	10.1	9.8	9.8	9.4
CO2 dry (meas), vol% dry***	12.0	10.9	10.1	12.3	8.7	8.3	8.5	6.2	10.0	8.5	9.5	10.3	10.1	9.7	9.5	10.4
SO2 dry (calc), ppmvd	790	335	200	280	1434	1135	600	539	1282	959	891	569	569	791	891	1245
SO2 dry (meas), ppmvd	790	335	200	280	1434	1135	600	539	1282	959	891	569	569	791	891	1245
NOx** dry (calc), ppmvd	184	236	250	250	280	270	290	264	264	250	260	260	260	260	250	270
NOx** dry (meas), ppmvd	184	236	250	250	280	270	290	264	264	250	260	260	260	260	250	270
N2O dry (meas), ppmvd	17.5	14.5	23.5	22.0	-	-	-	-	-	-	-	-	-	-	-	-
CO dry (calc), ppmvd	159	138	117	148	86	96	76	96	102	96	96	96	107	110	107	107
CO dry (meas), ppmvd	159	138	117	148	86	96	76	96	102	96	96	96	107	110	107	107

* Coal Ca (includes Ca, Na2 and K2)

** NOx is total nitrogen oxides reported as NO2

*** Following runs found instrument calibration off in mid range

TABLE 4-4.
Ohio Coal and Limestone Analyses
Feedstocks used in Pilot Runs

Holmes Limestone Company
Wayne Mine, Ohio Coal

Ultimate Analysis (as received):

Composition	Sample 1 Wt%	Sample 2 Wt%	Sample 3 Wt%	Average Wt%
Carbon	71.05	70.90	71.50	71.15
Hydrogen	4.59	4.18	4.54	4.44
Nitrogen	1.17	1.31	1.24	1.24
Oxygen	8.32	8.07	8.01	8.13
Sulfur	3.30	3.35	3.18	3.28
H2O	5.48	6.10	5.47	5.68
Ash	6.09	6.09	6.06	6.08
Total	100.00	100.00	100.00	100.00
HHV, Btu/lb	12,700	12,559	12,662	12,640
Lb SO2/MM Btu	5.19	5.33	5.03	5.18

Ash Analysis (typical for Ohio Seams 5,6,7):

Component	Wt. %
SiO2	41.46
Al2O3	24.26
TiO2	1.08
Fe2O3	26.95
CaO	2.00
MgO	0.82
K2O	1.80
Na2O	0.46
SO3	0.37
P2O5	0.28
SrO	0.06
BaO	0.00
MnO2	0.10
Undetermined	0.36
Total	100.00

Calculated coal ash Ca/S ratio (includes Ca, Na2, K2) = 0.037

National Lime & Stone Company
Bucyrus #17 Limestone

Chemical Analysis:

Composition	Wt. %
Insolubles (incl. SiO2)	2.55
Iron Oxide (Fe2O3)	0.20
Calcium Carbonate	80.00
Magnesium Carbonate (MgCO3)	17.00
Sulfur as SO3	0.25
Total	100.00

Loss on Ignition = 44 wt. %
Bulk Density = 95 lb/cu.ft.

Particle Size Distribution

Mesh	Wt% Retained (12 x 100)
8	Trace
12	10
16	18
30	33
50	24
100	12
200	2
-200	1
Total	100

Ohio Lime Company
Woodville Dolomite

Chemical Analysis:

Composition	Wt. %
Insolubles (incl. SiO2)	1.34
Iron Oxide (Fe2O3)	0.06
Calcium Carbonate	54.50
Magnesium Carbonate (MgCO3)	44.00
Sulfur as SO3	0.10
Moisture	0.10
Total	100.00

Loss on Ignition = 47.2 wt. %
Bulk Density = 87.9 lb/cu.ft

Particle Size Distribution

Mesh	<------ Wt% Retained -------> (10 x 30	(20 x 80	(-325)
8	Trace	-	-
10	1.9	-	-
16	55.7	Trace	-
20	31.1	2.4	-
30	7.3	15.7	-
60	4.0	55.2	-
80	-	13.1	-
100	-	5.7	-
140	-	3.3	-
200	-	2.1	0.1
325	-	2.5	2.9
-325	-	-	97.0
Total	100.0	100.0	100.0

TABLE 4-5.
Atmospheric Fluidized Bed Combustion Tests @ OARDC
Pilot Runs using Alaska Sub-Bituminous Coal

Run:	Run #49	Run #50
Date:	10/16/92	10/16/92
Time:	14:30	10:15
Category:		
Bed Material	Sand	Sand
Limestone	None	None
Particle Size	-	-
Lime Rate, lb/hr	-	-
Coal	Li'l Tonzana	Li'l Tonzana
Coal Feed, lb/hr	155	155
Coal Feed, MM Btu/hr	1.18	1.18
Ca/S Ratio*, Coal Ash only	1.19	1.19
Carbon in Ash, wt %	3.2	3.2
Carbon Conversion, wt %	99.4	99.4
Fl. Bed FG Outlet Temp., F	1606	1507
H. Ex. FG Outlet Temp., F	524	515
Heat Removed (HE), MM Btu/hr	0.797	0.880
Flue Gas Recirculation, %	5.4	54.3
SO2-Coal, lb/MM Btu	2.78	2.78
SO2-Flue Gas, lb/MM Btu	2.04	1.34
Sulfur Capture, %	26.5	52.0
NOx**-Flue Gas, lb/MM Btu	0.46	0.44
Fuel Bound N to NOx**, %	22.2	21.2
N2O-Flue Gas, lb/MM Btu	0.098	0.130
Fuel Bound N to N2O, %	4.7	6.3
CO-Flue Gas, lb/MM Btu	0.116	0.556
O2 dry (calc), vol% dry	13.0	6.3
O2 dry (meas), vol% dry	13.0	6.3
CO2 dry (calc), vol% dry	7.6	14.0
CO2 dry (meas), vol% dry***	7.3	12.7
SO2 dry (calc), ppmvd	473	569
SO2 dry (meas), ppmvd	473	569
NOx** dry (calc), ppmvd	140	120
NOx** dry (meas), ppmvd	140	120
N2O dry (meas), ppmvd	23	27
CO dry (calc), ppmvd	58	248
CO dry (meas), ppmvd	58	248

* Coal Ca (includes Ca, Na2 and K2)

** NOx is total nitrogen oxides reported as NO2

Little Tonzana Coal

Ultimate Analysis (as received):

Composition	Wt%
Carbon	46.90
Hydrogen	2.73
Nitrogen	0.48
Oxygen	15.50
Sulfur	1.06
H2O	24.97
Ash	8.36
Total	100.00
HHV, Btu/lb	7,613
Lb SO2/MM Btu	2.78

Selected Elemental Ash Analysis:

Composition	Wt%
Calcium	18.450
Magnesium	3.728
Potassium	0.589
Sodium	0.092
Phosphorous	0.061
Copper	0.036
Zinc	0.032
Nickel	0.013
Lead	0.008
Chromium	0.004
Cadmium	<0.2 ppmw

4.3.2 Sulfur Dioxide Capture

Sulfur dioxide capture via limestone addition to the fluid bed was as high as 88.6%, yielding a flue gas emission rate of 0.59 lb of SO2 per million Btu of coal fired. This was accomplished with the dolomitic limestone being fed at a rate to yield a Ca/S ratio of 4.26. The data indicated that the regulated emission requirement of 1.2 lb of $SO_2/10^6$ Btu of coal fired could be met with a limestone rate to yield a Ca/S ratio of ~3.0.

The sulfur dioxide capture relative to the Ca/S ratio when using calcitic limestone, is shown in Figure 4-4. Figure 4-5 is a similar graph using dolomitic limestone. Figure 4-6 shows the limestone to coal ratio versus flue gas sulfur dioxide. Whereas the dolomitic limestone gave the best performance based on Ca/S ratios, when considering limestone/coal ratios, the limestones perform similarly. The reason for this is that the dolomitic limestone has a calcium carbonate content of 54.5 wt% compared to the calcitic limestone with 80 wt%.

The effect of fluid bed temperature on sulfur dioxide capture is shown for both the Alaska and Ohio coal in Figure 4-7. To date, data is limited in assessing this effect, but trends can be seen from the data available. Further testing will be completed to better define the optimum temperature range for SO_2 capture. Based on other fluid bed systems, it is expected that the optimum temperature will be in the 1500 - 1550 °F range.

Whereas no limestone was fed into the combustor during the testing of the Alaska coal, the equivalent Ca/S ratio provided by the alkali components in the its ash yielded a Ca/S ratio of 1.19. The Ohio coal, on the other hand yields only a 0.04 Ca/S ratio based on coal ash alkali components.

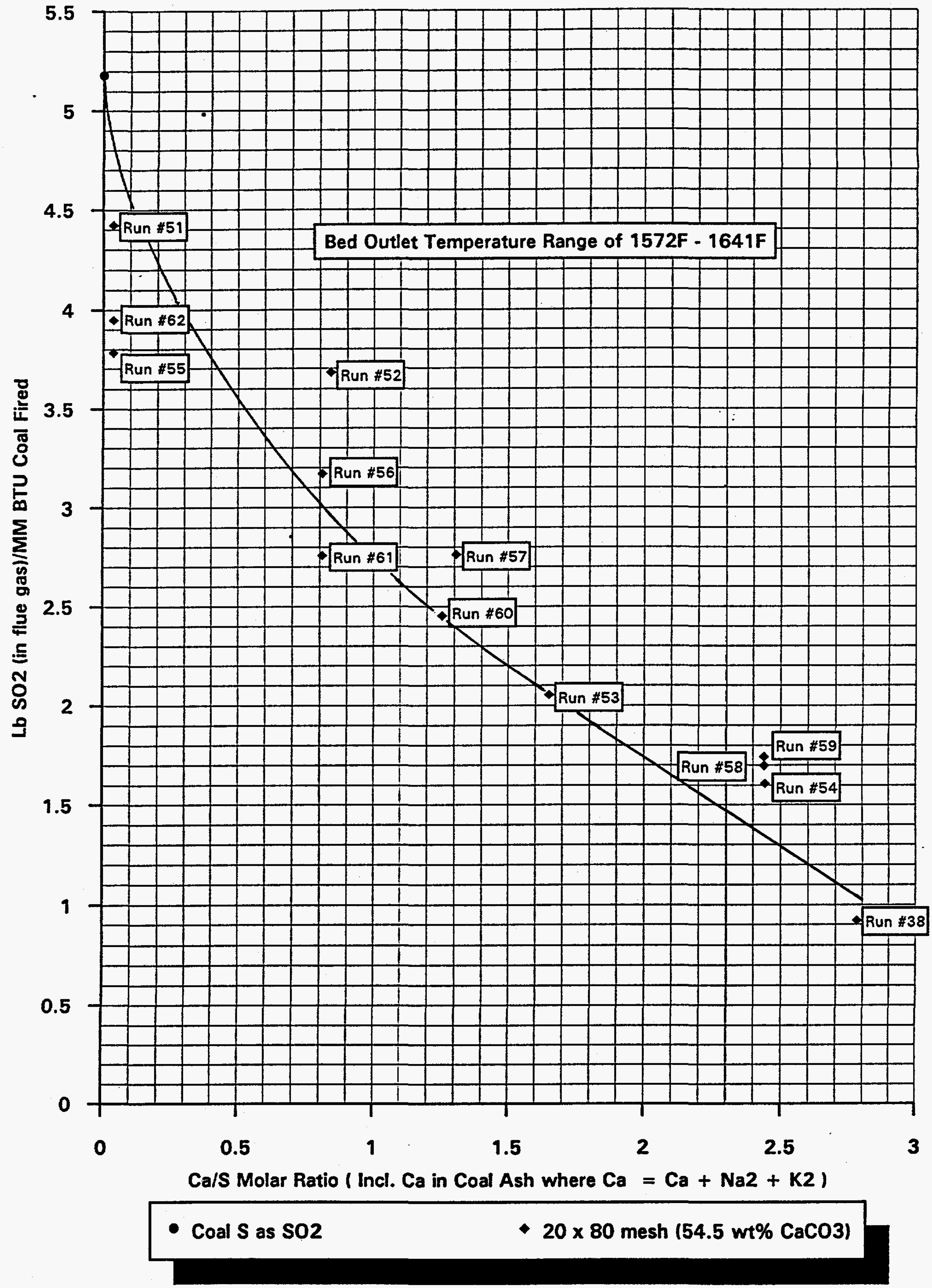


Figure 4-5. Ca/S Ratio versus SO2 w/dolomitic limestone

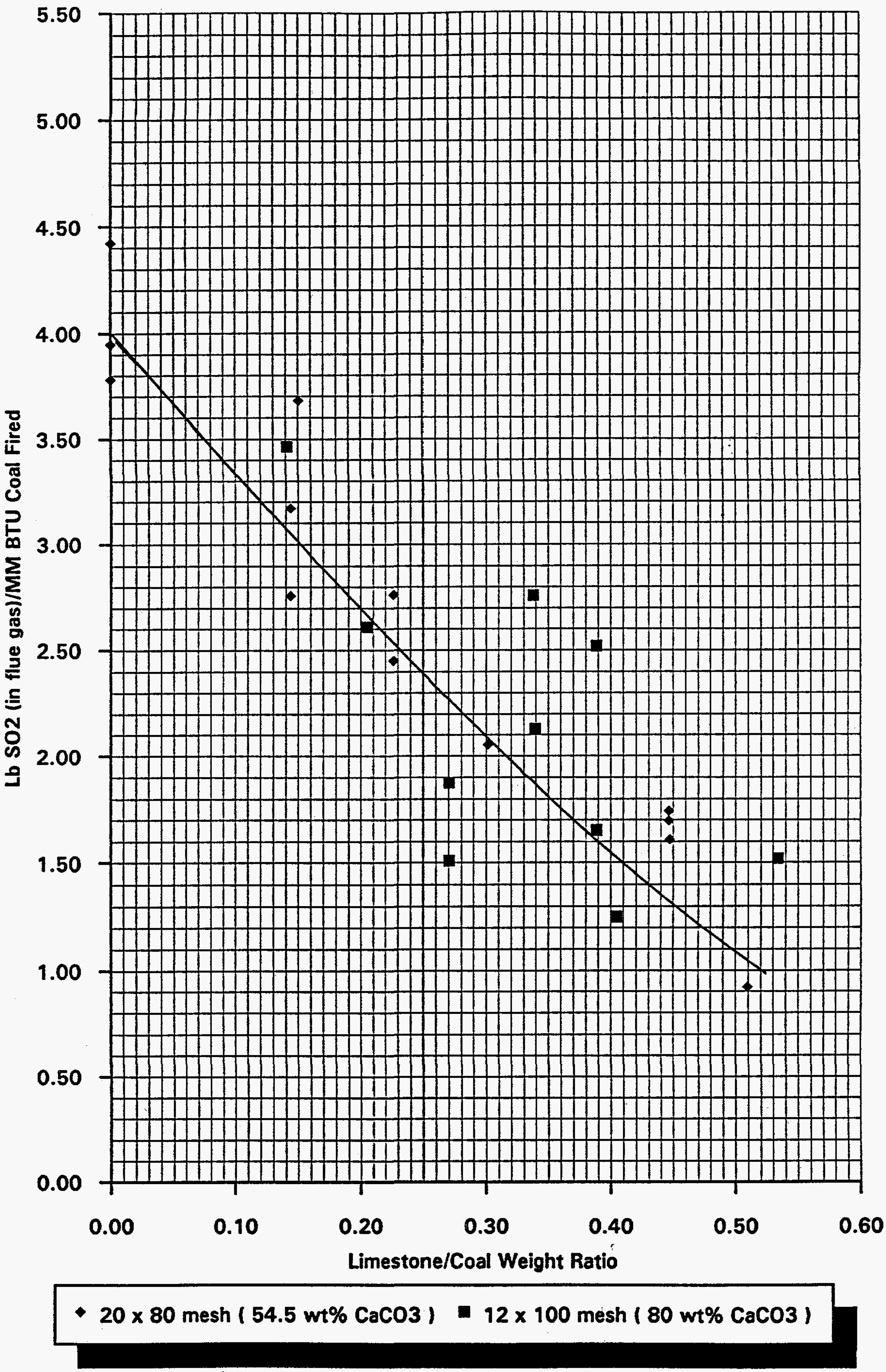


Figure 4-6. Limestone/coal versus SO2 emissions

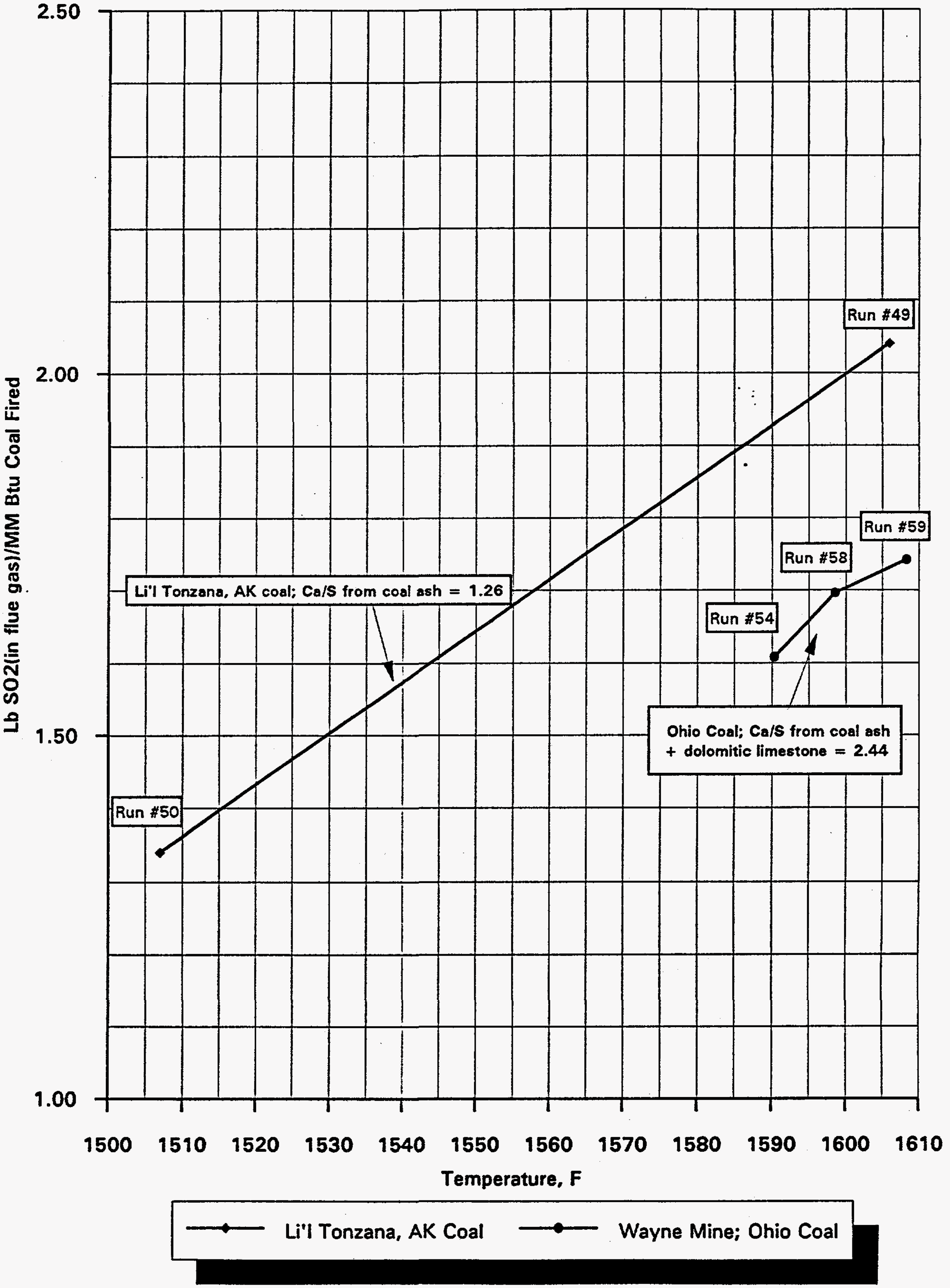


Figure 4-7. SO2 emissions versus bed temperature

Figures 4-8 and 4-9 show calcium utilization versus temperature for calcitic and dolomitic limestones, respectively. Whereas, the trend of better utilization at lower temperature is seen with the calcitic limestone, the dolomitic limestone does not clearly show this trend. The reason for this may be the effect of the increased magnesium carbonate content of the dolomite. The magnesium carbonate may limit the rate of pore pluggage in the limestone particles, allowing sulfur dioxide to penetrate the stone regardless of temperature. In future runs, further evaluations will be made on the effect of temperature on sulfur capture.

