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DESIGN, FABRICATION AND DEMONSTRATION OF AN INERT GAS GENERATOR

Prepared for

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

by

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on

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DISCLAIMER NOTICE

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16. Abstract

This report documents the work performed and the results obtained in a 2-year development of a Mobile Inert Gas Generator for use in the Bureau of Mines Remote Sealing System for fighting underground coal mine fires. The performance requirements of an inert gas generating system for the Remote Sealing System were clearly established. A thorough review of seven possible system designs meeting these requirements was conducted. An air cooled, distillate oil fired combustion type inert gas generator was selected for further detailed design, hardware fabrication, and performance testing.

The Inert Gas Generator constructed under this program has been thoroughly performance tested and has been operated in the field for approximately 200 hours. The system has met or exceeded all important performance requirements. The system was used in the fire fighting efforts at the Bethlehem Mines Corporation Cambria Division Mine 33 fire and contributed to the successful containment of the fire. The system was also employed in the demonstration of entire Remote Mine Sealing System at the Jenney Mine in the fall of 1978. The system is currently available for fighting any future underground coal mine fires.

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FOREWORD

This report was prepared by Foster-Miller Associates, Inc. (FMA), Waltham, Massachusetts under USBM Contract No. H0155053. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of PMSRC with Dr. Robert Chaiken acting as Technical Project Officer. Mr. Doyne Teets was the Contract Administrator for the Bureau of Mines. The Program Manager at FMA was Mr. John T. Dieckmann.

The help and cooperation of the following individuals and corporations are gratefully acknowledged.

- Dr. Robert Chaiken, USBM, Bruceton, PA
- Mr. Roger King, USBM, Bruceton, PA
- New England Sand and Gravel Corporation (they provided the site for the Flyash Conveying Demonstration at no charge)
- Bethlehem Mines Corporation, Cambria Division

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1. INTRODUCTION

Foster-Miller Associates, Inc. (FMA) has designed, fabricated, tested, and successfully demonstrated an Inert Gas Generator to be used as a major part of the U.S. Bureau of Mines' Remote Mine Sealing System.

The Remote Sealing System is used to fight underground coal mine fires using equipment and personnel all safely located at the ground surface. Using the Remote Sealing System, seals are emplaced in mine passageways between the fire zone of the mine and the rest of the mine, isolating the fire zone from the mine. The seals consist of fly ash that has been pneumatically conveyed through a borehole connecting the surface and the passageway. Enough fly ash is emplaced to fill the passageway cross-section. A water tight seal is constructed if a mixture of equal parts fly ash and Bentonite is substituted for straight fly ash.

A passageway seal is remotely emplaced by the following procedure:

a. A borehole is drilled and cased, providing a conduit from the surface to the passageway location to be sealed.

b. A sonar/closed circuit television (CCTV) camera package is lowered down the completed borehole to verify that the borehole has reached the desired passage location and assess conditions affecting seal emplacement.

c. The Inert Gas Generator is connected to the borehole and the fly ash supply (fly ash is brought on site by pneumatic bulk hauler trucks) and sufficient fly ash to create a seal is pneumatically transported down the borehole. The fly ash falls out of suspension underneath the borehole, forming a seal the width of the passage, 20 feet long at the top and 100 feet long at the bottom.

d. The froth-foam equipment is lowered down the borehole. An especially formulated, fire retardent polyurethane foam seal is emplaced on top of the fly ash seal, ensuring that the passage is tightly sealed.

e. Depending on underground conditions, the emplacement of the fly ash and froth foam materials may be monitored using the CCTV system or an acoustic seal checker.

The Remote Sealing System, which includes all the necessary equipment to perform the sealing operation, has been developed by FMA under contract to the USBM. The system consists of four major subsystems:

a. Inert Gas Generator

b. Downhole instrumentation, including a CCTV camera, sonar, and an acoustic seal checker, along with necessary winches to deploy the downhole packages.

c. Froth-foam seal topping system

d. Nitrogen enrichment seal emplacement system.

The design of the Inert Gas Generator is covered in detail in this report. The operation and maintenance of the Inert Gas Generator is covered in detail in Volume II, Operation and Maintenance Manual, also prepared under this contract. The following reports and manuals provide detailed descriptions of the design, operation and maintenance of the other major parts of the Remote Sealing System.

a. Berry, D. Randolph; K.R. Maser, D.A. Monaghan, A.R. Guzdar, Technical Report, "Extinguishing Coal Mine Fires by Remote Sealing." USBM Contract Report H0122-046, September 1973.

b. Monaghan, David A., Final Report, "Development of Inert Gas Generation System for Remote Sealing of Coal Mines." USBM Contract Report H0133069, July 1974.

c. Maser, Kenneth R., R.E. Wallhagen, and J.T. Dieckmann, Final Report, "Development of a Fly Ash - Cement Mine Seal System." USBM Contract Report H0144061, March 1975.

d. Wallhagen, Robert E., S.B. Douglas, and D.A. Monaghan, Final Report, "A Fire Retardant Froth Foam Seal Topping System for the USBM Remote Mine Sealing System." USBM Contract Report H0155061, December 1977.

e. Wallhagen, Robert E., S.B. Douglas, and D.A. Monaghan, Operations and Maintenance Manual, Volume II, "A Fire Retardant Froth Foam Seal Topping System for the USBM Remote Mine Sealing System." USBM Contract Report H0155061, December 1977.

f. Monaghan, David A., D.R. Berry and B.C. Brunelle, Final Report, "Design and Fabrication of Instrumentation for Remote Sealing of Underground Coal Mine Passageways." USBM Contract Report H0144004, July 1977.

g. Monaghan, David A., D.R. Berry and B.C. Brunelle, "Design and Fabrication of Instrumentation for Remote Sealing of Underground Coal Mine Passageways," Operations Manual, Volume II, USBM Contract Report H0144004, July 1977.

Inert gas is used as the fly ash seal transport medium (instead of fresh air) for two reasons.

a. The undesirability of introducing large volumes of fresh air in the vicinity of the fire

b. Under some conditions fresh air - mine atmosphere mixtures are explosive.

After the fire zone has been sealed, inert gas can be pumped into the fire zone. Under certain conditions, pumping inert gas into the fire zone can displace oxygen or prevent the influx of additional oxygen into the fire zone, effectively stopping the combustion process. Inert gas can be used effectively in certain other fire fighting applications.

In the remainder of this report the Inert Gas Generator is discussed in detail. The methodology that was followed to optimize the system design is discussed in Section 2. The system is described in detail in Section 3 and the results of the performance testing of the system are presented in Section 4.

2. SYSTEM DESIGN SYNTHESIS

This section of the report presents a detailed technical analysis of the design synthesis of an optimum inert gas generating system for the Remote Sealing System application.

The system design was formulated by combining a fundamental examination of the requirements of the Remote Sealing System application with the results of a thorough survey of the combustion equipment and heat transfer equipment industries. The result of this process was to define approximately ten viable inert gas generation systems that met the following three criteria:

a. The system is made up of major components that are commercially available as proven products, avoiding the development expense and risk of specially designed components for the application

b. The system met the requirements of the remote sealing application

c. Each system offered at least some attractive features.

These systems were then evaluated on a cost and overall performance basis.

Two primary system configurations were then compared in detail, a high pressure burn-cool system and a low pressure burn-cool-compress system that was ultimately developed, tested and demonstrated under this program. A description of the high pressure burn-cool system is presented in Appendix A. Descriptions of the five other systems that were given serious consideration prior to narrowing the choice down to two systems are presented in Appendix B.

The following subsections describe the design process in detail.

2.1 System Design and Performance Requirements

The Inert Gas Generator selected must meet certain basic requirements to economically provide the performance demanded of the Remote Sealing System. These requirements are listed in Table 1.

2.2 Evaluation of Alternatives

To meet the basic performance requirements, equipment must be selected or designed to perform four basic process functions on the inert gas stream.

a. Compression
b. Combustion
c. Cooling
d. Prevention of moisture condensation in the fly ash.

In all cases except direct quenched combustion, cooling is best accomplished in two steps:

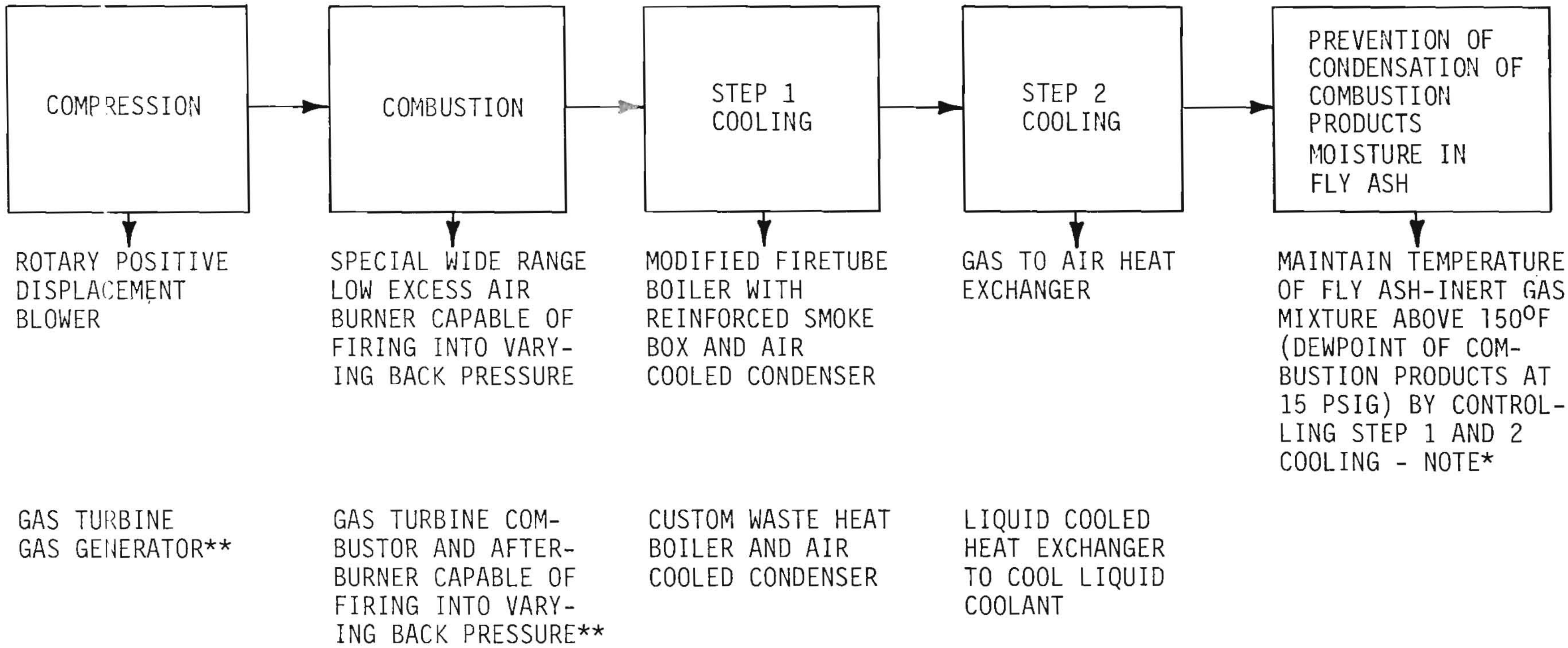
a. Step 1 - Cool the combustion products to 600° to $800^{\circ}F$, the normal range of stack temperatures for a fired heating device.

b. Step 2 - Cool to the required outlet temperature.

The four functions can be performed in one of two sequences, either compression-combustion-cooling-condensation prevention as shown in Figure 1 or combustion-cooling-condensation prevention-compression as shown in Figure 2. The system discussed in our proposal was based on the former sequence. The types of

Table 1. Design Requirements for Inert Gas Generator for Remote Sealing System

Item	Requirement
1	The inert gas should be provided by combustion of a commonly available fuel to minimize supply problems in the field and operating cost.
2	The system should be capable of delivering inert gas with an oxygen content adjustable within the range of 1 to 8 percent. Operating at the higher oxygen content reduces fuel consumption and should be used whenever possible. However, operation at the low oxygen concentrations may be essential for certain mine sealing operations.
3	The system should be capable of delivering a steady flow of inert gas in the range of 600 to 2200 SCFM. The high flow rate is required for emplacing the bulk of the seal. The flow rate must be gradually reduced to the lower value to finish the emplacement of seal.
4	To overcome the pressure lost conveying the fly ash, the Inert Gas Generator must be capable of supplying the inert gas at pressures up to 15 psig.
5	It must be capable of maintaining approximately constant flow under fluctuating back pressure conditions induced by slugging flow of fly ash.
6	Condensation of combustion product moisture (hydrocarbon combustion products are typically 8 to 9 percent water by weight) in the fly ash must be prevented. The addition of small amounts of liquid moisture alters the settling behavior of the fly ash enough to prevent reliable seal formation.
7	The delivery temperature of the fly ash-inert gas mixture must be below 200°F to be compatible with the froth foam seal topping material.
8	Since the system must operate in the field, its operation should absolutely minimize consumption of materials requiring delivery at site. Fuel will be consumed, but the use of other supplies and cooling water should be minimized and preferably eliminated.
9	The system must be capable of independent operation in the field. It should have adequate fuel storage capacity, cooling fluid storage capacity and an engine-generator set to provide electric power requirements.
10	The system must be portable and rugged - capable of withstanding transportation over the road and operation outdoors over a wide range of weather conditions.



*ONE OF THE PRINCIPAL ADVANTAGES OF THIS BASIC ARRANGEMENT IS THE ABILITY TO MAINTAIN A HIGH ENOUGH EXHAUST TEMPERATURE TO PREVENT CONDENSATION WITHOUT MOISTURE REMOVAL FROM THE COMBUSTION PRODUCTS. THEREFORE, DESICCANT MOISTURE REMOVAL AND STEP 2 COOLING THE COMBUSTION PRODUCTS TO REMOVE MOISTURE ARE NOT APPROPRIATE FOR THIS ARRANGEMENT.

