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EDS COAL LIQUEFACTION PROCESS DEVELOPMENT

Phase 5, Engineering Design Study of an EDS Illinois Bottoms Fired Hybrid Boiler, Interim Report

April 1984

Work Performed Under Contract No. FC05-77ET10069

Exxon Research and Engineering Company
Florham Park, New Jersey

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EDS COAL LIQUEFACTION PROCESS DEVELOPMENT

PHASE V

Engineering Design Study of an EDS
Illinois Bottoms Fired Hybrid Boiler

Interim Report

Report Prepared by
COMBUSTION ENGINEERING, INC.

April 1984

PREPARED FOR
UNITED STATES DEPARTMENT OF ENERGY
UNDER COOPERATIVE AGREEMENT NO. DE-FC05-77ET10069

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ENI

EDS COAL LIQUEFACTION PROCESS DEVELOPMENT - PHASE V
ENGINEERING DESIGN STUDY OF AN EDS
ILLINOIS BOTTOMS FIRED HYBRID BOILER

ABSTRACT

This is an interim technical progress report for U.S. Department of Energy Cooperative Agreement No. DE-FC05-77ET10069, EDS Coal Liquefaction Process Development - Phase V. Funding is shared by U.S. Department of Energy, Exxon Company, U.S.A. (a division of Exxon Corporation), Electric Power Research Institute, Japan Coal Liquefaction Development Company, Phillips Coal Company, Anaconda Minerals Company, Ruhrkohle A.G., and ENI. This agreement covers the period January 1, 1977 through December 31, 1985.

This interim report documents work carried out by Combustion Engineering, Inc. under a contract to Exxon Research and Engineering Company and was prepared by Combustion Engineering, Inc. This report is the second of two reports by Combustion Engineering, Inc. on the predevelopment phase of the Hybrid Boiler program and covers the results of an engineering design study of a Hybrid Boiler firing the vacuum distillation residue (vacuum bottoms) derived from processing Illinois No. 6 coal in the EDS Coal Liquefaction Process. The function of the Hybrid Boiler is to heat the coal slurry feed for an EDS coal liquefaction plant by a process coil in the convection section and to generate high pressure steam in the radiant section. The Hybrid Boiler design developed in this phase of the program is based on the results of a laboratory characterization program (reported in EDS Interim Report FE-2893-112), on Combustion Engineering, Inc.'s extensive experience as a designer and supplier of steam generating equipment, and on Exxon Research and Engineering Co.'s experience with the design and operation of process heaters.

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I. INTRODUCTION

Combustion Engineering has developed a hybrid boiler design capable of generating steam and providing process heating for the EDS coal liquefaction process by burning vacuum bottoms. The design is a result of the initial phase of development initiated in May, 1981. The hybrid boiler design resulted from the combined knowledge and experience of Combustion Engineering and Exxon Research & Engineering Co., supplemented by the results from the extensive vacuum bottoms fuel testing program described in FE-2893-112.

The completion of the initial phase of the design study resulted in the detailed design of a hybrid boiler firing Illinois vacuum bottoms and the combustion characteristics of the Illinois vacuum bottoms fuel. The comprehensive Illinois vacuum bottoms test program performed at Combustion Engineering's Kreisinger Development Laboratory determined the vacuum bottoms pulverization, combustion, fouling, and slagging characteristics. The detailed design of the hybrid boiler included unit performance, equipment selection and a cost estimate for the boiler island. The boiler island scope includes; boilers, pulverizers, firing system, fuel preparation system, FD fans, ID fans, PA fans, air heaters, soot blowers, precipitators, SO_2 scrubbers, bottom ash pyrites rejects and process coil ash removal system, and flyash removal system.

II. EXECUTIVE SUMMARY

The results of the 1981 Hybrid Boiler predevelopment program may be found in the Engineering Study reported here and in the laboratory evaluation reported in FE-2893-112. The Engineering Study focuses on the design and identification of areas for future study of an EDS vacuum bottoms fired Hybrid Boiler. The laboratory evaluation assessed the fuel and ash properties of the residue (vacuum bottoms) produced by the EDS coal liquefaction process.

The primary function of the Hybrid Boiler is to heat the coal slurry feed for an EDS liquefaction plant. This is accomplished by a process coil located in the convection section of the Hybrid Boiler. In addition, the radiant section of the Hybrid Boiler is used to generate high pressure steam for the plant.

The Hybrid Boiler design developed under this program is based on the results from a comprehensive combustion testing program in C-E's Fireside Performance Test Facility (FPTF) and Drop Tube Furnace System (DTFS) on the once through (low conversion) EDS residue from an Illinois No. 6 coal and less extensive (DTFS) testing on the residue bottoms recycle (high conversion) residue. Both Combustion Engineering's extensive experience as a designer and supplier of steam generating equipment, and Exxon Research and Engineering Co.'s (ER&E) extensive experience with the design and operation of process heaters were used in developing the design.

The Hybrid Boiler design utilizes a conventional, field proven furnace and superheater design, and standard auxiliary equipment. The Hybrid Boiler, however, includes a process coil which is not provided in typical boiler designs. This was a major consideration of the program. A second consideration was the fuel nozzle design. Water cooled fuel nozzles were specified for the Hybrid Boiler because of the low melting point of the residues.

The results of the Laboratory Evaluation affected several areas of the Hybrid Boiler design including furnace size, pulverizer size, superheater design, process coil design and firing system design. The combustion testing results indicated that at high temperatures the high conversion Illinois EDS residue has combustion properties similar to high volatile bituminous coals. However, at low temperatures the combustion testing indicated potential flame instability. The laboratory evaluation also indicates the Illinois EDS residue has the potential to generate NOx levels greater than the parent coal. Slagging and fouling potential of the low conversion residue was not significantly different from that of Illinois #6 coals. The effect of the higher ash content of the commercial residues was factored into the boiler design.

The Hybrid Boiler design developed under this program is not a significant departure from conventional coal fired steam generating unit designs. Combustion Engineering would design and fabricate a Hybrid Boiler with commercial guarantees. The following budget pricing was developed for four units operating in parallel at an Illinois plant site:

	Delivered	Delivered & Erected
Four (4) Hybrid Boilers	$166,900,000	$225,900,000
Flue Gas Clean up System (For Four Hybrid Boilers)	32,220,000	50,000,000
Total		$275,000,000

III. ENGINEERING STUDY

A. General Design Conditions

The hybrid boiler general design conditions for Illinois EDS vacuum bottoms are tabulated below. Additional predicted performance data may be found in Section C, "Summary of Performance Conditions".

Number of Units:	Four (4)
Steam Capacity:	487,200 lb/hr
SHO Pressure:	1250 psig
SHO Temperature:	925^{o}F
Feedwater Temperature:	250^{o}F
Process Fluid Flow:	2,170,000 lb/hr
Process Fluid Pressure:	2500 psig
Process Fluid Outlet Temperature:	840^{o}F
Process Fluid Inlet Temperature:	413^{o}F
Process Coil Heat Absorption Rate:	600 MBtu/hr
Steam/Process Fluid Heat Duty Ratio:	50%/50%
Sulfur Removal:	90%
Particulate In Flue Gas:	0.03 lbs/MBtu Fired
NOx In Flue Gas:	0.6 lbs/MBtu Fired
Vacuum Bottoms Surface Moisture:	2% by Weight
Unit Turn Down:	50% while maintaining 840^{o}F process coil outlet temperature

B. Design Considerations

The hybrid boiler may be regarded as a typical coal fired boiler modified to accommodate the requirements of the process coil. The heat exchanger containing the three (3) phase fluid (donor solvent, coal and hydrogen) is referred to as the process coil. Several unusual constraints and/or criteria imposed on the hybrid boiler design are addressed. One constraint is the size of the process coil in relation to normal heat absorbing surfaces. A second criterion is that the hybrid boiler must be designed to allow decoking of the process coil. During decoking, the process coil and internal decoking steam will reach 1300°F requiring special material and support designs. A third consideration is the high ash content in the vacuum bottoms. The ash content may be as high as 30 percent requiring design considerations to reduce the effects of erosion throughout the unit. A fourth consideration was the combustion characteristics of the EDS vacuum bottoms. The fuel preparation system and firing system design reflect these considerations.

There are two other criteria which were considered very carefully in the design of the hybrid boiler. These are the controllability and reliability of the unit. Since unit operation must be coordinated with the larger liquefaction process, these factors play an important role in determining the feasibility of the entire project.

The equipment to be designed by C-E includes all the major components of the boiler island. This scope fuel preparation system includes the furnace, fuel firing system, superheater, process coil, air heater, soot blowers, ash handling equipment, fans, electrostatic precipitator, flue gas desulfurization, ducts, dampers, and support steel.

The hybrid boiler design basis was specified by the Exxon Research and Engineering Company at the initial technical meetings held in March and April of 1981. These design conditions are tabulated in Section C, General Performance. These general conditions plus results for the laboratory testing of the vacuum bottoms, determined the parameters for the unit design. One important design parameter that affected the overall design of the hybrid boiler was the constraint of a 50%/50% split of heat duty between the process coil and the furnace and superheaters. This heat duty constraint directly affected furnace size, superheaters and process coil surface areas and surface arrangement. For coal fired boilers, heat absorption in the furnace and superheater approaches 70% of the total heat absorbed in the unit. In order to attain the appropriate split of heat duty without sacrificing a conservative furnace design, the use of gas recirculation was employed to reduce the heat absorption in the furnace and increase the heat absorption in the process coil.

Furnace

The hybrid boiler will be a natural circulation type unit with fusion welded furnace waterwalls. The furnace for the hybrid boiler is defined as the area enclosed by waterwall extending to the leading edge of the low temperature pendant superheater located above the furnace nose.

For vacuum bottoms firing, the furnace configuration becomes an important factor for proper operation. The characteristics of the fuel which includes slagging and fouling tendencies, flame stability and burnout rate have to be analyzed so that the furnace dimensions are properly sized. The two basic parameters to furnace sizing are the cross-sectional (plan) area and the furnace height. A factor for heat flux to the walls called the Net Heat Input per Plan Area (NHI/PA x 10^6 Btu/hr-Ft^2) is used to determine the cross-sectional area.

The vacuum bottoms will behave similar to a typical midwestern bituminous coal. Laboratory test results have indicated that the vacuum bottoms will exhibit slagging and fouling characteristics similar to a midwestern bituminous coal which is currently being fired at the Illinois Power Company, Baldwin Power Station. This station is operating at its NHI/PA design value of 1.9 with the Baldwin coal. Values for NHI/PA of up to 1.85 are currently used for midwestern bituminous coals. Normal utility design practice requires that a unit be designed to allow removal of slag at full load. The hybrid boiler furnace was conservatively designed using an NHI/PA of 1.4. The lower value provides a larger area for heat absorption, reducing the heat flux on the furnace walls. A smaller plan area (or higher NHI/PA) results in higher heat absorption by the furnace walls. The higher furnace gas temperatures cause the furnace deposits to bond more firmly to the tubes and also increases the tendency for slag to become fluid. The combination of higher bonding strength and fluid slag makes it difficult for the furnace wall blowers to remove the deposits. A larger furnace plan area provides more area for the ash to deposit, reducing deposit thickness resulting in easier removal and longer sootblower intervals.

A furnace height of 93.8 ft. was selected to provide adequate retention time of the fuel particle to ensure carbon burnout. The average retention time for the fuel in the furnace is approximately 1.9 seconds. Furnace height is also affected by the slagging characteristics of the fuel. The results from the laboratory testing have indicated the vacuum bottoms to be a slagging coal. Additional furnace height, therefore, has been included between the lowest fuel admission point in the furnace and the upper bend line of the water cooled coutant hopper section. The additional furnace waterwall surface in this area will lower heat absorption rates by increasing surface area, avoid running slag onto the sloped hopper section, and avoid bridging over the coutant opening.

The conservative design of the hybrid boiler furnace which minimizes the furnace wall slagging potential and maximizes carbon burnout can affect furnace turndown. The furnace gas combustion zone temperatures are predicted to be in the 2200^{o}F range at low loads. The laboratory combustion test results indicate that in the Drop Tube Furnace System Test Facility (DTFS) combustion instability could occur below gas temperatures of 2100 to 2000^{o}F. As discussed in the Fuel Firing System section, C-E currently predicts a 50% MCR load can be achieved without support fuel. Below 50% load support fuel may be required to avoid flame/ignition instability.

Furnace Circulation System

A natural circulation system operating at 1350 psig has been selected for the hybrid boiler. C-E has built units with drum operating pressures up to 2400 psig utilizing natural circulation. The furnace waterwall system and drum specification are tabulated in the Section I, Equipment Specifications. A drum (Fig. 6) size of 60 inches (internal diameter) was specified. The maximum capacity of the drum with SHO steam conditions of 1250 psig and 925°F is 600,000 lb/hr of steam, which is 23% above MCR capacity.

Natural or thermal circulation results from a density difference between the subcooled water in the downcomers and the saturated steam-water mixture in the furnace wall tubes. Subcooled feedwater is introduced in the steam drum where it locally mixes with recirculated saturated water. The liquid phase entering the downcomers is slightly subcooled. This water flows from the downcomers into a lower ring header, which feeds the furnace wall tubes. These tubes form the walls of the furnace enclosure, and the subcooled water is heated to saturation and steam is produced as the fluid rises in the tubes. A saturated steam-water mixture is collected in upper headers, leaves the furnace through relief tubes and enters the steam drum. In the drum, mechanical separation of the steam from the steam-water mixture occurs. The dry saturated steam passes from the drum to the superheater sections. The saturated water remains in the drum and is available for recirculation.

Overheating of furnace wall tubes can occur when either the heat flux is sufficiently high to cause departure from nucleate boiling (DNB) or if the overall exit quality of the steam is high enough to cause drying of the inner tube surface. The heat flux necessary for DNB increases as operating pressures decrease. At the design pressure and heat release rate used in the furnace design, DNB will not occur in the hybrid unit. The overall circulation ratio (Table 5) developed in the hybrid boiler ensures that the tubes will be wetted at the point of maximum steam quality.

The other main consideration in the design of the circulation system is the efficiency of the steam-water separation process occurring in the drum. For a fixed drum pressure, a minimum pressure drop is required for the mixture passing through the internals to provide dry steam. Both the overall circulation ratio and the velocity in the waterwall relief tubes play dominant roles in this desired pressure drop. The hybrid unit is designed so that proper steam separation occurs.

Superheater

The superheater for the hybrid boiler consists of three sections and is similar to conventional utility units. The first section consists of the encasement for the process coil referred to as a steam cooled backpass. Virtually all utility designs consist of a steam cooled backpass utilizing saturated steam to cool the walls in areas where gas temperatures will be above 1000°F. In the case of the hybrid boiler, saturated steam will be taken off the drum and piped to backpass headers where the steam will pass through tubes surrounding the process coil.

From the backpass, the steam travels to the pendant superheater located above the nose arch in the furnace. The steam will pass through the front low temperature pendant, then to a desuperheater (Fig. 7) before reaching the high temperature finishing pendant section. The desuperheater serves as the primary control mechanism for the steam temperature.

The low temperature pendant superheater will consist of twelve (12) assemblies spaced on 30 inch centers across the width of the unit. The depth spacing of each assembly will be closely spaced with only 3/8" clear between tubes. This design is known as platenized construction and is used in high gas temperature zones in the superheater. The platenized construction minimizes the ash buildup on the superheater tubes, allows normal ash deposits to build up on the superheater tubes without bridging across the assemblies.

The high temperature pendant section design was based on a balance between steam pressure drop and surface requirements. The depth spacing is two times the tube diameter allowing for use of the full circumference of the tube as effective heat absorbing surface. The fouling tendencies of this section will be less than the low temperature pendant since it is in a lower gas temperature zone. The width spacing of this section will be 18 inches between 20 assemblies which is still very conservative and will not pose bridging problems with regular use of the sootblowers.

Tubular Air Heater

A tubular air heater (Fig. 8) is placed after the process coil for final heat recovery from the flue gas. The flue gas temperature leaving the process coil during normal full load operation will be approximately 560°F. The air heater transfers this recovered heat to the secondary combustion air and lowers the flue gas temperature to 300°F. The exit flue gas temperature is limited by the SO_2 dewpoint due to corrosion considerations. The tubular air heater designed for the hybrid boiler consists of a three pass arrangement with air passing on the shell side and gas through the tubes. A steam coil air preheater has been included to allow the cold air entering the tubular air preheater to be preheated to avoid condensation on the tube gas side when operating at low loads or during periods of low ambient temperatures. Thermocouples placed on several cold end tubes will allow continuous monitoring of the cold end tube temperatures in the control room.

Recuperative (tubular) air heaters were chosen in lieu of a regenerative (Ljungstrom type) air heaters due to design considerations of the process coil. If a process coil tube were to develop a leak, the flammable process fluid would leak into the backpass and mix with the flue gas. The flue gas, having an O_2 content less than 4%, should not cause any immediate problems, but if mixed with air, the potential for ignition would increase. To minimize the potential of combustion of the flammable material from a leaking process coil tube, isolation from a high oxygen environment is desirable. Recuperative (tubular) air heaters will keep the air and gas streams separated. This contrasts with a regenerative system where an air leakage into the flue gas is unavoidable. C-E recommends that tubular air heaters be incorporated into the design of the hybrid boiler for the reason that it offers the safest design for the specified operating conditions.

Gas Recirculation System

The characteristics of the hybrid boiler design warrants the use of a gas recirculation system. The design heat duty of 600 MBtu's in each of the steam and process coil sections requires that the heat absorption distribution parameters be altered. In a typical coal fired steam generator approximately 70% of the heat is absorbed in the furnace and superheater sections. In order to shift the heat absorbed from the furnace to the process coil, gas recirculation is necessary. When using gas recirculation, cooler flue gas is admitted to the furnace. The additional flue gas absorbs some heat that would normally be absorbed by the furnace walls and superheater and carries this heat over to the process coil. The greater mass of flue gas transfers this heat to the process coil by increasing convective transfer rate. With the characteristics portrayed by the Illinois EDS hybrid boiler, a 30% gas recirculation rate is required to achieve the desired absorption profile.

The vacuum bottoms fired in the hybrid boiler will contain a substantial quantity of ash, up to 30 percent by weight. The flyash carryover will be equivalent to units firing high ash coals. Recirculating dirty flue gas would compound the quantity of flyash carryover increasing the rate of erosion of convective tubing throughout the unit. For the hybrid boiler design, the flue gas will be recirculated from the induced draft fan outlet which is located downstream of the electrostatic precipitator. The clean flue gas will be ducted to the furnace and introduced through openings in the furnace hopper coutant bottom as shown on the drawing No. EP-813-199. The flow of the recirculated gas will be regulated by louver dampers located in the duct. The available induced draft fan discharge pressure at all loads will be suitable to recirculate flue gas through the furnace bottom. This will eliminate the need for a separate flue gas recirculation fan. Experience has shown that high temperature gas recirculation fans have high maintenance and low availability tendencies.

Coal Pulverizers

The fuel pulverizing system for the Illinois EDS plant is capable of grinding both vacuum bottoms and the parent Illinois midwest bituminous coal. Four C-E Raymond Type RP Bowl Mills (Fig. 1) and four integral volumetric feeders (Fig. 2) will be provided. Each pulverizer is capable of grinding either vacuum bottoms or the parent Illinois bituminous coal. The pulverizing system will be capable of grinding the required quantity of vacuum bottoms to achieve the 100% MCR condition with three of the four pulverizers in service. With three pulverizers in service grinding the parent coal, a 57% MCR load can be achieved.

Each mill will pass 80% by weight of vacuum bottoms through 200 mesh (200 openings per inch) with a Hardgrove grindability of 100+ and will draw 132 kw based on a capacity of 41,000 lb/hr per mill. When grinding the parent coal, each mill will pass 70% by weight through 200 mesh with a Hardgrove grindability of 53.5 and will draw 80 kw based on a capacity of 14,875 lb/hr per mill.

Bench scale testing of the Illinois high ash vacuum bottoms showed some tendency toward pasting. However, pulverization tests indicate the Illinois high ash vacuum bottoms can be sucessfully pulverized in a C-E bowl mill without the use of any special conditions.

The pulverizer system will be pressurized by two primary air fans which provide transport and drying (if required) air for the fuel. Each primary air fan will discharge to the primary air steam air heater which in turn will discharge to a common duct which serves all four pulverizers. Each fan is capable of providing the transport air required to reach 67% of MCR capacity firing vacuum bottoms. If one primary air fan is out of service supplemental fuel gas can be fired at a firing rate of 33% MCR to maintain full load conditions.

Normal operation with the vacuum bottoms will not require the use of preheated air to the pulverizer due to the extremely low moisture content of the vacuum bottoms. With the steam air preheating system, the milling system can also handle additional surface moisture on the vacuum bottoms if required. Vacuum bottoms firing will require a transport air to fuel ratio of 1.3:1.0. When firing the parent coal, a minimum primary air temperature of 450°F with a transport air to fuel ratio of 2.5:1.0 is required to adequately dry the coal. Alternately the parent coal throughout can be increased if a higher primary air temperature is available. The single steam coil air heater installed in the primary air duct will provide the heat for the parent coal primary air.

C-E has included a steam inerting system and fire detection system for the pulverizers to snuff out any mill fires which may occur. Some coals have self-heating tendencies making them very reactive and they can ignite at lower temperatures. These characteristics can be seen primarily in western coals, especially lignites but they exist in all coals. The potential exists for a pulverizer fire or puff with both the parent coal and vacuum bottoms. As an additional measure of unit reliabiity, a steam inerting system has been included as part of the equipment supplied with the pulverizer firing system. A mill fire or puff can result in damage to the mill, components and the coal piping.

Firing System

The firing system for the hybrid boiler consists of four (4) tilting tangengial windbox assemblies (Fig. 4). These windboxes (Fig. 3) are located near each of the four corners of the furnace. Each windbox assembly consists of, four(4) solid fuel admission compartments, two (2) warm-up gas/secondary air compartments, three (3) secondary air compartments and two (2) overfire air compartments, arranged horizontally. Located in the furnace wall near each of these windboxes are three (3) self-monitoring gas ignitors and four (4) flame scanners.

These compartments are aimed tangentially to a small, imaginary circle in the furnace. This tangential firing produces mutually supporting fire streams and merges to create a swirling fireball within the furnace cavity. The tangential firing system inherently produces a low level of NOx. Diversion of up to 20% of the combustion air from the point at which devolatilization occurs decreases fuel NOx production and the lower temperatures associated with the fireball combustion reduces the production of thermal NOx. NOx production is further discussed in the Emission Control Equipment section.

The compartments in the windboxes have the capability of vertically tilting through a 60° arc. This tilting is performed simultaneously by all compartments in the furnace keeping them all at the same angle with respect to the horizontal. This tilting allows the heat absorption distribution in the hybrid boiler to be altered. Tilting of the compartments upward will reduce absorption of heat in the furnace and increase the radiant heat transfer to the superheat sections and increase the furnace outlet temperature of the gas. Tilting is one of the two methods of process fluid temperature control in the hybrid boiler. Gas recirculation, the other method of process fluid temperature control, has previously been discussed.

Testing of the high ash residue and the low ash residue has been performed in the Kreisigner Development Laboratory (KDL). Several firing system design and operating considerations resulting from the testing have been incorporated in the design of the hybrid boiler.

KDL has found that the residues have a low melting point (300°F - 400°F). This indicates that the incoming residue will undergo a phase change when passing through the nozzle assemblies. It is possible that residue deposits could build up on the nozzles resulting in partial or total blockage of the passage and coking of the deposited material. Water cooled fuel nozzles (Fig. 5) will be used in the hybrid boiler to minimize residue build up/coking.