Various particle sizes of limestones were tested; Figure 4-10 shows the effect of particle size on limestone calcium utilization. For both the dolomitic and calcitic limestones, it is seen that the smaller size of limestone performs better than the larger size. This phenomenon was expected, since it is well known that the larger the particle surface area, the greater the calcium utilization.

One of the parameters investigated was the effect of flue gas recycle on sulfur capture. With flue gas recycle, the concentration of SO_2 in the fluid bed increases and with this increase one could postulate that sulfur capture should increase due to the higher partial pressure of sulfur dioxide. Relative to the SO_2 concentration effect, no trend could be discerned with the calcitic limestone; however, with dolomitic limestone a trend was shown, see Figure 4-11.

4.3.3 NO_x Reduction

For all twenty nine runs shown in the tables, NO_x as nitrogen dioxide (NO_2) was analyzed. Nitrous oxides (N_2O) were analyzed for a seven of the runs shown, using a N_2O analyzer borrowed from EER's test site in Irvine, CA to complete these tests. The nitrogen oxide emission results for the runs are shown in Tables 4-2, 4-3 and 4-4.

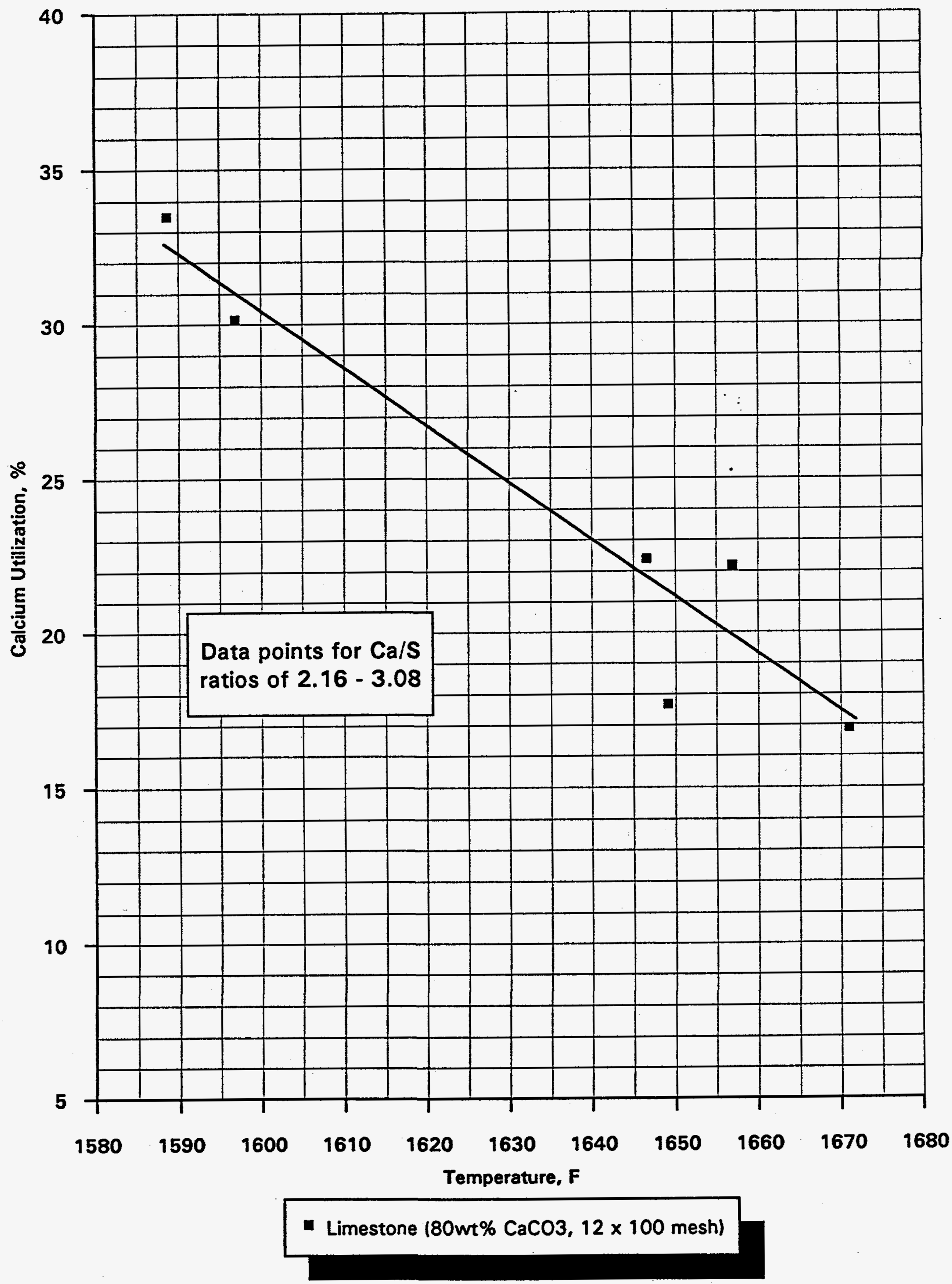


Figure 4-8. Calcium utilization versus temperature for calcitic limestone

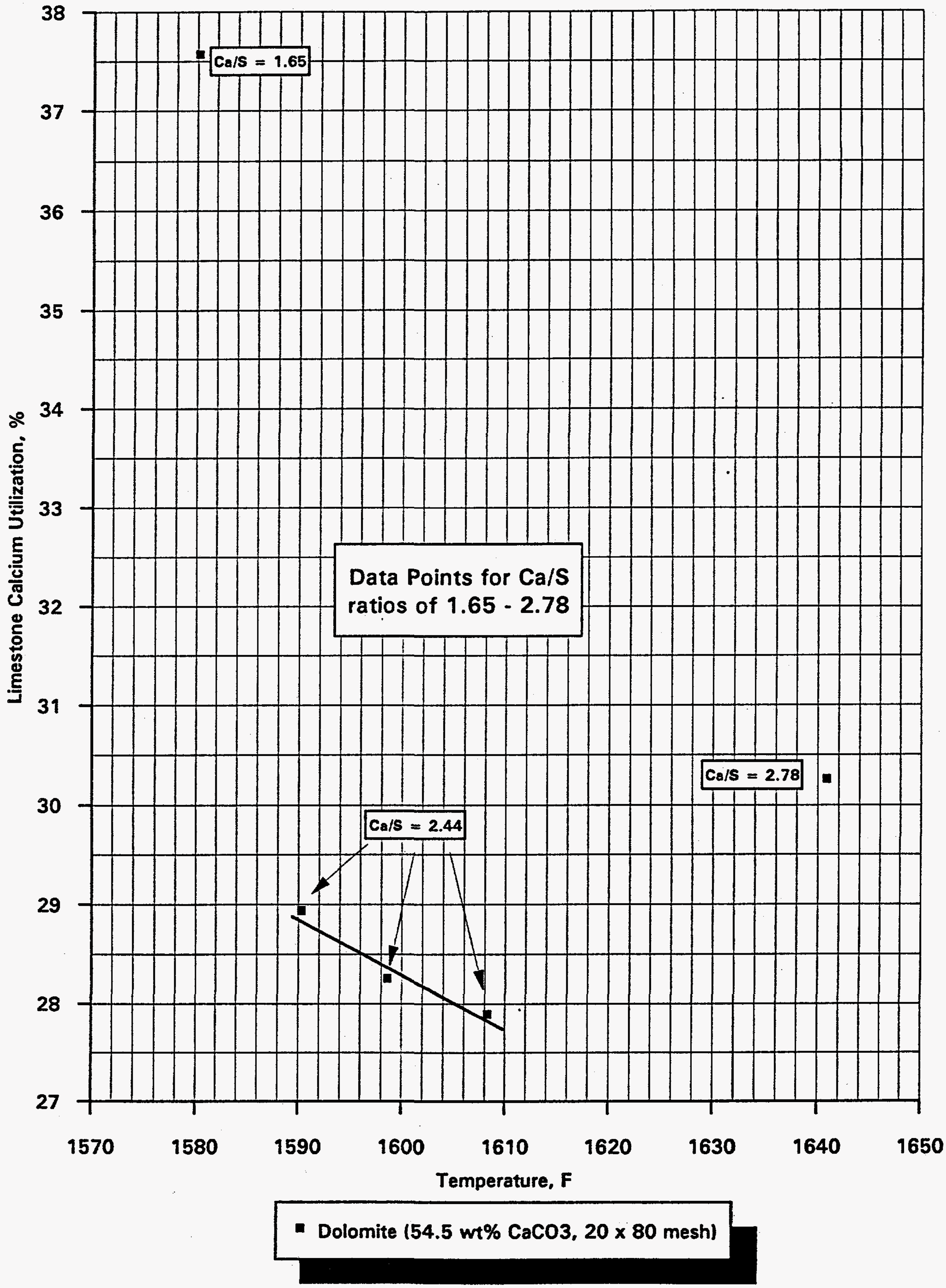


Figure 4-9. Calcium utilization versus temperature for dolomitic limestone

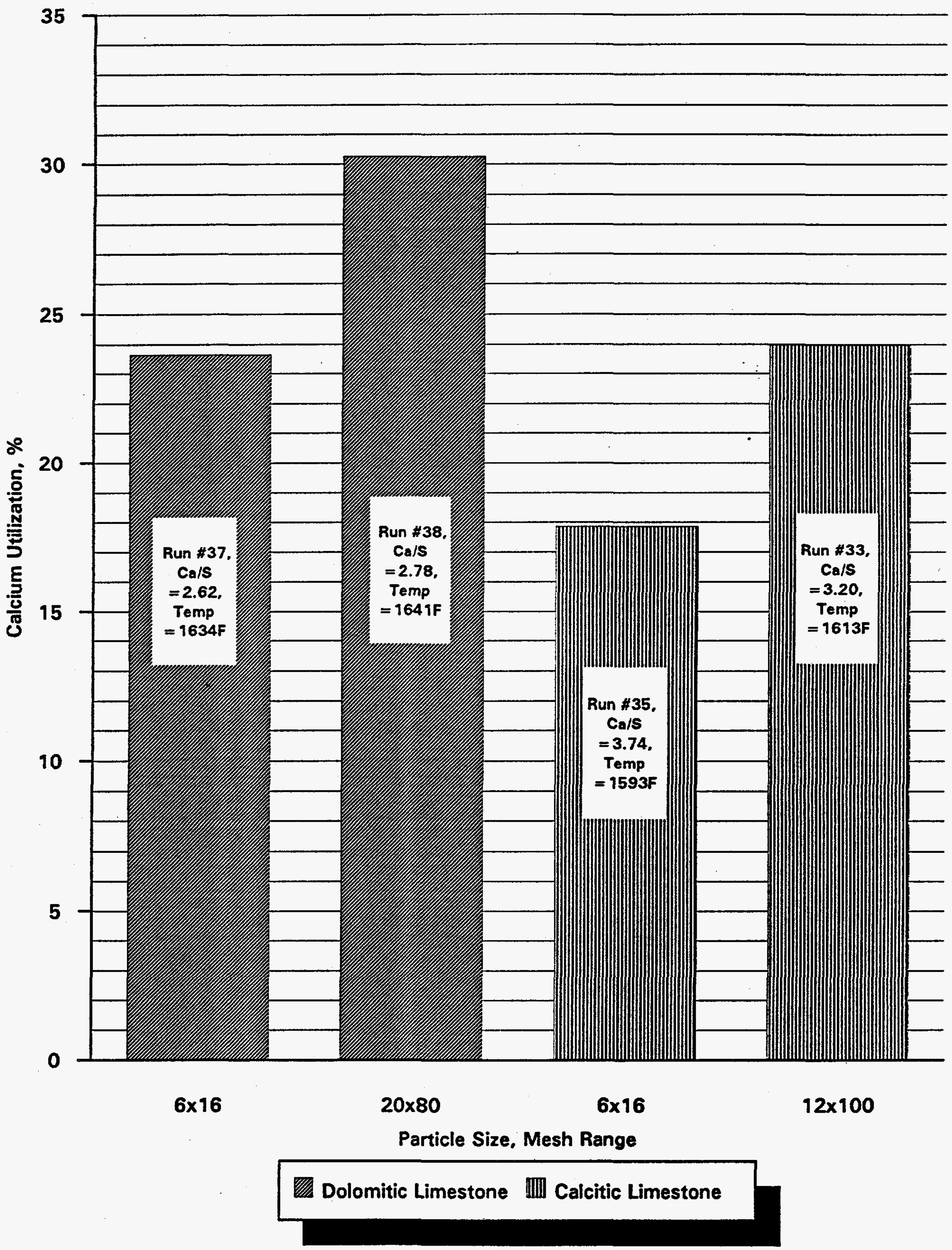


Figure 4-10. Calcium utilization versus limestone particle size

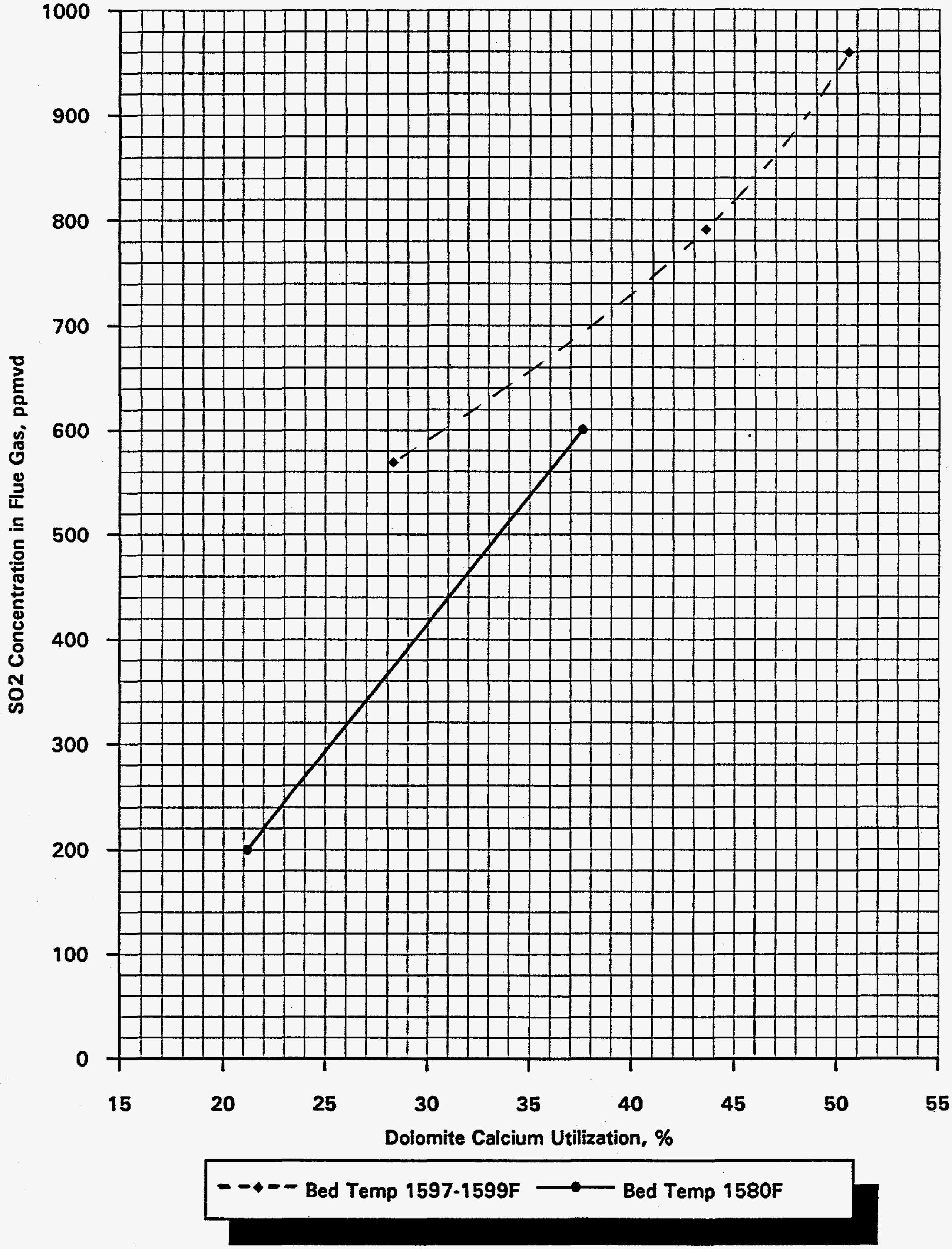


Figure 4-11. Calcium utilization versus concentration of SO2 in flue gas

The NO_x emissions for Ohio coal, for most runs, yielded NO_x emissions of 0.9 to 1.08 lb NO_x/MM Btu of coal fired. However, with increased flue gas recycle, the carbon monoxide (CO) levels would increase and at levels of 150 to 200 ppmvd, the NO_x emissions would drop. In one run, with 202 ppmvd CO in the flue gas, the NO_x dropped to 0.37 lb NO_x/MM Btu, see Figure 4-12. From the data analyzed to-date it would appear that total NO_x emissions can be controlled with flue gas recycle.

Alaska coal, which has a lower coal nitrogen content than the Ohio coal, yielded a NO_x emission level of approximately 0.45 lb NO_x/MM Btu. For the Ohio coal runs, where the oxygen content of the flue gas was 10% or greater (no or low flue gas recycle rates), the percent conversion of fuel bound nitrogen to NO_x was approximately 30%. With the Alaska coal. the conversion of fuel bound nitrogen to NO_x was 21 to 22% with flue gas O_2 content in the range of 6.3 to 13.0% ppmvd.

Although the fluid bed is operating at a temperature much less than the onset of thermal NO_x production, the data was evaluated to see if there was a temperature effect on NO_x emissions. From the data gathered for both the Ohio and Alaska coal tests, taking into consideration the data scatter, it would appear that there may be a very slight increase in NO_x production with an increase in temperature over the bed temperature operating range of 1500-1650 °F.

Regarding nitrous oxides, the N_2O emissions as a percent of fuel bound nitrogen varied from 2.1 to 3.3% for the Ohio coal and from 4.7 to 6.3% for the Alaska coal. During the Alaskan coal tests, as the flue gas recycle rate was being set and was increased to a high level, the CO concentration in the flue gas increased. The high CO resulted in a reduction of overall NO_x emissions; however, the N_2O emission rate increased. Since the N_2O is a reduced nitrogen oxide state, this observation seems reasonable.

