Chap 4
Ref 7

E/ET/12307-1669
(DE85001963)
Category UC-90e

Reference 15

DESIGN, CONSTRUCTION, OPERATION, AND EVALUATION OF A PROTOTYPE CULM COMBUSTION BOILER/HEATER UNIT

By
J. D'Aciermo
H. Richards
F. Spindler

October 1983

Work Performed Under Contract No.:AC21-78ET12307

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26505

By
Shamokin Area Industrial Corporation
Shamokin, Pennsylvania 17866

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1.0 SUMMARY

A process for utilizing anthracite culm in a fluidized bed combustion system was demonstrated by the design and construction of a prototype steam plant at Shamokin, Pa., and operation of the plant for parametric tests and a nine month extended durability test. The parametric tests evaluated turndown capability of the plant and established turndown techniques to be used to achieve best performance. Throughout the test program the fluidized bed boiler durability was excellent, showing very high resistence to corrosion and erosion.

A series of 39 parametric tests was performed in order to demonstrate turndown capabilities of the atmospheric fluidized bed boiler burning anthracite culm. Four tests were performed with bituminous coal waste (called gob) which contains 4.8-5.5% sulfur. Heating value of both fuels is approximately 3000 Btu/lb and ash content is approximately 70%. Combustion efficiency, boiler efficiency, and emissions of NO_x and SO_2 were also determined for the tests, which were conducted at the following conditions:

Zones Fluidized	1, 2 and 3
Bed Temperature	1432-1677°F
Bed Depth	36-61 inches
Superficial Velocity	3.5-5.3 ft/sec

In addition, particle size distribution for the culm feed varied considerably for the tests because changes in culm screen sizes were made between tests.

Test results demonstrate a 4.1/1.0 steam turndown capability and a range of boiler efficiency between 54.1% and 82.0%, without air preheater and ash cooler credits. Boiler efficiency is a linear function of combustion efficiency.

Analysis of test data shows that combustion efficiency is directly related to temperature of the fluidized bed. Results show that combustion efficiency of 95% and above is achieved at 1650°F bed temperature and higher. Combustion efficiency is also related to the level of steam production at bed temperature below 1600°F. In-bed injection of primary cyclone tailings results in 0.6-2.0% increase in combustion efficiency for gob fuel. In-bed injection of recycle solids does not have a measurable effect on combustion efficiency for culm fuel.

All tests with culm fuel were performed with limestone containing 65% $CaCO_3$. Sulfur removal is generally greater than 90% at Ca/S feed ratios of 2.6 and higher. The level of emissions in the boiler flue gas is low: 0.27-0.90 lb SO_2/MM Btu, 0.02-0.50 lb NO_x/MM Btu, and less than 0.1 lb CO/MM Btu.

Gob fuel has 4-5 times the amount of sulfur present in high sulfur bituminous coal on a unit energy basis. Because of the higher concentrations of SO_2 present, sulfur capture for gob fuel is higher than for culm fuel at a given ratio of Ca/S in the feed. Emissions of SO_2 were measured at 1.18 lb SO_2/MM Btu fuel input using limestone containing 80% $CaCO_3$. For this test a sulfur capture of 98.5% was demonstrated at a 2.7 Ca/S molar feed ratio. Emissions of CO for gob fuel are 0.17-0.28 lb CO/MM Btu fuel input.

The results of the extended durability test period are presented. In-bed and water wall tubes which are oriented essentially in a vertical direction (i.e. parallel to the gas flow) as well as the convective bank boiler tubes exhibited excellent corrosion and erosion resistance and had no malfunctioning during the 10,000 hours total test period. Component reliability was generally good but relatively minor problems in the area of I.D. fan erosion, exhaust dust collector bag seal leakage, ash transport pipe elbow wear and ash cooler cell (#1) defluidization did occur.

A problem of crushing culm at a sufficient rate to maintain 3 zone steam production was encountered especially during cold and wet weather periods since an uncovered stock pile is used. These items would require relatively minor cost and effort to resolve.

Analysis of the operating costs for this small plant indicates that the break-even condition at full load is at about $4.60 per 1000 PPH steam revenue.

2.0 OVERVIEW

2.1 Introduction

Mining of over five billion tons of anthracite coal for the last 150 years in Pennsylvania has deposited some 900 million yards of anthracite refuse above ground. Anthracite refuse is made up of breaker refuse (culm), silt, mine refuse and tunnel rock. The culm contains 20-30% coal and is, therefore, a low quality fuel which could be a valuable energy resource if an economical method of combustion were available in the vicinity. Burning of the culm in a fluidized bed combustor boiler is considered to be a feasible way of utilizing this fuel in an environmentally acceptable manner to produce low cost steam for local industry.

Fluidized bed technology has been used commercially in the fields of mining and metallurgy since the 1940's and more recently in chemical processing, heat-treating, and combustion systems. The fluidized bed combustor (FBC) is essentially a furnace which can burn a variety of fuels including coal. It consists of a vessel containing a bed of active particles such as coal, and inert particles such as coal ash, rock, and limestone. When combustion air is blown into the bottom of the bed through a grate-like distributor, the particles are lifted and suspended by the air. The result is a homogenous, turbulent motion of particles and gas which in appearance resembles a boiling liquid. Fluid bed combustion of the coal is very attractive from the standpoint of both combustion efficiency and heating surfaces immersed in the bed. The addition of a sulfur retaining sorbent, such as limestone, makes it possible to limit the sulfur oxide release to the atmosphere within environmentally acceptable levels.

At any given time, the solid material in the FBC contains only one to two percent combustible material, the balance being inert solids. Because of this, the FBC can burn materials of very low heating value such as anthracite culm.

In addition to fuel flexibility, the ability to control temperatures to capture sulfur within the bed and to provide lower emission of nitrogen oxides are major advantages of the FBC over other more conventional combustion systems.

Experimental combustion tests on a wide variety of anthracite culm samples had been successfully completed on a bench scale FBC at Morgantown Energy Technology Center (METC) of the U. S. Department of Energy (DOE) (Reference 1). These results led to the involvement of DOE in a program to stimulate and advance the utilization of the anthracite culm combustion process for steam generation/process heat application and to demonstrate the commercial viability of anthracite culm fueled, fluidized bed combustor/steam boilers.

Toward this goal an anthracite-culm-fueled fluidized bed boiler to produce 23,400 pounds per hour of steam was designed, constructed and tested, under the sponsorship of the DOE. The program was initiated in September, 1978 with the Shamokin Area Industrial Corporation (SAIC), a non-profit organization dedicated to economic development of the region, as prime contractor under a cost-sharing contract. The cost share by SAIC and others in the private sector was in the form of culm contribution, manpower services, and revenues from steam supply.

The program consisted of three phases:

1. AFB laboratory testing and plant design
2. Plant construction
3. Test evaluation and operation

The plant's final design was completed in July 1980 and construction was started in September of 1980 and completed in August, 1981. Following a check-out and commissioning period of 2 months plant performance and durability testing was conducted through April 1983 with over 10,000 hours of operation successfully completed.Some of the steam generated during plant operation was purchased by an industrial user - Cellu Products, a manufacturer of paper products located adjacent to the boiler plant. The balance of the steam produced was vented to the atmosphere.

The Project Team supporting SAIC included Curtiss-Wright Corporation, the overall program manager responsible for technical direction and management of the design, construction and operation activities; Dorr-Oliver, Inc. designed the process equipment and E. Keeler Company fabricated the fluidized bed boiler; Stone & Webster Engineering Corporation designed the fuel preparation, water treatment systems,foundations and structure as well as the overall plant integration. Curtiss-Wright also was responsible for the plant instrumentation and automated control system design, procurement of all materials and services, construction management and test supervision.

This report contains a description of the plant design, construction and operation activities including results of the performance tests and plant operating economics.

2.2 Objectives

The objectives of this program were to design, construct and operate a boiler utilizing anthracite culm in a fluidized bed combustion system for the generation of steam for industrial use.

The detailed specific objectives of this program included:

1. Establish a process for utilizing anthracite culm in a fluidized bed combustion system for steam generation.
2. Design and construct a prototype steam plant incorporating the above process.
3. Operate the plant for a sustained period to demonstrate:
   - Process Feasibility
   - Functional Reliability
   - Economical Operation
   - Pollution Control
4. Provide background and scaling data applicable to larger steam generation and heat process systems.

2.3 Conclusions

1. Shamokin AFB boiler turndown capability demonstrated by parametric testing, 4.1/1, is much higher than the design condition, 2.5/1; furthermore, an empirical model for this plant predicts even greater steam turndown can be achieved with the present boiler system.
2. Boiler efficiency, between 54.1% and 82.0%, is directly related to combustion efficiency. Boiler system efficiency would be greater if air preheater and ash cooler heat credits were included.
3. Combustion efficiency is a linear function of the fluidized bed temperature. Highest combustion efficiency, 90-95%, occurs at 1650°F and higher. At bed temperatures below 1600°F combustion efficiency is dependent upon steam production level.
4. Culm combustion efficiency for the Shamokin boiler is lower than the 95 - 99% achieved in combustion tests in the Keeler/Dorr-Oliver 12in. diameter fluidized bed. This difference is due to lower freeboard temperature in the Shamokin boiler compared to the 12in. test facility.
5. Sulfur capture of 90% or better at a Ca/S feed ratio of 2.6 or greater was demonstrated for the anthracite culm tested.
6. Higher sulfur capture is measured for gob compared to culm. Less than 1.2 lb SO_2/MM Btu fuel input (98.5% sulfur capture) is achieved at Ca/S molar feed ratio of 2.7/1.0 for gob fuel.
7. Emissions of NOx are generally below 0.5 lb NOx/MM Btu fuel input for culm.
8. Emissions of CO are less than 0.10 lb CO.MM Btu for culm and less than 0.3 lb CO/MM Btu for gob.

2.4 Recommendations

1. Continue to utilize the Shamokin AFBC boiler as a well instrumented R&D test facility for test evaluation of alternative coals, wastes and other waste fuels.
2. An extended test program for gob fuel is recommended to evaluate sulfur capture for a broad range of Ca/S feed ratios and for other types of limestone. The effect of bed temperature on both sulfur capture and gob combustion efficiency must also be established in order to fully evaluate the economics of gob fuel combustion in a fluidized bed boiler.
3. Modify the fuel feed system to evaluate the effects of in-bed injection on combustion and emission characteristics.
4. Modify the culm storage system to include a covered stock pile area to keep up with the prepared culm requirements for maximum (3 zone) steam production during severe weather conditions.
5. Modify the ash cooler to improve performance by preventing large particle segregation in the first zone.
6. Increase the capacity of the baghouse filter in order to reduce pressure loss and maintenance when operating at conditions for maximum steam production.
7. Consider the incorporation of a back pressure or extraction steam turbine for electric power generation.

3.0 PLANT DESIGN

The prototype culm combustion boiler was intended to furnish 20,000 lb/hr. of 150 psig steam to an adjacent factory owned by Cellu Products Company and other industrial users. Before selecting key process design parameters, laboratory bench scale tests were conducted and various boiler system arrangements were studied. The purpose of the bench scale tests was to provide the process data needed to design the boiler system when using the low heating value culm fuel and representative locally obtained (Shamokin vicinity) limestone as sulfur sorbent. Data needed included: combustion efficiency, sorbent requirements, emissions and heat transfer.

The scaled test work, which is fully reported in Reference 2, was performed on a 12 inch diameter fluid bed combustor which contained water cooled tubes in the bed and freeboard for the heat transfer investigation. Results of the testing showed excellent combustion efficiency (95%) and sulfur capture (90%) could be expected with the indicated clum feed size (crushed to pass 4 Tyler Mesh) and limestone feed (mean diameter=270 microns). The tests covered a broad range of fluid bed operating conditions, including:

Bed Temperature	1450 - 1650°F
Fluidization Velocity (Space Rate)	3.5 - 6.8 Ft/Sec
Bed Depth	3 - 6 Ft.
Calcium to Sulfur Mole Ratio	3 - 9.8

which encompassed the anticipated range of prototype boiler conditions. Heat transfer coefficients for the bed and freeboard regions were obtained for a range of fluidization and gas velocities.

In addition to the bench scale tests, several boiler system arrangements were studied for minimum projected system cost over a range of steam production rates from 20,000 lb/hr. to 100,000 lb/hr. The study included circular cross-section and rectangular cross-section water wall boilers, with integrated freeboard convection bank or separate waste heat recovery section. The lowest cost configuration and the one chosen for the prototype culm combustion boiler design is the rectangular water wall FBC boiler with a freeboard convection bank as shown in Figure 3.1.

The design parameters for the FBC boiler at 20,000 lb./hr. steam delivery included:

Combustion Efficiency	95%
Sulfur Capture	88%
Excess Air	30%
Fluidization Velocity	5.3 fps
Combustion Temperature	1550°F
Culm Heating Value, HHV	4012 Btu/lb

The projected normal range of operating conditions for the FBC boiler included:

Fluidization Velocity	3.5 to 6 fps
Combustion Temperature	1450 to 1650°F
Excess Air	20 - 50%
Bed Height	3 - 6 ft.
Steam Turndown	2.5 to 1
Culm Feed Rate Turndown	5 to 1
Limestone Feed Rate Turndown	10 to 1

The process flow diagrams and general material and energy balances for the culm fired FBC boiler plant are shown in Figures 3.2 to 3.5 and Table 3.1. Following is a discussion of the overall plant design which is fully reported in References 3 and 4.

The prototype culm fired FBC boiler plant is located at the SAIC Industrial Park located in Paxinos, Pennsylvania. The plant site measures approximately 650 ft. by 75 ft. (1.1 acres) and includes space for a 20,000 ton culm storage pile. Several hundred feed northeast of the site is a temporary storage plot for up to 20,000 tons of ash.

3.1 Feed Preparation and Storage (Figure 3.2)

The anthracite culm fuel is delivered by truck and is deposited into an unloading area from which a front loader transfers the culm to a conveying system. This transports the culm to a crushing and classifying system where the oversized are sent back to the crusher. From this operation

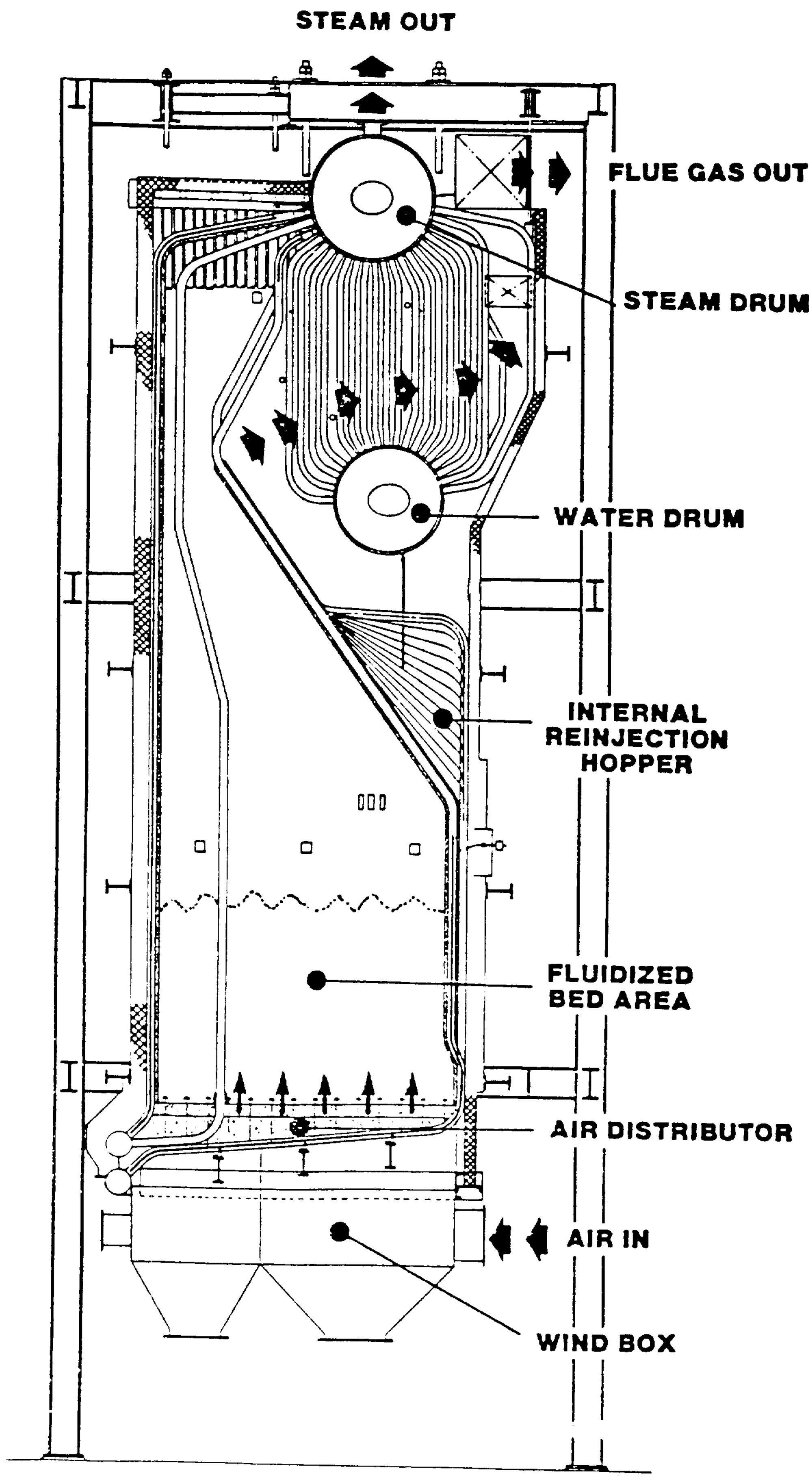
STEAM OUT
FLUE GAS OUT
STEAM DRUM
WATER DRUM
INTERNAL
REINJECTION
HOPPER
FLUIDIZED
BED AREA
AIR DISTRIBUTOR
AIR IN
WIND BOX

Figure 3.1

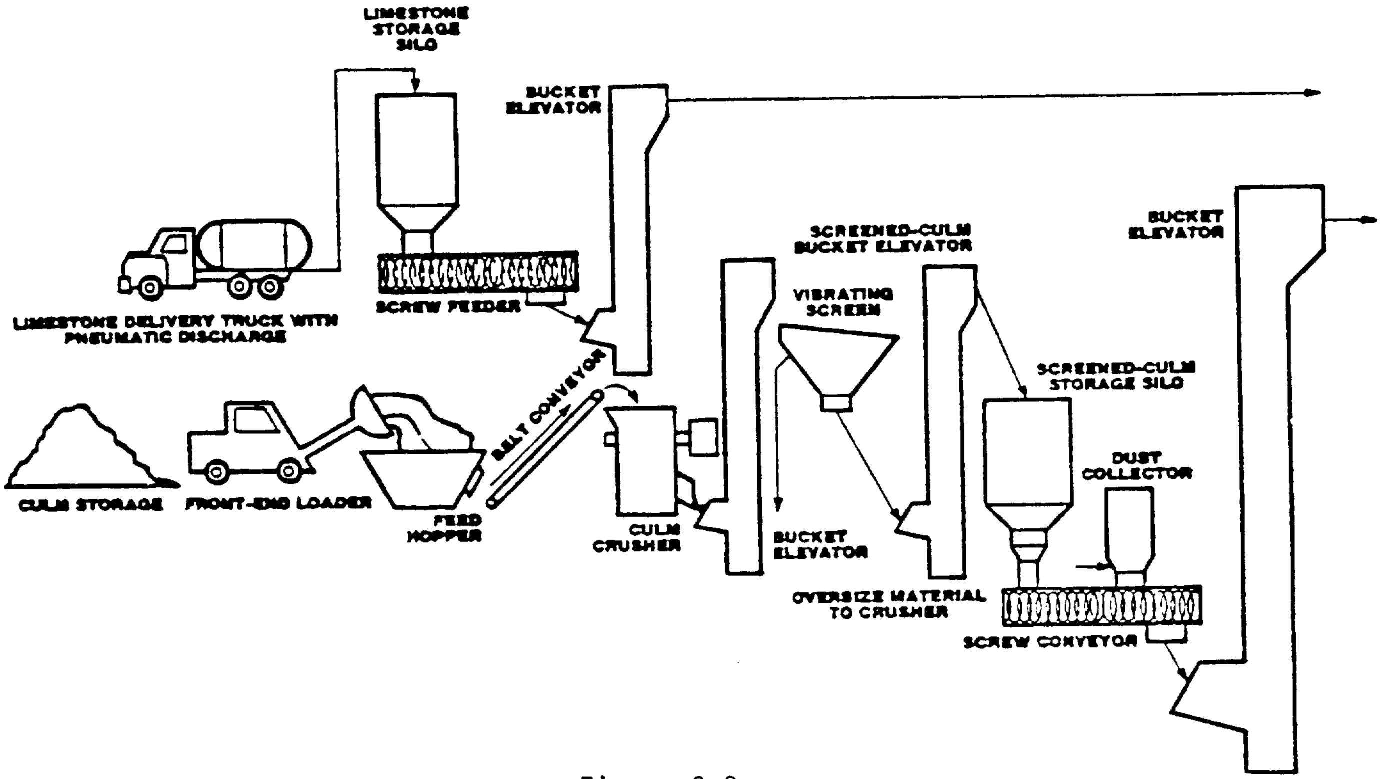

Figure 3.2

Feed Preparation and Storage

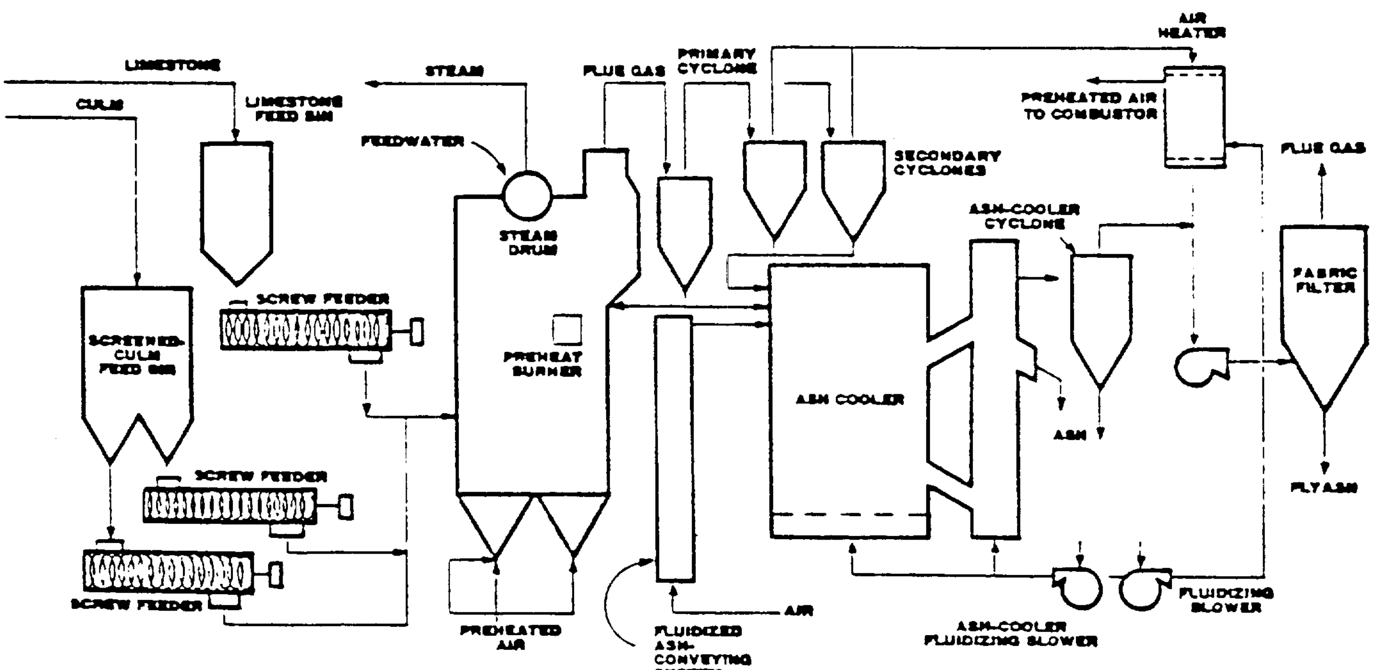

Figure 3.3

Boiler System

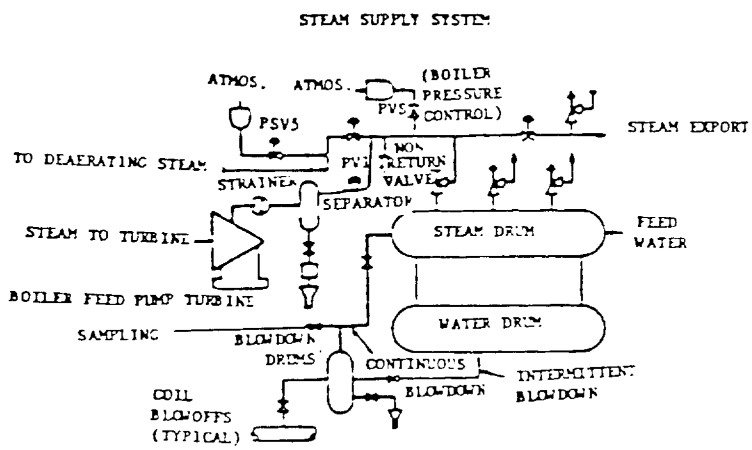

Figure 3.4

Steam Supply System

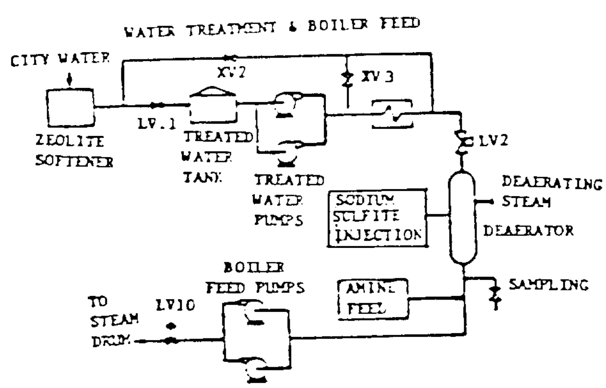

Figure 3.5

Water Treatment and Boiler Feed

TABLE 3.1

General Material Balance	
In	lbs/hr
Culm	8,188
Limestone	983
Air	46,880
Water	22,100
TOTAL	78,151
Out	
Ash	6,194
Gases	49,857
Steam	20,100
Blowdown	2,000
TOTAL	78,151

General Energy Balance	
Heat In	Btu/hr
Culm	32.85×10^6
Sulfation	0.33×10^6
TOTAL	33.18×10^6
Heat Out	
Gases	5.31×10^6
Steam	22.84×10^6
Blowdown	0.61×10^6
Calcination	0.50×10^6
Solids	0.31×10^6
Losses	3.61×10^6
TOTAL	33.18×10^6

Overall Efficiency -- 69.5%

the 1/4 x 0 culm is conveyed to the prepared culm silo. The prepared culm silo is sized to handle a 32 hour feed supply (for 4000 Btu/lb culm). From this hopper it is transported to the culm feed bin which holds approximately 4 hours of feed. The feed preparation and filling of the culm silo occurs during day shifts only.

Limestone is supplied to the combustor to capture the sulfur gases (sulfur dioxide) released from the combustion of the culm which then forms CaO and $CaSO_4$. These solid products end up mixed in the culm ash.

Sized limestone is delivered to the site via truck and pneumatically conveyed to a limestone storage silo. This silo stores approximately a week's supply of stone. From the silo, the material passes through a bucket elevator and then into the limestone fe-d hopper. This feed hopper is designed to hold a day's supply of material. The feed preparation and filling of the culm silo occurs during day shifts only.

3.2 Screw Feeders (Figure 3.2)

Both culm and limestone is fed to the boiler with screw feeders. Two feeders are used for the culm and one for the limestone.

Variable speed motor drives are used on each feeder to permit culm feed rate to follow steam demand and combustion temperature, and to allow limestone feed rate to vary with the SO_2 emission control feedback signal.

3.3 Fluidized Bed Boiler System

A fluidized bed boiler of water wall design with in-bed boiler tubes and a convection section for the generation of steam is used (Figure 3.3). The fluid bed cross sectional area is 100 feet^2.

This application calls for the delivery of 20,000 lb/hr of 150 psig saturated steam. The boiler is designed to generate approximately half this steam capacity with in-bed and water wall tubes. The other half of the steam is generated by recovering the heat from the combustion gases in a convection section. The steam generated is at 200 psig and saturated. The steam pressure is reduced before the steam is supplied to the user.

To aid in start-up and turndown, the air plenum chamber is divided into three zones, each with its own air supply. One zone convering 64% of the bed area does not contain in-bed tubes. This area is always fluidized when steam is being generated and is the first bed section to be fluidized during start-up. The other two bed sections split the remaining 36% of the bed equally. These each contain in-bed boiler tubes and can be defluidized during turndown conditions. The boiler also contains an internal convection bank dust hopper with a flapper valve for recycling collected dust.

An oil fired burner is also included to serve as a preheat burner. This burner brings the bed up to soft coal combustion temperature. Soft coal is fed to bring the bed up to culm combustion temperature.

3.4 Primary Cyclone

Included in the boiler system is a primary cyclone. The refractory lined cyclone is of conventional design. It serves as the primary combustion gas clean-up stage and to recycle the collected ash and unreacted particulates back to the combustor. This recycling permits a high combustion efficiency, limestone utilization, heat transfer, and good fluidization. There is a provision to purge off some of the cyclone catch instead of recycling 100% of it. This permits greater operating flexibility in the boiler system.

3.5 Secondary Cyclones

The dirty gases leaving the primary cyclone are further cleaned in twin cyclones. The dust collected here is discharged to the ash cooler. When the boiler is turned down, one cyclone is shut off to maintain a high cyclone efficiency in the other cyclone.

3.6 Ash Cooler

The ash cooler receives ash from the FBC boiler, the primary and secondary cyclones, and cools it to approximately 250°F. It consists of a fluidized bed containing in-bed cooling coils. The water in the cooling coils is boiler feed water. This system recovers some of the sensible heat from hot ash and transmits it to the boiler feed water. Over 1×10^6 Btu/hr are recovered here. The ash cooler has its own air supply system and cyclone. The ash is discharged through rotary valves to the ash air conveying system which transports the ash to the bottom ash bin.

3.7 Air Preheater

The combustion gases leaving the twin cyclones are still at 660°F. To improve the energy efficiency of the boiler system, more energy is extracted from these gases in an air preheater before they are vented to the baghouse. The hot combustion gases flow inside the tubes of an air to gas shell and tube preheater and exit at 350°F. On the shell side combustion air from the blower is heated to 425°F before entering the combustor.

3.8 I.D. Fan

An induced draft fan is located between the air preheater and bag filter. This fan is used to control the pressure above the fluidized bed at a slightly negative level (i.e. -1.0 inches water).

3.9 Bag Filter

A conventional pulse-jet bag filter system is used to provide the final removal of particulates from the combustion gases before they are vented to the atmosphere. This system is designed to meet the federal and local particulate emissions codes. An air-cloth ratio of 6:1 was used.

3.10 Steam/Water Circuit (Figures 3.4 and 3.5)

The design condition calls for 20,000 lb/hr of feed water to be vaporized as the exported steam. Besides this, approximately 10% more feed water is used which is lost in the blowdown, and steam released from the deaerator and blowdown drum.

City water is used as the boiler feed water. This water is softened with a zeolite system. The softened water is fed through the ash cooler cooling circuit where it is heated slightly and then passes through the deaerator operating at 5 psig. The oxygen is further scavenged in the deaerator by the addition of sodium sulfite. From the deaerator the feed water is pumped to the steam drum. A neutralizing amine treatment is used to further prevent chemical attack. Two boiler feed water pumps are used. One pump is electrically driven and the second is turbine driven. The turbine drive is used in the event of a power outage or as a backup for the electrically driven pump.

Water from the steam drum feeds the three steaming circuits of the boiler:

1. The water walls
2. The in-bed tubes
3. The convection section

This boiler has all natural circulation circuits.

The steam/water mixtures from the three circuits exhaust to the steam drum where the water and steam are separated. The drum is at 200 psig.

Some of the steam produced is used within the system for the deaerator and blowdown. The bulk of the steam, 20,000 lb/hr, is reduced in pressure to 150 psig and sent to the user.

3.11 Control System

To achieve safe, efficient, and reliable operation, the control system is designed as a hierarchy of three distinct systems: the digital control system, the analog control system, and the safety interlock system (Figure 3.6).

Control for efficient operation and minimum exhaust emissions is provided by the digital control system. When not using the digital system, this control refinement is not possible and the analog system is used to control the process within preset conditions. The safety interlock system provides safety backup to the analog system and the failsafe design of the controls and instrumentation provide a final safety backup.

The AFB boiler control strategy utilizes conventional boiler control techniques where possible, but, as shown in Figure 3.7 it differs in several important respects due to the unique characteristics of the fluidized bed and the culm fuel. Whereas, in a conventional boiler, the excess air is fairly constant, in the AFB boiler excess air varies between 10% and 60% as space rate (fluidization velocity) varies. Over-fuel constraints during normal operation are not as critical as those in a conventional boiler because the excess air at the minimum fluidization space rate provides a large margin of safety. Because of the variable heating value of the culm (3000-5000 Btu/lb.) fuel feed rate does not accurately reflect Btu input and therefore, cannot be used directly as an input in the combustion control.

Figure 3.8 illustrates the AFB boiler control strategy. The steam drum pressure control varies culm feed rate to meet steam demand by maintaining a steam drum pressure setpoint. In a declining load situation, as the culm feed is reduced the bed temperature declines. When bed temperature reaches its selected minimum value the temperature controller reduces space rate to hold constant temperature. At minimum space rate in a single zone bed the temperature controller achieves further reduction by lowering bed height while still maintaining constant bed temperature. In the three zone fluidized bed with shutdown capability for two of the zones the routine as shown in Figure 3.9 is used to achieve further turndown. The zone control shuts down a zone when minimum overall space rate is reached which automatically causes space rate and bed temperature to return approximately to their maximum values. Continued load reduction then repeats the procedure until the new minimum space rate, after which the second zone is shut down and the process again repeats with one zone in operation.