Combustion of pulverized solid fuel in the furnace has two distinct phases. First, the volatile matter in the fuel evolves and ignites as the fuel is first exposed to the heat in the furnace. After this rapid devolatilization, the remaining char burns out over a relatively longer period of time. Work at KDL indicates that at temperatures less than 2300°F the commercial high ash residue volatile matter ignites and burns more slowly than that from the low ash residue or the comparison Kentucky bituminous coal.

The slow devolatilization and burning of the high ash residue leads to some concern about flame stability at reduced boiler loads where the gas temperatures present in the fireball might be low enough to delay the ignition. Furnace gas temperature predictions indicate that at the control load of 50% MCR, the high ash residue can be successfully fired without the use of support fuel. As load is further reduced toward 40% however, it is expected that support fuel will have to be used to maintain stable firing conditions.

Sootblower System

The sootblower system is a very important aspect of any coal fired steam generator. There are two major systems for the hybrid boiler. The first system is the furnace wall blower system used for removing slag deposits on the radiant furnace walls. Second, the convective sootblower system is located in the superheater and process coil region for the removal of flyash deposits. The blowing medium for the wall blowers and convective region retractable sootblowers will be steam taken off the low temperature superheater outlet header.

An extensive furnace wall blower system whose coverage is shown on the general arrangement drawing has been provided. Three elevations of wall blowers above the windbox elevation and two elevations of wall blowers below the windbox elevation has been specified. Due to the high slagging potential of vacuum bottom ash, this extensive wall blower system and regular sootblower operation is required to prevent slag build up and to remove the furnace wall deposits before they become plastic. The laboratory testing has indicated the vacuum bottoms ash deposits in the furnace tend to have high bonding strengths and be difficult to remove. The laboratory slagging behavior of the vacuum bottoms ash is similar to high iron Illinois and Ohio coals with which C-E has experience with successfully controlling furnace wall slag build up.

The convective sootblower arrangement consists of single sided retactable sootblowers located in the pendant superheater sections and the process coil. The retractable sootblowers traverse the width of the unit spraying steam 360° in a spiral pattern. Laboratory tests have indicated the vacuum bottoms ash in the convective region has a low fouling potential. However, some deposit build up will occur. It is expected the deposits will be lightly sintered and friable and will have low bonding strengths which will be easy to remove.

C-E does not recommend that a sootblower system be installed to clean the tubular air heater. C-E's experience has shown that plugging of the tubes is not a problem unless high sulfur fuel oil is being fired. The gas temperature entering the tubular is well below the ash fusion temperature meaning that the flyash is very dry and powdery and will not stick to the tubes. The tubes in the tubular air heater are straight with no bends or crevices for ash to accumulate. Example of units firing a high fouling coal and no provision for tubular air heater cleaning capability are listed in Table 6.

Fan Selection

The design of the hybrid boiler required the consideration of reliability as a major constraint when selecting equipment and equipment arrangements. The fan arrangement to be supplied for each unit was carefully analyzed before a design was selected. In order to reduce the potential for fan trips, redundancy must be incorporated in such a manner as to prevent unit outages yet obtain high fan efficiencies and low power consumption.

There are three sets of fans that control the operation of the unit. These fans include the forced draft (F.D.), induced draft (I.D.), and primary air (P.A.) fans. The primary air fan supplies the pulverizers with drying and fuel transport air. The forced draft fan supplies heated secondary air to the windbox for combustion. The induced draft fan maintains furnace pressure by pulling the flue gas out of the unit and pushing it through the SO_2 removal equipment and on to the stack. The induced draft fan also supplies the pressure for the flue gas recirculation system.

C-E analyzed the operational priorities of the EDS process set by ER&E. One consideration is that a unit trip would disrupt the coal liquefaction process and have serious operational consequences. To minimize the potential of a unit shutdown due to a fan trip, C-E has included two forced and induced draft fans each sized for 60% of the full load maximum continuous rating (MCR) condition. The two primary air fans are sized to deliver the air flow required by two pulverizers. At 100% MCR, only three mills are required which will require both P.A. fans to be in operation. With one primary air fan in operation, the unit will be able to reach 67 percent of MCR when firing the vacuum bottoms.

Emission Control Equipment

The emission control system is comprised of an electrostatic precipitator (ESP) and a wet flue gas desulfurization (FGD) system. Each unit will have its own ESP located after the tubular air heater and before the induced draft fans. All four hybrid boilers will share six FGD modules as shown in the drawing. The Hybrid Boiler system will meet current federal nitrogen oxide (NOx) (.6 $lb/10^6$ Btu) requirements.

The electrostatic precipitator provided for the hybrid boiler will be of the rigid frame type construction (Fig. 9). Five fields will be initially installed leaving space for an additional field in case requirements call for it in the future. The precipitator will be able to meet required emission levels with four of five fields in operation.

The reason for the redundant fields is to insure reliable operation of the ESP and avoid periods of capacity reduction due to a failure of a precipitator electrical field. Since there will not be a back up precipitator, any redundancy must be installed initially. The reliability of an ESP is very high and C-E recommends that this arrangement be employed in order to meet the reliability conditions desired by ER&E.

A wet flue gas desulfurization system will be employed in the hybrid boiler design. Crushed limestone is sprayed into the gas stream in the spray tower as a slurry. The sulfur oxides in the gas stream react with the calcium sulfate and sulfite. The residue falls to the bottom of the tower and is pumped out to a sludge handling system. The clean flue gas then flows to a steam reheater to heat the water saturated flue gas above the water dew point to avoid water condensation in the ductwork and stack.

Reliability of the design is the focal point of the selection and arrangement. The nature of the water-calcium slurry can cause spray nozzle plugging which will cause the module to be taken out of service when enough spray nozzles become plugged. The flue gas from all four hybrid boilers will flow to the center and feed into another plenum that serves six FGD modules. The purpose of the dual plenum arrangement is to assure even distribution of flue gas to the active modules. Each module will be sized to handle 100 percent MCR gas flow from one hybrid boiler. Four modules would be in service when all four boilers are operating. This would leave two modules out of service either for maintenance or in a standby mode. This arrangement gives the FGD system a 50 percent redundancy factor adding flexibility and reliability to the system. A 50 percent flue gas bypass duct will also be installed for use during start-up or if more than two modules are out of service. The common plenum arrangement allows any boiler FGD scrubber combination and affords the maximum boiler availability with the installed equipment.

The level of NOx produced by the hybrid boiler will be minimized by the design and configuration of the firing system. The firing system is designed to minimize production of fuel-bound NOx and thermal NOx. Fuel-bound NOx is controlled by driving the conversion of fuel nitrogen compounds to molecular nitrogen in the gas phase under fuel-rich/oxygen starved conditions and minimizes NOx formation. The production of thermal NOx is minimized by reducing peak flame temperatures.

The C-E firing system creates a fuel-rich condition by utilizing staged combustion. The use of overfire air compartments divert approximately 20% of the total air from the primary combustion zone. Also the ignition point is moved closer to the fuel nozzle by varying the velocity and quantity of air through the annulus of the fuel compartment. Both of these factors extend the duration of the fuel-rich primary combustion zone and reduce the formation of fuel-bound NOx.

Peak flame temperatures are reduced with the C-E firing system by slow mixing of fuel and air in the secondary combustion zone. Slow mixing is inherent with the tangential admission of fuel and air by windbox elevation. Also the addition of overfire air to the upper portion of fireball tends to reduce the mixing of fuel and air.

C-E predicts that with the utilization of a standard low NOx firing system a NOx level of 0.5 lb/million Btu fired will not be exceeded. However, laboratory testing performed by C-E on Illinois vacuum bottoms indicates there is a potential for high NOx formation. Based on the results of future testing, a determination will be made whether to retain the conventional firing system design, or to implement a low NOx modification such as Low NOx Concentric Firing System (LNCFS), Separating Gas Recirculation (SGR) or Pollution Minimum (PM) burner. These modifications have yet to be supplied in a commercial application in the United States.

Ash Removal System

Two distinct ash removal systems are incorporated in the hybrid boiler design. The first system removes pulverizer rejects, slag from the furnace bottom and flyash from the process coil. The second system will remove flyash collected in the air heater hopper and flyash in the hoppers located under the ESP fields.

In the first system, pulverizer rejects, such as mineral matter and tramp iron (pyrites), which are rejected from the pulverizer grinding process, are directed into temporary storage tanks (pyrites-reject hoppers). The pulverizer-reject hoppers are pressurized and wet store these materials. Level sensing devices in the hoppers indicate when emptying of the tank is necessary. A grate located in the bottom of the tanks can be opened and the stored material will be sluiced away through the use of jet pumps. Each pulverizer has associated with it, individual, pyrites-reject hoppers, jet pump and transfer lines.

The rejects from each of the pyrites-reject hopers feed into the Bottom Ash Submerged Scraper Conveyor (SSC). An SSC (Fig. 11) consists of a water impounded trough into which material falling through the furnace coutant falls. A continuous removal process is used in the SSC. Chains, connected by angle irons in a continuous ladder arrangement, remove material which has settled to the bottom of the SSC. The chain flight carries the material up a dewatering slope which allows excess water to return to the trough. At the top of the dewatering slope, the material, dewatered to 20% by weight water, drops into a clinker grinder. The clinker grinder reduces the size of the large pieces of fused ash to ease the transport of these waste materials. A second SSC, similar to the Bottom Ash SSC but without the long dewatering slope, is located under the process coil hopper. This SSC provides removal of material dropping out of the gas stream in the process coil section, and removal of material that has been deposited on the process coil and removed by the sootblowing process. The material from the process coil SSC is dropped into a chute rather than a clinker grinder. This chute directs process coil wastes to the Bottom Ash SSC providing a common removal point for bottom ash, process coil and pulverizer wastes. Provision is made for lateral movement of both SSCs to provide access to the boiler for maintenance purposes.

The second ash removal system is that designed to handle flyash accumulated in the air heater hopper and the precipitator ash hoppers. This system pneumatically transports this ash to a common 2-unit storage silo. Vacuum blowers located downstream of the silo provides the motive force and removal from the hoppers is done under suction. The ash is separated from the air through the use of cyclone separators and a final filtering stage.

Removal of the stored flyash from the silo may be accomplished by open-air or sealed means. A rotary ash conditioner is supplied for open-air removal. This device wets the ash exiting the silo to reduce blowing during transport. A straight telescoping ash unloader is provided for sealed removal. This device extends to the removal container to eliminate blowing of ash during the transfer.

Initial Start Up

During the initial start up of the EDS plant the fuels available for the hybrid boiler will be the parent Illinois Midwest Bituminous coal and a high Btu fuel gas. During the plant start up, 35% of full load capacity can be achieved by firing the parent coal using three of the four pulverizers. Fuel gas makes up the additional 65% of full load required to reach full load. It is expected the EDS plant will be in initial start up for four to six months. After the start up period the hybrid boiler will be capable of full load firing 100% vacuum bottoms without support fuel. A by-product high Btu gas will be available for ignition and warm up of the unit over the course of the plant life.

C. General Performance

Table 1: Fuel Analysis EDS Residue, Illinois Parent Coal

Table 2: Fuel Ash Analysis EDS Residue, Illinois Parent Coal

Table 3: General Design Conditions

Table 4: EDS Hybrid Boiler, Illinois Coal
-- EDS Residue Predicted Performance

Table 5: EDS Hybrid Boiler, Illinois Coal
-- EDS Residue, Circulation System Predicted Performance

Table 6: Partial List of C-E Coal Fired Units with Tubular Air Heaters and no Air Heater Sootblowing

Table 7: Comparison of Backpass Design Flue Gas Temperatures and Velocities for Coal Fired Units

Table 8: Full Load Process Coil Performance

TABLE 1

FUEL ANALYSIS

EDS RESIDUE

ILLINOIS PARENT COAL

	PARENT COAL		LOW ASH RESIDUE		HIGH ASH RESIDUE	
	AS RECEIVED	DRY & ASH FREE	AS RECEIVED	DRY & ASH FREE	AS RECEIVED	DRY & ASH FREE
Proximate (%Wt)						
Moisture	16.30	—	0.7	—	0.4	—
Volatile Matter	34.74	41.50	45.8	54.0	39.7	54.3
Fixed Carbon	39.76	47.51	39.0	46.0	33.4	45.7
Ash	9.20	10.99	14.5	—	26.5	—
TOTAL			100.0	100.0	100.0	100.0
Ultimate (%Wt)						
Moisture	16.30	—	0.7	—	0.4	—
Hydrogen	4.08	4.38	4.7	5.6	3.9	5.3
Carbon	58.02	69.32	72.0	85.0	64.3	88.0
Sulfur	3.70	4.42	2.6	3.0	2.2	3.0
Nitrogen	1.11	1.33	1.5	1.7	1.3	1.8
Oxygen	7.52	8.98	4.0	4.7	1.4	1.9
Ash	9.20	10.99	14.5	—	16.5	—
TOTAL			100.0	100.0	100.0	100.0
HHV (Btu/lb)			13,010	15,345	11,575	15,840
Pyritic Sulfur (%Wt)	1.30	—	0.1	—	0.1	—
Lb Ash/10^6 Btu	8.71	—	11.2	11.2	22.9	22.9
Grindability	53.5		Greater than 100		Greater than 100	
Melting Temp. (°F)			300° - 400°F		300° - 400°F	

TABLE 2
FUEL ASH ANALYSIS
EDS RESIDUE
ILLINOIS PARENT COAL

SAMPLE	LOW ASH RESIDUE	HIGH ASH RESIDUE	PARENT COAL
Ash Fusibility (%Wt)			
I.T. (°F)	2050	2080	2268
S.T. (°F)	2090	2120	2346
H.T. (°F)	2190	2230	2423
F.T. (°F)	2350	2380	2508
Ash Composition (%Wt)			
SiO_2	49.0	51.5	48.71
Al_2O_3	15.7	17.0	17.31
Fe_2O_3	18.8	15.7	19.34
CaO	4.9	4.6	4.55
MgO	0.8	1.2	0.97
Na_2O	1.1	1.2	1.35
K_2O	1.5	1.6	2.49
TiO_2	1.0	0.9	0.86
SO_3	5.4	5.8	3.18
TOTAL	98.2	99.5	98.76
Lb Ash/10^6 Btu	11.2	22.9	8.71
Base/Acid Ratio	0.41	0.35	0.43
Fe_2O_3/CaO Ratio	3.80	3.46	4.25
SiO_2/Al_2O_3 Ratio	3.13	3.03	2.81

TABLE 3

GENERAL DESIGN CONDITIONS

Number of Units:	Four (4)
Steam Capacity:	487,200 lb/hr
SHO Pressure:	1250 psig
SHO Temperature:	925°F
Feedwater Temperature:	250°F
Process Fluid Flow:	2,170,000 lb/hr
Process Fluid Pressure:	2500 psig
Process Fluid Outlet Temperature:	840°F
Process Fluid Inlet Temperature:	413°F
Process Coil Heat Absorption Rate:	600 MBtu/hr
Steam/Process Fluid Heat Duty Ratio:	50%/50%
Sulfur Removal:	90%
Particulate In Flue Gas:	0.03 lbs/MBtu Fired
NOx In Flue Gas:	0.6 lbs/MBtu Fired
Vacuum Bottoms Surface Moisture:	2% by Weight
Unit Turndown:	50% while maintaining 840°F process coil outlet temperature

Table 4

EDS Hybrid Boiler
Illinois Coal - EDS Residue
Predicted Performance

Description	Units	High Ash Residue 100% MCR	High Ash Residue 75% MCR	High Ash Residue 50% MCR	Low Ash Residue 100% MCR
Fuel Flow	lbs/hr	122,810	92,100	60,910	103,365
Evaporation	lbs/hr	487,200	365,400	243,600	487,200
Excess Air	%	20	20	20	20
Gas Recirculation	%	25.5	36.6	46.0	27.0
Tilt	Deg	0	+11	+30	0
Superheater					
Feedwater	°F	250	250	250	250
SH Outlet Press.	psig	1,250	1,250	1,250	1,250
SH Outlet Temp.	°F	925	925	925	925
Spraywater Temp.	°F	250	250	250	250
Spraywater Flow	lbs/hr	0	13,000	26,000	0
Gas Flow	lbs/hr	1,644,000	1,324,000	948,500	1,657,900
Gas Temp. ent. Platens	°F	2,073	1,978	1,935	2,075
Gas Temp. ent. Process Coil	°F	1,887	1,778	1,695	1,885
Gas Temp. ent. Air Heater	°F	559	535	510	555
Stack Temp.	°F	300	300	300	300
Process Coil					
Fluid Flow	lbs/hr	2,170,000	1,627,500	1,085,000	2,170,000
Coil Outlet Press.	psig	2,500	2,500	2,500	2,500
Coil Outlet Temp.	°F	840	840	840	840
Coil Inlet Temp.	°F	413	413	413	413
Heat Losses					
Dry Gas	%	4.53	4.39	4.24	4.53
Hydrogen & Moisture in Fuel	%	3.72	3.71	3.70	3.72
Moisture In Air	%	0.11	0.11	0.10	0.11
Unburned Combustible	%	0.25	0.25	0.25	0.25
Radiation	%	0.25	0.25	0.25	0.25
Unaccounted	%	1.50	1.50	1.50	1.50
Total Losses	%	10.36	10.21	10.04	10.36
Efficiency	%	89.64	89.79	89.96	89.64

TABLE 5

EDS HYBRID BOILER
ILLINOIS COAL-EDS RESIDUE
CIRCULATION SYSTEM
PREDICTED PERFORMANCE

FIRING RATE: MCR 487,200 LBS/HR EVAPORATION

	Front Wall	Rear Wall	Side Walls (Total)
Evaporation-(lbs/hr)	135,470	92,800	259,700
Water Flow-(lbs/hr)	1,625,700	1,252,500	3,377,300
Circulation Ratio	12	14	13
Velocity entering Tubes-(fps)	3.70	2.85	3.60
Velocity leaving Tubes-(fps)	7.45	5.40	7.00
Operating Pressure-(psig)	1,375	1,375	1,375
Operating Temperature-(°F)	587	587	587
Density at Lower Ring Header-(lbs/ft^3)	43.35	43.35	43.35
Density at Upper Collection Header-(lbs/ft^3)	21.61	22.88	22.48
Mean Fluid Density in Water Walls-(lbs/ft^3)	29.99	30.96	30.67

FIRING RATE: 50% MCR 243,600 LBS/HR EVAPORATION

	Front Wall	Rear Wall	Side Walls (Total)
Evaporation-(lbs/hr)	69,104	47,745	126,606
Water Flow-(lbs/hr)	1,433,905	1,098,129	2,797,201
Circulation Ratio	21	23	22
Velocity entering Tubes-(fps)	3.26	2.49	3.11
Velocity leaving Tubes-(fps)	5.27	3.88	4.96
Operating Pressure-(psig)	1,375	1,375	1,375
Operating Temperature-(°F)	587	587	587
Density at Lower Ring Header-(lbs/ft^3)	43.59	43.59	43.59
Density at Upper Collection Header-(lbs/ft^3)	26.96	28.01	27.61
Mean Fluid Density in Water Walls-(lbs/ft^3)	33.95	34.66	34.39

TABLE 6

PARTIAL LIST OF C-E
COAL FIRED UNITS WITH
TUBULAR AIR HEATERS AND NO
AIR HEATER SOOTBLOWING

	FUEL	EVAPORATION
Unit 1	High Volatile Bituminous	275,000 lbs/hr
Unit 2	Mid-West Bituminous	400,000 lbs/hr
Unit 3	Eastern Bituminous	350,000 lbs/hr
Unit 4	Semi-Bituminous	208,000 lbs/hr
Unit 5	Bituminous	500,000 lbs/hr
Unit 6	Bituminous	600,000 lbs/hr

TABLE 7

COMPARISON OF BACKPASS
DESIGN FLUE GAS TEMPERATURES AND VELOCITIES
FOR
TYPICAL C-E COAL FIRED UNITS

Unit 1 3,580,000 lb/hr Evap. 500 MW Eastern Bit.	—	1724°F / 58.7 fps	1535°F / 50.3 fps	—	1416°F / 43.1 fps	1327°F / 48.5 fps	—	1148°F / 56.1 fps	849°F / 55.2 fps
Unit 2 4,220,000 lb/hr Evap. 600 MW Midwest Bit.	1832°F / 71.0 fps	1704°F / 67.9 fps	—	—	1430°F / 64.5 fps	—	1243°F / 65.2 fps	—	—
Unit 3 3,800,000 lb/hr Evap. 520 MW Sub. Bit.	1794°F / 44.5 fps	1772°F / 66.4 fps	1638°F / 62.2 fps	1509°F / 58.7 fps	—	—	1242°F / 65.2 fps	—	—
Unit 4 4,150,000 lb/hr Evap. 560 MW Midwest Bit.	1794°F / 68.8 fps	1671°F / 66.4 fps	—	1525°F / 68.0 fps	1404°F / 62.9 fps	—	1184°F / 55.1 fps	—	—
EDS Hybrid Boiler Illinois EDS High Ash Vacuum Bottoms	1887°F / 28.4 fps	—	—	—	1376°F / 39.4 fps	—	—	—	1018°F / 29.7 fps

TABLE 8

FULL LOAD PROCESS COIL PERFORMANCE

PROCESS COIL SECTION

S_t/D_o (D_o = 4.5")	1.667	3.33	1.667
S_l/D_o (D_o = 4.5")	2.0	2.0	2.0
T_G (in/out) (°F) (Gas)	1018/560	1887/1376	1376/1018
T_F (in/out) (°F) (Process Fluid)	413/540	540/722	722/840
T_g (°F) (Avg. Gas Temp.)	789	1631	1197
T_f (°F) (Avg. Fluid Temp.)	476	631	781
LMTD	279	990	356
R_T (Overall Heat Transfer Rate)(1)	6.72	8.95	8.73
Material	304 SS	304 SS	304 SS
Conductivity - K (But-in/hr-ft^2 °F)	138	147	143
Process Fluid Coefficient (h_i)	244	275	225
D_o/D_i	1.45	1.45	1.45
Process Coil Absorption Rate (Btu/hr/ft^2) (2)	2720	12,850	4506

(1) The coil thickness used for the overall transfer rate calculation was fixed at the design point and used for the entire coil. Actual coil thicknesses will vary throughout its length.

(2) Absorption Rate in reference to the Inside Tube Surface.

D. Process Coil

The process coil is the heat exchanger through which the process fluid is preheated for the EDS process. Design guidelines for the process coil were provided by ER&E based on the operating experience of the EDS Coal Liquefaction Pilot Plant (ECLP) in Baytown, Texas. process coil arrangement can be seen on the hybrid boiler general arrangement drawing.

PROCESS COIL DESIGN CONDITIONS

- Heat duty: 600 MBtu/hr
  Process fluid flow rate: 2,170,000 lbs/hr
  Inlet temp: 413°F, Outlet temp: 840°F
  Pressure: 2500 psig
- 50/50 process/steam heat duty ratio
- Tube outside diameter: 4-1/2 in.
- 50% turndown
- Linear velocity of process fluid: 9 to 18 ft/sec.
- ± 5°F process outlet temperature
- Maximum film temperature: 900°F
- 1300°F steam temp. during decoking
- Inside film coefficient: See Figure 11
- Maximum heat transfer rates as a function of the process fluid temp: See Figure 12

SURFACE CONFIGURATION

Conventional utility steam generators utilize surface arrangements combining both vertical and horizontal configurations. The factors which influence the selection of one versus the other are:

- o Fuel properties
- o Economics
- o Compactness of the design
- o Minimizing of the boiler island plan area

A vertical surface configuration was specified for the process coil in order to prevent stratification of the process fluid and facilitate tube surface removal for maintenance purposes. The process fluid (a three phase mixture) is more easily separated in horizontal then vertical tubes. Long horizontal circuits would tend to cause seperation of phases due to density differences, and hence, localized overheating according to the thermal properties of each phase.

