MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TEST PROGRAM

CONTRACT NO. 14-32-0001-1237

RESEARCH AND DEVELOPMENT REPORT NO. 90
INTERIM REPORT NO. 1 FOR PERIOD OCTOBER 1972–JUNE 1974

PREPARED FOR

OFFICE OF COAL RESEARCH
UNITED STATES DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

REPORT PER-570-74

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ON
MULTICELL FLUIDIZED-BED BOILER
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POPE, EVANS AND ROBBINS INCORPORATED
CONSULTING ENGINEERS

AUGUST 1974
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Washington, D.C. 20402 - Price $10

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ABSTRACT

The objective of this program is to design, construct and test a multicell fluidized-bed boiler, as a pollution-free method of burning high-sulfur coal or burning highly corrosive coals without excessive maintenance problems. The fluidized-bed boiler will produce approximately 300,000 pounds of steam per hour. Steam pressure and temperature conditions were selected to meet requirements of the site at which the boiler will be installed.

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INTRODUCTION

General

The Government expressed its desire to have research and development work performed on a multicell fluidized-bed boiler operating under practical electric utility conditions, by entering into contract No. 14-32-0001-1237 with Pope, Evans and Robbins Incorporated on 5 October 1972. The work under contract No. 1237 follows the activities performed by PER under Contract No. 14-01-0001-478, as amended, and Contract No. 14-01-0001-1229. The previous work had indicated a high probability of success.

Tasks and Phases

The object of the program under Contract No. 14-32-0001-1237 is to test a multicell fluidized-bed boiler as a pollution-free method of burning high-sulfur coal or highly corrosive coals without excessive maintenance problems.

This objective is to be accomplished by designing, building, and operating a multicell fluidized-bed boiler under practical electrical utility conditions, in four technically distinct but chronologically overlapping phases:

Phase I. Boiler and Plant Design; Performance of Experiments to Optimize Certain Boiler Features.

Phase II. Fabrication, Installation and Component Testing.

Phase III. Demonstration Operation.

Phase IV. Preparation of Design and Operation Manuals and the Design of Utility Size Boilers.

This Interim Report covers work performed under Phase I of the contract between October 1972 and June 1974.

I. SUMMARY

1.1 Objectives of Work Covered by This Report

The work described in this report includes the tasks required under Phase I of the contract, as follows:

(a) Visits to, and evaluation of, potential sites offered by various electric utility companies and recommendations to the Contracting Officer. Factors to be considered:

(1) Minimal and undesirable environmental impact.

(2) Availability of desired coal types and ease of bringing in other types for experimental purposes.

(3) Availability of dolomite and limestone.

(4) Most favorable cost and research conditions.

(5) Boiler pressures and temperatures consistent with utility practice.

(b) Evaluate the availability and suitability of concepts for design of a fluidized bed combustion boiler, including PER's own.

(c) Assess experimental and pilot plant work needed and develop basic characteristics and specifications for the pilot plant.

(d) Prepare designs, specifications, and bidding documents leading to the requests for final design and construction subcontracts for a multicell fluidized-bed boiler in the capacity range of 300,000 pounds of steam per hour at operating conditions consistent with the selected host utility plant.

(e) Conduct experiments to optimize certain boiler features, including:

(1) Pressurized coal handling and metering to multiple coal-feed points.

(2) Optimize evenness of coal distribution from minimum injection points.

(3) Bed particle size classifier.

(4) Use of 1-1/4 inch diameter coal feed injection tubes.

(5) Proof of other design features as required by PER.

(f) Conduct a series of tests using as fuel a high nitrogen and a low nitrogen content coal. Select three bed temperatures and determine the effect of bed temperature and coal nitrogen on NO_x emission. Perform a sulfur balance.

(g) Prepare detailed plans, specifications and bid documents for purchase of the boiler and for construction of the fluidized bed boiler plant system in the approved host utility power plant.

(h) Advertise for, receive and evaluate competitive bids for the boiler and for construction of the fluidized bed boiler plant system in the host utility power plant.

1.2 Review of Significant Events

Between October 1972 and June 1974 contract period, the following significant events occurred:

Event	DATE	
Start of contract	October	1972
Site selection completed	February	1973
Rehabilitation of FBM (9 sq. ft. hot model) completed at Alexandria, Va. laboratory	March	1973
Site selection approved by OCR	March	1973
Evaluation of boiler manufacturers completed	March	1973
Selection of Foster Wheeler Corporation (FWC) and OCR approval	March	1973
Bureau of Mines laboratory tests completed at Alexandria	March	1973
PER boiler design completed	April	1973
FWC boiler evaluation redesign and cold component testing contract signed	May	1973
Modernization of the Alexandria analytical facilities completed	June	1973
Monongahela Power Company agreement signed	June	1973
Design verification tests started in the Alexandria laboratory	June	1973
Fluidized bed boiler plant design started	June	1973
Boiler redesign completed and released for bidding	October	1973
Salt tests completed in the Alexandria laboratory	October	1973
Boiler bids submitted by two manufacturers	November	1973
Bid evaluation completed and approved by OCR	December	1973
Notice to Proceed given to FWC for boiler fabrication	December	1973
Cold component testing in the Livingston, N.J. laboratory started	December	1973

	DATE	
Air distribution plate pre-selection tests in the Livingston laboratory completed	January	1974
Air pollution control permit filed in West Virginia	February	1974
High N_2 content coal NO_x tests completed in Alexandria	February	1974
Plant construction bids received from three contractors	February	1974
Request for additional funding submitted to OCR	February	1974
Plant construction bids submitted to OCR for evaluation	February	1974
Air pollution control hearing	February	1974
Coal feeder hot tests completed in the Alexandria laboratory	March	1974
Preliminary air distributor tests completed in the Alexandria laboratory	April	1974
Construction Contract No. 1 for Rivesville boiler support steel work signed	May	1974
Air pollution permit granted by the State of West Virginia	May	1974
Rivesville boiler support steel work started	May	1974
Coal feeder tests started in the Rexnord Inc. Louisville, Kentucky plant	May	1974
Furnace feed system design completed	June	1974
Combustion control system design completed	June	1974

1.3 Summary of Results

1.3.1 General

Substantial progress was made in the reporting period in minimizing the costs of sulfur oxide control in a fluidized-bed boiler. This was achieved by (a) learning how to operate the bed so as to minimize the quantity of makeup limestone required and (b) learning how to use an inexpensive, low-grade stone quarried in the immediate vicinity of Rivesville, West Virginia. Cost for raw stone of 3 cents per 10^6 Btu of fuel was indicated on the basis of a calcium-to-sulfur mole ratio of two for the 4.6 percent sulfur Sewickley Seam coal using the Greer stone at a delivered cost of $3.00 per ton. A number of other results are summarized below.

A complete and detailed plant design was prepared to support the prototype operation. Some novel auxiliary apparatus has required development because of the differences between a fluidized-bed boiler and conventional furnaces. The combustion control system also has unique features.

1.3.2 Laboratory Work at Alexandria

Work at the Alexandria, Virginia fluidized-bed combustion laboratory by Pope, Evans and Robbins between October 1972 and June 1974 used essentially the same equipment as had been in use since 1966. With the decision to proceed with the construction of a 30 MWE prototype boiler, funds became available to rehabilitate the existing laboratory. As a result of that and due to the purchase and use of new analytical equipment, it became possible to close material balances with remarkable accuracy.

The following is a summary of the work performed in and by the combustion laboratory, including experiments conducted and test results obtained during the reporting period.

1. A Bureau of Mines team from their Bruceton, Pennsylvania Laboratory performed a test in March 1973 in which the following operating conditions were used:

Firing Rate	625.5	pounds of coal/hour
	68.5	pounds of coal/hour, sq. ft.
	736,000	Btu/hour, sq. ft. of grate (after all losses)[1]
	122,700	Btu/hour, cu. ft. of furnace volume
	80,000	Btu/hour, sq. ft. of EPRS[2]
Air Rate	6,800	pounds air/hour
	745	pounds air/hour, sq. ft. of grate
Gas Rate	25.7	wet pounds-moles/hour, sq. ft. of grate
	10.2	feet/second at 1500°F bed temperature

The fluidized-bed was composed of partially sulfated (~12.4 wt. %S) Grove limestone. Fresh limestone was fed at a calcium-to-sulfur mole ratio of 2.0. The finished bed weighed 1,360 pounds or 148 pounds per sq. ft. of grate. The slumped or static bed depth was 1.8 ft.

NOTES: 1. 12.9% of input fuel appeared as high carbon flyash since Carbon Burn-up Cell was not operated.

2. There are 84 sq. ft. of effective projected radiant heat transfer surface within the furnace.

The Bureau of Mines produced the following sulfur balance for the Fluidized Bed Module (FBM): See Section 3

Inputs		Wt.lbs/hr.	%S	S,lbs/hr.	% of S
(a)	Coal	625.5	4.6	28.77	99.25
(b)	Limestone	182.5	0.1	.18	.62
(c)	Salt	14.4	0.3	.04	.13
		Total		28.99	100.00

Outputs		Wt.lbs/hr.	%S	S,lbs/hr.	% of S
(a)	Bottom Ash	97.5	12.7	12.36	45.8
(b)	Flyash				
	i. Collected	140	4.1	5.74	21.3
	ii. Entrained	23	6.21	1.43	5.3
(c)	Changes in bed over test period				
	i. Increase in mass	23.5	12.4	2.91	10.8
	ii. Increase in sulfur content (1265 lbs. @ S=0.4%)			1.27	4.7
(d)	Flue Gas	-	-	3.28	12.1
		Total		26.99	100.0

$$\text{Sulfur Recovery Percent} = \frac{\text{Output}}{\text{Input}} \times 100 = 93.1\%$$

This balance shows that 88% of the sulfur was controlled. Based on the actual heat input (corrected for losses), the emission was 0.98 pounds per 10^6 Btu. This may be compared with 1.2 pounds/10^6 Btu established by the U. S. Environmental Protection Agency for new coal-fired boilers.

2. Experiments were conducted with the coal normally used at the plant to determine the effect of bed-temperature on the oxides of nitrogen emissions. The three temperatures used were 1500°F, 1650°F and 1800°F. It was found that in the range of 1500° - 1650°F, bed-temperature did not effect NO_x emissions. The coal used is termed Sewickley Seam.

3. An experiment analogous to the one described above was attempted, using a coal known as Rich Mountain, containing an exceptionally high nitrogen content. The results of these experiments are summarized as follows:

			NO_x emission, Pounds $NO_2/10^6$Btu Input		
Coal	%N(maf)	%S	1500°F	1650°F	1800°F
Sewickley	1.48	4.6	0.22	0.23	0.30
Rich Mountain	2.02	0.7	0.35	0.36	0.65

4. The experiments with the Rich Mountain Coal yielded an interesting insight. When an attempt was made to duplicate the earlier Sewickley tests in every respect, including limestone-to-coal weight ratio, the limestone bed deteriorated and literally blew away. Rates as high as 2/3 pound limestone per pound coal could not keep the bed level stable. A chemically inert bed material was substituted for the limestone bed and the data reported above obtained.

   It was discovered in exploring the possible cause for the limestone's rapid loss of structure that $Ca(OH)_2$ had been detected in fluid-bed samples taken by the Bureau of Mines from their reactor at Morgantown. A sample was taken from the FBM in a way that precluded hydration from contact with humid air. On analysis by infrared spectroscopy the sample was found to contain 5.5 percent of $Ca(OH)_2$, despite the fact that 1500°F is substantially above the decomposition temperature of $Ca(OH)_2$. A satisfactory answer as to why the limestone had been destroyed was not found. It is believed to relate to the low sulfur content of the coal. It is unlikely that low sulfur coals such as Rich Mountain would ever be burned in limestone beds, since a coal ash bed would be acceptable with some limestone addition for emission control.

5. An extensive search for coals with both high sulfur and high nitrogen contents revealed the interesting observation that such coals are rare. High nitrogen contents, i.e., +1.6 percent (compared with the 1.0 to 1.4 percent N normally found), do not have sulfur contents above 2-1/2 percent. Samples obtained from potential sources proved the historical data false. Two potential sources were no longer being mined.

6. A search for beneficial uses for spent bed material (bottom ash) was begun. The assistance of the following organizations was sought:

    National Limestone Association

    Agricultural Departments in

    - Maryland
    - Ohio
    - Pennsylvania
    - Virginia
    - West Virginia

    Tennessee Valley Authority
    U. S. Department of Agriculture
    Consolidation Coal Company
    United States Steel Corp.
    Bethlehem Steel Corp.
    Coal Research Bureau, University of West Virginia
    I U Conversion Systems, Inc.
    Grove Lime Company
    Greer Limestone Company
    State of Maryland, Department of Highways
    National Gypsum Company

    Treating of acid mine drainage appears to be the most promising use of spent bed material near mining locations. Use in agriculture is also promising. In both cases, bed material which is high in sulfur (12.5 wt. percent) is undesirable and the boiler plant would have to use more stone to produce a saleable by-product. It is likely that an optimum value will be near 5 percent S and that the plant can receive limestone for sulfur oxide control at a relatively low net cost.

7. A crop of peanuts was growing in a plot at the Suffolk, Virginia Agricultural Experiment Station treated with a ton of high sulfur content spent bed material. The plants were reported as being healthy. The peanuts require calcium, normally provided as calcium sulfate, and the value of the by-product will only be known when the crop is harvested.

8. Coal is normally fed to the furnace after being crushed and screened to a top size of 1/4 inch. In special experiments much larger coal was used and it is anticipated that commercial units may feed coal with a top size of near 1 inch. Limestone is generally fed with a top size near 1/8 inch. This size difference allows a screen to be used to cleanse the lime bed of most of the non-inherent coal ash and so maintain the purity of the sulfur sorbent. For the Sewickley seam coal with a top size of 1/4 inch, about 38 percent of the raw coal is +8 mesh (USS). The coal's ash content, on the other hand, is finer with 23 percent being retained on the 8 mesh screen. A screen was built for use with the FBM in a continuous mode. The Sewickley coal ash was also found to be magnetic. The analysis of the coal was 19.3 percent Fe_2O_3, a value typical of many coals. A simple magnetic separator of the drum type could produce a bed material with 5 percent coal ash contamination. A more powerful separator could produce a product with 3 percent coal ash contamination.

9. A variety of air distributor designs were tested to determine their potential for use in the fluidized-bed boiler. Temperature measurements showed the plate temperature is approximately midway between the bed-temperature and the incoming air temperature. The greatest thermal stress is experienced when the hot fluid bed is slumped. A temperature excursion to about 100°F above the operating plate temperature occurs within 2 minutes. What is significant is that the plate will always be substantially cooler than the bed and the material selection need not be based on bed-temperature.

   A perforated plate performed well at full load but operation at half load caused part of the bed to slump. The perforated plate had a relatively low pressure drop even at full load which may explain its poor performance at half load. A plate formed from spaced profiled wire performed poorly because the rouge* deposits bridged the fine spaces (0.005 in.) between the wires. A plate fabricated by Procedyne Inc. performed well. The pressure drop was substantially above the value specified for both this plate and the profile wire plate. This experience indicates that a quality control procedure based on testing plate sections will have to be devised if prototype boiler is to perform efficiently.

10. A full load, design pressure drop of 16 inches H_2O at a 600°F air flow of 840 pounds/hour, sq. ft. was selected, based on experience, with part load operation. A lower limit for plate pressure drop of 4 inches H_2O at half load results in a 16 inch drop at full load.

11. *In situ* resistivity tests in the boiler's stack were performed. A resistivity of 1×10^8 ohms-cm was measured at 550°F. The *in situ* point did not lie on a curve (produced in the laboratory) of dust resistivity vs. temperature. The results were ambiguous and could not be used to select an electrostatic precipitator.

12. A coal feeder was tested which was slightly longer than the longest to be used in the prototype; about 5 ft. A coal was specially selected for the experiments which had a high fluidity as determined by ASTM procedures with the Giesler Plastometer. The initial softening temperature of the coal was 375°C, an average value. The feeder did not plug until the conveying air flow was reduced to less than 25 percent of the design rate. The prototype design provides for insulating the coal injectors from the bed temperature if needed. The FBM test results indicate that the coal injector can be a simple, uninsulated pipe.

13. Transient tests were run to gain insight into a fluidized-bed boiler's response to a sudden and substantial decrease in the steam demand. For the FBM it was found possible to respond to the transient pressure increase by reducing coal and air flow and so prevent the safety valves from lifting. A total stoppage in steam flow can be accommodated by a fluidized-bed boiler, without super-heater tubes in the bed, by slumping the bed.

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* Burning coal releases iron oxide which coats most stainless steel surfaces in the furnace.

Where superheaters are in the bed, cooling steam must be passed through the tubes. These findings are being included in the combustion control system design.

14. A novel method of starting the fluidized-bed boiler was developed by the Laboratory Supervisor. Coal can be burned on the bed within three minutes of the time the gas-fired startup burner is lit.

15. An attempt to develop an economical coal metering system which would divide a bulk coal stream into a number of smaller equal streams was not successful. A vibrating table feeder is now being tested to divide coal into six to eight equal streams.

16. A wide variety of continuous flue gas analyzers were used and evaluated, based on the following criteria: interferences, reliability, stability, speed of response, vendor service and frequency of calibration. Based on these criteria, PER rated the instruments, as described in the body of the report.

17. Sample pumps have been a continuing problem in the flue gas analysis system. A large rubber diaphragm pump provided by Beckman Instruments in 1968 was no longer manufactured and could not be repaired in 1973. A number of small diaphragm pumps failed. Vane type pumps failed. Three Metal Bellows, Inc. pumps failed after short service periods. Metal Bellows has provided PER with a pump they designed especially for this service, which has operated well for about six months. Two pumps provided by Contamination Controls, Inc. have served well.

18. A sample dryer fabricated by Perma Pure removes water vapor from the sample stream without altering the dry gas composition. Water vapor is a major interference in NDIR detection of SO_2 and NO; sometimes water was 1/2 of the total signal. A first attempt at using the dryer in lieu of a water cooled condenser and a refrigerator failed and the dryer was destroyed. The vendor replaced the unit which now polishes the preconditioned sample stream for the two water sensitive NDIR machines. This device was a major improvement in the state of the art and makes NDIR detection as useful as the more expensive UV, Chemiluminescent, etc., techniques.

19. A method for continuous recording of HCl content of flue gas is still not available. A chloride free petroleum coke was burned in a fluidized-bed of limestone with rock salt being added. Using bubblers to absorb gaseous chlorides from a filtered gas stream, it appears that less than 4 percent of the NaCl is converted to HCl. This contrasts with the coal-bound chlorides which are normally converted totally to HCl in boilers. Because of the small quantities involved, plus sampling and analysis problems, chloride balances are generally poor. For the test with petroleum coke, the material recovery was 98.9 percent; good closure.

20. After several years of using limestone from a Grove Lime Company quarry located in nearby Middleburg, Virginia, PER began using a West Virginia limestone that is available at very low cost (excluding transportation). This low grade stone from Greer, West Virginia is only 79.7 percent $CaCO_3$ compared with 97.7 percent $CaCO_3$ for the Virginia stone. The first attempt to use this stone was not successful. After some experimentation, it was learned how to calcine and sulfate the stone, so that it would not turn to powder and blow out of the bed. On a calcium-to-sulfur mole ratio basis, the Greer stone is superior to the Grove. The spent Greer stone is relatively inert - it can be dropped into water and no detectable heat is generated due to hydration.

21. Samples of spent Greer stone were leached in water repeating earlier experiments conducted at BCURA with more reactive materials. The Greer stone was relatively insoluble;less than 10 wt. percent went into solution. BCURA had detected substantial dissolution of a partially sulfated dolomite and limestone.

22. The FBM experienced its first tube failure in 9,000 hours of service, but it had no relationship to the fluidized bed. The failure was a crack on the side of a tube away from the fire at a weld between the furnace and the casing.

23. A horizontal tube bundle duplicating the details of the large prototype boiler was being designed for installation in the FBM as this reporting period ended.

1.3.3 Plant Engineering, Equipment Design and Fabrication

In October 1972 PER began a program of designing the installation of a 300,000 lbs/hr multicell fluidized-bed boiler (MFB) in an existing electric generating plant.

After a detailed investigation, covering items such as minimal undesirable environmental impact, availability of as-built drawings of the existing facility and other factors it was concluded that the Rivesville Power Station of the Monongahela Power Company was a desirable site selection. A detailed discussion covering the plant selection is in Section 4.2 "Site Selection".

The next task was to do the plant engineering, equipment design and fabrication of the fluidized-bed boiler installation.

The plant engineering comprised the installation of the fluidized-bed boiler and its auxiliary equipment and the integration of a new system with that already existing.

Although the existing facility was a coal-fired steam generation plant, additional systems were designed to be incorporated so as to meet the requirements of the new boiler.

A fuel preparation and storage system to prepare coal to the proper size and moisture content was designed. Coal is to be taken from the existing plant coal system, prepared and stored for ultimate injection into the fluidized-bed boiler.

A fuel feed system designed to convey the prepared coal from the storage facility to the furnace will also be incorporated.

Limestone, used in the combustion process, requires a preparation and storage facility. Since no limestone was utilized in the plant prior, a new system was designed.

Similar to the fuel feed system, a limestone feed system was designed.

Additional systems, such as the ash reinjection, electrical, bed material handling,fly ash collection, combustion control, steam, feedwater and others, were also designed to be added to the existing facility. A detailed discussion of all these systems is covered in Section 4.4 "Auxiliary System Design" of this report.

The next task was to design and fabricate the multicell fluidized-bed boiler to suit this application.

In June 1973, Foster Wheeler was contracted to evaluate the existing Pope, Evans and Robbins design of the Rivesville demonstration unit.

A concept of a utility sized unit, 800 MWE, was prepared mutually by Foster Wheeler and Pope, Evans and Robbins. Based on the concept for this very large boiler, substantial changes were made in the design concept of the 30 MWE unit for Rivesville. Foster Wheeler then prepared a detailed engineering design for the 30 MWE multicell fluidized-bed boiler.

After preparation of the steam generator arrangement drawings and competitive bidding for fabrication and erection of the Rivesville demonstration unit, Foster Wheeler Corporation was contracted to fabricate and erect the steam generator beginning December 6, 1973. Following preparation of the shop fabrication drawings and procurement of materials, fabrication began in February 1974. Shipment of completed components to the Rivesville, West Virginia site is scheduled to begin in July 1974 with field erection scheduled from August through November 1974.

A detailed summary of the boiler design and fabrication tasks are in Section 2.3 and 2.4. Appendix E and Appendix F contain additional details on the boiler design and fabrication tasks.

II. BOILER DESIGN AND FABRICATION

2.1 Background

A fluidized-bed boiler furnace integrates heat transfer with combustion to a greater extent than the conventional boiler furnace. The difference is so substantial as to be one of a kind rather than degree.

It is useful to visualize a large fluidized-bed boiler as a number of unit cells. The unit cell is a region of a large fluidized-bed boiler. The unit cell has a coal-injection point at its center and heat transfer surface arranged in the bed so as to remove much of the heat generated by the injected coal.

A number of conceptual designs for fluidized-bed boilers have been proposed; they all share the unit cell.

Work preceding the current contract was aimed at developing relatively small fluidized-bed boilers for use by industrial plants. Generally such boilers would be used to produce process steam, but it is useful to describe the size range in terms of the electrical power that could be produced by the steam. Industrial boilers are generally in the range of 5 to 50 MWE. Utility boilers are generally much larger; from 200 to 1300 MWE. Conceptual designs of industrial or utility size fluidized-bed boilers all use the unit cell.

An important difference between the unit cells in the utility boiler and the industrial boiler is that in the former much of the heat transfer surface is for superheating steam. Unlike a tube filled with boiling water, the superheater tube temperature continuously increases with distance from the inlet, and thus the superheater tube becomes a less effective heat sink.

Two design concepts were proposed for the 30 MWE prototype. (1) A design in which all boiling took place in vertical tubes using natural circulation, and all unit cells contained like amounts of horizontal superheater surface. This concept had the advantage of being rail transportable and could be viewed as the prototype for industrial-sized fluidized-bed boilers. (2) The alternate design was based on matching features in an 800 MWE conceptual design. Here horizontal boiling surface is used and superheaters are separately fired.

Because the goal of this program is to produce fluidized-bed utility boiler designs as rapidly as possible, the latter concept was selected for detailed design.

The choice was not simple because the decision to segregate superheater surface implies operation of the boiler with cells having different bed depths. This follows from the fact that the operating bed temperature, restricted to a relatively narrow range,will be kept constant by changing the heat transfer surface exposed to the bed as load changes. This is done by varying the depth of the fluidized-bed. It is impossible to precisely meet all of the system requirements unless bed depth can vary between boiler cell and superheater cell.

2.2 Selection of Boiler Manufacturer

Final detailed design of the PER 300,000 lbs/hr steam generating capacity fluidized-bed boiler necessitated the assistance of an experienced boiler manufacturer. In order to make a selection, the five largest U.S. boiler manufacturers were contacted. They were asked for an expression of interest in performing the designated engineering and design work, and for a statement of qualification and/or experience in fluidized-bed boiler design. Visits and informal discussions prepared each potential Subcontractor for the formal request which followed.

In response to the formal January 1973 inquiry, statements were received from these manufacturers:

Combustion Engineering, Inc.	Interested and qualified
The Babcock & Wilcox	Not interested at this time
Foster Wheeler Corporation	Interested and qualified
Riley Stoker Corporation	Could not participate at this time
Zurn Industries, Inc. (Erie City)	Could not participate at this time

Each of these manufacturers and their manufacturing facilities were visited. A brief description of the claimed fluidized-bed boiler design and/or research experience of the two companies qualified and expressing interest to assist PER follows:

Combustion Engineering, Inc.

C.E. became interested in fluidized-bed combustion in 1952 through contact with the late E. J. Houdry who was President of Oxy-Catalyst Inc. Mr. Houdry controlled Houdry Process Company which did much of the work on catalytic cracking of oil using moving and fluidized-beds. During 1952-53 the idea of burning fuel in a fluidized-bed of "catalytic material" was conceived by C.E.

Work was carried out in C.E. laboratories during 1954-55 to show that gas and oil could be burned and that heat could be extracted from the bed and that if scaling up were possible, a commercial steam generator could be designed.

During a 2-1/2 year period (January 1955 - June 1957), beds up to 6 sq. ft. were used for gas. Oil and coal were tested also to show that these fuels could be burned. Inert materials such as Al_2O_3 were used, as pellets, to form the bed. Due to attrition problems with the pellets, all fluid-bed research work was stopped in 1957.

Foster Wheeler Corporation

The Process Plants Division of Foster Wheeler up to March 1973 has designed and constructed 29 fluid catalytic cracking units ranging in capacity from 1,200 to 41,000 barrels per day. These fluid catalytic cracking plants use what is essentially a fluidized-bed combustor to regenerate the catalyst.

As a Subcontractor to Westinghouse Research Laboratories during December 1969 through late 1971 period, Foster Wheeler studied and selected the best concepts for application of fluidized-bed combustion, with sulfur oxide absorption, to utility power cycles. Conceptual steam generator designs were made for economic studies and required R & D was outlined.

Under subcontract to Gourdine Systems Inc., during June 1967 - September 1968 period, Foster Wheeler designed, built and operated a system burning coal under pressure, up to 30 atmospheres, discharging the products of combustion to an EGD (electrogasdynamic generator) at temperatures up to 2,000°F.

A fluidized-bed combustion test system at the Foster Wheeler Research Center consists of an 18-inch diameter fluid bed steam generator (horizontal tubes), designed to burn approximately 100 pounds coal per hour complete with the required coal preparation, transportation and feed systems, stack gas coolers and dust collector.

As a result of meetings held with officers of both companies, and an evaluation of the submitted experience statements of the two manufacturers, PER concluded that the Foster Wheeler Corporation was the more experienced manufacturer in fluidized-bed combustion systems, and that qualified manpower was available within the company to perform designated engineering and design services. Although Combustion Engineering had, or could develop, the technical resources to perform the work, the fact that it had done comparatively little or no design or development in the fluidized-bed combustion field for the past sixteen years, mitigated against their selection. It was felt that Foster Wheeler's current and applicable experience in fluidized-bed combustion systems would result in a faster integration of the PER know-how with Foster Wheeler's design skills.

OCR's approval was requested and received during the early part of 1973 to engage Foster Wheeler Corporation as a Subcontractor, to perform the required boiler design and component verification test work.

A subcontract to design the 300,000 lbs/hr steam generation capacity multicell fluidized-bed boiler (MFB) and to perform part of the required concurrent design verification test program was signed with the Foster Wheeler Corporation in May 1973.

2.3 Boiler Design

As a guide to the detailed design of a 30 MWE demonstration unit, PER and Foster Wheeler Corporation developed a design concept for an 800 MWE unit. Then the final design of the Rivesville demonstration unit could be based on the utility unit design concept. This permits obtaining a maximum amount of scale-up design information during operation. The 800 MWE unit concept was developed based on that it should provide for maximum operating availability, load turn down and flexibility of control. Since the fluidized-bed process lends itself to design with cells,the 800 MWE boiler concept involves an arrangement of multiple cells. To provide maximum plant availability the 800 MWE unit has been divided into four 200 MWE capacity modules that may be completely isolated from one another for inspection or maintenance of any module(s) while the remaining stay in operation. Each of the four modules has been divided into seven cells stacked vertically one above the other. The arrangement of a 200 MWE fluidized-bed module is shown schematically on Figure 2.1.

To provide for maximum control flexibility of each module, the heat transfer surface has been divided among the cells so the surface within the bed serves a different heating function in each cell. The type of heat transfer surface located in the fluidized-bed of each cell is also indicated on Figure 2.1. The physical dimensions of each cell are based on process and mechanical criteria. To provide for maximum shop fabrication, the dimensions of the cell are set so that an entire 200 MWE module can be shipped in two sections by barge or six sections by rail, thereby minimizing field erection expenses. The width of the unit was also limited by fuel injection requirements to 12'. The height of each cell has been determined based on process criteria where 4' is required for the fluidized-bed zone, 6' for a free board zone above the bed, 6' for convection heat transfer surface above the free board zone and another 4' for the air inlet plenum and flue gas exit. The overall dimensions of each cell of the 200 MWE module are indicated on Figure 2.2.

Following the development of the concept for an 800 MWE fluidized-bed steam generator Foster Wheeler evaluated the, then most recent, PER concept of the Rivesville unit. Based on this evaluation Foster Wheeler was to prepare the final steam generator design and engineering arrangement drawings. The evaluation of the PER unit design and the preparation of the final engineering design and arrangement drawings for the Rivesville unit were completed in September 1973 and December 1973 respectively. The details of this work are described in Appendix E.

The fluidized-bed steam generator design submitted to Foster Wheeler Corporation was revised based on mechanical and heat transfer considerations and the requirement for this

SCHEMATIC DIAGRAM
800 MW FLUIDIZED BED STEAM GENERATOR ARRANGEMENT

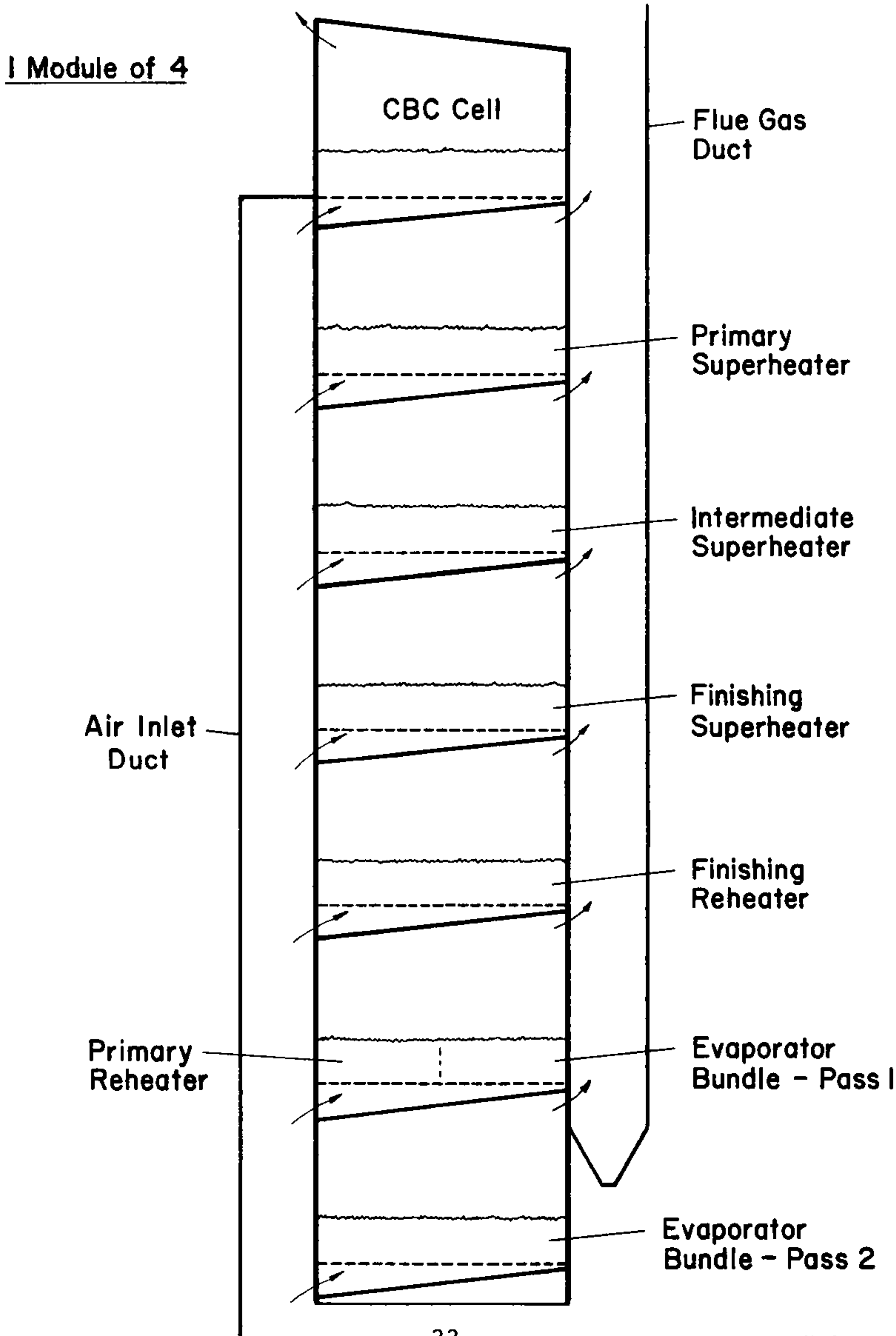
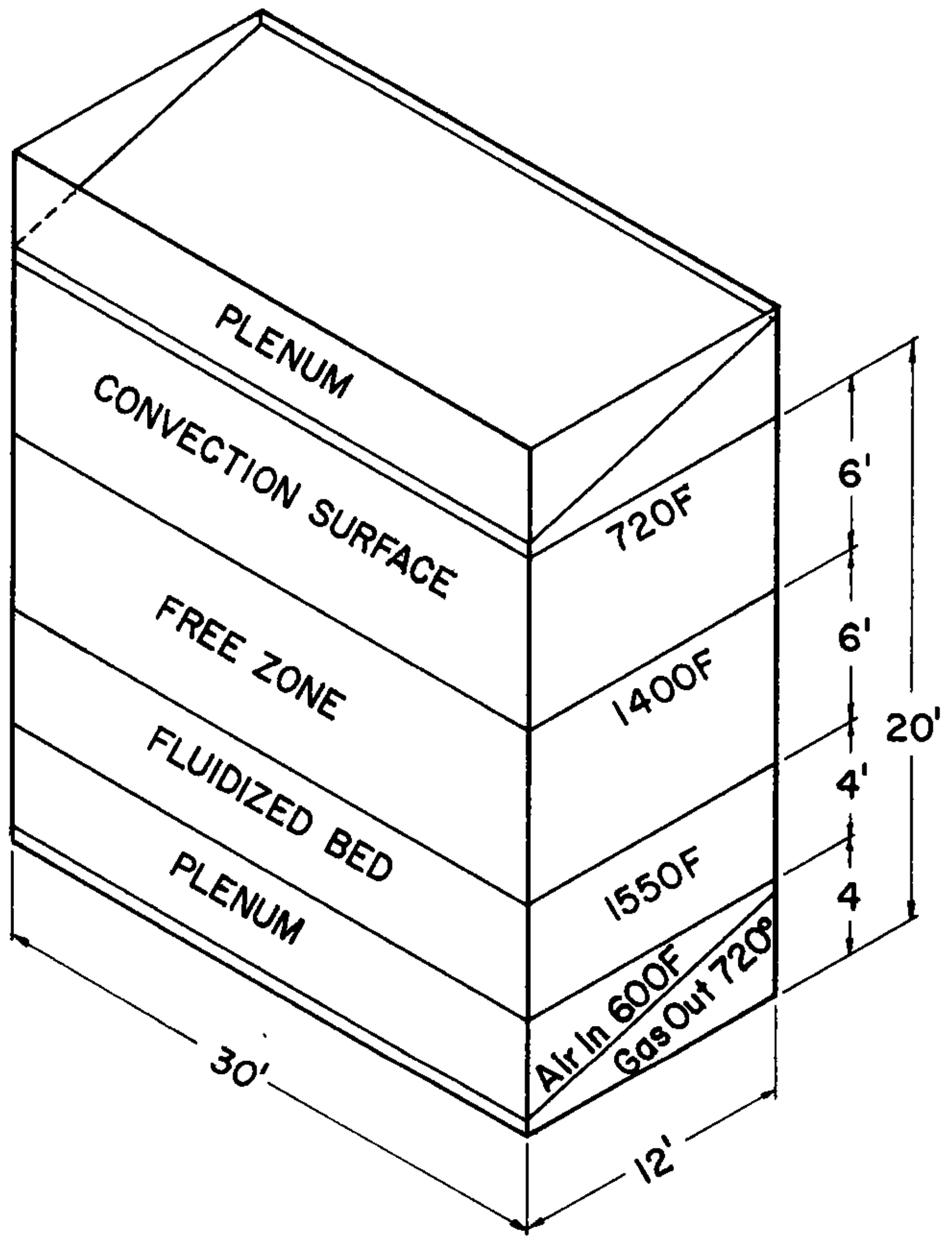


FIGURE 2.1

DEVELOPMENT OF CELL SIZE



unit to produce design information required to scale up to the 800 MWE utility unit size. The resulting arrangement of the Rivesville unit incorporates multiple cells that require scale up in only one dimension for application to the utility unit concept.

The heating functions of surface within the bed at the Rivesville unit have been divided to provide individual control of superheater and boiling heat transfer. The final design for the Rivesville demonstration unit incorporates horizontal boiling surface which requires the use of forced circulation pumps to insure proper fluid mass-flows through the boiler tubes. The design also incorporates the use of manufacturing techniques that will be used for fabrication of future fluidized-bed steam generators.

To aid in the selection of an air distributor design and in the arrangement of tubes within the fluidized-bed, a cold test program, involving construction and testing with a cold test model system, is in progress. The cold model test program also includes design verification testing for the steam generator auxiliary systems required to handle and feed fuel and limestone to the steam generator and extract and reinject the fluidized-bed material. The test program and materials involved are described in detail in Appendix E.

To reduce the total limestone requirement of the steam generator a system for regeneration of the partially sulfated bed material is being designed for use with cell A of the demonstration unit. The calcium sulfate regenerator is being designed to regenerate calcium sulfate to calcium oxide and SO_2. The calcium oxide will be returned to the fluidized-bed steam generator for re-use as a sulfur sorbent. The chemical engineering problems within the regenerator are presently being resolved and this effort will be followed by the mechanical arrangement of the regeneration system and preparation of the engineering drawings. The details of the regenerator design progress are described in Appendix E.

2.4 Boiler Fabrication

On December 6, 1973, Foster Wheeler Corporation was awarded a contract to fabricate and erect the 30 MWE fluidized-bed boiler at Rivesville, West Virginia. The contract required preparation of shop fabrication drawings, procurement of materials, component fabrication and field erection of all components. The procurement of accessory equipment, attached to the steam generator, not in the original contract was added to the Foster Wheeler scope of work as described in Appendix E.

During the preparation of the shop fabrication drawings, several design modifications were incorporated, including a revision of the downcomer arrangement to incorporate two forced circulation pumps. Shop fabrication of the drum began in February 1974 and 98% of all materials have been received by Foster Wheeler. Shipment of steam generator components to the Rivesville site is scheduled to begin July 12, 1974 and expected to continue through September 1974.

Field erection of the steam generator is to begin August 5, 1974 and continue through November 1974. Anticipated late delivery of auxiliary equipment, including valves and forced circulation pumps may delay the scheduled November 1974 hydrostatic tests and unit boil out. The fabrication and erection contract progress is described in Appendix F. Photographs of some steam generator components are provided in Appendix F.

III. EXPERIMENTS AND DESIGN VERIFICATION TESTS

3.1 Introduction

The majority of the fluidized-bed boiler development and design verification experiments are performed in the Alexandria, Virginia fluidized-bed combustion laboratory. This laboratory is operated by Pope, Evans and Robbins Incorporated and is used for two basic functions:

1. To achieve insights into the performance of a coal-fired, fluidized-bed boiler as a chemical-reactor;

2. To test, under the most realistic conditions available, the components which are to be used in the prototype plant now being fabricated.

It is often impossible to separate a component test from process insight. But it is essential to keep in mind the limitations inherent in any small piece of experimental apparatus. Although the FBM is the largest piece of equipment of its type in the world, it has a grate area of only 11.2 sq. ft.

Interest in the fluidized-bed boiler is widespread and a substantial amount of data has been generated in a wide variety of reactors ranging in size from 0.02 sq. ft. to 9.1 sq. ft. (the coal burning region of the FBM). The smaller reactors were heated and cooled through the reactor walls, the larger were cooled via tubes in the fluidized-bed. A variety of air distributors have been used; nine different research organizations selecting one, or several, as being most useful. It is little wonder that a wide variation in results have been reported from the eighteen systems used for gathering data and achieving insight into the nature of the process. Attempts at correlating important response variables,such as combustion efficiency or sulfur capture efficiency with control variables, such as bed depth of air rate, have not been successful, although general trends are apparent. One reason for this defect is that physical measurements are made on the bed - its temperature and its depth - while the response variables, e.g., gas composition and carryover analysis are made on samples withdrawn from the furnace (reactor) exhaust. Reactions occur in the freeboard, the space between the top of the fluid bed and the gas outlet. These chemical reactions and the reflux of bed material are difficult to measure and quantify and so they have been generally overlooked. Fortunately it is not generally necessary to understand why a system performs as it does to use it industrially. It is clear, however, that a great deal of interesting and potentially useful academic work would be generated by the successful application of the coal-fired, fluidized-bed boiler.

Using the FBM, the following was explored during this reporting period:

a. Startup of a fluidized-bed boiler from a cold iron status was developed into a routine operational procedure. It is believed that the technique will be applicable to the 30 MWE protytypes without substantial alteration.

b. Hot restart of the FBM has also become routine procedure. The FBM can be brought to full load from zero load in a matter of seconds. It is anticipated that the procedure will be directly applied in the 30 MWE prototype. The speed of load assumption will probably be determined by factors external to the boiler.

c. Coal injection using long, uninsulated tubes was explored and found feasible. Questions will remain on the technique until the 30 MWE prototype provides long-term operating data.

d. A variety of air distributors were tested in a search for a low cost,low pressure drop design giving adequate performance. This effort was continuing.

e. The Bureau of Mines test in March, 1973 pointed up the need for a technique to cleanse the lime bed of coal ash particles. A simple air classifier did not perform. A vibrating screen did permit the bed to remain high in calcium. The technique is to be applied directly to the 30 MWE prototype. Further work in this area is indicated.

f. Tests to provide independent proof of the pollution control aspects of the process were required and were performed. The lowest cost limestone (at Rivesville) was successfully used.

3.2 Full-Scale Boiler Module and Supporting Systems

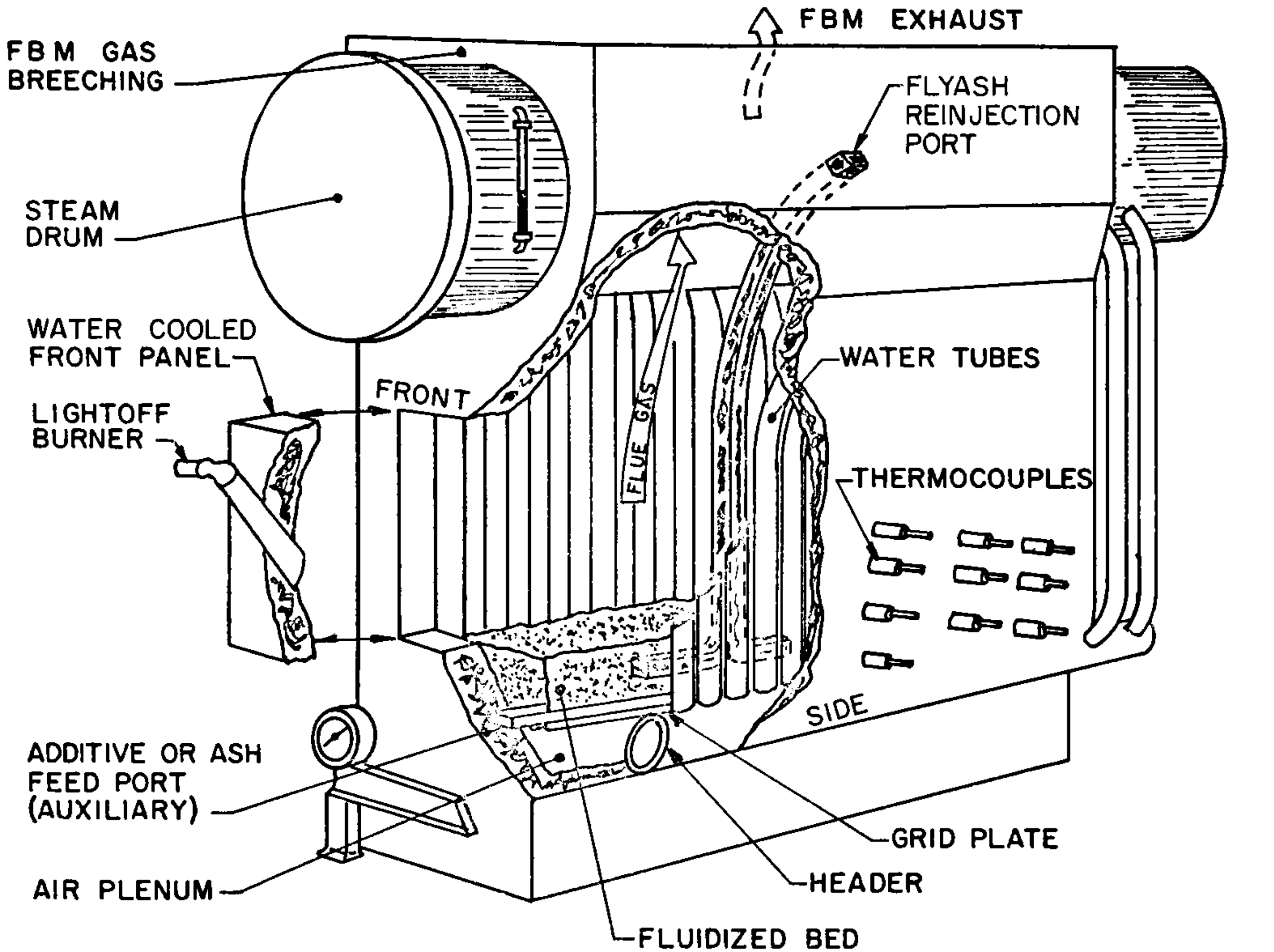
The full-scale boiler module, designated the FBM, is a boiler capable of generating steam at pressure; up to 300 psig. In this unit, the fluidized-bed is contained in a rectangular enclosure in which each wall is a row of vertical boiler tubes seal-welded so as to form a gas-tight enclosure.

A cut-away sketch of the FBM as it was, when first placed into service, in 1967 is provided in Figure 3.1. The FBM cross section is ∿18 x 72 inches, 9.1 square feet for flow. The bed is surrounded by vertical boiler tubes which extend from two cross headers below the grid plate to the steam drum. The boiler tubes are joined together by welded fins and are backed by insulation.

The combustion space is accessible through a water-cooled panel at the front of the unit. The panel contains a view port and a premix gas burner used to fire the bed during start-up. The burner directs a flame downward onto the front of the bed. For most of the tests described in the report, the coal feeders shown in Figure 3.2 were used. Other feeder designs have been used in other programs.

From the plenum at the base of the unit, air is directed upward through the air distribution grid. The grid used during most of the test consisted of a mild steel plate containing machined nozzles on 1¼" centers. The bed material used in the FBM tests was either limestone or sintered ash, either 8 or 6 mesh (USS). The static bed depth may be varied from 6" to over 30", although the useful range is narrower. A bed sampling pipe and valve are provided. Thermocouples were mounted throughout the bed, as shown in Figure 3.3.

In operation, the bed is raised to the ignition point of coal by use of the gas burner mounted in the front panel. Combustion of the coal begins in the vicinity of the light-off burner flame and propagates rapidly throughout the bed. Firing with a coal input of 600 lb/hr, the FBM produces 200 psig steam at the rate of 3,500 lb/hr. A water-cooled tube array just above the drum simulates the convection bank of a conventional boiler. 5000 lb/hr of steam can be generated.



1967 TO 1969

FIGURE 3.1 FLUIDIZED-BED MODULE (FBM) INTERNAL CONSTRUCTION

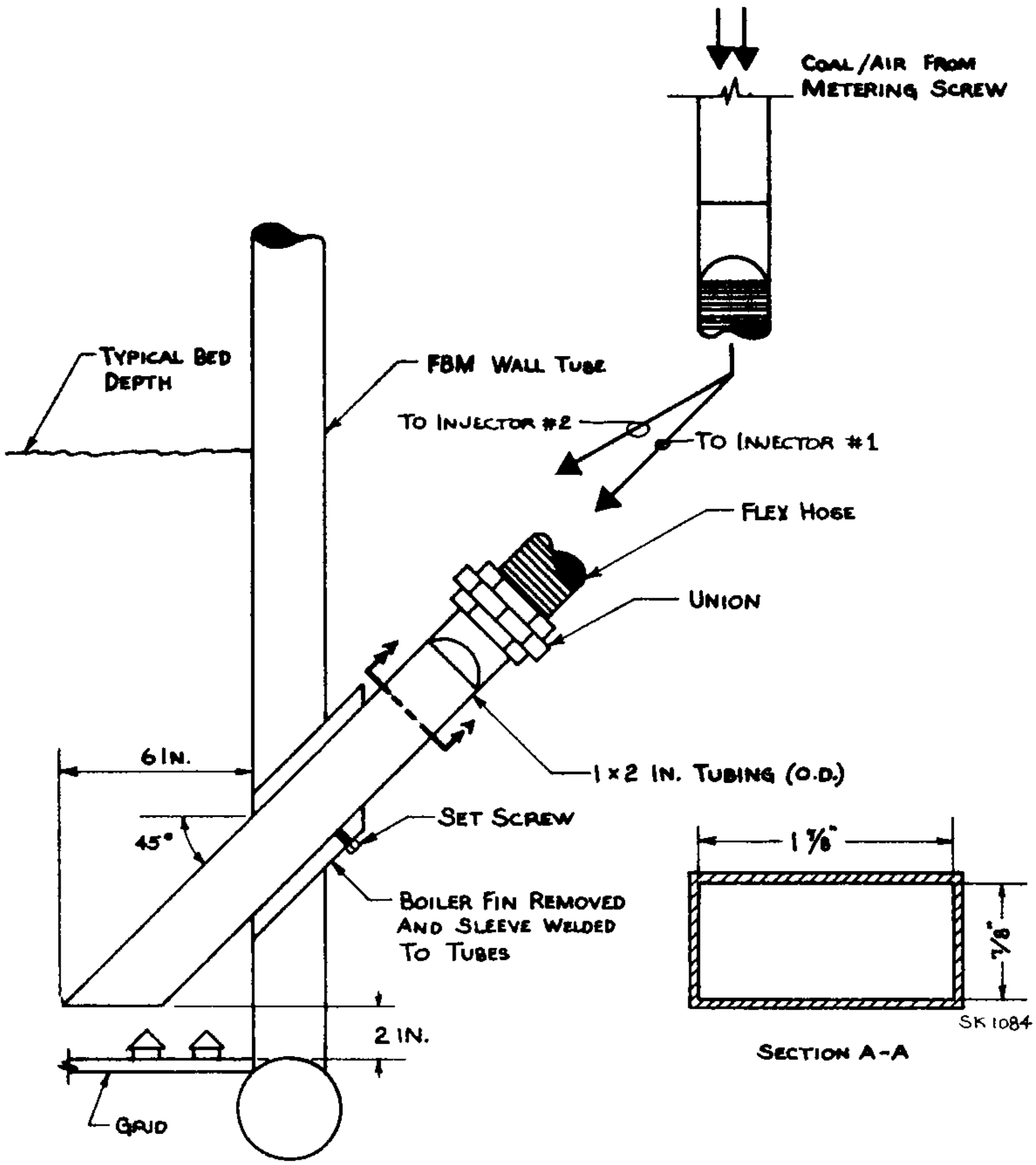


FIGURE 3.2 TYPICAL COAL INJECTOR IN FBM

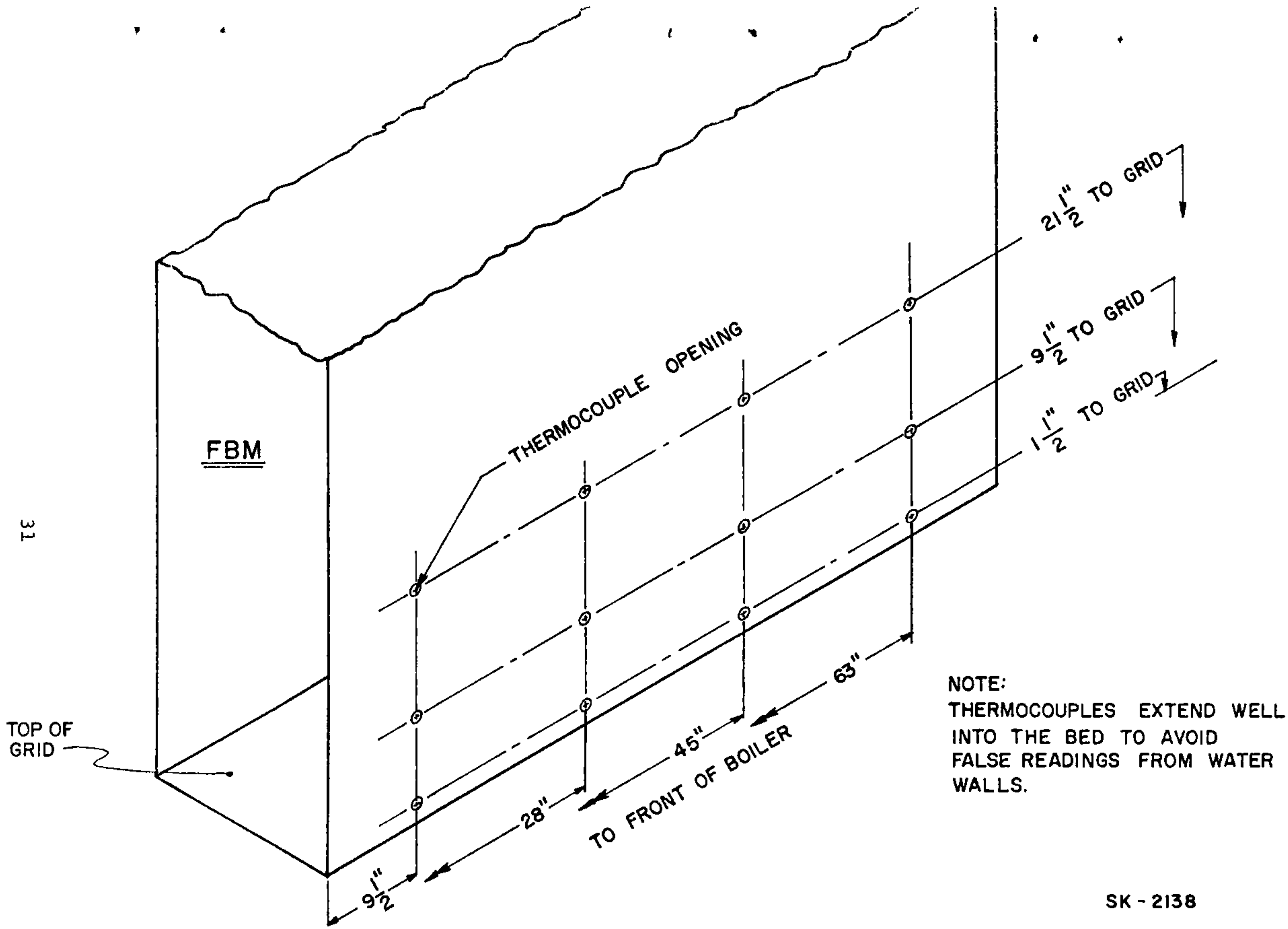


FIGURE 3.3 THERMOCOUPLE LOCATIONS - BED ZONE OF FBM

A schematic drawing of the FBM test system is shown in Figure 3.4. Air from an external forced-draft fan passes through the air preheater and into the FBM plenum. Coal feed is controlled by the speed of a screw feeder which drops the coal into a pneumatic feed tube leading to the injection ports. Sorbent materials are fed into the pneumatic injection line at a rate controlled by a variable speed drive. Ash from the dust collector flows through a star feeder and into a pneumatic transport line either to a bag for storage and weighing or to a Dempster Dumpster for removal to a land fill. Bed material to be airlifted for screening is withdrawn from the FBM via a small air slide.

Flue gas from the FBM passes across the simulated convection bank above the steam drum to reduce temperature before the gas enters the air preheater. As the flue gas passes through the air preheater, a portion of the fly ash drops out and is collected in the hopper (see Figure 3.4). The bulk of the fly ash is removed by a multi-cone collector down stream of the air heater.

The coarse fraction (ash knocked down by the preheater) is screw fed into the dust collector hopper. From the collector, the gas flows through a long duct to an induced draft fan via a venturi, which permits flue gas flow to be determined and then to atmosphere. A damper is provided in the ducting to control pressure in the combustion chamber. The system is operable without the induced draft fan, but is not usually run pressurized. An isokinetic sampler is provided for the study of stack particulate emissions.

3.2.1 Coal Supply System

Coal is crushed in a hammer mill and then screened on shaker table and the oversized recycled. A typical size distribution for the as-fed coal is shown in Figure 3.5.

Coal under ¼" is removed from the shaker via a screw and fed to a 50 ton storage silo. When coal is needed for an experiment it is removed from the silo via a screw at the bottom and air lifted to the weigh hopper in the combustion lab. The weigh hopper shown in Figure 3.6 rests on a 5,000 pound scale. At a coal rate of 600 pounds per hour the hopper and scale have a useable 5½ hour supply of coal. Tests of longer duration require intermittent filling of the

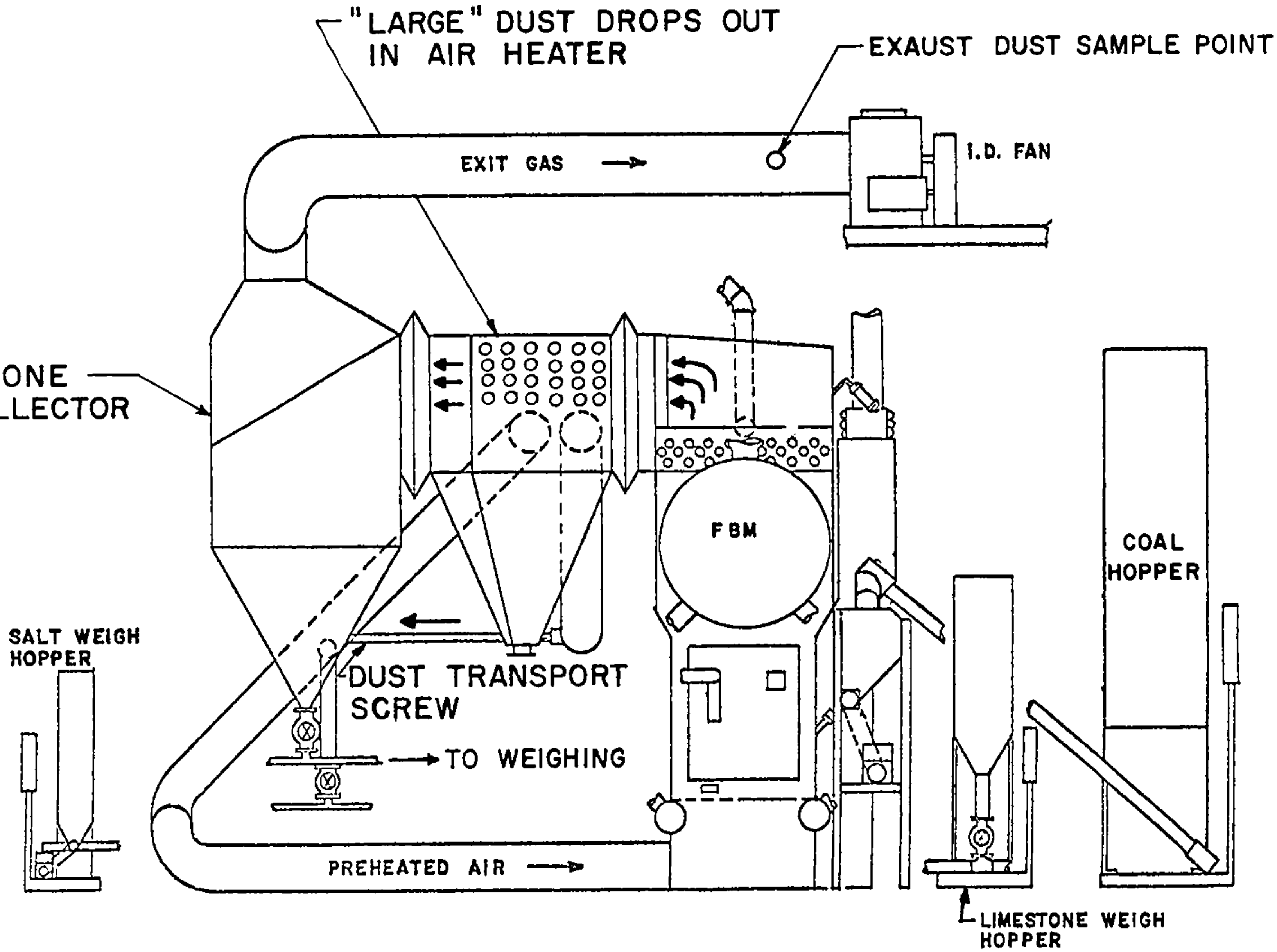


FIGURE 3.4 SCHEMATIC OF FBM TEST SYSTEM

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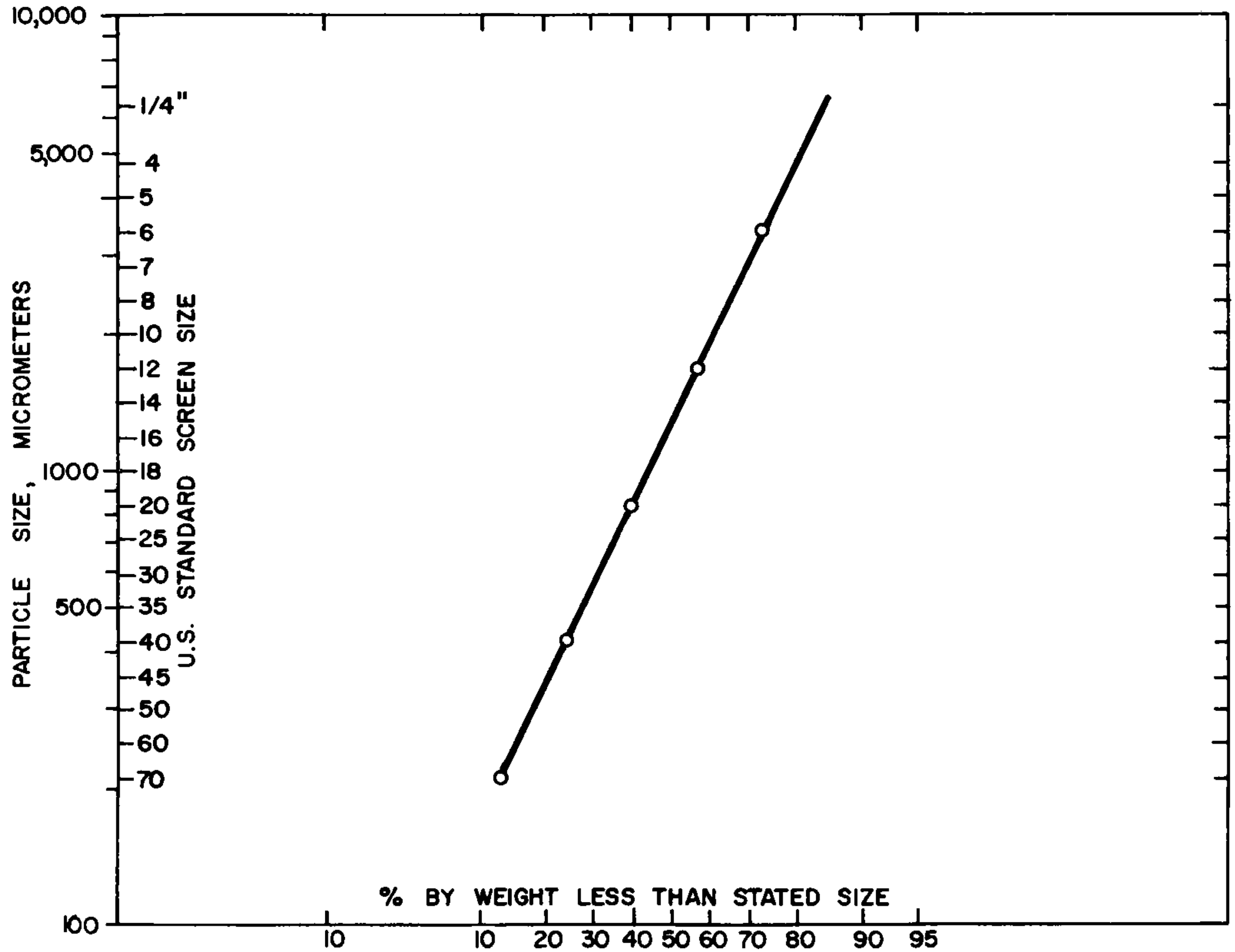

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FIGURE 3.5 SIZE DISTRIBUTION OF COAL (AS FED)

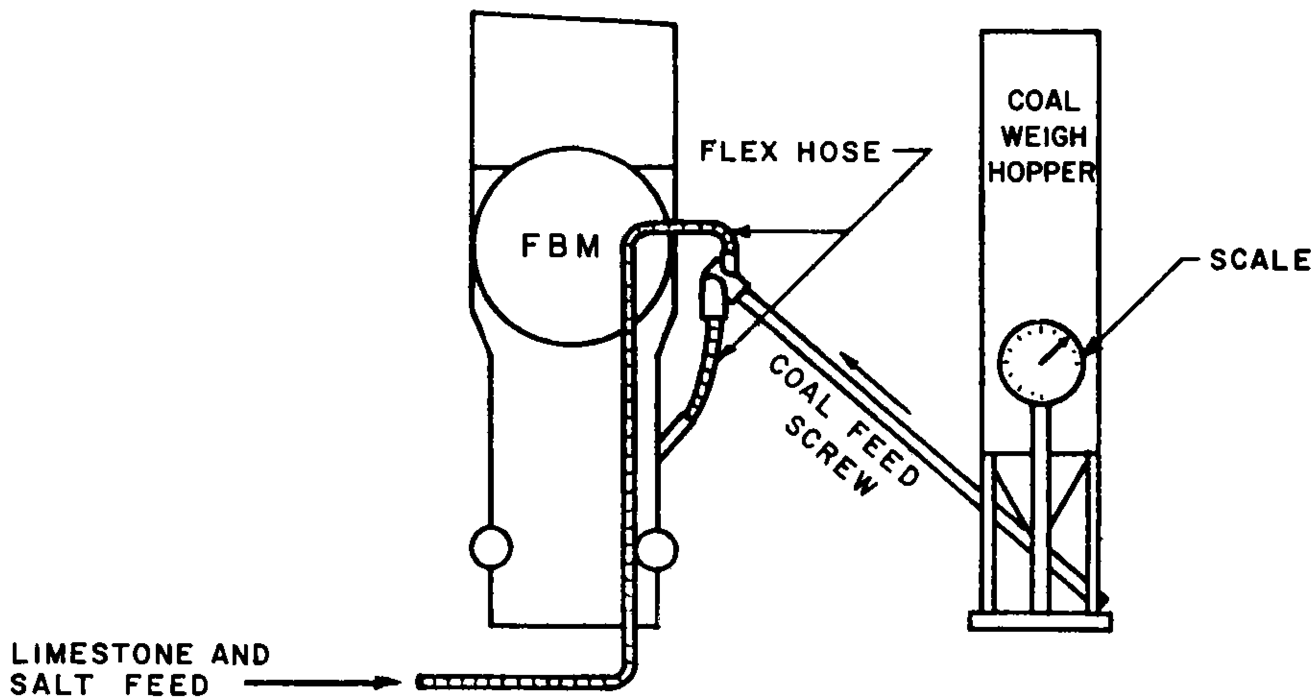

FIGURE 3.6 COAL FEED ON FBM

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weigh hopper. The filling is performed between rate and weight determinations.

3.2.2 Limestone Supply System

To prevent very large particles from passing into the system the limestone is screened to 8 mesh and stored in a bin. The limestone weigh hopper rests on a 1,000 pound scale and is filled from the bin as needed. The rate of limestone feed is set by a rotary valve rotated by a variable speed electric drive. A 2" rotary is as small a device as can be used for granular materials, but it has too great a pocket volume for the relatively low flows that are used. The pockets were partially filled-in so that the valve turns at about 25 rpm for 150 pounds of stone per hour. If the pockets were fully open the rpm would be much lower and the limestone would surge into the conveying air stream.

The hopper is sealed because the rotary valve can not seal against the conveying air stream pressure; about 30" H_2O.

3.2.3 Salt Supply System

Salt is received in 100 pound paper bags and stored in the lab. The salt used is the lowest grade available. When required the salt is screened to -¼" using a small hand seive and a bucket. The salt is placed in a weigh hopper with a 100 pound capacity, enough for 8 to 10 hours of operation. The hopper is necessarily sealed.

3.2.4 Conveying Air Systems

The process requires that coal be fed at the base of the bed. Limestone and salt could both be fed above the bed and thereby negate the necessity of feeding solids into a pressurized air stream. Unfortunately when salt and/or limestone was blown in above the bed the oxygen analyzers which map the homogeneity of the combustion respond to the above-bed conveying-air stream and made the mapping impossible. To allow effective O_2 mapping all granular materials are added at the base of the bed via the coal injectors.

Air conveying systems are normally constructed of 2" EMT which is usually used for electrical lines. For coal injection forced draft fan air is routed to pick up salt, the limestone and finally the coal.

Horizontal runs are avoided by routing almost every tube either up at 30° to 45° or down. Saltation of ¼" material (and occasional bigger pieces) is thus avoided at air velocities around 50 ft/second.

3.2.5 Main Air Supply and Control

A blower capable of providing as much as 8,000 pounds of air per hour at 42" H_2O pressure is used for all conveying and as combustion/fluidizing air. The air flow rate is set by a hand controlled damper. The fan is operated in the region of its head capacity curve where flow increases sharply with any decrease in system resistance. This means that a decrease in bed level causes the air flow to increase while an increase in bed depth tends to reduce air flow. These variations are compensated for by moving the damper or by changing the bed depth.

3.2.6 Flue Gas System and Control

The freeboard space of the FBM is operated at below atmospheric pressure so as to preclude flue gas and dust from entering the laboratory space. This is in accordance with conventional boiler practice.

A damper in the flue is set to maintain the gas pressure after the air preheater at ∼¼" H_2O below atmospheric. This means that the pressure in the furnace is closer to atmospheric. Samples are withdrawn for analysis as will be described below.

3.2.7 Water Supply

The FBM as a boiler requires water of a quality commensurate with the operating pressure of 200 psig. The boiler tubes are common carbon steel. Scale forming minerals are removed from the water via a common zeolite softener and the water is raised to 212°F, in an open tank which acts as a deaerating feedwater heater, by injecting live steam. In 9,000 operating hours there has been no evidence of tube overheating, scale formation or external corrosion.

3.2.8 Steam Control

Steam produced during experiments is vented to atmosphere. An air loaded regulating valve is used to impose a steam pressure on the boiler. The valve is normally set to control the pressure at 200 psig.

In order to test the boilers transient response the regulator is bypassed and the pressure controlled manually. The arrangement for doing this is described later.

3.2.9 Flyash Collection: Rate Determination

The dust which blows out of the furnace is knocked out by the preheater or the dust collector. The collector in use is grossly oversized for the normal operation of the FBM and the pressure drop is extremely low, ¼ to ½" H_2O. In parts of the system flyash dunes tended to form. As a result dust being collected had not necessarily left the furnace a moment before. To help close material balances, surfaces were added to the flue to prevent heavy duning.

Heavy duty vibrators were added to the hoppers to prevent flyash from accumulating on the hopper walls. A rotary unloads the dust hopper constantly and has given good service in an extremely abrasive duty. The dust stream may be sampled via a ½" pipe which protrudes into the center of a long radius elbow. The sample is collected by blowing into a small fiberglass bag. The procedure is far from isokinetic but samples taken this way compare well with samples removed with a thief from the collected flyash.

Flyash rates are determined by blowing the collected dust into 6 foot long, 18" diameter fiberglass bags. The bagged dust is too cool to burn (having been transported by ambient air) but will melt polyethelyne. There are two bags in place at all times---one in use and one in standby. At 30 minute (or more frequent) intervals quick opening gate valves are shifted so that the standby bag is receiving flyash and the partially filled bag may be weighed. A calibrated 300 pound scale is used to weigh the collected material.

3.3 Sample Systems

3.3.1 Furnace Exhaust

Because the potential for air preheater leaks, the decision was made to sample the undiluted stream at the furnace exit. A 3" pipe, slotted at the bottom, extends 6 feet, across the flue gas path as it rises out of the furnace. This averaging header, is exhausted via a small fan which carries the hot gas (+1000°F at the sample point) around the laboratory and into the dust collector after a sample is removed for analysis. Some details of the system are given in Figures 3.7 and 3.8.

3.3.2 Stack Sample

After the air heater and dust collector, a Bendix Poroprobe filter is installed in the duct and provides a diluted sample for analysis. This sample represents the composition of the flue gas. In general there is a decay in the NO value between the two sample points while the SO_2 content is proportional to the dilution.

3.3.3 Entrained Dust Sample

An isokinetic dust sampling train, based on the EPA recommended techniques, was assembled. The probe is used to sample dust from the 16" i.d. duct running along the roof of the lab. Velocities in this duct average 50 fps and rates are easily determined because a venturi is installed in the duct upstream of the sampling point.

3.3.4 Coal Sampling

The inclined screw moves coal out of the weigh hopper and up into the conveying air stream. The pipe in which the screw turns has a 1/2" hole drilled near its intersection with the weigh hopper. The hole is covered with a sheet metal shield held in place by a spring.

3.3.5 Bed Sampling

Samples of the fluidized-bed are withdrawn via a tube which penetrates the furnace wall 2-3/4" above the grate. A carbon steel butterfly valve is opened; a bucket catches bed until the stream is at red-heat and the sample-can then catches one quart. By this means it is insured that the sample

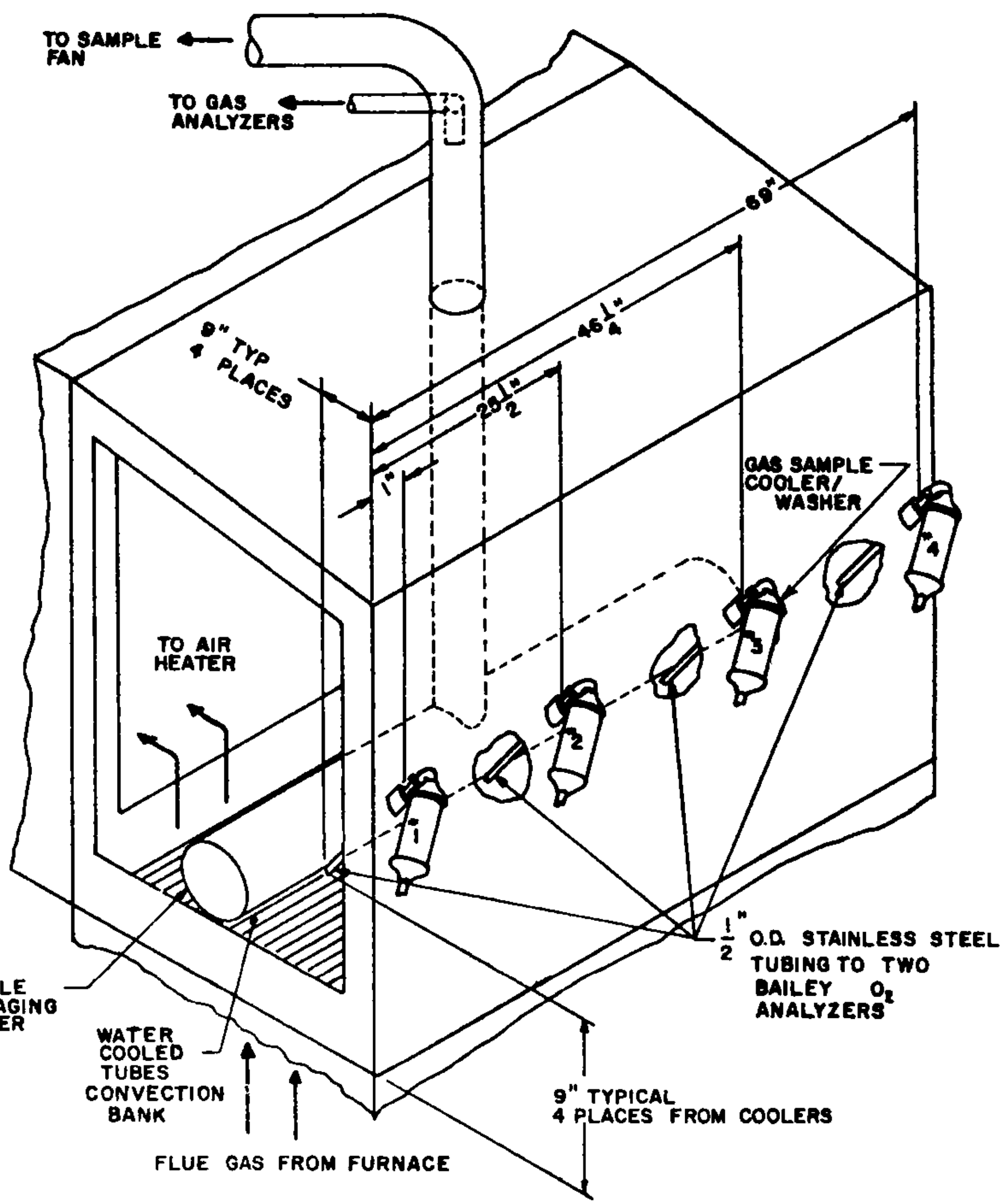

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FIGURE 3.7
LOCATION OF OXYGEN SAMPLING POINTS ON FBM

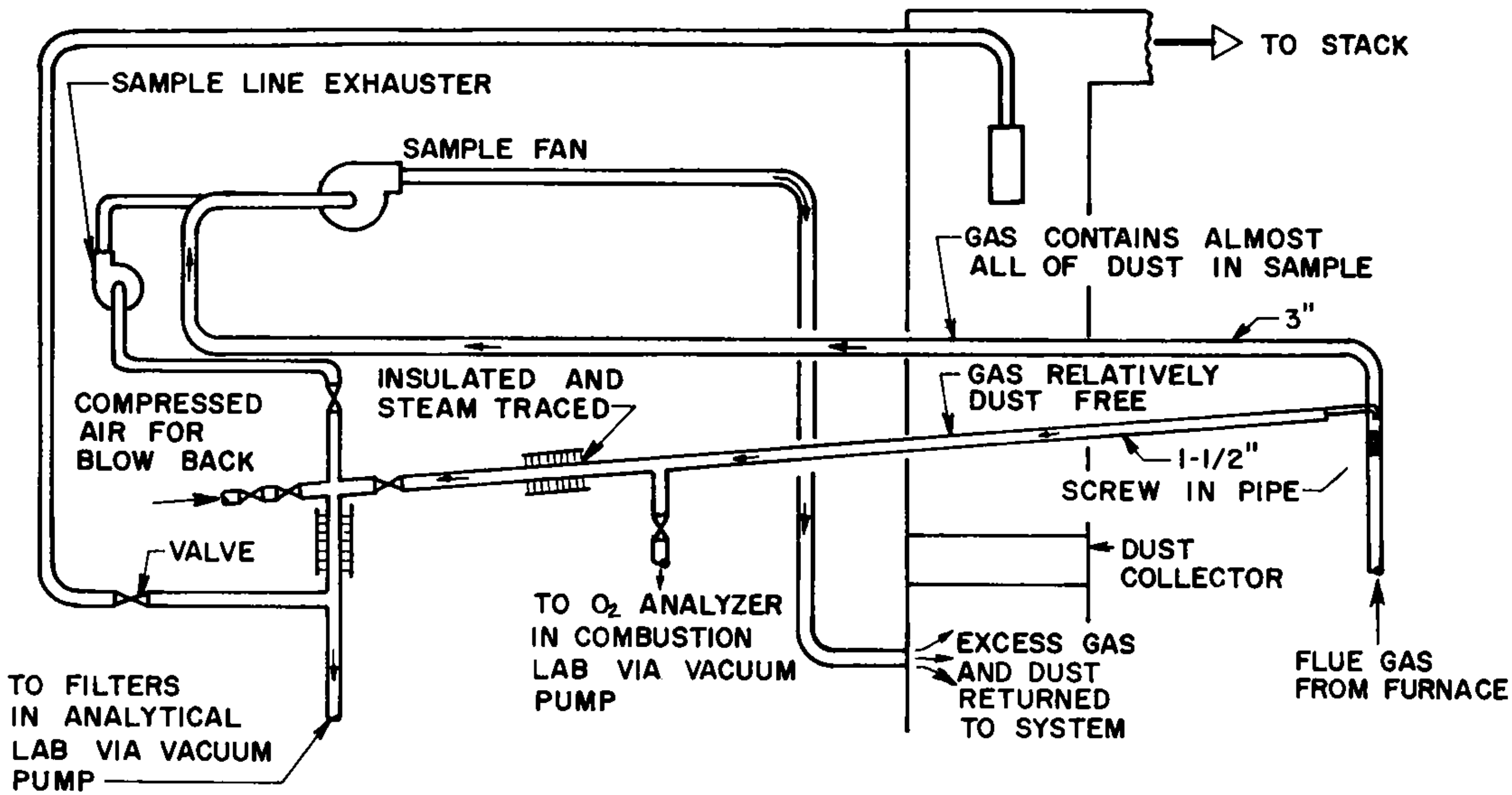


FIGURE 3.8 SCHEMATIC OF FBM SAMPLING SYSTEM

taken, fairly represents the bed composition at that point in time. A screen analysis of 300 pounds of bed removed via the valve was compared with the analysis of the total bed. This proved that some of the large stones "hide out" and are not removed via a line 2-3/4" above the grate level in proportion to their number in the population of bed material.

3.3.6 Sorbent Sampling

No provisions were made to sample the "as-fed" limestone or salt since it was not felt that composition would vary from the "as received" composition. Moisture is always low even though the limestone may be sopping wet. Limestone is not very porous and the material received has been double screened at the quarry.

3.3.7 Combustion Air

The properties and mass are defined by noting barometric pressure, relative humidity and orifice ΔP.

3.4 Analysis Systems/Sample Conditioning

3.4.1. Oxygen Analyzers

Three industrial (as opposed to laboratory) style oxygen analyzers are located in the combustion lab to guide the FBM's operators. The analyzers are extremely rugged having survived dirty water in lieu of a clean gas sample for 30 minutes without substantial change in calibration. Sample conditioning consists, first, of a minature scrubber, provided by the vendor. Because of the extreme dust loading at the point the samples are taken, these scrubbers plug frequently. The cool water-gas mixture then passes to a pump and washer set which removes most of the solids. A heated fiberglass filter follows. Because a massive sample is taken (most is vented at the washer or analyzer) the analyzers detect an imposed step-change within 20 to 30 seconds. Washing gas samples with water is an acceptable procedure if highly soluble gases are not present in high concentrations. For analysis of oxygen in flue gas the procedure is acceptable. When the bed of lime is regenerated the SO_2 content of the gas may be very high (several %) and the oxygen content low, less that 1%. Because these analyzers use hydrogen and have heated platinum filaments a SO_2-hydrogen reaction occurs which generates H_2S and deposits elemental sulfur on the filament. It would be best to avoid the use of this type of analyzer for low O_2 service.

3.4.2 Analytical Laboratory

The sample conditioning system consists of two parallel heated filters, a water cooled condenser, a "warm" pipe leading to the sample pump and a refrigerated cooler. The sample handling and preparation system has a response time of less than one minute.

(a) The filters are housed in an electrically heated, insulated enclosure. The enclosure temperature is maintained at ∿250°F. The viton O-rings which serve as seals have held up well and the assembled units are leak tight.

(b) The water cooled condenser is of the Friedrichs type. There is always some concern that a gas sample containing small quantities of SO_2 will lose SO_2 into the condensate. Condensate is therefore stored away from the gas path. Experiments showed that at the 200 to 500 ppm SO_2 level, normally seen, the loss into the condensate was negligible.

(c) A heated section of pipe connects the water cooled condenser to the sample pump. This was done in order to insure that no water condensed within the sample pump.

(d) Sample pumps provided by Metal Bellows, Model MB-111-10 and Models MB-155, failed in this service. Beckman Model 109A also failed. Metal Bellow Company replaced the defective units with a new design, Model MB-235, which has given noiseless, trouble free service for six months.

(e) A Hankison Model E-10SS refrigerator is used to chill the sample and remove most remaining water vapor.

(f) A novel dryer provided by Perma Pure is used to remove the last traces of moisture from the refrigerated sample before passing through the two Beckman NDIR machines dedicated to SO_2 and NO.

The unit now in use is Model PD 500-40. A larger model was tested for use in lieu of the water cooled condenser and refrigerator and was destroyed. Used as a polishing dryer the replacement unit performs well.

The dryer resembles a shell and tube heat exchanger with a ½" stainless steel tube as the shell. The tubes are a proprietary plastic which absorb water. A dry gas is passed through the shell and removes the moisture. Since Pope, Evans and Robbins was one of the first users of the device, it was tested with calibration gases. Dry calibration gas containing 560 ppm SO_2 was used to calibrate the NDIR. The gas was saturated with water and passed through the NDIR which then showed a much higher signal. The wet gas was then run through the dryer and the signal returned to the 560 ppm level.

The NDIR was zeroed with dry nitrogen. Wet nitrogen showed a rise; the dryer restored this to zero.

3.5 Gas Analysis Apparatus

3.5.1 Continuous Analyzers

Since 1967 fifteen different models of analyzers have been used in the laboratory. Of these only two rate excellent in each of the catagories: reliability, stability, parts and service, response and interferences. These are the Thermoelection Model 10 Chemiluminscent NO/NO_x analyzer and the Taylor Paramagnetic Oxygen Analyzer. Table 3.1 present our evaluation of the units tested.

A useful method for developing calibration curves for instruments with non-linear responses using one or two certified calibration gases was devised. Calibration gases containing SO_2 or NO in CO_2 and Nitrogen are blended with pure nitrogen and passed through the linearized CO_2 analyzer before passing through the analyzer being calibrated.

TABLE 3.1

Instrument Evaluation

Instrument	Usage	Reliability	Stability	Parts & Service	Response	Interferences
Beckman 215A NDIR	CO	C	B	B	A	B
Beckman 215A NDIR	SO_2	C	B	C	B	C
Beckman 864 NDIR	CO_2	D	B	B	A	A
Beckman 915A Flame	HC	B	B	N/A	A	A
Teco Chemilumen-scent	NO/NO_x	A	A	A	A	A
Beckman 215A NDIR	NO	B	B	B	B	C
Taylor Paramagnetic	O_2	A	A	N/A	A	A
Bailey TC	O_2	B	B	C	B	B
L&N Thermo Magnetic	O_2	B	A	N/A	B	C
Peerless NDIR	CO, CO_2, HC	N/A	C	N/A	C	C
Dupont UV	NO/SO_2	B	E	A	B	A
Teco UV	SO_2	N/A	B	A	A	A
Theta Sensor	SO_2	A	A	N/A	D	A
Miran IR Analyzer	General	C	E	N/A	E	E
Beckman TC	CO_2	C	C	C	C	D

Key

A = Excellent
B = Good
C = Fair
D = Poor
E = Unacceptable
N/A = No data

A curve is thereby generated because the CO_2 analyzer shows the proportions of the blend. One point on the curves was verified with a gas containing a different certified quantity of SO_2 or NO.

3.5.2 Calibration Gases

It is our practice to check new gases using wet chemistry if the new bottle does not compare properly with a bottle whose analysis we know. A substantial inventory of calibration gases is needed because deliveries often require three months.

3.5.3 Sample Distribution System

A relatively elaborate gas manifold was fabricated reflecting the requirement to check the several analyzers with various calibration gases. This system is shown in Figures 3.9 to 3.12.

3.5.4 Wet Chemical Techniques for Gases

Wet chemistry is used routinely for gaseous chlorides. Procedures for SO_2, SO_3 and NO_x are used occasionally as referenced in Appendix A. Water vapor content is determined by chilling a hot gas sample to condense water, passing through a preweighed desiccant and measuring the dry gas volume with a calibrated dry gas meter.

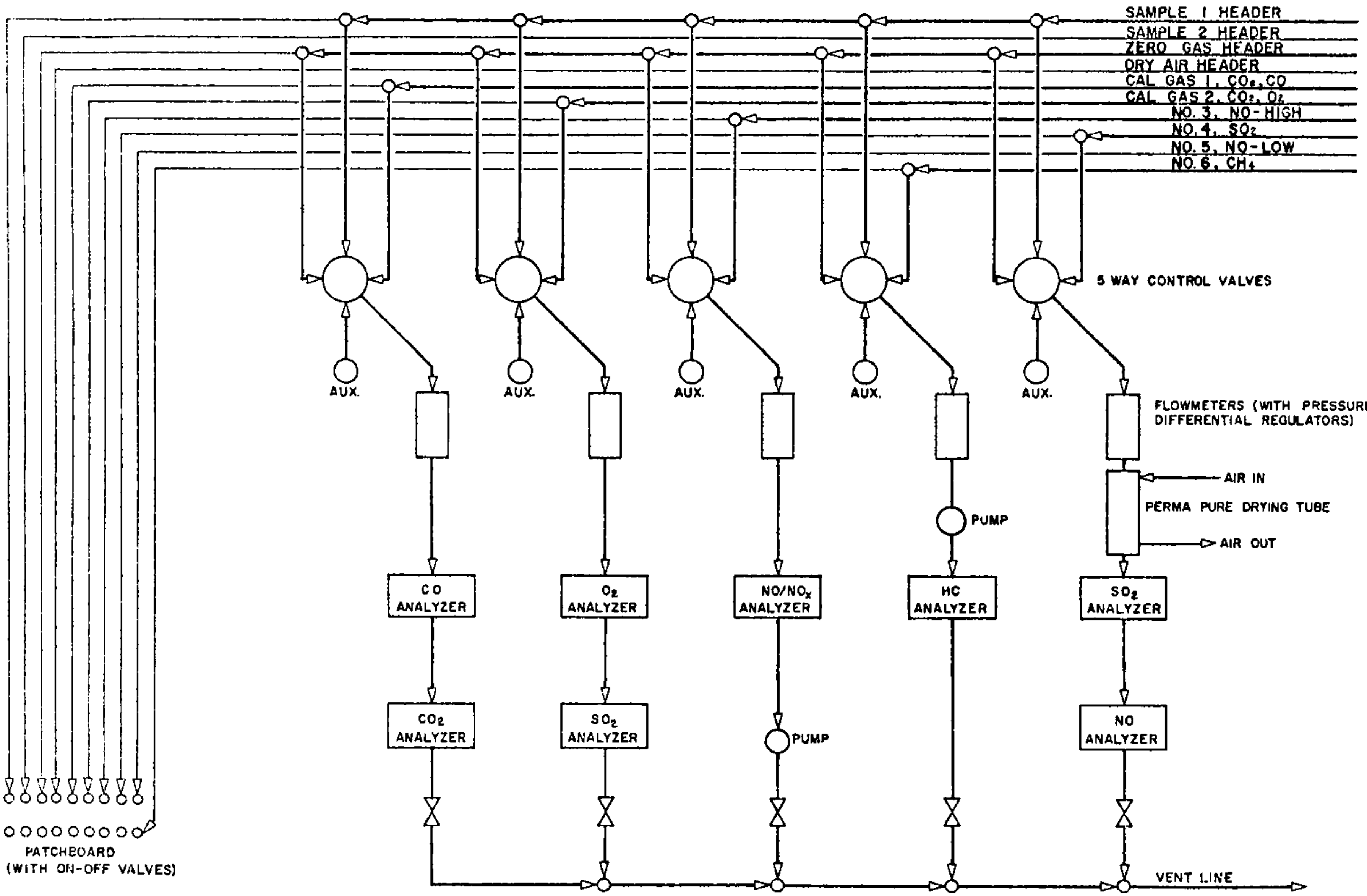
3.6 Analysis of Solids

3.6.1 Size Distribution

A standard set of sieves are used for sizing coal, limestone, salt, flyash and bed material. An MSA particle size analyzer (Whitby Centrifuge and Projector) is available for sub-sieve size particles.

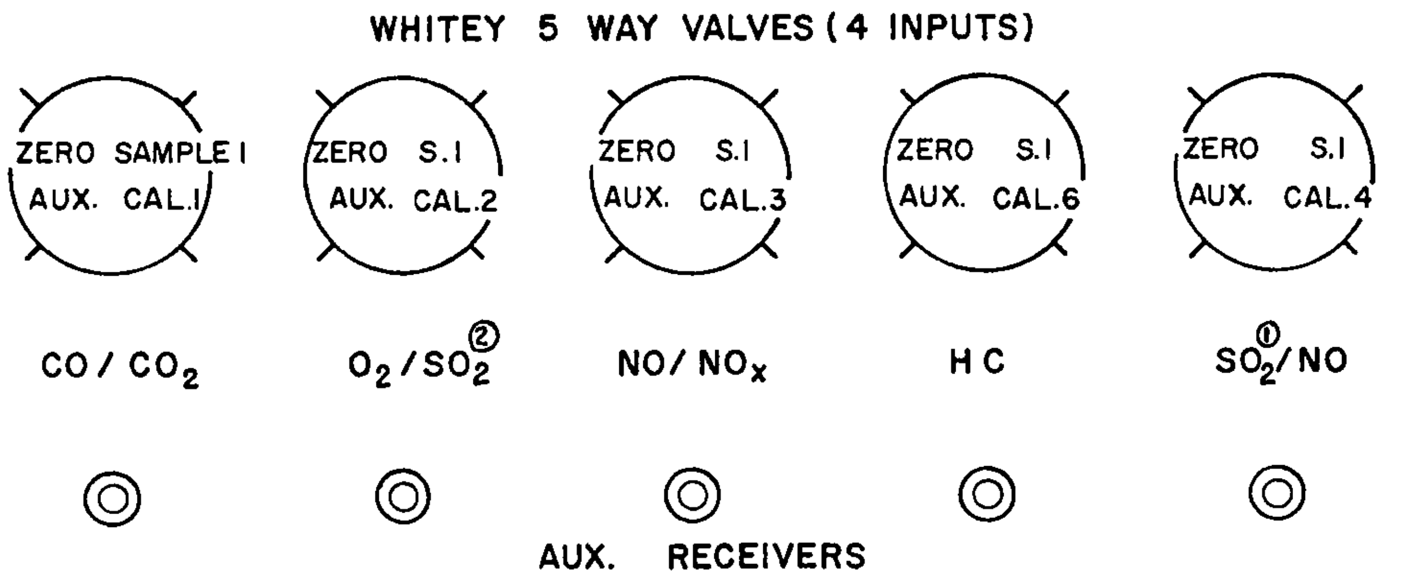
3.6.2 Sulfur in Coal, Flyash and Bed Material

A LECO Automatic Titrator is used for sulfur analysis of solids. The resistance furnace used in the period 1969 through 1972 could not decompose sulfur in bed samples. The induction furnace now in use can rapidly decompose any sample expected to be analyzed.



SK - 1094

FIGURE 3.9 BASIC FLOW SCHEMATIC - SAMPLE SYSTEM



NOTES

1. ALL VALVES, WHEN PUT TO AUX. POSITION, MAY RECEIVE FLOW FROM ANY OF THE 18 POSITIONS ON THE PATCHBOARD. COMBINATIONS OF TWO OR MORE FLOWS FROM THE PATCHBOARD BY THE USE OF A SIMPLE TEE, IS POSSIBLE. (IF DESIRED)

2. THE TWO SO_2 ANALYZERS ARE USED TO CHECK DIFFERENT SAMPLES FOR COMPARISON. SO_2 ANALYSER NO. 1 CAN BE ON FBM SAMPLE, WHILE NO. 2 IS ON REGENERATOR SAMPLE.

3. VALVES WERE ROTATED 45° FOR MAXIMUM SPACE UTILIZATION.

SK-1092

FIGURE 3.10 VALVE LABELING - FLOW CONTROL PANEL

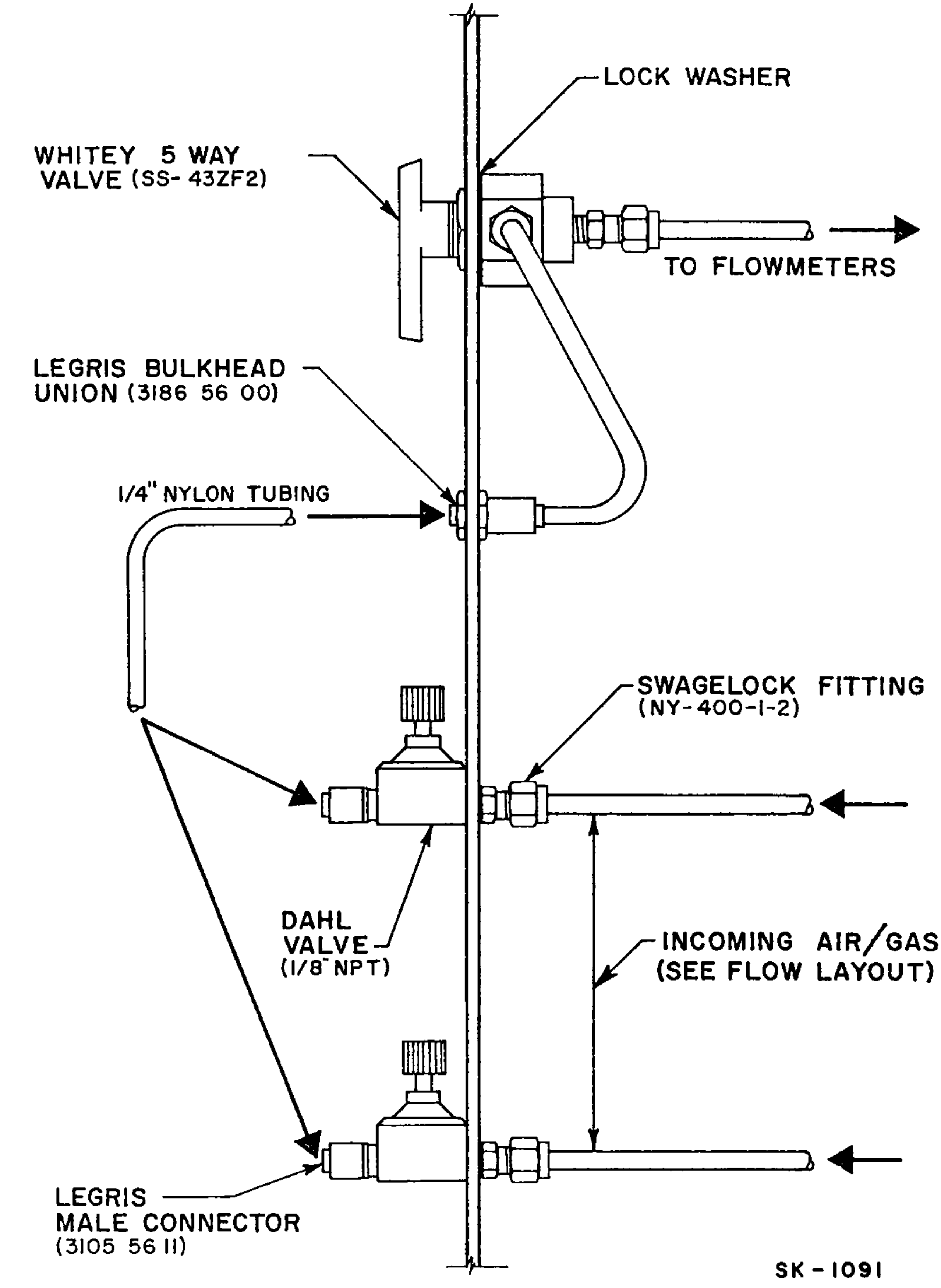
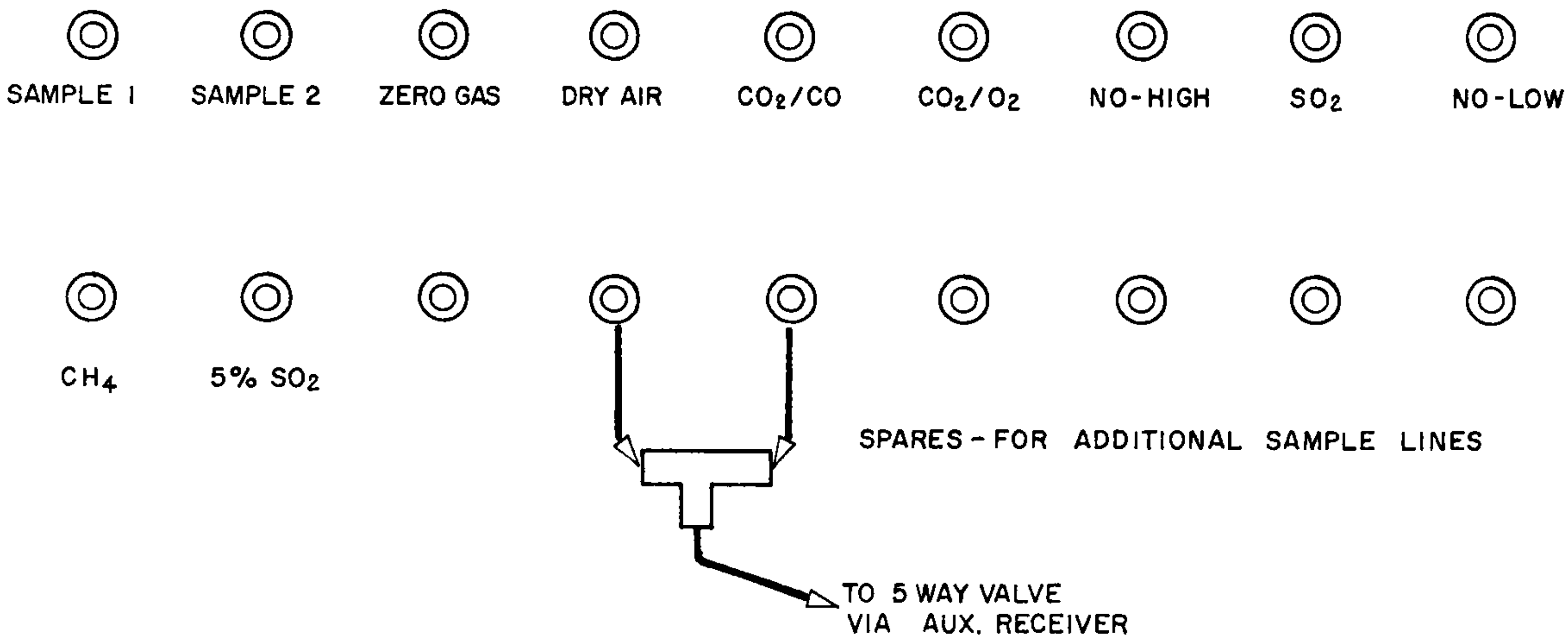


FIGURE 3.11 PATCHBOARD MOUNTING DETAIL



1. ALL PATCHBOARD CONNECTORS HAVE THEIR OWN ON-OFF VALVES. THIS IS A SAFETY MEASURE.

2. TWO GASES MAY BE MIXED, WITH A TEE, AS SHOWN.

SK - 1095

FIGURE 3.12 PATCHBOARD LABELING - SAMPLE SYSTEM

An interference due to chlorides has been discussed with others using this apparatus and work on its elimination is underway.

3.6.3 Carbon and Hydrogen in Coal, Flyash and Bed Samples

A Coleman Model 33 analyzer is used for this service.

3.6.4 Wet Chemistry

The references for procedures used for analysis of calcium, magnesium, chlorides, iron, aluminum and other ash constituents are given in Appendix B.

3.6.5 Commercial Laboratories

North American Exploration Incorporated in Charlottesville, Virginia, provides prompt, accurate and inexpensive analyses using atomic absorption spectrophotometry. Commercial Testing and Engineering Laboratories in Chicago, Illinois and Norfolk, Virginia are used for detailed coal analyses.

3.7 Materials

Two limestones and four coals and a delayed petroleum coke have been used in the period October 1972 through June 1974. Ultimate and proximate analyses of the fuels are given in Table 3.2. The plastic properties of two coals are given in Table 3.3. The two limestones used are described in Table 3.4. The salt used in some experiments is road salt. No vendor analysis is available. It was determined to be 98+% NaCl. The Bureau of Mines tests showed some calcium and sulfur; probably calcium sulfate.

3.8 Start-up of a Fluidized-bed Boiler

3.8.1 Cold Start-up of Fluidized-bed Boiler

Design for start-up of a fluidized-bed boiler presents a difficult problem. On the one hand it is desired to minimize the cost of auxiliary start-up burners and the amount of costly gas or oil required for start-ups. On the other hand the time required for a start-up must be minimized so that the fluidized-bed boiler does not suffer a competitive disadvantage when compared with the conventional boilers.

TABLE 3.2

Fuel Analysis Used in FBM

Ultimate Analysis As Rec'd.	Petroleum Coke	Sewickley Seam (W. Va.)	Loveridge Seam (W. Va.)	Rich Mounatin Stoker Coal	Middle Kittaning Seam (Ohio)
% Moisture	13.55	2.82	2.06	2.10	3.83
% Carbon	76.68	64.16	75.59	76.31	--
% Hydrogen	3.39	4.55	5.33	5.17	--
% Nigrogen	1.03	1.07	1.16	1.88	--
% Chlorine	.00	.01	.02	.13	--
% Sulfur	5.19	4.47	2.87	1.43	5.58
% Ash	.16	18.57	8.01	5.21	9.51
% Oxygen (diff)	.00	4.35	4.96	7.77	--
Proximate Analysis As Rec'd.					
% Moisture	13.55	2.82	2.06	2.10	3.83
% Ash	.16	18.57	8.01	5.21	9.51
% Volatile	9.28	35.76	38.06	38.53	42.41
% Fixed Carbon	77.01	42.85	51.87	54.16	44.25
BTU	13,194	11,815	13,642	13,820	12,092

TABLE 3.3

Plastic Properties of Coal - Gieseler Plastometer

	Max. Fluidity (DDPM)*	Initial Softening Temp. (DDPM) °C	Max. Fluid, Temp. °C	Solidification, Temp. °C	Temp. Range, °C	Torque, Gm. In.
Loverdige (W. Va.)	27,000	366	420	486	120	40
Sewickley Seam (W. Va.)	26,900	472	438	486	114	40

* Dial Divisions Per Minute

TABLE 3.4

Analysis of Sorbents
Percent by Weight

Constituent	Grove Limestone (1359)*	Greer Limestone
CaO	54.8	44.7
MgO	.7	1.9
Fe_2O_3	.1	.8
SiO_2	.6	10.5
Al_2O_3	.2	3.6
Others	--	1.1
Loss on Calcination	43.6	37.4

* 1359 is the number assigned this stone by EPA.

The start-up problem is basically one of raising the bed temperature, by external means, to the point where coal is autogeneous while protecting the boiler tubes which are in contact with the bed.

The following alternatives have been considered at various times.

1. Preheating the Fluidizing Air Via Duct Burners

This technique suffers from the major flaw that the duct work and the air distributor must be designed for high temperature service for the relatively infrequent start-ups. This technique was used in the period 1966 through 1968.

2. Premixing Gas and Air, Beneath the Grate and Burning Above and In the Bed

This technique was tested and found wanting in effectiveness and safety. However, it was used in England. Lurgi has applied the technique safely in commercial apparatus.

3. Firing Above the Bed

This method is used to start roasters, etc. in which a thick refractory lining can be used to store heat. It is useful in a fluidized-bed boiler in bringing the boiler to pressure and hence the tubes to the saturation temperature.

4. Firing Into the Bed

This technique is presently used in the FBM. Refinement of this start-up method has reduced the time required to bring the unit to operating condition from more than two hours to about 30 minutes. A start-up was monitored closely in May 1974 and the data is presented below.