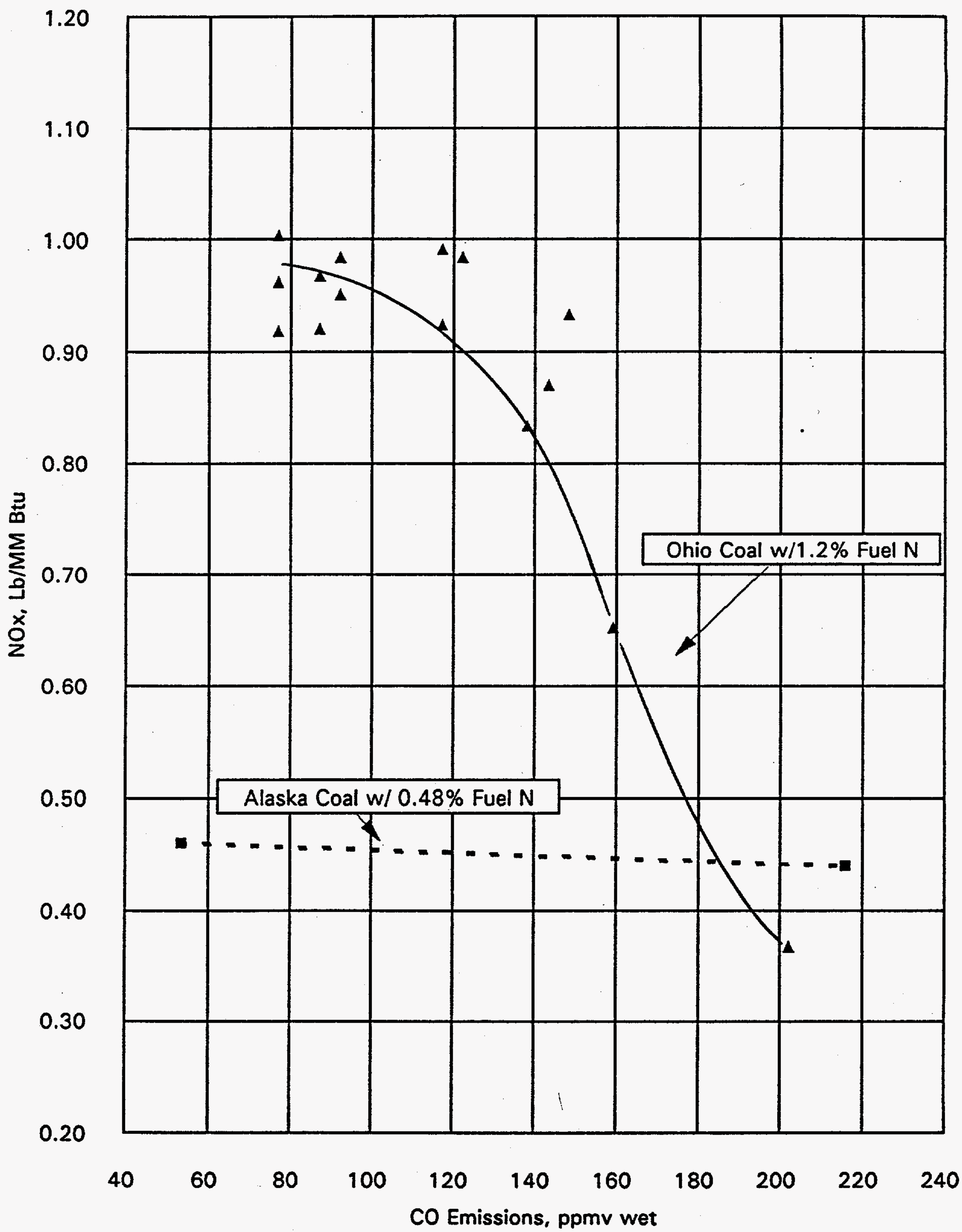


Figure 4-12. NOx as a function of carbon monoxide concentration

As a result of the operational evaluations and data analyses completed, the following conclusions were drawn:

1. It will be possible to meet a sulfur dioxide emission rate of 1.2 lb SO_2/MM Btu of coal fired by using a limestone addition rate that yields a Ca/S ratio of 2.5 to 3.5.
2. The data indicate that the use of recycled flue gas promotes better calcium utilization for capturing sulfur dioxide when using a dolomitic limestone; however, the calcitic limestone does not show this trend.
3. It appears that through the use of flue gas recycle control, the NO_x emissions may be reduced.
4. With calcitic limestone, a temperature effect on sulfur dioxide capture and calcium utilization is seen; however, with dolomitic limestone no trend is clear.
5. Based on Ca/S ratios, the dolomitic limestone out performs the calcitic limestone; however, based on weight ratios of limestone to coal feed, both limestones perform similarly. The reason for this is that even though the Ca/S ratio is lower for the dolomitic limestone, more of it is required due to the lesser weight percentage of calcium in dolomite compared to calcite.
6. Sub-bituminous coals, high in ash alkalinity like the Little Tonzana Alaska coal, will require less limestone addition to meet the regulation for SO_2 emissions because the ash alkali will also react with the sulfur dioxide liberated from the coal.
7. Both calcitic and dolomitic limestones, with smaller particle size ranges, yield better sorbent calcium utilization.
8. Based on Federal EPA regulations there are no regulations on NOx emissions or on ash disposal for units of the size contemplated for this AFBC technology.

In addition to the testing completed on the AFBC under the DOE contract, a student at The Ohio State University also ran experimental tests on the AFBC, using these tests for his doctoral thesis. A paper he and his advisor gave on this work is presented in the Appendix.

5.0 LEVEL 4 PROOF - OF - CONCEPT

At the conclusion of Level 2-3, a proposal was submitted to the Ohio Coal Development Office (OCDO) to commercially demonstrate the AFBC. The objective of the commercial demonstration project was to prove the economic/technical viability of small scale atmospheric fluidized bed combustion (AFBC) systems for use in the generation of hot water for greenhouse heating, when firing high sulfur coal. A team including the Energy and Environmental Research Corporation (EER); the Ohio Agricultural Research and Development Center (OARDC), The Ohio State University; the Will-Burt Company, Cedar Lane Farms, and the U.S. DOE (METC) submitted the proposal to the OCDO. The proposal was accepted and an award made to the team on April 1, 1994.

The host site for this demonstration was Cedar Lane Farms, Inc., a nursery near Wooster, Ohio. Cedar Lane Farms grows/produces roses, perennials, flowering hanging baskets, potted flowering plants, blooming annual and vegetable flats, pansy and primrose baskets and poinsettias. The greenhouse area under glass and heated by Cedar Lane Farms totals some 200,000 ft^2, the AFBC provides heat to a portion of this greenhouse area. The AFBC ties into an existing hot water heating system, heat being supplied by one coal-fired stoker and two natural gas fired hot water heaters.

5.1 Commercial Demonstration Project

The commercial demonstration phase of the AFBC corresponds with Level 4 of the U.S. DOE (METC), contract number DE-AC21-87MC23299. Level 4 is the proof-of-concept phase (commercial application) to be completed in three phases.

- Phase 1 - Engineering/Purchasing
- Phase 2 - Construction and Startup
- Phase 3 - Long Term Testing

5.1.1 Phase 1 - Engineering/Purchasing

The purpose of this phase of work was to complete the engineering design and purchase of equipment that was required in addition to the existing pilot plant equipment, for the commercial demonstration at Cedar Lane Farms. This work was the responsibility of EER, all engineering and purchasing activities was completed at EER's engineering offices in Orrville, Ohio. The design work consisted of 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 - Process Engineering

This task consisted of the development of mass and energy balances, process flow diagrams, preliminary piping and instrument diagrams, sizing of process equipment, and conceptual control logic.

Task 2 - Permits

EER completed permit applications for the installation and operation of the AFBC system and submitted them to the Ohio EPA.

Task 3 - Detail Design Engineering

This task included all of the detail engineering activities required for purchasing and installation of 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 4 - Purchasing

This task included the purchase of all new equipment required for the installation of the AFBC system at Cedar Lane Farms. Existing pilot plant equipment currently located at OARDC was moved to the Cedar Lane Farms facility. EER used its standard procurement procedures for purchase of equipment items which included multiple steps for QA/QC on all equipment purchased, including purchase order preparation and approval, and receipt and inspection of equipment. On all new equipment items purchased, at least three quotes for each equipment item were obtained from reputable vendors. Equipment was selected based on the following criteria; price, features, and services provided by vendor.

The completion of this phase of work resulted in an engineering design for the commercial facility using the AFBC w/FGR system that provides for high thermal efficiency; reduced sulfur dioxide emissions from the firing of high sulfur coal; reduced NO_x emissions, and 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.

5.1.2 Phase 2 - Construction and Startup

The construction activities included civil work at Cedar Lane Farms, installation of process, instrumentation and electrical equipment, process piping, and hookup of other utilities required for operation of the unit. It also included building modifications for equipment installation. Following construction, all of the process equipment, instruments and electrical wiring connections was checked out prior to start-up. This phase was the prime responsibility of the EER's engineering office personnel located at Orrville, Ohio, with assistance provided from OARDC personnel, located in Wooster, Ohio. EER subcontracted specific construction tasks to local mechanical contractors. During the start-up phase, EER trained the Cedar Lane Farm utility operators to operate the AFBC system.

The major tasks within Phase 2 were as follows:

Task 1 - Construction

This task consisted of the removal of equipment presently at OARDC and the re-location and re-installation of this equipment at Cedar Lane Farms. It also included the installation of new process, instrumentation and electrical equipment to provide a complete installation. This task also included civil and structural work.

Task 2 - Checkout of Equipment

Prior to start-up EER and the Cedar Lane Farms personnel checked out the equipment. EER contacted the Ohio EPA to obtain approval to operate. Although the formal permits had not been obtained, the EPA gave EER verbal approval to startup the unit.

Task 3 - Startup And Operator Training

Following checkout of equipment, EER and Cedar Lane Farms personnel started up the unit and tested it at various conditions to assess the overall operability of the unit. During this time frame, EER, trained the Cedar Lane Farm operators in the safe operation of the atmospheric fluidized bed combustion/hot water heating system.

The completion of Phase 2 will resulted in an AFBC w/FGR demonstration unit that is integrated into an existing commercial utility system for green house heating.

5.1.3 Phase 3 - Long Term Testing

Following successful startup, the long term testing program was initiated, but since the unit was started up in the spring of the year, only a limited amount of data was obtained prior to summer shutdown . The testing of the unit so far on the AFBC system has been done under the normal operating load requirements of Cedar Lane Farms. The Cedar Lane Farms heating load requirements determined the coal feed rate to the unit.

For the testing completed to date, data was recorded on a data logger. This data provided the necessary information to complete mass and energy balances around the unit and to determine the rate of SO_2 and NO_x emissions.

This phase is the prime responsibility of Cedar Lane Farms Corporation, located in Wooster, Ohio. EER engineering office personnel located at Orrville, Ohio, with assistance from OARDC personnel, located in Wooster, Ohio is to assist in operations, and also complete the testing and data reduction.

The major tasks within Phase 3 were as follows:

Task 1 - Operations Setup

This task will consist of running various tests to determine the best conditions for long term operation. During this task, the desired control point of oxygen in the flue gas will be determined, as well as the best temperature for sulfur control and the Ca/S ratio required to meet the 1.2 Lb SO_2/MM Btu of coal fired. This task has not been fully completed.

Task 2 - Normal Operations Mode

This task is the normal operations period when the AFBC will be run in a manner to meet the cyclic heating load of the Cedar Lane Farms green houses. This has been done but longer test programs still need to be completed.

Task 3 - Final Report

The final report will cover all of the aspects of the commercial demonstration project; design, construction, operations, data analysis and an updated economic assessment of the technology based on the information gained over the long term testing.

The successful conclusion of this phase will demonstrate a commercially viable clean coal technology that can be scaled up for use by small scale industrial, institutional and commercial users. This technology will then be marketed by the Will-Burt Company, with engineering performed by EER.

5.2 AFBC Design

The AFBC system is designed to fire -1/2 " coal. Limestone is fed with the coal to act as a sorbent for reduction of sulfur dioxide emissions. Sand, which is an inert material, is used as the fluid bed media. A simple auger/pneumatic feed system is used to feed coal and limestone into the combustor.

The AFBC proper is designed with simplicity as the prime input, recognizing that small scale operators do not have the resources to maintain a large staff, with the diverse talents necessary, to operate and maintain a complex system. The combustor is a cylindrical, refractory lined vessel with no heat transfer surfaces or pressure parts. The only maintenance that will have to be done on the combustor will be relegated to refractory and possibly grid plate repair.

A unique design feature of this fluidized bed combustor, is the use of flue gas recycle plus fresh air for feed throughput control. The flue gas recycle technique improves the overall thermal efficiency of this AFBC system by some 3.5% to 5%.

Further, by controlling the amount of fresh air being drawn into the system, the oxygen content at the exit of the fluid bed is controlled to maximize thermal efficiency and still provide for good combustion conditions within the fluid bed. When firing Ohio coal, by controlling the oxygen content at a level to yield approximately 200 ppmv of carbon monoxide in the flue gas, NO_x emissions can be significantly reduced.

During the pilot plant test runs and subsequent data analysis, certain questions were raised which needed to be resolved by long term testing in the commercial unit. First of all, in the pilot plant work, an air eductor was used to inject coal and limestone into the combustor through a sidewall near the top of the fluid bed. With the use of this injection point it was observed through the combustor viewport that a significant amount of coal was burning in suspension above the fluid bed. It was also expected that limestone was being entrained fairly rapidly from the bed.

By not having the coal combustion take place in the bed which has rapid heat transfer, it was felt that more NO_x production could be occurring with suspension burning due to higher localized temperatures. Further, by rapidly entraining a portion of the feed limestone out of the combustor, it was felt that the calcium utilization for sulfur capture was less than it would be were the limestone sorbent to stay in the bed longer.

A new coal feed system was designed to introduce coal and limestone, via an auger, into the center and bottom of the bed. This design was tested on the pilot unit and then used on the commercial unit. Further, suspension coal combustion and unreacted limestone entrainment from the bed should both be reduced with this new design. It was expected that this feature would reduce NO_x emissions somewhat and also improve sorbent utilization.

The second design change was to use sorbent re-injection to improve calcium utilization. A mechanical collector was installed on the flue gas line at the exit of the AFBC, prior to the waste heat recovery hot water heater, for the removal of large particles of sorbent and uncombusted char. The bottom conical section of the collector feeds into an eductor and recycle flue gas is used as the motive force to educt sorbent and char back into the fluid bed.

In the pilot plant operation the coal feed rate was set and flue gas recycle was automatically adjusted to maintain bed temperature. For the commercial demonstration, coal feed rate was controlled automatically to maintain the desired bed temperature, and recycle flue gas was automatically controlled to respond to the thermal load. Fresh air feed into the system was controlled to maximize efficiency and reduce NO_x emissions.

The hot water heater used in the commercial demonstration was slightly oversized to determine if greater coal heat inputs can be obtained. The commercial unit, using the same AFBC was designed for a maximum feed rate of 2.2 million Btu/hr of coal as opposed to the 1.5 million Btu/hr of coal design for the pilot unit. Larger size sand was used in the fluid bed so that superficial gas velocities could be increased. The higher the coal throughput per unit volume of the AFBC the lower is the fixed charge component of the operating cost to pay back the capital cost.

The Cedar Lane Farms demonstration unit was designed to use much of the existing equipment at the OARDC facility.

The new equipment that was purchased for the demonstration unit is delineated below:

• Coal Screen	- Required for screening of ROM coal, larger size to be used in coal stoker and -1/4" size to be fed to the AFBC. This screen was installed but kept plugging, so it was removed and replaced with the crusher discussed below.
• Coal Crusher	- The coal screen did not work, so a crusher was purchased to replace the screen. A partial rebate was obtained from the screen supplier.
• Coal and Limestone Conveyors	- Required for feed supply to storage bins
• Coal and Limestone Bins	- Required for feed supply to combustor and for storage
• Fluid Bed Combustor Revamp	- Upper refractory upgrade needed for long term testing
• Mechanical Collector	- Required to collect sorbent for re-injection
• Hot Water Heater	- Replacement for existing pilot unit, designed to better handle entrained solids
• Bag House	- Replacement for OARDC bag house loaned for pilot plant short term testing
• Water Pump	- Required for hot water recirculation
• Data Collection Instruments	- Required for full monitoring of long term pilot testing

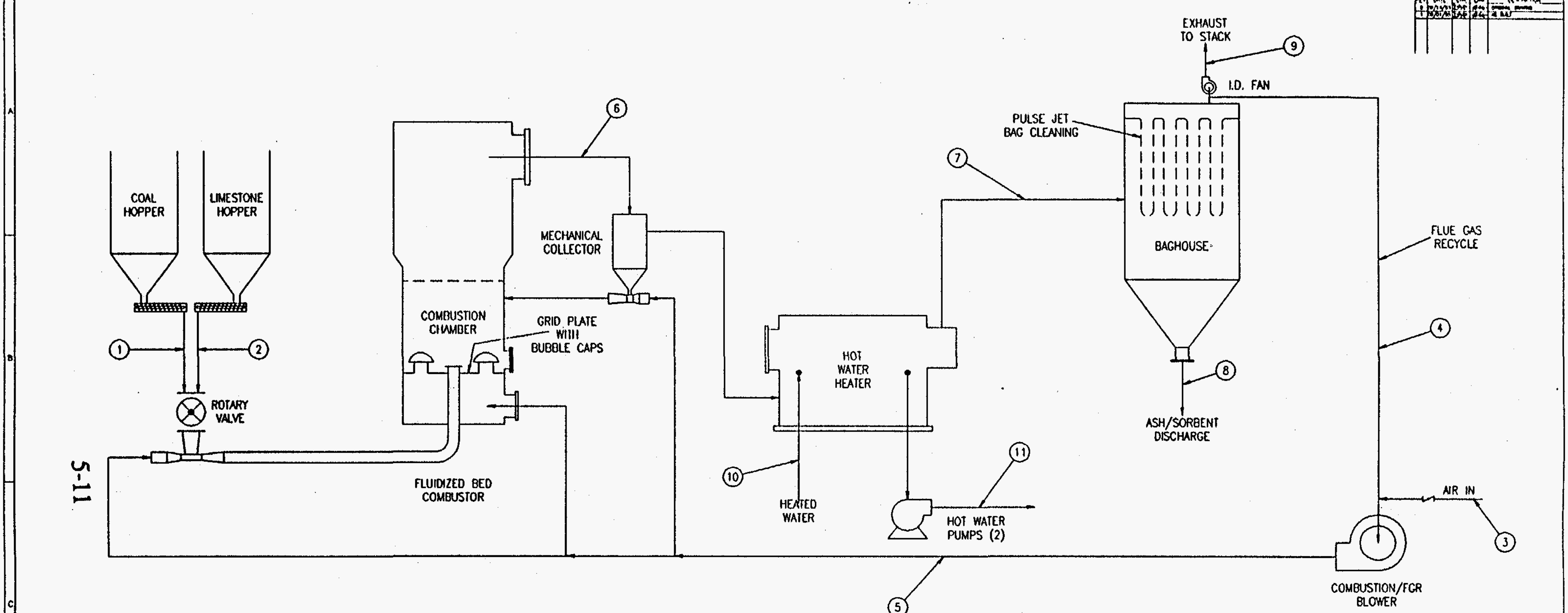
The balance of equipment and instruments was provided by moving the existing equipment and instruments from the OARDC facility to Cedar Lane Farms.

The AFBC operation at Cedar Lane Farms is monitored through use of a 16 point data logger. The data taken, included the following:

1) AFBC bed temperature
2) AFBC flue gas exit temperature
3) Temperature of the flue gas exiting the hot water heater
4) Stack temperature
5) Flue gas recycle temperature
6) Hot water heater inlet water temperature
7) Hot water heater outlet water temperature
8) Hot water recirculation rate, gpm
9) AFBC pressure, in. of water (negative)
10) Flue gas recycle rate, scfh
11) Stack gas oxygen content, %
12) Stack gas carbon monoxide content, ppmvd
13) Stack gas NO_x content, ppmvd
14) Stack gas SO_2 content, ppmvd

5.3 AFBC Process Description

The combustion system installed at Cedar Lane Farms uses an AFBC operating at 1500 to 1600°F, and at near atmospheric operating pressure, see the process flow diagram in Figure 5-1 and the equipment layout in Figure 5-2. Stoker coal (~2"×½" size) is unloaded using an existing belt conveyor that transports the coal to an existing coal storage bin. This bin provides the coal feed to both the coal-fired stoker and the AFBC. From the coal storage bin, the coal is augered to a jaw crusher that crushes the coal to a minus ½" size and the coal from the crusher feeds into a coal auger feed bin (see Figure 5-1).