The selection of a vertical surface configuration also facilitates maintenance of the process coil. Platen sections or individual tube removal can be accomplished easily through the hopper opening under the process coil. The submerged scraper conveyor can be rolled to one side allowing access to the entire process coil area. The necessary hoist capacity has been included to allow individual coil loop sections to be easily handled during maintenance operations.

HEAT TRANSFER RATE PREDICTION

C-E heat transfer standards were used in the design of the process coil. The process coil is substantially different from the superheater and reheater surface installed in the convection pass of a conventional steam generator. The tube OD, tube thickness, and inside film coefficient (Figure 11) all affect heat transfer. The C-E heat transfer standards were compared over a wide range of tube sizes and flow rates with several other heat transfer standards and were found to be in agreement.

DESIGN CONSIDERATIONS

The design conditions and the predicted heat transfer rates have been previously specified. The following defines how the design conditions were applied to the design of the process coil.

The fouling characteristics of the vacuum bottoms and current coal firing practices determined the transverse spacing of the process coil. The C-E laboratory test result indicate a rapid initial ash buildup but deposit buildup does not occur due to the low bonding strength of the deposits. The flue gas erodes any subsequent ash deposition. The laboratory test results also indicate the ash deposits become sticky as they approach the vacuum bottoms ash initial deformation temperature of 2080°. Deposits in the ash fusion temperature zone tend to build up between sootblowing cycles. A transverse spacing[1] of 15-1/2 inches has been specified for the process coil for flue gas temperatures greater than 1500°F.

Once the transverse spacing has been determined the optimum element height for the process coil is determined by maintaining a maximum velocity of 45 fps in the process coil to minimize the potential for flyash erosion with a high ash fuel and to maintain acceptable convective heat transfer. Table 7 compares flue gas velocities for several coal fired units.

The average fluid velocity in the process coil is 18 fps at full load and approximately 9 fps at half load. By maintaining the process coil

15 inch transverse corresponds to a 10-1/2 inch clear; 7-1/2 inch transverse, 3 inch clear.

fluid velocity below 18 fps, internal tube erosion will be minimized and fluid side pressure drop minimized.

To limit coking in the process coil, a constraint on heat transfer rates were specified by ER&E as shown on Figure 11. As previously discussed, C-E heat transfer standards were used in the design of the process coil.

The longitudinal (depth) spacing of the process coil was dictated by the bending requirements. If the radius of bend curvature is too small, it is difficult to produce a uniform bend with a large diameter heavy wall tube. With this constraint the depth spacing was kept to a minimum of two times the tube outer diameter which is nine inches. The cavity width for the sootblowers is two feet, which is a standard for coal firing.

PROCESS COIL PERFORMANCE AND PHYSICAL DESIGN

A three section process coil comprised of 48 individual tube circuits with an average circuit length of 3400 ft. was selected to satisfy the previously discussed constraints and conditions. Two counterflow and a parallel flow sections were specified as shown on Figure 16.

SECTION I (Low Temperature Section)

The low temperature section is located downstream of Section III the low temperature section, and upstream of the primary airheater. It consists of 48 single tube assemblies with a transverse spacing between assemblies of 7.5 inches (for more details refer to the equipment specifications). A counterflow configuration is used with the process fluid entering the section at 413°F and leaving at 540°F. The flue gas enters the section at 1018°F and leaves at 560°F.

SECTION II (Intermediate Temperature Section)

The intermediate section is located downstream of the finishing superheater section and waterwall screen and upstream of Section III. It consists of 24 double tube assemblies with a transverse spacing between assemblies of 15 inches (for more details refer to the equipment specification). A counter flow configuration is used with the process fluid entering the section at 540°F and leaving at 722°F. The flue gas enters the section at 1887°F and leaves at 1376°F.

SECTION III (High Temperature Section)

The high temperature section is located downstream of Section II and upstream of Section I. It consists of 48 single tube assemblies with a transverse spacing between assemblies of 7.5 inches (for more details refer to the equipment specifications). A parallel flow configuration is used with the process fluid entering the section at 722°F and leaving at 840°F. The flue gas enters the section at 1376°F and leaves at 1018°F. Section III is the most important section with respect to the absorption rate limitations, see Fig. 15. The design absorption rates are 7,700 Btu/hr-sq.ft. at the inlet of the section, where the fluid temperature is 722°F, and 2100 Btu/hr-sq.ft. at the outlet (840°F).

FLOW UNBALANCE AND GAS BYPASSING

The process coil will be subjected to some uneven flue gas distribution across the width of the unit. A typical mass flow and temperature profile at the coil entrance can be seen on Figure 7. The unbalance will decrease rapidly due to the resistance effects of the coil. Gas unbalance orginates from the turbulence created in the firing system and during gas turns.

By placing several waterwall screen tube sections upstream of the process coil, the gas unbalance generated in the furnace is dampened to acceptable levels. The mass flow and temperature profiles entering the process coil result in relatively constant gas flows and temperature across the width of the coil section. Since the process fluid in each tube will be controlled independently, any unbalance of the process fluid temperature can be adjusted by regulating flow of the process fluid to each individual element.

Gas bypassing is also possible through the bottom of the coil and the submerged scraper conveyor hopper. In order to minimize the bypassing, a baffle is located in the hopper. The cold flow modeling of the Hybrid Boiler (to be performed during the Summer of 1982) is expected to give valuable information with regard to both flow unbalance and gas bypassing. The results of the modeling will help in defining the number and location of the baffles which minimizes flow unbalance and gas bypassing.

PROCESS COIL ROOF TUBE SUPPORT

During the course of the hybrid boiler design, the support mechanism for the process coil was analyzed with several design configurations discussed between C-E and ER&E. The objective of the design was to arrange the support system in such a manner as to reduce the number of roof penetrations while providing for tube expansion of both the process coil and steam cooled encasement. Other constraints included dissimilar welds, erosion of support ties and exposure to 1900^{o}F flue gases.

The support system for the process coil can be seen on the attached drawing. A stainless steel hanger rod is welded to the top of each process coil loop. A tube lined with insulation is fitted over the supporting hanger rod to provide protection from erosion and temperature. The support (hanger) rod passes up through the steam cooled roof tubes and is bolted to a steel channel beam which runs from front to rear of the process coil. The channel beam is also used to support the steam cooled roof tubes. Clips are welded to each of the roof tubes and are free to slide on a bar welded to the channel, allowing room for roof tube expansion. The channel beams are supported with hangers connected to the unit support steel.

Using the support method described, dissimilar welds between supporting members is eliminated. The stainless steel hanger rods attached to the coil are thermally protected allowing the process coil and roof to cool the rod. Roof penetrations have been minimized reducing the area prone to flue gas leakage. The coil penetrates the roof only to enter or exit the heat transfer area. Coil expansion characteristics along its length are markedly different from the roof tubes. This arrangement provides for the coil and roof tubes to be commonly supported yet allowed to expand independent of each other. The process coil will be tied to adjacent tubes along its height by using flex and slip spacers. These devices allow for vertical movement due to expansion, but prevent front to rear and side to side sway of the tubes.

OPERATIONAL CONSIDERATIONS

The primary means of process fluid coil outlet temperature control is the firing rate. Increasing the firing rate and maintaining a constant process fluid flow will increase the process fluid coil outlet temperature. Conversely, decreasing the firing rate will decrease the process fluid coil outlet temperature.

The two other means of varying the heat absorbed by the process coil are gas recirculation and windbox tilt. A discussion on the effect of gas recirculation and windbox tilt may be found in Section C, Design Considerations.

During the design phase the topics of potential tube leaks and considerations for coil replacement were discussed. A tubular air preheater was selected to eliminate the contact of the flammable process fluid and combustion air in the event of a process coil tube leak. Preliminary discussions regarding leak detection equipment and operating considerations in this mode were discussed with the final recommendations deferred until more detailed study can be made during the 1982 Phase II program.

DECOKING

Coke formation on the inside of the process coil tubes insulates the process fluid heat transfer from the fluid and tube wall. This in turn raises the tube wall metal temperature. When the tube wall metal temperature approaches its design value the unit is shutdown and decoked. The hybrid boiler has been designed to allow decoking. The design takes into consideration the expansion and temperature profiles that will exist during this operation.

The decoking process involves two phases, spalling and burning. During the spalling phase the coil will be subjected to a 1350°F maximum metal temperature. Nitrogen followed by steam will be used to spall the coke. The steam used in spalling at 353°F, 125 psig will be introduced at the low temperature section tube inlet and rise up to 1300°F at the outlet. Due to the arrangement of the coil, the steam will approach 1300°F at the end of the low temperature section of the coil. The steam will be close to 1300°F throughout the intermediate and high temperature sections. The flue gas entering the coil will be approximately 1320°F and leave at 840°F. There will be essentially no heat transfer through the process coil intermediate and high temperature sections except for a small amount of heat absorbed in the steam cooled walls of the process coil encasement. Effectively, all the heat is absorbed by the process coil during decoking is absorbed by the low temperature section. This unusual absorption profile is due to the ratio of flue gas to decoking steam and to the extensive coil surface. The process coil arrangement exposes the high temperature section, that is susceptible to coking, to 1300°F steam and more effective spalling.

During the burning phase air is introduced at the low temperature section tube inlet and will rise to 1300°F at the high temperature tube outlet. Due to the possibility of localized overheating as a result of the burning process coil, metal temperatures must be carefully monitored.

Gas recirculation is used to temper the flue gas to the process coil. Control of the decoking steam temperature will be achieved by controlling firing rate and can be tempered using a combination of windbox tilt to control the furnace outlet gas temperature and gas recirculation as in normal operation.

E. Availability Analysis

The work performed during this design study was primarily concerned with investigating the practicality of applying C-E's knowledge of equipment component failure and its affect on availability to: develop predicted Hybrid Boiler System availability, determine potential areas of availability reduction and to analyze mean time between failure, and analyze mean time to repair major system components.

In general terms, equipment availability may be considered as that fraction of time that a system or components is capable of operation. Moreover, if the assumption is made that most steam generators in the C-E data program, because of their size, are either on line or being repaired and little time is spent on standby, then availability, exclusive of scheduled outages, could be defined as:

Availability =

Forced Outage Rate can also be defined in terms of equipment availability as:

Forced Outage Rate =

C-E has determined that the components causing most of the outages and load reductions can be classified into the following nine major components categories for the Hybrid Boiler.

I Waterwalls

II Superheater/Convective Process Coil

III Tubular Air Preheater

IV Sootblowers/Submerged Scraper Conveyor

V Controls

VI Fans

VII Pulverizers

VIII Precipitators/SO_2 Scrubbers

A preliminary evaluation of the Hybrid Boiler forced outage rate was made based on availability records of utility boilers in the 400 to 600 MW range. Based on this data, C-E predicts a forced outage rate of 8 to 10% is possible for the Hybrid Boiler based on good operating and maintenance procedures.

F. Cost Estimate

Scope of Equipment

Boiler Island

Four (4) Radiant Pulverized Coal/EDS

Vacuum Bottoms Fired Units - Each unit consisting of:

- Boiler and its Appurtances incl. Non-Return Valves
- Fusion Welded Waterwall
- Superheater & Desuperheater
- Steam Cooled Back Pass
- Tilting Tangential Windboxes
- Four (4) Coal/EDS Bottoms Silos
- Four (4) C-E Bowl Mills/Unit - complete with C-E Feeders
- Solid State Burner Controls (FSSS)
- Air Ductwork from F.D. Fan to Burner and Mills
- Gas Duct to Tubular Air Heater Outlet
- Gas Recirculation Duct to Furnace
- Secondary Tubular Air Heater and Steam Coil Air Heater
- Buckstays & Misc. Casing
- Setting and Insulation and Lagging
- Dual Primary Air Fans complete with Motors
- Dual Forced Draft Fan complete with Motors
- Dual Induced Draft Fans complete with Motors
- Complete Sootblower System with Pipings, Valves and Fittings
- Structural Steel for Boiler and its Auxiliaries with Platforms, Walkways and Ladders
- Process Coil - Fabricated with SA-213 TP 304 Material
- One (1) Common Stack for four units including Dampers
- Instruction Manuals
- Erection and Service Representative
- Freight to Illinois

Precipitators

Four (4) Rigid Frame Electrostatic Precipitators - Each unit consisting of:

- Precipitators, Flange to Flange
- Transitions
- Access
- Support Steel

Insulation and Lagging (material only)
Instruction Manuals
Gas Flow Model Study
Erection Representative
Service Representative
Freight

(Foundations and Buildings not included)

Flue Gas Desulfurization Island

Six (6) Wet Flue Gas Scrubbers Modules - Each unit consisting of:

Absorber System
Additive System
Flue Gas Reheater System
Auxiliary Equipment
Electrical Equipment
Instruction Manuals
Training Program
Design Model
Gas Flow Model Study
Erection Representative
Service Representative
Freight

(Foundations and Buildings not included)

Pricing

Four (4) Hybrid Boilers & Auxiliary Equipment	$ 75,075,000	$113,075,000
Four (4) Process Coils & Support (excluding Steam Cooled Enclosure)	$ 82,225,000	$ 99,225,000
Total Boiler Island	$157,300,000	$212,300,000
Four (4) Precipitators	$ 13,840,000	$ 23,428,000
Wet Flue Gas Desulfurization Systems for four (4) Hybrid Boilers	$ 18,380,000	$ 26,572,000
Total Flue Gas Cleanup	$ 32,220,000	$ 50,000,000

G. Equipment Specifications

Section I - Coal Preparation

Coal Silos

Pulverizers (Fig. 1, 2)

Section II - Fuel Firing System

Tangential Fired Windbox (Fig. 3, 4, 5)

Furnace Safeguard Supervisory System

Section III - Steam Generator and Process Coil

Drum (Fig. 6)

Furnace Wall System

Steam Cooled Wall System

Superheater and Process Coil (Fig. 7, 8, 9, 10, 11, 12)

Desuperheater (Fig. 13)

Section IV - Auxiliary Equipment

Secondary Air Heater (Fig. 14)

Fans

Gas Recirculation System

Ductwork

Sootblowing System

Stack

Section V - Flue Gas Clean Up System

Particulate Removal (Fig. 15)

Flue Gas Desulfurization

Bottom Ash, Process Coil Ash and Pulverizer Rejects Removal System (Fig. 16, 17, 18)

Pneumatic Fly Ash Removal System (Fig. 19)

Section VI - List of Drawings

SECTION I - COAL PREPARATION

<u>COAL SILOS</u>

Number of Silos: 4

Height: 74 ft.

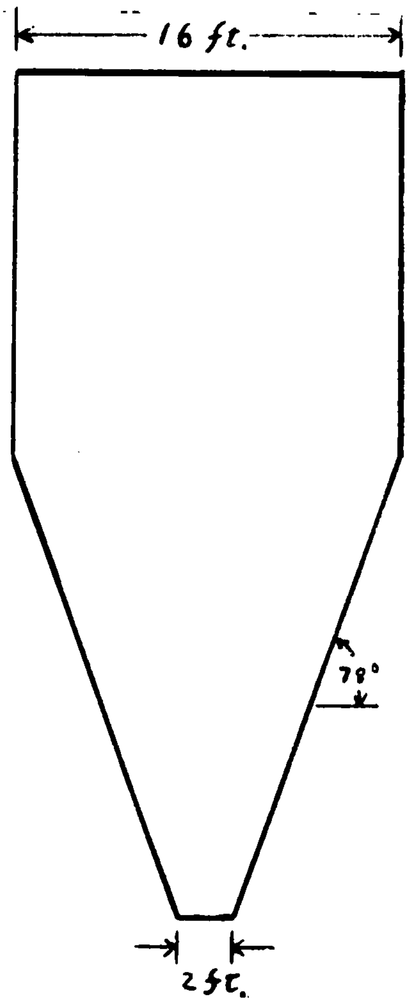
Diameter: 16 ft.

78° Hopper with a 2 ft. opening

Capacity: 10,600 ft^3

Diverter Valve

Manually operated knife-gate



PULVERIZERS

Number	Type	Size	Max. Capacity	Manufacturer
4	RP	623	52,500 lbs/hr Vacuum Bottoms 39,500 lbs/hr Coal	C-E Inc.

Included also in the pulverizing system are:

Integral volumetric Feeder

Pulverizer motor rated at 200 hp

Lube oil system

Seal air system

Spring loaded journal assembly

Steam inerting and fire detection system

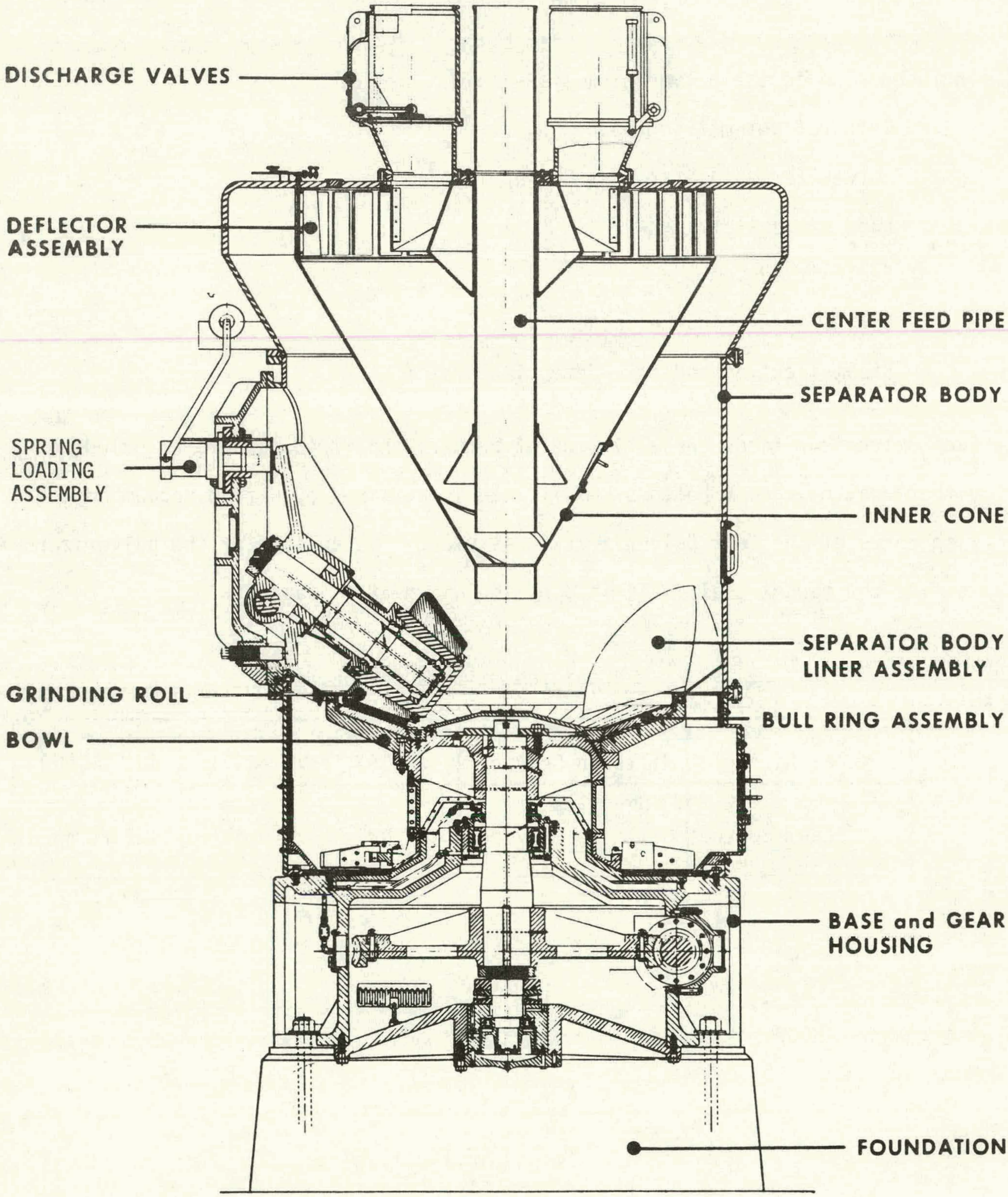
Each pulverizer feeds one elevation of burners and it is capable of grinding either coal or vacuum bottoms. Full load is attained by firing vacuum bottoms with three of the four pulverizers in service. The ability of the pulverizers to fire the parent coal is limited by the air heaters capacity.