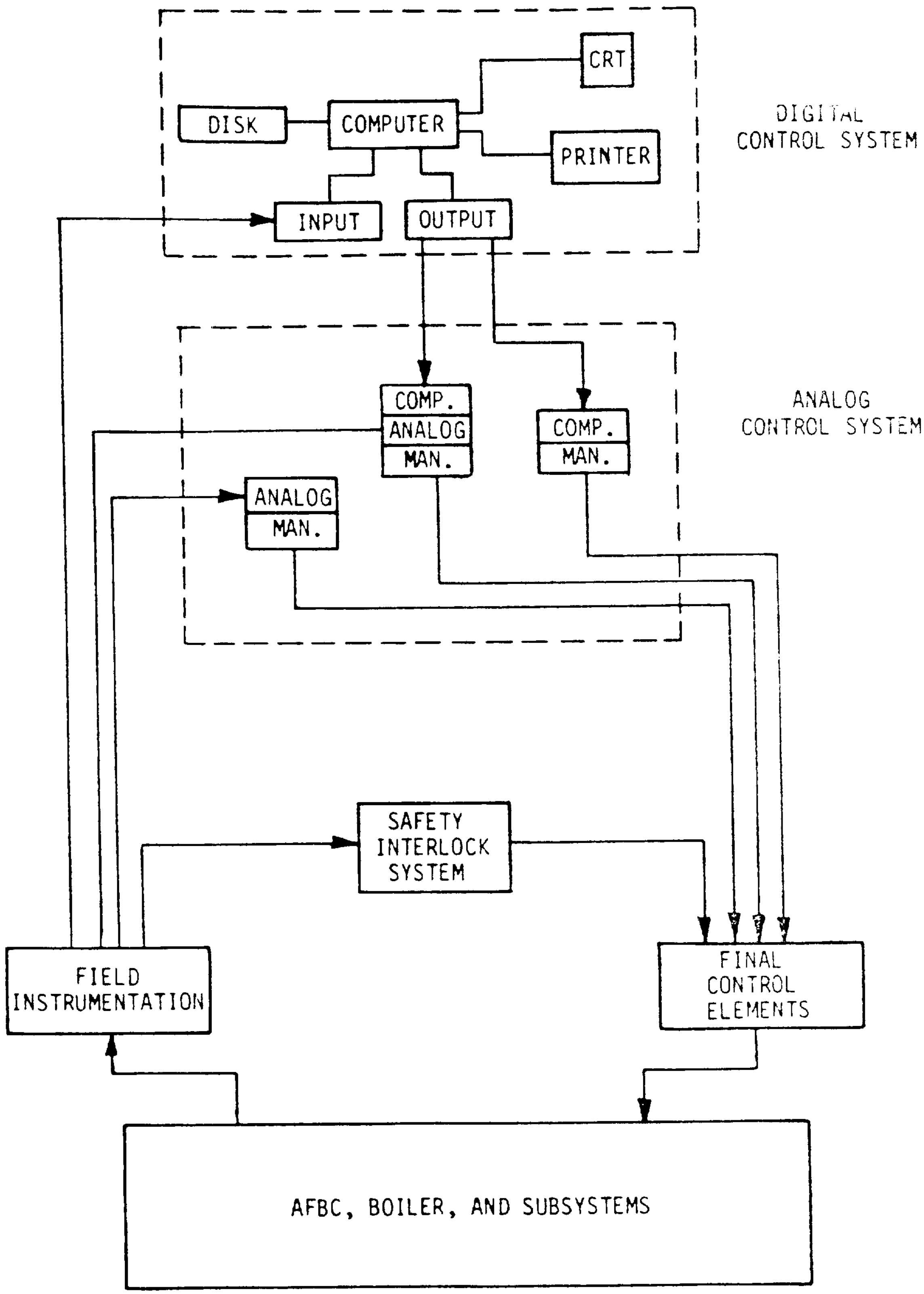

Figure 3.6 AFBB Process Control System

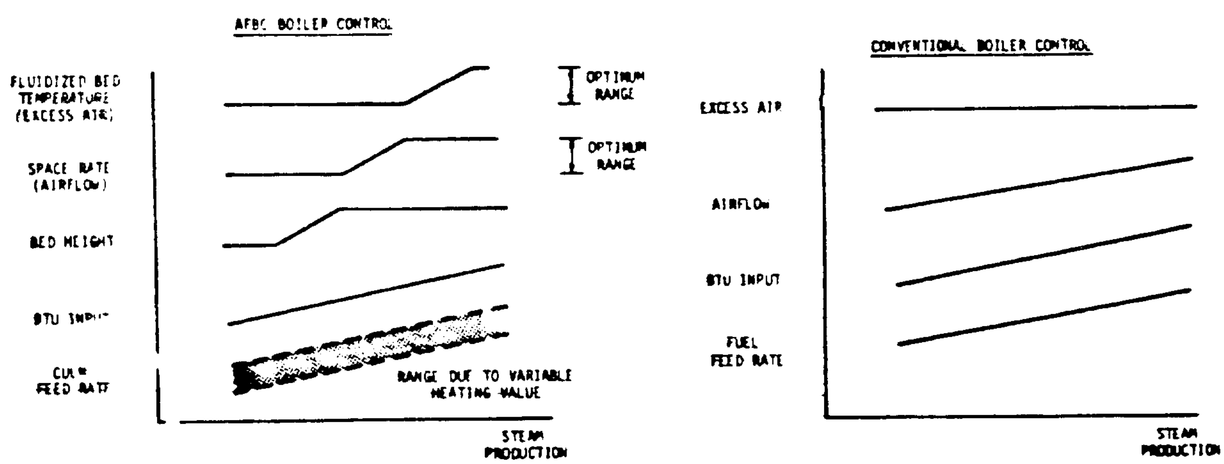

Figure 3.7 Comparison Between AFBB Control and Conventional Boiler Control

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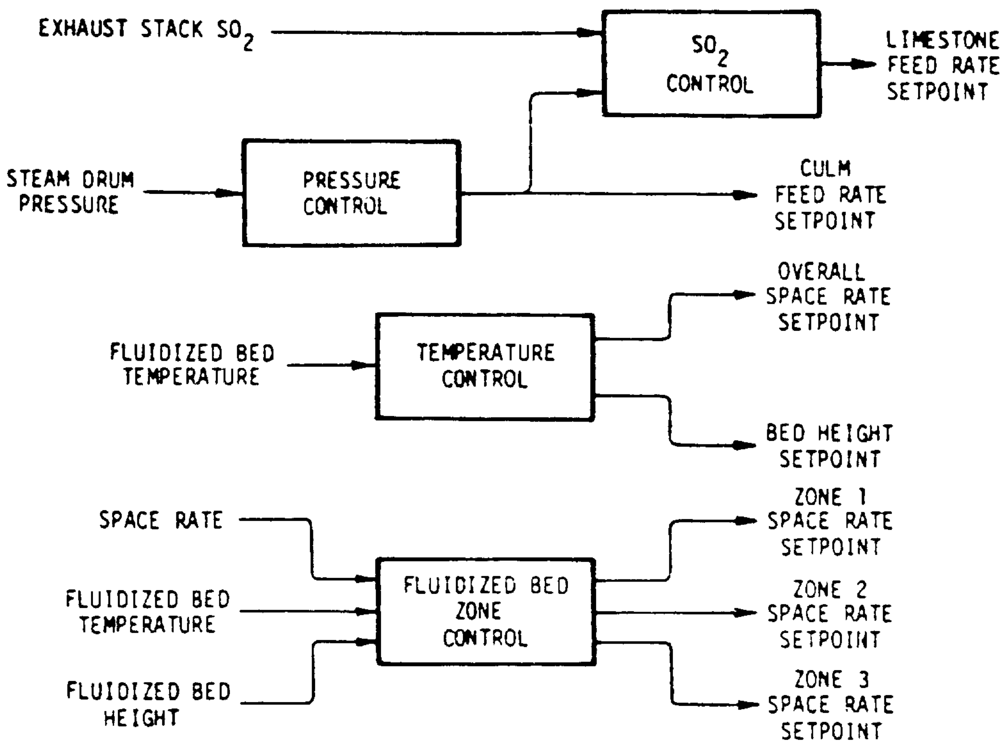


Figure 3.8 AFBB Control Strategy

It should be noted that the defined procedure was modified during the test program because it was found that large additions of low grade culm fuel when the bed was at minimum temperature caused severe quenching of the bed. Therefore, bed temperature was not allowed to reduce appreciably before initiating space rate reduction, and bed height reduction was used as the second power reduction step before shutdown of each bed. Final power turndown was then achieved by reduction of bed temperature.

For control of SO_2 emission, the limestone feed rate can be varied to maintain SO_2 concentration in the exhaust gas at an environmentally acceptable level. The limestone feed rate can be coarsely preset at a fixed ratio to culm feed rate. This ratio is based upon the average sulfur content of the culm (.6-7%S) and the sulfur caputre rate at an average bed temperature. To adjust the feed rate to correspond to actual conditions, it is fine-tuned by feedback from an SO_2 exhaust gas analysis system.

Fluidized bed height control is accomplished by varying ash removal rate, and balancing the rate of culm and limestone feed, to achieve the bed height setpoint established by the combustion control system.

3.12 Instrumentation

To implement the control strategy described, special applications of instrumentation and measurement are provided. The instrumentation is shown on the process and instrumentation diagrams presented in Reference 4 and listed in Table 3.2.

In-bed thermocouples measure bed temperature in eight locations (Figures 3.10). Annubars are used in air ducts to measure fluidizing air flow. This measured flow is corrected to bed temperature and pressure conditions and divided by the effective fluidized area to yield superficial velocity.

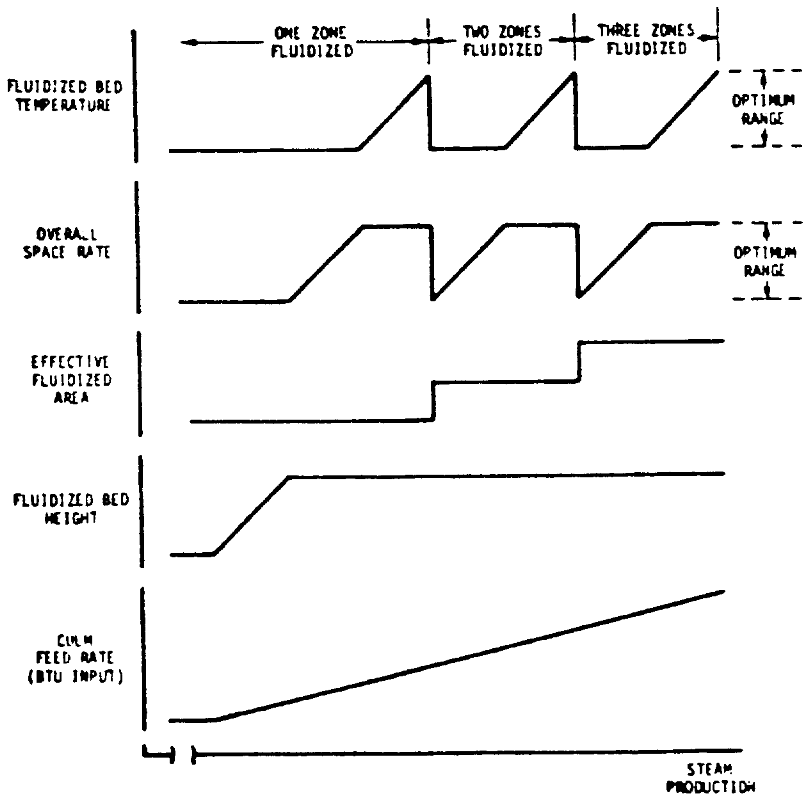


Figure 3.9 Operating Variables During Load-Following Turndown

TABLE 3.2

LIST OF INSTRUMENTATION

	TEMPERATURE - °F	DOE TAPE * HISTORICAL FILE NO.	REMARKS
TE - 1	Treated Water		
TE - 2	Ash Cooler Water In		
TE - 3	Ash Cooler Water Out		
TE - 4	Deaerator Water		
TE - 5	Boiler Feedwater	20	
TE - 6	Ambient	19	
TE -11	Windbox - Air Inlet	6	
TE -14	Combustor Bed-Zone 1-Lower	27	Below Cyclone Recycle Soids Return
TE -15	Combustor Bed-Zone 2-Lower	29	
TE -16	Combustor Bed-Zone 3-Lower	30	
TE -17	Combustor Bed-Zone 1-Lower	28	
TE -22	Ash Cooler Bed - Cell 1		
TE -23	Ash Cooler Bed - Cell 2		
TE -24	Ash Cooler Bed - Cell 3		
TE -25	Ash Cooler Exhaust Gas		
TE -26	Preheater - Flue Gas In		
TE -27	Preheater - Flue Gas Out		
TE -29A	Preheater - Combustion Air In		
TE -29B	Preheater - Combustion Air In		
TE -30	Preheater - Combustion Air Out		
TE -40	Baghouse - Flue Gas In	10,50	
TE -42	Combustor Bed - Zone 1 - Upper	32	
TE -43	Combustor Bed - Zone 1 - Upper	33	
TE -44	Combustor Bed - Zone 2 - Upper	34	
TE -45	Combustor Bed - Zone 3 - Upper	35	
TE -48	Convection Bank (Particulate Drop Out)	47	
TE -49	Combustor Freeboard	45	
TE -50	Convection Bank - Gas Out	7	
TE -51	Convection Bank - Gas In	46	
TE -57	Combustor Fluidizing Air Inlet		

TABLE 3.2 (Cont'd.)

	PRESSURES	UNITS	HISTORICAL FILE NO.
PT - 7	Export Steam	psig	25
PT - 8	Total Steam	psig	21
PT - 21	Windbox	inches of H_2O	43
PT - 37	Combustor Freeboard	inches of H_2O	44
PT - 43	Ash Coolèr Exhaust Gas	inches of H_2O	
PT - 52	Combustor Fluidizing Air Inlet	psig	11

	DIFFERENTIAL PRESSURES	UNITS	HISTORICAL FILE NO.
PDT - 24	Windbox/Combustor Bed Zone 1 Lower	inches of H_2O	37
PDT - 25	Windbox/Combustor Bed Zone 2 Lower	inches of H_2O	38
PDT - 26	Windbox/Combustor Bed Zone 3 Lower	inches of H_2O	39
PDT - 27	Combustor Bed Zone 1 -Upper/Lower	inches of H_2O	31
PDT - 28	Combustor Bed Zone 2 -Upper/Lower	inches of H_2O	41
PDT - 29	Combustor Zone 3 -Upper/Lower	inches of H_2O	42
PDT - 33	Combustor Bed Zone 1/Convection	inches of H_2O	36
PDT - 38	Primary Cyclone	inches of H_2O	48
PDT - 39	Secondary Cyclones	inches of H_2O	49
PDT - 41	Ash Cooler Windbox/Cell 2 Bed	inches of H_2O	55
PDT - 44	Preheater - Flue Gas	inches of H_2O	
PDT - 47	Ash Cooler Cell 2 Bed Upper/Lower	inches of H_2O	54

	FLOW RATE	UNITS	HISTORICAL FILE NO.
FT - 1	Ash Cooler Water	gpm	
FT - 2	Export Steam	pph	24
FT - 3	Total Steam	pph	22
FT - 4	Deaerator Steam	pph	23
FT - 5	Boiler Feedwater	gpm	26
FT - 6	Combustor Zone 1 Airflow	SCFM	3
FT - 7	Combustor Zone 2 Airflow	SCFM	4
FT - 8	Combustor Zone 3 Airflow	SCFM	5
FT - 11	Combustor Fluidizing Airflow	SCFM	
FT - 19	Ash Cooler Fluidizing Airflow	SCFM	

TABLE 3.2 (Cont'd.)

	LEVEL INDICATORS	UNITS	HISTORICAL FILE NO.
LT - 10	Steam Drum Water Level	Inches	
LT - 11	Combustor Bed Level	Inches	40
LT - 27	Steam Drum Water Level	Inches	56
	FEED BIN WEIGHTS	UNITS	HISTORICAL FILE NO.
WT - 1	Culm Feed Bin	LBS	8
WT - 2	Limestone Feed Bin	LBS	9
	CULM AND LIMESTONE SCREW FEEDERS	UNITS	HISTORICAL FILE NO.
ST - 1	Culm Screw Feeder - 1	RPM	51
ST - 2	Culm Screw Feeder - 2	RPM	52
ST - 3	Limestone Screw Feeder	RPM	53
	EXHAUST GAS ANALYSER	UNIT	HISTORICAL FILE NO.
AT - 1	Oxygen	%	12
AT - 2	Sulfur Dioxide	ppm	13
AT - 4-1	Carbon Monoxide-High Scale	%	14
AT - 4-2	Carbon Monoxide-Low Scale	ppm	15
AT - 5	Nitrogen Oxides	ppm	16
AT - 6	Carbon Dioxide	%	17
AY - 7	Stack Exit Opacity	%	18

* Several Files reserved for calculated data viz. space rate, feed rates, etc.

AFB PRESSURE INSTRUMENTATION

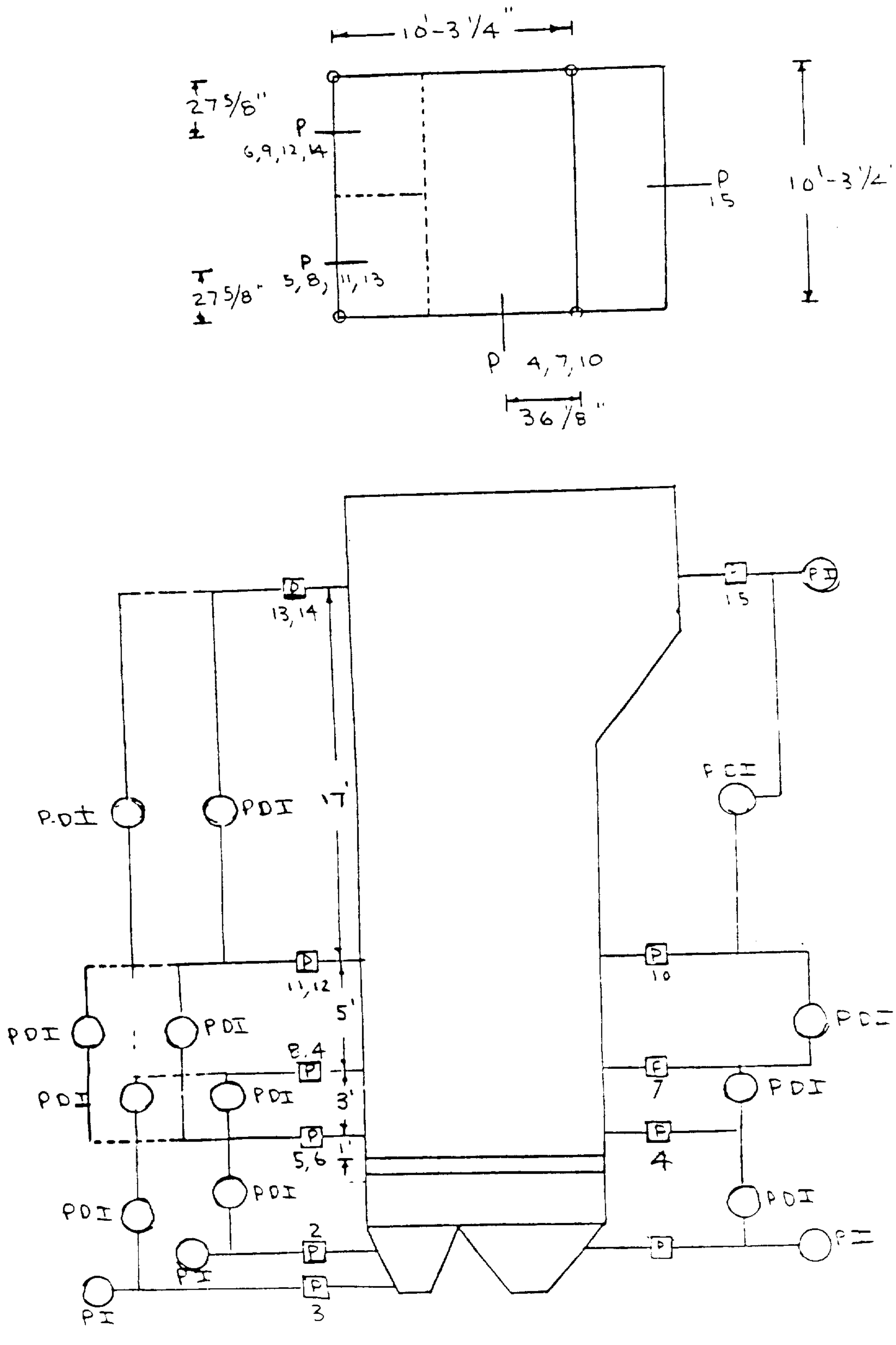


FIGURE 3.10

Differential pressure transmitters measure the pressure drop across the fluidized bed in several locations and are also used to calculate bed height. Pressure taps in the fluidized bed (Figure 3.11) and ductwork are continuously purged with clean air.

Weigh cells are used to measure culm and limestone feed bin weight. A digital system calculates feed rates as the rate of decrease of feed bin weights.

An exhaust gas analysis system continuously extracts exhaust gas through a shielded probe and heated sample line. Analyzers located in the control room continuously measure SO_2, NO_x, CO, CO_2 and O_2 concentration. The gas sample probe assembly is permanently mounted in the air preheater flue gas inlet duct. Solids are separated from the gas sample with a porous metal filter inside the sample probe assembly.

The gas analyzer system consists of vacuum pump, gas conditioner, condenser, and individual analyzers for O_2, CO_2, CO, SO_2 and NO_x:

Pulsed Fluorescent SO_2 Analyzer
Chemiluminescent NO_x Analyzer
Zirconium Cell for O_2
Infra-Red Analyzer for CO and CO_2

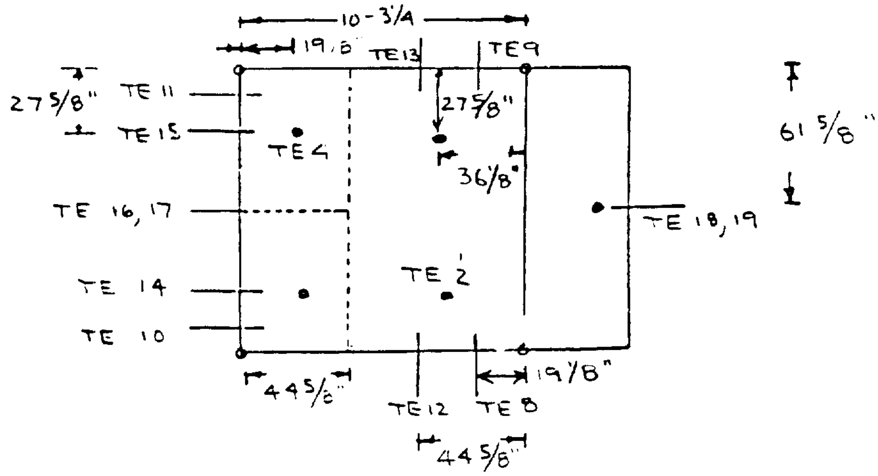
The vacuum pump continuously draws a gas sample from the sample probe assembly through approximately 160 ft. of 1/4" ID tygon tubing which is insulated and electrically heat traced to prevent condensation.

3.13 Data Acquisition

The process computer provides for on-line data acquisition. Up-to-date process data (displays), print-out of alarm messages and instrumentation fail and clear messages can be displayed by CRT and line printer. The computer can also provide periodic storage of historical data on disk for later transfer to magnetic tape.

Sixty-two (62) selected historical data variables and information (i.e., bed height, pressures, temperature, etc.) shown on Table 3.2 were programmed for storage as records along with the date and time on the computer disk as three separate files. File No. 1 is data that is stored every hour; File No. 2 is data that is stored every

AFB TEMPERATURE INSTRUMENTATION



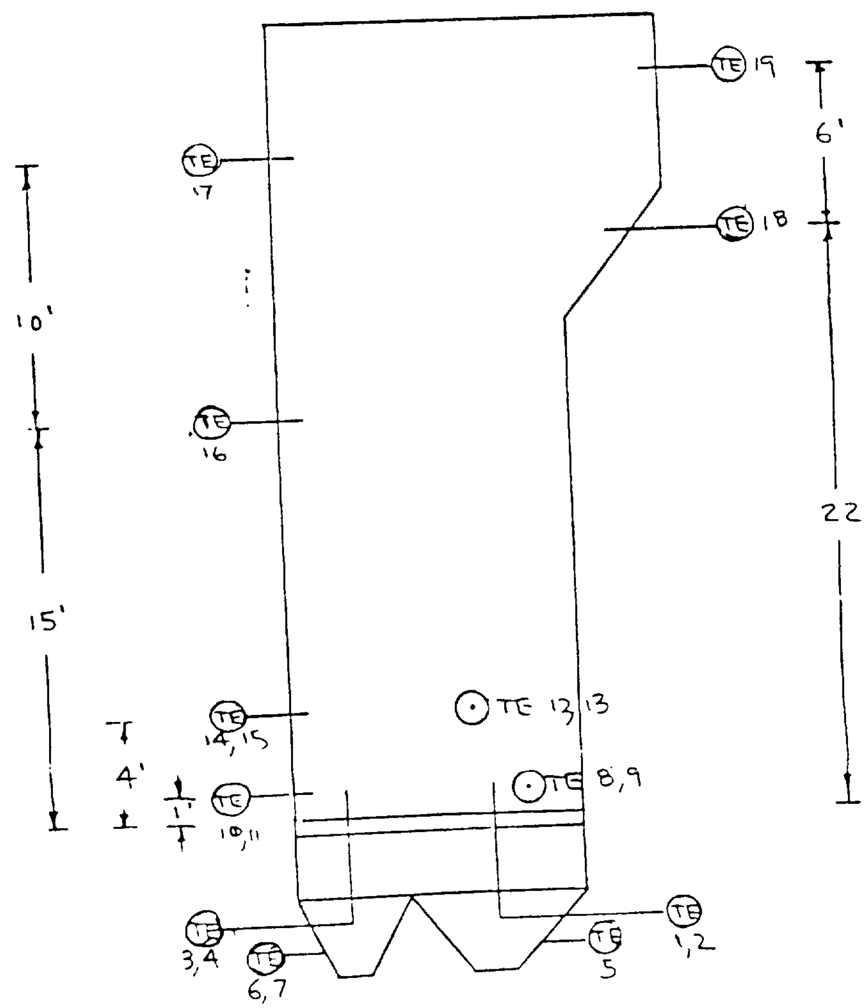


FIGURE 3.11

15 minutes and File No. 3 is data that is stored every (1) minute. The duration of resident time before the data is "over written" is forty-five (45) days for File No. 1; fifteen (15) days for File No. 2 and twenty-eight (28) hours for File No. 3.

4.0 PLANT CONSTRUCTION

Plant long lead construction was initiated in November 1979 with procurement of certified drawings for equipment and for installation of boiler foundations. Procurement of equipment was initiated in March 1980 with site erection beginning in September 1980. Construction management was under the direction of Curtiss-Wright Corporation with Stone and Webster Corporation providing support for the foundations; structural tower, and coal handling equipment. A General Contractor provided the construction services with the support of local subcontractors.

The majority of the equipment erection and boiler erection occurred during the winter of 1980-81.

A photograph of the boiler during erection is shown in Figure 4.1. Boiler hydrotest was completed by February 1981 and the plant construction was essentially complete by August 1981. Photographs of the completed plant are shown in Figures 4.2 through 4.4. A photograph of the control room is shown in Figure 4.5.

During the final month of construction, plant operating personnel were hired and training was initiated.

In-Process Construction of the Fluosolids Combustor With Integral Steam Drum - Front View

Figure 4.1

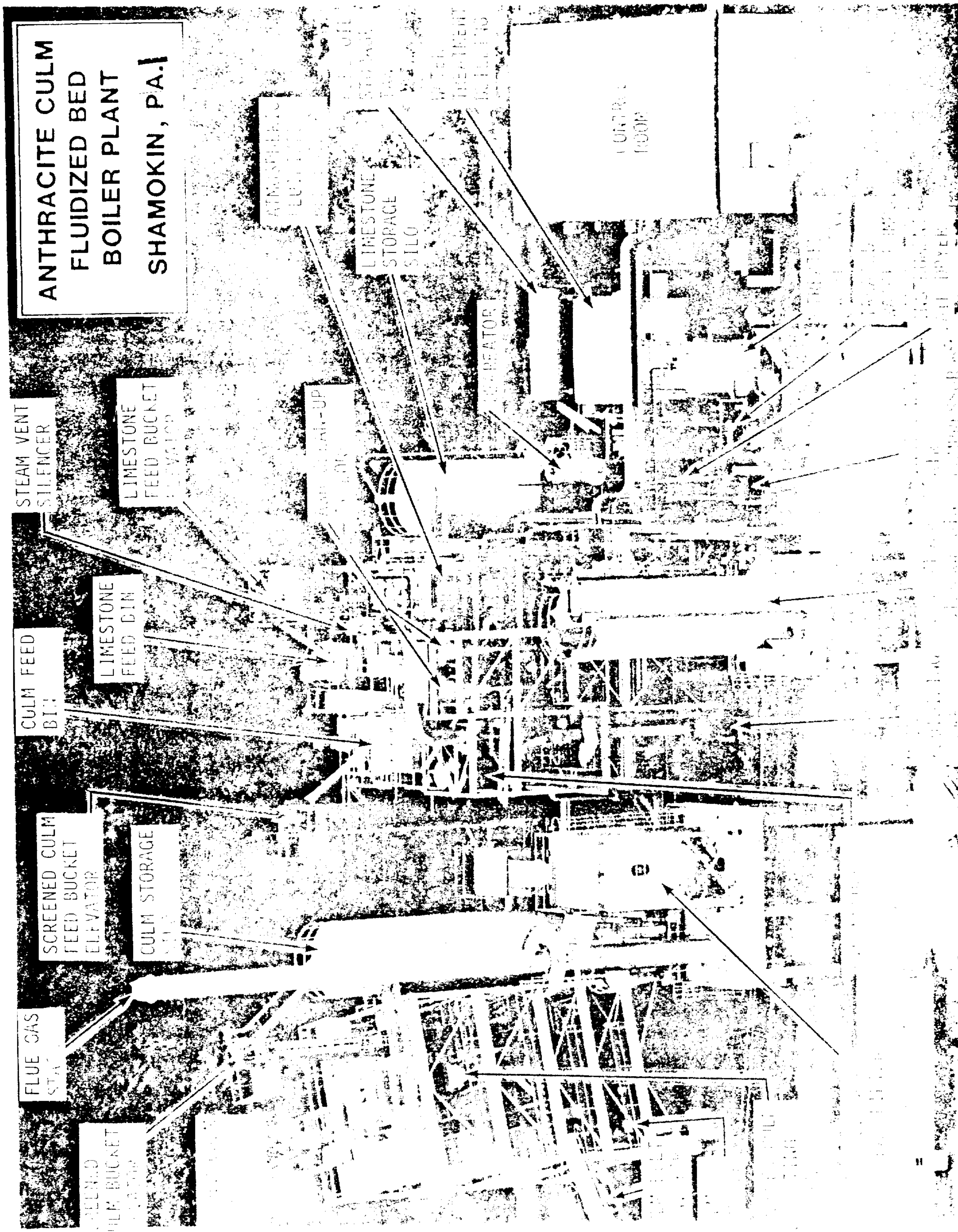

ANTHRACITE CULM
FLUIDIZED BED
BOILER PLANT
SHAMOKIN, PA.
STEAM VENT
SILENCER
LIMESTONE
FEED BUCKET
LIMESTONE
FEED BIN
SCREENED CULM
FEED BUCKET
ELEVATOR
CULM STORAGE
LIMESTONE
STORAGE
SILO

Figure 4.2

ATMOSPHERIC FLUIDIZED BED STEAM PLANT
ANTHRACITE CULM FIRED
SHAMOKIN, PA.

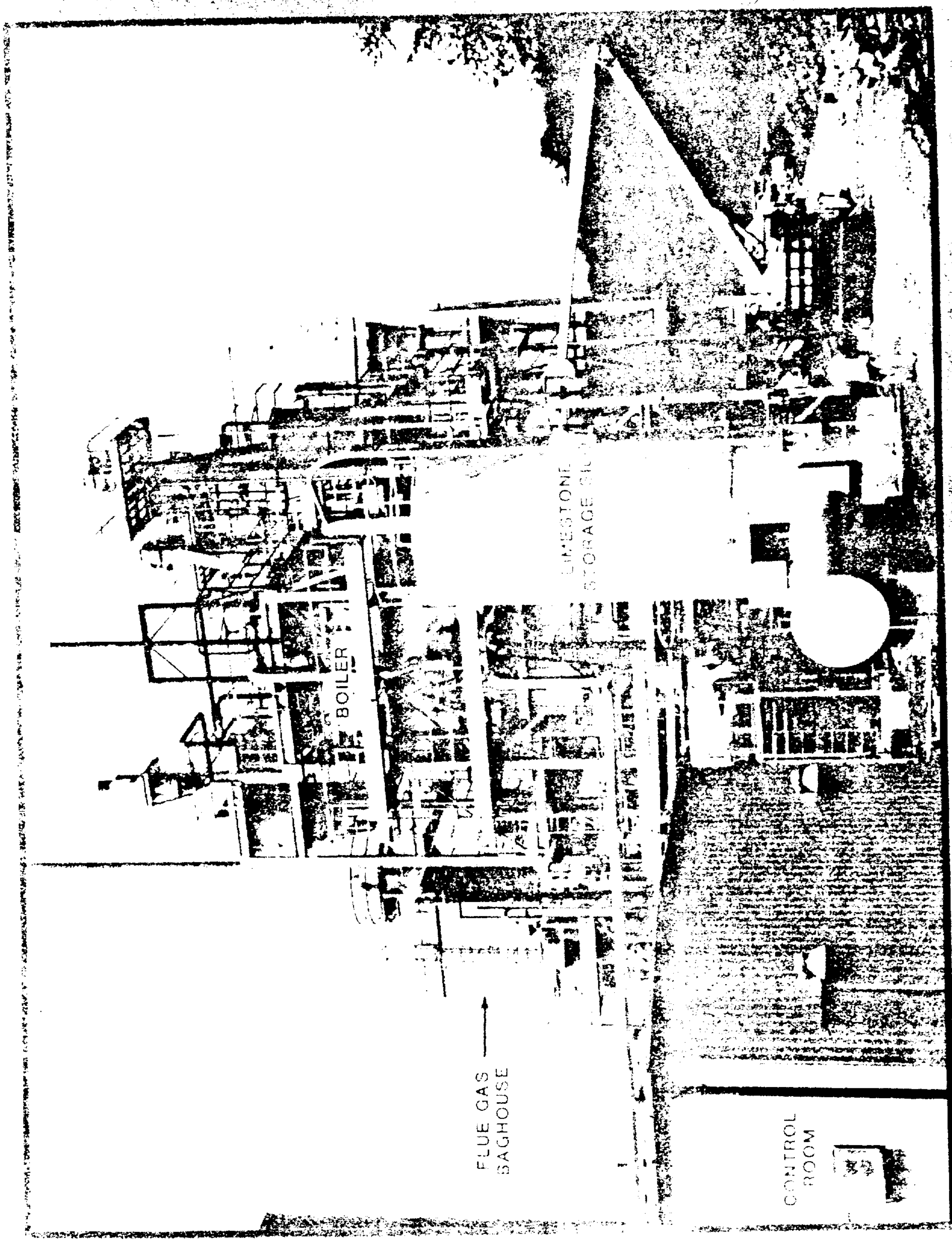


Figure 4.3

ATMOSPHERIC FLUIDIZED BED STEAM PLANT
ANTHRACITE CULM FIRED
SHAMOKIN, PA.