NOTE: HEAT INPUT = 2.3 X 10^6 BTU/HR

STREAM NUMBER	1	2	3	4	5	6	7	8	9	10	11
STREAM NAME	COAL FEED	LIMESTONE FEED	COMBUSTION AIR	FLUE GAS RECIRC.	COMBUSTION AIR + FGR	AFBC FLUE GAS	B.H. INLET FLUE GAS	B.H. ASH	STACK GAS	C.W. INLET	H.W. OUTLET
UNITS	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr	lbs/hr
C	124.5					1.2	1.2	1.2	0.0		
H	7.6										
O	14.2										
N	2.2										
S	5.7										
ASH	10.6	11.2				21.6	21.6	21.6	0.0		
H2O(l)	9.9									47461.4	47461.4
CH4											
O2			616.3	133	749.3	364.9	364.9		364.9		
N2			2035.4	1168.5	3203.9	3205.8	3205.8		3205.8		
H2O(v)			34.5	65.3	99.8	179.1	179.1		179.1		
CO2				270.1	270.1	741.1	741.1		741.1		
SO2				1.4	1.4	3.8	3.8		3.8		
NOx AS NO2				0.6	0.6	1.6	1.6		1.6		
CO				0.2	0.2	0.4	0.4		0.4		
CaCO3		44.7									
CaSO4						19.2	19.2	19.1			
CaO						17.2	17.2	17.2			
TOTAL	175.0	55.9	2686.2	1639.1	4325.3	4556.2	4556.2	59.3	4496.9	47461.4	47461.4
FLOW RATE, GPM										95	95
PRESSURE, PSIA	14.7	14.7	14.7	14.7					14.7	20	20
PRESSURE, in. H2O					30	-0.3	-0.2	-4			
TEMPERATURE, F	50	50	70	250	180	1550	335	250	250	107	137

Coal HHV (12,840 Btu/lb) Fuel to Hot Water Thermal Efficiency = 85.0%

AS BUILT

CUSTOMER NAME: CEDAR LANE FARMS

CUSTOMER ORDER NUMBER

Energy and Environmental Research Corporation

ATMOSPHERIC FLUIDIZED BED COMBUSTOR SIMPLIFIED PFD W/FGR HOT WATER SYSTEM

DRAWN DDR | CHECKED | ENGINEER RAA | PROJ MGR RAA | DATE 01 AUG 95 | SCALE NONE | JOB No 8808 | DWG P8808D-001 | REV 1 | SHT 1 OF 1

CAD FILE: G:\8808\P0800101

Figure 5-1.

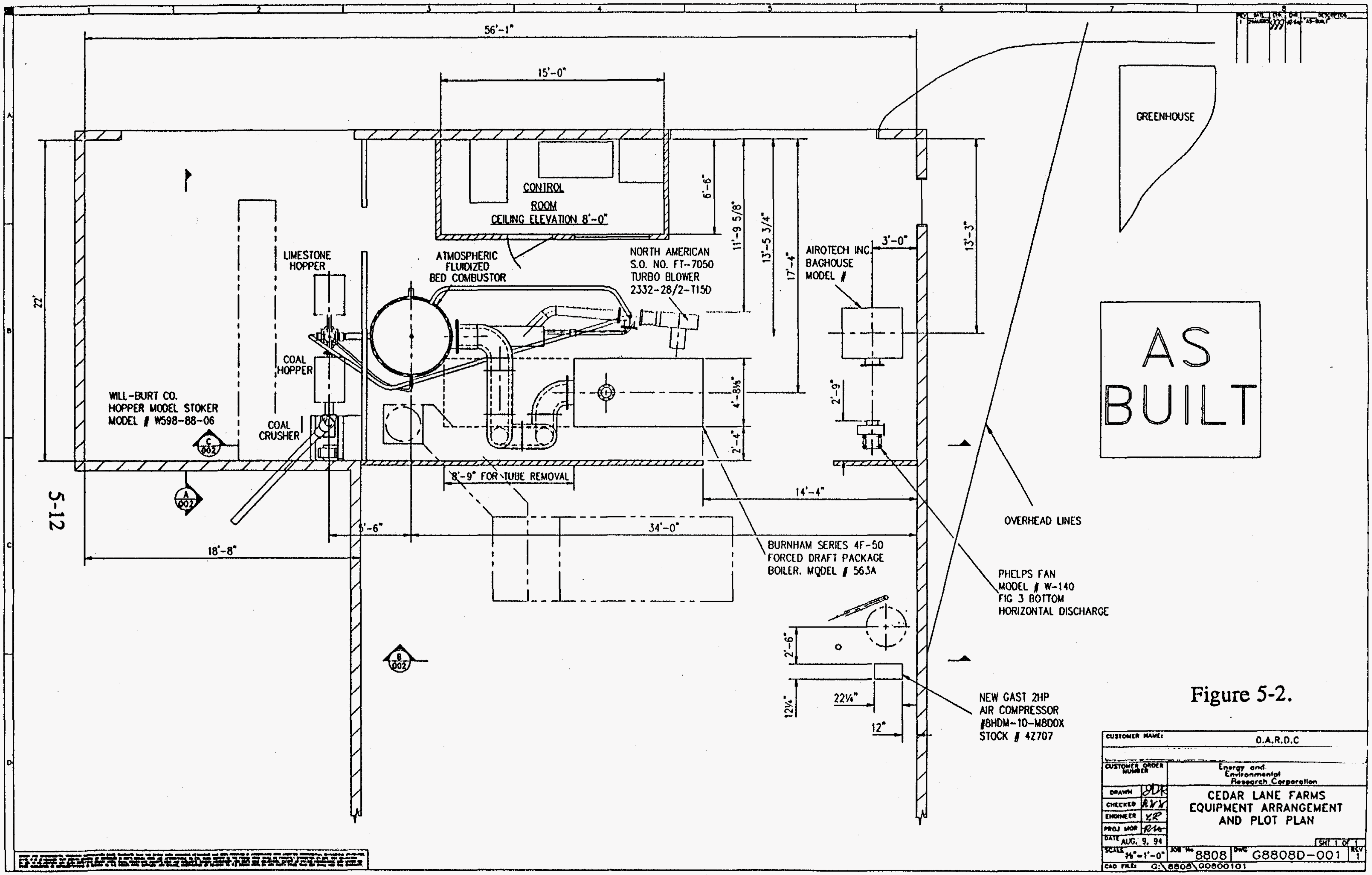

56'-1"
15'-0"
CONTROL ROOM
CEILING ELEVATION 8'-0"
6'-6"
11'-9 5/8"
13'-5 3/4"
17'-4"
13'-3"
3'-0"
22'
LIMESTONE HOPPER
ATMOSPHERIC FLUIDIZED BED COMBUSTOR
NORTH AMERICAN
S.O. NO. FT-7050
TURBO BLOWER
2332-28/2-T15D
AIROTECH INC.
BAGHOUSE
MODEL #
COAL HOPPER
WILL-BURT CO.
HOPPER MODEL STOKER
MODEL # W598-88-06
COAL CRUSHER
4'-8⅛"
2'-4"
2'-9"
8'-9" FOR TUBE REMOVAL
14'-4"
5'-6"
34'-0"
18'-8"
BURNHAM SERIES 4F-50
FORCED DRAFT PACKAGE
BOILER. MODEL # 563A
OVERHEAD LINES
PHELPS FAN
MODEL # W-140
FIG 3 BOTTOM
HORIZONTAL DISCHARGE
GREENHOUSE
AS BUILT
2'-6"
22¼"
12¼"
12"
NEW GAST 2HP
AIR COMPRESSOR
#8HDM-10-M800X
STOCK # 4Z707
CUSTOMER NAME: O.A.R.D.C
CUSTOMER ORDER NUMBER
Energy and Environmental Research Corporation
DRAWN
CHECKED
ENGINEER
PROJ MGR
DATE AUG. 9, 94
SCALE 3/16"=1'-0"
JOB No 8808
DWG G8808D-001
REV 1
SHT 1 OF 1
CAD FILE: G:\8808\G0800101
CEDAR LANE FARMS
EQUIPMENT ARRANGEMENT
AND PLOT PLAN

Figure 5-2.

The feed bin coal is augured into a standpipe that feeds a rotary lock feeder. In parallel to the coal feed, limestone from a separate feed bin is also augured into the standpipe. From the rotary feeder, coal and limestone fall into a pneumatic transport line. Recycled flue gas is used as the transport media. Coal and limestone are blown through a transport line, that enters the combustor wind box and then passes up through the center of the air distribution grid plate, into the bottom of the fluid bed. Graded sand is used as the inert fluid bed media. 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 exits the combustor and flows through a mechanical collector where large particles of coke and limestone are removed and pneumatically recycled back into the fluid bed. Recycled flue gas is also used here as the transport media. The purpose of this reinjection technique is to yield better calcium (limestone) utilization for SO_2 capture.

Hot flue gas from the collector then enters a waste heat recovery hot water heater. The cooled flue gas from the hot water heater exits at a temperature of approximately 300 °F and enters a bag house for particulate removal.

An induced draft fan on the exit of the bag house provides the motive force to draw the flue gas from the combustor, maintaining a slight negative pressure at the combustor flue gas outlet. The induced draft fan discharges into an atmospheric stack. Flue gas from the bag house is also recycled back to the windbox of the combustor for temperature control and supply of combustion air.

A controlled rate of fresh air is drawn into the suction of the recycle blower and is then mixed with the recycled flue gas. The rate of fresh air is controlled to maintain a set oxygen percentage in the flue gas exiting the fluid bed. The 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 bed. The recirculated water returning from the greenhouses enters the hot water heater at 120 °F and is heated up to 160 °F prior to flowing back to the greenhouses for space heating.

Mass and energy balances for the demonstration unit are shown in Table 5-1. The piping and instrument diagram for the Cedar Lane Farms AFBC system is shown in Figure 5-3.

5.4 Operations Assessment

The operation of the AFBC has been very successful in meeting the cyclical heating demand loads of the greenhouse. Because there are no heat exchanger tubes in the bed proper, it can be banked for five to six hours during the day when the heating demand is low and restarted with no auxiliary fuel. It requires very little operator attention; the system runs on automatic control and the only operator function normally required is to empty the flyash catch drum under the baghouse. Cedar Lane Farms (host site) is impressed with the operation and intends to use the AFBC, firing Ohio coal, as a first on, last off hot water heater in lieu of running their natural gas fired boiler.

The atmospheric fluidized bed combustion system was installed, started up and operated for extended periods of time at the CLF facility. It requires very little operator attention; the system runs on automatic control and the only operator function normally required is to empty the flyash catch drum under the baghouse. Combustor operation to date has been very successful but a few upgrades are required before it can be considered commercially acceptable. The 1.5 MM Btu/hr combustor used in the pilot test work at the OARDC was refurbished and used at CLF. It was modified to operate at a higher coal feed and has now successfully operated at 2.25 MM Btu/hr, a 50% increase in coal feed rate.

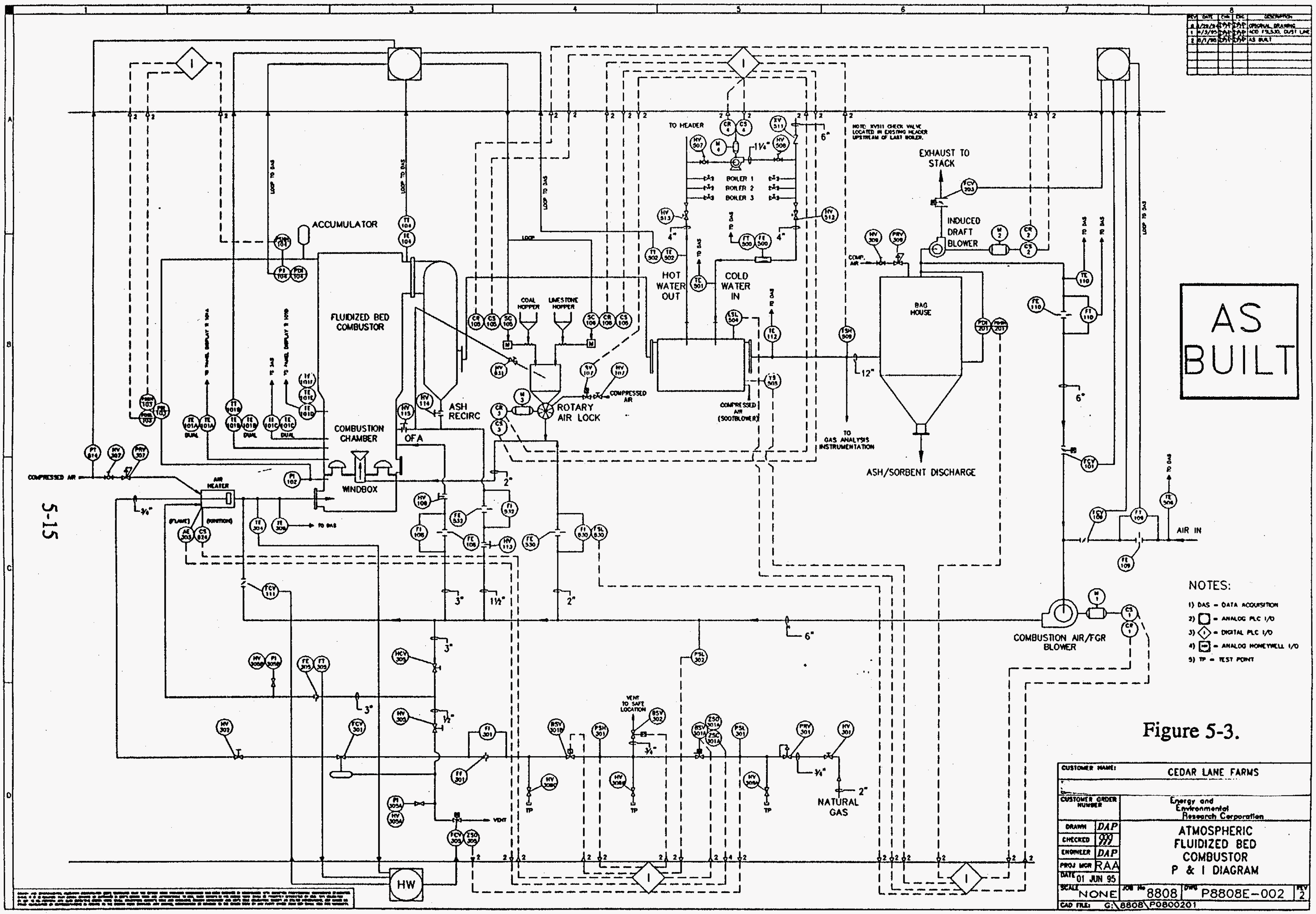

AS BUILT
ACCUMULATOR
FLUIDIZED BED COMBUSTOR
COMBUSTION CHAMBER
WINDBOX
OFA
ASH RECIRC
COAL HOPPER
LIMESTONE HOPPER
ROTARY AIR LOCK
COMPRESSED AIR
HOT WATER OUT
COLD WATER IN
TO HEADER
BOILER 1
BOILER 2
BOILER 3
COMPRESSED AIR (SOOTBLOWER)
TO GAS ANALYSIS INSTRUMENTATION
BAG HOUSE
ASH/SORBENT DISCHARGE
EXHAUST TO STACK
INDUCED DRAFT BLOWER
COMBUSTION AIR/FGR BLOWER
AIR IN
AIR HEATER
NATURAL GAS
VENT TO SAFE LOCATION
HW
NOTES:
1) DAS = DATA ACQUISITION
2) = ANALOG PLC I/O
3) = DIGITAL PLC I/O
4) = ANALOG HONEYWELL I/O
5) TP = TEST POINT
CUSTOMER NAME: CEDAR LANE FARMS
Energy and Environmental Research Corporation
ATMOSPHERIC FLUIDIZED BED COMBUSTOR P & I DIAGRAM
DRAWN DAP
CHECKED
ENGINEER DAP
PROJ MGR RAA
DATE 01 JUN 95
SCALE NONE
JOB No 8808
DWG P8808E-002
REV 2
CAD FILE: G:\8808\P0800201

Figure 5-3.

TABLE 5-1
OHIO BITUMINOUS COAL
2.2 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{COMBUSTION ZONE}

Basis: 60F & H2O(l)		TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:					
FEED		50			
12,640 Btu/lb actual					
Comp.	wt%				
C	71.15		124.5		
H	4.44		7.8		
O	8.13		14.2		
N	1.24		2.2		
S	3.28		5.7		
Cl	0.00		0.0		
Ash	6.08		10.6		
H2O(l)	5.68		9.9		
total	100.00				
Subtotal			175.0	-4.8	-842
NATURAL GAS (CH4)		60	0.0	0.0	0
23861 Btu/lb, HHV					
AIR	wt%	70			
O2	22.94		616.3	2.1	1322
N2	75.77		2035.4	2.4	4928
H2O(v)	1.28		34.5	1064.0	36700
(MW =	28.797)				
Subtotal	590 scfm		2686.2		42950
F.G. REC.	vol%	250			
O2	7.48		133.1	41.8	5562
N2	74.99		1168.4	46.7	54508
H2O(v)	6.51		65.3	1144.3	74691
CO2	11.02		269.9	40.8	11017
SO2,ppmv	427		1.5	29.7	45
HCl,ppmv	0		0.0	38.0	0
NOx,ppmv	248		0.6	40.8	26
CO,ppmv	181		0.3	49.0	14
Ash			0.0	41.8	1
Carbon			0.0	30.4	0
CaSO4	Gas MW =	29.465	0.0	38.0	1
CaO	352 scfm		0.0	34.2	1
			======		======
Total	100.00		1639.1		145865
	Mol. Wt.				
CaCO3	100.09	50	44.7		
Ash			11.2		
			======		======
Subtotal			55.9	-2.2	-123
Heat of Combustion					2194505
			======		======
TOTAL			4556.1		2382355
OUTPUT:					
FLUE GAS	vol%	1550			
O2	7.48		365.1	363.7	132790
N2	74.99		3205.6	392.5	1258061
H2O(v)	6.51		179.1	1806.5	323536
CO2	11.02		740.5	392.7	290771
SO2,ppmv	427		4.2	276.6	1155
HCl,ppmv	0		0.0	274.1	0
NOx,ppmv	248		1.7	392.7	683
CO,ppmv	181		0.8	399.1	309
Ash		sfgv =	21.8	327.8	7159
Carbon		6.55	1.2	238.4	297
CaSO4		fps	18.8	298.0	5590
CaO	Gas MW =	29.465	17.3	268.2	4650
	978 scfm				
Subtotal	100.00		4556.1		2025002
Heat Loss	15.00%				357353
			======		======
TOTAL			4556.1		2382355
	Mass Closure =		100.00%	Energy Closure =	100.00%