Predicted Mill Performance

57% Load Coal Firing	3 of 4 Mills in Service	24,103 lbs/hr-mill	110 kw/mill
100% Load Vacuum Bottom Firing	3 of 4 Mills in Service	40,936 lbs/hr-mill	132 kw/mill

FIGURE 1

C-E PULVERIZER
TYPE RP



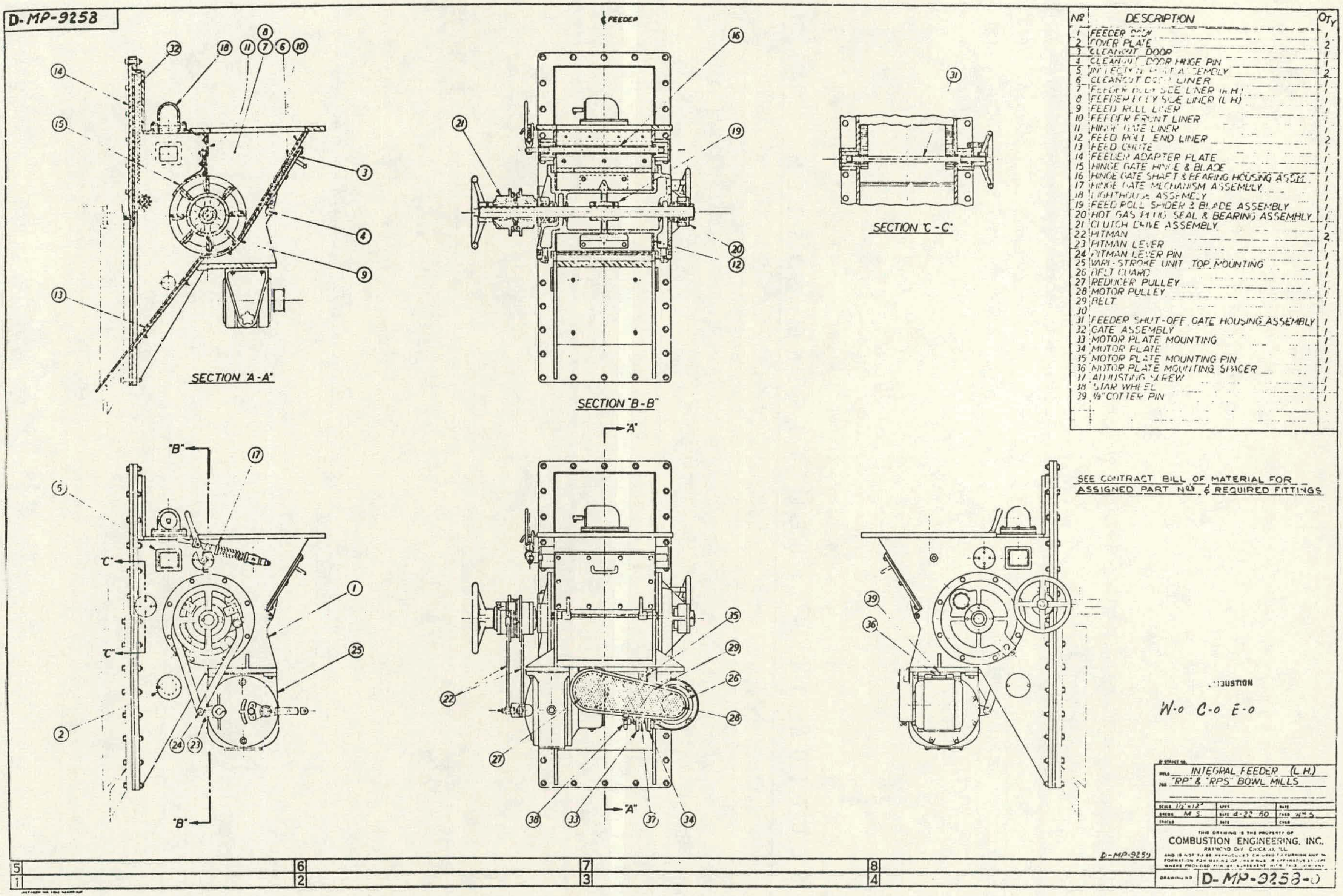

D-MP-9258
FEEDER
SECTION "A-A"
SECTION "B-B"
SECTION "C-C"
"A"
"B"
"C"
Nº DESCRIPTION QTY
1 FEEDER BODY 1
2 COVER PLATE 2
3 CLEANOUT DOOR 1
4 CLEANOUT DOOR HINGE PIN 1
5 2
6 CLEANOUT DOOR LINER 1
7 FEEDER SIDE LINER (R.H.) 1
8 FEEDER SIDE LINER (L.H.) 1
9 FEED ROLL LINER 1
10 FEEDER FRONT LINER 1
11 HINGE GATE LINER 1
12 FEED ROLL END LINER 2
13 FEED CHUTE 1
14 FEEDER ADAPTER PLATE 1
15 HINGE GATE HINGE & BLADE 1
16 HINGE GATE SHAFT & BEARING HOUSING ASSEM. 1
17 HINGE GATE MECHANISM ASSEMBLY 1
18 LIGHTHOUSE ASSEMBLY 1
19 FEED ROLL SPIDER & BLADE ASSEMBLY 1
20 HOT GAS SEAL & BEARING ASSEMBLY 1
21 CLUTCH DRIVE ASSEMBLY 1
22 PITMAN 2
23 PITMAN LEVER 1
24 PITMAN LEVER PIN 1
25 VARI-STROKE UNIT TOP MOUNTING 1
26 BELT GUARD 1
27 REDUCER PULLEY 1
28 MOTOR PULLEY 1
29 BELT 1
30
31 FEEDER SHUT-OFF GATE HOUSING ASSEMBLY 1
32 GATE ASSEMBLY 1
33 MOTOR PLATE MOUNTING 1
34 MOTOR PLATE 1
35 MOTOR PLATE MOUNTING PIN 1
36 MOTOR PLATE MOUNTING SPACER 1
37 ADJUSTING SCREW 1
38 STAR WHEEL 1
39 1/8" COTTER PIN 1
SEE CONTRACT BILL OF MATERIAL FOR ASSIGNED PART NOS. & REQUIRED FITTINGS
W-0 C-0 E-0
INTEGRAL FEEDER (L.H.)
"RP" & "RPS" BOWL MILLS
SCALE 1½" = 12"
DRAWN M.S.
DATE 4-22-60
THIS DRAWING IS THE PROPERTY OF
COMBUSTION ENGINEERING, INC.
DRAWING NO. D-MP-9258-0

FIGURE 2

SECTION II - FUEL FIRING SYSTEM

TANGENTIAL FIRED WINDBOX

Four (4) 18" windbox assemblies located in each corner of the furnace consisting of fuel and air compartments arranged vertically, complete with necessary insulation, ignitors, flame scanners, dampers and fuel connections, all shop assembled.

Four (4) water cooled, tilting fuel compartments per windbox assembly, capable of firing either coal or vacuum bottoms.

Two (2) IFM gas ignitors per windbox assembly

Three (3) Fireball Flame Scanners

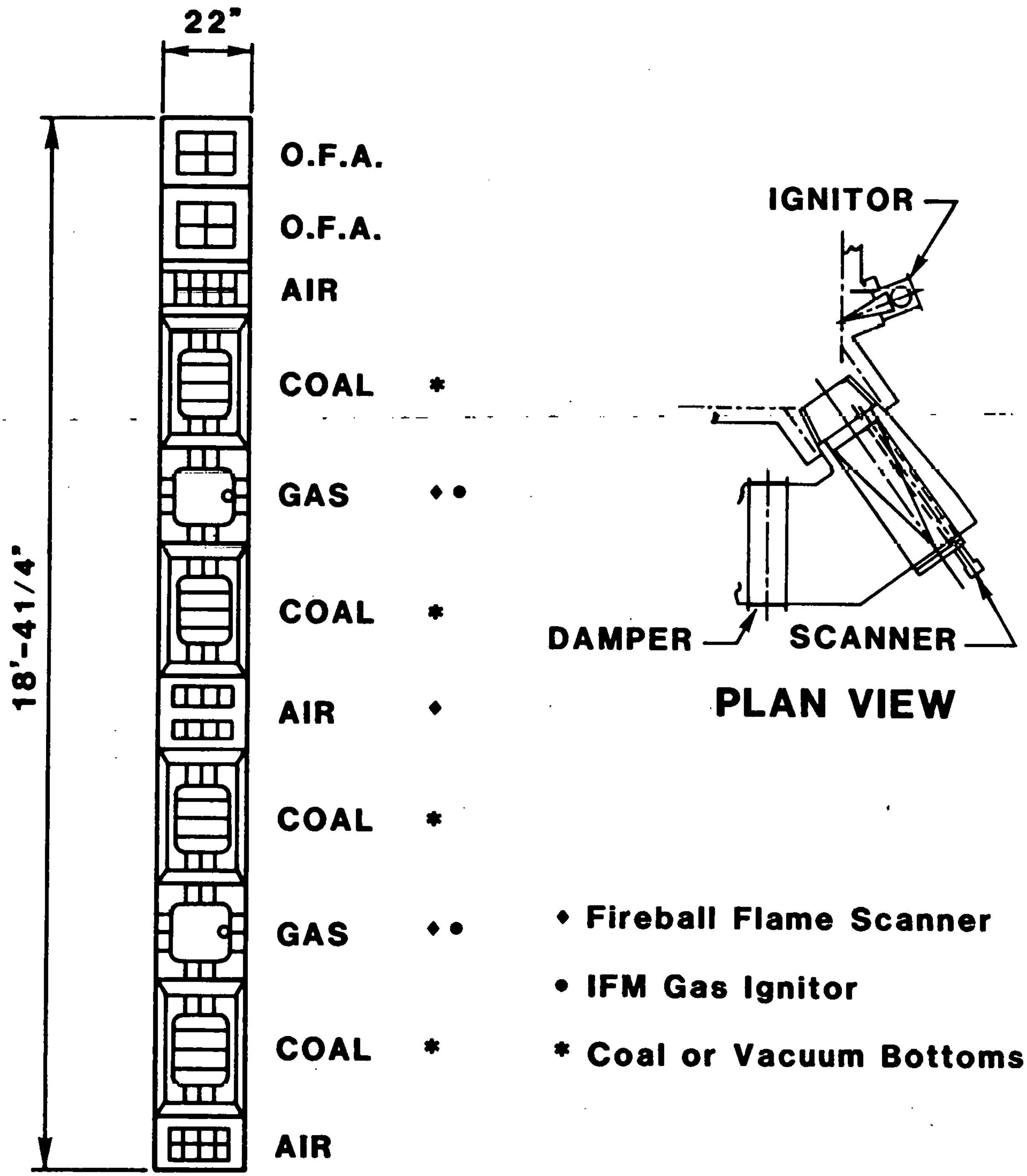
Two (2) Elevations of High Btu Gas Compartments

Two (2) Compartments of Overfire Air per windbox assembly

Fuel Pipe (from pulverizer to windbox): 12.75" OD with 0.375 in. thickness

C-E TANGENTIAL WINDBOX

FIGURE 3



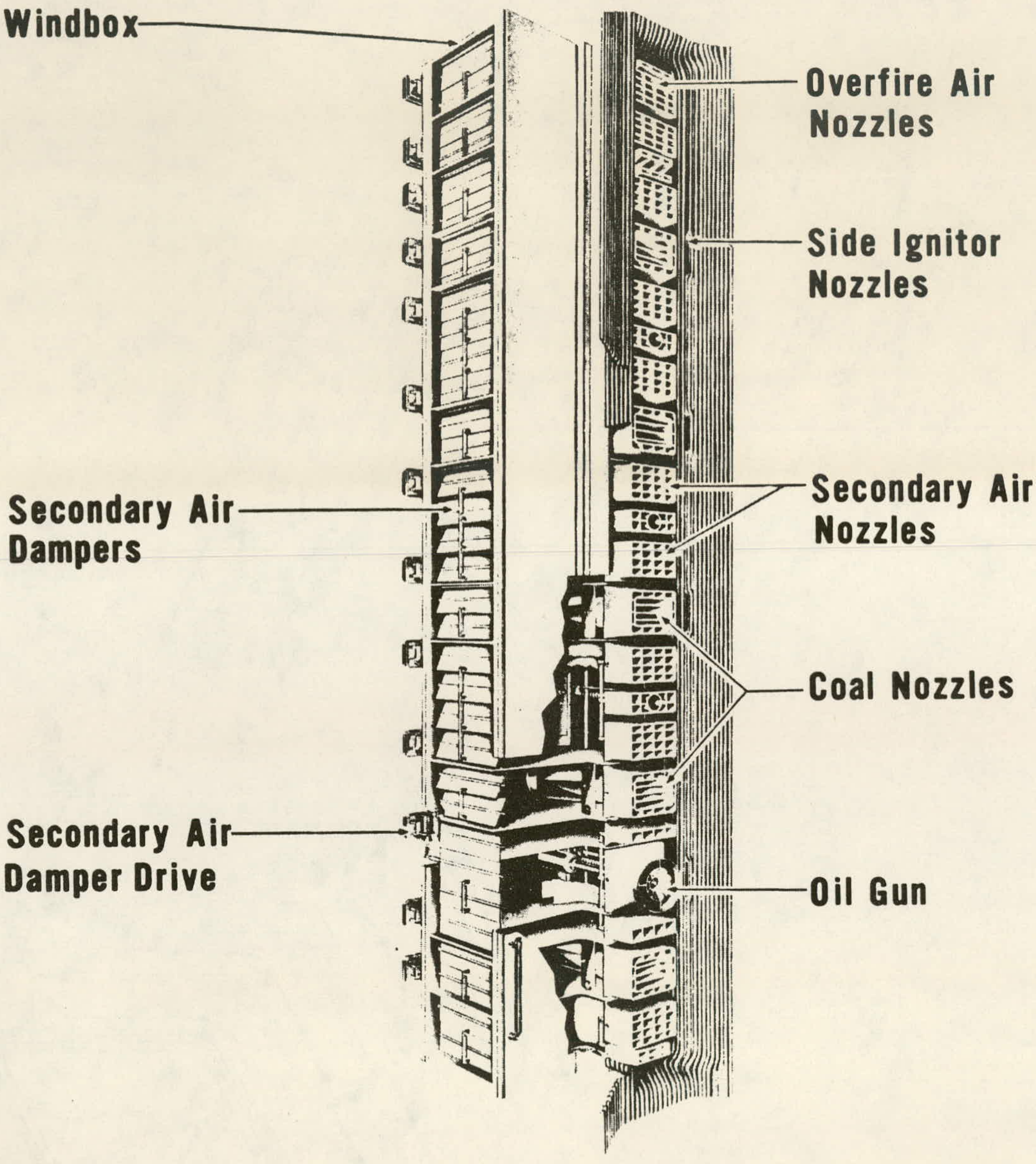
EXXON HYBRID BOILER
ILLINOIS COAL WINDBOX ASSEMBLY

NA-820155

FIGURE 4

TYPICAL

C-E TANGENTIAL FIRING WINDBOX



TFW
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POWER SYSTEMS

Illustration is typical of design, but does not necessarily show exact details of construction.

TYPICAL WATER-COOLED COMPARTMENT

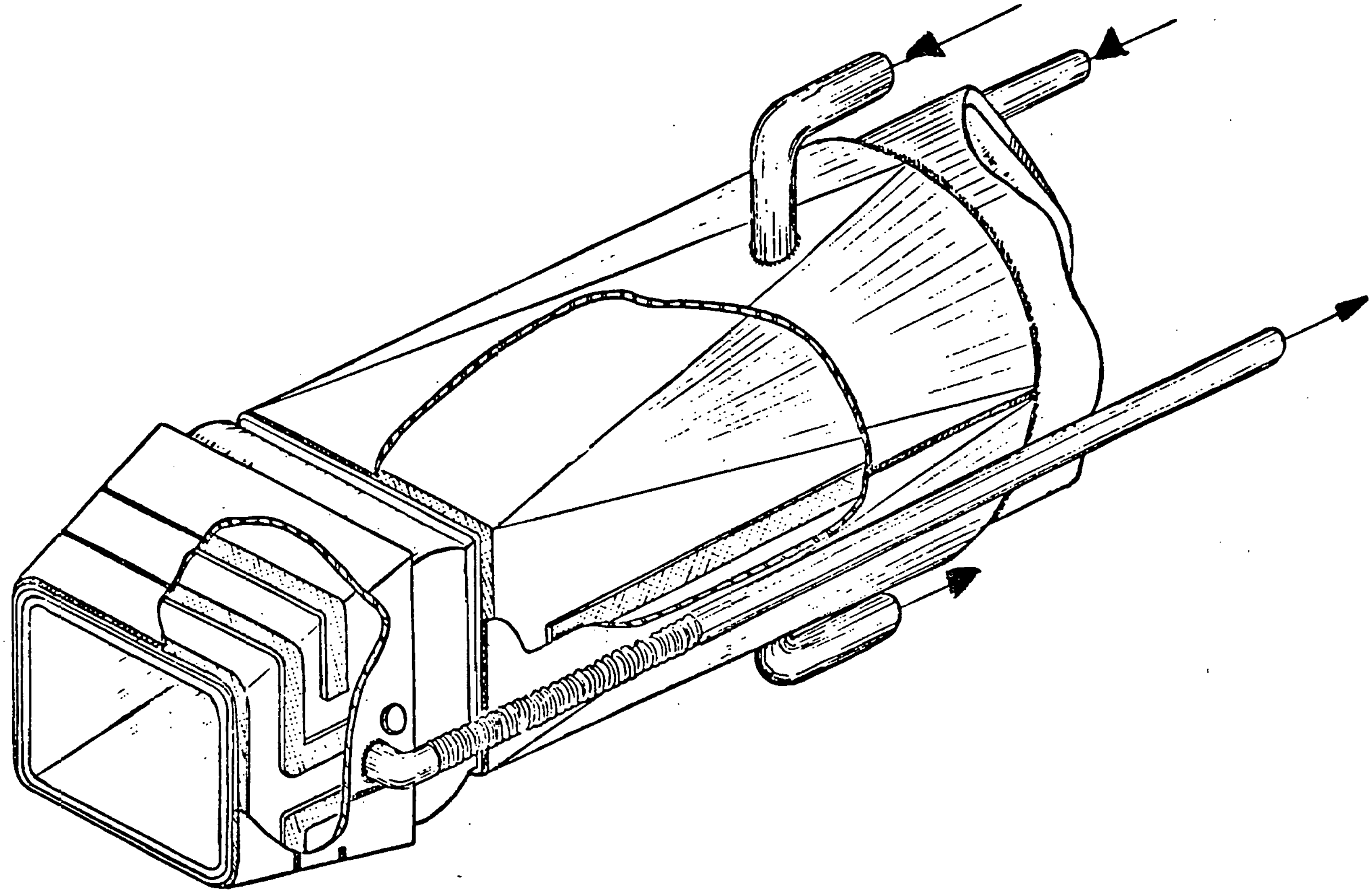


FIGURE 5

FURNACE SAFEGUARD SUPERVISORY SYSTEM

A FSSS will be provided for the automatic sequential control of the preparation, distribution, and admission of fuel and air into the furnace. The FSSS will perform the following functions, startup, shutdown, safety supervision, coordination, monitoring, and remote status display.

FSSS Equipment

One (1)	Control console insert (switches pushbuttons and indicating lamps)
One (1)	Control Cabinet
Eight (8)	Locally mounted ignitor control cabinets with integral mounted isolation valving
Eight (8)	Locally mounted warmup gas control cabinets
Twelve (12)	Fireball flame scanners
One (1)	Ignitor gas header double block and vent valve
Eight (8)	Ignitor gas trip valves
One (1)	Warmup gas header double block and vent valves
Eight (8)	Warmup gas elevation double block and vent valves

Miscellaneous pressure switches

SECTION III - STEAM GENERATOR AND PROCESS COIL

DRUM

Location	Number	Length*	Inside Diameter
Upper	1	25'0"	60"

(*) Weld to weld

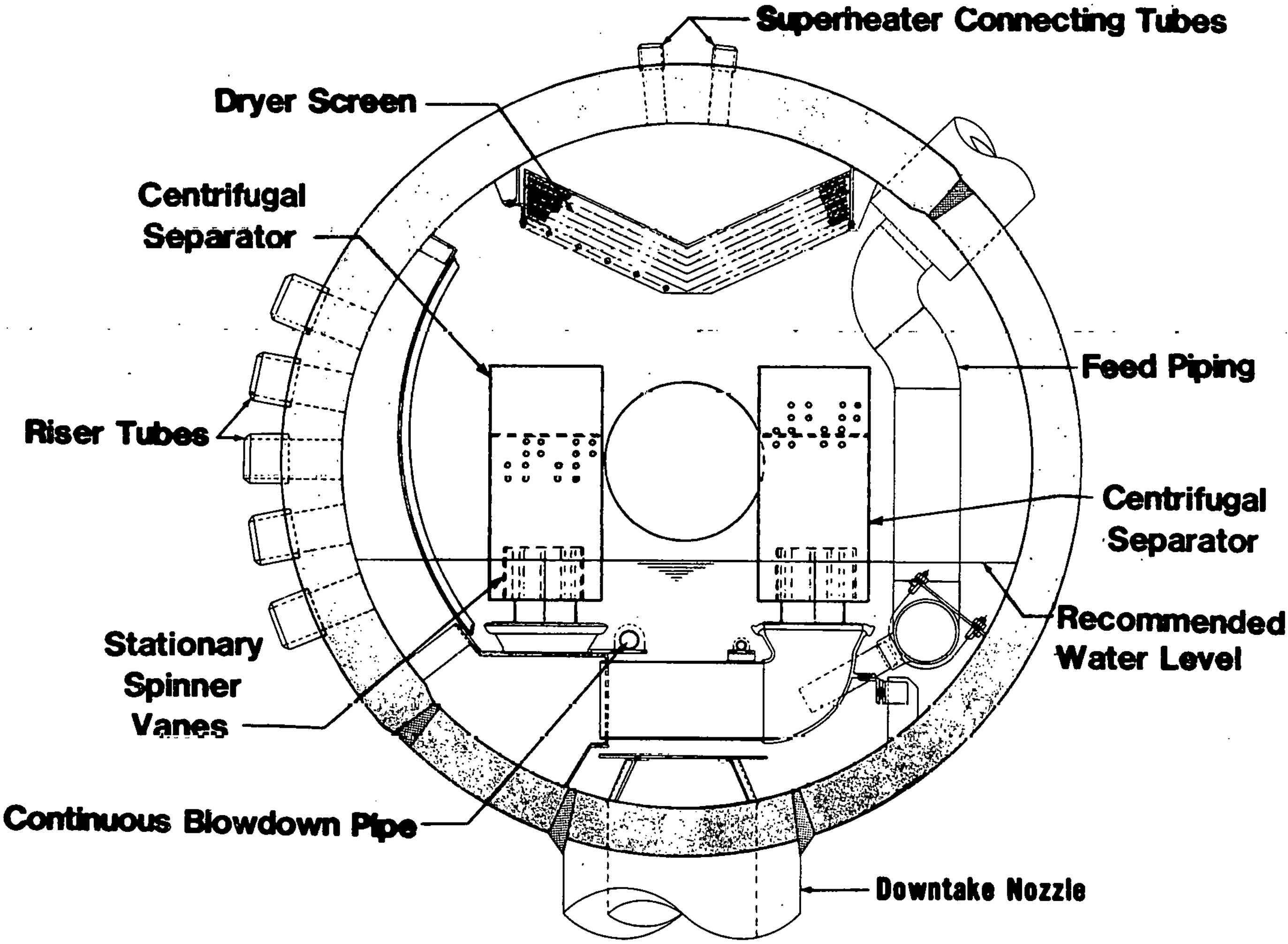
Centrifugal Separator Internals (Figure 6)

Downcomers

Number	Outside Diameter
2	18.00

FIGURE 6

DRUM INTERNALS
CENTRIFUGAL TYPE



CE POWER SYSTEMS

Illustration is typical of design, but does not necessarily show exact details of construction.

FURNACE WALL SYSTEMS

Location	Tubes Number	O.D.	MWT*	Type Construction
Furnace Front Wall @ Roof	120	2.500	.188	Fusion Welded
Furnace Rear Wall	120	2.500	.188	Fusion Welded
Furnace Side Walls	273	2.500	.188	Fusion Welded
Waterwall Relief Tubes				
Front Wall	30	5.563	.375	—
Rear Wall	30	5.563	.375	—
Side Walls	52	4.500	.300	—

(*) Minimum Wall Thickness

Lower Headers, O.D. = 16.00 in.

Upper Headers, O.D. = 8.625 in.

Approximate Furnace Projected Surface: 16,750 ft^2

Approximate Furnace Volume: 105,200 ft^3

Furnace Width: 29.917 ft.

Furnace Depth: 33.917 ft.

Furnace Gas-Side Pressure

The furnace will be capable of withstanding an internal pressure of ±26 in. of water gage.

STEAM COOLED WALL SYSTEM

Steam Cooled Wall Supply Tubes

Number	O.D.	MWT	Material
20	4.50 in.	0.300 in.	106 B

Cavity Walls

57 tubes wide

Material: SA-210

Spacing: 2.50 in.

MWT: .180 in.

OD: 2.00 in.

Process Coil Steam Cooled Walls

196 tubes wide

Material: T-1

Spacing: 4.00 in.

MWT: .180 in.

OD: 2.00 in.

FORM NO. 560 (6-58)

Combustion Engineering, Inc.

UTILITY PRODUCTS, PERFORMANCE DESIGN

Windsor, Conn.

SUPERHEATER, PROCESS COIL AND ECONOMIZER

Page No.

Contract No. 900347 Name EDS Hybrid Boiler No. of Blrs. 4

Boiler Type Nat. Circ. F.W. 29'-11" F.D. 33'-11" Burners Tilting Tangential

Fuel Illinois Coal or Vacuum Bottoms Specs.

Proposal

DESIGN PERFORMANCE DATA

Negotiation No.