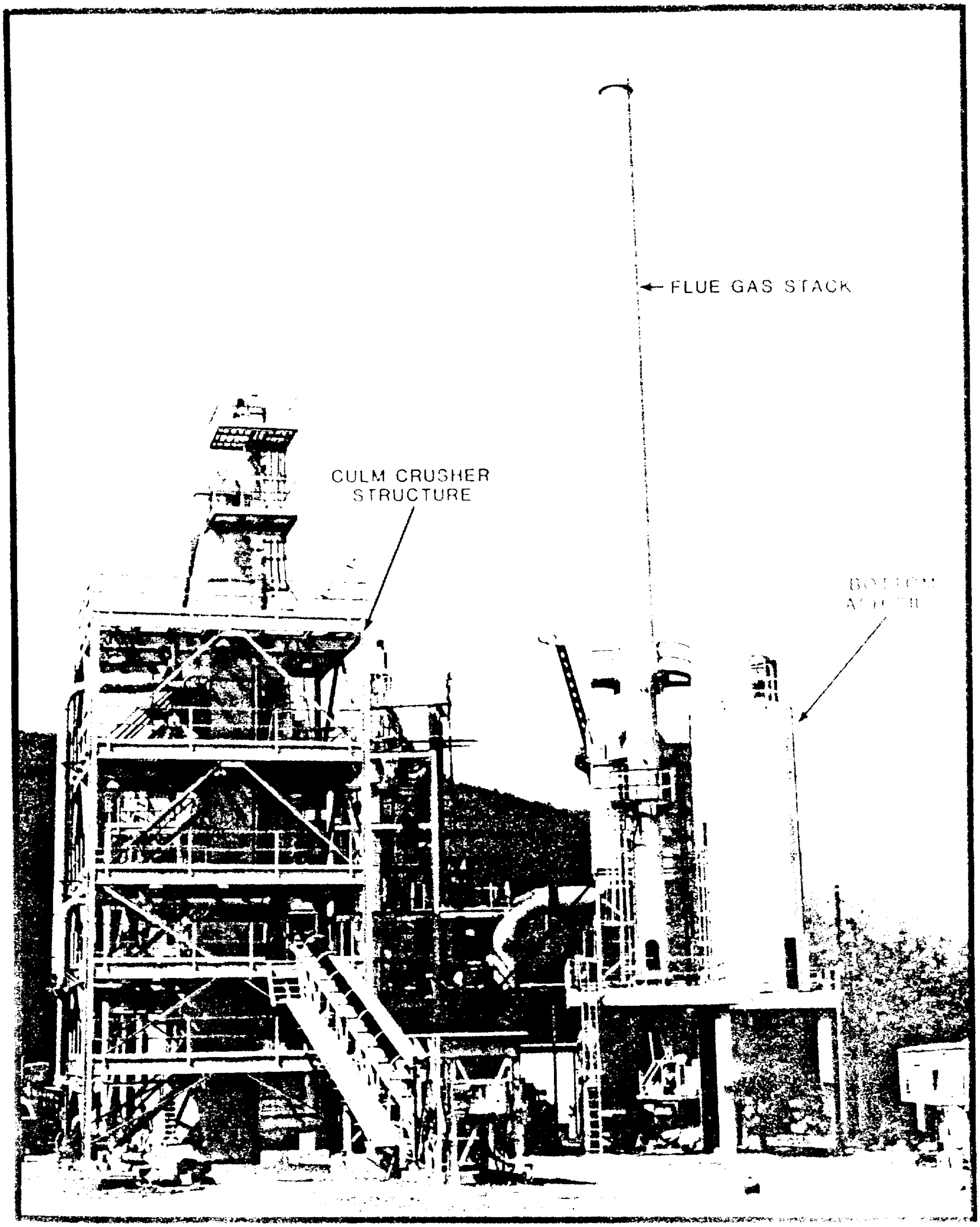


Figure 4.4

CONTROL ROOM FOR AFB BOILER PLANT

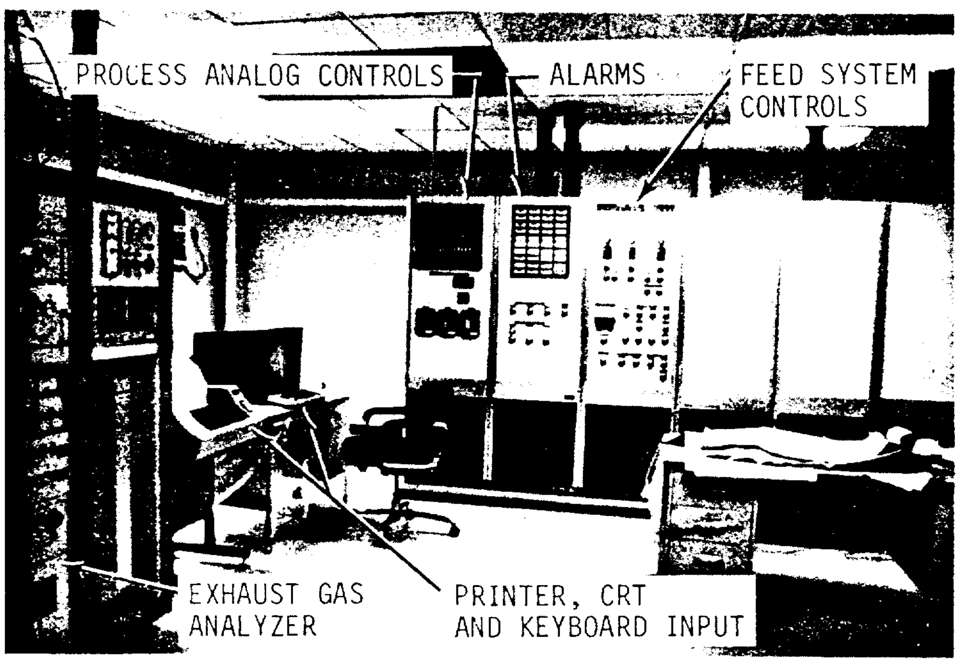


Figure 4.5

5.0 START-UP AND SHAKEDOWN

5.1 Equipment Shakedown

The purpose of the equipment shakedown was to ready the plant for the start-up and plant shakedown testing. Major rotating equipment of the plant was tested before the plant start-up. The operator training which was initiated during construction was reinforced by having the operators check out the operation of all the equipment.

The main and ash cooler fluidizing air blowers and ID Fan were started and run to establish operation within manufacturer specifications for vibration, motor amperage draw, surge, etc. and to exercise control valves and check-out associated alarms and interlocks.

The limestone screw feeder and anthracite culm screw feeders were started empty and were monitored for proper operation. All rotary valves were started, and monitored and operation verified.

5.2 Cold Flow Test, Boiler Boil Out and Refractory Cure

A cold flow test was conducted to check for air leaks throughout the system and measure constriction plate pressure differential in the combustor and ash cooler and also to air dry refractory lining. The combustor freeboard pressure was maintained in the range of 0 to -2 inches of water and the constriction plate pressure drops at various flows were measured and plotted. The pressure drops for various pieces of equipment were measured at different air flow rates. The purge air flows to various parts were checked.

Before the boiler was put into service for the first time, it was necessary to cure the refractories. These refractories were cured by first air drying and then gradually heating of the boiler by firing the preheat burner. At the same time, boil-out of the boiler was achieved.

The boil-out consists of removal of grease from the steam and water system by soda base solution. After boil-out and refractory cure, approximately 72 hours, the boiler was cooled, drained and flushed with clean water. A complete internal inspection was made and the system was then readied for initial start-up.

5.3 Plant Start-Up

Start-up of the boiler was initiated on 8/13/81 using limestone as starting bed material. During this initial start-up it was found that the bed temperature necessary to support culm combustion could not be reached using the oil fired start-up burner alone, so soft coal was added and a bed temperature to support culm combustion was obtained at 1450°F. After attaining culm combustion temperature, it was found that the bed temperature could not be maintained with culm only. A heat balance check showed higher than design heat extraction from bed wall tubes, and higher dust recirculation load with culm than anticipated.

The higher dust recirculation requires more bed heat input from fuel because the recirculated dust enters the bed at temperatures several hundred °F below bed temperature. To remedy this, castable insulation was installed over 21 ft^2 on each of the two side waterwalls. The insulating castable was added for the full width of Zone 1 up to a height of 3 feet. This castable addition brought the heat balance back within design limits and the boiler was then able to operate successfully on culm only.

5.4 Shakedown Tests

Following several minor plant adjustments described in the following paragraphs, the plant was run over a broad range of operating conditions as part of the general plant shakedown. The actual conditions which were observed are shown in Table 5.1. The general conclusion following these shakedown tests was that the plant was operating well for a prototype plant and no major changes were indicated before proceeding with the parametric performance tests.

The analysis of the culm used during the shakedown period (Table 5.2) showed that the HHV of the culm was considerably lower than the anticipated typical value (design case). Although detailed performance calculations were not intended based on the shakedown test data some observations were drawn.

The tests did demonstrate that the boiler could operate over the range of variables required for turndown. Bed temperature was varied from 1450°F to 1650°F, space rates were varied from 3.5 to 5.5 ft/sec, bed depth was varied from 3 to 5 feed and the fluidized zones were

TABLE 5.1

Shakedown Tests -- Operating Data

Test No.	1	2	3	4	5	6	7
Date	10/6	10/6	10/9	10/10	10/10	10/10	10/11
Time Start	14:00	21:00	16:45	01:00	12:00	23:30	17:00
Feed Screen Mesh	4	4	4	4	4	4	4
Zones Fluidized	1	1	1,2	1,2,3	1,2,3	1	1
Gross Steam, lb/hr	10,192	10,929	15,881	16,871	18,978	18,209	11,187
Wet Culm Feed, lb/hr	5,466	5,628	8,750	7,102	8,710	8,632	5,613
Limestone Feed, lb/hr	0	0	0	0	0	0	0
Primary Cyclone Recycle %	0	0	0	0	0	0	0
Avg. Bed Temp., °F	1,687	1,628	1,608	1,669	1,655	1,644	1,433
Avg. Bed Height, inches	40	48	53	48	57	56	47
Avg. Sp. Rate, ft/sec	3.5	3.5	3.7	3.75	3.72	5.4	4.85
Total Air Rate, scfm	3,169	3,132	4,206	5,236	5,248	4,841	4,859
Freeboard Temp., °F	1,120	1,138	1,185	1,243	1,290	1,315	1,116
Conv. Bank Inlet, °F	813	835	919	936	998	970	810
Conv. Bank Outlet, °F	484	490	533	538	551	552	510
Stack Oxygen, %	8.0	7.2	3.9	5.8	3.9	4.7	10.2

TABLE 5.2

Ultimate Analysis of Culm

Sample	9/3/81	9/30/81	Design Case
ULTIMATE ANALYSIS (% DRY BASIS)			
Carbon	20.04		27.02
Hydrogen	1.38		1.42
Nitrogen	0.50		0.66
Oxygen	3.34		3.48
Sulfur	0.72		0.57
Ash	72.18	71.08	66.85
Heating Value, HHV Btu/lb	3126	3513	4198

varied from 1 to 3.

A sample of bottom ash taken during this period contained only 0.4% unburned carbon, indicating good combustion efficiency. Boiler efficiencies were not determined because sampling procedures and laboratory analysis procedures had not been finalized nor were the tests run for long enough periods.

Sulfur capture was not demonstrated during these tests because the limestone feed bin was used to store soft coal so multiple start-ups could be facilitated. During later testing, the limestone feed bin was exhausted of soft coal and filled with limestone.

It was found that to operate at high capacity conditions with the low heating value high ash culm, the speed of the rotary valve discharging the primary cyclone collected solids to the ash cooler had to be increased; the fly ash baghouse pressure relief door needed better sealing to accommodate the increased pressure drop at higher capacity; and the capacity of the bottom ash bin vent had to be increased by installing longer filter bags. Full boiler capacity was limited by the culm preparation equipment since the screening operation of wet culm could not keep up with the culm feed rate requirements. The culm screening capacity appeared to be affected adversely by the raw culm moisture content. Therefore, the high space rate (5.5 ft/sec) and deep bed (5 feet) tests were made with only Zone 1 fluidized in the boiler. To remedy this operating problem, the stockpile of culm in a covered area or equipment for drying the surface moisture should be considered for future operation.

5.5 Equipment Inspection and Modification

Approximately 725 hours of operation were accumulated during the shakedown test of the plant between August 18 and October 30, 1981. The plant was shutdown for a thorough inspection before beginning the parametric test. Prior to this shutdown and during the shakedown test period, several changes were made to the plant equipment which should be noted.

Insulation was added to Zone 1 of the boiler to permit the boiler to self-sustain on culm alone as noted in the preceding paragraphs.

The pressure/vacuum relief valve for the fluid bed combustor was changed from a water seal arrangement to a mechanical weighted plate after several instances of leakage of water into the combustor flue gas.

A number of the rubber expansion joints used throughout the fluidizing air ducting cracked and had to be replaced. This problem was subsequently traced to a vendor's marginal design and quality control. Remedies included replacement expansion joints of 4 ply instead of 2 ply construction and improved fabrication techniques.

Upon inspection of the boiler after 725 hours, it was noted that some of the original refractory insulation was spalling off the front and rear walls of the boiler. Investigation suggested that improper setting and curing was the likely cause for the spalling, and after removing loose insulation and replacement, no further spalling was observed beyond what would be normally expected with similar boiler operating times and start-stop cycles.

Some difficulty was experienced in moving bed ash through the ash cooler during the shakedown testing so several changes were made during the inspection shutdown. The ash cooler is a 3 celled fluid bed and the movement of material was eased from cell to cell by enlarging the egress ports between cells and also additional fluidizing airflow was supplied to the cooler through piping modifications.

6.0 TEST SUMMARY

Thirty-nine (39) parametric tests were performed in an intermittent series between 10/29/81 & 11/30/83. The final four tests, 33-36, were performed with gob fuel; all other tests were with culm fuel. The objective of these tests was to check the boiler performance and turndown capabilities over the complete range of variables. These variables included: zones fluidized, bed depth, bed temperature, fluidization velocity, primary cyclone recycle, and Ca/S feed ratio.

Operating data and final results for the 39 tests are summarized in the table in Appendix 1. Independent variables are summarized in Table 6.1 and dependent variables are summarized in Table 6.2. Bed temperature range was 1432-1677°F. Freeboard temperature, measured adjacent to the convection bank, was 961-1412°F, and several tests were made below 1200°F. Because of these low temperatures, it is believed that little combustion, if any, takes place in the freeboard. All tests were conducted with an excess of combustion air, between 11% and 112%. The bed depths tested were 3, 4 and 5 feet, and fluidization velocity was 3.5-5.3 ft/sec.

The range in culm heating value was 3700 to 4780 Btu/lb (high heating value, dry basis) with 23-31% carbon and approximately 5% moisture. The heating value for gob was 2902 - 3023 Btu/lb with 16.9 - 17.7% carbon and 3.2% - 4.1% moisture. Fuel heating value is directly proportional to fuel carbon content (Figure 6.1).

Standard 4 mesh screens were employed in the culm crushing/screening section for a period of shakedown testing and for the first parametric test. However, during the first winter, cold and wet weather conditions caused considerable blinding and freeze-up of culm on the 4 mesh screens. These were replaced with 3 mesh screens for tests 2 through 4 after a hole was made on one screen while removing ice. To further increase screening capacity, a one-quarter-inch Tyrod (Tyler Screen Company) primary and a 3 mesh secondary screen were employed for tests 5 through 8. The Tyrod screen opening is ¼ inch by 3½ inch. Because of parallel culm flow to the long openings, flat "washer" size material passed through the screens. Since the combustor and ash cooler fluidized beds were not designed for this oversized material, standard 3 mesh screens were employed for tests 9 to 13. Tests 14 through 36 were made with 2½ mesh primary and 3 mesh secondary screens.

Because of the changes made to the culm screens, there is a wide variation in the size distribution of fuel feed for the tests, Table 6.3. Since a significant fraction of +4 mesh material was fed to the boiler, culm size was larger than design specifications for all but two of the tests.

TABLE 6.1 INDEPEND ENT VARIABLES

TEST (NO.)	ZONES	-FLUID BED -- TEMP. (DEG. F)	HT. (IN)	VEL. (FT/ SEC)	PRIMARY VALVE (%)	CYCLONE (LOC'N)	CA/S
1.0	1	1485	36	4.0	0	TPBED	5.5
2.0	1	1533	36	3.5	20	TPBED	3.1
3.0	1	1543	38	5.2	20	TPBED	4.4
4.0	1	1542	60	5.2	20	TPBED	5.1
5.0	2	1548	36	3.5	50	TPBED	2.9
6.0	3	1556	38	3.5	50	TPBED	3.7
7.0	3	1566	48	3.5	50	TPBED	3.4
8.0	2	1538	56	5.3	50	TPBED	3.9
9.0	3	1576	48	5.2	50	TPBED	4.5
10.0	3	1663	61	5.3	50	TPBED	3.5
11.0	3	1563	57	4.6	50	TPBED	2.6
12.0	3	1641	36	3.5	50	TPBED	3.4
13.0	3	1459	36	3.5	50	TPBED	3.3
14.0	2	1534	48	3.5	50	TPBED	3.2
15.0	3	1569	37	5.3	50	TPBED	4.4
16.0	3	1603	61	4.6	0	TPBED	2.6
17.0	3	1432	58	5.1	50	TPBED	2.9
18.0	1	1588	36	3.5	50	TPBED	3.2
19.0	1	1629	37	3.5	0	TPBED	3.8
20.0	1	1645	49	3.5	50	TPBED	3.1
21.0	1	1652	37	3.5	50	TPBED	4.8
22.0	1	1656	37	3.5	50	TPBED	3.7
23.0	1	1630	48	3.5	50	TPBED	3.5
24.1	3	1654	37	3.5	50	TPBED	2.4
24.2	3	1638	60	4.6	50	TPBED	2.3
25.1	1	1652	36	3.5	20	TPBED	3.7
25.2	1	1552	36	3.5	20	TPBED	4.4
26.0	1	1537	49	3.5	50	TPBED	3.3
27.0	1	1555	36	3.5	20	INBED	2.9
28.0	1	1536	36	3.5	20	INBED	2.9
29.0	1	1677	38	3.5	75	INBED	3.4
29.2	1	1665	38	3.6	50	INBED	2.3
30.0	1	1636	37	3.5	-1	NONE	2.6
31.0	1	1660	49	3.5	-1	NONE	3.7
32.0	1	1632	46	3.5	0	INBED	4.1
33.0	1	1536	37	3.5	-1	NONE	1.7
34.0	1	1527	38	3.5	-1	NONE	2.6
35.0	1	1552	38	3.3	50	INBED	1.8
36.0	1	1557	48	3.5	-1	NONE	2.7

TABLE 6.2 DEPENDENT VARIABL ES.

TEST (NO.)	FREE-BOARD (DEG. F)	TOTAL STEAM (LBS/HR)	FUEL (LBS/ HR)	SOR ENT (LBS / HR)	EXCESS AIR (%)
1.0	984	6937	3573	667	97
2.0	961	6342	2909	518	101
3.0	1085	9432	3980	598	97
4.0	1260	15475	6088	824	29
5.0	1023	9746	3914	425	73
6.0	1059	11826	4854	651	71
7.0	1132	13680	6066	844	46
8.0	1260	17367	8052	1450	42
9.0	1242	18514	8150	1483	57
10.0	1412	26570	10858	1568	11
11.0	1361	24894	10123	1025	8
12.0	1118	12938	5542	779	45
13.0	1044	10065	4903	728	95
14.0	1093	11453	5098	649	42
15.0	1199	16431	7382	1099	76
16.0	1345	24642	10873	1106	7
17.0	1235	20715	9415	1150	51
18.0	977	8085	2623	329	68
19.0	1028	8205	2860	348	77
20.0	1149	11075	3477	299	37
21.0	1027	8319	2645	375	76
22.0	1026	8206	2530	281	81
23.0	1113	10387	3135	337	47
24.1	1137	13934	4601	367	63
24.2	1369	22065	7724	523	36
25.1	1040	8103	2685	302	79
25.2	1001	7754	2577	290	99
26.0	1107	10929	3271	351	46
27.0	1003	8724	2814	271	79
28.0	1000	8823	2722	252	79
29.0	1064	10966	4010	544	31
29.2	1036	10149	3503	347	46
30.0	1034	8462	3081	258	73
31.0	1143	10909	3977	514	34
32.0	1112	11599	4289	622	29
33.0	1042	8697	4267	2470	40
34.0	1058	9106	4888	4123	22
35.0	1054	10190	4871	2586	18
36.0	1143	11396	5366	2897	11

Figure 6.1

Fuel Heating Value vs. Carbon Content

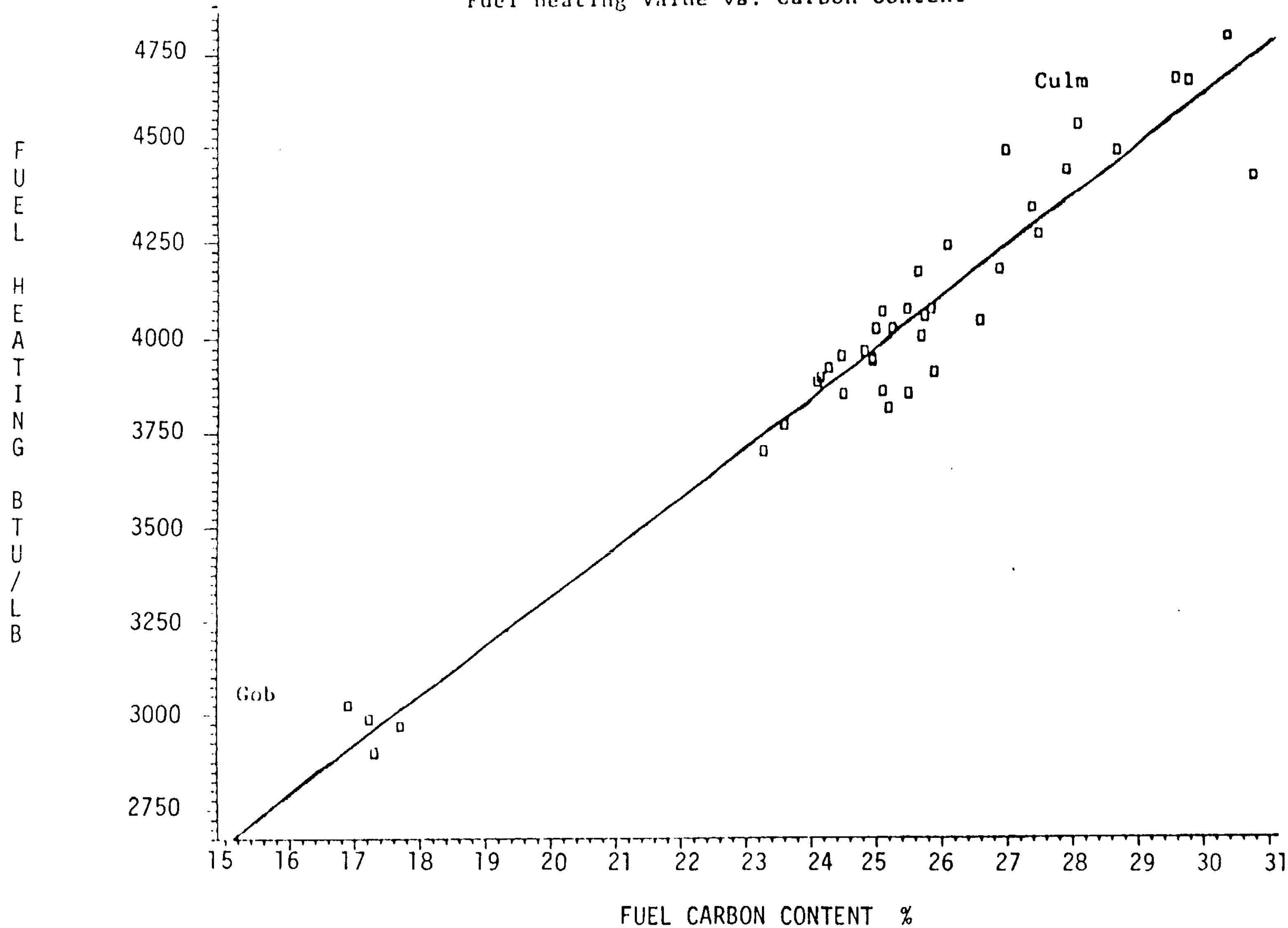


Figure 6.1

TABLE 6.3 SOLID FUEL SIZE DISTRIBUTION.

TEST (NO.)	---SCREEN ANALYSIS (PERCENT SMALLER THAN)--- -4 MESH	-8 MESH	-20 MESH	-60 MESH	-100 MESH	-150 MESH	-200 MESH	ARITH. MEAN SIZE (MM)	GEOMETRIC MEAN SIZE (MICRON)
1.0	87.1	69.4	31.3	8.0	3.5	2.1	1.1	2.00	663.8
2.0	95.8	60.0	28.2	9.6	5.8	3.9	2.4	2.10	593.8
3.0	96.1	61.1	17.0	8.6	5.4	3.7	2.4	2.20	677.5
4.0	97.2	68.6	32.8	8.6	4.0	2.0	0.8	1.87	647.2
5.0	86.3	56.9	24.3	5.6	2.8	1.5	0.7	2.33	825.0
6.0	88.0	61.5	28.1	8.3	4.3	2.4	1.3	2.17	675.8
7.0	86.5	60.9	30.0	10.3	5.8	3.8	2.6	2.17	577.0
8.0	91.2	59.5	26.5	10.1	6.5	4.6	3.0	2.18	572.4
9.0	87.2	57.0	27.4	10.9	6.7	5.0	3.5	2.26	549.7
10.0	91.7	55.7	26.8	10.2	6.8	5.0	3.7	2.24	554.2
11.0	91.5	54.4	24.3	9.0	5.3	3.4	1.7	2.31	663.8
12.0	95.2	64.9	31.9	10.6	6.2	3.1	1.6	1.97	580.4
13.0	91.8	56.3	25.2	7.2	4.2	2.6	1.5	2.26	712.5
14.0	92.9	63.4	29.4	8.2	3.8	2.2	1.2	2.06	674.5
15.0	94.2	68.7	31.2	10.5	5.2	2.9	1.6	1.92	592.1
16.0	89.5	60.4	29.9	12.3	7.6	4.9	3.2	2.14	521.3
17.0	87.3	44.5	16.3	5.2	2.8	1.7	1.0	2.65	945.1
18.0	94.4	66.0	32.5	9.6	4.5	2.8	1.5	1.96	609.4
19.0	99.8	69.0	29.2	10.2	6.4	4.0	2.4	1.86	562.2
20.0	100.0	74.5	36.3	13.0	8.3	5.5	3.5	1.67	462.5
21.0	100.0	68.6	30.5	11.3	7.0	4.5	2.7	1.85	531.4
22.0	94.6	69.6	34.8	11.7	7.0	4.3	2.4	1.85	518.3
23.0	95.4	64.3	35.2	11.4	6.3	3.8	2.1	1.94	540.4
24.1	96.8	64.2	28.0	8.4	4.4	2.6	1.5	2.02	655.8
24.2	98.1	70.9	35.3	10.9	6.4	4.1	2.5	1.78	525.0
25.1	93.8	59.1	27.0	8.6	4.1	2.1	0.9	2.16	699.7
25.2	94.3	59.4	28.1	9.8	5.0	2.6	1.3	2.13	645.1
26.0	95.7	69.8	36.3	10.6	5.0	2.7	1.2	1.82	575.9
27.0	94.2	62.9	29.1	8.1	4.4	1.9	0.8	2.06	686.5
28.0	92.4	51.9	23.3	6.7	3.1	1.6	0.8	2.37	809.5
29.1	96.0	62.2	28.3	8.6	4.0	2.1	1.0	2.06	681.6
30.0	96.3	61.9	24.9	7.0	3.4	0.3	0.1	2.11	809.7
31.0	89.7	48.3	20.2	6.1	2.8	1.2	0.5	2.50	898.3
32.0	95.0	62.9	29.2	9.3	4.4	2.7	1.5	2.05	638.8
33.0	94.4	69.2	35.5	8.7	3.6	1.7	0.5	1.87	646.4
34.0	94.9	69.1	32.3	8.1	4.1	2.2	0.9	1.90	650.3
35.0	91.5	57.4	24.9	7.3	3.9	2.2	1.1	2.25	735.5
36.0	91.9	55.4	21.8	5.8	2.8	1.5	0.6	2.32	850.5

Each test was performed over a 4 hour period preceded by a minimum 20 hour period to establish steady state operation. Readings were taken at one hour intervals to assure steady state and at 15 minute intervals during the test period. Samples of culm, cyclone solids and internal recycle solids were taken at 1 hour intervals and flow rates of culm, limestone and flyash were determined from weights recorded at the beginning and end of each run. Bottom ash weight was determined by difference.

During the scheduled shutdown of the boiler system in July of 1982, the parametric test data were analyzed to check the material balance for the steam and water streams. The material balance did not check consistently and the inaccuracy was traced to sporadic boiler feedwater flowrate data and an error in the design of the main steam flow orifice plate. The orifice plate design error was easily corrected by substitution of the correct pressure coefficient in the water flow algorithm.

Feedwater flowrate is measured with an orifice plate in a vertical line located approximately 15 ft above the pressure transmitter. The two water lines connecting the orifice pressure taps to the pressure transmitter were heat traced. However, water in these two lines froze on several occasions during the first winter so the lines were filled with antifreeze solution. Water density changes in these lines was found to be the primary cause of sporadic water flow readings. Since blowdown flowrate for initial boiler operation during warm weather was 5-10% of boiler feedwater and the feedwater data for all parametric tests in Appendix 1 is calculated based on total steam output, the 5% blowdown factor was assumed.

7.0 BOILER PERFORMANCE

7.1 Combustion Efficiency

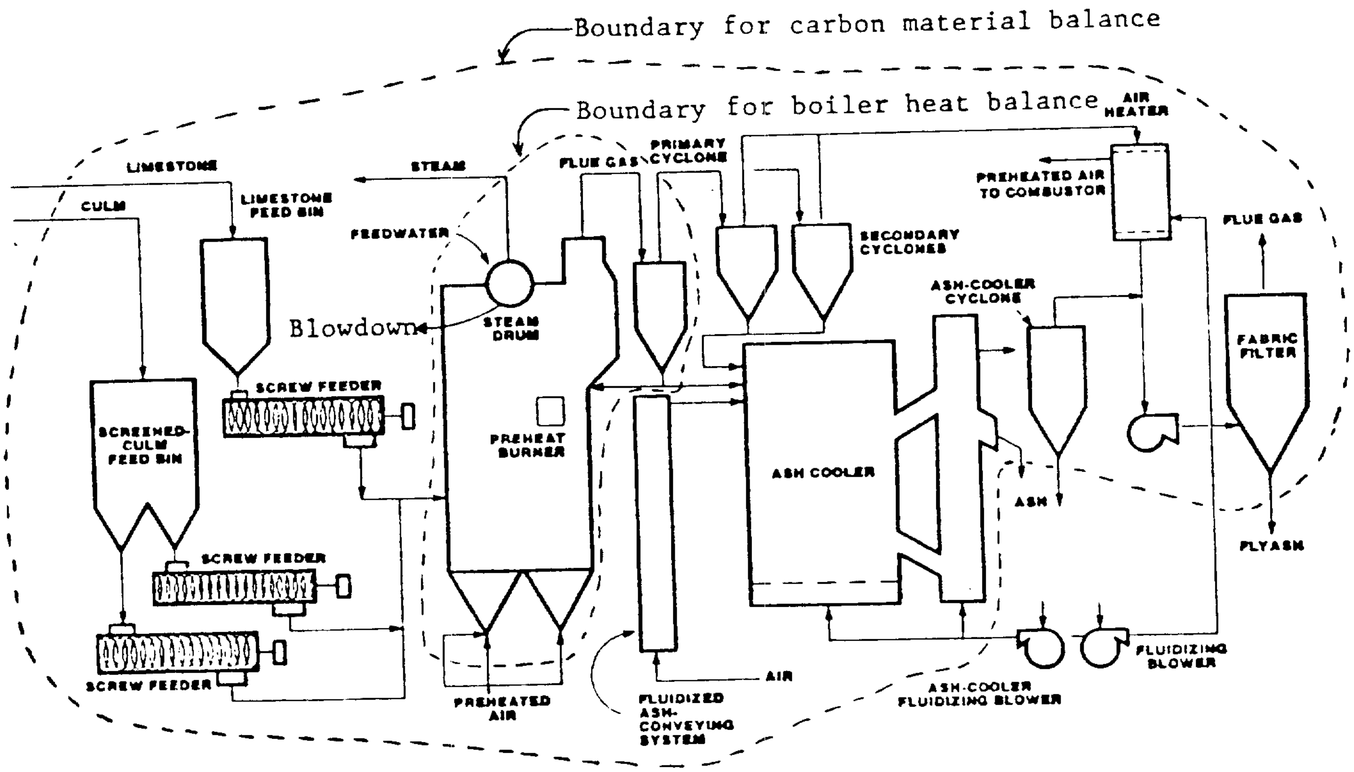
Two methods were employed to measure the extent of fuel combustion in the fluid bed boiler. First, a boiler heat balance was performed around the boundary shown in Figure 7.1 to determine the amount of heat input to the system from fuel combustion. Combustion efficiency is the ratio of the fuel heat input to fuel heating value, expressed as a percentage. Second, a material balance around the boundary shown in Figure 7.1 was performed to determine the amount of carbon burned. Carbon burn-up is the difference between the amount of carbon fed with the fuel and the amount of unburned carbon in the baghouse hopper and the ash cooler bin expressed as a percentage of carbon fed. Combustion efficiency and carbon burn-up sample calculations appear in Appendix 2.

Combustion efficiency data and key operating variables are summarized in Table 7.1. Carbon burn-up varied from 74.8% to 95.2% Carbon combustion efficiency falls in a broader range 72.0% to 103.5%. The relationship between combustion efficiency and carbon burn-up (Figure 7.2) shows considerable scatter.

Because of the nature of anthracite culm there is considerable variation in ash content and heating value, depending upon process operations at the coal cleaning facility. A composite fuel sample is made up of four individual samples taken at one hour intervals for each test.

Figure 7.1

Heat and Material Balances to Measure the Extent of Fuel Combustion



Boiler Heat Balance

Heat Inputs = Heat Outputs

Heat inputs = Net fuel combustion heat + Feedwater enthalpy + Air enthalpy + Heat of sulfation.