**NO STANDARD PISTON ENGINE EXISTS THAT WILL RUN PROPERLY WITH A 15 PSIG EXHAUST PRESSURE.

Figure 1. Basic Functions in Compression-Combustion-Cooling-Condensation Prevention

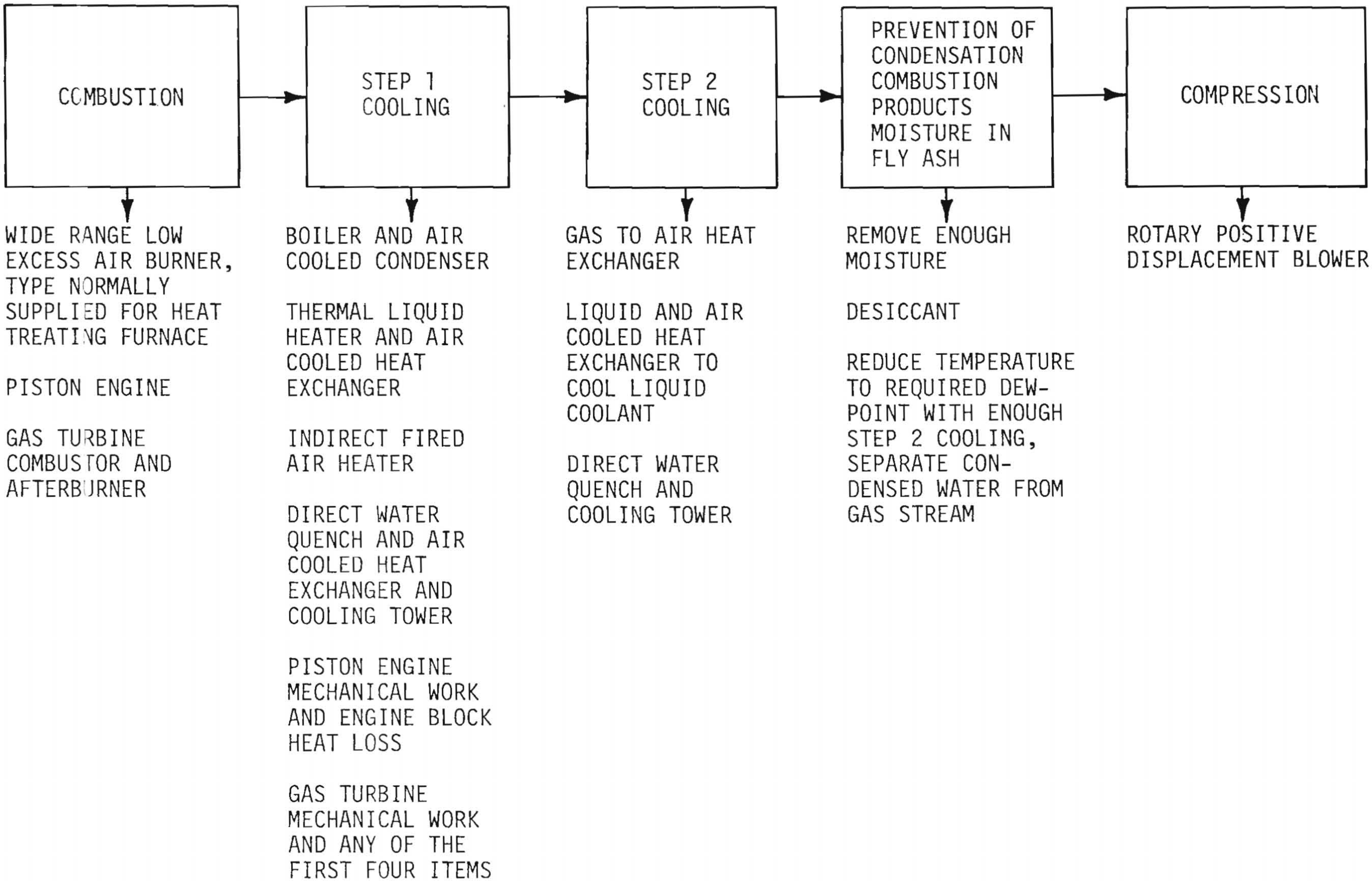


Figure 2. Basic Functions in Combustion-Cooling-Condensation Prevention-Compression

equipment available to perform these functions are also listed in Figures 1 and 2. The advantages and disadvantages of each of these two arrangements are summarized in Table 2. Several general conclusions can be drawn with regard to equipment that can be selected for each of the process functions.

2.2.1 Cooling Equipment

The choices for cooling equipment for Step 1 listed in Figures 1 and 2 are all viable options, each with performance, operation and cost advantages and disadvantages. None can be rejected out-of-hand without considering the overall costs and operating advantages and disadvantages associated with a complete Inert Gas Generator based on a suitable commercially available model of each type of cooling equipment.

Step 2 cooling on the other hand should be done with a gas-to-air heat exchanger. Gas-to-air heat exchangers are smaller, simpler, and less expensive than a pair of liquid coupled heat exchangers and do not require the cooling water used by direct quench cooling. A wide variety of gas-to-air heat exchangers are available from a number of manufacturers. Inlet temperatures in the 600° to 800°F range correspond to typical design temperatures for relatively inexpensive units of carbon steel construction.

2.2.2 Compression Equipment

A rotary lobe positive displacement blower is preferable for this application. It provides good control of the gas throughput, independent of back pressure and is cost competitive with an engine driven centrifugal compressor. One disadvantage is a relatively low upper limit on inlet temperature, typically about 160°F. This is not a particular problem for the proposed application because moisture removal is facilitated by cooling the gas to below this temperature.

Table 2. Comparison of the Two Basic System Arrangements

Advantages	Disadvantages
Compression-Combustion-Cooling-Condensation Prevention	
1. Only moderate cooling of combustion products is required (to 200°F). 2. High outlet temperature can be provided to prevent combustion products moisture condensation in fly ash. No moisture removal is necessary. 3. Assuming serious burner problems are not encountered, it will prove to be one of the lower cost alternatives.	1. Potential burner control problems. Although a reasonable amount of effort should produce controls providing a stable flame, oxygen concentration of inert gas will fluctuate somewhat. 2. Primary combustion gas cooling is limited to only one viable option, namely the industrial boiler with reinforced front and back. 3. Burner selection is limited, although a satisfactory burner is available. 4. Since the full moisture content of the combustion products remains with the inert gas, failure to maintain a high outlet temperature could, under certain circumstances, lead to a borehole plugging or failure to properly form the seal. 5. An interruption of fly ash flow coupled with a failure to cut the inert gas temperature back could result in damage to the lightweight fiberglass piping.
Combustion-Cooling-Condensation Prevention-Compression	
1. A fairly wide selection of burners are suitable. 2. Controls are completely standard. 3. Very close control is maintained of oxygen content over entire operating range. This is not an overriding consideration in itself, but it allows room for misadjustment in the field without causing an interruption in a sealing operation.	1. Additional combustion gas cooling is required. (Maximum blower inlet temperature 150°F.) 2. Additional equipment is necessary to prevent condensation of combustion products moisture in either a heat exchanger to reheat the inert gas before mixing with the fly ash or drying equipment to remove moisture before the inert gas is compressed and mixed with fly ash.

A gas turbine gas generator (a gas turbine engine less the power turbine) will provide ample gas delivery pressure, but the rate of gas throughput is highly dependent on back pressure.

2.2.3 Combustion Equipment

In systems based on a piston engine, the combustor is included in the engine. In systems based on the gas turbine, an afterburner is required. In all other systems, a burner capable of burning cleanly with less than 5 percent excess air (1 percent oxygen left in the combustion products) over a 5 to 1 turndown range is necessary. Burners for heat treating applications available from numerous manufacturers, typically provide this performance. Out of this group of burners, a burner having a flame pattern compatible with the furnace geometry of the Step 1 cooling equipment must be selected.

2.2.4 Prevention of Moisture Condensation in Fly Ash

Proper seal formation is dependent on the seal material being a free-flowing powder with negligible cohesive or attractive force between the particles. Dry fly ash is such a material. At the borehole exit velocities of the conveying gas, a crater forms underneath the borehole in the settled fly ash, forcing the accumulating seal to reach the upper corners of the mine passage before reaching and plugging the borehole. In this manner, a complete, or almost complete, seal is formed. The addition of a small amount of moisture drastically alters the settling properties of the fly ash. Cohesive forces between the fly ash particles, due to the surface tension of water, can be sufficient to resist formation of the crater under the jet action of conveying gas exiting the borehole. The seal then forms as a conical pile under the borehole, which plugs before fly ash has reached the upper corners of the passage.

This behavior was observed first during quarter scale tests with fly ash at FMA. Low pressure steam was injected into the conveying air at a mass flow rate approximately 1 percent that of the fly ash.

At the Joanne Mine sealing operation, water in a borehole led to premature plugging during seal emplacement.

Based on these experiences and the risk involved we selected the conservative option, to insure that under all possible conditions no moisture condenses on the fly ash prior to settling into the seal formation.

The fly ash-inert gas stream discharges from the borehole at or very close to standard atmospheric pressure. Therefore, if the discharge temperature of the fly ash-inert gas mixture is greater than the atmospheric pressure dewpoint of the inert gas, no moisture will be condensed on the fly ash at the borehole outlet. Dewpoint is plotted versus moisture content in Figure 3.

Two strategies for maintaining borehole discharge temperature of the inert gas-fly ash mixture above the dewpoint are available:

a. Maintaining the outlet temperature of the inert gas sufficiently high to insure that the temperature of the inert gas and fly ash after mixing exceeds the dewpoint of the combustion products.

b. Reducing the moisture content of the combustion products so the resulting dewpoint is below any expected fly ash-inert gas mixture temperature.

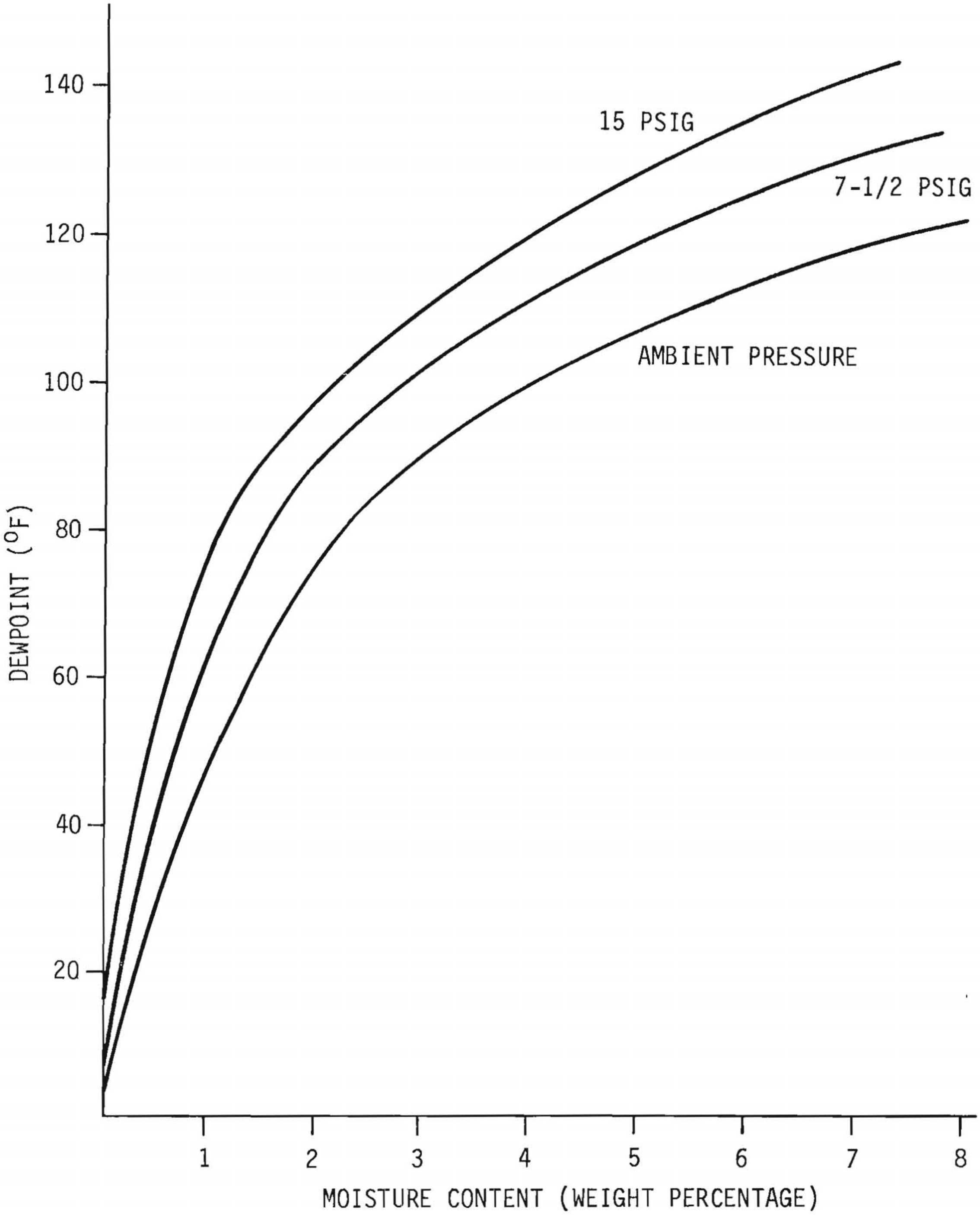


Figure 3. Dewpoint Versus Moisture Content

The first strategy is well suited to compress-burn-cool type systems since high outlet temperatures can be easily provided by controlling the Step 2 cooling. Figure 4 shows the minimum inert gas outlet temperature required to prevent condensation for a range of bulk fly ash temperature and a variety of fly ash-to-air ratios. Flows with 5 percent water content, corresponding to inert gas containing 8 percent oxygen, and 8 percent water content, corresponding to inert gas containing less than 1 percent oxygen are included.

The second strategy is practical for burn-cool-compress type systems, since the temperature of the combustion products must be reduced to below the blower inlet temperature limit of 160°F. Rotary desiccant matrix type dryers are the least expensive and most effective device for reducing the moisture content to acceptable levels. Their cost is less than one half the cost of the required additional heat exchanger surface. The Cargocaire "enthalpy exchanger," described in Section 3, is an example of this type of dryer. It is compact in size, provides excellent performance, is competitively priced, and is supplied by a local manufacturer, minimizing shipping cost, and maximizing availability of service. The model included in the recommended system will reduce the combustion products moisture content to a level closely approaching the moisture content of ambient air. For stoichiometric combustion products, the dewpoint of the combustion products after passing through the "enthalpy exchanger" is plotted versus ambient humidity in Figure 5. This resulting dewpoint is always within a few degrees of the ambient dry bulb temperature. Assuming that the fly ash temperature is not lower than 10°F below ambient dry bulb temperature, the mixture temperature of the fly ash and inert gas will always be above the dewpoint.