3.8.2 Energy Balance for Typical Start-up

During an FBM light-off, for a test in May 1974 the propane fuel rate was measured at 486 scfh, or 1,224,000 Btu/hr. In addition to this, however, close to 1,100,000 Btu's were available on light-off (on a progressive basis) as about 100 lbs of coal was well mixed with the bed prior to initiation of light-off. The local fluidization used for light-off in the front section of the FBM, caused the ignition of coal in the bed, thus supplementing the gas burner-produced heat in warming the bed. The major portion of the supplemental coal-furnished-heat was probably delivered in the first 36 minutes of a light-off period. It was assumed that about 75% was released in that period.

The FBM contained 1,270 lbs of cold water. There was approximately 3,300 lbs of steel in the FBM exposed to hot water and/or steam. The water warm-up, hence metal warm-up, was at an average rate of 8°F per minute, as measured. To raise the 1,270 lbs of water from 73°F to 387°F (saturation at 200 psig) required 398,000 Btu's for the water and about 104,000 Btu's for the steel. The gas burner in 36 minutes delivered 734,800 Btu's. In about 36 minutes the bed itself, weighing about 1,000 lbs reached a temperature of 1420°F (at burner) to 140°F (farthest point from burner).

Assuming an average temperature of 800°F, the bed would have picked up ∿175,200 Btu's. Out of an ∿1,500,000 Btu's supplied in the first 36 minutes, 677,800 Btu's would be picked up by the water, boiler metal, and bed. The remainder would be picked up by the convection bank, the breeching, the air heater, or as hot dust in the cyclones. Also obvious are all ambient heat losses and the heat emitted from the stack. The probable heat loss, in the 36 minutes, to the stack would be ∿225,000 Btu's, to the water cooled door ∿81,000 Btu's and to the convection bank ∿162,000 Btu's. This would account for about 1,145,000 Btu's, or 76 percent of the heat input during the first 36 minutes of the light-off period. With all the uninsulated surfaces of the duct work and equipment, it is conceivable that close to 24 percent of the heat was lost to the boiler room during a start-up.

The data on the water temperature during the start-up was plotted against time and this is shown in Figure 3.13. Figure 3.13 shows a four minute lag at the beginning of the light-off in which no change in water temperature is shown. The average bed temperature would have increased by 50°F in that four minutes. This lag is probably an artifact of where the water temperature was measured in the left cross header. This would be the last place that would "see" hot water as a natural convection circuit develops.

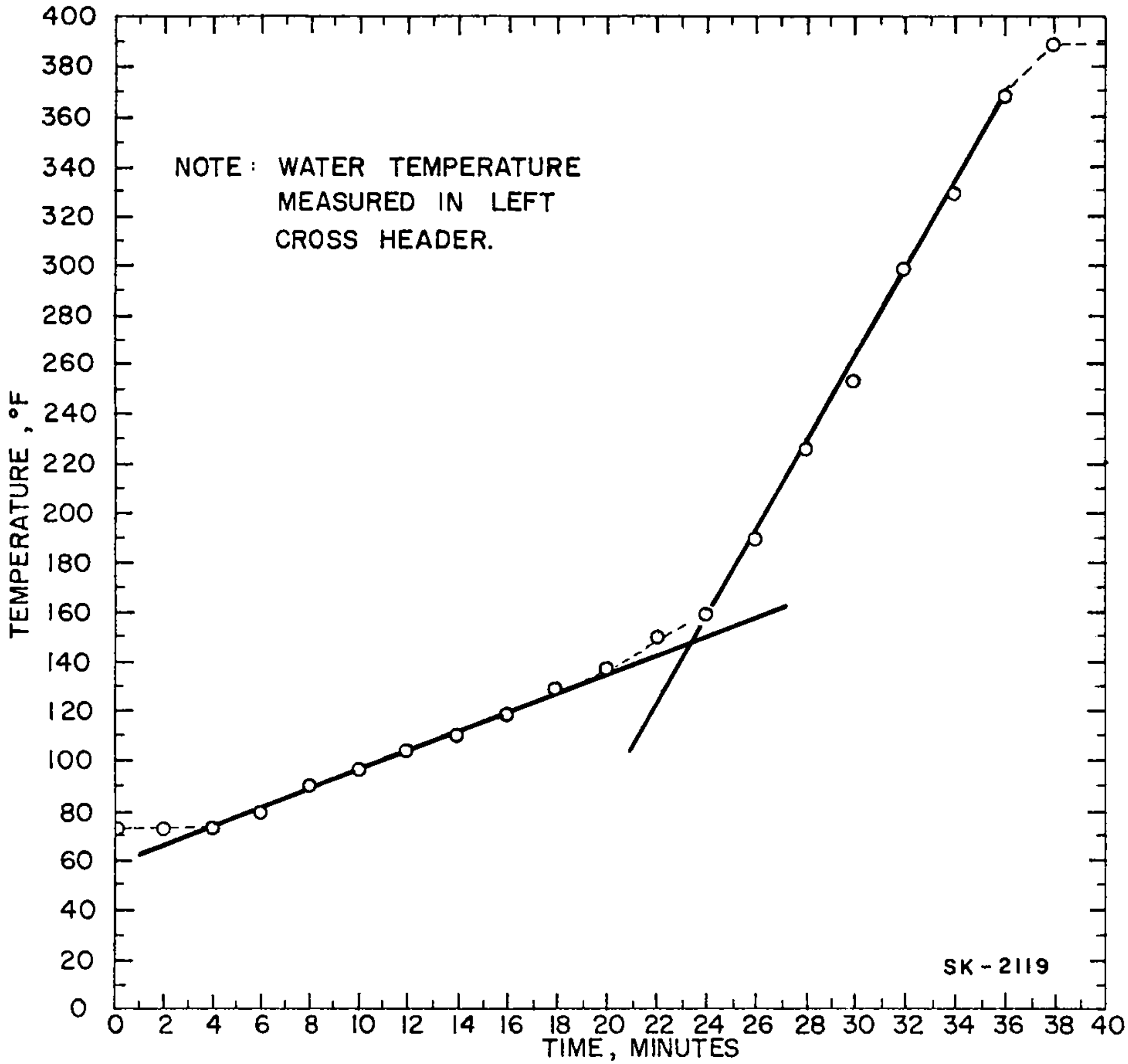


FIGURE 3.13 TEMPERATURE OF WATER IN FBM vs. TIME AFTER START OF LIGHTOFF

The second period between the fourth minute and the fourteenth shows a linear increase in water temperature at a rate of 5°F per minute. A third period in which the water temperature rise begins to accelerate as if the coal in the bed were beginning to generate sufficient heat to supplement the start-up burner. A fourth period between the 23rd and 36th minutes in which the rate of water temperature rises 18°F/minute reflects the exponential rise in energy release as coal begins to burn actively. The rate of water temperature rise drops to zero as steam production begins as the water reaches saturation for 215 psia.

3.8.3 Hot Restart of a Fluidized-bed Boiler

The fluidized-bed stores substantial energy (referenced to ambient conditions) in the form of hot bed material. When the bed is slumped by shutting the coal and air supply the rate of heat loss from the bed becomes very low. Energy leakage through the layer of bed near the boiler tubes and leakage to the "cool" upper surface causes the bed temperature to drop slowly toward ambient. A period of one to several hours will generally be available for banking a fluidized-bed boiler and then restarting with the use of an ignitor.

3.8.3.1 Results

Figure 3.14 shows the FBM bed temperature vs time for a typical experiment in which the bed was slumped, fans turned off and steam bottled up. The rate of temperature change is described by the equation

$$T = T_o \exp(-0.0847t)$$

where

T = Bed temperature at time "t", °F
T_o = Bed temperature at t=0, °F
t = Time after shutdown, hours (3.1)

Because the enclosure (the boiler walls) were maintained at 400°F the bed approaches this value slowly. The last point, taken at 17 hours after shutdown,was 500°F.

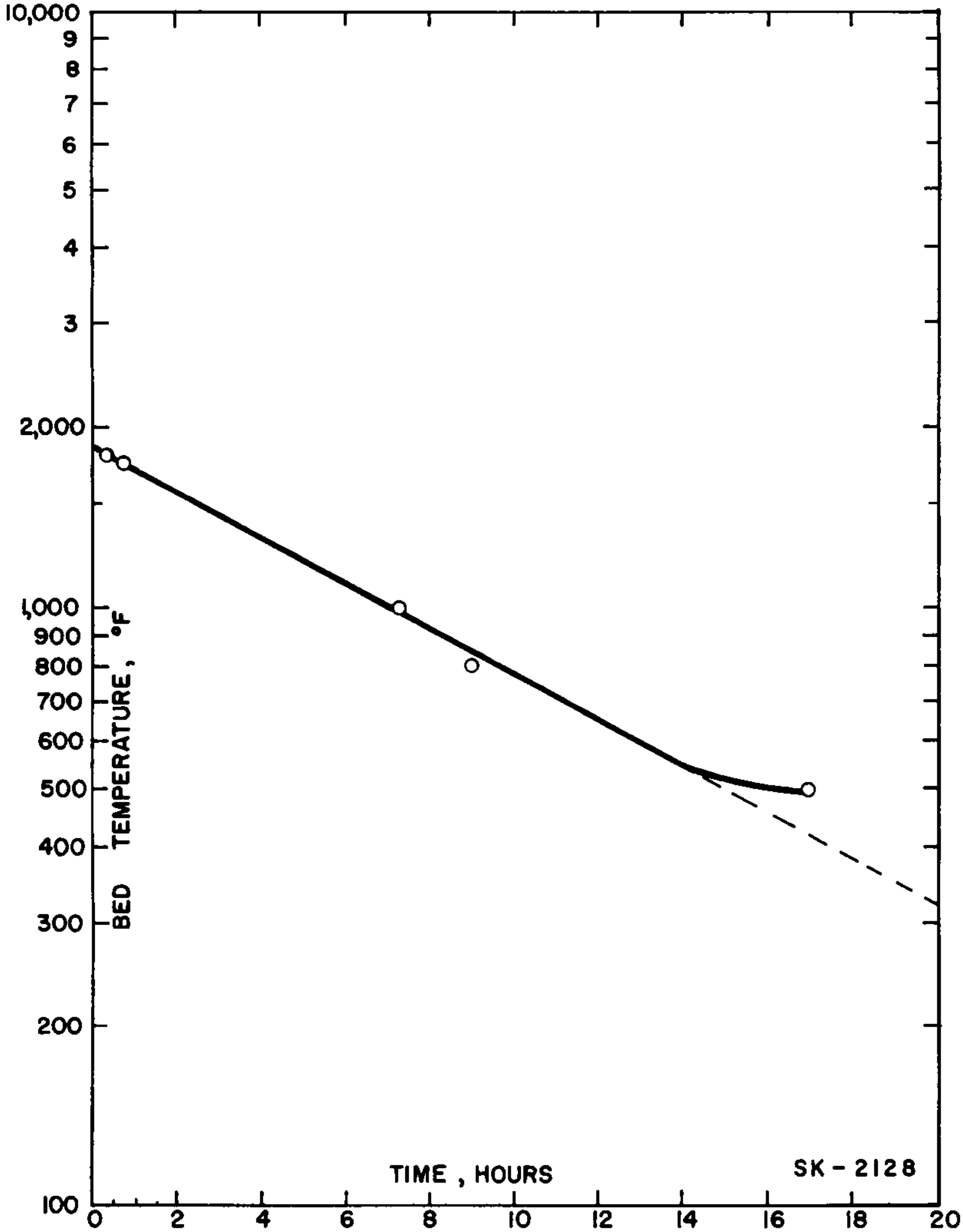


FIGURE 3.14 BANKED FBM BED TEMPERATURE VS. TIME AFTER SHUTDOWN

Assuming 1000°F to be the minimum bed temperature for hot restart and an operating temperature of 1550°F equation (3.1) shows

$$t = 5.2 \text{ hours}$$

Further experiments are anticipated to define the minimum temperature for safe restarting without use of an ignitor.

3.8.3.2 Hot Restart Following an Interruption in Fuel Supply

In conventional boilers special sensors continuously detect the presence of flame at the burner. If there is a flame out, the fuel supply is interrupted. This is necessary in an open furnace to prevent catastrophic explosions. There is no flame, per se, in a fluidized-bed boiler and, fortunately, the system can override a short interruption in fuel supply. If a fuel failure occurs bed temperature will drop exponentially. If fuel flow can be restored before too low a bed temperature is reached the load need not be lost.

3.8.4 Result of Fuel Supply Loss Experiments

Figure 3.15 shows FBM bed temperature vs time for an experiment in which fuel feed ceased but main and injection air flow continued. The steam flow was deliberately stopped and the pressure was maintained at 200 psig. For the conditions of the experiment the bed temperature initially followed the relationship.

$$T- T_o \exp(-4.8t) \qquad (3.2)$$

where

T, T_o and t have the same meanings as Equation (3.1).

The assumption is that 1000°F is the appropriate lower limit for restarting the fuel. Figure 3.15 shows that 5 minutes are available after a fuel failure at 1480°F, for resuming the fuel supply.

It should be obvious that the amount of energy stored in the bed is proportional to the bed mass while the energy lost to the fluidizing air is not. As the depth of bed increases

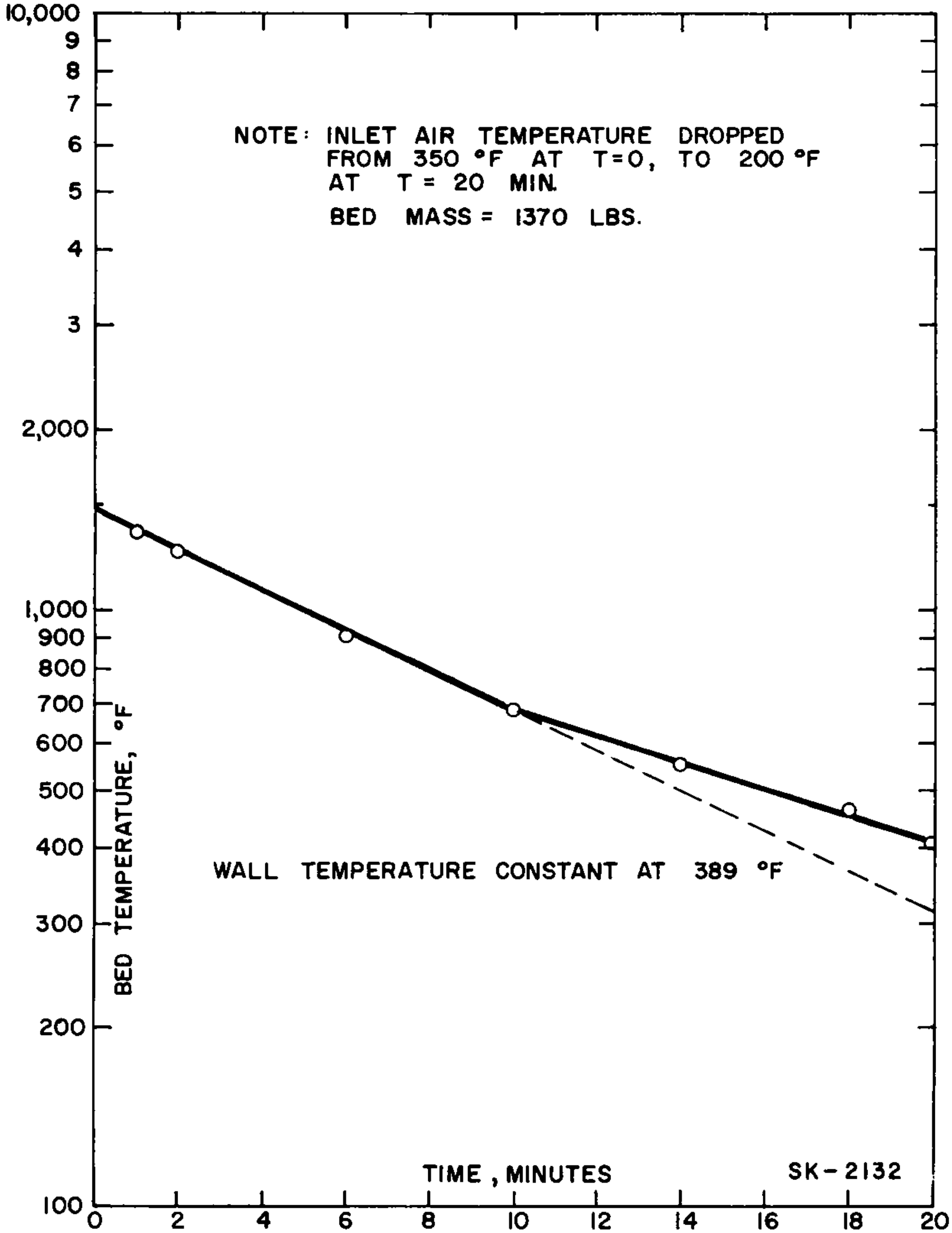


FIGURE 3.15 FBM BED TEMPERATURE VS TIME AFTER FUEL INTERUPTION

(for a given firing rate), the rate of temperature loss would decrease.

It is interesting to note that the fluidized-bed boiler can generate steam for a short period of time after the fuel supply has been cut off. Stoker fired boilers are also capable of this. The difference between a stoker and a fluidized-bed is that when fuel flow stops to the fluidized-bed the very small fuel inventory is depleted within 30 seconds.

The fact that full flow steam production persists for 90 seconds after coal flow ceases in the FBM leads to this valuable insight into the nature of the process. The tubes in a fluidized-bed are heated by the bed, not by the fuel. A control system cannot be designed without understanding this aspect of the process. See Appendix C for an analysis of the heat loss rate after the first two minutes.

3.8.5 Start-up of Large Fluidized-bed Boilers

Experiments are now being devised and planned which will answer some of the questions required for safe operation of the 30 MWE prototype and for design of much larger fluidized-bed boilers.

3.8.5.1 Questions Requiring Experimental Answers About Start-up

Regarding start-up of a large fluidized-bed boiler the following questions remain.

1. What is the lowest bed temperature at which bituminous coal will become autogeneous---without the assistance of an ignitor?

2. What control signals reliably indicate a failure of fuel supply? At what absolute bed temperature and rate of decrease in temperature should the fuel supply system be prevented from restarting?

3. On slumping a bed into a bank of superheater tubes, what cooling is required to prevent tube damage?

4. On a hot restart in which the steam generating cells are activated before the superheaters, what is the energy

loss by the superheater bed when "cool" saturated steam begins flowing through the superheater?

5. What reasonable expedients, such as use of low ignition-temperature fuels, can be taken to accelerate the start-up of a very large boiler?

6. What is the effective heat capacity of a stream of bed material containing burning coal particles, that is allowed to flow into a "cool" fluidized bed?

7. The analog of preventing superheater tube damage from a slumped bed is the question of heating the cool superheater bed via the flow of saturated steam through the tube bundle. What is the thermal diffusivity of a steady-state bed of partially sulfated lime?

3.9 Coal and Air Distribution in a Fluidized-bed Boiler

Air flow rates through the bed are set by the resistance of the system and air distributor. The designer's problem is to insure that system resistance is approximately equivalent in all areas of a large bed while achieving this equivalence at minimum average resistance.

If air flow is uniform oxygen is available to react with hot coal and provide a spatially uniform heat source. The second design problem is therefore to produce a spatially uniform coal distribution.

3.9.1 Air Pressure Drop Experiment Using Machined Nozzle Plate

An experiment was conducted on the FBM unit to verify actual pressure losses through the unit for proper fan design and drive selection. The following describes the test conditions:

1. Bed

The bed consisted of -8 mesh (USS) limestone, with some larger ash particles, which had been used in a previous test. Table 3.5 compares the particle characteristics with similar data for the Bureau of Mines test (3/22/73). A graphical representation of the particles size distributions is presented in Figure 3.16.

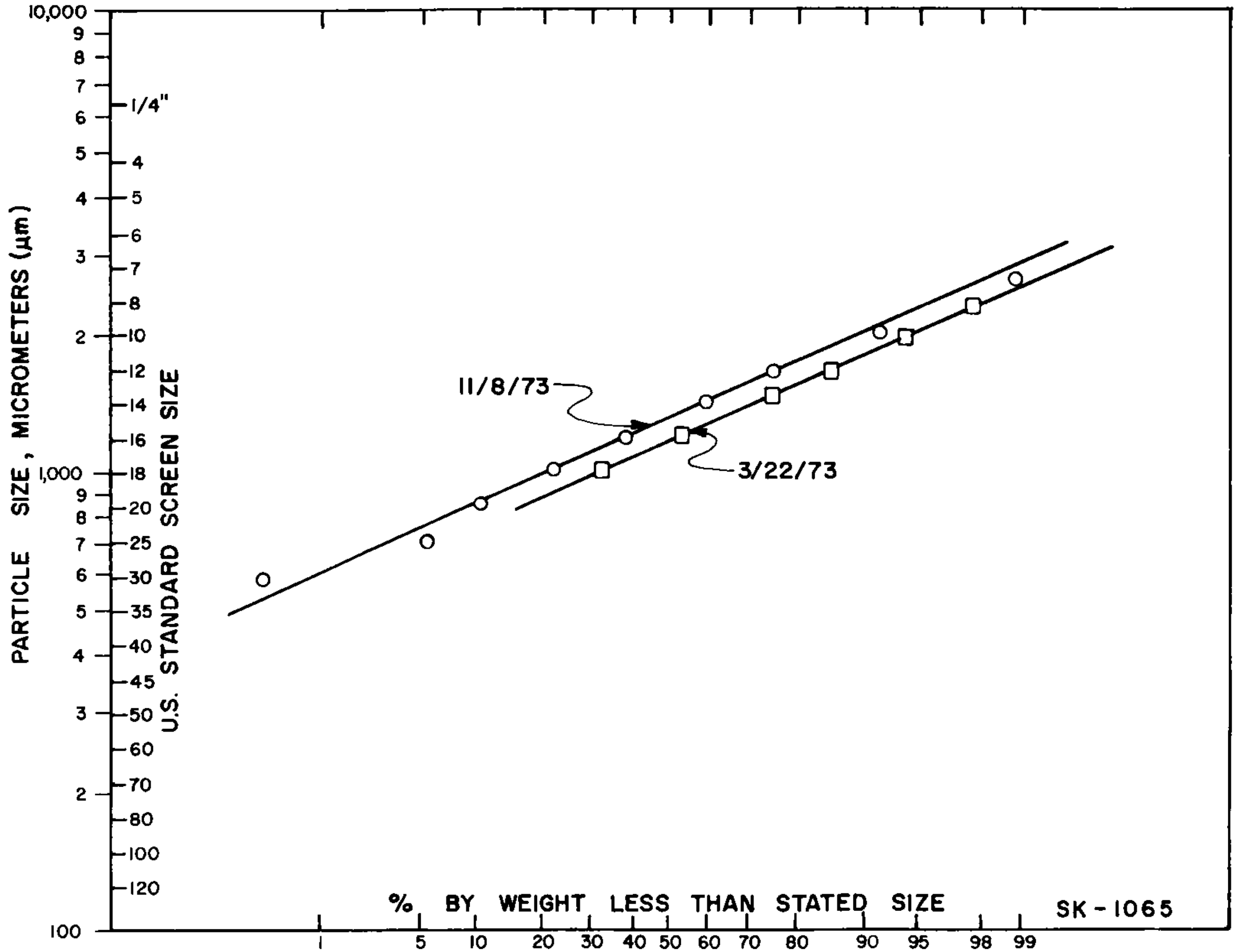


FIGURE 3.16 SULFATED LIMESTONE-BED SIZE DISTRIBUTION

TABLE 3.5

Comparison of Bed Particle Characteristics[1]

	Date Sample Was Fired	
	3/22/73	11/8/73
ρ_p, particle density, gm/cm^3	2.61	2.29
ρ_b, tapped bulk density, gm/cm^3	1.32	1.30
$\bar{d}_p$, mean particle diameter, micrometers[2]	1137	1222
Oversize fraction, x_i of +8 mesh (USS), %	2.2	1.0
Calculated minimum fluidization velocity, fps	2.14	2.11

(1) The bed of 3/22/73 contained 12.7% sulfur and can be considered a steady state bed. The similarity between samples 3/22/73 and 11/8/73 indicates the flow characteristics would be similar.

(2) $\bar{d}_p = \frac{1}{\sum \frac{x_i}{d_i}}$ where x_i is the weight fraction between two near sieve sizes and d_i is the average of the two hole sizes.

2. Grate (Air Distributor)

The nozzle pattern in the grate in use at the time of this test (11/9/73) is shown in Figure 3.17.1. The grate in use during the March test was about the same although the blockage of the outside row of nozzles was not deliberate. A typical nozzle is shown in Figure 3.17.2. The plate design was used in the FBM from 1967 through May 1974. Note that the live area of the grate is:

Live Area of Grate - 6.44 ft^2

The area for flow inside the furnace is:

Area for Flow - 9.136 ft^2

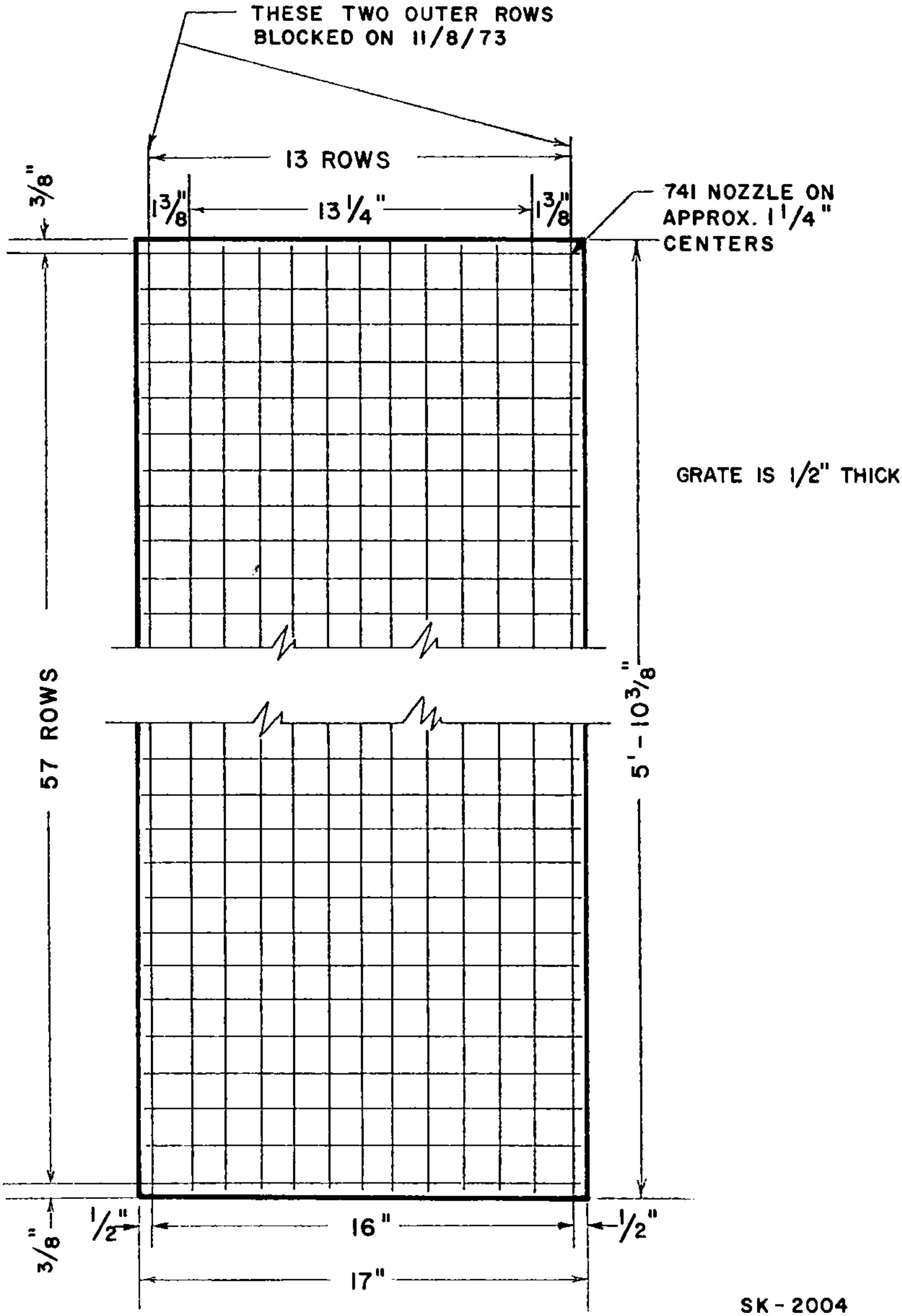


FIGURE 3.17.1 FBM GRATE ON 11/8/73

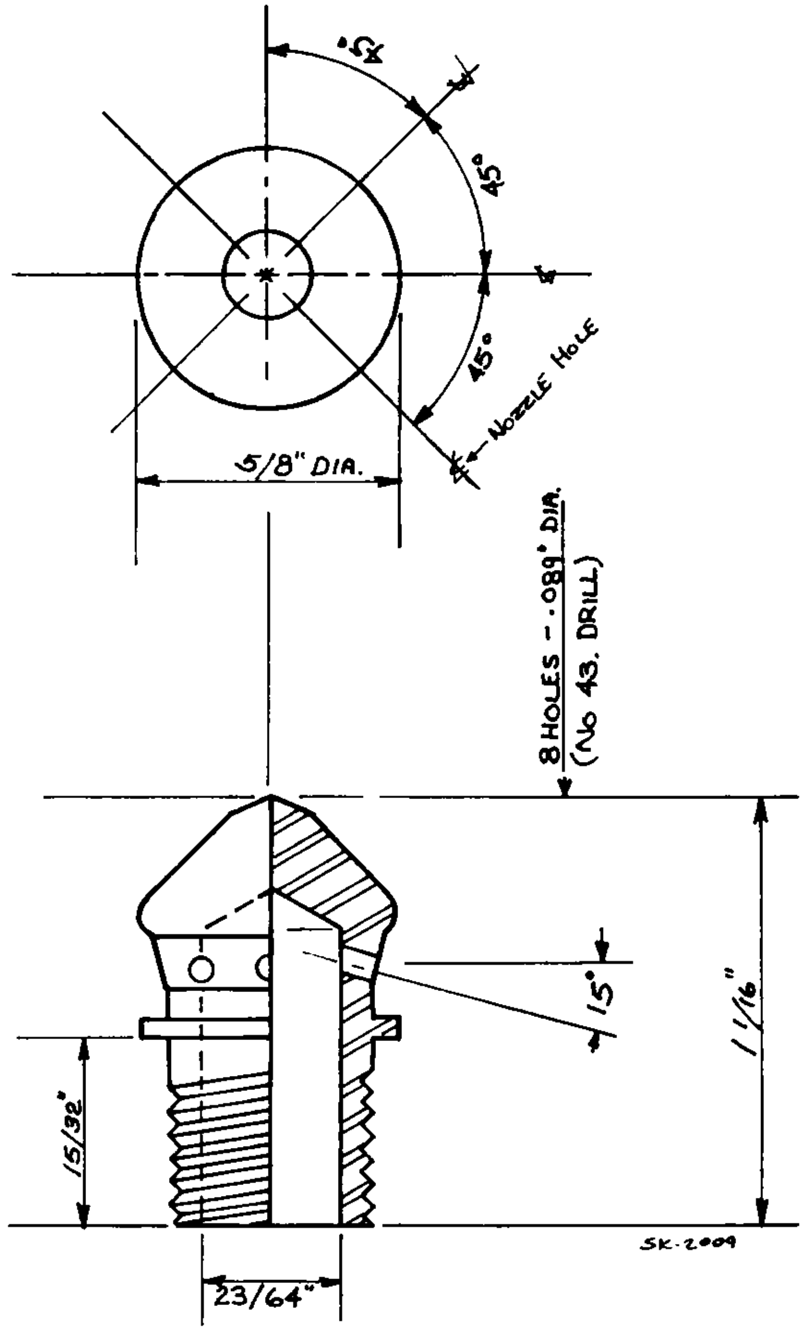


FIGURE 3.17.2 FBM GRID BUTTON- ALEX.

With this grate condition some of the bed weight must be supported by the base of the bed and not by the air flow.

3. Pressure Drop Data

Since a flow rate of ≈5,500 lb/hr is needed to fluidize a cold bed, a bed no deeper than 33.3 inches could have been used as shown in Table 3.6. Also shown in Table 3.6 are the values for a flow of 8,300 lb/hr, the air flow equivalent to a heat release rate of 893,000 Btu/hr ft^2. This is the same as the value selected for the 30 MWE prototype boiler now being fabricated.

TABLE 3.6

Calculation of Maximum Permissible Bed Depths in the Alexandria, Virginia FBM

		Inches of Water	
1.	Pressure at air heater outlet	48.0[(1)]	41.7[(2)]
2.	Pressure drop across orifice	2.9	6.7
3.	Pressure drop across grate plus 1½" of bed	7.3	13.9
4.	Pressure at base of bed Line 1 - [(2+3)+1.5]" H_2O[(3)]	39.3	22.6
5.	Maximum bed depth, Line 4/1.18" pressure drop per inch static depth	33.3	19.1
6.	Actual measured depth	N/A	19.25
7.	Value of ΔP per inch of static bed to equalize lines 5 and 6	N/A	1.007

Notes: (1) Computations based on air flow rate of 5,500 pounds of air at 90°F. Ambient temperature was ∿50°F during experiment on 11/9/73.

(2) Measured values at 8,300 lb/hr air flow with 90°F air.

(3) Drop across fluidized-bed ≈1" H_2O per inch of height.

N/A Not applicable.

3.9.2 Experimental Values

Table 3.7 below lists the conditions for the four test periods.

TABLE 3.7

Conditions for Fluidization Tests 11/9/73

	Test Condition No.			
	1	2	3	4
1. Hot or cold	------Cold------			Hot
2. Static Bed Depth, at start, (h_s), inches of water	19¼	15-3/4	13½	13½
3. Static Bed Depth, at end, inches of water	19¼	15-3/4	13½	13-1/8
4. Coal Feeder Air Flow, lb/hr	0	0	0	400
5. Weight of Bed, (W)[(1)],lbs	1204	985	844	844
6. Weight of Bed Removed, (ΔW), lbs[(2)]	Base	241	151	0

(1) $W = 62.4A\,(h_s)$
A = Internal Area of FBM = 9.136 ft^2

(2) Lines 5 and 6 are inconsistent by 7 to 10% because of errors in measuring bed depth. The actual bed weight was not determined by weighing but in previous tests the equation of Note 1 accurately reproduced the bed weight. Removal of bed and measuring static depth are always done in a consistent manner; the bed is fluidized and then defluidized just before the measurement.

Table 3.8 is a copy of the experiment log with some computed data added. The first item of interest is the apparent fact that the minimum fluidization velocity is a function of bed depth (see readings 4, 14 and 19 in Table 3.8). The texts on fluidization don't allow for this. The values are plotted in Figure 3.18 for extrapolation to a static bed depth of 24". The velocities are computed for the top of the bed, i.e. at the point where the pressure is lowest and therefore the gas volume greatest. Also recall that the internal area for flow is half-again as great as the live

	⓪	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮
RUN No.	STATIC BED DEPTH, IN.	PRESSURE DOWNSTREAM OF ORIFICE	MAIN ORIFICE ΔP	SUM ①+②	AIR FLOW RECORDER READING	COMPUTED AIR FLOW LBS./HR.	PLENUM PRESSURE	SUM ⑧+⑨	LOW BED	ΔP_L	1½"-13½"	1½"-25"	1½"-43"	HOOD	TEMPERATURE IN PLENUM °F	REMARKS
1	19¼	50+	0.3	--	100	1750	5.4	5.4	4.2	1.2	4.0	6.5	6.5	-0.3	86	
2		50+	0.9	--	210	3000	17.7	17.7	14.3	3.4	8.6	14.3	14.4	-0.2	90	
3		48.5	1.8	50.3	300	4250	26.8	26.9	21.3	5.6	13.2	21.3	21.3	-0.1	91	JUST "[illegible]"
4		46	2.85	48.9	390	5300	28.4	28.4	21.2	7.2	12.6	21.3	21.3	-0.2	91	FLUIDIZED HEIGHT = 20.5
5		41	4.5	45.5	500	6700	30.2	30.1	21.0	10.1	12.4	21.0	21.1	-0.1	90	
6		39	5.1	44.1	540	7200	31.9	32.0	20.8	11.2	12.2	19.6	20.6	-0.1	90	
7		37.5	5.7	43.2	565	7600	32.5	31.8	20.7	11.1	12.2	20.6	20.7	-0.2	89	
8		35	6.5	41.5	615	8100	34.1	33.9	20.8	13.1	12.6	20.5	20.5	-0.1	85.5	
9		35	6.7	41.7	620	8300	34.3	34.7	20.8	13.9	11.9	20.1	20.6	-0.05	88.5	
10		46	2.9	48.9	396	5400	28.3	28.2	21.0	7.2	12.6	20.9	20.9	-0.1	88.5	FLUID
11		48	2.1	50.1	320	4600	26.9	26.9	21.0	5.9	14.1	21.1	21.3	-0.3	89.5	STATIC [illegible]
12	15¼	50+	0.3		100	1750	4.1	4.0	2.8	1.2	4.1	5.1	5.2	-2.4	84	240.75 lbs removed
13		48.5	2.1	50.6	325	4600	22.8	22.6	16.8	5.8	13.4	16.6	16.7	-0.0	68.5	
14	–	47.5	2.5	50.0	355	5000	23.1	22.9	16.4	6.5	13.0	16.6	16.7	-0.2	89	FLUID
15		42	4.4	46.4	500	6600	26.5	26.5	16.6	9.9	12.4	16.3	16.3	+0.1	89	
16	13½	50+	0.3		110	1750	5.3	5.3	3.9	1.4	4.3	4.4	4.5	-0.5	88	151.5 lbs [illegible]
17		50	1.3		250	3600	15.8	15.9	11.4	4.5	11.0	11.1	11.2	-0.0	88.5	
18		48.5	2.1	50.6	330	4600	19.8	19.8	13.9	5.9	13.1	13.8	13.8	-0.1	88.5	Bubbling
19		48	2.3	50.3	340	4800	20.1	20.1	13.8	6.3	13.1	13.7	13.7	-0.0	89	FLUID
20		47	2.5	49.5	358	5000	20.4	20.5	13.9	6.6	13.0	13.7	13.6	-0.0	89	
21		30	8.3	38.3	650+	9200	29.6	29.6	13.3	16.3	12.0	13.0	13.3	-0.3	90	
22		49.5	2.0	51.5	310	3920	20.8	20.2	15.0	5.2	12.0	15.1	15.0	+1.0	240	Gas burner on, Tbed = [illegible]
23		46.5	3.3	49.8	425	4960	23.9	24.0	14.6	9.4	11.3	14.4	14.3	-0.4	260	Burner off, Tbed = [illegible]°F
24		44.5	4.2	48.7	485	5570	25.6	25.3	14.6	10.7	10.9	14.2	14.2	-0.2	280	Tbed = 1720°F
25		42	5.3	47.3	545	6120	26.5	26.7	13.5	13.2	10.3	13.6	13.2	-0.5	300	Tbed = 1710°F
26		44	4.5	48.5	505	5570	25.0	24.6	13.0	11.6	10.4	14.0	13.6	-0.9	320	Tbed = 1615°F
27																

EXPERIMENTAL LOG DATE 11/9/73

TABLE 3.8

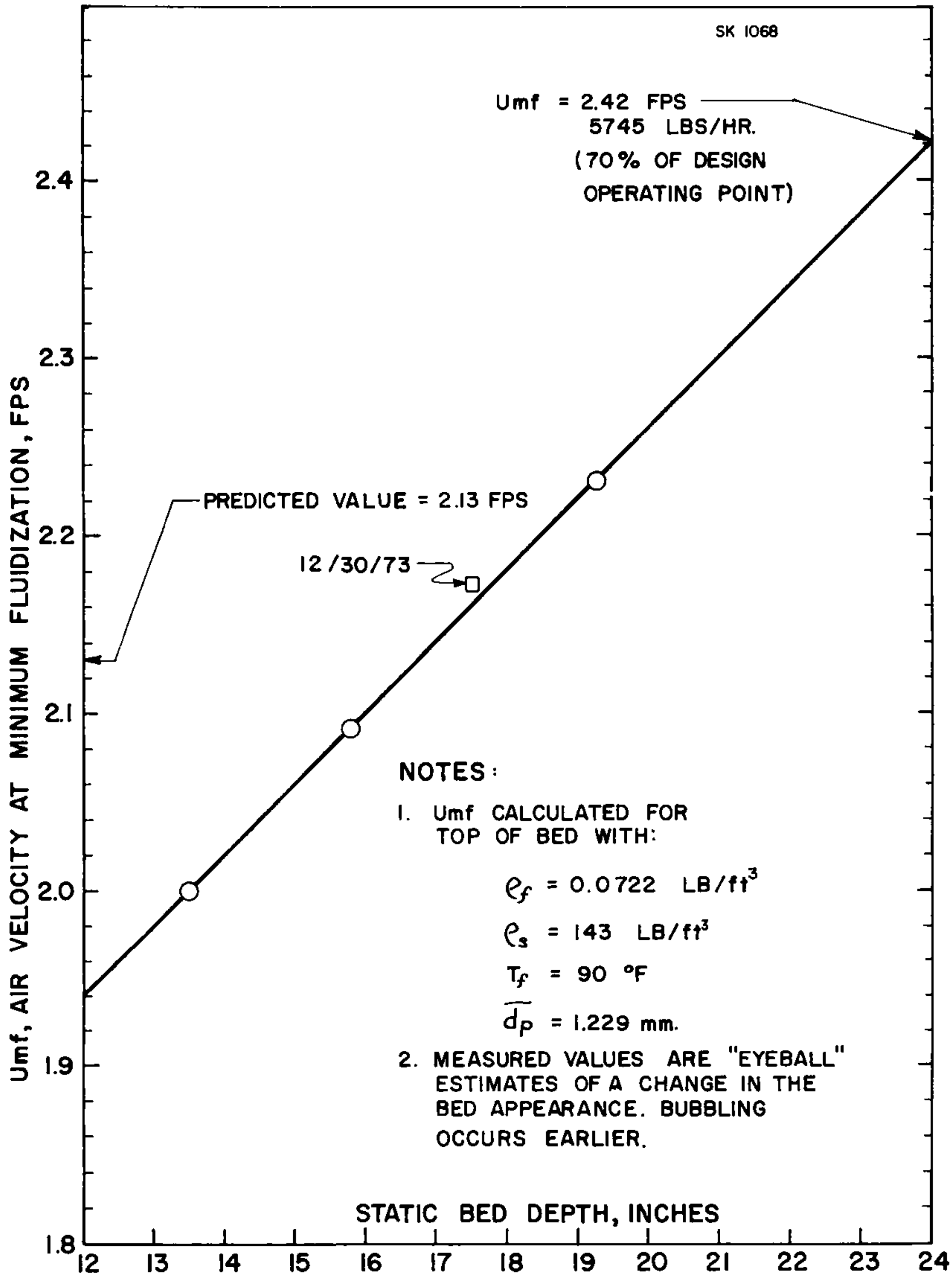


FIGURE 3.18 AIR VELOCITY AT MINIMUM FLUIDIZATION VS. STATIC BED DEPTH

area of the air distributor. So the deviation from theory may be explained by the fact that, in a sense, the FBM is conical vessel.

Notes for Table 3.8: (Pressures in inches of water)

Column No.:

1. Static pressure after air heater and main orifice.
2. Drop across 6.915" diameter orifice.
3. Pressure for fan curve and mass flow calculation.
4. Bailey meter reading. (An air flow/stream flow recorder.)
5. Computed flow using w_h, lb/hr = 11,102 $\sqrt{\Delta P \quad \rho_f}$
6. Pressure in plenum.
7. Sum of 8 and 9 should equal 6.
8. Reading at about 1½" above grid plate against atmosphere.
9. Drop across grid and ∿1½" of bed by cross connecting columns and 6 and 8's pressure taps.
10. Pressure tap at low bed against pressure tap about 13½" above grate. Should give fluid bed density.
11. For shallow beds this gives the total drop across bed.
12. If fluidized bed depth exceeds about 25" there would be a difference between this and column 11.
13. Pressure just after air heater against atmosphere. Could also be called draft.

3.9.3 Pressure Drop vs Bed Mass---"Missing Weight"

The texts on fluidization suggest that the following relationship should hold.

$$A = B$$

where

$$A = \frac{\text{Bed Weight, lbs}}{\text{Cross-Sectional Area, ft}^2} = \left(\frac{\text{Pounds-Weight}}{\text{Square foot}}\right)$$

and

$$B = \frac{\Delta P\text{, Press. Drop Across Bed, inch } H_2O \times 62.4 \ \frac{\text{lbs}}{\text{ft}^3}}{12''/\text{ft}}$$

$$= \left(\frac{\text{Pounds-Weight}}{\text{Square-foot}}\right) \qquad (3.3)$$

From Table 3.8 it can be seen that the pressure drop across the bed reaches its peak value just as the bed becomes fluidized and that further increase in flow does not increase pressure drop. For the three bed weights tested, Eq. (3.3) does not hold. This fact is summarized in Table 3.9.

TABLE 3.9

Weight of Fluid Bed vs Pressure Drop

Condition				
1. Bed Height (static), inches	19.25	15.75	13.5	13.5
2. Mass, pounds	1204	985	844	844
3. ΔP [(1½"to43")+1.5","H_2O]	22.8	18.2	15.2	15.7
4. A of Eq.(3.3), lb/ft^2	131.8	107.8	92.4	92.4
5. B of Eq.(3.3), lb/ft^2	118.6	94.6	79.0	73.8
6. A - B, lb/ft^2	13.2	13.2	13.4	10.8

It can be seen that for the cold tests a constant 13.+ lb/ft^2 is not supported by air flow pressure drop. There are three possible explanations:

1. The dead area around the periphery of the grate supports 13.2 lb/ft^2 x 9.136 ft^2 = 120 lbs of bed weight. This was checked when the grate holes were opened for higher flow rate tests and the effect persisted. Also, there is no realistic model that could account for such a large mass.

2. A channeled bed, poorly fluidized, would pass air through the bed without true fluidization and pressure drop would not equal mass.

3. There are some dead spaces on the grate.

3.9.4 Pressure Drop Across Grate

Based on these experiments a full flow, operational pressure drop across the grate of 16" (H_2O) is recommended.

This design value implies that at ½ load the drop would be only 4 inches.

It can be demonstrated that the grate does follow the square root law of an orifice; Figure 3.19 plots ΔP_{grate} vs $P_{orifice}$.

Figure 3.19 shows that when a bed is in place on the grate an additional pressure drop is experienced across the 1½" of fluidized solids. The straight line relationship, over a factor of 20, illustrates that the grate drop follows a law of the form.

$$\sqrt{\Delta P_G} = \frac{w_h}{K \sqrt{\rho_f}} \qquad (3.4)$$

where

w_h	(air flow, lb/hr ft^2)
K	(a constant to be determined experimentally)
ΔP_G	(pressure drop across grate, inches H_2O)
ρ_f	(density of air, lb/ft^3)

Figure 3.19 shows that during the hot test the relationship shifted toward a higher ratio of $\Delta P_G/\Delta P_o$.

The most reasonable explanation that can be offered for this shift is that when the furnace is hot, air passing through the nozzles is somewhat warmer than the air entering the plenum. If the air at the grate is warmer ρ_f at the grate is lower than at the main orifice and the ratio $\Delta P_G/\Delta P_o$ must rise.

In fact this observed shift provides a tool for estimating the temperature rise through the grate which would be difficult to determine directly, by measurement.

The following procedure was used:

1. It was assumed that Eq. (3.4) was valid and that during the cold tests at high flow rates (damper wide open):

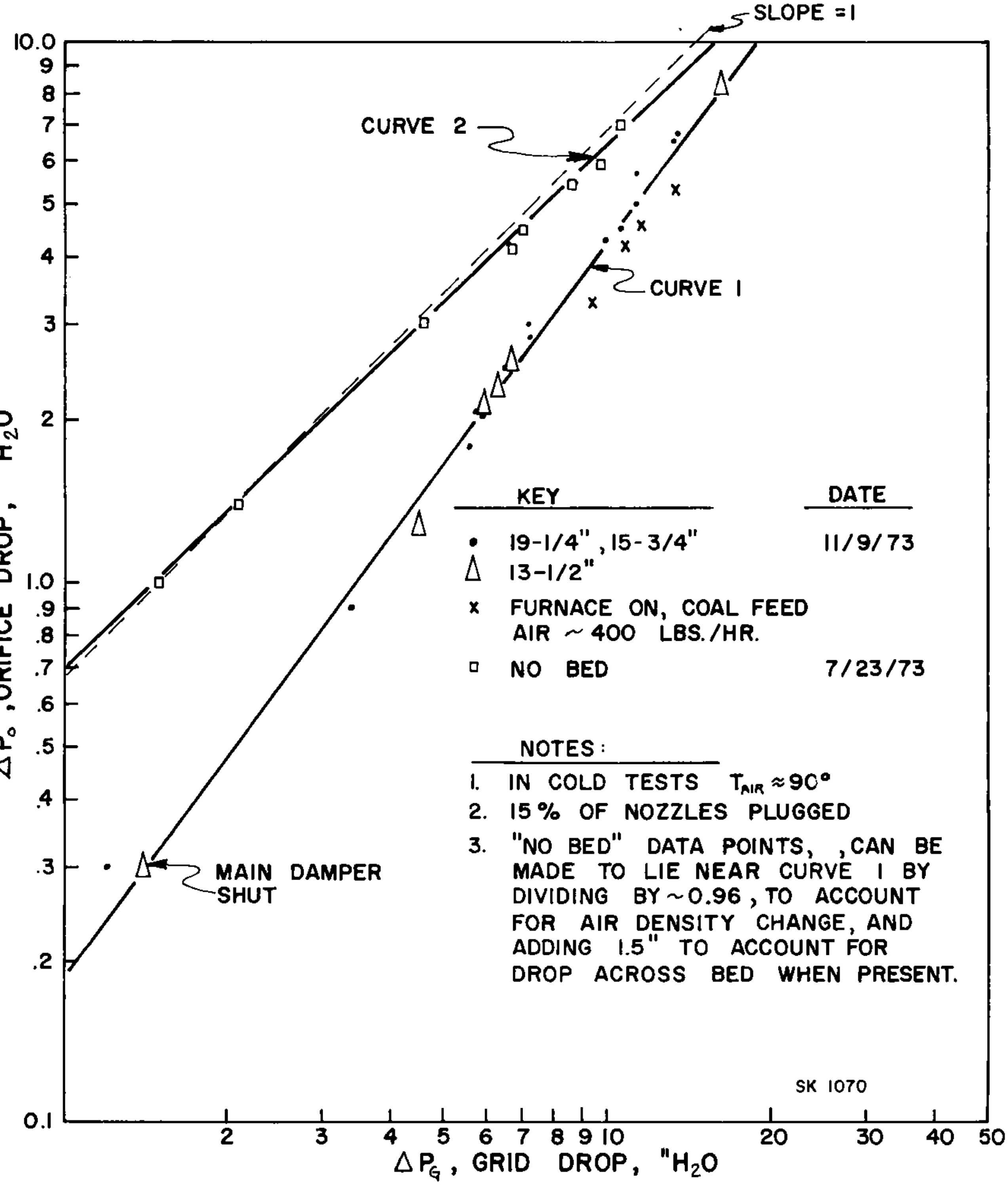


FIGURE 3.19 PRESSURE DROP ACROSS GRATE

$$\rho_f \text{ (at orifice)} = \rho_f \text{ (at grate)}$$

$$w_h \text{ (at orifice)} = w_h \text{ (at grate)}$$

2. It is assumed that "K" is independent of either the grate temperature or the gas temperature. This assumption is valid since the Reynolds number does not change much and the nozzle hole area expansion is ≈2 percent at 1200°F.

3. Using the data of Table 3.8 the value for "K" for the grid was computed. For example for reading 5

$$K_G = \frac{6700}{10.1\ (.0793)} = 7486$$

4. Using Eq. (3.4) with

$$w_h = 7486\ ,\ \Delta P_G \quad \frac{.0574}{T_f} \qquad (3.4A)$$

And the values for readings 24, 25 and 26 in Table 3.8, T_f(°R) was computed. The computed temperatures are shown in Table 3.10.

TABLE 3.10

Apparent Temperature Rise Across Air Distributor

Reading No.	T_f (at orifice),°R	T_f (by Eq.3.4A),°R	ΔT_f(Rise through grate) °F
24	740	858	118
25	760	861	101
26	780	914	134

These temperature rise values are reasonable for:

$$T_f = \frac{UA_G(T_{bed} - T_G)}{w_h c_p} = \frac{50\ (9.14)\ (1710\text{-}1250)}{6120 \times 0.24} = 143°F$$

The grate temperature used, 1250°F, had been measured in a prior experiment. The heat transfer coefficient was approximated as 50.

Another test for the reasonableness of the temperature rise is to compute the heat transfer coefficient "h", necessary to cause the 100°to 150°F, temperature rise in the air as it passes through the grate. Again for 6,120 lb/hr. For Reading 25

$$Q = w_h c_p \Delta T_{gas} = 6120\ (0.24)\ 101°F = 148,300 \text{ Btu/hr}$$

The heat is supplied by radiation and convection in the "hotter" plenum chamber at low velocities and in passing through the nozzles at high velocities.

$$h = \frac{w_h c_p \Delta T_{gas}}{A_{nozzles} \times (T_{nozzle} - T_{gas})} = 39$$

where

$$A_{nozzle} = 3.46 \text{ ft}^2$$

$$T_{nozzle} \simeq 1250°F$$

$$T_{gas} = \frac{300 + 401}{2} = 350°F$$

but

$$h = \frac{0.5 (V_s)^{0.8}}{\left(d_{nozzle}\right)^{0.2}} = 19$$

for flow air in tubes where:

$$V_s \simeq 73 \text{ fps}$$

$$d_{nozzle} = 23/64 \text{ inch}$$

Because the entire predicted temperature rise of the air cannot be explained by heat transfer while the gas is in the nozzles, an estimate was made of the radiation and convection heat pickup while the gas travels through the plenum. This calculation shows that, in fact, 70,000 Btu/hr could have been transferred to the gas while in the plenum.

3.9.5 Conclusions Regarding Grid Plate Design

The most conservative value measured in the experiment shows 1.18 inches (H_2O) of pressure drop per inch of static bed depth for material having a bulk density of 81.1 lb/ft^3. This density value is typical although a density of 85 lb/ft^3 is recommended for design.

The FBM air distributor, with approximately 15 percent of the nozzles deliberately blocked, had a pressure drop of ~12.4" at an air flow rate equivalent to a heat release rate of 893,000 Btu/ft^2 hour, the Rivesville design value. This drop was measured with air at 90°F. With 600°F air, the pressure drop would have been >24" H_2O. This latter value is much too high for full scale boiler design.

A value of 30 inches pressure drop through a 24 inch static bed should be used as a design value. A design value of 16"(H_2O) should be assumed for the full load pressure drop through the grid. Selection of this value means that at half load the drop across the grid would be 4"(H_2O), about the lowest permissible value.

3.9.6 Summary

1. At 4"H_2O pressure drop is as low a value as can be used. Below this value the coal feeders tend to plug and the oxygen distribution is poor.

2. If a $(\Delta P_G)_{min}$ = 4"H_2O the full load value, $(\Delta P)_{max}$, is established by the inherent turndown. A recommended 2:1 design implies $(\Delta P)_{max}$ = 16"H_2O.

3. If a plate is selected, the pressure drop versus flow data must be prepared for the gas at the temperature as it passes through the plate. For the Pope, Evans and Robbins system, the apparent

temperature rise varied for a number of test points from 45°F to 360°F. Considering how difficult it is to read the drop across the plate and keep the pressure taps clean, the recorded values are suspect---each inch of pressure drop is equivalent to a 100°F temperature rise in the calculated temperature. The "X" values on Figure 3.19 were carefully done with clean taps and indicate a 100°F rise.

4. If a proposed plate is tested cold and a pressure drop versus flow rate is determined, the operational drop must include the fact that the air will be preheated to 600°F <u>and</u> that an additional 100°F rise should be assumed as the gas passes through the plate.

3.10 Spouting of a Fluidized-bed by High Air Flow via Injectors

3.10.1 Analysis

Flaws in the uniformity of air distribution result in symptoms which are usually equivalent to those exhibited by flaws in coal distribution. The symptoms are variations in the gas composition leaving the bed. This is detected by noting differences in the O_2 content of gas samples removed from points at equal heights above the bed but at different horizontal points. A second symptom is poor sulfur oxide control.

A bed of partially sulfated lime will contain a substantial inventory of sulfur as $CaSO_4$. Values of 12 to 14 wt.%S are typical. $CaSO_4$ is readily decomposed in a combustion bed via

$$CaSO \ + 4CO \rightarrow CaS = 4CO_2 \qquad (3.5)$$

$$CaS + 3/2\ O_2 \rightarrow CaO + SO_2 \qquad (3.6)$$

One exception to the general observation that it is difficult to tell if the coal feed is poor or if the air is maldistributed is when gas samples taken above the coal injection points are rich in oxygen.

The major sympton of poor coal/air distribution are sharp differences in the oxygen profile above the convention bank. The oxygen sampling array is shown in Figure 3.7. A very poor oxygen profile is shown in Figure 3.20 (Data taken from the Bureau of Mines test of 3/22/73). Figure 3.21 shows the rather good oxygen profile during Test No. 513.

What might distinguish these two tests is the air flow used to transport coal and additives to the base of the bed.

During test 3/22/73 the air flow through a coal injector was 400-500 lb/hr. The air velocity at the outlet of the feeder (accounting for the coal volume) was $\geq$100 fps. The equivalent flow during Test No. 513 was 200 pounds of air per hour (discharge velocity $\approx$50 fps).

One text of fluidization suggests that if the kinetic energy of an air jet at the base of a fluidized bed exceeds the weight of the bed at that point, i.e. if

$$\left(\rho_g\right)\frac{u_o^2}{2g_c} > \left(L_{static}\right)\left(\rho_b\right) \quad \text{(gas channeling)} \qquad (3.7)$$

$$\left(\rho_g\right)\frac{u_o^2}{2g_c} < 3/4\left(L_{static}\right)\left(\rho_b\right) \quad \text{(no channeling)} \qquad (3.8)$$

where

ρ_g (gas density), gm/cm^3

u_o (velocity at pipe outlet), cm/sec

L_{static} (static bed depth), cm

ρ_b (bed's bulk density), gm/cm^3

For the 3/22/73 test kinetic energy of the jet may have exceeded the bed weight; for Test No. 513, it did not.

It is hypothesized that when the boiler is operating, coal injection air can cause an air channel or spout. This spout in turn allows additional air to pass through the air distribution plate so that the total air flows in the vicinity of coal feeders is higher than anticipated.

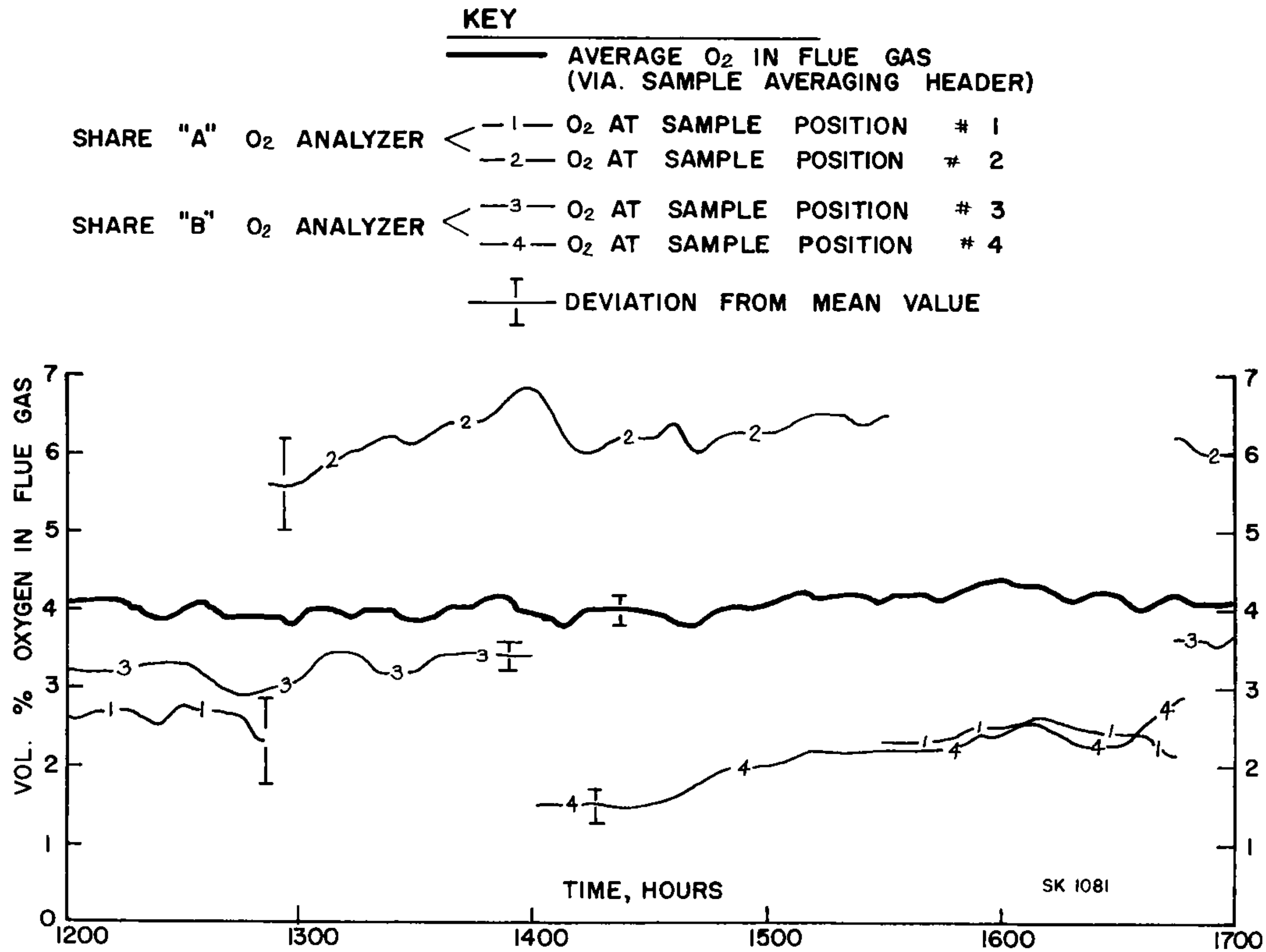


FIGURE 3.20 "POOR" OXYGEN PROFILE ACROSS FBM

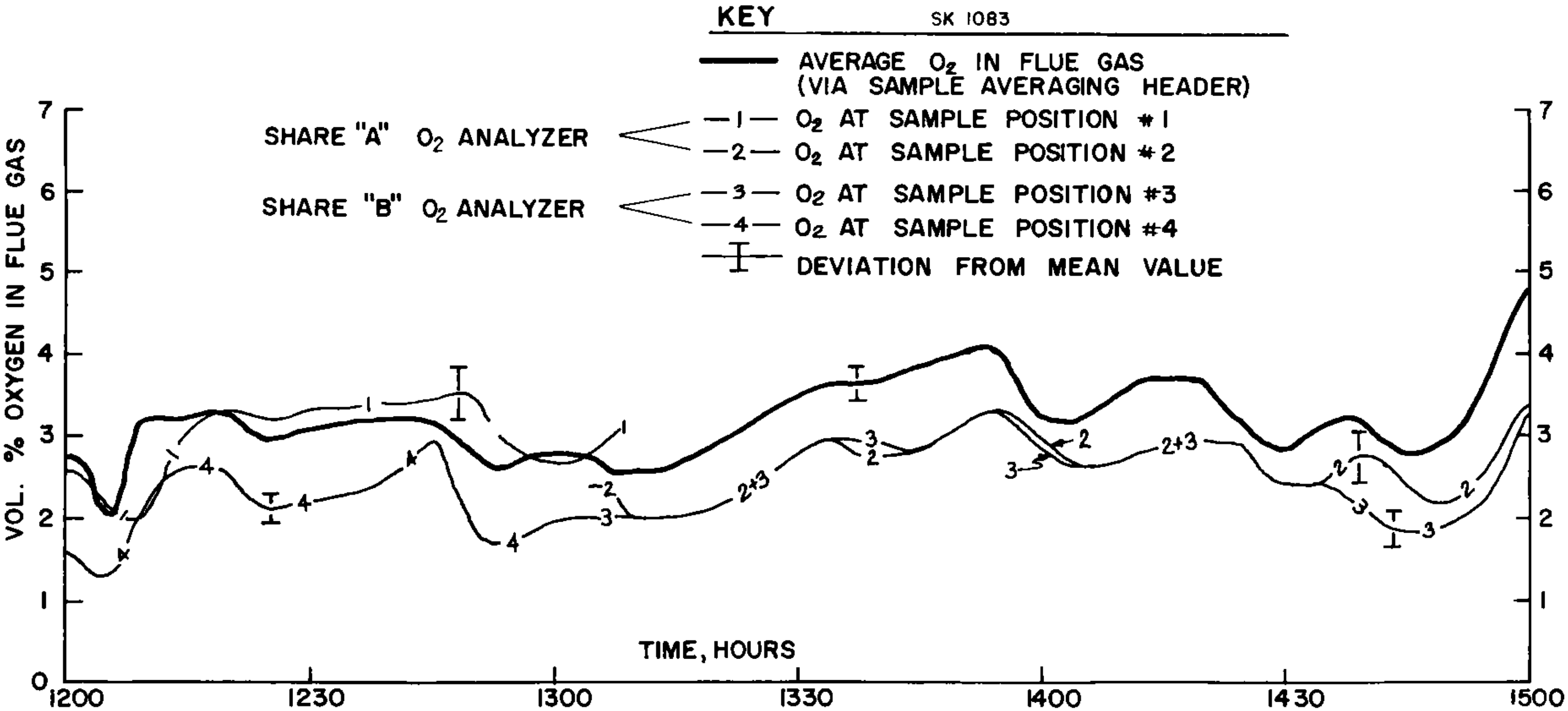


FIGURE 3.21 OXYGEN PROFILE ACROSS FBM

It can be seen that it would be difficult to prove this hypothesis experimentally. Assuming it to be correct, the coal, limestone and salt metering techniques were changed so that currently less than 400 pounds of air per hour are used for all injection functions. This is about 6 percent of total air flow compared with 17 percent previously.

3.10.2 Conclusions and Design Data

The conclusions that may be drawn from these results and hypothesis are:

1. Increasing bed depth (or mass) is one means of preventing the poor fuel air disbribution experienced in the past.

2. A low ratio of air-to-coal in feed tubes ($\sim$0.5 pounds air/pound fuel) is recommended. This means that the carrier air may not be used to keep long, uninsulated, coal feeder tubes cool.

3. Fuel injectors of the type shown in Figure 3.22 have performed well when the air rate is below about 250 pounds per hour. Air rates as low as 160 pounds per hour (14,000 pounds per hour per square foot of cross-section) have been effective and caking coals have not coked in the feeders.

4. Problems which were believed to be related to coal feeding or fines content appear now to have been related to perturbations to the air flow through the bed.

3.11 Evaluation of Alternative Air Distributor Designs

The air distributor discussed in the previous section, uses machined nozzles on close (1¼") centers. The cost of this effective design is high and lower cost alternatives are now being evaluated.

3.11.1 Criteria for Judging an Air Distributor for a Fluidized-bed Boiler

The following list includes the standards by which an air distributor is judged:

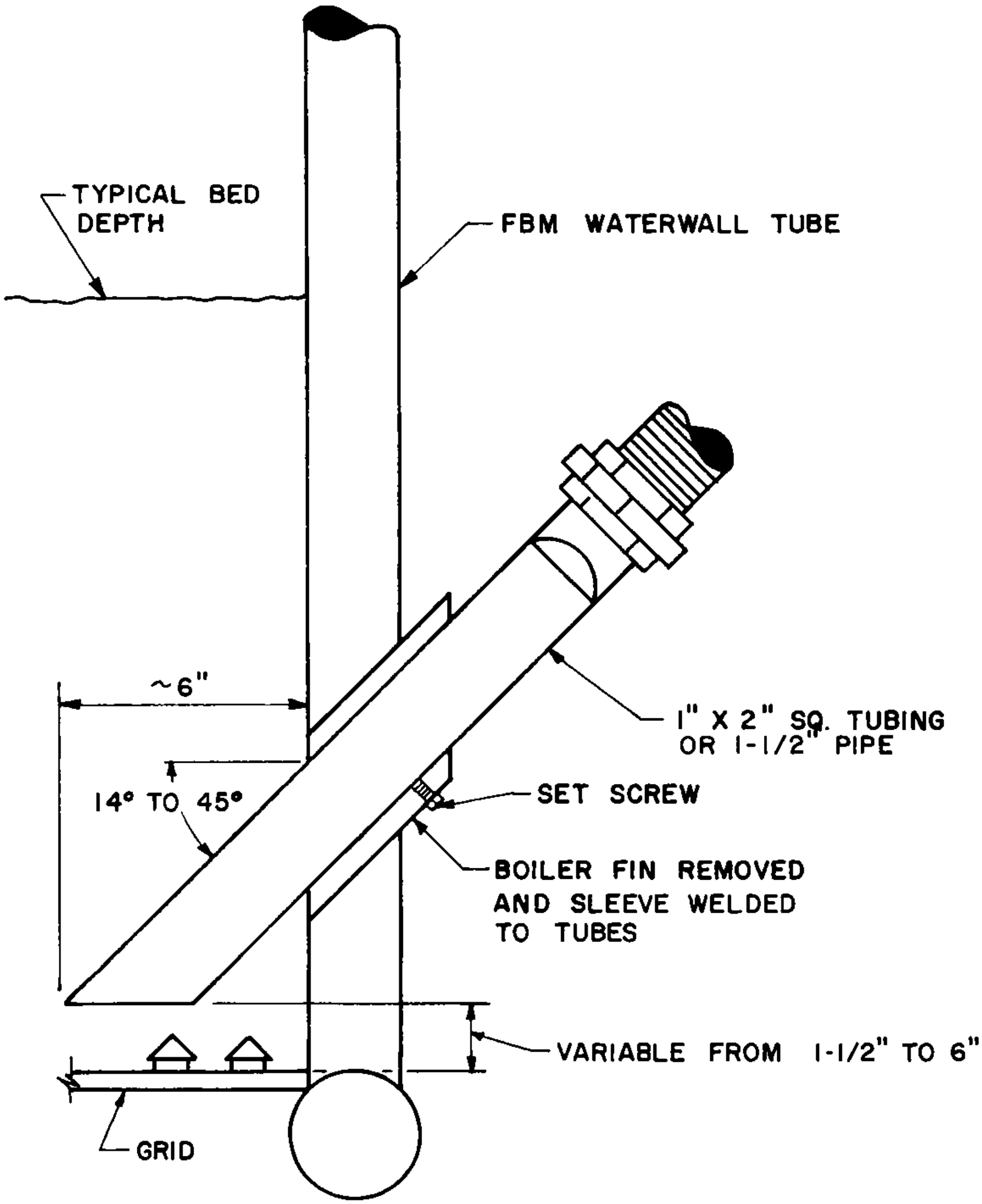


FIGURE 3.22 COAL INJECTOR

(a) Non-sifting.

(b) Relatively low pressure drop at design air rate.

(c) Pressure drop remains constant in time.

(d) Thermal expansion characteristics allow for sealing to plenum.

(d) Unaffected by high dust loading in incoming air.

(f) Unaffected by deliberate or inadvertent water flooding.

(g) Effective air distribution at the low flow rates required for part load operation.

(h) Corrosion resistant, i.e.,long lived for operating conditions which are not particularly severe.

(i) Does not trap large rocks but allows flow toward removal point.

3.11.2 Tests of Alternative Designs

Four alternative design concepts are currently being evaluated. These are:

(a) A simple perforated plate.

(b) A plate fabricated from closely spaced profiled wires manufactured by Johnson Screen Company. (See Figure 3.23)

(c) The proprietary plate design of Procedyne which is similar to a bubble cap or nozzle design but does not require machined elements. (See Figure 3.24)

(d) A Foster Wheeler design which involves a punched plate with fabricated covers.

Figure 3.25 compares the pressure drops of the plates tested. The ordinate of the figure is ΔP_o, the drop across the main air supply orifice in inches of water. It can be converted to mass inflow using the equation:

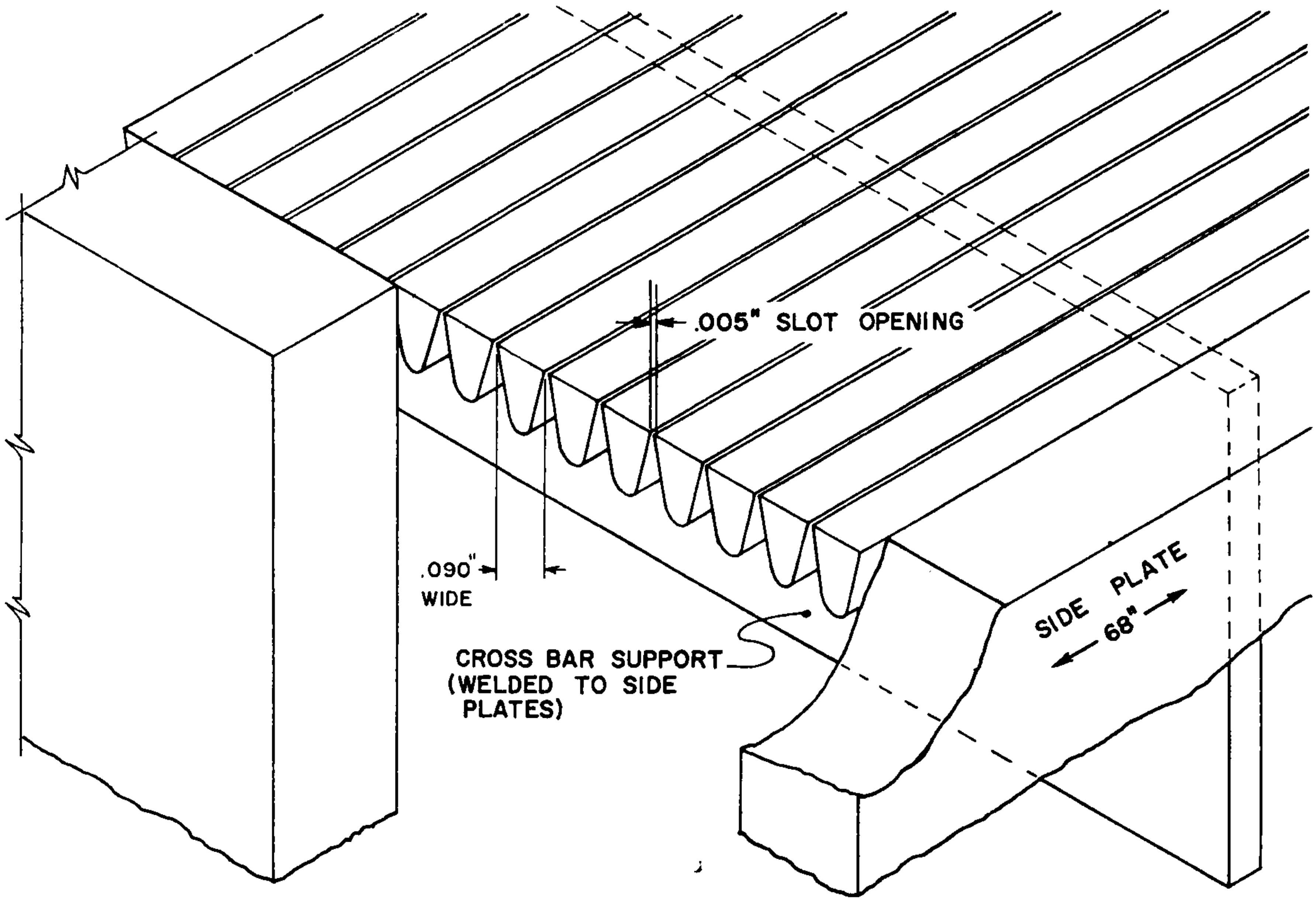


FIGURE 3.23 JOHNSON SCREEN - SLOT DETAIL

SK-2102

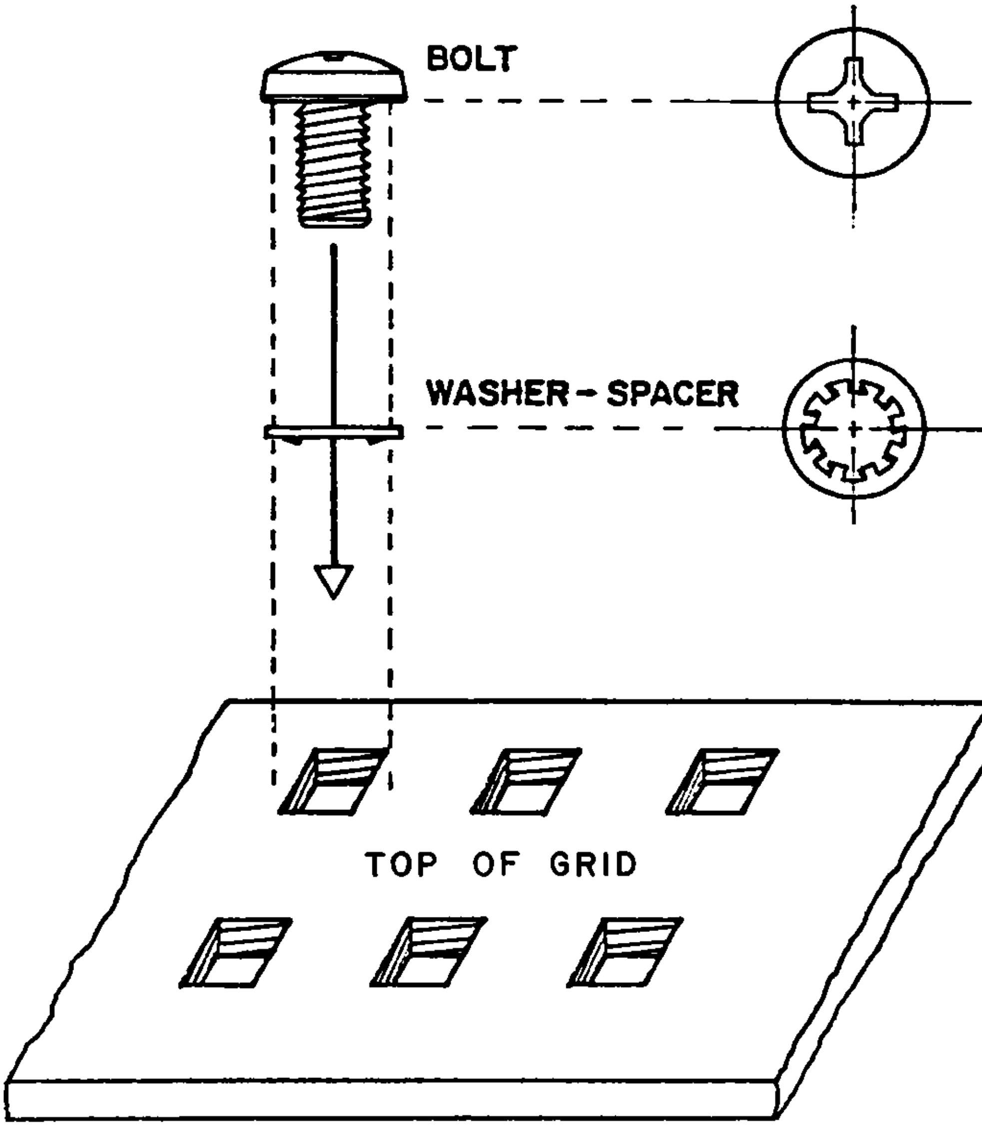


FIGURE 3.24
PROCEDYNE PLATE NOZZLE ASSEMBLY

SK-2103

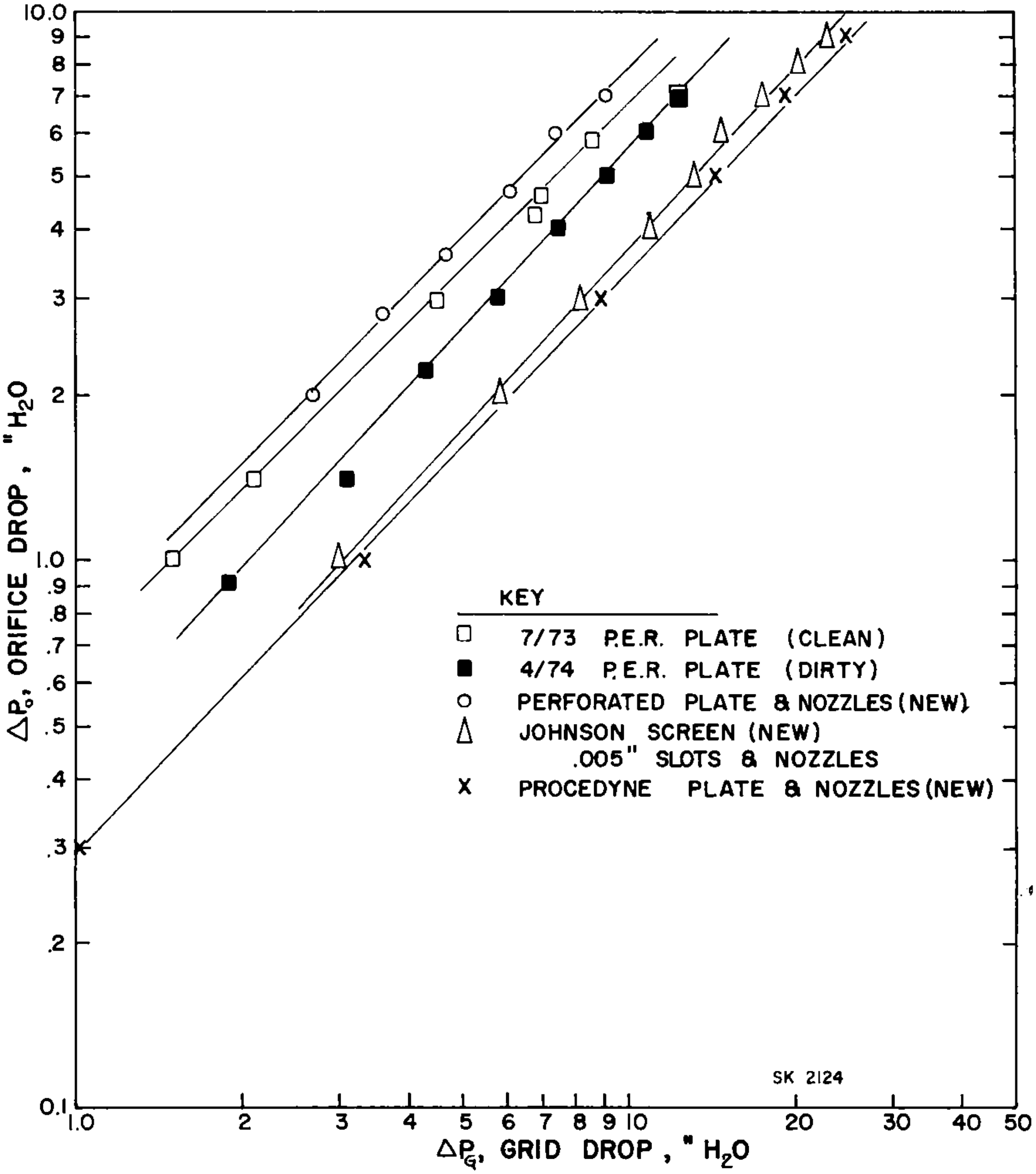


FIGURE 3.25 GRID PLATE FLOW DATA

$$W_h\text{, lb/hr} = 11{,}110\ \sqrt{\Delta P_o\ (\rho)} \qquad (3.9)$$

where

ρ = density of air, lb/ft^3

Recall that the internal area of the FBM is 9.136 sq. ft.

For the three plates tested to date it was found that two of the vendors could not provide a unit with the pressure drop specified.

The prototype design for cold pressure drop results is based on a clean plate performance of:

ΔP = 14" H_2O with a flow rate of 840 lb/hr, sq.ft. of air at 600°F with a density of 0.043 lb/cu. ft.

For a plate which follows an orifice pressure drop---and all do (See in Figure 3.25 that the slopes ~ 1)---an overall coefficient, K, can be computed for evaluating results at different conditions

$$K = \frac{W_h}{\sqrt{\Delta P\ (\rho)}}$$

For the conditions specified

$$K = 1083 = \frac{840}{\sqrt{14(.043)}}$$

The perforated plate had been designed and ordered before the installation details had been established and was designed for K = 1150. The measured valve was K - 1210 an insignificant error. The two vendor designed plates were far from the selected value. This data summarized in Table 3.11:

TABLE 3.11

Comparison of Specified Pressure Drop VS Pressure Drop Actually Provided for Air Distributors

Plate Design	Pressure Drop Parameter, K*	
	Specified	Measured
Perforated Plate	1150	1210
Johnson Screen, #90 wire .005" spacing	1300	730
Procedyne	1083	720

* $K = W/\sqrt{\Delta P(\rho)}$, see text for definition.

The obvious conclusion on cold pressure drop tests is that quality control is of critical importance in the specification of an air distributor of any design other than our own machined nozzles (which are always consistent and easily checked with three numbered drills acting as go/no-go gauges). The checking of a perforated plate is also simple.

In hot tests the perforated plate performed poorly at very low air flow rates where $\Delta P < 1.5"$ H_2O. The front third of the FBM bed slumped while the rear two thirds continued to operate. This is unacceptable.

The Johnson screen changed drastically after the first hot test. It appears that the spaces had been bridged by the iron oxide or rouge which is released by burning coal. Considering that the clean pressure drop was excessive this blinding was unacceptable. See Figure 3.26.

The Procedyne plate was unaffected by several hot tests. The no-bed pressure drop was consistent with the as-delivered value after each operation. As noted earlier the as-delivered pressure drop was well above the value specified. The plate did not sift and operated well at low loads. A test of bed depth vs minimum fluidizing velocity was run for

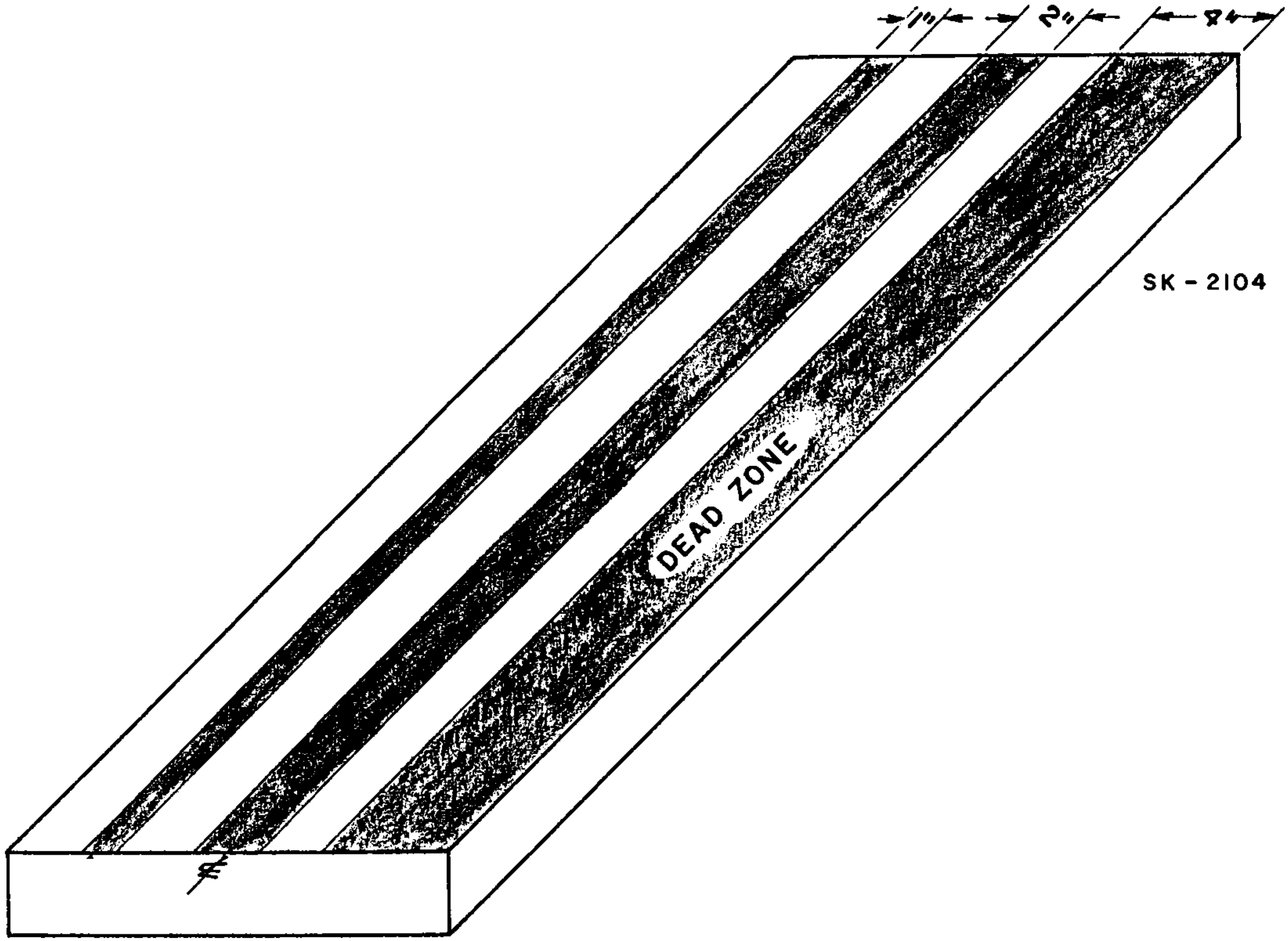


FIGURE 3.26 PLUGGING PATTERN ON JOHNSON SCREEN

the Procedyne plate. Figure 3.27 contrasts sharply with the data presented earlier for our machined nozzle plate. Considering the difficulty of precisely defining the on-set of fluidization, the Procedyne plate gives a U_{mf} value independent of bed mass (depth).

3.12 Coal Feeding

As noted earlier achievement of a homogeneous heat source within the fluidized-bed requires that hot coal and air be available uniformly in the appropriate proportions. The air distributor is designed to direct air through the shallow bed, equally, over the large cross section. Typically air is provided via some type of orifice on ½" to 1½" centers. Coal, on the other hand, can not be distributed as the air is and the frequency of coal injection points is restricted by economic considerations. Coal injections on six foot centers are proposed for the prototype.

There are essentially two separate problems to be solved. First it is necessary to subdivide the total supply of coal into a number of equal streams for each coal injector. The second design problem involves the injector itself, that is, the device that puts coal at the base of the bed. The division problem and injection problem were both given attention.

3.12.1 Experiments with a Screw Feeder/Divider

One early design of the prototype boiler showed it having 48 coal injections points in the main bed. Each feeder was to serve an area of nine ft^2 and, at full load, inject about 600 pounds of coal per hour. A mass flow conveyer and two variable feed screws were to be used. This system is shown in Figure 3.28.

The concept for this feeder is illustrated in Figure 3.29. A mass flow conveyor picks up coal from the bunkers and provides it to the metering screw. The mass flow conveyor, labeled A, carries a circulating load of coal, i.e., it moves more coal than is actually being used so that the drop tubes to the metering screw, labeled B, are always full. The coal drops into the inlets of the metering screw, is moved by the screw about one foot, where the coal drops into the injection pipe, labeled C, in Figure 3.29. The rate at

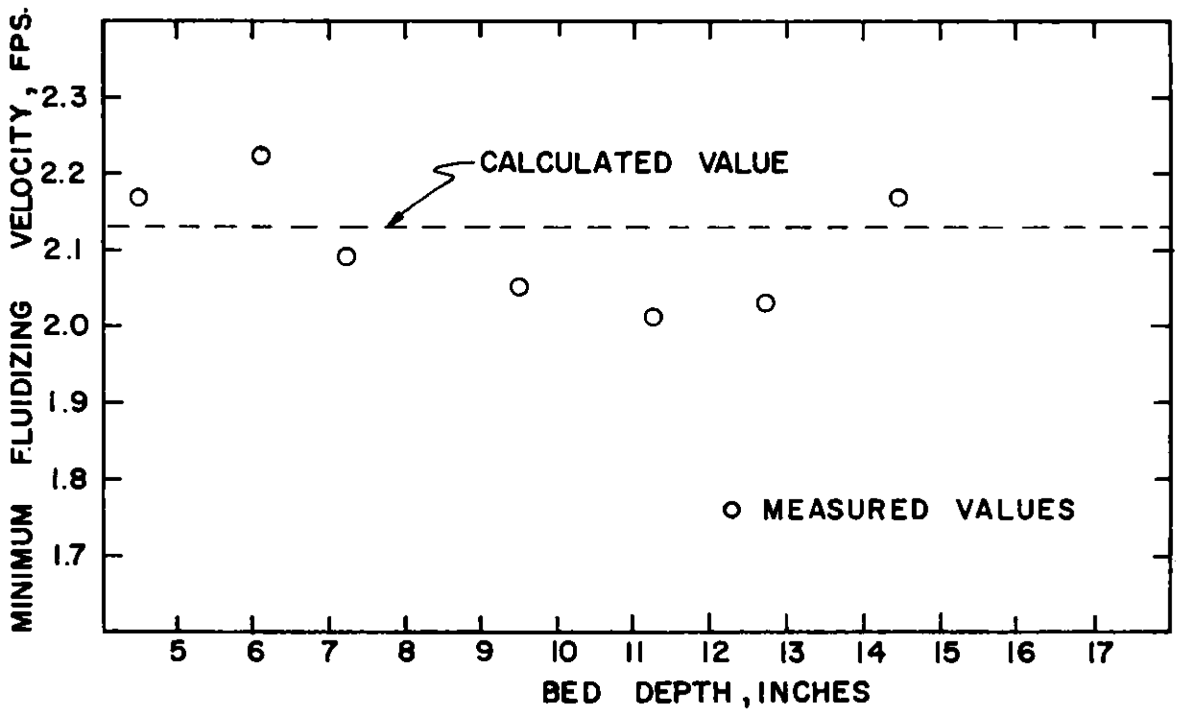


FIGURE 3.27 PROCEDYNE PLATE DATA

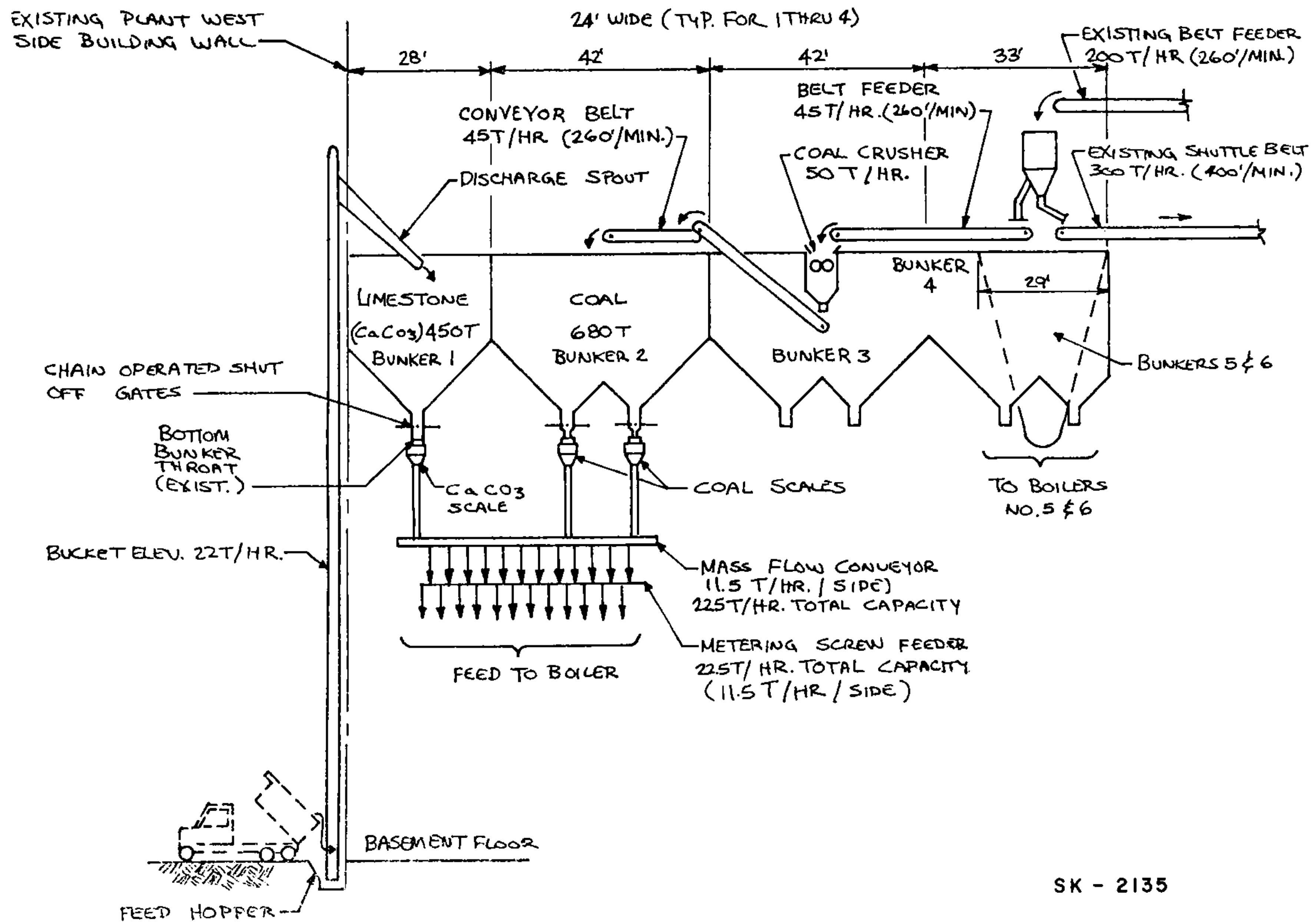
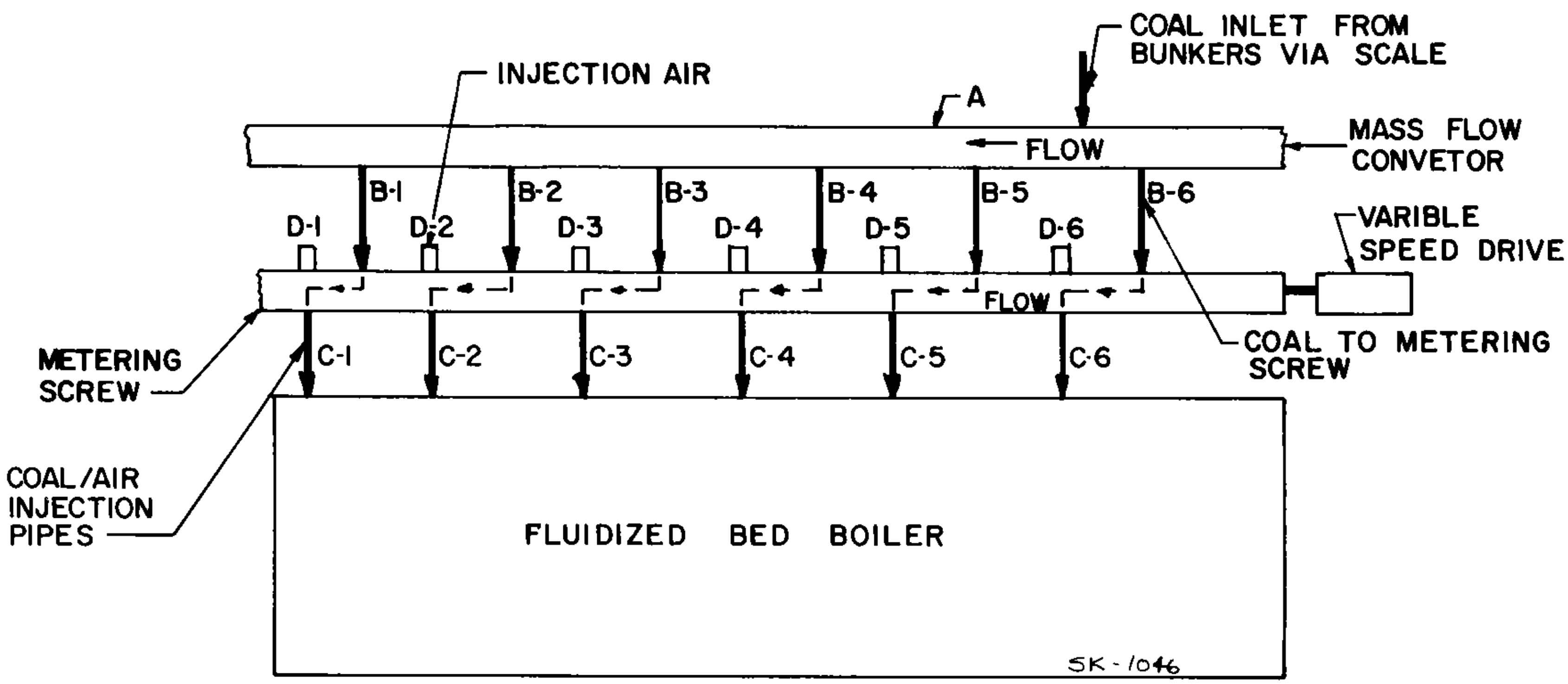


FIGURE 3.28 COAL AND LIMESTONE SYSTEM SCHEMATIC DIAGRAM



(SEE TEXT FOR EXPLANATION)

FIGURE 3.29 - COAL FEEDING SYSTEM FOR LARGE FLUIDIZED-BED BOILER

which coal is fed is controlled by the variable speed drive also shown on the sketch.

The coal is transported through the tubes, C, by the injection air which enters at D and actually blows the coal out of the screw.

This air must be at sufficient pressure to overcome all frictional losses and in addition, overcome the pressure at the base of the bed which may be as high as 30"w.c..

A second function served by the coal injection air is to provide combustion air for coal fines which burn rapidly in the vicinity of the coal inlet point.

It may be seen from Figure 3.29, that air introduced at D-1 is intended for injection tube C-1. This air will flow through C-1 only, if the coal in the screw between points 1 and 2 offers sufficient resistance and the pressures at all points are approximately equal. The mass flow conveyor, A, must also be sealed and under pressure or injection air would flow up through the B tubes into the mass flow conveyor. If the air flowed up at a sufficient rate, it could prevent coal from dropping into the B tubes.

A small hopper and screw, shown in Figure 3.30, were fabricated for use on the FBM as a simulation of the concept described above.

In January 1973, coal feeding problems were experienced because the hopper constructed to simulate the mass flow conveyor, A, leaked air. The symptom of a problem would be a sudden and sharp increase in residual oxygen. It could be noted that coal was not being fed through one of the two injectors by listening to the injection tubes, i.e., when coal is being fed, it can be heard striking the sides of the tube. The coal feed could be restored by striking the hopper with a hammer, which would probably collapse the coal over the air spout inside the hopper and allow coal to enter the screw again. This problem was resolved by sealing the leaks and pressurizing the hopper. The first pressurization line, a 1" hose, came from the coal feed inlet header which at operating conditions has a pressure of about 36"w.c.. A second pressurizing line was made of 2" metal flex hose connected to the main air inlet header which has a pressure of

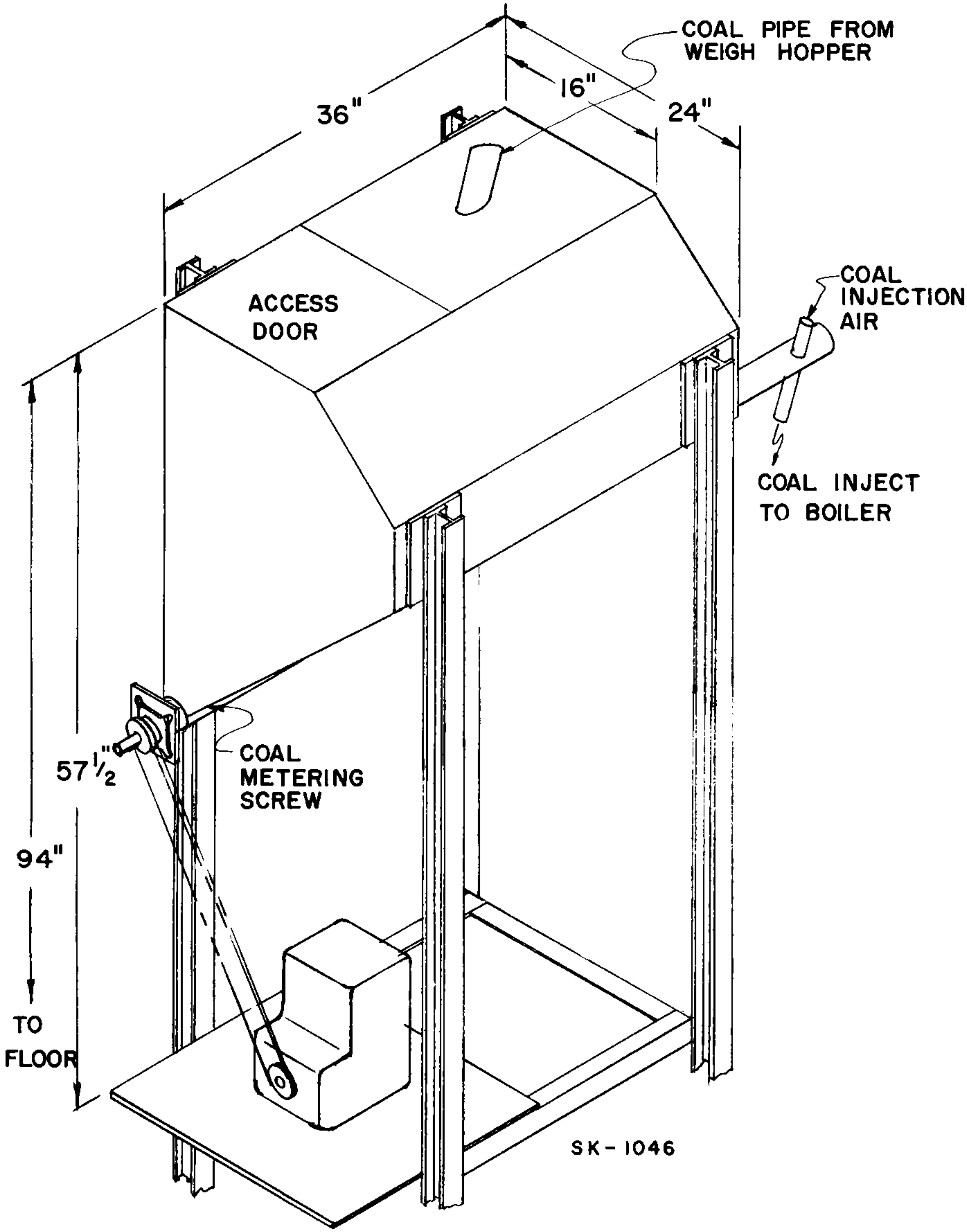


FIGURE 3.30 PRESSURIZED BUNKER AND SCREW

50"w.c. . A venturi was installed to determine if there were any flow through this line.

The next problem noted with this coal feeder, was a periodic residual oxygen excursion. The period, or cycle time, was seen to be the same as that for the main coal feeder screw, which periodically started to refill the small hopper above the metering screw.

It was noted that excursions began before the coal screw actually started. This indicated that the excursion might be related to the level in the hopper. The corrective action taken was to move the lower bindicator, which started the refilling screw, to a higher position. This did not actually cure the problem and the periodic excursion continued. A manometer connected to the metering screw hopper to monitor hopper pressure was observed and it was noted that the hopper pressure would increase 2" w.c. each time the filling screw started. This could mean that there was air leakage through this inclined filling screw and this leakage was reduced when coal is actually being moved.* The air that leaked to the atmosphere via the screw was not available to flow into the boiler and the excess oxygen would drop. When the screw started, the air leakage would drop and more air would enter the boiler. One final observation was that the oxygen excursion appeared to begin just before the filling screw turned on. This could be explained if it was assumed that when the coal level in the hopper was low, the coal could be blown back out of the metering screw, and so the coal rate would drop. It was not possible to determine if an increase in excess oxygen was the result of an increase in air flow or a decrease in coal flow.

The cure for these problems was to connect the filling screw starter so that it ran each time the top bindicator signaled. By this means, the hopper was kept nearly full. By slowing the filling screw, the time-on for the filling screw was long

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* It was postulated that when the inclined screw was still, air cut channels through the coal and vibration packed the coal lower in the flights, allowing a path for the air to flow. When the screw was turning, the flights were full and air could not flow through the screw.

and the operation more nearly simulated the continuous coal feed system intended for the prototype. The danger of that arrangement was that the metering hopper could empty and the coal flow stop.

A second problem with the coal metering screw, was binding. The diameter of flights of the screw were almost precisely the same as the tube into which the screw was inserted. Also, all of the flights were approximately equally spaced. This means that when coal was picked up, as at point B-1 of Figure 3.29, and the coal moved into the tube, toward the drop out (point C-1) that binding may occur. If, for example, at one point inside the tube, the pitch was slightly less than average, the coal would be compressed. If the coal were all coarse, breakage of the particles would allow the mass to compress. When, however, the fines content was high, there could be no further compaction and the screw must stop. This occurred at one point in the experimental feeder tube, and in fact, there was an 1/8" reduction in pitch at this point. The weld connecting the shaft and flight was ground out to enlarge the volume in this space, which did no good. Next, the entire length of flight was ground down to reduce its diameter so as to provide compacted coal on outlet to the flight behind or forward over the top of the flight. This cured the binding problem.

The screw selected for this test application was inappropriate. A tightly fitting screw should have the pitch increase as it moves forward, so that there is always an increasing volume available.