Heat outputs = Steam enthalpy + Blowdown enthalpy + Flue gas enthalpy + Fly ash enthalpy + Latent heat + Bed ash enthalpy + Heat of calcination + Radiation heat loss.

$$\left(\frac{\text{Net Fuel Combustion Heat}}{\text{Total Fuel Input Heat}}\right) \times 100 = \text{Combustion efficiency, \%}$$

Carbon Material Balance

Total carbon input = Fuel input x (% carbon in fuel/100)

Solid carbon output = Flyash x (% carbon in flyash/100)
+ Ash bin x (% carbon in ash bin/100)

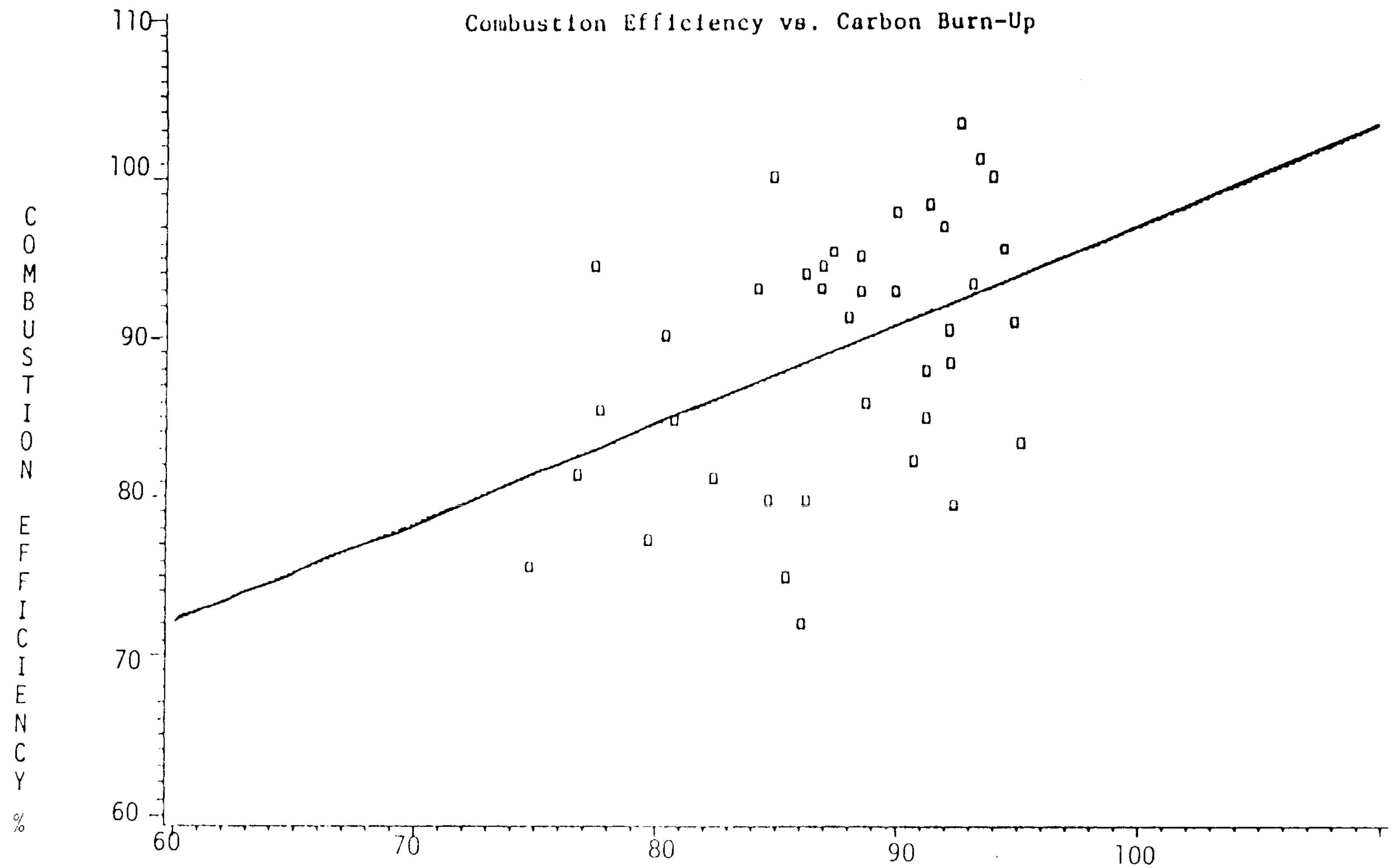
$$\text{Carbon burn-up} = \frac{(\text{Total carbon input} - \text{Solid carbon output}) \times 100\%}{\text{Total carbon input}}$$

Table 7.1

RUN NO.	ZONES	BED HT. IN	VEL. FT/SEC	XS AIR %	CYCLONE POS. %	CYCLONE LOC'N.	TEMPERATURE BED DEG. F.	TEMPERATURE FB DEG. F.	STEAM LBS/HR	CARB. BURN %	COMB. EFF. %	BOIL. EFF. %
1.0	1	36	4.0	97	0	TPBED	1485	984	6937	80.8	84.9	58.2
2.0	1	36	3.5	101	20	TPBED	1533	961	6342	88.8	86.0	60.1
3.0	1	38	5.2	97	20	TPBED	1543	1085	9432	91.3	85.0	62.2
5.0	2	36	3.5	73	50	TPBED	1548	1023	9746	92.3	88.5	67.3
6.0	3	38	3.5	71	50	TPBED	1556	1059	11826	91.3	88.0	66.0
7.0	3	48	3.5	46	50	TPBED	1566	1132	13680	86.3	79.9	60.9
8.0	2	56	5.3	42	50	TPBED	1538	1260	17367	79.7	77.4	57.6
9.0	3	48	5.2	57	50	TPBED	1576	1242	18514	76.8	81.4	60.1
10.0	3	61	5.3	11	50	TPBED	1663	1412	26570	82.4	81.3	62.6
11.0	3	57	4.6	8	50	TPBED	1563	1361	24894	77.7	85.5	66.3
12.0	3	36	3.5	45	50	TPBED	1641	1118	12938	90.8	82.3	61.3
13.0	3	36	3.5	95	50	TPBED	1459	1044	10065	85.4	75.0	54.1
14.0	2	48	3.5	42	50	TPBED	1534	1093	11453	92.4	79.5	59.1
15.0	3	37	5.3	76	50	TPBED	1569	1199	16431	84.7	79.9	58.3
16.0	3	61	4.6	7	0	TPBED	1603	1345	24642	86.1	72.0	56.8
17.0	3	58	5.1	51	50	TPBED	1432	1235	20715	74.8	75.6	57.2
18.0	1	36	3.5	68	50	TPBED	1588	977	8085	87.0	94.5	73.5
19.0	1	37	3.5	77	0	TPBED	1629	1028	8205	88.6	93.0	71.6
20.0	1	49	3.5	37	50	TPBED	1645	1149	11075	90.1	97.9	78.8
21.0	1	37	3.5	76	50	TPBED	1652	1027	8319	92.0	97.0	75.4
22.0	1	37	3.5	81	50	TPBED	1656	1026	8206	93.2	93.4	73.2
23.0	1	48	3.5	47	50	TPBED	1630	1113	10387	94.9	91.0	73.2
24.1	3	37	3.5	63	50	TPBED	1654	1137	13934	92.2	90.4	70.9
24.2	3	60	4.6	36	50	TPBED	1638	1369	22065	95.2	83.4	65.0
25.1	1	36	3.5	79	20	TPBED	1652	1040	8103	88.1	91.2	70.9
25.2	1	36	3.5	99	20	TPBED	1552	1001	7754	93.5	101.3	78.5
26.0	1	49	3.5	46	50	TPBED	1537	1107	10929	94.1	100.1	80.7
27.0	1	36	3.5	79	20	INBED	1555	1003	8724	90.0	92.9	73.4
28.0	1	36	3.5	79	20	INBED	1536	1000	8823	92.7	103.5	82.0
29.1	1	38	3.5	31	75	INBED	1677	1064	10966	94.5	95.7	75.4
29.2	1	38	3.6	46	50	INBED	1665	1036	10149	84.9	100.1	79.6
30.0	1	37	3.5	73	-1	NONE	1636	1034	8462	91.4	98.5	77.1
31.0	1	49	3.5	34	-1	NONE	1660	1143	10909	86.3	94.1	74.6
32.0	1	48	3.5	29	0	INBED	1632	1112	11599	87.4	95.4	74.7
33.0	1	37	3.5	40	-1	NONE	1536	1042	8697	86.9	93.1	70.4
34.0	1	38	3.5	22	-1	NONE	1527	1058	9106	77.5	94.5	67.1
35.0	1	38	3.5	18	50	INBED	1552	1054	10190	88.6	95.1	73.2
36.0	1	38	3.5	11	-1	NONE	1557	1145	11396	84.3	93.1	74.9

Figure 7.2

Combustion Efficiency vs. Carbon Burn-Up



The wide range in percent carbon burn-up and carbon combustion efficiency reflects errors caused by fluctuation of culm heating value and carbon content from minute to minute. In addition, it is likely that samples of ash from the ash bin and baghouse hopper do not accurately represent the average composition of these ash streams.

The seventeen (17) runs between October 29, 1981 and June 24, 1983 made up the first phase of the parametric testing period. Carbon burn-up varied from 74.8% to 92.4% and combustion efficiency varied from 72.0% to 90.1%. In order to optimize sulfur capture most of these runs were conducted between 1530°F and 1590°F bed temperature.

The primary objective of the second phase of twenty-two (22) tests, performed between November 24, 1982 and April 30, 1983, was to demonstrate the effect of bed temperature, freeboard temperature and in-bed recycle on combustion efficiency. Most of these tests were conducted at 1590°F to 1680°F as shown in Figure 7.3.

Combustion efficiency and carbon burn-up increased significantly in the second phase of testing, Figures 7.4 - 7.5. The effect of bed temperature on combustion efficiency and carbon burn-up is shown in Figures 7.6 - 7.7. Although there is a large amount of scatter in the data the trend shown is an increase in carbon burn-up and combustion efficiency with increasing bed temperature.

The combined effect of bed temperature and steam output on combustion efficiency is shown in Figures 7.8 and 7.9 for runs with greater than 30% excess air. Combustion efficiency for steam output less than 10,000 lb/hr is slightly higher than for greater than 10,000 lb/hr steam output, Figure 7.8. This difference due to the magnitude of output is largest at the low (1400°F-1600°F) bed temperature range. A similar relationship is shown for carbon burn-up, Figure 7.9.

The data in Figures 7.8 - 7.9 show that combustion efficiency is 5% - 10% lower and carbon burn-up is 2% to 6% lower at high load and at 1400°F - 1600°F bed temperature. Fluidized bed operating conditions at high steam output (greater than 10,000 lb/hr) are generally high fluidizing velocity and/or more than one zone fluidized (see operating data in Table 7.1. Thus, freeboard space rate is much higher compared to runs with less than 10,000 lb/hr steam output. Elutriation is therefore much higher for high-load opreation.

Combustion efficiency generally decreases with increasing number of zones fluidized (Figure 7.10). Since freeboard gas velocity increases in direct proportion to the number of zones fluidized, bed particle elutriation generally increases with increasing number of zones fluidized.

The trends from Figures 7.8 - 7.10 indicate that combustion efficiency is directly related to elutriation of particles out of the fluid bed. Once particles are elutriated out of the bed and splash zone they tend not to re-enter the high temperature bed. Gas velocity in the freeboard increases as the gases travel up the freeboard due to the inward sloped front boiler wall (Figure 3.3). In addition, both the ash collected in the convection bank and the recycled primary cyclone tailings are discharged 4 ft above the gas distributor (the primary cyclone tailings discharge point is 1 ft above the distributor for in-bed recycle runs). Thus, recycled particles will become re-elutriated when bed height is 3 - 4 feet.

Figure 7.3

SHAMOKIN PARAMETRIC TEST RESULTS

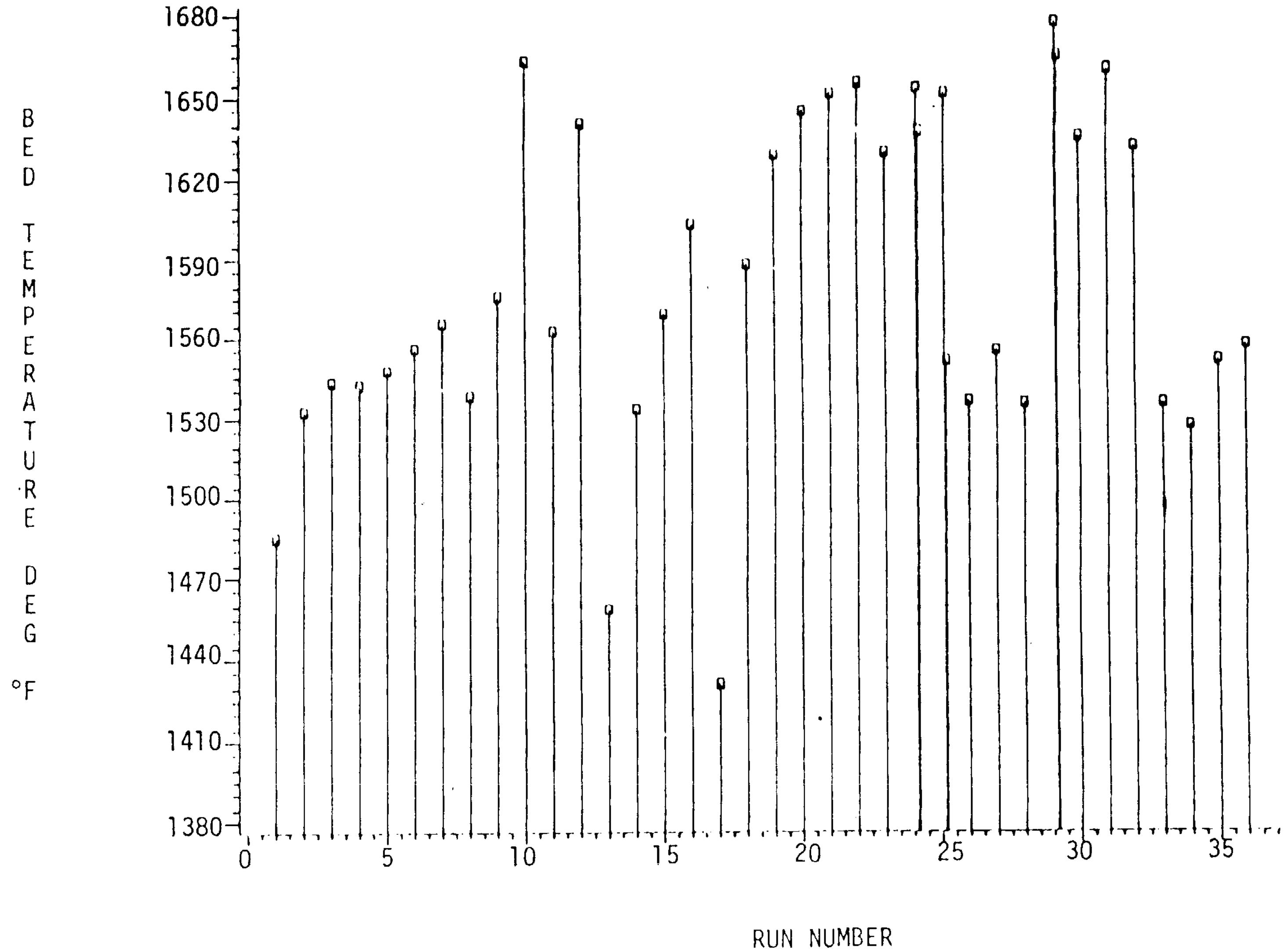
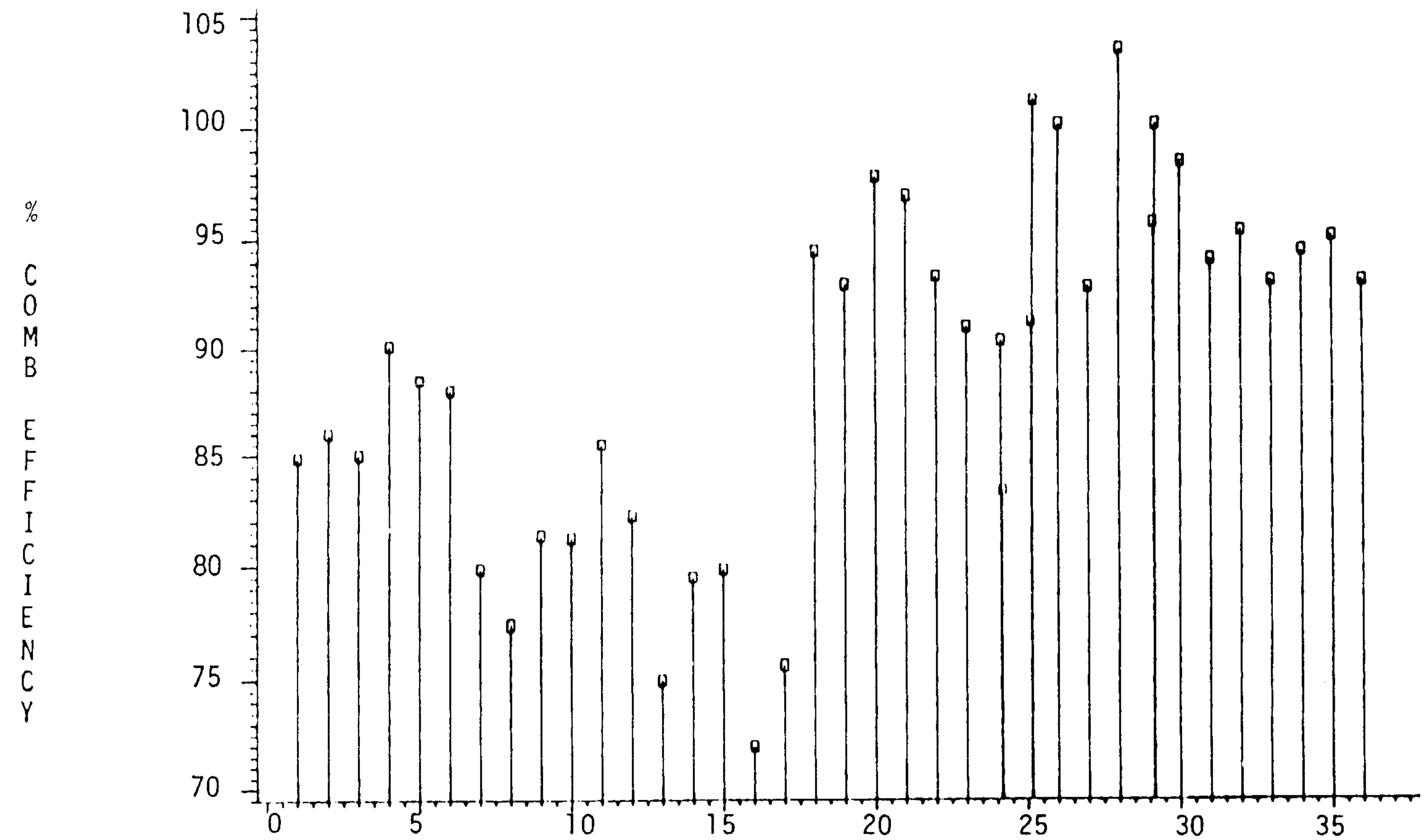


Figure 7.4

SHAMOKIN PARAMETRIC TEST RESULTS



<u>Figure 7.5</u>

CARBON BURN-UP FOR PARAMETRIC TESTS

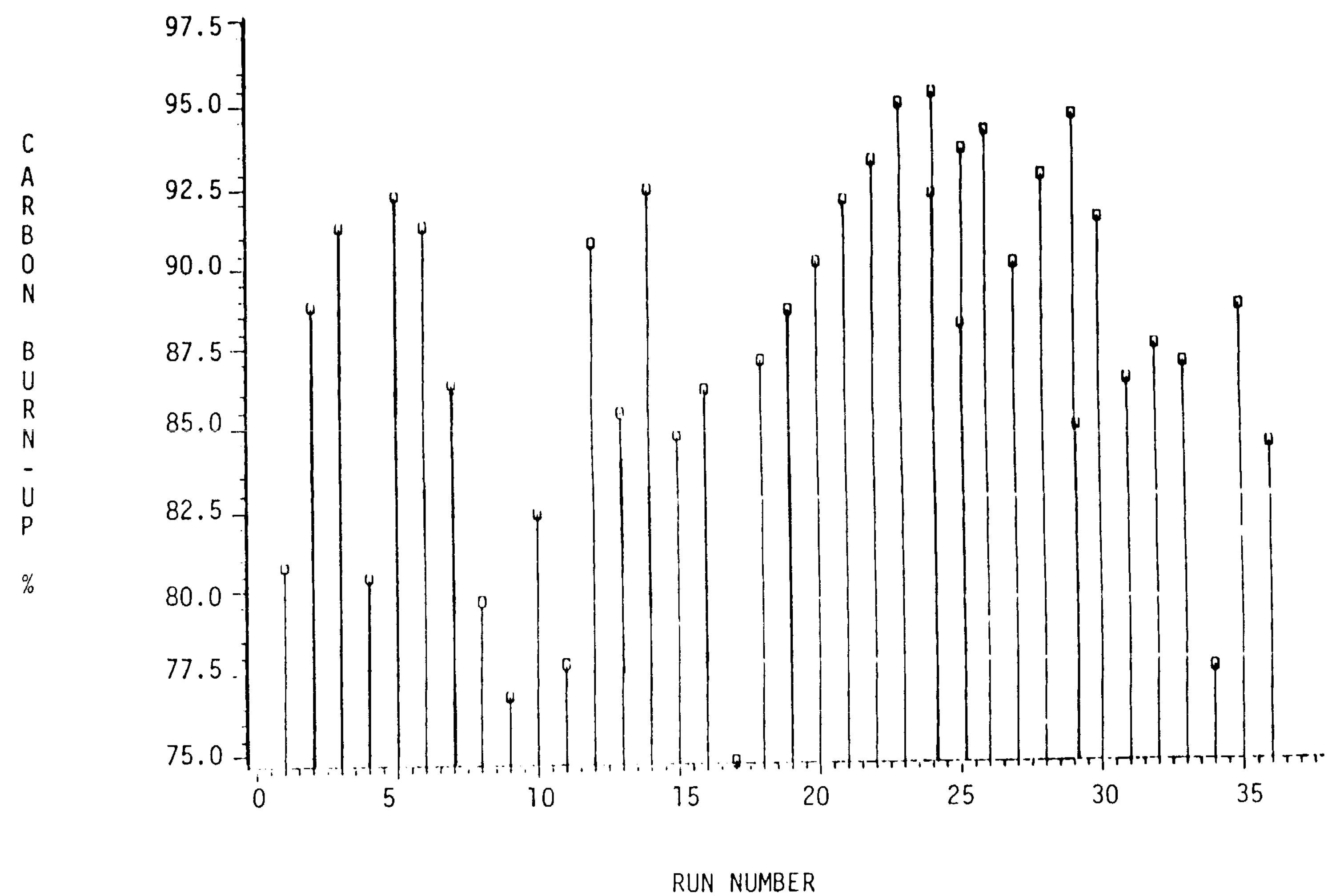


Figure 7.6

COMBUSTION EFFICIENCY VS BED TEMPERATURE

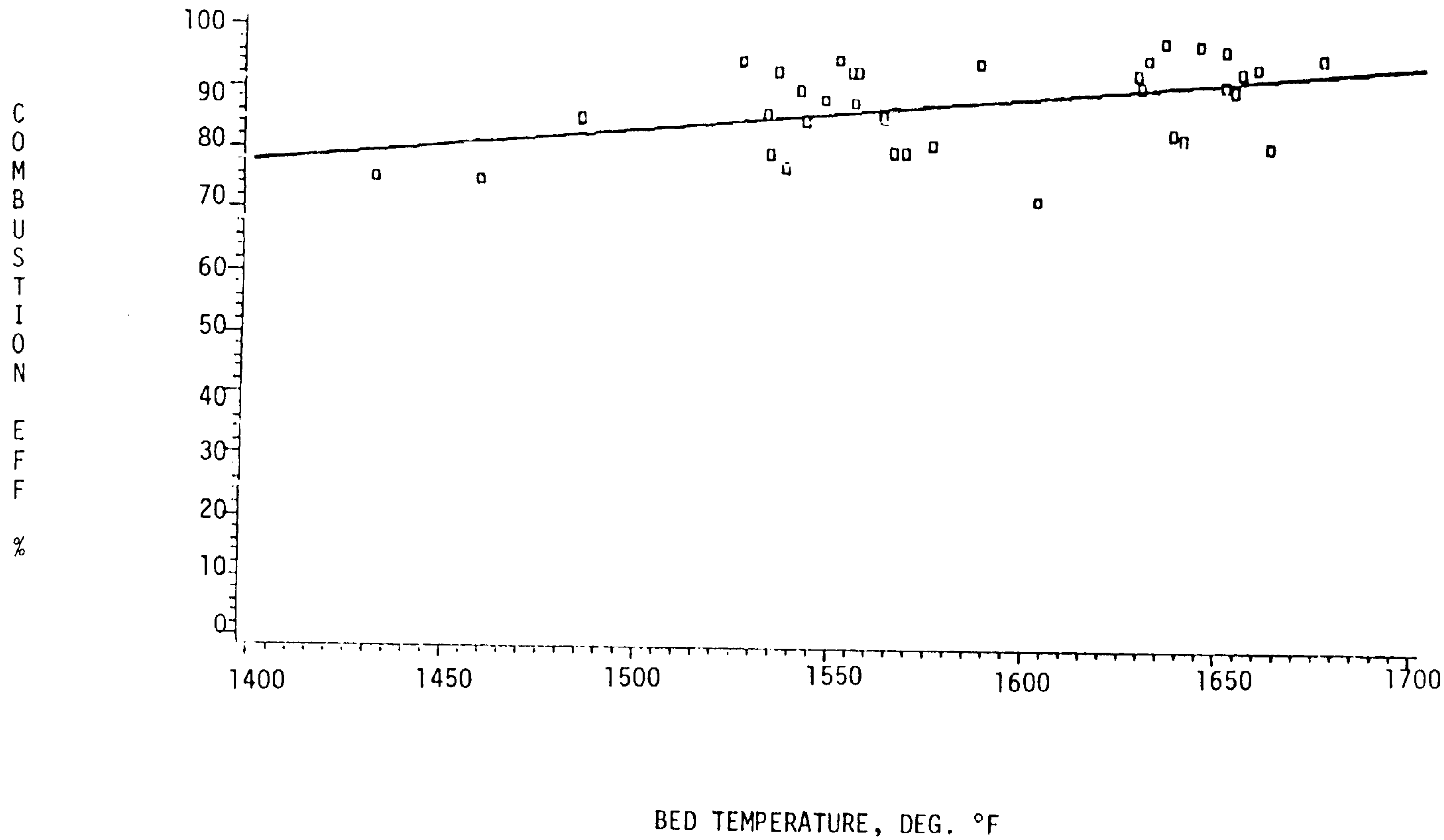


Figure 7.7

CARBON BURN-UP VS BED TEMPERATURE

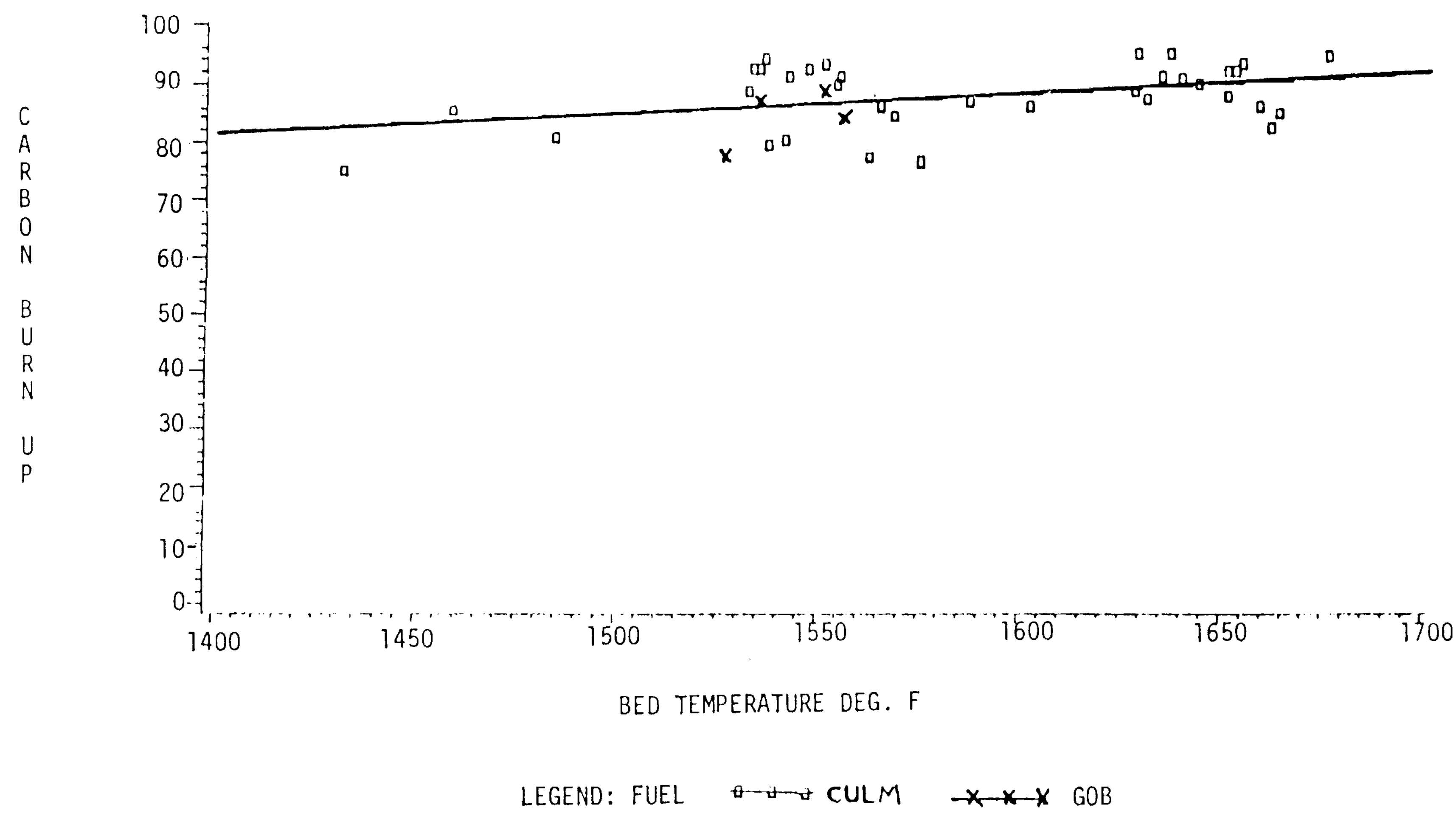


Figure 7.8

COMBUSTION EFFICIENCY VS BED TEMP. AND STEAM OUTPUT

EXCESS AIR GE 30%

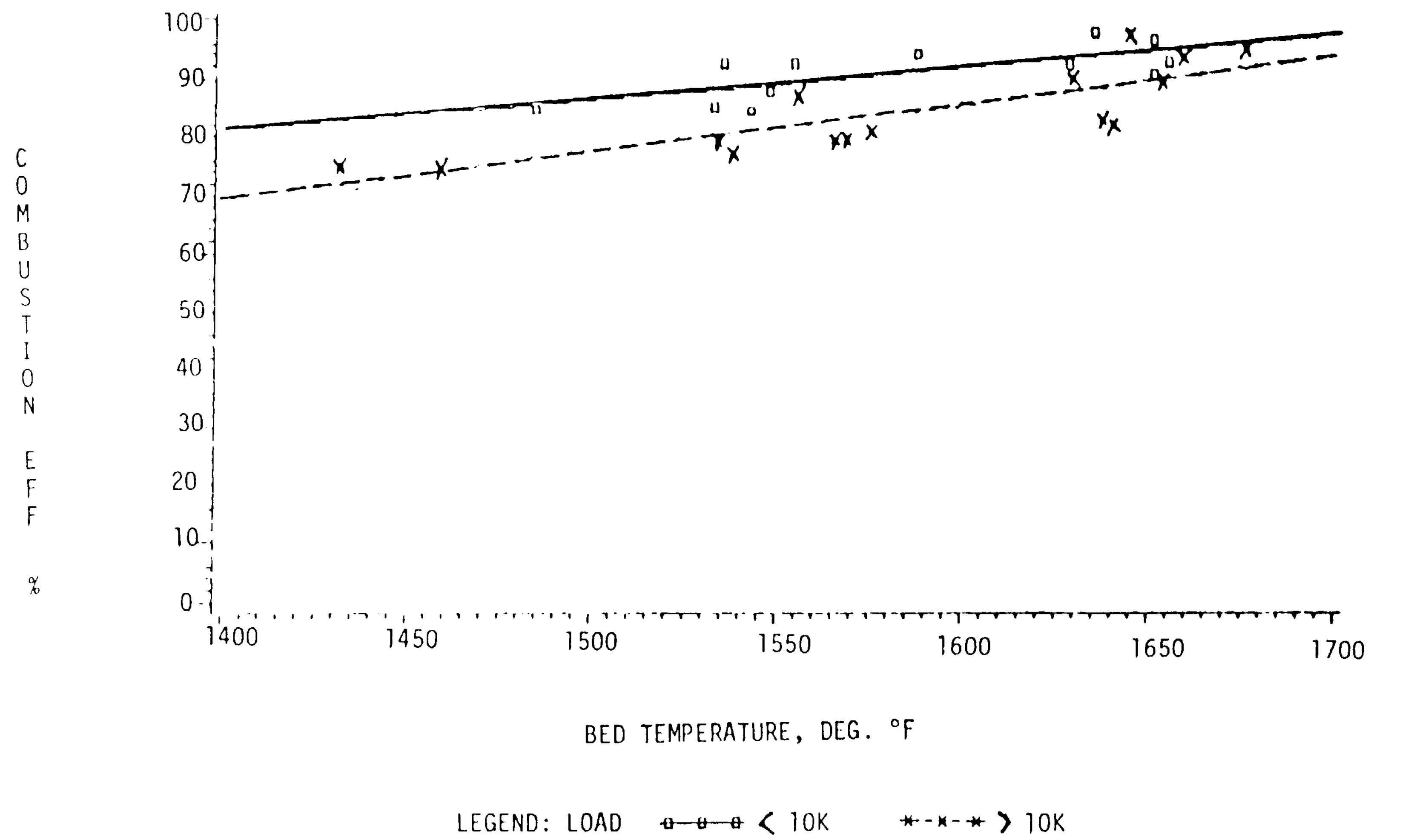


Figure 7.9

CARBON BURN UP VS BED TEMPERATURE AND STEAM OUTPUT

EXCESS AIR GE 30%

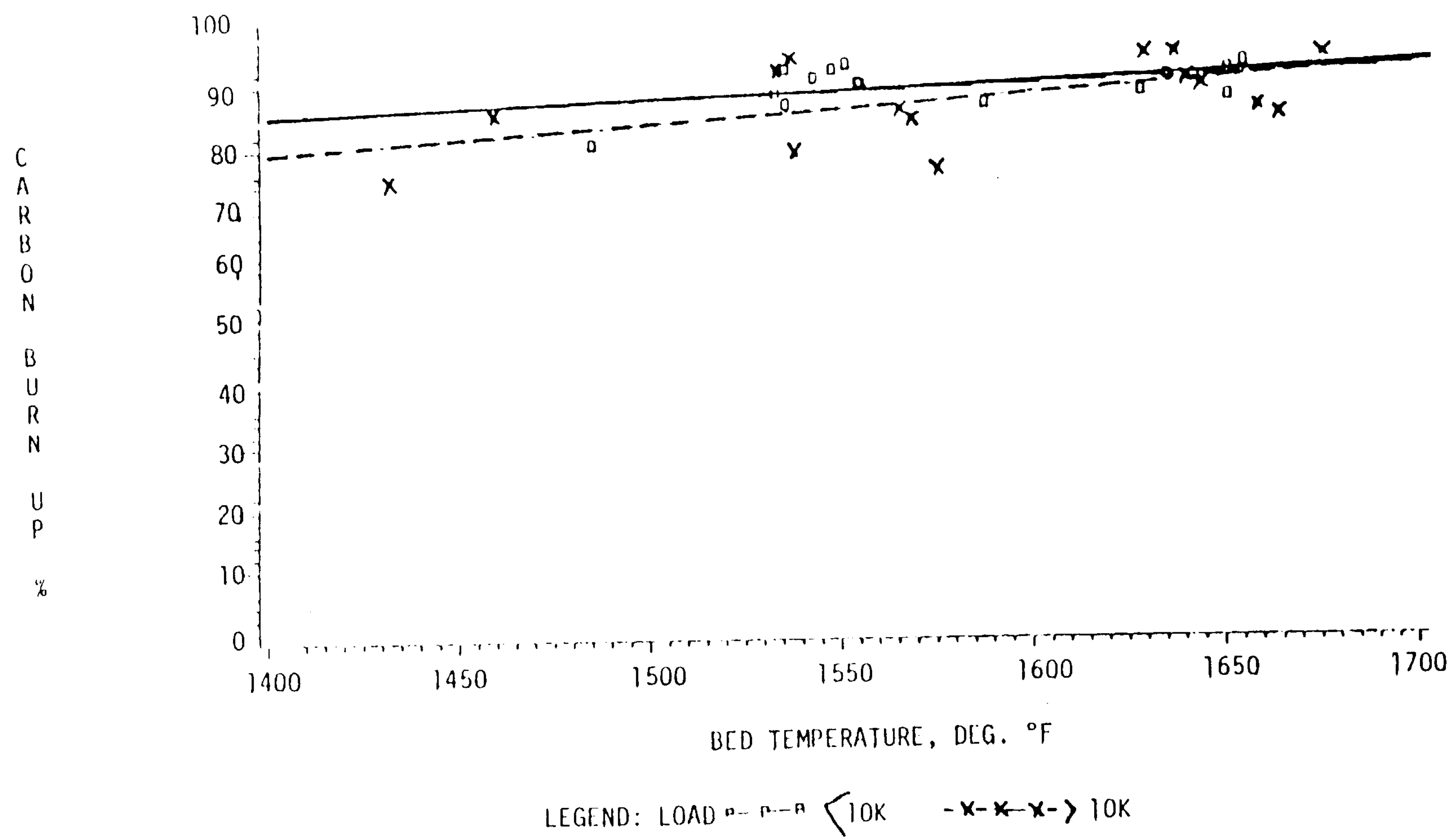
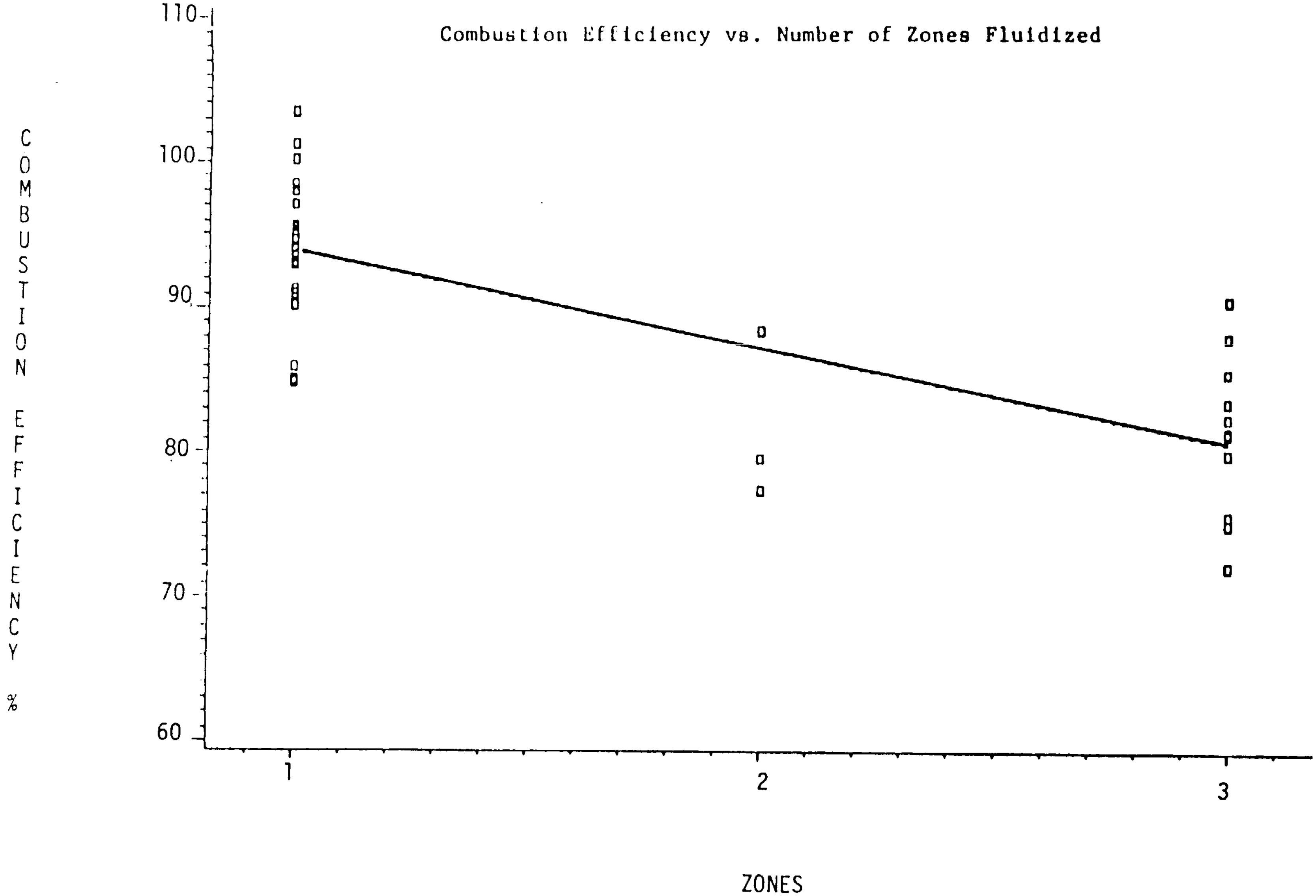


Figure 7.10

Combustion Efficiency vs. Number of Zones Fluidized



Freeboard temperature, measured near the inlet to the convection bank, is 961 -1412^{O}F with most tests conducted at 1000 - 1100^{O}F. Little or no combustion of low quality fuels occurs at these temperatures, and gases are cooled quickly by radiation to the water cooled freeboard membrane walls.