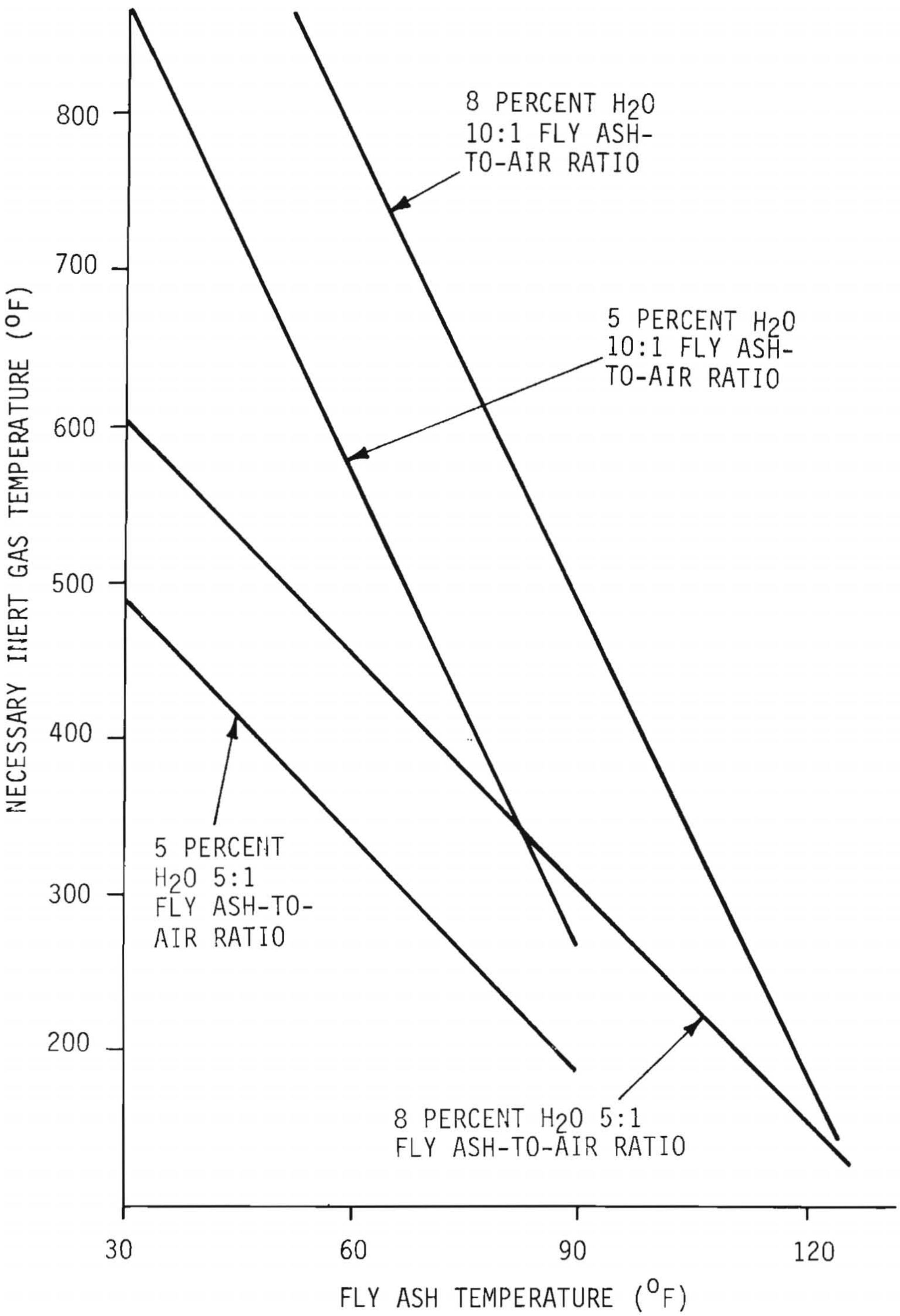


Figure 4. Inert Gas Temperature Required to Prevent Moisture Condensation

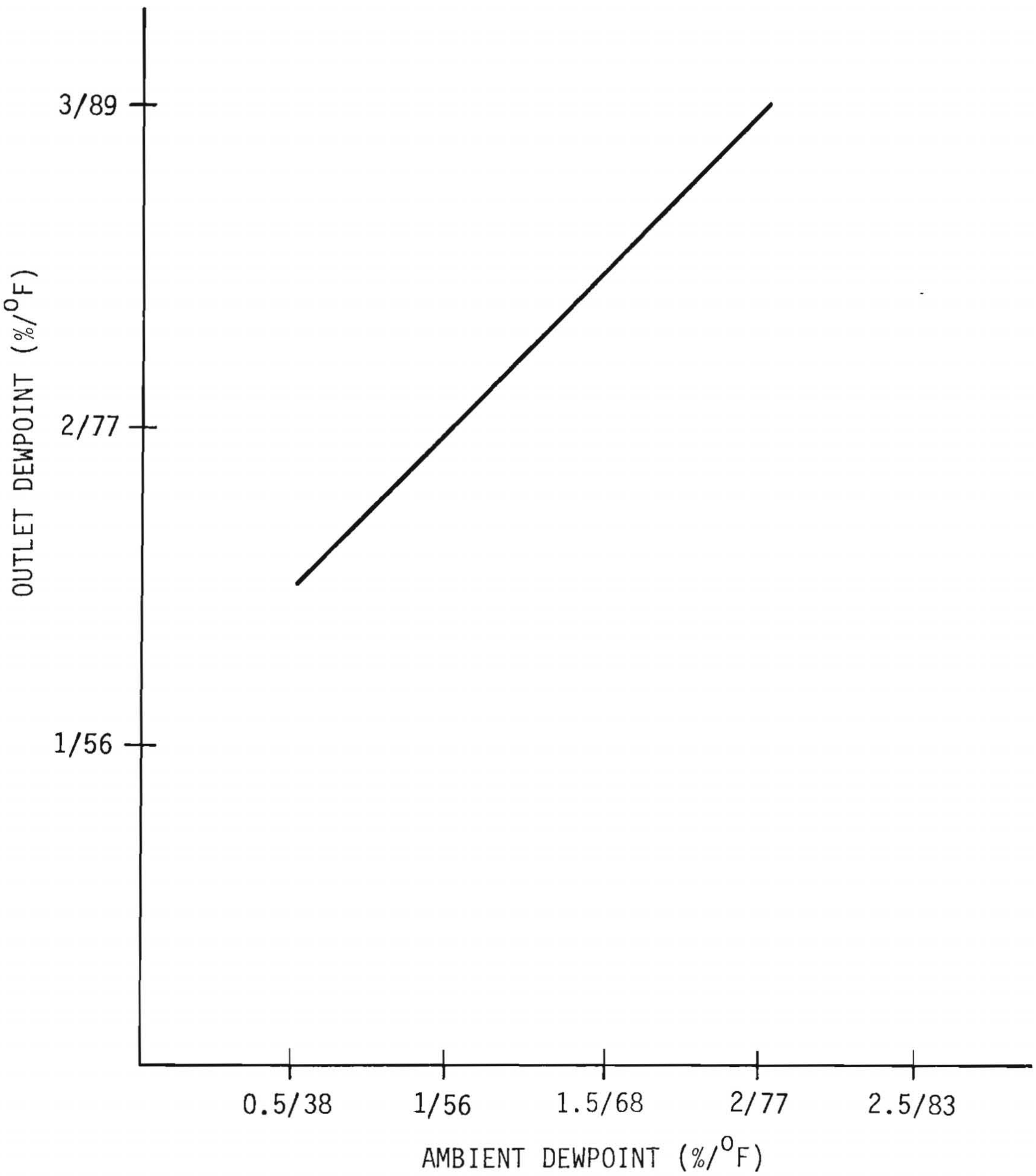


Figure 5. Outlet Dewpoint From Rotary Matrix Desiccant Dryer

2.3 Viable Alternative Systems and Selection Criteria

Based on the conclusions presented in the preceding section, seven alternative system configurations worthy of further evaluation were identified. These systems are listed in Table 3. Each was given further consideration because they offered some particular advantage or advantages in terms of size, weight, cost, reliability, or overall ease of use in conditions under which the Remote Sealing System must operate.

The preliminary evaluation of each alternative was based on a survey of commercially available and routinely fabricated equipment that could be used to implement a given system concept. From the equipment available, those components providing required performance and satisfying dimensional constraints at the lowest cost were selected. This produced a preliminary system design based on available hardware. Operation of the overall system was considered and a preliminary layout of the components on the trailers was prepared. A preliminary system cost and weight estimate was also prepared.

Table 3. Viable Alternative Systems

Item	System Type
1	Compress-Burn-Boiler
2	Burn-Thermal Liquid Heater-Compress
3	Direct Quenched Combustion
4	Engine Combustion
5	Gas Turbine-Afterburner
6	Burn-Boiler-Compress
7	Burn-Air Heater-Compress

The overall advantages and disadvantages of each approach were considered. The major considerations included the following:

a. Economics - initial, operating and maintenance costs
b. Reliability and ease of operation in the field
c. Maintainability
d. Transportability - minimum size and weight
e. Ruggedness - for off road mobility
f. Supply logistics
g. Ease and speed of field setup
h. Impact of adverse weather conditions.

It was concluded that the compress-burn-boiler system, as presented in some detail in Appendix A, would satisfy all the requirements. This alternative was also economically attractive.

This approach, however, does have a number of inherent disadvantages; including the quantity of water required to fill the boiler and the precautions necessary to prevent freezing of the system water during overnight cold weather shutdowns.

Furthermore, the arrangement of the positive displacement blower providing combustion air to the burner represents a departure from normal burner applications. While several manufacturers expressed interest in providing a satisfactory burner system, the quoted prices reflected the development risk in providing a burner package of this type.

As an alternative with no major disadvantages, FMA decided, with the Bureau's approval, that the burn-thermal liquid heater-compress system was the most desirable approach and should be built. It is described in detail in the following section.

3. SYSTEM DESCRIPTION

The FMA Inert Gas Generation system produces product gas to the specifications of Table 1 by following several distinct process steps:

a. Low excess air combustion of distillate fuel oil in air, producing combustion products containing less than 1 percent oxygen.

b. Primary combustion product cooling and secondary combustion product cooling.

c. Moisture removal.

d. Compression (up to 15 psig) of the inert gas to pressures required for fly ash conveying.

These steps are detailed on the system flow diagram shown in Figure 6. During operation, combustion air is mixed with atomized fuel oil in a Pyronics forced draft burner. The fuel-air mixture is burned within the furnace section of an International-Lamont TH type thermal liquid heater, producing combustion products containing less than 1 percent oxygen. The combustion products are cooled in the thermal liquid heater by a combination of radiant and convective heat transfer to the coolant tubes in the heater. The coolant, a petroleum based heat transfer fluid, is continuously circulated between the heater and an air-cooled, finned tube heat exchanger, rejecting heat acquired in the burner to ambient air. The combustion products exit the thermal liquid heater with a temperature between 500° and 800°F, requiring additional cooling.

The additional cooling is provided by a Z-Duct stack gas heat recovery heat exchanger. In this unit, the combustion products, running counterflow to fan-forced ambient cooling air,

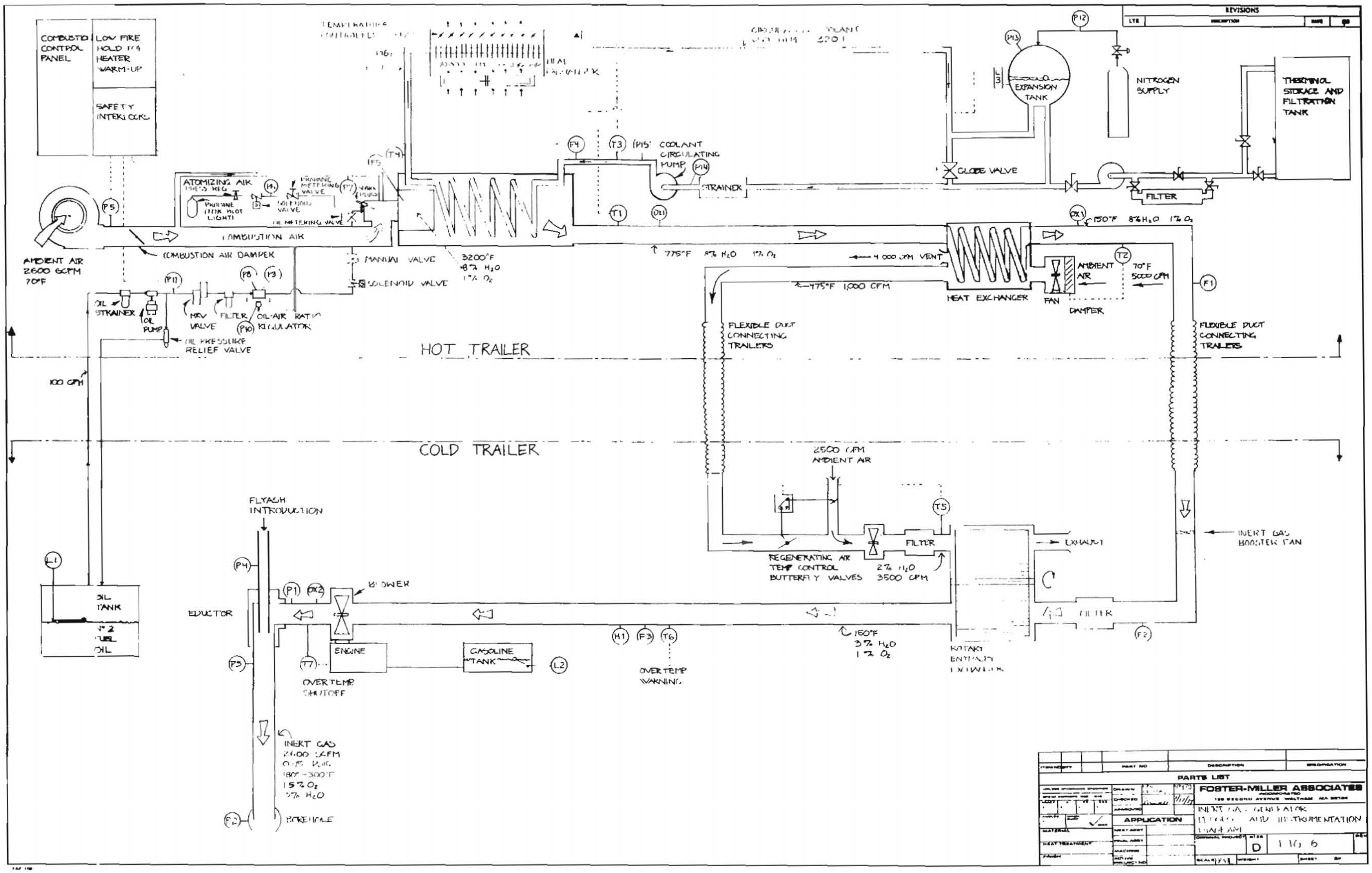


Figure 6. Inert Gas Flow Diagram

are cooled to temperatures less than 300°F. The moisture content of the combustion products is then lowered to a level acceptable for fly ash conveying by passing through a Cargocaire rotary disc "enthalpy exchanger." The "enthalpy exchanger" rotating disc consists of a desiccant impregnated asbestos honeycomb matrix. Moist air to be dried passes through one-half of the rotating disc while heated dry air passes through the other half, continuously regenerating the desiccant. Moisture in the combustion products is transferred to the regenerating air provided by mixing ambient air with the hot exhaust cooling air from the Z-Duct Heat Exchanger.

If an oxygen content greater than 1 percent is permitted in the inert gas, the cooled, dried combustion products may be diluted with ambient air to minimize fuel consumption. This mixture of cooled, dried combustion products and dilutant air constitute inert gas, suitable for both fly ash conveying for remote seal emplacement and mine atmosphere inerting. The pressure required for fly ash conveying is provided by the engine-blower package supplied by Gardner-Denver.

In addition to the equipment directly performing the actual process steps to generate suitable inert gas, the system includes the necessary support equipment for independent operation in the field. An 85 kilowatt gasoline engine driven electric plant provides power to drive the cooling fans, the combustion air blower and oil pump, the coolant circulation pump, and the control system. Fuel tanks with capacity for a full day of operation at full system output are included in the system. An enclosed control console with all instrumentation and controls necessary to control and monitor system operation is provided. In addition to instrumentation and controls required to control the inert gas delivery rate and oxygen and moisture content, the control system includes instrumentation necessary to monitor the operation of the major components and interlocks and alarms to prevent damage to the system in the event of a malfunction in the system.