	SUPERHEATER	PROCESS COIL
CONTROL TEMPERATURE °F	925	840
CONTROL RANGE LB/HR.	243,600 - 487,200	1,085,000 - 2,170,000
CONTROL TYPE	Tilt/Spray	Gas Recirculation
PRESSURE AT OUTLET PSIG.	1250	2500

ARRANGEMENT DATA

Quantities indicated are per boiler. Heating surfaces are gas touched unless specified otherwise.

SECTION	NO. ASSEMB.	NO. ELEM.	NO. LOOPS	SPACING — INS. S_T	SPACING — INS. S_L	TUBE O. D. INS.	HEATING SURFACE LN. FT.	HEATING SURFACE DEVEL.—FT^2	HEATING SURFACE PROJ.—FT^2	
SH Platen	12	60	1	30.00	2.375	2.00	4,380	-	1,294	
SH Pendant	20	80	1	18.00	4.000	2.00	4,580	-	1,805	
Process Coil										
Int.Temp.Section	24	48	6	15.00	9.000	4.50	23,000	27,140	-	
High Temp.Section	48	48	12	7.50	9.000	4.50	48,550	54,290	-	
Low Temp.Section	48	48	24	7.50	9.000	4.50	92,100	108,570	-	

Remarks

Engineer Date Reviewed with

Revised

Combustion Engineering, Inc.

CE 2506 (2/63)

UTILITY PRODUCTS, PERFORMANCE DESIGN

SUPERHEATER, PROCESS COIL AND ECONOMIZER

Page No.__________

Contract No. 900343 Name EDS Hybrid Boiler

HEADERS, PIPING AND MISC. DATA

Quantities indicated are per boiler.

ITEM	NO. REQ'D.	O. D. INS.	I. D. OR THICK - INS.	A. S. M. E. SPEC.	DESIGN PRESS. PSIG	DESIGN TEMP. °F	NIPPLE DESIGN TEMP. °F	CONNECTIONS
SH Platen Inlet	1	10-3/4	1.00	SA- 106 B	1500	700		
SH Platen Outlet	1	12-3/4	1.00	SA- 335 P-12	1500	800		
SH Pendant Inlet	1	14	1.094	SA- 335 P-12	1500	800		
SH Pendant Outlet	1	14	1.50	SA- 335 P-12	1500	1000		
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				
				SA-				

Remarks

Engineer Date Rev.

PROCESS COIL

Material: SA-213 TP-304H

Specifications

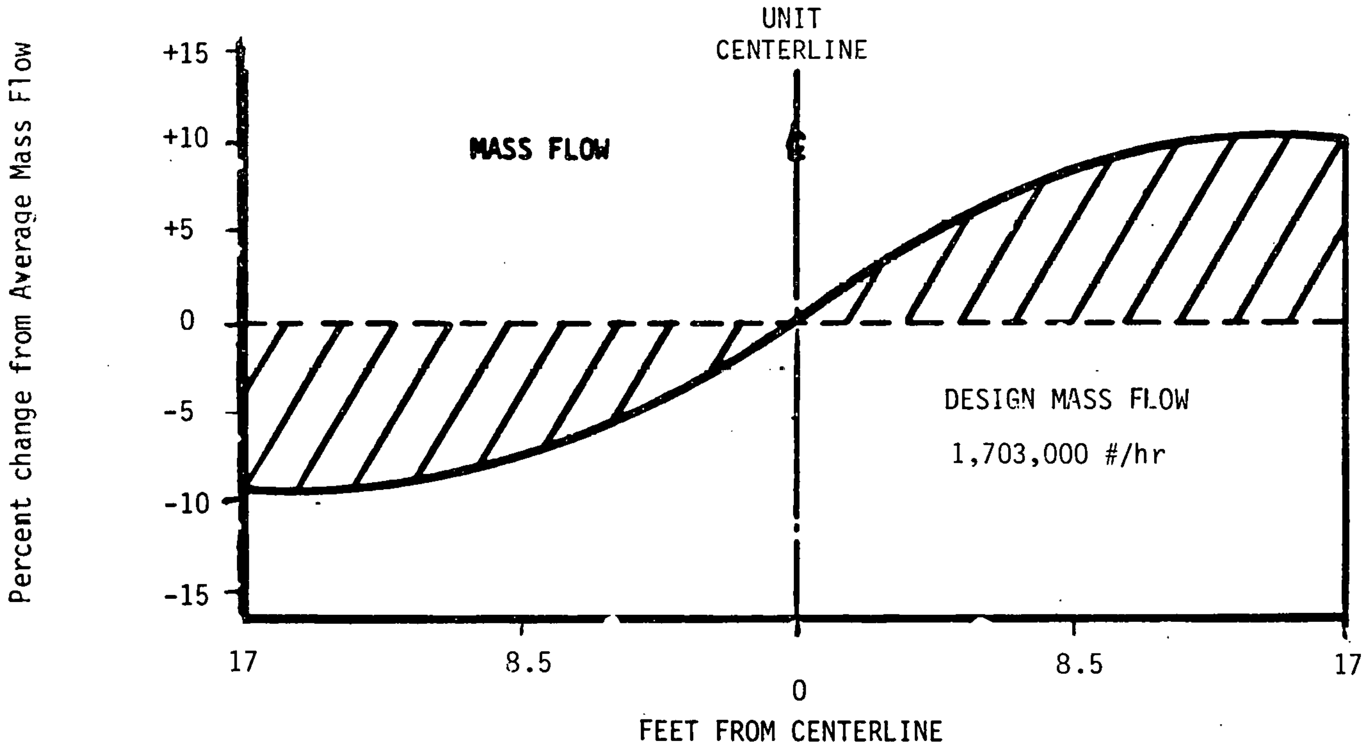
	Tube O.D.	MWT	Tubes Deep	S_T	S_L
Intermediate Temp. Section	4.50 in.	.612 in.	24	15 in.	9 in.
High Temp. Section	4.50 in.	.661 in.	24	7.5 in.	9 in.
Low Temp. Section	4.50 in.	.612 in.	48	7.5 in.	9 in.

FIGURE 7

EDS HYBRID BOILER

MASS FLOW AND TEMPERATURE PROFILES

The mass flow and temperature profiles shown below are the predicted unbalance values entering the process coil. These values do not account for the mediating effects of the screen tubes and cavity upstream of the coil entrance.



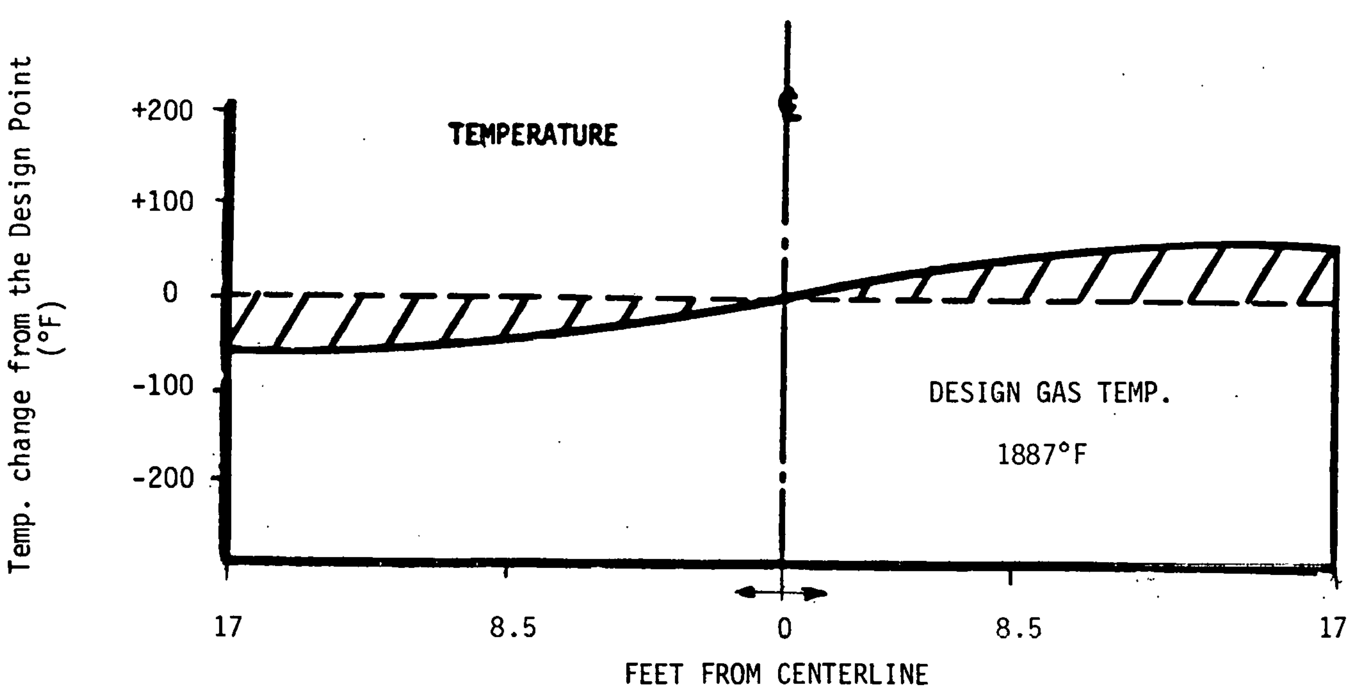
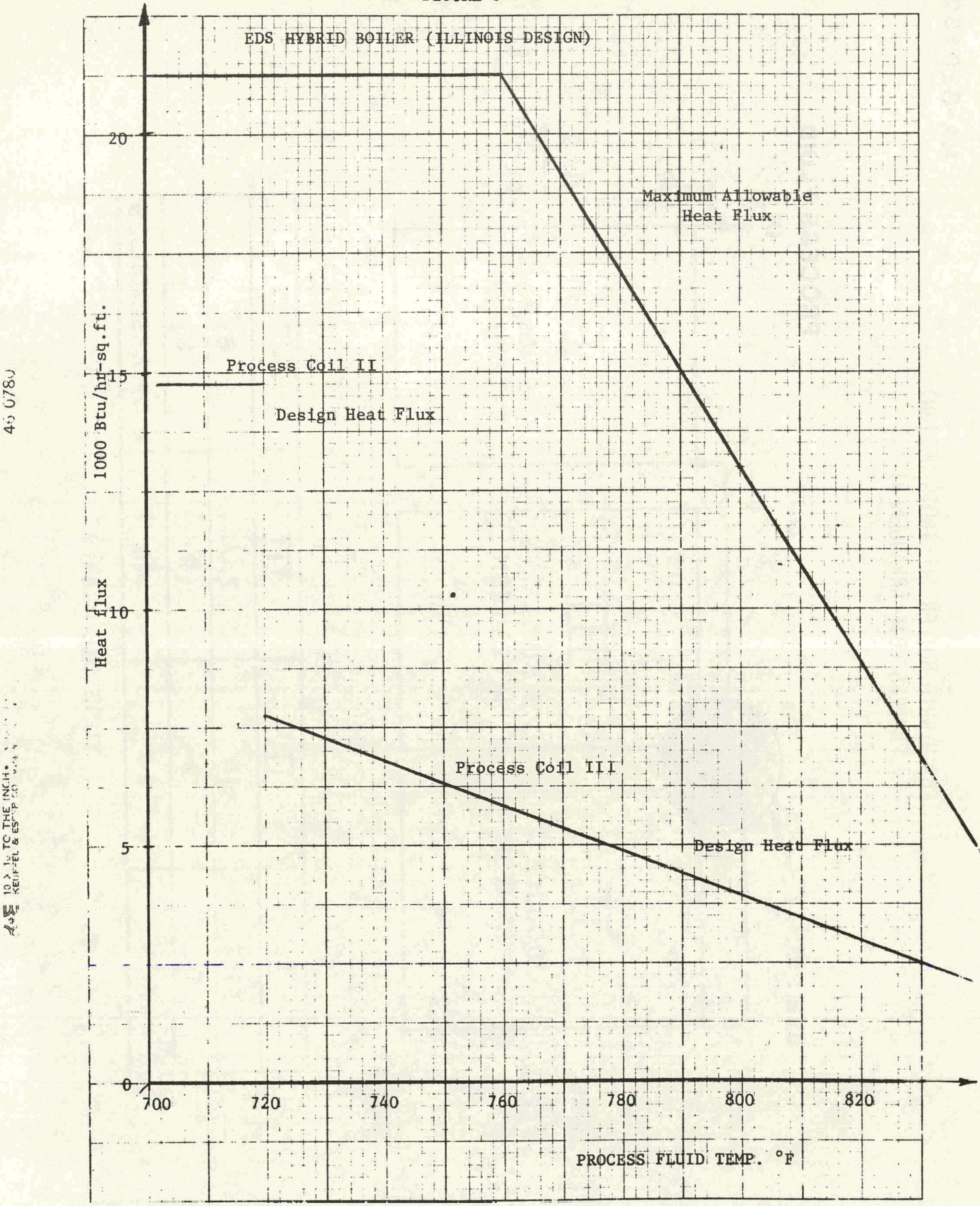
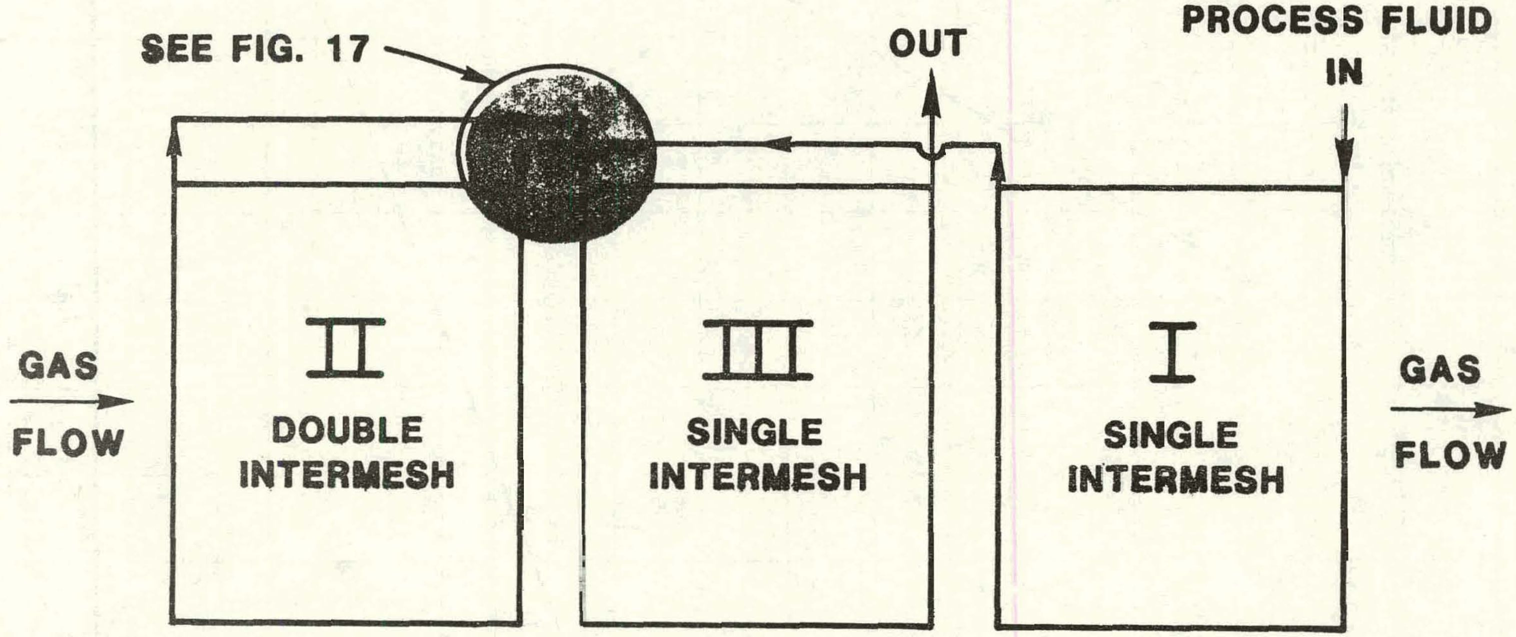


FIGURE 8


EDS HYBRID BOILER (ILLINOIS DESIGN)
Maximum Allowable
Heat Flux
Process Coil II
Design Heat Flux
Process Coil III
Design Heat Flux
Heat flux 1000 Btu/hr-sq.ft.
20
15
10
5
0
700
720
740
760
780
800
820
PROCESS FLUID TEMP. °F

EDS HYBRID BOILER (ILLINOIS DESIGN)
PROCESS COIL ARRANGEMENT



I	II	III	
7 1/2	15	7 1/2	S_T
9	9	9	S_L
48	24	48	# OF ASSEMBLIES

TUBE O.D. = 4 1/2"