Freeboard temperature during the first 17 tests was 300^{O}F - 500^{O}F lower than bed temperature. A 3/4 inch layer of insulation was installed on both side walls of the freeboard prior to Test 18 to reduce radiation and convection heat transfer to waterwalls in the freeboard. The front and back walls of the freeboard were insulated during all tests.

Analysis of freeboard temperature data at low and high loads showed less than 30^{O}F increase in freeboard temperature due to the added layer of refractory. The temperature increase due to added refractory was not sufficient to cause a measurable change in combustion efficiency and emissions.

To assess the effect of in-bed recycle on performance, 6 tests were performed with gravity injection of tailings from the primary cyclone 12 in. above the bottom of the fluid bed and 5 tests were performed with this line blanked for no recycle. All other tests were performed with primary cyclone tailings discharged 4 ft above the bottom of the bed. The internal flow rate of particles from the convection bank hopper to a discharge point 4 ft above the bottom of the bed was not altered during all 39 parametric tests.

With culm fuel, comparison of in-bed and over-bed injection data shows no consistent difference in carbon burnup but from 3.1 to 4.6% average improvement in combustion efficiency with in-bed injection. When injection is zero or blanked off there are average reductions in carbon burnup of 1.3% and in combustion efficiency of 1.9% from those values for in-bed injection. Those conclusions found over the following ranges in operating conditions with 1 zone and 3.5 ft/sec space rate:

1533-1555^{O}F, 36 in. bed height, 79-101% excess air - (Tests 2, 25B, 27 and 28)

1630-1677^{O}F, 37-49 in. bed height, 31-81% excess air - (Tests 20-23 and 29.1-29.2)

1632-1660^{O}F, 37-49 in. bed height, 29-73% excess air - (Tests 30-32)

Results of gob fuel tests at 1527-1557^{O}F show a 0.6-2.0% increase in combustion efficiency for Test 35 with in-bed injection of recycle compared to Tests 33, 34 and 36 with no recycle. Carbon burn-up was 88.6% for in-bed recycle injection compared to 77.5-86.9% for no recycle.

The following operating variables were also studied in search of possible links to combustion efficiency in the fluidized bed boiler:

excess air
fluidization velocity
bed height
fuel size
fuel heating value

No direct relationship was found between these variables and combustion efficiency or carbon burn-up.

Results of culm combustion studies conducted in a 12 in. diameter Keeler/Dorr-Oliver fluidized bed facility showed 94.9 - 99.2% carbon burn-up at bed temperatures of 1445 - 1655°F . Both the bed and freeboard sections of the laboratory reactor are externally heated to bring the reactor to operating temperature, hold the fluidized bed at reaction temperature, and offset heat losses. Freeboard exit gas temperature is maintained at the same temperature as the bed by regulating the amount of external heat around the freeboard.

The major difference between the Shamokin boiler and the laboratory unit is radiation cooling of unburned particles and gases in the freeboard of the Shamokin boiler compared to an adiabatic freeboard of the laboratory unit. The combined effect of low freeboard temperatures and elutriation of unburned fuel particles out of the fluid bed are the cause of lower combustion efficiency and carbon burn-up in the Shamokin boiler compared to the laboratory unit.

7.2 Emissions

A gas sample probe assembly is permanently mounted in the air preheater flue gas inlet duct. Solids are separated from the gas sample with a porous metal filter inside the sample probe assembly. The ½" metal tubing on the downstream side of the filter occasionally became plugged with a solid material which was removed easily by rodding out.

A gas analyzer system supplied by Pace Industries is located inside the boiler control room. The system (Figure 7.11) consists of vacuum pump, gas conditioner, condenser, and individual analyzers for O_2, CO_2, CO, SO_2 and NO_x:

Pulsed Fluorescent SO_2 analyzer

Chemiluminescent NO_x analyzer

Zirconium Cell Analyzer for CO_2

Infra-Red CO_2 and CO Analyzer

The vacuum pump continuously draws a gas sample from the sample probe assembly through approximately 160 ft of ¼" ID tygon tubing which is insulated and electrically heat traced to prevent condensation.

To ensure accuracy in emissions data for the test program the NO_x, CO and SO_2 gas analyzers were calibrated prior to each of the 39 tests. Emissions data for the parametric test program are summarized in Table 7.2. No data are available for NO_x, CO and SO_2 for several tests because of malfunctions in individual components of the gas analyzer system.

Figure 7.11

Gas Analysis System

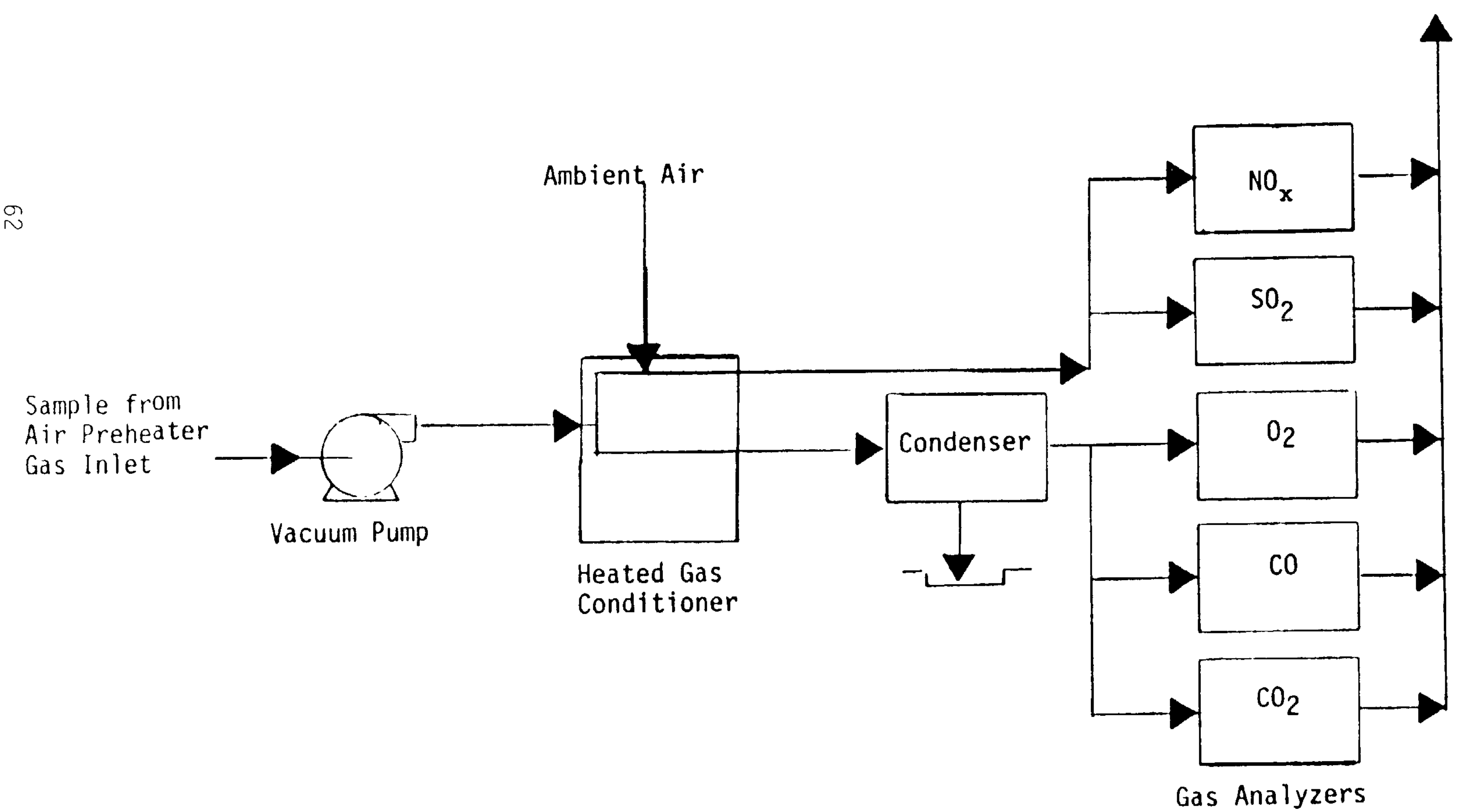


TABLE 7.2

Emission Data for Parametric Tests

Run No.	Gas Res. Time sec	Gas Vel. ft/sec	Ca/S	Temperature Bed	Temperature Free-Board	NO_2 ppm (Calc.	NO_2 lb/mm Btu as NO_2)	CO ~~CO_2~~ ppm	CO ~~CO_2~~ lb/mm Btu	SO_2 ppm	SO_2 lb/mm Btu	SO_2 Capture %
1.0	0.8	4.0	5.5	1,485	984	--	--	--	--	100	0.33	93
2.0	0.9	3.5	5.1	1,533	961	--	--	--	--	82	0.27	94
3.0	0.6	5.2	4.4	1,543	1,085	--	--	--	--	123	0.41	90
4.0	1.0	5.2	5.1	1,542	1,260	--	--	--	--	100	0.23	93
5.0	0.9	3.5	2.9	1,548	1,023	183	0.40	--	--	98	0.30	94
6.0	0.9	3.5	3.7	1,556	1,059	121	0.26	21	0.02	115	0.34	92
7.0	1.1	3.5	3.4	1,566	1,132	106	0.18	87	0.08	110	0.26	95
8.0	0.9	5.3	3.9	1,538	1,260	292	0.47	24	0.02	122	0.27	94
9.0	0.8	5.2	4.5	1,576	1,242	303	0.56	26	0.03	121	0.31	93
10.0	1.0	5.3	3.5	1,663	1,412	89	0.12	19	0.01	127	0.23	95
11.0	1.0	4.6	2.6	1,563	1,361	53	0.07	36	0.03	180	0.34	93
12.0	0.9	3.5	3.4	1,641	1,118	95	0.16	47	0.05	119	0.29	94
13.0	0.9	3.5	3.3	1,459	1,044	93	0.20	31	0.04	134	0.40	92
14.0	1.1	3.5	3.2	1,534	1,093	78	0.13	22	0.02	154	0.35	92
15.0	0.6	5.3	4.4	1,569	1,199	161	0.32	27	0.03	135	0.38	90
16.0	1.1	4.6	2.6	1,603	1,345	21	0.02	90	0.06	215	0.34	91
17.0	0.9	5.1	2.9	1,432	1,235	45	0.07	88	0.08	256	0.59	86
18.0	0.9	3.5	3.2	1,588	977	--	--	--	--	--	--	--
19.0	0.9	3.5	3.8	1,629	1,028	--	--	--	--	--	--	--
20.0	1.2	3.5	3.1	1,645	1,149	--	--	--	--	--	--	--
21.0	0.9	3.5	4.8	1,652	1,027	--	--	--	--	--	--	--
22.0	0.9	3.5	3.7	1,656	1,026	--	--	--	--	--	--	--
23.0	1.1	3.5	3.5	1,630	1,113	--	--	--	--	--	--	--
24.1	0.9	3.5	2.4	1,654	1,137	--	--	--	--	--	--	--
24.2	1.1	4.6	2.3	1,638	1,369	--	--	--	--	--	--	--
25.1	0.8	3.5	3.7	1,652	1,040	--	--	--	--	--	--	--
25.2	0.8	3.5	4.4	1,552	1,001	--	--	--	--	--	--	--
26.0	1.2	3.5	3.3	1,537	1,107	--	--	--	--	--	--	--
27.0	0.8	3.5	2.9	1,555	1,003	--	--	--	--	219	0.63	91
28.0	0.9	3.5	2.9	1,536	1,000	--	--	--	--	199	0.64	91
29.1	0.9	3.5	3.4	1,677	1,064	--	--	--	--	226	0.51	95
29.2	0.9	3.6	2.8	1,665	1,036	--	--	--	--	250	0.64	93
30.0	0.9	3.5	2.6	1,636	1,034	--	--	65	0.08	299	0.90	89
31.0	1.1	3.5	3.7	1,660	1,143	--	--	61	0.05	326	0.74	92
32.0	1.1	3.5	4.1	1,632	1,112	--	--	101	0.09	325	0.70	92
33.0	0.9	3.5	1.7	1,536	1,042	--	--	241	0.28	2,178	6.33	92
34.0	0.9	3.5	2.6	1,527	1,058	--	--	254	0.28	1,556	4.23	95
35.0	0.9	3.5	1.8	1,552	1,054	--	--	273	0.28	2,429	6.28	91
36.0	1.1	3.5	2.7	1,557	1,143	--	--	186	0.17	505	1.18	99
Avg									0.089			

NO_x and SO_2 emission levels are on wet basis. CO emissions level is on dry basis. Lb/mm Btu refers to the total lbs of emissions based on 1 mm Btu total fuel input. Emissions are measured with probe located at air preheater inlet.

7.2.1 Sulfur Dioxide Emissions

The current compliance level of SO_2 emissions from industrial fluidized bed boilers is approximately 1.2 lb SO_2/MM Btu fuel input. Anthracite culm contains 0.7 - 1.0% sulfur which corresponds to 4.5-6.5 lb SO_2/MM Btu based on a heating value of 3100 Btu/lb. A comparable high grade coal (12500 Btu/lb) would contain 2.8-4.1% sulfur on the same fuel input basis.

Bituminous gob fuel for tests 33-36 contains 4.8-5.5% sulfur and has a heating value of 2930-3080 Btu/lb (dry basis). The SO_2 generated by combustion of gob fuel sulfur in these tests was 32.3-36.9 lb/MM Btu fuel input.

The level of sulfur capture required to meet current compliance levels of SO_2 emissions for culm is about the same as that for typical high grade coal with high sulfur content. However, bituminous gob waste contains 4-5 times the amount of sulfur found in typical high grade bituminous coal. The constraints imposed on a boiler burning bituminous gob are several times higher than the norm.

The range of SO_2 emissions with culm fuel was 82 - 326 ppm which corresponds to 0.27 - 0.90 lb SO_2/MM Btu (Table 7.2). The range of SO_2 emissions with gob fuel was 505-2429 ppm which corresponds to 1.18 - 6.33 lb SO_2/MM Btu.

Sulfur retention greater than 90% was achieved in all but two tests at Ca/S molar feed ratio greater than 2.6 for culm and at Ca/S molar feed ratio greater than 1.7 for gob. The higher sulfur retention achieved at a given Ca/S ratio with gob is due to the higher concentration of SO_2 gas available for sorption.

The effect of Ca/S molar feed ratio on sulfur retention for the Shamokin boiler and the 12 in. test combustor is shown in Figure 7.12. In addition to the laboratory test data in Figure 7.12, several tests at 3.0 Ca/S resulted in sulfur capture between 30% and 50%. Sulfur capture for the commercial unit is generally equal to or greater than sulfur capture achieved in the laboratory unit.

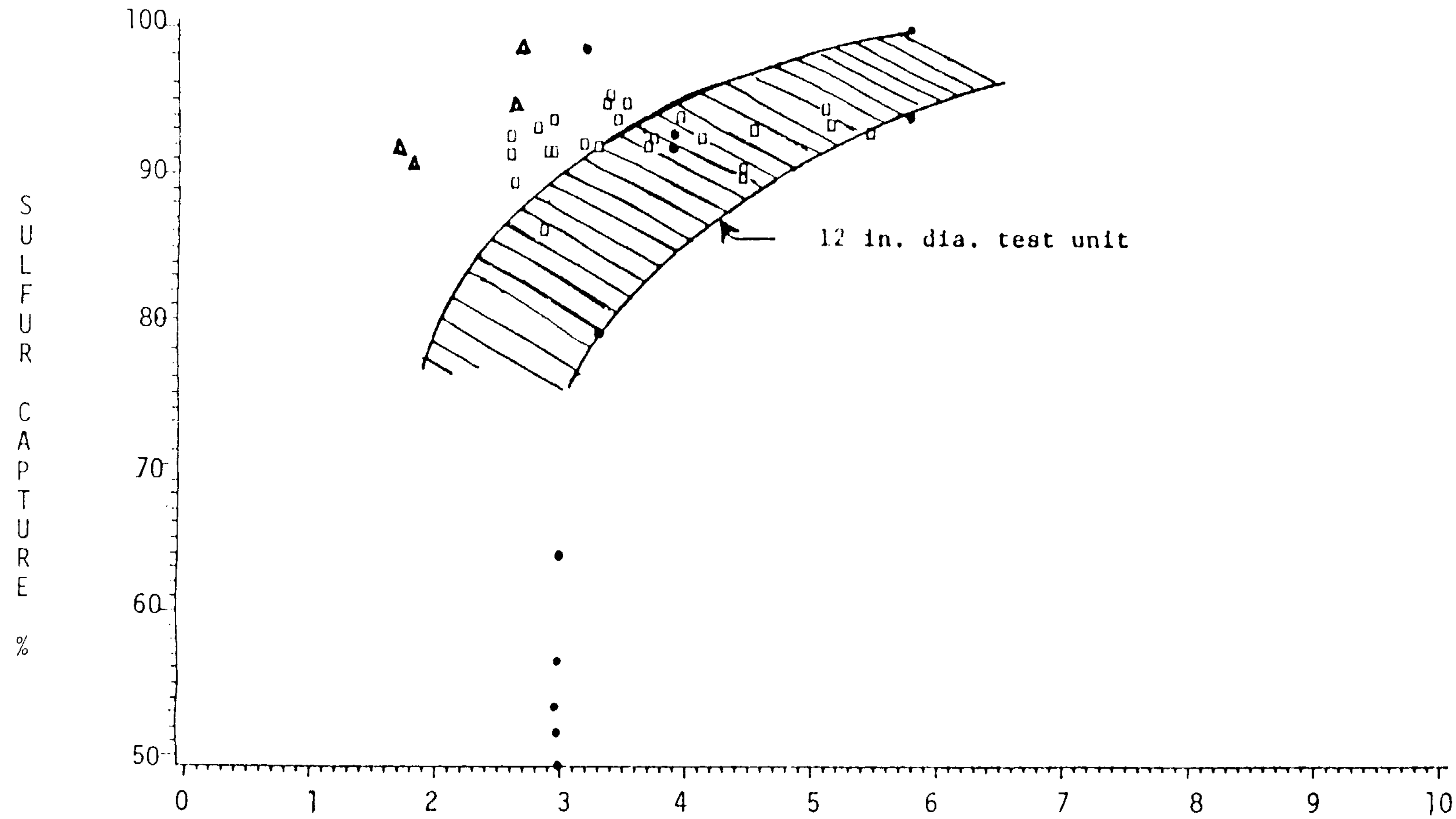
Sulfur retention increases with gas residence time in the fluid bed for Ca/S molar feed ratio greater than 3.0 with culm fuel as shown in Figure 7.13. Tests with Ca/S feed ratio less than 3.0/1 exhibit lower sulfur retention at a given gas residence time.

A typical chemical and size analysis of the Meckley limestone used in the parametric testing with culm is given in Table 7.3. This limestone was generally 65% $CaCO_3$ and 5% $MgCO_3$ and was sized at -4 mesh.

Figure 7.12

SULFUR CAPTURE VS CA/S FEED RATIO

(Data for Shamokin boiler and 12 in. dia. test fluid bed combustor)



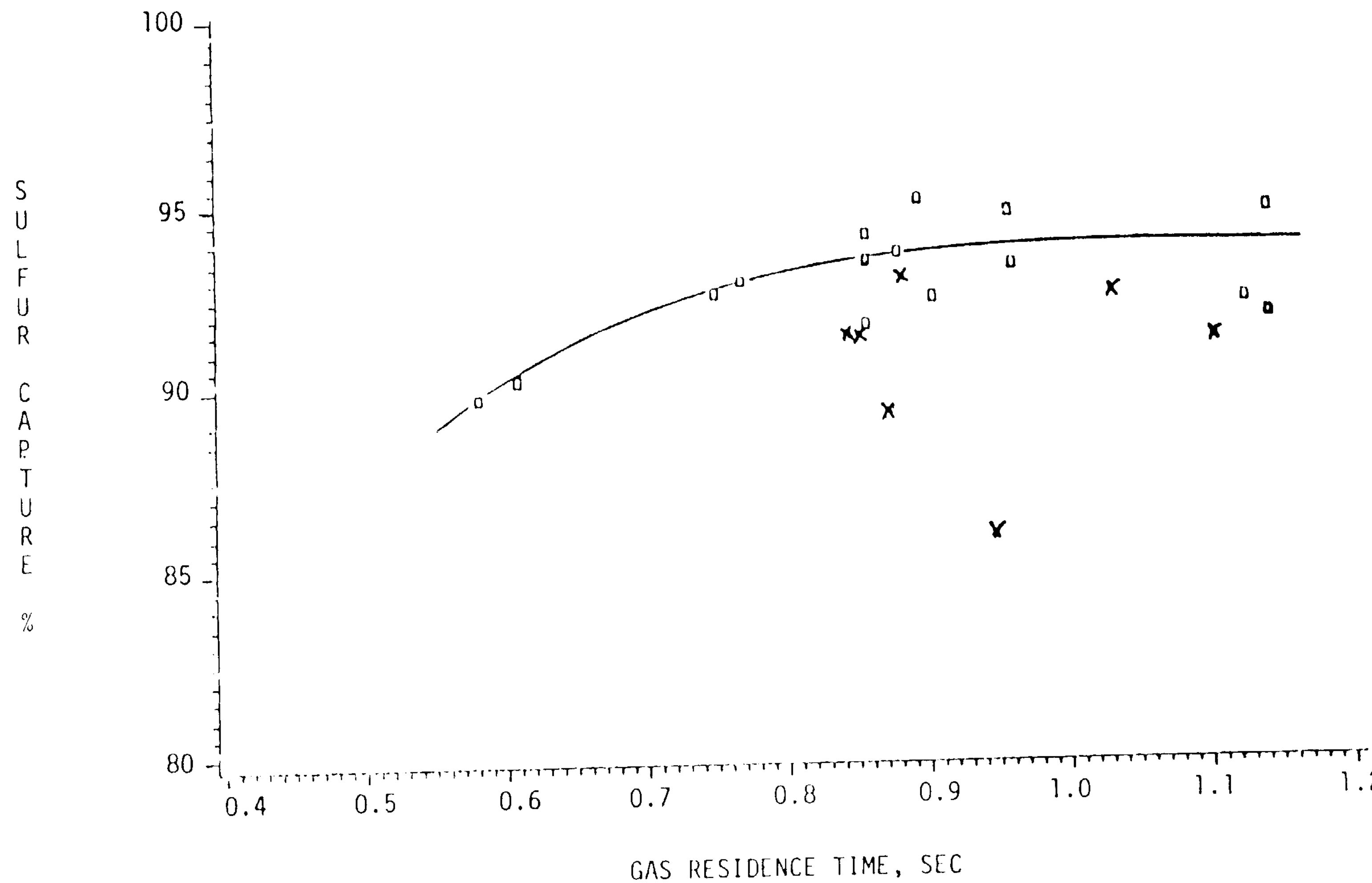
LEGEND: FUEL □ □ □ CULM △ △ △ GOB

Laboratory Test Data (Ref. 2) • • •

Figure 7.13

SULFUR CAPTURE VS GAS RESIDENCE TIME AND CA/S RATIO

CULM FUEL TESTS



LEGEND: RATIO —□—□—□— GT3.0 x x x LT3.0
RATIO DENOTES CA/S FEED RATIO

Table 7.3

Typical Analysis of Meckley Limestone Company Limestone

	(Wt %)	U.S. Sieve Size (Mesh)	% Passing
$CaCO_3$	65.3	4	100
$MgCO_3$	5.0	8	97.7
SiO_2	17.5	20	62.9
Al_2O_3	1.0	60	29.6
Fe_2O_3	1.2	100	21.9
H_2O	0.77	150	17.6
Other	9.2		

Because of the high sulfur content of gob the limestone feed requirement was beyond the limit of the original limestone screw conveyor. However, a five-fold increase in screw capacity was achieved by installing a larger sprocket on the vari-speed drive. No problems with the feeder were encountered after the 1-hour installation was complete.

Gob fuel emissions data are summarized in Table 7.4. Only four tests could be performed in the time that was available. The boiler was shut-down due to exhaustion of funds following Test 36 on April 30, 1983.

Sulfur removal efficiency greater than 98% is necessary in order to reduce SO_2 emissions with gob fuel below 1.2 lb SO_2/MM Btu fuel input. Results of tests 33 and 34 showed that sulfur retention increased from 91.8% to 94.6% when Ca/S feed ratio was increased from 1.7 to 2.6. However, SO_2 emission was only reduced from 6.33 lb/MM Btu to 4.23 lb/MM Btu.

The objective of Test 35 was to demonstrate the effect of recycle of primary cyclone tailings on sulfur retention for the high sulfur gob fuel. Results showed no improvement in sulfur capture with in-bed injection of cyclone tailings compared to no recycle of cyclone tailings.

The objective of Test 36 was to demonstrate the effect of a higher quality limestone and increased gas residence time in the bed on sulfur capture. Results showed that sulfur capture increased to 98.5% and SO_2 emission was reduced to 1.18 lb/MM Btu. Since $CaCO_3$ content of the limestone used in this test was only 80.0% it is not considered to be a high grade limestone. However, the reactivity of the substitute limestone was significantly greater, since sulfur capture increased from 94.6% (Test 34) to 98.5% (Test 36). Gas residence time in the fluid bed for Test 36 was 0.2 seconds higher than Test 34 due to an increase in bed height from 38 in. to 48 in.

Table 7.4

SO_2 Emissions for Gob Fuel Tests

(Bed Temperature 1527 - 1557°F)

Recycle	Test No.	Gob lb/hr	Limestone lb/hr	Gob %S	Limestone % $CaCO_3$	Ca/S	SO_2 PPM	SO_2 Capture	SO_2 lb/MM Btu
None	33	4287	2470	5.49	49.0	1.7	2178	91.8	6.33
None	34	4888	4123	5.23	49.0	2.6	1556	94.6	4.23
In-Bed	35	4871	2586	4.76	49.0	1.8	2429	90.8	6.28
None	36	5366	2897	5.35	80.0	2.7	505	98.5	1.18

7.2.2 Nitrogen Dioxide Emissions

Emissions of NO_x are low for the parametric tests, ranging between 21 and 303 ppm which corresponds to 0.02 to 0.56 lb NO_x/MM Btu culm feed calculated as NO_2. NO_x emissions were below 0.5 lb/MM Btu for all but one of the 13 tests with NO_x emissions data. Analysis of the test results shows that NO_x emissions are related to gas residence time in the bed, Ca/S feed ratio, and CO emissions.

Nitrogen oxides produced in AFB combustors are generally believed to be produced by oxidation of the nitrogen present in both solid and gaseous fuel. Reduction reactions play an important role in reducing NO_x to N_2 and CO_2; the important reducing species present in fluidized bed combustors are carbon and CO. Results for the parametric tests show that NO_x emissions decrease with increasing gas residence time in the fluidized bed (Figure 7.14), which can be attributed to increased contact time between NO_x and carbon as the gas residence time is increased.

NO_x emissions increase with an increase in Ca/S feed ratio which suggests that the NO_x reduction and SO_2 sorption reactions in the fluidized bed are interrelated, (Figure 7.15). This phenomenon has also been observed in the B&W 6 ft x 6 ft fluidized bed test facility in Alliance, Ohio[3].

7.2.3 Carbon Monoxide Emissions

Because of low levels of carbon and volatile matter in anthracite culm, carbon monoxide emissions are very low, generally below 100 ppm. CO emissions and NO_x emissions are interrelated since NO_x is consumed by reducing species such as CO and C. Although CO levels are quite low with culm the inverse relationship between CO and NO_x emissions which occurs with high grade soft coal is also demonstrated for culm (Figure 7.16).

Table 7.5

CO Emissions data for Shamokin Boiler and Laboratory Scale Combustor

(0.8-1.1 sec. gas residence time in bed, 1534-1576°F bed temperature, 3.2-5.5 Ca/S)

Keeler/D-O 12 in. dia. Fluid Bed		Shamokin Boiler	
Test	PPM	Test	PPM
24	220	6	21
29*	208	7	87
30**	227	8	24
31	241	9	26
32	208	11	36
36	175	14	22
37	190	15	27
Avg	210	Avg	35

* Ca/S = 9.6

** Dolomite Sorbent

Figure 7.14

NOX EMISSIONS VS GAS RESIDENCE TIME IN BED

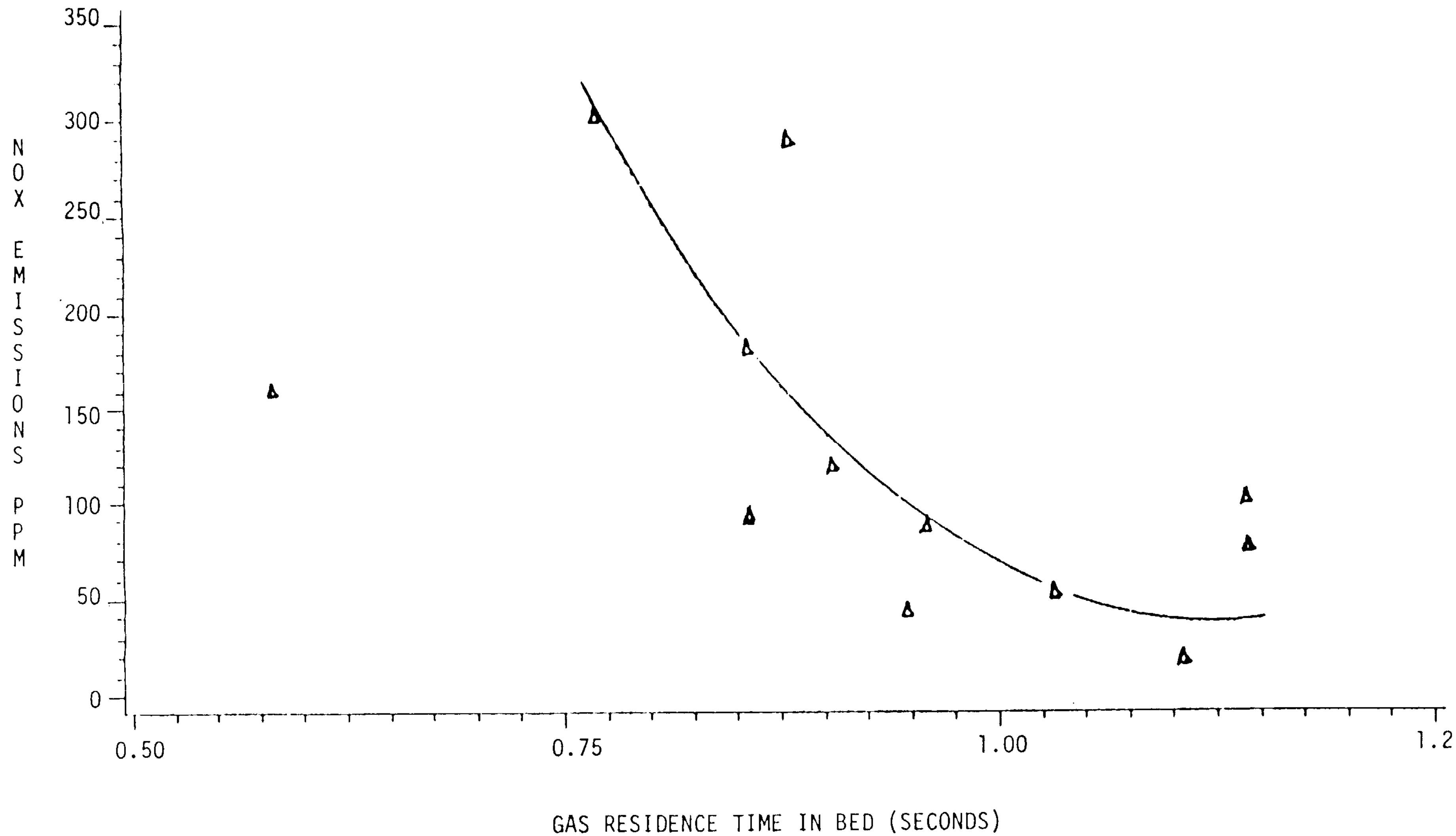


Figure 7.15

NOX EMISSIONS VS CA/S FEED RATIO

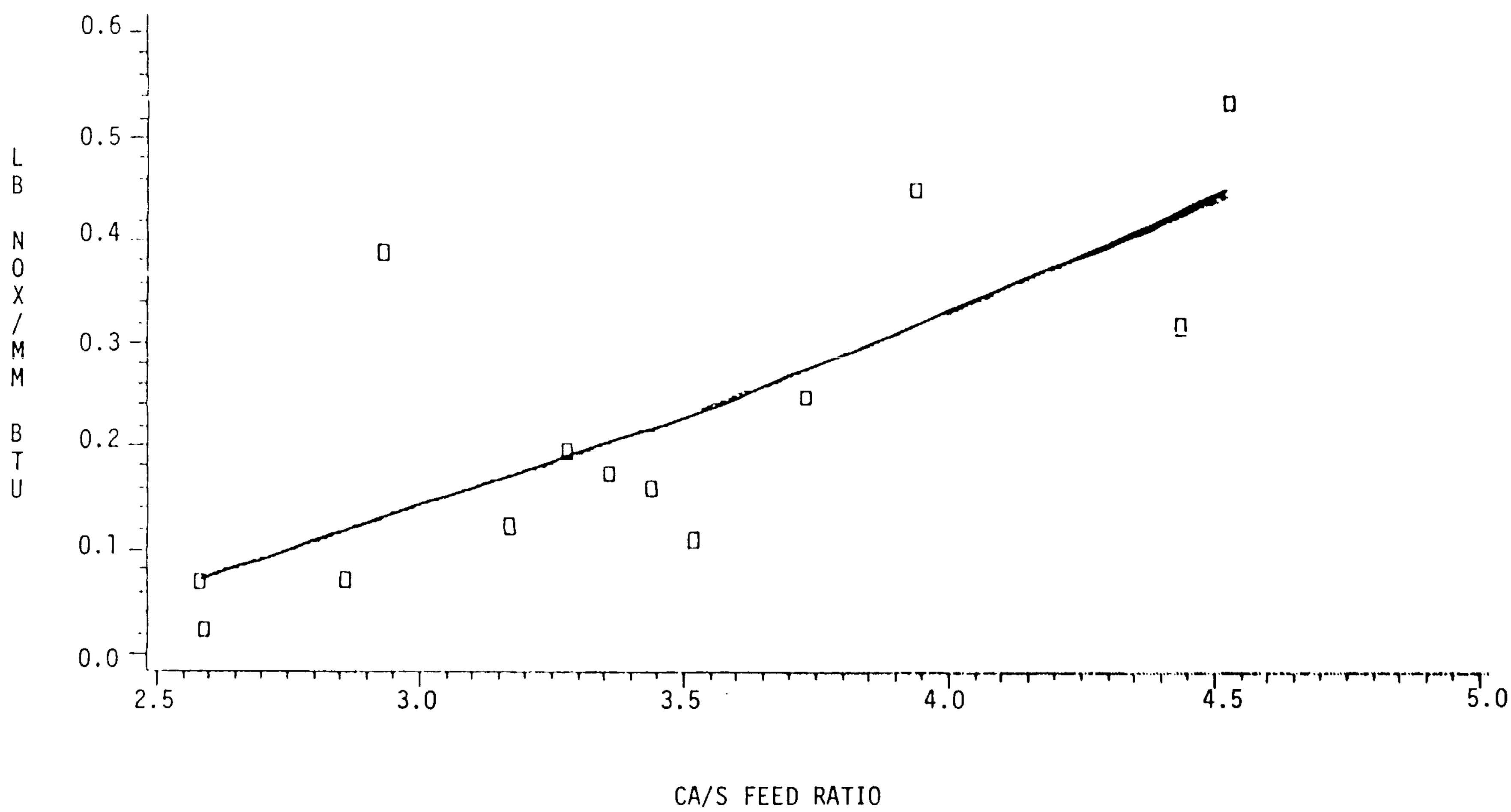
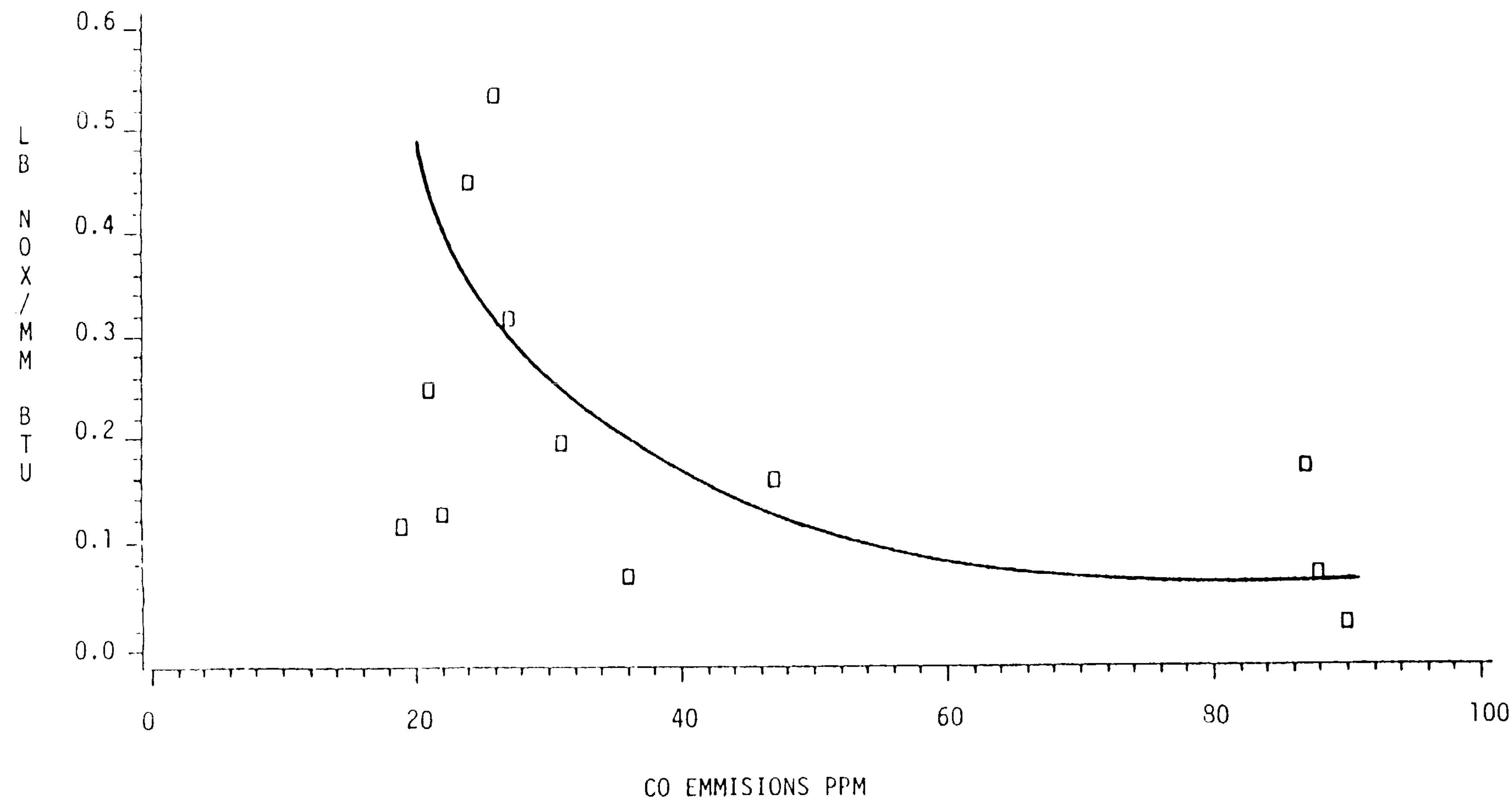


Figure 7.16

NOX EMISSIONS VS CO EMISSIONS



CO emissions for Shamokin and the Keeler/Dorr-Oliver 12 in. diameter combustor are summarized in Table 7.5. Emissions of CO are 4-5 times greater in the laboratory unit compared to Shamokin. This is primarily due to longer gas residence time in the freeboard for Shamokin.