The entire system is mounted on two low bed trailers so the system can be rapidly transported to the field.

The system can be quickly set up in the field and is simple to operate. Setup and operation instructions are included in Volume II, Operations and Maintenance Manual, also prepared under this contract.

Figure 7 is a drawing of the system when set up for a field operation. The location of the major system components is indicated in the figure.

The system hardware is described in Sections 3.1 through 3.7. Appendix C is a listing of the manufacturers of the major system components and their mailing addresses and telephone numbers.

3.1 Combustion System

The combustion system was manufactured by Pyronics, Inc., Cleveland, OH. The combustion system performs several important functions so that clean combustion products with consistent composition are produced at a desired rate.

a. Oil atomization and mixing with combustion air; flame retention

b. Oil and air supply

c. Oil and air proportioning

d. Sequencing the ignition process

e. Fault condition protection.

The major combustion system subsystems are constructed around these functions. The main subsystems are:

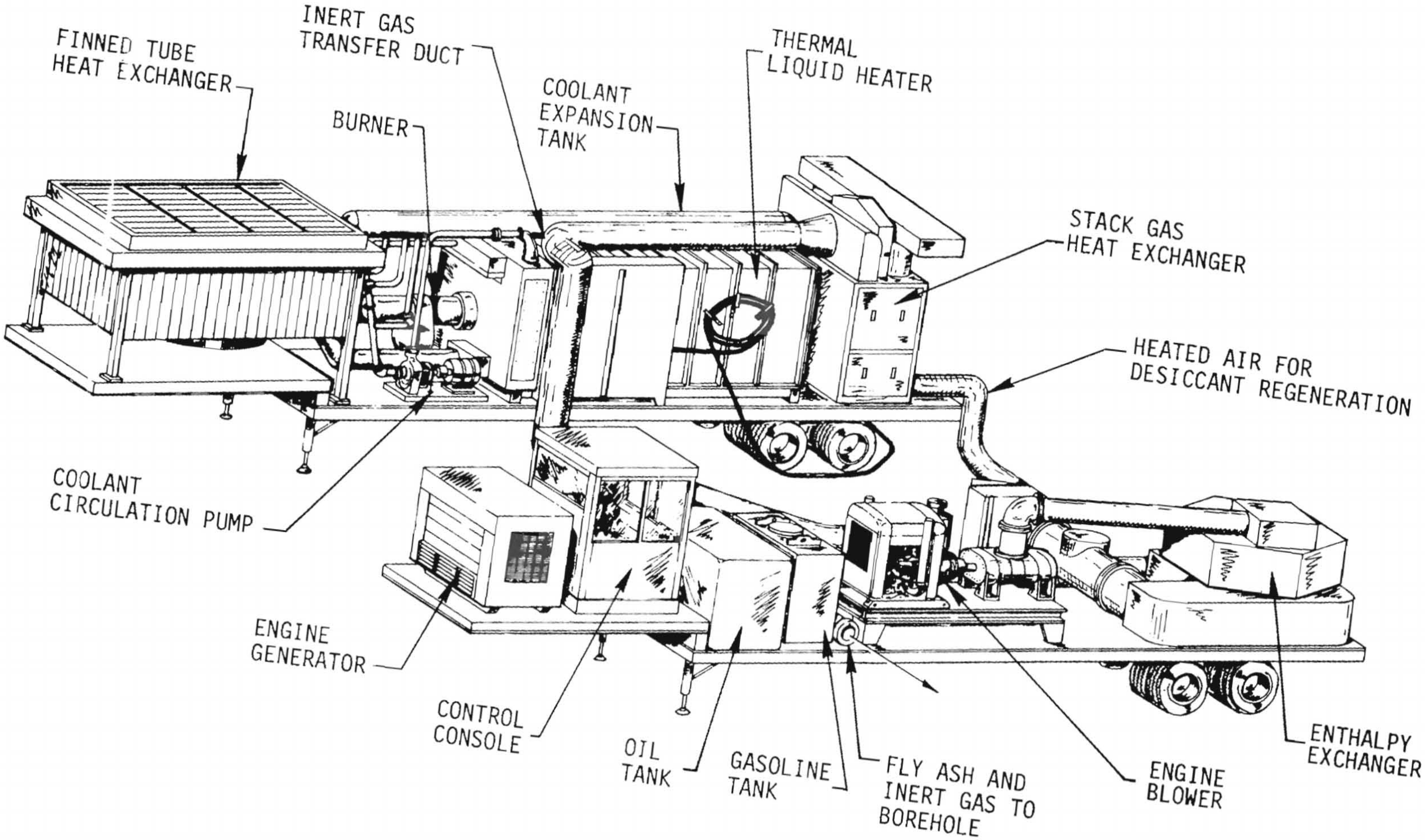


Figure 7. Inert Gas Generation System

a. The burner head and block

b. Oil pump and combustion air blower

c. Fuel-air ratio regulator

d. Electronic controls to sequence ignition and provide fault protection.

These subsystems are described in the following sections.

3.1.1 Burner Head and Block

A cross sectional view of one of the "tunnels" in the burner block is shown in Figure 8. The burner block in the inert gas generator has three of these tunnels cast in the same block. Oil enters the burner head through a metering valve, then passes through the oil nozzle. The oil nozzle consists of a number of

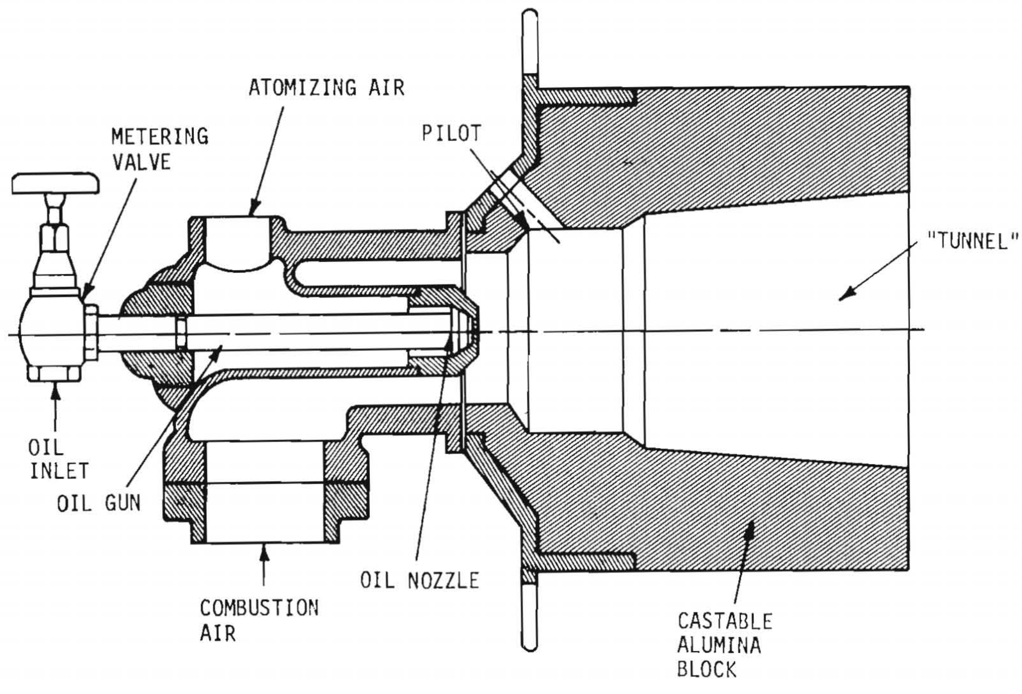


Figure 8. Burner Block Arrangement

radial-tangential outlets arranged in a ring around the end of the oil gun so that the oil is injected with a spinning motion. Atomizing air supplied at main combustion air pressure (1 to 2 psi) flows over the spinning inlet oil perpendicular to the direction of injection, shearing off oil droplets and forming a fine mist. The main combustion air passage is an annular space surrounding the oil nozzle and atomizing air passage. At the upstream end of the burner tunnel, the main combustion air stream and the atomizing air-oil droplet mixture combine into a combustible air-oil mixture. Once ignited by the pilot, the oil-air mixture burns with a stable flame in the stepped refractory burner tunnel. In addition to the port provided for the pilot (shown in Figure 8), two other ports (not shown) are provided for a flame sensor and a sight glass.

The combustion system will operate on ASTM No. 2 fuel oil (common household heating oil) or No. 1 and 2 diesel oil.

3.1.2 Combustion Air Blower and Oil Pump

The combustion air blower and oil pump are used to supply air and oil to the burner at the required pressure. The air pressure is used to generate turbulence at the burner, to promote thorough mixing of the combustion air and oil droplets. Oil pressure is largely used to allow control of the oil flow over a wide flow range. The combustion air blower is a centrifugal blower with an outlet pressure of 1-1/2 psig and a capacity of 2500 SCFM. It is driven by a 25 horsepower electric motor. The oil pump is a rotary gear pump with a discharge pressure of 100 psig and a capacity of 2 gallons per minute. It is driven by a 1/3 horsepower electric motor. Oil pumped in excess of the combustion system requirements is returned to the main oil tank through a relief valve.

3.1.3 Fuel-Air Ratio Regulation

The fuel-air ratio is regulated by two major components:

a. The oil-air ratio regulator (OAR)

b. The metering valve on each burner head

The location of these components in the oil and air inlet lines is indicated in the upper left-hand corner of Figure 6. The OAR maintains the ratio between the main combustion air pressure drop across the burner and the oil pressure drop across the metering valve and burner at a constant ratio of 1 to 32 over the range of burner output. The burner air passage and the metering valve both have orifice flow characteristics, i.e., the flow through the orifice is proportional to the square root of the pressure drop across the orifice. By maintaining a constant ratio of the oil and air pressure drops across the burner, a constant ratio of the two flows through the burner is also maintained. The metering valve is used to adjust the ratio of the oil and air flows to the correct fuel to air ratio.

3.1.4 Electronic Combustion Control System

The combustion control system performs three major functions.

a. Provides safe sequencing of the burner ignition sequence and system warm up, in accordance with Factory Mutual (FM) and Factory Insurance Association (FIA) safety standards.

b. Provides a simple means of controlling the burner firing level.

c. Provides a means of automatically shutting off the burner oil supply in the event of loss of flame or other fault conditions.

Ignition

The oil flame is ignited by a gas pilot which in turn is ignited by a spark plug. The following sequence is used to light the burner:

a. Purge the combustion chamber. The maximum flow of combustion air is forced through the combustion chamber for 30 seconds (automatically timed). Purging the combustion chamber exhausts any combustible fuel-air mixture which may have accumulated in the combustion chamber.

b. Reduction of combustion air flow from maximum to minimum, because the burner lights more reliably at low fire

c. Energizing spark plugs and opening pilot gas supply valve

d. Verification of successful ignition of the pilots

e. Opening oil supply valve.

After successful ignition of the burner, the burner and thermal liquid heater are warmed up gradually with the burner held at forced low fire until the normal operating temperature is reached.

Control of Firing Level

The firing rate of the burner is controlled by throttling the main combustion air supply upstream of the burner. Because a constant fuel-to-air ratio is maintained, the firing rate and combustion air flow rate are proportional to each other. Throttling of the combustion air supply is accomplished by the motorized butterfly valve shown in the upper left-hand corner of Figure 6 (combustion air damper). The valve is actuated automatically during the ignition and warmup sequence described above. After the system has been warmed up, the valve is actuated by a pair of pushbuttons, one to open the valve, the other to close the valve.

Shut-Off for Fault Conditions

An important safety feature included in the combustion system is the fault condition shut off. This falls into two main categories:

a. Flame out
b. Limit shut off.

An ultra-violet flame detector installed in each of the three burner tunnels senses a flame out. Limit shut off is actuated by fault conditions measured by other instruments. Each instrument measures an important process variable (a flow, a temperature, a pressure, etc.) that either must not exceed a predetermined value or must not fall below a predetermined value. A limit switch on the instrument is opened when the fault condition occurs. All the limit switches are wired together in series and together are called the limit circuit. The opening of any one of these switches causes the oil supply to the burner to be shut off and an alarm to be sounded. The process variables that are accounted for in the limit circuit are tabulated in Table 4.

3.2 Cooling System

The cooling system reduces the temperature of the hot combustion products from flame temperatures in excess of 3000°F to

Table 4. Process Variables in the Combustion System Limit Circuit

Process Variable	Maximum (Minimum) Value	Consequence of Exceeding (Falling Below) Value
T1 (Inert Gas Temperature at Thermal Liquid Heater Outlet)	775°F	Possible damage to stack gas heat exchanger
T4 (Coolant Temperature at Thermal Liquid Heater Outlet)	500°F	Thermal expansion of coolant beyond capacity of expansion tank
Fuel Oil Pressure	(60 psig)	(Inadequate oil pressure at high fire)
Combustion Air Pressure	(1 psig)	(Inadequate air pressure for atomizing fuel oil)
Coolant Flow Rate	550 gal per min	Inadequate coolant velocity in heater tubes causing high film temperature, coolant degradation, and possible damage to tube walls
Coolant Level in the Expansion Tank	(1/10 full)	(Pump cavitation, air entrainment in coolant, heater tube hot spots)
Coolant Level in the Expansion Tank	9/10 full	Possible exceeding of expansion tank capacity
Stack Gas Heat Exchanger Fan Motors	Must be running	Damage to stack gas heat exchanger if no cooling air circulation
Coolant Pump Motor	Must be running	This backs up the coolant flow meter limit switch

an outlet temperature below 200^{o}F. The heat of combustion is rejected to ambient air. The major parts of the cooling system are:

a. Thermal Liquid Heater
b. Coolant Circulation Loop
c. Air-cooled Coolant Heat Exchanger
d. Stack gas heat exchanger.

The four major parts are described in detail below.

3.2.1 Thermal Liquid Heater

The thermal liquid heater used in the Inert Gas Generator is an International-Lamont Model TH-9 heater with special fiber type refractory insulation manufactured by International Boiler Works in East Stroudsburg, PA. The header and tube bundle arrangement and the coolant flow and combustion air flow patterns are illustrated in Figure 9. The tube bundles and headers are covered with approximately 6 inches of insulation and enclosed in a gusseted plate steel outer shell. The burner fires directly into the furnance where a substantial portion of the heat of combustion is radiated to the coolant tubes lining the furnace. The combustion products are forced to the top and rear of the furnace by the baffle. Then the combustion products flow down through the convective heating section and out the flue gas outlet. The design of the heater results in high heat transfer efficiency between the combustion products and coolant with a low combustion product pressure loss (less than 2 inches W.C.) through the heater.