TABLE 5-1
OHIO BITUMINOUS COAL
2.2 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{HOT WATER HEATER}

Air Leakage = 0.00% Ctrl. Air
Cooling Water = 94.9 gpm

Basis: 60F & H2O(l)			TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:						
FLUE GAS	vol%		1550			
O2	7.48		8.00	365.1	363.7	132790
N2	74.99		dry	3205.6	392.5	1258061
H2O(v)	6.51			179.1	1806.5	323536
CO2	11.02			740.5	392.7	290771
SO2,ppmv	427			4.2	276.6	1155
HCl,ppmv	0			0.0	342.8	0
NOx,ppmv	248			1.7	392.7	683
CO,ppmv	181			0.8	399.1	309
Ash				21.8	327.8	7159
Carbon				1.2	238.4	297
CaSO4				18.8	298.0	5590
CaO				17.3	268.2	4650
(MW =	29.465	)		----------------		----------------
Subtotal	100.00			4556.1		2025002
COOLING WATER			107			
H2O(l)				47461.4	47.0	2230686
AIR LEAK.	wt%		70			
O2	22.94			0.0	2.1	0
N2	75.77			0.0	2.4	0
H2O(v)	1.28			0.0	1064.0	0
(MW =	28.797	)		----------------		----------------
Subtotal	0	scfm		0.0		0
				======		======
TOTAL				52017.6		4255688
OUTPUT:						
FLUE GAS	vol%		335			
O2	7.48			365.1	61.1	22299
N2	74.99			3205.6	67.9	217605
H2O(v)	6.51			179.1	1183.2	211906
CO2	11.02			740.5	60.1	44536
SO2,ppmv	427			4.2	43.6	182
HCl,ppmv	0			0.0	55.6	0
NOx,ppmv	248			1.7	60.1	105
CO,ppmv	181			0.8	70.3	54
Ash				21.8	60.5	1321
Carbon				1.2	44.0	55
CaSO4				18.8	55.0	1032
CaO				17.3	49.5	858
(MW =	29.465	)		----------------		----------------
Subtotal	100.00			4556.1		499954
HOT WATER			137			
H2O(l)				47461.4	77.0	3654528
Blowdown @ 0.0%			137	0.0	77.0	0
Heat Loss	5.00%					101206
				======		======
TOTAL				52017.6		4255688

Mass Closure = 100.00% Energy Closure = 100.00%

TABLE 5-1
OHIO BITUMINOUS COAL
2.2 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{BAG HOUSE}

EFFICIENCY = 99.7 %

Basis: 60F & H2O(l)		TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:					
FLUE GAS	vol%	335			
O2	7.48		365.1	61.1	22299
N2	74.99		3205.6	67.9	217605
H2O(v)	6.51		179.1	1183.2	211906
CO2	11.02		740.5	60.1	44536
SO2,ppmv	427		4.2	43.6	182
HCl,ppmv	0		0.0	55.6	0
NOx,ppmv	248		1.7	60.1	105
CO,ppmv	181		0.8	70.3	54
Ash			21.8	60.5	1321
Carbon			1.2	44	55
CaSO4			18.8	55.0	1032
CaO			17.3	49.5	858
(MW =	29.465)		=======		=======
TOTAL	100.00		4556.1		499954
OUTPUT:					
FLUE GAS	vol%	250			
O2	7.48	8.00%	365.1	41.8	15260
N2	74.99	dry	3205.6	46.7	149555
H2O(v)	6.51		179.1	1144.3	204931
CO2	11.02		740.5	40.8	30227
SO2,ppmv	427		4.2	29.7	124
HCl,ppmv	0		0.0	38.0	0
NOx,ppmv	248		1.7	40.8	71
CO,ppmv	181		0.8	49.0	38
Ash			0.1	41.8	3
Carbon			0.0	30.4	0
CaSO4			0.1	38.0	2
CaO			0.1	34.2	2
(MW =	29.465)		----------		----------
Subtotal	100.00		4497.1		400212
B.H. SOLIDS		250			
Ash			21.8	41.8	911
Carbon			1.2	30.4	38
CaSO4			18.7	38.0	711
CaO			17.3	34.2	591
			----------		----------
Subtotal			59.0		2251
Heat Loss	19.50%				97491
			=======		=======
TOTAL			4556.1		499954

Mass Closure = 100.00% Energy Closure = 100.00%

TABLE 5-1
OHIO BITUMINOUS COAL
2.2 MM Btu/hr Coal Fired
MASS AND ENERGY BALANCE
{FLUE GAS RECYCLE}

Flue Gas Recycle @ 36.4%

Basis: 60F & H2O(l)		TEMP. F	LB/HR	BTU/LB	BTU/HR
INPUT:					
FLUE GAS	vol%	250			
O2	7.48	8.00%	365.1	41.8	15260
N2	74.99	dry	3205.6	46.7	149555
H2O(v)	6.51		179.1	1144.3	204931
CO2	11.02		740.5	40.8	30227
SO2,ppmv	427		4.2	29.7	124
HCl,ppmv	0		0.0	38.0	0
NOx,ppmv	248		1.7	40.8	71
CO,ppmv	181		0.8	49.0	38
Ash			0.1	41.8	3
Carbon			0.0	30.4	0
CaSO4			0.1	38.0	2
CaO			0.1	34.2	2
(MW =	29.465)				
	965 scfm		======		======
TOTAL			4497.1		400212
F.G. REC.	vol%	250			
O2	7.48		133.1	41.8	5562
N2	74.99		1168.4	46.7	54508
H2O(v)	6.51		65.3	1144.3	74691
CO2	11.02		269.9	40.8	11017
SO2,ppmv	427		1.5	29.7	45
HCl,ppmv	0		0.0	38.0	0
NOx,ppmv	248		0.6	40.8	26
CO,ppmv	181		0.3	49.0	14
Ash			0.0	41.8	1
Carbon			0.0	30.4	0
CaSO4			0.0	38.0	1
CaO			0.0	34.2	1
(MW =	29.465)				
	352 scfm		----------		----------
Subtotal			1639.1		145865
STACK	vol%	250			
O2	7.48	8.00%	232.0	41.8	9698
N2	74.99	dry	2037.3	46.7	95046
H2O(v)	6.51		113.8	1144.3	130240
CO2	11.02		470.6	40.8	19210
SO2,ppmv	427		2.7	29.7	79
HCl,ppmv	0		0.0	38.0	0
NOx,ppmv	248	0.5	1.1	40.8	45
CO,ppmv	181	lb/MM Btu	0.5	49.0	24
Ash			0.0	41.8	2
Carbon			0.0	30.4	0
CaSO4			0.0	38.0	1
CaO			0.0	34.2	1
(MW =	29.465)				
	614 scfm		----------		----------
Subtotal			2858.1		254347
			======		======
TOTAL			4497.1		400212

Mass Closure = 100.00% Energy Closure = 100.00%

OPERATIONS SUMMARY

Sulfur In	5.18	lb SO2/MM Btu	SO2 Removal	=	76.9%
Sulfur Out	1.20	lb SO2/MM Btu	Ca/S Ratio Estimat	=	2.5
NOx	0.5	lb NO2/MM Btu	Thermal Efficienc	=	64.4%
Particulate	0.05	lb/MM Btu	Flue Gas Recycle	=	36.4%

The increase in the design coal feed rate was accomplished by increasing the superficial gas velocity through the combustor from approximately 5 ft/sec to approximately 8 ft/sec. It was desirable to increase the coal feed rate to improve system economics, the greater the throughput per unit volume, the lower the capital cost per million Btu of coal fired.

With the new control system at CLF, the system will start up, shut down and bank itself automatically. The combustor will stay in a banked condition without a need for fuel for some five to six hours, a feature very important to meet the cyclical demand load for greenhouse heating and other small industrial heating applications.

Further, with this particular AFBC which uses a sand bed and has no internal heat transfer surfaces, there are no ash-calcium agglomerates formed in the bed. All of the ash and sorbent are blown from the combustor to a downstream baghouse. This feature reduces the risk of an operator being burned with hot ash and also reduces operating labor costs somewhat.

5.4.1 Added Expenditures

During the construction and startup phases of the AFBC demonstration project there were additional construction and startup expenditures required over the amount originally budgeted. The total expenses for material and labor during the engineering-construction phase of the project, over and above that originally budgeted was approximately $50,400. Funds were transferred from the testing program to cover these added costs. In addition there are some minor modifications that need to be made to the unit to make it commercially acceptable. EER, in association with the Will-Burt, OARDC and Cedar Lane Farms has submitted a proposal to the Ohio Coal Development Office to obtain additional funds to complete the project. This proposal is discussed further in Section 7.0.

The added expenditures occurred are shown in Table 5-2 and are also explained item by item in the text that follows.

TABLE 5-2. ADDED EXPENDITURES

Expenditure	Cost
1. Control System	$17,080
2. Electrical Service	$10,470
3. Coal Handling/Preparation	$6,660
4. Dust Collector Cartridges	$4,740
5. Coal Feed System	$4,380
6. Miscellaneous	$7,070
Total	**$50,400**

5.4.1.1 Control System

The original proposal assumed that the control system used during the pilot testing at the OARDC would be used again at CLF. While discussing operations with CLF during the engineering phase, it became evident that the mostly manual control system used at OARDC would not be sufficient to allow the AFBC to operate in the cyclical operational mode required by the greenhouse. The CLF application required that the AFBC operate automatically as the demand for hot water varied throughout the day. The AFBC needed to be controlled so that it would shutdown and start backup automatically with little to no operator attention. During the spring months when the heat load is very cyclical, on-off cycling could occur five or six times in a 24-hour period. The automatic starting and stopping simply could not be done with the OARDC control system. A decision was therefore made to convert to a programmable logic control (PLC) system which could handle the sequential starting, stopping and banking as well as the modulating control of the AFBC when operating.

There was a conscious effort placed in the selection of the PLC system to find the lowest cost unit with the capability necessary to do the job. Further, as many components as possible were used from the old system to save on added expense. The cost of the new control system with hardware, software, programming, cabinet and labor was $17,080. The new control system was very successful; the system will start up and shut down automatically and bank itself for up to six hours at a time without the need of fuel addition to maintain bed temperature.

5.4.1.2 Electrical Service

At the time that the original proposal was submitted to OCDO, it was believed that sufficient electrical power was available within the existing electrical service at CLF. It became clear during detailed engineering that the existing service was not adequate to handle the additional load requirements of the AFBC system.

The existing service consisted of a 400 amp main system that was split through two 200 amp subsystems. One subsystem supplied power to the west complex and the other supplied power to the east complex. The new boiler room was located adjacent to the existing boilers as part of the east complex. A close check of the power requirement of the east complex indicated that it was near capacity without the additional load requirement of the AFBC.

In discussions among CLF, EER, and Ohio Power it was decided to increase the main service to 600 amps. This would provide ample power for all areas of the complex and supply the requirements of the AFBC installation. The cost of the new service with material and labor was $10,470. CLF shared some of the expanded electrical service costs. The new electrical service provided the power required and has performed well since installation.

5.4.1.3 Coal Handling/Preparation

The AFBC was installed beside an existing underfeed coal stoker, and both units receive coal from the same coal bin. A vibrating coal screen was installed to screen the ¾"x 0" coal from the stoker coal normally received by CLF. At the time the decision was made to use a coal screen, CLF was experiencing problems with coal fines pluggage in its coal stoker. The AFBC doesn't handle coal sizes above ¾", so that screening was a chosen as a practical approach to solve the stoker problem and also provide coal feed to the AFBC. The coal handling system was designed to convey coal from the coal bin to the screen. The screened coal would then fall into the AFBC coal feed hopper and the larger coal would be returned to the coal bin to supply a coarser coal feed to the stoker.

During the startup phase of the project it became apparent that the vibrating screen was not acceptable due to continued coal screen pluggage problems. In discussions between EER and the manufacturer it was determined that the screen would need to have major modifications to have a chance of working properly. Even after the modifications were made there was no guarantee from the manufacturer that the screen would work. It was then decided to remove the screen and replace it with a small crusher that would reduce stoker coal size to the -¾" needed for the AFBC. The screen manufacturer allowed a partial credit for the return of the vibrating screen which left a differential cost of installing the crusher, including material and labor, of $6,660.

5.4.1.4 Dust Collector Cartridges

The dust collector for this project included cartridges made of pleated Nomex felt with a Gore-Tex membrane covering. Nomex bags were used in the OARDC bag house during the pilot testing of the combustor. During the AFBC startup, a routine inspection of the cartridges showed an apparent deterioration of the Gore-Tex membrane on the cartridges.

Further investigation by the cartridge manufacturer, W.L. Gore, showed that the Nomex felt was actually deteriorating under the Gore-Tex membrane, allowing the membrane to break loose from the felt. It was determined that the deterioration was a result of an acid attack from the cyclical operation of the AFBC, which allowed the temperature in the dust collector, during shutdown periods, to drop below the sulfuric acid dew point.

W.L. Gore recommended replacing the Nomex cartridges with Ryton cartridges, an acid resistant felt with a Gore-Tex membrane. This was done and the cost of the cartridge change, including material and labor, was $4,740. The new cartridges appear to be resisting acid attack and performed satisfactorily from installation to season shutdown, a period of approximately one month.

5.4.1.5 Coal Feed System

In the original proposal to OCDO it was indicated that the AFBC coal feed system would be converted from a pneumatic top bed injection system to a bottom bed feed auger system. During completion of testing at OARDC, before pilot plant shutdown, it was determined that the auger system would not work. A modified bottom bed feed pneumatic system was then designed and installed, and the system worked well over several short duration test periods prior to shutting down the pilot plant operation. During the startup phase at CLF, certain limitations appeared in the bottom feed pneumatic system. Unlike the OARDC application, at CLF the system had to startup and shutdown automatically and also run continuously over extended periods of time. The fuel transport line from the rotary airlock into the bottom of the fluid bed occasionally would plug. This required the operator to shutdown the system and clean out the pipe. The pluggage generally occurred during periods of low air flow, as the system was starting up or shutting down.

The other problem with the coal feed system was the tramp air leaking past the rotary airlock which would blow coal fines back through the coal and lime feed augers into the hoppers. These fines would build up in the lower part of the hoppers, above the feed augers, and cause bridging. The air leakage problem was solved by adding a vent line from the rotary airlock riser to the combustor at a point above the bed level. The combustor draft was set more negative to increase the effectiveness of the vent. A low differential pressure switch was added to the transport air line to trip the coal feed system if the pressure dropped too low, indicating a pluggage. This feature did not prevent feed pipe pluggage, but did prevent the airlock from becoming plugged, making clean out much easier. A clean out port was added to allow easier cleaning without completely shutting down the system. Several changes were also made to the control system to decrease the possibility of low transport air flow. The cost of all of these modifications, including material and labor was $4,380.

5.4.1.6 Miscellaneous

In addition to the major items discussed above there were also added costs, not originally budgeted which included a $4,750 cost greater than anticipated by the piping contractor, and a hot gas pipe relocation due to a clearance problem of $1,000. For marketing purposes a scale model of the combustor was purchased and a project sign installed at Cedar Lane Farms for a combined cost of $1,320 exceeding the original estimate.

5.5 Data Analysis

In the short term operation of the AFBC at Cedar Lane Farms, a very limited amount of data was collected and analyzed during normal operating conditions during the months of April and May 1995. The data that was taken for certain run periods of time during normal operations in April and May, 1995 was analyzed. Tables 5-3 and 5-4 show the test results for the combustion of Ohio coal using dolomitic limestone as the SO_2 sorbent at Ca/S ratios of 2.5 and 1.75 respectively.

TABLE 5-3. CEDAR LANE FARMS AFBC DATA - APRIL, 1995

Dolomitic Limestone as SO2 Sorbent

Date:	4/7/95	4/7/95	4/8/95	4/8/95	4/22/95	4/23/95	4/23/95	4/24/95
Time:	17:45-18:45	19:20-20:20	00:00-03:50	04:40-08:40	19:59-23:59	00:00-04:00	04:00-08:00	04:00-08:00
Fluid Bed Combustor:								
Coal* feed rate, lb/hr	191	191	152	152	142	137	140	137
Coal feed rate, MM Btu/hr	2.42	2.42	1.92	1.92	1.80	1.73	1.77	1.73
Limestone** feed rate, lb/hr	82	82	65	65	61	59	60	59
Ca/S molar ratio	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Calcium utilization	30.1	30.1	27.9	27.9	31.0	30.2	29.5	27.0
Combustor outlet temperature, F	1477	1477	1553	1553	1552	1551	1544	1550
Hot Water Heater:								
Outlet flue gas temperature, F	346	346	360	374	335	337	345	351
Water inlet temperature, F	116	116	127	127	114	115	121	130
Water outlet temperature, F	156	156	166	166	137	135	144	156
Water rate, lb/hr	32,500	32,500	34,000	34,000	51,000	51,500	48,000	46,500
Heat to water, MM Btu/hr	1.30	1.30	1.33	1.33	1.17	1.03	1.10	1.21
Thermal efficiency,%	53.80%	53.80%	68.96%	68.96%	65.30%	59.43%	62.34%	69.76%
Flue Gas Composition:								
Oxygen, vol %	10.1	10.1	9.4	9.4	8.6	8.5	8.4	8.0
Carbon Dioxide, vol %	9.4	9.4	10.1	10.1	11.0	11.1	11.2	10.7
Carbon Monoxide, ppmv	213	213	205	205	180	126	121	104
Sulfur Dioxide, ppmv	370	370	481	481	382	607	452	581
Nitrogen Oxides, ppmv	385	385	332	332	289	254	244	214
Air Emissions:								
SO2, lb/MM Btu (Base***)	4.74	4.74	4.74	4.74	4.74	4.74	4.74	4.74
SO2, lb/MM Btu	1.18	1.18	1.44	1.44	1.07	1.17	1.25	1.54
NOx, lb/MM Btu	0.89	0.89	0.72	0.72	0.59	0.51	0.49	0.41

* *Coal sulfur @ 3.0 wt%*

** *Dolomitic limestone @ 21.82% Ca, 20 x 100 mesh*

*** *Fired in a conventional burner with no sulfur capture*

TABLE 5-4 CEDAR LANE FARMS AFBC DATA - MAY, 1995

Dolomitic Limestone as SO2 Sorbent

Date:	5/3/95	5/3/95	5/4/95	5/5/95	5/6/95	5/6/95	5/6/95	5/7/95	5/7/95
Time:	00:00-04:00	04:00-08:00	19:59-23:59	02:30-06:30	01:00-04:00	04:00-08:00	20:59-23:59	00:00-04:00	04:00-08:00
Fluid Bed Combustor:									
Coal* feed rate, lb/hr	137	132	121	121	135	139	145	146	146
Coal feed rate, MM Btu/hr	1.73	1.67	1.53	1.53	1.71	1.76	1.83	1.85	1.85
Limestone** feed rate, lb/hr	41	40	36	36	41	42	44	44	44
Ca/S molar ratio	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Calcium utilization	39.2	38.9	39.6	41.9	39.8	39.6	39.9	40.3	40.8
Combustor outlet temperature,	1550	1553	1553	1553	1552	1552	1552	1552	1553
Hot Water Heater:									
Outlet flue gas temperature, F	351	333	352	352	343	337	342	341	341
Water inlet temperature, F	130	114	136	136	121	114	109	114	117
Water outlet temperature, F	156	134	169	169	151	139	146	143	144
Water rate, lb/hr	46,500	51,000	34,500	34,500	43,000	45,500	35,500	45,500	44,000
Heat to water, MM Btu/hr	1.21	1.02	1.14	1.14	1.29	1.14	1.31	1.32	1.19
Thermal efficiency,%	69.76%	61.09%	74.38%	74.38%	75.54%	64.69%	71.61%	71.44%	64.32%
Flue Gas Composition:									
Oxygen, vol %	9.3	9.3	8.8	9.0	9.1	9.3	9.1	9.1	9.2
Carbon Dioxide, vol %	9.9	9.7	9.7	9.6	10.0	9.8	9.8	9.8	9.8
Carbon Monoxide, ppmv	149	156	108	120	137	141	134	151	156
Sulfur Dioxide, ppmv	504	511	513	439	493	492	492	479	463
Nitrogen Oxides, ppmv	268	245	372	372	259	245	291	250	233
Air Emissions:									
SO2, lb/MM Btu (Base***)	4.74	4.74	4.74	4.74	4.74	4.74	4.74	4.74	4.74
SO2, lb/MM Btu	1.49	1.52	1.46	1.26	1.44	1.46	1.43	1.40	1.36
NOx, lb/MM Btu	0.57	0.53	0.76	0.76	0.55	0.53	0.61	0.53	0.50

* *Coal sulfur @ 3.0 wt%*

** *Dolomitic limestone @ 21.82% Ca, 20 x 100 mesh*

*** *Fired in a conventional burner with no sulfur capture*

Table 5-5 show the test results for the combustion of Ohio coal using calcitic limestone as the SO_2 sorbent at a Ca/S ratio of 2.5. The coal, dolomitic and calcitic limestone analyses were the same as that used for the test work at OARDC in Level 2-3 (refer back to Table 4-4 for complete analyses).