With the changes listed above, the coal feeder operated consistently and was used through May 1973.

3.12.2 Vibrating Table Feeder/Divider

A vibrating table has the capacity to divide a stream of granular solids into a number of smaller streams of approximately equal volume. A vendor's plant test showed a marked difference in the relative weights moving through each tube.

The FBM performs well with two injectors and a simple divider. There is no reason to expect the split to be precise yet an O_2 profile shows reasonable uniformity. In order to get a feel for the permissible error in the split, a simple test was run with the FBM feeders.

The coal feed tubes were disconnected from the injectors and connected to the large bags normally used for flyash weighing.

It is virtually impossible to duplicate the pressure profile that the base of an active fluidized-bed imposes, but the bags did impose a uniform drop and hence air flow. Table 3.12 shows the results of these experiments with the variable speed drive set to feed 600 lb/hr.

TABLE 3.12

Coal Feeder Distribution Test-May 1974

	Test Duration, minutes	
	10	20
Feeder No. 1	54 lbs	118 lbs
Feeder No. 2	41 lbs	84 lbs
Total	95 lbs	202 lbs
Hourly Rate	570 lbs/hr	606 lbs/hr
Percent Difference = $100\left(\frac{FD'R\#1}{FD'R\#2} - 1\right)$	33%	41%

A substantial variation is revealed by the data of Table 3.12, indicating the FBM performs well despite a poor split between feeders. This suggests that some tolerance may be permitted in the design of the coal divider for the prototype.

Tests planned later in 1974 after a horizontal tube bundle is fabricated for the FBM are expected to indicate that bed mixing is poorer with the bundle and the less difference between injectors can be tolerated.

3.12.3 Experiments with the 14° Injector

As noted earlier the coal delivery problem has two parts---subdivision and injection. With the completion of a tube bundle design*the appropriate coal injector angles and lengths were derived. There are two injector lengths, a short unit at 39° below the horizontal and a long 14° unit.

Transport considerations established the internal injector tube diameter as 1½". The important questions to be answered were:

(a) Would coal coke in a long, hot feeder tube?

(b) Could such a tube be cantilevered from the furnace wall?

(c) How would a plugged feeder be removed for cleaning and reinserted?

To answer these questions a series of tests were run using the normal Sewickley coal and one other coal recommended as being particularly difficult to feed. (See "Materials" for coal data) Our own experience with long injectors had been favorable over the years, but reports by others indicated coke formation in injectors only a few inches long. A description of the experiments follows.

1. Test No. 531: Test No. 531 in the FBM used the new coal feeder tube installed through the FBM front water-cooled door. The feeder tube is 304 stainless steel, schedule 80, 1½" pipe. (Figure 3.31) The feeder was installed at a 14° angle from the horizontal and extended to within 12 inches of the back wall giving a feeder length of about five feet. At this length and angle the tube is totally submerged in the bed during operation and almost totally submerged even when a normal bed of 18-20 inches is periodically banked. A thermocouple was installed one inch from the feeder exit and positioned away

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* See Appendix E for the 30 MWE boiler details.

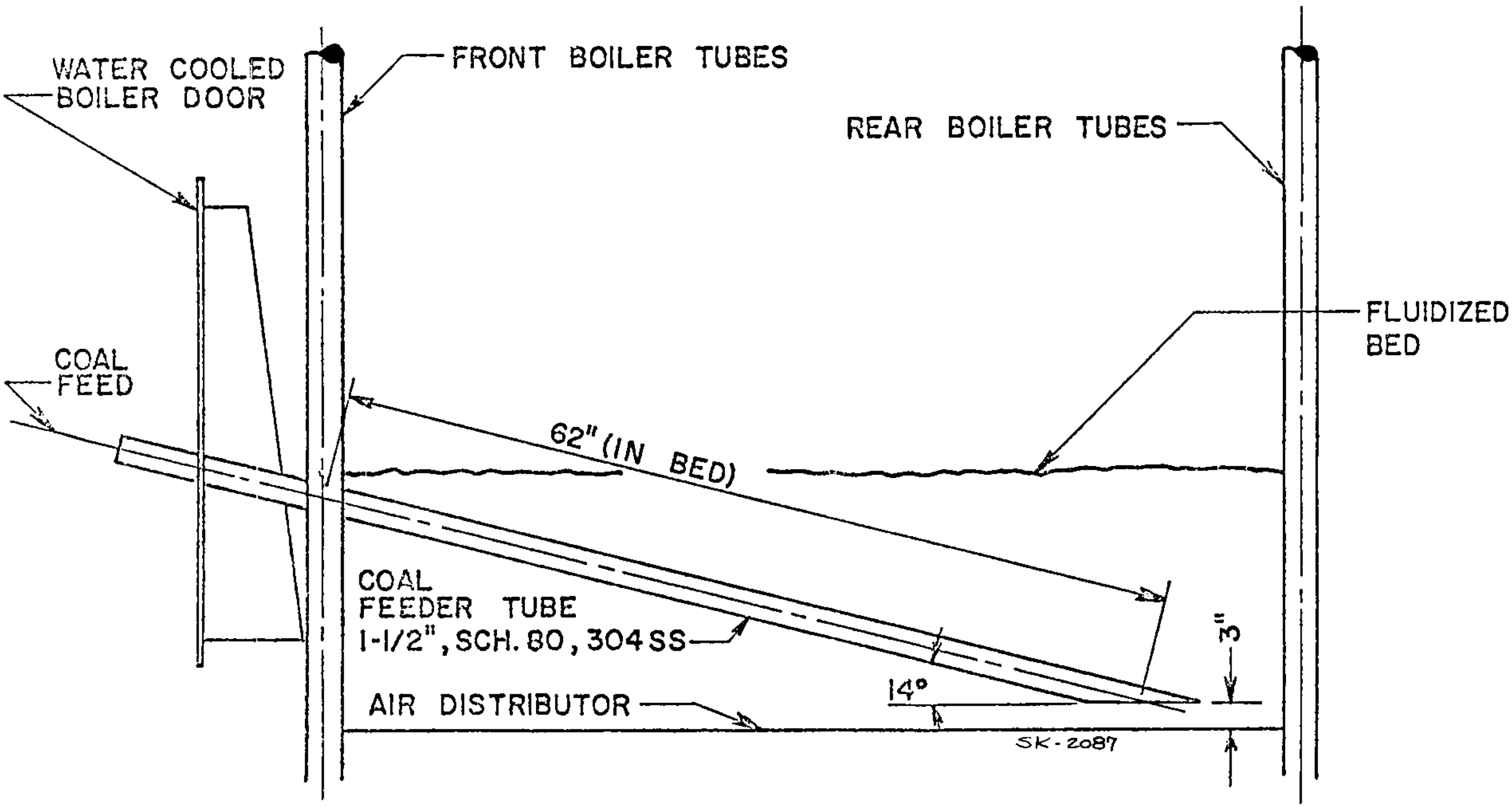


FIGURE 3.31 COAL FEEDER IN FBM.

from the wall. This was done in order to monitor the bulk temperature at that point during operation. The feeder tube end was supported by a bracket welded to the air distributor. The feeder tube end was approximately three inches above the grid plate.

The boiler was lit-off and the bed temperature was brought up to 1500°F. Because of the feeder exit position, relative to the back and side walls, poor fuel distribution was obvious. Fortunately smoking was minimal making continuation of the test possible. The bulk temperature at the tube exit reached ∿800°F with 700°-750°F a typical value. The coal blowing through the tube at 80 fps appeared to shield the thermocouple from radiation from hot surfaces. This was apparent as the indicated temperature would rise immediately when the coal was shut off but air flow maintained, i.e., the thermocouple now received direct radiation from the tube wall. Sewickley seam coal (-¼") was used for the test. Banking the bed after shutting off coal flow caused the temperature at the end of the tube to rise to about 1300°F (in the tube). Fluidizing the bed and restarting the coal feed, in that order, produced no problems as there was no apparent caking or pluggage even though a small sight-port at the end of tube revealed the entire tube was at red heat prior to the start of coal feeding. When the run was terminated and the feeder tube was pulled, no warping was seen nor were there any inside coke deposits on the tube metal. The tube had acquired an external red coating that was easily removed with a teflon spatula. Its analysis was magnetic Fe_2O_3, the rouge released by the coal burning in the bed.

2. <u>Tests No. 534 through 540</u>: It was shown that one half pound of air per pound of coal was more than adequate, providing a feed velocity of 80 fps. This was used although the tube would not plug operating substantially below (less than half) that figure. It was also demonstrated that, if necessary, the injector could be put into and removed from the boiler by one man. Two type K thermocouples were used to monitor the coal feeder bulk outlet temperature and the feeder tip metal temperature. Several

interesting discoveries were made with these thermocouples:

(a) With the bed banked the tube metal temperature approaches the bed temperature.

(b) If the air is not kept flowing through the bed for several minutes after the coal is shut off, the carbon inventory in the bed close to the feeder exit will burn slowly giving a rising temperature function in the localized area of the feeder exit (peculiar to FBM geometry).

(c) A hot spot exists somewhere above the feeder outlet at substantially above the bed bulk temperature (∿200°F above) corresponding to a burner flame.

(d) Locating one feeder tube below another will result in a hot spot in the upper tube caused by the bottom tube "flame" regime, Test 536.

(e) With the feeder tube metal at the banked bed temperature ∿1500°F, the boiler can be restarted immediately without plugging the feeder tube; with the coal feeder air obviously turned on first.

(f) The tube metal and bulk temperatures are fairly constant from inlet to outlet as determined from total length profile of temperature, Tests 536 and 540.

(g) With the end restraint removed and the feeder tube permitted to pulse in the bed, no significant warpage occurs at the normal operating temperature.

Test 534 was typical of the feeder tube tests: Sewickley seam coal was used and the operating conditions and pertinent information were as follows:

Coal Feed	∿600 lb/hr
Limestone Feed	∿168 lb/hr
Salt Feed	∿ 15 lb/hr
Coal Feeder Air	∿300 lb/hr
Starting Bed Height	15½ inches
Finished Bed Height	21½ inches
Bed Temperature Profile	1200°-1460°F typical
Combustion Air	5000 lb/hr

The spread in bed temperature was caused by the improper fuel distribution caused by the feeding of coal into only the one back corner of the boiler as described previously. For normal operations, the feeder tube temperatures were as follows:

(a) Tube metal at tip: 1400°-1440°F typical.

(b) Bulk at tip: 690°-730°F typical (probable radiation effect from the wall).

When the bed was banked the following was observed by the two thermocouples:

(a) Tube metal at tip - rose from 1415°to 1547°F in 10 minutes.

(b) Bulk at tip - rose from 693°to 1525°F in 10 minutes.

After ten minutes the temperatures peaked and started to slowly drop. The rise in the tube metal temperature was examined during further tests (535 and 536) and it was discovered that the temperature rise could be controlled by the length of time the air was permitted to pass through the bed and feeder after the coal feed was stopped. Simultaneous stopping caused rises up to 350°F and two minutes of air flow virtually eliminated any rise. The coal feeder air rate was checked periodically during Test 534. A drop in air rate can be attributed to a steady increase of bed depth and hence back pressure. There was a six inch increase in bed in the 132 minute test period. The increased bed depth could have been compensated for but was not---yet no plugging occurred.

The entrance velocities to the feeder tube varied from a peak of 89 fps at start-up to a low of 64 fps at +132 minutes.

The Loveridge coal had been recommended as a very "sticky" coal, and ten tons were bought. It was later learned that the Sewickley seam coal that had been used for over two years was almost as sticky (see "Materials" for data on these coals).

Test 536 was made to test a light-off procedure for smoke control. Smoke is generated in the FBM until the bed reaches a high enough homogenous temperature that eliminates smoking. The five foot feed tube was left in place and supplied with air via a separate air feed line with its own orifice plate. The two old coal feeders were reinstalled to test the light-off procedure,(Figure 3.32).The bed temperature was brought up to a typical 1550°F feeding coal through the two feeders whose relative position was below the long feeder. The air flow rate through the long feeder was held at 310 lb/hr or roughly a 76.5 fps entrance velocity. A therm-ocouple was pulled along the inside metal surface of the long feeder in one foot intervals giving an internal temperature profile that suggested that a "flame" zone exists above each of the two "old" feeder tube outlets causing the substantially above bulk bed temperature regions in the idle long injector. This had been suspected in the past and could be an important design consideration when locating dual feed points (one above the other) in commercial boilers; the longer feeder might pass over the "flame" regime of the shorter one causing a hot spot which could be troublesome. The magni-tude of the increase in temperature of the "flame"

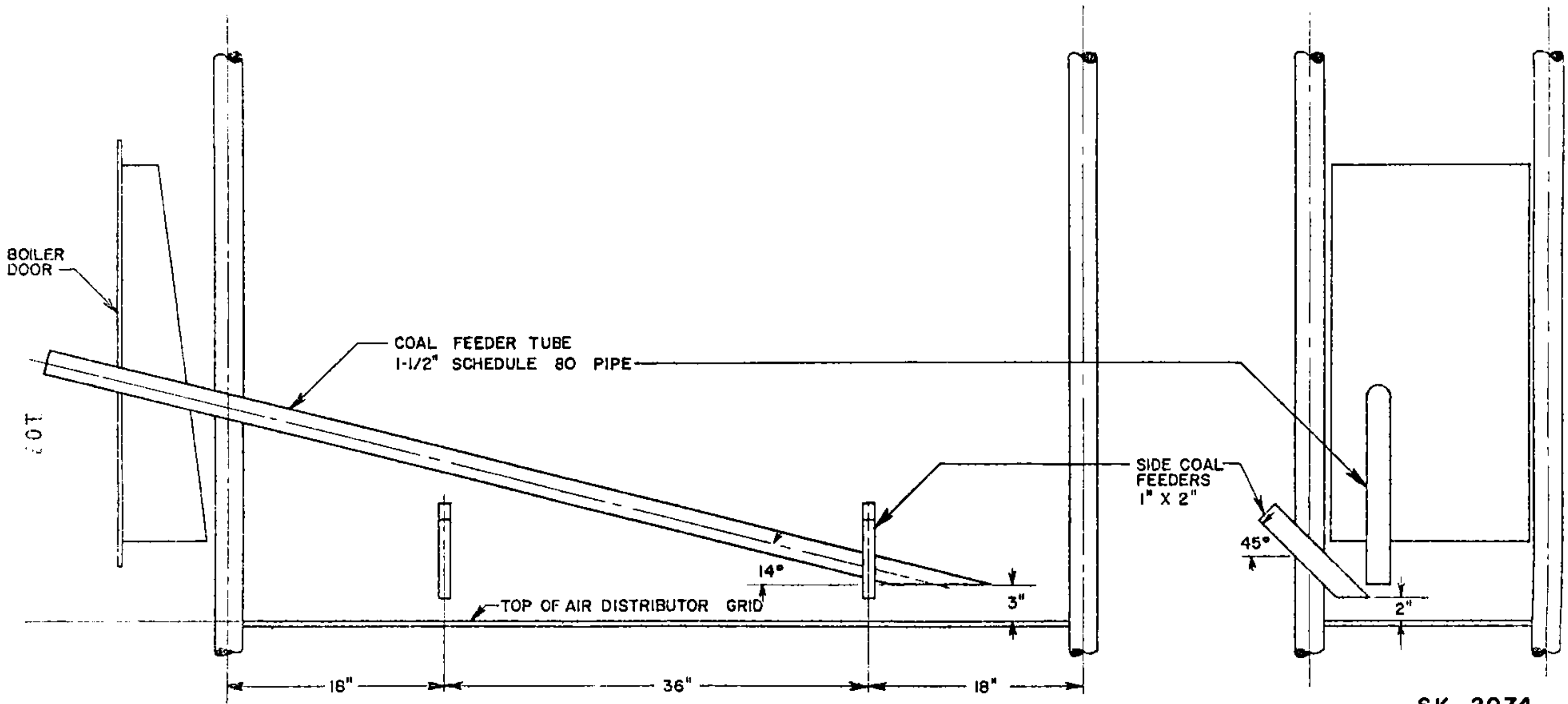


FIGURE 3.32 FEEDER TUBE LOCATIONS - RUN 536

regime above the bulk temperature of ∿200°F obviously does not hinder sulfur capture nor produce excess amounts of NO_x.

Test 540 was made with Sewickley seam coal and the five foot long feeder was deliberately plugged by lowering the coal feeder air rate to the necessary low limit. The lowering of the feeder air rate was done in ten steps starting at 300 lb/hr with plugging at ∿35 lb/hr or at ∿9 fps entrance velocity. There was a significant reduction in coal feed rate as evidenced by a 70°F bed temperature drop during the 35 minutes the ten step air reduction was made, however, it was very difficult to plug the feeder. The plugged feeder was removed, cleaned, replaced and the boiler restarted within minutes.

The internal bulk temperature is seen to be relatively constant throughout the length of the feeder tube. Based on a submerged length of 61 inches and an O.D. of 1.9 inches, the overall heat transfer coefficient U_n can be calculated, if the measured bulk temperature at the tip is correct, as 56.8 Btu/hr,ft^2,°F where:

$$U_n = \frac{Q}{A \times LMTD}$$ Assume: air inlet temperature = 100°F

and

U_n = overall heat transfer coefficient, Btu/hr,ft^2,°F

A = heat transfer area, ft^2

Q = heat added, Btu/hr

LMTD = Log mean temperature difference, °F

the values are

A = 2.53 ft^2 outside surface

LMTD = 1070°F

$$Q = (\text{lb/hr coal} + \text{lb/hr air})\ (Cp\ \underline{avg})(°F\ \text{rise})$$

$$Cp\ \underline{avg} = \frac{Cp\ air+2(Cp\ coal)}{3}\ \text{if}\ \frac{\text{lb/hr coal}}{\text{lb/hr air}} = 2$$

Avg Bulk Temp. = 415°F

$Cp\ \underline{avg} = 0.255$ at 415°F

Q = 153700 Btu/hr

$$U_n = \frac{Q}{A \times LMTD} = 56.8\ \text{Btu/hr,ft}^2\text{,°F}$$

The U value of 56.8 is obviously too high suggesting that the bulk temperature thermocouple was too close to the side wall. Further experiments are being planned and the hardware designed to measure a more representative bulk temperature in the feeder tube close to the tip. However, it is almost impossible to truly measure the temperature of a "lean" coal/air mixture flowing through a small, red-hot tube---radiation is too strong. Shielding is impractical.

Assuming a more realistic temperature rise of ~300°F in the 61 inch feeder tube length, the U value would become:

$$U_n = \frac{Q}{A \times LMTD}$$

where

$Q = 68{,}850$ Btu/hr

therefore

$U_n = 25.2$ Btu/hr,ft^2,°F

A U value of 25 is more credible than 56.8 although further tests should confirm the actual value. Even without further testing, it can be definitely concluded from these completed tests that the use of such feeders is a practical method of feeding coal into a fluidized-bed.

3. Conclusions: Tests with a five foot long pipe acting as a coal injector proved the following:

   (a) The injector does not plug under steady state normal operating conditions---a severe test was imposed using the Loveridge (a Pittsburgh seam) coal.

   (b) The injector performed well feeding:

      (1) Coal

      (2) Coal and salt

      (3) Coal and limestone

      (4) Coal, limestone and salt

   The total solids rate exceeded 800 pounds per hour.

   (c) The bed was banked repeatedly, the injector soaked to bed temperature, the blower restarted and the coal feed started, before the blower was up to speed, without plugging.

   (d) The injector could be replaced by one man in a few minutes.

   (e) If a feeder has no air flowing through it and the bed is fluidized the bed material will pack in a tube having a 14° angle. The tube must be removed for cleaning.

   (f) An end support would probably keep the tube rigid but the tube as a cantilever caused no problems.

   (g) 304 stainless steel gave acceptable performance at 1550°F bed temperature.

3.13 Maintaining the Size Distribution and Chemical Purity of the Bed

A fluidized-bed boiler can accept, as a feed, materials having a wide size distribution. Obviously very large, inert particles will not be fluidized but will sink to the grate. The exact meaning of "very large" depends on the system configuration. In some simple experiments in 1968 granite stones, up to 2½" in diameter, were mobile in the bed---not necessarily fluidized, but mobile.

The furnace is to be fed two different substances, coal and limestone. If the coal were ash free there would be no reason to crush and screen, both feed stocks to the same top size. The sizing of the feeds would be established so as to minimize costs. It was found that limestone crushed to pass through a six mesh or eight mesh (USS) screen performs well as a sulfur acceptor.

As coal size increases (neglecting the effect of ash) the combustor performance improves in that less carbon is carried over and fewer coal injectors are needed to maintain a good oxygen profile.

The effectiveness of heat transfer surface immersed in the bed <u>increases</u> as the average bed particle size <u>decreases</u>.

Optimizing the apparatus and process therefore involves a number of trade-offs on just the matter of size of feed. It was found that a -8 mesh bed is "good" for heat transfer and sulfur capture. It was found that -¼" or -½" coal is "good" for even combustion.

3.13.1 Experiments in Size Maintenance Via Screening

1. <u>Description of Feed</u>: The size distributions for the as-fed limestone and coal are shown in Table 3.13.

   (a) <u>Size Distribution</u>: Table 3.14 shows the size distribution of a "starter" bed of partially sulfated limestone cleansed of most +8 mesh particles. Also shown in Table 3.14 is the distribution of a "steady-state" bed produced as follows:

TABLE 3.13

Size Distribution of Feed Material to Fluidized Bed (Most Tests in 1973)

	Wt. Percent Less Than	
Mesh Size (USS)	Limestone*	Coal**
½	100	100
¼	100	97.3
6	100	80.4
8	98.56	68.4
10	90.72	62.9
12	77.36	56.9
14	60.97	52.9
16	37.49	47.3
18	14.53	41.5
20	4.99	36.4
25	1.96	--
30	0.97	27.9
40	0.60	21.4
80	0.40	--
100	0.20	9.4
200	0.03	5.2
325	0	--

* Test No. 514 (No. 1359 Limestone)
** Test No. 516 (Rivesville Sewickley Seam)

(1) Starter bed: -8 mesh fraction of a fluidized-bed (fines blown out).

(2) Coal: limestone feed ratio 4:1.

(3) Coarse bed removed: limestone feed ratio 2:3.

(4) Size distributions of feed stocks: Table 3.13.

(b) Changes in Bed Analysis: As the bed changes in size due to the accumulation of the larger coal ash particles it also changes in chemical composition for the same reason.

TABLE 3.14

Size Distribution of Starter and Steady State Beds

	Wt. Percent Less Than	
Mesh Size (USS)	Starter Bed	Steady State Bed**
¼	100.00	100.00
6	100.00	98.80
8	100.00	96.00
12	79.35	76.20
20	7.25	6.96
30	.35	.36
40	.02	.02

* See text for description of test conditions.
** Sampling for coarse particles is subject to large errors.

Table 3.15 shows the change in aluminum and calcium content for the Bureau of Mines Tests (3/21/73 and 3/22/73):

TABLE 3.15

Changes in Composition of "Lime" Bed Material as Coal Ash Accumulates

Test	Wt. Percent in Bed Samples			
	3/21/73		3/22/73	
Time	Al	Ca	Al	Ca
Hr 4	1.14	36.5	1.54	35.5
Hr 6	1.31	33.1	1.72	35.3
Hr 8	2.08	31.3	2.33	34.8

Note: Calcium comes mostly from the limestone fed. Aluminum comes mostly from the coal ash.

The aluminum content is an indication of the accumulation of ash in the bed.* As the bed becomes enriched in aluminum it loses calcium and must perform more poorly in sulfur oxide control.

2. Tests 502, 503 and 504: A simple elevated vibrating screen was used as an experimental bed-particle classifier. When this device was used , it was able to maintain the cleanliness of the bed over the period of the test at about 36 wt. percent calcium.

* The coal ash was 10.4 percent Al on a calcium free basis.

Table 3.16 shows the data for the performance of the classifier.

The information that can be gleaned from Table 3.16 is as follows:

(1) Of the 1800 pounds of ash fed with the coal only 70.8 pounds joined the +1/8" fraction in the bed, i.e., 3.9% was +8 mesh and tough enough to retain its size. But 31.6% of the coal was +8 mesh (Table 3.13).

TABLE 3.16

Bed Classifier Performance During Test 502, 503 and 504

		Weights, lbs.*			
		Total	+8 Mesh	-8 Mesh	%+8 Mesh
1.	Start Bed	1113.5	38.5	1075	3.46
2.	Removed from system via classifier				
	a. Test 502 (1500°F)	132.2	20.2	112	15.3
	b. Test 503 (1650°F)	93.5	17.5	76	18.7
	c. Test 504 (1800°F)	31.0	4.0	27	12.9
	d. Between test periods	164.7	29.4	135.3	17.9
3.	Removed via blowdown valve**	1456.5	22.2	1434.3	1.5
4.	End Bed	422.9	16.0	406.9	3.78
5.	Lines 2+3+4	2300.9	109.3	2191.5	4.75
6.	Added to system via coal, Line 5 - Line 1	--	70.8	--	--
	-¼" Coal fed	10,273	(17.5%Ash)		
	-8 Mesh limestone fed	2,461			

* Weights are true weights, not estimates based on pressure drops.

** This is the same valve through which bed samples are withdrawn.

(2) The feed rate to the classifier cannot be measured directly. However, the rate can be derived from the data given:

(a) Assume that the percent oversized in the feed to the classifier (recall that the -8 mesh fraction is returned directly to the boiler) is identical to that found in the blowdown stream, i.e., 1.52 wt. percent.

(b) In tests 502 and 503 which took precisely 8 hours, 37.7 pounds of +8 mesh material were removed in the blowdown.

(c) The total flow to the air lift is:

$$\frac{37.7 \text{ pounds of } +8 \text{ mesh}}{8 \text{ hours } (0.0152 \text{ pounds of } +8 \text{ mesh/pound of classifier feed}}$$

= 310 pounds of feed to classifier/hour

(3) Some coarse ash "hides-out" in the bed. The start and end values for oversize, 3.46 percent and 3.78 percent respectively, are higher than found in the bed samples removed via the blowdown valve.

3. The conclusions drawn from these experiments are:

(a) It is possible to separately optimize the size distribution of the limestone and coal feed to a fluidized bed boiler if:

(1) The coal is very low in ash (probably about 5 percent) or

(2) The ash has a <u>very</u> small fraction that is coarse and tough or

(3) A system for separating the +8 mesh fraction is provided.

(b) For the unwashed Sewickley seam coal (this is one of the worst coals ever used from the point of view of tough +8 mesh ash) a feed rate of 25 percent of the bed mass per hour to a classifier will maintain a limestone bed relatively pure. For the Rivesville boiler this rate must be 15,000 to 20,000 pounds per hour.

(c) Continuously operating the classifier cooled the bed since the apparatus is essentially uninsulated and used a cold ($\sim$90°F) air lift. (The return temperature hasn't been measured but it's probably +500°F). If 20,000 pounds per hour of bed were cooled 1050°F in being cleansed the system would lose 4.6 x 10^6 Btu/hr or 1.1 percent of the fuel energy input. This is unacceptably high and therefore a method of preventing this loss must be found. A number of alternatives are being explored.

3.13.2 Magnetic Separation as a Method of Maintaining the Chemical Activity of Fluidized-bed of Lime

Tests were run on bed samples resulting from Test No. 519. A sample of the finished bed (that is the bed material at the end of the test, cooled with fluidizing air and stored in the furnace at least overnight) was used.

At the request of the magnetic separator vendor, Pope, Evans and Robbins removed the +8 mesh fraction by screening. The vendor's test machine divides the "head sample" or "original" into four streams. The weight fraction found in each stream depended on the magnetic properties of the particles.

The separated samples were then submitted for elemental analysis so that the following might be determined:

(1) Whether the most magnetic fraction could be "sold" as iron ore.

(2) If the process could remove coal ash without removing a substantial quantity of the limestone. The results are summarized in Table 3.17.

Table 3.17 shows very effectively that more than one half of the ash is removed at the expense of only two percent of the calcium. About 3/4 of the ash can be removed at the expense of 6.5 percent of the calcium. It was assumed that iron content is a good indicator of ash content, and this can be seen in Table 3.18.

TABLE 3.17

Results of Magnetic Separation Test of -8 Mesh Bed Material

Test 519

Products of Separation	Weight of Original Sample Appearing in this Product Percent	Calcium Weight Percent	Iron Weight Percent	Fraction of Total Calcium and Iron Appearing in Each Product of Separation: Calcium	Iron
1st Removed	6.7	10.9	13.6	.0202	.5875
2nd Removed	6.2	26.1	3.85	.0449	.1537
3rd Removed	3.1	30.6	1.58	.0263	.0315
Net Removed	84.0	39.0	0.42	.9086	.2274
Totals	100.0	--	--	1.000	1.000

Table 3.18 shows a more detailed analysis for the sample. For the -¼" size Sewickley seam coal, 60 to 80 percent of the ash is light enough to leave the bed as flyash. The balance, 20 to 40 percent, is heavy enough to be retained in the limestone bed. If the tough, coarse ash fraction is high, the bed would progressively become richer in ash. It is estimated that a fluidized bed of limestone, in which the ash content is below 20 percent, is effective for sulfur capture. Above 20 percent bed ash content, the sulfur capture deteriorates.

Three methods are available to maintain the relative purity of a limestone bed.

(1) The bed may be drained at a rate sufficient to maintain the ash content at, say 16 percent. The approximate rate of limestone addition required to do this for the Sewickley seam coal is at 2.3 Ca/S mole ratio. This is more than the value actually needed if bed ash control were not important. See Figure 3.33.

(2) About 5 to 15 percent of the ash in a -¼" size Sewickley seam coal is removed in passing the bed over an 8 mesh screen. Some of the limestone is also removed, but the quantity is generally low. Figure 3.34 shows the performance using a screen to maintain bed purity at 16 percent ash based on the assumption that 10 percent of the ash will be in the +8 mesh fraction. For this, the arrangement of Ca/S mole ratio is at 2.15. A reasonable value and typical of current FBM operations.

(3) The ash content of a bed of No. 1359 limestone can be reduced to a very low value by magnetic separation as shown in Table 3.17. About 75 percent of the ash from a bed sample (-8+20 mesh) can be removed via magnetic separation at the expense of about 6½ percent of the calcium content. Figure 3.35 illustrates the case where screening and magnetic separation were both used, and no bed material was discarded as blowdown. For this case, the Ca/S mole ratio is 2.1. This is about the minimum needed to maintain effective sulfur capture for the Sewickley coal and the No. 1359 limestone. The above analysis is flawed by a lack of

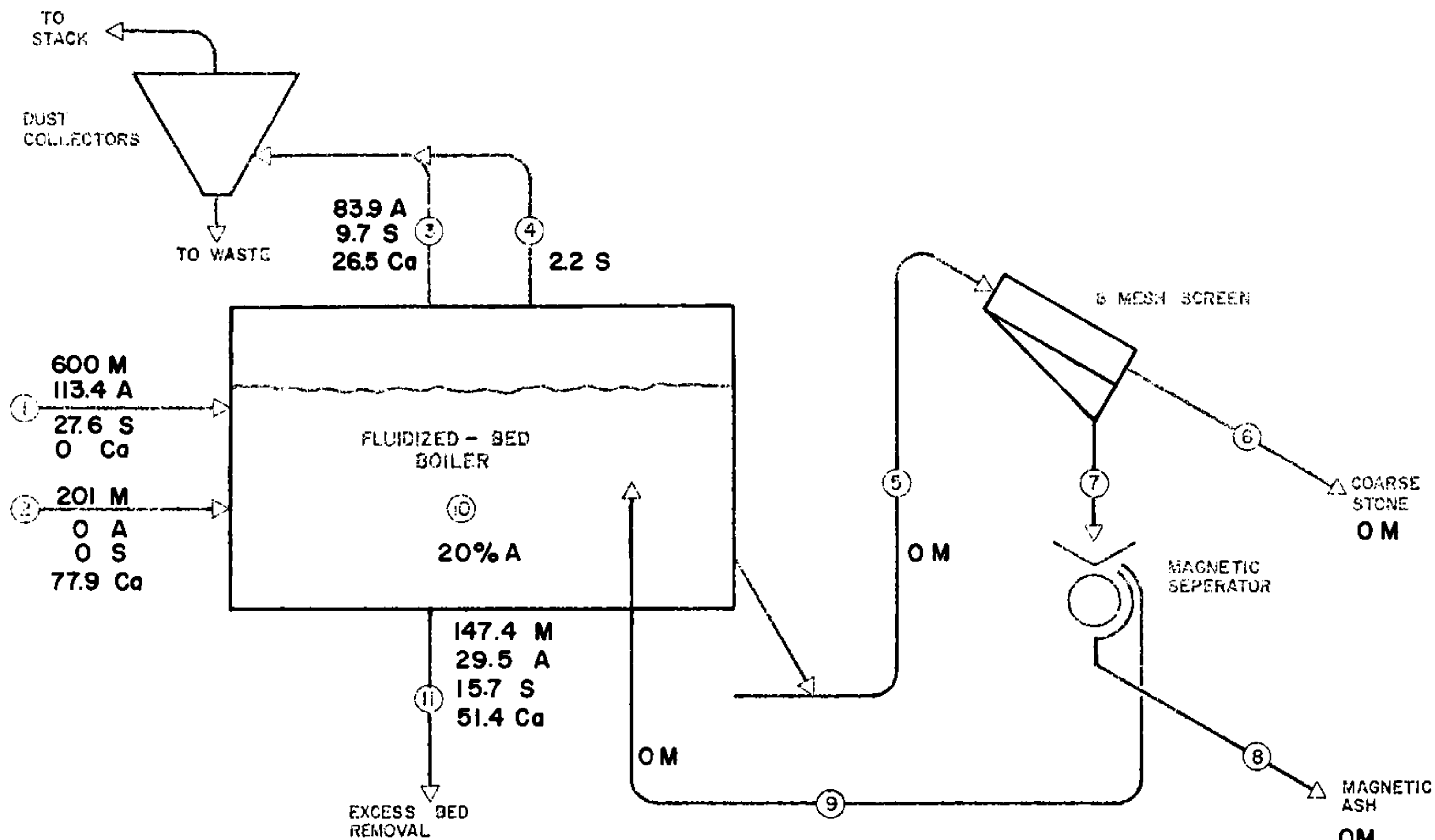
TABLE 3.18

Analysis of Magnetically Separated -8 Mesh Bed Material

Test 519

PRODUCT STREAM		ANALYSIS OF REMOVED (CALCINED) MATERIAL			
		1st	2nd	3rd	Not Removed
Ca	Weight Percent	10.90	26.1	30.6	39.00
Mg	" "	.62	N/A	N/A	0.43
Fe	" "	13.60	3.85	1.58	0.42
Si	" "	18.40	N/A	N/A	1.14
Al	" "	N/A	N/A	N/A	0.42
Na	" "	2.40	N/A	N/A	0.20
V	" "	0.86	N/A	N/A	0.34
Ti	" "	0.42	N/A	N/A	0.04
S	" "	2.70	8.97	11.72	14.52
Z	ppm	145	N/A	N/A	35
Co	"	70	N/A	N/A	90
Pb	"	215	N/A	N/A	180
Cl	"	15	N/A	N/A	N/A
Mn	"	335	N/A	N/A	N/A
Cu	"	175	N/A	N/A	N/A
Sn	"	10	N/A	N/A	N/A
Ni	"	320	N/A	N/A	N/A
As	"	N/A	N/A	N/A	N/A
P	"	N/A	N/A	N/A	1.6
Weight loss on heating to 600°C, percent		0.05	1.79	2.40	4.51
Percent of original sample		6.7	6.2	3.1	84.0

N/A = Not available



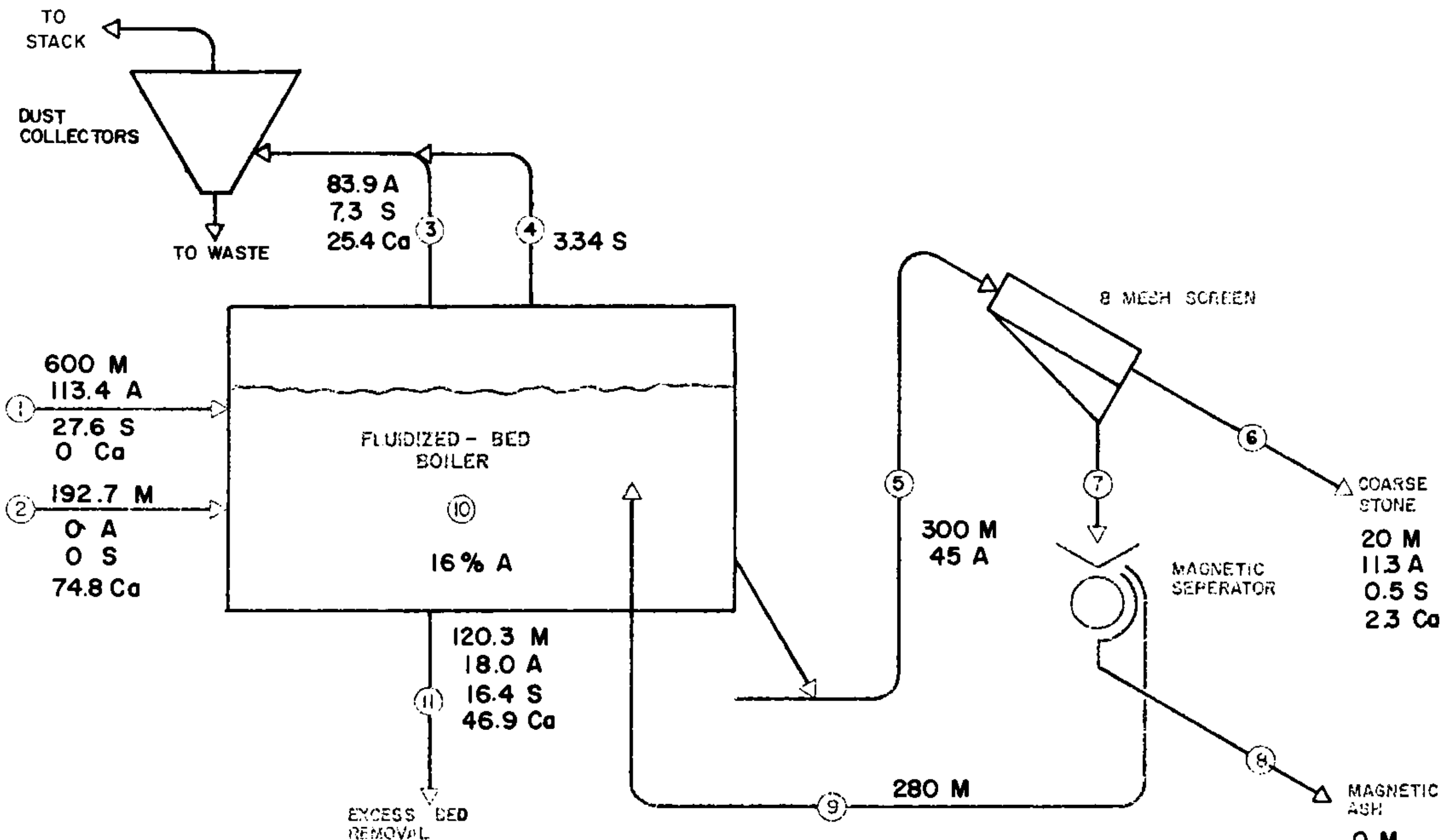
KEY SK-2149

(1) COAL IN	(5) STREAM FOR CLEANING	(9) CLEAN STREAM
(2) LIMESTONE IN	(6) COARSE STONE OUT	(10) BED
(3) FLYASH & DUST OUT	(7) STREAM TO MAGNET	(11) DISCHARGED BED
(4) FLUE GAS OUT	(8) MAGNETIC FRACTION OUT	

A = ASH, LBS/HR.
Ca = CALCIUM, LBS/HR.
S = SULFUR, LBS./HR.
M = MASS, LBS./HR.

(ASH CONTROL VIA. BLOWDOWN)

FIGURE 3.33 ASH, SULFUR & CALCIUM BALANCE



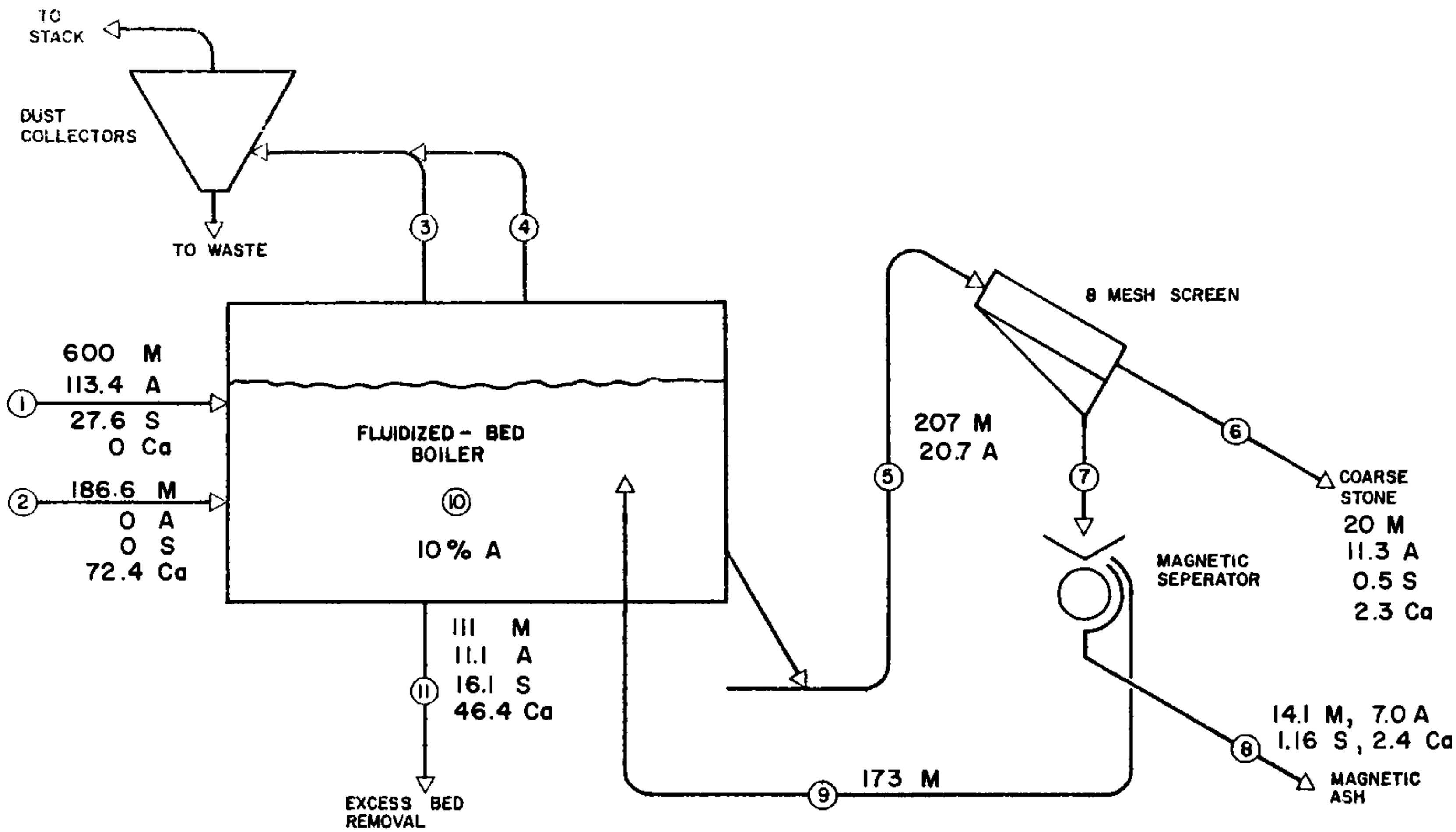
KEY

SK-2150

(1) COAL IN	(5) STREAM FOR CLEANING	(9) CLEAN STREAM
(2) LIMESTONE IN	(6) COARSE STONE OUT	(10) BED
(3) FLYASH & DUST OUT	(7) STREAM TO MAGNET	(11) DISCHARGED BED
(4) FLUE GAS OUT	(8) MAGNETIC FRACTION OUT	

A = ASH, LBS./HR.
Ca = CALCIUM, LBS./HR.
S = SULFUR, LBS./HR.
M = MASS, LBS./HR.

(ASH CONTROL VIA BLOWDOWN AND SCREENING)
FIGURE 3.34 ASH, SULFUR & CALCIUM BALANCE



KEY

(1) COAL IN	(5) STREAM FOR CLEANING	(9) CLEAN STREAM
(2) LIMESTONE IN	(6) COARSE STONE OUT	(10) BED
(3) FLYASH & DUST OUT	(7) STREAM TO MAGNET	(11) DISCHARGED BED
(4) FLUE GAS OUT	(8) MAGNETIC FRACTION OUT	

A = ASH, LBS./HR.　　Ca = CALCIUM, LBS./HR

S = SULFUR, LBS./HR.　　M = MASS, LBS./HR

(ASH CONTROL VIA BLOWDOWN, SCREENING AND MAGNETIC SEPARATION)

FIGURE 3.35 ASH, SULFUR & CALCIUM BALANCE

consistent data from tests run to a steady-state "rock" content. An attempt will be made to remedy this by attempting a balance for the ash constituents such as silica, alumina and hematite (iron oxide). This is especially difficult for the Greer stone which is also rich in these compounds.

Data produced by others (British, Bureau of Mines, Argonne, Esso, etc.) was reviewed to see if there was any indication of ash content increase in a bed consisting mostly of limestone. If this problem has been considered, it was not explicitly discussed.

3.14 Load Following in a Fluidized-bed Boiler

In 1968 experiments showed that the FBM possessed an inherent turndown capability which permitted steam production to be varied while holding constant the bed depth, the bed temperature and the excess air---in apparent violation of the consensus of the literature on fluidized-bed heat transfer. Experiments were conducted in April 1974 to verify earlier finding, in the bed temperature range required for sulfur capture.*

The fluidized-bed gains energy from the fuel burned within the bed and loses energy via three major routes:

(1) Heat transfer to boiler tubes touched by the bed.

(2) Raising the temperature of the gases and solids which pass through the bed.

(3) Radiation to cool surfaces above and below the bed.

When the quantity of fuel fed to the bed is reduced, the quantity of air is proportionally reduced. Therefore if the bed temperature remains constant the energy removed from the bed via hot gas is directly proportional to the fuel input, i.e., turndown is achieved for one half the energy.

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* The 1968 work was done at ∿1800°F bed temperature, much too hot for good sulfur control; 1450°F to 1550° is the design range now.

The components of energy loss which are usually not considered air rate (firing rate) dependent are the radiation and the direct contact loss. These are described by:

$$\text{Radiation Loss} = Q_1 = FA_r\sigma(\varepsilon_b T_b^4 - \alpha_w T_w^4) \qquad (3.10)$$

and

$$\text{Direct Contact Loss} = Q_2 = UA_w(T_b - T_w) \qquad (3.11)$$

where

Q_1 = Radiative heat loss from top of bed, Btu/hr

F = View factor, dimensionless $\equiv$ 1

A_r = Radiating top surface of fluidized-bed, sq.ft.

σ = Stefan-Boltzman constant for a black-body
0.173 x 10^{-8}Btu/sq.ft.,hr, $°R^4$

ε_b = Emmissivity of fluidized-bed, (—)

T_b = Temperature of fluidized-bed

Temperature of gas leaving fluidized-bed, °F

α_w = Absorptivity of boiler tubes, (—)

Q_2 = Heat loss to water walls by direct contact heat transfer; Btu/hr

T_w = Temperature of water in boiler tubes
$\approx$Temperature of tubes surface, °F

U = Overall heat transfer coefficient between bed at T_b and water at T_w, Btu/hr, sq.ft., °F

A_w = Surface area of tubes "touched" by fluidized-bed, sq.ft.

If Equation 3.10 is examined it can be seen that two of the terms could vary with coal and air flow. These are A_r and ε_b. The area, A_r, would vary as it is defined A_r as the area of the top of the turbulent fluidized-bed. As the air flow is decreased the quantity of bed material thrown into the free board is reduced and the "area" of the top of the bed is reduced. The emissivity, ε_b, of this "cloud" of red particles may also decrease with decreasing air flow. Actually measuring the radiation loss from the bed is difficult. It is possible, however, to compute a probable value.

Assume that $\varepsilon_b T_b^4 >> \alpha_w T_w^4$

and $F = 1$

Then

$$Q_1 = A_r \varepsilon_b \sigma T_b^4 \qquad (3.10A)$$

and

$$U_r = \frac{Q_1}{A_r (T_b - T_w)}$$

where

U_r = The effective radiative heat transfer coefficient

$$U_r = \frac{\varepsilon_b T_b^4}{T_b - T_w} = 23 \frac{\text{Btu}}{\text{hr}} \text{ per ft}^2 \text{ of bed area}$$

for $\varepsilon_b = 1$, $T_b = 1500°F$, $T_w = 389°F$

This is a relatively high coefficient and would account for a substantial energy loss from the bed---assuming again that, ε_b, the emissivity is close to unity and A_r, the area of the "top" of the bed is large. In Appendix C it is suggested that the use of a hemi-cylinder describes the top of the hot fluidized-bed. For the FBM, this model yields $A_r \approx 14.35$ ft^2. But it is conceivable that at full load---with a very turbulent bed---that the entire free board is filled with a radiating mass of particles which "reflux".

The water cooled surface within the furnace, including the steam drum and the entire wall tube area, is ∿120 square feet.* If the 80 ft^2 cool area above a two foot deep fluidized-bed (free board) were radiated to at 23 Btu/sq.ft./hr/°F, the bed would lose $\sim 2\times10^6$Btu/hr into the free board. This value, 2×10^6Btu/hr, is equal to the heat loss from the bed due to direct contact heat transfer to the tubes actually within the actively fluidized-bed. A loss on this order is, in fact, necessary to explain the bed temperature actually measured assuming that about 15 percent of the energy release occurs in the free board and not within the fluidized-bed at full load.

It is therefore reasonable to assume that part of the turndown capability of the FBM arises from a reduction of the product $A_r\varepsilon_b$ in Equation 3.10A with declining air flow (hence declining turbulence in the fluidized-bed).

Equation 3.11 describes the bed energy loss via direct contact heat transfer. The factors that may be velocity (firing rate) dependent are:

U, the heat transfer coefficient, and

A_w, the area of wall exposed to the active bed.

The literature of fluidization** suggests that the heat transfer coefficient should not decline with decreasing velocity. This is illustrated in Figure 3.36.

Figure 3.36 does show that h_w (U in our nomenclature) decreases with decreasing superficial velocity v_o (v in our nomenclature). However, the range in which h_w declines with decreasing velocity is too narrow to be useful. Figure 3.37 shows quantitative data that is reasonably close to the velocity, size and temperature conditions that are of interest. The experimental data of Figure 3.37 shows that h_w (or U) should <u>not</u> decrease with decreasing velocity. If U of Equation 3.11 does not decline then the mechanism by which the heat loss from the bed is linear with velocity is a decline

---

* The FBM has 140 ft^2 of water cooled surface when the tubes outside the furnace are included.

** For example Gelperin and Einstein in "Fluidization" edited by Davidson and Harrison, Academic Press.

in the exposed area, A_w. This has been experimentally verified in the FBM via the observation that, at low loads, the thermocouples two inches above the air distributor indicate that the base of the bed is cool. This, of course, means that the bottom of the bed is not fluidized and any heat transfer surface near the bottom is inactive.

A third factor which would permit bed temperature to remain constant despite decreasing fuel input is an increase in the fraction of the fuel which burns in the bed. It is reasonable to expect that as the superficial gas velocity decreases, more of the volatile matter released by the coal would burn within the bed and less would burn in the free board. No useful data has been published which would permit an assessment of this factor. Experimental determination of afterburning would be extremely difficult in the FBM as it requires sampling the gas composition just above the bed surface.

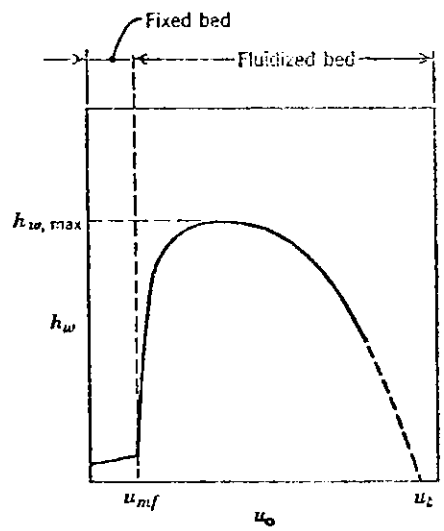

FIGURE 3.36 INFLUENCE OF GAS VELOCITY ON THE BED-WALL HEAT TRANSFER COEFFICIENT IN FLUIDIZED BEDS[1]

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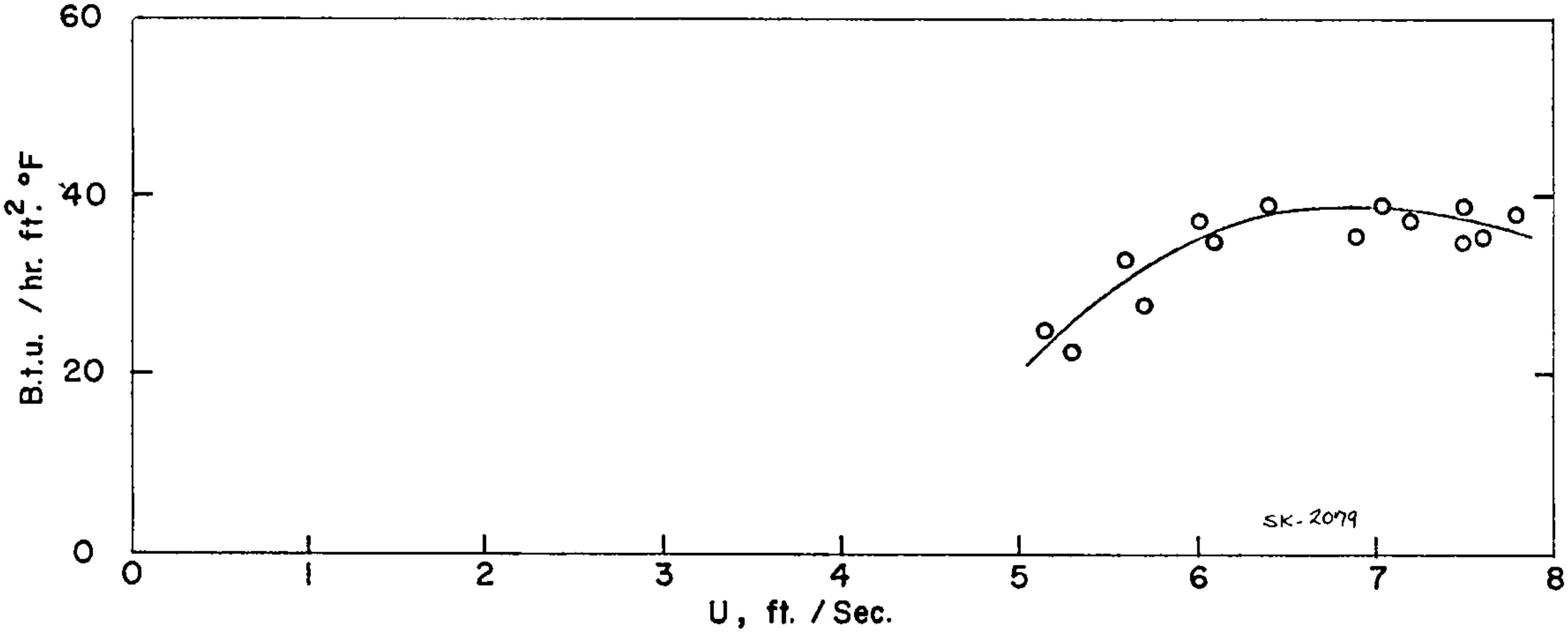
[1] T. Shirai, *Kagaku Kogaku* (Chem. Eng. Japan), 29, 928 (1965)



NOTES:

T_B = 500°C

d_e = 1.66 mm.

FIGURE 3.37 HEAT TRANSFER IN A FLUIDIZED BED

(KHARCHENKO AND MAKHORIN, 1964)

Summarizing, it is postulated that three effects act in the same direction so as to maintain the bed temperature of the fluidized-bed boiler constant with changing load:

(1) A reduction in energy radiated to the free board with decreasing air flow.

(2) A reduction in the area of tubing exposed to an actively fluidized-bed with decreasing air flow.

(3) An increase in the combustion efficiency of the fluidized-bed with decreasing air flow.

Results: Test No. 543A was conducted to determine the effect of a rapid load reduction on performance. Figure 3.38 illustrates the relationship between the valves which were used to regulate load. Referring to Figure 3.38 the normal operation is as follows:

Normal: Valves 4 and 6 are fully closed, valve 5 is fully open, air loading to valve 3 regulates pressure in the steam drum at 200 psig. Total flow rate of steam is indicated by pressure drop across orifice No. 2. Safety valve No.1 is set to open at ~250 psig. Valve 3 moves so as to maintain the pressure constant at 200 psig regardless of fuel input and steam production.

Transient Test: Valve 6 is opened to by-pass about one half the steam flow (the transient will be imposed by quickly closing valve 6). Valve 7 is used to adjust the fraction of steam flowing through the by-pass. Valve 4 is opened to by-pass valve 3 which is still loaded to maintain 200 psig. When the pressure at the drum drops below 200 psig valve 3 is in its fully closed position. Valves 4 and 5 are adjusted to maintain the steam pressure at about 150 psig. 150 psig was chosen as the base line for the transient test so that valve 3 would act as a safety valve, i.e., a pressure build-up would be limited to 50 psig and the drum safety, valve 1, would not open.

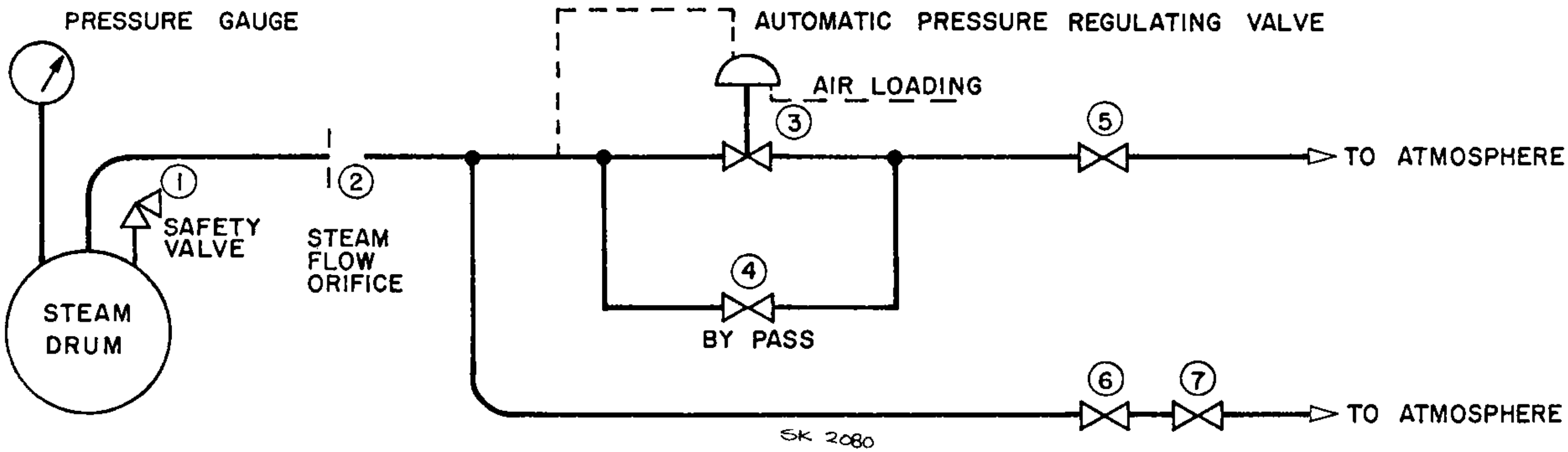


FIGURE 3.38 LOAD REGULATING VALVES

The basic purpose of Test 543A was to determine if the technique described above could impose an adequate transient or whether a new valve arrangement would be needed. Table 3.19 illustrates the results of this first test.

TABLE 3.19

Transient Behavior of FBM for a Sudden Load Change
Test 543A

Column 1 Time From Change in Load, min.	Column 2 Steam Pressure with Coal and Air Flow Unchanged psig	Column 3 Steam Pressure with Coal and Air Flow Reduced psig
0	150	150
½	158	---
1	---	---
1½	---	---
2	168	165
2½	---	---
3	189	---
3½	200	---
4	---	188
4½	---	---
5	---	192
5½	---	---
6	---	---
6½	---	---
7	---	200

After the test data was reduced it was determined that the load drop was to less than one third of the design firing rate. While the average superficial velocity, 3.8 fps, was substantially above the minimum fluidization velocity the front one third of the bed had "turned-off". This can occur when the air distributor has a relatively low pressure drop when compared with the drop through the fluidized-bed. At an air flow rate of 2500 lb/hr at 350°F, the pressure drop across the perforated plate air distributor, in use for Test 543A, would be on the order of 1½". The pressure in the plenum chamber was ∿24". This large pressure drop difference explains readily why one third of the plate can "turn-off". A 4"H_2O minimum pressure drop is recommended through the distributor for a 50 percent turndown capability.

Test 543B was conducted to reproduce the transient of Test 543A and also to probe the exact point at which this perforated plate air distributor was ineffective. Table 3.20 lists the data for the slow (10 to 20 minutes per step) change in coal and air rate. The points in Table 3.20 were not run in the order listed, but were actually run as follows: 630, 505, 450, 420, 360, 330, 600, 630, 720, 660 lbs of coal/hour. The bed depth was increasing as the test continued, and this explains why the two periods at the 630 lb/hr rate (830,000 Btu/hr/sq.ft. of grate area) would yield two different bed temperatures.

Table 3.20 shows quite well that a 2:1 turndown is easily achieved simply through control of air and fuel <u>and</u> that operation near 3 percent excess O_2 is possible over this range, i.e., the boiler efficiency does not deteriorate with decreasing load.

The entire bed temperature difference, ∿80°F, from full load (∿10^6Btu-fed/hr/sq.ft. of grate area) to half load is about equal to the change in the inlet air temperature.

A transient test was then conducted, just as in Test 543A except valve 7 (Figure 3.38) was partly closed. This was done so that when valve 6 was fully opened the fraction of steam by-passed would be lower than in Test No. 543A and the transient would be smaller when valve 6 was closed.

Table 3.21 presents the data for Transient Test 543B. This transient experiment, Test 543B, can be considered successful

TABLE 3.20

Transient Behavior of FBM for Gradual Load Changes

Test 543B

Coal Rate lb/hr	Inert Air Temp., °F	Bed Temperature, °F Center(#4)	Bed Temperature, °F Low(#8)	Furnace Exit Gas, Temp; °F(#15)	Air Rate lb/hr	Excess
720	365	1510	1500	1250	5900	2.7
660	365	1535	1520	1245	5100	2.9
630 -1	335	1535	1510	1200	5000	2.8
630 -2	335	1475	1450	1215	5050	3.4
600	320	1475	1455	1200	4900	3.5
505	320	1580	1460	1155	4000	2.7
450	310	1490	1435	1130	3400	2.9
420	295	1450	1440	1100	3100	3.0
360	290	1450	1420	1075	2900	3.4
330	280	1280	935	1050	2600	3.5

-1, -2 Designate separate periods at a coal rate of 630 lb/hr.

TABLE 3.21

Transient Response of FBM to Sudden Load Change - Test 543B

Time from[1] Change in Load, Minutes	Steam Pressure[2] with Coal and Air Flow Unchanged, psig	Steam Pressure[3] with Coal and Air Flow Reduced, psig
0	150	150
0.5	155	---
1	158	150
1.5	162	150
2.0	---	155
2.5	175	159
3.0	180	160
3.5	186	---
4.0	190	162
4.5	192	164
5.0	195	164
5.5	Valve	---
6.0	3	---
6.5	opened	---
7.0		164
7.5		Steady

1 Change in load imposed by closing valve 6 (Figure 3.38) thus reducing steam flow. In Test 543B flow was reduced from 4100 lb/hr to 3100 lb/hr by closing the valve.

2 Coal flow 660 lb/hr, air flow 5100 lb/hr, bed temperature 1510°F, excess O_2 3 percent. When valve 6 was closed no other changes were made and valve 3 opened.

3 Coal flow of 380 lb/hr was desired but variable speed drive is poor guide to true rpm. Actual coal rate was 420 lb/hr. Bed temperature dropped 60°F.

despite the 14 psig pressure rise. At the end of the experiment the steam flow recorder was observed. After the coal flow was stopped, the FBM continued to produce 3100 lb/hr of ∿150 psig steam for 75 seconds before the pressure began to decay. The bed temperature dropped 400°F in four minutes. As noted previously, it is the fluidized-bed, not the fuel, which generates the steam. The fuel heats the bed.

3.15 Pollution Control Aspects and Uses for By-Products of Fluidized-bed Combustion

Standards set by the U. S. Environmental Protection Agency for new coal-fired boilers set targets for this development work. These are:

(1) Less than 1.2 pounds of SO_2 per 10^6 Btu of heat input.

(2) Less than 0.7 pounds of NO_x, expressed as NO_2, per 10^6 Btu of heat input.

(3) Less than 0.1 pounds of particulate matter emitted per 10^6 Btu of heat input.

Experiments to date indicate that emissions from a fluidized-bed boiler can be maintained below these standards and that values as low as 50 percent to 85 percent of the standard can be achieved at reasonable cost.

There continues to be a number of anomalies in the NO_x and SO_2 aspects of the process which will only be answered by

(1) Commercial operation of relatively large systems for thousands of hours.

(2) Serious study in academic institutions on the nature of fluidized-bed combustion of coal and reactions of sulfur with lime.

3.15.1 Sulfur Oxides

Work done prior to October of 1972 by Pope, Evans and Robbins established the potential of limestone as a suitable bed material in a fluidized boiler for effectively capturing the sulfur while still meeting the normal operating criteria.

A bed operating temperature of 1450°F to 1550°F was found to be optimum for the atmospheric fluidized-bed capture of sulfur through the following overall reaction:

$$CaO+SO_2+\frac{1}{2}O_2 \rightleftarrows CaSO_4$$

A flue gas residual O_2 of 3 to 4 percent was found to be the optimum operating point when balancing sulfur capture and combustion efficiency.

Regeneration in a separate vessel of a partially sulfated bed holding 3 percent sulfur was found to be feasible.* The addition of sodium chloride with the coal and limestone in the FBM was found to have a reactivating effect on a saturated bed allowing further sulfur capture. Both of these developments provided alternate cycle choices depending on specific site parameters and reduced the amount of limestone feed to the boiler needed for any given coal.

The work done since October 1972 has been aimed primarily at process condition optimization for maximum sulfur capture and hardware development and/or optimization. It has been firmly established that using a calcium to sulfur mole ratio of $\sim$2 to determine the limestone feed rate to the process (calcium in the limestone to the sulfur in the coal) results in SO_2 emissions below the EPA limit of 1.20 pounds SO_2 per 10^6 Btu of heat input. Tests were performed in March 1973 in the presence of U.S. Bureau of Mines personnel. The four hour tests (emissions monitored for four hours) were performed with a high sulfur Sewickley seam coal with the following ultimate analysis:

Constituent	Percent by weight
H	4.8
C	67.8
N	1.2
O	5.9
S	4.6
Ash	15.8
Btu/lb	12,340

* The basic regeneration cycle was successful when a bed with a 3 percent sulfur content was passed through the regeneration vessel with a residence time such that it returned to the FBM with a ½ to one percent sulfur content.

The limestone used was analyzed as 95.6 percent $CaCO_3$ (Grove 1359). A sulfur balance was prepared using the following information:

	Wt,lb	% S	lb S
Total Coal Fed	2502	4.6	115.09
Total Limestone Fed	729.8	0.1	0.73
Total Salt Fed	57.5	0.3	0.17
			115.99 lb sulfur in

	Pounds sulfur out	Percent
Bed Material Removed (390 lb)	49.43	45.8
Bed Inventory (1265 lb at ΔS=0.4%)	5.06	4.7
Bed weight increase (94 lb at 12.4%S)	11.66	10.8
Flyash collected (560 lb)	22.96	21.3
Flyash entrained	5.72	5.3
Flue gas	13.11	12.1
	107.94	100.0

The sulfur recovery during this period was 93.1 percent (107.94/115.99)100. The SO_2 emission for the test ranged from 0.8 to 1.0 pound SO_2 per 10^6 Btu heat input at a Ca/S mole ratio of 2. Burning a 4.6 percent sulfur coal in the FBM and feeding limestone at a rate equivalent to Ca/S = 2 resulted in an 88 percent sulfur oxide control.

In January 1974 a truckload of limestone was purchased from the Greer Limestone Company of Greer, West Virginia. The Greer quarry was the closest one to the Rivesville, West Virginia site. The local limestone was therefore tested for all the qualities needed for fluidized bed application. The limestone proved well suited and has been used since January 1974 in almost all FBM testing. Table 3.22 gives an analysis of both the Grove limestone, No. 1359 used previously, and Greer limestone. The Greer stone has the higher silica content and less CaO after ignition yet captured sulfur as well as or better than the 1359. An example of the performance of the Greer stone is shown in Figure 3.39, the mass balances for Test 537 run with Loveridge coal containing 2.5 percent sulfur. At a Ca/S mole ratio of 2.5, the SO_2 emission was 0.61 pounds per 10^6 Btu or one half the EPA limit. Other runs with the Greer stone at lower Ca/S mole ratios have also given excellent results; i.e., Test 530 Ca/S = 1.7, coal sulfur = 4.1 percent, SO_2 = 0.67 pounds per 10^6 Btu and Test 539 Ca/S = 1.2, coal sulfur = 3.0 percent, SO_2 = 0.73 pounds per 10^6 Btu. The Greer stone has shown to be an excellent feedstock for the fluidized-bed boiler not only in terms of sulfur capture and resistance to attrition but also in terms of economics as it is local, available and reasonably inexpensive.

TABLE 3.22

Analysis, Percent by Weight After Ignition

Constituent	Grove Limestone(1359)	Greer Limestone
CaO	97	71.2
MgO	1.2	3.0
Fe_2O_3	0.22	1.3
SiO_2	1.07	16.7
Al_2O_3	0.29	5.8
Others	--	1.8
Loss On Calcination	43.6	37.4

While the SO_2 emission is a direct function of the Ca/S mole ratio used to determine the limestone feed rate, the feedrate can also be effected by bed material attrition, especially when burning lower sulfur coals where the Ca/S mole ratio might exceed 2 (Test 537) as the maintenance of a constant bed

MASS BALANCE FOR TEST 537

INPUTS, LBS.	TOTAL	ASH	CARBON	SULFUR	OXYGEN	HYDROGEN	NITROGEN	CALCIUM
COAL (DRY)	1840.2	180.7	1390.1	48.4	89.6	95.6	21.2	14.2
LIMESTONE (DRY)	467.9	77.3	49.0	1.3	190.6	--	--	149.7
SALT (DRY)	33.5	--	--	.1	--	--	--	--
MAIN AIR (DRY)	19896.7	--	--	--	4616.0	5.4	15022.1	--
CONVEYING AIR (DRY)	1361.3	--	--	--	315.8	.4	1027.8	--
MOISTURE (IN COAL, L.S., AND AIR)	73.9	--	--	--	65.7	8.2	--	--
TOTAL INPUT, LBS.	23673.5	258.0	1439.1	49.8	5277.7	109.6	16071.1	163.9

OUTPUTS, LBS.	TOTAL	ASH	CARBON	SULFUR	OXYGEN	HYDROGEN	NITROGEN	CALCIUM
DUSTS								
FLYASH —								
COLLECTED	396.2		98.7	20.8	41.6	2.4	--	80.8
EMITTED	45.7		2.2	3.2	6.4	.3	--	7.4
COARSE SOLIDS								
BED MATERIAL—								
BLOWDOWN	176.5		2.6	16.1	31.5	.4	--	44.9
CHG. IN ANALYSIS		*	(1.2)	(1.2)	21.8	.4	--	31.1
CHG. IN MASS	21.5		--	--	--	--	--	--
GASES								
CO_2	5260.8		1434.8	--	3826.0	--	--	--
CO	107.3		46.0	--	61.3	--	--	--
SO_2	15.2		--	7.6	7.6	--	--	--
SO_3	--		--	--	--	--	--	--
NO	6.2		--	--	3.3	--	2.9	--
N_2	17305.4		--	--	--	--	17305.4	--
O_2	735.8		--	--	735.8	--	--	--
HxCy (CH_4)	17.9		13.4	--	--	4.5	--	--
HCl	4.2		--	--	--	.1	--	--
H_2O	1085.7		--	--	965.1	120.6	--	--
TOTAL OUTPUT, LBS.	25178.4		1596.5	46.5	5700.4	128.7	17308.3	164.2

	TOTAL	ASH	CARBON	SULFUR	OXYGEN	HYDROGEN	NITROGEN	CALCIUM
% RECOVERY	106.4		110.9	93.4	108.0	117.4	107.7	100.2

FIGURE 3.39

depth (hence temperature) is essential at any given boiler load (hence coal feed rate). The effect on the SO_2 emission in that case would be one of having a lower SO_2 emission than necessary, just to meet the EPA limit requirements. Essentially there is a minimum feed rate for limestone, independent of coal sulfur, which is adjusted (raised) when dictated by the Ca/S mole ratio.

The meeting of the EPA limit of 1.2 lb/SO_2 per 10^6 Btu heat input presents no problems for the atmospheric fluidized-bed boiler using a limestone bed for any of the coals tested.

3.15.2 Oxides of Nitrogen

All indications from the extensive work done prior to October 1972 were that the fluidized-bed combustion of coal produced relatively low NO_x emissions even though the coal generally contained a significant amount of chemically bound nitrogen.

Work performed since October 1972 has proven that the limit of 0.7 pounds NO_2 per 10^6 Btu heat input presents no compliance problem for the atmospheric fluidized-bed boiler. The fluidized-bed boiler possesses the natural characteristics of producing minimum NO_x emissions at optimum operating conditions for both sulfur capture and thermal efficiency.

In any boiler, the combustion process results in the formation of oxides of nitrogen. Two species, NO and NO_2, dominate, and together they are normally referred to as NO_x. The major oxide produced is nitric oxide, NO. It is formed from both the combination of the nitrogen and oxygen contained in the combustion air (thermal fixation) at the elevated temperatures and from the oxidation of nitrogen chemically bound in the fuel. The primary factors determining the amount formed are (1) the combustion temperature, (2) the amount of excess air supplied to the combustion zone, (3) the residence time at the combustion temperature (4) the amount and percent conversion of the fuel nitrogen and (5) for conventional boilers the size of the unit. The NO formed can react with any O_2 remaining to form NO_2, however, the amount formed is small. Generally, well below 10 percent of the NO formed is converted to NO_2 as the residence time and temperature severely limit the reaction. Once emitted from the stack to the relatively low temperature atmosphere, the

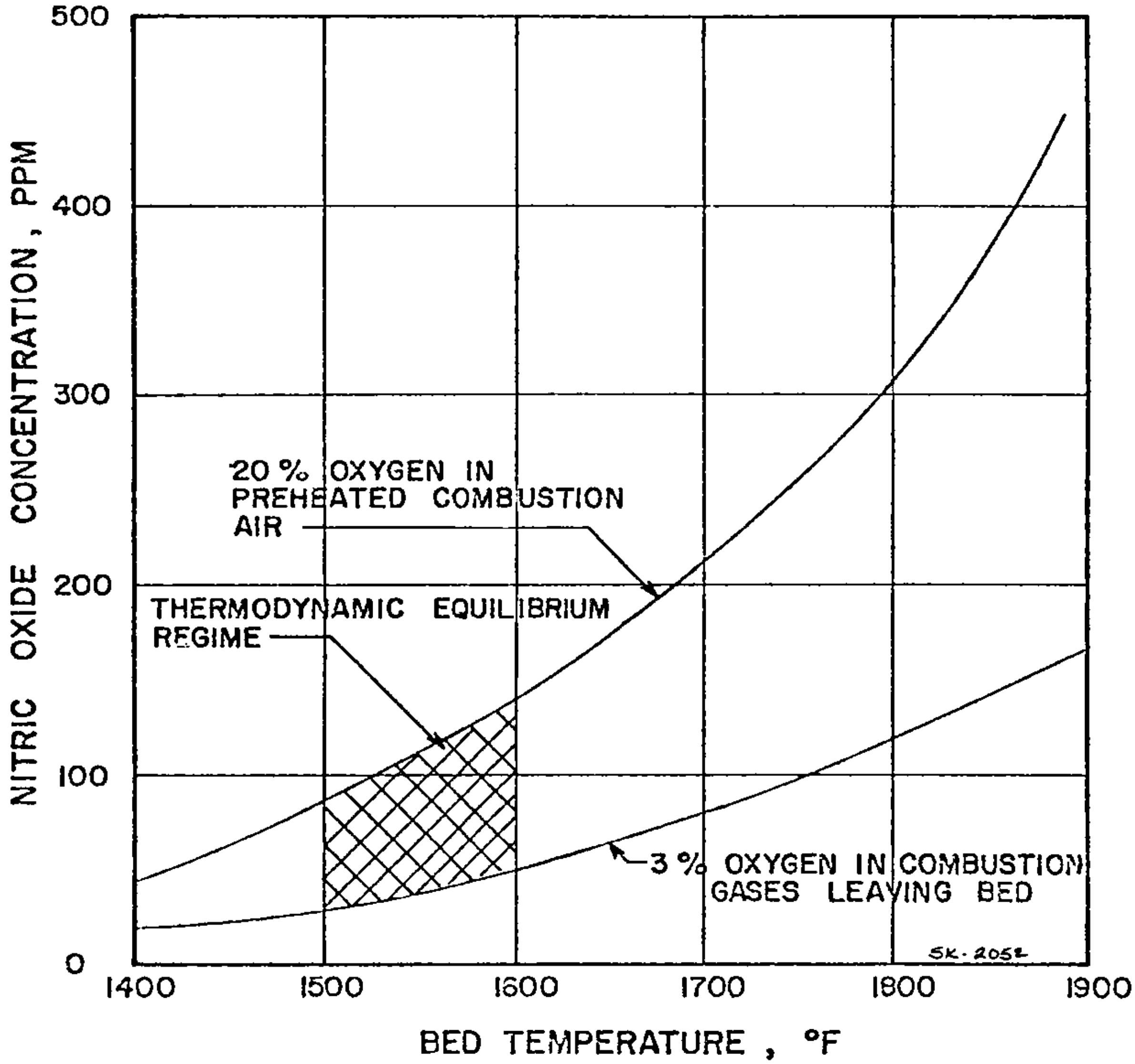
NO is slowly oxidized to NO_2 by the oxygen of the air or the reaction accelerated by the photochemical reactive hydrocarbons in the presence of sunlight.

The normal operating conditions of 1500°F combustion temperature and 3 percent flue gas O_2 level are important factors in enabling the fluidized-bed boiler to achieve low NO_x emissions. In a fluidized-bed boiler burning coal, the fuel nitrogen plays the major role in the total NO_x emission. As fluidized-bed combustion takes place at 1500°F to 1600°F for optimum sulfur capture, the thermal NO_x (formed by thermal fixation of nitrogen in the combustion air) tends to be very low as depicted by the range of the shaded area of Figure 3.40.

Tests performed in 1973 and early 1974 in the FBM specifically investigated the NO_x production based on specific combustion temperatures and fuel nitrogen. The tests were performed at 1500, 1650 and 1800°F bed temperatures. At each temperature two types of coal were used having the following ultimate analyses on a moisture and ash free basis:

	Coal No. 1 Ultimate Analysis (MAF) percent by wt.	Coal No. 2 Ultimate Analysis (MAF) percent by wt.
Carbon	81.08	82.33
Hydrogen	5.62	5.58
Nitrogen	1.48	2.02
Chlorine	0.14	0.14
Sulfur	5.76	1.54
Oxygen (by diff)	5.92	8.39

The results of the tests are plotted on Figure 3.41. It can be seen that the measured NO_x values are well in excess of the equilibrium values for thermal NO_x shown in Figure 3.40. However, they are substantially below the EPA limit in the 1500°to 1800°F temperature range. The thermal NO_x component can be assumed to be low as depicted on Figure 3.40.



SHADED AREA REPRESENTS THE NORMAL OPERATING TEMPERATURE RANGE FOR FLUIDIZED BED BOILERS.

FIGURE 3.40 THERMAL FIXATION OF NITROGEN FROM COMBUSTION AIR

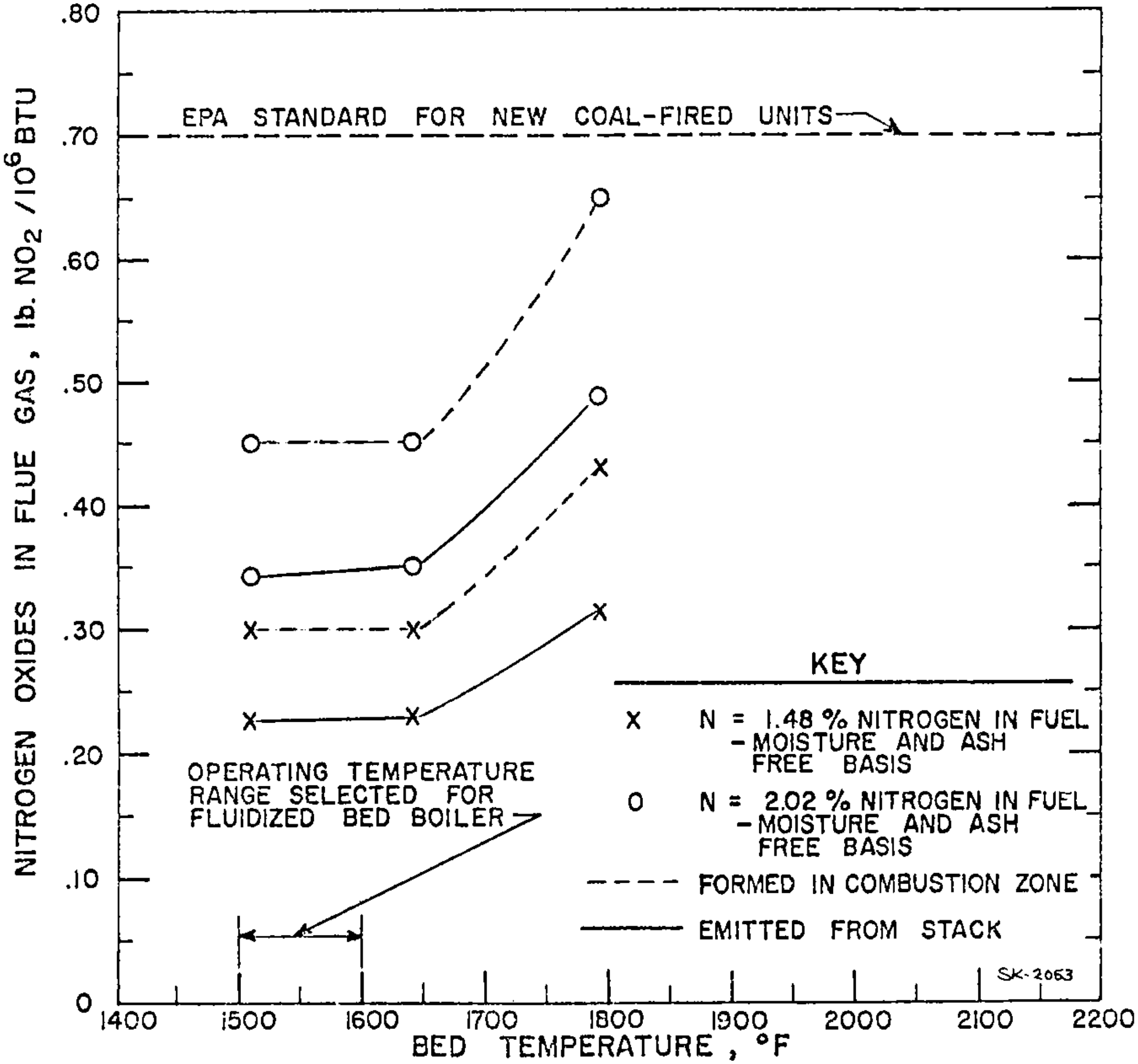


FIGURE 3.41 NO_X IN FLUE GAS

The fuel NO_x component therefore results from a fuel nitrogen conversion to NO of from 7.25 percent at 1500°F to 7.17 percent at 1800°F for these tests. Other tests have shown up to 10 percent conversion. The conversion of fuel nitrogen to NO_x does not appear to be affected by the combustion temperature difference, 1500°F to 1800°F, as tested in fluidized-bed combustion.

The NO_x emitted is less than the amount initially formed during combustion. It has been shown that once combustion gases leave the top of the furnace they are still subject to oxidation and/or interaction. For example, in the FBM, NO_x emission values drop between the top of the combustion zone and the stack to a far greater degree than can be accounted for by dilution via air in-leakage caused by the slightly negative pressure of the system at that point. An explanation of of the NO_x reduction is related to the following reaction:

$$2CO + 2NO \rightarrow 2CO_2 + N_2 \qquad (3.13)$$

A decrease in CO and NO concentration has been observed with on line gas analyzers.

Although NO is thermodynamically unstable at lower temperatures, it decomposes at such a slow rate that cooling, from the top of the furnace at 1500°F to stack exit at ∿600°F through economizers, air heaters, and cyclones, would not be expected to change the NO_x concentration by any appreciable amount through the following reaction:

$$2NO \rightarrow N_2 + O_2 \qquad (3.14)$$

Actual reductions (from combustion zone to stack) of NO_x concentration of 35 percent to 45 percent have been observed with known air in-leadage dilution effects of ∿15 percent.

When using a limestone bed for sulfur control, the sulfur capture efficiency is strongly temperature dependent. The optimum bed temperature for sulfur capture is near 1500°F. Sulfur capture efficiency falls off rapidly over 1650°F. Figure 3.41 shows that NO_x production does not increase significantly when the bed temperature is raised from 1500°F to 1650°F. Interdependencies exist between SO_2 production, SO_2 capture, NO_x production and other competing intermediate reactions. These interdependencies dampen the temperature effect on NO_x production between 1500°and 1650°F giving great stability in terms of operational transients (sudden load changes) which are commercial realities. It was found that the ratio of NO_x emissions for runs with high fuel nitrogen coal to the low fuel nitrogen coal was slightly less than the ratios of fuel nitrogens for the two coals. These results confirmed that the fuel nitrogen contributes heavily to the total NO_x emitted from fluidized-bed combustion. The key point is that the EPA limit for NO_x emissions was easily met at the optimum sulfur capture and combustion efficiency conditions for all coals. The NO_x control is simply a function of good management of the normal process variable controls.

3.15.3 Gaseous Chlorides

The addition of sodium chloride along with coal and limestone was found to enable greater utilization of the bed material in the sulfur capture mechanism in work performed prior to October 1972. Some concern arose over the conversion of the NaCl to HCl in the combustion process in addition to the HCl normally produced from the chlorine chemically bound in the coal.

The results of tests performed after October 1972 suggest that very little of the salt fed actually is used in the process and that at 1500°F about one pound of NaCl per hour per square foot of bed surface was evaporated and carried off with the flue gas. Examinations of the convection bank (horizontal tube surface above the bed) revealed no significant accumulation after $\sim$4 years of intermittent operation with NaCl addition.

Results of the tests also suggest that the conversion rate of NaCl to HCl is also very low amounting to $\sim$ one third of the total HCl emission.

Three runs were made in December 1973 with petroleum coke for the purposes of (1) determining the suitability as a fluidized-bed boiler fuel and (2) making chlorine balances and accounting for NaCl added to the process as the fuel contained no chlorine. Data for Test No. 518 is given in Table 3.23. The fuel feed rate was set for 525 lb/hr with 185 lb/hr limestone feed and 12 lb/hr salt feed to accommodate the 5.2 percent sulfur content of the fuel and the well used bed. Table 3.24 gives a chlorine mass balance for Test 518 for 2 hours. The accountability of the chlorine was excellent, confirming earlier preliminary findings which suggested that the majority of the chlorine was in the fine particulate dust getting by the cyclone. The dust was sampled isokinetically with a heated probe isokinetic particulate sampling rig and the majority of the chlorine was picked up on the filter.

TABLE 3.23

OPERATING CONDITIONS - TEST NO. 518

Ingredient Feed Rates	
Coke	522 lb/hr
Limestone	184.5 lb/hr
Ca/S Mole ratio	2.16
NaCl	12.3 lb/hr
Flue Gas Composition, Vol. % (Dry)	
Avg O_2	3.0 percent
CO_2	15.8 percent
SO_2	400 ppm
NO	200 ppm
Process Conditions and Results	
Avg. Bed Temperature	1500°F
Static Bed Depth	18 inches
Avg. Fly Ash Carbon	69.6 percent
Avg. Fly Ash Sulfur	4.2 percent

The HCl in the flue gas was determined by passing the hot filtered flue gas through a sampling train of water filled impingers. A dry test meter was used to determine sample rate and a stack line venturi used to establish the flue gas stack line velocity and flow rate.

The major conclusion of three petroleum coke tests was that little of the NaCl undergoes a conversion yielding HCl, hence the salt process is both environmentally and operationally sound.

TABLE 3.24

Chlorine Mass Balance For Test 518
(2 Hour Test)

	Input (lbs.)	Cl (lbs.)
Coke	1044	0
Limestone	369	0
Salt	24.6	14.93
Air (wet)	10650	0
Total Input	12088	14.93
	Output (lbs.)	**Cl (lbs.)**
Flue Gas	11200.0	.54
Fly Ash	305.6	2.29
Dust	43.65	8.68
Bed*	--	3.00
Bed**	113	.26
Bed***	22	--
Total Output	11684	14.77
Percent Recovery	96.7	98.9

* Change in Analysis
** Blowdown
*** Change in Mass

3.15.4 Control of Particulates

The FBM was equipped with a low (~½"H_2O) pressure drop cyclone dust collector. All testing done in the FBM suggests that the flue gas dust loading from a fluidized-bed boiler will be certainly no more difficult and probably easier to control than that of a large conventional boiler.

The feed stocks to the process have a large top size; thus the particulates leaving the combustion zone would reflect the size distribution of the feed stock.

3.15.4.1 Mechanical Dust Collection

In a number of tests it has been determined that about 85 percent (by weight) of the fly ash produced in the FBM is removed from the gas stream in either the air preheater or the multicone mechanical dust collector as shown in Figure 3.42. Figure 3.43 shows size distribution data typical of the FBM fly ash.

The efficiency would be expected to improve at the higher pressure drops typical of commercial dust collectors. For example, at $\Delta P = 3''H_2O$ a collection efficiency of ≈ 90 would be expected. The remaining particulate would be collected by an electrostatic precipitator.

Two aspects of mechanical dust collection from a fluidized-bed boiler are unusual.

(1) The mass of material carried over.

(2) The size distribution of this material.

There is a very substantial increase in loading to the collector. It is also clear that hopper sizing and unloading apparatus must anticipate the high throughput.

The dust would burn in the hoppers if they were not kept emptied. With these special problems in mind effective mechanical collectors can be selected to remove 90 to 95 percent of the dust leaving the fluidized-bed boiler. The remaining dust would be collected in the precipitator.

3.15.4.2 Electrostatic Precipitation

Tests were conducted in October 1973 with the cooperation of Cottrell Environmental Sciences to determine the precipitation properties of the dust produced by the FBM operating

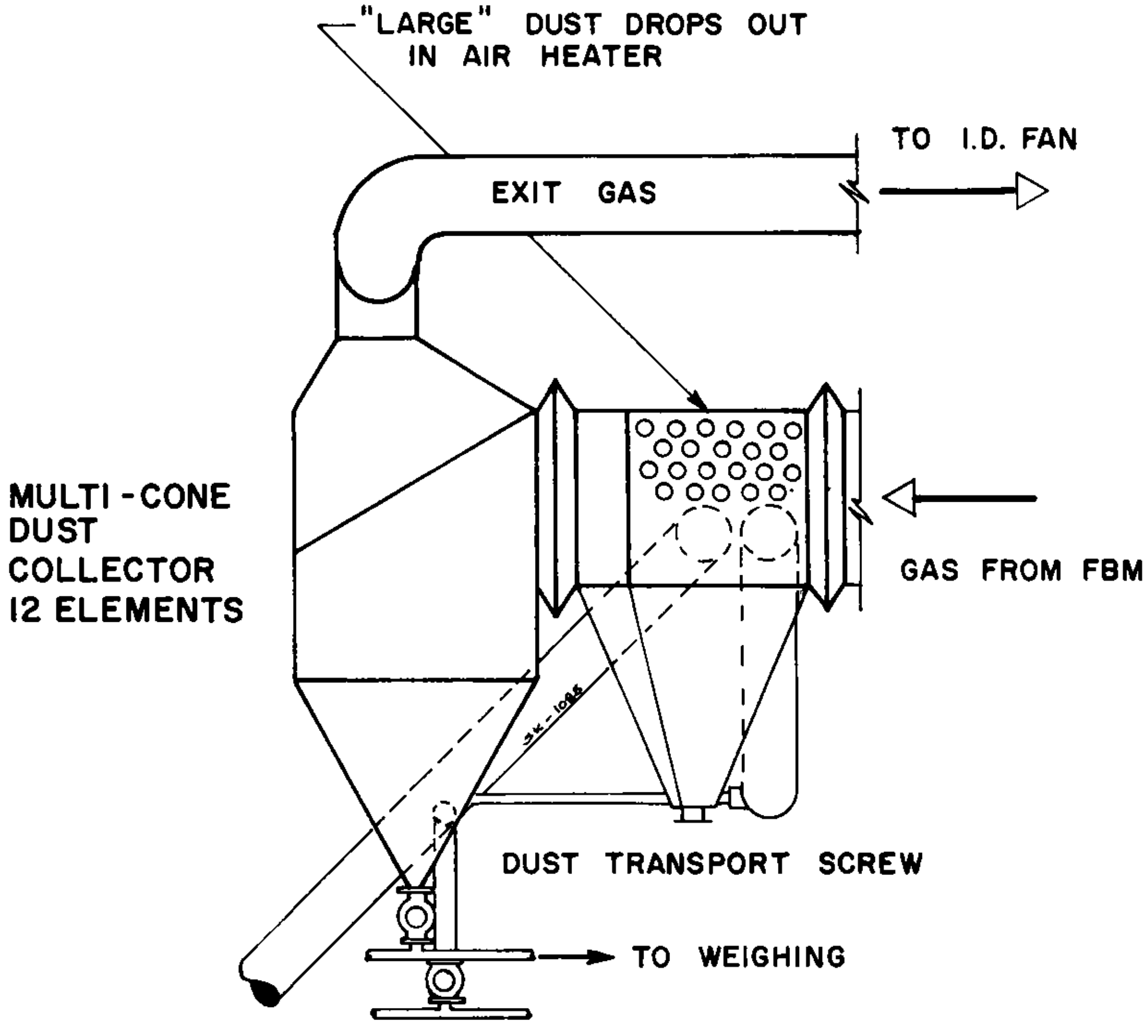


FIGURE 3.42 DUST COLLECTION SYSTEM

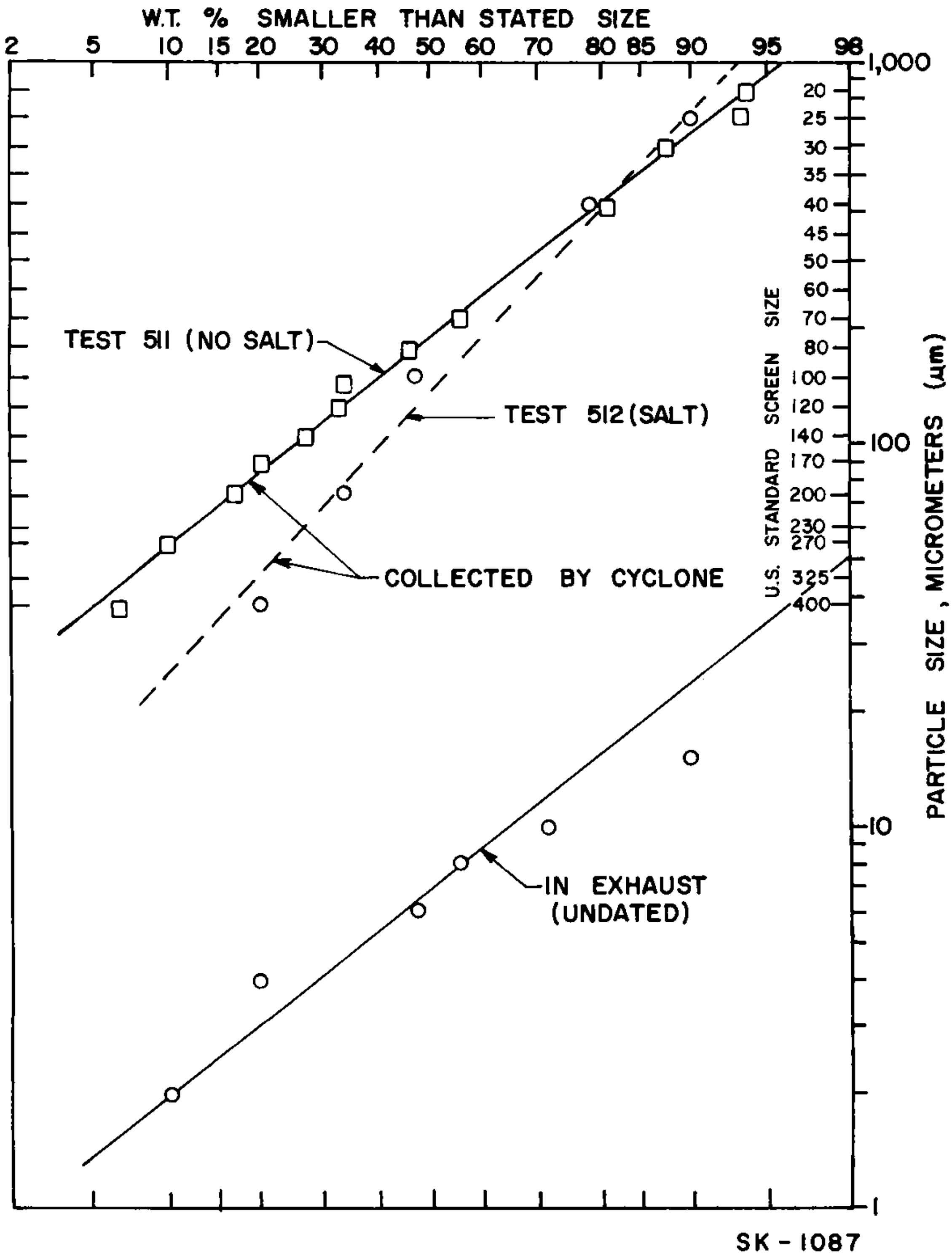


FIGURE 3.43 FLYASH SIZE DISTRIBUTION

as listed in Table 3.25 below.

TABLE 3.25

Test Conditions for *In Situ* and Laboratory Resistivity Tests of the FBM Flyash*

Test No.	1	2	511	512
Nominal bed temperature°F	1500	1500	1500	1500
Gas flow, lb/hr	N/A	N/A	6000	6000
Gas temperature at sampling point, °F	N/A	N/A	550	650
Salt added	No	Yes	No	Yes
Sample loss on ignition	N/A	N/A	31.2	21.5

* The duct shown in Figure 3.42 had an internal diameter of 16 inches. The bed was 1359 limestone; the coal Sewickley seam. Prior to the in situ tests Cottrell Environmental Sciences had tested two dust samples as collected from the induced draft fan blades.

N/A = Not applicable or not avaiable.

Figure 3.44 presents the data provided by Cottrell Environmental Sciences and additional data on analogous processes. Figure 3.44 reveals the following:

(1) There are significant (two order of magnitude) differences between the *in situ* and laboratory resistivity data obtained with FBM dust. Generally the in situ results are considered the more valid.

(2) A hot precipitator (∿600°F gas) would be effective for the salt-free dust of Test 511 (the points marked "Δ" Figure 3.44). However, for the dust of

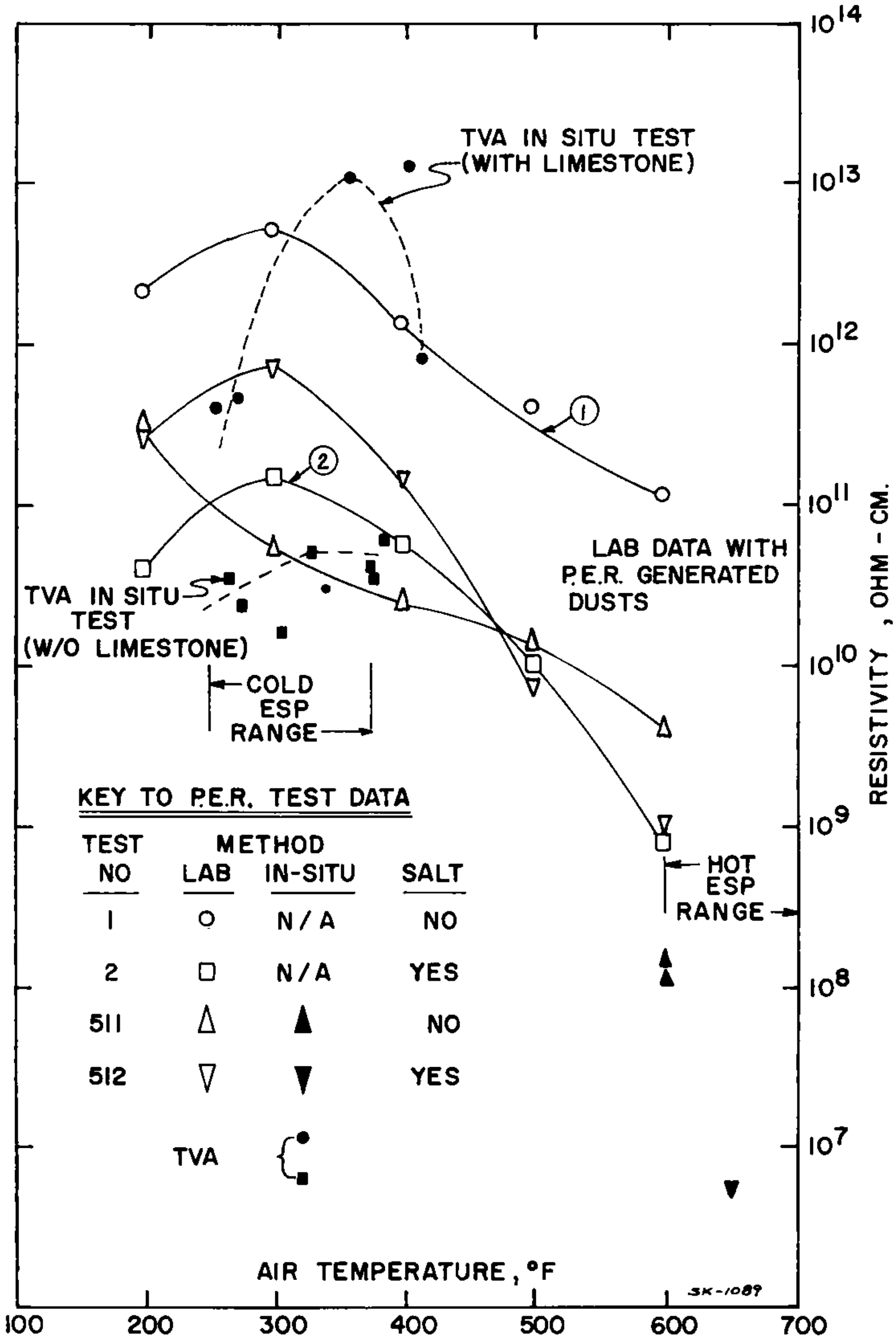


FIGURE 3.44 RESISTIVITY DATA

Test 512 where salt was added the *in situ* resistivity is less than 10^7 ohm-cm at 650°F and this 10^7 ohm-cm value is the generally accepted lower limit for good performance.

(3) If the "cool" laboratory results are valid, a cold precipitator (∿250°F) would not be effective since $2x10^{10}$ ohm-cm is the generally accepted upper limit for good collection, but

(4) If the curves that might be constructed, using the in situ points, were roughly parallel to the lab data for the same dust, a cold precipitator would be effective.

Since plant arrangement designs were to be finished before more difinitive test data could be obtained, a precipitator temperature had to be selected. A hot unit was selected for the following reasons:

(1) A cold unit actually would have been more expensive at Rivesville (based on equal gas velocity designs). This follows from the selection of a high pressure fan and a Ljungstrom type air heater ---leakage increases the gas volume past the air heater to a greater extent than cooling can compress the flue gas.

(2) There is little evidence that the hot unit will not work; there has been considerable debate as to whether a cold unit will have the desired efficiency.

(3) The use of a regenerative air heater before the precipitator inevitably leads to deposits. These deposits break off and enter the combustion air stream.

There had been some concern as to the potential for blocking the air distributor. With the precipitator ahead of air heater the deposits will be very light.

(4) The question as to deposits and ability to collect at cold conditions can be answered at Rivesville by turning off the hot precipitator for an appropriate period of time. *In situ* resistivity tests there will be substantially more reliable than any that could be run at Alexandria.

3.16 Uses for By-Products of Fluidized-Bed Boilers

Coal and limestone are fed to a fluidized-bed combustion chamber and produce heat, sulfur free gases, fine powders and coarse granular solids.

A substantial and ongoing effort is being made to find ecologically sound methods of disposing of the sludge of the lime/limestone wet scrubbing processes.[2] The problem of sludge disposal is cited often, by potential users, as a reason to delay installation of wet scrubbers. As the time for startup of the prototype unit is approaching an effort to find uses for the fluid bed by-products has been started in order to avoid resistance to the application of fluidized-bed boilers on the grounds that the "ash" cannot be disposed of.

There is little similarity between scrubber sludge and fluid bed blowdown. The initial effort is toward finding outlets for the bed blowdown which is expected to average 5000 pounds per hour. This material is easily divisible into three fractions, each with a different potential application.

The coarse stone removed from the bed is a relatively lime-free "rock". It is the calcined mineral-matter of the coal which was large enough and tough enough to remain whole in the bed and pass over the 8 mesh screen. Samples of this material have been submitted to the University of West Virginia and IU Conversion Systems for their analysis and evaluation.

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[2] Jones, J. W. and Stearns, R. D. "Waste Products from Throwaway Flue Gas Cleaning Processes-Ecologically Sound Treatment and Disposal", EPA's Flue Gas Desulfurization Symposium, New Orleans, La., May 14-17, 1973.

It is believed that about one-half of this material (the non-magnetic fraction of the coarse product) could be sold as a closely sized aggregate, -¼"+8 mesh, since the non or weakly-magnetic particles have good compressive strength. The University of West Virginia was asked to evaluate this use.

It is probable that the quantities of iron and aggregate which can be recovered at the prototype unit may be too small to justify the separate handling the storage of, at most, 10 tons per day. In this case the coarse stone may be dumped into the plants ash silo for eventual transport to the ash dump.

The -8 mesh fraction of the bed blowdown is a mixture of the smaller particles of calcined coal mineral matter (ash) and the lime/anhydrite. A sample of this product was beneficiated by Exolon, a manufacturer of magnetic separators. The non-magnetic fraction, 84 percent of the total, has most of the calcium and very little iron as shown in Table 3.26.

The magnetic fraction of the -8 mesh bed blowdown (the small stones or ash particles) might be beneficated for recovery of iron values (at very large boiler sites) disposed to a landfill or sold as a closely sized aggregate, -8+20 mesh .

The bulk of the bed blowdown is the by-product we've named lime/anhydrite and it is the most important to find uses for. The following applications have been or are still being considered:

(1) The Christopher Coal Company has evaluated a sample for use in several nearby acid mine drainage control projects.

(2) National Gypsum evaluated a sample for use in wall board manufacture.

(3) At the suggestion of the National Limestone Institute, we contacted the Departments of Agriculture of several states. The product might be applied to soil as ground limestone. The trace elements added by the coal ash might also be useful.

TABLE 3.26

Coal Ash Contamination*
of Benificated Lime/Anhydrite

	Raw Limestone #1359		Lime/Anhydrite
Ca	38.8	percent	39.0
Mg	0.51	"	0.43
Fe	0.101	"	0.42
Al	0.15	"	0.42
Si	0.23	"	1.14
Na	0.027	"	0.20
K	0.08	"	0.34
Ti	0.012	"	0.0380
Zn	4	ppm	35
Cu	10	"	35
Ni	36	"	195
Co	28	"	90
Pb	43	"	180
As	70	"	--
P	1.6	"	1.6

* Sewickley coal ash 9.5 percent Al. On this basis the Lime/Anhydrite contains approximately 3 percent coal ash.

(4) Unlike the No. 1359 limestone, the used Greer stone does not rapidly air flake or react strongly when mixed with water, in fact, there is no detectable reaction at all.* The Greer stone was leached as described in Appendix D. It appears on the basis of this limited evaluation that the lime/anhydrite could be mixed with the rest of the plant's ash for disposal to the ash dump.

(5) Although not a likely use for the prototype unit the lime/anhydrite could be fed to wet scrubbers serving conventional boilers in lieu of higher priced lime or less reactive raw limestone.

(6) A ton of unbeneficated spent bed was used in place of gypsum on an experimental plot of peanuts at the Suffolk, Virginia Agricultural Experiment Station. In June 1974 the crop was healthy. Definitive results await the harvest.