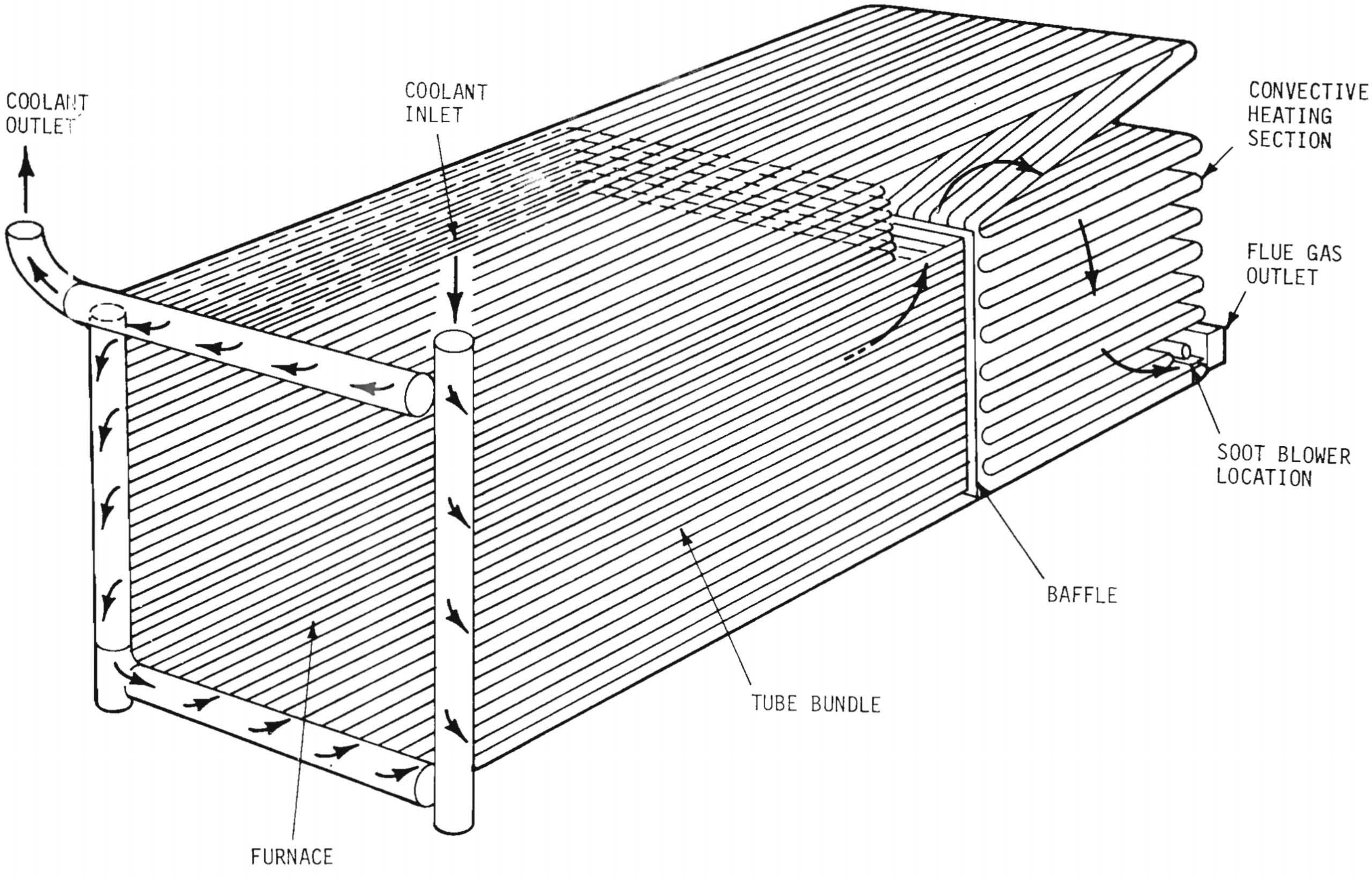


Figure 9. Flow Diagram - Thermal Liquid Heater

3.2.2 Coolant Circulation Loop

The coolant circulation loop provides connecting piping between the thermal liquid heater and the air-cooled coolant heat exchanger, a pump for circulating the coolant through the loop, and an explosion tank to accommodate the variation of coolant volume over the range of system operating temperatures. A flow schematic of the coolant loop is included in the complete system flow diagram, Figure 6.

The coolant circulating pump was manufactured by Dean Brothers Pumps, Inc., Indianapolis, IN. It is capable of pumping appproximately 650 gallons per minute through the coolant system. It is driven by a 20 horsepower electric motor.

The coolant circulating loop was fabricated and installed by Middlesex Welding Co., Woburn, MA.

3.2.3 Air-Cooled Coolant Heat Exchanger

The air cooled heat exchanger was supplied by the MRM division of Ecodyne Corporation, Massillon, OH. It is a forced draft horizontal core, two pass finned tube heat exchanger with temperature control louvers. The unit is pictured in Figure 10. Cooling air is forced across the finned tube core by a single 7-foot diameter propeller fan belt driven by a 15 horsepower electric motor. The temperature control louvers are actuated by a proportional control feedback loop maintaining a set outlet temperature from the heat exchanger (and a set inlet temperature to the thermal liquid heater). Maintaining a constant coolant temperature over the range of system output promotes maximum longevity of the thermal liquid heater.

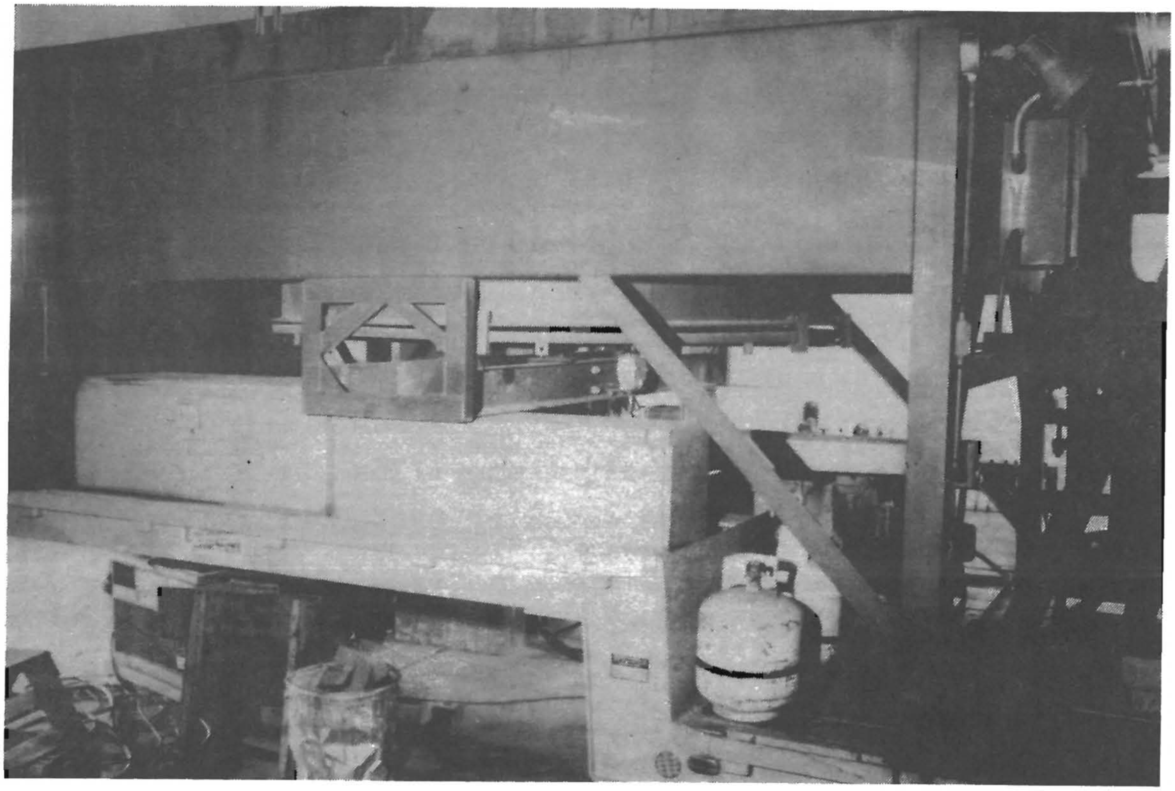


Figure 10. Air Cooled Finned Tube Heat Exchanger

3.2.4 Stack Gas Heat Exchanger

The combustion products exiting the thermal liquid heater have been cooled to a temperature of 500°F to 800°F. The stack gas heat exchanger reduces this temperature to below 300°F by direct transfer to ambient air. The Z-Duct heat exchanger is a counterflow heat exchanger. It consists of a single folded energy transfer surface fitted within a duct in such a way as to divide it into two separate yet intermeshed passages. Heat is transferred from the hot inert gas steam through the heat transfer surface to the cooling (ambient) air steam. The exhaust cooling air from the Z-Duct is used to "regenerate" the drying wheel.

The performance of the original heat exchanger, the Hughes Heatbank, was not entirely satisfactory, necessitating its replacement with the Z-Duct unit. The details of this are discussed in Appendix E.

3.3 Inert Gas Dryer

A substantial portion of the combustion product moisture in the inert gas stream is removed by the inert gas dryer. The dryer is a model EC7500 Econocaire Enthalpy Exchanger manufactured by Cargocaire Engineering Corporation, Amesbury, MA. The main features of this type of air dryer are illustrated in Figure 11. The heart of the dryer is the enthalpy exchanger wheel. The wheel consists of an asbestos honeycomb matrix that has been impregnated with lithium chloride, a desiccant salt. The wheel rotates slowly inside a metal enclosure that is divided into two halves, one for the air stream to be dried, the other for the

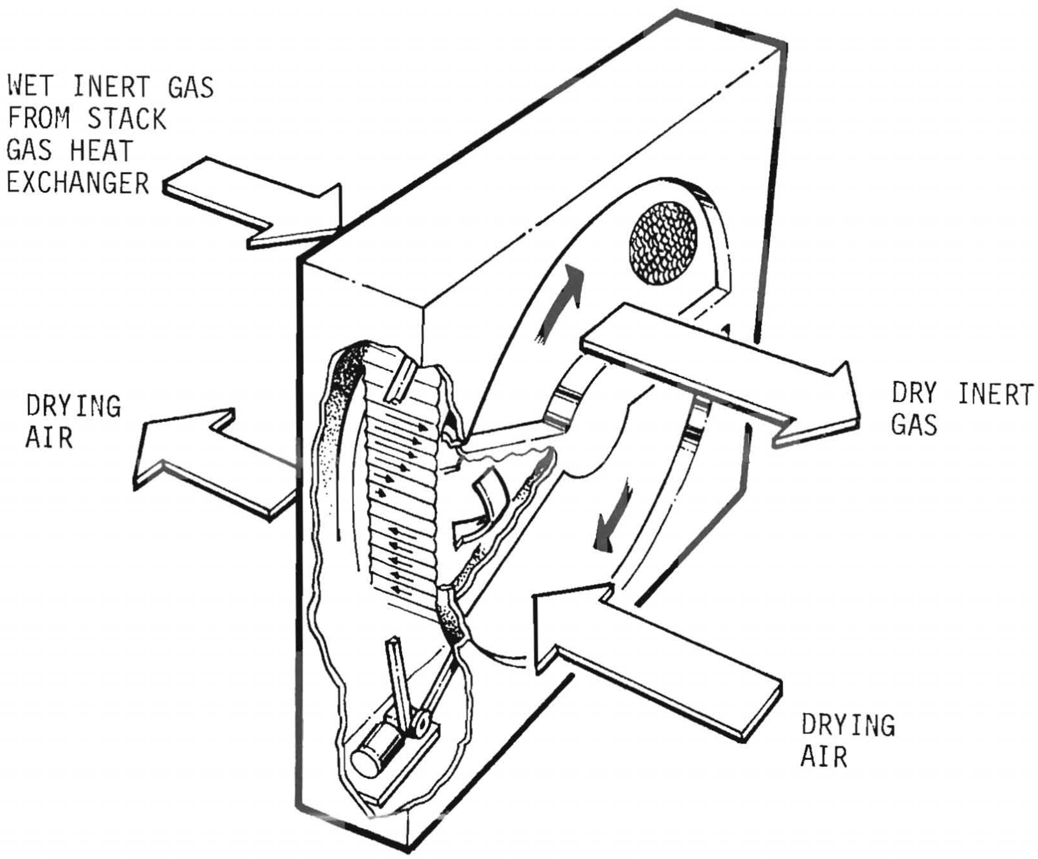


Figure 11. Inert Gas Dryer

drying ("regenerating") air. As the wheel rotates, it passes alternately through one air stream and then the other. Duct work carrying the two air streams is attached to the faces of the wheel.

In the Inert Gas Generator, as the enthalpy exchanger wheel passes through the wet inert gas stream it absorbs moisture, drying the inert gas in the process. As the wheel passes the drying air stream, the absorbed moisture is desorbed, drying the wheel and preparing it for another pass through the wet inert gas stream.

The drying air is a mixture of ambient air and exhaust cooling air from the stack gas heat exchanger (Section 3.2.4). The proportions of the mixture are regulated by a pair of temperature controller actuated butterfly valves (Figure 6) to a temperature between 130^{o} to $140^{o}F$. The increased air temperature increases the moisture removal capacity of the drying air stream.

The enthalpy exchanger, in addition to acting as a gas dryer, also acts as a highly effective sensible heat exchanger. This sensible heat exchange capacity provides reserve cooling capacity if the performance of the stack gas heat exchanger should undergo any degradation in the field.

3.4 Blower and Fly Ash Conveying System

The primary use of the inert gas generator is to supply conveying gas for remotely emplacing mine passage seals. The inert gas generator includes the equipment needed for fly ash seal emplacement. Figure 12 is a flow schematic for the fly ash conveying equipment which includes:

a. Engine-blower package
b. Eductor
c. Fly ash hose, connecting piping and borehole fittings.