CO emissions for gob fuel tests (33-36) are much higher than CO emissions with culm (Table 7.2). High CO emission level with bituminous gob fuel compared to anthracite culm fuel is due to the higher level of volatile matter occuring in bituminous coal compared to anthracite coal. CO emissions for gob are 186 to 273 ppm whereas CO emissions for culm are 21 to 101 ppm. Expressed on a fuel input basis the CO emissions for gob fuel tests are low, 0.17-0.28 lb. CO/MM Btu fuel input.

The solid sample analysis of test point 5 is presented as typical in Table 7.6. Tables 7.7 and 7.8 present the sample analysis of the feeds for this test point.

7.3 Boiler Efficiency

Boiler efficiency was determined by dividing net heat gain by steam plus blowdown by total fuel heat input to the boiler. Boiler efficiency by this output/input method varies between 54.1% and 82.0% (Table 7.1). The wide variation in boiler efficiency is due to the wide range in combustion efficiency as shown in Figure 7.17.

The linear relationship between steam output and fuel input is shown in Figure 7.18. The steam output/fuel input mass ratio decreases steadily from 2.7/1.0 at low load to 2.3/1.0 at high load. The same trend is shown in the plot of steam output to heat input, Figure 7.19.

Boiler efficiency and combustion efficiency for the high capacity tests generally fall in the lower half of the ranges in efficiency measured for the parametric tests. The high capacity tests were performed with all three zones fluidized and with 4.6-5.3 ft./sec fluidizing velocity. Since freeboard space rates for these conditions are 1.6 to 2.4 times higher compared to 1 zone and 3.5 ft./sec, elutriation is much higher for the high load tests. Lower boiler efficiency is due to the decreased carbon combustion efficiency resulting from increased elutriation at high load operating conditions. In addition, lower combustion efficiency occurs at high freeboard space rate because of reduced gas residence time in the freeboard (see Section 7.1).

7.4 Turndown

A multiple regression analysis was performed on operating variables to derive an empirical steam production model. Zones fluidized, bed depth, superficial velocity and bed temperature were found to be the most important variables which determine steam production. The optimum steam production correlation (Figure 7.20) shows good agreement with test results. Steam turndown capabilities predicted by the model, Table 7.9 and Figure 7.21, show a wide overlap in steam production for 1, 2, and 3 zone operation.

TABLE 7.6

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

(3) PRIMARY CYCLONE SOLIDS SAMPLE ANALYSIS DATA

COMPONENT	PERCENT BY WEIGHT
C	8.93
C (FUEL)	8.78
S	0.567
CaO	4.89
$CaSO_4$	2.41
SiO_2	42.57
Al_2O_3	23.11
Fe_2O_3	2.84
MgO	1.33
L O I	11.06
OTHER	
SIEVE ANALYSIS	
SIZE MICRONS	PERCENT PASSING
300	99.80
150	79.98
50	36.60

BULK DENSITY	55.70
AVERAGE MICRON SIZE	

SAMPLE NO. ______

(4) BED ASH SAMPLE ANALYSIS DATA

COMPONENT	PERCENT BY WEIGHT
C	2.23
C (FUEL)	2.20
S	1.13
CaO	6.99
$CaSO_4$	4.80
SiO_2	53.13
Al_2O_3	23.72
Fe_2O_3	2.40
MgO	1.39
L O I	2.79
OTHER	
SIEVE ANALYSIS	
SIZE MICRONS	PERCENT PASSING
3350	91.90
1700	83.09
1200	75.85

BULK DENSITY	80.03
AVERAGE MICRON SIZE	

SAMPLE NO. ______

SAMPLE SOLID ANALYSIS

(6) BAG HOUSE FLY ASH SOLIDS SAMPLE ANALYSIS DATA

COMPONENT	PERCENT BY WEIGHT
C	3.15
C (FUEL)	3.06
S	0.941
CaO	5.07
$CaSO_4$	4.00
SiO_2	45.60
Al_2O_3	25.18
Fe_2O_3	3.11
MgO	1.34
L O I	4.54
OTHER	
SIEVE ANALYSIS	
SIZE MICRONS	PERCENT PASSING
100	83.30
70	18.72
40	7.45

BULK DENSITY	37.2
AVERAGE MICRON SIZE	

SAMPLE NO. ______

DATE: 4-15-82

TEST No. 5

FORM 1503

TABLE 7.7

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

(1)

ANTHRACITE CULM

ANTHRACITE CULM DELIVERED TO SITE SCREENED ¼"
CONTAINING APPROXIMATELY 6 PERCENT SURFACE MOISTURE

PROXIMATE ANALYSIS		ULTIMATE ANALYSIS (A)		PREPARED CULM SIEVE ANALYSIS (AT COAL BIN)	
COMPONENT	% BY WEIGHT	COMPONENT	% BY WEIGHT	SIZE	% PASSING
INHERENT MOISTURE	4 99	ASH	66 80	4 MESH	86 30
VOLATILE MATTER	8 34	SULPHUR	0 86	8 MESH	56 90
FIXED CARBON	22 37	HYDROGEN	0 98	20 MESH	2A 3
ASH	64 30	CARBON	23 83	60 MESH	5 6
		OXYGEN		100 MESH	2 8
OTHER		NITROGEN	0 47	150 MESH	1 5
TOTAL		OTHER MOIST.	1 83	200 MESH	0 7
SULPHUR	0 603	TOTAL			
% TOTAL MOISTURE					100%

SCREEN By SAIC

CULM SOURCE
STATE AND COUNTY ________________

	ACTUAL	ESTIMATED
BULK DENSITY #/FT³	62.40	60
HHV, BTU/# AS RECEIVED	3846 (A)	

CULM SAMPLE ANALYSIS DATA

FORM 1501

DATE OF SAMPLE: 4-15-82 SAMPLE NO.: TEST No. 5

(A) BY DOE-METC

TABLE 7.8

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

(2)

LIMESTONE	
DELIVERED SCREENED TO ¼ INCH BY 0 WITH A SURFACE MOISTURE OF 3%. APPROXIMATELY 85% $CaCO_3$	
CHEMICAL ANALYSIS	
COMPONENT	AS RECEIVED % BY WEIGHT
$CaCO_3$	70.9
$MgCO_3$	6.65
SiO_2	14.61
Al_2O_3	1.44
Fe_2O_3	1.00
H_2O	0.94
TOTAL	

AS RECEIVED LIMESTONE SIEVE ANALYSIS	
U. S. S. SIZE	% PASSING
1/4"	100
4 MESH	100
8 MESH	96.5
20 MESH	57.7
60 MESH	27.3
100 MESH	20.2
150 MESH	16.6

SAMPLE NO. TEST 16.5 screen by SAIC

SAMPLE WEIGHT (BEFORE SCREENING) 759.4 GRAMS

SAMPLE WEIGHT (AFTER SCREENING) 751.8 GRAMS

ANALYSIS PERFORMED BY Wilson Testing Lab
Shamokin, Pa. 17872

DATE: 4-15-82

LIMESTONE SAMPLE ANALYSIS DATA

FORM 1502

Figure 7.17

BOILER EFFICIENCY VS COMBUSTION EFFICIENCY

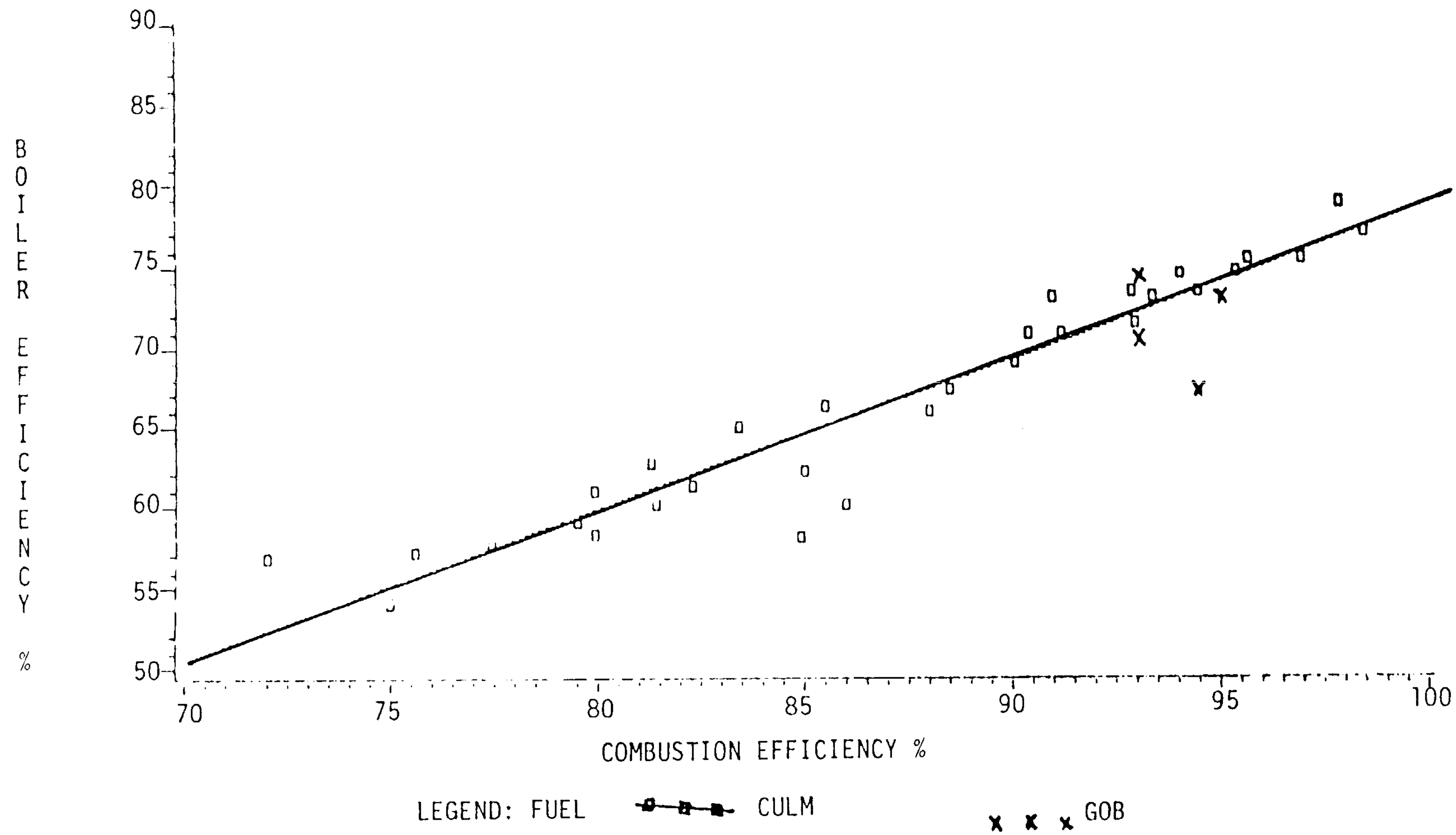


Figure 7.18

STEAM PRODUCTION VS FUEL INPUT

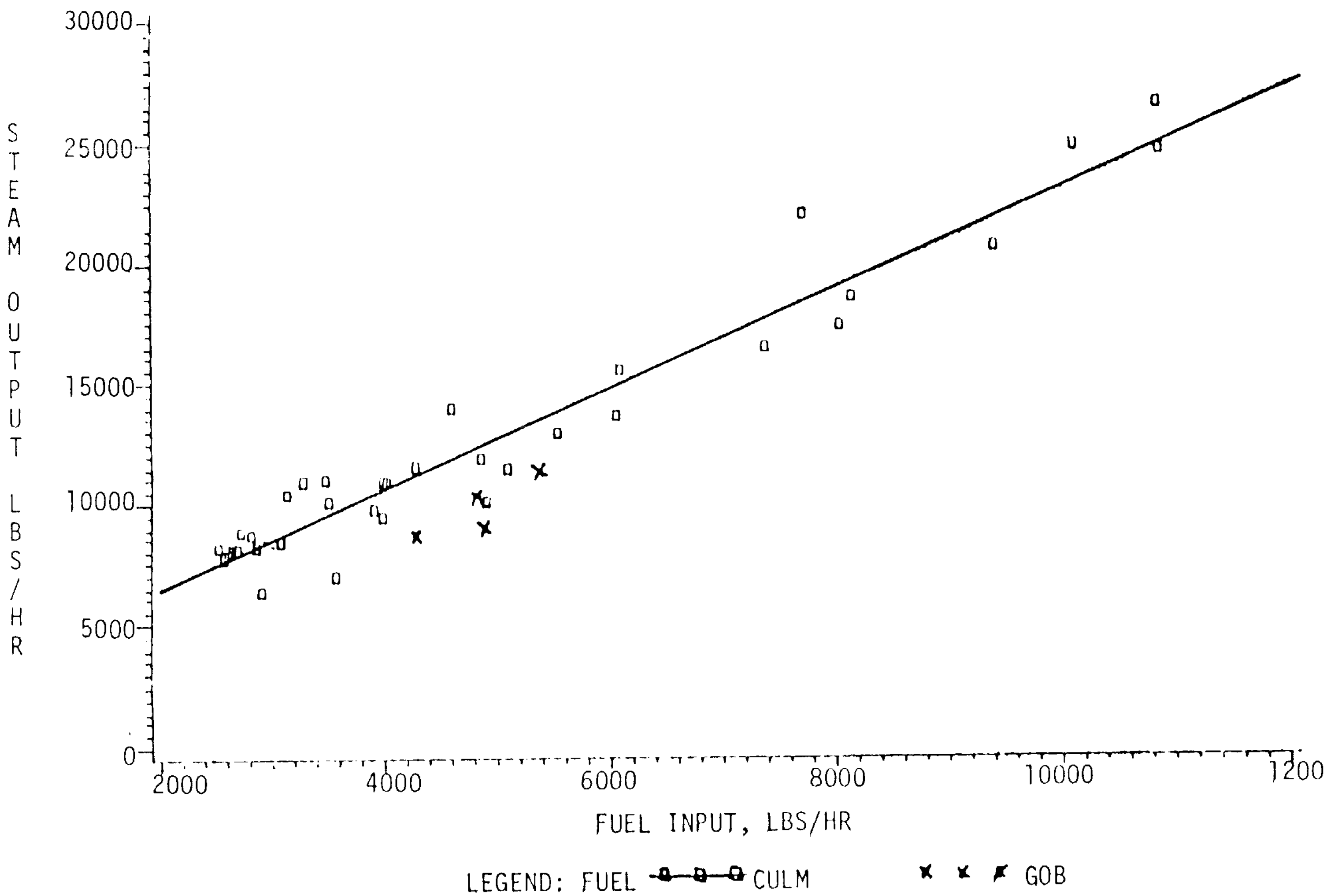


Figure 7.19

STEAM PRODUCTION VS FUEL HEAT INPUT

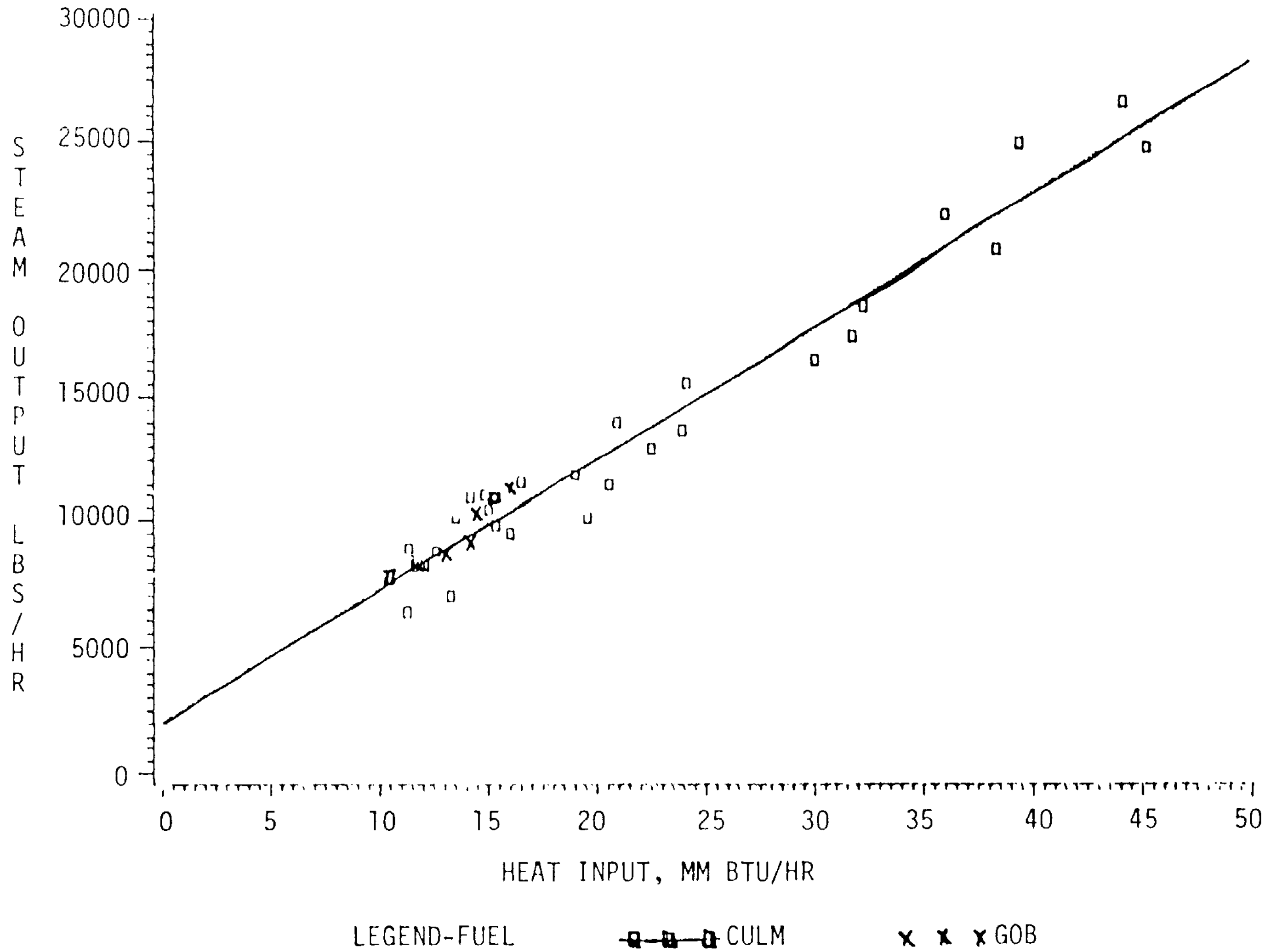
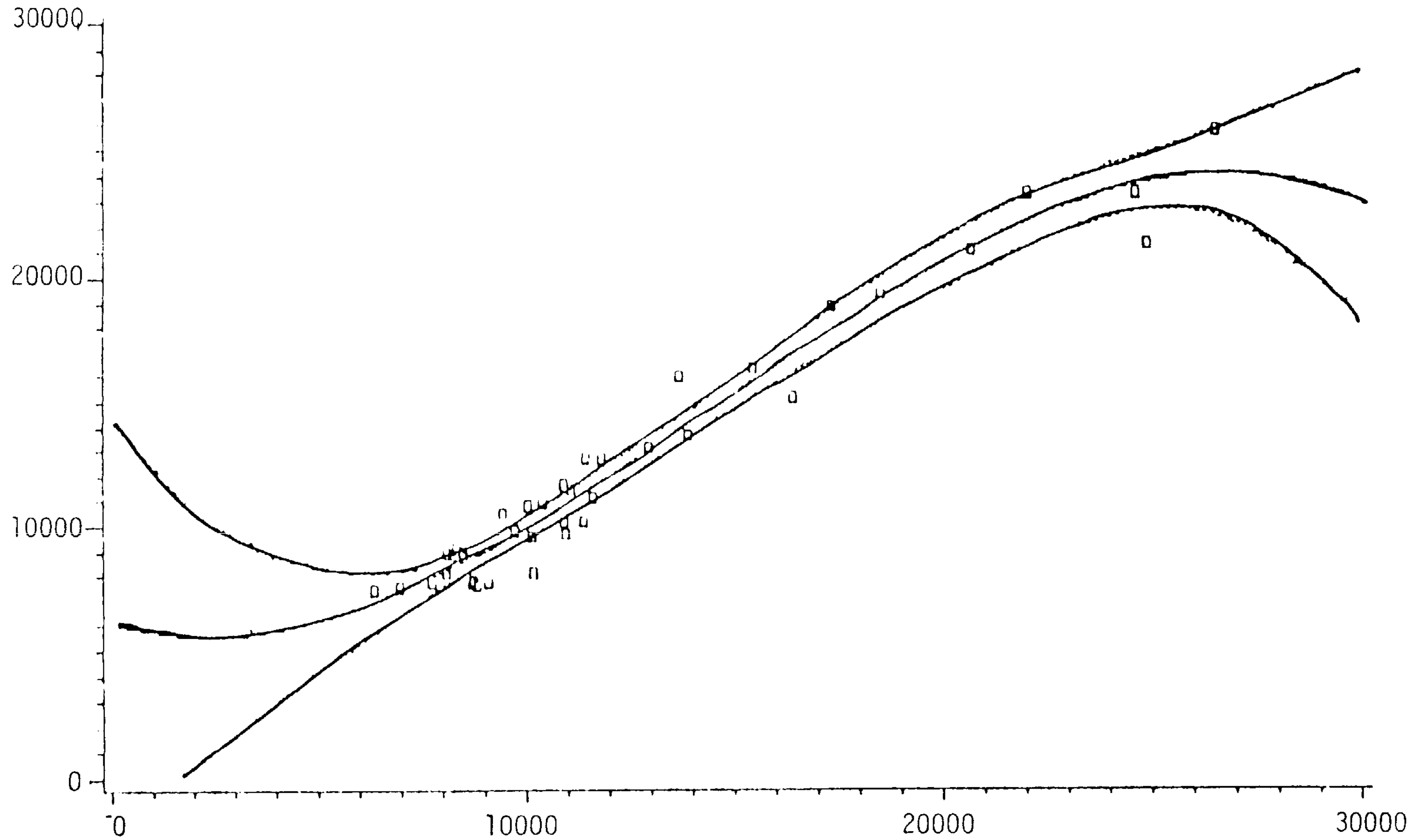


Figure 7.20

STEAM PRODUCTION CORRELATION



Z=NO. ZONES, D=BED DEPTH (IN), V=FT/SEC, T=DEG. °F
WITH 95% CONFIDENCE LIMITS

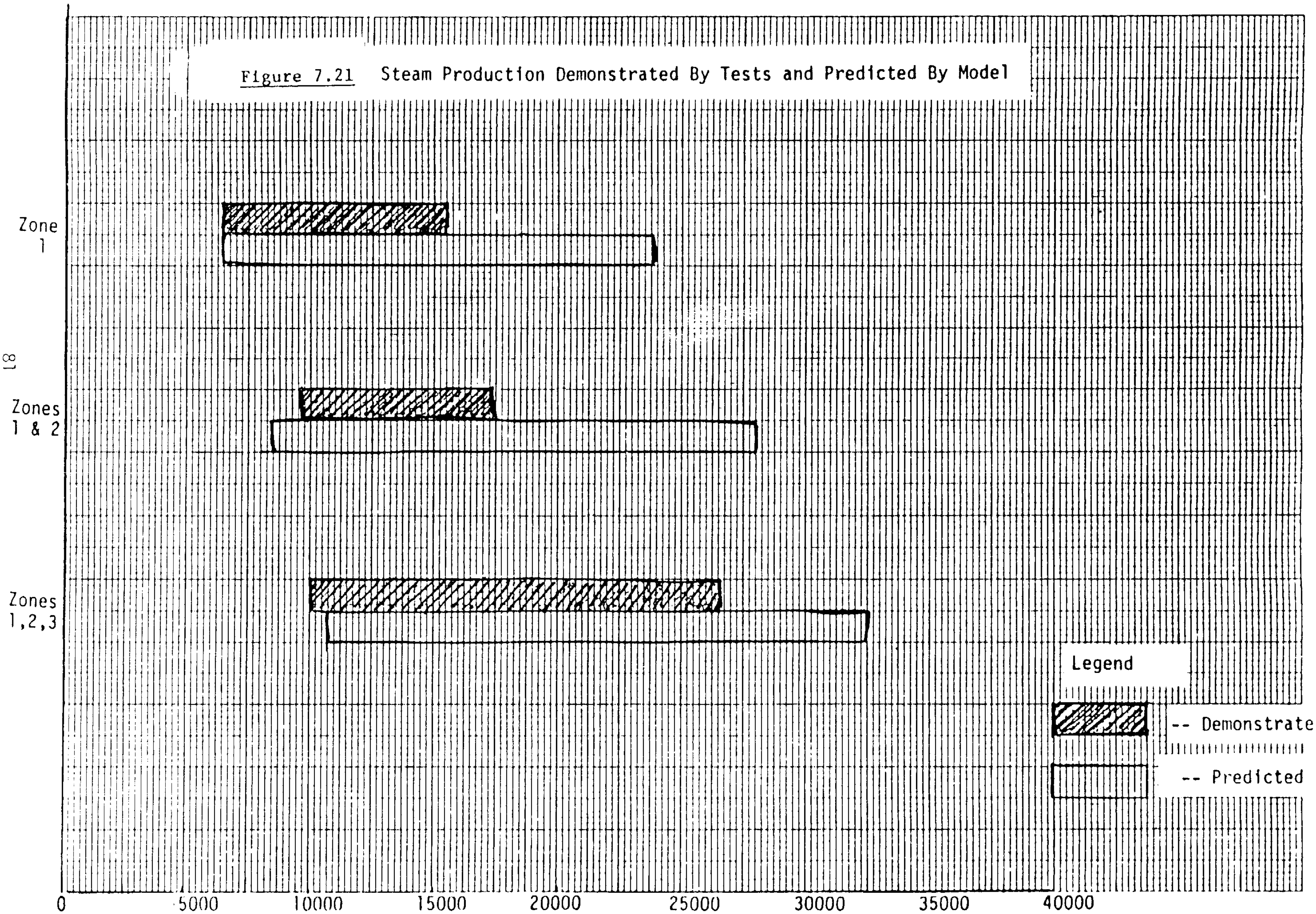


Figure 7.21 Steam Production Demonstrated By Tests and Predicted By Model

Table 7.9

Steam Turndown Capabilities From Steam Production Model (lb/hr)

Zones Fluidized	1	1 & 2	1, 2, & 3
Low load	6400	8500	10700
High load	23800	28100	32500

Operating Conditions	Low Load	High Load
Bed height (in)	36	72
Bed temperature (°F)	1450	1700
Superficial velocity (ft/sec)	3.5	6.0

Maximum production capability which is limited (primarily by the size of the fluidizing air blower) to 6 ft bed height and 6.0 ft/sec, is predicted to be 32,500 lb/hr. Thus, although the demonstrated turndown is 4.2/1, predicted turndown may be as much as 5.1/1. Both the demonstrated turndown and the predicted maximum turndown are much better than turndown based on design specifications, 2.5/1.

Analysis of combustion efficiency and boiler efficiency data (Section 7.2 and 7.3) shows that optimum conditions occur when freeboard space rate is kept at a minimum. The steam production model can be used to determine operating conditions for optimum performance at a given load. For example, for one-half of predicted maximum steam load, 16,250 lb/hr, the boiler should be operated at 1 zone, 3.5 ft/sec and 72 inch bed height. For three-quarters of predicted maximum steam load, 24,400 lb/hr, the boiler should be operated at 2 zones, 4.5 ft/sec and 72 inch bed height.

8.0 DURABILITY TESTING

Extended testing for durability and reliability of the plant and its equipment was initiated in January 1982. Following a shutdown for inspection and maintenance during July 10 to August 8, 1982, the Durability Test period was resumed and continued through the end of the test program in April 1983. Over 5600 hours of operation were accumulated during this period. The objective of this period was to accumulate operating and maintenance experience data as specified by the DOE which could be used as data for other fluidized bed boiler programs. A description of the data collected is contained in the following sections.

In addition to the accumulation of operating and maintenance data, parametric test points continued to be run throughout the Durability Test phase. The purpose of the added parametric testing, which is described in Sections 6 and 7, was to evaluate the effect of changes to the plant equipment (i.e., boiler freeboard refractory insulation, in-bed recycle of cyclone catch) and changes in operating conditions (i.e., higher bed temperature). Finally, the feasibility of operating on a high sulfur bituminous waste fuel which was not part of the original test plan,was conducted.

With the exception of times during which parametric tests were conducted, the plant was run in a turned-down operating mode during extended testing because of the limited steam required by the user. A summary of the plant availability during this period is shown in Table 8.1. The times eliminated from the available hours during December 1982 and April 1983 related to preparations for parametric tests and totaled 258 hours. The plant availability of 92.4% is excellent for a prototype plant after less than one year in service. In fact, periods of 1000 hours of continuous operation without an interruption in steam supply, were accomplished beginning in less than 6 months of service.

8.1 Financial Data

Financial data were accumulated in several categories as defined by DOE. A summary of the accumulated costs is shown in Table 8.2. These data were supplied for use in an analysis for preparation of Reference 6. Table 8.3 presents as typical monthly quantities of consummables and

TABLE 8.1

SHAMOKIN ANTHRACITE CULM FB BOILER

EXTENDED TEST PLANT AVAILABILITY

Period	Hours Run (Fluidized)	Hours Available	Percent Availability
Aug. 9 - Aug. 31, 1982	540	540	100.
Sept. 1 - Sept. 30	718	720	100.
Oct. 1 - Oct. 31 *(Water & Elect. Service Interrupted to Plant)	736.5*	744	99.
Nov. 1 - Nov. 30	720	720	100.
Dec. 1 - Dec. 31, 1982 Planned shutdown for Refractory Installation & Maintenance	368	558 (1)	66
Jan. 1 - Jan. 31, 1983 Replaced Baghouse bags & Seals	679	744	91.
Feb. 1 - Feb. 28	672	672	100.
Mar. 1 - Mar. 31 Installed Cyclone Recycle Pipe Extension and Baghouse Seals	668.5	744	90.
April 1 - April 30, 1983 Evaluated Bituminous Waste & Low Temp. Start on Culm	528.5	648 (2)	82.
Cumulative Availability	5630.5	6090	92.5

(1) Excludes planned shutdown for refractory installation (186 hours)

(2) Excludes planned investigation of low temperature ignition of culm (72 hours)

TABLE 8.2

SHAMOKIN ANTHRACITE CULM-FIRED BOILER OPERATING COST SUMMARY

CATEGORY	1982 AUG.	SEPT.	OCT.	NOV.	DEC.	1983 JAN.	FEB.	MAR.	APRIL
SAIC Labor @ $8.3/Man-HR	$17,466	$17,997	$19,061	$18,154	$17,687	$19,195	$17,419	$18,844	$17,306
Electricity @ $.05/KW/HR	13,269	16,382	15,352	16,498	12,018	15,904	16,184	14,587	11,403
Water @ $1.31/1000 GAL	1,368	1,761	1,638	1,613	1,210	1,897	1,600	1,686	1,743
Start-Up Oil @ $1.10/GAL	1,430			1,567	1,544		505	1,451	
Insurance	4,369				9,924	813	813	813	813
Loader Fuel	519	39		98	57	39			579
Maintenance									
General Maint.	2,335	760	4,350	1,110	3,850	6,565	6,030	5,385	2,040
Computer & Tape Rec.			790	620	620	620	170	170	
Gas Analyser		1,223						1,402	
Sample Analysis	764	764	764		1,852		616		1,395
Subtotal	41,520	38,926	41,955	39,660	48,762	45,033	43,337	44,233	35,279
Limestone Cost @ $5.50/TON.	296	633	792	666	275	517	484		
Steam Revenues @ $2.595 Per 1000 LB/HR	3,367	5,545	5,419	5,861	3,591	5,150	6,160	6,050	3,724

Note (1) Rates shown are average over an extended period
(2) Steam revenue rate includes credit for standby boiler charges
(3) Electricity rates include demand charge
(4) Labor rate includes 30% overhead and are average covering various skills

TABLE 8.3

SHAMOKIN ATMOSPHERIC FLUIDIZED BED POWER PLANT

D.O.E. CONTRACT DE-AC21-78ET12307

SUMMARY OPERATING DATA FOR AUGUST 1982

(PLANT START UP AT 8/9/82 0800)

Total Operating Time 8/9/82 - 8/31/82	540 Hrs.
Feeds: (Estimated Total Quantity Used During Reporting Period)	
Total Culm Feed [1.]	790 Tons
Limestone [1.]	53.8 Tons
Start-Up Coal	1800 Lbs.
Start-Up Burner Oil	804 Gallons
Utilities	
Electric Power Used 8/9/82 - 8/31/82	243,960 KW-Hr
Water - Total Consumed	1,061,000 Gallons
Boiler Feedwater 8/9/82-8/31/82	484,170 Gallons
Process Steam Generated "	3,898,400 Lbs.
Revenue	
Steam delivered to Cellu Products 1297.6 X 10^3 lb.steam 8/9/82-8/30/82	$3367.