5.5.1 Coal and Sorbent

Over the testing periods one coal and two limestones were tested in the combustor. The coal and limestones tested were as follows (complete analyses shown in Table 4-4):

Coal:

Wayne Mine Coal - High Sulfur Bituminous Ohio Coal

Limestone:

National Lime and Stone Limestone - 80 wt% $CaCO_3$ Calcitic Limestone
Ohio Lime Company - 54.5 wt% $CaCO_3$ Dolomitic Limestone

5.5.2 Sulfur Dioxide Capture

The Ohio coal being fired during the testing of the Cedar Lane Farms system had a sulfur content of 3 wt% and a higher heating value of 12,650 Btu/lb which translates to 4.74 lb SO_2/MM Btu. The best temperature for sulfur dioxide capture when using dolomitic limestone as a sorbent appears to be in the range of 1500 to 1550°F (see Figure 5-4).

Sulfur dioxide capture via dolomitic limestone addition at a Ca/S ratio of 2.5 to the fluid bed yielded flue gas emission rates as low as 0.98 lb of SO_2 per million Btu of coal fired.

TABLE 5-5 CEDAR LANE FARMS AFBC DATA - MAY, 1995

Calcitic Limestone as SO2 Sorbent

Date:	5/12/95	5/13/95	5/15/95	5/16/95	5/17/95*	5/18/95	5/18/95	5/18/95	5/19/95
Time:	21:00-23:00	00:00-06:30	21:00-23:00	01:00-06:15	00:49-02:41	01:15-07:00	11:00-15:00	16:00-20:00	01:00-05:00
Fluid Bed Combustor:									
Coal** feed rate, lb/hr	147	143	175	175	186	150	149	138	126
Coal feed rate, MM Btu/hr	1.86	1.81	2.21	2.21	2.35	1.90	1.88	1.75	1.59
Limestone*** feed rate, lb/hr	30	29	36	36	38	31	31	28	26
Ca/S molar ratio	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Calcium utilization	46.8	49.3	47.1	51.6	50.2	50.6	49.8	49.1	49.8
Combustor outlet temperature,	1552	1554	1543	1545	1534	1552	1552	1552	1552
Hot Water Heater:									
Outlet flue gas temperature, F	339	350	351	353	349	335	335	335	335
Water inlet temperature, F	106	127	119	122	113	103	92	109	104
Water outlet temperature, F	131	155	146	157	159	136	120	132	125
Water rate, lb/hr	50,500	29,500	47,000	27,000	23,000	33,500	47,500	50,000	51,000
Heat to water, MM Btu/hr	1.26	0.83	1.27	0.95	1.06	1.11	1.33	1.15	1.07
Thermal efficiency,%	67.89%	45.66%	57.32%	42.69%	44.97%	58.26%	70.56%	65.88%	67.19%
Flue Gas Composition:									
Oxygen, vol %	9.7	9.5	9.9	10.4	10.0	10.3	10.2	10.0	9.6
Carbon Dioxide, vol %	10.8	9.3	9.0	8.5	8.6	8.9	8.9	9.0	0.3
Carbon Monoxide, ppmv	112	112	101	98	86	99	116	106	102
Sulfur Dioxide, ppmv	279	219	279	143	185	173	190	211	203
Nitrogen Oxides, ppmv	299	255	463	317	380	294	214	244	249
Air Emissions:									
SO2, lb/MM Btu (Base****)	4.74	4.74	4.74	4.74	4.74	4.74	4.74	4.74	4.74
SO2, lb/MM Btu	0.86	0.66	0.84	0.46	0.58	0.55	0.61	0.67	0.61
NOx, lb/MM Btu	0.67	0.56	1.04	0.76	0.87	0.69	0.50	0.56	0.55

* *Skewed Ca/S ratio so more limestone fed at lower rates*

** *Coal sulfur @ 3.0 wt%*

*** *Calcitic limestone @ 32.04 wt% Ca, 12 x 100 mesh*

**** *Fired in a conventional burner with no sulfur capture*

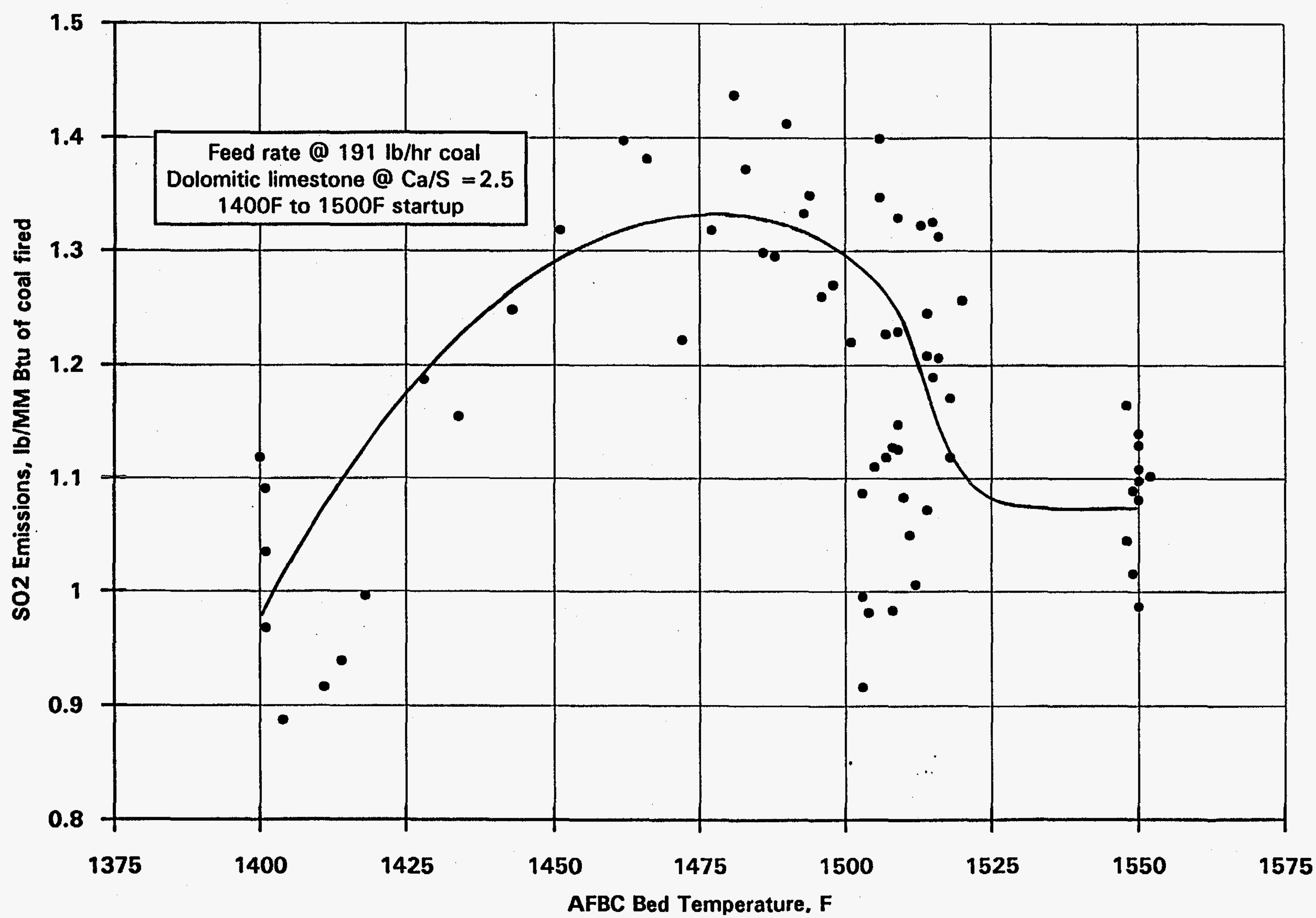


Figure 5-4. SO2 emissions versus fluid bed temperature

Figure 5-5 shows the effect on sulfur dioxide capture when feeding dolomitic limestone at rates to yield Ca/S ratios of 1.75 and 2.5. The data indicates that the regulated emission requirement of 1.2 lb of $SO_2/10^6$ Btu of coal fired could be met with a dolomitic limestone rate to yield a Ca/S ratio of ~2.0. The calcitic limestone performed better with sulfur dioxide capture at a Ca/S ratio of 2.5 to the fluid bed yielding flue gas emission rates as low as 0.44 lb of SO_2 per million Btu of coal fired (see Figure 5-5).

5.5.3 NO_x Reduction

The nitrogen oxide emission results for the runs are shown in Tables 5-3, 5-4 and 5-5. Generally the NOx emissions were lower than that observed during pilot plant operation, ranging from 0.41 to 1.07 lb NOx/MM Btu.

In Figure 5-6, a correlation between carbon monoxide in the flue gas and NOx emissions is shown, the trend, like the pilot plant operations shows NOx emissions reducing with increased CO levels. During the use of the dolomitic limestone, the levels of NOx were lower when feeding limestone at the higher rate to achieve a Ca/S ratio of 2.5, also see Figure 5-6. The limestone may be capturing some NOx as calcium nitrate.

5.5.4 Thermal Efficiency

The thermal efficiency of hot water out to fuel in for the various run periods examined ranged from 43% to 75%. For some of the runs there was a buildup of sorbent/flyash in the boiler which could account for the low efficiency. Also, flue gas recycle rates have not yet been optimize to yield the highest efficiencies that might be obtained.

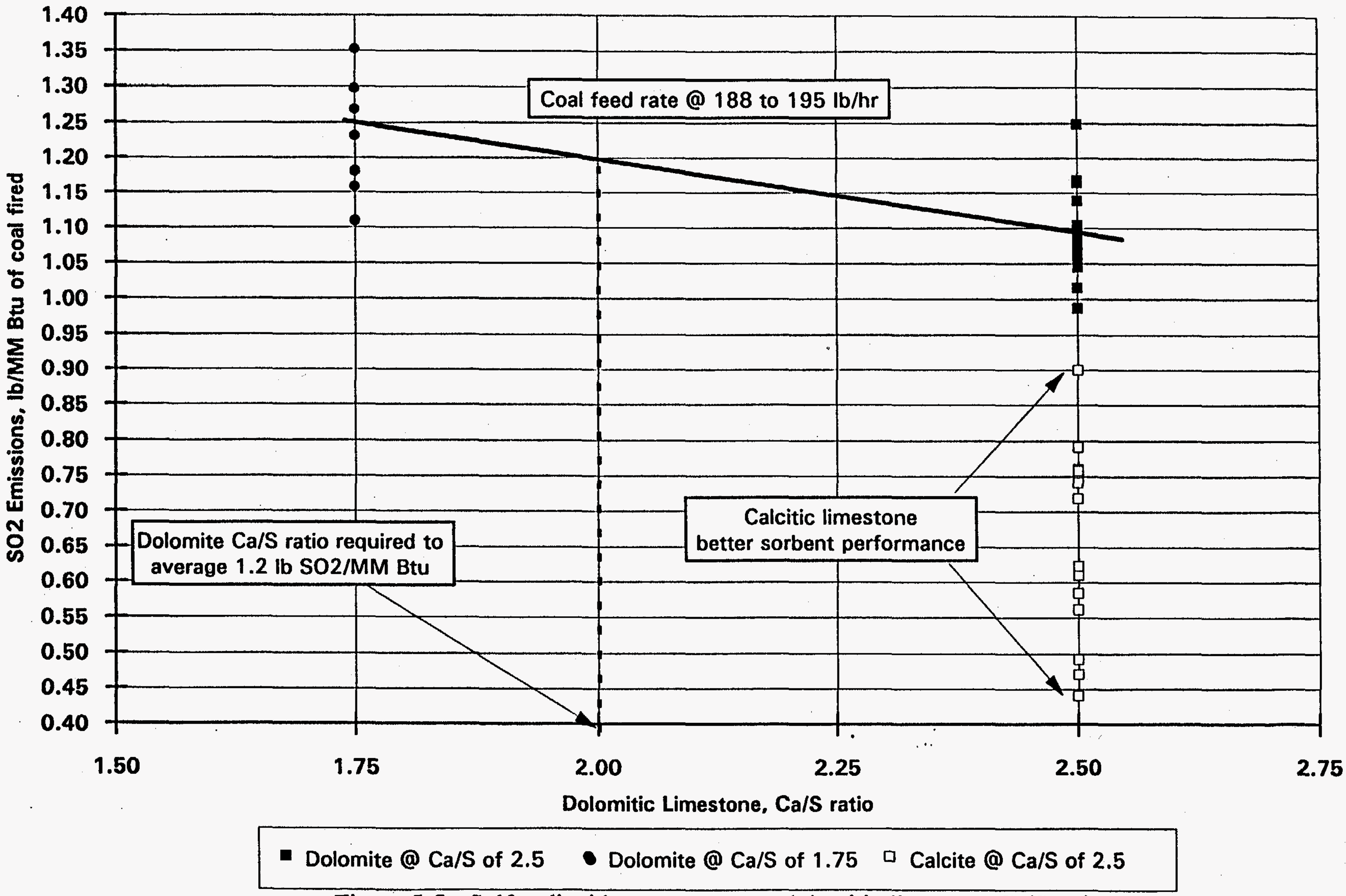


Figure 5-5. Sulfur dioxide capture versus dolomitic limestone Ca/S ratio

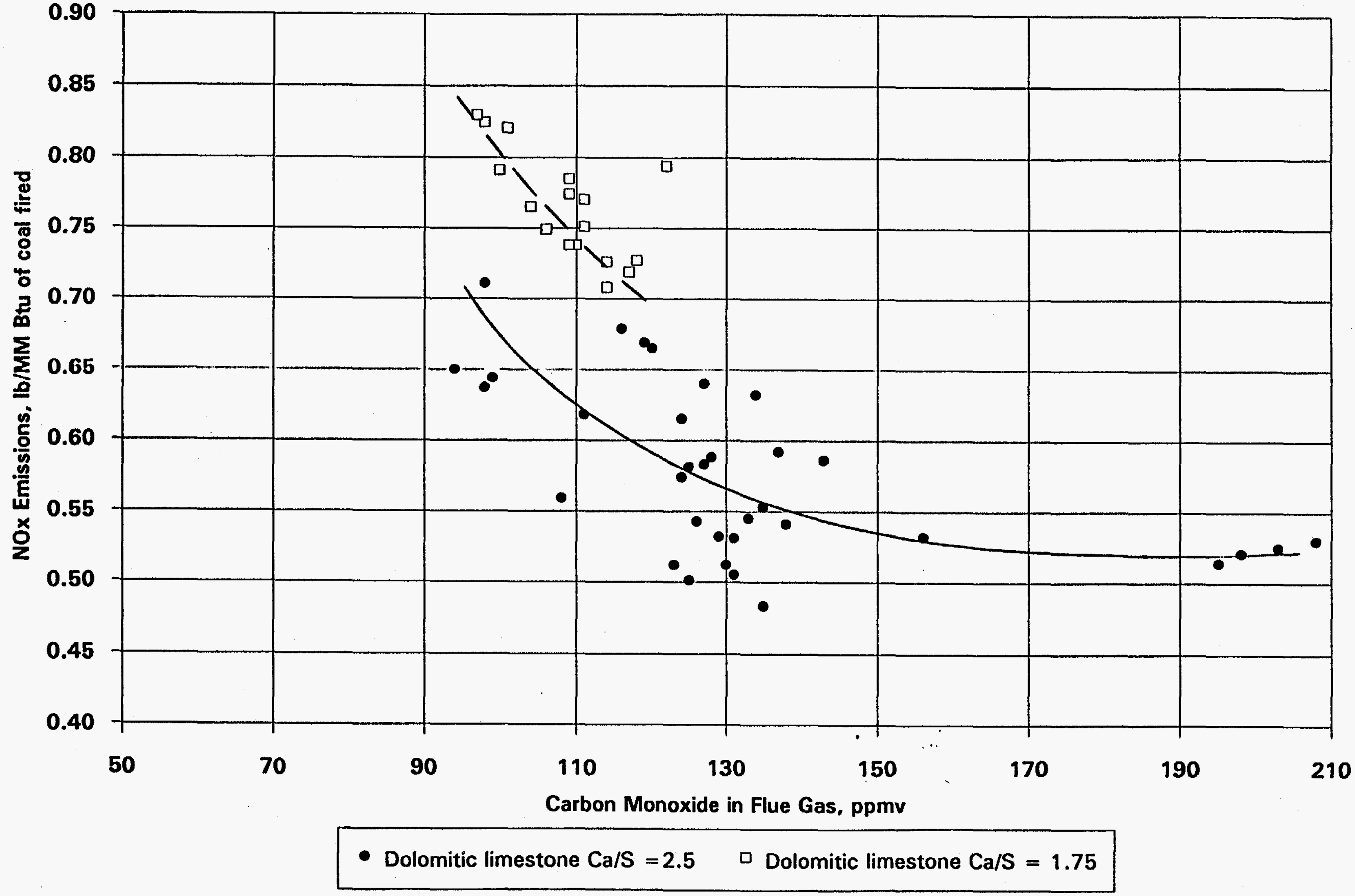


Figure 5-6. NOx emissions versus flue gas CO concentration

6.0 ECONOMICS/MARKETS

6.1 Economics

The prototype unit at the Cedar Lane Farms facility is not an economic size that could compete with the firing of natural gas in a package hot water heater or boiler; however, based on the current cost differential between coal and natural gas, with a four-fold increase in size the AFBC does start being competitive with natural gas fired heaters/boilers. This is due to the capital cost economy of scale. At larger sizes than a four-fold increase over pilot plant scale, the AFBC becomes even more cost competitive. The design scaleup considerations for larger commercial AFBC units are as follows:

- The outside diameter of the combustor proper, will be limited based on over-the-road travel clearance considerations. For economic reasons, it is desirable to shop fabricate rather than field fabricate the combustor.

- For large units, multiple coal-limestone feed points may be desirable. However, multiple units of the auger system that is to be tested could be used to satisfy this need.

- Combustion/recycle gas distribution through grid plate distributors has been proved for large fluidized bed combustors. This is not considered a problem for scale-up.

- The rest of the system, waste heat recovery, baghouse, blowers, and pumps are units that are commercially available in both small and large sizes.

- The controls to be used are applicable, no matter the size of the system.

For economic comparison of the coal-fired AFBC system with a natural gas fired system, a unit sized in accord with the following site evaluation basis was used. This 7.8 MM Btu/hr AFBC is in the lower size range that one could typically market for small scale industrial, commercial, and institutional use.

AFBC Site Evaluation Bases

Ohio Site

The Ohio site is a generic one wherein a 7.8 MM Btu/hr coal input fluidized bed combustor would be used to produce hot water for a green house or hospital application.

Climate:

Elevation = assume 1000 ft. above sea level

Temperature Range = 0°F winter to 90°F in summer

Labor Cost:

Operating Labor @ $15/hr

Construction Labor @ average of $52/hr

Limestone Supply for AFBC:

Limestone is assumed to be supplied from a local supplier in the State. FOB Mine @ $10/ton + $0.08/ton mile. Assume AFBC site within a 60 mile radius of limestone quarry, delivered price = $15/ton.

Coal Supply for AFBC:

Coal is assumed to be supplied from a local supplier in the State. High sulfur bituminous coal FOB Wayne Mine @ $30/ton plus $0.08/ton mile. Assume AFBC site within a 50 mile radius of coal mine. Delivered coal cost estimated at $34/ton.