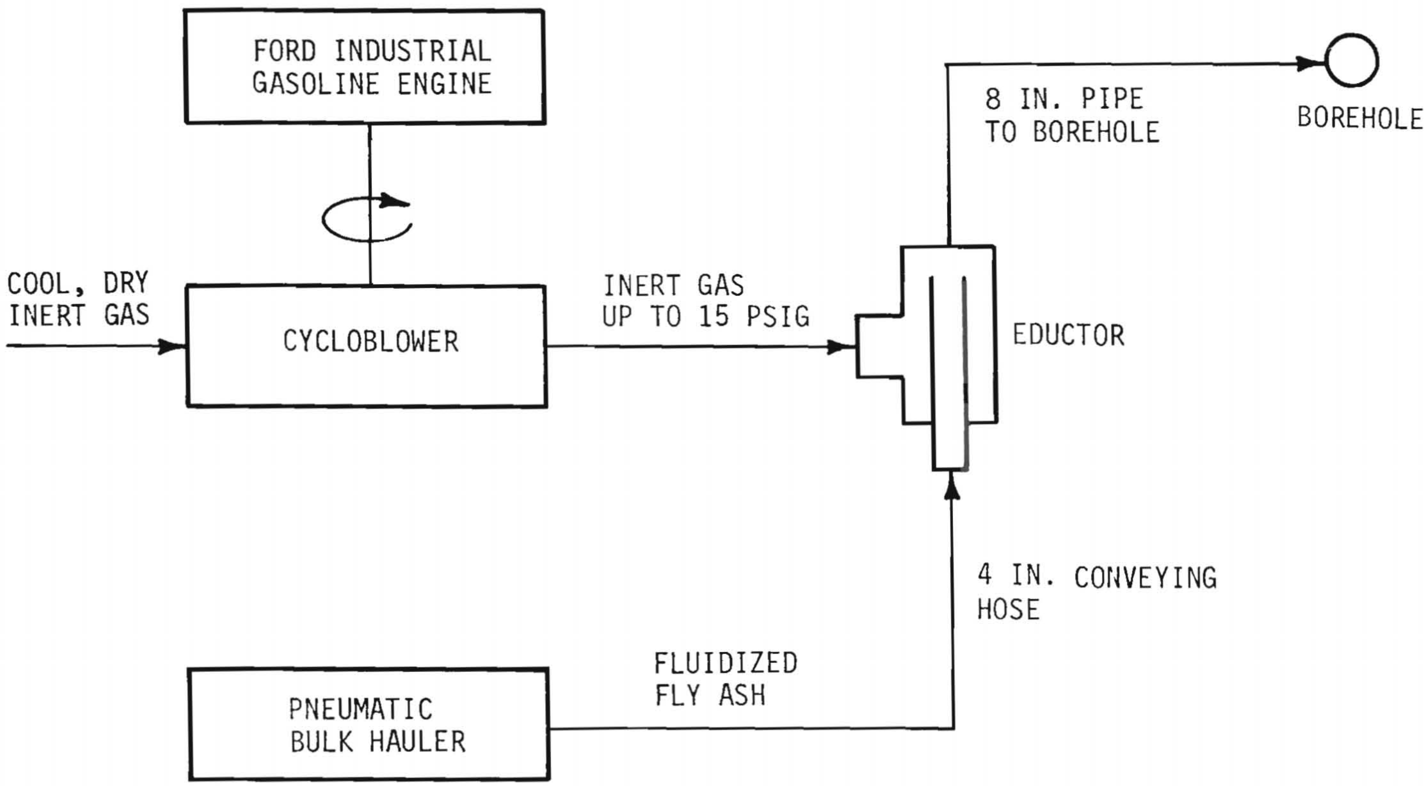


Figure 12. Blower and Fly Ash Conveying System Schematic

3.4.1 Engine-Blower Package

The engine-blower package was supplied by the Cycloblower division of Gardner-Denver, located in York, PA. The package consists of a 534 cubic inch Ford industrial gasoline engine and a Model 9CDL-18 Cycloblower rotary positive displacement blower. The positive displacement blower delivers a controlled flow rate of inert gas, independent of back pressure, to the fly ash conveying line.

3.4.2 Eductor

Fly ash transferred from a pneumatic bulk hauler is mixed with the inert gas stream in the eductor, Figure 13. The eductor is designed so the fly ash remains in suspension when the fly ash stream from the bulk hauler is mixed with the inert gas stream.

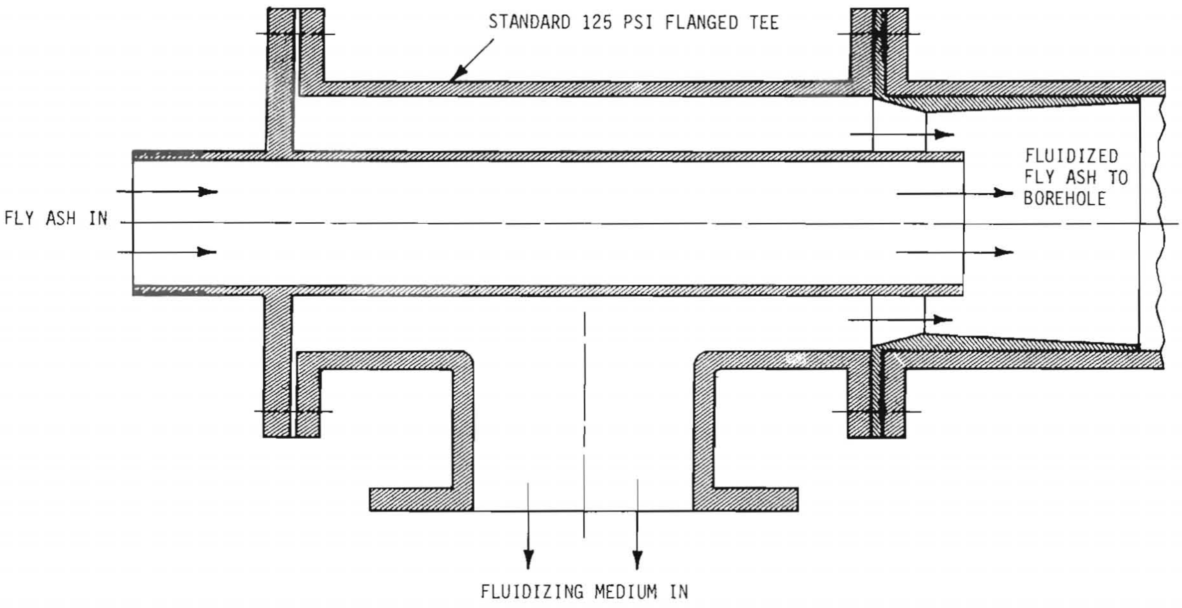


Figure 13. Fly Ash Eductor Assembly

3.4.3 Fly Ash Hose, Piping Borehole Fittings

The Inert Gas Generator includes enough hose, pipe, and fittings to allow complete setup of the fly ash conveying system.

The fly ash hose includes six, 50-foot lengths of 4-inch pneumatic conveying hose with the standard Kamlock fittings used on pneumatic bulk haulers.

The 200 feet of lightweight 8-inch diameter fiberglass pipe and 30 feet of 8-inch flexible hose carries the fly ash laden inert gas stream from the eductor to the borehole fittings.

Various cast iron pipe fittings are included to mate the horizontal 8-inch pipe to vertical boreholes between 6 and 8 inches in diameter.

3.5 Electric Power System

The Inert Gas Generator uses electric power to drive cooling fan motors, power instrumentation and control devices, provide night lighting, power the control cab space conditioning system and provide auxiliary power to other equipment on site. The electric system is completely self-contained and includes a gasoline engine driven 75 kilowatt electric plant and the necessary distribution components and wiring to deliver the electric power to the different loads in the system. The arrangement of the electric system is indicated in Figure 14. The 480 VAC, 60 Hertz, 3-phase electric power is generated and delivered to the main electric distribution center on the hot trailer. From here electric power is supplied to the various hot trailer loads and 480 VAC, 60 Hertz, 3-phase power is supplied to the cold trailer distribution center. The cold trailer distribution center in turn supplies the power requirements of the cold trailer.

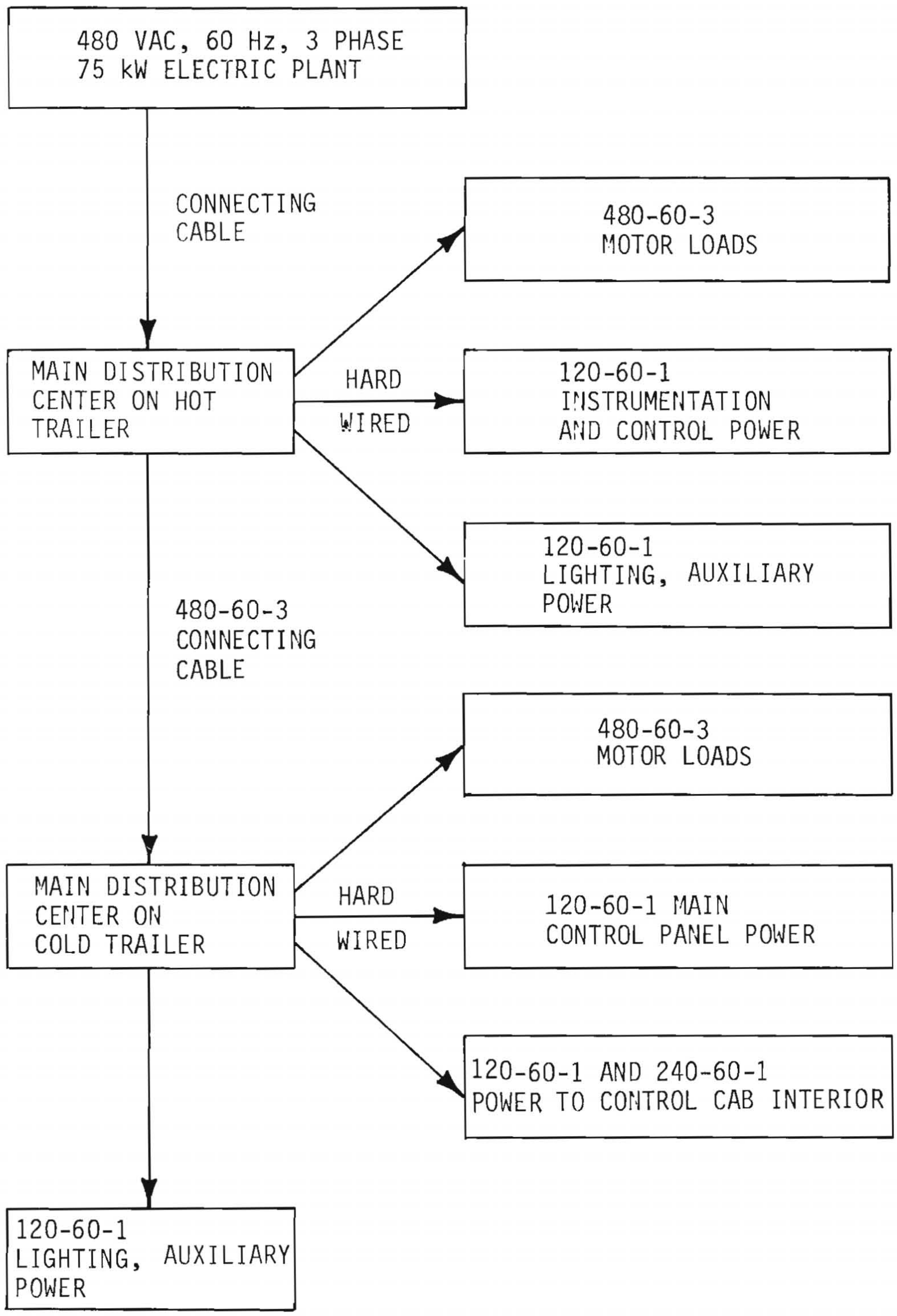


Figure 14. Arrangement of Inert Gas Generator Electric Power System

The generator is a Kohler Model 85R71, manufactured by the Kohler Co., Kohler, WI.

Each of the distribution centers contains the following equipment:

a. Main circuit breaker/disconnect switch

b. Step down transformer to provide 120 and 240 volt single phase power

c. Individual circuit breakers for short-circuit protection

d. Motors starters with motor overload protection

e. Ground fault detection.

3.6 Instrumentation and Controls

The instrumentation and control system has been designed to allow operation and monitoring of the complete Inert Gas Generator system from the main control panel, Figure 15, located on the cold trailer or operation and monitoring of the hot trailer alone from a control and instrument panel located on the right-hand side of the hot trailer, Figure 16.

Operating controls include:

a. ON-OFF pushbutton-pilot light stations for each cooling fan, the coolant pump, the drying wheel motor, the combustor air blower, the booster fan, and the oil pump