FIG. 9

EDS HYBRID BOILER ILLINOIS EDS
PROCESS COIL ARRANGEMENT

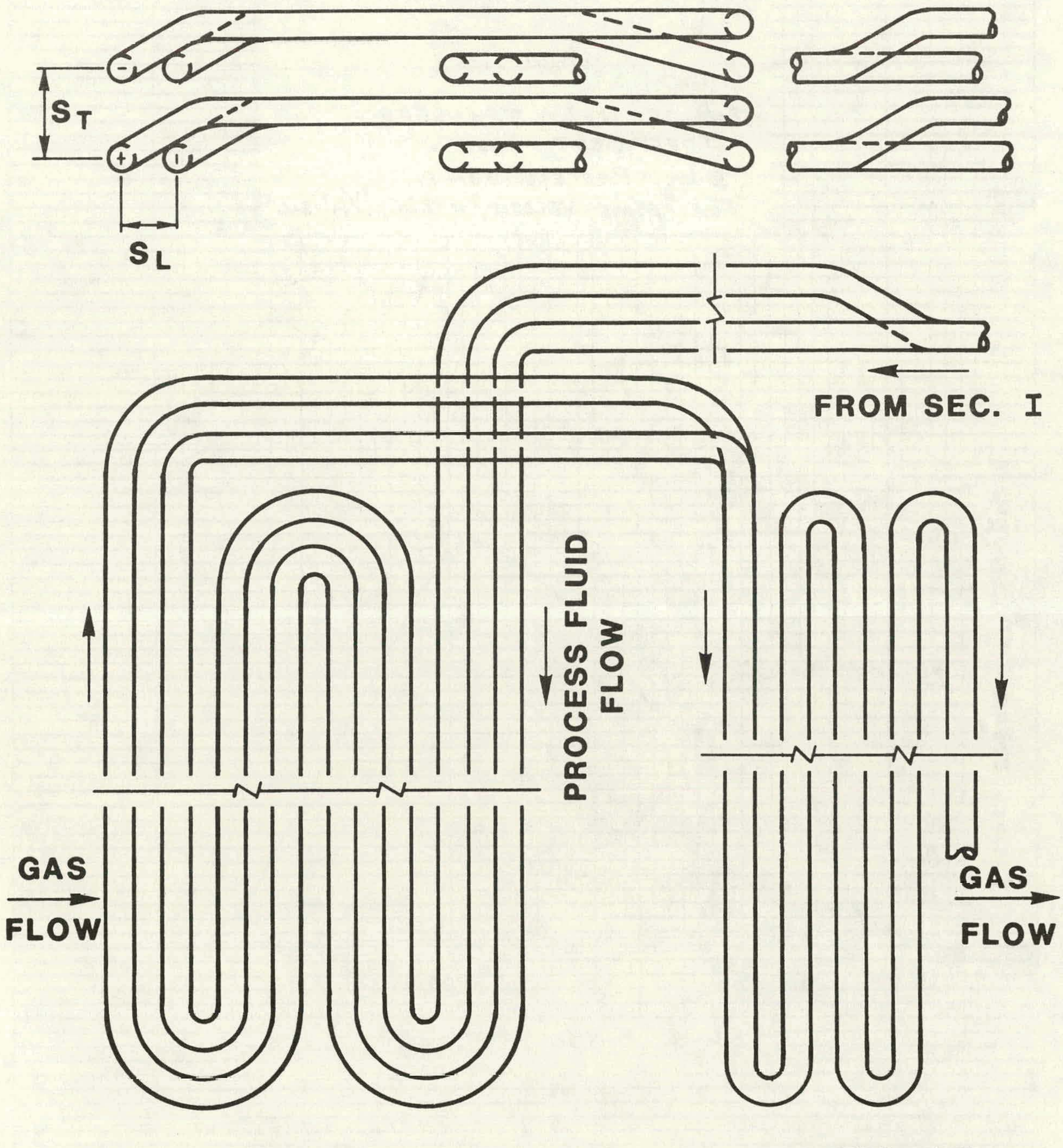


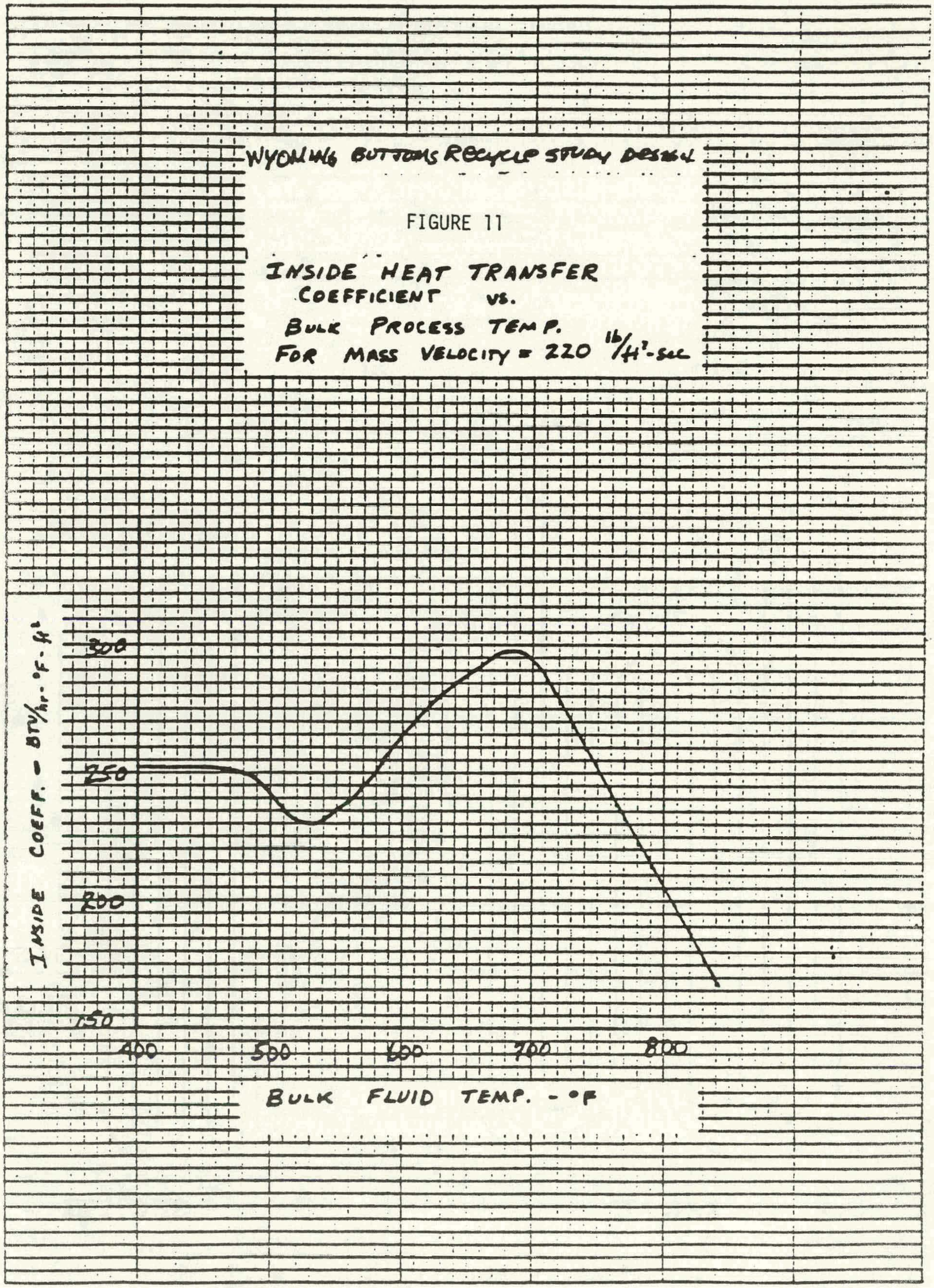
FIG. 10

NA-820153

WYOMING BUTTONS RECYCLE STUDY DESIGN

FIGURE 11

INSIDE HEAT TRANSFER COEFFICIENT VS. BULK PROCESS TEMP. FOR MASS VELOCITY = 220 lb/ft²-sec



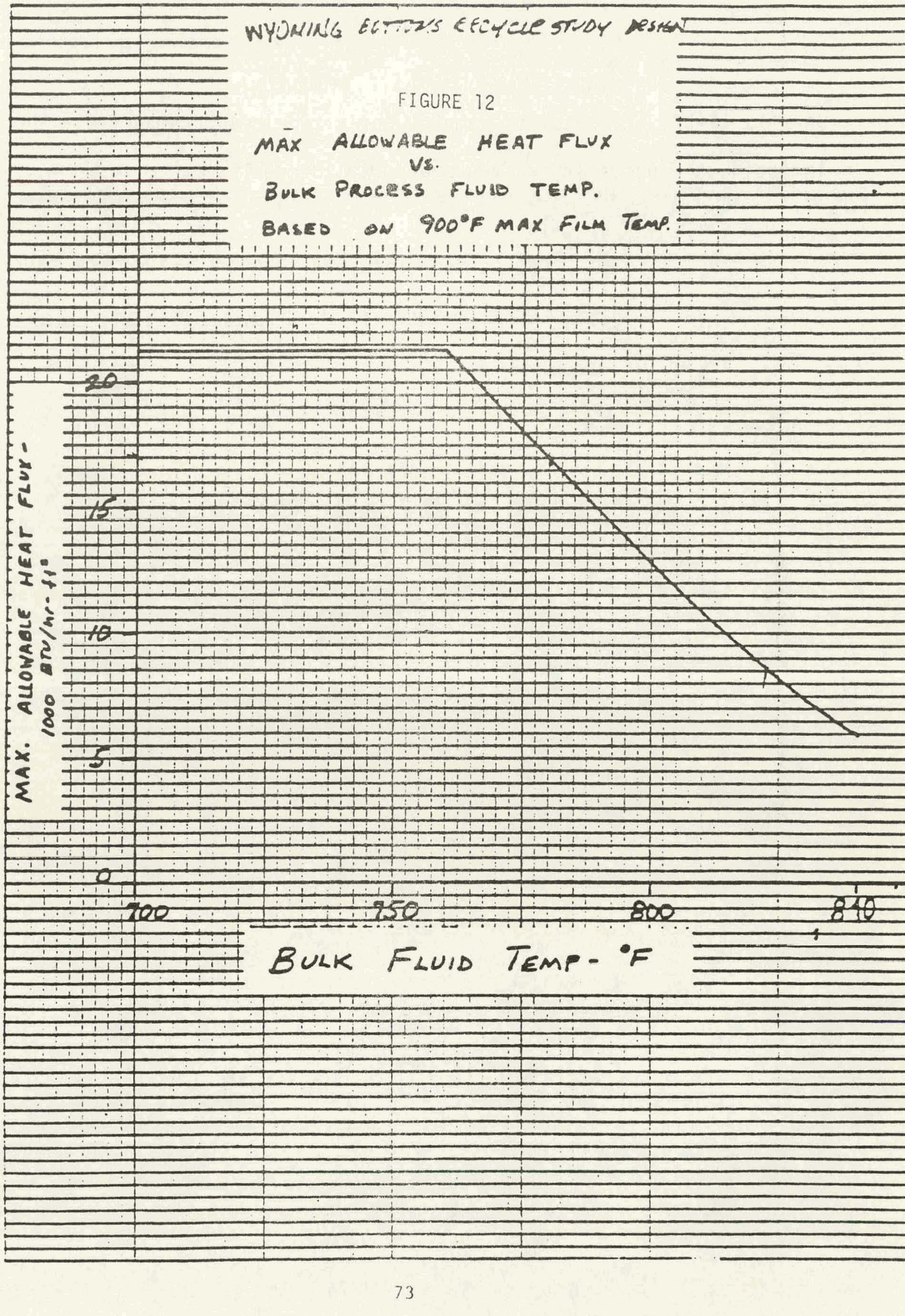


FIGURE 12

MAX ALLOWABLE HEAT FLUX
VS.
BULK PROCESS FLUID TEMP.
BASED ON 900°F MAX FILM TEMP.

DESUPERHEATER

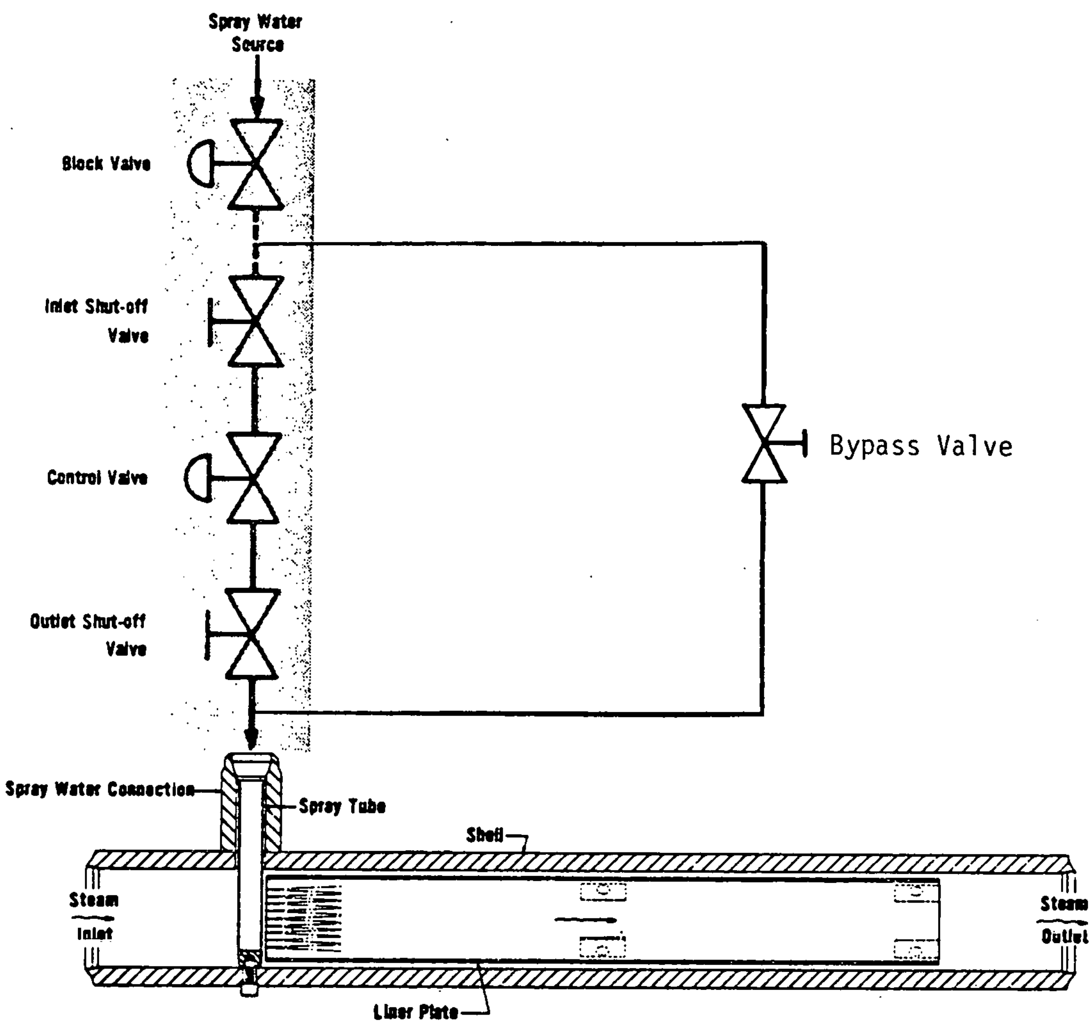
One (1) 12-3/4 in. outside diameter spray type desuperheater for the steam, including the necessary valves and spray internals.

Spray temperature: 250°F

Maximum spray flow: 50,000 lbs/hr

FIGURE 13

C-E DESUPERHEATER



POWER SYSTEMS

Illustration is typical of design, but does not necessarily show exact details of construction.

SECTION IV - AUXILIARY EQUIPMENT

SECONDARY AIR HEATER

3-pass tubular air heater with the gas through the tubes and secondary air over the tubes (see Figure 8).

Diameter of tubes:	2.5 inches
Thickness:	12 gauge
Number of tubes wide:	113 per pass
Number of tubes deep:	50 per pass
Tubes spacing - width:	3.125 inches
Tubes spacing - depth:	3.125 inches
Tube material:	SAE-1010
Total heating surface:	283,255 sq.ft.

C-E TUBULAR AIR HEATER

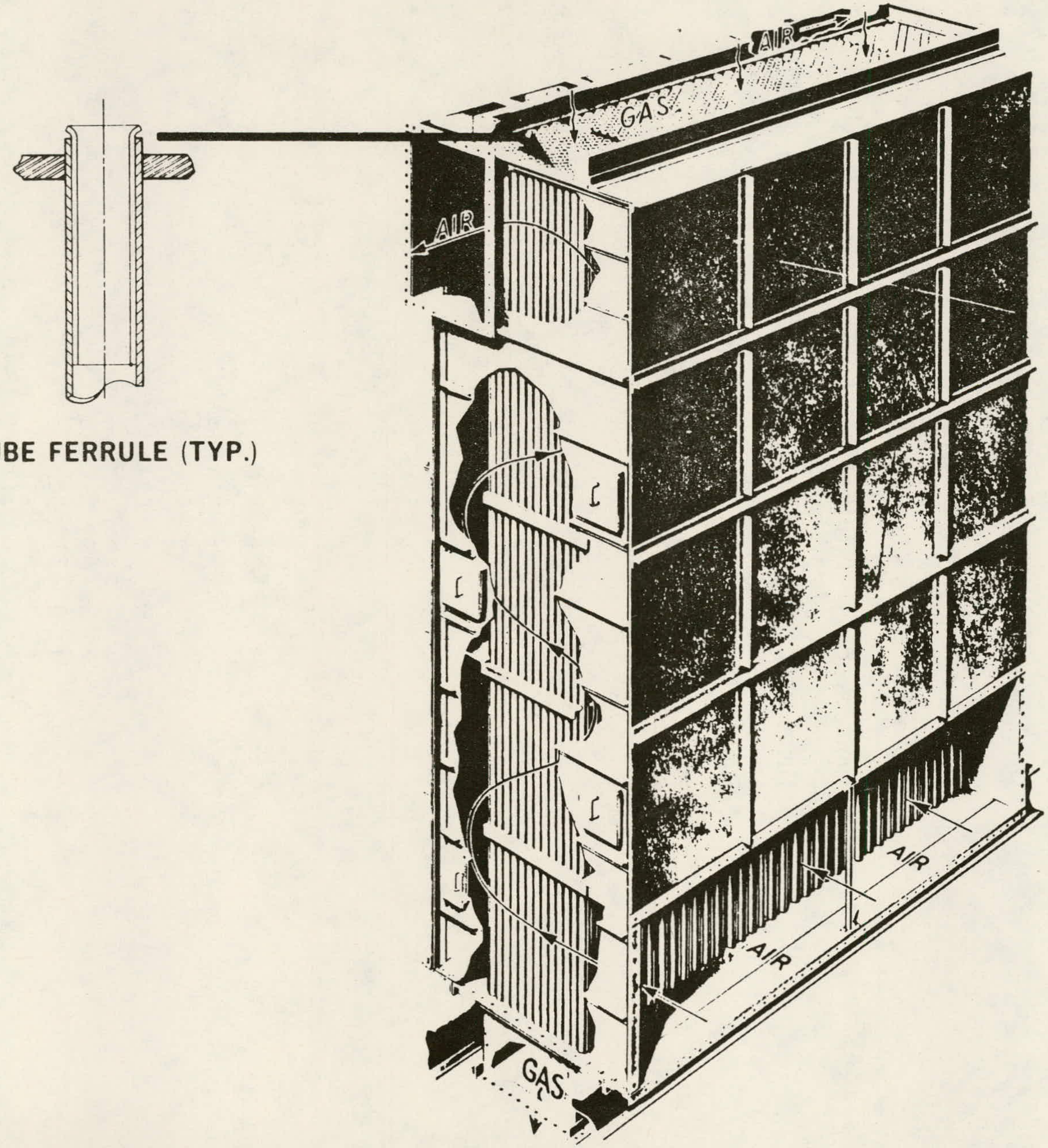


FIGURE 14

FANS

The fan specifications are such that the fans can provide 60% of the full flow rate with either one forced draft or one induced draft fan out of service. If one primary air fan is out of service, 66% air flow to the mills can be achieved. All fans are motor driven, constant speed units.

Primary Air Fan

Description	Actual	Test Block
Number of Fans	2	-
Volumetric Flow (cfm)	114,000	142,590
Static Pressure Rise (in.wg)	29.0	43.5
Operating Speed (rpm)	1800	1800
Type of Control	Inlet Vanes	Inlet Vanes

Forced Draft Fan

Description	Actual	Test Block
Number of Fans	2	-
Volumetric Flow (cfm)	634,900	761,900
Static Pressure Rise (in.wg)	13.10	18.85
Operating Speed (rpm)	1800	1800
Type of Control	Inlet Vanes	Inlet Vanes

Induced Draft Fan

Description	Actual	Test Block
Number of Fans	2	-
Volumetric Flow (cfm)	1,021,750	1,226,100
Static Pressure Rise (in.wg)	-10.4/+12.00	-14.55/16.80
Operating Speed (rpm)	900	900
Type of Control	Inlet Vanes	Inlet Vanes

GAS RECIRCULATION SYSTEM

Gas is recirculated from the outlet of the induced draft fan to the bottom of the furnace for process coil outlet temperature control. +12.00 in.wg at the outlet of the ID fan assures adequate head to recirculate the flue gas.

Control of the gas flow is provided through two sets of dampers; one in the main duct to the stack and another one in the GR duct.

GR duct cross-section: 32 sq.ft.

DUCTWORK

The ductwork included in C-E's scope of supply:

Air Ducts

From the outlet of the forced draft fan to the secondary air heater. From the outlet of the secondary air heater to the windbox.

In the primary air system, from the outlet of the P.A. fans to the pulverizer.

Gas Ducts

From the outlet of the process coil to the inlet of the secondary air heater.

Between the outlet of the secondary air heater and the electrostatic precipitator.

Ductwork associated with the I.D. fans and into ducts acting as 4 unit common plenum's between the ESP and the FGD modules.

Gas recirculation ductwork running from the outlet of the induced draft fans to the bottom of the furnace.

Duct connecting the six FGD modules to the stack.

SOOTBLOWING SYSTEM

The following electrically operated, automatic-sequential equipment are included in the Sootblowing System:

- 60 Wall Blowers

  Each blower includes an electric motor drive, mechanically operated valve with adjustable pressure control, stellited valve seats and disc.

- 39 Retractable Blowers With 30 ft. Travel

For the individual sootblower location see drawing EP-813-199-4

STACK

All four Hybrid Boilers in the boiler island designed for the Illinois location feed into a single common stack.

Material:	Corten Steel
Gas Temperature:	300°F
Stack Diameter:	23.5 ft.
Stack Height:	250 ft.

Stack Thickness:

Elevation	Thickness
0-60 ft.	3/4 in.
60-80 ft.	5/8 in.
80-140 ft.	1/2 in.
140-200 ft.	3/8 in.
200-250 ft.	1/4 in.

SECTION V - FLUE GAS CLEAN UP SYSTEM

ELECTROSTATIC PRECIPITATOR

The electrostatic precipitator has frame work for six fields with five fields initially installed. Each field contains discharge and collection electrodes, electrode rappers for cleaning. Underneath the field is a hopper for temporary storage of particulate.

Scope of Supply

Precipitator, flange to flange

Transitions

Access

Support Steel

Insulation and Lagging (material only)

Instruction Manuals

Gas Flow Model Study

Erection Representative

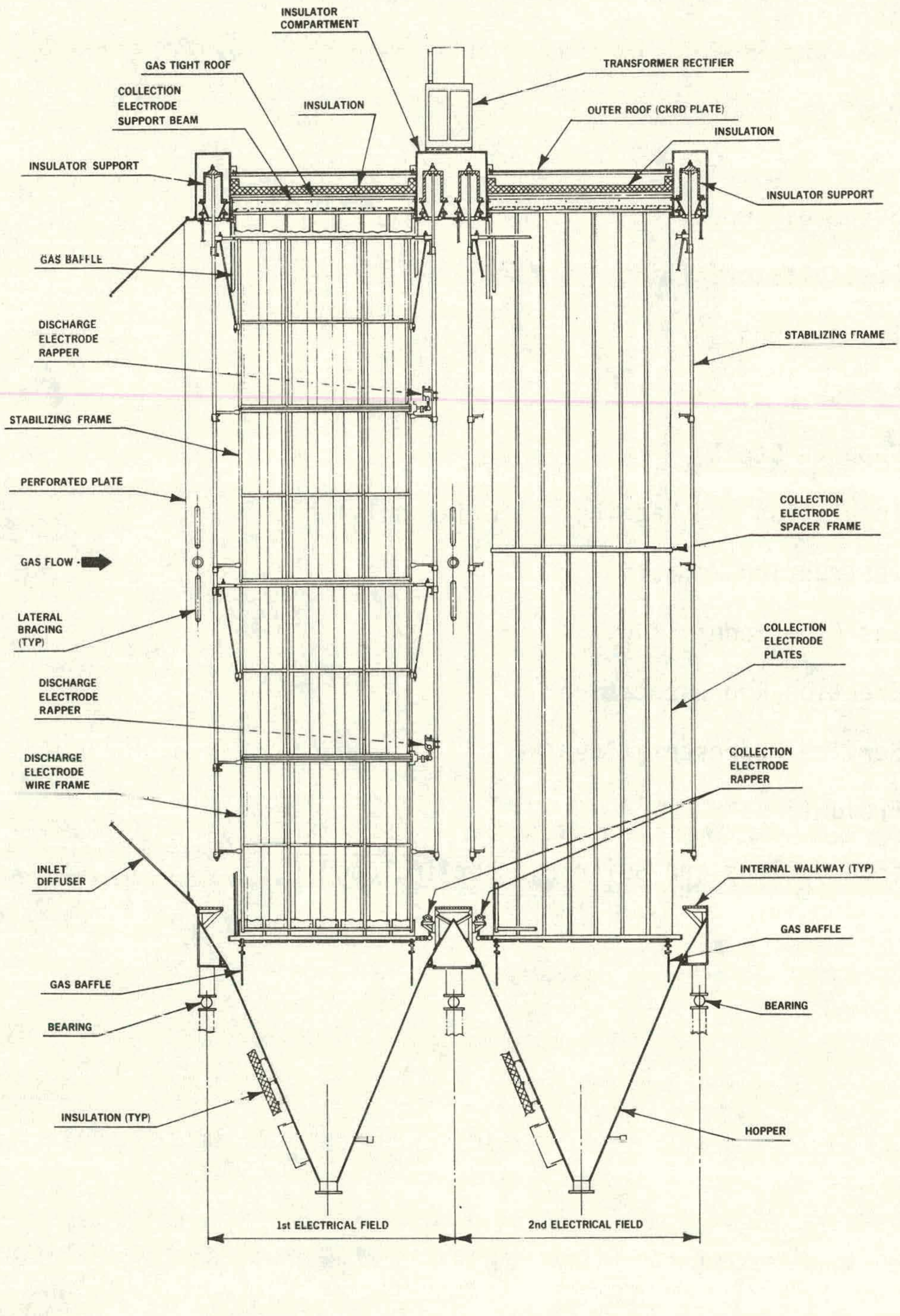
Service Representative

Freight

(Foundations and Buildings not included)

FIGURE 15

C-E WALTHER PRECIPITATOR



PREC/CEW
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POWER SYSTEMS

Illustration is typical of design, but does not necessarily show exact details of construction.

EDS HYBRID BOILER

ILLINOIS EDS DESIGN

WET SCRUBBER - SCOPE OF SUPPLY

(Foundations and buildings are not included)

Absorber System:

Absorbers

Reaction Tanks

Mixers

Spray Pumps & Drives

Spray Piping

Auxiliary Equipment:

Ductwork, Dampers & Expansion Joints

Insulation & Lagging

Structural Steel & Platforms

Blower System

Control System

Wash Water Pump & Drive

Wash Water Piping

Misc. Piping & Hangers & Supports

Additive System:

Milling Equipment (incl. drives), Ball Mills

Sotrage Bins

Storage Tank & Mixer

Feed Pumps & Drives

Additive Piping

Balance of Plant:

Electrical Equipment

Reheat System:

Services:

Instruction Manuals

Training Program

Design Model

Gas Flow Model Study

Erection Representative

Service Representative

Freight

BOTTOM ASH, PROCESS COIL ASH AND PULVERIZER REJECTS REMOVAL SYSTEM

Both the bottom ash, falling through the opening at the bottom of the furnace, and the flyash collected from the process coil hopper will be collected in submerged scrapper conveyors (SSC). The process coil SSC will discharge through a chute into the bottom ash SSC to provide a common point for removal.

Pulverizer rejects, consisting of tramp iron and heavy mineral matter will be rejected from the pulverizer into temporary storage tanks. The contents of these tanks will be sluiced to the bottom ash SSC for removal from the system.

The Pulverizer Rejects Removal System per boiler consists of:

- 4 - Pyrites hoppers, 1/pulverizer, 13 ft^3 capacity of the pressurized type
- 4 - Pulverizer-to-hopper discharge chutes with knife edged isolation gate

Each hopper will be furnished with:

- 1 - Jetting nozzle
- 1 - Level indicator
- 1 - Hinged access panel
- 1 - steel grate for manual removal of rejects larger than 1½ inches
- 1 - Floodlight
- 4 - Jet pumps will be furnished to carry rejects to the bottom ash SSC.
- 4 - Individual rejects hopper to bottom ash SSC transfer lines

FIGURE 16

C-E Submerged Scraper Conveyor (SSC)

DESCRIPTION

The C-E Submerged Scraper Conveyor (SSC) is a device that continously removes bottom ash from under the furnace of steam generators. Operation is simple. Ash enters the SSC through the bottom throat of the furnace (or is discharged from a grate) into a water-filled trough. Angle flights attached to continuous moving parallel chains scrape the ash along the bottom of the trough and up an inclined section. Effectively dewatered, the ash drops off the end of the inclined section into a transfer chute, through a clinker grinder for transport to a disposal point. The flights then begin a return cycle under the water-filled trough, through an exposed dry trough area, to enter again the water-filled trough. Water temperature in the trough is maintained at 140F—the same as in a conventional water impounded bottom ash hopper.

This method of mechanical conveying eliminates the need for pumps, pump motors, valves, piping and fittings otherwise required with water conveying methods. It also eliminates the power needed to drive this equipment. Since dewatering is accomplished on the inclined section of the SSC, dewatering vessels are not required. The final, dewatered ash contains 20 to 25% water by weight.