When the regenerator is used, a product, called lime, can be produced. The sulfur content of this product could range from 0 to 1¼ percent with a lower value of 0.5 percent S most likely. These estimates of sulfur content are based on on experience operating a continuous regenerator in 1971. Insufficient data was obtained to permit a selection of the optimum level of sulfur rejection in the regenerator. It is clear however, that if the value of a low sulfur lime is $20.00 to $30.00 per ton the process should be run so as to maximize limestone throughput and saleable lime production.

If SOCTAP[3] predictions for stack gas scrubbing systems were met, a market of 21,000,000 tons per year of CaO could exist in 1980. This compares with the 22,000,000 ton, as $CaCO_3$,

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* It reacts violently with a strong acid.

3 Sulfur Oxide Control Technicology Assesment Panel [SOCTAP], "Final Report on Projected Utilization of Stack Gas Cleaning Systems by Steam Electric Plants", submitted to the Federal Interagency Committee, Evaluation of State Air Implementation Plans, April 15, 1973.

national ag lime[4] market. Since a 300 MWE fluidized-bed boiler would produce about 25,000 TPY of blowdown lime, the wet scrubber market (applied to pulverized coal boilers) could be satisfied by 800! 300 MWE fluid bed boilers operating with a regenerative cycle.

3.17 Limestone Loss from the Fluidized Bed

An examination of Table 3.14 shows that particles under about 20 mesh (USS) do not remain in the bed. Table 3.13 gives a typical limestone size distribution and indicates that only 5 percent of the feed stone* is -20 mesh. Using just these two facts, a first hypothesis would be that 95 percent of the calcium feed (as $CaCO_3$) would be retained in the bed and would be drained with the bottom ash. However, an examination of the material balances for a number of experiments indicates that from 30 to over 50 percent of the calcium is carried out of the bed.

This loss is not the effect of mechanical wear of the particles. Data reported from the Foster Wheeler cold model studies shows trivial loss rates of uncalcined limestone. Cold tests in the FBM showed very little loss of used bed material.**

The rate at which limestone leaves the system is an important design consideration. However, the factors which cause a limestone particle to lose its structural integrity are still unknown. Experiences in the FBM experimental program and some tentative hypothesis are offered here. In those cases where a catastrophic loss of bed material was suffered, a technique was found for overcoming the loss.

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4 National Limestone Institute, Inc., "A Handbook for the Ag Lime Salesman", Revised Edition, 1973.

* The limestone is generally a double screened product when delivered from the quarry.

** If a bed of partially sulfated limestone is fluidized with humid air for an extended period the particles will hydrate and turn to powder.

3.17.1 Loss of Dolomite 1337

Tests in the FBM showed that the dolomitic limestone No. 1337 by EPA was unsuitable for making a bed. In one experiment about 300 pounds of -3/4" stone was added through the site port over a 20 minute period to an ash bed. On examination it was found that the quantity of dolomite remaining in the bed was very low. A few large particles were found resting on the grate compared with the thick layer expected.

It was concluded from this experience that dolomite, at least dolomite No. 1337, was unsuitable for use as a bed material in a fluidized-bed boiler operating at high velocities.

3.17.2 Loss of Limestone 1359 When Firing Rich Mountain Coal.

Tests 505 through 510 were attempts at using a low-sulfur, high nitrogen coal with bed temperatures of 1500°F and 1800°F. The dust loading increased significantly with the use of this coal and plugging problems in the sample system increased. Control of bed level became a problem suggesting either a sulfur content effect on limestone bed-particle durability or suggesting a boiler tube leak which could give a like effect of high dust loading from limestone particle breakdown.

As no obvious water leak was apparent inside the boiler spaces, the immediate conclusion was that an alternate coal with high sulfur as well as high nitrogen should be utilized for comparative purposes in a limestone bed. A search for such a coal was undertaken. No such coal was located. Attention turned to the cause of the limestone loss and the decision was made to burn the low-sulfur coal in a bed of crushed refractory.

All previous attempts made to burn this low-sulfur, high-nitrogen coal under conditions identical to those for the high-sulfur normal-nitrogen coal confirmed that it was impossible. A limestone bed, using the same stone* used for the past five years, could not be produced despite feed rates in excess of 250 pounds per hour,** when starting with a fresh limestone bed.

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* The limestone is supplied by Grove Lime Company and has been designated as No. 1359 by EPA.

** This is about four times the value normally needed to maintain a bed level with no drainage.

The events occuring just prior to and during the initial Rich Mountain coal tests were reviewed to pursue the loss problem.

Because test 504 had been run with the high sulfur coal, it was decided to use a fresh bed of raw limestone. It had been normal experience that a bed made up entirely of raw stone was more difficult to ignite than a used bed. When the raw stone was heated and coal combustion was begun there was substantial loss of mass. When the calcining period was completed there was a rapid bed temperature increase (10°F/min) since the energy required to drive off the CO_2 was now available to increase the bed temperature. For the coal used in tests 505 and 509 the bed temperature continued to rise indicating that bed depth was dropping despite the fact that the limestone feeder was full open (400 lb/hr). No data could be obtained until the system was stabilized so the decision was made to reduce coal and air (and thereby reduce velocity) so as to retain more of the limestone. A stable system was achieved at 450 pounds of coal/hour with 150 pounds of limestone per hour. For this coal:limestone ratio, the molar calcium-to-sulfur ratio was 15.

This compared with the Sewickley coal test where a 50 pound per hour limestone rate (at 600-620 lb/hr coal rate) would have maintained a constant bed depth. The situation with the high-nitrogen coal was a new one. In all previous tests with limestone beds such a massive loss of limestone had never been experienced.

At this point an accidental wetting of the bed unexpectedly destroyed it. Since very little of the high nitrogen coal remained, a new bed was built, using the high sulfur Rivesville coal. The purpose of this effort was to calcine and partially sulfate a bed of lime so that the now scarce high nitrogen coal would not be wasted in bed preparation. While this bed building effort was not a careful experiment it was possible to build a relatively deep bed. The evidence therefore pointed to a difference between the two coals as the primary reason that the Sewickley coal could be burned in a limestone bed while the high nitrogen coal could not. It was hypothesized that the difference in sulfur content between the two coals was the significant factor.

A fresh, uncalcined limestone particle enters the furnace at ambient conditions. It is rapidly heated to the point where CO_2 evolution begins. At this point in time some CaO exists---presumably near the surface of the relatively large particle. The environment for the particle in the midst of the burning bed contains sulfur species, carbon species, hydrogen and hydroxyl ions. A variety of chemical reactions occur within the pores of the lime, some of which lead to the production of $Ca(OH)_2$. If enough of this is formed the lime structure breaks down and the stone turns to dust. If the bed is heavily sulfated the new stone is also exposed to a rich SO_2 environment as sulfur is exchanged between particles.*

If the newly forming CaO sites are quickly sulfated the decrepitation due to hydration is avoided.

This hypothesis was supported by experiments conducted at Bureau of Mines in Morgantown, West Virginia. They analyzed bed samples by an infrared technique and identified $Ca(OH)_2$. At the time this work was first reported the results appeared doubtful since $Ca(OH)_2$ decomposes at 580°C. It was assumed that sampling errors had occurred and that the samples had been exposed to air and had picked up moisture. Discussions with Bureau of Mines personnel left the results in doubt. It was agreed to submit samples which were cooled from red heat in a water vapor free atmosphere.

A second hypothesis by which the particles could be hydrated involves exposure to "cool" air near the air distributor and in collisions with water cooled surfaces. *

In reviewing the volumunous data produced in England, it appears that this second hypothesis is probably not valid. When the same limestone (No. 1359) was used in a six inch reactor with a water cooled coil most of the lime accumulated in the bed.

In a search of available sources on fluidized-bed combustion no other examples were found of the use of a low sulfur coal with limestone addition.

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* It was hypothesized previously that sulfur in a burning bed is not tightly held but may move between particles.

The possible implications of these tests with this low sulfur coal were reported at the time (August 1973) as follows:

(a) The physical integrity of limestone is favored by exposure to sulfur.

(b) It is possible that limestone could be used as a bed material for a low sulfur coal if the starter bed is heavily sulfated.

(c) From a review of British data it appears that 2.0 percent S in coal is acceptable for lime beds.

(d) If low sulfur coals cannot be burned in a limestone bed then an ash bed with limestone addition is required for pollution control. Regeneration is then inefficient. However, for low sulfur coals recovery of sulfur values would not normally be economical.

In the report for September 1973, the low S coal's composition was documented along with the results of the tests done at the Bureau of Mines. It was concluded that the coal was responsible for the destruction of the structure of the limestone since the 1359 limestone had been used without problems for years at our laboratory and at many other laboratories.

Figure 3.45 shows that the low sulfur Rich Mountain coal is a high-volatile A bituminous, but so was the coal used in Test 1001 which did not result in limestone destruction.

The swelling properties for the Rich Mountain coal were also not unusual.

It was concluded that the cause of the high rate of limestone loss was due to the low sulfur content of the Rich Mountain coal compared with others burned in limestone rich beds.

Of the 10 tons of Rich Mountain coal originally purchased, only 2,450 pounds remained. Test No. 517 was run with the remaining Rich Mountain coal. The starting bed was made from fifteen 100 pound bags of A.P. Green's "Mizzou Castable", the most readily available inert material with particle properties reasonably close to that of partially sulfated -8 mesh limestone.

Name of Mining Company . . . . Ten Tex Coal Corp.

Location . . . . Motch, Tennessee
Claiborne County

Type of Mine . . . . Deep

Seam . . . . Rich Mountain

Type of Cleaning . . . . Washed

1-1/4" x 1/4" STOKER

ANALYSIS

Proximate:	As Received	Dry	Moisture Ash Free
Moisture	3.00%	-	-
Volatile	41.90	43.20%	44.20%
Fixed Carbon	52.90	54.50	55.80
Ash	2.20	2.30	-
Ultimate:			
Hydrogen	5.8 %	5.6 %	5.8 %
Carbon	79.4	81.8	83.7
Nitrogen	2.2	2.2	2.3
Oxygen	9.4	7.1	7.2
Sulfur	1.0	1.0	1.0
Ash	2.2	2.3	-
BTU	14,270	14,700	15,050

FUSION

Initial Deformation . . . . 2410° F
Softening . . . . 2540° F
Fluid . . . . 2680° F
Free Swelling Index 4.5
Hardgrove Index 53

FIGURE 3.45 RICH MOUNTAIN COAL ANALYSIS

The results of this experiment are summarized in the material balance for Test 517 (included here as Figure 3.46) and in the Certificate of Analysis (Figure 3.47).

The materials balance and detailed composition shows that the calcium was accumulating in the bed as the more fragile crushed refractory was blowing away. Only 12 percent of the feed calcium was lost to the bed as dust. The bed analyses shows the calcium content increasing while alumina content drops. It is suspected that had there been sufficient coal to continue, the bed would have become a mixture of limestone and coal ash.

These results suggest that the one original error was to fire the Rich Mountain coal in a bed of raw limestone. There is nothing especially aggressive about Rich Mountain coal. It does not appear that there is an absolute lower limit for permissible coal suflur content for use with limestone beds --- if a starter bed of inert material is used.

3.17.3 Loss of Greer Stone

After almost six years of using the No. 1359 limestone for virtually all experiments, the selection of Rivesville, West Virginia as the site for the prototype boiler required that a local limestone be found which could be used. A quarry at nearby Greer, West Virginia had a suitably sized product (given that large quantities would be used) available at low cost. This was the logical first choice and a truckload was ordered.

A bed of raw Greer stone was fired for Test No. 529. The loss on calcination was severe. High makeup rates did not result in an increase in bed depth. Because bed depth and bed temperature are related, the bed temperature during this period was 1800°F and above.

The high loss rate was unexpected and during this part of the experiment it appeared that this inexpensive but low grade stone was unsuitable. The coal and air rates were reduced so as to reduce the bed temperature and lower the superficial velocity since it appeared that fines loss might be the problem and no salt was fed.

FIGURE 3.46

MASS BALANCE FOR TEST 517

INPUTS, LBS.	TOTAL	ASH	CARBON	SULFUR	OXYGEN	HYDROGEN	NITROGEN	CALCIUM
COAL (DRY)	1534.5	95.8	1194.0	15.70	121.5	80.0	29.3	5.1
LIMESTONE (DRY)	310.0	9.2	36.8	.30	145.5	--	--	118.2
SALT (DRY)	0	--	--	--	--	--	--	--
MAIN AIR (DRY)	13877.1	--	1.7	--	3219.4	3.8	10652.2	--
CONVEYING AIR (DRY)	1226.7	--	.2	--	284.6	.3	941.6	--
MOISTURE (IN COAL, L.S., AND AIR)	59.7	--	--	--	53.1	6.6	--	--
TOTAL INPUT, LBS.	17017.0	105.0	1232.7	16.0	3824.1	90.7	11623.1	123.3

OUTPUTS, LBS.	TOTAL	ASH	CARBON	SULFUR	OXYGEN	HYDROGEN	NITROGEN	CALCIUM
DUSTS								
FLYASH —								
COLLECTED	407.0		205.5	4.31	33.7	4.48	--	12.2
EMITTED	71.8		38.7	1.15	5.9	1.01	--	3.1
COARSE SOLIDS								
BED MATERIAL—								
BLOWDOWN	230.0		6.0	.49	4.4	--	--	13.8
CHG. IN ANALYSIS	--		20.5	4.48	84.2	1.28	--	106.2
CHG. IN MASS	2.4		--	--	--	--	--	--
GASES								
CO_2	3241.4		884.0	--	2357.4		--	--
CO	62.5		26.8	--	35.7	--	--	--
SO_2	13.4		--	6.74	6.74	--	--	--
SO_3	--		--	--	--	--	--	--
NO	10.1		--	--	5.4	--	4.7	--
N_2	12092.6		--	--	--	--	12092.6	--
O_2	505.2		--	--	505.2	--	--	--
HxCy (CH_4)	16.3		12.2	--	--	4.08	--	--
HCl	.3		--	--	--	.0	--	
H_2O	696.3		--	--	618.9	77.4	--	--
TOTAL OUTPUT, LBS.	17349.3		1193.7	17.2	3657.5	88.3	12097.3	135.3

	TOTAL	ASH	CARBON	SULFUR	OXYGEN	HYDROGEN	NITROGEN	CALCIUM
% RECOVERY	102.0		96.8	107.5	95.6	97.4	104.1	109.7

December 11, 1973

Pope, Evans & Robbins
Suite 503
320 King Street
Alexandria, VA 22314

Attention Mr. Shelton Ehrlich

CERTIFICATE OF ANALYSIS

Data obtained on seven samples submitted by Mr. Ehrlich and received 11/19/73.

A. MAJOR CONSTITUENTS:

	% Ca	% Mg	% Fe	% Al	% Si	% Na	% K	% Ti
L-1359 [1/]	38.8	0.51	0.101	0.15	< 0.23	0.027	0.08	0.012
B-517-1130	2.90	0.25	4.930	13.40	16.82	0.832	0.80	1.00
B-517-1230	3.95	0.48	5.440	13.20	15.93	0.704	0.64	0.94
B-517-1400	7.95	0.60	5.630	11.00	14.16	0.800	0.92	0.89
C-517-0000 [2/]	5.09	0.80	13.230	9.50	18.74	0.640	1.02	0.60
F-517-1230	2.80	0.08	4.128	10.00	12.29	0.240	0.14	0.60
K-516-S	11.26	0.04	22.463	3.80	< 0.23	1.280	0.01	0.05

B. TRACE ELEMENTS:

	In ppm							
	Zn	Cu	Ni	Co	Pb	As	P	Cl %
L-1359 [1/]	4	10	36	28	43	70	1.6	< 0.02
B-517-1130	74	54	93	50	42	90	0.6	< 0.02
B-517-1230	64	34	105	46	33	60	2.6	< 0.02
B-517-1400	81	30	97	53	50	70	2.3	< 0.02
C-517-0000 [2/]	376	250	152	110	164	120	15.7	0.22
F-517-1230	120	58	64	30	82	NES [3/]	11.1	< 0.02
K-516-S	10	6	62	13	34	350	1.6	1.50

C. MAJOR CONSTITUENTS REPORTED AS OXIDE-PERCENTAGES:

	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2	Na_2O	K_2O	TiO_2	Approx.% Tr.Elem.	Total
L-1359 [1/4/]	54.32	0.85	0.144	0.28	< 0.5	0.036	0.10	0.02	.03	56.18
B-517-1130	4.06	0.41	7.050	25.33	36.0	1.121	0.96	1.67	.06	76.66
B-517-1230	5.53	0.80	7.779	24.95	34.1	0.949	0.77	1.57	.04	76.45
B-517-1400	11.12	0.99	8.051	20.79	30.3	1.078	1.11	1.48	.06	74.98
C-517-0000 [2/]	7.12	1.33	18.919	17.95	40.1	0.863	1.23	1.00	.18	88.69
F-517-1230	3.92	0.13	5.903	18.90	26.3	0.323	0.17	1.00	.06	56.71
K-516-S	15.75	0.07	32.122	7.18	< 0.5	1.725	0.01	0.08	.07	57.40

1/ Limestone
Coal Ash
3/ Not enough sample
4/ Reported as % $CaCO_3$,
L-1359 is 95.75% $CaCO_3$

Respectfully submitted:

NORTH AMERICAN EXPLORATION, INC.

Donald W. Foss, Senior Geochemist

DWF:jpa

FIGURE 3.47 CERTIFICATE OF ANALYSIS

With the temperature reduced to ∿1500°F and the lower velocity, the Greer stone began to stay in the bed. Turning the salt on at that point accelerated the loss rate again. Turning the salt off stabilized the bed.

The sulfur content of the bed was followed as Test 529 progressed. At 6 percent S the salt was turned on again with no adverse affects on bed particle retention. After twelve hours the test was voluntarily terminated at 7 percent sulfur in the bed.

Greer stone at this point in time appeared a reasonable candidate for use with the condition that the initial calcination be accomplished in the 1500°F range.

The second test of a candidate limestone is its ability to (a) spend a weekend in the cold furnace exposed to humid air and then (b) be reignited without excessive loss due to air flaking (hydration). The Greer stone passed this test exceedingly well.

The final test for suitability involves regeneration. Regeneration involves periodic exposure to 1950 to 2000°F temperatures. Tests for the cyclic properties of Greer stone are being planned.

3.18 Tests in 5" x 20" Cold Model

3.18.1 General - Tests on a 5" x 20" plexiglass cold model were performed at the Foster Wheeler's Research Laboratory to gain insights into the performance characteristics of various air distribution grids and tube bundle arrangements. The testing with this small plexiglass model was performed for screening purposes, i.e. to select the best performing grid designs and tube bundle arrangements for further testing in a large 6' x 6' cold test model presently being erected at Foster Wheeler Laboratory. The large cold test model will be used for tests of material handling systems for a) bed material extraction, b) bed material re-cycle and c) fuel injection in order to verify the designs selected for installation at the Rivesville demonstration unit. Testing on the small plexiglass model is complete and testing on the large 6' x 6' model is scheduled to begin in September 1974.

3.18.2 Air Distribution Grid Test Results

Five air distributor designs have been tested in the small plexiglass model. The details of each grid design are described in Appendix E. The testing resulted in all plates producing a formation of large bubbles with some bubbles attaining the full vessel cross section before reaching the tube bundle. The bubble formation from nozzle-type grid design used for several years in the FBM in Alexandria appeared in discreet areas rather than at random as with other plates and resulted in rounder, centrally located bubbles. All other plates tended to give random ,ixing of the bubbles across the width of the test model and although the nozzle-type grid arrangement resulted in a visibly different bubble formation characteristic, the adverse effect on bed mixing behavior was not acute. Motion picture studies indicated little difference in fluidizing characteristics of the grid designs tested. Based on the small model test results, a Johnson screen grid design was selected for use on the large test model based on cost. Since this grid design had not been previously used in a hot unit a Johnson screen was used in the FBM as noted in Section 3.

3.18.3 Tube Bundle Arrangement Test Results

The cold model test program, detailed in Appendix E, indicated 41 possible tube bundle arrangements that could be tested in the small plexiglass model. Of these possible tests, 29 were completed. Analysis of the motion pictures and the test data indicate that the configuration of the tube bundle located in the fluidized bed has an effect on the pressure loss through the bed and on the quality of fluidization. The staggered tube bundle arrangement in general gave better fluidization characteristics than the inline arrangements which showed problems of laning. The tests indicate that the violence of the bubbling in the fluidized bed can be substantially reduced by a) locating the tube bundle closer to the air distribution grid, b) increasing the mean particle size of the bed material and c) decreasing the vertical pitch of the tube bundle.

3.18.4 Sloped Distribution Grid Tests

A test to determine the ability to segregate large bed particles to a specific area of the fluidized bed was performed on the small plexiglass model. The tests indicated that for fluidizing velocities below 6ft/sec oversized particles, 3/4" x 1/2", gravel can be separated to the lower section of the fluidized bed. From these test results it was apparent that a sloped distribution grid would not be useful in segregating oversized particles at fluidizing velocities above 6 ft/sec. Testing of a small zone within a fluidized bed at reduced fluidizing velocities may result in the ability to segregate oversized particles to a zone of reduced fluidizing velocity.

IV. AUXILIARY SYSTEMS DESIGN AND DEVELOPMENT

4.1 General

The program goals could be more expeditiously met if the prototype boiler was located in a utility power plant and run by the plant operators. The alternative was to build a larger pilot plant. This latter course was never considered as a reasonable alternative because of a) the extra costs involved, b) the fact that operability by a normal crew was an important feature to be demonstrated, and c) the fact that the hour-to-hour fluctuations in load, the system imposed emergencies, etc., were impossible to simulate but vital parts of a development and test program.

Auxiliary systems are required to operate the boiler and to integrate the boiler and the host plant. The fluidized-bed boiler requires some auxiliary systems which are quite standard and a few which require development.

4.2 Site Selection

Between October 1972 and February 1973, PER considered as potential sites for installation and test operation of the fluidized-bed boiler, the following electric utility company plants:

Potomac Electric Power Company - Benning Station, Washington, D. C.

Monongahela Power Company - Rivesville, W. Va.

Virginia Electric Power Corporation - Richmond, Va.

Baltimore Gas and Electric Company - Baltimore, Md.

The following factors were considered in the evaluation of the potential sites offered (or considered for a possible offer) by the electric utility companies:

(1) Minimal undesirable environmental impact.

(2) Availability of high-sulfur coal supplies and ease of bringing in, storing and preparing other coal types for experimental purposes.

(3) Availability, cost and feasibility of supply of acceptable limestone.

(4) Favorable cost and research conditions.

   (a) Availability of space within existing plant to house the fluidized-boiler and auxiliary equipment.

   (b) Satisfactory structural conditions, building foundations and availability of drawings and technical information on same for design of new support framing and structures.

   (c) Availability of existing equipment and auxiliary systems; e.g., coal and ash storage and handling facilities, feedwater treatment and supply, piping connection points, electrical services, etc.

   (d) The extent of cooperation offered by the utility company, e.g., coordination of steam generation, flexibility of existing plant operation, standby boiler operation, fuel deliveries, maintenance assistance, use of supporting facilities, machine shops, water chemistry laboratory, etc.

   (e) Flexibility of existing plant facilities to operate in parallel with a test unit whose operation is determined by test and research requirements.

(5) Availability of "as-built" drawings from in-plant files for mechanical, electrical, structural and all other required systems, including instrumentation and controls.

(6) Boiler pressures and temperatures most consistent with normal modern utility practice.

(7) Location of the site (as it effects travel and other expenses).

(8) Site conditions for possible rail and/or waterway delivery of the new boiler.

(9) Availability of low cost ash disposal sites and/or ash disposal area owned by the electric utility company.

Of the four electric utility plants, the Monongahela Power Company's Rivesville Power Station, Rivesville, Marion County, West Virginia offered the most favorable conditions for installation and operation of a 300,000 lbs/hr steam generating capacity fluidized-bed boiler.

Allegheny Power Service Corporation, (part of the Allegheny Power System), managers of the Monongahela Power Company operation,expressed a desire to have the fluidized-bed boiler installed and operated in their plant, and that:

(a) Space for the boiler was available in the Rivesville Power Station's existing boiler room. Four low pressure boilers had been removed, leaving a substantial open area. Space adjacent to the boiler room was also offered if that proved more desirable.

(b) Concrete lined bunkers for storage of coal and/or limestone were available above the old boiler room and coal handling facilities were near by. Only an interconnecting conveyor would be required to deliver coal into the bunkers.

(c) Existing station facilities for water makeup, treatment and storage were available and believed to be adequate for this project.

(d) Boiler feed pumps, feedwater heaters, and deaerators available for delivery of boiler water at acceptable pressure, temperature and quality for the project.

(e) By installation of proper connecting headers and valving, steam from the fluidized-bed boiler could be delivered into an existing 1250 psig, 925°F steam header from which it would be delivered to an operating turbogenerator.

(f) Utilities normally needed at a power station, such as service water, control and station air, electric service at 120/240/480/2300 volts, available in the plant.

(g) Existing flyash storage silo, bottom ash basins and own ash disposal site available for use by this project.

(h) Existing structure and foundations (originally serving the four low pressure boilers) available and adequate for the boiler.

(i) Station chemist and laboratory available for boiler water quality and steam quality work.

(j) Plant maintenance personnel, machine shop, and other maintenance facilities available.

(k) High sulfur content Pittsburgh and/or Sewickley coals normally used in the plant.

(l) Existing plant drawings available in plant files.

(m) Population near the plant, in the town of Rivesville and in nearby areas, would welcome a project of this type.

Considering the favorable conditions and the electric power company's desire to have the boiler located in their plant, PER recommended and OCR approved the fluidized-bed boiler being installed in the Monongahela Power Company's Rivesville Power Station in Marion County, West Virginia.

An agreement between PER and the Monongahela Power Company was signed June 1973 for the installation and operation of the 300,000 lbs/hr steam generating capacity multicell fluidized-bed boiler in the power company's Rivesville, West Virginia power station.

4.3 Host Plant Existing Equipment

Existing steam and power generating equipment in the Monongahela Power Company's Rivesville, West Virginia plant consists of the six pulverized coal fired steam generators and four steam turbogenerators:

Existing Power Generating Units

Unit No.	Capacity MW Rated	Capacity MW Actual	Year Installed	Type	Comments
1	10	12	1919	Condensing	Retired, Nov. 1973
2	10	12	1919	Condensing	Retired, Nov. 1973
3	20	23	1923	Condensing	Retired, Nov. 1973
4	25	26	1936	Extraction	Retired, Nov. 1973
5	35	50	1943	Condensing	-
6	65	94	1957	Condensing	-

Existing Steam Generating Units

Unit No.	Capacity Lbs/hr	Year Installed	Operating Conditions	Comments
5	325,000	1936	1250 psig/935°F	Retired, Nov. 1973
6	325,000	1936	1250 psig/935°F	Retired, Nov. 1973
7	480,000	1943	1250 psig/935°F	-
8	900,000	1957	1275 psig/950°F	-

The 300,000 lbs/hr capacity multicell fluidized-bed boiler (MFB) will be connected to the existing 1250 psig/935°F superheated, high-pressure steam system. This system is directly connected to existing Boiler No. 7 and supplies Turbogenerator No. 5.

Operation of Turbogenerator No. 5 (maximum steam flow to the unit at 440,000 lbs/hr) will be limited in the future to requirements of the power supply grid system, to which this plant provides part base load, part peaking capacity.

Economical operation of the MFB will be based on operation of Turbogenerator No. 5. Continuous MFB operation could be maintained, without capacity limitation, if all or part of the steam produced by the MFB is utilized by Turbogenerator No. 5, and any excess over and above the amount consumed in water cooled condensers. In case of atmospheric blow, treated water makeup must be added to the boiler feedwater system, through the existing feedwater deaerators, to supplement lost water quantity from the otherwise closed system.

Existing water treatment system (demineralizer) capacity is 120 gpm, with a total capacity of 260,000 gallons between regenerations. Regeneration downtime required for the system is 6 hours. Normal operational cycle at present is 5 to 7 days between regenerations.

The existing water treatment system is, therefore, sufficient to supply required makeup water to the new fluidized-bed boiler in case of operation with atmospheric blowing of the generated steam.

The new boiler and the auxiliary equipment is being located in the northwest corner of the existing power plant with a floor area of approximately 5,000 square feet (67' x 76'). This area of the plant is clear of any existing equipment, due to the removal, sometime ago, of the four large low pressure boilers. With the exception of the existing coal bunkers, which are to be used for the new fluidized-bed boiler, there are no framing levels above the boiler room floor to the roof.

The multicell fluidized-bed boiler is being located in the former 25'-0" access bay. Existing steel framing will be removed in this bay to provide clear area for the boiler. The existing floor slab and framing will also be removed and reframed in order to accommodate the new boiler.

New framing for equipment support and access platforms will be supported by existing columns.

The existing roof will be modified to support the new electrostatic precipitator, I.D. and F.D. Fans.

The new stack will be supported at the high roof level on existing stack steel plate girder framing.

The two existing bunkers on the west end will be used to serve the fluidized-bed boiler. The most westerly bunker will be used for limestone storage and will be partitioned from the adjacent bunker which will be used for coal storage. The east side of this bunker will also be partitioned so that a third bunker could be used for coal preparation equipment.

The existing electrical system at the site will be modified with a view towards providing the electrical power required by the fluidized-bed boiler.

Since existing Boilers No. 5 and No. 6 have phased out, it was determined that there would be more than adequate power available at the existing 2300 volt switchgear.

The existing 2300 volt oil circuit breakers have 600 ampere frames. Existing current transformers will require replacement. It is anticipated that the existing protective relays may be reused.

All power requirements at 2300 volts, 227/480 volts and 120/208 volts will be derived from the above mentioned oil circuit breakers via new transformers and distribution equipment as required.

4.4 Auxiliary Systems Design

4.4.1 Fuel Preparation and Storage

The fuel preparation and storage system is designed to process 50 tons of coal per hour to the correct size and moisture conditions for injection into the new fluidized-bed boiler.

When fuel processing is required, coal is taken from the plant's existing coal system. The moisture of the plant's coal supply varies and the top size ranges to approximately 2 inches.

The coal in this state is conveyed and deposited in the new coal dryer, located at elevation 935'-0". The dryer is located within what was orignally one of the unused coal bunkers which will be renovated for the coal preparation equipment.

The dryer, which is a parallel-flow rotary type, will remove moisture by using 600°F air, from the air supply system, as the drying media.

Once adequately dried, the coal is discharged into a crusher where it is reduced in size to 1/4 inch top size.

Should the coal as received from the existing coal system be sufficiently dry, the operating personnel may by-pass the coal dryer and discharge the coal directly into the coal crusher.

The dry, sized coal is then transported to an existing coal storage bunker where it is stored until required. A schematic flow diagram describing this system is presented in Appendix G on Drawing 406 "Coal and Limestone Supply and Storage Systems - Schematic Flow Diagram".

4.4.2 Fuel Feed to Furnace

The fuel feed system takes coal from the coal storage bunker, described in Section 4.4.1 "Fuel Preparation & Storage", then weighs, conveys and regulates the coal feed into the fluidized-bed boiler.

The coal,upon being discharged from the north and south coal storage bunker hoppers, is weighed by scale conveyors, one scale at each hopper discharge, and is conveyed to three coal storage bins located in the plant at elevation 925'-6". The three bins, the north, south and east side of the boiler, gravity-feed coal, at a rate regulated by rotary feeders, into feed pipes as illustrated on Drawing 418 "Furnace Feed Systems - Schematic Flow Diagram" in Appendix G. The rotary valves, each designed to discharge 6,000 lbs/hr from the north and south bins and 3600 lbs/hr from the Carbon Burnup Cell bin, will vary the discharge rate as a function of the system steam pressure.

The coal is then mixed in the fuel feed pipe with limestone as described in Section 4.4.4.

The mixture of coal and limestone is fed to vibrating table feeders by means of rotary valves. The vibrating table divides the coal into a number of channels which connect to the lines which feed coal into the injectors. Each cell, A, B and C, is equipped with two vibrating feeders, one on the north size and one on the south side, while the Carbon Burnup Cell is equipped with one. To impel the coal to the base of the bed, air from the auxiliary air system is introduced at the vibrating feeder.

Fuel in the form of high combustible fly-ash is reinjected into the Carbon-Burnup Cell. The operation of the fly-ash system is described in Section 4.4.6 "Flue Gas Cleaning and Ash Reinjection".

4.4.3 Limestone Preparation and Storage

Limestone to be used in removing sulfur from the combustion process is delivered to the plant by a pneumatic truck, with the limestone prescreened prior to delivery to insure a particle size of minus 1/8 inch.

The delivery truck, equipped with its own blower system, will transport the limestone through a pneumatic transfer pipe to a cyclone collector located in the plant above the new limestone storage bunker at a rate of 60 tons per hour. The material once separated from the air is deposited in the collector's hopper and discharged by gravity into the limestone bunker.

The limestone storage bunker has a storage capacity of 450 tons and was constructed from part of an existing coal storage bunker.

Stored limestone is supplied, as required, by gravity into the fuel feed system, as discussed in Section 4.4.2 "Fuel Feed to Furnace". A schematic flow diagram of this system is illustrated on Drawing 406 "Coal and Limestone Supply and Storage Systems - Schematic Flow Diagram" in Appendix

4.4.4 Limestone Feed to Furnace

The feed system accepts the limestone from the storage bunker, then weighs, conveys and regulates the quantity of material to be injected into the Fluidized-Bed Combuster (FBC). An illustration of the system is shown on Drawing 418 "Furnace Feed Systems Schematic Flow Diagram" in Appendix G.

The material once discharged from the storage bunker is first weighed. After weighing, the limestone is transported by bucket elevators and conveyors to three (3) bins located at elevation 929'-6" above the boiler. One bin is located on the north side, the second on the south side and the third on the east side of the boiler.

The number and locations of the bins enable the limestone to be gravity fed into the feed system. The north and south bins are supplied with the same type weighing and conveying system, with the east bin supplied from the south bin system.

The north and south bins are equipped with three discharge connections and rotary feed valves at the bottom, with the east bin supplied with one. Each is designed to supply 6,000 lbs/hr from the north and south bin and 3,600 lbs/hr from the east bin, but each can vary the rate as a function of the combustion process as described in Section 4.4.10 "Controls". A description of the rotary feeders and vibrating feeders is given on Drawing 422 "Furnace Feed Systems - Schedules".

Before injection, the limestone is mixed with the coal. To accomplish this required mixing, the limestone is fed, by gravity, through rotary feed valves located at the discharge of the bins. The rotary feed valves control the quantity of limestone entering the coal feed pipe where the limestone is then mixed with coal.

The combined coal/limestone stream is then fed to vibrating feeders which blend the two constituents and divides the mixture to supply the fuel injectors in the boiler as described in Section 4.4.2 "Fuel Feed to Furnace".

4.4.5 Air Supply and Flue Gas System

The air supply and flue gas system is designed to supply air for combustion and to convey the products of combustion through gas cleaning equipment and discharge those gases to atmosphere.

The supply system can provide up to 362,000 lbs/hr of air primarily for combustion by means of a forced draft fan to be installed on the plant roof. Atmospheric air is drawn in by the fan and is raised to 76 inches of water column.

The air then passes through the preheater where its temperature is increased to 600°F using the products of combustion as the heating source.

The hot air is then used for processes such as coal drying and in the bed material system, with the major portion, 358,000 lbs/hr, used as fluidizing combustion air.

Combustion air for the fluidized bed boiler is supplied to the furnace from the bottom of the boiler as illustrated on Drawing 102 "General Arrangement - Longitudinal Section" in Appendix . Each cell is equipped with a damper which is the quantity of air entering the cell. The damper is controlled by the combustion controller.

The flue gas system which accepts effluent from the combustion and other processes, routes the gases through gas conditioning equipment and discharges them to atmosphere.

The gases, approximately 400,000 lbs/hr at full load, are primarily boiler exhaust gases or products of combustion (p.o.c.) at 730°F. The p.o.c. first pass through mechanical dust collection equipment and an electrostatic precipitator where particulate concentration of the gases is reduced. These items are discussed in Section 4.4.6 "Flue Gas Cleaning and Ash Reinjection".

After the gases are cleaned, they pass through the air preheater previously mentioned in this section where the gas temperature is reduced to 275°F.

Upon exiting the preheater, the cooled gases are received by an induced draft fan, located on the roof, which is capable of producing a 20 inch of water column negative pressure on the system, compensating for the pressure drop in the flue gas system. The clean, relative cool gases enter a new steel stack and are discharged to atmosphere at elevation 1,065'-8".

Drawings 101, 102, 103, and 403 in Appendix G illustrate the "Air Supply and Flue Gas Systems".

4.4.6 Flue Gas Cleaning and Ash Reinjection

The ash reinjection system takes the high carbon flyash from the mechanical cyclones and/or the electrostatic precipitator and injects the flyash into the Carbon Burnup Cell of the fluidized-bed boiler. The flue gas cleaning system is designed to reduce the particulate concentration of the exhaust gases to 15 pounds per hour at full load. The gas cleaning system consists of three mechanical dust collectors and an electrostatic precipitator. The design is diagrammatically displayed on Drawing 405 "Fly Ash Collection and Reinjection Systems Schematic Flow Diagram".

Fly-ash Collector No. 1 receives exhaust gases from Cell D, the Carbon Burnup Cell, at a rate of 40,000 lbs/hr containing 13,120 lbs/hr of solids. The mechanical collector is designed to remove 12,460 lbs/hr of solids from the gases leaving 660 lbs/hr which is carried over into the exhaust system.

The third fly-ash collector, No. 3, will receive gas from the regenerator at a rate of 12,000 lbs/hr containing 400 lbs/hr of solids. This collector removes 380 lbs/hr of solids leaving 20 lbs/hr in the exhaust gases.

The gases from the boiler collectors and small quantities from other processes are combined and enter the electrostatic precipitator at a rate of 406,000 lbs/hr with 1,440 lbs/hr solids. The precipitator collects 1,425 lbs/hr leaving 15 lbs/hr entrained in the gas flow.

The off gas of the regenerator is recycled to the F.D. fan inlet for recycle through the furnace. If the regenerator performance warrants, a sulfur recovery system may be provided.

The fly-ash reinjection system is provided to refire the highly combustible fly-ash collected from collectors No. 1 and 3 and possibly the electrostatic precipitator. The fly-ash collected in the hoppers of this equipment is gravity fed by means of rotary feed valves into a pneumatic conveying system using 600°F air from the air supply system as discussed in Section 4.4.5, "Air Supply and Fly Ash System". The ash is conveyed by the air stream to the fluidized-bed boiler where it is then injected into the Carbon Burnup Cell. A total of 15,560 lbs/hr of high carbon fly-ash is reinjected into the Carbon Burnup Cell.

The ash reinjection system is diagrammatically illustrated on Drawing 405 "Fly-Ash Collection and Reinjection Systems - Schematic Flow Diagram" in Appendix G.

4.4.7 Bed Material Handling System

The bed material handling system is designed to remove 80,000 lbs/hr of bed material from the fluidized-bed boiler, separate undesirable particles and reinject desirable material back into the furnace. Any bed material unsuitable for reinjection is discharged into the existing ash silo.

Bed material is discharged from the boiler cells through four (4) rotary feeder valves into an air slide located under the boiler at a rate of 20,000 lbs/hr each.

The material is then carried by the air slide, deposited in a vibrating screen where material 1/8 inch or less passes through and is collected in a classifier. These fine particles are then discharged by a rotary feeder from the classifier into a vacuum line which transfers the material to the bed material storage bin located at elevation 920'-0" in the Plant. As required, this material is then returned to the boiler cells and regenerator with rates controlled by rotary feed valves.

The material larger than 1/8 of an inch is collected at the base of the screen and discharged by a rotary feeder into a pneumatic system which transfers the material to the material cooler.

Once the bed material is cooled, it is then discharged into a pneumatic system that transfers the material to the existing ash silo located outside the Plant.

A diagrammatic representation of the bed material handling system is on Drawing 404 "Bed Material Handling and Storage Systems - Schematic Flow Diagram" in Appendix G.

4.4.8 Fly Ash Collection and Storage

The fly ash collector and storage system is designed to receive ash removed from the boiler exhaust gases, as described in Section 4.4.6 "Flue Gas, Cleaning and Ash Reinjection".

The system collects from fly ash collector No. 2 and from the electrostatic precipitator by means of a pneumatic system. The material is then conveyed to the existing silo located outside of the plant.

The pneumatic system is supplied with air from two blowers which deliver 530 SCFM at 14 psig.

Fly ash is fed into the pneumatic system at a rate of 12,460 lbs/hr from collector No. 2 using air lock knife valves located at the hopper discharge.

It is then combined with 1300 lbs/hr of fly ash entering the system from the electrostatic precipitator pneumatic system, which is fed by means of air lock valves similar to that of the fly ash collector No. 2.

The total 13,885 lbs/hr of ash is discharged into the existing silo.

A diagrammatic representation of the fly ash collection and storage system is on Drawing 405 "Fly Ash Collection and Reinjection System - Schematic Flow Diagram" Appendix G .

4.4.9 Steam and Boiler Feedwater System

The new steam system illustrated on Drawing 401 "Steam and Boiler Feedwater Systems" in Appendix G is designed to handle 300,000 lbs/hr.

Steam at 1270 psig is introduced into the existing system by a connection to the high pressure line from Boiler No. 7 presently serving Turbogenerator No. 5.

The system will then maintain a continuous supply of 300,000 lbs/hr of superheated steam as described in Section 4.3 of this report.
The boiler feedwater system illustrated on Drawing 401, will supply the new boiler with 300,000 lbs/hr of feedwater from the plant's existing system. Water is supplied at pressures between 1800 and 2500 psig through a new 6 inch boiler feed line which supplies both the new boiler and the regenerator.

4.4.10 Control System

The control system is designed to control the quantity of fuel injected into the boiler, the amount of limestone supplied to the furnace bed, the fly ash reinjection to the Carbon Burnup Cell and the bed material discharge rate.

Fuel injection, which is primarily a function of steam system pressure and temperature, is regulated by rotary coal feeders, as discussed in Section 4.4.2 "Fuel Feed to Furnace". As steam pressure increases or decreases, the fuel injection rate decreases or increases respectively.

The limestone injection rate is primarily a function of the sulfur dioxide in the boiler exhaust. Rotary feed valves respond to a signal from an analyzer/transmitter which defines the sulfur dioxide content of the gases. As the amount of sulfur dioxide in the gases increases, additional limestone is added to the bed. As the sulfur dioxide content decreases, the rate of limestone input is decreased.

The fly ash reinjection system receives fly ash from collectors No. 1 and No. 3 and the electrostatic precipitator. The rate of injection is regulated by three (3) rotary feed valves on their respective systems. The valves regulate the discharge rate of fly ash as a function of furnace draft and other conditions in the Carbon Burnup Cell.

The bed material discharge is controlled by rotary feed valves as discussed in Section 4.4.7 "Bed Material Handling System". These valves vary discharge rate as a function of bed level by receiving a signal from a pressure transmitter indicating furnace bed pressure.

A diagrammatic representation of the control system is on Drawing 415 "Combustion Control and Miscellaneous Control Systems - Schematic Control Diagram in Appendix

4.4.11 Electrical System

The electrical distribution system draws power from an available and dedicated 7500 KVA, 11.5 KV-4160/2400 volt, 3 phase, 60 Hertz transformer. The actual demand load is anticipated to be approximately 5,000 KVA. the 1,000 horsepower I.D. Fan and 2500 horsepower F.D. fan each operate at 4160 volts. A 2,000 KVA unit substation transforms 4160 volts to 480/277, 3 phase, 4 wire, 60 Hertz for the power and lighting requirements of the installation. Small dry type transformers convert 480 volts to 208/120 volts for receptacle and miscellaneous other requirements. The 4.16 KV switchgear and 2,000 KVA unit substation is installed in the Electrical Equipment Room. The Electrical Equipment Room is adjacent to the Control Room. In addition to the systems control panel, there are three control centers in the Control Room. Complete boiler control and monitoring exclusive of the precipitator is possible from the Control Room. Precipitator control equipment is located on elevation 930.

4.4.12 Analytical Laboratory

An analytical laboratory has been designed to be included at the Rivesville site to support the demonstration of the prototype fluidized-bed boiler operation. The laboratory will fulfill the following major functions:

1) Provide continuous analysis and recording of flue gas for the following gases with analysers that have been tested for reliability and accuracy:

   (a) SO_2
   (b) NO_x
   (c) CO_2
   (d) CO
   (e) O_2
   (f) Unburned hydrocarbons

(2) Provide intermittent analyses and recording of flue gas at alternate locations through alternate sample loops such as:

   (a) Carbon-Burnup Cell
   (b) Regenerator
   (c) Stack outlet
   (d) Flue close to combustion zone

(3) Provide intermittent analyses of the gases and particulates based on EPA isokinetic procedures and using well tested apparatus.

(4) Provide intermittent analyses by wet methods when needed for special tests or where known interferences can invalidate results obtained by other means.

(5) Provide a full range of solids constituent analyses of coal, flyash, bed material and limestone for use in closing heat and materials balances and pollutant emission levels.

(6) Provide boiler water analysis for guiding boiler chemical treatment on a day by day basis.

Materials and corrosion analyses will be provided by independent source who has both the equipment and personnel with expertise to evaluate the fluidized-bed environment effect on the chosen materials.

Roughly 1200 square feet have been allotted for laboratory spaces at Rivesville. This space has been double decked (600 square feet each level) and placed close to the boiler and the boiler control room. The laboratory will be provided with all essential services and hardware to permit completion of all the above tasks accurately, safely, and promptly.

V. CONCLUSIONS

5.1 Achievements

1. At the close of the reporting period, the fabrication of the 30 MWE fluidized-bed boiler was progressing. Demolition at the Rivesville Power Plant was underway and erection of steel to support the main steam drum had started. The drum which had been fabricated at the Mountain Top, Pennsylvania shop of Foster Wheeler had arrived at the site.

2. Experiments in the FBM, the 9 sq. ft. hot-test boiler, indicated that relatively small quantities of an impure, inexpensive limestone could be used to meet EPA sulfur oxide emission standards.

3. Based on the experimental data presented, the State of West Virginia approved the construction of the 30 MWE installation at Rivesville.

4. A ton of spent lime was used to provide calcium for a peanut crop being grown at an agricultural experiment station. The lime tends to concentrate some coal ash impurities, and the plants were healthy at the end of June.

5. A 36 sq. ft. cold model had been designed and was under construction. The results derived using this large research tool will represent a three-dimensional system.

6. A conceptual design for an 800 MWE fluidized-bed boiler was prepared, made up of four 200 MWE modules. In this way, a substantial degree of shop fabrication could be used.

7. Studies continued to show that the fluidized-bed boiler would cost 20% less than an equivalent conventional boiler which included a stack-gas scrubber.

5.2 Problem Areas

1. Operation of test rigs used for development of the fluidized-bed boiler have indicated no major obstacles to commercial success. All told, such systems have over 30,000 operating hours. The most extensive testing has been done in the FBM at Alexandria, Va. Here 9,000 hours of service have not indicated erosion or corrosion rates that would lead to rapid failure of boiler tubes. It is still necessary to demonstrate the long term operability of the fluidized-bed boiler and developmental auxiliaries. This may be considered the major problem area.

2. A low cost coal injector has been demonstrated as operable. A single injector provides 10^7 Btu/hr. It would be desirable if this could be increased substantially so that very large boilers would need fewer injectors. Numerous low-cost coal injectors would not be undesirable if an inexpensive method can be developed for dividing a bulk coal stream into a number of equal smaller streams. Development of a vibrating table feeder to accomplish this task had not been completed at the end of this reporting period.

3. Operation with low SO_2 emissions at minimum limestone rates requires the separation of coal ash from the bed without excessive lime loss. Means are available to accomplish this, but they are presently costly and complex. A substantial improvement will be made when a simplified bed cleansing system is devised.

   Work in the following areas is indicated: (a) increasing the top size of the coal feed; (b) further development of air classifiers as an alternative or supplement to screening; and (c) exploiting the magnetic properties of most coal ash particles by development of magnetic separators.

4. Finding environmentally acceptable and, hopefully, beneficial uses for the effluent solids of the fluidized-bed boiler would reduce costs and enhance acceptability. For the coarse lime/anhydrite

the picture is encouraging,but serious applications studies by potential users await the availability of tonnage quantities. For the Rivesville site, the local limestone is relatively inert when heavily sulfated and may be acceptable land fill. Again proper evaluation awaits the existence of a "real" ash heap.

5. The solid waste burden can be substantially reduced if lime can be regenerated and reused,and if an economical process for utilizing concentrated SO_2 stream is available. Work on this latter problem is clearly beyond the scope of this project, but regeneration studies are planned. The substantial work done in 1971 and reported in EPA-R2-72-021 proved that batch regenerations using direct coal injection as a reductant were feasible. The continuous process tests were difficult to control because the regenerator attached to the FBM was so small (0.7 sq. ft.). Sorbent attrition rates were very low, but the operability problems were severe. The basic conclusion was that the regeneration process could be made to work at a reasonable scale.

6. Automated fluidized-bed test rigs have been built by several laboratories. The FBM operates essentially unattended,with no automation,demonstrating the process to be fundamentally stable. However, the integration of the fluidized-bed boiler and a turbine generator is yet to be demonstrated. Controls which will simultaneously reduce steam production while maintaining steam temperature, bed temperature, and excess air at the set points have yet to be demonstrated. The problems for the fluidized-bed boiler are unique but in some respects appear less severe than the problems solved for pulverized coal firing in which; (a) furnace explosions are an ever present possibility; and (b) coordination of pulverizers with burners requires the input of several parameters.

   A control simulator is to be built for the fluidized-bed boiler and thus will reduce the number of control problems faced when the actual boiler is operated.

7. The selection of an air distributor which meets the requirements of effective performance at low pressure drops and which is also inexpensive has not been completed. There are several promising candidate designs and these were being evaluated in the hot test model when the reporting period ended. Some problems may not appear in one-hundred hours of service,but will after 5,000 hours. Whatever selection is made for the 30 MWE unit, it must be considered experimental until several thousand operating hours have been recorded-over the entire load range, with severe transients and with a variety of coals and limestones.

VI. RECOMMENDATIONS

Grant a DO-E-2 priority for Rivesville long delivery items in order to advance the schedule.

Expand the research and test program by funding pending proposals. Provide funds for automation at the Alexandria laboratory of materials handling and data acquisition/reduction.

Support relevant research by academic and contract organizations to explore the anomalies discovered during the development program. Provide for interaction between the researchers and the developers.

The single most important recommendation is that the work be continued as programmed.

Appendix A. Analytical Procedures

A. Isokinetic sampling of stack gas (moisture, hydrogen chloride, particulate).

Sampling Location

The stack sampling point must be at least eight diameters upstream and two diameters downstream from any flow disturbance.

Sampling Procedure

The isokinetic sampling procedure outlined in Reference A-1 is used exclusively, incorporating pm EPA type sampling train. Sample volume is at least ten standard cubic feet.

Calculation of Moisture Content (Condensation Method)

Referring to Reference A-1 the moisture content is determined from the collected condensate and the calculated volume of water vapor in the saturated gas volume at the last point of liquid-gas contact.

$$MC_s = \frac{V_w}{V_t} \times 100 = \frac{V_c + V_v}{V_c + V_m} \times 100$$

where

MC_s = Moisture content of stack gas in volume percent

V_t = Total volume of gas plus water vapor at meter conditions in ft^3

V_w = Total water vapor at meter conditions in ft^3

V_c = Equivalent gaseous volume of condensed water at meter conditions in ft^3

V_v = Volume of saturated water vapor at meter in ft^3

V_m = Indicated gas volume at meter in ft^3

Determination of Hydrogen Chloride

The impinger solutions and washings are combined and analyzed for chloride ion according to ASTM D512-67 as described in A-2.

$$\%HCl \text{ in flue gas} = \frac{\text{grams } Cl^{-} (0.0223)}{V_t} \times 100$$

Determination of Particulate Concentration

The particulate matter in the cyclone and on the filter is weighted.

$$PC_s = \frac{(\text{weight in grams})}{V_t \times \frac{T_s}{T_m} \times \frac{P_m}{P_s}} \times \frac{7000}{454}$$

where

PC_s = Particulate concentration at stack conditions in grains/ft^3

V_t = Total gas volume at meter conditions

T_s, P_s = Temperature, pressure of stack

T_m, P_m = Temperature, pressure of meter

References

A-1 H.B.H. Cooper, A.T. Rossano, Jr., Source Testing for Air Pollution Control, Environmental Research and Applications, Inc., Wilton, Connecticut, 06897, 1971.

A-2 1972 Annual Book of ASTM Standards, American Society for Testing and Materials, Easton, Maryland, USA, Revised 1972.

B. Sulfur Dioxide and Sulfur Trioxide in Flue Gas.

Sampling Procedure

The isokinetic sampling system is used. If it is desired to measure sulfuric acid mist, the cyclone and filter are by-passed and a suitable paper filter is placed between impingers No. 1 and No. 2. Impinger No. 1 is filled with 80 percent isopropanol and impingers No. 2 and No. 3 are filled with 3 percent hydrogen peroxide.

Analysis

After a suitable gas volume has been drawn, impinger No. 1 and the filter paper (if used) are combined and analyzed for sulfuric acid mist plus sulfur trioxide using the barium perchlorate thorin method. Impingers No. 2 and No. 3 are combined and analyzed for sulfur dioxide in the same way.

For details refer to: Federal Register, Volume 36, Number 247, Part II, Standards of Performance for New Stationary Sources.

C. Nitrogen Oxides in Flue Gas

Sampling Procedure

A filtered gas sample is drawn into an evacuated flask containing eight drops of four percent hydrogen peroxide and 10 ml of 0.1N sulfuric acid. The mixture is allowed to sit over night on a shaker table and then the solution is analyzed for NO_x according to the phenoldisulfonic acid method outlined in the reference A-4.

Reference

A-4 J. F. Smith, J. A. Hultz, A. A. Orning, Sampling and Analysis of Flue Gas for Oxides of Sulfur and Nitrogen, U. A. Department of The Interior Paper.

Appendix B. Analysis of Solid Samples

Wet Chemical Analysis

Wet Chemical Analysis are performed according to ASTM recommended methods.

Aluminum	ASTM D2331
Calcium, Magnesium Oxides	ASTM D2331
Chloride ion	ASTM D512-67
Iron	ASTM D1068
Silica	ASTM D2331
Sulfate	ASTM D2331

For details refer to: 1972 Book of ASTM Standards
American Society for Testing and Materials
Eastern, Md. U.S.A. Revised 1972

Appendix C. Behavior of a Fluidized-Bed Boiler When Coal Flow Ceases

TABLE OF CONTENTS OF APPENDIX C

FIGURES

Analysis

Two transient experiments were conducted at the conclusion of four hour steady state tests. A test involved shutting fuel flow and recording bed temperature. A simple model was used to account for the loss of temperature, by the bed, and this compared well with the experiments.

The loss by radiation from the top of the bed is given by

$$Q_1 = FA_r\sigma(\varepsilon_b T_b^4 - \alpha_w T_w^4) \qquad \text{(C-1)}$$

(See Nomenclature)

For the top of a fluidized-bed radiating to a water cooled enclosure F = 1.

The area of the top of the bed is assumed to have a shape equivalent to a hemi-cylinder so that

$$A_r = \frac{\pi}{2}A_b = 14.35 \text{ sq. ft.} \qquad \text{(C-2)}$$

The emmisivity of a fluidized-bed, ε_b, is assumed to be unity i.e. a hot fluidized-bed is a black body.

The absorbtivity of the boiler tubes, α_w, is assumed to be unity because the surface is carbon.

The heat lost to the water walls touched by the fluidized bed is given by

$$Q_2 = UA_w(T_b - T_w) \qquad \text{(C-3)}$$

Values on order of 50 Btu/hr, sq.ft, °F have been measured in the operating system and should be used in computing transient behavior at ~1500°F. However, for the case here where the radiative component of U disappears rapidly as the bed cools, the value U=40Btu/hr, sq.ft, °F was used. More realistically U should vary as a function of temperature and superficial velocity. The surface area of the wall touched by the fluidized-bed is the product of the perimeter of "couragated" water wall, P_w, and the depth of the fluidized-bed, h_b.

For the air distributor used in these experiments the active height of the fluidized-bed in contact with the boiler tubes is reduced by the fact that a dead zone existed around the periphery. For this case then

$$A_w \approx P_w(h_b - \Delta h_b)/12 \qquad (C-4)$$

T_b and T_w are as defined for Equation C-1 h_b is uncertain but assumed to be equal to the bed expansion, i.e., $h_b = h_b' \therefore A_w \approx P_w h_b'/12$. The final component of heat loss is to the fluidizing and coal injection air.

$$Q_3 = C_{p_a} M_a (T_b - T_a) \qquad (C-5)$$

The specific heat for air, C_{p_a}, was computed as a function of temperature.

The air flow, M_a, was the sum of the measured fluidizing and coal injection air.

The air temperature entering the bed, 95% of M_a, decreases with time because a tubular air preheater is installed on the FBM. The value of T_a is recorded and was used in the calculation.

The source of the energy loss is described by Equations C-1, C-3 and C-5 in the hot fluidized bed (after coal flow stops). The energy lost by the bed is described by

$$Q_b = Q_1 + Q_2 + Q_3 \qquad (C-6)$$

and

$$Q_b = C_{p_b} M_b (T_b^o - T_b) \qquad (C-7)$$

The specific heat of the bed was varied with temperature as if it were all $CaSO_4$. The value is an approximation of the true value which varies with temperature and composition, i.e., fraction of $CaSO_4$, CaO, $Ca(OH)_2$, $CaCO_3$, Al_2O_3, Fe_2O_3, SiO_2, Na_2SO_4, etc.

The mass of the bed, M_b, is assumed constant through the cooling process although some dust must be lost. In tests of this it was found that without coal feed the fly ash collection rate drops to 1/3 the operating value in the first 30 minutes and 1/10th in the second 30 minutes after the coal and limestone feed were stopped. The total, about 30 pounds, is trivial compared to the bed mass. Also, it seems likely that the flyash collected after the coal flow stops actually originates from the hopper sides and from the "dunes" that formed on the horizontal surfaces in the breeching -- not from the fluidized bed.

In measuring bed mass it was found that the mass is accurately described by

$$M_b = h_b' (A_b) \rho_b \qquad \text{(C-8)}$$

The static bed height, h_b', is determined by banking the furnace. An end of the transient test period at $t=t_f$ was defined as the time that the heat loss rate from the bed, dQ_b/dt, became less than 5% of the initial heat loss rate, i.e.,4500 Btu/min against 100,000+Btu/min initial.

The heat loss process is described by

$$dQ_1/dt + dQ_2/dt + dQ_3/dt = dQ_b/dt \qquad \text{(C-9)}$$

Between $t=0$ and $t=t_f$ is described by

$$\int_{t=0}^{t_f} dQ_1 + \int_{t=0}^{t_f} dQ_2 + \int_{t=0}^{t_f} dQ_3 = \int_{t=0}^{t_f} dQ_b \qquad \text{(C-10)}$$

There is no analytical solution to this equation but it may be solved numerically in small time stops.

Results

At the conclusion of the Test 520 the coal was shut-off while the boiler blowdown valves were open. This caused the steam pressure to drop rapidly and the calculations were done with T_W = 250°F. Figure C-1 shows the recorded bed temperature and the temperature computed from Equation C-10. Figure C-2 shows components of the calculated heat loss rate vs. time. Figure C-3 plots the loss rate in a way that illustrates the equivalence of gas loss and the loss to the furnace.

At the end of Test 529-C the steam pressure was forced to remain at 200 psig (until the bed temperature dropped to below 550°F) so that for most of the fast loss period T_W = 380°F. Figures C-4, 5, and 6 describe this test.

Conclusions

1. A first attempt at describing the transient behavior of a fluidized-bed boiler was reasonably successful.

2. Assuming that 1000°F is the minimum bed temperature at which hot-restart should be attempted, a fluidized-bed boiler operator has about four minutes to reestablish coal feed after a filure i.e., the system is very safe.

NOMENCLATURE

A_b = Flat area of top of bed

= 9.136 ft.^{2} (Accounts for "corrugated" surface of water wall)

A_r = Radiating top surface of fluidized-bed, sq. ft.

A_w = Surface area of tubes "touched" by fluidized-bed, sq. ft.

C_{p_a} = Specific heat of air, Btu/lb,°F

C_{p_b} = Specific heat of bed material, Btu/lb,°F

F = View factor, dimensionless $\equiv$ 1

h_b = height of fluidized bed, in.

h_b' = height of static bed after it was fluidized and then defluidized, in.

M_a = Air flow through fluidized-bed, lbs/hr

P_w = Perimeter of wall = 239.7 in.$\approx$20 ft.

Q_1 = Radiative heat loss from <u>top</u> of bed, Btu/hr

Q_2 = Heat loss to water walls by direct contact heat transfer; Btu/hr

Q_3 = Heat loss to air flowing through fluidized bed, Btu/hr

T_b = Temperature of fluidized bed

= Temperature of gas leaving fluidized bed, °F

T_b° = Temperature of fluidized-bed at t=0, i.e. when coal flow is stopped, °F

T_w = Temperature of water in boiler tubes

= Temperature of tubes surface, °F

t = time from start of test, minutes

t_f = final time at end of test, minutes

U = Overall heat transfer coefficient between bed at T_b and water at T_w, Btu/hr, sq. ft., °F

α_a = Absorbivity of boiler tubes, (-)

ε_b = Emmissivity of fluidized bed, (-)

ρ_b = tapped density of bed material, lbs/cu.ft.

σ = Stefan-Boltzman constant for a black body 0.173×10^{-8} Btu/hr,sq. ft.,°R

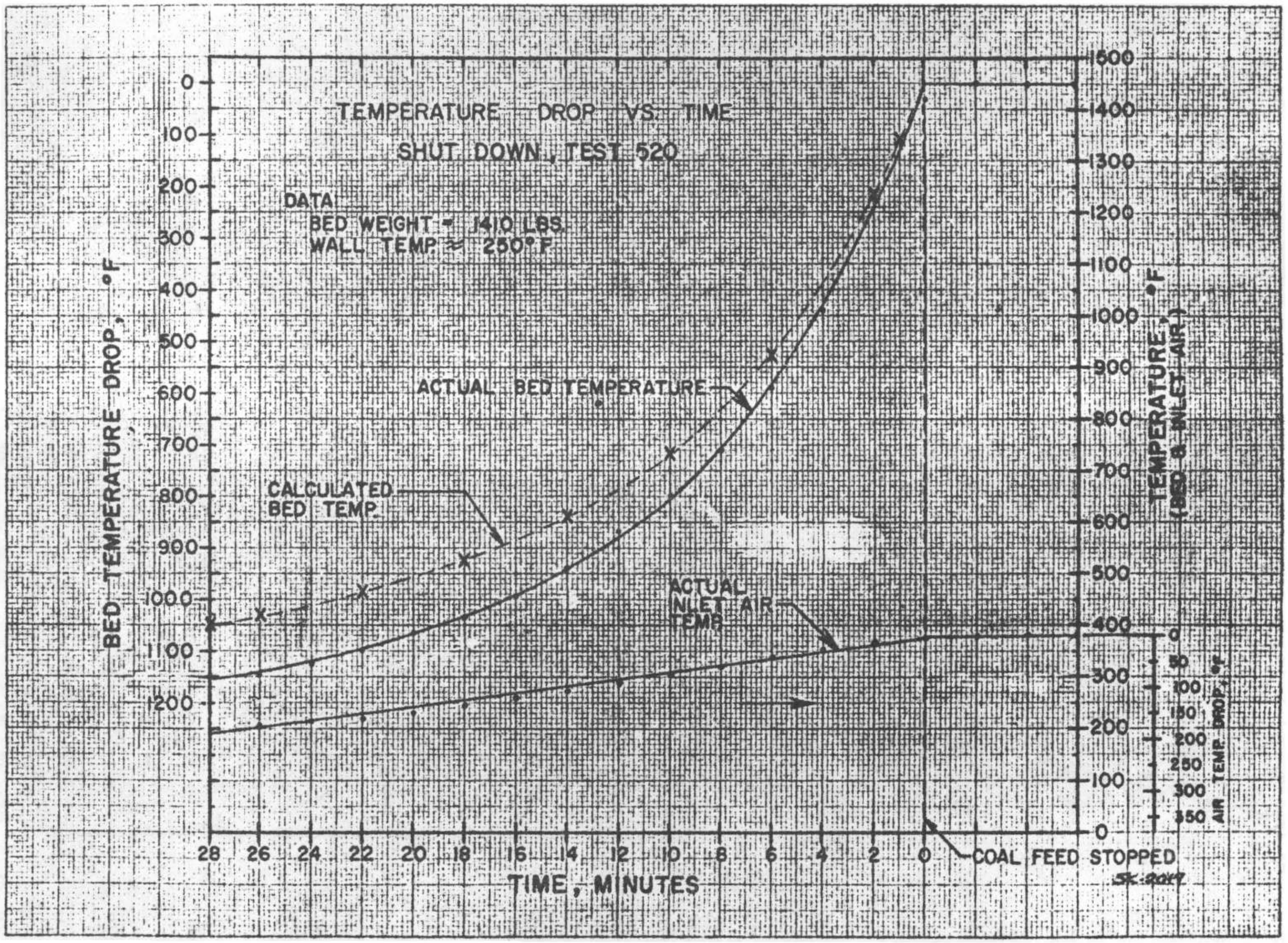

FIGURE C-1. TEMPERATURE DROP VS. TIME, TEST 520

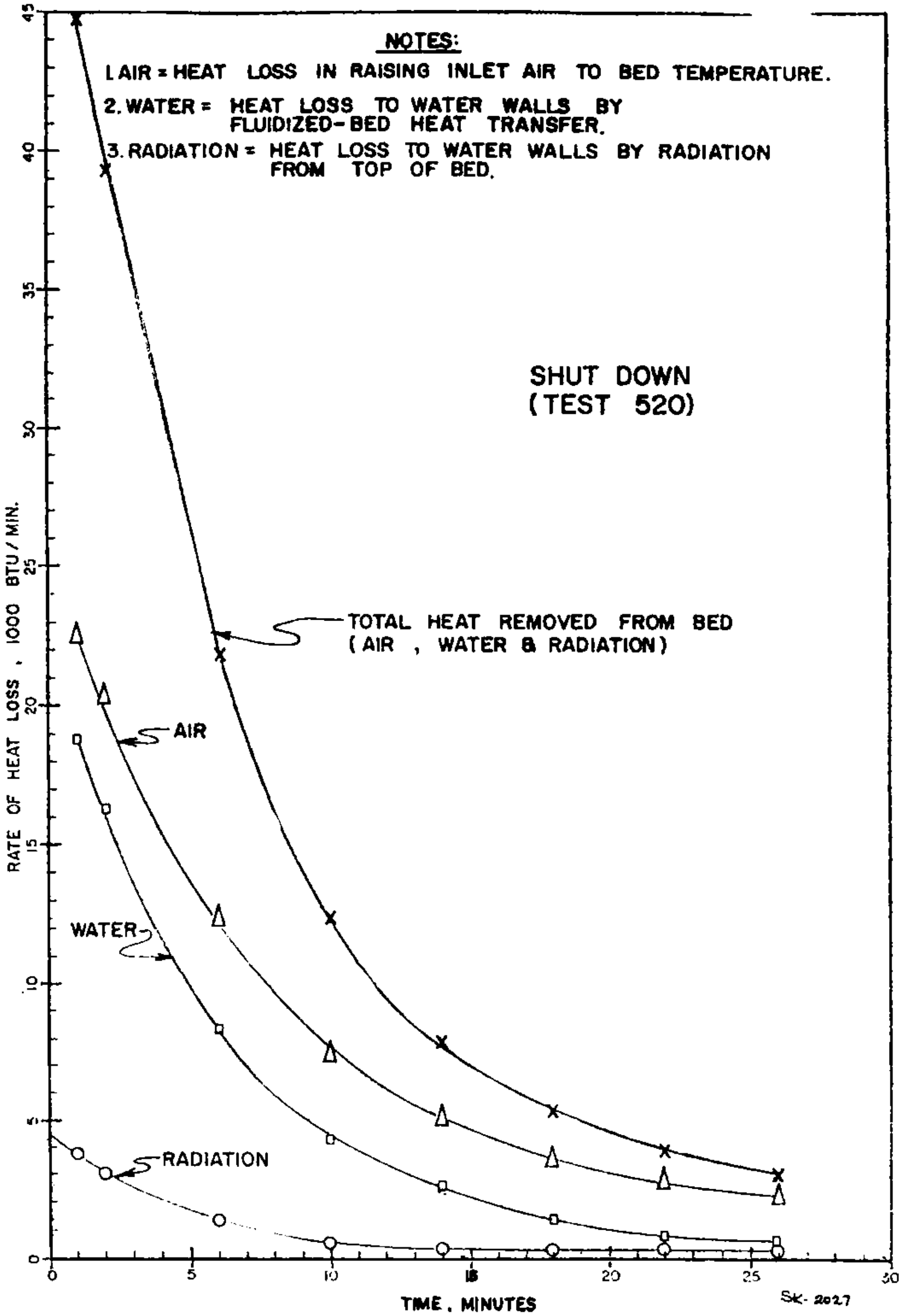

FIGURE C-2. SHUT DOWN , TEST 520

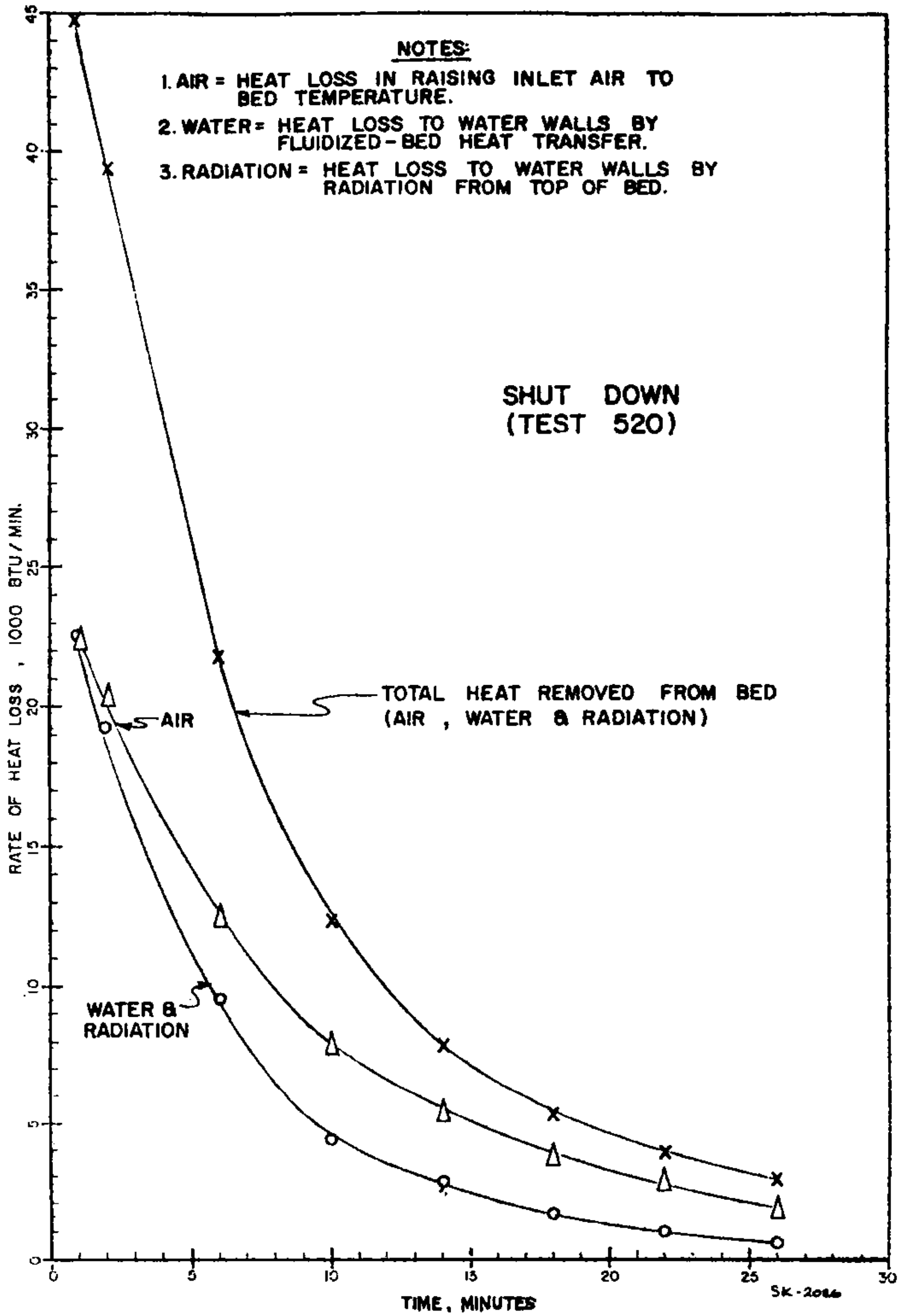

FIGURE C-3 SHUT DOWN, TEST 520

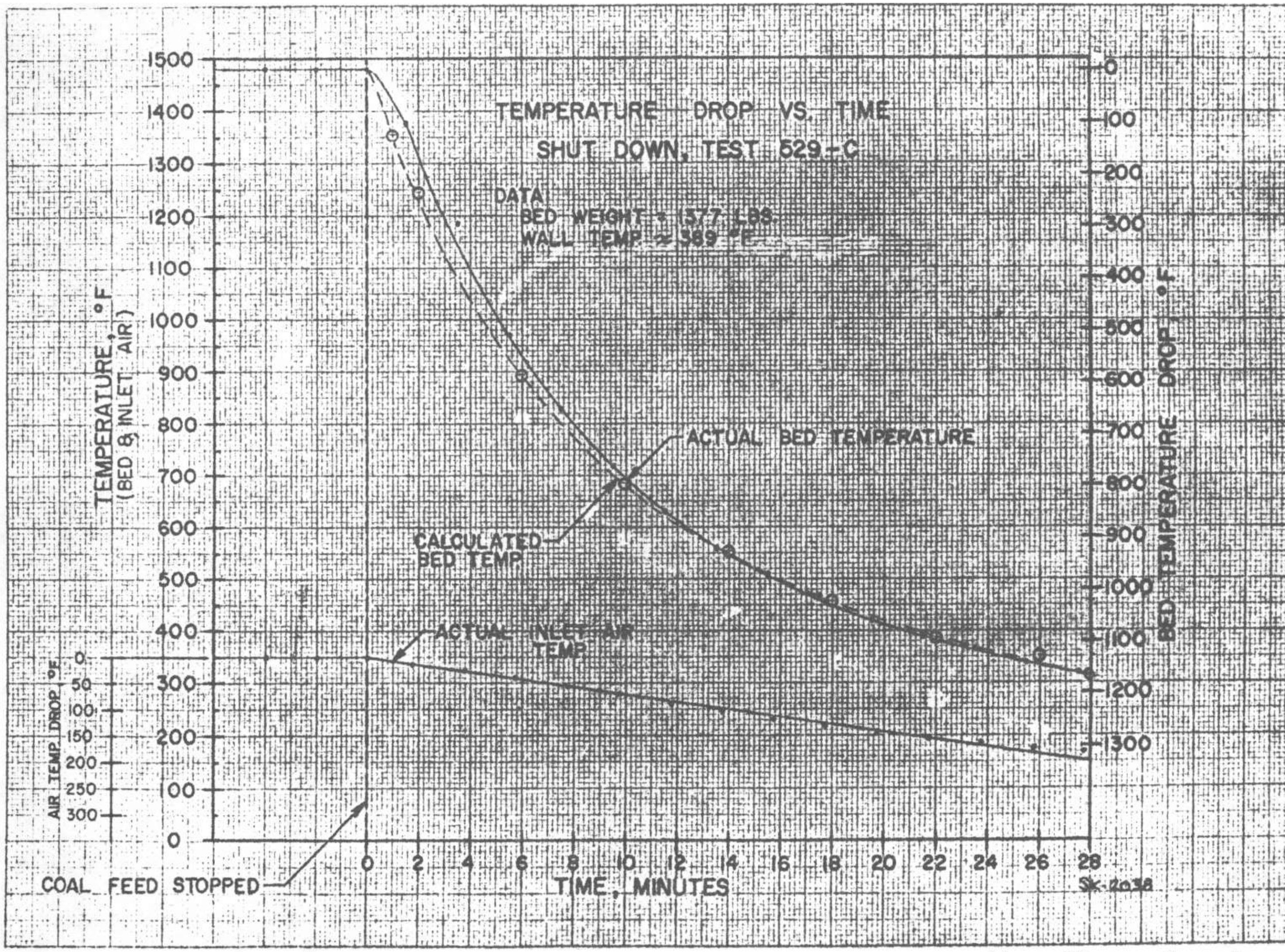

FIGURE C-4. TEMPERATURE DROP VS. TIME, TEST 529-C

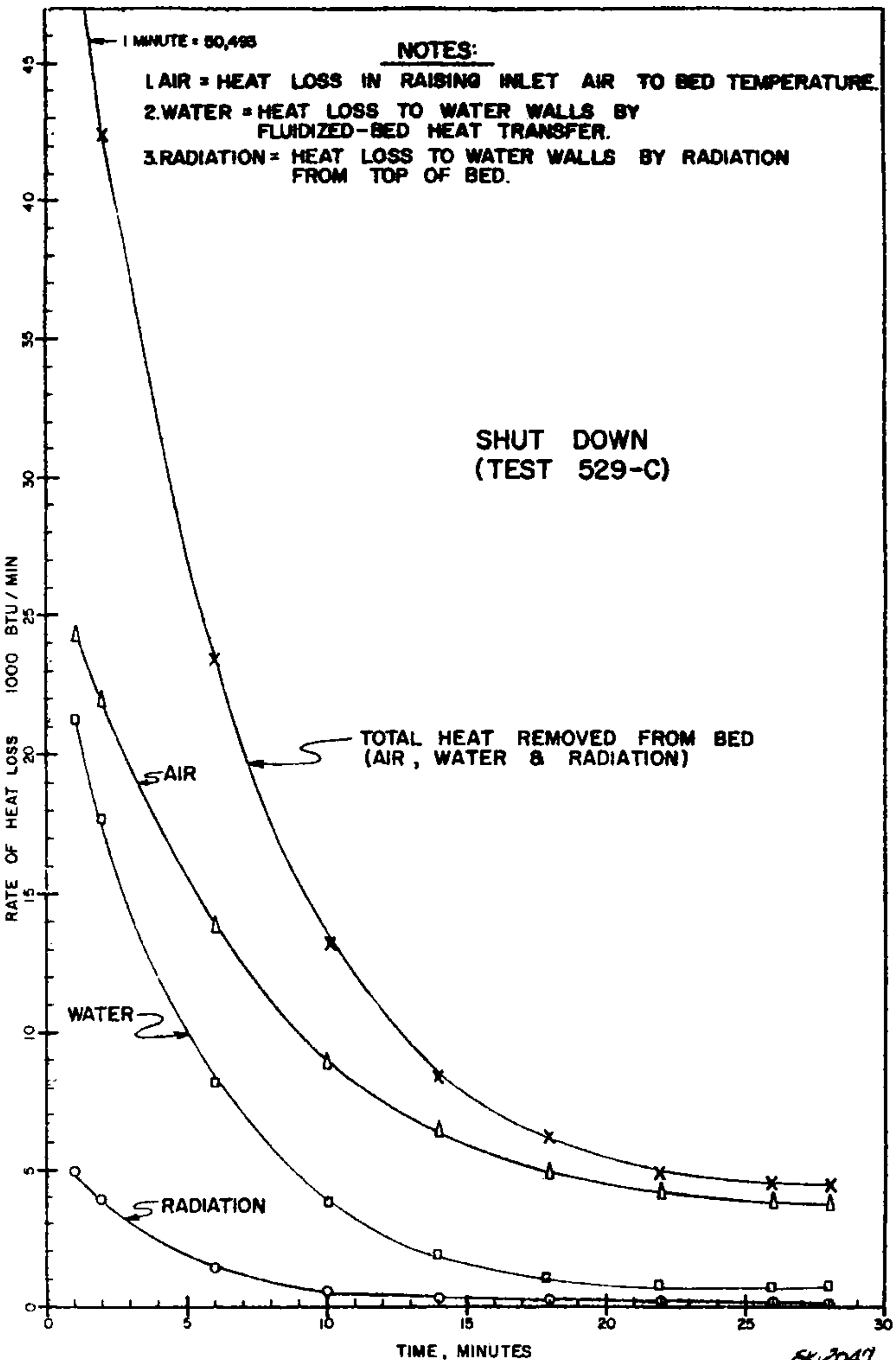

FIGURE C-5. SHUT DOWN, TEST 529-C

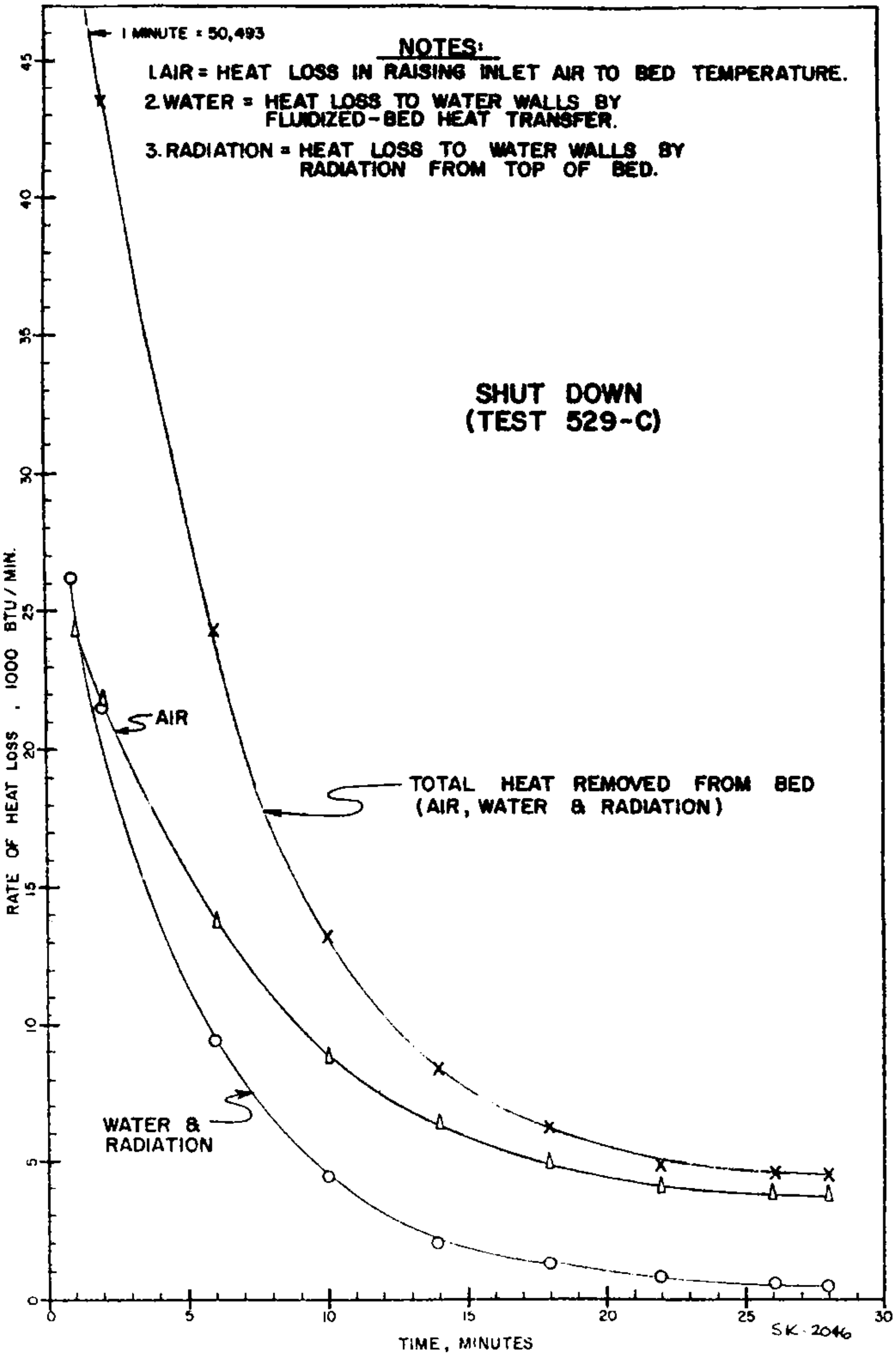

FIGURE C-6 SHUT DOWN, TEST 529-C

Appendix D. Leaching of Bed Material

PER has undertaken a series of experiments designed to determine the effects of water leaching on partially sulfated limestone and on coal ash. To date, three experiments have been completed.

A. Experiment No. 1

Bed material from Test 537 (Greer limestone) was divided into two groups, large rocks and small rocks (ash and bed). The samples were leached in both the crushed and uncrushed condition. In addition the leaching solution of the uncrushed samples were changed each day. The pH of the solutions was measured at the beginning of the experiment and at the end of each one (1) day time period using an Orion pH meter and pH electrodes. The meter was standardized each day with buffer solutions. The leaching solutions were distilled water, equilibrated with air.

The results of Experiment No. 1 are shown in Table D-1.

TABLE D-1
Leaching Experiment No. 1

pH Values[1]

Sample	0 Day	Day 1	Day 2	Day 3
Large Rocks[2] (uncrushed)	7.4	10.6	10.2	10.3
Small Rocks & Bed (uncrushed)	10.6	12.3	12.6	12.6
Crushed Large Rocks	--	9.1	10.0	10.2
Crushed Small Rocks	--	12.3	13.1	13.1

Notes:

[1] pH of leaching solution is measured by Orion pH meter and electrodes.

[2] Large rocks separated visually.

B. Experiment No. 2

Three different one gram samples of sulfated bed were leached in 250 milliliters of air-equilibrated, distilled water, for four days. At the end of that time, the solutions were filtered and tested for pH, Ca and Mg. The samples were uncrushed. The solid samples were also analyzed in the normal manner for Ca, Mg and sulfur.

The results of Experiment No. 2 are shown in Table D-2.

TABLE D-2
Leaching Experiment No. 2

Sample	A	B	C
Analysis of Samples			
Ca^{++}, percent by weight	22.6	24.6	32.1
Mg^{++}, percent by weight	Trace	Trace	0.83
S, percent by weight	11.3	10.6	7.04
Analysis of Solutions			
pH	11.5	11.8	11.5
Ca, mg	32.7	41.7	38.9
Mg, mg	0	0	0
SO_4, mg	--	--	--
Proportion Dissolved			
Ca^{++}, percent by weight	13.6	17.4	12.8
Mg^{++}, percent by weight	0	0	0
S, percent by weight	--	--	--

Sample Identification:
A Test 530-1550
B Test 530-1200
C Test 529

C. Experiment No. 3

A bed sample from Test 537 was divided into three groups-composite as received, magnetic portion and non-magnetic portion. The uncrushed samples were leached in distilled water for three days in closed vessels. At the end of three days the solutions were filtered and analyzed for pH, Ca^{++}, Mg^{++}, S and solubility. The solid composite sample was independently analyzed in the normal manner for Ca, Mg and sulfur. The results of Experiment No. 3 are shown in Table D-3.

TABLE D-3
Leaching Experiment No. 3

Sample	A	B	C
Analysis of Samples			
Ca^{++}, percent by weight	27.7	--	--
Mg^{++}, percent by weight	Trace	--	--
S, percent by weight	11.5	--	--
Analysis of Solutions			
pH	12.2	11.0	12.2
Ca^{++}, mg	145.8	29.8	133.9
Mg^{++}, mg	0	0	0
SO_4, mg	181.0	--	--
Insoluble percent	93.0	94.9	95.2
Proportion Disolved			
Ca, percent by weight	15.0	--	--
Mg, percent by weight	0	--	--
SO_4, percent by weight	12.2	--	--
Sample percent by weight	7.0	5.1	4.8

Sample Identification:
A Test 539 1605 Composite
B Test 539 1605 Magnetic
C Test 539 1605 Non-magnetic

D. Observations

1. All samples are alkaline.

2. High pH associated with small rocks and bed particles.

3. Smaller particles leach more completely than larger ones.

4. Less than 20 percent of the calcium is leached into solution.

5. Less than 15 percent of the sulfate is leached into solution.

6. Less than 10 percent of the samples is water soluble.

7. Magnesium does not leach out.

E. Comparison with BCURA Results

BCURA made the following observations in their November 1973 report to OCR.

1. "High pH (in the range of 10.5 to 11.6). The solution were therefore all alkaline."

2. "High or complete extraction of sulphate from the samples." PER observed much, much lower extraction of sulfate on the as-received sample.

3. "At least half of the calcium extracted from the samples." PER observed less than 20 percent extraction of calcium.

4. "Negligible extraction of magnesium." Magnesium extraction was not detectable in PER's test because

   (a) Greer stone is low in magnesium and

   (b) Extraction was low

Appendix E

Report 14-32-0001-1237-FWC-1

MULTICELL FLUIDIZED-BED STEAM GENERATOR DEVELOPMENT

Steam Generator Design, Systems Development and Model Testing

Foster Wheeler Corp.
110 South Orange Ave.
Livingston, New Jersey 07039

July 1974

Interim Report for Period June 1973 – June 1974

Prepared for
Pope, Evans and Robbins Incorporated
11 East 36th Street
New York, New York 10016

PREFACE

This report describes the development and design of a 300,000 lb/hr fluidized bed steam generator; the development of steam generator auxilliary systems and the development of a cold model test system for component design verification.

The work was carried out by Foster Wheeler Corporation as a sub-contract to Pope, Evans and Robbins, Inc. under the Office of Coal Research, Department of the Interior, USA Contract No. 14-32-0001-1237 beginning in June 1973 and scheduled for completion in January 1975.

The work described herein includes the engineering design and preparation of arrangement drawings for the fluidized bed demonstration unit scheduled for erection at Rivesville, West Virginia; preparation of specifications and solicitation of prices for auxilliary equipment directly attached to the steam generator; design of a calcium sulfate regenerator; preparation of a program for cold model testing to verify auxilliary systems design; and design, construction and testing of a 36 ft^2 cold test model.

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1.0 BACKGROUND AND WORK SCOPE

This interim technical report describes all work completed from the start of work on June 7, 1973 through May 31, 1974 under Foster Wheeler Corporation contract 2-58-2126 which is a sub-contract to Pope, Evans and Robbins, Inc. under the Office of Coal Research contract 14-32-0001-1237. The work under this contract involves the design of a 300,000 lb/hr capacity 1350 psig, 925F superheated steam generator burning coal in a fluidized bed of limestone for location at the Monongahela Power Company, Rivesville, West Virginia, the development and design of a calcium sulfate regeneration system and component testing for development support of the system design.

The work scope for this contract is divided into five phases which are defined as follows:

1.1 Phase I - Functional Design Study and Recommendations.

Undertake an engineering analysis of the 300,000 lb/hr capacity 1350 psig, 925F superheated steam generator design as submitted by Pope, Evans and Robbins, Inc. to determine (i) the functional adequacies of circulation and performance of the steam generator and (ii) the structural adequacy of the overall mechanical aspects of the design. Design modification recommendations resulting from this study will be reported.

1.2 Phase II - Engineering Work

1.2.1 Technical Specifications - Prepare a performance analysis of the steam generator arrangement resulting from the Phase I study to determine pressure part surface requirements, diameters, thickness, material requirements plus steam, air and gas pressure losses and boiler efficiency.

1.2.2 Arrangement drawings - Prepare arrangement drawings to show design dimensions and location of the steam generator pressure parts, inlet plenum, economizer outlet flue, insulation, casing and support steel. These arrangement drawings will contain sufficient information for a competent detailer to prepare shop fabrication drawings.

1.2.3 Bill of material - Prepare a complete bill of material to include quantities, sizes and material specifications for ordering material required for the steam generator resulting from item 1.2.2.

1.2.4 Purchase Specifications - Prepare requisitions for purchase of materials in item 1.2.3.

1.2.5 Fabrication and Erection Instructions - Prepare instructions for the shop or field erection of the steam generator specified in items 1.2.1 and 1.2.2.

1.3 Phase III - Equipment Specifications and Regenerator Design.

1.3.1 Equipment Specifications - Perform the following work:

A. Preparation of technical specifications, drawings and bid documents for equipment and piping system specialties directly attached to the steam generator or required for the safe and reliable operation of the boiler, including but not limited to: forced circulation pumps, safety valves, ignition burners, non-return valves, drain and vent valves, level gauges, valve and slide gate actuators.

B. Solicitation of price quotations (bids) including delivery schedules, from a minimum of three(3) manufacturers or suppliers for each of the items included under paragraph 1.3.1A.

C. Analysis and evaluation of the submitted price quotations and delivery schedules, selection and recommendation of vendors for the purchase of equipment required and described under paragraph 1.3.1A based on price quotations received, competence of vendors, delivery dates and suitability of the equipment offered for the intended purpose, in order to realize the greatest possible benefit to the Government.

1.3.2 Regenerator Design - Design of a calcium sulfate regenerator system for use with the steam generator designed under Phase II. Such design is to be based on test information received from Pope, Evans and Robbins, Inc.

1.3.3 Regenerator Arrangement Drawings - Prepare detailed engineering arrangement, equipment, flow and material balance drawings plus technical specifications and bid documents for solicitation of fabrication and installation construction subcontract cost proposals (bids) for the regenerator design completed under paragraph 1.3.2.

1.4 Phase IV - Design Concept Selection.

Perform an engineering study to select the best design concept or concepts for equipment required for (i) fuel metering and injection, (ii) bed material extraction, classification, transfer, regeneration and injection; (iii) ignition. Based on the recommended concepts from the above analysis, a test program will be developed to demonstrate the operation of any equipment applications that are not presently in commercial use or to demonstrate the operation of any new equipment requiring development. A report will be prepared defining each test to be performed and will include necessary test data requirements, instrumentation and equipment requirements, schedules and cost estimates.

1.5 Phase V - Cold Test Model.

Prepare a design for and erect a cold test model to perform necessary development tests as determined under Phase IV. The work of Phase V involves the following tasks:

1.5.1 Task 1 - Prepare a detailed design for a fluidized bed cold test model and associated test equipment and instrumentation. The plan area of the test fluidized bed will be approximately 36 square feet.

1.5.2 Task 2 - Solicit bids for material and equipment required in the fabrication and erection of the test model and purchase such materials and equipment based on the best bids.

1.5.3 Task 3 - Fabricate, erect and instrument the test model in the Foster Wheeler Corporation Research Facility.

1.5.4 Task 4 - Perform the following tests required for the test program developed in Phase IV:

A. Air distribution plate designs selected in Phase IV will be tested in the model to determine if uniform fluidization can be obtained and that no plugging of flow ports or back flow of bed material occurs. The best candidate distribution plate design will be selected based on the results of these tests with due consideration given to cost of manufacture of the plates.

B. Various tube bundle arrangements selected in Phase IV, differing in transverse and longitudinal pitch, will be tested in the cold model to study the effects on fluidization. Distance from the distributor plate to the bottom of the tube bundle will be varied in these tests. Initial testing in this task will consist of screening tests in existing small (5" x 20") essentially two dimensional cold fluidized bed model so that obviously poor arrangements can be eliminated from further consideration at minimum expense.

C. Various fuel injection arrangements selected in Phase IV will be tested for efficient distribution of fuel within the model bed when the bed contains the optimum tube arrangements selected according to paragraph 1.5.4B. Based on the results of these tests some adjustment may be made in the distance from the distributor plate to the bottom of the tube bundle.

D. Schemes for removing and re-injecting bed material will be tested, with particular attention given to removal of oversized and heavy particles from the bed. It is anticipated that a sloped distribution plate will be tried as a means of concentrating heavy and/or oversized particles in one area for ease of removal.

E. As a step toward devising a practical light off method for fluidized beds containing tube bundles, tests will be made to see if suitable local fluidization can be established in one zone of the bed from which heating surface has been omitted while the remainder of the bed remains relatively quiescent. It is anticipated that this may provide a means to readily ignite one zone of the bed from which ignition can be propagated upon complete fluidization of the entire bed.

1.5.5 Task 5 - Design, procure materials for, erect and test an ash feed system to determine operating characteristics for the fly ash re-injection system required for carbon burn-up cell fuel injection.

2.0 WORK COMPLETED - PHASE I

Specifications, design calculations and engineering drawings for a "Multicell Fluidized Bed Boiler" were submitted for analysis by Pope, Evans and Robbins, Inc. The submitted specifications define a natural circulation steam generator with a capacity of 300,000 lb/hr at 925F outlet temperature and 1270 psig designed for the fluidized bed combustion of coal in a bed of limestone at 1550F. The submitted steam generator design was analyzed to check the circulation, performance and mechanical aspects of the design. As a result of this analysis and based on current commercial manufacturing methods, recommendations for design modifications were submitted to Pope, Evans and Robbins, Inc. (PER) in an interim report on September 6, 1973. The results of the work completed under Phase I are described in the following paragraphs.

2.1 Analysis of submitted design.

Based on the design parameters listed in Table E-1, the submitted fluidized bed steam generator design has been analyzed with respect to the performance, circulation and mechanical aspects. The results of this analysis are as follows:

2.1.1 Performance - For the fluidized bed design to operate successfully, the velocity of the gases must be maintained at the proper level to provide good fluidization, sufficient air for combustion and good SO_2 absorption. Also, the operating bed temperature must be maintained at 1450-1550F for maximum SO_2 absorption. The fluidized bed is characterized by isothermal operation with a relatively constant heat transfer coefficient and, in accordance with PER's instructions, this coefficient has been set at 40 Btu/hr, sq ft, F for the unit design. With the above parameters in mind, the heat input to the fluidized bed must be balanced against the heat absorbed by the tube surfaces and the heat leaving with the flue gas to maintain a 1550F temperature. The heat input to the bed includes the preheated combustion air and fuel heat release, and the heat leaving the bed includes the sensible heat of the flue gas plus miscellaneous heat losses. If the fluidizing velocity, air preheat temperature and excess air parameters are fixed, the amount of fuel heat input is also fixed at the value required for proper combustion. Since the above values, including the heat transfer coefficient, have been fixed, the only variable remaining for design of the fluidized bed, is the amount of heat transfer surface located in the bed zone. Figure E-1 indicates that the submitted design would be adequate for a heat transfer coefficient of 57 Btu/hr, sq ft, F, however, theory has shown a lower coefficient would be anticipated for horizontal tubes. The use of a heat transfer coefficient of 40 Btu/hr, sq ft, F would result in a bed temperature of approximately 1800F.

Table E-1

Fluidized Bed Combustion

Design Parameters

Primary Bed

Operating temperature - - - - - 1550F
Superficial gas velocity - - - 12 ft/sec
Static Bed Depth - - - - - - - -24 inches
Overall Heat Transfer coefficient
to 48" above air distribution grid - - 40 Btu/hr, sq ft,F
40% of lime feed leaves with dust products
60% of lime feed leaves with bed tap products
10% sulfur input escapes as SO_2
90% sulfur input captured as $CaSO_4$
100% of fuel ash leaves with dust
0% carbon contained in bed tap products
90% combustion efficiency (10% of total fuel heat input escapes with dust)
85% of available heat released to bed (to 4 ft above grid)
15% of available heat released to Free Zone
Design for 3% excess O_2 in off-gas

Carbon Burnup Cell (CBC)

Operating temperature - - - - 2000F
Superficial gas velocity - - 9 - 10 ft/sec
Static bed depth - - - - - - 24 inches
Overall heat transfer coefficient to 48" above air distribution grid - 40 Btu/hr, sq ft, F
Excess air - - - - - - - - - 25%
90% Combustion efficiency

Figure E-1

Primary Bed Heat Balance
(based on design calculations submitted by PER)

Total heat input to primary furnace (from fuel and air preheat) = 362,048,700 BTU/hr

Total boiling heat surface in primary bed = 1167.7 + 287.2 = 1454.9 Ft^2

MTD boiling surface = 1550 - 592 = 958 F

Total superheater surface in primary bed = 2005 Ft^2 MTD = 746 F

Total heat absorbed from primary bed is as follows:

(1454.9 Ft^2)(40 Btu/hr, sq ft, F)(958F) +

(2005 Ft^2)(40 Btu/hr, sq ft, F)(746F) = 115,581,000 Btu/hr

Total heat leaving primary bed in off-gas at 1550F as follows:

Sensible heat in Flue gas @ 1550F = 402.75 Btu/lb
Flue gas flow = 319,588 lb/hr

(402.75 Btu/lb)(319,588 lb/hr) = 128,714,000 Btu/hr

Heat losses charged to primary bed:

Radiation loss	1,120,900 Btu/hr
Manufacturers Margin	5,592,800
Moisture in Air Loss	14,094,000
	20,807,700 Btu/hr

Summation of bed heat distribution:

Absorbed by heating surface	115,581,000 Btu/hr
Heat in off-gas	128,714,000
Heat losses	20,807,700
Total heat used in primary bed	265,102,700 Btu/hr

With 85% of the primary furnace heat released in the fluidized bed zone, the total heat input to the bed is as follows:

.85(325,453,300 Btu/hr) + (36,595,400) = 313,230,700 Btu/hr

The 265,102,700 Btu/hr heat distribution does not account for the 313,230,700 Btu/hr heat input to the bed; therefore, the bed temperature would increase to achieve a heat balance. Iterating the above figures results in a heat balance with a bed temperature of approximately 1800F. A 1550F temperature would be achieved if the heat transfer coefficient were 57 as against 40 Btu/hr, sq ft, F specified.

Therefore, the proportion of heat transfer surface located in the bed zone must be revised to maintain the bed temperature at 1550F. In order to operate at the lower bed temperature, additional heating surface must be added to the bed zone and, therefore, this zone will require redesign.

2.1.2 Circulation - During the operation of a steam generator there must be a continous supply of water delivered to the inlet of the steam generating tubes in order that the output of the unit be sustained. This supply of water is termed the "circulation" in the unit. Adequate circulation occurs when there is sufficient flow of water into a circuit to provide for safety of the heated tubes. Two classes of circulation are recognized. Their identification depends on the source of the force which is required to move the water and steam-water mixture through the circulation system:

1) Natural circulation, in which the motivating force is an invisible thermal pump, and

2) Forced circulation, in which the motivating force is derived partly from the invisible thermal pump and partly from a mechanical pump.

In a natural circulation system, the rate of flow that can be produced is governed by flow resistance and differences in density between the downcomer circuit and the upward flowing, heated circuits. Control of these resistances will enable the designer to apportion an adequate flow of water to parallel circuits.

The design submitted by HER uses the natural circulation method with five partition and enclosure walls of riser tubes located along the length of the drum. For the analysis of the circulation characteristics of this design, the tubes receiving the most heat were selected. The arrangement and dimensions of the selected circuit are shown on Figure E2. The location of the selected circuit is shown on Figure E3 in the upper left hand corner. This particular circuit was expected to receive more total heat than the tubes forming the outside wall or the tubes forming the "wall" at the centerline of the unit.

A computer analysis of the static and frictional pressure characteristics of the selected circuit was performed to

CIRCULATION ANALYSIS

CIRCUIT DESCRIPTION

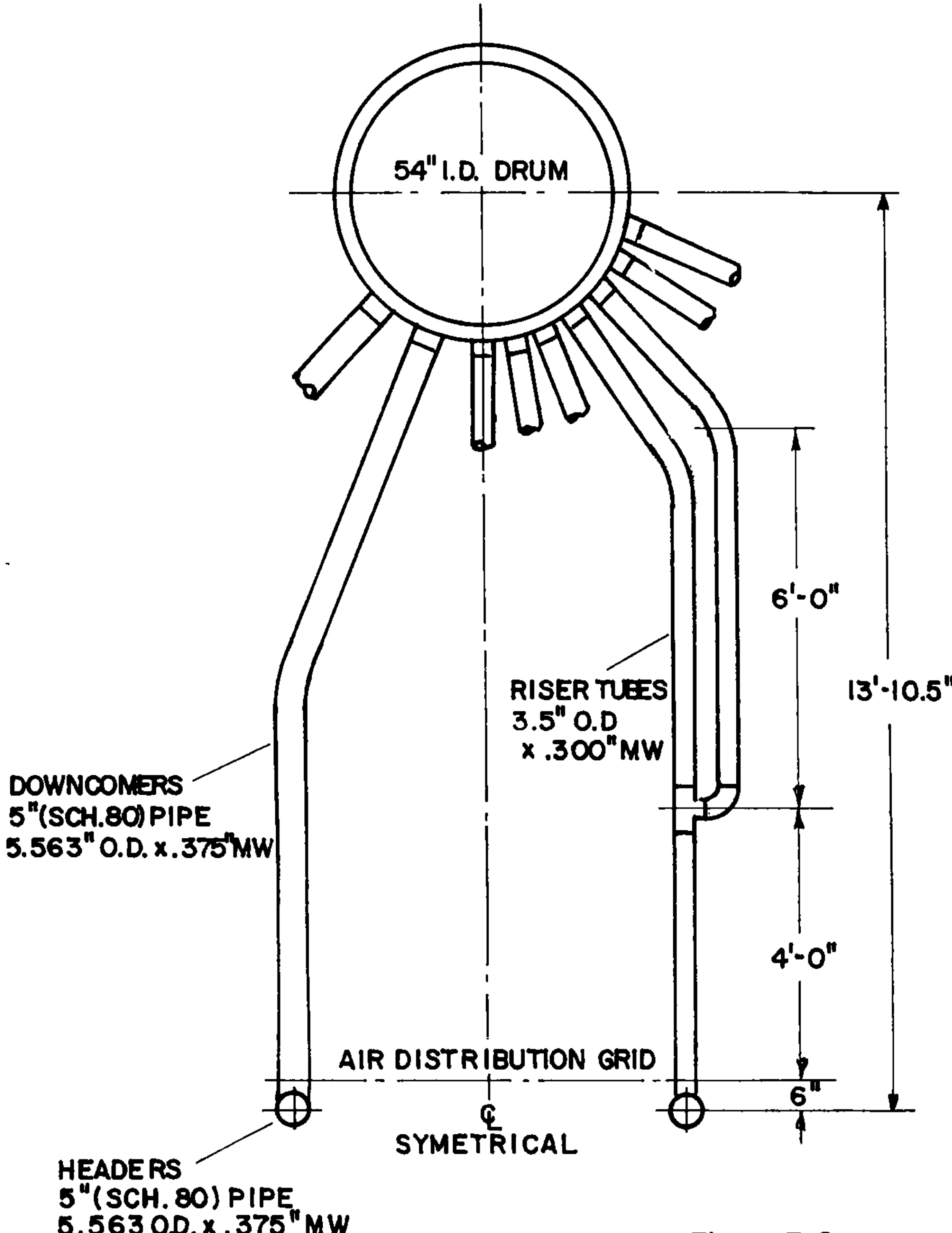
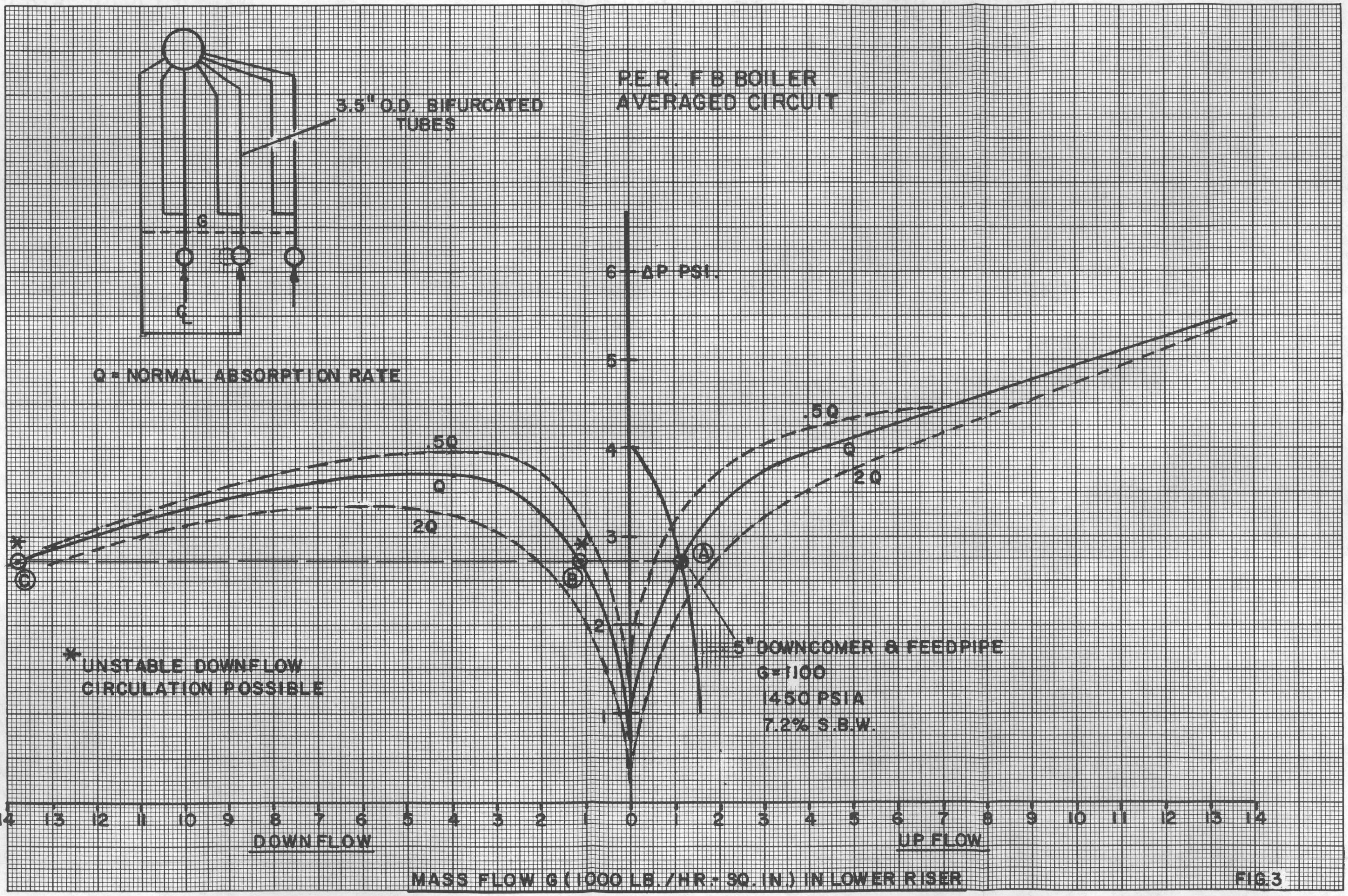


Figure E-2



P.E.R. F B BOILER
AVERAGED CIRCUIT
3.5" O.D. BIFURCATED TUBES
G
Q = NORMAL ABSORPTION RATE
ΔP PSI.
.5Q
Q
2Q
A
B
C
*UNSTABLE DOWNFLOW CIRCULATION POSSIBLE
5" DOWNCOMER & FEEDPIPE
G=1100
1450 PSIA
7.2% S.B.W.
DOWN FLOW
UP FLOW
MASS FLOW G (1000 LB./HR.-SQ.IN.) IN LOWER RISER
FIG.3

FIGURE E-3

determine if stable flow conditions should be expected throughout the circuit. Based on this analysis Figure E-3 is a plot showing the predicted flow characteristics of the chosen circuit for the expected absorption rate and for one-half and twice the expected absorption rate. Plotted thereon is a curve of the available pressure head with the 5" downcomer and feeder pipes. This curve intersects the expected absorption rate at the solution point for the particular circuit investigated. This solution point for the total circuit flow shows an acceptable 7.2% steam by weight at the outlet of the circuit tubes. The intersection, Point A, at 1100 lbs/hr -sq.in. indicates that the thermal pumping action through the circuit tubes due to the heat absorbed equals the pressure available in the unheated section of the circuit. This intersection is on the upflow side of the curve but there are also two other operating points, points B and C, at which the circuit could also operate and these points are on the downflow side of the curve. This indicates that an unstable flow condition is possible where some of the circuit tubes may operate in the downflow condition. This is an unacceptable condition since the behavior of the circuit would be unpredictable and its action could not be exactly defined. Because an unstable flow condition is predicted, the circuit tubes would be subjected to cycling, stagnation and/or starvation and may overheat thus leading to subsequent failure.