AUGUST RATE/QUANTITY DATA

	Period	Quantity	Rate	Total
Labor	8/1 - 8/31/82	2161.25 Hr.	$8.0815/Hr	$ 17,466.21
Water	7/30- 8/31/82	1,061,000 Gal	$1.2893/1000 Gal.	$ 1,368.00
Power	8/4 - 9/2/82	262,880 KW-Hr	$ .050476/KW Hr	$ 13,269.00

1. Feed Bin Weight Scales Used to Record weight consumed per day.

and others. Table 8.4 presents a summary of average monthly expenses and revenues for the April 1982 through August 1983 operating at part load. This table also shows the estimated monthly expenses and revenues at full load. This summary indicates that the boiler is economically viable at steam revenues above $4.62 per 1000 pph.

In general, it should be noted for this test data that only a fraction of the total plant steam capacity was sold and this at a low rate. The rate was originally negotiated on the basis that the prototype boiler may initially have a low availability and therefore, an existing boiler at the user's facility would need to be kept on standby. As shown by the plant availability data in Table 8.1 this assumption proved pessimistic.

It is projected that a competitive rate of $5.00 to $6.00 per 1000 pounds of steam would adequately cover the operating cost of the prototype plant if the full 20,000 pph of steam capacity were sold. However, due to the general economic conditions in the country, location of new industrial plants at the Shamokin Industrial Park or expansion of the current user's facilities did not materialize during the program period. Therefore, future operation of the boiler plant at competitive rates for sale of steam remains unclear.

Analyses of both steam boilers and cogenerating plants scaled from the prototype culm fired plant suggest that plants in the 20,000 to 100,000 pph range can be economically viable with reasonable steam sales (Ref. 6). Cogeneration using extraction of back-pressure steam turbines enhances profitability especially in the larger plant sizes.

8.2 Service Experience Data

The service experience data compiled for each month during the Durability Test phase included the record forms listed below as well as a monthly data tape and material chemical analyses for monthly performance data. The data tape for the month included the record of Tape File No. 1 (hourly record of 62 data variables as identified on Table 3.2). The service experience forms and chemical analyses forms compiled each month are listed below and the March 1983 data is included in Appendix 4 as typical.

TABLE 8.4

SHAMOKIN AFB BOILER PLANT

AVERAGE MONTHLY COST SUMMARY

COMPARISON OF R & D PERIOD VS COMMERCIAL OPERATION

	ACTUAL APR. 82 - AUG. 83 PART LOAD		ESTIMATED FOR FULL LOAD	
A. Operating Expense				
SAIC Labor	$ 18,125		$ 18,125	
Electricity	14,622		20,000	
Water	1,613		3,200	
Start-Up Oil	722		725	
Insurance	1,765		1,765	
Loader Fuel	148		400	
Maintenance				
General	3,603		6,000	
Computer & Tape Recorder	332		1,000	
Gas Analyzer	292		300	
Sample Analysis	684		300	
Subtotal	$ 41,906		$ 51,815	
B. Purchasing Expense				
Limestone	523		1,500	(1)
Culm		(3)	5,000	
Ash Disposal	NA		4,900	
Total Expenses	$ 42,429		$ 63,115	
C. Revenues				
Steam Revenues	4,985		61,315	(2)
Ash Revenues	-		1,800	
Total Revenues	$ 4,985		$ 63,115	

(1) At $2/Ton

(2) At $4.62/1000 PPH and 92% Availability

(3) Supplied at no cost

DOE Form No.	Data Contained (Appendix 3)
1202	Material Delivery and Removal and Power Used
1203	Labor Used - Operating and Maintenance
1401	Corrective Maintenance Record
1402	Preventative Maintenance Record
1501	Culm Sample Analysis Data (Table 7.7)
1502	Limestone Sample Analysis Data (Table 7.8)
1503	Ash Sample Analysis Data (Table 7.6)

The service record for the major equipment is discussed in Section 9, Mechanical Performance. The monthly data was supplied to DOE so that these data and comparable and consistent data compiled from other DOE funded fluidized bed plants could be entered in a computerized data bank (taped performance data variables.)

9.0 MECHANICAL PERFORMANCE

From August 18, 1981 through April 30, 1983, 10,128 hours of operation were accumulated on the prototype culm boiler. The tests occurred in three periods as follows:

Shakedown	-	725 Hours -	8/18/81 - 10/30/81
Parametric Test	-	1861 Hours -	11/16/81 - 12/15/81, 4/15/82 - 6/24/82, 4/27-30/83
Durability Test	-	7542 Hours -	12/18/81 - 4/15/82, 6/24/82 - 4/27/83

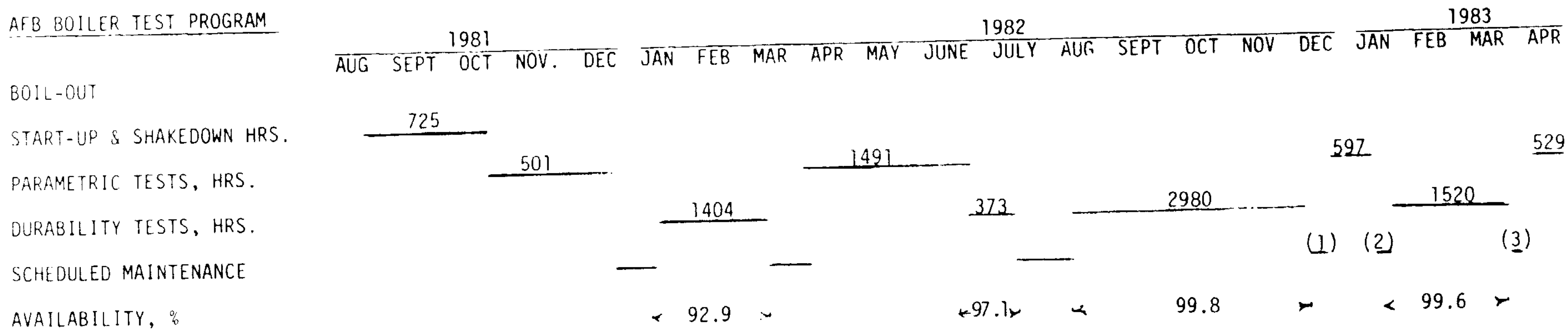
An overall picture of the test program is depicted on Figure 9.1. There was some overlap of test objectives, i.e., parametric tests continued to be run through April 30, 1983. Throughout the test program periodic scheduled shutdowns were made to perform routine maintenance, major equipment refurbishment, modifications to plant equipment, piping, instrumentation, etc., and in addition, unscheduled shutdowns due to plant malfunctions or external outages did occur. In the following sections the mechanical performance for the various equipment areas of the plant is discussed except that already described for the shakedown test period (Section 5.5).

9.1 Receiving, Preparation and Storage - Culm and Limestone

Culm crushing, transporting and feeding proceeded at a slower rate than the normal design rate due to difficulty in handling wet (up to 10% moisture, as received) material especially during below freezing temperatures. The original plant design concept included an enclosure around the entire structure. Radiated heat from the boiler and process ducting was expected to minimize handling problems associated with wet culm during cold weather. The enclosure was eliminated during the plant's final design because of DOE funding constraints, and heat tracing and small, localized enclosures were planned as substitute measures. The installation of heat tracing and enclosures continued into the winter of 1981/1982 with considerable interruption of testing due to frozen culm in bucket elevators, silos, bins, screw feeders, etc. The interruptions finally lead to a postponement in running at operating conditions above minimum load until the spring of 1982, whereupon the high load parametric testing continued.

It should be noted that the capital expense required to weatherize the culm processing operation ($100,000.) was not economically warranted for the limited scope of the planned test program. Since the steam demand of the local user could be met at minimum plant load the only requirement was to plan higher load parametric tests for those periods when weather was not severely cold and/or wet.

Significant improvement was made however and no culm processing related interruption in testing occurred during the winter of 1982/1983. A summary of the equipment modifications made and those required to reach full rating is provided in Table 9.1.



NOTES: (1) BOILER REFRACTORY REWORK

(2) BAGHOUSE SEAL REPLACEMENT

(3) ID FAN REWORK AND INSTRUMENT AIR COMPRESSOR SERVICE

FIGURE 9.1

TABLE 9.1

CULM RECEIVING PREPARATION AND STORAGE MODIFICATIONS

PROBLEM	COMPLETED
FLOW BLOCKAGES DURING PROLONGED RAIN AND SNOW OR SUB FREEZING TEMPERATURES	HEATED ENCLOSURES AROUND CRITICAL FEED CHUTES USING AIR FROM F. D. BLOWER
	HEATED CULM SCREEN USING AIR FROM F. D. BLOWER
	SS TY-ROD SCREEN TO REDUCE CLOGGING & BLINDING IN EXTREME COLD WEATHER
	SPACE HEATER UNDER STORAGE SILO
	STAINLESS STEEL LINER IN CRITICAL CHUTES & DUCTS AND IN FEED BIN CONES
	ENCLOSURE AROUND LOWER SECTION OF FEED BIN AND ENTRANCE TO SCREW FEEDERS
	REMOVOABLE COVERS ON SCREW FEEDERS TO PROVIDE ACCESS FOR CLEARING OF BLOCKAGES
	RECOMMENDED
CULM PROCESSING AND FEED CAPACITY LIMITED DURING WET OR SEVERE SUB-FREEZING CONDITIONS	PROVIDE COVERED STORAGE AREA FOR 1000 TONS OF CRUSHED CULM AND CONVEYOR TO PREPARED CULM SILO
	PROVIDE ENCLOSURE FOR FEED BIN AND SCREW FEEDERS HEATED BY FLUID BED BOILER RADIATED HEAT

9.2 Fluidized Bed Boiler System

9.2.1 Fluidized Bed Boiler

The fluidized bed boiler ran extremely well for a prototype unit; with relatively few modifications required to provide trouble free operation. As mentioned in Section 5.5 minor modifications were made during the shakedown period including: refractory insulation was added to adjust the heat balance and improperly cured refractory was repaired.

During the early parametric test period, at 1200 to 1400 hours total running time, several changes were made to reduce clinker formation and prevent clinkers from flowing into the ash removal fluoseal. It was surmised that airflow leakage into zones 2 and 3 when they were not fluidized, led to clinker formation within these zones. The shutoff of airflow to these zones was modified and was made bubble tight, and thereafter clinker formation was much reduced and was usually traceable to operating procedures such as overfueling, etc.

To prevent clinkers from moving from the boiler into the ash removal fluoseal, a screen or cage with a minimum opening 1-1/2 inches as shown in (Figure 9.2) was constructed over the 6" ash drain on the boiler floor. Again, considerable improvement was noted in ash removal as far as blockages caused by clinker was concerned.

The remaining changes to the boiler were made in support of parametric tests and included (1) evaluation of fuel freeboard refractory insulation and (2) in-bed vs above-bed recycling of cyclone catch. In December 1982, after 7500 hours of operation, 1-1/2 inches of refractory insulation was added to the bare sidewalls only of the boiler freeboard from a height above the windbox of 6 ft. up to a height of 22 ft. above the windbox. The front and rear walls were refractory lined from the beginning of the test program so the addition of refractory on the sidewalls represented a condition of 100% freeboard refractory insulation versus 50% for the preceeding 7500 hours of testing. Performance results with the additional refractory are discussed in Section 7.1. Mechanically, no problems were noted with the installation of the refractory and the condition of all refractory was good at the end of the program with 10,128 total hours of operation.

ASH DRAIN PIPE SCREEN

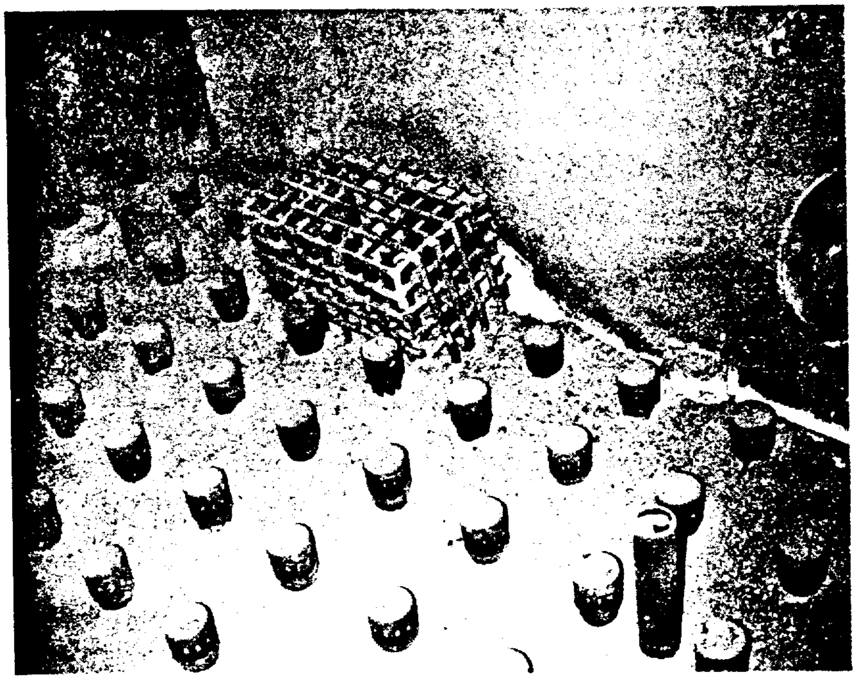


Figure 9.2

ASH RECYCLE PIPE EXTENSION

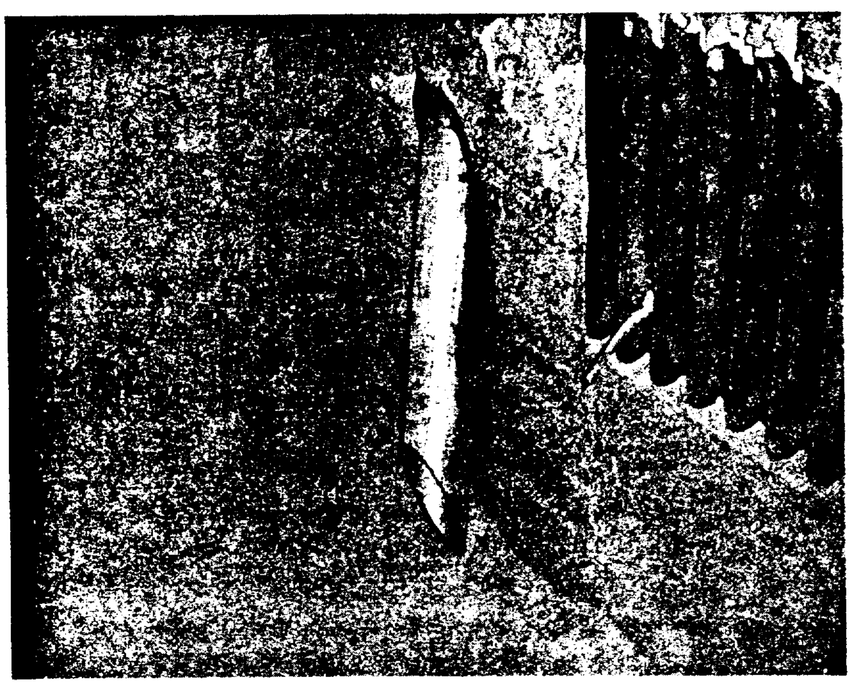


Figure 9.3

In March 1983, the cyclone recycle pipe was extended into the boiler, Figure 9.3, to evaluate the effect of recycle in-bed versus above-bed. Performance results are discussed in Section 7.1 and 7.2.1. Mechanically, no problems were noted with 6 inch SS recycle pipe which ran for over 500 hours at bed temperatures up to 1675°F.

Tube wear measurements were taken at periodic intervals throughout the test. Due to scatter on the ultrasonic readings, the data should be viewed with some reservation. Wall tubes in the active bed region showed a thickness reduction over 7500 hours (period from baseline measurement to the end of the test program) of .015 inches. The original tube thickness was .170 inches. This wear (two tubes on the sidewall of zone 1 were left uncovered by refractory for the duration of the test) equates to .020 inches per 10,000 hours. In the splash zone above the bed, wear dropped to 1/3 to 1/2 of this rate and in the free board thickness loss appears negligible. The in-bed tubes only achieved 650-900 hours of operation (zones 2 and 3,respectively) and though thickness loss may be greater than that for the wall tubes, the data is widely scattered.

It is recommended that suitable means be taken in the tube design and fabrication to provide a minimum tube life of 50,000 hours either by adjustment of original thickness, or protection with alonizing or chromatizing.

A metal specimen holder was mounted at the wall of the boiler at the location of the unused in-bed fuel feed port which is in zone 1 and is always immersed within the bed. Although 3500 hours of exposure was recorded the control specimen, Inco 600, which was expected to suffer moderate to severe sulfidation attach, was relatively unaffected and so meaningful conclusions regarding the samples of sigmatized 310, SS 347 and 253 cannot be drawn. Apparently the location of the specimens was such that attack was mild compared to that generally expected and reported in similar fluid bed environments. Visual inspection showed essentially no loss of material due to erosion.

No problems were associated with the water/steam side of the boiler.

9.2.2 Recycle Cyclone

The ash recycle cyclone performed as expected with no mechanical degradation apparent after completion of the 10,128 hours of testing. Boiler performance as a function of the amount of collected ash which was recycled is discussed in Section 7.1. The recycle valve performed well but it was noted that some recycled ash was flowing to the boiler when the valve was in the fully closed position, so a blanking plate was installed to evaluate the effect of zero recycle.Also the length of the recycle pipe was extended late in the test program to evaluate in-bed versus above-bed ash recycling.

9.2.3 Fluoseal

The main Fluoseal, which is a valve/lift arrangement used to drain ash from the boiler and transport the ash to the ash cooler, required some modification during the test program. Also, it was not possible to operate the Fluoseal in a continuous manner as was originally intended. The Fluoseal is essentially a fast fluid bed which entrains the ash and lifts it up to a downcomer leading into the top of the ash cooler. Ash flow is intended to be controlled by airflow which is introduced at the bottom of the Fluoseal. The minimum continuous flow rate for the Fluoseal was too high for constant ash removal so the Fluoseal was operated as a batch removal device with operation once every several hours for a continuous period of 1/3 to 1/2 hour at a time. During a major portion of the test program, culm feed to the boiler was screened to a larger particle size to accommodate wet culm processing difficulties and the larger feed size may have contributed to the problems associated with continuous operation of the Fluoseal.

Also the Fluoseal was refractory lined internally with 6 inches of A.P. Green KS-4 refractory which abraided considerably during the first several 1000 hours of plant operation and this had an adverse affect on ash removal performance. At the 4500 hour point, the Fluoseal was relined with A.P. Green Lo-Abraide refractory and very little abrasion was evident over the subsequent 5600 hours of operation. Ash removal continued as a batch procedure.

Difficutly in batch operation with the Fluoseal was experienced when clinkers which formed in the boiler or Fluoseal could not be fluidized.

9.2.3 (Continued)

These conditions occurred infrequently after installation of the screen over the boiler ash drain and were usually traceable to operating procedure such as overfueling.

9.3 Ash System

9.3.1 Ash Cooler

The Ash Cooler is a 3 celled fluidized bed wherein boiler bed ash is cooled to 300°F and boiler feedwater recovers the heat given up by the ash. The cooler did not perform as intended in several respects although the oversized culm for the boiler fuel bed undoubtedly adversely affected the cooler performance. The cooler fluidized satisfactorily for periods up to several days but then one or more cells would defluidized due to an accumulation of oversize ash material.

The cells had individual windbox compartments and walls dividing the beds from one another. A weir at the top of the beds and a 4" x 8" hole in the separating wall at the bottom of the beds, allowed ash flow from cell 1 to cell 2 to cell 3. At the bottom of cell 3 is a drain leading to a Fluoseal for removal of ash to the penumatic conveying system which transports ash to the ash storage silo. Following defluidization of two of the three cells which ultimately led to excess ash temperature at the cell 3 discharge point,each compartment of the ash cooler was manually drained following which cooler operation was resumed. Attempts to resolve the operating problems with the ash cooler were not immediately successful so the system was operated in the manual mode described, for the duration of the test program. System development effort was concentrated instead, on acquiring parametric and extended operation data and an optimizing boiler performance.

9.3.2 Ash Transport Pipes

The Fluoseal at the exit of cell 3 of the ash cooler transported the ash to a hopper and from there ash was pneumatically conveyed to the ash storage silo. The metal elbows used in the dense-phase pneumatic piping system for ash transport eroded through the wall in 500 to 2000 hours of operation and were either replaced with new elbows or repaired with metal-filled epoxy. The elbows were made from Ni-Hard material and had wear plates welded at the turn of the elbow. Improved elbow materials and designs should be considered for longer time between replacements.

9.3.3 ID Fan

At the top of the Fluoseal, the airflow used to lift the ash from the ash cooler drain to the ash hopper, was mixed with the ash cooler exit fluidizing airflow and this mixed airflow was passed through a cyclone to remove entrained particulate. The large amount of entrained particulate led to a significant amount of particulate carryover past the ash cooler cyclone into the ID Fan and baghouse. Erosion of the leading edges of ID fan blade traceable to the ash cooler particulate carryover and necessitated weld repair to the blades at 4500 hours and 7500 hours.

At the 7500 hour operating point, a change was made to the Ash Cooler Fluoseal exit whereby a settling chamber was added to reduce the entrained ash being lifted into the ash cooler cyclone. Subsequent inspection of the ID fan indicated that entrained particulate was substantially reduced with attendant reduction in fan blade wear.

9.3.4 Flue Gas Baghouse

The main flue gas exited the secondary cyclone, passed through the pre-heater and ID fan and then into a pulse-jet baghouse. Indications are that the baghouse which was sized for a 6:1 air-to-cloth ratio, was too small for this application, and a 3:1 to 4:1 air-to-cloth ratio is recommended for similar applications. The baghouse pressure drop was quite high at high load conditions and the blowoff of the pressure relief door on the baghouse caused curtailment of some test conditions.

About 1/3 of the Nomex bags required replacement over the 10,128 hours of testing and bag inspection showed failure to be mechanically induced. There were no signs of excessive chemical attack in the baghouse.

A silicon rubber seal, (Figure 9.4) used to seal the venturi and bag assembly to the baghouse, degraded by shrinking or embrittling over time with the result that dust leakage around the seal led to a visible stack exit. A change in seal material to Viton improved the seal life to some degree, however the seal life (1000-2000 hrs) remains inadequate. A better material, i.e., a fabric seal or improved rubber seal is needed to provide a reasonable service interval.

BAGHOUSE SEAL FOR VENTURE AND BAG

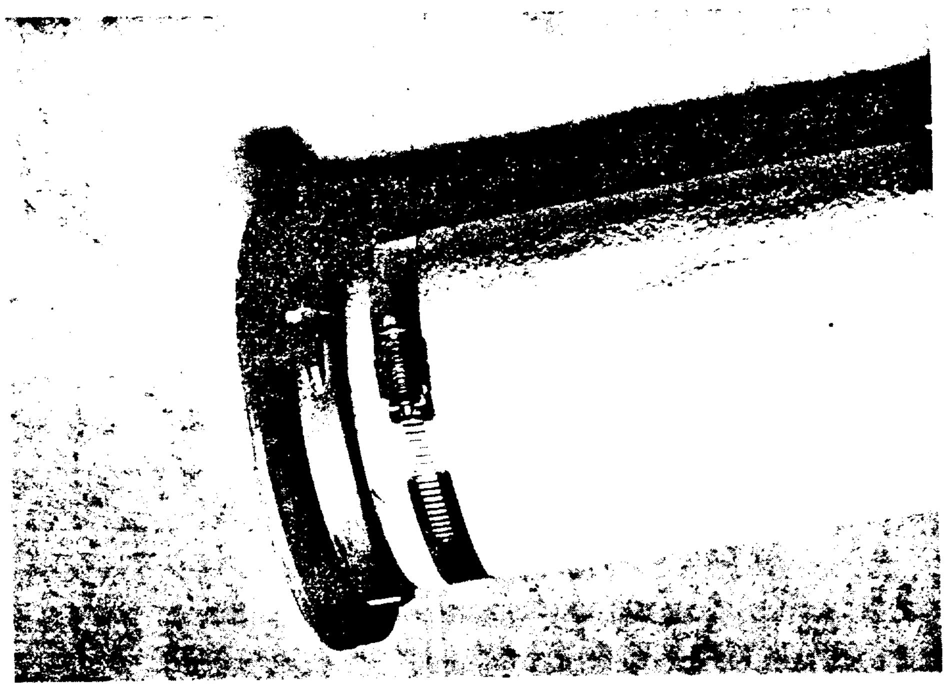


Figure 9.4

9.4 Controls and Instrumentation

The computer control system and instrumentation generally performed well throughout the test program. During the majority of the test program the computer operated the plant by holding a preset fuel flow, and the data was logged and printed every half hour. The minimal effort required by the plant operators gave the impression that the plant control and operation was fully automated, except for some material handling operations such as loading culm in the feed hopper and trucking away collected ash, and some maintenance duties. However, as a result of the batch operation dictated by the Fluoseal, the load following control loop could not be implemented and computer control was limited to holding present conditions. The automatic temperature control however, did control bed temperatoure to ± 10 to 15°F when ash was not being removed from the bed. The data log and several displays used by the operators when running the plant are shown in Appendix 4. The original records of all the data are maintained at the plant site. Selected data was also recorded on 9 track tape and submitted to DOE. The parameters recorded on tape are shown in Table 3.2 and a typical data block is shown Appendix 5.

During the early months of the test program operational problems with the computer were encountered which were traced to dust contaminating the computer disk. The disk system was enclosed in a "clean-room" atmosphere with filtered air and the problem was corrected. A similar operational problem was encountered with the 9 track tape recorder midway into the test program. After many weeks of trouble-shooting, the recorder was exchanged for a seemingly identical recorder which functioned properly. The contractor's original recommendation was to use a disk data recorder instead of the tape format which was preferred by DOE for compatability reasons. A disk recorder is preferred because data can be recorded almost as fast as the computer can supply the stored data. Recording the data on tape took up to several hours per data point and the potential for problems either with the recorder or computer are considerably greater during the much longer time spent recording data.

An intermittent problem arose with the electronic clock in the computer. The problem was exhibited by an abrupt time shift in the computer clock and because data storage time is limited (see Section 3.3.4) loss of data could and sometimes did result. The clock operation appears to be sensitive to radio frequency interference. Replacing the computer clock card helped reduce the sensitivity but a redesign of the computer clock system seems advisable.

Instrumentation difficulties were confined largely to problems brought about by wet and freezing weather conditions. Installation of local enclosures, sealing of control cabinets, and heat tracing were extensively used to protect equipment and instrumentation after the plant enclosure was cancelled. Some shorting and freezing of electrical connections and water/steam instruments occurred, expecialy during the 1981/1982 winter, but as the aforementioned remedies were provided, the frequency of such occurrances reduced significantly.

The gas analyzer operation was adversely affected by dust and condensate in the gas sample.The analyzer was run continuously with a 5 minute purge of clean air every half hour to attempt to minimize accumulation. A screen filter was used in the probe assembly to remove dust particles.

To alleviate the problems due to dust contamination, a revised procedure is recommended which reduces gas sample analyzer on-line time with purge maintained for the remaining time, (i.d., analyzer operation for 5-10 minutes every few hours). Alternatively, daily system preventative maintenance may be required to assure reliable operation. The gas analyzer's condensate removal system was modified during the test program to improve removal efficiency. The air-cooled condenser was replaced with a water-cooled condenser and although some improvement was noted, contamination continued to be a problem. The zirconium cell used for oxygen analysis was damaged on several occassions by the excess condensate. A change to an in-situ type oxygen probe is recommended for similar applications in the future. The in-situ type analyzer which operates on the sample at temperatures well above the dew point was just becoming available at the time the Shamokin analyzer was procured and reliability was not well documented.

10.0 REFERENCES

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3. Preliminary Design of Prototype Unit, Curtiss-Wright Corporation Report Number FE 3269-16A, September 1979.
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5. Fluidized Bed Combustion Development Facility and Commercial Utility, AFBC Design Assessment, Quarterly Technical Progress Report, (January through March 1981), Babcock and Wilcox Co., August 1981.
6. Klett, M.G., and Dowty, T.E., Operating Cost and Sensitivity Analysis for the Shamokin Fluidized Bed Boiler, Gilbert Associates Inc. Report R-08-3279-060, June 1983.

11.0 APPENDICES

APPENDIX 11.1 PARAMETRIC TEST DATA

Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Date	10/29/81	12/10/81	12/13/81	12/15/81	4/15/82	4/22/82	4/30/82	5/5/82	5/7/82	5/18/82	5/21/82	5/29/82	6/1/82	6/10/82	6/21/82
Zones	1	1	1	1	1,2	1,2,3	1,2,3	1,2	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3	1,2	1,2,3
Bed T, °F	1485	1533	1543	1542	1548	1556	1566	1538	1576	1663	1563	1641	1459	1534	1569
Sp Vel,ft/sec	4.0	3.5	5.2	5.2	3.5	3.5	3.5	5.3	5.2	5.3	4.6	3.5	3.5	3.5	5.3
Air rate,scfm	3950	3333	4934	4977	4247	5110	5124	6458	7565	7398	6777	4941	5405	4285	7705
Bed Ht, in.	36	36	38	60	36	38	48	56	48	61	57	36	36	48	37
Steam, lb/hr	6937	6342	9432	15,475	9746	11,826	13,680	17,367	18,514	26,570	24,894	12,938	10,065	11,453	16,431
Fuel, lb/hr	3573	2909	3980	6088	3914	4854	6066	8052	8150	10,858	10,123	5,542	4,903	5,098	7382
Steam/culm	1.94	2.18	2.37	2.54	2.49	2.44	2.26	2.16	2.27	2.45	2.46	2.33	2.05	2.25	2.23
Limestone,lb/hr	667	518	598	824	425	651	844	1450	1483	1568	1025	779	728	649	1099
Feedwaterlb/hr	7284	6659	9928	16,289	10,259	12,448	14,400	18,281	19,488	27,919	26,204	13,619	10,595	12,056	17,296
Steam, psig	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Feedwater, °F	231	230	230	228	238	235	234	231	231	227	226	236	234	233	233
Wdbx T, °F	274	257	287	294	268	265	257	275	304	313	290	287	280	284	307
Frbd T, °F	984	961	1085	1260	1023	1059	1132	1260	1242	1412	1361	1118	1044	1093	1199
CB inlet, °F	715	704	778	935	762	784	849	958	932	1149	1060	835	781	829	902
CB outlet, °F	474	460	505	538	491	508	527	557	567	610	588	518	510	507	561
Ca/S ratio	5.46	5.1	4.45	5.15	2.93	3.73	3.36	3.94	4.53	3.52	2.58	3.44	3.28	3.17	4.44
Sulfur capt.	92.6	94.2	90.2	93.3	93.5	92.4	94.7	93.7	92.9	94.7	92.5	93.5	91.7	91.9	89.7
Comb Eff, %	84.9	86.0	85.0	90.1	88.5	88.0	79.9	77.4	81.4	81.3	85.5	82.3	75.0	79.5	79.9
Excess air, %	97.3	101.4	97.0	29.0	73.1	71.0	46.3	41.5	56.5	11.1	8.4	44.9	94.6	41.6	76.3
Boiler Eff,%	58.2	60.1	62.2	69.1	67.3	66.0	60.9	57.6	60.1	62.6	66.3	61.3	54.1	59.1	58.3
Prim Cyc Valve%	0	20	20	20	50	50	50	50	50	50	50	50	50	50	50
Ash bin, %C	4.80	3.33	2.43	5.73	2.20	2.55	4.22	6.44	7.18	5.78	6.46	2.74	4.91	2.15	5.09
Baghouse, %C	4.98	3.15	3.45	5.75	3.06	3.40	3.52	3.60	5.10	4.72	7.13	3.48	3.49	3.64	3.36
Carbon burn %	80.0	88.8	91.3	80.4	92.3	91.3	86.3	79.7	76.8	82.4	77.7	90.8	85.4	92.4	84.7
Fuel %C dry	23.28	25.09	25.26	24.47	24.27	25.89	24.95	24.96	24.82	25.84	24.15	25.76	25.70	26.59	25.09
FuelBtu/lb dry	3700	3857	4019	3950	3918	3908	3936	3943	3961	4070	3891	4053	3997	4040	4062
Fuel, % H_2O	9.2	5.2	4.4	6.1	4.8	4.8	5.1	4.2	3.8	3.2	3.8	5.3	4.3	5.1	5.2
Fuel, % +4M	12.9	4.2	3.9	2.8	13.7	12.0	13.5	8.8	12.8	8.3	8.5	4.8	8.2	7.1	5.8

APPENDIX 11.1 (Con't)