The continuous removal feature of this system eliminates the requirement for ash storage space under the boiler; hence, reduced boiler setting height is possible without resorting to the use of a pit as was common practice a few years ago. The realization of maximum cost savings from this feature will result only when the SSC is specified in the original boiler design—that is, at the time a proposal is prepared for boiler bid.

The entire SSC, including the inclined section, is mounted on wheels and can be rolled out on rails from under the furnace. This feature allows complete access to the SSC for maintenance. It also provides full access to the furnace through the furnace bottom throat.

The SSC is shipped in two or three pieces. This greatly reduces erection manhours as compared to conventional bottom ash hopper systems.

By its very nature, continuous ash removal eliminates hopper storage under the furnace and imposes the requirement that bottom ash be continuously transported to ultimate disposal. If full time transport to a disposal site is not possible, some type of intermediate storage of the dewatered bottom ash will be required.

The SSC can receive pyrites and economizer ash and thus serve as a transfer tank. In some industrial applications, where water quenching of high carbon content fly ash to eliminate the fire or explosion hazard is desirable, the back-end fly ash is also deposited into the water trough of the SSC. These applications above also result in a single plant ash discharge inherently simplifying the disposal of ash.

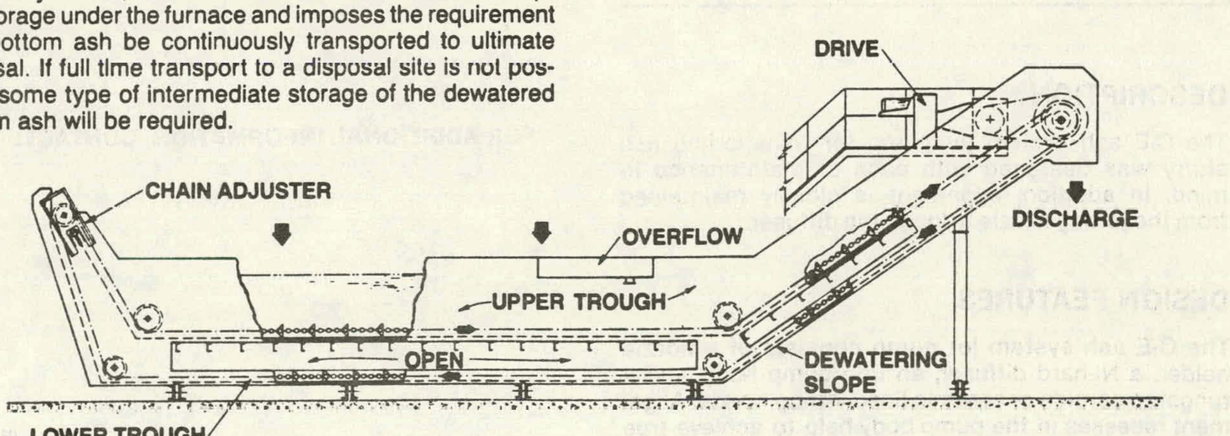
BENEFITS

- Provides continuous bottom ash removal
- Uses less pumping power and less water than pipeline systems
- Costs less to erect than conventional bottom hoppers
- Accomplishes dewatering without the use of dewatering vessels
- Is easily moved for access to the furnace
- Allows reduced boiler setting height
- Provides low-cost, water quenching system for high combustible ash with minimum use of real estate

SPECIFICATIONS

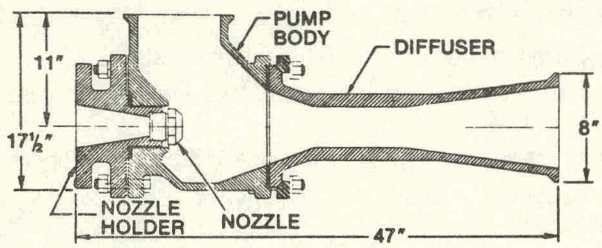
- Hydraulic or mechanical variable speed drive
- Water-flushed submerged bearings
- Carbon steel plate construction
- Low pressure cooling water
- Case hardened alloy steel chains
- Manual chain tensioning device
- Automatic chain flight cleaner

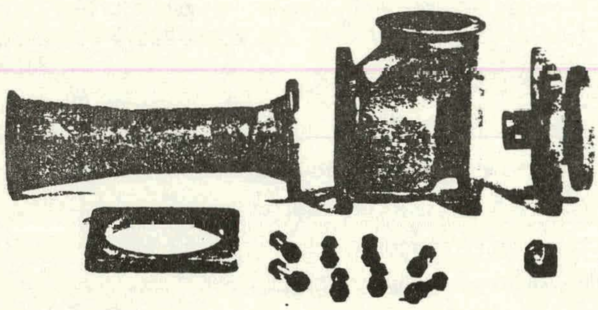
FOR ADDITIONAL INFORMATION, CONTACT:

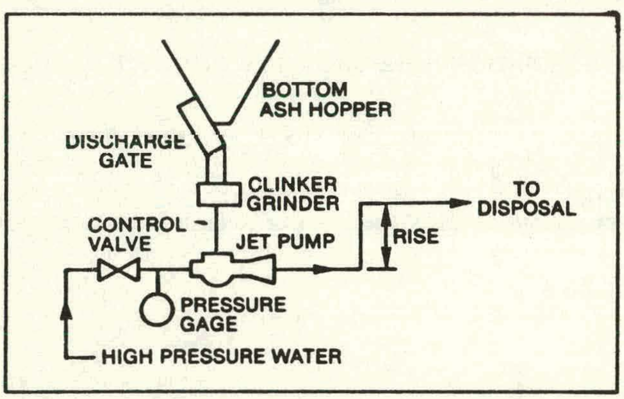


08 PRINTED IN U.S.A. 81
3M

C-E ash system jet pump







DESCRIPTION

The C-E ash system jet pump for transporting ash slurry was designed with ease of maintenance in mind. In addition, alignment is closely maintained from the jetting nozzle through the diffuser.

DESIGN FEATURES

The C-E ash system jet pump consists of a nozzle holder, a Ni-hard diffuser, an iron pump body, and a tungsten carbide or ceramic-lined jetting nozzle. Alignment recesses in the pump body help to achieve true alignment and reduce the possibility of gasket blowout.

BENEFITS

- Gives self regulating ash flow capability.
- Quick disassembly of component parts reduces maintenance downtime.
- Close alignment helps to maintain high efficiency.
- Low number of assembly parts simplifies maintenance and operation.

SPECIFICATIONS

Nozzle holder........... *standard 6-inch 300# flange*

Ni-hard diffuser............... *Brinell hardness: 550 (minimum); range of sizes available*

Pump body .... *nodular iron, Brinell hardness: 400 (minimum); sizes tailored to individual systems*

Jetting nozzle......... *tungsten carbide or ceramic lining avai[illegible]*

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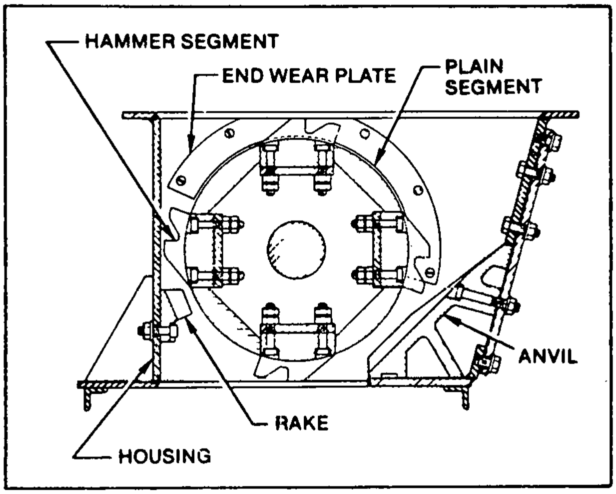
03 PRINTED IN U.S.A. 82
2M
PSG-6612

FIGURE 18

C-E Model 830 clinker grinder



DESCRIPTION

The C-E Model 830 clinker grinder is an improved design that will effectively reduce bottom ash so it can be transported in a pipeline sluice conveyor while providing high reliability and power plant availability.

DESIGN FEATURES

The C-E Model 830 clinker grinder has been developed in light of today's power plant operating requirements for maintainability and reliability. Component materials have been selected with severe duty requirements in mind. Major features of the C-E Model 830 clinker grinder include:

- Tripod bearing-supports: *to reduce shock loading transmitted from the grinder to the bearings.*
- Access panel: *access is provided to the grinder wear elements from the outside.*
- Replaceable hammers and anvils: *the C-E design simplifies maintenance by providing replaceable hammers, plain segments and anvils.*
- Shaft seals: *a new, improved arrangement reduces leakage through the grinder.*
- Single roll design: *reduces the weight, horsepower and number of moving grinder parts.*
- Detached drive motor: *allows easier removal of the grinder.*

BENEFITS

- Increased safety for maintenance personnel by permitting outside access to wear parts.
- Time to replace worn wear elements is reduced.
- Smaller number of shafts, shaft sleeves and bearings provides improved maintainability.
- Motor drive does not have to be removed from the clinker grinder housing for grinder changeout.
- Less grinder downtime due to reduced seal leakage.

SPECIFICATIONS

Seals require clean filtered water at a constant flow.

Water pressure of 20 psi is required.

Housing and non-wear parts are supplied in carbon steel or stainless steel.

Wear elements are constructed of work-hardening manganese steel.

10 hp, 440V gear motor drive.

FOR ADDITIONAL INFORMATION, CONTACT:

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2M
PSG-6187

PNEUMATIC FLYASH REMOVAL SYSTEM

Flyash removed from the gas stream by the electrostatic precipitator and that falling from the gas stream in the air heater hopper will be pneumatically conveyed from the Hybrid Boiler. A vacuum transport system will be used for this service.

The pneumatic transport system for each unit will consist of:

25 - Air cylinder operated flyash intake valves
 1/unit for the air heater hopper
 24/unit for ESP hoppers

25 - Hopper maintenance gates

7 - Spring loaded air intake check valves, 1 at the end of each pneumatic leg

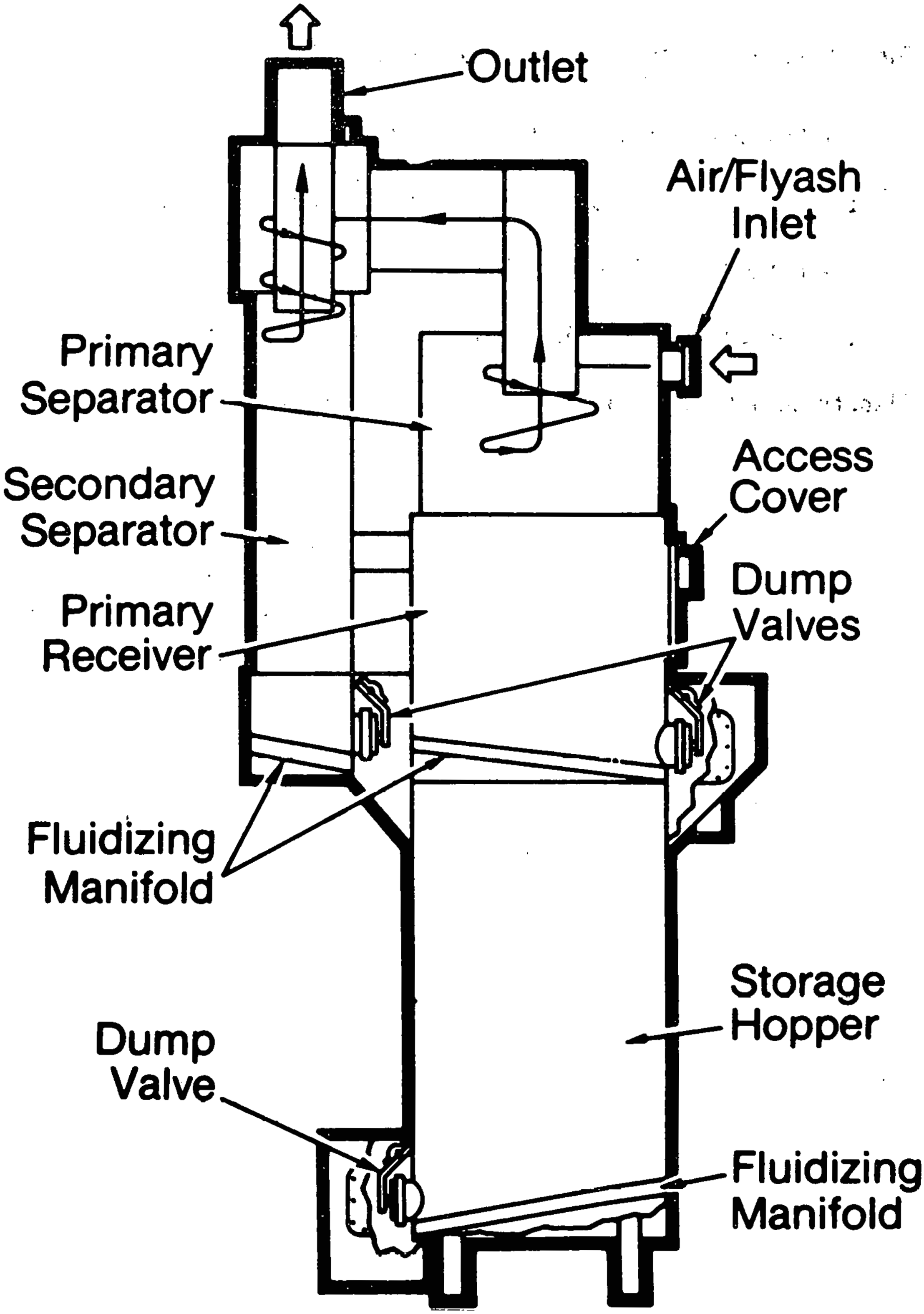
1 - Rotary blower vacuum producers per unit with 1 common spare

5 - Blower segregation valves

Each pair of units discharges to a common silo. This silo will consist of:

1 - 40 ft. diameter, 53,000 ft^3 storage silo consisting of:
 2 - dual cyclone continuous separation modules
 2 - silo bag filters acting as tertiary separation
 1 - telescoping dry silo discharge chute
 1 - rotary, wet ash, conditioning discharge chute
 2 - fluidizing air blowers
 2 - fluidizing air heaters
 Silo fluidizing air troughs
 1 - silo vent

FIGURE 19



Dual-cyclone module for continuous separation of flyash and transport air (used on vacuum-pneumatic systems).

The Submerged Scrapper Conveyor System consists of:

1 - Process coil SSC with 5 hp drive

1 - Process coil SSC to bottom ash SSC gravity chute

1 - Bottom ash SSC with 5 hp drive

1 - Bottom ash SSC clinker grinder with 10 hp drive

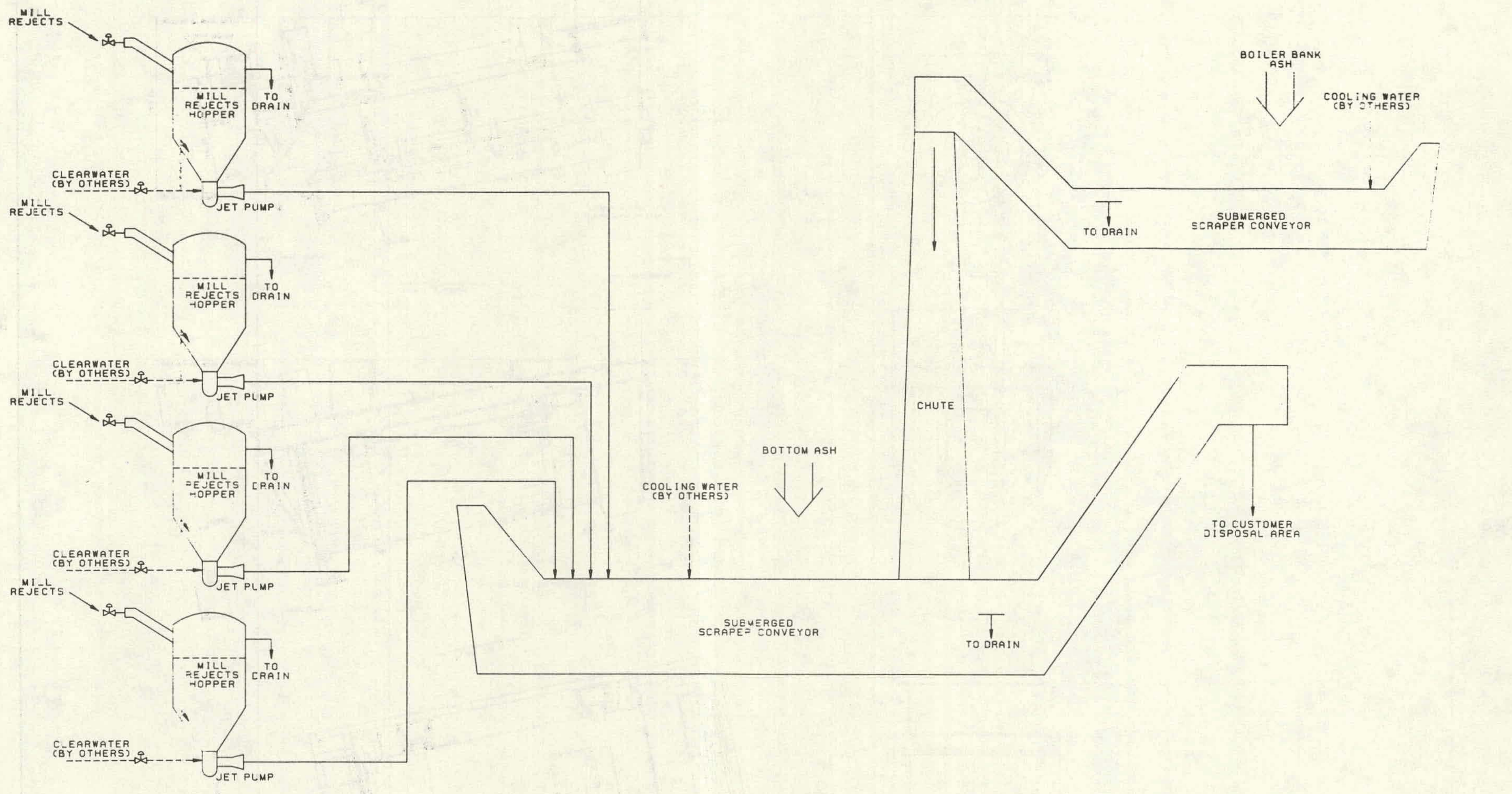
Also, track sufficient for 10 feet of SSC roll-away will be provided.

SECTION VI - LIST OF DRAWINGS

List of Drawings

AD-823-025-0	Boiler Ash and Mill Rejects Removal Hybrid Boiler
DP-812-066-0	Process Coil Support
EP-793-024-1	Arrangement of C-E Rotary Ash Conditioner-Model 36 - Standard
EP-813-199-4	General Arrangement and Plan View Hybrid Boiler - Illinois Design
EP-823-139	Air and Gas Flow Schematic - Boiler Hybrid Boiler - Illinois EDS
EP-823-140	Clean-up System Gas Flow Schematic - Hybrid Boiler

AD-823-025 REVISION



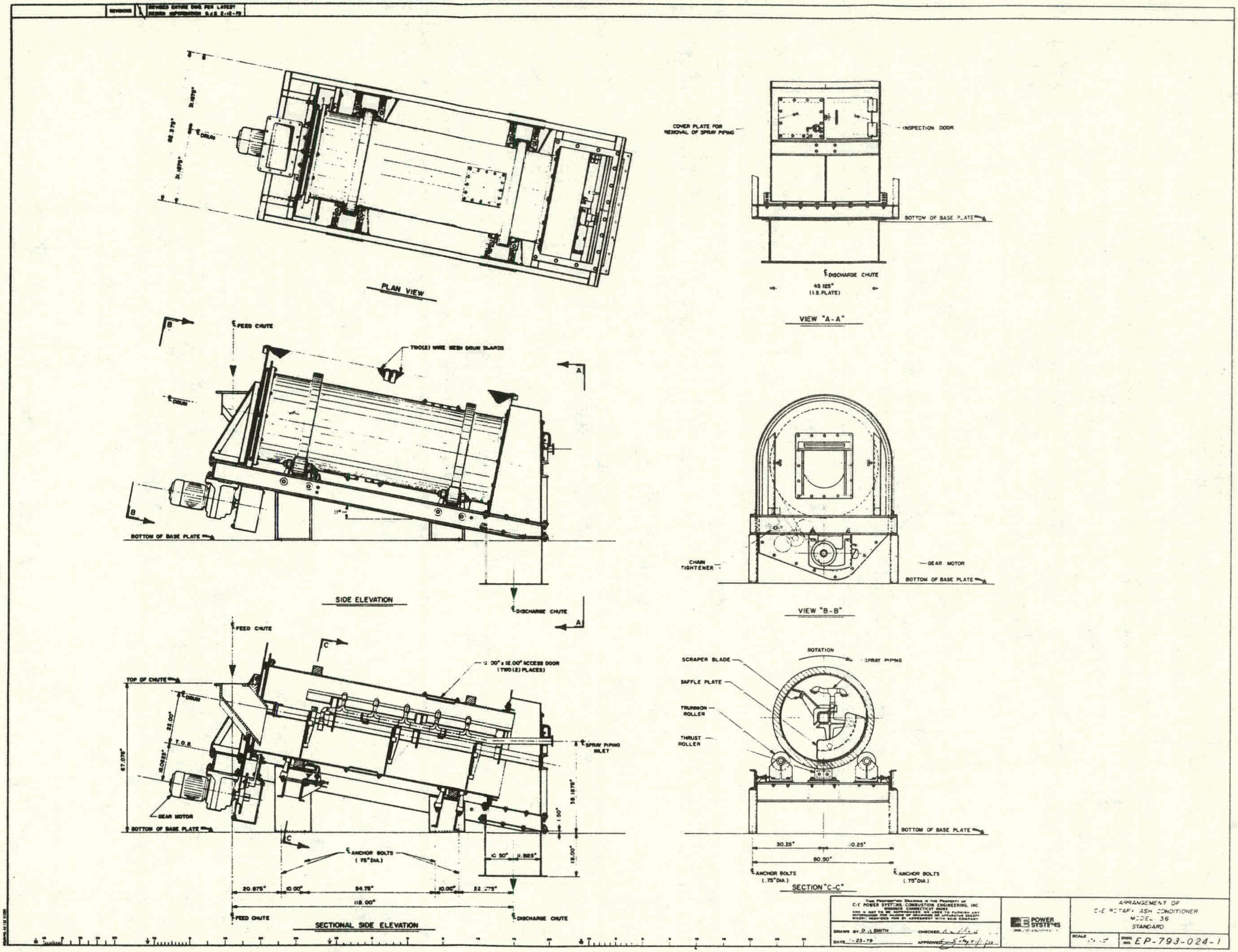
ATTENTION: ANY REVISION TO THIS DRAWING MUST BE MADE BY THE INTERACTIVE GRAPHICS GROUP.
PEAD823025

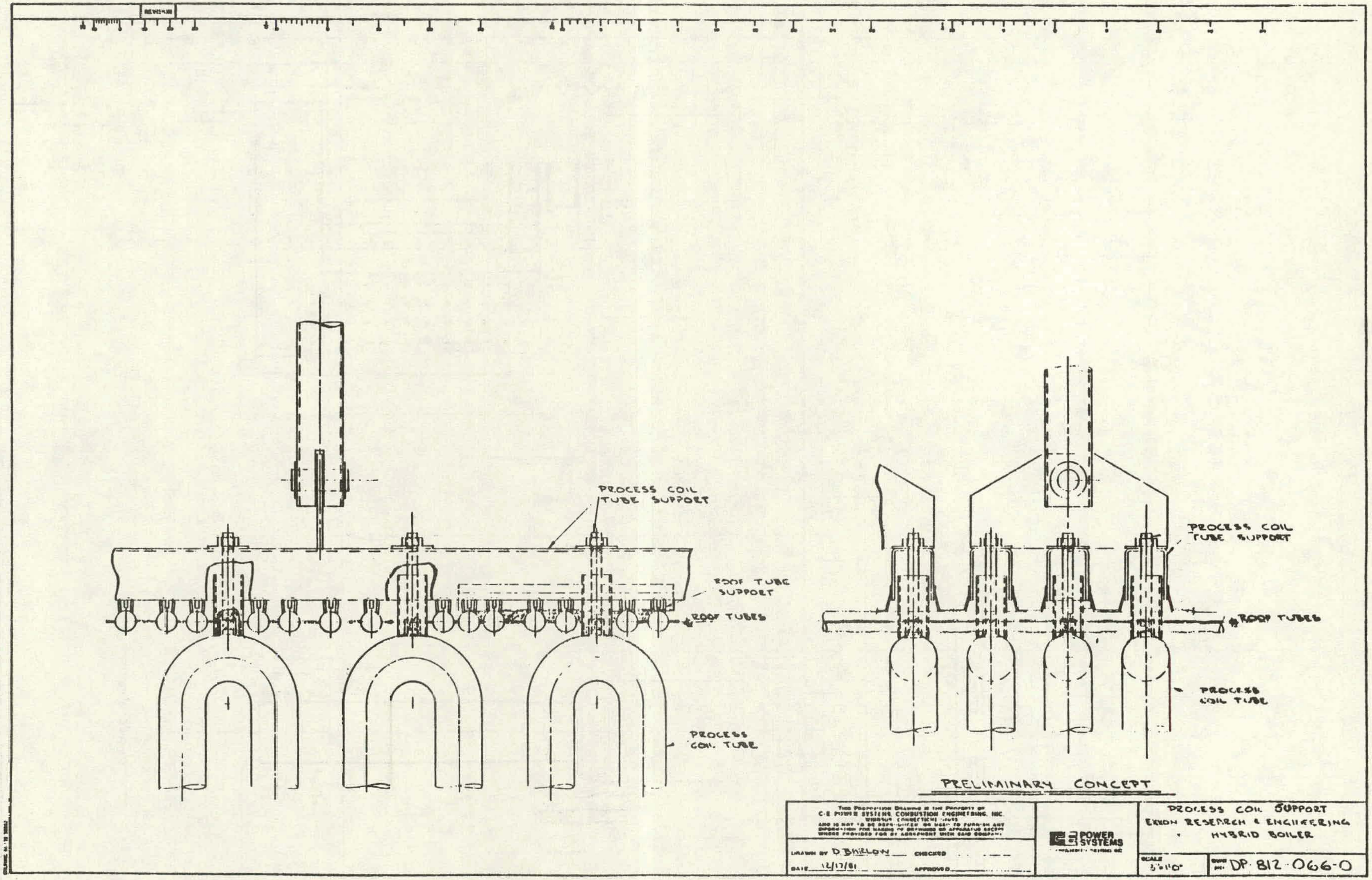
DRAWN BY J.CHRISTY	CHECKED
DATE 5-20-82	APPROVED R.D.K.