In addition to the possible unacceptable flow condition outlined above, there are other aspects of the submitted design in the circulation and steam drum areas that need modifications.

The steam drum of the submitted design (60" OD x 3" wall) is oversized. A 48" OD x 2.5" wall size is more than adequate for the required steaming capacity and pressure conditions. The 60" OD drum size is approximately 42% heavier than the 48" OD drum, thus resulting in unnecessary costs.

Experience has indicated that a downcomer arrangement with multiple connections at each end of the drum, would lead to the formation of strong vortexes at these locations. This would result in the undesireable capture of steam vapor in the downcomers, robbing the circuit of its natural circulation capability.

The central location of the drum over the unit centerline and the arrangement of heating surface in the flue gas stream beyond the drum in the submitted design, makes this highly susceptible to drum expansion and stress problems especially during the start-up procedure (and shut down) when transient heating of the drum, in sections, by gases at a relatively high temperature differential with the drum surface, occurs. This temperature differential is in the order of 1200F.

2.1.3 Mechanical - Modern manufacturing methods and procedures for forming and fabricating steam generator pressure components involve the use of automatic bending and welding equipment. The use of automated fabrication techniques ensures consistent, high quality results while reducing manufacturing time and costs. The submitted design includes the use of multiple, welded pipe fittings which require manual welding for fabrication. For example, the superheater bends require at least one manual weld in order to incorporate the 180 degree bend, whereas, this bend is accomplished automatically without welds on a modern tube bending machine.

In addition, the submitted design includes many bifurcates and trifurcates which could be a source of uneven flow distribution that could lead to unstable boiler circuit conditions.

The arrangement of superheater surface in the submitted design requires threading each tube through five walls of boiler surfaces resulting in fabrication, erection and maintenance difficulties as well as requiring the weld mentioned above for every superheater tube that crosses the boiler width. Also, the superheater tubes are supported by the membrance fin at the center and side walls and continuous movement of these tubes, due to unit operation, relative to the membrane fins would result in chafing of the tube material. The superheater tubes pass through a casing seal mechanism prior to connecting to the headers. These seals are bolted (not welded) and, therefore, are not easy to make gas tight. Leakage would result in burnout of the casing material in the high-temperature fluidized bed zone.

In the submitted design, only the boiler drum is supported at its ends by beams hung from the building steel. The economizer is supported by the casing above the steam drum. This casing is seal welded to the boiler enclosure walls by use of a scalloped bar. However, this scalloped bar is not a structural member and there are no visible means of support for the enclosure walls or the superheater tubes and headers supported by these walls.

2.2 Recommendations

The design analysis, Paragraph 2.1, indicates that problems in the performance, circulation and mechanical areas would be encountered with the submitted design. The following summarizes the major recommendations resulting from the design analysis:

1. Performance - The assignment of heating surface area to the various unit furnctions should be revised to obtain appropriate operating temperature based on the heat transfer coefficient selected for horizontal surface. Therefore, it is recommended that the surface adjustment be accomplished by a change in unit design that better reflects the present concept of a utility sized fluidized bed boiler.

2. Circulation - Horizontal boiler surface resulting from the above recommendation will require the use of a forced circulation pump.

3. Mechanical - It is recommended that the drum be located over the front wall of the unit to simplify piping arrangements and eliminate stress problems associated with a drum exposed to hot flue gases.

As a result of the above recommendations, the pressure part design for the demonstration unit has been redesigned to approximate the utility unit concept developed since the completion of the submitted design. This has been done to minimize any difficulties in scaling up from the demonstration unit size. The design developed herein has been arranged based on two main objectives; (1) The bed plan dimension should be as large as possible and (2) The unit should be divided into cells with separate heating functions.

2.3 Description of Recommended Design.

Table E-1 is a list of the basic design parameters based on information given by PER and upon which the design of the unit is governed. Using the parameters and the objectives mentioned in Paragraph 2.2 the layout of the unit was established. The unit was divided into separate cells, three of which were almost equal in size with the fourth cell (the CBC) smaller in width due to its own design parameters. The dimensions of the cells were influenced by shipping limitations, duty requirements, and the anticipation of the use of this particular cell (or module) size or a mutation of it, in the future, for building up to larger unit sizes.

The four cells with separate heating functions are called the finishing superheater, primary superheater, boiler and Carbon Burnup Cell (CBC). How they were formed will be explained later. Figure E4 is a schematic showing the arrangment of the new design and the location of the different types of heat transfer surface and functions. The economizer sections are counterflow (the hot flue gas passes up through the bank while, in the opposite direction, the cold economizer water flows down through the tubes) and in series so that the feedwater enters Economizer 1 and flows through Economizer 2, 3 and 4 in order. The boiler function consists of five sections operating in parallel. Boiler sections 1 through 4 are shown in Figure E4 with the fifth section consisting of the enclosure and partition walls. The partition walls between the cells are the membrane type, i.e. finned tubes without refractory protection. Since the boiler sections contain horizontal tubes receiving heat, a forced boiler water circulation pump has been included to maintain the necessary circulation rate through these horizontal tubes.

Figure E5 is a schematic of the circuitry of the new unit design. The circuitry includes an economizer recirculation line and control valve to ensure economizer flow during start-up as well as an attemporator spray for emergency superheater temperature control. Figure E6 (EG-5-339A) is an isometric schematic of the unit showing flow of the fluid from the boiler feed pump inlet to the finishing superheater outlet.

In addition to the two main objectives stated earlier, there are other items that must be proved; multicell operation with all the necessary controls that go with it, ability to light off one cell after the other and the ability to provide means of load control in a fluidized bed multi-cell unit by varying the bed depth, bed temperature, fuel rate, gas velocity, etc. To accomplish this, the new unit arrangement has been designed to allow for sequential start-up beginning in the CBC and progressing to the adjoining cell until all four cells are in operation. The cells are separated by finned tube partition walls, each containing an opening above the distribution grid. These openings may be opened to allow communication between cells during start-up or closed to permit changing bed level or temperature in individual cells for control function. Load turn-down is accomplished by changing the bed temperature and level within the feasible operating limits. Further turn down may be accomplished by removing the primary superheater cell from service while continuing to fire the remaining cells.

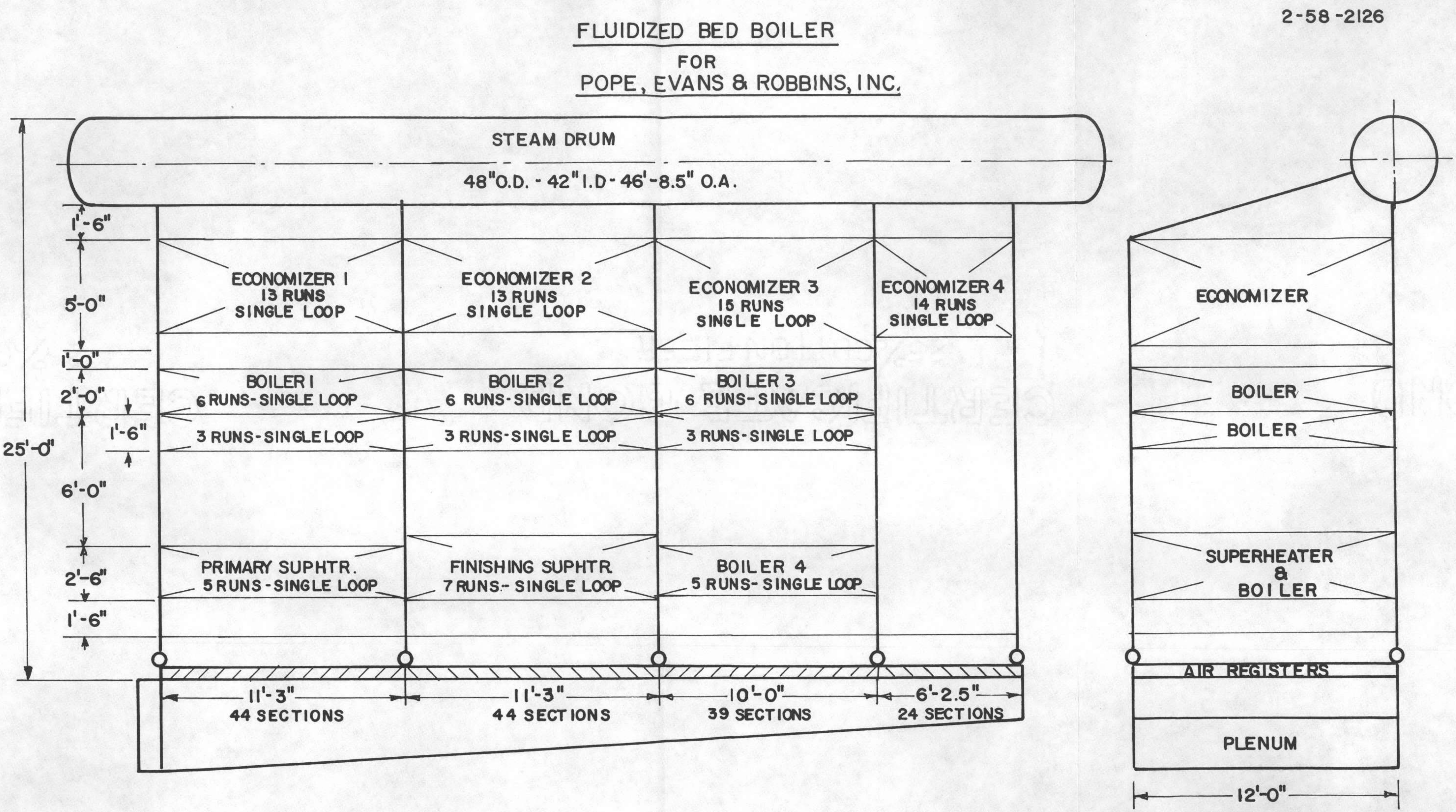


FIG. 4

7/26/73

FIGURE E-4

FLUIDIZED BED STEAM GENERATOR CIRCUIT SCHEMATIC

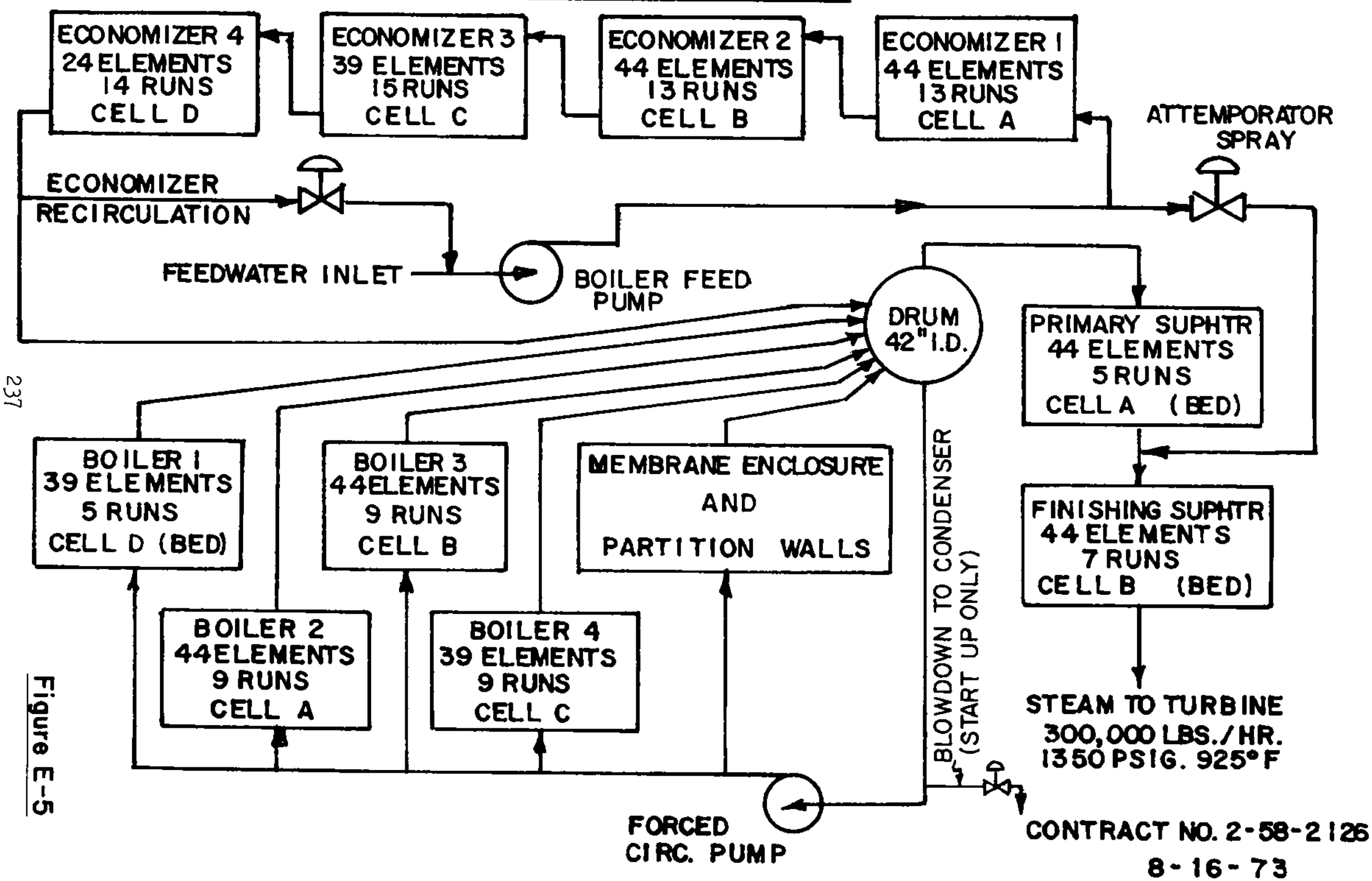


Figure E-5

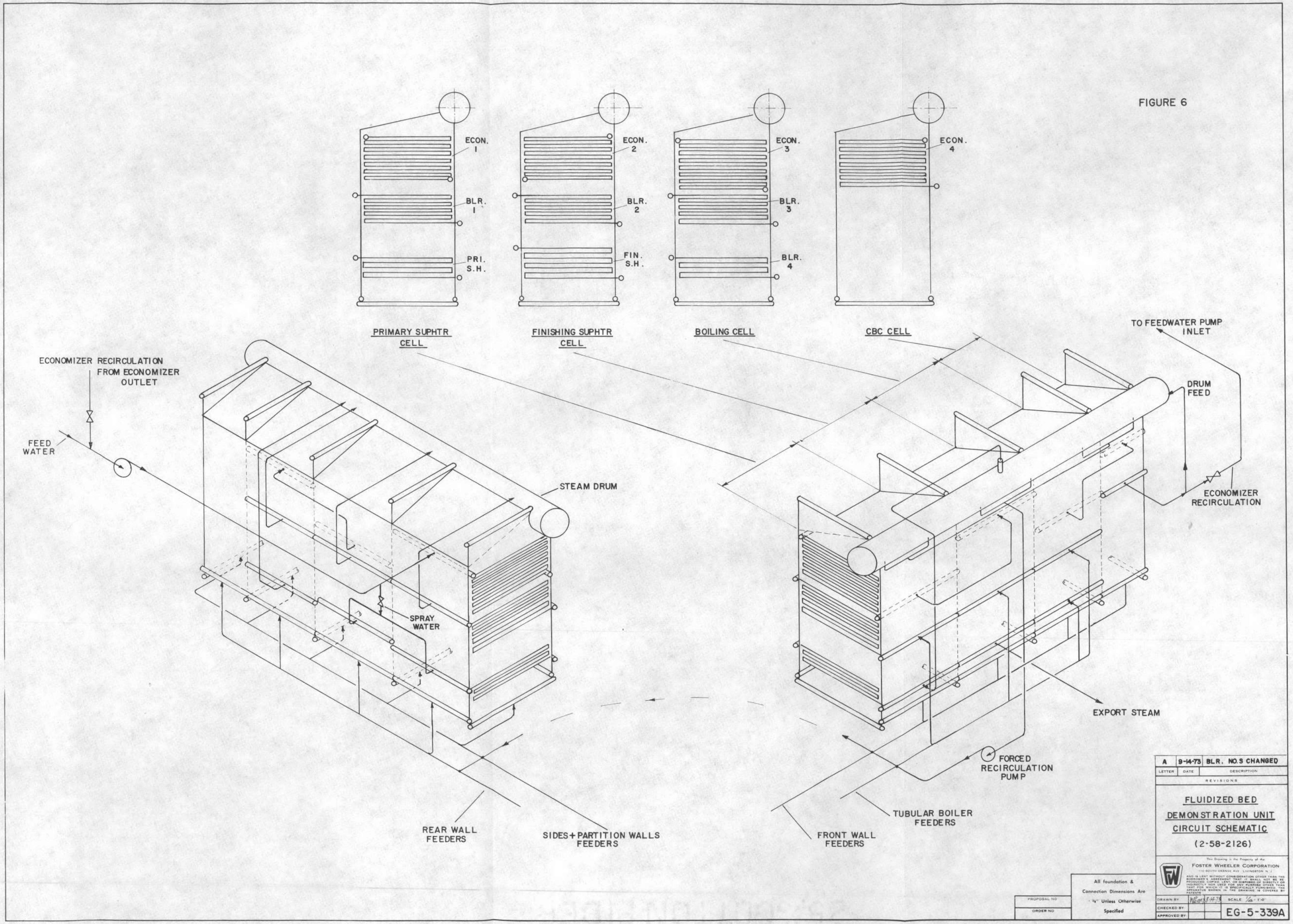


FIGURE 6
ECON. 1
BLR. 1
PRI. S.H.
ECON. 2
BLR. 2
FIN. S.H.
ECON. 3
BLR. 3
BLR. 4
ECON. 4
PRIMARY SUPHTR CELL
FINISHING SUPHTR CELL
BOILING CELL
CBC CELL
TO FEEDWATER PUMP INLET
ECONOMIZER RECIRCULATION FROM ECONOMIZER OUTLET
FEED WATER
DRUM FEED
ECONOMIZER RECIRCULATION
STEAM DRUM
SPRAY WATER
EXPORT STEAM
FORCED RECIRCULATION PUMP
TUBULAR BOILER FEEDERS
REAR WALL FEEDERS
SIDES + PARTITION WALLS FEEDERS
FRONT WALL FEEDERS
A 9-14-73 BLR. NO.S CHANGED
LETTER DATE DESCRIPTION
REVISIONS
FLUIDIZED BED
DEMONSTRATION UNIT
CIRCUIT SCHEMATIC
(2-58-2126)
This Drawing is the Property of the
FOSTER WHEELER CORPORATION
110 SOUTH ORANGE AVE LIVINGSTON N. J.
AND IS LENT WITHOUT CONSIDERATION OTHER THAN THE BORROWER'S AGREEMENT THAT IT SHALL NOT BE REPRODUCED, COPIED, LENT, OR DISPOSED OF DIRECTLY OR INDIRECTLY NOR USED FOR ANY PURPOSE OTHER THAN THAT FOR WHICH IT IS SPECIFICALLY FURNISHED. THE APPARATUS SHOWN IN THE DRAWING IS COVERED BY PATENTS
All foundation & Connection Dimensions Are ± 1/8" Unless Otherwise Specified
PROPOSAL NO
ORDER NO
DRAWN BY
SCALE 1/4" = 1'-0"
CHECKED BY
APPROVED BY
EG-5-339A

FIGURE E-6

The following analysis will provide the reasoning behind the unit redesign in the areas of performance, circulation and mechanical design:

2.3.1 Performance - Figures E-7 through E-12 show the calculations for the heat absorption duties for the economizer, boiler and superheater sections of the steam generator, the unit efficiency and the heat balance of the entire unit including the assignment of required heating surface for the various duties. Once it was decided to sectionalize the unit into multiple cells, it was necessary to make some decisions on the distribution of heating surface based on engineering judgement. Individual cell heat balance calculations indicated that additional heating surface should be provided in the fluidized bed zones. The amount of additional surface desired, made it impractical to add as vertical tubes, therefore, the switch to horizontal tubes was made. The same analysis applies to the boiler surface located above the bed zone.

The decisions on distribution of heating surface were made as follows (see Figure E5 for cell identification):

1. No horizontal heating surface in the bed zone of the CBC (for fuel ignition reasons), only economizer surface in the convection zone.

2. Cell C, next to the CBC and first cell to be ignited after the CBC, to have horizontal boiler surface in the bed zone as well as in the convection zone.

3. Superheater surface to be split 50-50 between primary and finishing sections and located in the bed zone.

4. Cell B to have horizontal bank of finishing superheater surface in bed zone with horizontal boiler surface in convection zone.

5. Cell A to have horizontal bank of primary superheater surface in bed zone with horizontal boiler surface in convection zone.

6. Horizontal economizer surface will be in convection zone of cells A, B, C and D and

FIGURE E-7

UNIT OUTPUT AND EFFICIENCY SUMMARY

Conditions - Boiler Feed Water - 290,000 lb/hr @ 385 F & 1545 psia
- Spray Water - 10,000 lb/hr @ 385 F & 1545 psia
- Superheater out - 300,000 lb/hr @ 925 F & 1365 psia

	Temperature	Pressure	Enthalpy
Economizer in	385 F	1545 psia	358 Btu/lb (L)
Economizer out	545 F	1515 psia	543 Btu/lb (L)
(.29 mm lb/hr), Δ's	160 F	30 psia	185 Btu/lb
Boiler in (Sat'd - 50°)	545 F	1515 psia	543 Btu/lb (L)
Boiler out (Sat'd.)	595 F	1485 psia	1168.7 Btu/lb (V)
(.29 mm lb/hr), Δ's	50 F	30 psia	625.7 Btu/lb
Superheater in	595 F	1485 psia	1168.7 Btu/lb (V)
Superheater out	925 F	1365 psia	1449.6 Btu/lb (V)
(.29 mm lb/hr), Δ's	330 F	120 psia	280.9 Btu/lb
Spray in	385 F	1545 psia	358 Btu/lb (L)
Spray out	925 F	1365 psia	1449.9 Btu/lb (V)
(.01 mm lb/hr), Δ's	540 F	180 psia	1091.6 Btu/lb

Economizer Duty Q = .29 mm lb/hr x 185 Btu/lb = 53.6 mm Btu/hr
Boiler Duty Q = .29 mm lb/hr x 625.7 Btu/lb = 181.8 mm Btu/hr
Superheater Duty Q = .29 mm lb/hr x 280.9 Btu/lb +
.01 mm lb/hr x 1091.6 Btu/lb = 92.4 mm Btu/hr
Total output 327.8 mm Btu/hr

Efficiency

	Losses as Fired	PER
Unburned Carbon	1.45	1.45
Moisture in fuel	3.86	4.42
Wet Gas Losses	4.36	4.30
Radiation	0.33	0.33
Mfg. & Unacc.	1.50	1.50
Solids Losses	0.56	0.00
	12.06	12.00
Efficiency	87.94%	88.00%

Key

mm = millions
Δ's = differences
Q = heat duty, Btu/hr
HHV = higher heating value, Btu/lb of coal
AH = air heater
L = liquid
V = vapor

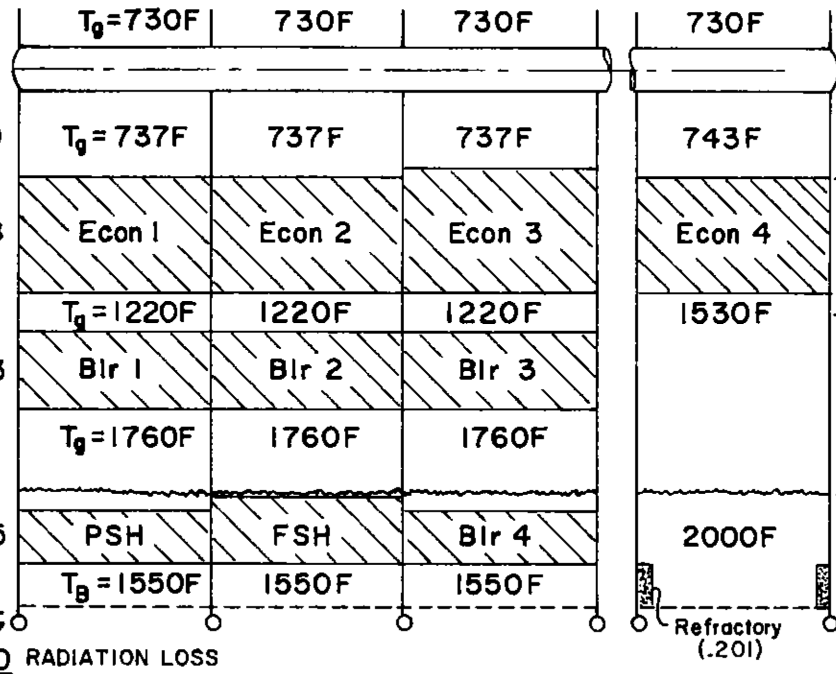
Required output - 327.8 mm Btu/hr
Required input - 372.6 mm Btu/hr
Fuel Rate - 28,700 lb/hr

Based on Pittsburgh Seam No. 8 Coal, 13,000 Btu/lb HHV, 270F uncorrected Gas temperature leaving A.H. and 100F air temperature entering AH.

DUTY BUDGET - PHASE I

Enclosure Wall Duty
Primary Cells

Height = 23 ft.	U_o	$\left(\frac{S_o}{1000}\right)$	$\left(\frac{\Delta T}{1000}\right)$	$= Q_w$
4.5'	5	.880	.138	.60
5'	7	1.132	.375	2.98
1.5' / 3.5'	10	.756	.890	6.73
4.5'	13.5	.850	1.055	12.11
4'	50	.756	.950	36.15
		4.374		58.57
				-1.00 RADIATION LOSS
				57.57



Enclosure Wall Duty
CBC

U_o	$\left(\frac{S_o}{1000}\right)$	$\left(\frac{\Delta T}{1000}\right)$	$= Q_w$
5	.200	.143	.14
7	.301	.536	1.13
12	.476	1.165	6.66
50	.164	1.400	11.52
	(.201)		19.45
	1.178	Rad. Loss	= .23
			19.22

Tube Bundle Duty

	U_o	$\frac{S_o}{1000}$	$\frac{\Delta T}{1000}$	$= Q_w$
Econ 1	7.65	3.600	.541	14.90
Econ 2	8.40	3.600	.492	14.90
Econ 3	8.10	3.675	.446	13.28
Econ 4	9.59	2.110	.520	10.52
Blr 1	10.50	2.385	.865	21.66
Blr 2	10.50	2.385	.865	21.66
Blr 3	10.50	2.118	.865	19.31
Blr 4	35.30	1.225	.955	42.38
PSH	38.30	1.383	.871	46.20
FSH	32.80	1.936	.728	46.20
				251.01

Total Duty

Primary Walls	57.57	327.80
CBC Walls	19.22	
Tube Bundles	251.01	

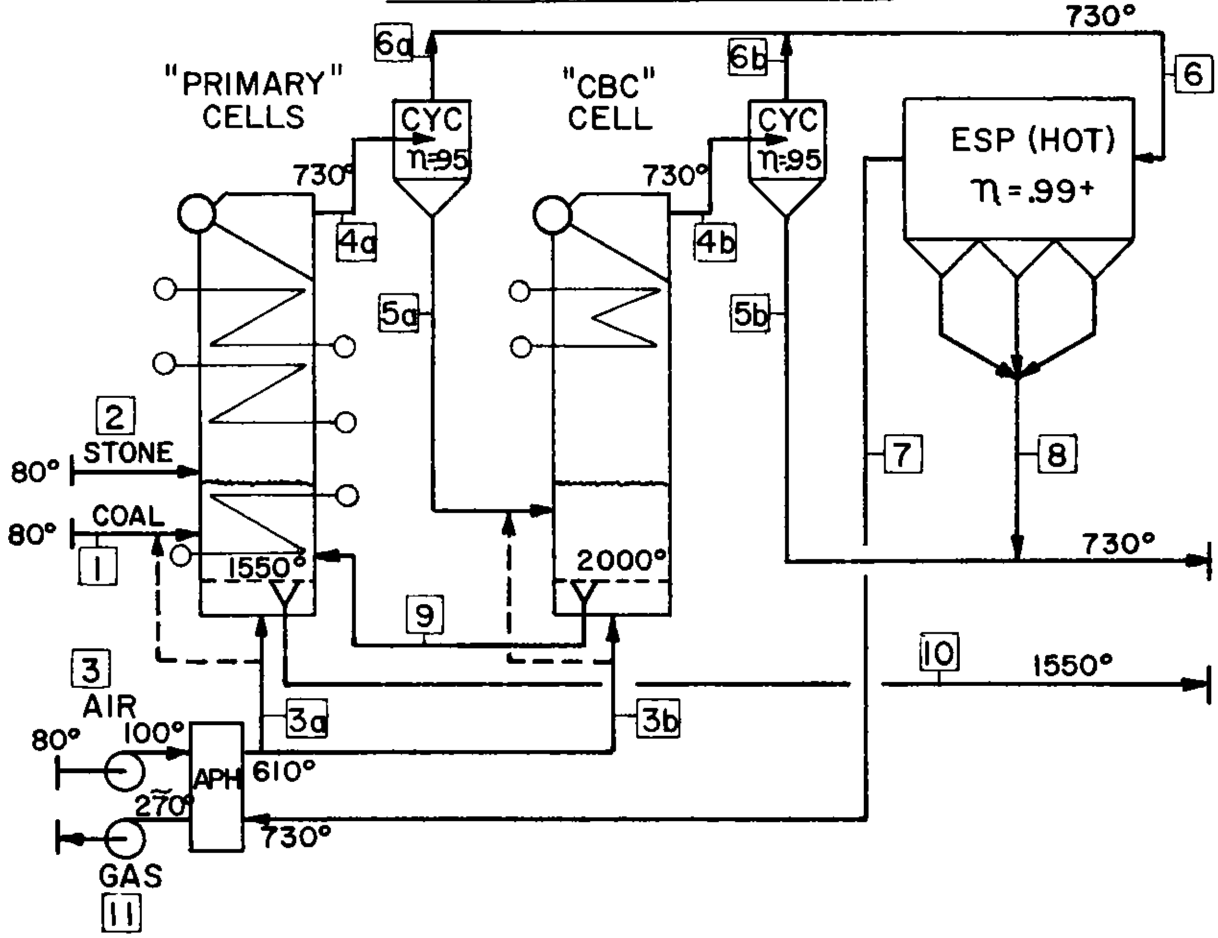
LEGEND

U_o = Heat Transfer Coefficient
S_o = Heat Transfer Surface (ft^2)
ΔT = Mean Temp. Diff. (F)
T_g = Gas Temp. (F)
T_B = Bed Temp. (F)
Q_w = Heat Transfer Duty (10^6 BTU/hr)

Figure E-8

Figure E-9

MATERIAL FLOW DIAGRAM



KEY COMPOSITIONS

[1] COAL WT.%		[2] STONE WT.%		[3] AIR VOL.%		[6a] GAS VOL.%		[6b] GAS VOL.%	
C	71.20	$CaCO_3$	98.96	N_2	77.38	CO_2	13.93	CO_2	14.81
H_2	5.07	CaO	.14	O_2	20.57	H_2O	8.91	H_2O	2.05
S	4.30	MgO	.30	H_2O	2.05	SO_2	.03	SO_2	.00
H_2O	3.30	SiO_2	.50		100.00	N_2	74.00	N_2	77.38
N_2	1.30	Fe_2O_3	.10			O_2	3.13	O_2	5.76
O_2	6.33		100.00				100.00		100.00
ASH	8.50								
	100.00								

HHV = 13000 BTU/lb

WEIGHT & HEAT FLOW SUMMARY

STREAM	WEIGHTS - lb/lb FUEL			WEIGHT FLOW lb/hr	HEATING CONTENT				HEAT FLOW mmBTU/hr
	GASEOUS	SOLIDS	TOTAL		h_{80+} BTU/lb	RHV' BTU/lb	RHV BTU/lb	TOTAL BTU/lb	
1		1.00	1.00	28,674	.0	12339.0	12339.0	12339.0	353.81
2		.27	.27	7,776	.0	.0	.0	.0	.00
3	11.95		11.95	342,563	5.1	.0	.0	5.1	1.74
3a	10.66		10.66	305,717	133.6	.0	.0	133.6	40.84
3b	1.29		1.29	36,846	133.6	.0	.0	133.6	4.92
4a	11.51	.28	11.79	338,041	168.5	1300.0	110.3	278.8	94.24
5a		.27	.27	7,716	168.5	1235.2	4590.1	4758.6	36.72
6a	11.50	.01	11.51	329,917	168.5	64.8	5.6	174.1	57.44
4b	1.36	.10	1.46	41,962	163.0	124.0	84.7	247.7	10.39
5b		.09	.09	2,707	163.0	117.8	1247.9	1410.9	3.82
6b	1.36	.01	1.37	39,255	163.0	6.2	4.5	167.5	6.58
6	12.87	.02	12.89	369,579	168.0	71.0	5.5	173.5	64.12
7	12.87	.00	12.87	369,060	168.0	.0	.0	168.0	61.99
8		.02	.02	519	168.0	71.0	3922.7	4090.7	2.12
9		.09	.09	2,601	525.0	.0	.0	525.0	1,37
10		.23	.23	6,727	392.0	.0	.0	392.0	2.64
11	12.87	.00	12.87	369,060	48.6	.0	.0	48.6	17.94

HEAT IN 1 + 3 = 355.55
HEAT OUT 5b + 8 + 10 + 11 = -26.52
329.03
-RADIANT LOSS -1.23
OUTPUT 327.80 mm

+MASS IN 1 + 2 + 3 = 379013
-MASS OUT 5b + 8 + 10 + 11 = -379013
0 lb/hr

h_{80+} = SENSIBLE HEAT ABOVE 80°F - BTU/lb STREAM
RHV' = NET REACTION HEATING VALUE ABOVE 80°F - ADJUSTED FOR STONE REACTIONS - BTU/lb FUEL
RHV = " " — BTU/lb STREAM

Figure E-10

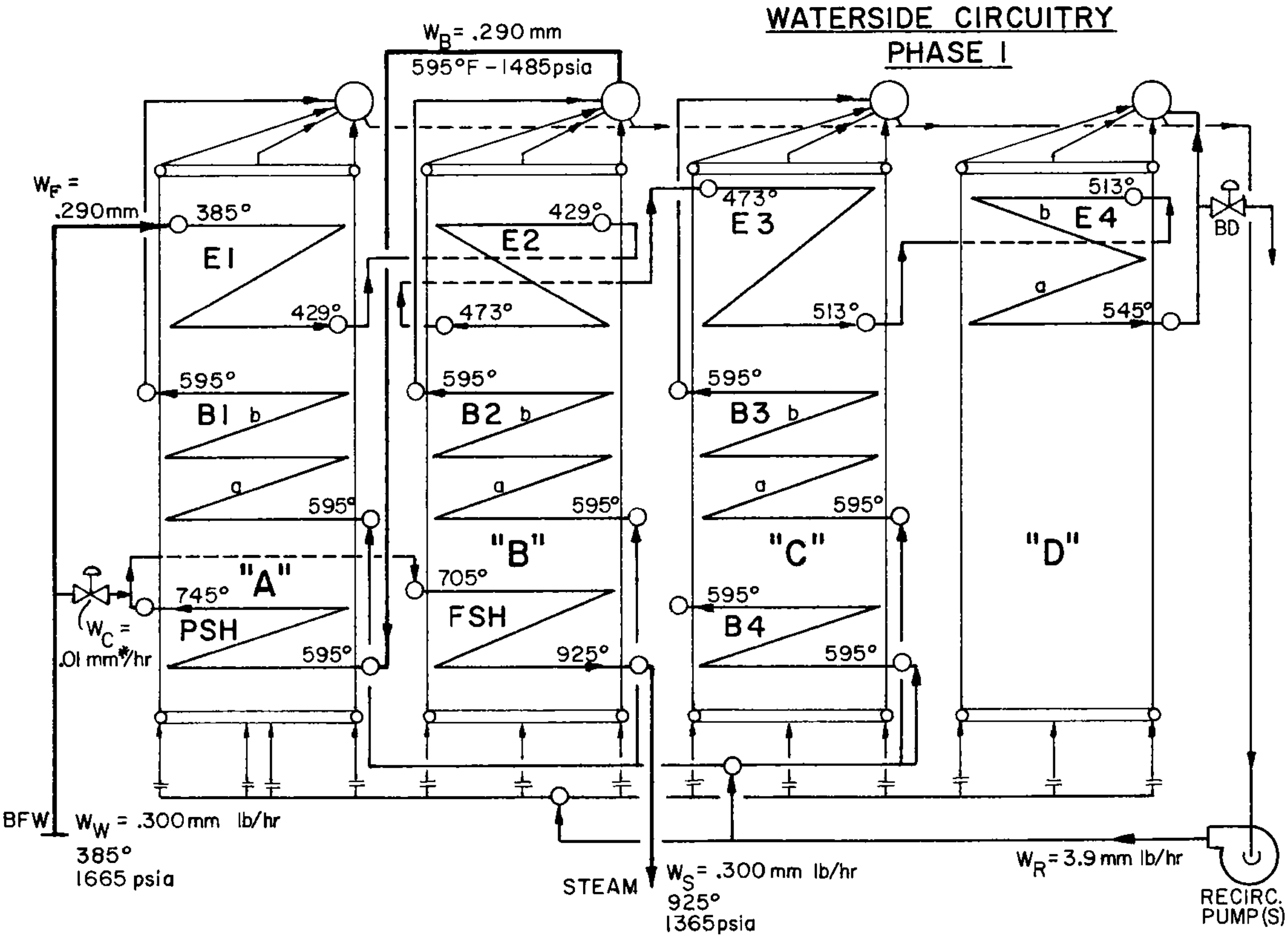

WATERSIDE CIRCUITRY
PHASE I
W_B = .290 mm
595°F - 1485 psia
W_F =
.290 mm
385°
E1
429°
429°
E2
473°
473°
E3
513°
513°
b
E4
a
545°
BD
595°
B1 b
a
595°
595°
B2 b
a
595°
595°
B3 b
a
595°
"A"
"B"
"C"
"D"
745°
PSH
595°
705°
FSH
925°
595°
B4
595°
(W_C =
.01 mm*/hr
BFW
W_W = .300 mm lb/hr
385°
1665 psia
STEAM
W_S = .300 mm lb/hr
925°
1365 psia
W_R = 3.9 mm lb/hr
RECIRC.
PUMP(S)

Figure E-11

Figure E-12

TUBULAR SURFACING

WATERWALLS - 2" O.D. x .180" MW SA 210A1 – ½" FINS x ¼" THICK
547 WATERWALL TUBES → 5555 ft^2 TOTAL
DEVELOPED HEATING SURFACE (4377 ft^2 M.B. + 1178 ft^2 C.B.C.)
DUTY – 57.57 mm B/hr M.B. + 19.22 mm B/hr C.B.C.

BANKS	SECTION	No. of Runs	OD	M.W.	Mat'l (ASTM)	SURFACE ft^2	DUTY mm B/hr
B1 a	44	3	1¾	.180	210-A1	2385	21.66
b	44	6	2	↓	↓		
B2 a	44	3	1¾	↓	↓	2385	21.66
b	44	6	2	↓	↓		
B3 a	39	3	1¾	↓	↓	2118	19.31
b	39	6	2	↓	↓		
B4	39	5	2	↓	↓	1225	42.38
						8113	105.01
E1	44	13	2	.180	210-A1	3600	14.90
E2	44	13	↓	↓	↓	3600	14.90
E3	39	15	↓	↓	↓	3675	13.28
E4 a	24	3	↓	↓	↓	2110	10.52
b	24	11	↓	↓	↓		
						12,985	53.60
PSH	44	5	2	.180/.200	213-T2/T22	1383	46.2
FSH	44	7	2	.180/.210	T22/TP304H	1936	46.2
						3319	92.4

EACH TUBE RUN 12 ft. EFFECTIVE LENGTH

TUBE ARRAYS

E 1, 2, 3, 4b, B1b, B2b, B3b	– 6" S_T	2" S_L	STAGGERED
E 4a, B1a, B2a, B3a	– 6" S_T	2.645" S_L	↓
B4, PSH, FSH (IN BED)	– 6" S_T	2.645" S_L	↓

KEY
mm B/hr = millions of BTU/hr
OD = Outside Tube Diameter, inches
M.W. = Minimum Wall Thickness, inches
M.B. = Main Boiler

7. Economizer surface in the CBC was set first based on required outlet gas temperature and the available heat coming off the bed. The economizer surface in the other cells was set so that the water temperature to drum would be no more than 50F below saturation temperature.

2.3.2 Circulation - Since the new unit design includes a forced circulation pump in the boiler circuit, the potential for unstable circuits has been eliminated. Figure E-13 shows the results of a circulation analysis of the vertical enclosure walls of the new unit design. The figure indicates no unstable flow condition using the forced circulation pump. For the normal absorption rate, the intersection of the available head and the circuit pressure drop at point A, which is 5.75 psi, on the upflow side of the curve does not have another intersection with the normal absorption rate curve on the downflow side of the curve. Therefore, no unstable operating condition is possible. In fact, the condition, where one tube may have an absorption rate of double the normal rate and another tube may have an absorption rate of only one-half the normal rate, does not cause an unstable condition to exist. This is evident by the intersection of the available head and the circuit pressure drop for double the normal absorption rate at point B (5.1 psi) not having an intersection with the one-half normal absorption rate curve. During subsequent design stages for this unit, the circulation will be analyzed in detail to give proper orificing of the parallel circuits to achieve the correct design flow in each tube. All other boiler circuits will show similar stable flow characteristics.

For comparison, Figure E-13 shows how the circuit would act without the forced circulation pump in the boiler circuit. The available head from the "heat pump" and the system pressure drop intersect at point C (3.6 psi) on the upflow side of the curve but just like the submitted design, it also has two points of intersection on the downflow side at points D and E. This means that the circuit would have an unstable circulation characteristic and would not be acceptable.

Other disadvantages of the earlier design have been eliminated by equally distributing the downcomers along the steam drum which has been relocated over the

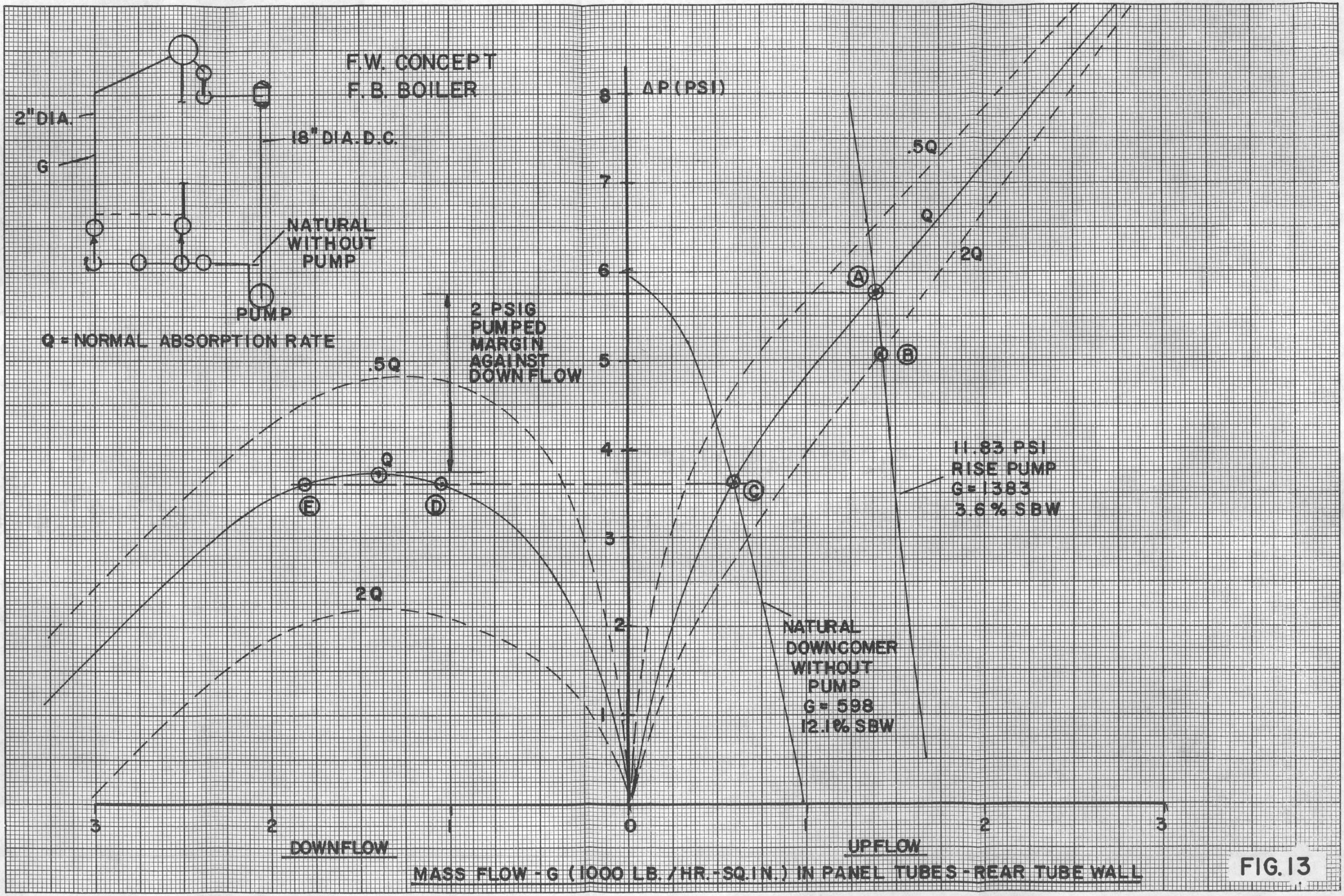

F.W. CONCEPT
F.B. BOILER
2"DIA.
G
18"DIA.D.C.
NATURAL WITHOUT PUMP
PUMP
Q = NORMAL ABSORPTION RATE
ΔP (PSI)
2 PSIG PUMPED MARGIN AGAINST DOWNFLOW
.5Q
Q
2Q
A
B
C
D
E
11.83 PSI RISE PUMP G = 1383 3.6 % SBW
NATURAL DOWNCOMER WITHOUT PUMP G = 598 12.1% SBW
DOWNFLOW
UPFLOW
MASS FLOW - G (1000 LB./HR.-SQ.IN.) IN PANEL TUBES - REAR TUBE WALL
FIG. 13

FIGURE E-13

front wall of the unit. In addition, economizer surface has been located between the steam drum and the furnace proper resulting in much lower gas temperatures at the steam drum location. The gas/water temperature differential will be about 100F.

2.3.3 Mechanical - The new unit design will be top supported from existing or new steel. The drum is to be supported by straps or "horseshoe" type supports from the building steel. The unit frontwall is supported by the drum and the rearwall, which are supported from the building steel by hanger rods. All of the horizontal heating surface inside the unit is supported by lugs on the enclosure wall tubes.

Location of the steam drum to the front wall simplifies the arrangement for the downcomer piping and the exit flue design. The location of the drum above the front wall and the location of economizer surface between the horizontal boiler surface and the drum, eliminates design problems of a drum in the hot gas zone.

3.0 WORK COMPLETED - PHASE II

Engineering work under this phase was completed in December 1973 and resulted in the Engineering Design of the 300,000 lb/hr fluidized bed steam generator recommended as a result of the work completed under Phase I. The engineering work completed under Phase II is described in the following paragraphs:

3.1 Technical Specifications.

The work completed under this task has been divided into several areas to best define the thermal design of the steam generator. The main areas of concern are (1) fuels and combustion, (2) unit thermal performance, (3) furnace heat balance, (4) unit surfacing and heat transfer, (5) water and steam side hydraulics, (6) superheater material selections, (7) water and boiling tube material selections.

3.1.1 Fuels and Combustion - Since the plant at Rivesville, West Virginia receives fuel from several locations the design of this unit has been based on a nearby coal for which a complete analysis was available. The coal selected was Pittsburgh seam #8 with a HHV of 13,000 Btu/lb. Also, since the source of limestone for the Rivesville unit had not been defined, the analysis was assumed to be equivalent to BCR1359 limestone. The chemical analysis for both the coal and limestone are shown on Table E-2. Table E-2 also indicates the development of the limestone demand assuming a requirement of 2 moles calcium oxide per mole of sulfur in the fuel. Combustion of the specified fuel in the main fluidized bed cells (cells A, B and C) is at an excess air level of 18%. At this excess air level and with the fluidizing velocity specified approximately 10 lb carbon/lb of coal-fed elutriates as unburned combustible. This unburned combustible is collected in a mechanical dust collector and used to fuel the CBC. The results of the combustion reaction in the main fluidized beds are indicated on Table E-3. The results of combustion of the unburned combustible from the main fluidized beds in the CBC are shown on Table E-4. As indicated on Table E-4 the combustion in the CBC takes place with an excess air level of 25%. The combined combustion analysis for the entire unit results in an excess air level of 18.72% and the requirement of 11.71 lbs of combustion air/lb of coal-fed.

TABLE E-2

Fuel and Limestone Specifications

Coal - Pittsburgh Seam #8
HHV = 13000 Btu/lb

Coal			Ash		
Species	Weight %		Species	Weight %	lb/100 lb Coal
C	71.20		SiO_2	45.30	3.85
H_2	5.07		Fe_2O_3	27.30	2.32
O_2	6.33		Al_2O_3	21.20	1.80
N_2	1.30		CaO	1.90	.16
S	4.30		K_2O	1.80	.15
H_2O	3.30		TiO_2	1.00	.09
Ash	8.50		MgO	.60	.05
	100.00		Na_2O	.20	.02
			P_2O_5	.10	.01
			Misc.	.60	.05
				100.00	

Limestone - BCR 1359 Assumed
Reaction Heating Value = 50 Btu/lb Fuel

Species	Weight %		Species	Weight %	lb/100 lb Fuel
$CaCO_3$	92.3		CaO	55.52	15.04
CaO	3.8		CO_2	40.58	11.00
SiO_2	.5		SiO_2	.50	.14
MgO	.3		MgO	.30	.08
Fe_2O_3	.1		Fe_2O_3	.10	.03
H_2O	3.0		H_2O	3.00	.81
	100.0			100.00	27.10

Limestone Demand - Assume 2 moles CaO per 1 mole S in fuel required

$$\frac{1}{100} \times \frac{4.3\%\ S}{32.06\ S_{mw}} \times \frac{2\ \text{moles}}{1\ \text{mole}} \times \frac{56.08\ CaO_{mw}}{55.52\%\ CaO} = 27.10\ \frac{\text{lb stone}}{100\ \text{lb fuel}}$$

Key
% S,CaO = weight %
S_{mw}, CaO_{mw} = molecular weight, lbs/lb-mole

TABLE E-3

MAIN BED COMBUSTION CALCULATION

Cells A, B and C

Species	Mol.Wt.	Combined lb/100 lb Coal Feed	Moles/100 lb Coal	Moles O_2 Req'd. to react with Species	Combustion Air Extra-Moles	Resulting Combustion Gas-Moles	Combustion Gas Wt. %
C	12.01	61.29	5.10	5.06	-	-	-
CO	28.01	0.00	-	.02	-	0.04	0.10
CO_2	44.01	9.22	0.21	-	-	5.27	20.60
H_2	2.01	5.07	2.51	1.26	-	-	-
H_2O	18.01	3.98	.22	-	0.74	3.48	5.56
S	32.06	4.30	.13	0.13	-	-	-
SO_2	64.06	0.00	-	0.06	-	0.01	0.08
O_2	32.00	6.33	.19	-0.19	1.14	1.14	3.24
N_2	28.15	1.30	.05	-	28.13	28.18	70.42
CaO	56.08	15.04	.27	-	-	0.15(Solid)	100.00
$CaSO_4$	136.14	0.00	-	-	-	0.12(Solid)	
				6.34			
		plus 18% Excess Air		1.14			
				7.48			

Combustion Air Species (Moles)

N_2	28.13
O_2	7.48
H_2O	0.74
	36.35

Combustion Results

.0991	lb C/lb Coal Escapes as unburned
10.45	lb Air/lb Coal Required
11.26	lb Gas/lb Coal Formed

Note: Not all combustion completes in the main beds.
Approximately 15% of reaction heat is released in the freeboard.
The freeboard zone (1-2 ft. above the bed) will contain CH_4, CO, C, CaS which continue to burn.

TABLE E-4

CBC BED COMBUSTION CALCULATION

Species	Mol.Wt.	Combined lb/100 lb Coal	Moles / 100 lb Coal	Moles O_2 Req'd. to react with Species	Combustion Air Extras-Moles	Resulting Combustion Gas-Moles	Combustion Gas Wt. %
C	12.01	8.68	0.72	0.72	-	-	-
CO_2	44.01	1.77	0.40	-	-	0.76	24.58
H_2O	18.01	0.13	0.01	-	0.09	0.10	1.28
O_2	32.00	0.00	-	-	0.18	0.18	4.23
N_2	28.15	0.00	-	-	3.40	3.40	69.91
				0.72			100.00
			Plus 25% excess air	0.18			
				0.90			

Combustion Results*

0.01 lb C/lb Coal Escapes as unburned
1.26 lb Air/lb Coal Required
1.37 lb Gas/lb Coal Formed

Combustion Air Species (Moles)

N_2	3.40
O_2	.90
H_2O	.09

*based on total coal feed to main beds

To determine the overall unit combustion requirements the fan, air preheater and dust collector efficiencies were assumed. These assumed values resulted in a combustion air inlet temperature of 607F. Based on the information developed in the following paragraphs the total fuel rate and unit efficiency was determined and a material balance calculated. The results of the material balance are shown in a flow diagram form on Figure E-14.

3.1.2 Unit Thermal Performance - The steam generator design is required to produce 300,000 lbs/hr of superheated steam at 925F and 1350 psig with a feedwater flow of 300,000 lbs/hr at 385F and 1650 psig. The economizer duty was selected so that the drum feedwater would enter with 50F sub-cooling to a drum steaming at 1471 psig. For superheater temperature control 10,000 lb/hr of feedwater is bypassed around the economizers boiler and primary superheater for spray temperature control. Based on the circuit arrangement developed and recommended in Phase I the heating duty required for each section of the steam generator is indicated on Figure E-15.

The steam generator thermal efficiency has been calculated by the heat loss method and the calculated heat loss and unit efficiency are listed on Table E-5. The boiler efficiency of 87.187% indicated, results in a fuel heat input requirement of 374.75 x 10^6 Btu/hr. Based on this, the total fuel, limestone and combustion air feed requirements plus the product flue gasses and solids are also tabulated on Table E-5.

Based on the combustion analysis listed on Table E-3 and the requirement for a design superficial fluidizing velocity of 12 ft/sec and bed temperature of 1550F the size requirement for the main fluidized bed may be calculated. Using the combustion gas flow from Table E-3 and the total fuel feed rate of 28,827 lb/hr from Table E-5 the total gas flow from the main fluidized beds calculates to 325,000 lb/hr. At 1550F and atmospheric pressure this gas flow translates to 4590 cubic ft/sec and at the design fluidizing velocity of 12 ft/sec a 382 ft^2 plan area is required for the main fluidized beds. A unit width of 12 ft was selected for shipping and fuel injection purposes and with this dimension fixed the length of the main fluidized beds (cells A,B and C) is approximately 32 feet. As indicated in Table E-1 the CBC design fluidizing velocity is 9 ft/sec with a bed temperature of 2000F. Based on the gas flow per lb/coal feed indicated on Table E-4 and the total coal

P.E.R.(OCR) FBB 2-58-2126 MATERIAL BALANCE

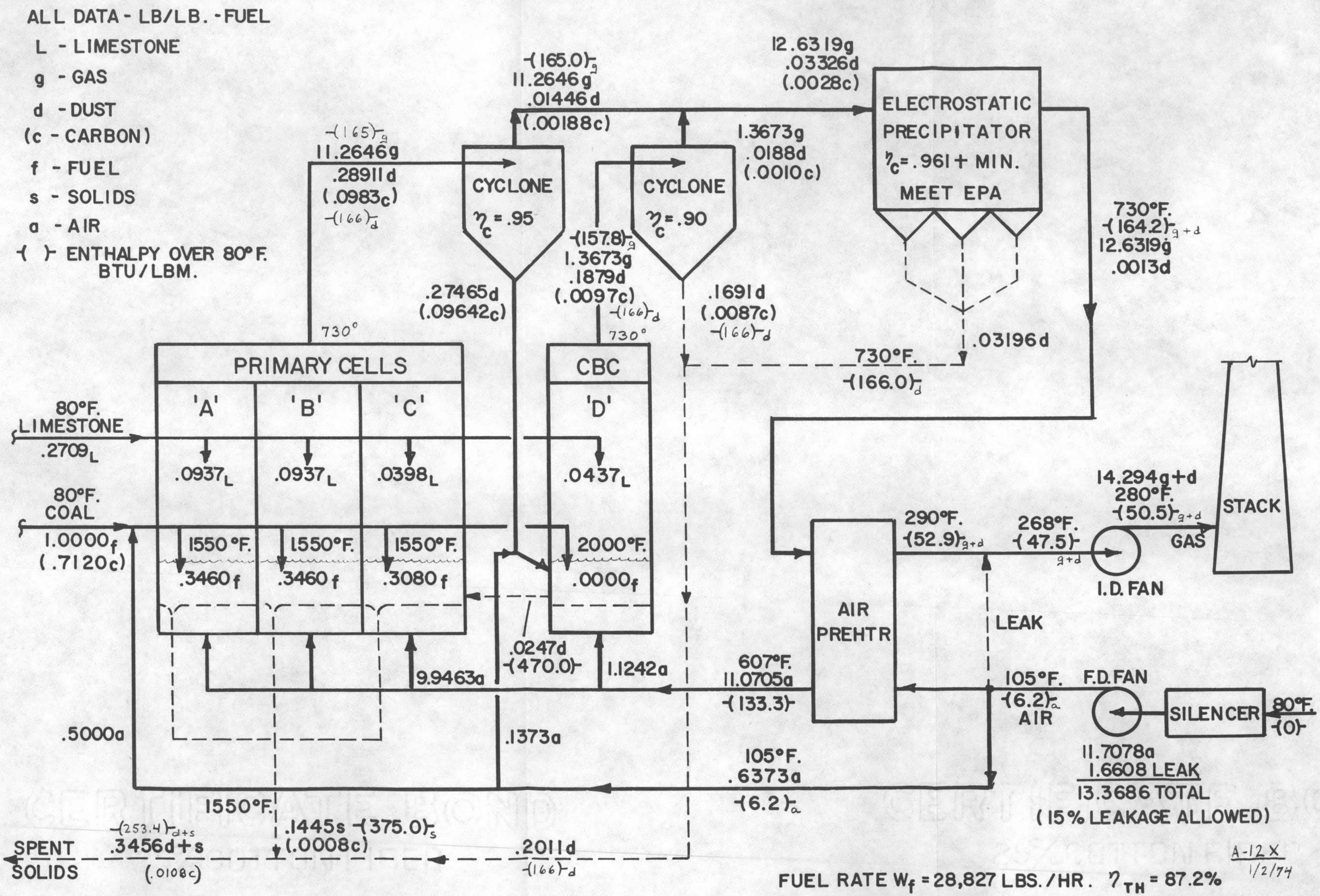


FIGURE E-14

TABLE E-5

UNIT EFFICIENCY

	Heat Losses Btu/lb Coal	Efficiency Losses %
1. Unburned carbon	173.55	1.336
2. Combustible gases (CO)	110.66	.851
3. Fuel and stone moisture	509.65	3.920
4. Moist gas loss (net)	596.30	4.587
5. Solids loss (net)	37.63	.289
6. Radiation loss	42.90	.330
7. Mfg. margin + UAF	195.00	1.500
Total loss	1665.69	12.813

HHV = 13,000 Btu/lb coal
Boiler efficiency = 100 - 12.813 = 87.187%

Total Unit Input and Output

Net thermal output required	326.73 mm Btu/hr from fuel
Fired Heat input required	374.75 mm Btu/hr as coal

Feed	
W_f - Fuel rate required	28,827 @ HHV = 13,000
W_l - Stone rate required	7,809
W_a - Combustion air total	337,503
	374,139 lb/hr
Products	
W_g - Flue gases total	364,139
W_s - Spent solids & ash	10,000
	374,139 lb/hr

Key
UAF = unaccounted for
HHV = higher heating value, Btu/lb
mm = millions

feed determined according to Table E-5 the gas flow from the CBC is 39,400 lb/hr. This results in a plan area for the CBC of 72.5 square feet and with a pre-selected unit width of 12 feet the CBC length is approximately 6 feet.

3.1.3 Furnace Heat Balance - Since the size of the enclosure and partition waterwalls is determined by the overall unit dimensions, the heat transfer duty of these surfaces was first estimated based on expected heat transfer coefficients and gas temperatures in various zones. The waterwalls in cells A, B and C have been divided into seven (7) zones and the waterwalls in the CBC have been divided into five (5) zones as indicated on Figure E-16. Following an iterative design technique the gas to-water temperature differential and overall heat transfer coefficient for each zone was determined and the results are tabulated on Table E-6. As shown on Table E-6 the heat transfer into the waterwalls was calculated to be 74.73×10^6 Btu/hr less a radiation loss to atmosphere of 1.24×10^6 Btu/hr resulting in a net waterwall heating duty of 73.49×10^6 Btu/hr. Since the waterwalls are part of the boiling circuit and Figure E-15 indicates a total boiling duty of 181.45×10^6 Btu/hr the total remaining boiling duty to be absorbed by other tube surface is 107.96×10^6 Btu/hr.

Since the main fluidized beds are designed to operate at 12 ft/sec superficial fluidizing velocity and a bed temperature of 1550F the total heat transfer duty of the fluidized beds in cells A, B and C may be easily determined with a heat balance. Also, since the entire superheater is to be located in the fluidized bed zone and the duty of the waterwalls in this zone is already known the remaining bed duty can be assigned to horizontal boiling surface. The heat balance and assignment of heating duties is indicated on Table E-7. As indicated on Table E-7 the primary superheater and finishing superheaters were split based on having an equal heating duty. The location of the tube surface for the heating functions listed on Table E-7 is shown on Figure E-16. Table E-7 also lists the heat balance for the CBC (cell D).

The determination of fluidized bed heat transfer duty for the primary superheater (cell A), finishing superheater (cell B) and boiler 4 (cell C) plus the waterwall duties in the main fluidized beds and the CBC

TABLE E-6

WATER WALL HEAT ABSORPTION

Cells A, B and C

ZONE (see Fig.16)	U_W Btu/hr Ft^2F	S_W Ft^2	ΔT F	Q_W 10^6 Btu/hr
1	50.00	717	950	34.05
2	13.51	730	1069	10.54
3	12.73	263	1054	3.53
4	8.87	263	763	1.78
5	7.58	365	600	1.66
6	7.09	941	367	2.45
7	5.00	1364	135	.92
		4643		54.93

CELL D

ZONE (see Fig.16)	U_W Btu/hr Ft^2F	S_W Ft^2	ΔT F	Q_W 10^6 Btu/hr
1	50.00	191	1400	13.40
2	12.45	435	1171	6.34
3	12.30	68	825	.69
4	6.81	175	428	.51
5	4.78	301	139	.20
		1170		21.14
Less for refractory lining in Zone 1				-1.34
				19.80

Total Water Wall Duty

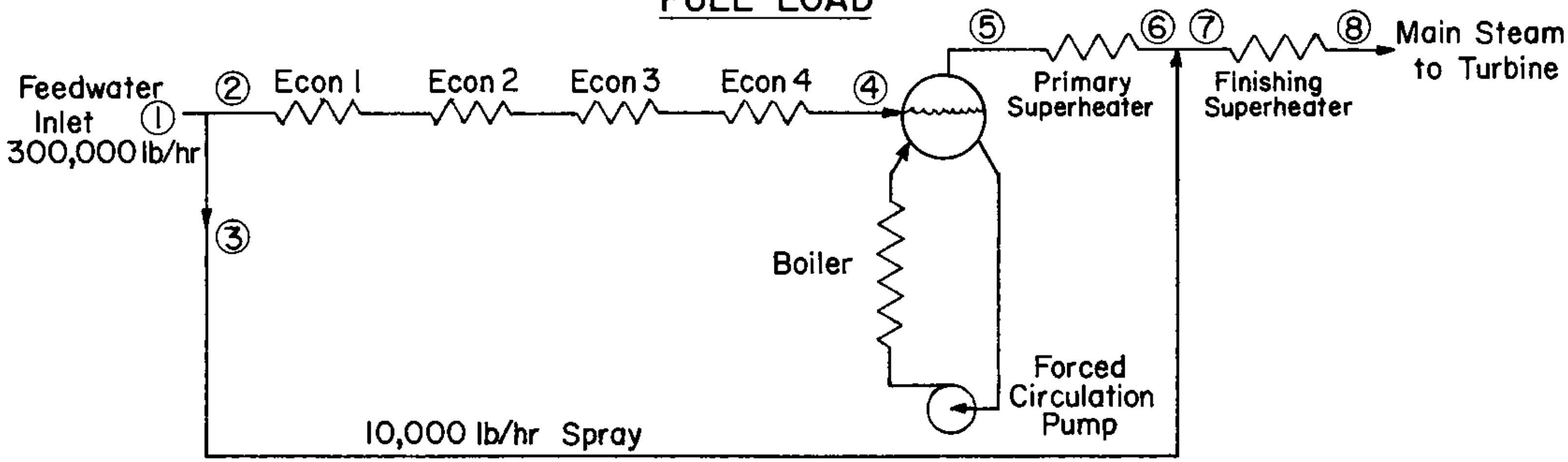
Cells A, B and C	54.93 x 10^6 Btu/hr
Cell D	19.80
	74.73
Radiation Loss	-1.24
Net Duty	73.49 x 10^6 Btu/hr

U_W = Waterwall Heat Transfer Coefficient (Overall)
S_W = Developed Heat Transfer Surface
ΔT = $T_{avg.Gas} - T_{water}$
Q_W = Heat transfer to water

FIGURE E-15

UNIT HEATING DUTY REQUIREMENTS

FULL LOAD



FLUID CONDITIONS

Location	Flow lb/hr	Temp °F	Enthalpy BTU/lb
1	300,000	385	358.0
2	290,000	385	358.0
3	10,000	385	358.0
4	290,000	546	543.0
5	290,000	595	1168.7
6	290,000	746	1328.0
7	300,000	702	1295.7
8	300,000	925	1449.6

HEATING DUTY REQUIRED

Economizer

$290{,}000\,(543.0 - 358.0) = 53.65 \times 10^6$ BTU/hr

Boiler

$290{,}000\,(1168.7 - 543.0) = 181.45 \times 10^6$ BTU/hr

Superheater

$290{,}000\,(1449.6 - 1168.7) + 10{,}000\,(1449.6 - 358.0)$

$= 92.38 \times 10^6$ BTU/hr

TOTAL DUTY	327.48×10^6 BTU/hr
Heat Input by Pump	.75
Net Thermal Duty Required	326.73×10^6 BTU/hr

TABLE E-7

FLUIDIZED BED HEAT BALANCE

1. Heat Input to Beds

	Cells A, B & C	Cell D
Air Preheat (607F)	38.22 x 10^6 Btu/hr	4.32 x 10^6 Btu/hr
Fuel (28,827 lb/hr)	267.35	33.16
Primary Air (.5 lb//lb coal)	0.09	0.02
Solids (with fuel to CBC)	-	1.32
Solids (from cell D to cell C)	.34	-
	306.00 x 10^6 Btu/hr	38.82 x 10^6 Btu/hr

2. Heat Leaving Beds (w/o heat absorption by tubes)

	Cells A, B & C	Cell D
Bed Material Extraction	1.56 x 10^6 Btu/hr	-
Elutriated Solids	3.13	2.64
Flue Gas	132.17	20.69
Radiation	-	3.09
Solids (from cell D to cell C)	-	.34
	136.86 x 10^6 Btu/hr	26.76 x 10^6 Btu/hr

Heat Absorption required in the main beds
(cells A, B & C) = 306.00 - 136.86 = 169.14 x 10^6 Btu/hr

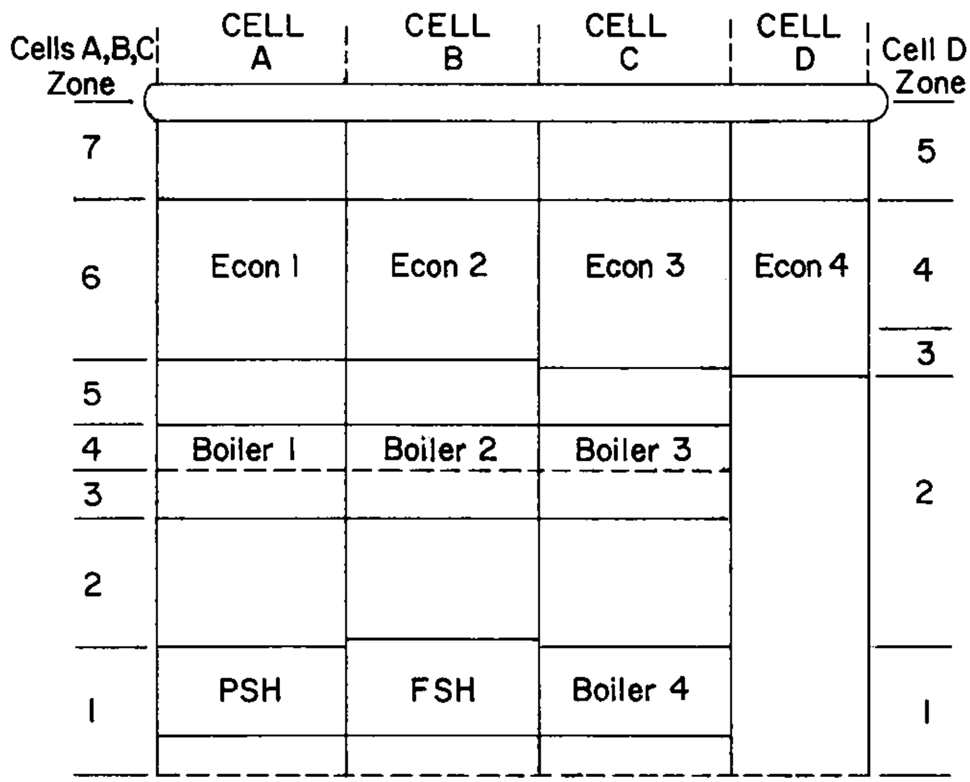
Heat Absorption required in CBC (cell D)
= 38.82 - 26.76 = 12.06 x 10^6 Btu/hr

Duty Budget in Beds

	Cells A, B & C	Cell D
Waterwalls	34.05 x 10^6 Btu/hr	12.06 x 10^6 Btu/hr
Primary Superheater	46.19	-
Finishing Superheater	46.19	-
Horizontal Boiler (B4)	42.71	-
	169.14 x 10^6 Btu/hr	12.06 x 10^6 Btu/hr

FIGURE E-16

UNIT WATERWALL SURFACE by ZONE



KEY

Econ = Economizer

PSH = Primary Superheater

FSH = Finishing Superheater

(cell D) permits defining the total heat input to each cell and the placement of the cell partition walls. With the width of each cell already selected at 12 feet and a main fluidized bed plan area of 382 square feet as developed in paragraph 3.1.2, the lengths of cells A, B and C calculates to 11.25 feet, 11.25 feet and 10 feet, respectively. The length of the CBC (cell D) calculates to 6.2 feet.

With a total required boiling surface duty of 180.70 x 10^6 Btu/hr and a duty of 116.20 x 10^6 Btu/hr accounted for by the waterwalls and horizontal boiler located in the fluidized bed (cell C), the remaining boiling heat transfer duty of 64.50 x 10^6 Btu/hr must be accomplished by the convection surface located above the main fluidized beds. Of this remaining boiling duty 22.33 x 10^6 Btu/hr has been assigned to boiler banks 1 and 2 located in cells A and B respectively and 19.84 x 10^6 Btu/hr has been assigned to boiler bank 3 in cell C.

The total economizer duty has been divided so that each of the four (4) cells has a gas exit temperature of 730F. The economizer duty assignments for each cell break down as follows:

Cell	Surface Description	Duty 10^6 Btu/hr
A	Economizer 1	14.55
B	Economizer 2	14.55
C	Economizer 3	12.99
D	Economizer 4	11.56
		53.65 x 10^6 Btu/hr

With the heating duty assignments determined above the horizontal tube bundle arrangements and surface requirements are determined according to paragraph 3.1.4.

3.1.4 Unit Surfacing and Heat Transfer - The horizontal tubes located in the fluidized beds and dust laden convection passes have been arranged on a staggered pattern to minimize dust crowning on the top side of the tubes and promote better fluidization characteristics within the beds. For the tube surface located in the fluidized bed the tube spacing has been selected to maintain a constant superficial velocity between the diagonals and laterals of the tube array and to introduce a more uniform resistance in the fluidized bed to reduce the possibility of large bubbles propagating through vertical lanes.

The horizontal convection boilers have been designed with an inlet surface that acts as a radiant trap with a minimum of convection heat transfer. The inlet surface of these boilers are wide spaced to limit convection and after the radiant trap section the back spacing is reduced to retain maximum heat transfer coefficient as the gas temperature is reduced. The same radiant trap concept is used in the CBC cell economizer inlet section. Gas velocities in the convection surface are limited to control tube erosion with high dust loadings and to provide a minimum requirement for soot blowing equipment. If tube erosion and dust lay-down do not appear to be a problem in this demonstration unit, tighter, more efficient surface arrangements will be used on future installations. To permit the larger solid particles tossed from the fluidized bed to return to the beds before entering convection surface a freeboard zone 4 feet in height has been maintained between the fluidized bed and the lower convection boilers.

Stable internal flow regimes while heating and boiling water inside tubes dictate that certain minimal mass velocities be maintained as a function of absorption rates, temperatures and steam qualities. To meet waterside mass velocity criteria and to provide the required heat transfer surface the use of 2" diameter tubes with conservative wall thicknesses are indicated. 1-3/4" diameter tubes have been selected for use in the radiant trap sections to provide the proper mass velocities. Since this is a demonstration unit and previous operating experience cannot acurately dictate variations in heat transfer coefficients and possible tube erosion, conservative tube wall thicknesses have been selected throughout this unit.

Since approximately 45% of the sensible heat input to the fluidized beds must be removed by heat transfer surface other than waterwalls and the absorption rates to this surface are approximately 35,000 Btu/hr ft^2 with a sensible heat input to the fluidized bed of 200,000 Btu/hr, cu ft, this dictates a requirement of approximately 2.5 ft^2 of heat transfer surface for every cubic foot of fluidized bed. To provide this surface in compact space using commercial practices horizontal tubular serpentine coils are indicated.

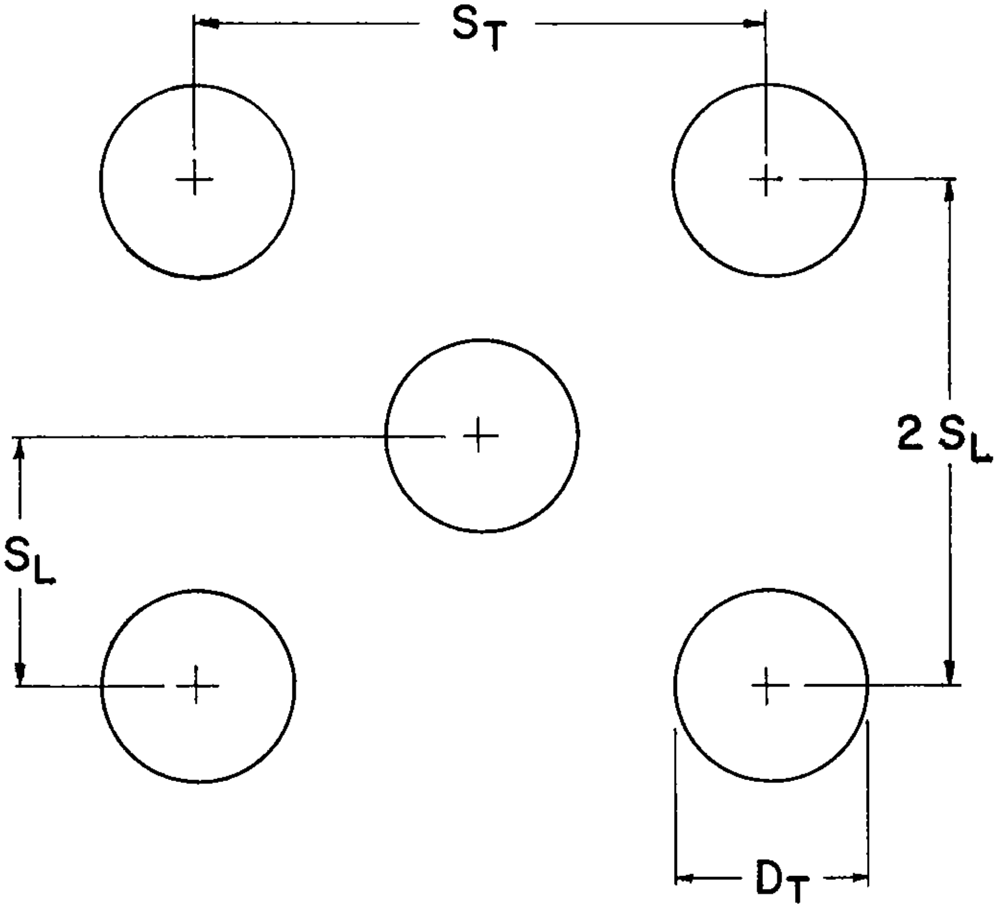
With a drum pressure of 1470 psig anticipated for normal operating conditions and a peak drum pressure of 1500 psig anticipated, the design pressure of the drum has been set at 1600 psig.

A tube size of 2" O.D. spaced on 3" centers was selected for the enclosure and partition waterwalls based on mass flow and mechanical criteria. For support of the horizontal tubes within the unit it is advantageous to set the horizontal tube spacing such that the tube coils line up with the vertical tubes in the enclosure walls. The requirement for tubes to penetrate the enclosure walls for connection to collection headers dictates that the horizontal surface must be arranged parallel to the 12' dimension of each cell.

A heat transfer coefficient of 40 Btu/hr, sq ft, F was selected for determination of surface requirements of the horizontal tubes in the fluidized bed zones. Since the length of each horizontal tube is set at 12' by the fluidized bed dimension and the number of tubes that can be located in each horizontal row is set by a 3" spacing criteria and a 2" O.D. tube size has been selected the only variables remaining for determination of the tube arrangement within each fluidized bed are the vertical spacing and number of tube rows. To maintain the inter-tube superficial velocity constant between the diagonals and laterals of the tube array, the spacing of the tubes within the fluidized beds have been selected as shown on Figure E-17. It is not always practical to install the exact amount of tube surface within the steam generator based on the heat transfer calculations due to mechanical limitations requiring that each horizontal length of tubing traverse the entire width of the unit. The surface requirements for the convection boiler banks and economizers have been calculated according to conventional methods for heat transfer to horizontal tubes. Table E-8 lists the tube surface requirements calculated for each horizontal tube bundle and the actual surface installed due to mechanical

FIGURE E-17

FLUIDIZED BED HORIZONTAL TUBE SPACING



S_T = 6"

S_L = 2⅝"

D_T = 2"

TABLE E-8

Horizontal Tube Surfacing

Tube Bundle	Calculated Tube Surface Required	Actual Tube Surface to be Installed
Economizer 1	3301	3600
Economizer 2	3577	3600
Economizer 3	3488	3675
Economizer 4	2356	2356
Boiler 1	2358	2350
Boiler 2	2358	2350
Boiler 3	2089	2082
Boiler 4	1118	1225
Primary Superheater	1131	1383
Finishing Superheater	1854	1936

limitations. The gas side pressure loss from the top of the fluidized bed to the steam generator pressure part exit has been calculated at 0.7" H_2O for cells A, B and C and 0.6" H_2O for cell D.

3.1.5 Water and Steam Side Hydraulics - The use of horizontal tubes for boiling duty in this unit presents some unusual circulation problems. Since separation of the steam/water mixture in the horizontal boiling tubes cannot be tolerated, the mass flow must be maintained to keep the fluid within the froth or dispersed flow regimes. This flow requirement results in an overall circulation ratio between the horizontal circuits and the vertical waterwalls of 13.4/1. For this circulation ratio a total force of approximately 30 psi in addition to the natural circulation effects is required. This additional driving force is supplied by two (2) inline forced circulation pumps which have been specified according to paragraph 4.1.

The start-up sequence for this demonstration unit requires light-off of the CBC first, which will yield essentially full load flue gas temperature at the inlet to economizer 4 prior to production of steam and establishment of flow through the economizer. This high gas temperature at the economizer inlet cannot be tolerated with no flow in the economizer, therefore, an economizer recirculation line is required to maintain flow through the economizer during start-up. This recirculation line has been included to take advantage of the driving head of the forced circulation pumps to force boiler water flow through the economizer during light-off and low load operation until sufficient feedwater is established for cooling of the economizer surface. The hydrostatic pressure loss through the steam generator has been determined for the normal full load operating condition of 300,000 lb/hr steam output and for an experimental maximum steam flow condition of 360,000 lb/hr. Table E-9 lists the system pressure losses for each of the conditions analyzed. The additional pressure loss through the finishing superheater and spray header for the experimental maximum load of 360,000 lb/hr is due to an additional spray water flow of 60,000 lb/hr.

3.1.6 Superheater Material Selections - the material selections for the primary and finishing superheaters are

TABLE E-9

STEAM AND WATER CIRCUIT PRESSURE LOSS

Circuit Description	Normal Full Load 300,000 lb/hr P, psi	Experimental Maximum Load 360,000 lb/hr P, psi
Control, Check and Block Valves	235	198
Feedwater Supply to Economizer 1 inlet	20	20
Economizer 1	12	12
Economizer 2	12	12
Economizer 3	13	13
Economizer 4	23	23
Economizer 4 outlet to Drum Outlet	10	10
Drum outlet to Primary Superheater inlet	5	5
Primary Superheater	32	32
Spray Header	20	25
Finishing Superheater	37	66
Finishing Superheater outlet to Stop-check valve	6	9
	425 psi	425 psi

Block Valve inlet pressure	= 1775 psig
Total Circuit Pressure loss	= -425
Outlet Pressure to stop check valve	= 1350 psig

conservative. Pilot unit testing has indicated that fluidized bed temperature and heat transfer rates are unusually uniform throughout the bed volume. The heat transfer coefficient used to design the primary and finishing superheaters is 40 Btu/hr, sq ft, F as discussed in paragraph 3.1.4. To determine the maximum steam outlet temperature from a hypothetical "worst tube" a conservative heat transfer coefficient of 55 Btu/hr sq ft, F has been used. At full load flow the design outlet steam temperature from the primary superheater is 746F and application of the upset condition to any one or more tubes in the primary superheater would result in an outlet steam temperature from those tubes of 841F. The finishing superheater was designed for a steam outlet temperature of 925F based on an inlet temperature of 702F which is obtained from spraying the primary superheat outlet with 10,000 lb/hr of feedwater. The finishing superheater "worst tube" is also calculated with a heat transfer coefficient of 55 Btu/hr, sq ft, F and results in a outlet temperature of 975F if the spray water flow is maintained at 10,000 lb/hr.

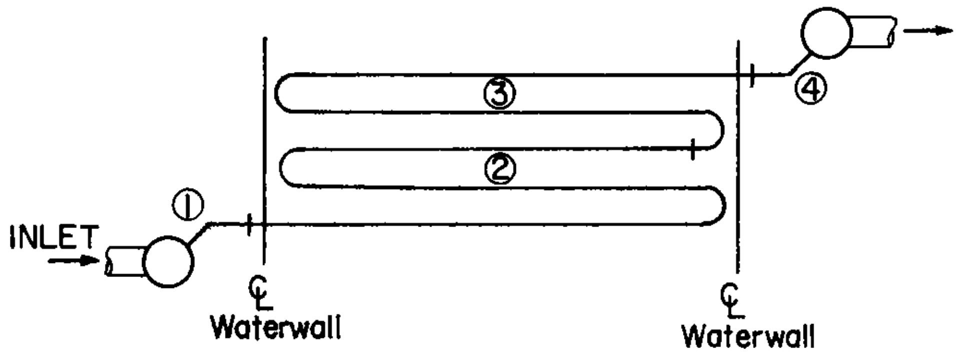
The material and tube wall thickness selections for both the primary and finishing superheaters have been selected using an even more conservative heat transfer coefficient of 70 Btu/hr, sq ft, F. The mean metal temperature of an average tube in the circuit has been determined with this conservative heat transfer coefficient based on the original bed temperature of 1550F. Figure E-18 shows the material and tube thickness specified for both the primary and finishing superheaters and indicates the location of the material changes.

3.1.7 Water and Boiling Tube Material Selections - The tube materials for the economizers, horizontal boiler sections and enclosure and partition waterwalls have been conservatively selected. The majority of the tubing in this surface has been specified as 2" O.D. with a minimum wall thickness of 0.180" and SA-210-A1 material. The only location where an alternate tube size has been specified are the radiant elements of the horizontal boiler bundles above each bed in cells A, B and C and the lower radiant tubes of Economizer 4 in cell D where a tube size of 1-3/4" O.D. with a minimum wall of .180" and material of SA-210-A1 has

FIGURE E-18

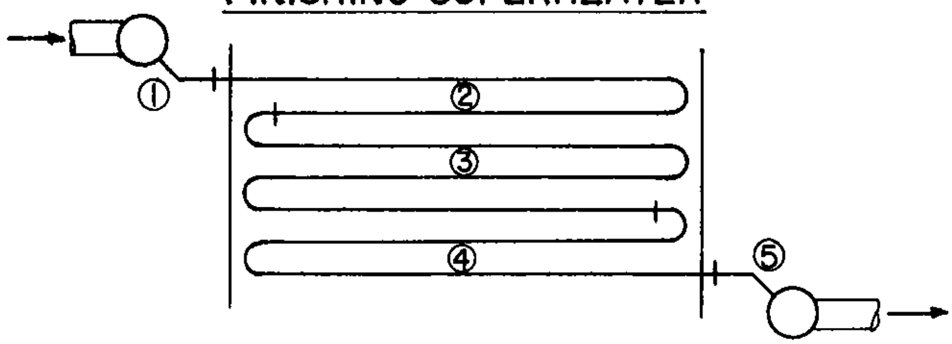
SUPERHEATER MATERIAL SELECTIONS

PRIMARY SUPERHEATER



LOCATION	MATERIAL *	Minimum Wall Thickness-in.
1	SA-210C	0.165
2	SA-213 T2	0.180
3	SA-213 T22	0.200
4	SA-213 T2	0.165

FINISHING SUPERHEATER



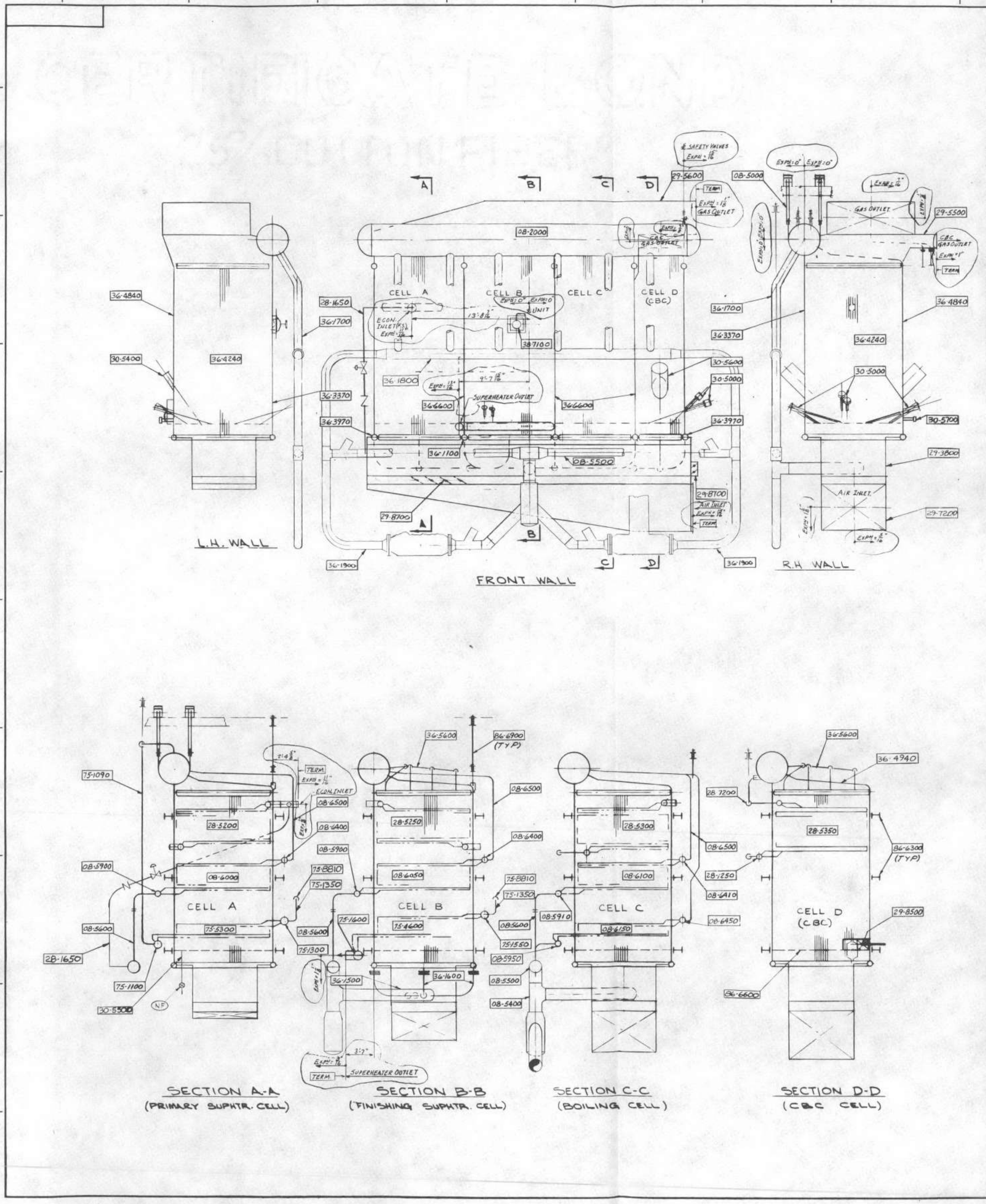
LOCATION	MATERIAL *	Minimum Wall Thickness-in.
1	SA-213 T2	0.165
2	SA-213 T22	0.180
3	SA-213 TP304 H	0.180
4	SA-213 TP304 H	0.210
5	SA-213 T22	0.200

* ASTM Specification No.

been selected. The maximum mean metal temperature of any of these boiling and water tubes will occur in the horizontal boiler bank B-4, located in the fluidized bed of cell C. Under design conditions the mean metal temperature of a boiling tube in Boiler 4 will be 620F with an upset mean-temperature of 630F. This is well below the maximum mean-metal-temperature permitted by the ASME boiler codes for the tube material selected and wall thickness specified. The conservative wall thickness has been selected to help maintain a maximum mass flow rate within the tubes and provide an additional margin for erosion plus mechanical strength for the horizontal tubes within the bed. It is anticipated that operating information from the demonstration unit will indicate that no problems will result from designing the water and boiling tubes closer to the boiler code limit, thereby reducing the cost of this type of steam generator.

3.2 Steam Generator Arrangement Drawings.

The engineering arrangement drawings for this steam generator were completed to the level required for cost estimating the fabrication and erection of the unit in October 1973. Between October and December 1973 work continued on the engineering arrangement drawings for the addition of details and analysis of the structural arrangement. Difficulties in procuring a single forced circulation pump resulted in revising the downcomer arrangment to provide for the use of two (2) pumps in parallel. This change and others were completed under the boiler fabrication and erection sub-contract awarded to Foster Wheeler Corporation in December 1973. Figure E-19 indicates the general arrangement of the demonstration unit as it is to be constructed in Rivesville, West Virginia. This figure indicates a section through each of the four cells and defines the major components of the unit. The arrangement of the enclosure wall pressure parts are shown in more detail on Figures E-20 and E-21, which describe the tubing arrangement of the front and rear and sidewalls of the steam generator. Figure E-21 also indicates the arrangement of the economizer re-circulation line required for start-up of the unit. The arrangement of the horizontal tube bundles in each cell is shown on Figure E-22. This figure also indicates the location of the partition wall openings between each cell to permit subsequent ignition of one cell from the other. As indicated on Figure E-22 each of the tube bundles is supported from the front and rear enclosure



LIST OF SHOP FABRICATED ITEMS

PART NO	DESCRIPTION
08-2000	42" I.D. DRUM
08-2700	DRUM INTERNALS
08-5000	DRUM HANGERS
08-5400	BOILER RECIRCULATION LINE
08-5500	BOILER INLET MANIFOLD
08-5900	BOILER INLET HEADERS
08-6000	BOILER COILS - CELL A
08-6050	BOILER COILS - CELL B
08-6100	BOILER COILS - CELL C (UPPER)
08-6150	BOILER COILS - CELL C (LOWER)
08-6400	BOILER OUTLET HEADERS
08-8900	BOILER NAME PLATES
08-6450	BOILER OUTLET HDR-CELL C (LOWER)
08-5950	BOILER INLET HDR-CELL C (LOWER)
08-6410	BOILER OUTLET HDR-CELL C (UPPER)
08-5910	BOILER INLET HDR - CELL C (UPPER)
28-1250	ECON INLET HDR - CELL D
28-1310	TRANSFER LINE TO CELL B
28-1360	TRANSFER LINE TO CELL C
28-1410	TRANSFER LINE TO CELL D
28-5200	ECON CELL A
28-5250	ECON CELL B
28-5300	ECON CELL C
28-5350	ECON CELL D
28-7200	ECON FEED TO DRUM
28-1650	ECON RECIRCULATION LINE
29-3800	PLENUM CHAMBER
29-4500	DOORS FOR FLUES & DUCTS
29-5500	FLUE-CBC EXIT
29-5600	FLUE-BOILER EXIT
29-7200	AIR INLET DUCT
29-8500	DAMPERS-SLIDE GATE
29-8700	DAMPERS + FRAMES - CONTROL
30-5000	COAL INJECTION SLEEVE W/FLG
30-5200	CAPPED COAL INJECTION SLEEVE
30-5400	STONE INJECTION SLEEVE W/FLG
30-5600	IGNITOR PORTS
30-5500	STONE EXTRACTION LINES
30-5700	ACCESS PORTS
36-1500	WATERWALL FEEDER MANIFOLD
36-1700	DOWNCOMERS
36-1800	DOWNCOMER MANIFOLD
36-1900	DOWNCOMER RECIRCULATION LINE
36-3370	FRONTWALL PANELS
36-4240	SIDEWALL PANELS
36-4840	REARWALL PANELS
36-6600	PARTITION WALL PANELS
36-4940	R.W. TUBES (RISERS - LOOSE)
38-3400	SIDE ENCLOSURE + SEALS
38-6020	REAR ENCLOSURE + SEALS
38-6090	FRONT ENCLOSURE + SEALS
38-7100	DOORS
38-8000	INSTRUMENT CONNS

LIST OF SHOP FABRICATED ITEMS

PART NO	DESCRIPTION
75-1090	STEAM SUPPLY LINE
75-1100	PRIMARY SUPHTR INLET HDR
75-1300	PRIMARY SUPHTR OUTLET HDR
75-1350	SUPHTR TRANSFER LINE
75-1550	FINISHING SUPHTR INLET HDR
75-1600	FINISHING SUPHTR OUTLET HDR
75-4600	FINISHING SUPHTR ELEMENTS
75-5300	PRIMARY SUPHTR ELEMENTS
75-8810	SPRAY CONTROL HDR
86-6300	HORIZONTAL BUCKSTAYS
86-6600	GRID PLATE SUPPORT STEEL
86-6900	REARWALL & BLR RISER HGRS

LIST OF DIRECT SHIPPED PURCHASED ITEMS

CODE NO	PART NO	REQ NO	DESCRIPTION	PURCH ORD. NO	VENDORS NAME
1400	36-4120	FY	SIDEWALL RISERS	N-31921	CORNELL UNDERHILL
1400	36-5600	FY	PARTITIONWALL RISERS	do.	do
1400	08-5600	FY	BOILER CELL SUPPLY LINE	do.	do
1400	36-1600	FY	WATERWALL FEEDERS	do.	do
1400	08-6500	FY	BOILER RISERS	do.	do
1400		AY	HANGERS, SPRINGS		
			INSULATION & LAGGING		
			REFRACTORY		
1400		AV	SAFETY VALVE NOZZLE		
1400		AU	BACKING RINGS		
1400		Z	BELLOWS		
1400	08-2126	ET	WIRE MESH ASSEMBLY	N-31987	
3000	39-2126	CF	SAFETY VALVES		
3000	39-2126	CH	MISCELLANEOUS VALVES	N-32550	
3000	39-2126	CM	CONTROL VALVES		
3000	39-2126	GA	BOILER RECIRCULATING PUMPS		

NOTES

1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."

REVISIONS

LETTER	DATE	DR. INIT.	DESCRIPTION
E	4-4-74	H.H.	ADDED TERM POINTS & EXPNS. ADDED CODE NO'S, PART NO'S REQN NO'S & PURCH. ORD. NO'S FOR DIRECT SHIPPED ITEMS
D	3-29-74	TRB H.H. P	IN LIST OF SHOP FAB. ITEMS, DELETED PART "29-8710 & 86-6400 AND PART" 30-5700, 08-6410 & 08-5910 AND CHANGED PART NOS. 08-5900 [illegible] IN SECT. C-C ACCORD.
C	2-6-74	HH	ADDED PART NO. 36-1900. DELETED; 28-1100, 28-1150, 28-1200, 28-1300, 28-1350, 28-1400, 28-1450, 36-1100, 36-1300, 36-1600, 36-2550, 36-3770, 36-3970 & 36-4740. 08-5600, 36-1600, 36-4120, 36-5600 & 08-6500 WERE SHOP FAB.
B	1-30-74	H.H.	REVISED PART No.
A	1-18-74	H.H.	updated

LIST OF SHOP FABRICATED ITEMS & DIRECT SHIPPED PURCHASED ITEMS
MULTICELL FLUIDIZED BED STEAM GENERATOR

DRAWING NUMBER	SCALE	REVISION
58-2126-5-20	3/16" = 1'-0"	E

DWG. MADE & APPROVED BY	INITIAL	DATE	CONT. NO. 2-58-2126
DRAFTSMAN	SWD	12-7-73	ORDER NUMBERS
CHECKER	JK	12-13-73	
SQUAD LEADER			
SECTION HEAD			
CONT. SUPV.			