	16 6/25/82	17 6/24/82	18 11/24/82	19 12/29/82	20 12/30/82	21 12/31/82	22 1/10/83	23 1/12/83	24A 1/18/83	24B 1/20/83	25A 2/24/83	25B 2/25/83	26 2/28/83	27 4/8/83	28 4/9/83	29 4/11/83	29B 4/21/83
Zones	1,2,3	1,2,3	1	1	1	1	1	1	1,2,3	1,2,3	1	1	1	1	1	1	1
Bed T, °F	1603	1432	1588	1629	1645	1652	1656	1630	1654	1638	1652	1552	1537	1555	1536	1677	1655
Sp Vel, ft/sec	4.6	5.1	3.5	3.5	3.5	3.5	3.5	3.5	3.5	4.6	3.5	3.55	3.54	3.55	3.55	3.53	3.59
Air rate, scfm	6583	8004	3249	3211	3182	3165	3183	3199	4955	6581	3167	3339	3361	3329	3359	3131	3154
Bed Ht, in.	61	58	35.8	36.9	49.2	36.7	47.6	37.1	59.5	35.7	35.7	49.3	36.1	36.3	37.9	37.6	37.6
Steam, lb/hr	24,642	20,715	8085	8205	11,075	8319	8206	10,387	13,934	22,065	8103	7754	10,929	8724	8823	10,966	10,149
Fuel, lb/hr	10,873	9415	2623	2860	3477	2645	2530	3135	4601	7724	2685	2576	3271	2814	2722	4010	3503
Steam/culm	2.27	2.20	3.08	2.87	3.18	3.15	3.24	3.31	3.03	2.86	3.02	3.01	3.34	3.10	3.24	2.73	2.90
Limestone, lb/hr	1106	1150	329	348	299	375/rpm	281	337	367	523	302	290	351	271	252	544	3.47
Feedwater lb/hr	25,939	21,805	8510	8636	11,658	8757	8638	10,934	14,667	23,226	8529	8162	11,504	9183	9287	11,543	10683
Steam, psig	200	200	185	190	190	190	190	190	190	190	190	190	190	190	190	190	190
Feedwater, °F	228	230	234	234	233	235	238	237	235	229	237	237	236	236	236	236	232
Wdbx T, °F	310	288	290	293	292	305	300	299	272	267	295	286	290	290	290	290	298
Frbd T, °F	1345	1235	977	1028	1149	1027	1026	1113	1137	1369	1040	1001	1107	1003	1000	1064	1036
CB inlet, °F	1054	974	712	763	875	763	763	844	845	1042	775	748	880	789	800	890	842
CB outlet, °F	578	570	482	476	499	477	489	503	521	591	488	485	517	486	492	511	501
Ca/S ratio	2.59	2.86	3.17	3.76	3.12	4.8	3.66	3.55	2.36	2.26	3.7	4.4	3.28	2.88	2.93	3.38	2.8
Sulfur capt.	91.2	86.0	-	-	-	-	-	-	-	-	-	-	-	91.4	91.4	95.1	93.0
Comb Eff, %	72.0	75.6	94.5	93.0	97.9	97.0	93.4	91.0	90.4	83.4	91.2	101.3	100.1	92.9	103.5	95.7	100.1
Excess air, %	7.4	51.0	68.2	76.9	37.2	75.5	80.5	46.7	63.1	35.9	79.3	98.6	46.2	78.8	79.0	30.9	45.5
Boiler Eff, %	56.8	57.2	73.5	71.6	78.8	75.4	73.2	73.2	70.9	65.0	70.9	78.5	80.7	73.4	82.0	75.4	79.6
Prim Cyc Valve%	0	50	50	0	50	50	50	50	50	50	20	20	50	20*	20*	75*	50*
Ash bin, %C	3.60	7.08	4.70	4.28	3.81	3.26	2.44	1.80	1.94	1.49	5.08	1.29	1.51	3.41	2.05	1.46	5.37
Baghouse, %C	7.12	9.31	3.90	2.90	3.05	2.84	3.59	3.18	6.01	3.54	3.20	4.45	4.28	4.43	4.08	2.47	2.52
Carbon burn %	86.1	74.8	87.0	88.6	90.1	92.0	93.2	94.9	92.2	95.2	88.1	93.5	94.1	90.0	92.7	94.5	84.9
Fuel %C dry	25.26	25.47	27.93	26.1	27.5	30.8	29.6	30.4	28.1	29.8	28.7	25.0	27.4	27.0	26.0	25.2	24.5
FuelBtu/lb dry	4164	4071	4430	4230	4260	4410	4670	4780	4550	4660	4480	4020	4330	4480	4170	3810	3850
Fuel, % H_2O	3.3	4.8	4.75	4.79	4.68	4.83	4.99	5.18	5.70	4.73	4.87	4.47	4.18	5.49	4.93	4.57	4.79
Fuel, % +4M	10.5	12.7	4 mesh	4 mesh	4 mesh	2¼/3	2¼/3	2¼/3	2¼/3	2¼/3	2¼/3	2¼/3	2¼/3	2¼/3	2¼/3	2¼/3	2½/3

* In-bed cyclone recycle for tests 27-36

APPENDIX 11.1 (Con't)

	30	31	32	33	34	35	36
	4/22/83	4/23/83	4/24/83	4/27/83	4/28/83	4/29/83	4/30/83
Zones	1	1	1	1	1	1	1
Bed T, °F	1636	1660	1632	1536	1527	1552	1557
Sp Vel,ft/sec	3.52	3.55	3.55	3.53	3.54	3.53	3.55
Air rate,scfm	3199	3172	3220	3370	3391	3344	3340
Bed Ht, in.	36.9	48.7	48.0	36.9	37.5	37.9	48.3
Steam, lb/hr	8462	10909	11599	8697	9106	10190	11396
Fuel, lb/hr	3081	3977	4280	4287	4888	4871	5366
Steam/culm	2.75	2.74	2.71	2.03	1.86	2.09	2.12
Limestone,lb/hr	258	514	622	2470	4123	2586	2897
Feedwaterlb/hr	8907	11483	12209	9155	9585	10726	11996
Steam, psig	190	190	190	190	190	190	190
Feedwater, °F	234	233	232	234	234	234	234
Wdbx T, °F	299	309	300	312	320	318	324
Frbd T, °F	1034	1143	1112	1042	1058	1054	1143
CB inlet, °F	764	841	882	792	811	874	871
CB outlet, °F	479	495	512	512	522	541	528
Ca/S ratio	2.62	3.69	4.12	1.72	2.63	1.81	2.69
Sulfur capt.	89.2	91.8	92.3	91.8	94.6	90.8	98.5
Comb Eff, %	98.5	94.1	95.4	93.1	94.5	95.1	93.1
Excess air, %	72.7	33.8	28.6	39.6	21.7	18.0	10.9
Boiler Eff,%	77.1	74.6	74.7	70.4	67.1	73.2	74.4
Prim Cyc Valve%	Blanked	Blanked	0*	Blanked	Blanked	50*	Blanked
Ash bin, %C	2.51	4.14	4.03	3.57	3.52	3.01	2.55
Baghouse, %C	2.98	3.92	3.58	2.71	3.78	3.22	4.32
Carbon burn %	91.4	86.3	87.4	86.9	77.5	88.6	84.3
Fuel %C dry	23.6	24.1	25.5	16.9	17.3	17.69	17.22
FuelBtu/lb dry	3770	3880	3850	3023	2902	2966	2990
Fuel, % H_2O	5.07	4.59	5.11	4.14	3.83	3.21	3.98
Fuel, % +4M	3.7	10.3	5.0	5.6	5.1	8.5	8.1

APPENDIX 11.2

Sample Calculations (Test No. 5)

A. Boiler tube heat transferred, Btu/hr

Heat Out (Btu/hr)		
Steam ‹ 200 psig		
9746 lb/hr x 1200 Btu/lb	=	11,695,200
Blowdown 388°F		
513 lb/hr x 360 Btu/lb	=	184,680
Total		11,879,880
Heat In (Btu/hr)		
Feedwater 238°F		
10259 lb/hr x 206 Btu/lb	=	2,113,354
Heat gain in boiler (by difference)		9,766,526

B. Free water, lb/hr

Dry culm feed rate (lb/hr)		
3914 lb/hr x 0.952	=	3726
Free water feed rate (lb/hr)	=	188
Total		3914
Limestone water (lb/hr)		
425 lb/hr x 0.06	=	4
Total free water		192

C. Bottom ash, lb/hr

Input		
Culm ash 3726 lb/hr x .677	=	2522.5
Lime 421 lb/hr x .60	=	252.6
Total theoretical ash		2775.1
Output		
Flyash = 675 lb/hr x .9546	=	644.4
Ash bin = Y x .9721	=	.9721Y
Total		644.4 + .9721Y

Input = Output

Y = 2192 lb/hr bottom ash

D. Carbon Burn-Up

Combustion efficiency by carbon balance (Based on carbon analyses of DOE (culm) and wilson Laboratory (ash))

Culm carbon = 3726 x .2427	=	904.30	
Ash carbon			
Ash bin carbon = 2224.3 x .022	=		48.93
Fly ash carbon = 675 x .0306	=		20.66
Total carbon in ash			69.59

$$\% \text{ carbon burned} = \frac{904.30 - 69.59}{904.30}(100) = 92.3\%$$

E. Ca/S Ratio
Sulfur in culm = 3726 x .00876 = 32.64 lb/hr = 1.02 lb mole/hr
Calcium in limestone = 425 x .709 x (40/100) = 119.4 lb/hr = 2.98 lb mole/hr
Mole ratio = 2.98/1.02 = 2.93
Mole ratio of Ca/S = 2.81 for zero net heat of reaction
Theoretical Ca = 1.02 lb mole S x 2.81 = 2.87 lb mole Ca
Excess Ca = 2.98 - 2.87 = 0.11

F. CO_2 liberated by limestone calcination, lb/hr

CO_2 from $CaCO_3$ = 421 lb/hr x .709 x (44/100)	=	131.3
CO_2 from $MgCO_3$ = 421 lb/hr x .0665 x (44/84.3)	=	14.6
Total CO_2		145.9

G. Overall boiler heat balance, Btu/hr

Dry combustion products 4247 ft^3/min x 1.02 ÷ 387 ft^3/lb mole x 60 min/hr x 29.5 lb/lb mole x 0.26 Btu/lb °F x (491°F - 70°F)	=	2,168,704
Free water 192 lb/hr x 1229 Btu/lb	=	235,968
Water from fuel H_2 3726 lb/hr x 0.01 ÷ 2 lb/lb mole x 18 lb H_2O/lb mole x 1229 Btu/lb	=	412,084
Excess limestone calcination 0.119 lb mole/hr x 76,500 Btu/lb mole	=	9,104
CO_2 from limestone 146.1 lb/hr x 0.21 Btu/lb°F x (491°F - 70°F)	=	12,917
Carry-over (25% of total ash) 0.25 x 2913 lb/hr x 0.25 Btu/lb °F x (491°F -70°F)	=	76,648
Bed ash (75% of total ash) 0.75 x 2913 lb/hr x 0.25 Btu/lb °F x (1548 - 70°F)	=	807,265
Boiler tube heat transfer	=	9,766,526
Radiation heat loss	=	240,000
Total heat out		13,729,216
Preheated air 4247 ft^3/min ÷ 387 ft^3/lb mole x 29 lb/lb mole x 0.23 Btu/lb °F x (267°F - 70°F)	=	865,196
Heat liberated by culm combustion (by difference)		12,864,020

H. Combustion Efficiency
Combustion efficiency by enthalpy balance method
Heating value calculated
12,864,020 Btu/hr ÷ 3726 lb/hr = 3453 Btu/lb dry culm

Heating value measured
3846 ÷ 0.9817 = 3918 Btu/lb dry culm

APPENDIX 11.3 TYPICAL SERVICE DATA

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

(102) DATE	(103)	(104) BOTTOM ASH REMOVED 1.	(105) FLY ASH REMOVED 2.	(106) TOTAL LIMESTONE DELIVERED	(107) FUEL OIL DELIVERED	(108) TOTAL POWER USED 3.	(109) MISCELLANEOUS SUPPLIES (e.g. WATER TREATMENT CHEMICALS, GASES, FABRIC FILTERS, VACUUM TRUCK)	(110)
DAY	HOUR	TONS	~~TONS~~ lbs	TONS	GALLONS	KWH	DESCRIPTION	DELIVERED COST
8-3		~1-1/2	~400	24.2			water treatment chemicals	1008.51
8-4		tons/hr	lbs/hr	23.9	1300			
8-21				25.0				
8-24				22.5				
Total						243,960		

REMARKS
1. Estimated from mass balance i.e. total culm plus limestone input minus flyash removed. Bottom ash is removed once a day and is not directly weighed
2. Measured for ~6 Hour run each day by collecting in a truck and weighing
3. KW HR used from startup on 8/9/82 through 8/31/82

DATE BEGINNING: 8/9/82

DATE ENDING: 8/31/82

MATERIAL DELIVERY AND REMOVAL AND POWER COSTS

FORM 1207

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

AUGUST 1982

			MANHOURS
1.	TOTAL DIRECT LABOR OPERATING MANHOURS (INCLUDING SUPERVISION and Plant Manager		2131.75
2.	TOTAL MAINTENANCE LABOR MANHOURS (ASSIGNABLE TO FLUIDIZED BED BOILER)		29.50
3.	MAINTENANCE SUB CONTRACTS FOR EQUIPMENT	- MANHOURS	
	FOR INSTRUMENTATION	- MANHOURS	
	FOR OTHER	- MANHOURS	
	TOTAL SUB CONTRACTS		
	GRAND TOTAL		2161.25

5. PER CENT AVAILABILITY: From 8/9/82 0800 (Start Up) through August 31, 1982

$$\frac{\text{HOURS OPERABLE}}{\text{HOURS OPERABLE + HOURS INOPERABLE}} \times 100\% = \frac{(540)}{(540) + (4^*)} \times 100\% = 99.3 \text{ \% AVAILABILITY}$$

*Operable hours are defined as time which unit was capable of producing steam and not necessarily actual operating time.

* First 4 hours of start-up during which plant is incapable of producing steam

MONTHLY DATA August 1982 LABOR COST: OPERATING, AND MAINTENANCE

DATE 9/20/82

FORM 1203

1. Includes 375 man hours for 8/1 through 8/7 during which plant was shutdown for maintenance prior to start of extended test run.

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

DATE	EQUIPMENT	TIME DOWN		TIME UP	
		DATE	HOUR	DATE	HOUR
8/25/82	Ash Pneumatic Conveying System				

PROBLEM: Repair of worn out elbows . These elbows were removed from the Ash System prior to start up on 8/9/82, and were available for reconditioning.

CORRECTIVE MEASURE: Patch 2 - 90° Elbows with Nordbak wearing compound - an epoxy and ceramic bead abrasion resistant compound. After repair the elbows are available as spares Replacement requires shutdown of the ash system only.

PARTS USED

PART NO.	DESCRIPTION	QTY.	COST
	Nordbak Wearing Compound		$212.
	(epoxy/ceramic beads)		
	1 kit repairs 8-10 elblows		

MAINT. MAN HOURS 120

MATERIAL COST $212.00

SHEET 2 OF 9

TAG NO. W119

CORRECTIVE MAINTENANCE

FORM 1401

APPENDIX 11.3 (Con't)

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

EQUIPMENT NAME: Instrument Air Compressor ELEVATION: Grade

EQUIPMENT TAG: R-205

NOTE: OMIT LUBRICATION MANHOURS AND MATERIAL COST FROM RECORD BELOW

DATE	NAME	MAN HOURS	MATERIAL COST	DESCRIPTION	PARTS USED	
					PART NUMBER	QTY
8/13/82		0.5	-	Clean Intake Air Filter		
8/23/82		0.5	-	Replace Intake Air Filter		1
8/31/82		0.5		Clean Intake Air Filter		

YEAR 1982

PREVENTIVE MAINTENANCE RECORD

FORM 14

APPENDIX 11.3 (Con't)

SHAMOKIN ATMOSPHERIC FLUIDIZED BED BOILER PLANT

OPERATING COST DATA

AUGUST 1982

Date 9/20/82

Phase III Start-Up & Oper. Task No. 2.2 Task Title Extended Testing & Evaluation

Category Maintenance Budget $5675/Month for Maintenance

CWC P.O. No. SM122899 CWC P.O. Value

Invoice No.	Date	ACTUAL Amount	ACTUAL Cumulative Amount	PLANNED Cumulative Amount	Remarks
122899-A	8/1	$ 47.00			Piezo Crystal
B	8/11	176.00			Analog Panel Brd Repair
D	8/17	78.30			Spare Bearings
E	8/18	79.95			Manometer
F	8/23	23.10			Water Test Syringes
G	8/24	76.00			Valve Pack.Rings
H	8/25	65.11			Mag. Detec.Head
I	8/30	156.74			2-4" Butterfly Valves
J	8/31	69.48			Misc. Hardware Supplies
L	8/31	170.11			Misc. Plumbing Supplies
M	8/31	14.00			Trash Removal

Revision

No.	Description	Date	No.	Description	Date

APPENDIX 11.4 TYPICAL RAW DATA DISPLAYS

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LOG II - OPERATING DATA          SHAMOKIN AFB BOILER                                  1983    3/24 11 16

FLUIDIZED BED----ZONE I-------ZONE II-------ZONE III-----------
LOWER BED        TE14A 1687   TE15A  397    TE16A  430 DEGF
                 TE17A 1711                            DEGF
                 PDT27   8 0                           IWC
UPPER BED        TE42A 1691   TE44A  489    TE45A  493 DEGF
                 TE43A 1697                            DEGF
                 PDT33   1 7                           IWC
DIST  PLATE      PDT24  21 9  PDT25 -0 1    PDT26  4 0 IWC
TOTAL BED        LT11   15 2  PDT28  4 3    PDT29  0 5 IWC
AIRFLOW          FT6    3050  FT7   ****    FT8      0 SCFM
SPACE RATE(FE)           3 5        ****          0 0 FPS
SPACE RATE(DF)           3 2                          FPS
OVERALL FLUIDIZED BED-----------
BED HEIGHT              35 1 IN
TOTAL AIRFLOW          ***** SCFM
SPACE RATE (FB)         **** FPS
WINDBOX-------------------------
              FT21      37 4 IWC
              TE11A      289 DEGF

FREEBOARD-----------------------------
                 FT37      -0 5 IWC
                 TE49      1028 DEGF
CONVECTION SECTION--------------------
INLET            TE51       806 DEGF
OUTLET           TE50       498 DEGF
LOWER            TE48       437 DEGF

CULM STORAGE--------------------------
UA2 SYSTEM ON
LSH21  SILO
LSL22  SILO

LIMESTONE STORAGE SYSTEM--------------
LSH23  SILO
LSL24  SILO

BOTTOM ASH REMOVAL--------------------
UA3 SYSTEM ON
LSH25 BIN

CULM FEED--------------------------
FEED BIN        WT1      30550 LBS
W202A FEEDER ST1           269 RPM
W202B FEEDER ST2           271 RPM
CULM FEED RATE            2896 PPH
UA4 BIN FILL SYSTEM ON
LSH15 CULM FEED BIN

LIMESTONE FEED---------------------
FEED BIN        WT2       1220 LBS
W204 FEEDER  ST3           366 RPM
LIMESTONE FEED RATE        305 PPH
UA1 BIN FILL SYSTEM OFF
LSH11 LIMESTONE FEED BIN HIGH

PREHEAT BURNER---------------------
XA1  MAIN FUEL OFF
XC 0
FIRING RATE  ZT8              1 %
EXHAUST GAS ANALYSIS---------------
XA  SYSTEM POWER ON
XA  CALIBRATION OFF
XA  BACKFLUSH OFF
O2              AT1  *****   %
SO2             AT2    159   PPM
CO              AT4-1 ****   %
CO              AT4-2   63   PPM
NOX             AT5    168   PPM
CO2             AT6   ****   %

INSTRUMENT AIR COMPRESSOR------------
XA32 COMPRESSOR ON
PSL49 DISCH  PRESS NORMAL
PSL 9 DISCH  PRESS

AMBIENT AIR  TE6        45   DEGF

CYCLONES---------------------------------
PRIMARY          PDT38      1 3 IWC
SSL12 W208 ROTARY VALVE ON
SECONDARY        PDT39      2 3 IWC
SSL13 W210A ROTARY VALVE ON
SSL14 W210B ROTARY VALVE ON
ASH COOLER-------------------------------
AIR INLET        FT19     1996  SCFM
CELL 1           TE22      105  DEGF
CELL 2           TE23      137  DEGF
CELL 3           TE24      114  DEGF
GAS OUTLET       TE25      134  DEGF
GAS OUTLET       FT43     -0 7  IWC
DIST  PLATE      PDT41     8 0  IWC
FLUID  BED       PDT47    33 1  IWC
FEEDWATER        FT1       105  GPM
WATER INLET      TE2        93  DEGF
WATER OUTLET     TE3        93  DEGF

AIR PREHEATER----------------------------
GAS SIDE         PDT44     1 8  IWC
FLUE GAS IN      TE26      403  DEGF
FLUE GAS OUT     TE27      314  DEGF
AIR IN           TE29      191  DEGF
                 TE29      191  DEGF
AIR OUT          TE30      288  DEGF

FLUIDIZING AIR HEADER--------------------
                 TE57      288  DEGF
                 PT52      6 1  PSIG

BAGHOUSE---------------------------------
AIR INLET        TE40      228  DEGF
TSH40 AIR INLET TEMP
XA29 CO2 FIRE SYSTEM

EXHAUST STACK----------------------------
OPACITY          AY7      ****  %

COMB  FLUIDIZING BLOWER------------------
XA28 BLOWER MOTOR ON
ZSL5 AIR INLET VALVE OPEN
AIR INLET        FT11     6545  SCFM
SURGE BLEED              *****  SCFM

ASH COOL  FLUIDIZING BLOWER--------------
XA27 BLOWER MOTOR ON
AIR INLET        FT19     2010  SCFM

FLUE GAS ID FAN--------------------------
XA17 FAN MOTOR ON

STEAM DRUM--------------------------------
WATER LEVEL     LT10     -0 1 IWC
                LT27     -1 2 IWC
                LSHH7
                LSH7
                LSL7
                LSLL7
                LSLL8
PRESSURE        PT8       191 PSIG
TOTAL STEAM     FT3      9390 PPH
DFAER  STEAM    FT4      2784 PPH
VENT STEAM               3055 PPH
EXPORT STEAM    FT2      3609 PPH
                PT7       160 PSIG
BLOWDOWN                    0 PPH
DEAERATOR---------------------------------
WATER TEMP      TE4       234 DEGF
LSH4 WATER LEVEL
LSL3 WATER LEVEL

FEEDWATER---------------------------------
                FT5        20     GPM
                         9870     PPH
                TE5       236     DEGF
PSL2 HEADER PRESS   NORMAL
XA30 P101A PUMP MOTOR OFF
PSL54 PUMP DISCH  PRESS   NORM
PSL55 PUMP DISCH  PRESS   NORM

WATER TREATMENT---------------------------
PSL53 CITY WATER PRESS  NORMAL
LSL5 NEUT  AMINE TANK
LSL6 SOD   SULFITE TANK

TREATED WATER FEED------------------------
WATER TANK      LY1       7 6     FT
PSL3 HEADER PRESS   NORMAL
PSL4 HEADER PRESS
XA31A P102A PUMP MOTOR ON
XA31B P102B PUMP MOTOR ON
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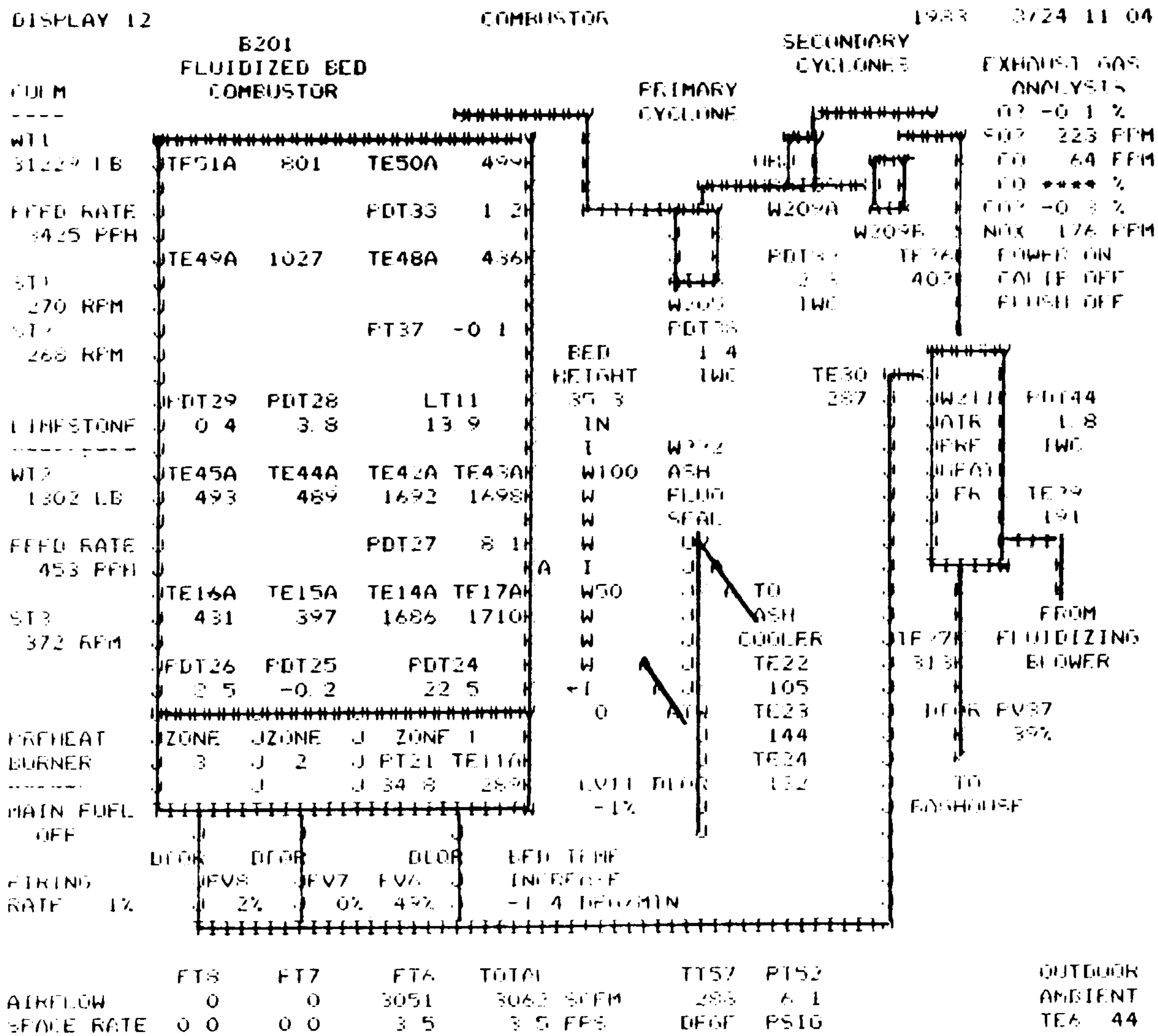
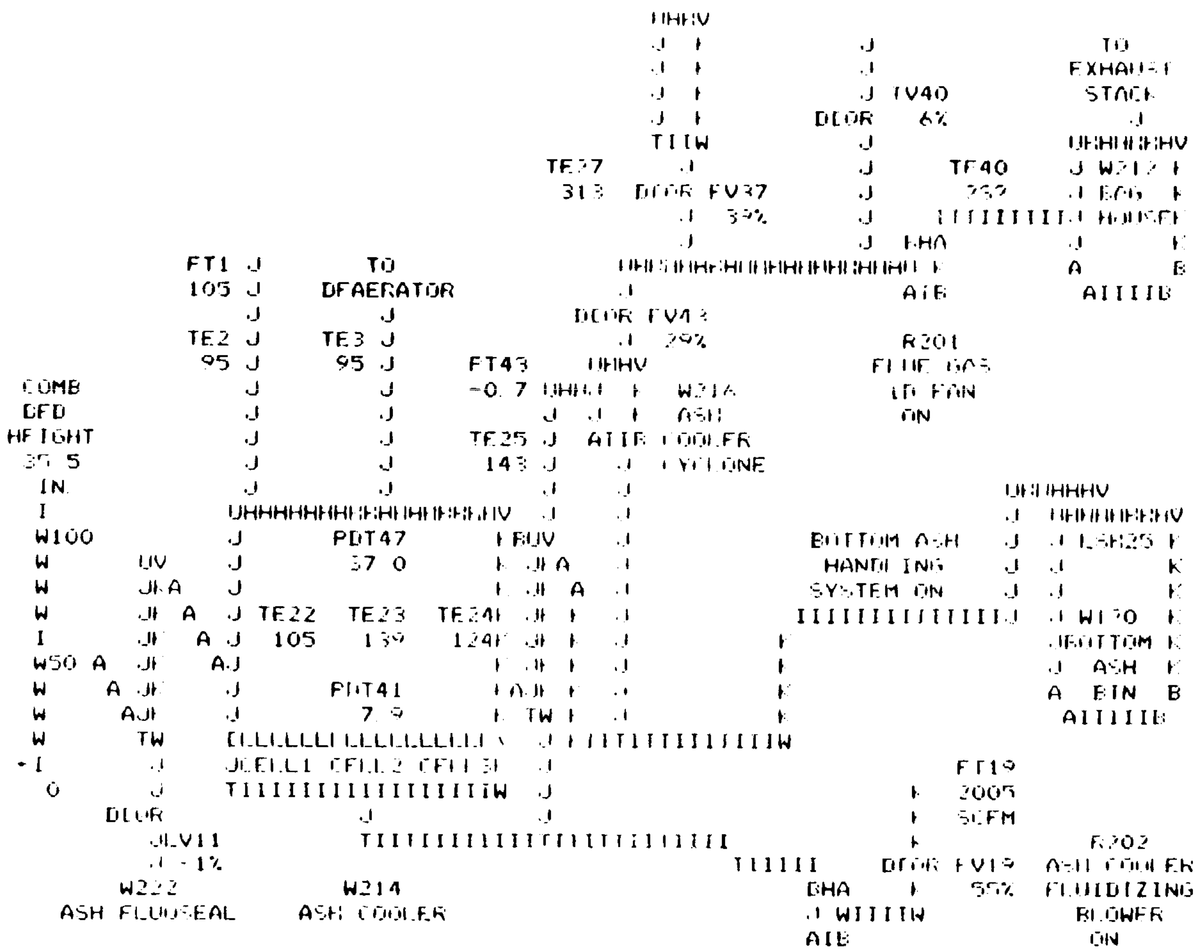
APPENDIX 11.4 (Con't)



APPENDIX 11.4 (Con't)

DISPLAY 13 ASH HANDLING SYSTEM 1983 3/24 11 08



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DISPLAY 14              STEAM / WATER SYSTEMS                    1983    3/24 11 09

 TREATED WATER PUMPS
                                                  FT1              VENT STEAM
    FHHHHHHHHVHHHHHHHHHHHHHHHHHHHHV   105               2984 PPH
   IW         IW     PSL3  PSLL4      K   GPM                            J          EXPORT
  BHA        BHA      NOR             K                                  J          STEAM
 UU FL M   UU FL M                    K   TE2                            J
 JAIB      JAIB                       K    94       FT4      FV3  DEGR              FT2
 J    ON   J    ON                    K DEGF        2760     21%   J                3583
 JP102A    JP102B        UHHHV        K             PPH             J    FV56  PPH
 TIIIIIIIIIIIIII         J  UHHHHHHHHHHV                            J     J
                K        J  J   W214   K      ULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLMLLLLLL
                K        J  J   ASH    K      K              FT3   J         FT7
                K        J  J  COOLER  K      K  LT   LT     9341  J         160
                K        J  TIIIIIIIIIIW      K  10   27     PPH   J         PSIG
     0101       K        J                    K                    J
  TREATED WATERK         J TE3                K   8  8H+S  EHHHHHHHHHHHHHHHHHHHHHHHA
     TANK       K        J   93               K   6  6R   B LSHH7                   A
                K        J DEGF               K   4  4R  B  LSH7                     A
   EHHHHHHHHA   K        J               FCV5 K   2  2R  J      STEAM DRUM           K
 UHJ  LY1   K   K        J                  J K   2  2HO J     FT8 191 PSIG          K
 J J 7 6 FT K   K        HHHHHJJLLLLLLLLLLLLLMLLL 4  4R  A  LSL7                     B
 J J        K   K           JK     G104       K   6  6R   A LSLL7         LSLL8   B
 J J  TE1   K   K           JK   DEAERATOR    K   -  -R  UAIIIIIIIIIIIIIIIIIIIIIIIIIBV
 J J 93 DEGFKIIW            JK                K      H-S J                           K
 J TIIIIIIIIIW          EHHHHHHHHHHHHHHHHA    K -0 1 -1 3 TIIII          LV10       K
 J                       J  LSH3          K   K  IWC IWC        J           33% DEGR
 J                      UJTE4  232 DEGF K     KIIIIIII          J                   K
 J                      JJ  LSL4          K          T          Y                   K
 JUHHHHHHHHV            JAIIIIIIIIIIIIIIB   FHHHHHHHVHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 TJ G101   K               J           K        K K  PSL2   J       FEEDWATER
 JZEOLITE K       FROM G103   J        K        K K   NOR   J
 JSOFTENERK       SOD  SULF   J    PSLL54 K PSLL55 K         J     FT5 19 39 GPM
 TIIIIIIIIW       LSL6        J    NORMAL K NORMAL K         J          ***** PPH
     K                        J        IIIIW      IIW K BJ   J
     K                        J       BHA        BHA   KE J  J     TE5 **** DEG
     K  PSL5                  J   UHJ FLL M  UU FFFFFFJ J    J
     K  NORMA         UHHHHHHHHJ  J AIB      JAIB    A J     J
     K                 J      J  JP101A OFF JP101B   AJ      J
     K            FROM G102   TIITIIIIIIIIIIJ                JBLOWDOWN
    FROM          NEUT  AMINE                                J**** PPH
    CITY          LSL5           BOILER FEED PUMPS
    WATER
```

APPENDIX 11.5 TYPICAL DATA BLOCK

= Data

Date Measured (MMDDYY)	Time Measured (HH MM)	Trend Index No. 3	Trend Index No.4
60182	801	3513.64	962.231
964.671	283.297	511.038	37635.7
3023.57	314.45	6.3	3.26562
124.062	4.0625E-03	8.40625	95.3125
3.28125	22.0625	69.9525	238.742
200.062	8682.78	2501.56	1695.21
157.109	22.6991	1447.08	1457.08
1441.62	1444.89	8.76062	1445.99
1448.17	1438.89	1444.89	1.14381
23.9205	24.8223	25.4517	16.0996
7.74104	9.20686	38.657	-.955632
1042.03	780.463	441.104	1.90312
2.10937	314.45	381.875	382.5
571.25	41.6756	12.4604	.533041
3.52245	3.50514	3.49926	3.51464
4936.75	785.162	50.5245	38.0586
Trend Index No. 61	Trend Index No. 62	Trend Index No. 63	Trend Index No. 64

APPENDIX 11.5 (Con't)

FILE #				
1 - 4	DATE	TIME	FT-6-SCFM- ZONE 1	FT-7-SCFM- ZONE 2
5 - 8	FT-8 (SCFM-ZONE 2)	TE-11A (ZONE 1 WINDBOX)	TE-50A (CONVECT. OUTLET)	WT1 (CULM FEED BIN)
9 -12	WT2 (LIME BIN)	TT-40 (BAGHOUSE INLET)	PT-52 (FLUIDIZING AIR HEATER)	AT1 - O_2
13-16	AT2-SO_2	AT4-1- CO HIGH	AT4-2- CO LOW	AT5 - NO_X
17-20	AT6- CO_2	AY7 - OPACTIY	TE-6-AMBIENT	TE-5 - FEEDWATER (STEAM DRUM)
21-24	PT-8 (STEAM DRUM)	FT-3 (STEAM DRUM PPH)	FT-4 DEAERATOR PPH	FT-2 EXPORT PPH
25-28	PT-7 EXPORT	FT-5 FEEDWATER GPM	TE-14A ZONE 1 LOWER	TT-17 ZONE-1 MID
29-32	TE-15A ZONE 2 LOWER	TE-16A ZONE 2 LOWER	PDT-27 ZONE 1 LOWER-MID	TE-42A ZONE 1 UPPER
33-36	TE-43A ZONE 1 UPPER	TE-44A ZONE 2 UPPER	TE-45A ZONE 3 UPPER	PDT-33 ZONE 1 CONVECT.
37-40	PDT-24 ZONE 1 WINDBOX	PDT-25 ZONE 2 WINDBOX	PDT-26 ZONE 3 WINDBOX	LT 11 BED LEVEL
41-44	PDT-28 ZONE 2 LOW-MID	PDT-29 ZONE 3 LOW-MID	PT-21 ZONE 1 COMB/ WINDBOX	PT-37 FREEBOARD
45-48	TE-49A FREEBOARD	TE-51A CONVECT INLET	TE-48A CONVECT LOWER	PDT-38 PRIM. CYC
49-52	PDT-39 SEC CYC	TT-40 BAGHOUSE INLET	ST-1 CULM FEED W202A	ST-2 CULM FEED W202B
53-56	ST-3 LIME FEED W204	PPT-47 ASH COOLER CELL 2	PDT-41 ASH COOLER WIND/CELL 2	LT-27 STEAM DRUM WATER LEVEL
57-60	FPS ZONE 1 SPACE RT	FPS ZONE 2 SPACE RT	FPS ZONE 3 SPACE RT	FPS OVERALL SPACE RT
61-64	NN-5 CULM FEED PPH	NN-6 LIME FEED PPH	NN-10 BED DENSITY LB/FT^3	NN-11 BED GEIGHT - IN

ALL TEMPS. - °F; ALL PRESSURES - PSIG

*U. S. GOVERNMENT PRINTING OFFICE: 1985-544-063/10478