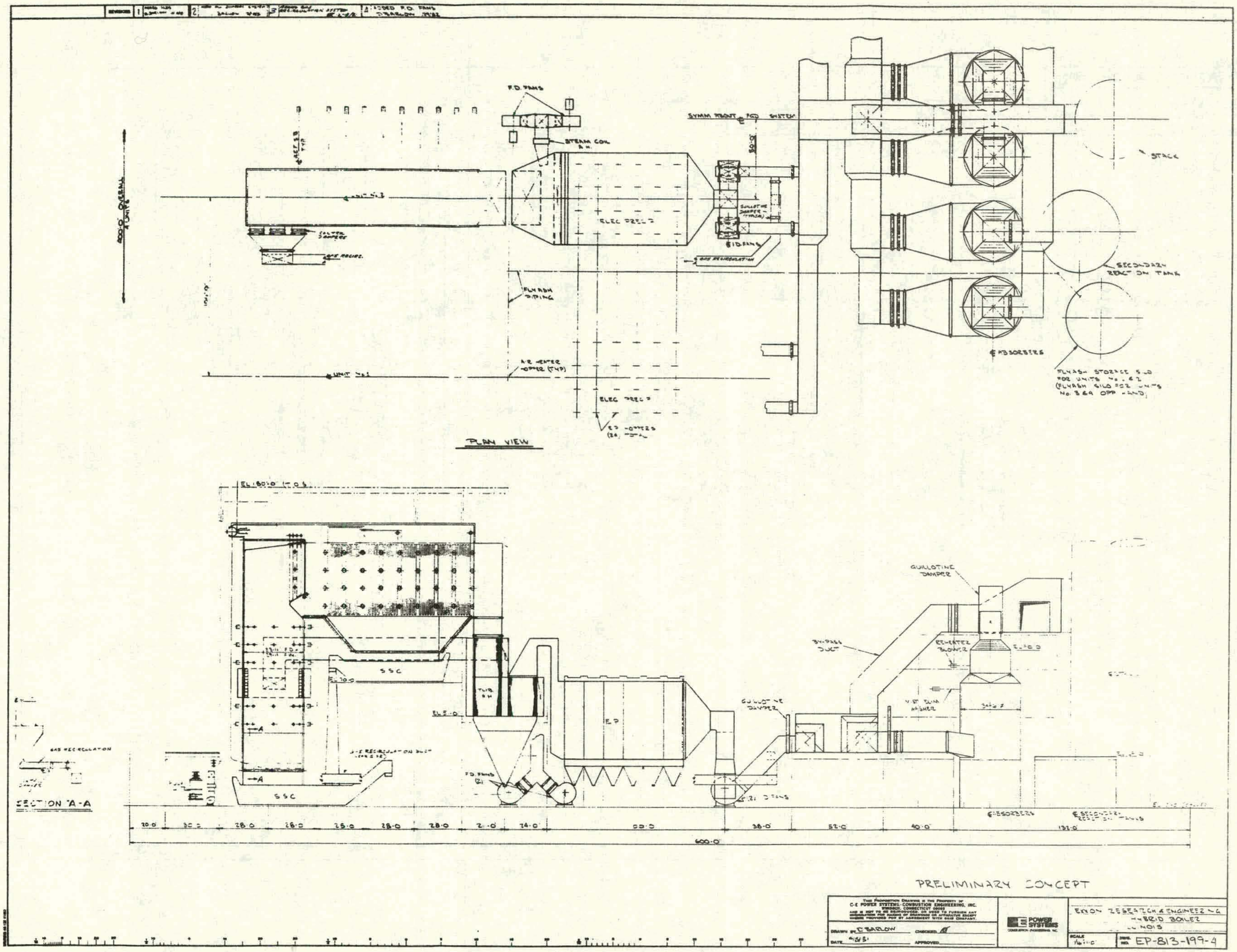
C-E POWER SYSTEMS
COMBUSTION ENGINEERING, INC.

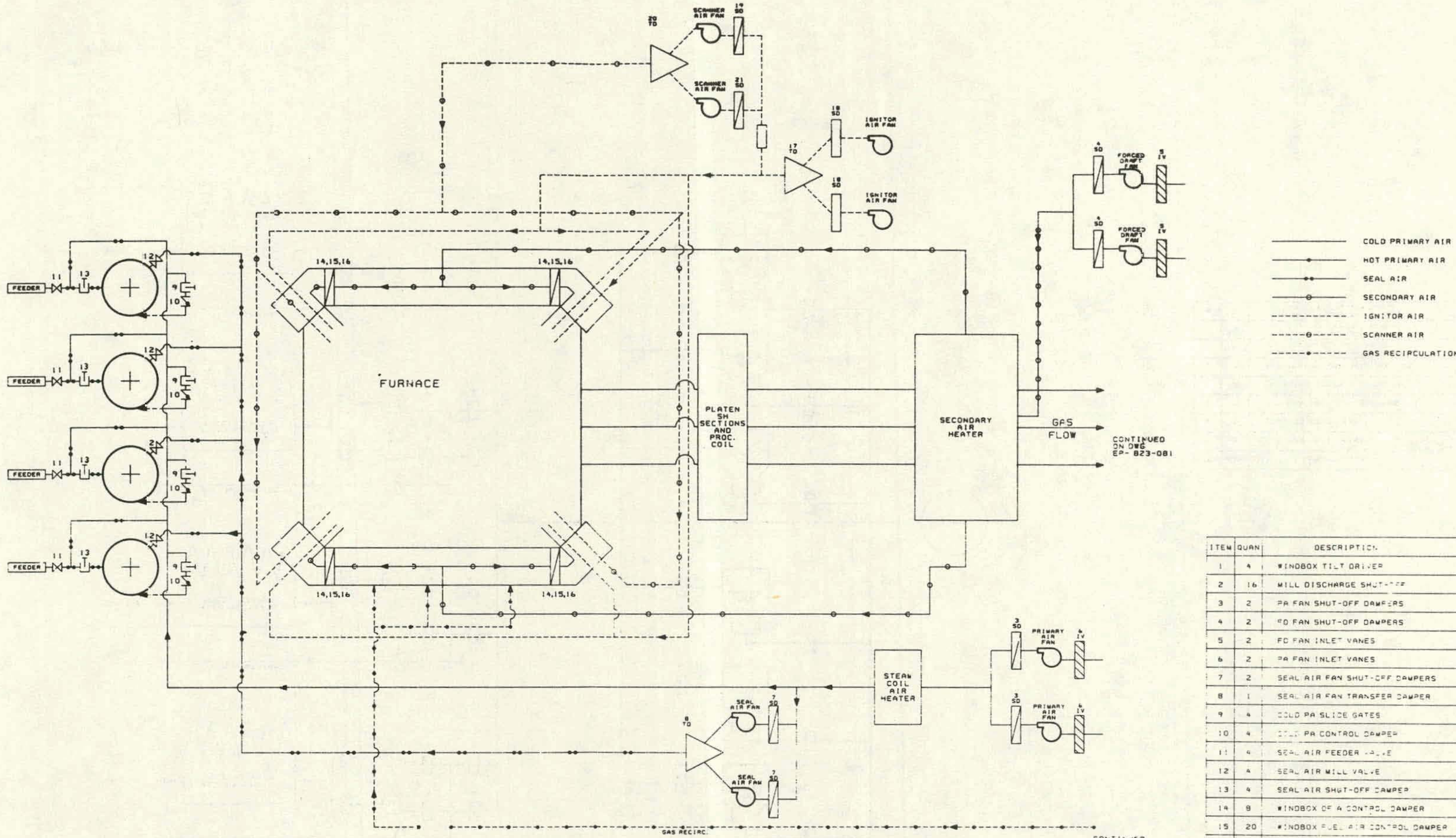
BOILER ASH AND MILL REJECTS REMOVAL
HYBRID BOILER

SCALE NONE | DWG NO. AD-823-025-0


PLAN VIEW
VIEW "A-A"
COVER PLATE FOR REMOVAL OF SPRAY PIPING
INSPECTION DOOR
BOTTOM OF BASE PLATE
℄ DISCHARGE CHUTE
45.125" (I.S. PLATE)
℄ FEED CHUTE
TWO(2) WIRE MESH DRUM GUARDS
℄ DRUM
SIDE ELEVATION
VIEW "B-B"
CHAIN TIGHTENER
GEAR MOTOR
TOP OF CHUTE
12.00" x 12.00" ACCESS DOOR (TWO (2) PLACES)
SPRAY PIPING INLET
T.O.S.
67.078"
22.00"
38.1875"
1.50"
18.00"
℄ ANCHOR BOLTS (.75" DIA.)
20.875"
10.00"
94.75"
10.00"
22.375"
118.00"
SECTIONAL SIDE ELEVATION
ROTATION
SPRAY PIPING
SCRAPER BLADE
BAFFLE PLATE
TRUNNION ROLLER
THRUST ROLLER
30.25"
30.25"
60.50"
SECTION "C-C"
C-E POWER SYSTEMS, COMBUSTION ENGINEERING, INC.
POWER SYSTEMS
DRAWN BY D. J. SMITH
DATE 1-23-79
ARRANGEMENT OF C-E ROTARY ASH CONDITIONER MODEL 36 STANDARD
DWG. NO. EP-793-024-1


PROCESS COIL
TUBE SUPPORT
ROOF TUBE
SUPPORT
ROOF TUBES
PROCESS
COIL TUBE
PROCESS COIL
TUBE SUPPORT
ROOF TUBES
PROCESS
COIL TUBE
PRELIMINARY CONCEPT
DRAWN BY D. BHILLON
CHECKED
DATE 12/17/81
APPROVED
POWER SYSTEMS
PROCESS COIL SUPPORT
EXXON RESEARCH & ENGINEERING
HYBRID BOILER
SCALE
DP-812-066-0


F.D. FANS
STEAM COIL A.H.
ELEC PRECIP
STACK
SECONDARY REACTION TANK
FLYASH PIPING
ELEC PRECIP
PLAN VIEW
GUILLOTINE DAMPER
BY-PASS DUCT
E.P.
SSC
SECTION 'A-A'
600-0
PRELIMINARY CONCEPT
C-E POWER SYSTEMS-COMBUSTION ENGINEERING, INC.
WINDSOR, CONNECTICUT
DRAWN BY C BARLOW
CHECKED
DATE
APPROVED
POWER SYSTEMS
COMBUSTION ENGINEERING, INC.
EXXON RESEARCH & ENGINEERING
HYBRID BOILER
SCALE
DWG. NO. EP-813-199-4



ITEM	QUAN	DESCRIPTION	OP
1	4	WINDBOX TILT DRIVER	[illegible]
2	16	MILL DISCHARGE SHUT-OFF	[illegible]
3	2	PA FAN SHUT-OFF DAMPERS	[illegible]
4	2	FD FAN SHUT-OFF DAMPERS	[illegible]
5	2	FD FAN INLET VANES	[illegible]
6	2	PA FAN INLET VANES	[illegible]
7	2	SEAL AIR FAN SHUT-OFF DAMPERS	[illegible]
8	1	SEAL AIR FAN TRANSFER DAMPER	—
9	4	COLD PA SLICE GATES	[illegible]
10	4	COLD PA CONTROL DAMPER	[illegible]
11	4	SEAL AIR FEEDER VALVE	[illegible]
12	4	SEAL AIR MILL VALVE	[illegible]
13	4	SEAL AIR SHUT-OFF DAMPER	[illegible]
14	8	WINDBOX OF A CONTROL DAMPER	[illegible]
15	20	WINDBOX FUEL AIR CONTROL DAMPER	[illegible]
16	12	WINDBOX [illegible] AIR CONTROL DAMPER	[illegible]
17	1	IGNITOR TRANSFER DAMPER	—
18	2	IGNITOR SHUT-OFF DAMPER	[illegible]
19	2	SCANNER AIR SHUT-OFF	[illegible]
20	1	SCANNER AIR TRANSFER DAMPER	—

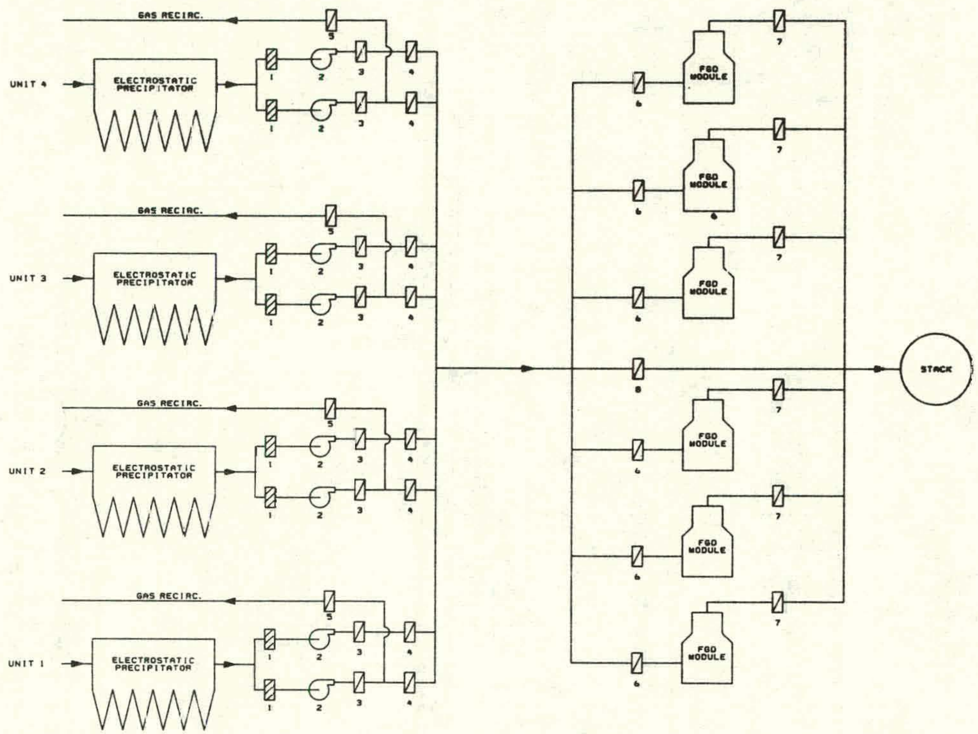
DRAWN BY J.M. FALES CHECKED
DATE 5-4-82 APPROVED

POWER SYSTEMS COMBUSTION ENGINEERING, INC.

AIR & GAS FLOW SCHEMATIC - BOILER
HYBRID BOILER-ILLINOIS EDS

SCALE NONE
DWG. NO. EP-823-139-0

EP-823-140 REVISIONS



ITEM	QUAN	DESCRIPTION
1	8	I.D. FAN INLET VANES
2	8	INDUCED DRAFT FANS
3	8	I.D. FAN SHUT-OFF DAMPERS
4	8	PRESSURE CONTROL DAMPERS
5	4	GAS RECIRC. CONTROL DAMPERS
6	6	FLUE GAS DESULFURIZATION INLET ISOLATION DAMPERS
7	6	FLUE GAS DESULFURIZATION OUTLET ISOLATION DAMPERS
8	1	FLUE GAS DESULFURIZATION BYPASS CONTROL DAMPER

DRAWN BY J.M.FALES CHECKED
DATE 6-23-82 APPROVED

C-E POWER SYSTEMS

CLEAN-UP SYSTEM GAS FLOW SCHEMATIC
HYBRID BOILER
ILLINOIS EDS DESIGN

SCALE NONE
DWG. NO. EP-823-140-0

GLOSSARY AND ABBREVIATIONS

ADP: Availability Data Program

Assembly: Coplanar tubes in the direction of the gas flow.

BET: Brummer, Emmet, Teller

C-E: Combustion Engineering, Inc.

Circulation Ratio: The ratio of the mass flow rate of the water fed to the steam generating tubes to the steam flow rate generated.

Counter Flow: Flow type in which the hot end of the one fluid and the cold of the other are in the same cross section, and vice versa.

Devolatilization: Reaction the coal undergoes when it is heated.

$$\text{Volatile Matter} \xrightarrow{1100\text{ - }1500°F} CH_4 = \text{Char} + HC + \Delta H,$$

where HC indicates hydrocarbons higher than CH_4 and ΔH the heat released (exothermic reaction)

DNB: Departure from nucleate boiling

DTFS: Drop Tube Furnace System

ECLP: EDS Coal Liquefaction Pilot Plant

Electrostatic Precipitator (ESP): Fly ash removal system. Suspended particles in the gas are electrically charged and then driven to collecting electrodes by an electrical field.

ER&E: Exxon Research and Engineering Company

ESP: electrostatic precipitator

Fireball Flame Scanner: Flame monitoring device, detecting the presence or absence of flame.

FD: forced draft

Forced Draft Fan: Fan providing the required pressure to introduce the secondary air to the furnace.

FGD: Flue Gas Desulfurization System

Fouling: The adherence of ash on the convection surface.

FPTF: Fireside Performance Test Facility

FSSS: Furnace Safeguard Supervisory System

Furnace Height: From the centerline of the lower header to the furnace roof.

Fusion Welding: Molten metal deposited by welding arcs between the tubes.

Gas Recirculation (GR): Flue gas is taken from the main gas stream and reintroduced into the furnace. It is normally used for steam temperature control.

ID: induced draft.

IFM Ignitor: Ionic Flame Monitoring Ignitor

Induced Draft Fan: Fan providing the required static head to assure flow of the combustion products from the furnace to the stacks.

KDL: Kreisinger Development Laboratory

KHB: Kentucky high volatile bituminous (coal)

LNCFS: low NO_x concentric firing system

Longitudinal Spacing (S_L): The distance between the centerlines of two consecutive tubes in the direction of the gas flow.

MCR: Maximum Continuous Rating (Full Load)

MTBF: Mean Time Between Failures

MTTR: Mean Time to Repair

Net Heat Input (NHI): Net heat released inside the furnace; include the following:

i) Gross fuel heat input based on high heating value of the fuel.

ii) Sensible heat, calculated above $80^{o}F$, contained in the fuel, preheated air and recirculated gas, and

iii) Heat content of the fuel atomizing steam above $80^{o}F$ (when such steam is used).

From the previous items, the latent heat of vaporization of liquid water in the fuel and water formed from the hydrogen, along with the combustible loss are subtracted:

NHI/PA: Net Heat Input Per Plan Area

OD: Outside Tube Diameter

Overfire Air: Air introduced at the top of the windbox

PA: primary air

Parallel Flow: Flow type in which the hot ends of both fluids are in the same cross section.

Pendant Superheater: Tube assemblies hanging vertically to the direction of the gas flow.

Plan Area (furnace): Cross section of the furnace vertically to the direction of the gas flow; (width) x (depth).

Platenized Pendant: Assemblies with small longitudinal spacing (clear space between tubes small).

PM: pollution minimum

Primary Air: Air needed to transport and drying of the coal.

Primary Air Fan: Fan providing the required static head for the Primary Air System.

Recuperative Air Heater (tubular): It utilizes the heat contained in the products of combustion to preheat the combustion air. It is essentially a nest of straight tubes expanded into tube sheets and enclosed in a reinforced steel casing. Air or gas are running through the tubes.

Regenerative Air Heater: In a rotating plate-type air heater, heat-storage plate elements are heated progressively in a flowing gas stream, and then rotated by mechanical means into an air stream where the stored heat is released.

R_c: Convective Heat Transfer Rate, $\frac{Btu}{hr\text{-}sq.ft.\text{-} F}$

R_n: Non-luminous Heat Transfer Rate

R_t: Total Heat Transfer Rate; $R_t = R_c + R_n$

Secondary Air: Air required for combustion of the fuel.

SGR: separating gas recirculation

SHO: superheater outlet

Slagging: Fused deposits or resolidified molten material that forms primarily on furnace walls.

SSC: Submerged Scraper Conveyor; Continuous Ash Removal System

Steam Quality: Ratio of steam leaving to water entering the heated circuit. Quality is the inverse of the circulation ratio.

TGA: Thermogravimetric Analysis

TGS-2: Perkin Elmer Model TGS-2 thermogravimetric analysis apparatus

Transverse Spacing (^{S}T): The distance between the centerlines of the consecutive assemblies.

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