OCR MULTICELL FLUIDIZD BED STEAM GENERATOR

DESIGNED BY: FOSTER WHEELER CORP. FOR POPE EVANS & ROBBINS INC

DWG. NO. 58-2126-5-20

THIS DRAWING SUPERSEDES
THIS DRAWING SUPERSEDED BY

FIGURE E-19

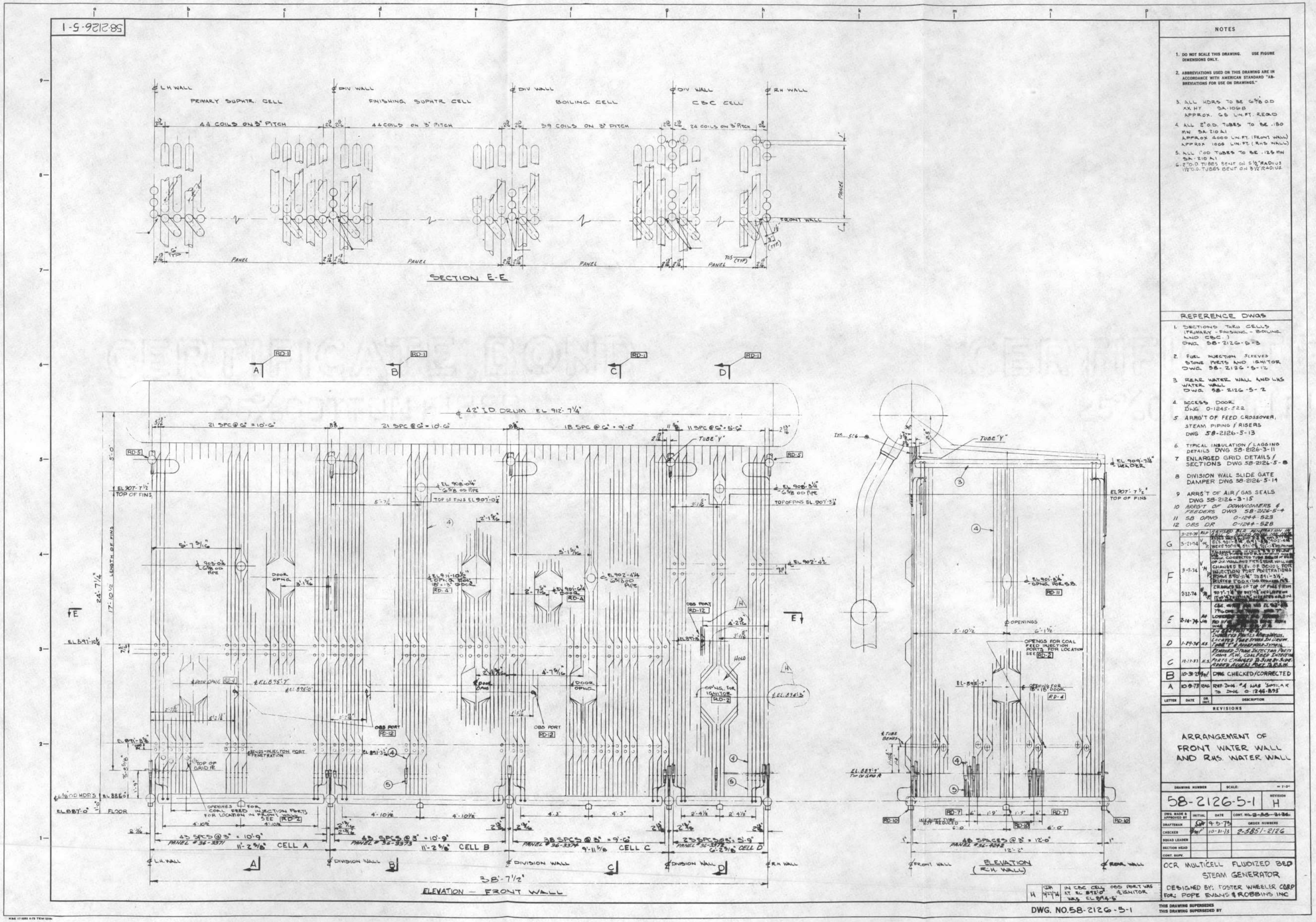

SECTION E-E
PRIMARY SUPHTR. CELL
FINISHING SUPHTR CELL
BOILING CELL
CBC CELL
44 COILS ON 3" PITCH
39 COILS ON 3" PITCH
24 COILS ON 3" PITCH
42" I.D. DRUM EL 912'-7¼"
ELEVATION – FRONT WALL
CELL A
CELL B
CELL C
CELL D
ELEVATION (R.H. WALL)
NOTES
1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."
3. ALL HDRS TO BE 6⅝ O.D XX HY SA-106B APPROX. 65 LIN.FT. REQD
4. ALL 2" O.D. TUBES TO BE .180 MW SA 210 A1 APPROX 4000 LIN.FT. (FRONT WALL) APPROX 1000 LIN.FT. (RHS WALL)
5. ALL 1" OD TUBES TO BE .125 MW SA-210 A1
6. 2" O.D. TUBES BENT ON 5½" RADIUS 1½" O.D. TUBES BENT ON 3½" RADIUS.
REFERENCE DWGS
1. SECTIONS THRU CELLS (PRIMARY - FINISHING - BOILING AND CBC.) DWG 58-2126-5-3
2. FUEL INJECTION SLEEVES STONE PORTS AND IGNITOR DWG 58-2126-5-12
3. REAR WATER WALL AND LHS WATER WALL DWG 58-2126-5-2
4. ACCESS DOOR DWG 0-1245-522
5. ARRG'T OF FEED CROSSOVER, STEAM PIPING / RISERS DWG 58-2126-5-13
6. TYPICAL INSULATION / LAGGING DETAILS DWG 58-2126-3-11
7. ENLARGED GRID DETAILS / SECTIONS DWG 58-2126-5-8
8. DIVISION WALL SLIDE GATE DAMPER DWG 58-2126-5-14
9. ARRG'T OF AIR / GAS SEALS DWG 58-2126-3-15
10. ARRG'T OF DOWNCOMERS & FEEDERS DWG 58-2126-5-4
11. SB OPNG 0-1244-523
12. OBS DR 0-1244-528
C 12-17-73 H.S. REMOVED STONE INJECTION PORTS FROM F.W., COAL FEED INJECTION PORTS CHANGED TO SIDE BY SIDE. ADDED ACCESS PORT TO R.S.W.
B 10-31-73 DWG CHECKED/CORRECTED
A 10-9-73 RAG REF. DWG. #4 WAS 'SIMILAR TO DWG. 0-1246-893'
LETTER DATE DR. INIT. DESCRIPTION
REVISIONS
ARRANGEMENT OF FRONT WATER WALL AND RHS. WATER WALL
DRAWING NUMBER SCALE: = 1'-0"
58-2126-5-1 REVISION H
DRAFTSMAN 9-5-73
CHECKER 10-31-73
ORDER NUMBERS 2-5851-2126
OCR MULTICELL FLUIDIZED BED STEAM GENERATOR
DESIGNED BY: FOSTER WHEELER CORP FOR: POPE EVANS & ROBBINS INC
THIS DRAWING SUPERSEDES
THIS DRAWING SUPERSEDED BY
DWG. NO. 58-2126-5-1

FIGURE E-20

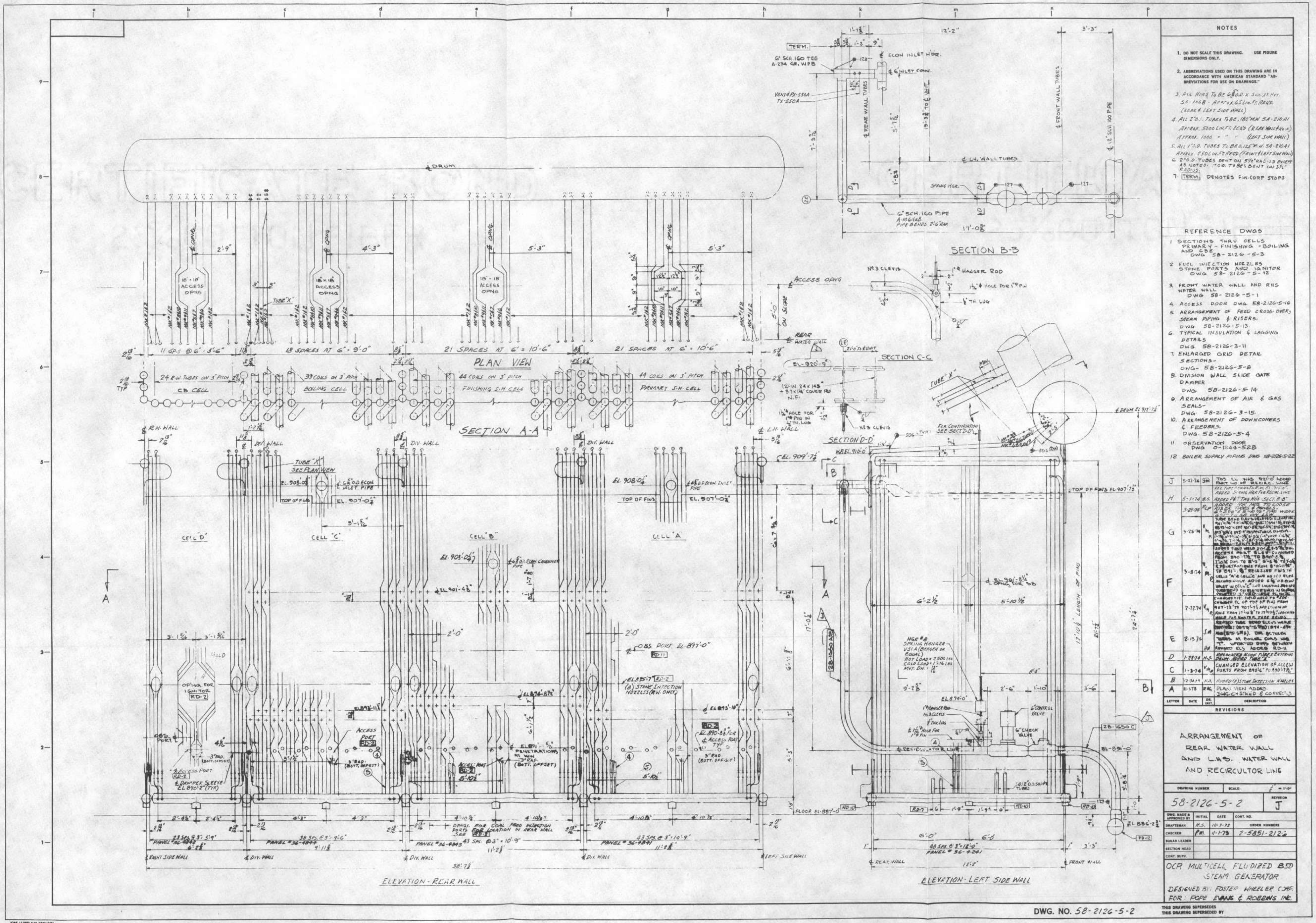
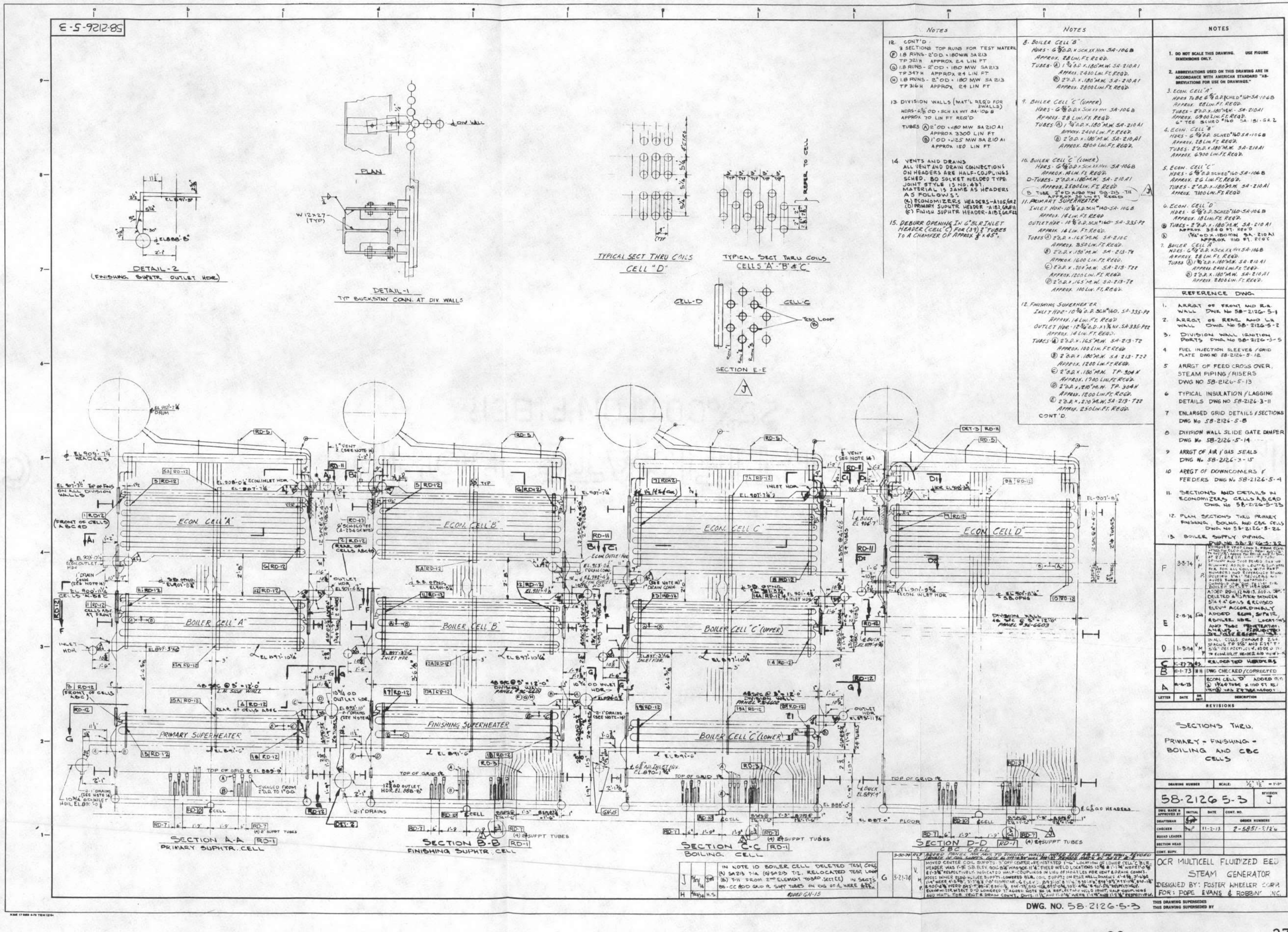

NOTES
1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."
3. ALL HDRS TO BE 6⅝ O.D. x SCH XX HVY. SA-106B - APPROX. 65 LIN. FT. REQ'D. (REAR & LEFT SIDE WALL)
4. ALL 2" O.D. TUBES TO BE .180" M.W. SA-210 A1 APPROX. 5000 LIN. FT. REQ'D (REAR WALL & ROOF) APPROX. 1000 " " " (LEFT SIDE WALL)
5. ALL 1" O.D. TUBES TO BE 0.125" M.W. SA-210 A1 APPROX. 250 LIN. FT. REQ'D (FRONT & LEFT SIDE WALL)
6. 2" O.D. TUBES BENT ON 5½" RADIUS EXCEPT AS NOTED. 1" O.D. TUBES BENT ON 3½" RADIUS.
7. TERM. DENOTES F.W. CORP STOPS
REFERENCE DWGS
1 SECTIONS THRU CELLS PRIMARY - FINISHING - BOILING AND CBE DWG 58-2126-5-3
2 FUEL INJECTION NOZZLES STONE PORTS AND IGNITOR DWG 58-2126-5-12
3 FRONT WATER WALL AND RHS WATER WALL DWG 58-2126-5-1
4 ACCESS DOOR DWG. 58-2126-5-16
5 ARRANGEMENT OF FEED CROSS-OVER, STEAM PIPING & RISERS. DWG 58-2126-5-13.
6. TYPICAL INSULATION & LAGGING DETAILS DWG 58-2126-3-11
7. ENLARGED GRID DETAIL SECTIONS - DWG - 58-2126-5-8
8. DIVISION WALL SLIDE GATE DAMPER DWG. 58-2126-5-14
9. ARRANGEMENT OF AIR & GAS SEALS - DWG. 58-2126-3-15.
10. ARRANGEMENT OF DOWNCOMERS & FEEDERS. DWG. 58-2126-5-4
11 OBSERVATION DOOR DWG 0-1244-528
12 BOILER SUPPLY PIPING DWG 58-2126-5-22
REVISIONS
C 1-3-74 CHANGED ELEVATION OF ACCESS PORTS FROM 890'-6" TO 890'-7½"
B 12-30-73 ADDED (8) STONE INJECTION NOZZLES
A 11-1-73 PLAN VIEW ADDED. DWG. CHECKED & CORRECTED
ARRANGEMENT OF REAR WATER WALL AND L.H.S. WATER WALL AND RECIRCULTOR LINE
DRAWING NUMBER 58-2126-5-2
SCALE: ½" = 1'-0"
REVISION J
DRAFTSMAN H.S. 10-7-73
CHECKER P.M. 11-1-73
ORDER NUMBERS 2-5851-2126
OCR MULTICELL FLUIDIZED BED STEAM GENERATOR
DESIGNED BY: FOSTER WHEELER CORP.
FOR: POPE EVANS & ROBBINS INC.
THIS DRAWING SUPERSEDES
THIS DRAWING SUPERSEDED BY
PLAN VIEW
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
ELEVATION - REAR WALL
ELEVATION - LEFT SIDE WALL
CELL "D"
CELL "C"
CELL "B"
CELL "A"
DWG. NO. 58-2126-5-2

FIGURE E-21



SECTIONS THRU. PRIMARY - FINISHING - BOILING AND CBC CELLS
58-2126-5-3
OCR MULTICELL FLUIDIZED BED STEAM GENERATOR
DESIGNED BY: FOSTER WHEELER CORP.
FOR: POPE, EVANS & ROBBINS INC.
DWG. NO. 58-2126-5-3
SECTION A-A
PRIMARY SUPHTR. CELL
SECTION B-B
FINISHING SUPHTR. CELL
SECTION C-C
BOILING CELL
SECTION D-D
CBC CELL
ECON CELL "A"
ECON CELL "B"
ECON CELL "C"
ECON CELL "D"
BOILER CELL "A"
BOILER CELL "B"
BOILER CELL "C" (UPPER)
BOILER CELL "C" (LOWER)
PRIMARY SUPERHEATER
FINISHING SUPERHEATER
DETAIL-1
TYP BUCKSTAY CONN. AT DIV. WALLS
DETAIL-2
(FINISHING SUPHTR OUTLET HDR)
PLAN
TYPICAL SECT THRU COILS CELL "D"
TYPICAL SECT THRU COILS CELLS "A" "B" & "C"
SECTION E-E
NOTES
REFERENCE DWG.
REVISIONS

FIGURE E-22

walls and the tube spacing is maintained by ladder type tube ties. The arrangement of the interconnecting risers and feeders for each of the steam generator circuits is shown on Figure E-23. Figure E-24 indicates the arrangement of the downcomer system required for the installation of two (2) forced circulation pumps. Due to site conditions it was necessary to maintain the entire downcomer system in a single plane as indicated in section A-A of Figure E-24. Check valves have been located at the outlet of each forced circulation pump to permit emergency operation with one pump out of service. If failure of both forced circulation pumps occurs during unit operation, check valves 2-A and 2-B on the boiler inlet manifold are designed to open and permit establishment of maximum flow by natural circulation. The entire boiling circuit including horizontal boilers and waterwalls may be drained through the connections on the downcomer system near each pump outlet. The support hanger arrangement for this manifold arrangement is also indicated on Figure E-24.

The flue and duct arrangements were revised since the original drawing issue of October 1973 due to space limitations at the Rivesville site. The combustion air inlet duct and plenum are described on Figure E-25. The sides of the plenum have been brought in approximately 2' from the centerline of the front and rear waterwalls to permit the bed material extraction lines to penetrate at the highest feasible elevation so room would be available for the bed material handling equipment. The gas exit flue, shown on Figure E-26 has been arranged to permit exit of the flue gas from cells A, B and C at the right hand end of the unit and exit of the flue gas from cell D off the rear of the unit. A restriction in headroom required that the exit flue for cells A, B and C be extended beyond the rear wall of the unit to maintain the flue gas velocity within design limits for erosion. Expansion bellows are provided at the penetrations of each riser through the exit flue.

Figures E-19 through E-26, described above, represent a portion of the engineering arrangement drawings prepared under this contract. These drawings were selected for inclusion in this interim report to show the engineering design and arrangement of the major components that make up the Rivesville demonstration unit.

3.3 Bill of Material and Purchase Specifications.

A complete bill of material as been prepared specifying all components required for fabrication of the steam generator.

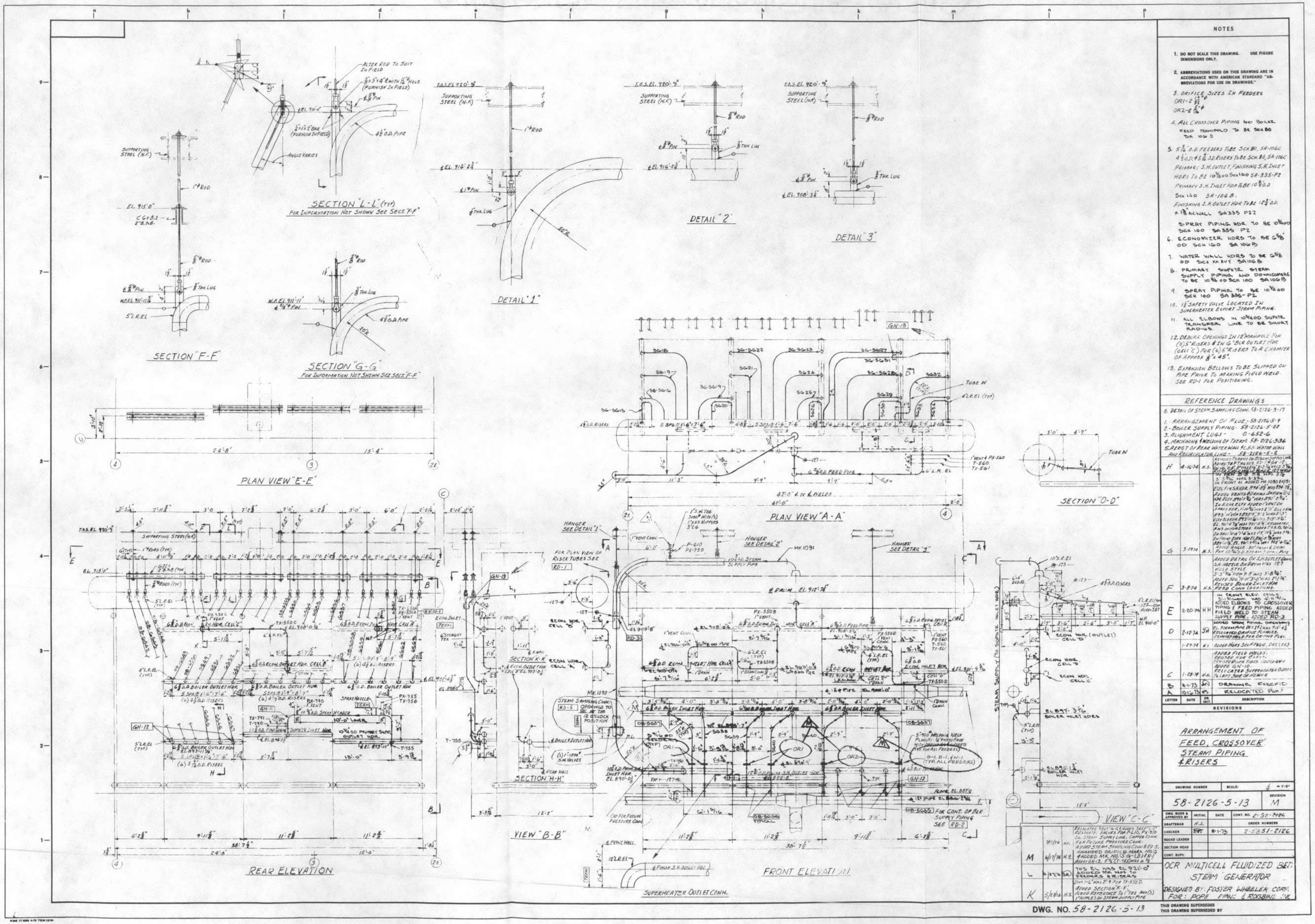

NOTES
1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."
SECTION "L-L" (TYP)
SECTION "F-F"
SECTION "G-G"
DETAIL "1"
DETAIL "2"
DETAIL "3"
PLAN VIEW "E-E"
PLAN VIEW "A-A"
SECTION "D-D"
SECTION "K-K"
SECTION "H-H"
VIEW "B-B"
VIEW "C-C"
REAR ELEVATION
FRONT ELEVATION
SUPERHEATER OUTLET CONN.
REFERENCE DRAWINGS
REVISIONS
ARRANGEMENT OF FEED, CROSSOVER STEAM PIPING & RISERS
DRAWING NUMBER 58-2126-5-13
REVISION M
OCR MULTICELL FLUIDIZED BED STEAM GENERATOR
DESIGNED BY: FOSTER WHEELER CORP.
FOR: POPE EVANS & ROBBINS INC
DWG. NO. 58-2126-5-13
THIS DRAWING SUPERSEDES
THIS DRAWING SUPERSEDED BY

FIGURE E-23

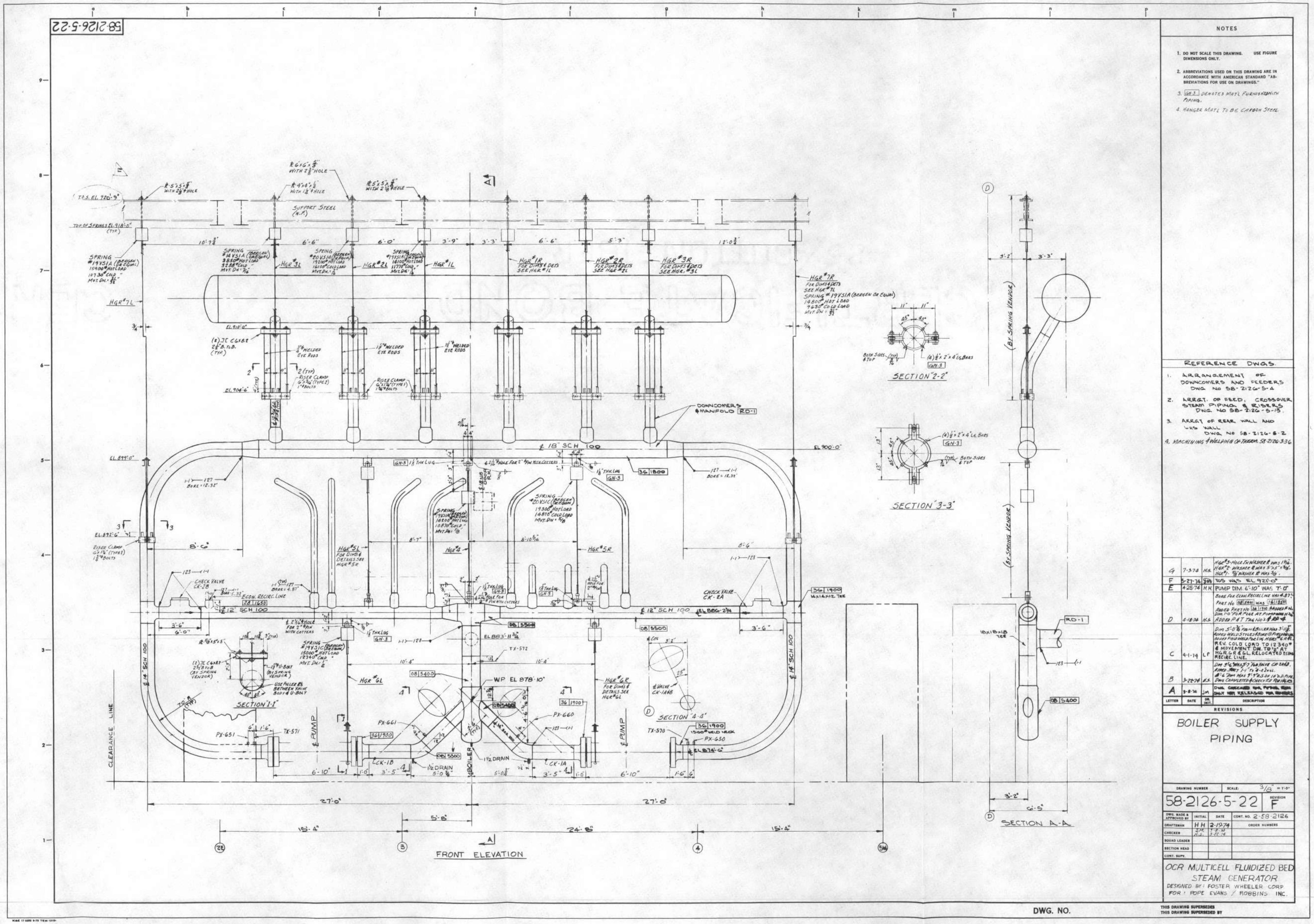

58-2126-5-22
NOTES
1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."
3. GH-3 DENOTES MAT'L FURNISHED WITH PIPING.
4. HANGER MAT'L TO BE CARBON STEEL.
REFERENCE DWGS.
1. ARRANGEMENT OF DOWNCOMERS AND FEEDERS DWG NO 58-2126-5-4
2. ARRGT. OF FEED, CROSSOVER STEAM PIPING & RISERS DWG NO 58-2126-5-13
3. ARRGT OF REAR WALL AND L.H.S. WALL DWG NO 58-2126-8-2
SECTION 2-2
SECTION 3-3
SECTION 1-1
SECTION 4-4
SECTION A-A
FRONT ELEVATION
DOWNCOMERS & MANIFOLD RD-1
18" SCH 100
12" SCH 100
14" SCH 100
CLEARANCE LINE
SUPPORT STEEL
WP EL 878'-10"
BOILER
PUMP
27'-0"
REVISIONS
LETTER
DATE
DR. INIT.
DESCRIPTION
BOILER SUPPLY PIPING
DRAWING NUMBER
SCALE: 3/8" = 1'-0"
58-2126-5-22
REVISION F
DWG. MADE & APPROVED BY
INITIAL
DATE
CONT. NO. 2-58-2126
DRAFTSMAN
H H
2-19-74
ORDER NUMBERS
CHECKER
SQUAD LEADER
SECTION HEAD
CONT. SUPV.
OCR MULTICELL FLUIDIZED BED STEAM GENERATOR
DESIGNED BY: FOSTER WHEELER CORP
FOR: POPE EVANS / ROBBINS INC.
DWG. NO.
THIS DRAWING SUPERSEDES
THIS DRAWING SUPERSEDED BY

FIGURE E-24

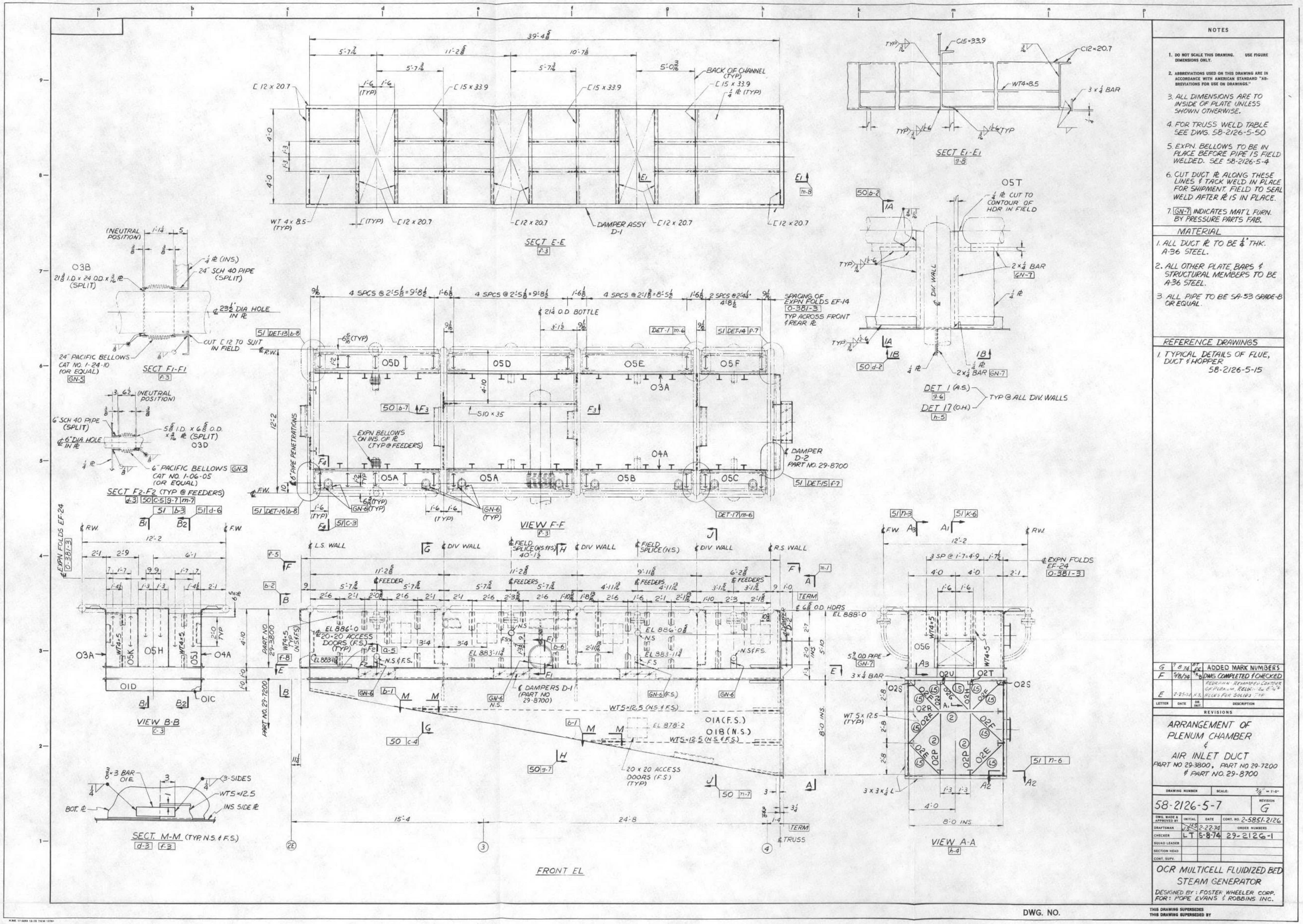
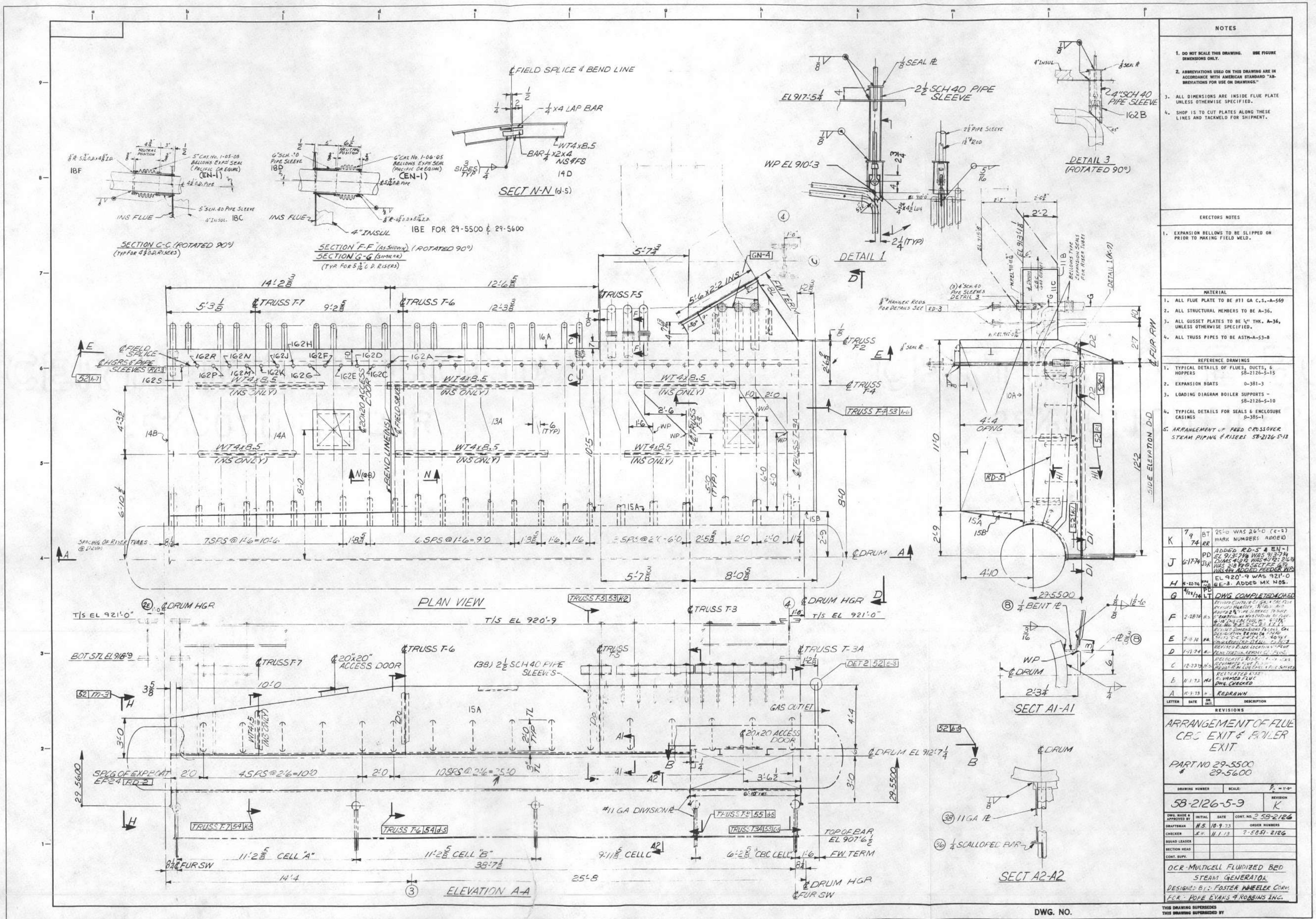

NOTES
1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."
3. ALL DIMENSIONS ARE TO INSIDE OF PLATE UNLESS SHOWN OTHERWISE.
4. FOR TRUSS WELD TABLE SEE DWG. 58-2126-5-50
5. EXPN. BELLOWS TO BE IN PLACE BEFORE PIPE IS FIELD WELDED. SEE 58-2126-5-4
6. CUT DUCT ℞ ALONG THESE LINES & TACK WELD IN PLACE FOR SHIPMENT. FIELD TO SEAL WELD AFTER ℞ IS IN PLACE.
7. GN-7 INDICATES MAT'L FURN. BY PRESSURE PARTS FAB.
MATERIAL
1. ALL DUCT ℞ TO BE 1/4" THK. A-36 STEEL.
2. ALL OTHER PLATE, BARS & STRUCTURAL MEMBERS TO BE A-36 STEEL.
3. ALL PIPE TO BE SA-53 GRADE-B OR EQUAL.
REFERENCE DRAWINGS
1. TYPICAL DETAILS OF FLUE, DUCT & HOPPER 58-2126-5-15
SECT E-E
SECT E1-E1
SECT F1-F1
SECT F2-F2 (TYP @ FEEDERS)
VIEW F-F
VIEW B-B
SECT. M-M (TYP. N.S. & F.S.)
FRONT EL
VIEW A-A
DET 1 (A.S.)
DET 17 (O.H.)
TYP @ ALL DIV. WALLS
G ADDED MARK NUMBERS
F DWG COMPLETED & CHECKED
REVISIONS
ARRANGEMENT OF PLENUM CHAMBER & AIR INLET DUCT
PART NO 29-3800, PART NO 29-7200 & PART NO. 29-8700
58-2126-5-7
G
2-5851-2126
29-2126-1
OCR MULTICELL FLUIDIZED BED STEAM GENERATOR
DESIGNED BY: FOSTER WHEELER CORP.
FOR: POPE EVANS & ROBBINS INC.
DWG. NO.

FIGURE E-25



NOTES
1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."
3. ALL DIMENSIONS ARE INSIDE FLUE PLATE UNLESS OTHERWISE SPECIFIED.
4. SHOP IS TO CUT PLATES ALONG THESE LINES AND TACKWELD FOR SHIPMENT.
ERECTORS NOTES
1. EXPANSION BELLOWS TO BE SLIPPED ON PRIOR TO MAKING FIELD WELD.
MATERIAL
1. ALL FLUE PLATE TO BE #11 GA C.S.-A-569
2. ALL STRUCTURAL MEMBERS TO BE A-36.
3. ALL GUSSET PLATES TO BE ¼" THK. A-36, UNLESS OTHERWISE SPECIFIED.
4. ALL TRUSS PIPES TO BE ASTM-A-53-B
REFERENCE DRAWINGS
1. TYPICAL DETAILS OF FLUES, DUCTS, & HOPPERS 58-2126-5-15
2. EXPANSION BOATS 0-381-3
3. LOADING DIAGRAM BOILER SUPPORTS - 58-2126-5-10
4. TYPICAL DETAILS FOR SEALS & ENCLOSURE CASINGS 0-385-1
5. ARRANGEMENT OF FEED CROSSOVER STEAM PIPING & RISERS 58-2126-5-13
REVISIONS
A REDRAWN
ARRANGEMENT OF FLUE CBC EXIT & BOILER EXIT
PART NO 29-5500 & 29-5600
DRAWING NUMBER 58-2126-5-9
REVISION K
DRAFTSMAN H.S. 10-9-73
CHECKER 11-1-73
ORDER NUMBERS 2-5851-2126
OCR-MULTICELL FLUIDIZED BED STEAM GENERATOR
DESIGNED BY:- FOSTER WHEELER CORP.
FOR:- POPE EVANS & ROBBINS INC.
THIS DRAWING SUPERSEDES
THIS DRAWING SUPERSEDED BY
PLAN VIEW
ELEVATION A-A
SECT N-N
DETAIL 1
DETAIL 3 (ROTATED 90°)
SECT A1-A1
SECT A2-A2
SIDE ELEVATION D-D
DWG. NO.

FIGURE E-26

As an example of this bill of material a listing of tubing requirements for a majority of the heat transfer surface is indicated on Figure E-22. The purchase specifications required for procurement of all material for the steam generator have been prepared and this material has been purchased under the boiler fabrication and erection sub-contract.

3.4 Fabrication and Erection Instructions.

A detailed inspection, fabrication and assembly sequence was prepared and included in the PER cost proposal solicitation for fabrication and erection of the Rivesville demonstration unit on October 8, 1973. The inspection, fabrication and assembly sequence described step-by-step requirements for fabrication of each of the major components of the unit and defined inspection requirements at the various phases of fabrication and assembly.

4.0 WORK PROGRESS - Phase III.

As described in paragraph 1.3 the work for this phase involves preparation of technical specifications, solicitation of price quotations and evaluation of submitted price quotations for piping systems specialties directly attached to the steam generator plus design of a calcium sulfate regeneration system. The work required for preparation of specifications and solicitation and evaluation of price quotations was completed on June 26, 1974. Engineering of the calcium sulfate regenerator design is currently in progress and preparation of the regenerator arrangement drawings will be released following approval of the completed regenerator design. The following paragraphs describe the work completed for Phase III.

4.1 Equipment specifications

4.1.1 Forced circulation pumps - Specifications for the forced circulation pumps were completed and issued on December 6, 1973. The original demonstration unit design included provisions for a single forced circulation pump; however, feedback from the pump manufacturers indicated that the pump required would need to be developed. To avoid the need for developing new pump designs the steam generator arrangement was revised to incorporate two (2) half capacity pumps which can be supplied from presently available designs. The performance specifications for the half capacity pumps are shown on Table E-10. The evaluation of the vendor responses was completed in January 1974 and recommendations were made to PER for purchase of two pumps from United Pumps.

4.1.2 Ignition burners - Two ignition burners are required for light-off of the demonstration unit and will be located on the CBC. Specifications for the burners were initially issued on December 12, 1973. Since the initial vendor responses to these specifications did not conform, the specifications were re-written and re-submitted to the vendors on May 15, 1974. Table shows the design requirements for the ignition burners. The vendor responses have been evaluated and recommendations for purchase of the burner equipment have been made to PER.

4.1.3 Valves - Specifications for control, check, block and miscellaneous boiler trim valves were issued on January 14, 1974. Table E-12 indicates the design require-

TABLE E-10

Forced Recirculation Pumps

2 Required

Operating Conditions, each pump

Liquid - Treated Boiler Water
Temperature - 601F (max 610F)
Specific Gravity - .677
Suction Pressure - 1535 psig (1700 psig max.)
Discharge Pressure - 1570 psig
Flow - 5750 gal/min

Construction - Inline Type

Suction Nozzle 14" 1500# RF flange - horizontal
Discharge Nozzle 14" 1500# RF flange - horizontal
Design - 1700 psig @ 625F
Hydrotest - 2550 psig min

Motor Drives

440 volt, 3 phase, 60 hz. TEFC
Induction type

Site Data

Temperature - 120F max., 32F min.
Indoors

TABLE E-11

Ignition Burners

2 Required

Design Requirements (each burner)

Heat Release - 4 million btu/hr max.
Fuel - API #2 fuel oil
Excess air - 3 to 15%
Combustion air temp. - 625F max. (80 to 110F start-up)
Combustion air pressure - 36" to 72" H_2O
Throat Velocity - 200 ft/sec (approx.)
Burners to be located to fire downwards at 45° from horizontal onto a fluidized bed
Throat of burner to see 2000F during boiler operation
Flame Throw - 4-6 ft.

Accessories Required

Air Control Dampers and Operators
Flame Detection Equipment
Control Cabinet and Controls
Burner Front Piping
Noise Attenuation (if required)

TABLE E-12

Valves

Design Requirements

Control Valves

Function	No. Req'd.	Size	Pressure psig	Max ΔP psi	Temp-F
CV-1 Spray	1	2"x1½"x2"	2000	2000	400
CV-2 Feedwater	1	4"	2000	2000	400
CV-4 Surface Blow-off	1	1½"	1600	1650	606
CV-6 Economizer Recirculation	1	6"	1600	200	606
CV-7 Bottom Blowdown	1	1½"	1600	1700	606
Block					
BV-1 Spraywater	1	2"	2000	2000	850
BV-2 Feedwater	1	4"	2000	2000	400
BV-4 Surface Blowoff	1	1½"	1600	1650	606
BV-7 Bottom Blowdown	1	1½"	1600	1700	606
Check					
CK-1 Recirculation Pump	2	14"x12"x14"	1600	50	606
CK-2 Boiler Manifold	2	12"	1600	50	606
CK-3 Feedwater	1	4"	2000	100	400
CK-4 Spraywater	1	2"	1600	100	650
CK-5 Economizer Recirculation	1	6"	1600	200	606
CK-6 Steam Non-Return	1	6"	1600	1600	1000
Miscellaneous Trim					
Drains	22	1"	1600	1600	606
Drains	4	1½"	1600	1600	606
Vents	9	1"	1600	1600	606
Pressure Gauge	29	1"	1600	1600	606
Level Instrument	4	2"	1600	1600	606
Level Instrument	16	1"	1600	1600	606
Level Instrument	4	¼"	1600	1600	606
Flow Instrument	8	1"	1600	1600	606

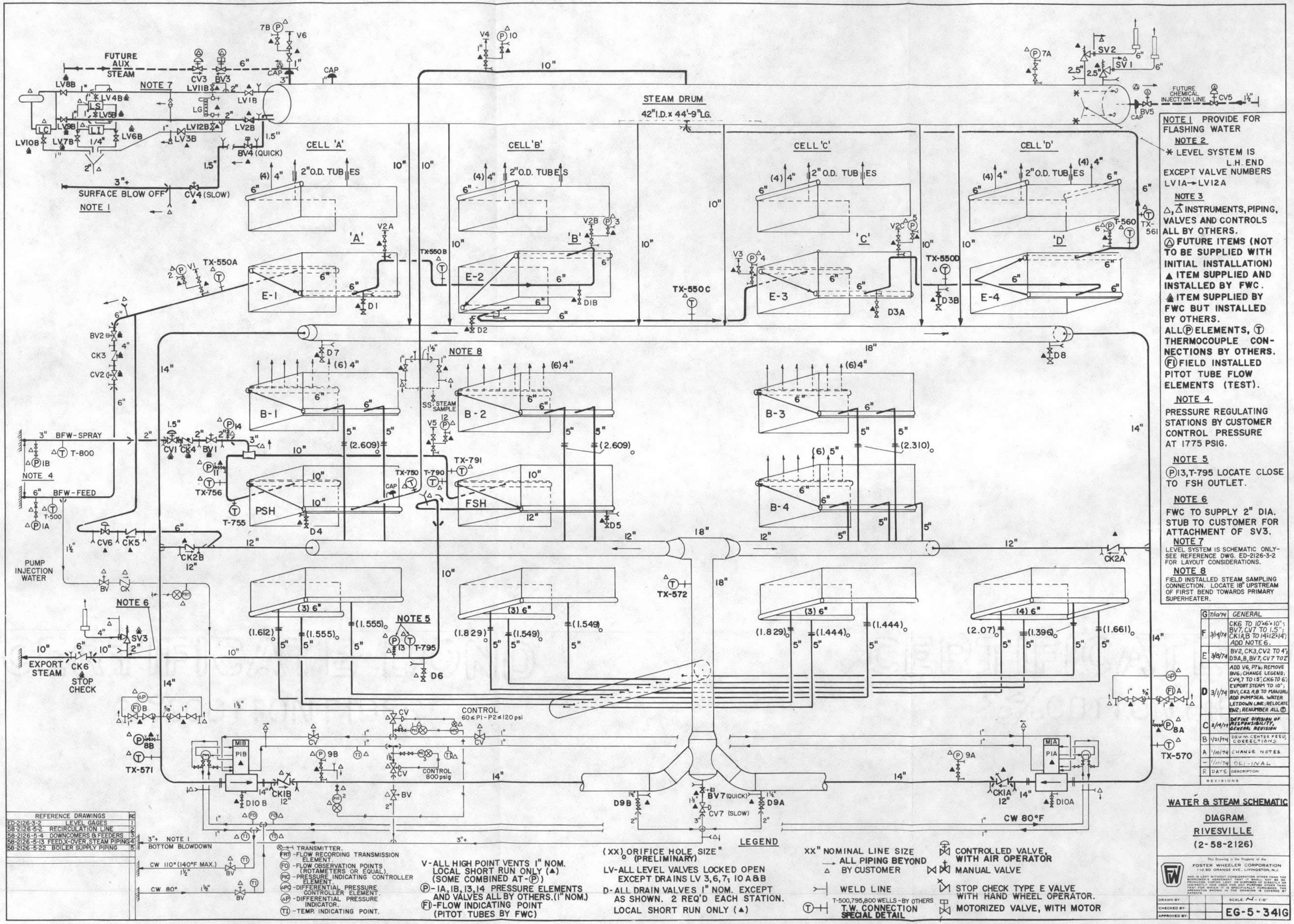
ments for each valve specified and the location of these valves in the steam generator system is indicated on the water and steam schematic diagram, Figure E-27. Vendor responses to the specifications were received and recommendations for purchase made to PER in February 1974. The recommended vendors for the valves included Valtek Corporation for control valves and Rockwell for all remaining valves.

4.1.4 Safety valves - Specifications for supply of the steam generator safety valves were issued on December 10, 1973. Table E-13 indicates the design requirements for these valves. An analysis of the offers by responding vendors resulted in recommendation for purchase from Consolidated Valves (Dresser) in January 1974.

4.1.5 Level gauge units - Specifications for the drum level gauge units were solicited on January 11, 1974 and the resulting responses were evaluated resulting in a recommendation for purchase from Yarway Corporation in February 1974. The specifications for the Drum Level gauge units required a design pressure of 1600 psig and temperature of 606F. The units were to include a vision water column and gauge assembly, shut-off valves, connections suitable for mounting level alarms and indicators, reflector hood and mirror assemblies.

4.1.6 Slide-gate actuators - Three pneumatic cylinder type actuators are required to operate the slide gate dampers between fluidized bed cells. Specifications for these actuators were solicited on January 18, 1974 and analysis of the submitted responses resulted in recommendation for purchase of these units from Bailey Meter Company. The specifications required that the actuator be of the pneumatic cylinder type with full stroke position control. The design requirements for these actuators are indicated on Table E-14.

4.1.7 Fuel injection sleeve isolation devices - These devices are required to prevent the back-flow of hot bed material through the coal injection sleeve during extraction of the coal injection nozzle during boiler operation. The specifications for these devices were first issued on January 24, 1974. The responses to these specifications were priced in an unacceptable range and alternate types of devices were specified on March 12, 1974. From the responses received two recommendations were made to PER in June 1974. The



FUTURE AUX STEAM
NOTE 7
STEAM DRUM
42" I.D. x 44'-9" LG.
CELL 'A'
CELL 'B'
CELL 'C'
CELL 'D'
2" O.D. TUBES
SURFACE BLOW OFF
NOTE 1
BV4 (QUICK)
CV4 (SLOW)
E-1
E-2
E-3
E-4
NOTE 8
STEAM SAMPLE
B-1
B-2
B-3
B-4
PSH
FSH
BFW-SPRAY
BFW-FEED
NOTE 4
PUMP INJECTION WATER
NOTE 6
NOTE 5
EXPORT STEAM
STOP CHECK
CONTROL 60 ≤ P1-P2 ≤ 120 psi
CONTROL 800 psig
BV7 (QUICK)
CV7 (SLOW)
CW 80°F
FUTURE CHEMICAL INJECTION LINE
NOTE 1 PROVIDE FOR FLASHING WATER
NOTE 2
* LEVEL SYSTEM IS L.H. END EXCEPT VALVE NUMBERS LV1A → LV12A
NOTE 3
△, INSTRUMENTS, PIPING, VALVES AND CONTROLS ALL BY OTHERS.
FUTURE ITEMS (NOT TO BE SUPPLIED WITH INITIAL INSTALLATION)
▲ ITEM SUPPLIED AND INSTALLED BY FWC.
ITEM SUPPLIED BY FWC BUT INSTALLED BY OTHERS.
ALL (P) ELEMENTS, (T) THERMOCOUPLE CONNECTIONS BY OTHERS.
(FI) FIELD INSTALLED PITOT TUBE FLOW ELEMENTS (TEST).
NOTE 4
PRESSURE REGULATING STATIONS BY CUSTOMER CONTROL PRESSURE AT 1775 PSIG.
NOTE 5
(P)13, T-795 LOCATE CLOSE TO FSH OUTLET.
NOTE 6
FWC TO SUPPLY 2" DIA. STUB TO CUSTOMER FOR ATTACHMENT OF SV3.
NOTE 7
LEVEL SYSTEM IS SCHEMATIC ONLY-SEE REFERENCE DWG. ED-2126-3-2 FOR LAYOUT CONSIDERATIONS.
NOTE 8
FIELD INSTALLED STEAM SAMPLING CONNECTION. LOCATE 18" UPSTREAM OF FIRST BEND TOWARDS PRIMARY SUPERHEATER.
REFERENCE DRAWINGS
ED-2126-3-2 LEVEL GAGES
58-2126-5-2 RECIRCULATION LINE
58-2126-5-4 DOWNCOMERS & FEEDERS
58-2126-5-13 FEED, X-OVER, STEAM PIPING
58-2126-5-22 BOILER SUPPLY PIPING
BOTTOM BLOWDOWN
CW 110° (140°F MAX.)
CW 80°
TRANSMITTER.
(FRT) - FLOW RECORDING TRANSMISSION ELEMENT.
(FO) - FLOW OBSERVATION POINTS (ROTAMETERS OR EQUAL).
(PIC) - PRESSURE INDICATING CONTROLLER ELEMENT.
(DPC) - DIFFERENTIAL PRESSURE CONTROLLER ELEMENT.
(ΔP) - DIFFERENTIAL PRESSURE INDICATOR.
(TI) - TEMP. INDICATING POINT.
V - ALL HIGH POINT VENTS 1" NOM. LOCAL SHORT RUN ONLY (▲) (SOME COMBINED AT-(P))
(P) - 1A, 1B, 13, 14 PRESSURE ELEMENTS AND VALVES ALL BY OTHERS. (1" NOM.)
(FI) - FLOW INDICATING POINT (PITOT TUBES BY FWC)
(XX) ORIFICE HOLE SIZE" (PRELIMINARY)
LV - ALL LEVEL VALVES LOCKED OPEN EXCEPT DRAINS LV 3, 6, 7, 10 A & B
D - ALL DRAIN VALVES 1" NOM. EXCEPT AS SHOWN. 2 REQ'D EACH STATION. LOCAL SHORT RUN ONLY (▲)
LEGEND
XX" NOMINAL LINE SIZE
ALL PIPING BEYOND BY CUSTOMER
WELD LINE
T-500, 795, 800 WELLS - BY OTHERS
T.W. CONNECTION SPECIAL DETAIL
CONTROLLED VALVE, WITH AIR OPERATOR
MANUAL VALVE
STOP CHECK TYPE E VALVE WITH HAND WHEEL OPERATOR.
MOTORIZED VALVE, WITH MOTOR
REVISIONS
WATER & STEAM SCHEMATIC DIAGRAM
RIVESVILLE
(2-58-2126)
FOSTER WHEELER CORPORATION
110 SO. ORANGE AVE., LIVINGSTON, N.J.
EG-5-3416

FIGURE E-27

TABLE E-13

Safety Valves

Design Requirements

Valve No.	SV-1	SV-2	SV-3
Location	Drum	Drum	Superheater Outlet
Number Required	1	1	1
Design Pressure - PSIG	1600	1600	1600
Design Temperature - F	625F	625F	1000F
Type	Spring	Spring	Spring
Size Inlet	$2\frac{1}{2}$"	$2\frac{1}{2}$"	2"
Size Outlet	6" RF	6" RF	4" RF
Set Pressure - PSIG	1600	1550	1400
Capacity - lb/hr	180,000	120,000	60,000

TABLE E-14

Slide Gate Actuator

3 Required

Design Requirements

Type: Air Piston
Stroke: 18" max. (0" to 12" normal)
Stroke time: 8 seconds max. (3-6 seconds normal)
Force: 1000 lb. maximum (600-800 lb. normal)
Control: Continuous over the stroking range
Air Pressure: 60 psig min. (60-80 psig)
Limit Switches: 125 volts D.C., .5 amp
Control Signals: 4-20 milli amperes
Plant Power: 440 volt, 60 Hz, 3 phase A.C. and 110 volt, 60 Hz, 1 phase A.C.

first recommendation was for an aspirating device that uses compressed air to seal against the back-flow of hot furnace gases and bed material. The second recommendation was for a sliding disc valve that will isolate the coal injection sleeve after extraction of the coal injection nozzle. The first recommendation for the aspirating device will result in a slightly more expensive installed system however this type of device offers maximum safety to operating personnel. The slide disc valve arrangement when operated could permit hot gases and bed material to blow back through the sleeve prior to closure of the valve.

4.2 Calcium Sulfate Regenerator Design

A calcium sulfate regeneration system is being designed for use with cell A of the Rivesville, West Virginia unit. The regenerator is being designed to regenerate calcium sulfate ($CaSO_4$) to lime (CaO) and sulfur dioxide (SO_2). The regeneration reaction requires raising the temperature of the calcium sulfate from a maximum of 1550F to approximately 2000F. The concept for the calcium sulfate regenerator involves the use of a fluidized bed process with the combustion of coal providing heat for the necessary temperature increase of the calcium sulfate material. It is advantageous to maintain good thermal efficiency within the regenerator to minimize the heat input requirement. The combustion of fuel for the heat input to the regenerator dilutes the SO_2 concentration of the product gas. Since this product gas must be treated for removal of the SO_2, the size and sophistication of the treatment system is dependent upon the quantity of gas and concentration of SO_2 therein. The regeneration of calcium sulfate to lime and SO_2 is sensitive to reaction temperature, partial pressure of reducing gases (CO) and dwell time of the individual calcium sulfate particles within the reaction chamber.

The design of the regenerator vessel is in progress and reaction requirements that dictate maximum thermal efficiency indicate a refractory lined, insulated vessel with a maximum air inlet temperature to the air distribution grid. Since this regenerator vessel is being designed to contain a chemical reaction that is sensitive to changes in temperature and gas composition, a gas-phase chemical equilibrium calculation has been made to determine the theoretical chemical make-up of the regenerator off-gases for the design concept selected.

A computer program has been used to analyze the gas phase equilibrium for four conditions as follows:

4.2.1 Case 1 - The feed gas to the program, derived from a combustion calculation, compares well with the computer values for the equilibrium gas analysis for this base case. The regenerator combustion gas analysis and calculated equilibrium gas analysis for this case are tabulated on Table E-15.

4.2.2 Case 2 - This equilibrium analysis differs from Case 1 in that the quantity of coal fired is about 10% less than for the base case. Case 2 shows the sensitivity of the reaction to efficient heat utilization. Table E-16 lists the composition of the regenerator combustion gases and the calculated gas equilibrium for that condition.

4.2.3 Case 3 - In Cases 1 and 2 there was no residual O_2 in the off-gas. In Case 3 the regenerator effluent of the base case, Case 1, is diluted with the standard air shown on Table E-17 to yield 0.45 mole percent O_2 in the off-gas. This excess air condition has been simulated to determine the reduction of gas pollutants in the form of H_2, CO, CH_4, H_2S and COS. The results of the Case 3 analysis are tabulated on Table E-18.

4.2.4 Case 4 - This analysis repeats the base case, Case 1, but with additional steam or water feed to yield approximately 15 mole percent H_2O in the equilibrium gas composition. This case was performed to aid in the determination of formation of low melting temperature eutectics within the regenerator vessel with an increase in moisture content within the reaction zone. The equilibrium gas analysis is tabulated on Table E-19.

The gas phase equilibrium studies performed on the combustion gas analysis resulting from the preliminary regenerator design indicates SO_2 levels in the vicinity of 5% are theoretically possible with an anticipated level somewhat less. Regenerator design is continuing with emphasis on increasing the SO_2 content of the off-gases and reducing the total off-gas volume requiring treatment for removal of potential pollutants.

TABLE E-15

Regenerator Off-Gas Composition - Case 1

t = 2000F, p = 1.0 atmosphere

Component	Gas Composition, Mol %	
	Feed Gas (1)	Calculated Equilibrium Gas
H_2	0.0	0.168
N_2	67.92	67.91
CO	0.650	0.513
CO_2	15.88	16.02
CH_4	0.0	$(0.59)(10^{-12})$
H_2O	10.77	10.58
H_2S	0.0	0.0202
SO_2	4.76	4.78
COS	0.0172	0.00208

(1) Composition of regenerator off-gas determined by combustion analysis.

(2) CH_4, H_2 and CO included in all tables to allow check on steam-methane reaction K. Trace quantities of "pollutants" included to allow estimates of these tobe made based on equilibrium.

TABLE E-16

Regenerator Off-Gas Composition

Case 2 (Sensitivity Test)

t = 2000F, p = 1.0 atmosphere

	Gas Composition, Mol %	
Component	Feed Gas (1)	Calculated Equilibrium Gas
H_2	0.0	0.1724
N_2	67.31	67.31
CO	0.725	0.530
CO_2	15.92	16.13
CH_4	0.0	$(0.6626)(10^{-12})$
H_2O	10.77	10.58
H_2S	0.0	0.02409
SO_2	5.26	5.25
COS	0.0191	0.002491

(1) Composition of regenerator off gas determined by combustion analysis.

(2) CH_4, H_2 and CO included in all tables to allow check on steam-methane reaction K. Trace quantities of "pollutants" included to allow estimates of these to be made based on equilibrium.

TABLE E-17

Standard Air Composition[1]

Component	Mol %
N_2	77.3830
O_2	20.5702
H_2O	2.0468

(1) Composition used for combustion analysis.

TABLE E-18

Regenerator Off-Gas Composition

Case 3

t = 2000F, p = 1.0 atmosphere

Component	Calculated Equilibrium Gas (Mol. %)(1)
H_2	$(0.411)(10^{-4})$
N_2	68.51
CO	$(0.126)(10^{-3})$
CO_2	15.96
CH_4	$(0.2159)(10^{-26})$
H_2O	10.46
H_2S	$(0.2923)(10^{-12})$
SO_2	4.61
COS	$(0.302)(10^{-13})$
O_2	0.455

(1) Results from reacting 0.0400 moles of standard air to one mole of Case 1 feed gas.

(2) CH_4, H_2 and CO included in all tables to allow check on steam-methane reaction K. Trace quantities of "pollutants" included to allow estimates of these to be made based on equilibrium.

TABLE E-19

Regenerator Off-Gas Composition

Case 4

t = 2000F, p = 1.0 atmosphere

Components	Calculated Equilibrium Gas (Mol %)[1]
H_2	0.2102
N_2	64.54
CO	0.433
CO_2	15.28
CH_4	$(0.6937)(10^{-12})$
H_2O	14.97
H_2S	0.01885
SO_2	4.54
COS	0.001305

(1) Results from reacting 0.0677 moles of water to one mole of Case 1 feed gas.

(2) CH_4, H_2 and CO included in all tables to allow check on steam-methane reaction K. Trace quantities of "pollutants" included to allow estimates of these to be made based on equilibrium.

5.0 WORK COMPLETED - PHASE IV

Work under this phase was completed in December 1973 and the final reports were submitted to PER on October 15, 1973 and January 15, 1974. These final reports included a project plan for testing on a cold model of systems required for operation of the Rivesville, West Virginia Demonstration Unit, and a project plan for additional testing required to develop the fluidized bed combustion process to the utility steam generator scale. Prior to preparation of the test plan for the cold model an analysis of concepts for systems to perform (1) fuel metering and injection, (2) bed material extraction, classification, transfer, regeneration and injection and (3) ignition was made. The following paragraphs describe the concepts considered, the cold model test program and follow up project plan.

5.1 Design Concept Selection.

5.1.1 Fuel Metering and Injection Systems - Pilot Unit testing at the PER Alexandria, Virginia facility indicates that fuel injection is required at the center of every nine (9) square feet of fluidized bed plan area. This requirement dictates that fuel and limestone must be distributed evenly to multiple points within each individual cell of the Rivesville, West Virginia unit. The methods considered for fuel distribution included individual feeders for each injection point, a screw feeder arrangement with multiple inlets and outlets feeding to individual pneumatic lines for each feed point and a pressurized vibrating type distributor feeding fuel and limestone to multiple points in each cell. The concept of individual feeders was discarded due to excessive costs, and poor operating records with screw feeders moving coal led to the elimination of the second concept. Since vibrating distributors have shown the ability to distribute evenly to multiple extraction points and have a good operating and maintenance record this concept was selected for use at the Rivesville demonstration unit. There was no question that the technique for injecting the fuel into the fluidized bed should be pneumatic, however, the physical arrangement of the pneumatic injection line required some consideration. Pilot unit testing at Alexandria, Virginia has shown that the preferred arrangement of injecting the fuel up through the air distribution grid would lead to problems of fuel line plugging and erosion. The best experience has been using a straight, downflow arrangement which required significant injection line length inside the fluidized bed combustion zone. It was anticipated that this arrangement would lead to coking problems and decided that the downflow injection line would be used for the Rivesville demonstration unit and tested at the Alexandria pilot unit.

5.1.2 Bed Material Handling - Various systems for bed material extraction were considered, including rotary feeders, double slide gate arrangements and vibrating feeders. Since vibrating feeders are the only of these devices with proven experience at temperatures around 1500F and with reasonable cost the vibrating feeder was selected as the best device for metering high temperature bed material out of the fluidized bed unit. The gas pressure seal with this type of feeder will be provided by a vertical leg of static bed material. The size classification of extracted bed material will be done with a vibrating screen system. There is some question regarding the life expectancy of the vibrating screens and further investigation of the techniques for classification and for screen design is required.

Since there is an efficiency benefit if the bed material is kept close to the extraction temperature the device selected for lifting the bed material from the classifying system should be one that minimizes heat losses. The system selected for Rivesville is a pneumatic system which has been proven for use with high temperature solids. A heat benefit would be realized if a low heat loss bucket elevator system that would operate satisfactorily while transporting solids at temperatures between 1500 and 2000F is developed.

Once the hot bed material has been lifted from the classification system it must be injected into the calcium sulfate regenerator. Since this device will be operating at 2000F or higher and the bed material will be close to 1500F prior to injection any moving equipment for transporting or injecting the bed material will be difficult to design and costly to manufacture. Analysis of several possibilities resulted in the use of a vibrating feeder accepting the hot bed material from a hopper and injecting the bed material into the regenerator by gravity. Extraction of the regenerated bed material from the calcium sulfate regenerator will be by overflowing a weir and flowing the regenerated material into the fluidized bed steam generator by gravity.

5.1.3 Fluidized Bed Ignition - Since the method used at the Alexandria, Virginia pilot unit involving an ignition burner fired down on the bed material has proven to operate satisfactorily, it was decided this technique would be used to light off the Rivesville, West Virginia demonstration unit. Alternate techniques for ignition of a fluidized bed cell with horizontal tubes immersed in the bed must be developed for scale up of the process to utility units using vertically stacked cells.

5.1.4 Air Distribution Grid - Since the cost of the nozzle button air distribution grid used in the pilot unit would be excessive for large commercial units it was decided that alternate designs should be constructed and tested, attempting to reduce costs and improve performance.

5.1.5 Tube Bundle Arrangement - Since horizontal tubes had not been tested in the pilot unit it was decided that various tube bundle arrangements should be tested in a cold model to determine the fluidizing characteristics and the best of these arrangements would be used in the Rivesville demonstration unit.

5.2 Cold Model Testing Program

To achieve the best possibility of success upon start-up of the Rivesville demonstration unit, the concepts for auxilliary systems developed according to paragraph 5.1 should be tested to determine their operating characteristics. To provide maximum information at minimal cost the test program will involve two (2) cold model test units. A small unit (5" x 20") erected at Foster Wheeler expense will be used for rapid screening of tube arrangements, distributor plates, etc. A large cold model (6' x 6') to be built under this project will be used for testing of the most promising candidates of the screening tests, and for tests where a small model would be inappropriate, such as the bed material extraction system. The following paragraphs describe the cold model test systems and the test program.

5.2.1 Cold model test systems - The small model consists of a rectangular (5" x 20") plexiglas box 12' high. Below the model is a 2' deep plenum chamber. The distributor plate is sandwiched between the model and the plenum chamber and is flanged for easy removal and replacement. The horizontal tube bundle in the bed is located from 1' to 3' above the air distributor and interchangeable plexiglass sheets and removeable polyethylene tubes allow the tube arrangement to be varied.

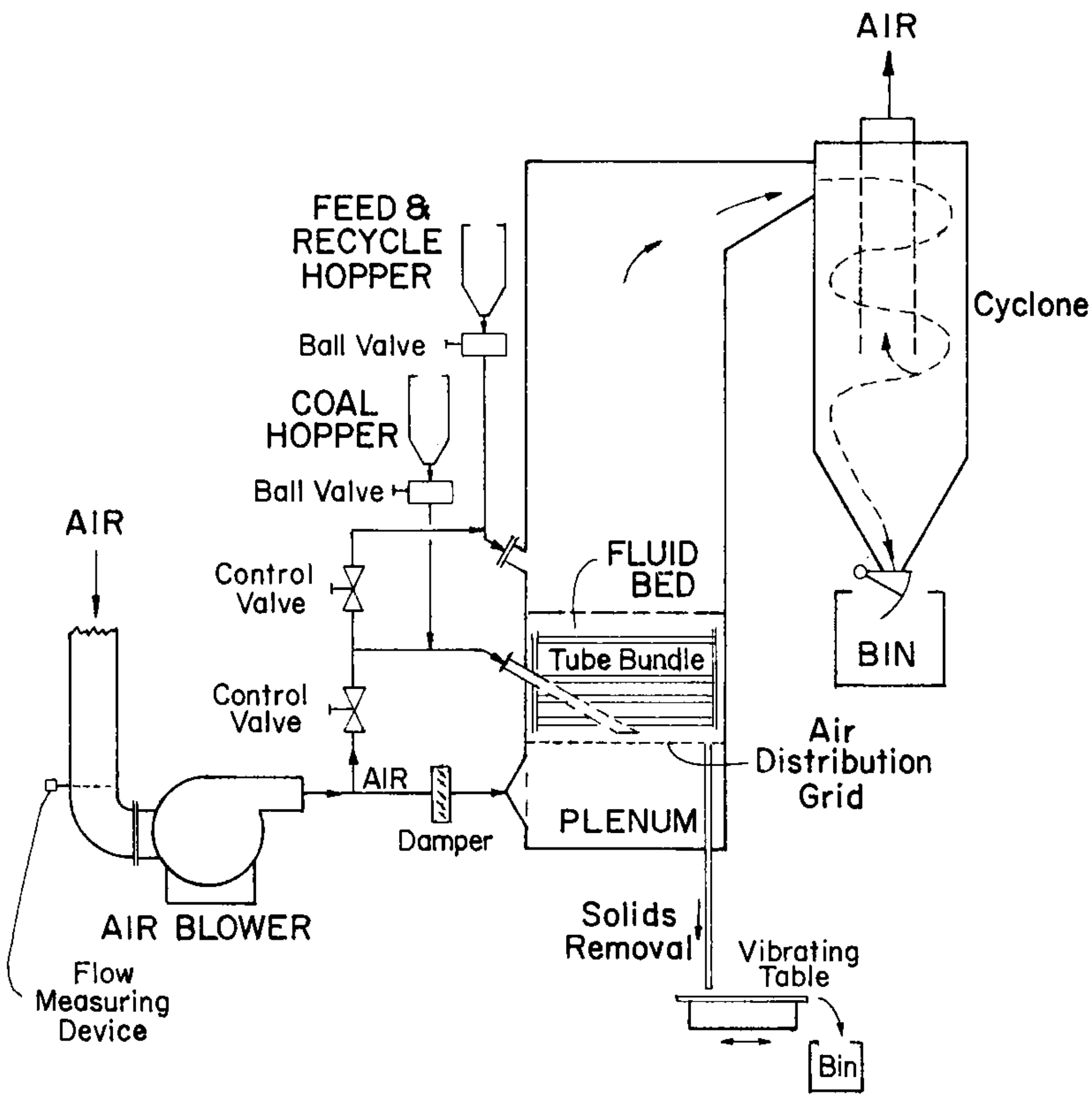
Fluidizing air from a high pressure axial blower discharges into a surge tank and passes through an air flow measurement orifice prior to entering the plenum chamber. The air passes through the plenum, air distribution grid, bed material and into a cyclone separator and bag filter to exhaust into the laboratory. Dust elutriated from the bed is collected in a calibrated glass tube for determination of elutriation rates. The system is designed for steady state batch operation and there are no provisions for feed injection or material removal on a continuous basis.

The large cold model consists of a 6' square steel chamber, 11' in height with plexiglass windows positioned to allow visual observation of the bed. Below the model is a 2' deep plenum chamber. An air distribution plate, which consists of six (6) 2' x 3' sections, is positioned between the plenum chamber and the bed. The model is supported to provide a 4' clearance from the floor to accomodate the bed removal equipment. As in the small model, interchangeable steel tube sheets and removable steel pipes allow wide variation in the tube bundle arrangement. The tube bundle begins a minimum of 1' above the distribution grid and can extend to 5' above the distribution grid.

A schematic of the large cold model system is shown on Figure E-28. Air is supplied to the model by two (2) high pressure centrifugal blowers controlled by individual controlled dampers in each blower outlet duct. The air passes into the plenum through the distributor grid and bed and into a cyclone separator to exhaust through an exit duct from the laboratory. Coal or an alternate feed material will be fed from a hopper through a rotary feeder and pneumatically fed into the bed by a sloped pipe. The bed feed and recycled material will be fed by gravity from a hopper into the side of the model approximately 1' above the bed level. The bed material extraction system consists of a vertical pipe extending down through the plenum and discharging onto a vibrating feeder for flow control.

<u>FIGURE E-28</u>

<u>36 SQ. FT. FLUIDIZED BED COLD TEST MODEL-SCHEMATIC</u>



5.2.2 Test Program - The test program has been divided into two sections with section one involving screening tests in the small model and section two involving testing on the large model. All tests in the section one screening tests will be performed at a superficial velocity of 4 to 8' per second with limestone bed material sizes of 6 x 16 mesh and $\frac{1}{4}$" x 6 mesh. The initial screening tests involve testing seven (7) air distributor designs. The nozzle grid arrangement used at the Alexandria, Virginia pilot unit will be used as a base for comparison of performance of the other designs. Using the most favorable air distribution grid tests will be performed to determine the most promising arrangements for horizontal tube bundles. Four (4) variables will be considered for the tube bundle screening tests including the longitudinal pitch, transverse pitch, tube diameter and tube arrangement (either inline or staggered). Physical limitations impose restrictions upon the allowable values of these variables. These restrictions are a longitudinal pitch of two times the outside tube diameter, a transverse pitch which is a function of steam generator waterwall spacing and a minimum tube diameter of $1\frac{1}{2}$". A total of forty-one (41) possible tests have been considered as indicated on Table 20, however, any trends discovered early in the testing may be cause to eliminate some of the subsequent tests. The third criteria to be tested on the small model involves sloping the air distribution grid to determine the ability to classify oversized bed material to one location within the vessel.

Testing on the large model will involve a superficial fluidizing velocity of 4 to 12' per second, limestone bed material size of 6 x 16 mesh and $\frac{1}{4}$" x 6 mesh and an air distribution grid selected from the screening tests. The mechanical aspects of the fuel injection arrangement scheduled for use at the Rivesville unit including the angular orientation of the fuel feed pipes, air fuel ratio, distance of injection nozzle from the air distributor, and horizontal distribution of the fuel from each feed point will be tested. The mechanical aspects of the bed material handling system will be tested to determine the operating characteristics of the bed material extraction system, bed material re-injection system and the mixing of the re-injected material within the fluidized bed. Operation of the fluidized bed at various fluidizing velocities and use of localized fluidization will be done to determine advantages of various load turn down techniques.

TABLE E-20

TUBE BUNDLE SCREENING TESTS CONSIDERED

TEST NO.	S_T	S_L	D_t	Arrangement	Tube Surface to Bed Volume Ratio	Lateral Spacing (see Figure E-17
	in.	in.	in.		ft^2/ft^3	$(S_T-2D_t/2)$ in.
1	6	5.29	2	Staggered	6.464	1
2	4½	5.178	2	Inline	6.464	-
3	5	3	1½	Staggered	9.67	1
4	5	5	1½	Staggered	6.69	1
5	5	7	1½	Staggered	5.12	1
6	4½	3	1½	Staggered	10.47	3/4
7	4½	5	1½	Staggered	7.25	3/4
8	4½	7	1½	Staggered	5.54	3/4
9	4	3	1½	Staggered	11.42	½
10	4	5	1½	Staggered	7.91	½
11	4	7	1½	Staggered	6.05	½
12	3½	3	1½	Staggered	12.57	¼
13	3½	5	1½	Staggered	8.70	¼
14	3½	7	1½	Staggered	6.65	¼
15	6	4	2	Staggered	7.85	1
16	6	6	2	Staggered	5.89	1
17	6	8	2	Staggered	4.71	1
18	5½	4	2	Staggered	8.38	3/4
19	5½	6	2	Staggered	6.28	3/4
20	5½	8	2	Staggered	5.03	3/4
21	5	4	2	Staggered	8.98	½
22	5	6	2	Staggered	6.73	½
23	5	8	2	Staggered	5.39	½
24	4½	4	2	Staggered	9.67	¼
25	4½	6	2	Staggered	7.25	¼
26	4½	8	2	Staggered	5.80	¼
27	7	5	2½	Staggered	6.60	1
28	7	7	2½	Staggered	5.21	1
29	7	9	2½	Staggered	4.30	1
30	6½	5	2½	Staggered	6.97	3/4
31	6½	7	2½	Staggered	5.50	3/4
32	6½	9	2½	Staggered	4.54	3/4
33	6	5	2½	Staggered	7.37	½
34	6	7	2½	Staggered	5.82	½
35	6	9	2½	Staggered	4.81	½
36	5½	5	2½	Staggered	7.84	¼
37	5½	7	2½	Staggered	6.19	¼
38	5½	9	2½	Staggered	5.11	¼
39	4	3.7	1½	Inline	7.91	-
40	5½	6	2	Inline	5.03	-
41	5½	6.7	2½	Inline	5.11	-

5.3 Test program for scale up to utility unit size.

Previous pilot plant studies and conceptual design studies have shown that there are certain areas of technology which require further development for the successful application of the fluidized bed concept to large utility steam generators. Those areas not already under study, which require further examination on a cold test model, include the following:

a. Erosion of tubes and attrition of bed material.
b. Particulate feeding and particulate transport - metering and division of material.
c. Residence time of particles in the bed as a function of particulate size, bed depth, gas velocity, distributor design and feed point location.
d. Combustion rates of coal particles in a fluidized bed for varing particle size and rank of coal.
e. Lateral bed circulation including normal diffusion rates and forced circulation.
f. Heat transfer about the periphery of a tube as a function of appropriate bed parameters.

The above tests have been proposed as part of this program as an aid to increase the probability of success of a utility size fluidized bed steam generator. Following is a description of each of the proposed tests.

5.3.1 Tube erosion and limestone attrition - It is proposed that an all metal cold fluidized bed be constructed which is capable of continuous long term automatic operation for the purpose of evaluating tube erosion and limestone attrition. The bed could be small (5" x 20" in size) and should be constructed of a multiplicity of compartments to accomodate more than one test parameter at a given time. Bundles would be constructed of tubes of different materials varying in degree of hardness and during operation the bundles would be inspected at regular intervals to evaluate the degree of wear by location and the material selection. The attrition of the limestone would be evaluated by measuring the change in the size of the bed material at regular intervals as well as the weight of attrited limestone elutriated from the fluidized bed.

5.3.2 Particulate transport - Transportation of coal and/or limestone to and from storage to the fluidized bed requires selection of a system which meters a stream of flowing solids and divides the stream into a finite number of equal streams. Equipment is available in various stages of development and degrees of capability which will handle individual functions such as metering or flow dividing. Operation of this equipment must be proven as a single system meeting the requirements of the fluidized bed combustor.

Particulate metering and division of flow to a multiplicity of feed points are the primary problem areas in particulate transport. Fifty or more inches of water pressure differential have been sealed in conventional coal feed systems by proper design of the coal stand pipe upstream of the coal feeders. Pressure drop, velocity, tube diameter, etc. and fuel feed lines are adequately treated in the literature and need no further investigation at this time. Erosion rates within the feed lines should be determined on a demonstration plant. Normally erosion can be minimized through good design.

At least one system, and preferably more, should be proven on a pilot plant level to ensure the success of handling in the fluidized bed combustion system. Therefore a pilot unit test is proposed to evaluate feed systems of different designs. It is suggested that the pilot unit consist of a closed feed loop including a storage system, interchangeable feed system, feed lines, individual collecting tanks and weigh cells and a return system.

5.3.3 Residence time of particles in the fluidized bed - The residence time for particles of various size in the fluidized bed should be determined as a function of the bed operating parameters so as to predict carbon carryover and bed composition as well as improved coal feeder design. This work can be carried out on the existing cold model test system by adding a suitable coal feed system. The program would require measuring of the feed material flow rate, elutriation rate and the change in the bed concentration at equilibrium conditions.

5.3.4 Combustion rate of particles of coal varying in size and rank - Little is known about the combustion of individual coal particles in the fluidized bed as a function of particle size, coal rank or bed temperature. Knowledge of combustion rates of various species of coal along with residence time should provide a means of predicting carbon carryover as a function of coal size and rank. It should also provide some insight regarding the temperature of the coal particle during combustion which might be helpful in predicting ignition, caking, agglomeration and minimum sustaining combustion temperature for various ranks of coal as well as providing a better understanding of heat transfer during combustion. The program would require constructing a micro-fluidized bed into which particles of coal of a given size could be injected. The rate of temperature rise of the fluidized bed would be controlled by controlling heat input. The temperature excursion of the fluidized bed with time would be an indication of rate of combustion from the onset to completed combustion. Micro-fluidized beds have been used with some success in differential thermal analysis and calibration of thermo-couples.

5.3.5 Bed mixing - Bed mixing is the ability to evenly distribute material injected into the fluidized bed. It is a function of bed size, feed size, number of feed points and other pertinent operating parameters such as bed height and gas velocity. The bed mixing is also dependent upon residence time and combustion rate.

Bed mixing basically involves two modes of material transport, natural circulation involving the diffusion of material throughout the bed and forced circulation using some external forces to excite the rate of diffusion of solid material. Forced circulation is particularly important with regard to circulation of material to specific locations within the bed as a means of providing local bed cleansing as well as a means of exchanging material between adjacent reactors. Forced circulation is also important as a means of creating good bed mixing as well as creating concentration gradients. By internally circulating the bed material between the fluidized bed combustor, Carbon Burnup Cell and regenerator, it should be possible to do away with difficult and costly external particulate transport systems.

A two phased program is proposed to evaluate bed mixing of solid material. The first phase is directed at evaluating bed mixing of fuel material in a large cold model by diffusion mechanism as a function of fuel feed size and number of feed points. The second phase of the program is directed at the circulation of bed material as part of an effort to cleanse a bed of large ash particles within the confines of the fluidized bed cell.

5.3.6 Heat transfer around the periphery of the tube - Overall heat transfer coefficients presently being used are of the order of magnitude of 40-50 Btu/hr, sq ft, F providing a heat flux to the tube surface submerged in the bed of 30,000 to 50,000 Btu/hr, sq ft. This is a very modest number if the heat transfer coefficient can be considered uniform over the entire tubes surface. However, recent tests on a cold flow model have indicated that this is not the case. During several tests it was noted that dead spots existed on top of the tube surfaces and particle voids existed below the tube surface. Only one or two cases appear in the literature in which the investigators report examination of peripheral heat transfer to the tube surface. Both cases confirm these observations. Noack indicated that the heat transfer rates may differ by as much as a factor of 2 or 3 depending on the location on the tube surface and degree of fluidization. The highest heat transfer was reported on the side of the tube and much lower heat transfer rates were reported on the top and bottom of the tube. It is proposed that heat transfer tests be run on a cold model where the heat transfer rates can be correlated with fluidization characteristics as well as bed and bundle design.

6.0 Work Completed - Phase V

As described in paragraph 1.5, work under this phase involves construction of a cold test model and performance of tests derived from phase IV which are described in paragraph 5.0. The work scope for this phase is divided into five tasks and the work completed in each task is described in the following paragraphs.

6.1 Task 1, 2 and 3 - Cold Model Design, Procurement and Erection.

The cold test model has been designed with a square fluidized bed, 6' on each side, fluidized by air with a maximum superficial velocity of 12 ft/sec. The model has been located at the Foster Wheeler Corporation Research facility and arranged as shown on Figure E-29 (RD-731-97E). The test model draws air from outdoors through an air inlet duct feeding two centrifugal fans. Each of these fans is rated at 16,500 CFM with a pressure increase across the fan of 70" H_2O. Each fan is controlled with an outlet damper and discharges to the test model air plenum below the distribution grid. The test chamber of the model is approximately 12' high and discharges through one side to a cyclone dust collector which exhausts through an outlet duct to atmosphere. Construction of the test model was delayed approximately five months due to late delivery of the main air supply fans. Presently all materials have been received and construction of the model is continuing with a schedule completion date of September 1, 1974. Construction of the main body of the model is essentially complete and most of the remaining work involves construction of the auxilliary test equipment around and within the model. Figure E-30 (RD-740-42) indicates the equipment arrangement required for the completion of the test program on the large cold model. All of the equipment for this system has been received at the FWC Research facility and is presently being erected. Figure E-31 is a photograph of the cyclone dust collector inlet in its erected position. Figures E-32, E-33 and E-34 are photographs of the model in its partially erected state.

6.2 Task 4 - Cold Model Testing

Since the lead time for the erection of the large cold test model was significant and Foster Wheeler Corporation had erected a 5 x 21" plexiglass cold test model it was decided that screening tests to determine air distribution designs and tube bundle arrangements with the best characteristics would be carried out on this small model. The cost of testing on this smaller model is significantly less than the large test model and the plexiglas model offers good visibility for fluidized bed characteristics with various tube bundle arrangements. The small model would not be useful for testing the fuel injection, bed extraction and other material handling systems scheduled for the large

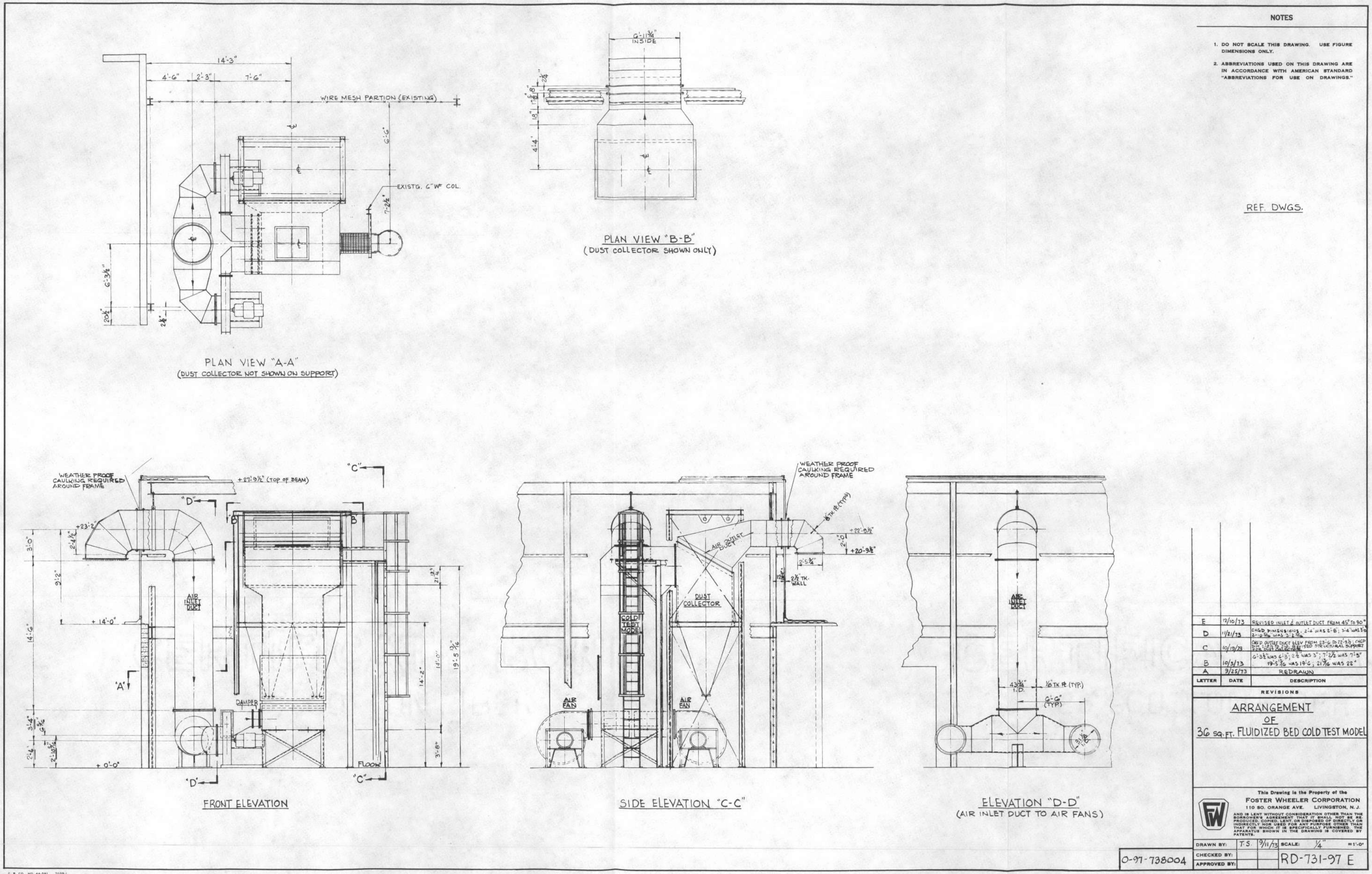
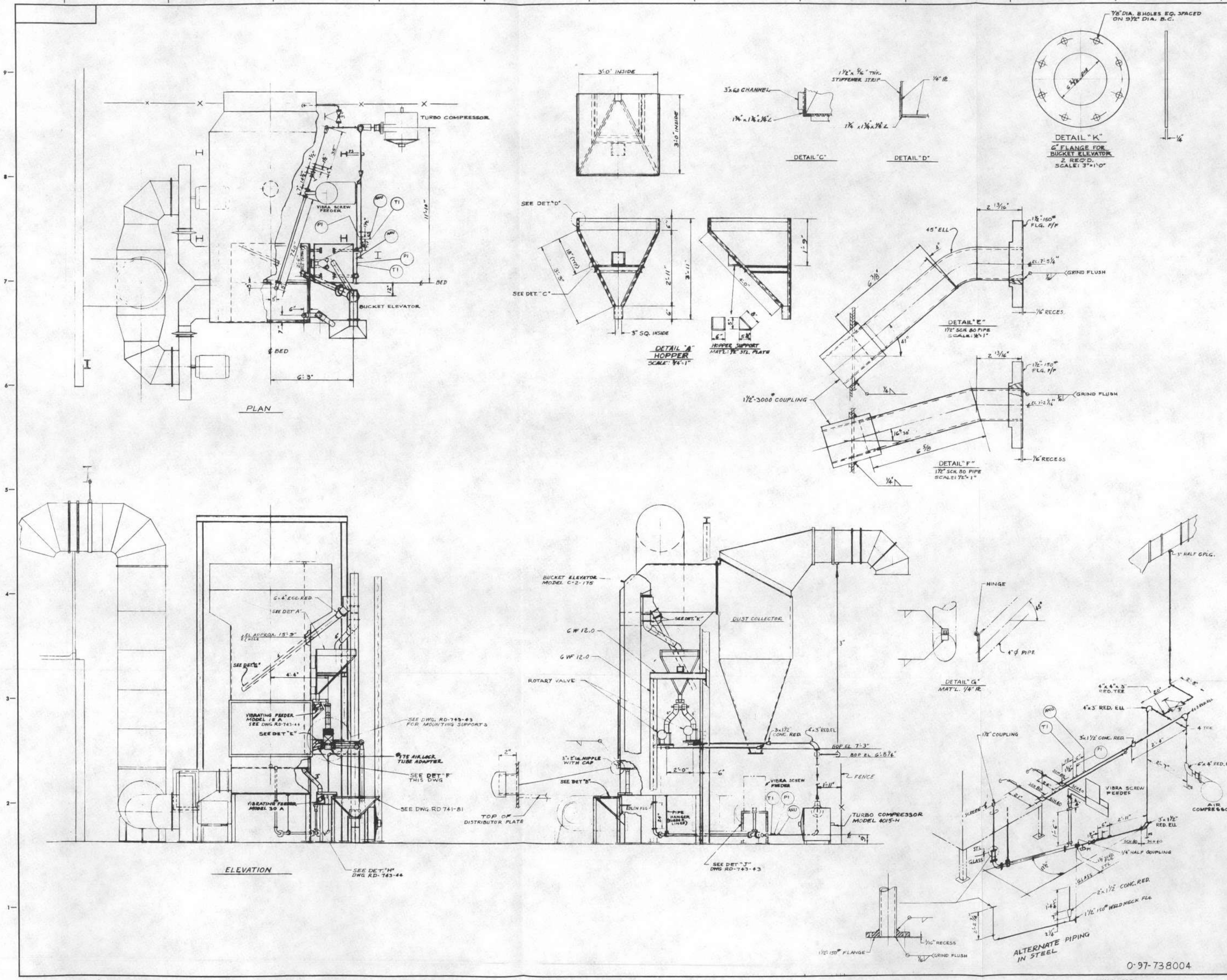

NOTES
1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."
REF. DWGS.
WIRE MESH PARTION (EXISTING)
EXISTG. 6" WF COL.
PLAN VIEW "A-A"
(DUST COLLECTOR NOT SHOWN ON SUPPORT)
6'-11¾" INSIDE
PLAN VIEW "B-B"
(DUST COLLECTOR SHOWN ONLY)
WEATHER PROOF CAULKING REQUIRED AROUND FRAME
+27'-9½" (TOP OF BEAM)
AIR INLET DUCT
DAMPER
FLOOR
FRONT ELEVATION
COLD TEST MODEL
AIR OUTLET DUCT
DUST COLLECTOR
AIR FAN
SIDE ELEVATION "C-C"
AIR INLET DUCT
ELEVATION "D-D"
(AIR INLET DUCT TO AIR FANS)
E 12/10/73 REVISED INLET & OUTLET DUCT FROM 45° TO 90°
D 11/21/73 CHGD DIMENSIONS, 2'-4" WAS 2'-8"; 3'-4" WAS 3'-0" 2'-10 5/16" WAS 3'-2 5/16"
C 10/19/73 CHG'D OUTLET DUCT ELEV FROM 23'-6 TO 22'-9½; CHGD DIM 2'-8½ TO 2'-0. REVISED STRUCTURAL SUPPORT FOR DUST COLLECTOR
B 10/3/73 6'-3½" WAS 6'-3; 2½" WAS 3"; 7'-2½ WAS 7'-3" 19'-5 13/16 WAS 19'-6; 21 13/16 WAS 22"
A 9/25/73 REDRAWN
LETTER DATE DESCRIPTION
REVISIONS
ARRANGEMENT OF 36 SQ. FT. FLUIDIZED BED COLD TEST MODEL
This Drawing is the Property of the FOSTER WHEELER CORPORATION 110 SO. ORANGE AVE. LIVINGSTON, N. J.
AND IS LENT WITHOUT CONSIDERATION OTHER THAN THE BORROWER'S AGREEMENT THAT IT SHALL NOT BE REPRODUCED, COPIED, LENT, OR DISPOSED OF DIRECTLY OR INDIRECTLY NOR USED FOR ANY PURPOSE OTHER THAN THAT FOR WHICH IT IS SPECIFICALLY FURNISHED. THE APPARATUS SHOWN IN THE DRAWING IS COVERED BY PATENTS.
DRAWN BY: T.S. 9/11/73 SCALE: ¼" = 1'-0"
CHECKED BY:
APPROVED BY:
0-97-738004
RD-731-97 E

FIGURE E-29



NOTES

1. DO NOT SCALE THIS DRAWING. USE FIGURE DIMENSIONS ONLY.
2. ABBREVIATIONS USED ON THIS DRAWING ARE IN ACCORDANCE WITH AMERICAN STANDARD "ABBREVIATIONS FOR USE ON DRAWINGS."

LETTER	DATE	DR. INIT.	DESCRIPTION

REVISIONS

EQUIPMENT ARRANGEMENT for 36 SQ.FT. FLUIDIZED BED COLD TEST MODEL

DRAWING NUMBER: RD-740-42 — SCALE: = 1'-0" — REVISION

DWG. MADE & APPROVED BY	INITIAL	DATE	CONT. NO.
DRAFTSMAN	AW		ORDER NUMBERS
CHECKER			
SQUAD LEADER			
SECTION HEAD			
CONT. SUPV.			

THIS DRAWING SUPERSEDES
THIS DRAWING SUPERSEDED BY

FIGURE E-30

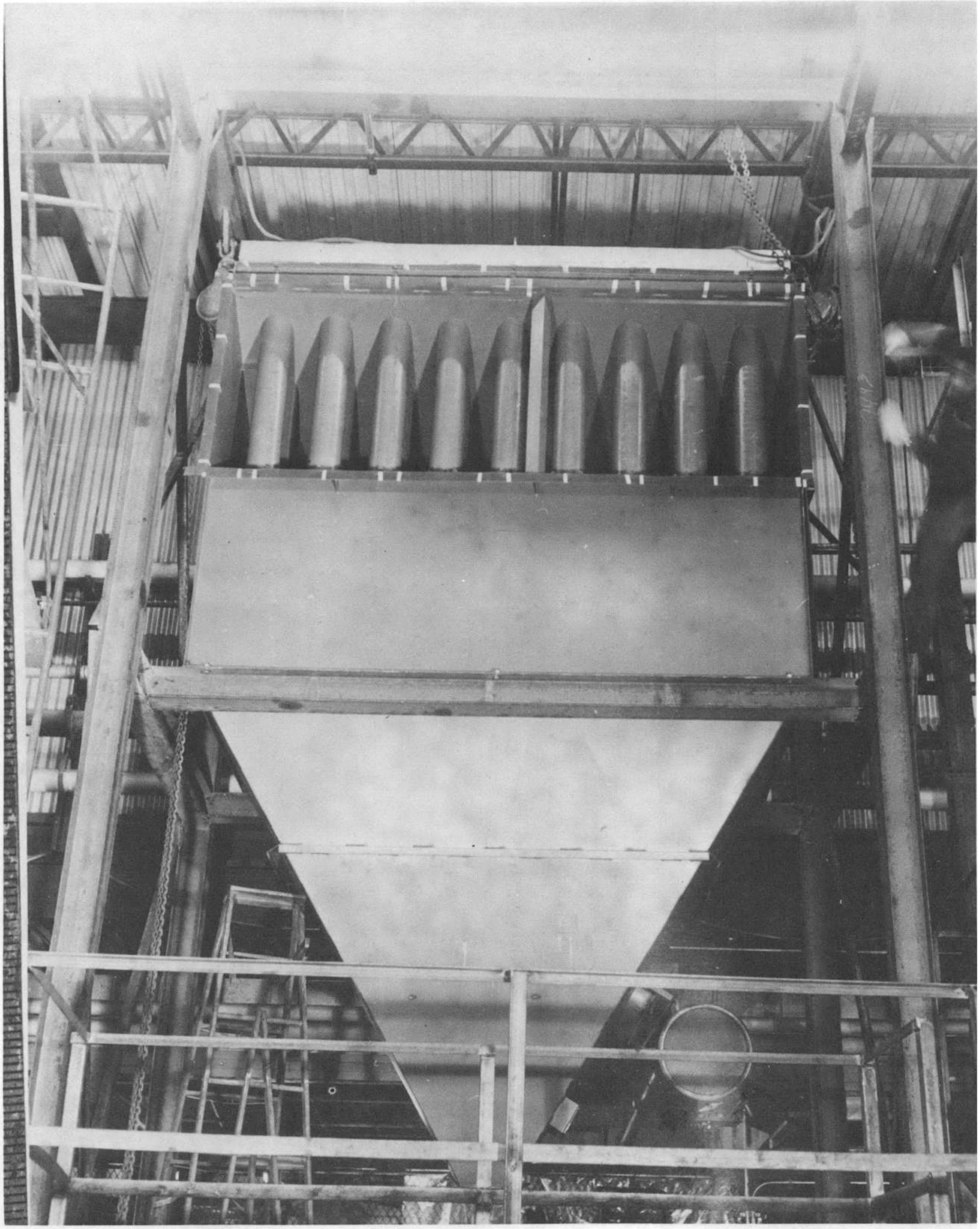


FIGURE E-31 COLD MODEL DUST COLLECTOR

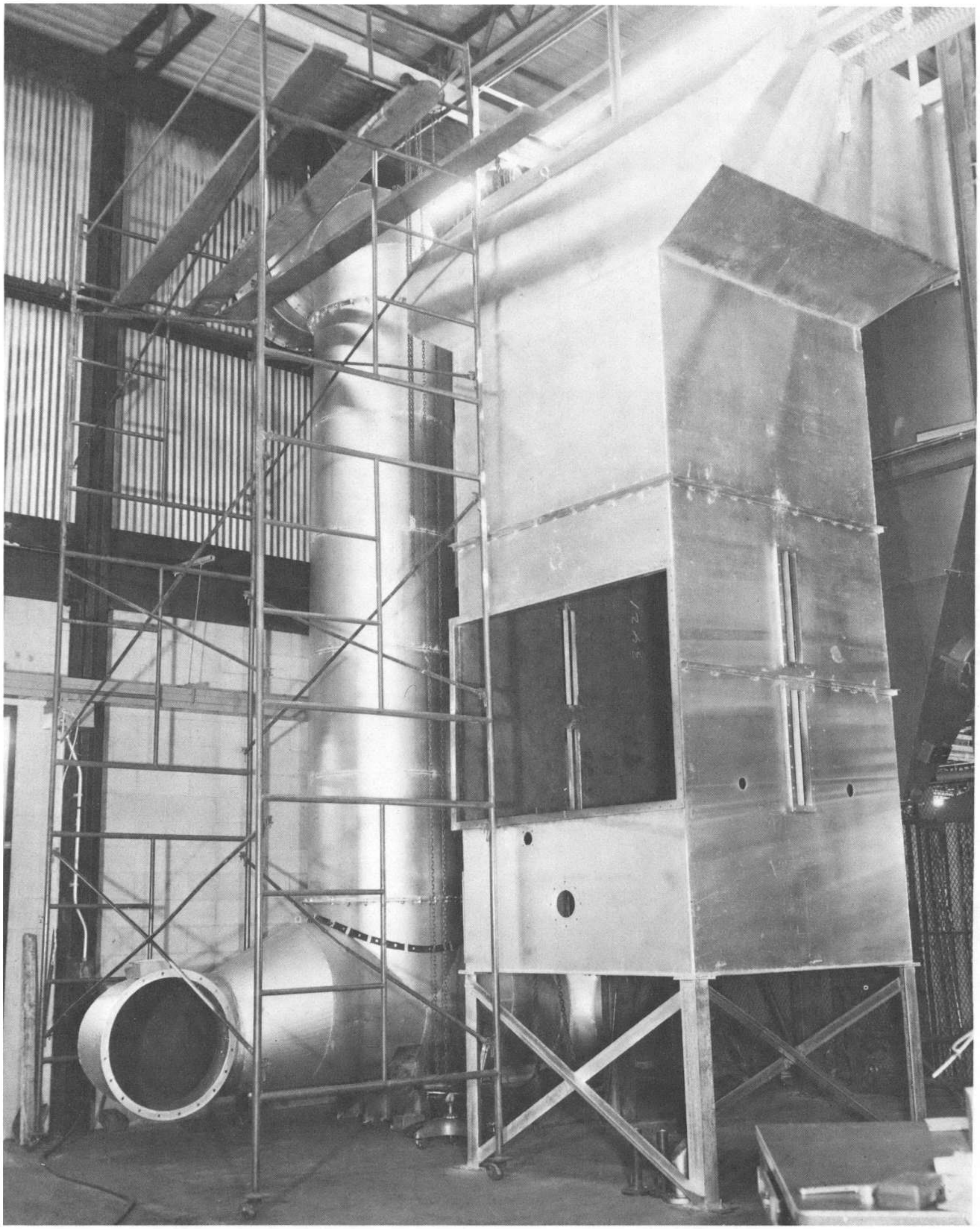


FIGURE E-32 CONSTRUCTION OF COLD MODEL

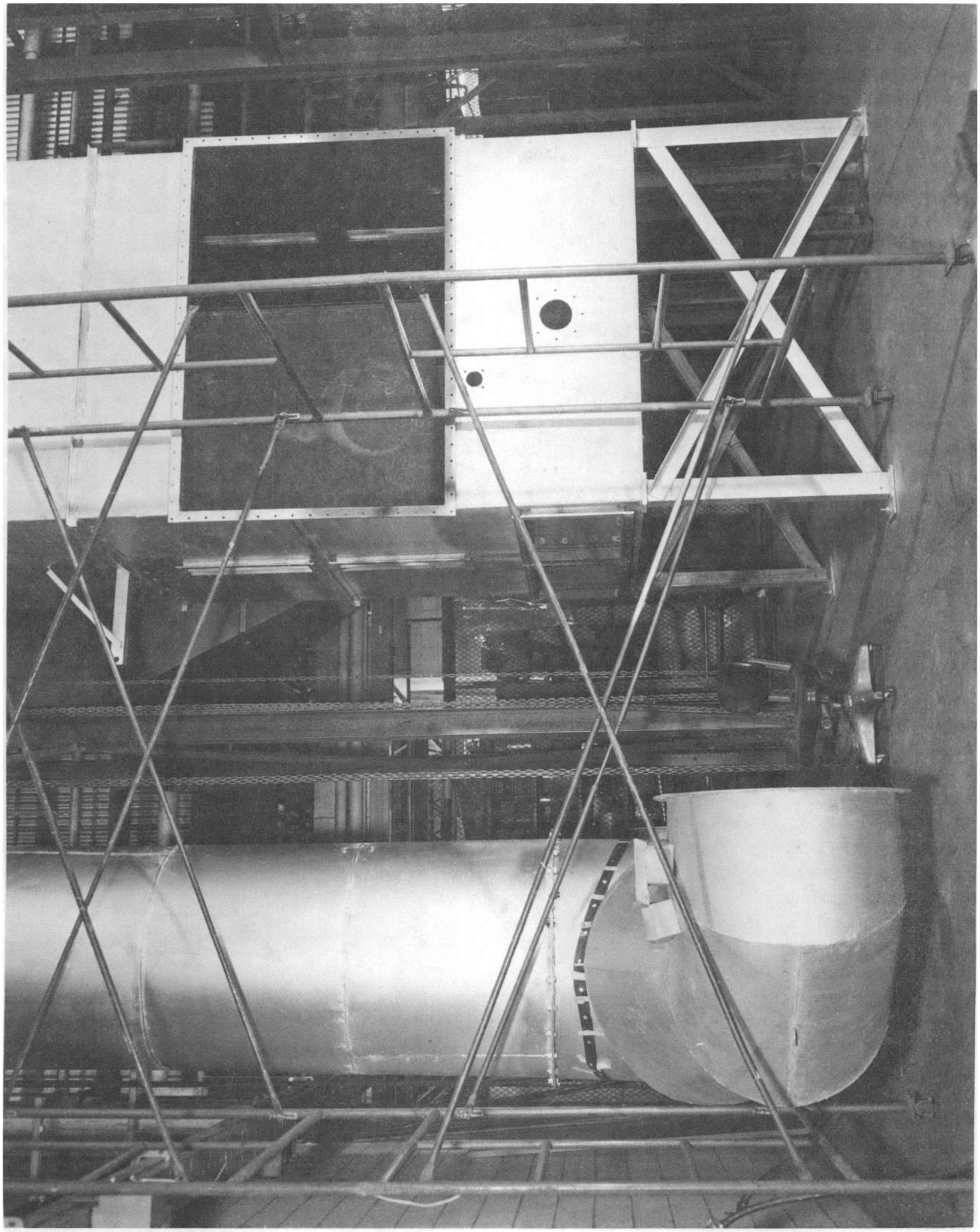


FIGURE E-33 CONSTRUCTION OF COLD MODEL

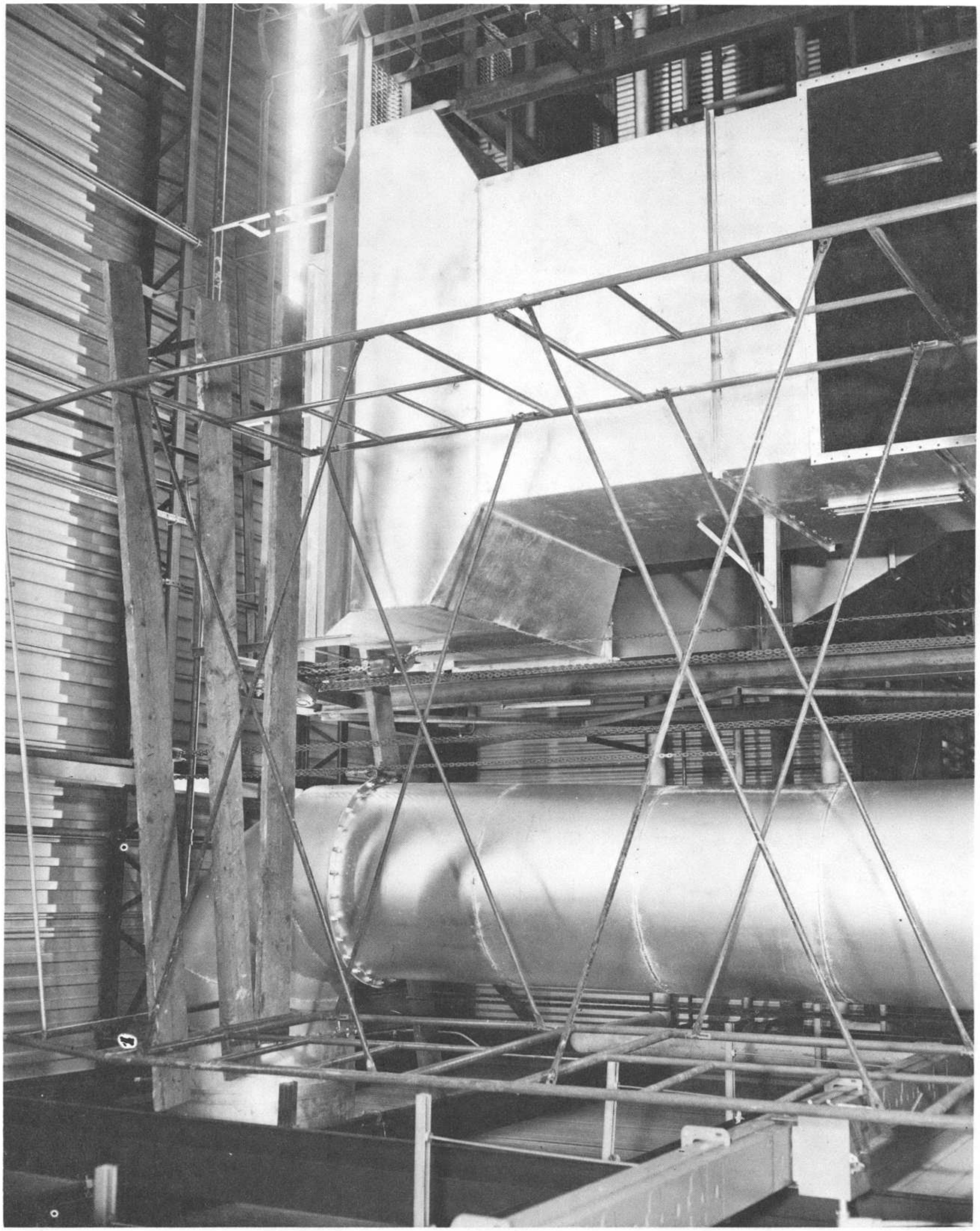


FIGURE E-34 CONSTRUCTION OF COLD MODEL

test model. Figure E-35 is a photograph of the small test model showing the plenum area and the bed zone indicating a staggered tube bundle arrangment. The air distribution grid is located just below the plexiglass section of the model. Figure E-36 is a photograph of a tube bundle within an active fluidized bed in which some of the bubble formation can be seen.

The screening tests on the small test model have been completed and involved testing of air distribution plate designs, tube bundle arrangements and the effect of a sloped distribution grid on particle size classification. The following paragraphs discuss the screening tests results.