b. IGNITION and RESET pushbuttons to control burner pilot startup

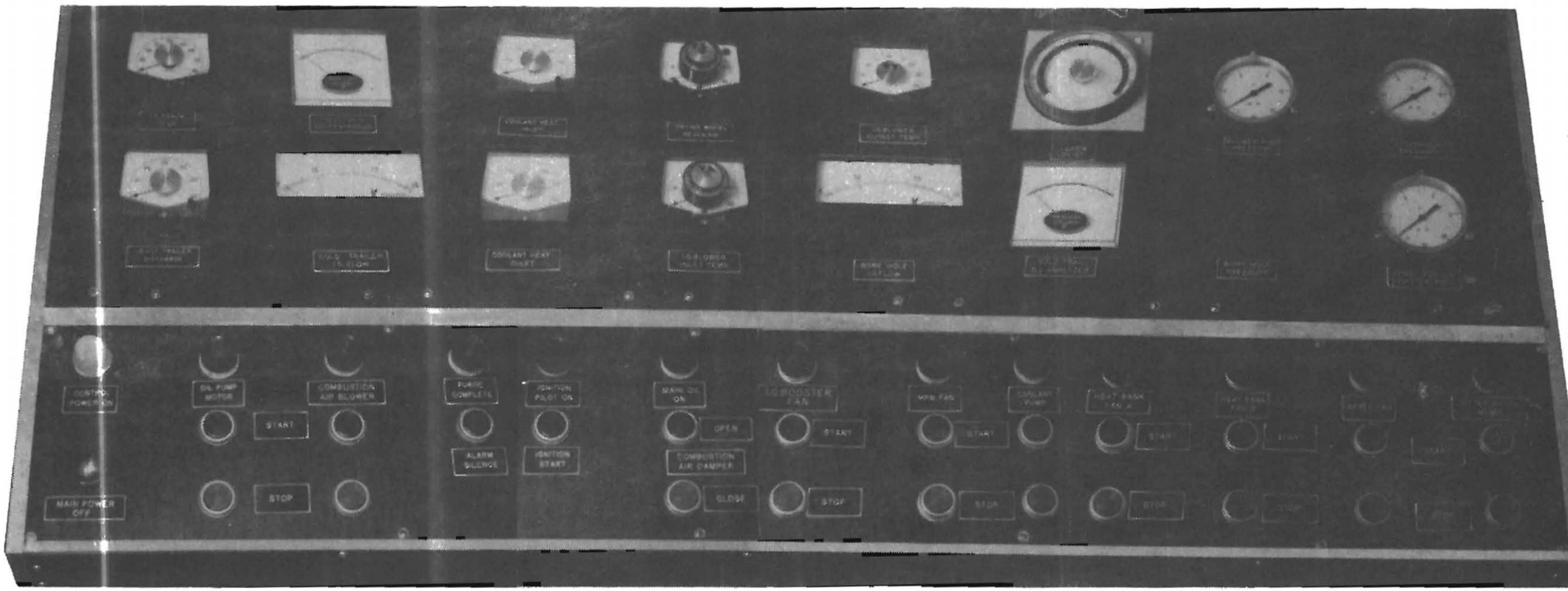


Figure 15. Main Control Panel

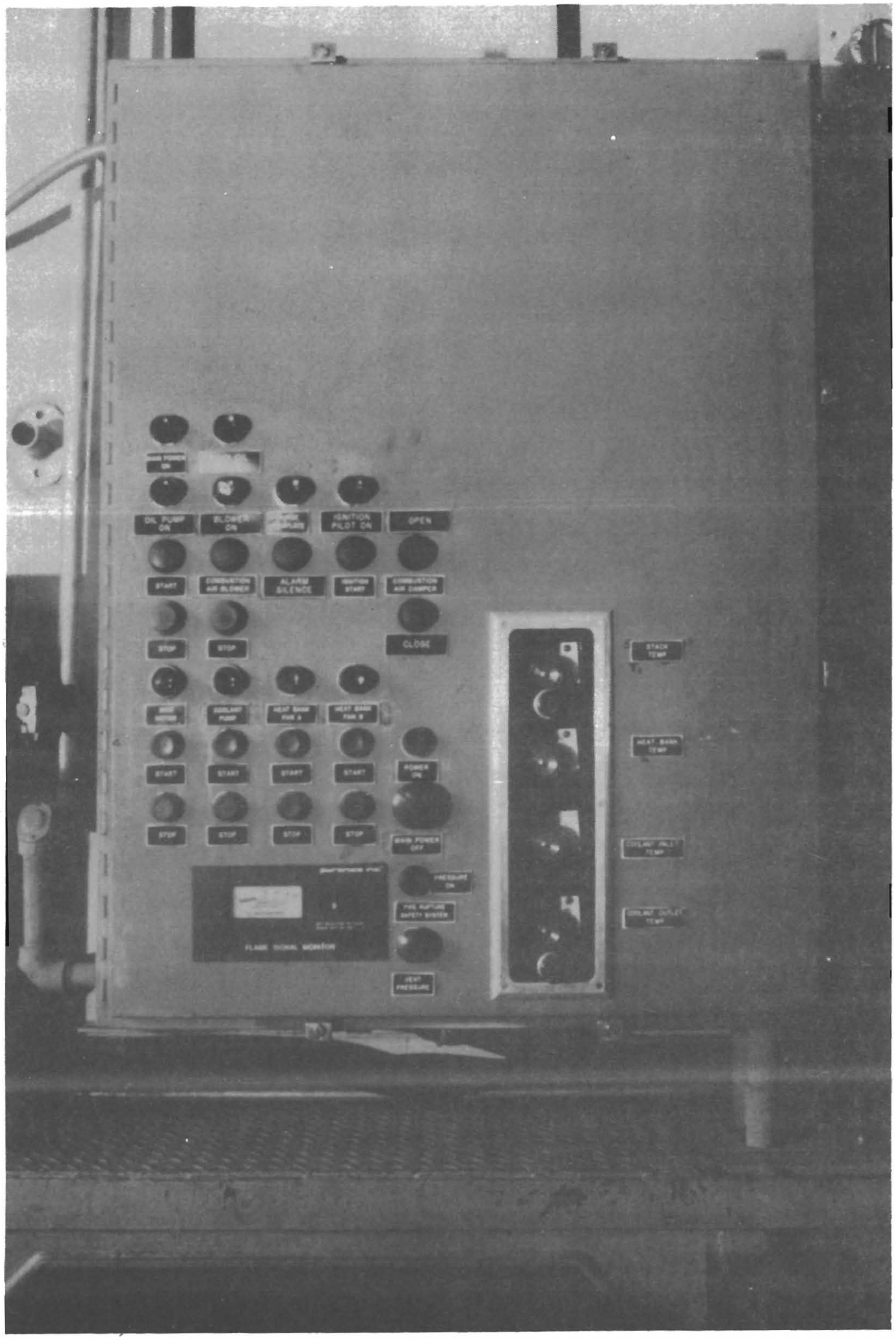


Figure 16. Hot Trailer Control Panel

c. Manual reset oil valve operating lever to start oil supply to burner

d. INCREASE-DECREASE pushbuttons to control burner firing rate

e. Three needle valves for adjusting the burner pilots

f. Three needle valves for adjusting the oil/air ratio

g. Blower engine ignition switch, choke, and variable speed throttle.

All but d. and g. are used only for system start-up and shut-down. The INCREASE-DECREASE pushbutton controls the rate of 1 percent oxygen inert gas production. The blower throttle controls the blower speed, setting the air flow down the borehole. By balancing the two flows relative to each other, the oxygen content of the inert gas to the borehole is controlled. Complete operating instructions are included in Volume II, Operation and Maintenance Manual prepared under this contract.

The instrumentation in the system has been designed to facilitate complete monitoring of the operation of the system, including both complete information on the condition of the inert gas produced by the system and complete information on the system operating condition to provide early warning of impending operating problems. The instrumentation includes a number of automatic safety shut-downs, most of which are discussed in Section 3.1, and a number of alarms. The sensor locations of the instrumentation are indicated in the system flow diagram, Figure 6. The instrumentation in the system is summarized in Table 5.

Table 5. Summary of Inert Gas Instrumentation

Figure 6 Designation	Description	Sensor Location	Indicator Location	Control Action	Instrument Manufacturer
T1	Inert gas temperature at thermal liquid heater stack	Heater stack discharge duct	Hot and cold trailer instrument panels	Burner limit	Love Controls Corp.
T2	Inert gas temperature at stack gas heat exchanger discharge	Stack gas heat exchanger discharge duct	Hot and cold trailer instrument panels	Control cooling air flow to the stack gas heat exchanger, maintaining itself at desired level	Love Controls Corp.
T3	Coolant temperature at thermal liquid heater inlet	Thermal liquid heater inlet nozzle; coolant heater discharge nozzles	Hot and cold trailer instrument panels	Burner low fire hold switch. Coolant temperature control	Love Controls Corp.; Honeywell
T4	Coolant temperature at thermal liquid heater outlet	Thermal liquid heater outlet nozzle	Hot and cold trailer instrument panels	Burner limit	Love Controls Corp.
T5	Dryer drying air temperature	Drying air inlet to drying wheel	Cold trailer instrument panel	Maintain T5 at desired level by actuating proportioning valves	Love Controls Corp.
T6	Inert gas temperature at blower inlet	Dryer to blower connecting pipe	Cold trailer instrument panel	Blower inlet over-temp alarm	Love Controls Corp.
T7	Inert gas temperature at blower outlet	Blower discharge pipe	Cold trailer instrument panel	Blower over-temperature shut off	Love Controls Corp., Allen-Bradley

Table 5. Summary of Inert Gas Instrumentation (Continued)

Figure 6 Designation	Description	Sensor Location	Indicator Location	Control Action	Instrument Manufacturer
F1	Inert gas flow rate from hot trailer	Hot trailer inert gas discharge pipe	Hot trailer instrument panel	None	Ellison Instruments
F2	Inert gas flow rate from hot trailer	Cold trailer inert gas inlet pipe	Cold trailer instrument panel	None	Ellison Instruments
F3	Inert gas flow rate through the blower	Blower inlet pipe	Cold trailer instrument panel	None	Ellison Instruments
F4	Coolant flow rate through the thermal liquid heater	Thermal liquid heater coolant inlet pipe	Hot trailer instrument panel	Burner limit	Ellison Instruments; ITT Barton
OX1	Inert gas oxygen content at hot trailer discharge or thermal liquid heater discharge	Samples taken from thermal liquid heater discharge duct or stack gas heat exchanger discharge	Hot trailer and cold trailer instrument panels	None	Teledyne Analytical Instruments
OX2	Inert gas oxygen content at blower discharge	Sample taken at blower discharge	Cold trailer instrument panel	None	Teledyne Analytical Instruments
P1	Blower discharge pressure	Blower discharge pipe	Cold trailer instrument panel	None	U.S. Guage
P2	Pressure at the top of the borehole	Borehole pipe fitting	Cold trailer instrument panel	None	Tyco Instruments
P3	Pressure of fly ash-inert gas mixture just downstream of the eductor	Immediately downstream of eductor	Cold trailer instrument panel	None	U.S. Guage

Table 5. Summary of Inert Gas Instrumentation (Continued)

Figure 6 Designation	Description	Sensor Location	Indicator Location	Control Action	Instrument Manufacturer
P4	Fly ash pressure just upstream of the eductor	Fly ash inlet pipe	Cold trailer instrument panel	None	U.S. Guage
P5-P11	Combustion air, pilot gas, and oil pressure in combustion system	At the various parts of the combustion system	At the various parts of the combustion system	Burner limits	U.S. Guage; Mercoid
P12-P13	Nitrogen supply pressure, coolant expansion tank pressure	Nitrogen supply line	Nitrogen supply line	None	U.S. Guage
P14-P16	Pressures in coolant piping system	Coolant piping	Coolant piping	Actuate pipe rupture safety pump shutdown	U.S. Guage; Allen-Bradley
H1	Inert gas dewpoint as delivered by the blower	Blower inlet pipe	Cold trailer instrument panel	None	Honeywell
L1	Fuel level - oil tank	Oil tank	Oil tank	None	Scully Signal Company
L2	Fuel level - gasoline tank	Gasoline tank	Gasoline tank	None	Scully Signal Company
L3	High and low level switch for coolant expansion tank	Coolant expansion tank	None	Burner limit	Gems-DeLaval

3.7 Other Supporting Equipment

The remaining equipment in the Inert Gas Generator is the support equipment that allows the system to operate independently in the field. This includes:

a. The trailers
b. Fuel tanks
c. Tools.

The two trailers were manufactured by Schertzer Sales Corporation, Somerville, MA. Each is a drop bed trailer with an overall width of 8 feet and a raised deck 10 feet long at the forward end. The hot trailer is 45 feet long overall and has a pneumatic ("air-ride") suspension. The cold trailer is 43 feet long and has a conventional spring suspension.

The fuel tanks were manufactured by Weymouth Engineering Co., East Weymouth, MA. Each tank has sufficient capacity for the system to run at full output for 12 to 15 hours. Under normal remote sealing system operating conditions, the fuel supply is adequate for 24 hours of operation. The capacity of the gasoline tank is 300 gallons and the capacity of the oil tank is 1000 gallons. The fuel tanks were designed in accordance with applicable DOT regulations concerning tanks for transporting hazardous materials.

The tools normally carried with the system include the normal handtools (pliers, wrenches, screwdrivers, hammers, etc.) used for setting up borehole piping. Also included are tools that allow field diagnosis and correction of minor electrical problems and diagnosis and correction of other minor problems.

4. SYSTEM PERFORMANCE TESTS

The Inert Gas Generator has been thoroughly performance tested. The testing falls into five categories:

a. Hot trailer initial startup and performance test

b. Cold trailer startup and complete system performance test

c. Bethlehem mine fire field operating experience (Cambria Mine Division, Ebensburg, PA, February-March, 1977)

d. Fly ash conveying demonstration

e. One hundred hour performance test

The hot trailer was performance tested as soon as its fabrication was complete because it contains the more complex portions of the Inert Gas Generator. When the system was being prepared for the Bethlehem mine fire, the portions of the cold trailer then completed were started and then run with the hot trailer. When the cold trailer assembly was completed, an extensive set of complete system tests were run. Valuable field operating experience was gained at the Bethlehem mine fire. The fly ash conveying demonstration provided a low cost demonstration of the ability of the Inert Gas Generator to convey and emplace fly ash sealing material. The 100 hr test served to provide an extended period of operation to verify the field-worthiness of the system. Each of the five sets of tests is discussed in the following section.

4.1 Hot Trailer Test

The hot trailer testing served two purposes:

a. Verify overall operation and performance of hot trailer

b. Measure individual component performance against component manufacturer's performance claims.

Overall operation of the hot trailer including operating controls, electrical equipment, coolant circulation system, instrumentation, etc. has been satisfactory.

The important manufacturer's component performance specifications are summarized in Table 6. The actual measured performance of each of these components is compared in the same table. All the major components performed at levels equalling or exceeding performance claims except the Hughes stack gas heat exchanger which has since been replaced with the Z-duct heat exchanger. This problem is discussed in Appendix E.

4.2 Complete System Test

The testing of the complete system accomplished several objectives:

a. Verify the performance of the individual cold trailer components

b. Test the operability of the complete Inert Gas Generator from the main control panel

c. Verify the overall performance of the Inert Gas Generator.

Table 6. Hot Trailer Component Performance Summary

Component	Performance Measure	Specified	Actual
Burner	Maximum output flow rate	2500 SCFM	2600 SCFM
	Turndown	5 to 1	6 to 1
	Minimum fuel-to-air ratio consistent with clean combustion	1 percent excess oxygen	0.7 percent excess oxygen
Thermal Liquid Heater	Heat exchange effectiveness	86.5 percent	86 percent
	Maximum combustion products pressure drop	1.9 in.WC	<2 in.WC
Air Cooled Coolant Heat Exchanger	Maximum coolant to ambient temperature difference to reject rated heat load of 105 x 10^6 BtuH	375°F	315°F
Z-Duct Heat Exchanger	Full load heat exchanger efficiency	68 percent	70 percent
	Maximum I.G. pressure drop at full load	1.2 in.WC	0.75 in.WC
	Leakage between sides	0	Negligible

The performance of two major components on the cold trailer is of particular interest.

a. The inert gas dryer
b. The engine-blower package.

The manufacturer's performance claims and the observed performance are compared in Table 7. The equipment meets or exceeds the performance claims with one exception -- there is some "cross-contamination" between the drying air and inert gas streams in the inert gas dryer.

Operation of the Inert Gas Generator from the main control panel on the cold trailer is quite satisfactory. The motor control pushbuttons and the burner control pushbuttons are all operational. The instrumentation provided on the main control panel monitors all of the important process variables in the system and functions properly. The remote indicator for the hot trailer oxygen analyzer has been observed to drift a small amount relative to the main indicator on the hot trailer, but is easily

Table 7. Cold Trailer Component Performance Summary

Component	Performance Measure	Specified	Actual
Inert Gas Dryer	Moisture exchange effectiveness	90 percent	85 percent
	Heat exchanger effectiveness	90 percent	>97 percent
	Leakage between sides	0	Enough to add 1 percent oxygen to inert gas
Engine Blower	Flow rate	2900 ACFM	2900 ACFM
	Discharge pressure	15 psig	15 psig

readjusted with a single potentiometer. Once the system has been started, all operation and monitoring of the system operation is accomplished from the cold trailer. The blower throttle (controlling blower speed) is located at the blower engine control panel, approximately 15 feet away from the main panel. The remainder of the system is operated and monitored from the main control panel.

In Table 8, the overall performance of the Inert Gas Generator is compared with the performance specifications listed in Section 2. The system performance meets or exceeds these specifications except for the low oxygen content at high inert gas flow rate specification.

At inert gas flow rates up to 1500 scfm the oxygen content can be varied between 1 and 8 percent. At an inert gas flow rate of 2600 scfm the lowest oxygen content achievable is 1.5 percent.

At 2600 scfm, the combustion system can deliver clean combustion products with an oxygen content as low as 0.8 percent. However, leakage across the face seals of the drying wheel increases the total oxygen content to approximately 1.5 percent.

Oxygen contents of 1.5 percent at the higher inert gas flow rates do not pose any operational problems for remote seal emplacement. The oxygen content of the mixture of inert gas and bulk hauler unloading air will still be well below 8 percent. For the most effective use of the system for inerting, however, the lowest possible oxygen content is desirable.