Wayne Mine, Ohio Coal

and Ash Analyses

Coal Delivered: Bituminous Coal, size 2" x 0" unwashed

Coal Analyses(as received):

Ultimate Analysis

Component	Wt %
Carbon	71.15
Hydrogen	4.44
Oxygen	8.13
Nitrogen	1.24
Sulfur	3.28
Moisture	5.68
Ash	6.08
Total	100.00

Higher Heating Value:
HHV = 12,640 Btu/lb
Coal Sulfur = 5.18 Lb SO_2/MM Btu
Calculated Ca/S ratio of ash = 0.04
where, Ca = Ca + Na2 + K2

Ash Analyses:

Major and Minor Elements as Oxides:

Component	Wt %
SiO_2	41.46
Al_2O_3	24.26
TiO_2	1.08
Fe_2O_3	26.95
CaO	2.00
MgO	0.82
Na_2O	0.46
K_2O	1.80
P_2O_5	0.28
SrO	0.06
BaO	0.00
MnO_2	0.13
Other	0.36
Total	100.00

Capital and operating costs were developed for the 7.8 MM Btu/hr coal-fired AFBC to produce 6.57 MM Btu/hr of hot water, see Table 6-1. Capital and operating costs were also developed for a natural gas fired hot water heater that would produce 6.57 MM Btu/hr of hot water, see Tables 6-2 and 6-3.

Following the development of capital and operating costs, economic projections were made assuming an 8% discounted cash flow return on investment (DCF-ROI) for both the coal-fired AFBC case and the natural gas fired case. A twenty year project life was assumed and the Modified Accelerated Cost Recovery System (MACRS) was used for depreciating equipment. These analyses are shown on DCF-ROI spreadsheets. Table 6-4 shows the AFBC case, and Tables 6-4, 6-5, 6-6 and 6-7 are for the natural gas case at various natural gas costs ($3, $4.50, and $6/MM Btu).

TABLE 6-1.

Ohio Site - AFBC for Hot Water Heating Application

7.80 MM Btu/hr of Coal Fired

6.57 MM Btu/hr of Hot Water

Total Plant Investment

Base Case

Major Equipment	$225,877
Instruments	$40,260
Supplies	$32,202
Construction Labor	$69,940
Engineering*	$21,600
Subtotal	$389,879
Project Contingency @ 15%	$58,482
Total Plant Investment (TPI)	$448,361

* Engineering cost based on distribution over five identical units

Projected Operating Costs*

Base Case

	Annual Use	Cost/Unit	Cost/ Yr	(Hot Water) Cost/MM Btu
Raw Material:				
Coal	2,222 tons	$34 /ton	$75,533	$1.60
Limestone	852 tons	$14 /ton	$11,930	$0.25
Utilities:				
Electricity	318,240 kWhr	$0.06 /kWhr	$19,094	$0.40
Water	694 Mgal	$0.75 /Mgal	$520	$0.01
Ash Disposal:	841 tons	$10 /ton	$8,413	$0.18
Labor:				
Operating	2,920 mnhrs	$15 /mnhr	$43,800	$0.93
Maintenance @ 60% of 3% of TPI			$8,070	$0.17
Supervision @ 20% of O & M labor			$10,374	$0.22
Supplies:				
Operating @ 30% of operating labor			$13,140	$0.28
Maintenance @ 40% of 3% of TPI			$5,380	$0.11
Admin. and Gen. Ovhd. (60% of total labor):			$37,347	$0.79
Insurance and Taxes (2.7% of TPI):			$12,106	$0.26
Total Operating Costs			**$245,708**	**$5.20**

* 300 days per year @ 100% Btu output

TABLE 6-2.

Ohio Site - Natural Gas Fired Boiler for Hot Water Heating Application

7.73 MM Btu/hr of Natural Gas

6.57 MM Btu/hr of Hot Water

Total Plant Investment

Major Equipment	$58,005
Instruments	$12,400
Supplies	$7,000
Construction Labor	$46,075
Engineering	$15,000
Subtotal	$138,480
Project Contingency @ 15%	$20,772
Total Plant Investment (TPI)	$159,252

Projected Operating Costs*

	Annual Use	Cost/Unit	Cost/ Yr	(Hot Water) Cost/MM Btu
Raw Material:				
Natural Gas @ 85% efficiency	55,652 MM Btu	$4.50 /MM Btu	$250,433	$5.29
Utilities:				
Electricity	26,845 kWhr	$0.06 /kWhr	$1,611	$0.03
Water	694 Mgal	$0.75 /Mgal	$520	$0.01
Labor:				
Operating	876 mnhrs	$15 /mnhr	$13,140	$0.28
Maintenance @ 60% of 3% of TPI			$2,867	$0.06
Supervision @ 20% of O & M labor			$3,201	$0.07
Supplies:				$0.00
Operating @ 30% of operating labor			$3,942	$0.08
Maintenance @ 40% of 3% of TPI			$1,911	$0.04
Admin. and Gen. Ovhd. (60% of total labor):			$11,525	$0.24
Insurance and Taxes (2.7% of TPI):			$4,300	$0.09
Total Operating Costs			**$293,450**	**$6.20**

* 300 days per year @ 100% Btu output

TABLE 6-3.

Ohio Site - Natural Gas Fired Boiler for Hot Water Heating Application

6.57 MM Btu/hr of Hot Water

Projected Operating Costs*

Natural Gas Cost @ $3/MM Btu

	Annual Use	Cost/Unit	Cost/ Yr	(Hot Water) Cost/MM Btu
Raw Material:				
Natural Gas @ 85% efficiency	55,652 MM Btu	$3 /MM Btu	$166,955	$3.53
Utilities:				
Electricity	26,845 kWhr	$0.06 /kWhr	$1,611	$0.03
Water	694 Mgal	$0.75 /Mgal	$520	$0.01
Labor:				
Operating	876 mnhrs	$15 /mnhr	$13,140	$0.28
Maintenance @ 60% of 3% of TPI			$2,867	$0.06
Supervision @ 20% of O & M labor			$3,201	$0.07
Supplies:				$0.00
Operating @ 30% of operating labor			$3,942	$0.08
Maintenance @ 40% of 3% of TPI			$1,911	$0.04
Admin. and Gen. Ovhd. (60% of total labor):			$11,525	$0.24
Insurance and Taxes (2.7% of TPI):			$4,300	$0.09
Total Operating Costs			$209,972	$4.43

* 300 days per year @ 100% Btu output

Projected Operating Costs*

Natural Gas Cost @ $6/MM Btu

	Annual Use	Cost/Unit	Cost/ Yr	(Hot Water) Cost/MM Btu
Raw Material:				
Natural Gas @ 85% efficiency	55,652 MM Btu	$6 /MM Btu	$333,911	$7.06
Utilities:				
Electricity	26,845 kWhr	$0.06 /kWhr	$1,611	$0.03
Water	694 Mgal	$0.75 /Mgal	$520	$0.01
Labor:				
Operating	876 mnhrs	$15 /mnhr	$13,140	$0.28
Maintenance @ 60% of 3% of TPI			$0	$0.00
Supervision @ 20% of O & M labor			$2,628	$0.06
Supplies:				$0.00
Operating @ 30% of operating labor			$3,942	$0.08
Maintenance @ 40% of 3% of TPI			$1,911	$0.04
Admin. and Gen. Ovhd. (60% of total labor):			$9,461	$0.20
Insurance and Taxes (2.7% of TPI):			$4,300	$0.09
Total Operating Costs			$371,423	$7.84

* 300 days per year @ 100% Btu output

TABLE 6-4.
Discounted Cash Flow - Return on Investment
6.57 MM Btu/hr Hot Water Output - Coal Fired AFBC

Basis:
20 Year Project Life
15 Years Modified Accelerated Cost Recovery System (MACRS) on Total Plant Investment
100 Percent Equity Capital
Return on Investment 8.0%
Federal (34%) + State (5%) Taxes = 39%

X (Annual Revenues Required)	=	$317,559 /yr
Steam (300 days/yr @100% capacity)	=	47,287 MM Btu/yr
Energy Cost	=	**$6.72 /MM Btu**

Desired DCF-ROI	=	8.0%
Total Plant Investment (TPI)	=	$478,864
Working Capital	=	$21,623
Startup Cost	=	$49,142
Annual Raw Material Cost	=	$87,463
Annual Net Operating Cost	=	$245,708
Annual Gross Operating Cost	=	$245,708
Period of Construction, yrs	=	0.333

Interest During Construction	=	0.027 I
ROI During Construction	=	$12,757

IDC = I*%ROI*(yrs constr.)
Discount Factor, H = [1/(1+ i)^n]
i = interest
n= number of years of life, n = 1 (for end of 1st yr), etc.

Working Capital: Sum of raw materials inventory of 14 days at full rate
+ materials and supplies @ 0.9% of TPI
+ net receivables @ 1/24 energy sales revenues

Startup Cost: 20% of total gross operating cost

End of Year	C Depreciation	E Net Income After Taxes			F Investment	G Cash Flow (C+E-F)				H Discount Factor @ 0.08	DCF (F x G)			
0				-0.610 *S	1.027 * I+ W		-1.027 * I	-0.610 * S	- W	1		-1.03 * I	-0.610 * S	-1 * W
1	0.0500 * I	0.61 * (X - N)	-0.0305 * I		0	0.61 * (X - N)	0.01950 * I			0.9259	0.5648 * (X - N)	0.0181 * I		
2	0.0950 * I	0.61 * (X - N)	-0.0580 * I		0	0.61 * (X - N)	0.03705 * I			0.8573	0.5230 * (X - N)	0.0318 * I		
3	0.0855 * I	0.61 * (X - N)	-0.0522 * I		0	0.61 * (X - N)	0.03335 * I			0.7938	0.4842 * (X - N)	0.0265 * I		
4	0.0770 * I	0.61 * (X - N)	-0.0470 * I		0	0.61 * (X - N)	0.03003 * I			0.7350	0.4484 * (X - N)	0.0221 * I		
5	0.0693 * I	0.61 * (X - N)	-0.0423 * I		0	0.61 * (X - N)	0.02703 * I			0.6806	0.4152 * (X - N)	0.0184 * I		
6	0.0623 * I	0.61 * (X - N)	-0.0380 * I		0	0.61 * (X - N)	0.02430 * I			0.6302	0.3844 * (X - N)	0.0153 * I		
7	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5835	0.3559 * (X - N)	0.0134 * I		
8	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5403	0.3296 * (X - N)	0.0124 * I		
9	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5002	0.3052 * (X - N)	0.0115 * I		
10	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.4632	0.2825 * (X - N)	0.0107 * I		
11	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.4289	0.2616 * (X - N)	0.0099 * I		
12	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3971	0.2422 * (X - N)	0.0091 * I		
13	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3677	0.2243 * (X - N)	0.0085 * I		
14	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3405	0.2077 * (X - N)	0.0078 * I		
15	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3152	0.1923 * (X - N)	0.0073 * I		
16	0.0295 * I	0.61 * (X - N)	-0.0180 * I		0	0.61 * (X - N)	0.01151 * I			0.2919	0.1781 * (X - N)	0.0034 * I		
17	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2703	0.1649 * (X - N)	0.0000 * I		
18	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2502	0.1527 * (X - N)	0.0000 * I		
19	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2317	0.1413 * (X - N)	0.0000 * I		
20	0.0000 * I	0.61 * (X - N)	0.0000 * I		0 * I - W	0.61 * (X - N)	0.00000 * I		+W	0.2145	0.1309 * (X - N)	0.0000 * I		0.21455 *W
Total	1.0000 * I	12.20 * (X - N)	-0.6100 * I	-0.610 *S	1.02664 * I	12.2 * (X - N)	-0.6366 * I	-0.61 * S			5.9891 * (X - N)	-0.8006 * I	-0.610 * S	-0.78545 *W

DCF equation for determining revenues (X) to provide for required ROI:
5.9891 X = 5.9891 N + 0.8006 I + 0.610 S + 0.7855 W

TABLE 6-5.

Discounted Cash Flow - Return on Investment

6.57 MM Btu/hr Hot Water Output - Natural Gas Fired Heater
$4.50/MM Btu Cost of Natural Gas

Basis:
20 Year Project Life
15 Years Modified Accelerated Cost Recovery System (MACRS) on Total Plant Investment
100 Percent Equity Capital
Return on Investment 8.0%
Federal (34%) + State (5%) Taxes = 39%

X (Annual Revenues Required) = $323,852 /yr
Steam (300 days/yr @100% capacity) = 47,287 MM Btu/yr
Energy Cost = $6.85 /MM Btu

Desired DCF-ROI = 8.0%
Total Plant Investment (TPI) = $159,252
Working Capital = $26,614
Startup Cost = $58,690
Annual Raw Material Cost = $250,433
Annual Net Operating Cost = $293,450
Annual Gross Operating Cost = $293,450
Period of Construction, yrs = 0.167

Interest During Construction = 0.013 I
ROI During Construction = $2,123

IDC = I*%ROI*(yrs constr.)
Discount Factor, H = [1/(1+ i)^n]
i = interest
n = number of years of life, n = 1 (for end of 1st yr), etc.

Working Capital: Sum of raw materials inventory of 14 days at full rate
+ materials and supplies @ 0.9% of TPI
+ net receivables @ 1/24 energy sales revenues

Startup Cost: 20% of total gross operating cost

End of Year	C Depreciation	E Net Income After Taxes	F Investment	G Cash Flow (C+E-F)	H Discount Factor @ 0.08	DCF (F x G)
0		-0.610 *S	1.013 *I+ W	-1.013 *I -0.610 *S -W	1	-1.01 *I -0.610 *S -1 *W
1	0.0500 *I	0.61 *(X-N) -0.0305 *I	0	0.61 *(X-N) 0.01950 *I	0.9259	0.5648 *(X-N) 0.0181 *I
2	0.0950 *I	0.61 *(X-N) -0.0580 *I	0	0.61 *(X-N) 0.03705 *I	0.8573	0.5230 *(X-N) 0.0318 *I
3	0.0855 *I	0.61 *(X-N) -0.0522 *I	0	0.61 *(X-N) 0.03335 *I	0.7938	0.4842 *(X-N) 0.0265 *I
4	0.0770 *I	0.61 *(X-N) -0.0470 *I	0	0.61 *(X-N) 0.03003 *I	0.7350	0.4484 *(X-N) 0.0221 *I
5	0.0693 *I	0.61 *(X-N) -0.0423 *I	0	0.61 *(X-N) 0.02703 *I	0.6806	0.4152 *(X-N) 0.0184 *I
6	0.0623 *I	0.61 *(X-N) -0.0380 *I	0	0.61 *(X-N) 0.02430 *I	0.6302	0.3844 *(X-N) 0.0153 *I
7	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.5835	0.3559 *(X-N) 0.0134 *I
8	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.5403	0.3296 *(X-N) 0.0124 *I
9	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.5002	0.3052 *(X-N) 0.0115 *I
10	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.4632	0.2825 *(X-N) 0.0107 *I
11	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.4289	0.2616 *(X-N) 0.0099 *I
12	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.3971	0.2422 *(X-N) 0.0091 *I
13	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.3677	0.2243 *(X-N) 0.0085 *I
14	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.3405	0.2077 *(X-N) 0.0078 *I
15	0.0590 *I	0.61 *(X-N) -0.0360 *I	0	0.61 *(X-N) 0.02303 *I	0.3152	0.1923 *(X-N) 0.0073 *I
16	0.0295 *I	0.61 *(X-N) -0.0180 *I	0	0.61 *(X-N) 0.01151 *I	0.2919	0.1781 *(X-N) 0.0034 *I
17	0.0000 *I	0.61 *(X-N) 0.0000 *I	0	0.61 *(X-N) 0.00000 *I	0.2703	0.1649 *(X-N) 0.0000 *I
18	0.0000 *I	0.61 *(X-N) 0.0000 *I	0	0.61 *(X-N) 0.00000 *I	0.2502	0.1527 *(X-N) 0.0000 *I
19	0.0000 *I	0.61 *(X-N) 0.0000 *I	0	0.61 *(X-N) 0.00000 *I	0.2317	0.1413 *(X-N) 0.0000 *I
20	0.0000 *I	0.61 *(X-N) 0.0000 *I	0 *I- W	0.61 *(X-N) 0.00000 *I +W	0.2145	0.1309 *(X-N) 0.0000 *I 0.21455 *W
Total	1.0000 *I	12.20 *(X-N) -0.6100 *I -0.610 *S	1.013333 *I	12.2 *(X-N) -0.6233 *I -0.61 *S		5.9891 *(X-N) -0.7873 *I -0.610 *S -0.78545 *W

DCF equation for determining revenues (X) to provide for required ROI:
5.9891 X = 5.9891 N + 0.7873 I + 0.610 S + 0.7855 W

TABLE 6-6.

Discounted Cash Flow - Return on Investment

6.57 MM Btu/hr Hot Water Output - Natural Gas Fired Heater
$3.00/MM Btu Cost of Natural Gas

Basis:
20 Year Project Life
15 Years Modified Accelerated Cost Recovery System (MACRS) on Total Plant Investment
100 Percent Equity Capital
Return on Investment 8.0%
Federal (34%) + State (5%) Taxes = 39%

X (Annual Revenues Required)	=	$237,691	/yr
Steam (300 days/yr @100% capacity)	=	47,287	MM Btu/yr
Energy Cost	=	$5.03	/MM Btu

Desired DCF-ROI	=	8.0%
Total Plant Investment (TPI)	=	$159,252
Working Capital	=	$19,128
Startup Cost	=	$41,994
Annual Raw Material Cost	=	$166,955
Annual Net Operating Cost	=	$209,972
Annual Gross Operating Cost	=	$209,972
Period of Construction, yrs	=	0.167

Interest During Construction	=	0.013 I
ROI During Construction	=	$2,123

IDC = I*%ROI*(yrs constr.)
Discount Factor, H = [1/(1+ i)^n]
i = interest
n = number of years of life, n = 1 (for end of 1st yr), etc.

Working Capital: Sum of raw materials inventory of 14 days at full rate
+ materials and supplies @ 0.9% of TPI
+ net receivables @ 1/24 energy sales revenues

Startup Cost: 20% of total gross operating cost

End of Year	C Depreciation	E Net Income After Taxes			F Investment	G Cash Flow (C+E-F)				H Discount Factor @ 0.08	DCF (F x G)			
0				-0.610 *S	1.013 * I+ W		-1.013 * I	-0.610 * S	- W	1		-1.01 * I	-0.610 * S	-1 * W
1	0.0500 * I	0.61 * (X - N)	-0.0305 * I		0	0.61 * (X - N)	0.01950 * I			0.9259	0.5648 * (X - N)	0.0181 * I		
2	0.0950 * I	0.61 * (X - N)	-0.0580 * I		0	0.61 * (X - N)	0.03705 * I			0.8573	0.5230 * (X - N)	0.0318 * I		
3	0.0855 * I	0.61 * (X - N)	-0.0522 * I		0	0.61 * (X - N)	0.03335 * I			0.7938	0.4842 * (X - N)	0.0265 * I		
4	0.0770 * I	0.61 * (X - N)	-0.0470 * I		0	0.61 * (X - N)	0.03003 * I			0.7350	0.4484 * (X - N)	0.0221 * I		
5	0.0693 * I	0.61 * (X - N)	-0.0423 * I		0	0.61 * (X - N)	0.02703 * I			0.6806	0.4152 * (X - N)	0.0184 * I		
6	0.0623 * I	0.61 * (X - N)	-0.0380 * I		0	0.61 * (X - N)	0.02430 * I			0.6302	0.3844 * (X - N)	0.0153 * I		
7	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5835	0.3559 * (X - N)	0.0134 * I		
8	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5403	0.3296 * (X - N)	0.0124 * I		
9	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5002	0.3052 * (X - N)	0.0115 * I		
10	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.4632	0.2825 * (X - N)	0.0107 * I		
11	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.4289	0.2616 * (X - N)	0.0099 * I		
12	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3971	0.2422 * (X - N)	0.0091 * I		
13	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3677	0.2243 * (X - N)	0.0085 * I		
14	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3405	0.2077 * (X - N)	0.0078 * I		
15	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3152	0.1923 * (X - N)	0.0073 * I		
16	0.0295 * I	0.61 * (X - N)	-0.0180 * I		0	0.61 * (X - N)	0.01151 * I			0.2919	0.1781 * (X - N)	0.0034 * I		
17	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2703	0.1649 * (X - N)	0.0000 * I		
18	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2502	0.1527 * (X - N)	0.0000 * I		
19	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2317	0.1413 * (X - N)	0.0000 * I		
20	0.0000 * I	0.61 * (X - N)	0.0000 * I		0 * I - W	0.61 * (X - N)	0.00000 * I		+W	0.2145	0.1309 * (X - N)	0.0000 * I		0.21455 *W
Total	1.0000 * I	12.20 * (X - N)	-0.6100 * I	-0.610 *S	1.013333 * I	12.2 * (X - N)	-0.6233 * I	-0.61 * S			5.9891 * (X - N)	-0.7873 * I	-0.610 * S	-0.78545 *W

DCF equation for determining revenues (X) to provide for required ROI:
5.9891 X = 5.9891 N + 0.7873 I + 0.610 S + 0.7855 W

TABLE 6-7.