6.2.1 Air distribution plate tests - Five air distributor designs have been tested in the model including (1) a perforated plate, (2) Johnson screen grates, (3) Foster Wheeler angle cover design, (4) Procedyne nozzles, and (5) nozzle buttons used in the P.E.R. pilot unit. Photographs of each of the air distribution plates are shown in Figures E-37 through E-41. Each distribution plate was tested for air pressure differential across the plate with no fluidized bed above the plate and separately with the plate and the fluidized bed present. High speed motion pictures were taken of the fluidized bed above each distribution grid for visual analysis of bed mixing and bubble formation. The testing showed that in general all plates produced the formation of large bubbles with some bubbles attaining the full bed cross-section in size before reaching the tube bundle. The bubble formation from the PER nozzle button arrangement appeared in discreet areas rather than at random as with other plates and resulted in rounder, centrally located bubbles. All other plates tended to give ramdon mixing of the bubbles across the width of the test model and although the PER nozzle arrangement resulted in a visibly different bubble formation characteristic the adverse affect on bed mixing behaviour was not acute. Based on the motion picture studies, it is evident that for the majority of the plates tested the type of plate does not affect the bubble formation and mixing within the fluidized bed. Consequently the small model air distributor screening test alone cannot be used to select a plate for use in the large cold model, but an additional criteria such as cost must be used. The grid plates were compared on a cost and delivery basis and this comparison resulted in the selection of the Johnson screen design for use in the large cold test model. Since the Johnson

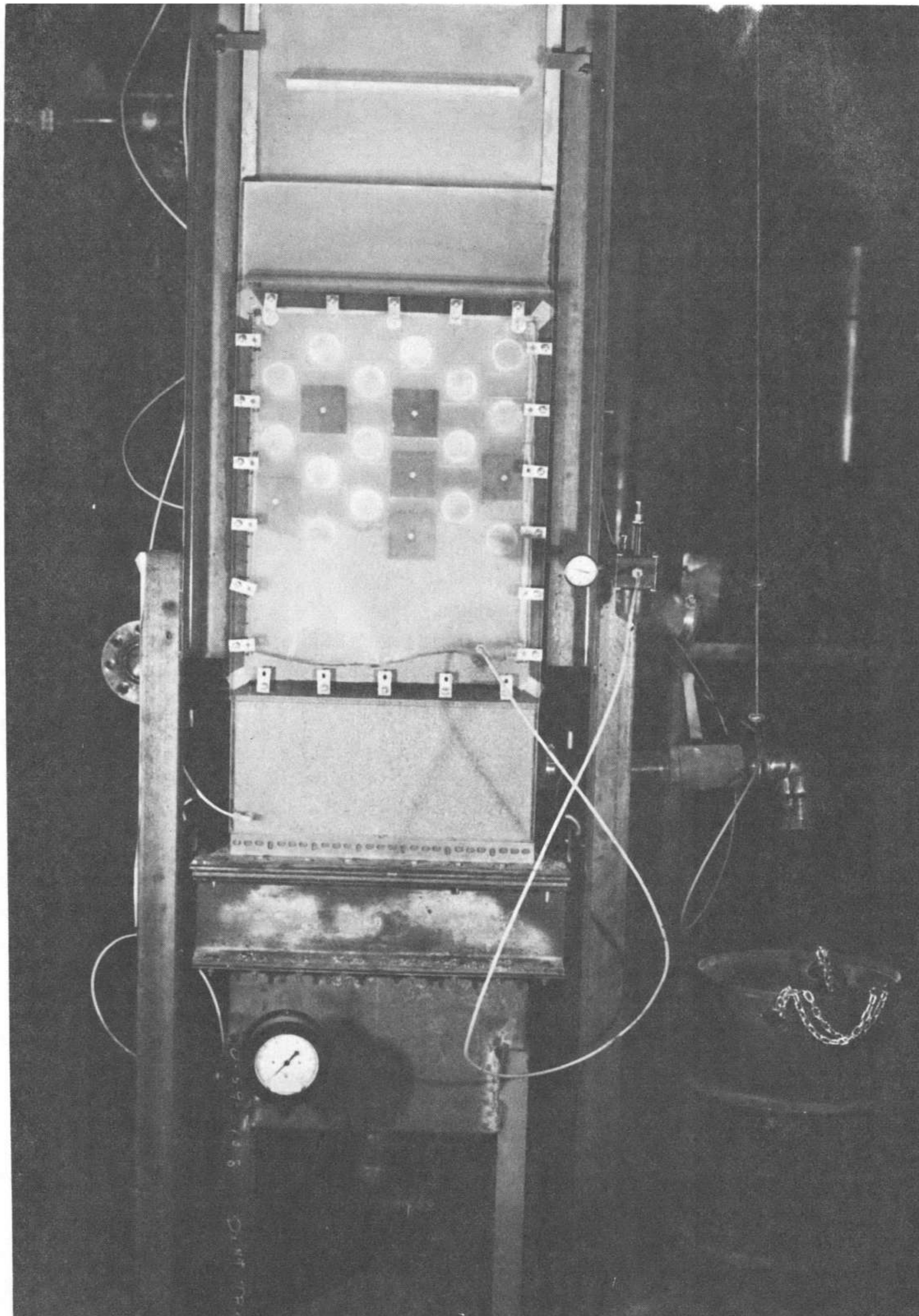


FIGURE E-35 SMALL COLD MODEL TEST FACILITY

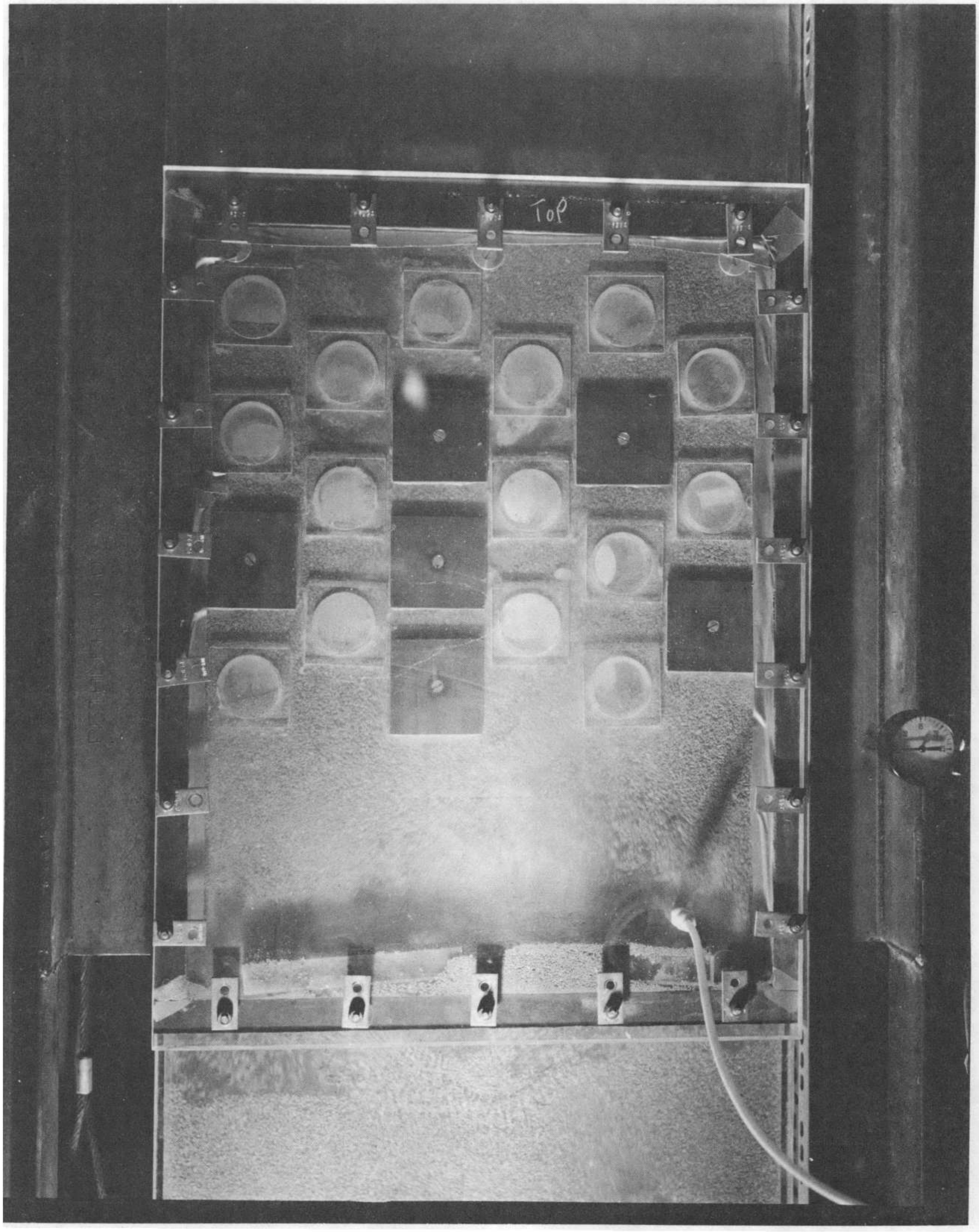


FIGURE E-36 TUBE BUNDLE TEST IN SMALL COLD MODEL

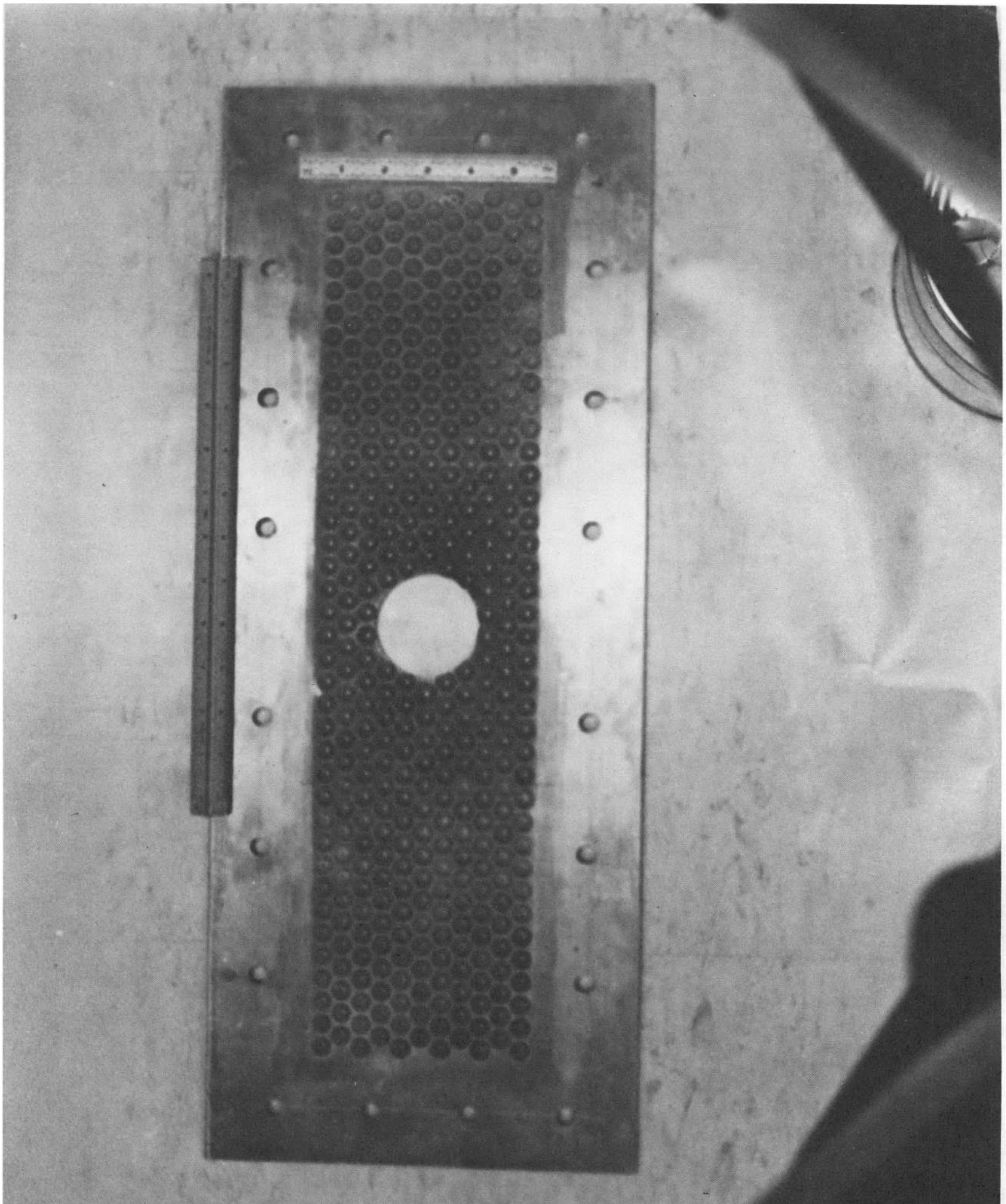


FIGURE E-37 PERFORATED PLATE AIR DISTRIBUTION GRID

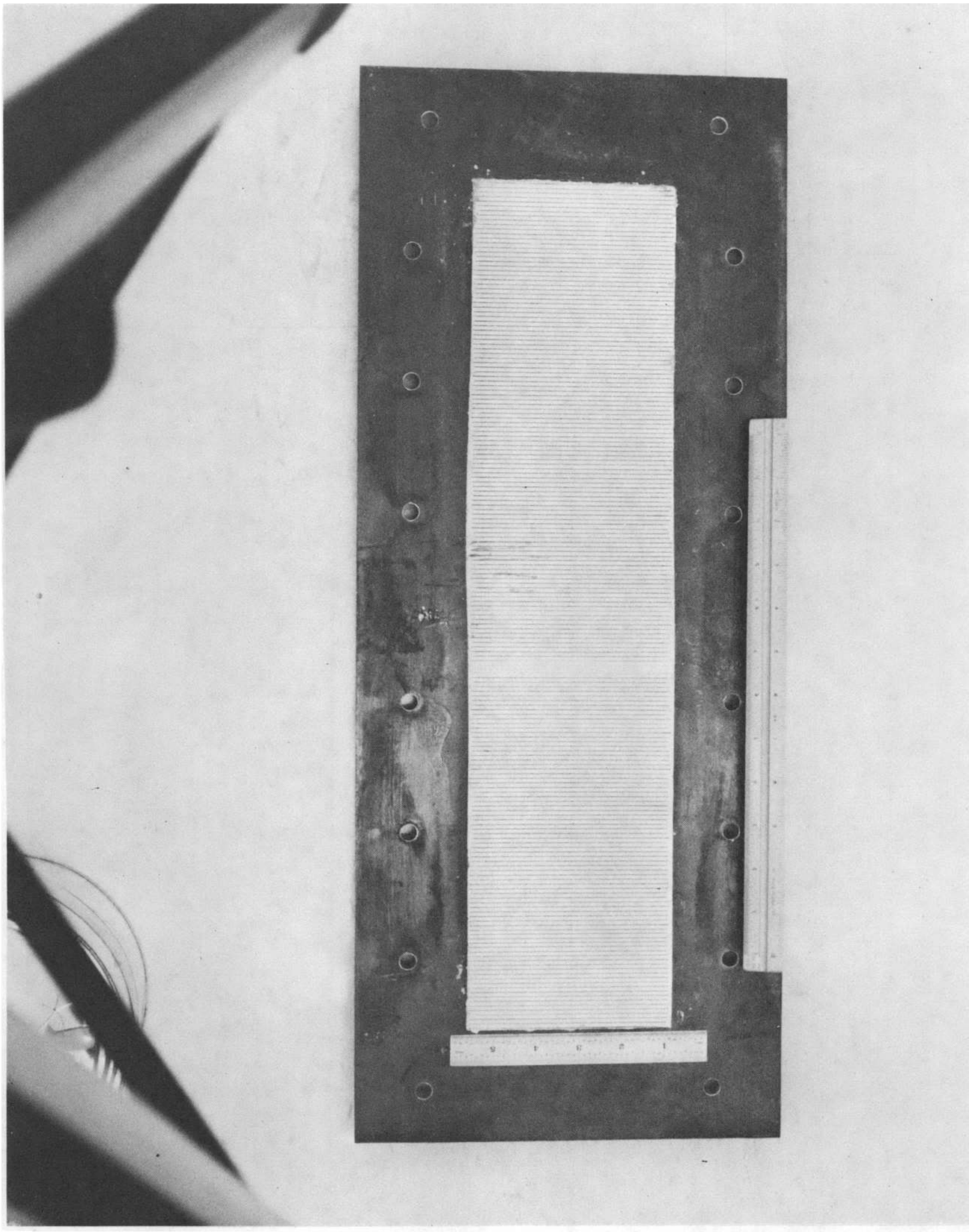


FIGURE E-38 JOHNSON SCREEN AIR DISTRIBUTION GRID

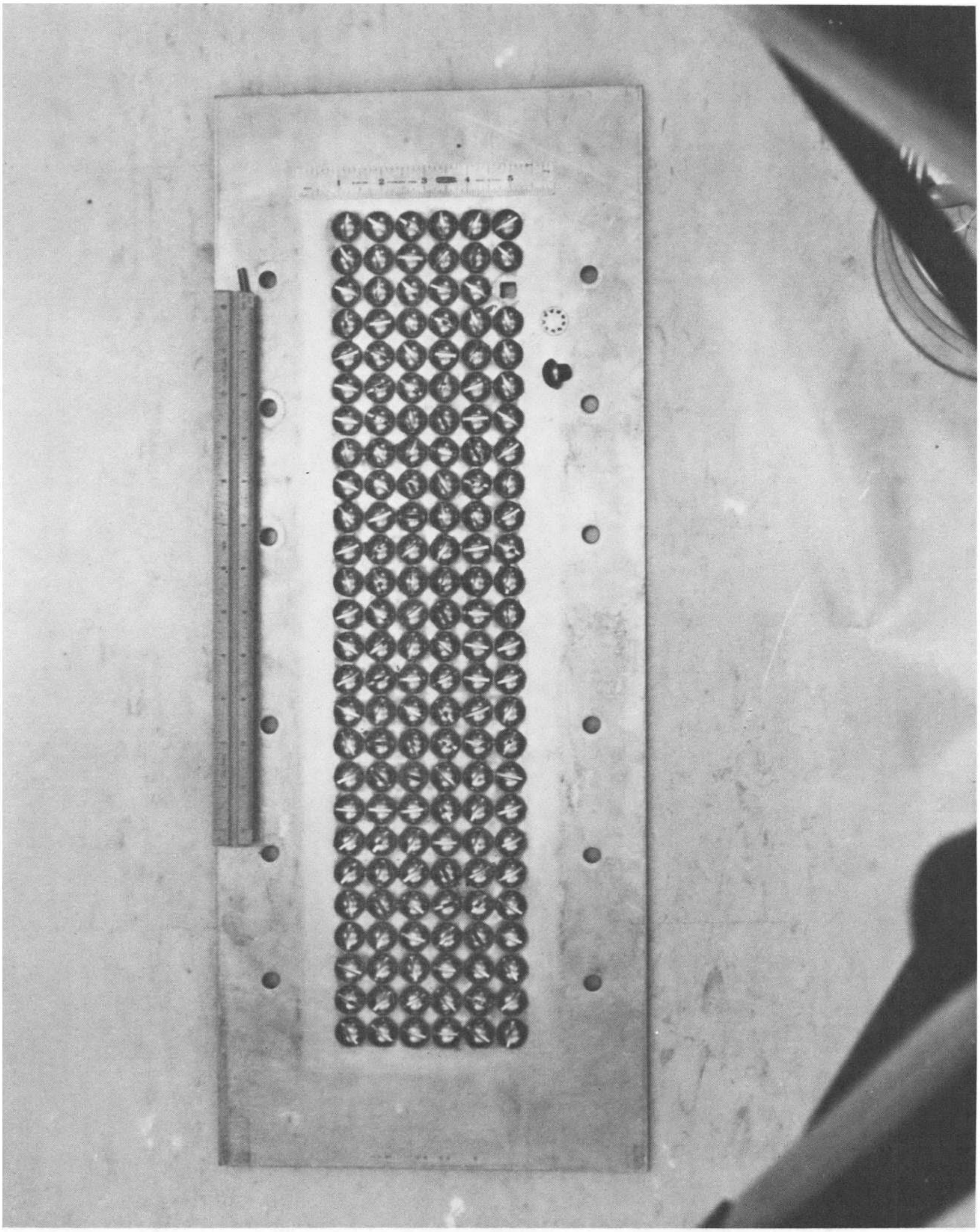


FIGURE E-39 PROCEDYNE CORP. AIR DISTRIBUTION GRID

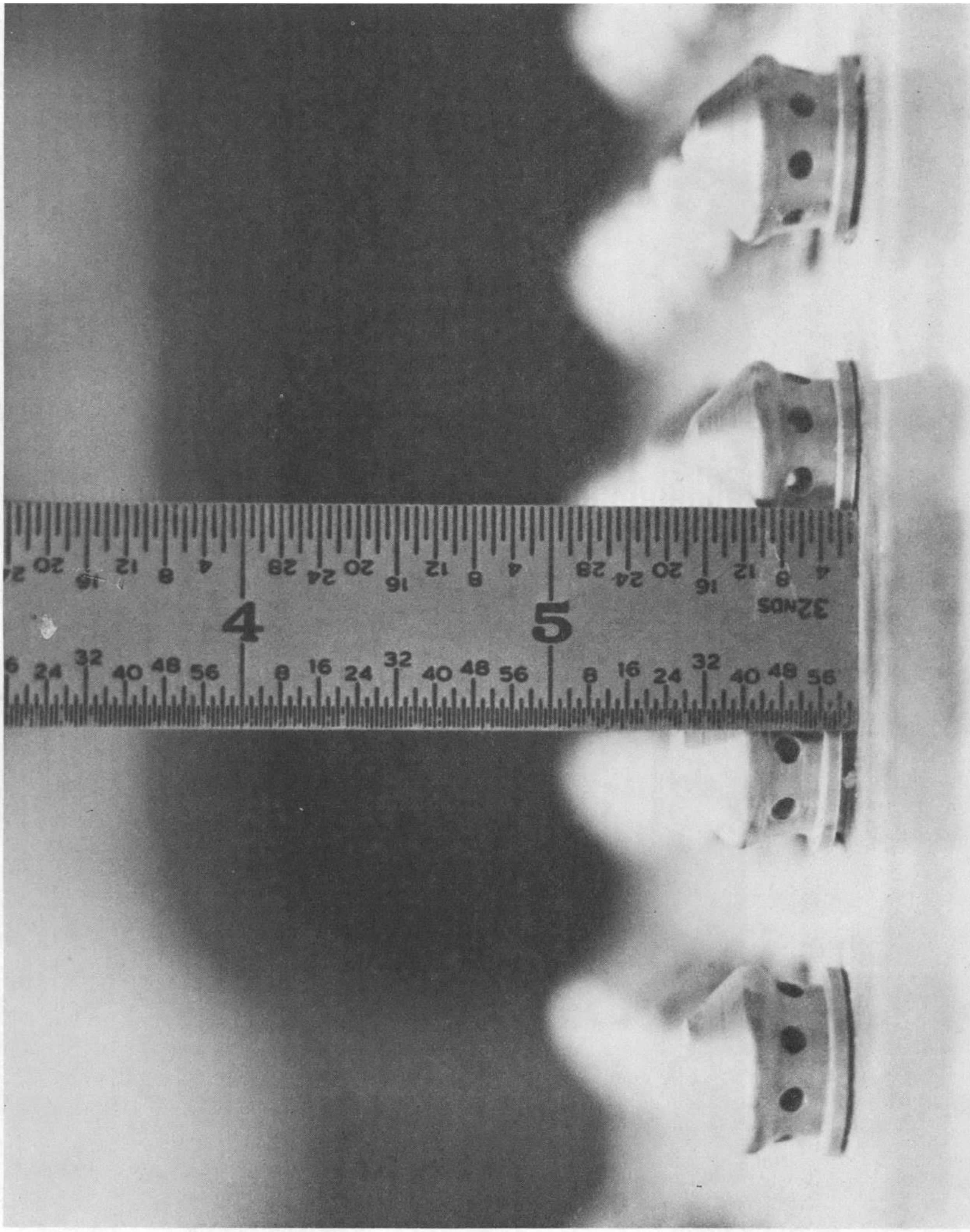


FIGURE E-40 P.E.R. NOZZLE BUTTON AIR DISTRIBUTION GRID

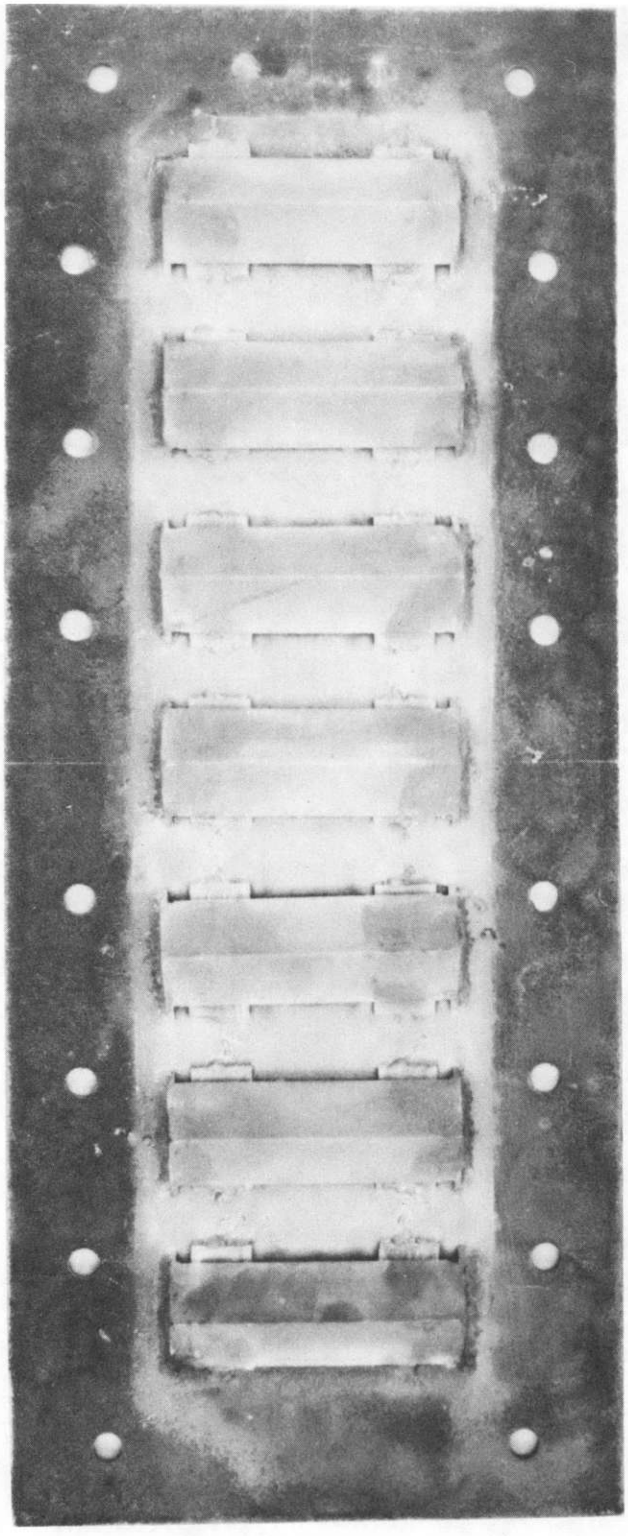


FIGURE E-41 FWC ANGLE COVER AIR DISTRIBUTION GRID

Screen design is a welded construction and affects of high temperature upon the slot openings were not known based on the cold model testing, a recommendation for further testing of this grid plate in the Alexandria pilot unit was made.

6.2.2 Tube bundle testing - The tube bundle testing on the small test model was completed in May 1974 and analysis of data from these tests is being analyzed. Table E-21 lists the tube arrangements that have been tested. The bed material for all tests was limestone sized to 6 x 16 mesh except where indicated otherwise. Data for each test was taken for air velocities from 2 to 8 ft/sec and the variations in pressure drop through the bed are being compared to the pressure drop through a bed with no tube bundle. High speed motion pictures were taken of each test for visual comparison of the fluidizing characteristics. Analysis of the motion pictures and the evidence of the test data to date, indicate that the configuration of the tube bundle located in the fluidized bed has an affect on the pressure loss through the bed and on the quality of fluidization. The staggered tube bundle arrangement in general gave better fluidization characteristics than the inline arrangements which showed problems of laning. The tests indicate that the violent bubbling of the fluidized bed can be dampened by (a) locating the tube bundle close to the air distribution grid, (b) increasing the mean particle size of the bed material and (c) decreasing the vertical pitch of the tube bundle. Further analysis of the motion pictures and the pressure drop data will be performed and as much quantitative data as possible extracted from these data sources. Figure E-36 is a photograph of one of the staggered pitch tube bundle arrangements tested.

6.2.3 Sloped distribution grid tests - A test to determine segregation of large bed particles was performed prior to modifying the small model to accept a sloped air distribution plate. The results of a test using 3/4" x ½" gravel as oversize material appears in Table E-21. The procedure used was to add the charge of oversized material to the bed and fluidize the bed at 8½ ft/sec superficial velocity for fifteen minutes. The desired velocity was then set and the bed was run at this velocity for twenty minutes. At the conclusion of the test, the material in the bottom 3" of the model above the distributor was removed and the weights of each size (or oversize) material recorded. As is evident from

TABLE E-21

SUMMARY

SMALL COLD MODEL TUBE BUNDLE TEST

Test No.	D_t	S_t	S_1	Tube Arrangement	Comments
1	1	6	5.29	S (Staggered)	Rivesville Tube Bundle
2	2	6	4	S	
3	2	6	6	S	
4	2	$5\frac{1}{2}$	4	S	
5	2	$5\frac{1}{2}$	6	S	
6	2	5	4	S	
7	2	5	6	S	
8	2	5	8	S	
9	$7\frac{1}{2}$	4	7	S	
10	$1\frac{1}{2}$	5	3	S	
11	$1\frac{1}{2}$	5	5	S	
12	$1\frac{1}{2}$	$4\frac{1}{2}$	3	S	
13	$1\frac{1}{2}$	$4\frac{1}{2}$	5	S	
14	$1\frac{1}{2}$	6	4	S	
15	$1\frac{1}{2}$	7	4	S	
16	2	6	5.29	S	Rivesville Tube Bundle-Distance to Distributor Plate Reduced to 6"
17	$2\frac{1}{2}$	7	7	S	
18	$2\frac{1}{2}$	$6\frac{1}{2}$	5	S	
19	$2\frac{1}{2}$	$6\frac{1}{2}$	7	S	
20	$2\frac{1}{2}$	6	5	S	
21	$2\frac{1}{2}$	6	7	S	
22	2	4	4	I (Inline)	
23	2	$3\frac{1}{2}$	$3\frac{1}{2}$	I	
30		Bed Void of Tubes			
31	7	5	$2\frac{1}{2}$	S	
96	$2\frac{1}{2}$	6	5	S	Repeat Test 20 Dec. Vel.
97	2	4	4	I	Bed Material $\frac{1}{4}$ x 6M
98	$1\frac{1}{2}$	5	5	S	Repeat Test 11 Dec. Vel.
99	$1\frac{1}{2}$	5	5	S	Repeat Test 11 Inc. Vel.

Note: All tests Procedyne Distributor
All tests except 97 use 6 x 16M Limestone

Table E-22, there is no appreciable separation of the gravel from the limestone until the superficial velocity is reduced to 6 ft/sec or less. Since operation of the fluidized bed demonstration unit will be at 12 ft/sec, this separation technique cannot be used since the data indicates that appreciable separation at this velocity is not possible with the size particles used. Since the testing of a sloped distribution grid depends on the ability to segregate large particles to the lower section of the fluidized bed and since the data on Table E-22 indicates that this cannot be done at design fluidized bed velocities the testing of a sloped distribution plate was eliminated from the test schedule.

TABLE E-22

OVERSIZE MATERIAL SEGREGATION ANALYSIS

BED MATERIAL

Material: Limestone
Size: 6 x 16 Mesh
Density: 86.1 lb/ft^3

OVERSIZE MATERIAL

Material: Gravel
Size: 3/4" x ½"
Density: 184 lb/ft^3

Superficial Velocity Ft/Sec	Wt. Bed Material Removed, lbs.	Wt. Oversize Material Removed, lbs.	Total Wt. Removed, lbs.	Percent Oversize %
0 (Initial)	114 (Charged	12 (Charged)	126 (Charged	9.52
8	19 (Removed)	2.5 (Removed)	21.5 (Removed)	11.63
7	19.5	2	21.5	9.30
6	16	5	21.0	23.8
5	10.5	10.5	21.0	50.0

7.0 Acknowledgements

The work described in this paper was performed by personnel in the Equipment Division and Research Division of Foster Wheeler Corporation. The author wishes to acknowledge Messrs. R. D. Stewart, T. A. Riley, D. Lorelli, R. W. Bryers, J. A. Bazan, T. W. Shults and T. Taylor for their valuable contributions to the development of Fluidized Bed Steam Generators.

Appendix F

Report 14-32-0001-1237-FWC-2

MULTICELL FLUIDIZED-BED STEAM GENERATOR DEVELOPMENT

Shop Fabrication and Field Erection Phases

Foster Wheeler Corp.
110 South Orange Ave.
Livingston, New Jersey 07039

July 1974

Interim Report for Period December 1973 — June 1974

Prepared for
Pope, Evans and Robbins Incorporated
11 East 36th Street
New York, New York 10016

PREFACE

The shop fabrication and on site erection phases, covered by this interim report, are the intermediate steps in the development of the multi-cell fluidized bed steam generator. Earlier phases, under the same prime contract, provided basic design criteria that was used in the decision making process leading to the present steam generator design. The shop fabrication of the steam generator has begun and the field erection of the unit is scheduled to commence in August 1974. The final phases of the overall development program will cover the entire unit operation, which includes peripheral equipment such as fuel feed, limestone feed, bed tapping and a future limestone regenerator, and refinements to the unit design through its operation.

CONTENTS OF APPENDIX F

1.0 BACKGROUND AND WORK SCOPE

This interim report describes all work completed from the start of work on December 6, 1973 through May 31, 1974 under Foster Wheeler Corporation contract 2-5851-2126 which is a subcontract from Pope, Evans and Robbins, Inc. who have received the prime contract from the Office of Coal Research under contract 14-32-0001-1237. The work under this contract covers the shop fabrication and field erection of a 300,000 lb/hr, 1350 psig, 925°F superheated steam generator for burning coal in a fluidized bed of limestone. Also included under this contract is the development of shop detail drawings and boiler material and accessory equipment requisitions and purchase orders. This steam generator will be located at the Rivesville Power Station of Monongahela Power Company in Rivesville, West Virginia.

The work scope for this contract can be divided into separate categories as follows:

1.1 Drawings - Arrangement and Detail.

After unit design has been finalized and arrangement drawings completed, prepare detail drawings for the shop fabrication of the various parts of the unit.

1.2 Shop Fabrication.

Using fabrication detail drawings from paragraph 1.1 above, manufacture parts for field assembly of steam generator.

1.3 Accessory Equipment Purchase.

Initiate purchase requisitions and orders for pumps, valves, gauges, and other required accessory equipment.

1.4 Field Erection.

Assemble steam generator at jobsite, hydrotest, boil out and prepare unit for operation.

2.0 PROGRESS

2.1 Drawings.

Initially, preliminary general arrangement drawings and piping schematics were prepared by Foster Wheeler Corporation, as part of their separate contract (No. 2-58-2126) with Pope, Evans and Robbins, Inc. and the Office of Coal

Research for the design of the steam generator, to establish a basis for the preparation of detail drawings and material requisitions.

Early unit arrangement was continually affected by design decisions which had an effect not only on the arrangement drawings but also on the material requirements. In one case, the decision was made to use two half capacity boiler recirculation pumps in the downcomer/feeder water system instead of one full capacity pump. This decision resulted in the redesign of the downcomer/feeder water system and increased the material requirements of the steam generator. The amount of additional design work and drawings revisions resulted in a request for an extension of the unit completion date. This request was subsequently granted.

Design work on the steam generator has progressed to the point where all general arrangement and shop fabrication drawings have been completed except for the ignitor burners and the individual coal feed shut off devices. The design of the grid plate has not been finalized, however, the grid plate support steel design and drawings have been completed.

2.2 Shop Fabrication.

Shop fabrication of the steam generator began in February 1974 when steel plate was received in Foster Wheeler shops to be rolled to form the steam drum. Ninety-eight percent of the material for the steam generator has now been received and fabrication of many of the parts has begun. Boiler parts are in various stages of completion with about fifteen percent of the fabrication work completed. The enclosed photographs, Figures F-1 to F-7,show the extent of the fabrication work on some parts of the steam generator.

Shipment of material from the Foster Wheeler Corporation shops should begin in July 1974 and is expected to continue through the month of September 1974.

2.3 Accessory Equipment Purchase.

Purchase requisitions and purchase orders for accessory equipment have been issued immediately after release of these items by Pope, Evans and Robbins, Inc. Accessory equipment already on order includes boiler recirculation pumps, control, check, safety and miscellaneous valves and drum level gauges. Shipment of this equipment is scheduled to begin in July 1974 and continue up to and including March 1975. The boiler recirculation pumps and some large check and block valves are the longest lead time items resulting in their shipments extending into 1975.

2.4 Field Erection.

A detailed erection and commissioning program was developed. This program is presented in chart form (see illustration PCN-2126 attached hereto) and is a step-by-step sequence of activities for the steam generator erection, from start of construction to boil out of the unit. Each activity is described therein and the week that it starts and the duration of the activity is also provided.

Erection is scheduled to begin in August 1974 and continue through the month of November 1974. The hydrostatic test is scheduled in November 1974 with unit boil out following approximately one month later.

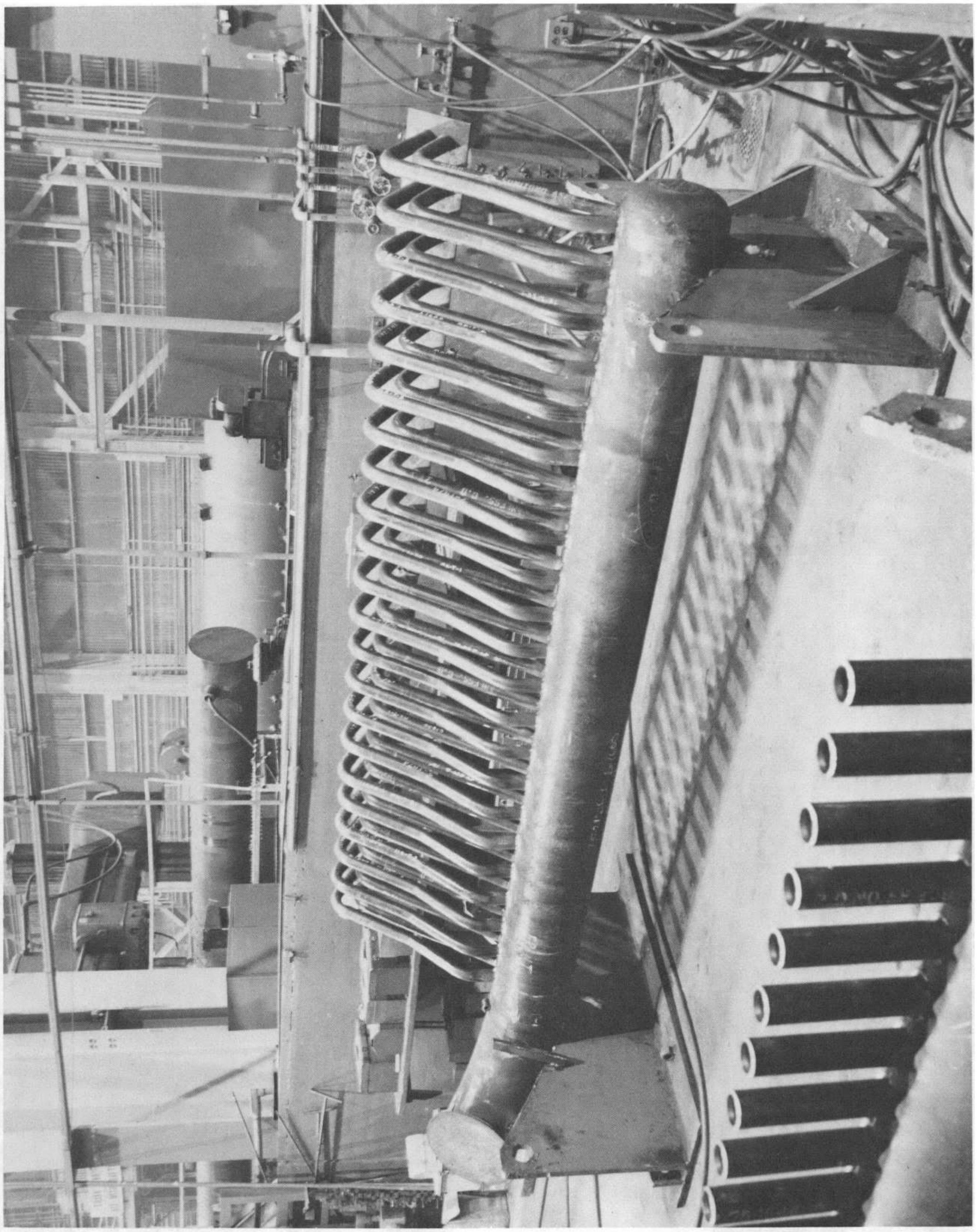


FIGURE F-1 FINISHING SUPERHEATER OUTLET HEADER

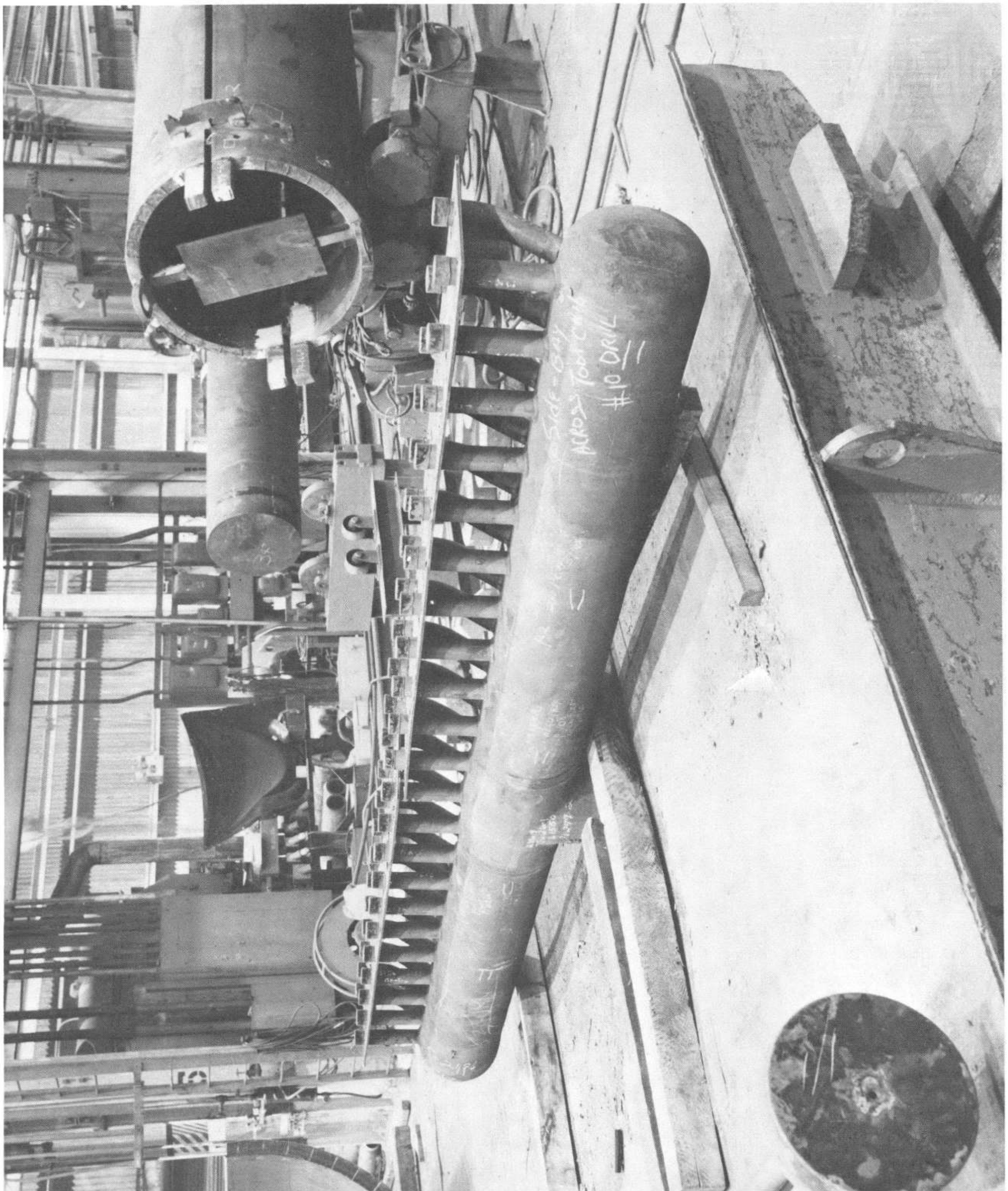


FIGURE F-2 FINISHING SUPERHEATER INLET HEADER

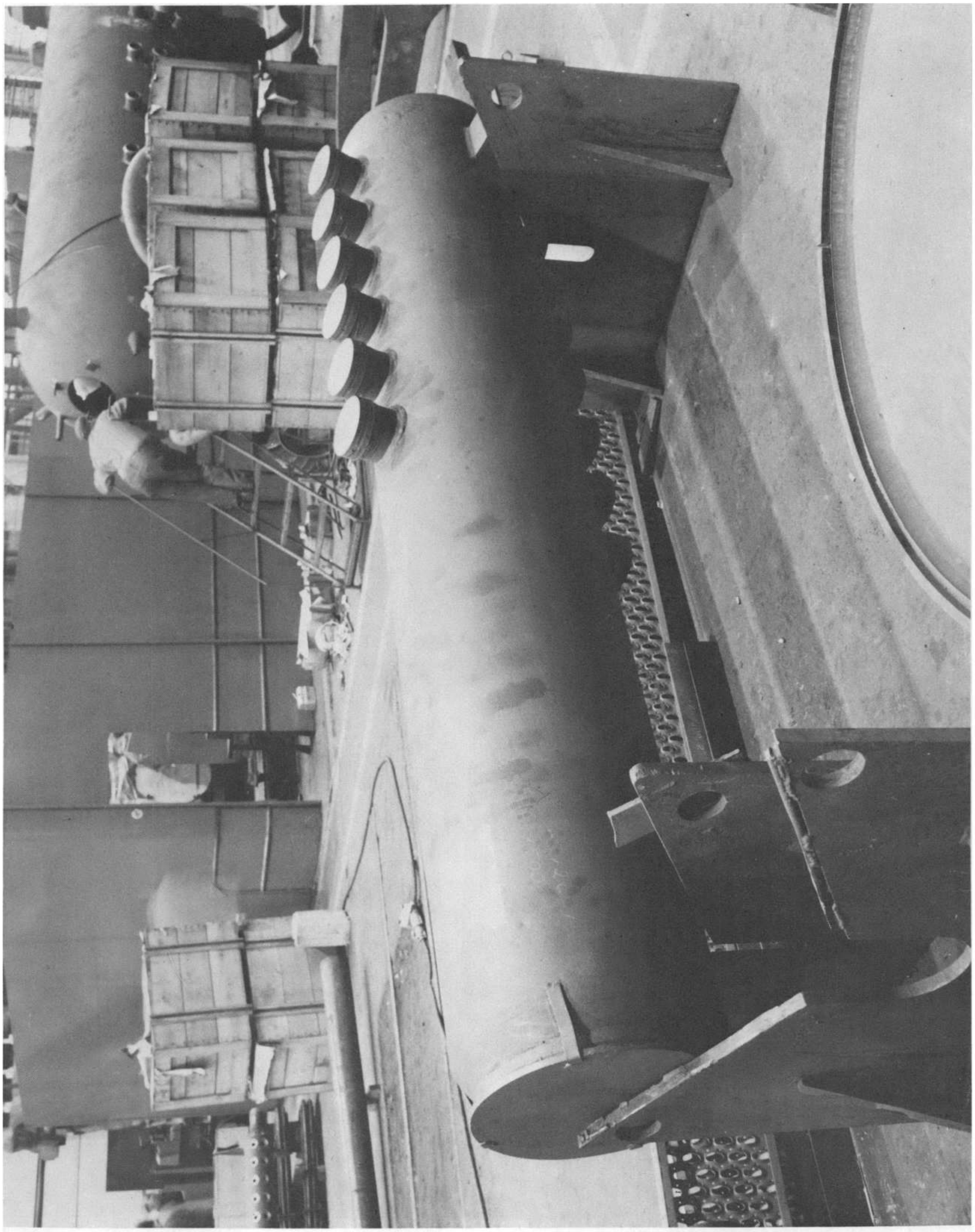


FIGURE F-3 WATERWALL FEEDER MANIFOLD

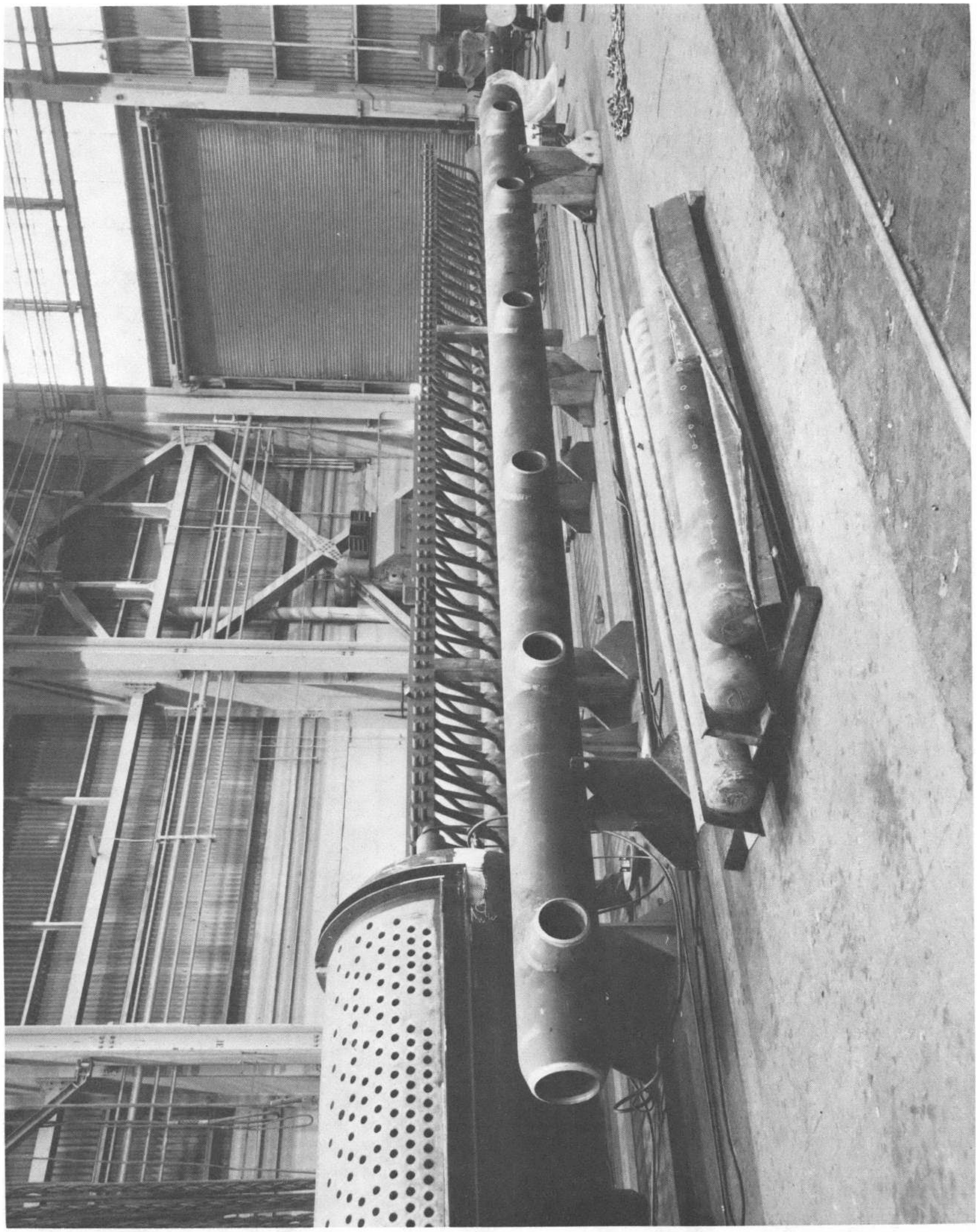


FIGURE F-4 DOWNCOMER MANIFOLD

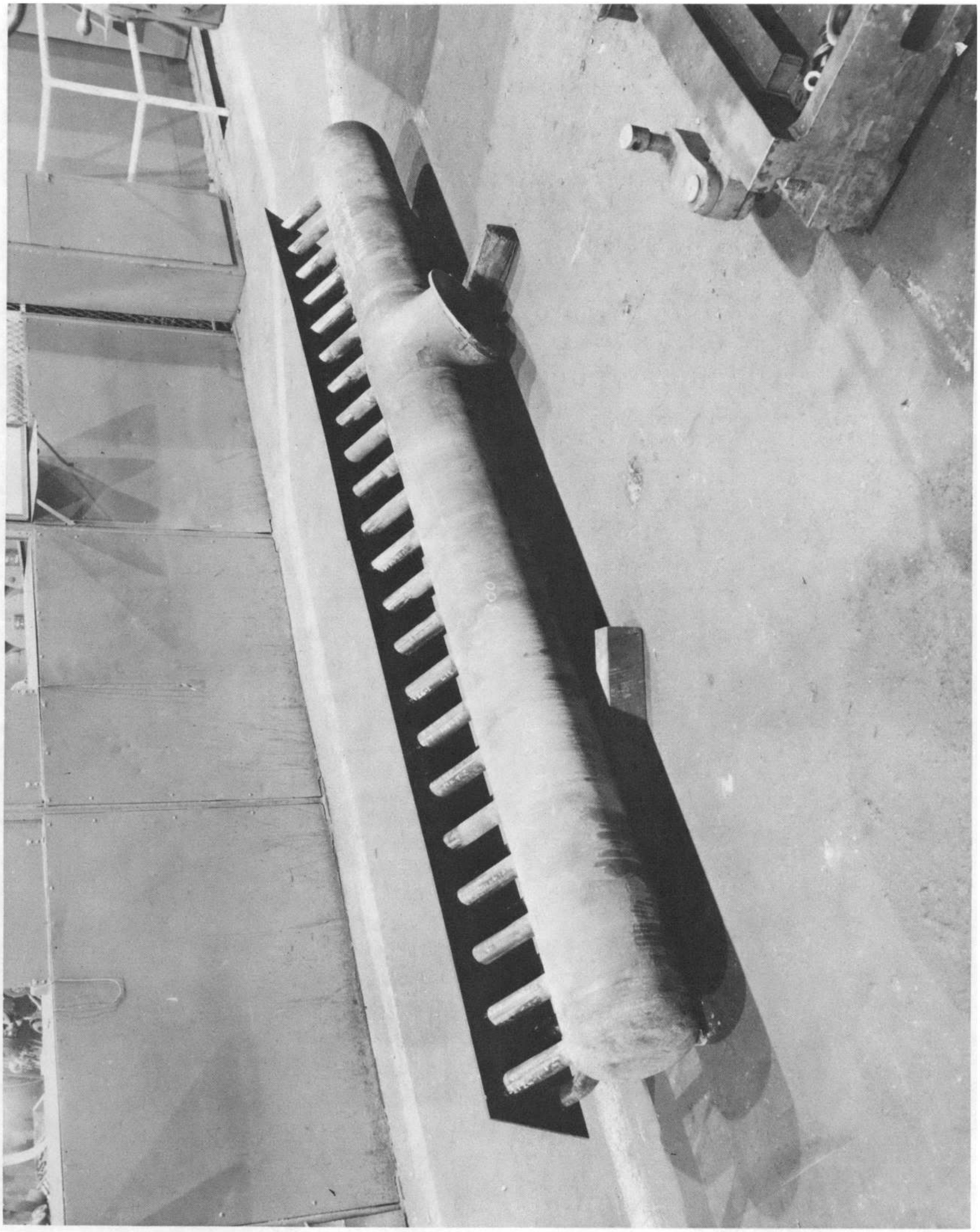


FIGURE F-5 PRIMARY SUPERHEATER OUTLET HEADER

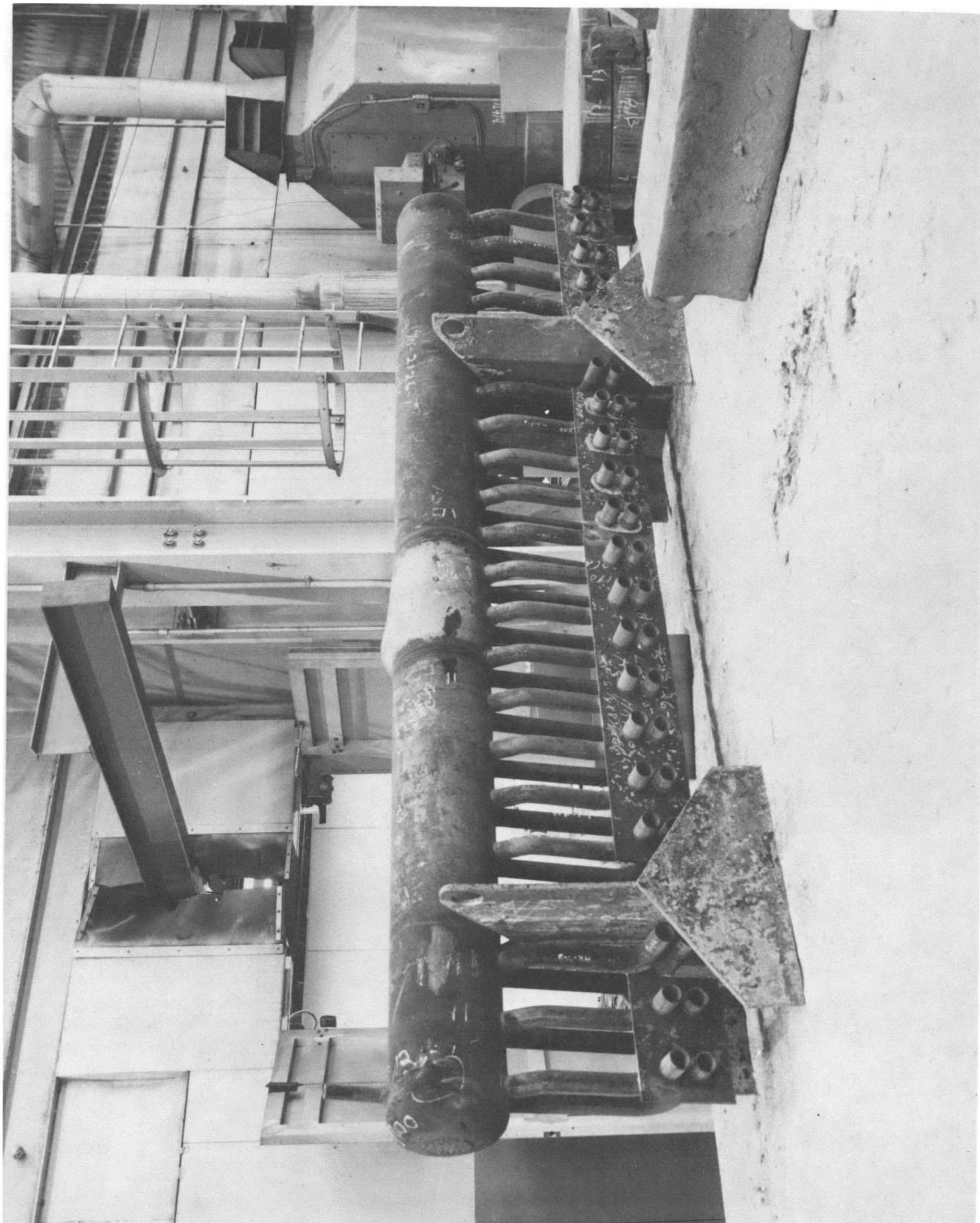


FIGURE F-6 PRIMARY SUPERHEATER INLET HEADER

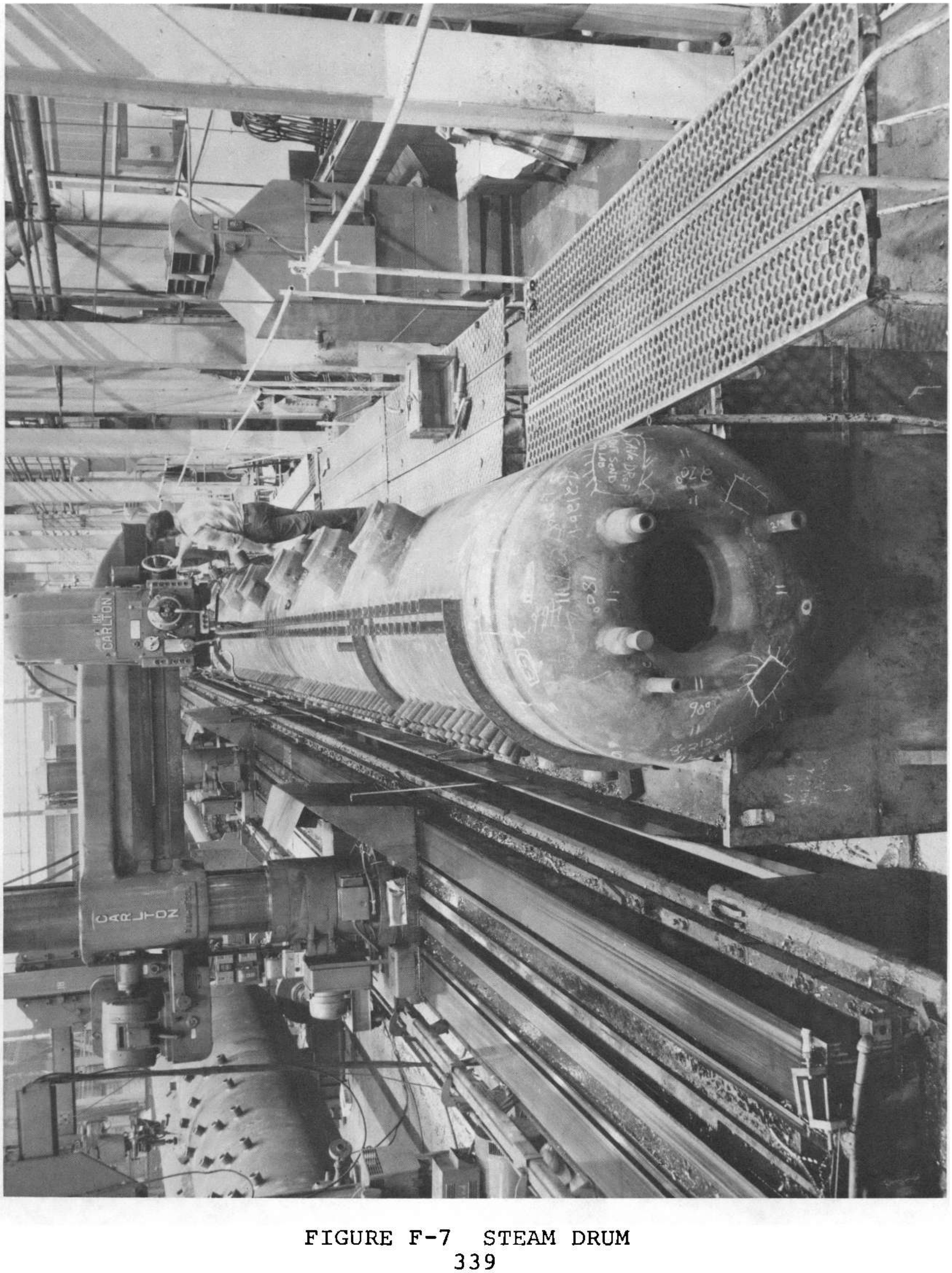


FIGURE F-7 STEAM DRUM

MILESTONE DATES

WEEK No. 1 – AUG. 5, 1974 – START ERECTION
WEEK No. 14 – NOV. 4, 1974 – HYDRO
WEEK No. 16 – NOV. 18, 1974 – AIR TEST
WEEK No. 18 – DEC. 2, 1974 – BOIL OUT

PCN CALENDAR

WEEK NO.	START DATE	WEEK NO.	START DATE
1	AUG 5, 1974	12	OCT 21, 1974
2	12	13	28
3	19	14	NOV 4
4	26	15	11
5	SEP 2	16	18
6	9	17	25
7	16	18	DEC 2
8	23	19	9
9	30	20	16
10	OCT 7	21	23
11	OCT 14, 1974	22	DEC 30, 1974

REV. 0 — 3/13/74 — CONTRACT NO: 7-32-2126

FOSTER WHEELER CORP.
110 SOUTH ORANGE AVE. LIVINGSTON, N.J. 07039

FLUIDIZED BED STEAM GENERATOR

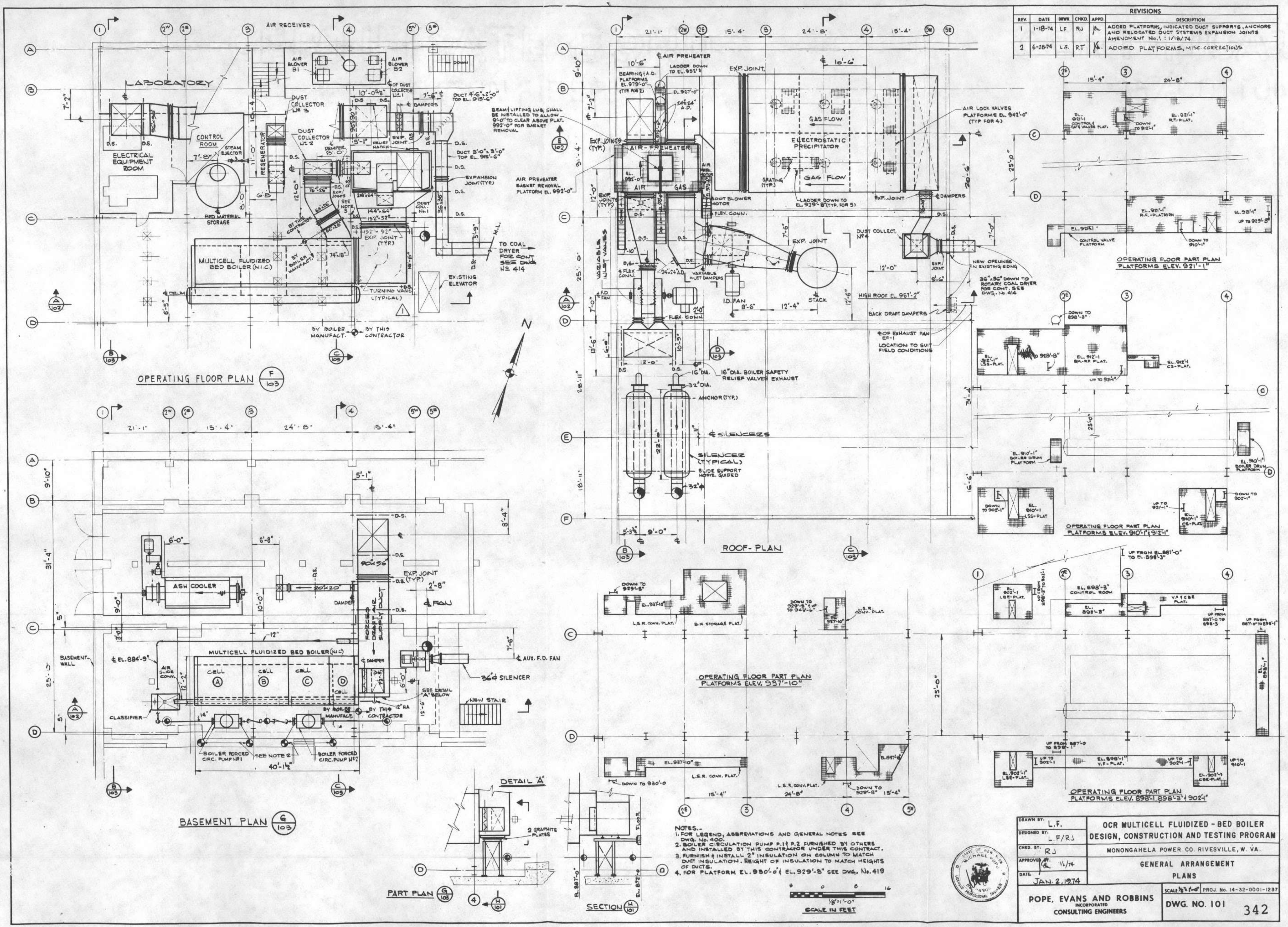
RIVESVILLE POWER STATION

PRECEDENCE CONTROL NETWORK

DRAWING NO. PCN-2126 — REV. 0

FIGURE F-8

APPENDIX G
DESIGN CONSTRUCTION DRAWINGS



REVISIONS					
REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	1-18-74	LF	RJ	[signature]	ADDED PLATFORMS, INDICATED DUCT SUPPORTS, ANCHORS AND RELOCATED DUCT SYSTEMS EXPANSION JOINTS AMENDMENT No.1 : 1/18/74
2	6-28-74	L.F.	RT	[signature]	ADDED PLATFORMS, MISC. CORRECTIONS

NOTES.-
1. FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES SEE DWG. No. 400.
2. BOILER CIRCULATION PUMP P.1 & P.2 FURNISHED BY OTHERS AND INSTALLED BY THIS CONTRACTOR UNDER THIS CONTRACT.
3. FURNISH & INSTALL 2" INSULATION ON COLUMN TO MATCH DUCT INSULATION. HEIGHT OF INSULATION TO MATCH HEIGHTS OF DUCTS.
4. FOR PLATFORM EL. 930'-0" & EL. 929'-8" SEE DWG. No. 419

STATE OF NEW YORK · MICHAEL POPE · LICENSED PROFESSIONAL ENGINEER

DRAWN BY: L.F.
DESIGNED BY: L.F/RJ
CHKD. BY: RJ
APPROVED BY: [signature] 1/2/74
DATE: JAN. 2, 1974

OCR MULTICELL FLUIDIZED - BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM

MONONGAHELA POWER CO. RIVESVILLE, W. VA.

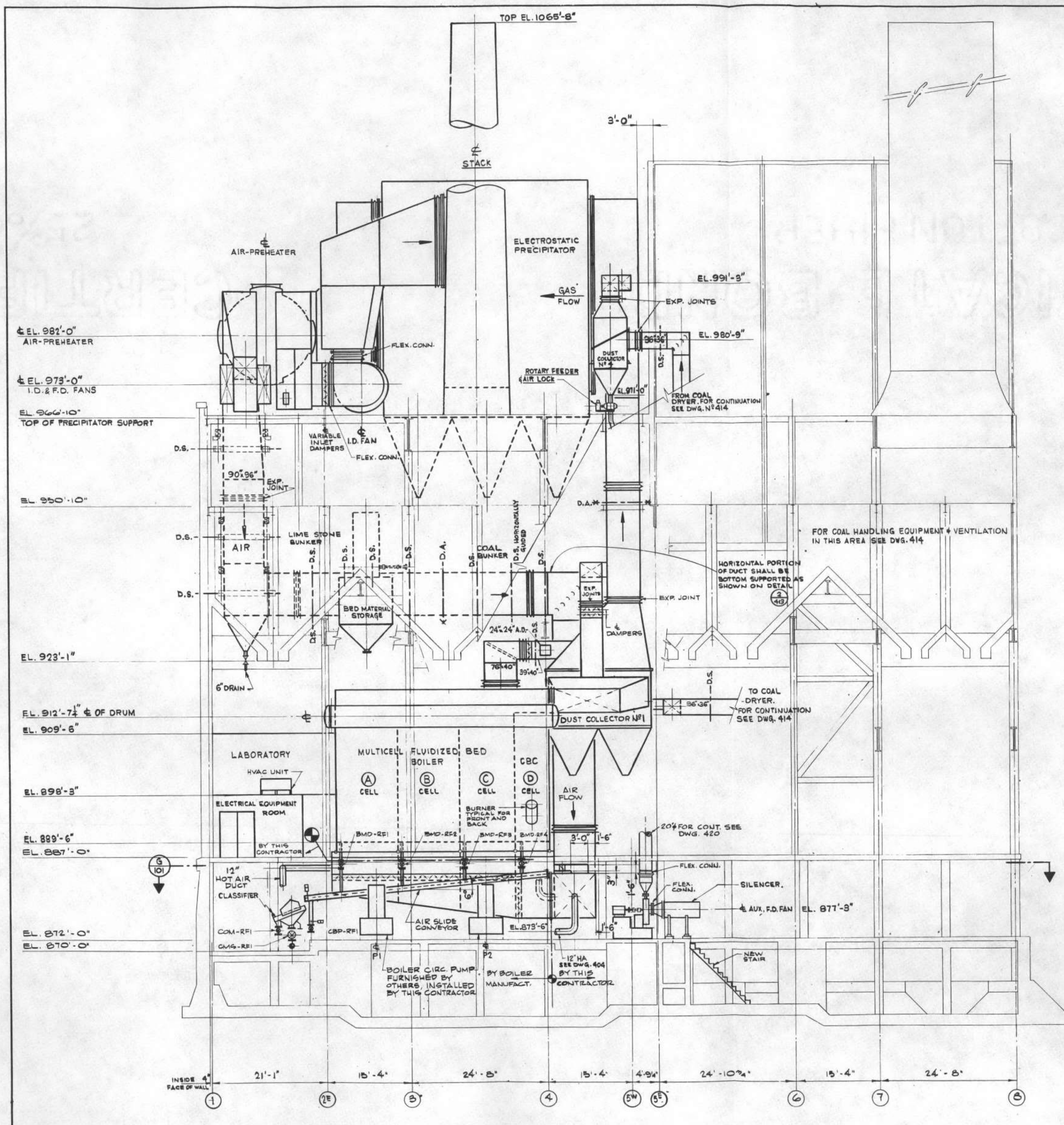
GENERAL ARRANGEMENT PLANS

POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS

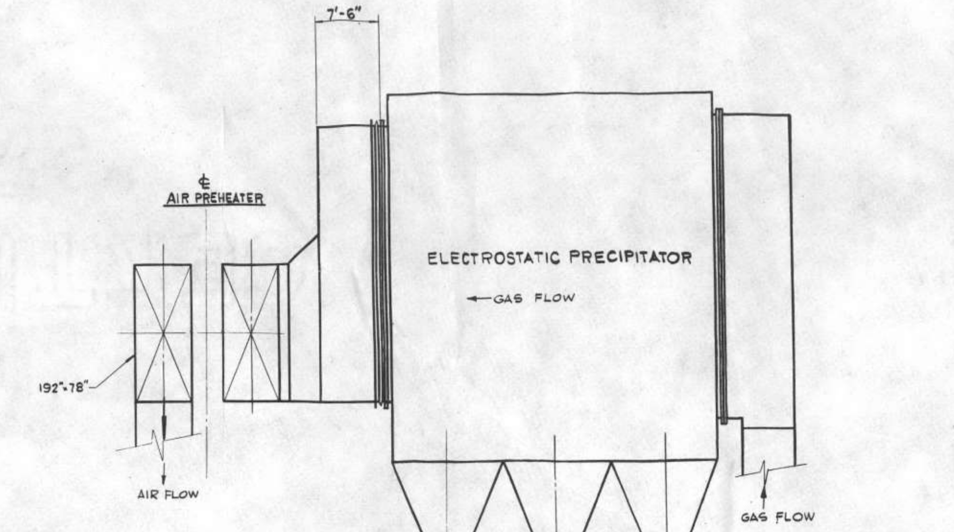
SCALE: 1/8" = 1'-0"   PROJ. No. 14-32-0001-1237

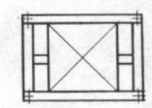
DWG. NO. 101

REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	1-18-74	LF	RJ	[signature]	INDICATED DUCT SUPPORTS, ANCHORS AND RELOCATED DUCT SYSTEMS EXPANSION JOINTS AMENDMENT № 1: 1/16/74
2	6-28-74	L.F	RJ	[signature]	ADDED COAL BUNKER, SHAPING STEEL PLATES, NOTES & RELOCATED AA PIPING

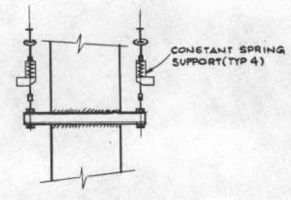


SECTION (A/101)





PLAN

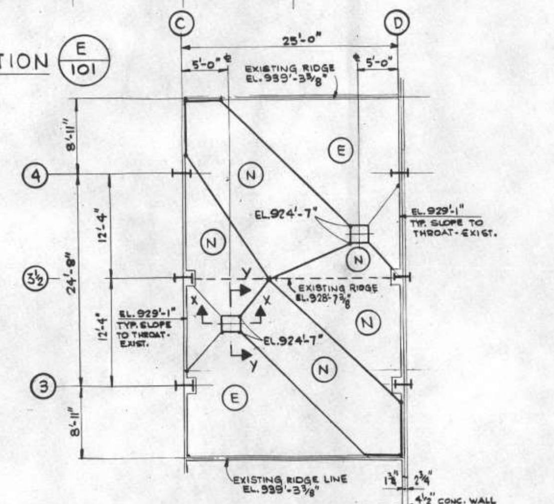


ELEVATION

TYPICAL VERTICAL DUCT SUPPORT

(NOT TO SCALE)

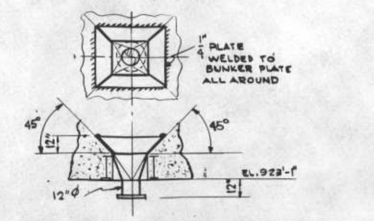
SECTION (E/101)



COAL BUNKER PLAN

NEW SHAPING PLATES

(SCALE: ⅛"=1'-0")



SECTION X-X

SECTION Y-Y

SCALE: ¼"=1'-0"

NOTES

1- FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES, SEE DWG. No. 400.

2- (E) EXISTING BUNKER STEEL PLATE

(N) NEW BUNKER STEEL PLATE

3- NEW STEEL PLATES FOR BUNKER INSTALLED AT A SLOPE OF 45° TOWARDS BUNKER WALLS. PLATE THICKNESS THE SAME AS EXISTING, MINIMUM ⅜" AFTER WELDING OF NEW PLATES, COVER WITH CONCRETE TO MATCH EXISTING BUNKER.

4- ESTIMATED MATERIAL QUANTITIES FOR NEW BOTTOM SHAPING OF EXISTING COAL BUNKER:

⅜" STEEL PLATE	15 TONS
STRUCTURAL STEEL	10 TONS
REINFORCED CONCRETE	30 CU. YDS.

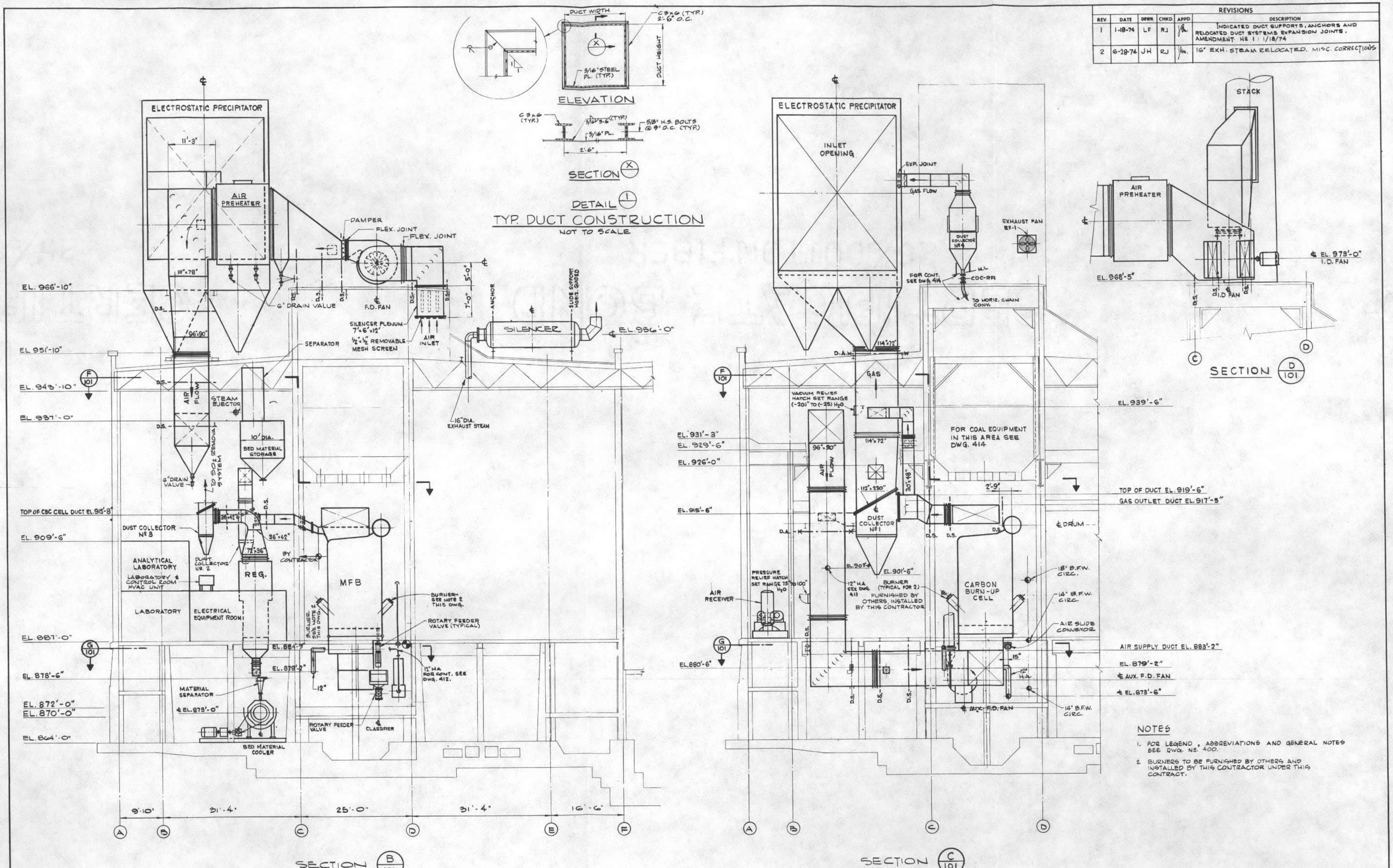
5- ELEVATIONS SHOWN ARE APPROXIMATE.

SCALE IN FEET

8 0 8 16

⅛"=1'-0"

DRAWN BY: L.F.	OCR MULTICELL FLUIDIZED - BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: LF/RJ	
CHKD. BY: RJ	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: [signature] 1/2/74	GENERAL ARRANGEMENT LONGITUDINAL SECTION
DATE: JAN. 2, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: ⅛"=1'-0" PROJ. No. 14-32-0001-1237
	DWG. NO. 102



REV.	DATE	DRWN.	CHKD.	APPD.	REVISIONS DESCRIPTION
1	1-18-74	LF	RJ		INDICATED DUCT SUPPORTS, ANCHORS AND RELOCATED DUCT SYSTEMS EXPANSION JOINTS. AMENDMENT Nº 1 : 1/18/74
2	6-28-74	JH	RJ		16" EXH. STEAM RELOCATED, MISC. CORRECTIONS

NOTES

1. FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES SEE DWG. Nº 400.
2. BURNERS TO BE FURNISHED BY OTHERS AND INSTALLED BY THIS CONTRACTOR UNDER THIS CONTRACT.

DRAWN BY: L.F.
DESIGNED BY: LF/RJ
CHKD. BY: RJ
APPROVED BY: 1/1/74
DATE: JAN. 2, 1974

OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM

MONONGAHELA POWER CO. RIVESVILLE, W. VA.

GENERAL ARRANGEMENT TRANSVERSE SECTIONS

POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS

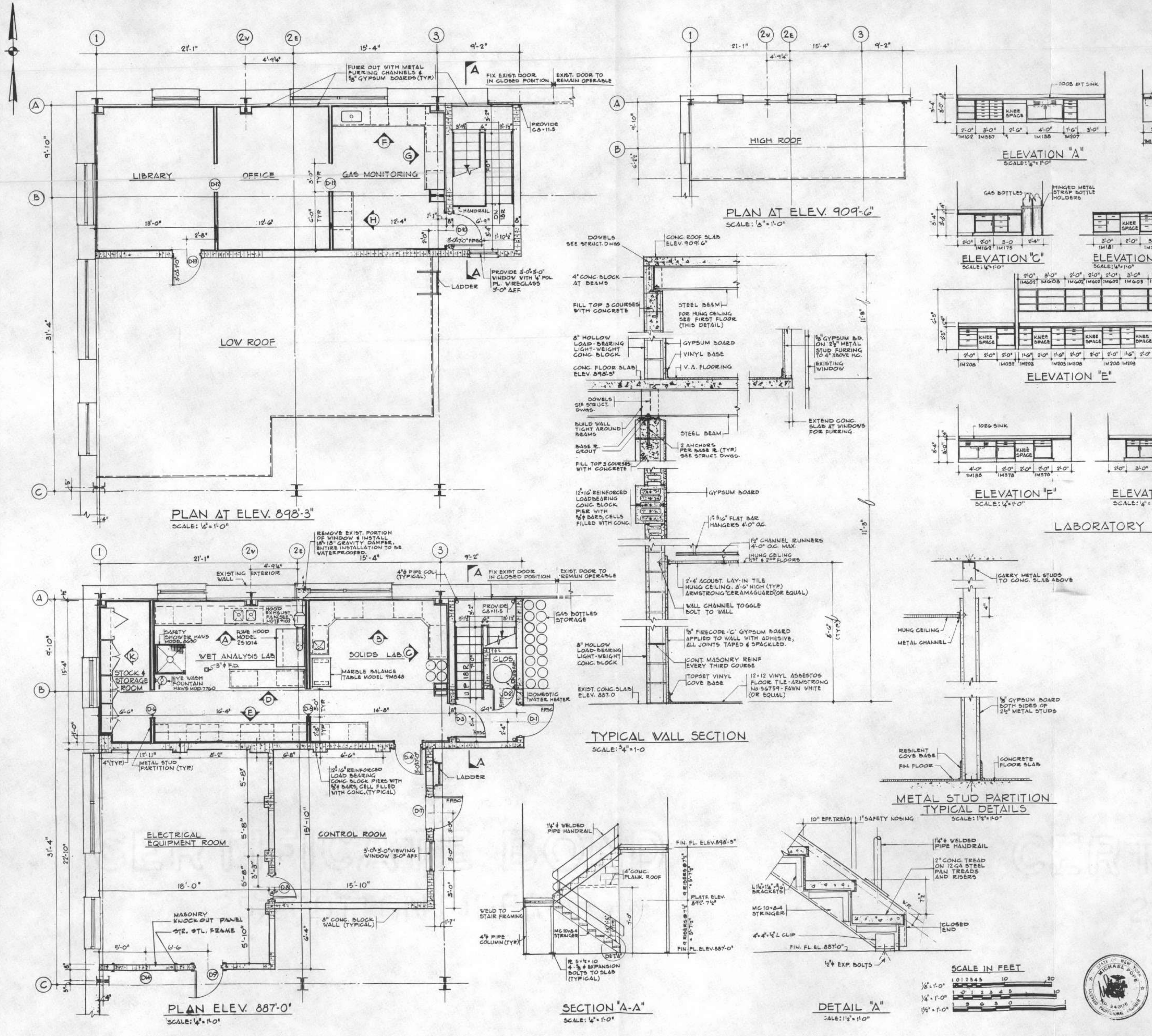
SCALE: 1/8"=1'-0" PROJ. No. 14-32-0001-1237

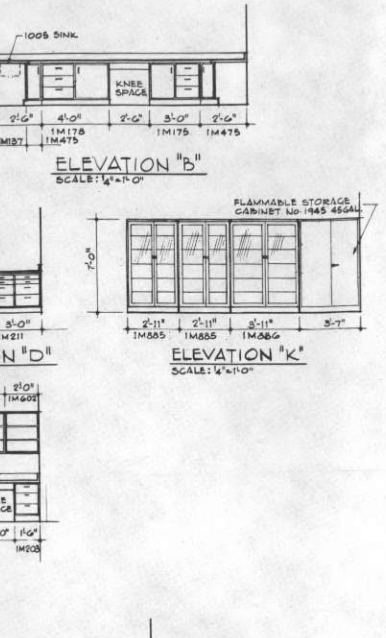
DWG. NO. 103

344

REVISIONS

REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	18JAN.74	C.C.	L.R.H.	[signature]	RELOCATED DR. D-8 AND PIERS - AMENDMENT No. 1 1-18-74
2	14JUN.74	J.H.	L.R.H.	[signature]	RELOCATED DOOR D-8 AND PIERS.





NOTES:

1. LEGEND
   - METAL STUD & GYPSUM BOARD PARTITION FIN. FLOOR TO 4" ABOVE HUNG CEILING, STUDS TO SLAB ABOVE.
   - CONCRETE BLOCK PARTITION
   - AFF — ABOVE FIN. FLOOR
   - FPSC — FIREPROOF SELF CLOSING
2. FOR DOOR SCHEDULE SEE DRAWING No. 202
3. FOR REFLECTED CEILING GRID SEE DRAWING No. 511 & 512
4. FURNISH AND INSTALL METAL LABORATORY EQUIPMENT AS MANUFACTURED BY KEWAUNEE SCIENTIFIC EQUIPMENT CORPORATION OR APPROVED EQUAL. EQUIPMENT FURNISHED SHALL BE SIMILAR TO KEWAUNEE EQUIPMENT SHOWN ON THIS DRAWING.
5. LABORATORY EQUIPMENT TOPS SHALL BE KEWAUNEE KEMROCK WITH 4" BACKSPLASH, OR APPROVED EQUAL. PROVIDE ALL CUTOUTS FOR SERVICES AS REQUIRED.
6. SAFETY SHOWER CABINET AND EYEWASH STATION SHALL BE MODEL 8600 AND 7760-B RESPECTIVELY, AS MANUFACTURED BY HAWS DRINKING FAUCET COMPANY OR APPROVED EQUAL. (SHOWER CAB. LESS EYE WASH)(FILTER UNIT 9070 FOR EYE WASH). FURNISH ALL REQUIRED APPURTENANCES.
7. HUNG CEILING AND RESILIENT FLOORING IN CONTROL ROOM, AND ALL LABORATORY ROOMS, STOCK STORAGE ROOM, OFFICE AND LIBRARY.
8. FLAMMABLE STORAGE CABINET MODEL 1945 AS MANUFACTURED BY EAGLE MANUFACTURING CO. OR APPROVED EQUAL.
9. FOR PLUMBING RISER DIAGRAM SEE DETAIL 1 DRAWING 411.
10. EXHAUST DUCT SIZE FROM FUME HOOD SHALL BE AS PER MANUFACTURER REQUIREMENTS.

DRAWN BY: L.A.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: RH/LA	
CHKD. BY: L.R.H	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: [signature] 1/2/74	LABORATORY, CONTROL & ELECTRICAL ROOMS PLANS AND SECTIONS ARCHITECTURAL
DATE: JAN. 2, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: AS NOTED PROJ. № 14-32-0001-1237
	DWG. NO. 201 345

LEGEND

SYMBOL	IDENTIFICATION
	NEW PIPING & EQUIPMENT
	EXISTING PIPING & EQUIPMENT
-X—X-	REMOVE EXISTING PIPING & EQUIPMENT
	REDUCER
	GATE VALVE
	GLOBE VALVE
	SWING CHECK VALVE
	STOP CHECK VALVE
	CONTROL VALVE
	MOTOR OPERATED VALVE
	SOLENOID VALVE
	THREE-WAY SOLENOID VALVE
	ANGLE VALVE
	SAFETY RELIEF VALVE
	KNIFE GATE VALVE
	HOSE VALVE
	SAMPLE CONNECTION
	FLOAT OPERATED VALVE
	VENT
	BUTTERFLY VALVE
	DRAIN
	Y-STRAINER
	CAP
	BLIND FLANGE
	REDUCER (CONCENTRIC)
	REDUCER (ECCENTRIC)
	PLUG COCK
	VACUUM BREAKER
Y	FUNNEL
	FLOW ORFICE
	EXPANSION JOINT OR FLEXIBLE JOINT
	PIPE UNION
	NEEDLE VALVE OR PLUG VALVE
	HOSE CONNECTION
M	ELECTRICAL MOTOR
	FAN OR PUMP
PCV-5	PRESSURE CONTROL VALVE STATION
TCV-5	TEMPERATURE CONTROL VALVE STATION
TS	STEAM TRAP STATION
T	STEAM TRAP
M	MOTOR DRIVEN EQUIPMENT
	CYLINDER OPERATOR
	SINGLE BLADE DAMPER
	DOUBLE BLADE DAMPER
	HAND AUTO STATION
	SCREW FEEDER
	ROTARY FEEDER & AIR LOCK
	AIR LOCK
M	METER
	CONTRACTORS WORK STARTS HERE
	INSTRUMENT (PNEUMATIC OR ELECTRONIC) LOCAL
	INSTRUMENT (PNEUMATIC OR ELECTRONIC) PANEL MOUNTED
	INSTRUMENT ALARM (PNEUMATIC OR ELECTRONIC) - PANEL MOUNTED
	ELECTRICAL OR ELECTRONIC CONTROL SIGNAL
	TEMPERATURE INDICATER (THERMOMETER)
OR	PRESSURE GAGE
	FLANGED CONN.
-----	CONTROL SYSTEM TUBING
	DUCT EXPANSION JOINT
6 / 103	SECTION OR DETAIL DESIGNATION DWG. WHERE SECTION OR DETAIL APPEARS

INSTRUMENT IDENTIFICATION

SYMBOL	IDENTIFICATION
DC	DRAFT CONTROLLER
DG	DRAFT GAUGE
DT	DRAFT TRANSMITTER
FC	FLOW CONTROLLER
FI	FLOW INDICATOR
FR	FLOW RECORDER
FS	FLOW SWITCH
FT	FLOW TRANSMITTER
FRIT	FLOW RECORDER INDICATOR TOTALIZER
LC	LEVEL CONTROLLER
LI	LEVEL INDICATOR
LR	LEVEL RECORDER
LS	LEVEL SWITCH
LT	LEVEL TRANSMITTER
LG	LEVEL GAUGE (GLASS)
PI	PRESSURE INDICATOR
PC	PRESSURE CONTROLLER
PG	PRESSURE GAUGE
PS	PRESSURE SWITCH
PT	PRESSURE TRANSMITTER
TC	TEMPERATURE CONTROLLER
TI	TEMPERATURE INDICATOR
SDI	SMOKE DENSITY INDICATOR
TRI	TEMPERATURE RECORDER INDICATOR
TS	TEMPERATURE SWITCH
TW	TEST WELL
TT	TEMPERATURE TRANSMITTER
HLA	HIGH LEVEL ALARM
LLA	LOW LEVEL ALARM
O_2T	OXYGEN TRANSMITTER
O_2RI	OXYGEN REORDER INDICATOR
O_2C	OXYGEN CONTROLLER
$(NO_x)RI$	NITROGEN OXIDE RECORDER INDICATOR
$(SO_2)RI$	SULPHUR DIOXIDE RECORDER INDICATOR
$(CO_2)RI$	CARBON DIOXIDE RECORDER INDICATOR
ΔP	DIFFERENTIAL PRESSURE
LRI	LEVEL RECORDER INDICATOR
PR	PRESSURE RECORDER
TR	TEMPERATURE RECORDER
LPA	LOW PRESSURE ALARM
HPA	HIGH PRESSURE ALARM
LTA	LOW TEMPERATURE ALARM
HTA	HIGH TEMPERATURE ALARM
SDA	SMOKE DENSITY ALARM
LFA	LOW FLOW ALARM
HSDA	HIGH SMOKE DENSITY ALARM
SO_2C	SO_2 CONTROLLER (LIMESTONE FEED CONTROL)
TP	TEST PRESSURE
HLI	HIGH LEVEL INDICATOR

PIPING SYSTEM ABBREVIATIONS

ABBREVIATIONS	VALVE	IDENTIFICATION
BD OR BDC	BDV	BLOW-OFF OR BLOW DOWN
BFW	BFWV	BOILER FEED WATER (2500/2400 PSIG)
CF	CFV	CHEMICAL FEED (2500 PSIG)
HPS	HPSV	MAIN STEAM-1400 PSIG HIGH PRESSURE STEAM
HPC	HPCV	CONDENSATE - HIGH PRESSURE (1250 PSIG)
MPS	MPSV	MEDIUM PRESSURE STEAM (250 PSIG)
MPC	MPCV	CONDENSATE - MEDIUM PRESSURE (245 PSIG)
CBD	CBDV	CONTINUOUS BLOW DOWN
D OR DR	DRV	DRIP OR DRAIN - STEAM LINES & EQUIP. DRAINS
FOR	FORV	FUEL OIL RETURN
FOS	FOSV	FUEL OIL SUPPLY
CA	CAV	INSTRUMENT AIR (CONTROL AIR 60 PSIG)
RV	RVV	RELIEF VALVE - FOR ALL SERVICE EXCEPT BOILERS
V	VV	VENT
PS		PIPE SUPPORT
ML		MATCH LINE
RF		ROTARY FEEDER
CO		CLEAN OUT
HW		HOT WATER
CW		COLD WATER
DS		DUCT SUPPORT
NIC		NOT INCLUDED IN THIS CONTRACT.
IPS	IPSV	INTERMEDIATE PRESSURE STEAM (600 PSIG)
LPS	LPSV	LOW PRESSURE STEAM (30 PSIG)
EXS		EXHAUST STEAM (60 PSIG)
IPC		CONDENSATE, - INTERMEDIATE PRESSURE (600 PSIG)
LPC		LOW PRESSURE CONDENSATE (30 PSIG)
IA		INSTRUMENT AIR
PA		PLANT AIR
BF		BLIND FLANGE
FLG		FLANGE
BW		BUTT WELDED
SW		SOCKET WELDED
SD		SHOWER DRAIN
F.D.		FLOOR DRAIN
MFB		MULTICELL FLUIDIZED BED BOILER
CBC		CARBON BURN UP CELL
REG		REGENERATOR
ECO		ECONOMIZER
AD		ACCESS DOOR
DT		DOUBLE TUB
BM		BED MATERIAL
HA		HOT AIR (600° F 60" H_2O OPERATING)
BA		BLOWER AIR (14 PSIG 170° F OPERATING)
FA		FLY ASH
DS		DUCT SUPPORT
CCS		CHAIN CONVEYOR SUPPORT
DA		DUCT ANCHOR
C		COAL
L		LIMESTONE
CL		COAL & LIMESTONE
AA		AVX. AIR (60" H_2O & AMBIENT TEMP.)
CV		CONTROL VALVE
MV		MANUAL VALVE
COV		CHAIN OPERATED VALVE
RF		ROTARY FEEDER
VF		VIBRATING FEEDER
PF		FEEDER PIPE
FJ		FLEXIBLE JOINT
CVC		COAL VIBRATING CONVEYOR
LVC		LIMESTONE VIBRATING CONVEYOR
CS		COAL SCALE
LS		LIMESTONE SCALE
CBE		COAL BUCKET ELEVATOR
LBE		LIMESTONE BUCKET ELEVATOR
LRC		LIMESTONE REPLER CONVEYOR
NIC		NOT IN CONTRACT
S		SOUTH OF COLUMN LINE 'D'
N		NORTH OF COLUMN LINE 'C'

GENERAL NOTES

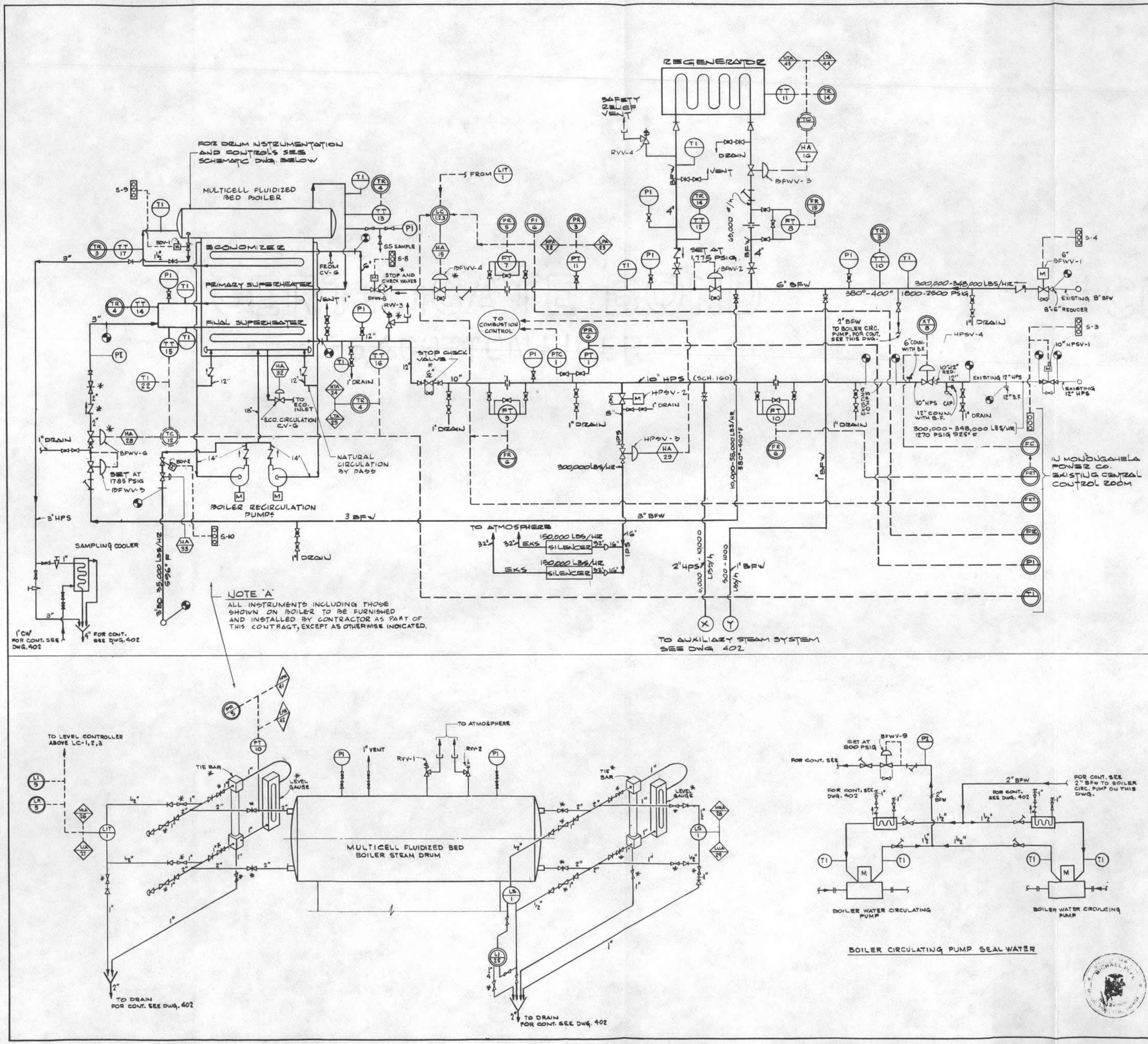
1. DESIGN IS BASED ON APPROXIMATE ANTICIPATED SIZES OF EQUIPMENT. CONTRACTOR SHALL MODIFY DESIGN FOR ENGINEERS APPROVAL WHERE REQUIRED FOR ACTUAL EQUIPMENT PURCHASED.
2. CONTRACTOR SHALL VERIFY ALL DIMENSIONS AT THE JOB SITE BEFORE PURCHASE OF EQUIPMENT AND BEFORE PROCEEDING WITH FABRICATION AND ERECTION OF WORK.
3. FOR WEIGHTS AND MATERIALS OF PIPES AND FITTINGS, SEE SPECIFICATIONS.
4. FOR INSULATION OF PIPES AND EQUIPMENT, SEE SPECIFICATIONS.
5. LOCATION AND SIZE OF EQUIPMENT CONNECTIONS SHALL BE CHECKED WITH CERTIFIED SUPPLIERS PRINTS AND FIELD CHECKED WITH ACTUAL EQUIP. BEFORE FABRICATION OR INSTALLATION OF PIPING.
6. ALL PIPING 2" AND UNDER ARE SHOWN DIAGRAMMATICALLY ONLY. EXACT LOCATION SHALL BE DETERMINED BY THE CONTRACTOR IN THE FIELD.
7. SMALL SIZE PIPING SHOWN ON THE FLOW DIAGRAMS BUT NOT SHOWN ON THE PIPING DRAWINGS SHALL BE FIELD RUN, IN AN APPROVED MANNER AND LOCATION, AS INDICATED ON THE FLOW DIAGRAMS.
8. ALL ELEVATIONS SHOWN FOR PIPE LINES ARE CENTER LINE ELEVATIONS, EXCEPT WHERE OTHERWISE NOTED.
9. SLOPE ALL STEAM PIPE LINES IN THE DIRECTION OF FLOW, EXCEPT WHERE OTHERWISE SHOWN ON THE DRAWINGS.
10. TRAP ALL IPS, MPS & LPS STEAM SUPPLY LOW POINTS.
11. FOR SUPPORT OF EQUIPMENT SEE STRUCTURAL DRAWINGS.
12. FURNISH DRAIN LINES FROM EQUIPMENT AND SPECIALTIES TO NEAREST FLOOR DRAIN.
13. ALL DRAIN PIPE LINES SHALL BE SLOPED MINIMUM 1/8" PER 1'-0", EXCEPT WHERE OTHERWISE SHOWN OR NOTED.
14. WHERE RAISED FACE STEEL FLANGE MEETS WITH A FLAT FACE FLANGE, THE RAISED FACE SHALL BE REMOVED, (USE FULL FACE GASKETS FOR FLAT FACE FLANGES).
15. FURNISH AND INSTALL INSTRUMENTS, INSTRUMENT CONNECTIONS, CONTROL DEVICES, STRAINERS, CONTROLLERS AS SHOWN ON THE FLOW AND/OR PIPING DIAGRAMS.
16. CONTRACTOR SHALL FURNISH AND INSTALL PLUGGED DRAIN CONNECTION FOR ALL PIPE LINE LOW POINTS (EXCEPT IPS, MPS & LPS STEAM LINES) AND VENT CONNECTIONS WITH 1/2" VENT VALVE AT ALL PIPE LINE HIGH POINTS (EXCEPT STEAM LINES).
17. ALL EQUIPMENT AND EQUIPMENT CONNECTIONS MUST BE DESIGNED TO TAKE CARE OF THE ADDITIONAL FORCES AND MOMENTS INTRODUCED BY THE PIPING SYSTEM ON THEM.
18. CONTRACTOR SHALL FURNISH AND INSTALL ALL NECESSARY PIPE HANGERS AND SUPPORTS, EXPANSION JOINTS, ANCHORS, GUIDES AND SLEEVES REQUIRED FOR PROPER SYSTEM OPERATION WHETHER SHOWN ON THE DRAWINGS OR NOT, AT NO EXTRA COST TO THE OWNER.
19. EACH AND ALL INSTRUMENTS, PNEUMATIC OR DIRECT ACTUATED LOCAL OR PANEL MOUNTED SHOWN ON THE SCHEMATIC FLOW DIAGRAMS ARE NEW AND SHALL BE FURNISHED AND INSTALLED BY THE CONTRACTOR AS PART OF THIS CONTRACT.
20. ALL INSTRUMENTS AND CONTROL DEVICES, DAMPERS, DAMPER OPERATORS, VALVES, VALVE OPERATORS, INCLUDING THOSE SHOWN ON THE BOILER SHALL BE FURNISHED AND INSTALLED BY THIS CONTRACTOR AS PART OF THIS CONTRACT.
21. FOUR (4) AIR SUPPLY DAMPERS INSIDE THE BOILER AIR PLENUM WILL BE FURNISHED & INSTALLED BY OTHERS. OPERATORS AND CONTROLLERS FOR THESE FOUR (4) DAMPERS AND ALL ADDITIONAL DAMPERS AND OPERATORS, COMPLETE SHALL BE FURNISHED AND INSTALLED BY THIS CONTRACTOR.
22. CONTRACTOR SHALL FURNISH AND INSTALL THERMOWELLS, WITH REAMS TO SUIT INSERTED ELEMENT. FOR EACH AND ALL TEMPERATURE SENSING ELEMENT USED ON THE PIPING SYSTEMS, IN ACCORDANCE WITH ASME CODE REQUIREMENTS. IMMERSION OF THE THERMOWELLS INTO THE FLOWING STREAM SHALL NOT BE LESS THAN 3". IN A PIPE LINE 4" DIA. OR SMALLER IN SIZE THE WELL MUST BE INSERTED IN AN ELBOW OR TEE AND AND WHERE POSSIBLE ARRANGED AXIALLY IN THE PIPE FACING THE ONCOMING FLOWING MEDIA. IN PIPE LINES SMALLER THAN 4" DIA. THE ELBOW OR TEE SHALL BE ONE SIZE LARGER THAN THE LINE; AND IN PIPE LINE 2" DIA. OR SMALLER, AN ENLARGED SECTION OF PIPE EQUAL IN SIZE TO THE ELBOW OR TEE SHALL BE FURNISHED AND INSTALLED IMMEDIATELY UPSTREAM OF THE ELBOW OR TEE SO AS TO AVOID SERIOUS IMPEDANCE OF FLOW BY THE WELL. IN PIPE LINES 6" AND ABOVE THE THERMOWELL SHALL BE IMMERSED SO THAT THE TIP OF THE WELL WILL REACH ℄ OF PIPE 1 1/2. FOR PIPE LINES 12" DIA. AND ABOVE THE IMMERSION SHALL BE MORE THAN 6.
23. EACH THERMOWELL IN THE BFW SYSTEM SHALL BE INSTALLED IN A PIPE BOSS WHICH IS WELDED TO THE PIPE ALL AROUND, IN ACCORDANCE WITH CODE REQUIREMENTS, AND DRILLED & REAMED THROUGH (BOSS AND PIPE WALL) AFTER STRESS RELIEVING WITH THE PIPE.
24. CONTRACTOR SHALL SUBMIT DETAILS FOR HIS PROPOSED THERMOWELL INSTALLATION FOR ENGINEERS APPROVAL.
25. FOR TYPICAL DUCT CONSTRUCTION SEE DETAIL NO. 1 DWG. NO. 103
26. ALL PANEL MOUNTED CONTROLLER SHALL BE THE MANUAL/AUTOMATIC TYPE AND SHALL BE LOCATED ON THE FRONT OF THE DESIGNATED PANEL.
27. PIPE LINE SCHEDULE NUMBERS SHALL BE SELECTED IN ACCORDANCE WITH THE SPECIFICATIONS, BASED ON SYSTEM, FLOW, PRESSURE, TEMPERATURE, MATERIAL AND STRESS CONDITIONS.
28. PIPE SCHEDULE FOR HPS (HIGH PRESSURE STEAM) PIPE LINES SHALL BE MIN. SCH 160 FOR ALL LINE SIZES.
29. PIPE SCHEDULE FOR BFW (BOILER FEED WATER) PIPE LINES SHALL BE MINIMUM SCH 160 FOR ALL PIPE LINE SIZES.
30. ALL EXPANSION (FLEXIBLE) JOINTS IN THE DUCT AND PIPING SYSTEMS SHALL BE SUITABLE FOR SIMULTANEOUS COMBINED AXIAL, LATERAL & ANGULAR MOVEMENT, AND EACH SHALL BE FURNISHED AND INSTALLED WITH SELF EQUALIZING STABILIZING TIE RODS.
31. ALL DUCT AND PIPING SUPPORTS AND HANGERS SHALL BE THE CONSTANT, SPRING TYPE, UNLESS OTHERWISE SHOWN OR APPROVED.

REVISIONS

REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	1-18-74	RAS	L.F.	[signature]	REVISED ABBREV. & ADDED GENERAL NOTES 26 THRU 31 AMENDMENT No. 1 : 1/18/74
2	6-14-74	J.H.	RJ	[signature]	ADDED ABBREV. & SYMBOLS

STATE OF NEW YORK · MICHAEL POPE · LICENSED PROFESSIONAL ENGINEER · No. 27806

DRAWN BY: VIC	OCR MULTICELL FLUIDIZED - BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: VIC	
CHKD. BY: JG	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: [signature] 1/4/74	LEGEND, INSTRUMENT IDENTIFICATIONS, ABBREVIATIONS AND GENERAL NOTES MECHANICAL
DATE: JAN. 2, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE · PROJ. NO. 14-32-0001-1237 · DWG. NO. 400

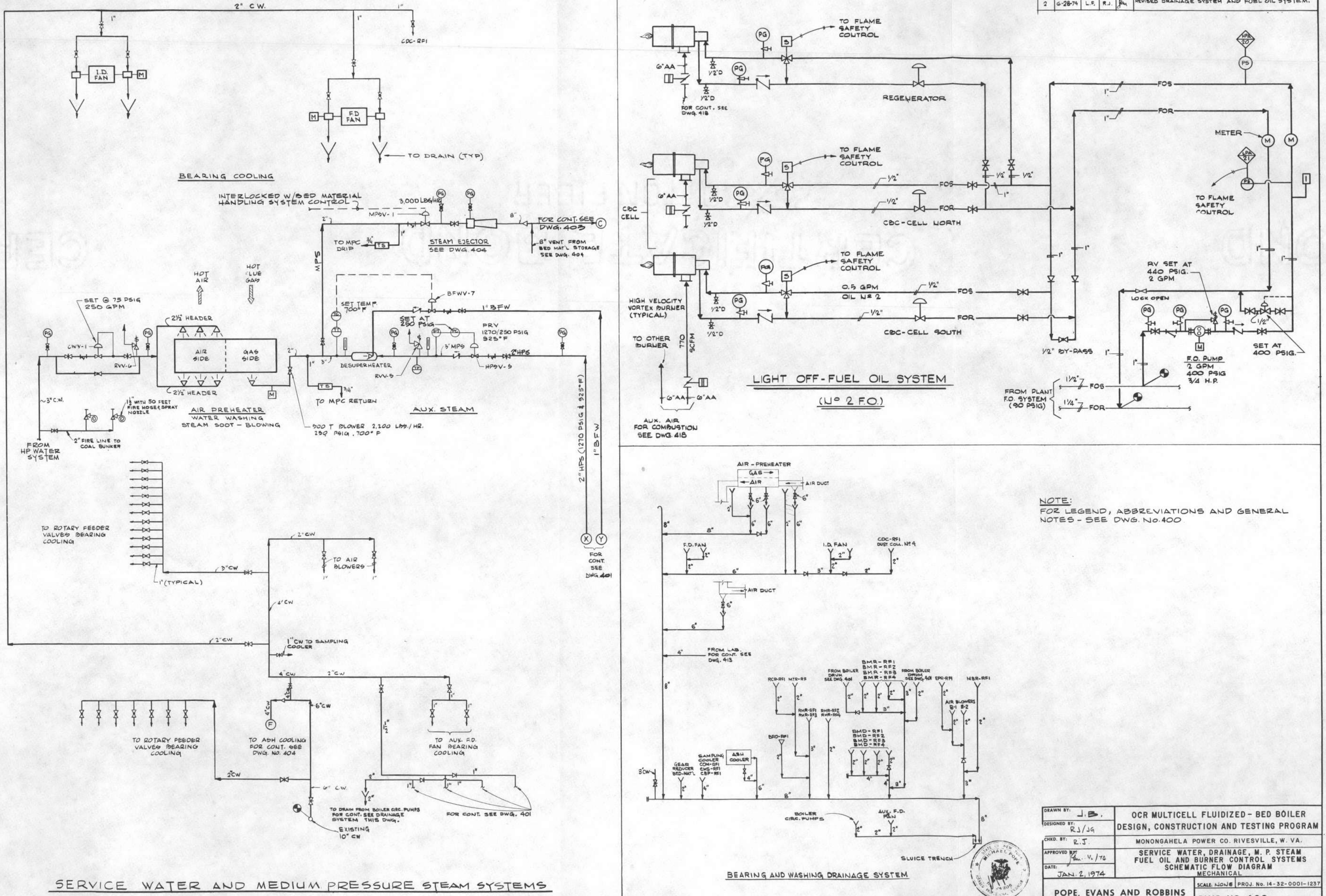


REVISIONS					
REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	1-18-74	L.F.	R.J.	[signature]	ADDED DRAIN VALVES, SAMPLING COOLER AMENDMENT No. 1 : 1/18/74
2	2-1-74	L.F.	K.M.	[signature]	DEFINED ITEMS INSTALLED AND/OR FURNISHED BY OTHERS AMENDMENT No. 2; 2/1/74
3	6-28-74	J.G.	R.J.	[signature]	REVISED CONTROLS

NOTE:

1. FOR LEGEND ABBREVIATIONS AND GENERAL NOTES SEE DWG. No. 400
2. ASTERISK (*) INDICATES MATERIAL OR EQUIPMENT FURNISHED BY OTHERS FOR INSTALLATION BY THIS SUB-CONTRACTOR.
3. AREAS CIRCLED AND SINGLE ITEMS DESIGNATED "N.I.C." DEFINE WORK AND MATERIAL NOT INCLUDED IN THIS SUB-CONTRACT.

DRAWN BY: J.B.	OCR MULTICELL FLUIDIZED - BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: JG	
CHKD. BY: RJ	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: [signature]	STEAM AND BOILER FEED WATER SYSTEMS SCHEMATIC FLOW DIAGRAM MECHANICAL
DATE: JAN. 2, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE — PROJ. No. 14-32-0001-1237 — DWG. NO. 401



REVISIONS

REV.	DATE	DRWN	CHKD	APPD.	DESCRIPTION
1	1-18-74	L.F.	R.J.		ADDED FIRE LINE, REVISED C.W. SYSTEM AMENDMENT NR 1: 1/18/74
2	6-28-74	L.F.	R.J.		REVISED DRAINAGE SYSTEM AND FUEL OIL SYSTEM.

NOTE:
FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES - SEE DWG. No. 400

DRAWN BY: J.B.
DESIGNED BY: RJ/JG
CHKD. BY: R.J.
APPROVED BY: 1/74
DATE: JAN. 2, 1974

OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM

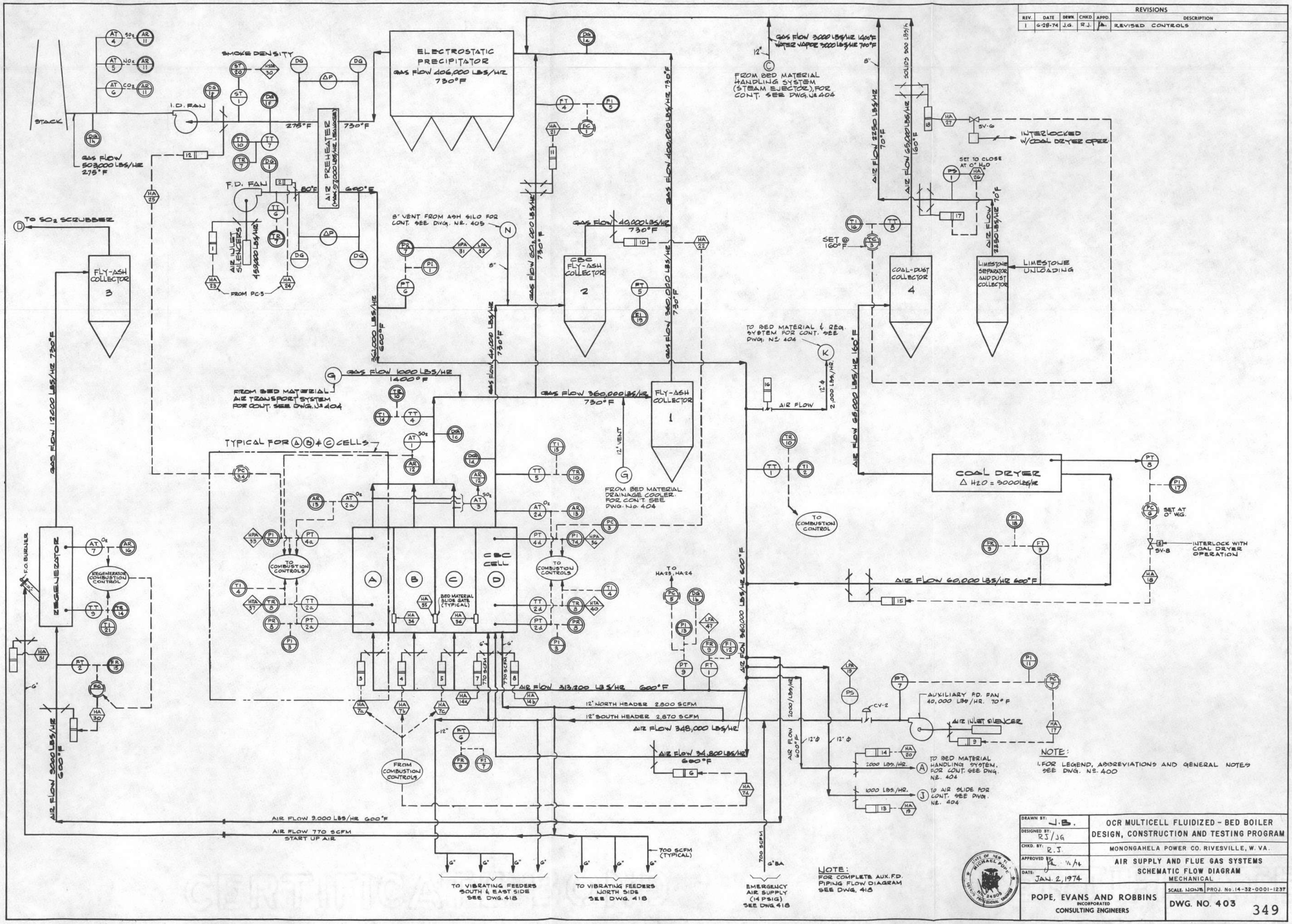
MONONGAHELA POWER CO. RIVESVILLE, W. VA.

SERVICE WATER, DRAINAGE, M. P. STEAM FUEL OIL AND BURNER CONTROL SYSTEMS SCHEMATIC FLOW DIAGRAM MECHANICAL

POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS

SCALE: NONE PROJ. No. 14-32-0001-1237

DWG. NO. 402

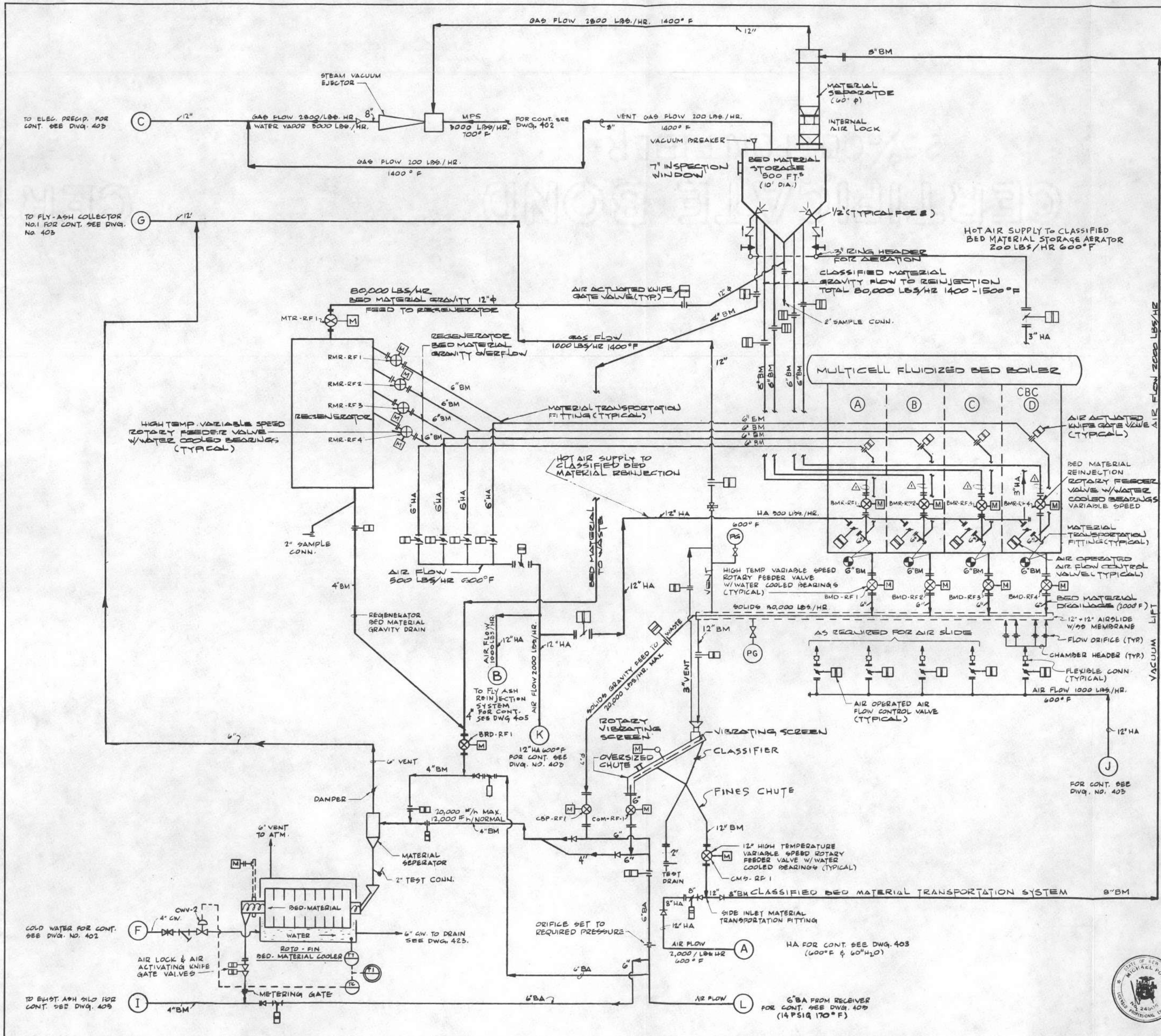


REVISIONS

REV.	DATE	DRWN	CHKD	APPD	DESCRIPTION
1	6-28-74	J.G.	R.J.		REVISED CONTROLS

NOTE:
1. FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES SEE DWG. NO. 400

DRAWN BY: J.B.	OCR MULTICELL FLUIDIZED - BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: RJ/JG	
CHKD. BY: R.J.	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY:	AIR SUPPLY AND FLUE GAS SYSTEMS SCHEMATIC FLOW DIAGRAM MECHANICAL
DATE: JAN. 2, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE PROJ. No. 14-32-0001-1237
	DWG. NO. 403



REVISIONS					
REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	1-18-74	L.F.	R.J.	Jhn.	REDUCERS DELETED. AMENDMENT № 1: 1/18/74
2	6-28-7	L.F.	R.J	Jhn.	STEAM EJECTOR SUPPLY REVISED

ROTARY FEEDER SCHEDULE

ROTARY FEEDER №	SIZE	SYSTEM	BED MATERIAL CAPACITY MIN. Lbs/HR.	BED MATERIAL TEMP. °F MAX.	REMARKS
BMD-RF1 BMD-RF2 BMD-RF3 BMD-RF4	6" 6" 6" 6"	BED MATERIAL DRAINAGE	20,000 20,000 20,000 20,000	2,000 2,000 2,000 2,000	BASEMENT
BMR-RF1 BMR-RF2 BMR-RF3 BMR-RF4	6" 6" 6" 6"	BED MATERIAL REINJECTION	20,000 20,000 20,000 20,000	1,700 1,700 1,700 2,000	OPERATING FLOOR
RMR-RF1 RMR-RF2 RMR-RF3 RMR-RF4	6" 6" 6" 6"	REGENERATOR MATERIAL REINJECTION	20,000 20,000 20,000 20,000	2,000 2,000 2,000 2,000	OPERATING FLOOR N.I.C.
MTR-RF1	12"	MATERIAL TO REGENERATOR	80,000	2,000	OPERATING FLOOR N.I.C.
BRD-RF1	4"	BED MATERIAL STORAGE & REGENERATOR DRAINAGE	5,000	2,000	BASEMENT
CBP-RF1	6"	CLASSIFIED BY-PASS TO WASTE	20,000	2,000	BASEMENT
CMS-RF1	12"	CLASSIFIED MATERIAL TO STORAGE	80,000	2,000	BASEMENT
EPR-RF1	4"	ELEC. PRECIP. REINJECTION TO CBC.	1,300	1,000	OPERATING FLOOR
RCR. RF1	4"	REG. COLL NO. 3 REINJECTION TO CBC	400	1,000	OPERATING FLOOR N.I.C.
MBR-RF1	6"	MFB. COLL. NO. 1 REINJECTION TO CBC	15,000	1,000	OPERATING FLOOR
CDC RF1	6"	COAL DUST COLL No. 4 TO BUNKER	10,000	300	COAL DUST MATERIAL ROOF
COM-RF1	6"	CLASSIFER OVERSIZED MATERIAL	10,000	2,000	BASEMENT

NOTES:

1. FOR LEGEND ABBREVIATION AND GENERAL NOTES SEE DWG. № 400
2. ALL TRANSPORT AIR QUANTITIES ARE APPROXIMATE. EXACT AIR QUANTITIES TO BE DETERMINED BY EQUIP. MFR.

DRAWN BY: J.B.
DESIGNED BY: J.G./R.J.
CHKD. BY: R.J.
APPROVED BY: Jhn. 1/2/74
DATE: JAN. 2, 1974

OCR MULTICELL FLUIDIZED - BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM

MONONGAHELA POWER CO. RIVESVILLE, W. VA.

BED MATERIAL HANDLING AND STORAGE SYSTEMS
SCHEMATIC FLOW DIAGRAM
MECHANICAL

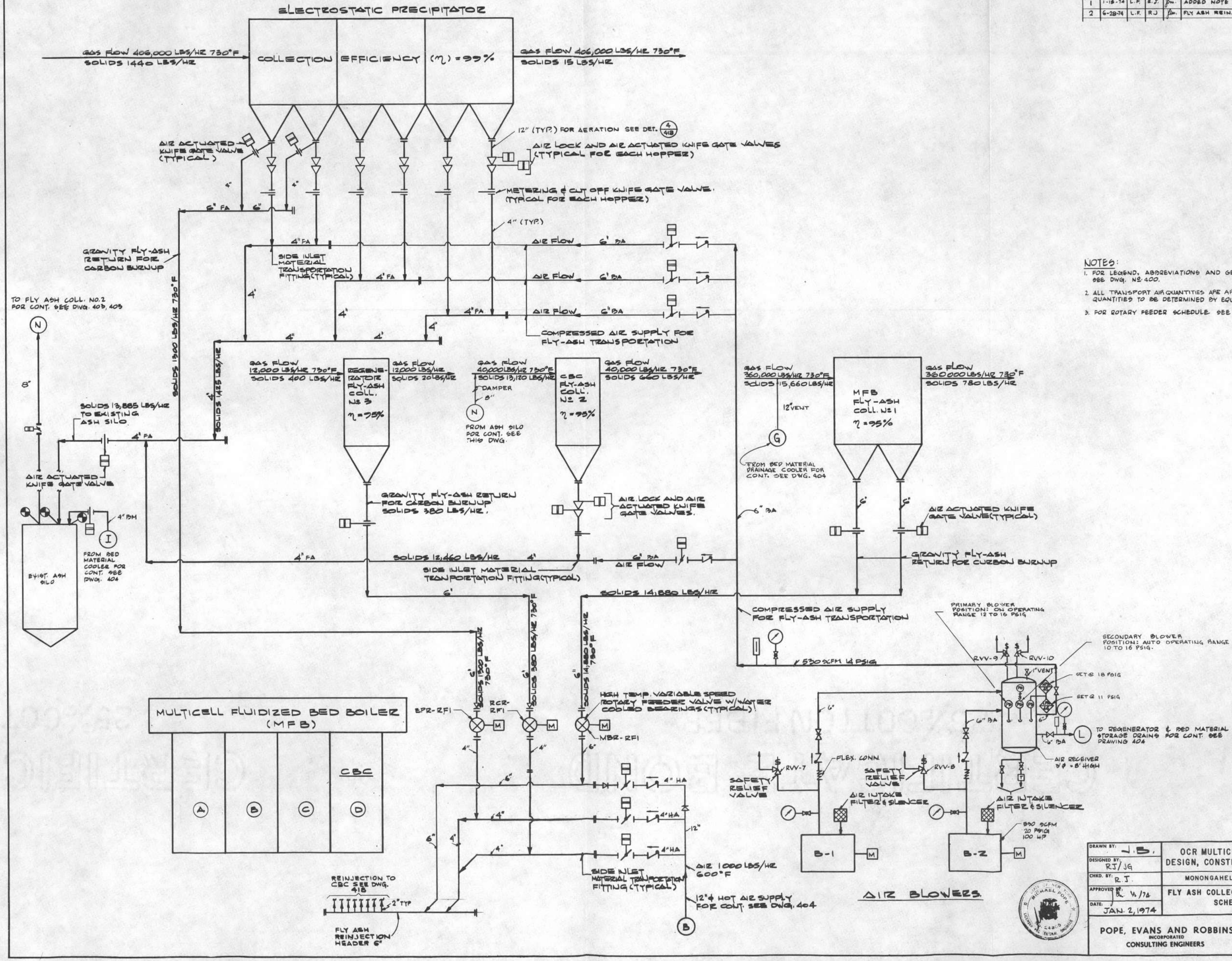
STATE OF NEW YORK · MICHAEL POPE · No. 24010 · LICENSED PROFESSIONAL ENGINEER

POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS

SCALE: NONE | PROJ. NO. 14-32-0001-1237

DWG. NO. 404

REV.	DATE	DRWN.	CHKD.	APPD.	REVISIONS DESCRIPTION
1	1-18-74	L.F.	R.J.	[illegible]	ADDED NOTE AMENDMENT No. 1: 1/18/74
2	6-28-74	L.F.	RJ	[illegible]	FLY ASH REINJECTION REVISED



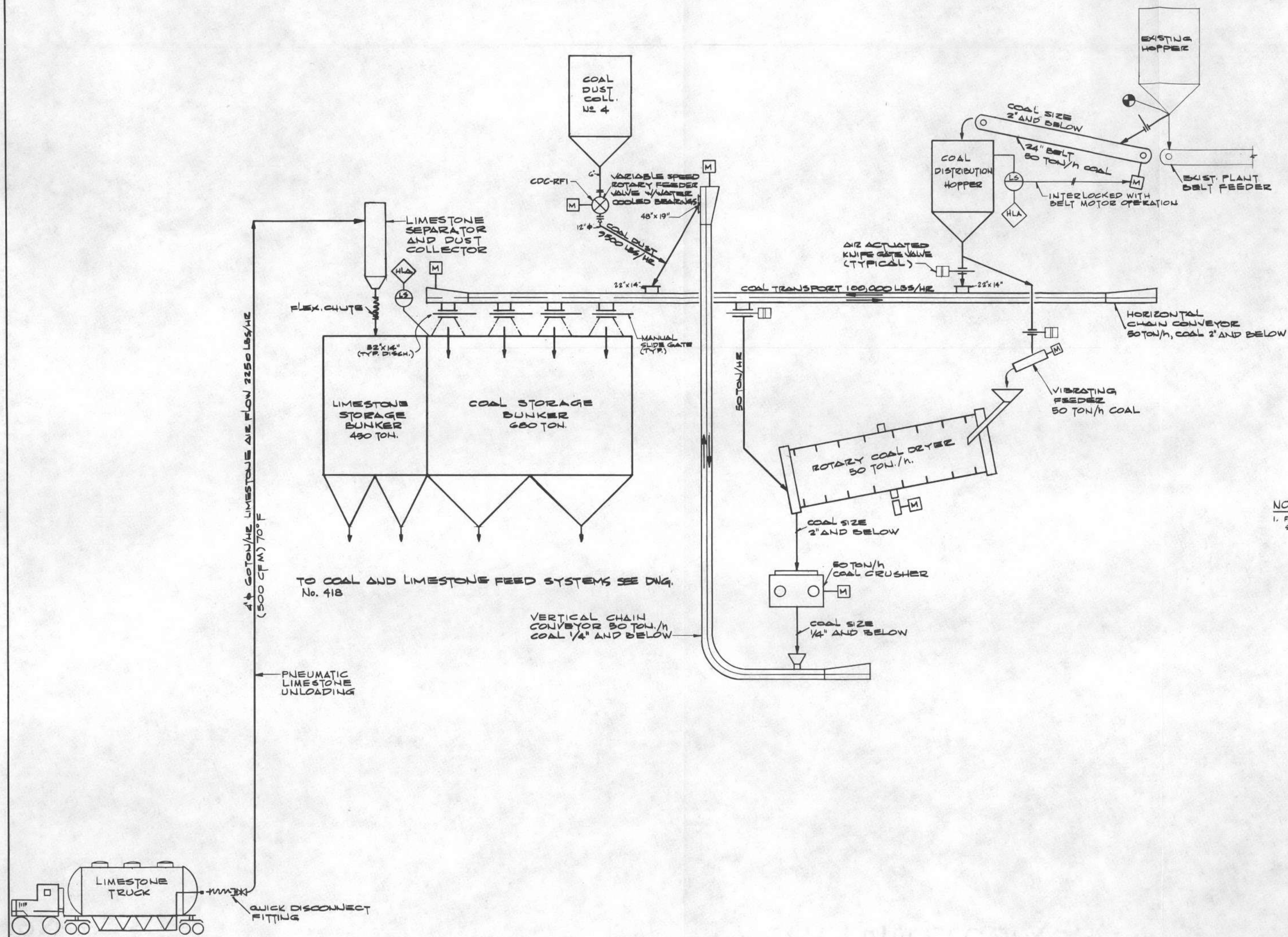
NOTES:

1. FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES SEE DWG. No. 400.
2. ALL TRANSPORT AIR QUANTITIES ARE APPROXIMATE. EXACT AIR QUANTITIES TO BE DETERMINED BY EQUIP. MFR.
3. FOR ROTARY FEEDER SCHEDULE SEE DWG. No. 404

DRAWN BY: J.B.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: RJ/JG	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
CHKD. BY: R.J.	FLY ASH COLLECTION AND REINJECTION SYSTEMS SCHEMATIC FLOW DIAGRAM MECHANICAL
APPROVED: [illegible] 4/76	SCALE: NONE / PROJ. NO. 14-32-0001-1237
DATE: JAN. 2, 1974	DWG. NO. 405

POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS

REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	JUNE-14-76	L.F	RT		REVISED NOTE



NOTE:

1. FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES SEE DWG. No. 400.

DRAWN BY: J.B.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: R.J./J.G.	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
CHKD. BY: R.J.	COAL AND LIMESTONE SUPPLY AND STORAGE SYSTEMS SCHEMATIC FLOW DIAGRAM MECHANICAL
APPROVED BY: 1/2/74	
DATE: JAN. 2, 1974	SCALE NONE · PROJ. No. 14-32-0001-1237
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	DWG. NO. 406

STATE OF NEW YORK · MICHAEL POPE · 24808 · LICENSED PROFESSIONAL ENGINEER

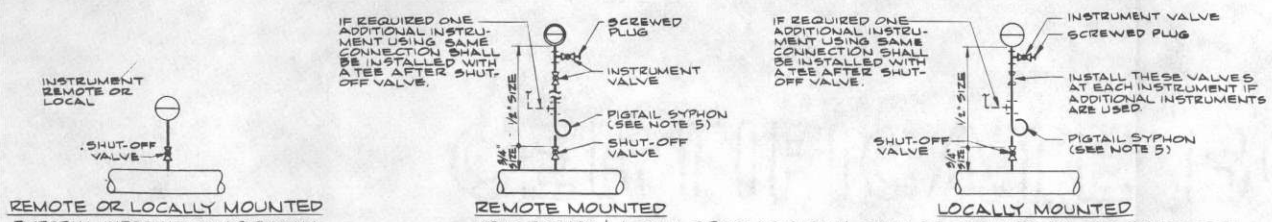
CONTROL VALVE SCHEDULE

VALVE No.	SIZE INCHES ⌀	DESCRIPTION	VALVE BODY: PRESS. CLASS LBS.	VALVE BODY: ENDS	SYSTEM	SERVICE: MAX. TEMP. °F	SERVICE: PRESSURE-PSIG INLET	SERVICE: PRESSURE-PSIG OUTLET	SERVICE: FLOW LBS/HR	CONTROL	REMARKS
HPSV-1	10	FLOW	1,500	BW	HPS	1,000	1,265	1,265	350,000	HPS TO PLANT	MOTOR-OPERATED GATE
HPSV-2	8	FLOW	1,500	BW	HPS	1,000	1,270	1,270	300,000	EXH. STM. TO ATM.	MOTOR-OPERATED GATE
HPSV-3	6	PRESSURE-FLOW	1,500	BW	HPS	1,000	1,270	30	300,000	EXH. STM. TO ATM.	DOUBLE SEATED
HPSV-4	10	FLOW	1,500	BW	HPS	1,000	1,270	1,265	350,000	HPS TO PLANT	SINGLE SEATED
HPSV-5	2	PRESSURE	1,500	SW	HPS	1,000	1,270	250	10,000	HPS TO MPS	SINGLE SEATED
MPSV-1	2	FLOW	300	SW	MPS	700 / 1,000	250	245	3,000	MPS TO EJECTOR	SINGLE SEATED
BFWV-9	2	PRESSURE	1,500	SW	BFW	500				BFW FROM BOILER CIRC. PUMP SEAL WATER SYSTEM.	
BFWV-1	6	FLOW	1,500	BW	BFW	500	(*) 1,850	1,850	350,000	BFW-TO BOILER	MOTOR-OPERATED GATE
BFWV-2	6	PRESSURE	1,500	BW	BFW	500	(*) 1,800	1,775	350,000	BFW-TO BOILER	DOUBLE SEATED
BFWV-3	4	TEMP.	1,500	BW	BFW	500	(*) 1,800	1,775	65,000	BFW-TO REGENERATOR	SINGLE SEATED
BFWV-4	6	FLOW	1,500	BW	BFW	500	(*) 1,775	1,765	350,000	BFW-TO BOILER	SINGLE SEATED **
BFWV-5	3	PRESSURE	1,500	BW	BFW	500	(*) 1,800	1,775	60,000	BFW-TO BOILER DESUPERHEATER	DOUBLE SEATED
BFWV-6			1,500	SW	BFW	500	(*) 1,775	1,765	60,000	BFW-TO BOILER DESUPERHEATER	SINGLE SEATED **
BFWV-7	1	TEMP.	1,500	SW	BFW	500	(*) 1,800	350	1,000	BFW-TO MPS DESUPERHEATER	SINGLE SEATED
BFWV-8	6	FLOW	1,500	BW	BFW	500	(*) 1,775	1,775	350,000	BFW-TO BOILER	MOTOR OPERATED GATE
CWV-2	4	TEMP.	150	FLANGED	CW	150	80	70	200,000	BED MATERIAL COOLER WATER DISCH. TEMP.	SINGLE SEATED
CWV-1	3	PRESSURE	300	BW	CW	150	100	75	12,500	CW-TO AIR PRE-HEATER WASH	SINGLE SEATED

(*) NORMAL OPERATING PRESSURE INDICATED, MAXIMUM PRESSURE = 2,400 PSIG

SAFETY RELIEF VALVE SCHEDULE

VALVE No.	SIZE (APPROX.)	DESCRIPTION	VALVE BODY: PRESS. CLASS LBS.	VALVE BODY: ENDS	SYSTEM	SERVICE: MAX. TEMP. °F	SERVICE: OPERATING PRESSURE PSIG	SERVICE: SET PRESS. PSIG	SERVICE: MAX. OVER-PRESS. %	SERVICE: CAPACITY AT OVER-PRESSURE LBS/HR.	REMARKS
RVV-1	3" x 6"	PRESSURE STM.	2,500 / 300	BW / FLG'D.	BOILER DRUM	625	1,405 PEAK 1,460	1,600	3	180,000	1,700 PSIG MAX. (FURNISHED AND INSTALLED BY OTHERS)
RVV-2	3" x 6"	PRESSURE STM.	2,500 / 300	BW / FLG'D.	BOILER DRUM	625	1,405 PEAK 1,460	1,550	3	120,000	1,700 PSIG MAX. (FURNISHED AND INSTALLED BY OTHERS)
RVV-3	2" x 3"	PRESSURE STM.	2,500 / 300	BW / FLG'D.	FINAL SUPER HTR. DISCHARGE	1,000	1,270	1,400	3	60,000	1,700 PSIG MAX. (FURNISHED AND INSTALLED BY OTHERS)
RVV-4	2" x 3"	PRESSURE STM.	2,500 / 300	BW / FLG'D.	REGENERATOR BFW	650	1,840	2,000	3	70,000	1,700 PSIG MAXIMUM
RVV-5	2" x 3"	PRESSURE STM.	600 / 150	FLANGED	MPS	950	250	275	10	10,000	1,700 PSIG MAXIMUM
RVV-6	3" x 4"	PRESSURE WATER	150 / 150	FLANGED	CW	150	75	90	10	250 GPM	1,700 PSIG MAXIMUM
RVV-7	2" x 3"	PRESSURE AIR	150 / 150	FLANGED	BA	300	20	25	10	600 SCFM	1,700 PSIG MAXIMUM
RVV-8	2" x 3"	PRESSURE AIR	150 / 150	FLANGED	BA	300	20	25	10	600 SCFM	1,700 PSIG MAXIMUM
RVV-9	2" x 3"	PRESSURE AIR	150 / 150	FLANGED	BA	300	20	25	10	600 SCFM	1,700 PSIG MAXIMUM
RVV-10	2" x 3"	PRESSURE AIR	150 / 150	FLANGED	BA	300	20	25	10	600 SCFM	1,700 PSIG MAXIMUM

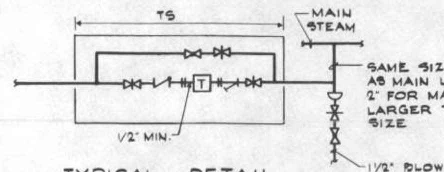


REMOTE OR LOCALLY MOUNTED
PICTORIAL INFORMATION AS SHOWN ON THE FLOW DIAGRAMS AND PIPING DWG'S. FOR TRUE PICTURE SEE OTHER PARTS OF DETAIL 7/413

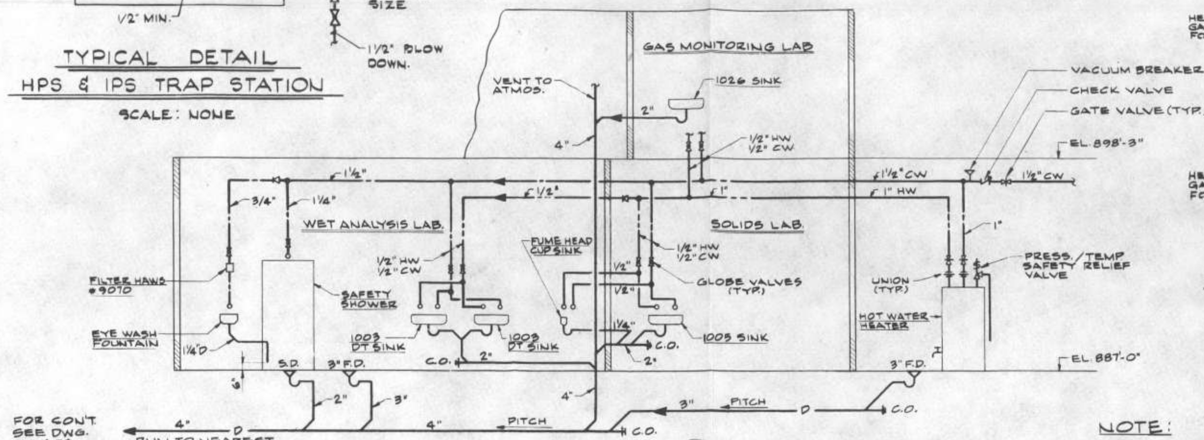
REMOTE MOUNTED — LOCALLY MOUNTED
TRUE PICTURE & ACTUAL PIPING AS SHOWN SHALL BE FURNISHED BY THIS CONTRACTOR

DETAIL 7/413

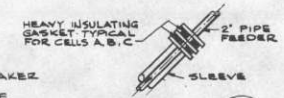
INSTRUMENT VALVING METHODS (PRESSURE 101 PSIG AND ABOVE AND TEMPERATURE 200°F AND ABOVE)
SCALE: NONE



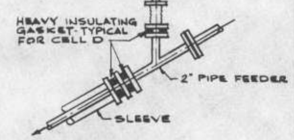
TYPICAL DETAIL
HPS & IPS TRAP STATION
SCALE: NONE



DETAIL 1/201
LABORATORY PLUMBING RISER DIAGRAM
SCALE: NONE

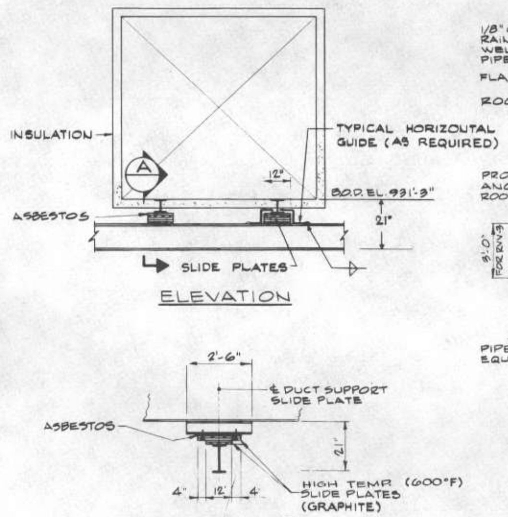


DETAIL 7/413
SCALE: NONE

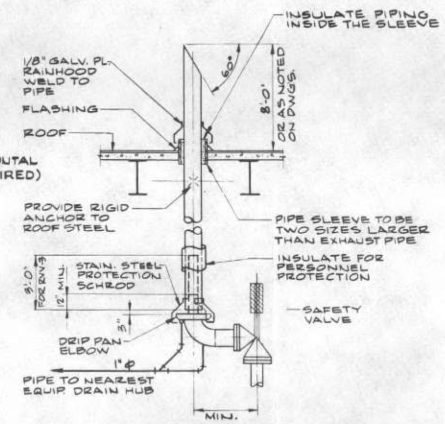


DETAIL 8/413
SCALE: NONE

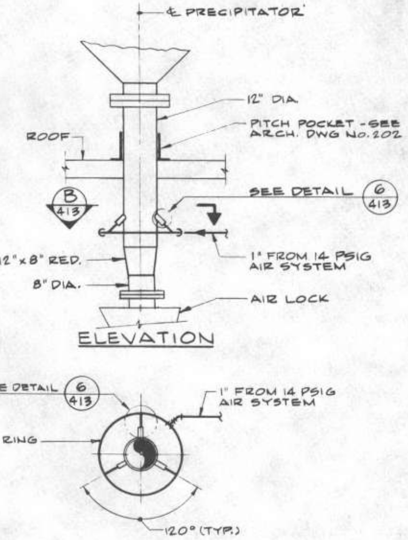
NOTE:
FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES - SEE DWG. No. 400



DETAIL 2/413
TYP. HORIZ. DUCT SLIDE SUPP'T.
SCALE: NONE

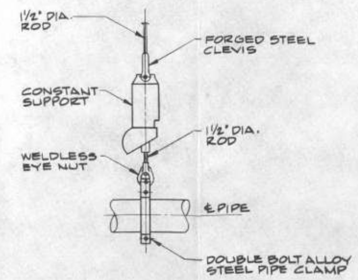


DETAIL 3/413
TYP. SAFETY VALVE PIPING THRU ROOF
SCALE: NONE

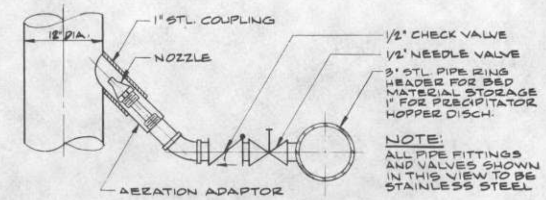


DETAIL 4/413
TYP. AIR RING AERATION ASSEMBLY
SCALE: NONE

NOTES: (FOR INSTRUMENT VALVING METHODS)
1. STATIC PRESSURE TRANSMITTERS AND CONTROLLERS SHOULD BE VALVED AS IF THEY WERE REMOTE MOUNTED PRESSURE GAUGES.
2. PRESSURE SWITCHES SHOULD BE VALVED AS IF THEY WERE LOCALLY MOUNTED PRESSURE GAUGES.
3. CONNECTIONS ON FLOW DIAGRAMS LABELED (TP) SHOULD BE TREATED AS LOCALLY MOUNTED PRESSURE GAUGES BUT WITHOUT TEST TEES OR PIGTAILS.
4. NO MORE THAN ONE ADDITIONAL INSTRUMENT SHALL BE ADDED TO PRIMARY CONNECTIONS.
5. REQUIRED FOR SYSTEMS WITH OPERATING TEMPERATURE ABOVE 200° F.
6. ASTERISKS(**) DENOTES FURNISHED BY OTHERS FOR INSTALLATION BY THIS SUB-CONTRACTOR.



DETAIL 5/413
PIPE SUPPORT (PS-1 THRU PS-23)
SCALE: NONE

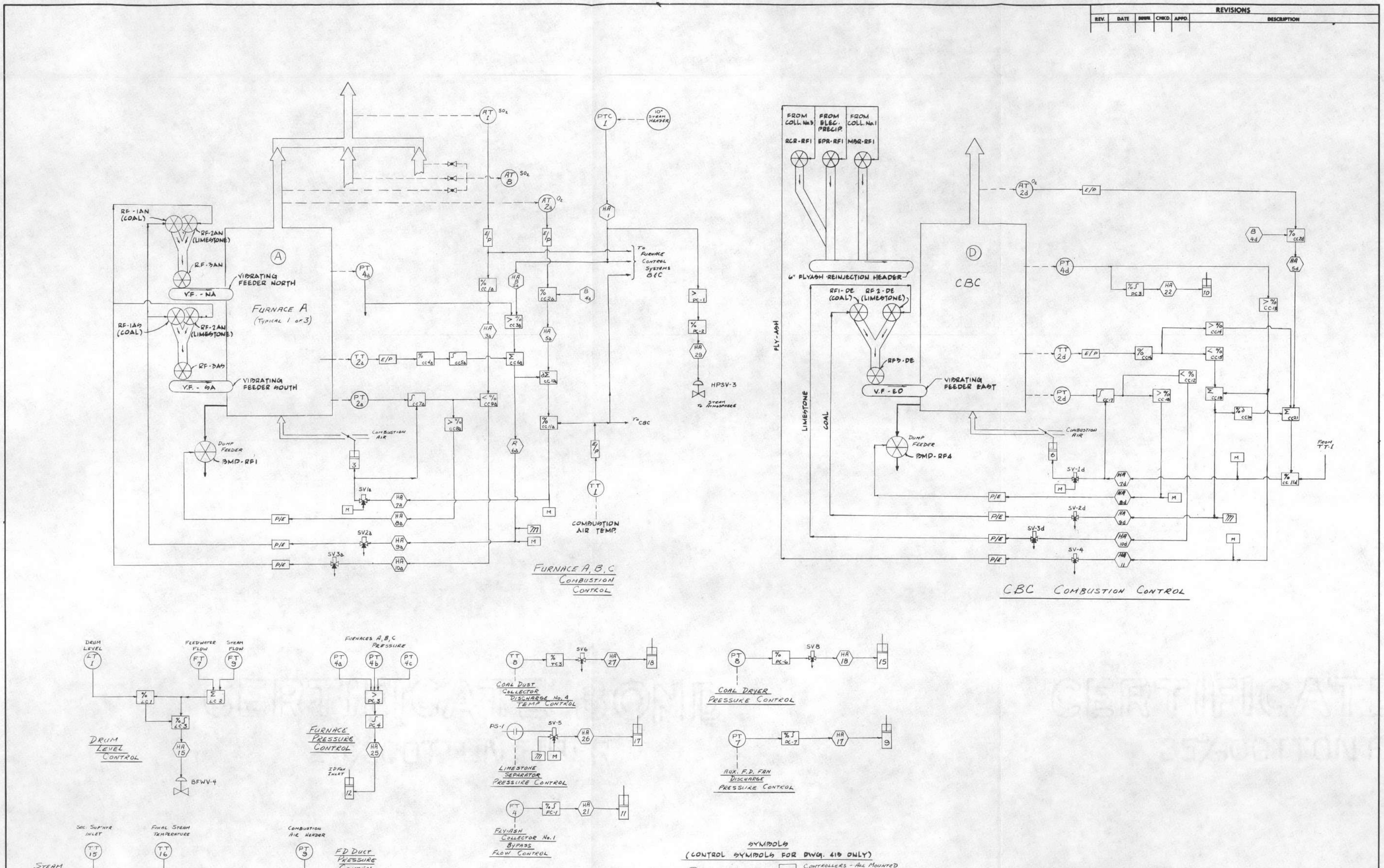


DETAIL 6/413
SCALE: NONE

REVISIONS

REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	1-18-74	RAS	RJ	Jm.	REVISED DETAIL 2/413 ADDED CWV-2 DATA. TRAP STATION DET. SHOWN. AMENDMENT No. 1 : 1/18/74
2	2-1-74	L.F.	KM.	Jm	REVISED CONTROL AND RELIEF VALVE SCHEDULES AMENDMENT No. 2 : 2/1/74
3	6-28-74	J.G.	RJ.	Jm.	ADDED DETAIL 7, 8 & REVISED CONTROL VALVE SCHEDULE

DRAWN BY: B.S.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: J.G.	
CHKD. BY: R.J.	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: 1/2/74	SCHEDULES, MISC. SECTIONS AND DETAILS
DATE: JAN. 2, 1974	MECHANICAL
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: AS NOTED — PROJ. NO. 14-32-0001-1237 — DWG. NO. 413



DRAWN BY:
DESIGNED BY: GC/RJ
CHKD. BY: KM/RJ
APPROVED BY: 6/16/74
DATE: JUNE 14, 1974

OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM

MONONGAHELA POWER CO. RIVESVILLE, W. VA.

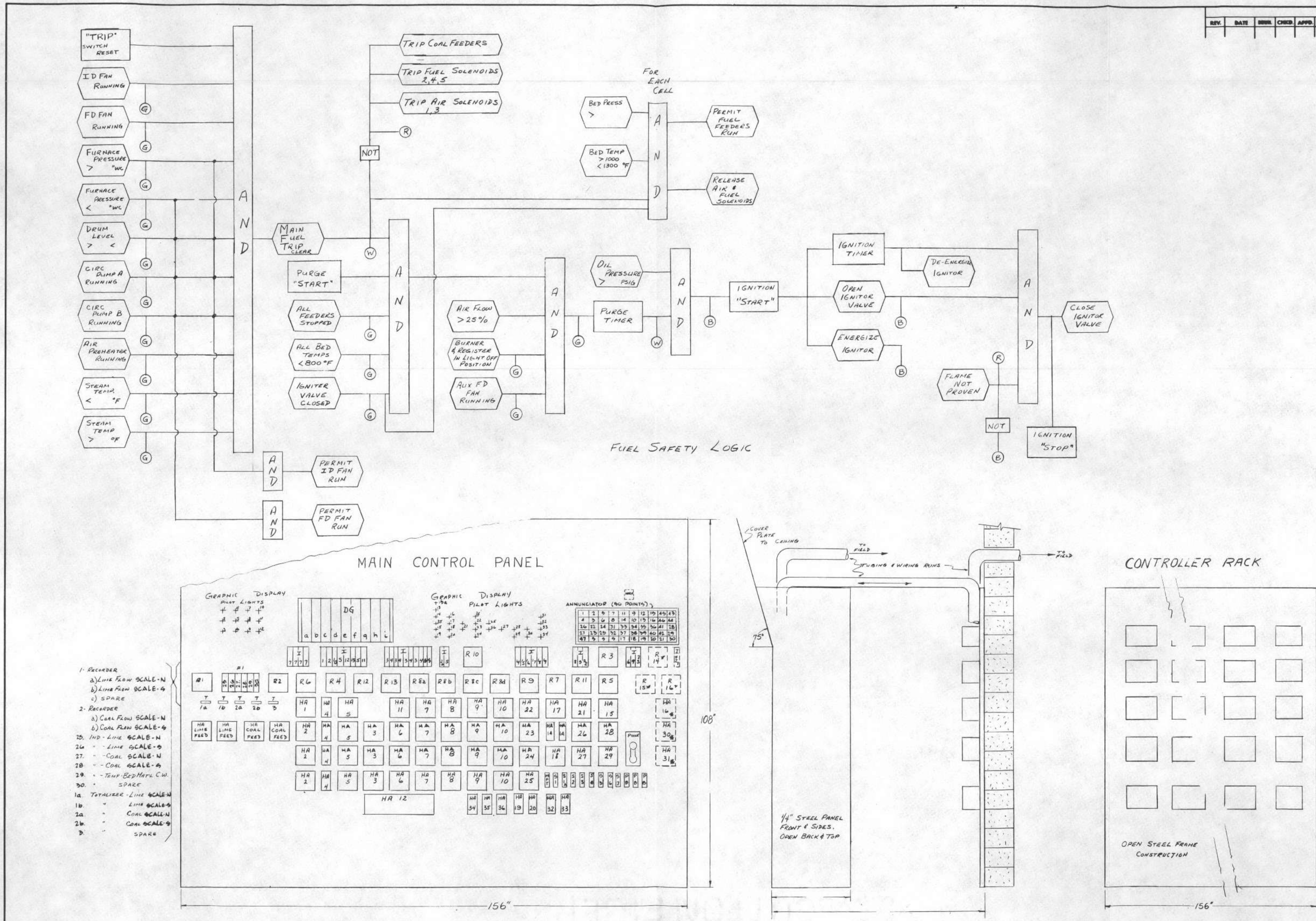
COMBUSTION CONTROL AND MISCELLANEOUS CONTROL SYSTEMS SCHEMATIC CONTROL DIAGRAM MECHANICAL

POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS

SCALE: NONE PROJ. No. 14-32-0001-1237

DWG. NO. 415

REVISIONS					
REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION



* NOT IN CONTRACT PROVIDE OPENING FOR FUTURE

FOR INSTRUMENT NAMEPLATES & IDENTIFICATION, SEE DWG No. 417

DRAWN BY: [signature]	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: GC/KH.	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
CHKD. BY: KH/RS	CONTROL PANEL & FUEL SAFETY LOGIC
APPROVED: [signature] 6/14/74	MECHANICAL
DATE: JUNE 14, 1974	SCALE NONE · PROJ. No. 14-32-0001-1237
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	DWG. NO. 416

REV.	DATE	DRWN	CHKD.	APPD.	DESCRIPTION

REVISIONS

AT — FIELD MOUNTED ANALYZER-TRANSMITTERS

ITEM	QUAN	SERVICE	LOCATION	RANGE	SIGNAL TO:
AT-1	1	SO_2	MAIN FURN UPTAKE		R-12, CC
AT-2	4	O_2	FURNACE OUT		R-13, CC
AT-3	1	SO_2	ANY FURN. (A,B,C)		R-12
AT-4	1	SO_2	I D FAN DISCH		R-11
AT-5	1	NO_x	ditto		R-11
AT-6	1	CO_2	ditto		R-11
* AT-7	1	O_2	REGEN UPTAKE		R-16
ST-1	1	SMOKE	I D FAN SUCTION		I-20

TT — FIELD MOUNTED TEMPERATURE TRANSMITTERS

ITEM	QUAN	FUNCTION	RANGE	SIGNAL TO:
TT-1	1	AIR HEATER, AIR OUT		R-10, I-2, CC
TT-2	4	FURNACE BED		R-8, I-4, CC
TT-3				
TT-4	1	GAS, MAIN FURNACE UPTAKE		R-10, I-14
TT-5	1	GAS, CBC UPTAKE		R-10, I-15
TT-6	1	AIR, FD FAN DISCHARGE		R-7
TT-7	1	GAS, I D FAN INLET		R-7, I-10
TT-8	1	GAS AT COAL DUST COLLECTOR		TC-3, I-16
* TT-9	1	REGEN GAS IN		R-H
* TT-10	1	BOILER FEEDWATER		R-3
* TT-11	1	REGENERATOR		R-H
* TT-12	1	REGENERATOR, WATER OUT		R-H
TT-13	1	STEAM, SATURATED		R-4
TT-14	1	STEAM, PRI. SUPERHEATER		R-4
TT-15	1	STEAM, DESUPERHEATED		I 22, TC
TT-16	1	STEAM, FINAL		R4, TC-2
TT-17	1	WATER, ECONOMIZER OUT		R3

DG — PANEL MOUNTED DRAFT GAUGES

ITEM	FUNCTION	RANGE
DG 1a	F.D. FAN DISCH. - AIR	0 TO 100" WC
DG 1b	FURNACE & CBC INLET - AIR	0 TO 100" WC
DG 1c	MAIN FURNACE UPTAKE - GAS	+10" TO -10" WC
DG 1d	CBC UPTAKE - GAS	+10" TO -10" WC
DG 1e	PRECIP. INLET - GAS	0 TO -20" WC
DG 1f	AIRHEATER OUTLET - GAS	0 TO -20" WC
DG 1g	ID FAN INLET - GAS	(-5 TO -5" WC)
DG 1h	STACK	
DG 1i	SPARE	

FT — FIELD MOUNTED FLOW TRANSMITTERS

ITEM	FUNCTION	RANGE	SIGNAL TO:
FT-1	MAIN COMBUSTION AIR		I-12, R-9
* FT-2	REGENERATOR AIR		R-15
FT-3	AIR TO COAL DRYER		I-18, R-9
FT-4	FLYASH COLLECTOR BY PASS		I-5, FC-1
FT-5	FROM FLYASH COLLECTOR-1		I-19
FT-6	CBC COMBUSTION AIR		I-7
FT-7	FEEDWATER TO BOILER		R-5, I-6, LC
* FT-8	FEEDWATER TO REGENERATOR		R-15
FT-9	TOTAL STEAM		R-6, LC
FT-10	STEAM TO MONONGAHELA		R-6
FT-11	LIME SCALE NORTH		
FT-12	LIME SCALE SOUTH		
FT-13	COAL SCALE NORTH		
FT-14	COAL SCALE SOUTH		

PT — FIELD MOUNTED PRESSURE TRANSMITTERS

ITEM	QUAN	FUNCTION	RANGE	SIGNAL TO:
PTC-1	1	MASTER CONTROLLER		CC
PT-1	1	MAIN STEAM		R-6
PT-2	4	FURNACE BED		R-8, I-3, CC
PT-3				
PT-4	4	FURNACE DRAFT		I-7, CC, PC-3, 4
PT-5				
PT-6	1	AIR HEATER OUT		R-7, I-1
PT-7	1	AUX FD FAN DISCH		I 11, PC-7
PT-8	1	COAL DRYER		I 17, PC-6
PT-9	1	COMBUSTION AIR		I 13, PC-5
PT-10	1	BOILER DRUM		R-5
PT-11	1	BOILER FEEDWATER		R-3

LT — FIELD MOUNTED LEVEL TRANSMITTERS

ITEM	QUAN	FUNCTION	RANGE	SIGNAL TO
LIT-1	1	BOILER DRUM LEVEL		R-5, I-9, LC
LS-1	1	BOILER DRUM LEVEL		I-23

R — PANEL MOUNTED STRIP CHART RECORDERS

ITEM	QUAN	NO. PENS	SERVICE	SIGNAL FROM
1	1	3	LIME SCALES-FLOW	
2	1	3	COAL SCALES-FLOW	
3	1	3	FEEDWATER	FT7, TT-10, 17
4	1	3	STEAM	TT-13, 14, 16
5	1	3	DRUM	LIT, PT-10, FT7
6	1	3	STEAM	PT1, FT9, 10
7	1	3	FD FAN	PT6, TT6, 7
8	4	3	FURNACE A,B,C,D	TT2, PT2, 4
9	1	3	AIR FLOWS	FT 1, 3, 6
10	1	3	FLUE GAS TEMP	TT 1, 4, 5
11	1	3	FLUE GAS ANALYSIS	AT 4, 5, 6
12	1	2	FURNACE SO_2	AT 1, 3
13	1	4	FURNACE O_2	AT 2
* 14	1	3	REGEN TEMPS	TT 9, 11, 12
* 15	1	2	REGEN FLOWS	FT 2, 8
* 16	1	1	REGEN O_2	AT-7

I — PANEL MOUNTED INDICATORS

ITEM	QUAN	SERVICE	SCALE	SIGNAL FROM:
PI-1	1	PRESS. AIR HTR OUT		PT-6
TI-2	1	TEMP AIR HTR OUT		TT-1
PI-3	4	FURNACE BED PRESS.		PT2
TI-4	4	FURNACE TEMP.		TT2
FI-5	1	FLOW, FLASH COLLECT. BYPASS		FT-4
FI-6	1	FEEDWATER FLOW		FT-7
PI-7	4	FURNACE DRAFT		PT-4
XI-8	1	HPSV-4 VALVE POS'N		
LI-9, 25	2	DRUM LEVEL		LIT-1, LS-1
TI-10	1	TEMP, IDFAN IN		TT-7
PI-11	1	AUX FD DISCH PRESS		PT-7
FI-12	1	COMB. AIR FLOW		FT-1
PI-13	1	COMB AIR PRESS		PT-9
TI-14	1	MAIN GAS TEMP		TT-4
TI-15	1	CBC GAS TEMP		TT-5
TI-16	1	COAL DUST COLL TEMP		TT-8
PI-17	1	COAL DRYER PRESS		PT-8
FI-18	1	COAL DRYER AIR FLOW		FT-3
FI-19	1	FLASH COLL. FLOW		FT-5
I-20	1	SMOKE		ST-1
* TI-21	1	REGEN GAS TEMP		TT-9
TI-22	1	DESUPHTD STEAM TEMP		TT-15
23	1	"		LS-1
24	1	"		

* NOT IN CONTRACT

HA — PANEL MOUNTED CONTROL STATIONS

ITEM	QUAN	FUNCTION	SERVICE	ASSOC VALVE OR DAMPER ACTUATOR
1	1	HA	PLANT MASTER	
2	3	HAB	FURNACE A,B,C MASTER	
3	3	HA	A,B,C SO_2	
4	4	B	FURNACE O_2 BIAS	
5	4	HA	FURNACE O_2	
6	3	R	A,B,C AIR/FUEL RATIO	
7	4	HA	COMBUSTION AIR	DAMPERS 3, 4, 5, 6
8	4	HA	DUMP FEEDERS	
9	4	HA	COAL FEEDERS	
10	4	HA	LIMESTONE FEEDERS	
11	1	HA	CBC FLYASH FEEDER	
12	1	PB/HA	BURNER STARTPANEL	
13				
14	2	H	CBC START UP AIR	DAMPER 7 & 8
15	1	HA	FEEDWATER	BFWV-4
* 16	1	HA	REGEN FEEDWATER	BFWV-3
17	1	HA	AUX FD FAN	DAMPER 9
18	1	HA	COAL DRYER	DAMPER 15
19	1	H	AIR TO AIR SLIDE	DAMPER 13
20	1	H	AIR TO BED MATL HNDLNG	DAMPER 14
21	1	HA	GAS FLOW CONTROL	DAMPER 11
22	1	HA	CBC DRAFT CONTROL	DAMPER 10
23	1	HAB	FD FAN CONTROL (IN)	DAMPER 1
24	1	HAB	FD FAN CONTROL (OUT)	DAMPER 2
25	1	HA	I D FAN CONTROL	DAMPER 12
26	1	HA	LIMESTONE SEPARATOR	DAMPER 17
27	1	HA	COAL DUST COLL.	DAMPER 18
28	1	HA	STEAM TEMP CONTROL	BFWV-6
29	1	HA	STEAM BLOW-OFF	HPSV-3
* 30	1	HA	REGEN AIR FLOW	DAMPER
* 31	1	HA	REGEN START UP	DAMPER
32	1	HA	ECONOMIZER CIRC	CV-6
33	1	H	BOILER BLOW-DOWN	CV-7
34	1	H	BEDTRANSFER GATE	
35	1	H	" " "	
36	1	H	" "	

S/PB — PANEL MOUNTED SELECTOR SWITCH, PUSHBUTTON STATIONS

ITEM	QUAN	FUNCTION	
MFT	1	MAIN FUEL TRIP	TRIP / RESET
S-1, 1a, 2	3	FD FAN, AUX F.D. FAN, I.D. FAN	ON / OFF
S-3	1	VALVE HPSV-1	OPEN / CLOSE / STOP
S-4	1	VALVE BFWV-1	OPEN / CLOSE / STOP
PB	1	ANNUNCIATOR	TEST / ACK. / RESET
PB	2	PURGE, IGNITION	START / STOP
S-5	1	RECIRC. PUMP No. 1	
S-6	1	RECIRC. PUMP No. 2	
S-7	1	F.D. PUMP No. 1	
S-8	1	VALVE BFWV-8	
S-9	1	VALVE BDV-1	
S-10	1	VALVE BDV-2	

⌧ — PANEL MOUNTED PILOT LIGHTS

ITEM	NAMEPLATE	COLOR	CONTACT DEVICE
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13	I.D. FAN RUNNING	G	MCC
13a	AUX FD FAN RUNNING	G	MCC
14	FD FAN RUNNING	G	MCC
15	FURNACE DRAFT OK	G	
16	DRUM LEVEL OK	G	
17	CIRC PUMP A RUNNING	G	MCC
18	CIRC PUMP B RUNNING	G	MCC
19	AIR PREHTR RUNNING	G	MCC
20	FINAL STEAM TEMP	G	
21	MAIN FUEL TRIP	R/W	MFT
22	ALL FEEDERS STOP	G	MCC
23	BED TEMP < 800	G	
24	LIGHT OFF POSITION	G	ZS
25	PURGE START	G	LOGIC
26	PURGE COMPLETE	W	LOGIC
27	OK TO START	B	LOGIC
28	OIL VALVE OPEN	B	ZS
29	IGNITION ON	B	ZS
30	FLAME OK	B/R	FS
31-4	(4) OK START FEEDERS	W	LOGIC

ANNUNCIATORS

POINT	LEGEND	CONTACT
1.	COAL HANDLING SYSTEM-NORTH EMERGENCY SHUT DOWN	
2.	COAL BIN-NORTH-HIGH LEVEL AND SYSTEM SHUT DOWN	
3.	COAL BIN-NORTH-LOW LEVEL	
4.	COAL HANDLING SYSTEM-SOUTH EMERGENCY SHUT DOWN	
5.	COAL BIN-SOUTH-HIGH LEVEL AND SYSTEM SHUT DOWN	
6.	COAL BIN-SOUTH-LOW LEVEL	
7.*	COAL BIN-EAST-HIGH LEVEL	
8.	COAL BIN-EAST-LOW LEVEL	
9.*	LIMESTONE BIN-NORTH HIGH LEVEL	
10.	LIMESTONE BIN-NORTH LOW LEVEL	
11.	LIMESTONE HANDLING SYSTEM NORTH-EMERGENCY SHUT DOWN	
12.*	LIMESTONE BIN-SOUTH HIGH LEVEL	
13.	LIMESTONE BIN-SOUTH LOW LEVEL	
14.	LIMESTONE HANDLING SYSTEM SOUTH-EMERGENCY SHUT DOWN	
15.*	LIMESTONE BIN-EAST HIGH LEVEL	
16.	LIMESTONE BIN-EAST LOW LEVEL	
17.	AUX. F.D. FAN-POWER LOSS	
18.*	SOLENOID VALVE (CV-4)-OPEN	
19.	AUX. AIR-LOW PRESSURE	
20.	BURNER OIL PRESSURE-HIGH	
21.	BURNER OIL PRESSURE-LOW	
22.	BFW PRESS HIGH	R3
23.	BFW PRESS LOW	R3
24.	STEAM TEMP HIGH	R4
25.	STEAM TEMP LOW	R4
26.	DRUM LEVEL HIGH	LIT-1
27.	DRUM LEVEL LOW	LIT-1
28.	DRUM LEVEL HIGH HIGH	
29.	DRUM LEVEL LOW LOW	
30.	SMOKE	I20
31.	FD PRESS HIGH	R7
32.	FD PRESS LO	R7
33.	FURN DRAFT HIGH	I7A
34.	FURN DRAFT HIGH	I7B
35.	FURN DRAFT HIGH	I7C
*	INDICATION ONLY, NO SOUND	

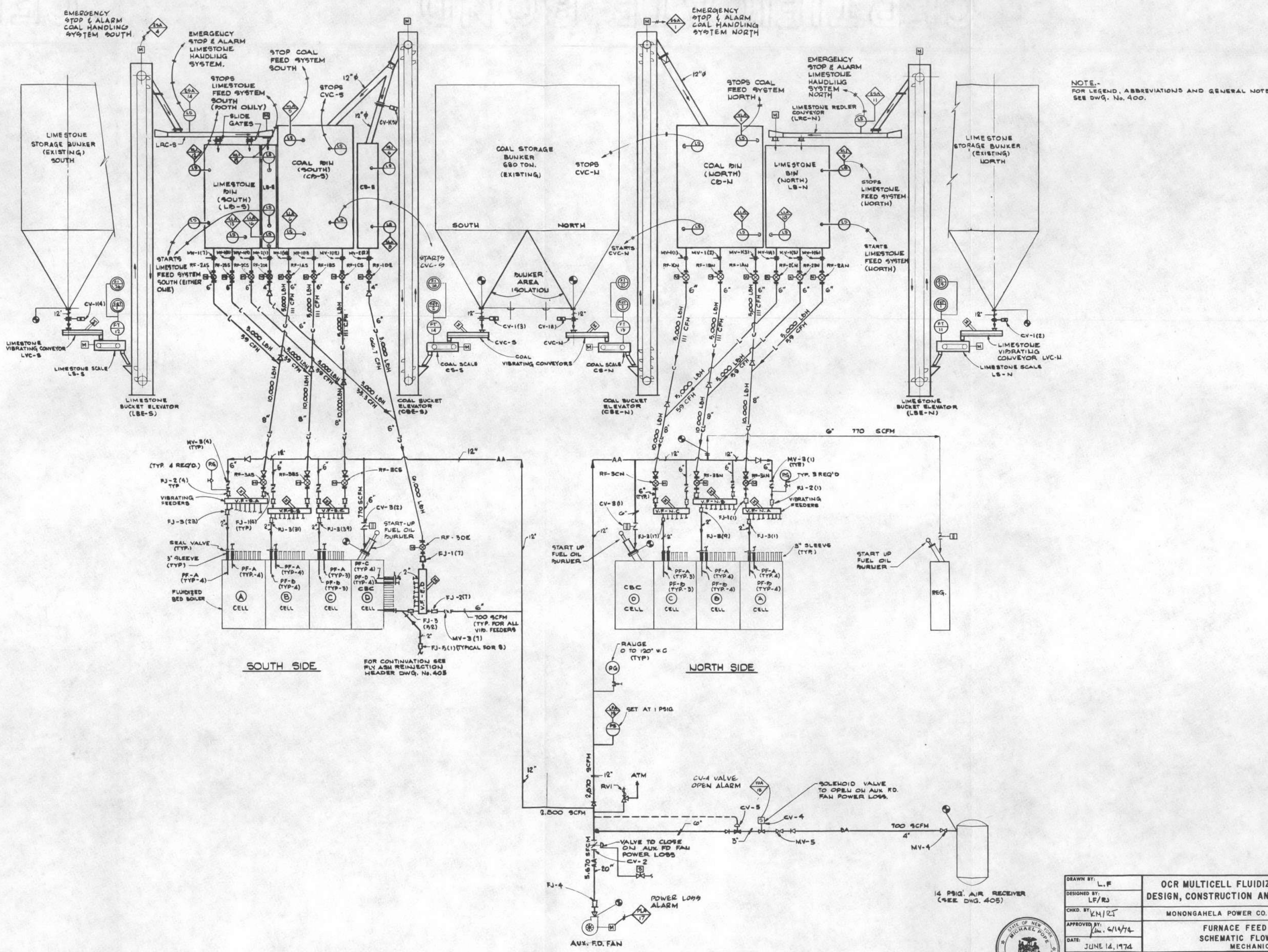
POINT	LEGEND	CONTACT
36.	FURN DRAFT HIGH	I7D
37.	FURN TEMP HIGH	R8A
38.	FURN TEMP HIGH	R8B
39.	FURN TEMP HIGH	R8C
40.	FURN TEMP HIGH	R8D
41.	DRUM PRESS HIGH	R-5
42.	DRUM PRESS LOW	R-5
43.*	REG. TEMP HIGH	
44.*	REG. TEMP LOW	
45.	AIR RECEIVER HIGH PRESS (14#)	
46.	AIR RECEIVER LOW PRESS (14#)	
47.	COMB. AIR-FLOW-LOW	
*	INDICATION ONLY, NO SOUND	

DRAWN BY: GC.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: GC/KM.	
CHKD. BY: KM/RJ	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: [signature] 6/14/74	INSTRUMENTATION SCHEDULE
DATE: JUNE 14, 1974	MECHANICAL
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE — PROJ. No. 14-32-0001-1237
	DWG. NO. 417

REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION

REVISIONS

NOTE.- FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES SEE DWG. No. 400.



DRAWN BY: L.F	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: LF/RJ	
CHKD. BY: KM/RT	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: 6/14/74	FURNACE FEED SYSTEMS SCHEMATIC FLOW DIAGRAM MECHANICAL
DATE: JUNE 14, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE PROJ. No. 14-32-0001-1237
	DWG. NO. 418

REVISIONS					
REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION

ROTARY FEEDER'S SCHEDULE

ROTARY FEEDER No	APPROX. SIZE (NOTE "E")	AREA SERVED	MATERIAL FEED	MATERIAL DENSITY (MIN) LBS/FT³	CAPACITY MATERIAL LBS/HR MIN.	MAX.	DESIGN	MAX. TEMP °F	MOTOR HP (MIN)	MANUFACTURER'S MODEL No	REMARKS
RF-1AN	6"	CELL-A NORTH	COAL	45	500	5,000	6,000	200	1/2	THE ALLEN SHERMAN-HOFF CO. INC. TYPE "D"	VARIABLE SPEED *
RF-2AN	4"		LIMESTONE	85	125	5,000	6,000	↓	1/2		
RF-3AN	6"	↓	COAL & LIMESTONE	45-85	—	10,000	12,000		3/4		W/SEAL 3 PSIG CONST. SPEED
RF-1AS	6"	CELL-A SOUTH	COAL	45	500	5,000	6,000		1/2		VARIABLE SPEED *
RF-2AS	4"		LIMESTONE	85	125	5,000	6,000		1/2		
RF-3AS	6"	↓	COAL & LIMESTONE	45-85	—	10,000	12,000	↓	3/4		W/SEAL 3 PSIG CONST. SPEED
RF-1BN	6"	CELL-B NORTH	COAL	45	500	5,000	6,000	200	1/2		VARIABLE SPEED *
RF-2BN	4"		LIMESTONE	85	125	5,000	6,000		1/2		
RF-3BN	6"	↓	COAL & LIMESTONE	45-85	—	10,000	12,000		3/4		W/SEAL 3 PSIG CONST. SPEED
RF-1BS	6"	CELL-B SOUTH	COAL	45	500	5,000	6,000		1/2		VARIABLE SPEED *
RF-2BS	4"		LIMESTONE	85	125	5,000	6,000		1/2		
RF-3BS	6"	↓	COAL & LIMESTONE	45-85	—	10.000	12.000	↓	3/4		W/SEAL 3 PSIG CONST SPEED
RF-1CN	6"	CELL-C NORTH	COAL	45	500	5,000	6,000	200	1/2		VARIABLE SPEED *
RF-2CN	4"		LIMESTONE	85	125	5,000	6,000		1/2		
RF-3CN	6"	↓	COAL & LIMESTONE	45-85	—	10,000	12,000		3/4		W/SEAL 3 PSIG CONST. SPEED
RF-1CS	6"	CELL-C SOUTH	COAL	45	500	5,000	6,000		1/2		VARIABLE SPEED *
RF-2CS	4"		LIMESTONE	85	125	5,000	6,000		1/2		
RF-3CS	6"	↓	COAL & LIMESTONE	45-85	—	10,000	12,000	↓	3/4		W/SEAL 3 PSIG CONST. SPEED
RF-1DE	4"	CELL-D EAST (CBC)	COAL	45	0	3,000	3,600	200	1/2		VARIABLE SPEED *
RF-2DE	4"		LIMESTONE	85	0	3,000	3,600		1/2		
RF-3DE	6"	↓	COAL & LIMESTONE	45-85	—	6,000	7,200	↓	3/4	↓	W/SEAL 3 PSIG CONST SPEED

* SPEED VARIATION BY COMBUSTION CONTROL SYSTEM

VIBRATING-CONVEYORS, BUCKET-ELEVATORS, REDLERS & SCALES.

CONVEYOR No	SIZE (APPROX)	EQUIP. TYPE	AREA SERVED	MATERIAL FEED	MATERIAL DENSITY (MIN) #/FT.³	CAPACITY MATERIAL TON/H MIN.	MAX.	DESIGN	MAX. TEMP °F.	MOTOR HP (NOTE "C")	MANUFACTURER'S MODEL No	REMARKS
CVC-N	18"×16"×16'-6"	VIBRATING CONVEYOR	NORTH	COAL	45	1	10	12	200	5.0	REX-CARRIER DIVISION MODEL-IBLL 1,840 S, 7 GAGE	DUST TIGHT ENCLOSURE
CVC-S	18"×16"×16'-6"		SOUTH	"	45	1	10	12		5.0		
LVC-N	18"×16"×16'-6"		NORTH	LIMESTONE	85	1	10	12		5.0		
LVC-S	18"×16"×16'-6"		SOUTH	"	85	1	10	12	↓	5.0		
CBE-N	13"×36"×50'-6"	BUCKET ELEVATOR	NORTH	COAL	↓	—	10	14	200	3.0	STEPHENS-ADAMSON CC-085-8×5×7 3/4	CONTINUOUS CHAIN
CBE-S	13"×36"×50'-6"		SOUTH	"		—	10	14		3.0		
LBE-N	13"×36"×50'-0"		NORTH	LIMESTONE		—	10	14		3.0		
LBE-S	13"×36"×50'-0"		SOUTH	"	↓	—	10	14	↓	3.0		
LRC-N	8"×11"×47'-0"	REDLER	NORTH	LIMESTONE	↓	—	10	14	200	3.0	STEPHENS-ADAMSON HORIZONTAL-REDLER SIZE 7	CONTINUOUS CHAIN
LRC-S	8"×11"×47'-0"		SOUTH	"		—	10	14	↓	3.0		
CS-N	36"×24"×6'-0"	SCALE	NORTH	COAL	45	1	10	14	200	1/2	VIBRA-SCREW INC. VIBRAMETRIC-WEIGH BELT FEEDER	20" BELT
CS-S	" " "		SOUTH	"	45	1	10	14		1/2		
LS-N	" " "		NORTH	LIMESTONE	85	1	10	14		1/2		
LS-S	" " "		SOUTH	"	85	1	10	14	↓	1/2		

VIBRATING FEEDERS SCHEDULE

VIBRATING FEEDER No	SIZE (APPROX) W×L	AREA SERVED	MATERIAL FEED	MATERIAL DENSITY (MIN) LBS/FT³	MATERIAL CAPACITY LBS/H MIN.	MAX.	DESIGN	MAX. TEMP °F	MOTOR HP (MIN)	MANUFACTURER'S MODEL No	REMARKS
VF-NA	24"×12'-0"	CELL-A NORTH	COAL & LIMESTONE	45-85	1,000	10,000	12,000	200	1	REX NORD CARRIER MODEL-FD	SEE NOTE "A"
VF-NB	24"×11'-9"	CELL-B NORTH			1,000	10,000	12,000		1		
VF-NC	18"×9'-9"	CELL-C NORTH			1,000	10,000	12,000		1		SEE NOTE "B"
VF-SA	24"×12'-0"	CELL-A SOUTH			1,000	10,000	12,000		1		SEE NOTE "A"
VF-SB	24"×12'-0"	CELL-B SOUTH			1,000	10,000	12,000		1		
VF-SC	18"×8'-10"	CELL-C SOUTH			1,000	10,000	12,000		1		SEE NOTE "B"
VF-ED	24"×11'-6"	CELL-D EAST	↓	↓	600	6,000	7,200	↓	1	↓	SEE NOTE "A"

CONTROL, MANUAL & RELIEF VALVES-SCHEDULE

VALVE No	SIZE	QTY.	DESCRIPTION	VALVE BODY DESIGN & CLASS LBS.	VALVE BODY ENDS	SYSTEM	SERVICE MAX. TEMP. °F	SERVICE OPERATING PRESS PSIG.	SERVICE FLOW	REMARKS
CV-1	12"	5	KNIFE GATE CI BODY/SS BLADE	125	FLANGED	COAL OR LIMESTONE	200	10	—	AERODYNAME-1902 CYLINDER OPERATED
CV-2	20"	1	BUTTERFLY	150	FLANGED	AUX AIR		3	6.000 SCFM	CYLINDER OR DIAPHRAGM OPERATED
CV-3	6"	2	BUTTERFLY	150	FLANGED	AUX AIR		3	800 SCFM	CYLINDER OR DIAPHRAGM OPERATED
CV-4	3"	1	GATE	150	FLANGED	AUX AIR		20	700 SCFM	SOLENOID OPERATED
CV-5	3"	1	SELF CONTAINED SPRING OPERATED	150	FLANGED	AUX AIR	↓	20	700 SCFM	MINIMUM PRESS DROP 10/3 PSIG.
MV-1	6"	12	KNIFE GATE CI BODY/SS BLADE	125	FLANGED	COAL & LIMESTONE	200	10	—	AERODYNE 1902 MANUAL OPERATED
MV-2	4"	2	↓	125	FLANGEG	↓		10	—	
MV-3	6"	7	BUTTERFLY	150	FLANGED	AUX AIR		3	700 SCFM	
MV-4	4"	1	GATE	150	FLANGED	AUX AIR		20	700 SCFM	
MV-5	2"	1	GATE	150	FLANGED	AUX AIR	↓	20	700 SCFM	
RV-1	3×4	1	RELIEF	150	FLANGED	AUX AIR		SET AT 4 PSIG.	700 SCFM	10 % OVERPRESSURE

FLEXIBLE JOINTS-SCHEDULE

FLEXIBLE JOINT No	SIZE	QTY.	DESCRIPTION	PRESSURE PS-1-G OPERATING	PRESSURE PS-1-G DESIGN	SYSTEM	MAX. TRAVEL MAX. TEMP. °F	MAX. TRAVEL AXIAL	MAX. TRAVEL LATERAL	REMARKS
FJ-1	6"	7	BELOW W/SS LINER	3	50	COAL & LIMESTONE	200	1.5"	1.5"	FLANGED JOINT SUITABLE FOR CONTINUOUS VIBRATION OF CONVEYOR
FJ-2	6"	7	BELOW	3	50	AUX. AIR		1.5"	1.5"	
FJ-3	2"	52	BELOW W/SS LINER	3	50	AUX. AIR	↓	1.5"	1.5"	
FJ-4	20"	1	BELOW	3	50	AUX. AIR		—	—	FOR AUX. F.D. FAN VIBRATION ISOLATOR
FJ-5	2"	8	STAINLESS STEEL BELOW W/SS LINER	3	50	FLY ASH REINJECTION	750	1.5"	1.5"	

COAL & LIMESTONE BINS SCHEDULE

BIN No	SIZE (W×L×H)	AREA SERVED	MATERIAL STORED	CAPACITY TONS (NOTE "F")	VENTS No	VENTS SIZE	MANHOLE No	MANHOLE SIZE	HANDHOLE HINGED No	HANDHOLE HINGED SIZE	REMARKS
CB-N	(2'-6")×14'×15'	NORTH CELLS-A,B,C	COAL	10.25	1	12"Φ	1	18"×24"	2	12"×12"	
CB-S	(2'-6")×16'×15'	SOUTH CELLS-A,B,C		11.70	1	12"Φ	1	18"×24"	2	12"×12"	
CB-E	(2'-6")×4'×15'	EAST CBC	↓	2.93	1	12"Φ	1	18"×24"	1	12"×12"	
LB-N	(1'-6")×14'×9'	NORTH CELLS-A,B,C	LIMESTONE	8.00	1	12"Φ	1	18"×24"	2	12"×12"	
LB-S	(1'-6")×16'×9'	SOUTH CELLS-A,B,C		9.15	1	12"Φ	1	18"×24"	2	12"×12"	
LB-E	(1'-6")×4'×9'	EAST CBC	↓	2.3	1	12"Φ	1	18"×24"	1	12"×12"	

COAL & LIMESTONE PIPE FEEDERS-SCHEDULE

FEEDER No	SIZE	LENGTH (APPROX)	AREA SERVED	QTY.	DESCRIPTION	REMARKS
PF-A	2"Φ	6'-7"	CELLS A,B,C.	22	STAINLESS STEEL PIPE FLANGED	
PF-B	2"Φ	4'-6"	↓	22		
PF-C	2"Φ	5'-9"	CELL D	4		
PF-D	2"Φ	4'-7"	↓	4	↓	

NOTES

A) SUPPLIED WITH 8-2" FLANGED NOZZLES FOR MATERIAL OUTLET, 1'-0" FLANGED NOZZLE FOR AIR INLET & 1-NOZZLE FOR MATERIAL INLET (SAME SIZE AS ROTARY FEEDER). DUST TIGHT ENCLOSURE.

B) SUPPLIED WITH 6-2" FLANGED NOZZLES, FOR MATERIAL OUTLET. AIR INLET & MATERIAL INLET NOZZLES-SAME AS DESCRIBED IN NOTE. DUST TIGHT ENCLOSURE.

C) ALL MOTOR HP SHALL BE AS SHOWN ON SCHEDULE, OR AS RECOMMENDED BY EQPMT. MFR.

D) WELDING ELECTRODES FOR HPS PIPING 8018 B-2.

E) ROTARY FEEDER SIZE TO BE DETERMINED BY EQPMT. MFR, AND COVER CONTROL RANGE SHOWN.

F) BASED ON COAL DENSITY OF 45 LBS/FT.³, AND LIMESTONE DENSITY OF 85 LBS/FT.³.

G) ALL CONSTANT SPEED MOTORS SHALL BE SUITABLE FOR OPERATION ON 3Φ, 480V, 60 HERTZ.

H) ALL VARIABLE SPEED MOTORS SHALL BE SUITABLE FOR OPERATION ON 115 VOLTS D.C.

DRAWN BY: L.H.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: RJ	
CHKD. BY: KM	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: 6/18/–	FURNACE FEED SYSTEMS SCHEDULES MECHANICAL
DATE: JUNE –, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE — PROJ. No. 14-32-0001-1237
	DWG. NO. 422

REVISIONS					
REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	6-14-74	C.C.			MISC. REVISIONS

LEGEND (FOR ONE-LINE DIAGRAMS ONLY)

DWG Nos. 502 & 503

- LIGHT SOLID LINE WORK INDICATES EXISTING EQUIPMENT TO REMAIN, UNLESS OTHERWISE NOTED.
- HEAVY SOLID LINE WORK INDICATES EQUIPMENT FURNISHED, INSTALLED AND CONNECTED BY THE CONTRACTOR.
- HEAVY DASHED LINE WORK INDICATES FUTURE INSTALLATION.
- RELAY OPERATOR LINE.
- INDICATES EQUIPMENT ENCLOSURE.
- 1200A — MEDIUM VOLTAGE AIR CIRCUIT BREAKER, DRAW-OUT TYPE, 3 P., 4.16 KV. "1200A" - INDICATES BREAKER RATING IN AMPERES.
- 600AF / 400AT — LOW VOLTAGE AIR CIRCUIT BREAKER, DRAW-OUT TYPE, 3P, 480 V.AC., MANUALLY OPERATED. "600 AF" - INDICATES 600 AMP. FRAME SIZE. "400AT" - INDICATES 400 AMP. TRIP RATING.
- 2d / 15AT — MOLDED CASE CIRCUIT BREAKER, 3P, 480 V.AC. OR 120 V.A.C. AS REQUIRED, UNLESS OTHERWISE NOTED. "2d" - INDICATES CIRCUIT BREAKER CLASS PER FEDERAL SPEC. W-C.-375a "15AT" - INDICATES 15AMP. TRIP RATING.
- 30A — 3P, 480 V.AC. NON-FUSED DISCONNECT SWITCH, UNLESS OTHERWISE NOTED. "30A" - INDICATES SWITCH RATING IN AMPERES.
- 600A/J — CURRENT LIMITING FUSE "600A" - INDICATES FUSE RATING IN AMPERES. "J" - INDICATES NEMA CLASS.
- DISTRIBUTION TRANSFORMER. "Δ" - INDICATES "DELTA" CONNECTED WINDINGS. "Y" - INDICATES "GROUNDED WYE" CONNECTED WINDINGS.
- 400/5 — CURRENT TRANSFORMER. "3" - INDICATES QUANTITY. "400/5" - INDICATES 400 TO 5 AMP. RATIO.
- 480-120V. POTENTIAL TRANSFORMER OR C.P.T. "2" - INDICATES QUANTITY.
- 1200/5 — WINDOW TYPE CURRENT TRANSFORMER TO ENCOMPASS THREE PHASE, AND NEUTRAL CONDUCTORS WHERE REQUIRED. "1200/5" - INDICATES 1200 TO 5 AMP. RATIO.
- SHUNT TRIP COIL.
- PLUG-IN DEVICE.
- DRAW-OUT DEVICE.
- INDICATES SPLICE OR BOLTED CONNECTION.
- 200 — MOTOR - NUMBER INDICATES HORSEPOWER RATING.
- ACROSS THE LINE A.C. MAGNETIC STARTER - NON-REVERSING, 3P, 480 V.A.C. WITH BUILT-IN, FUSE PROTECTED, 480-120 V. CONTROL POWER TRANSFORMER. "2" - INDICATES NEMA SIZE.
- ACROSS THE LINE A.C. MAGNETIC STARTER, REVERSING, 6P, 480 V.A.C. WITH BUILT-IN, FUSE PROTECTED, 480-120V. CONTROL POWER TRANSFORMER. "0" - INDICATES NEMA SIZE.
- ACROSS THE LINE D.C. MAGNETIC STARTER, REVERSING-ADJUSTABLE SPEED, 120V. D.C.
- SILICON-CONTROLLED RECTIFIER.
- (4) CABLE AND CONDUIT IDENTIFICATION NUMBER - SEE CABLE AND CONDUIT SCHEDULE - DWG'S. No. 509 & 510
- INDICATING LIGHT.
- PUSHBUTTON - MOMENTARY CONTACT, UNLESS OTHERWISE NOTED.
- H-O-A — SELECTOR SWITCH. "H-O-A" - INDICATES "HAND-OFF-AUTO". "O-A" - INDICATES "OFF-AUTO".
- P — PILOT ACTUATING DEVICE. "P" - INDICATES PRESSURE SWITCH.
- GROUND CONNECTION.
- POWER RECEPTACLE - 30A, 3φ, 480V.
- RHEOSTAT.
- 3φ, 480 VOLTS MOTOR SPACE HEATER.

- 1φ, 480 V.A.C. PRECIPITATOR TRANSFORMER-RECTIFIER UNIT CONTROL CABINET.
- 1φ, 480 V.A.C. PRECIPITATOR TRANSFORMER-RECTIFIER UNIT.
- R.C.C. — 1φ, 120 V.A.C. PRECIPITATOR COLLECTING IMPACT RAPPERS CONTROL CABINET.
- V.C.C. — 1φ, 120V. A.C. PRECIPITATOR EMITTING VIBRATORS CONTROL CABINET.
- 5 KV., CABLE TERMINATOR.
- 51, A — RELAY OR INSTRUMENT, SEE RELAY AND INSTRUMENT LEGEND. ONE REQUIRED UNLESS OTHERWISE NOTED. "3" - INDICATES REQUIRED QUANTITY.
- 20A — A.C. CONTACTOR - ELECTRICALLY HELD - 3P, 480V. A.C. WITH BUILT-IN, FUSE PROTECTED, 480-120V CONTROL POWER TRANSFORMER "20 A" - INDICATES CONTACTOR RATING IN AMPERES.
- R.T.D. — RESISTANCE - TEMPERATURE DETECTOR.
- ACROSS THE LINE A.C. MAGNETIC STARTER - MULTI-SPEED, 6 P., 480 V. A.C. WITH BUILT-IN, FUSE PROTECTED, 480-120 V. CONTROL POWER TRANSFORMER. "1" - INDICATES NEMA SIZE.

LEGEND (FOR POWER PLANS ONLY)

DWG. Nos. 504, 505, 506 & 508.

- CONDUIT RUN EXPOSED ABOVE FLOOR PLAN AND/OR PLATFORM OF INDICATED ELEVATION, UNLESS OTHERWISE NOTED.
- CONDUIT RUN EXPOSED BELOW FLOOR PLAN AND/OR PLATFORM OF INDICATED ELEVATION.
- CONDUIT TURNING TOWARD OBSERVER.
- CONDUIT TURNING AWAY FROM OBSERVER.
- CONDUIT RISER - UP AND DOWN.
- JUNCTION BOX.
- (4) CABLE AND CONDUIT IDENTIFICATION NUMBER - SEE CABLE AND CONDUIT SCHEDULE - DWG. Nos. 509 & 510
- NON-FUSED DISCONNECT SWITCH WITH NUMBER OF POLES AND AMPERE RATING AS SHOWN ON ONE-LINE DIAGRAM.
- STARTER, NON-REVERSING, TYPE AND SIZE AS SHOWN ON ONE-LINE DIAGRAM.
- STARTER, REVERSING, TYPE AND SIZE AS SHOWN ON ONE-LINE DIAGRAM.
- 277/480V., 3φ, 4W PANEL.
- 120/208V., 3φ, 4W PANEL.
- POWER RECEPTACLE - 30A., 3φ, 480V.
- T — 480-208Y/120 V. DRY TYPE STEP-DOWN TRANSFORMER.
- INTERCOM TELEPHONE HANDSET STATION - WALL MOUNTED 5'-0" ABOVE FINISHED FLOOR, UNLESS OTHERWISE NOTED.
- INTERCOM SPEAKER - SEE SPECIFICATIONS. MOUNT APPROX. 8'-0" ABOVE FINISHED FLOOR.

LEGEND (FOR LIGHTING PLANS ONLY)

DWG. Nos. 511 & 512

- LP-A-1,3,5 — HOME RUN TO LIGHTING PANEL "A", CIRCUITS "1, 3, 5". EACH HALF ARROW INDICATES A SINGLE POLE CIRCUIT. CROSS-HATCHED LINES INDICATE QUANTITY OF #12 AWG. CONDUCTORS IN RIGID CONDUIT, UNLESS OTHERWISE NOTED. "G" - INDICATES #12 AWG. GROUND CONDUCTOR.
- LPA-6 — HOME RUN TO LIGHTING PANEL "A", CIRCUIT "6". ARROW INDICATES A MULTI-POLE CIRCUIT. ALL OTHER DESIGNATIONS HAVE SAME MEANING AS ABOVE.
- CONDUIT RUN EXPOSED. CROSS-HATCHED LINES HAVE SAME MEANING AS ABOVE. CONDUIT WITHOUT CROSS-HATCHED LINES DESIGNATES 2# 12 AWG. CONDUCTORS.
- CONDUIT RUN CONCEALED IN HUNG CEILING AND/OR WALL. ALL OTHER DESIGNATIONS HAVE SAME MEANING AS ABOVE.
- SR — 2 3/4" x 1 7/16" SURFACE METAL RACEWAY SUITABLE FOR WIRING AND FLUSH MOUNTING OF STANDARD WIRING DEVICES RATED UP TO 50 AMP.
- M.H.10' A, 5a — 1'x4' INDUSTRIAL TYPE FLUORESCENT LIGHTING FIXTURE - PENDENT, 277 VOLT. "MH. 10'" - INDICATES MOUNTING HEIGHT IN FEET ABOVE FINISHED FLOOR OR PLATFORM. "A" - INDICATES FIXTURE TYPE - SEE FIXTURE SCHEDULE, DWG. No. 508 "5" - INDICATES CIRCUIT NUMBER. "a" - INDICATES SWITCH DESIGNATION CONTROLLING FIXTURE.
- A, 5a — 2'x4' FLUORESCENT LIGHTING FIXTURE - RECESSED 277 V. ALL OTHER DESIGNATIONS HAVE SAME MEANING AS ABOVE.
- M.H.10' A, 5a — MERCURY VAPOR LIGHTING FIXTURE - BRACKET TYPE, 277 V. ALL OTHER DESIGNATIONS HAVE SAME MEANING AS ABOVE.
- DUPLEX RECEPTACLE - WALL MOUNTED - 15A, 125V., 2P, 3W, GROUNDED. "5" - INDICATES CIRCUIT NUMBER.
- SINGLE RECEPTACLE - WALL MOUNTED - 20A, 125 V, 2P., 3 W., GROUNDED, TWIST-LOCK TYPE. "5" - INDICATES CIRCUIT NUMBER.
- SINGLE RECEPTACLE - WALL MOUNTED - 30A, 125 V., 2P., 3W., GROUNDED, TWIST-LOCK TYPE. "5" - INDICATES CIRCUIT NUMBER.
- SINGLE RECEPTACLE - WALL MOUNTED - 50A, 125V., 2P, 3W., GROUNDED, TWIST-LOCK TYPE. "5" - INDICATES CIRCUIT NUMBER.
- $a — SINGLE POLE SWITCH - 20A., 277 V. RATED A.C. ONLY. "a" - INDICATES FIXTURE TO BE CONTROLLED.
- W.P. — INDICATES EQUIPMENT IN WEATHERPROOF ENCLOSURE.
- E.X. — INDICATES EQUIPMENT SUITABLE FOR CLASS 2, DIV. 1, GROUP F, HAZARDOUS LOCATION.
- 277/480 V. LIGHTING PANEL.
- 120/208V. RECEPTACLE PANEL.
- JUNCTION BOX.
- 1/2" FLEXIBLE CONDUIT WITH 2#12 AWG. CONDUCTORS RUN CONCEALED IN HUNG CEILING, UNLESS OTHERWISE NOTED.
- $3a — THREE WAY SWITCH - 20A, 277V. RATED A.C. ONLY. "a" - INDICATES FIXTURE TO BE CONTROLLED.
- SINGLE RECEPTACLE - WALL MOUNTED - 30A, 250V, 2 P., 3W., GROUNDED, TWIST-LOCK TYPE "5" - INDICATES CIRCUIT NUMBER.

INSTRUMENT AND RELAY LEGEND

A	AMMETER.
AS	AMMETER SWITCH.
V	VOLTMETER.
VS	VOLTMETER SWITCH.
TB C	TEST BLOCK - "C" - CURRENT; "P" - POTENTIAL.
CS	BREAKER CONTROL SWITCH.
46	PHASE-BALANCE CURRENT RELAY.
49	THERMAL RELAY.
49S	THERMAL (STALLED) RELAY.
49/50	THERMAL AND INSTANTANEOUS OVERCURRENT RELAY.
50	INSTANTANEOUS OVERCURRENT RELAY.
50/51	TIME OVERCURRENT WITH INSTANTANEOUS TRIP ATTACHMENT.
50N/51N	RESIDUAL GROUND TIME OVERCURRENT RELAY WITH INSTANTANEOUS TRIP ATTACHMENT.
50/GS	INSTANTANEOUS GROUND SENSING RELAY.
51	TIME OVERCURRENT RELAY.
51/GS	TIME OVERCURRENT GROUND FAULT RELAY.
86	LOCKING-OUT RELAY.
87	DIFFERENTIAL RELAY.
47	PHASE-SEQUENCE VOLTAGE RELAY.
47X	AUXILIARY RELAY TO DEVICE "47."

ABBREVIATIONS

A	AUTO.
A.C.	ALTERNATING CURRENT.
A.F.F.	ABOVE FINISHED FLOOR.
A. OR AMP.	AMPERE.
APPROX.	APPROXIMATE.
CAB.	CABINET.
C.I.R.	COLLECTING IMPACT RAPPER.
C.B. OR CKT. BKR.	CIRCUIT BREAKER.
C. OR CDT.	CONDUIT.
C.P.T.	CONTROL POWER TRANSFORMER.
D.C.	DIRECT CURRENT.
DISC.	DISCONNECT.
E.V.	EMITTING VIBRATOR.
F.D.	FORCED DRAFT.
G. OR GND.	GROUND.
H.	HAND.
I.D.	INDUCED DRAFT.
J.B.	JUNCTION BOX.
L.P.	LIGHTING PANEL.
LTG.	LIGHTING.
M.C.C.	MOTOR CONTROL CENTER.
N.C.	NORMALLY CLOSED.
N.O.	NORMALLY OPEN.
N. OR NEUT.	NEUTRAL.
O.	OPEN.
P.B.	PULL BOX.
R.F.	ROTARY FEEDER.
R.P.	RECEPTACLE PANEL.
SW.	SWITCH.
V.	VOLT.
MAX.	MAXIMUM.
H.V.	HIGH VOLTAGE.
L.V.	LOW VOLTAGE.
SWGR.	SWITCHGEAR.
N.I.C.	NOT IN CONTRACT.
EL. OR ELEV.	ELEVATION

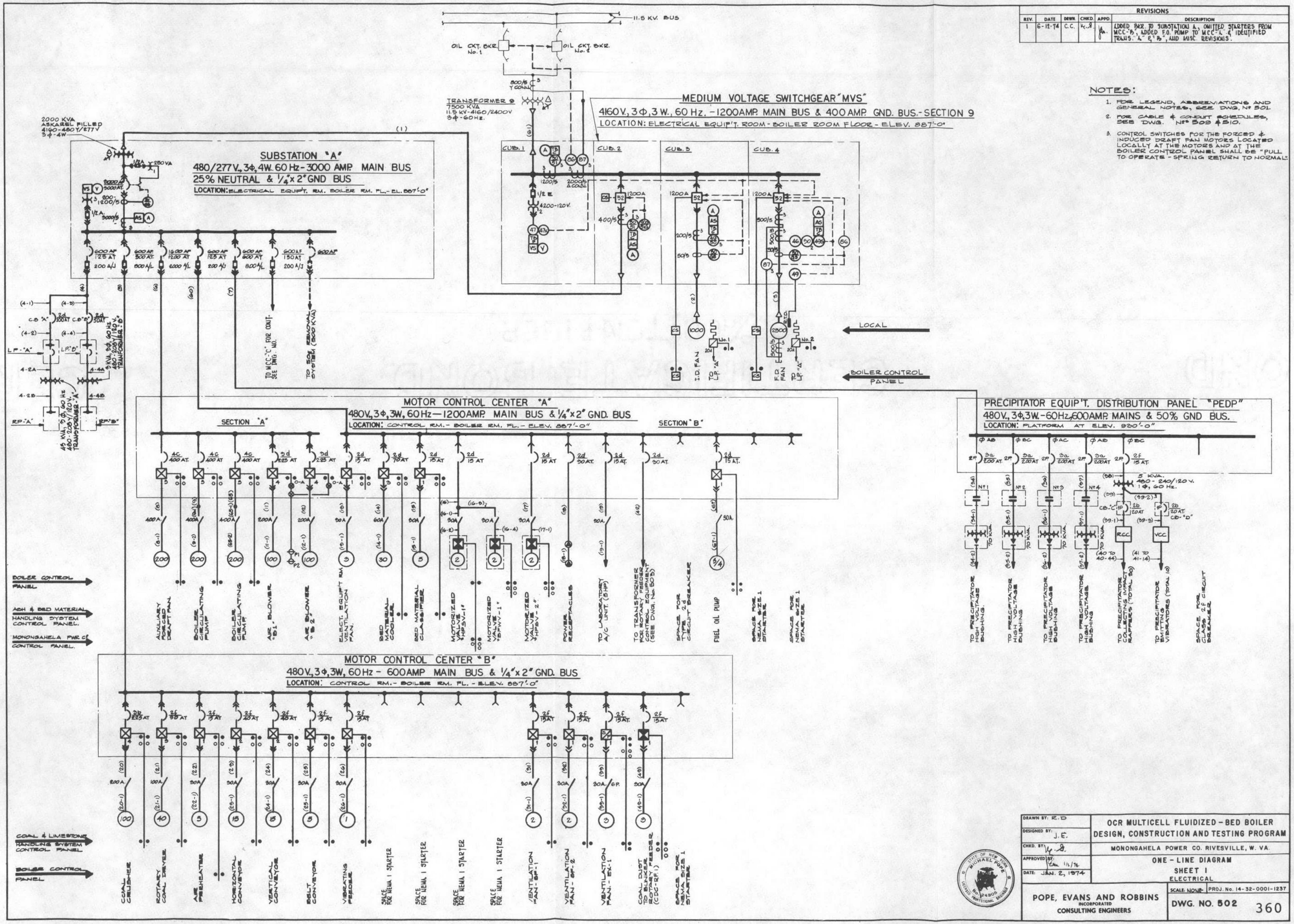
GENERAL NOTES

1. ALL ELECTRICAL EQUIPMENT SHOWN ON THE DRAWINGS AND/OR REQUIRED FOR THE FULL INTEGRITY OF THIS CONTRACT SHALL BE FURNISHED, INSTALLED AND CONNECTED BY THE CONTRACTOR, EXCEPT WHERE EQUIPMENT SHOWN IS IDENTIFIED AS "EXISTING" OR OTHERWISE NOTED ON THE DRAWINGS.
2. EXCEPT WHERE SPECIFICALLY DIMENSIONED OR OTHERWISE LOCATED BY PERTINENT DETAILS, THE ROUTING OF POWER AND CONTROL CONDUITS, AS SHOWN ON POWER PLANS, IS APPROXIMATE. THE CONTRACTOR MAY MODIFY POWER AND CONTROL CONDUIT ROUTINGS SHOWN ON DRAWINGS DUE TO EXISTING FIELD CONDITIONS, PROVIDED PROPER PULLBOXES WILL BE INSTALLED TO FACILITATE CABLE PULLING AND/OR SUPPORT. CONDUIT ROUTINGS, AS SHOWN ON LIGHTING PLANS, ARE DIAGRAMMATIC ONLY, EXACT ROUTING AND METHOD OF SUPPORT SHALL BE DETERMINED IN THE FIELD.
3. LIGHTING FIXTURES SHALL BE LOCATED SUBSTANTIALLY AS SHOWN ON THE LIGHTING PLANS, BUT AVOIDING INTERFERENCE WITH EXISTING OR NEW EQUIPMENT. IF LOCATION OF ANY FIXTURE DEPARTS APPRECIABLY FROM THE LOCATION SHOWN ON THE PLAN, THE ADJACENT LIGHTING FIXTURE SHALL BE ADJUSTED AS MAY BE NECESSARY TO RETAIN SUBSTANTIALLY UNIFORM ILLUMINATION OF THE AREA.
4. MOUNTING HEIGHTS FOR THE PANELS SHALL BE 6'-6" MAX. TO THE TOP OF CABINET - SEE SPEC'S.
5. MOUNTING HEIGHT FOR SWITCHES SHALL BE 4'-6" A.F.F. TO THE CENTER LINE.
6. RECEPTACLES SHALL BE MOUNTED 1'-6" A.F.F. OR PLATFORM, UNLESS OTHERWISE NOTED ON THE DRAWING.
7. WHEN SWITCH DESIGNATION IS OMITTED, FIXTURE IS CONTROLLED FROM LIGHTING PANEL.
8. FOR LIGHTING & RECEPTACLE WIRING, CONDUITS SHALL BE SIZED IN ACCORDANCE WITH THE NATIONAL ELECTRICAL CODE.
9. REFER TO THE SPECIFICATIONS FOR THE EXTENSION OF THE EXISTING INTERCOM SYSTEM. MINIMUM CONDUIT SIZE FOR THE INTERCOM SYSTEM SHALL BE 1."

STATE OF NEW YORK · MICHAEL POPE · LICENSED PROFESSIONAL ENGINEER · No. [illegible]506

DRAWN BY: J.H.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: J.E.	
CHKD. BY: [illegible]	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: [illegible]	LEGEND, GENERAL NOTES AND ABBREVIATIONS ELECTRICAL
DATE: JAN. 2, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE · PROJ. No. 14-32-0001-1237
	DWG. NO. 501

REV.	DATE	DRWN.	CHKD.	APPD.	REVISIONS DESCRIPTION
1	6-12-74	C.C.			ADDED BKR. TO SUBSTATION A., OMITTED STARTERS FROM MCC-"B", ADDED F.O. PUMP TO MCC-"A" & IDENTIFIED TRANS. "A" & "B", AND MISC. REVISIONS.



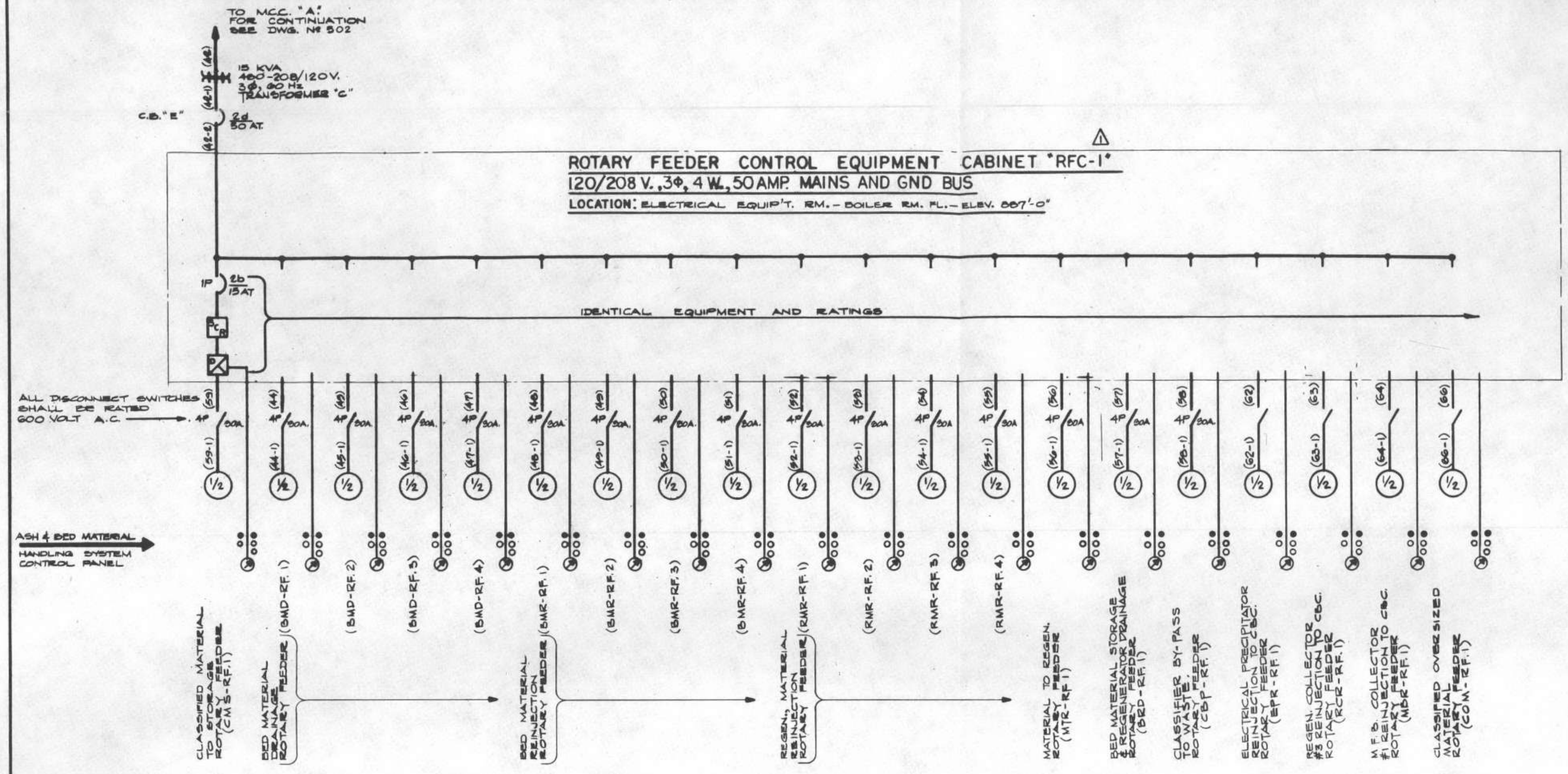
NOTES:

1. FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES, SEE DWG. Nº 501.
2. FOR CABLE & CONDUIT SCHEDULES, SEE DWG. Nº 509 & 510.
3. CONTROL SWITCHES FOR THE FORCED & INDUCED DRAFT FAN MOTORS LOCATED LOCALLY AT THE MOTORS AND AT THE BOILER CONTROL PANEL SHALL BE "PULL TO OPERATE - SPRING RETURN TO NORMAL".

DRAWN BY: R.D.	OCR MULTICELL FLUIDIZED-BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: J.E.	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
CHKD. BY:	ONE-LINE DIAGRAM SHEET 1 ELECTRICAL
APPROVED BY:	
DATE: JAN. 2, 1974	SCALE: NONE · PROJ. No. 14-32-0001-1237
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	DWG. NO. 502

360

REV.	DATE	DRWN.	CHKD.	APPD.	DESCRIPTION
1	6-14-74	C.C.	[illegible]	[illegible]	IDENTIFIED EQUIPMENT



NOTES:

1. FOR LEGEND, ABBREVIATIONS AND GENERAL NOTES, SEE DWG. Nº 501
2. FOR CABLE AND CONDUIT SCHEDULES, SEE DWG. Nºs 508 & 510.

DRAWN BY: R.D	OCR MULTICELL FLUIDIZED - BED BOILER DESIGN, CONSTRUCTION AND TESTING PROGRAM
DESIGNED BY: J.E.	
CHKD. BY: [illegible]	MONONGAHELA POWER CO. RIVESVILLE, W. VA.
APPROVED BY: [illegible] 1/1/74	ONE - LINE DIAGRAM SHEET 2 ELECTRICAL
DATE: JAN. 2, 1974	
POPE, EVANS AND ROBBINS INCORPORATED CONSULTING ENGINEERS	SCALE: NONE — PROJ. No. 14-32-0001-1237 — DWG. NO. 503