Discounted Cash Flow - Return on Investment

6.57 MM Btu/hr Hot Water Output - Natural Gas Fired Heater
$6.00/MM Btu Cost of Natural Gas

Basis:
20 Year Project Life
15 Years Modified Accelerated Cost Recovery System (MACRS) on Total Plant Investment
100 Percent Equity Capital
Return on Investment 8.0%
Federal (34%) + State (5%) Taxes = 39%

X (Annual Revenues Required)	=	$404,364	/yr
Steam (300 days/yr @100% capacity)	=	47,287	MM Btu/yr
Energy Cost	=	$8.55	/MM Btu

Desired DCF-ROI	=	8.0%
Total Plant Investment (TPI)	=	$159,252
Working Capital	=	$33,864
Startup Cost	=	$74,285
Annual Raw Material Cost	=	$333,911
Annual Net Operating Cost	=	$371,423
Annual Gross Operating Cost	=	$371,423
Period of Construction, yrs	=	0.167

Interest During Construction	=	0.013 I
ROI During Construction	=	$2,123

IDC = I*%ROI*(yrs constr.)
Discount Factor, H = [1/(1+ i)^n]
i = interest
n= number of years of life, n = 1 (for end of 1st yr), etc.

Working Capital: Sum of raw materials inventory of 14 days at full rate
+ materials and supplies @ 0.9% of TPI
+ net receivables @ 1/24 energy sales revenues

Startup Cost: 20% of total gross operating cost

End of Year	C Depreciation	E Net Income After Taxes			F Investment	G Cash Flow (C+E-F)				H Discount Factor @ 0.08	DCF (F x G)			
0				-0.610 *S	1.013 * I+ W		-1.013 * I	-0.610 * S	- W	1		-1.01 * I	-0.610 * S	-1 * W
1	0.0500 * I	0.61 * (X - N)	-0.0305 * I		0	0.61 * (X - N)	0.01950 * I			0.9259	0.5648 * (X - N)	0.0181 * I		
2	0.0950 * I	0.61 * (X - N)	-0.0580 * I		0	0.61 * (X - N)	0.03705 * I			0.8573	0.5230 * (X - N)	0.0318 * I		
3	0.0855 * I	0.61 * (X - N)	-0.0522 * I		0	0.61 * (X - N)	0.03335 * I			0.7938	0.4842 * (X - N)	0.0265 * I		
4	0.0770 * I	0.61 * (X - N)	-0.0470 * I		0	0.61 * (X - N)	0.03003 * I			0.7350	0.4484 * (X - N)	0.0221 * I		
5	0.0693 * I	0.61 * (X - N)	-0.0423 * I		0	0.61 * (X - N)	0.02703 * I			0.6806	0.4152 * (X - N)	0.0184 * I		
6	0.0623 * I	0.61 * (X - N)	-0.0380 * I		0	0.61 * (X - N)	0.02430 * I			0.6302	0.3844 * (X - N)	0.0153 * I		
7	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5835	0.3559 * (X - N)	0.0134 * I		
8	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5403	0.3296 * (X - N)	0.0124 * I		
9	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.5002	0.3052 * (X - N)	0.0115 * I		
10	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.4632	0.2825 * (X - N)	0.0107 * I		
11	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.4289	0.2616 * (X - N)	0.0099 * I		
12	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3971	0.2422 * (X - N)	0.0091 * I		
13	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3677	0.2243 * (X - N)	0.0085 * I		
14	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0:3405	0.2077 * (X - N)	0.0078 * I		
15	0.0590 * I	0.61 * (X - N)	-0.0360 * I		0	0.61 * (X - N)	0.02303 * I			0.3152	0.1923 * (X - N)	0.0073 * I		
16	0.0295 * I	0.61 * (X - N)	-0.0180 * I		0	0.61 * (X - N)	0.01151 * I			0.2919	0.1781 * (X - N)	0.0034 * I		
17	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2703	0.1649 * (X - N)	0.0000 * I		
18	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2502	0.1527 * (X - N)	0.0000 * I		
19	0.0000 * I	0.61 * (X - N)	0.0000 * I		0	0.61 * (X - N)	0.00000 * I			0.2317	0.1413 * (X - N)	0.0000 * I		
20	0.0000 * I	0.61 * (X - N)	0.0000 * I		0 * I - W	0.61 * (X - N)	0.00000 * I		+W	0.2145	0.1309 * (X - N)	0.0000 * I		0.21455 *W
Total	1.0000 * I	12.20 * (X - N)	-0.6100 * I	-0.610 *S	1.013333 * I	12.2 * (X - N)	-0.6233 * I	-0.61 * S			5.9891 * (X - N)	-0.7873 * I	-0.610 * S	-0.78545 *W

DCF equation for determining revenues (X) to provide for required ROI:

5.9891 X = 5.9891 N + 0.7873 I + 0.610 S + 0.7855 W

The results of these economic projections are shown in Figure 6-1. An AFBC system sized to deliver 6.57 MM Btu/hr of hot water is competitive with a new natural gas fired system when the cost of natural gas is $4.40/MM Btu. This is within the range of current natural gas prices charged to small scale users. In 1994, Cedar Lane Farms paid, on average, $4.30/MM Btu for natural gas.

6.1 Markets

The coal industry in all states that have high sulfur coal reserves, has seen a dramatic negative impact on coal consumption because of the ever increasing environmental constraints imposed on the industries burning these coals. This negative impact has been very dramatic in the industrial/commercial marketplace. For instance, according to the 1991 State Energy Data Report, from 1960 to 1991, annual coal use in Ohio by commercial and industrial entities has dropped from 27,730 tons in 1960 to 8,822 tons in 1991, a 68% decrease. To reverse this trend and place coal once again as the fuel of choice, low cost environmentally acceptable technologies must be developed.

The AFBC system currently under sponsored development by the U.S. DOE is one system that has the potential to reverse this 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 fabrication. This AFBC system can process run of mine coal of any ash, moisture or sulfur content. It is amenable for use with all types of coal. 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. Whereas for coal-fired units under 100 MM Btu/hr there are no Federal limits for NO_x emissions, the AFBC incorporates a flue gas recycle technique which not only can be used to reduce NO_x emissions, but also increases the overall thermal efficiency of the system.

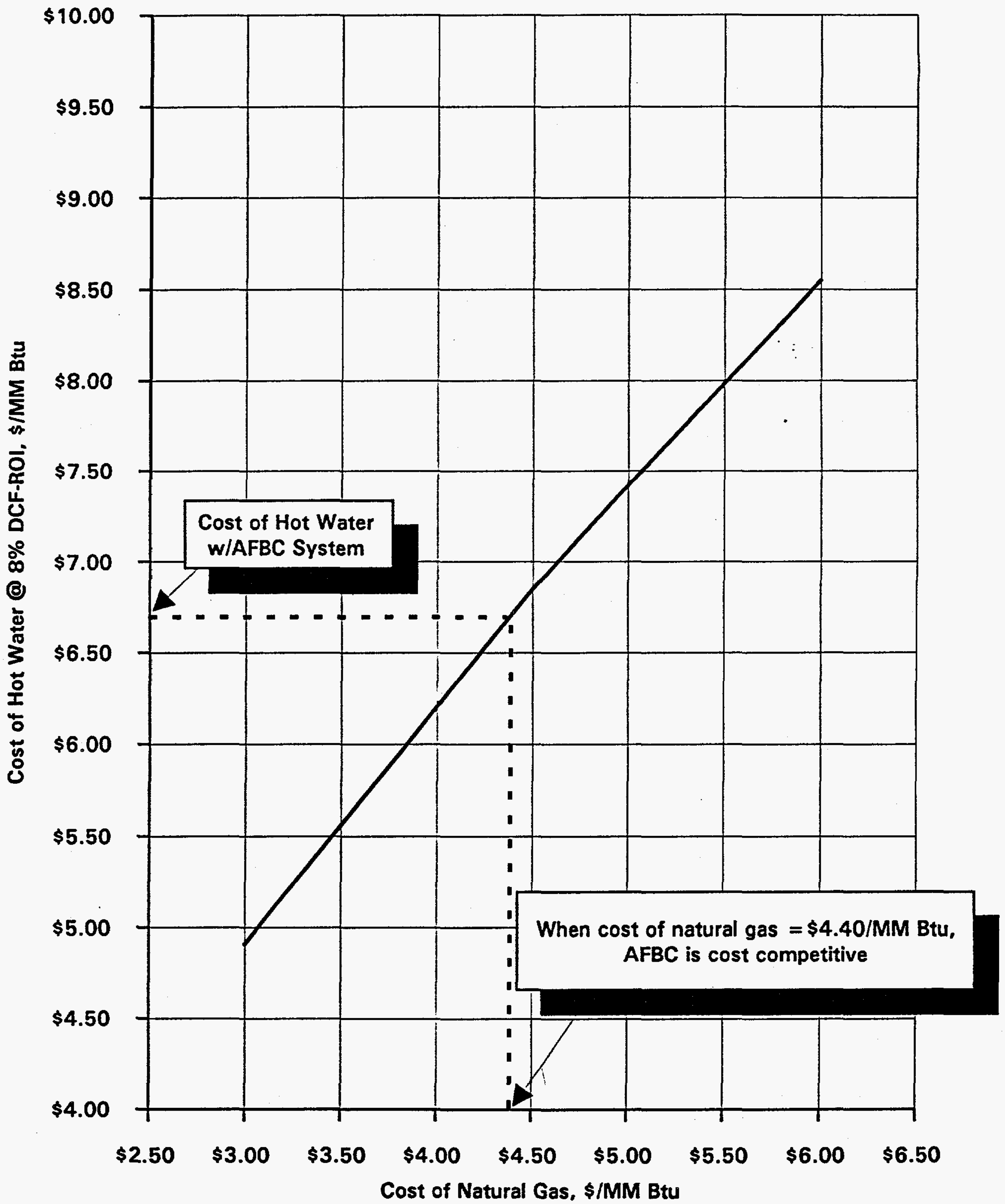


Figure 6-1. 6.57 MM Btu/hr hot water heater, natural gas versus AFBC

The successful development and widespread implementation of this system, could well 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 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.

In addition to the use of the AFBC for production of hot water and steam; EER is evaluating its use for co-generating electrical power and producing hot water or steam for district heating/cooling and/or industrial use. EER has developed a power generation design based on a hot air Brayton cycle which can yield, fuel in to electric power out, of 20-25% thermal efficiency (see ASME paper in Appendix). When including waste heat recovery for heating use, the overall system thermal efficiency increases to 50 to 55% efficiency. The coal-fired AFBC Brayton cycle will be cost competitive with diesel fired electrical generators. These systems could be operated to continuously supply power, so that when purchased power outages occurred there would be an un-interrupted supply of power to critical components, as required by certain end users.

The EER team already has in place a marketing strategy for the technology. The Will-Burt Company is the team member who will fabricate and market the technology. Will-Burt 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 for those size units which must meet SO_2 emission limits.

This technology can readily be used to comply with all facets of the Federal Clean Air Act Amendments of 1990. The EER team and the U.S. DOE are very enthusiastic about the potential of this AFBC technology and are looking forward to working with the OCDO toward the successful commercialization of the AFBC system.

7.0 PLANNED DEVELOPMENT

The development team for the Small Scale Atmospheric Fluidized Bed Combustion System is requesting additional funds from the Ohio Coal Development Office (OCDO) under Grant Agreement No. CDO/D-931-10 for the project. The additional funding is required to 1) complete a commercial scale design and to develop detailed fabrication costs so that firm quotes may be provided to potential clients, 2) help offset increased construction and startup expenditures, 3) correct a few minor operational problems and 4) complete the long range test program. A time extension is also being requested, changing the end date of the contract from 12/31/95 to 6/30/96.

The project team, consisting of the Energy and Environmental Research Corporation (EER), the Will-Burt Company (Will-Burt), the Ohio Agricultural Research and Development Center (OARDC) and Cedar Lane Farms (CLF) believe in the technology and are ready to fund the additional costs to the project at a share in compliance with the 50% funding requirement as set forth in the existing OCDO grant agreement. The U.S. Department of Energy will not be participating in the added cost sharing due to recent funding cutbacks, the cost share will be provided by the industrial members of the team only. The project team is asking for an increase in funds from the OCDO of **$72,650**, bringing the total grant request to **$410,798**. The project team will contribute a total of **$414,524**.

Based on the successes of the AFBC demonstration to date, the Will-Burt Company (Will-Burt) has made a decision to increase its project cost share to rapidly promote the commercialization of the AFBC. Included in the proposed extension will be a detail design and cost estimate for an economically sized commercial (10 MM Btu/hr) AFBC.

The scope of work proposed to be completed consists of certain process modifications to make the system completely operable, parametric testing of the AFBC and reporting, and design and costing of a full scale commercial size AFBC for use in commercialization of the technology.

7.1 Process Modifications

Based on the operations to date there are still three areas of the AFBC need to be modified; the induced draft capacity needs to be increased, a method for removing ash/sorbent from the hot water heater fire box needs to be installed and a better method needs to be incorporated for ash removal and disposal from the bag house. These process modifications are described in some detail as follows.

7.1.2 Induced Draft Fan

The AFBC operation is currently limited by the flow rate capacity of the induced draft (ID) fan. To maintain a negative draft on the system it was necessary to limit the total mass flow of air and recycled flue gas through the combustor. The current system is using the same ID fan that was used on the pilot project that was designed for a coal feed rate input of 1.5 MM Btu/hr.

The system is now capable of firing 2.25 MM Btu/hr of coal, but at such a rate, when the bag house pressure drop increases above 4" water column drop (its design value), at times the AFBC will go slightly positive in pressure due to the limited ID fan capacity. It is proposed to use the low cost option of replacing the present ID fan wheel with a larger wheel to increase fan capacity and still be within the required motor size.

7.1.3 Boiler Ash Removal

During engineering it was known that if a heat exchanger with horizontal tube passes was selected for the system that 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 heating boiler was the least cost, and with the addition of automatic sootblowers, it appeared that the particulate problem would be minor. Further, the Will-Burt Company who is marketing the combustor recommended the horizontal boiler be used due to the potential it would add to the retro-fit market. Because of these considerations it was decided to use a conventional fire-box design similar to the existing coal stoker fired unit at CLF.

During the AFBC operation in the spring of this year, it became evident that sorbent and ash were accumulating in the fire box of the hot water heater. The ash level increased in the fire box and eventually solids were carried over to the second pass tubes. The ash then began to settle in the transition box between the second and third pass tubes where the sootblowers are located. Eventually the lower row of tubes became completely blocked with loose ash and sorbent. With the current system, it is very difficult to remove the ash from the bottom of the boiler due to the length of time needed to cool the fire box down from an operating temperature of 1500°+F to where the ash can be handled. Also, the only access to the fire box is through a 16" manhole at the back end of the boiler.

EER proposes to correct this problem by installing an eductor through the water wall in the rear lower corner of the firebox. This eductor will be insulated to protect it from the high fire box temperatures, and will be run either continuously or intermittently to remove excessive buildup of ash. The ash/sorbent will be educted to the bag house for collection and disposal. The addition of this eductor system will also provide the information required to evaluate the system for use on future retrofit applications. Will-Burt anticipates that one of the target markets for the combustor will be to retrofit existing boilers now using gas, oil, or older coal burning equipment.

7.1.4 Dust Collector Ash Disposal

The dust collector is currently equipped with a 55 gallon drum for ash removal. This method of ash handling is very difficult because of the weight of the drum when it is full. It is very difficult for one person to safely handle a drum containing an accumulation of 4-6 hours of ash and sorbent. It is proposed to provide an attachment that can be placed on CLF's existing forklift that can be used to remove and dump the drum. Some minor structural member modifications will need to be completed on the bag house to allow fork lift access to the drum.

7.2 Long Term Testing

The operational time for the AFBC to date has been limited due to the seasonal warm weather conditions occurring within two to three months after startup of the unit. The heating season ended June 1, 1995. The system will be started up after the boiler ash removal system is installed. Preliminary data taken during the limited run time was encouraging, with sulfur dioxide capture results better and NOx emissions lower than those seen during the pilot project. A complete set of parametric test runs still need to be completed to adequately assess the performance of the AFBC. Incorporated into this AFBC for testing purposes only, was the ability to stage the fluid bed combustion air. Staged combustion will be tested to determine its effectiveness for reducing NOx emissions. The test work proposed includes the testing phase scope of work as set forth in the grant agreement plus the staged combustion testing.

7.3 Commercial Unit Design

The AFBC installed at Cedar Lane Farms is a prototype model. It was not sized to be economical for sale to the small industrial user market, but was large enough to demonstrate the technology. The next step toward commercialization is the design and testing of a larger pre-production AFBC which will be an economical size that can be competitively marketed. Will-Burt determined that the pre-production AFBC system should be designed to fire approximately 10 MM Btu/hr of coal. The combustor will be square (6' x 6' ID), rather than round, making it more amenable for Will-Burt to manufacture.

The new boiler/hot water heater, unlike the CLF unit will have vertical tube gas passes rather than horizontal tube passes. This feature will preclude ash/calcium solids buildup in the heat exchanger tubes. Further, sorbent re-injection will occur from a hopper under the first downward pass of the heat exchanger. With this system, more sorbent will be captured and re-injected, than that for the CLF system. Therefore there is the potential of further reducing the Ca/S ratio required to lower SO_2 emissions down to the 1.2 lb/MM Btu level. Also, with this type of heat exchanger, having a vertical down pass followed by a vertical up pass, all of the flyash and sorbent leaving the combustor will either be recycled if the particles are large, or will be carried with the gas to the downstream baghouse. The new heat exchanger configuration will also allow for a more compact and energy efficient (less heat loss) design. Designed properly, it is believed that the need for soot-blowing can be eliminated. This feature will reduce auxiliary equipment cost and reduce operating costs slightly.

The design to be completed by EER will consist of completion of the following:

Mass and Energy Balances
Process Flow Diagram
Piping and Instrument Diagram
AFBC System Isometric Drawings
Equipment List
Instrument List
Single Line Electrical Diagram
Capital Cost Estimate

Will-Burt will use the detail design and cost estimate developed by EER to develop definitive manufacturing costs for the system. Following the design and evaluation effort, a new host site will be sought for the demonstration of the improved technology at the pre-production scale. Following successful installation and testing of the pre-production model, Will-Burt will be prepared to market the commercial AFBC to small scale industrial markets in Ohio and throughout the world.