Table 8. Comparison of Overall System Performance with Table 1 Performance Requirements

Performance Requirement	Actual System Performance
Use commonly available fuel to produce gas	Use No. 2 fuel oil or diesel fuel
Inert gas oxygen content adjustable between 1 and 8 percent	Adjustable between 1 and 8 percent at output flows up to 1500 SCFM. Adjustable between 1.5 and 8 percent at flows of 2600 SCFM
Deliver inert gas flows adjustable between 600 and 2200 SCFM	Can deliver between 400 and 2600 SCFM
Deliver gas against back pressures up to 15 psig	15 psig
Maintain approximately constant flow against fluctuating back pressures	10 percent maximum drop-off in flow between no back pressure and maximum (15 psig) back pressure
Prevention of condensation in fly ash	Most of the combustion product moisture is removed. The gas has been used to convey fly ash satisfactorily (see Section 4.4).
Delivery temperature of fly ash - inert gas temperature below 200°F	Much less than this
Minimum consumption of materials delivered to site.	System consumes only fuel and passageway sealing materials
Field operable without external support	Unit is completely self contained, including electric generator, sheltered operator station, and 24 hours fuel storage
Capable of withstanding over the road transport	Unit sustained only minor damage on 1000 mile trip to Bethlehem mine fire (Section 4.3). Those weaknesses were corrected

4.3 Performance at Bethlehem Mine Fire

During March 1977 the Inert Gas Generator was used in the fire-fighting operations at the Bethlehem Mines Corporation, Cambria Division Mine 33. During the operation of the system, several positive results were achieved. As could be expected with a system undergoing use in the field for the first time, a number of problems were also encountered. The identification and correction of these problems has resulted in a more reliable, roadworthy system.

Several important accomplishments were achieved by the Inert Gas Generator during the fire-fighting operation.

a. A total of 12 hours of successful mine inerting

b. Ten days of standby availability at 80 percent of the system design capacity

c. Successfully withstanding 1000 miles of over-the-road transportation.

The inerting operation led directly to reductions in methane levels generated by the fire and restoring safe conditions in the mine. As a result, men were permitted underground to continue fire fighting operations. During the 10-day standby period, the system was test operated at 80 percent of full capacity for a total of 18 hours. The system withstood over-the-road transportation quite well. One coolant piping expansion joint failed on the trip to the mine (discussed below). Otherwise, the system sustained no damage.

Several problems were encountered during the field operation.

a. Ruptured coolant expansion joint

b. Coking of inside tube surfaces in the thermal liquid heater

c. Soot formation during combustion resulting in soot coating of much of the heat exchange surface.

Although the system as a whole withstood the 500-mile over-the-road trip quite well, one of the coolant piping expansion joints ruptured during the trip and approximately half of the system coolant was lost due to leakage. When the system arrived at the mine fire site, the ruptured expansion joint was not noticed (heavy rains had washed the spilled coolant off of the trailer deck). The lost coolant from the system resulted in very low coolant flow rates through the thermal liquid heater. Under the time pressure of the fire emergency the system was hurriedly test fired.

After a short period of time it was noticed that the system was not operating properly. The system was shut down and the ruptured expansion joint was discovered. When the system had been test fired with low coolant flow through the thermal liquid heater, the maximum allowable coolant temperature had been exceeded. The high temperature resulted in partial breakdown of the therminol 60 coolant, "coking" the inner surface of the coolant tubes in the thermal liquid heater, reducing the heat transfer effectiveness of the heater.

The expansion joint that ruptured was a "short" model with small allowable lateral displacements. Flexing of the trailer bed produced displacements in excess of the allowable levels, causing the rupture. The problem has been solved by removing the expansion joint and one other "short" expansion joint from the coolant piping and replacing them with blind flanges during transportation. A therminol storage tank and transfer pump have been installed to drain the therminol in the coolant piping to allow for removal of the expansion joints.

The coke deposited on the inner tube surface of the thermal liquid heater was removed by a chemical cleaning process. This was performed at the facility of a chemical cleaning contractor, the Oakley Service Co. of Metuchen, NJ.

The soot formation and deposition problem developed during the 12-hour inerting operation. Inspection of system components revealed large accumulations of soot in the stack gas heat exchanger and the blower inlet filter. In addition, the blower filter was wet. The source of difficulty was the fuel/air ratio proportioning system (Section 3.1.3). If variable pressures downstream of the burner are expected, a furnace reference pressure line must be connected to the oil-air ratio regulator. The correct fuel-to-air ratio is established by maintaining a constant ratio between the fuel pressure drop and the combustion air pressure drop across the burner. If the pressure downstream of the burner is always very close to atmospheric, the reference line need not be connected; the reference connection on the oil-air ratio regulator is simply vented to atmosphere. During operation at the mine fire wet combustion products soaked the blower filter, increasing the air flow resistance through it. This caused a buildup in back pressure, increasing the pressure downstream of the burner. Without the reference pressure line, this was "interpreted" as an increase in combustion air flow through the burner, calling in turn for increased fuel flow so that operation was fuel rich. The fuel rich operation resulted in the soot formation.

The soot problem was solved by thoroughly cleaning out the system using compressed air and detergent solutions and installing a furnace reference pressure line. The fuel-to-air ratio was readjusted. Sooting and fuel-air ratio control problems have not been experienced with the system since these repairs were made.

The overall experience at the mine fire was valuable. Field operating experience was acquired. Field reliability problems were identified and permanently corrected as a result of the experience.

4.4 Fly Ash Conveying Demonstration

The final test of the Inert Gas Generator was a demonstration of the ability of the system to provide inert gas suitable for conveying fly ash from the Inert Gas Generator to the borehole and ultimately to the injection point in the mine passage. To accomplish this, the remote sealing equipment was deployed as it normally would be in a remote sealing operation. Fly ash was injected at the eductor and conveyed through 150 feet of horizontal piping into covered, dust-controlled waste containers. Accomplishing this with no appreciable moistening of the fly ash in the process would provide a high level of confidence that subsequently the system could be successfully field demonstrated by emplacing a number of fly ash seals in actual mine entries.

The system was operated over the complete operating range that would be used in a remote sealing operation. The three major operating variables are:

a. Blower back pressure
b. Inert gas flow rate
c. Inert gas oxygen content.

Blower back pressure varies between 0 and 15 psig, independent of flow rate. The inert gas flow rate varies between 600 and 2600 SCFM, with the higher flow rate used to emplace the bulk of the seal and a gradual reduction of the flow rate used to finish the emplacement of the seal. The inert gas oxygen content varies between 1 and 8 percent. At higher flow rates it can be varied over this range to suit operating conditions, while at low flow rates it would be set at the low end of the range.

A photograph of the equipment used for the demonstration is illustrated in Figure 17. The Inert Gas Generator was set up normally. Fly ash was brought into the site in a pneumatic bulk hauler as in a mine sealing operation. Fly ash was transferred from the bulk hauler to the fly ash eductor on the Inert Gas Generator via 4-inch pneumatic conveying hose. The fly ash was conveyed from the Inert Gas Generator through 8-inch fiberglass pipe to two 50 cubic yard waste containers. Each waste container had plywood covers with dust control provided by a chimney vacuum truck drawing a small vacuum (several inches of water) on the waste container and filtering the used inert conveying gas before discharging it.

The normal instrumentation on the inert gas generator was used to take test data.

The demonstration was carried out in an unused stone and sand quarry pit of the New England Sand and Gravel Co.

The Fly Ash Conveying Demonstration was conducted on September 13, 1977. The procedure was witnessed by:

R. King	USBM-PMSRC
G. Colaizzi	USBM - Division of the Environment - Denver
R. Berry	FMA
A. Guzdar	FMA
D. Monaghan	FMA

Figure 17. Equipment for Fly Ash Conveying Demonstration

In the demonstration, one pneumatic bulk hauler load of fly ash (52,000 pounds) was injected into the inert gas stream from the Inert Gas Generator. The fly ash was conveyed to large covered waste containers located approximately 150 feet from the Inert Gas Generator. During the conveying operation, the inert gas flow rate and oxygen content was varied over the range that would be used to emplace a fly ash seal. Performance data at these operating points is tabulated in Table 9. Qualitatively, the pneumatic conveying performance was excellent. There was no evidence of conveying line plugging or wetting of the fly ash by combustion product moisture. The fly ash settled out in the waste container in the desirable crater shaped pattern and remained dry and free flowing.

A complete set of the performance data taken during the demonstration is included in Appendix D.

Table 9. Summary of Fly Ash Conveying Demonstration Performance Data

Test No.	Inert Gas Oxygen Content (%)	Inert Gas Dewpoint (°F)	Inert Gas Flow Rate (ft^3/min)	Inert Gas Back Pressure (psig)
1	3.2	100	1920	2-1/2 to 3
2	3.8	104	2160	3-1/2 to 4
3	7.3	92	1900	3 to 6
4	4.2	82	1360	1-1/2 to 2

4.5 Inert Gas Generator 100-hr Test

The 100-hr test of the Inert Gas Generator served several objectives:

- Verification that the Inert Gas Generator was a field-worthy, dependable system, that could be relied upon for the Remote Sealing System Demonstration at the Jenney Mine.

- Uncover any shortcomings of the equipment under extended periods of operation where they could be corrected under non-emergency circumstances.

- Test the recently installed Z-duct heat exchanger.

- Develop experienced system operators for the Remote Sealing System Demonstration and future emergencies.

The test was conducted between August 17 and September 9, 1978. Approximately 1 week prior to August 17 was required to set up and debug the system. The time period of the test included 1-1/2 weeks of downtime for the repairs and minor upgrading described below.

The test was conducted at the site of a local gravel quarrying operation, simulating field conditions. The test sequence was planned to simulate the fly ash seal emplacement with varying requirements of inert gas oxygen concentration and supply pressure as presented in Table 10. The 20-hr simulated seal emplacement cycle consisted of 16 hr of operation at full capacity, 2 hr at 2/3 capacity, and 2 hr at 1/3 capacity - bulk seal emplacement followed by filling in the top of the seal. The tests were run around the clock.

Table 10. Test Sequence for 100 Hour Test

Time Period	Inert Gas Flow-Cold Trailer	Blower Discharge Pressure	"Borehole" Oxygen Concentration	Comments
0-1 Hrs	500 SCFM	0	1 - 3%	Warm up period
1-16 Hrs	2600 SCFM	12 PSIG	8%	Emplace bulk of first seal
16-18 Hrs	1400 SCFM	8 PSIG	5%	Begin first seal finish
18-20 Hrs	600 SCFM	4 PSIG	1%	Finish first seal
20-36 Hrs	2600 SCFM	12 PSIG	1%	Emplace bulk of second seal
36-38 Hrs	1400 SCFM	8 PSIG	1%	Begin second seal finish
38-40 Hrs	600 SCFM	4 PSIG	1%	Finish second seal
40-56 Hrs	2600 SCFM	12 PSIG	5%	Emplace bulk of third seal
56-58 Hrs	1400 SCFM	8 PSIG	4%	Begin third seal finish
58-60 Hrs	600 SCFM	4 PSIG	3%	Finish third seal
60-76 Hrs	2600 SCFM	12 PSIG	4%	Emplace bulk of fourth seal
76-78 Hrs	1400 SCFM	12 PSIG	4%	Begin fourth seal
78-80 Hrs	600 SCFM	12 PSIG	4%	Finish fourth seal
80-96 Hrs	2600 SCFM	12 PSIG	3%	Emplace bulk of fifth seal
96-98 Hrs	1400 SCFM	12 PSIG	3%	Begin fifth seal finish
98-100 Hrs	600 SCFM	12 PSIG	3%	Finish fifth seal
100-100½ Hrs	2000 SCFM	0	3%	Start system shut down
100½-101 Hrs	-	-	-	Complete system shut down

During the first 50 hr of the test, several problems were encountered:

a. Erratic firing of the burners caused by partially clogged oil nozzles.

b. Excessive dilution of the inert gas caused by air leaks around the drying wheel.

c. Inaccurate burner oxygen concentration measurements caused by stratification of the combustion gases and single point gas sampling from the flue.

d. Failure of the drive shaft of the coolant circulation pump.

These problems were corrected as follows:

- The oil gun assemblies were removed, disassembled, cleaned and reinstalled. The removal and reinstallation process can be accomplished in a matter of minutes - the cleanup process is more time consuming. Spare gun assemblies were procured so that any clogging of oil nozzles encountered in the future can be corrected without any significant downtime.

- Excessive dilution of the inert gas in the drying wheel was caused by a previously undetected leak between the inert gas discharge plenum and the housing of the wheel. The direction of rotation of the drying wheel had inadvertantly been reversed when modifications to the cold trailer electrical system had been made. The reversed rotation of the drying wheel eliminated the purge section from operation, allowing a carry-over of regenerating air into the inert gas stream. The leak was sealed and wheel rotation direction was corrected, effectively eliminating air dilution of the inert gas.

- The combustion system consists of three separate burner heads. It had been assumed the combustion products would be well mixed when passing through the thermal liquid heater. Therefore, a single gas sampling port was used for withdrawing an inert gas sample for measurement of the oxygen level. It was discovered that contrary to this assumption, the combustion products do not mix substantially and that sampling points installed left, center, and right on the flue gas connection from the thermal liquid heater, provided individual readings of the oxygen concentration of the combustion gas from the individual burner heads. The improved gas sampling system was installed, allowing precise adjustment of the fuel-air ratio at each burner head.

- Pump drive shaft failure was corrected by rebuilding the drive shaft/bearing/oil seal portion of the pump. The shaft failed in fatigue caused by misalignment of the motor shaft and pump shaft. Misalignment is caused by a slight (approximately 0.020 in. to 0.050 in.) twisting of the base caused by twisting of the trailer bed over the road. The problem will be avoided in the future by checking the shaft alignment and correcting it if necessary each time the hot trailer is moved to a new field location.

During the pump coupling repair downtime, steps were taken to increase the blower capacity to accommodate the increased gas flow requirement of the silo-rotary airlock fly ash injection system. A capacity increase of 400 scfm (to 2600 scfm) was achieved by two modifications:

a. A less restrictive duct connecting the drying wheel to the inlet of the blower was installed.

b. The regenerating air temperature to the drying wheel was lowered after establishing that this had no adverse effect on the moisture removal capacity of the drying wheel. The blower inlet temperature of the inert gas was reduced as a result of this, increasing the density of the gas at the blower inlet, increasing the mass flow rate at a given blower speed.

The test was resumed and successfully completed. The most important system performance parameters that were demonstrated during the test are summarized below.

Maximum inert gas output	2600 scfm
Minimum O_2 concentration at full output (2600 scfm)	1.5 percent
Minimum O_2 concentration at specified output (2200 scfm)	1.1 percent

5. CONCLUSIONS

The inert gas generator has been constructed and successfully tested. Over 200 hours of total operation time has been logged. It is now available for fighting underground mine fires.

The inert gas generator can supply inert gas with a very low oxygen concentration (1.5 percent) at a rate of 2600 scfm for approximately $0.60 per thousand cubic feet. The cost of nitrogen delivered to the site ranges from $8.00 to $12.00 per thousand cubic feet depending upon the total volume required and the site location.

The remote sealing system demonstration was conducted during the fall of 1978 at the USBM's Jenney Mine. It successfully demonstrated the capabilities of the inert gas generator and the remote sealing system as a whole to the coal mining industry and mining regulatory agencies. The results of the demonstration will be published under USBM Contract No. H0188105 as a three volume report in the near future.

APPENDIX A

COMPRESS-BURN-BOIL SYSTEM

Our system based on compressing ambient air to the inert gas delivery pressure, mixing with fuel oil and burning, and cooling the resulting combustion products in a fire tube boiler is shown in Figure A-1. The process features of the system are shown schematically in Figure A-2. With the blower speed set to provide the desired inert gas flow rate, ambient air is compressed and directed to the burner where it mixes with fuel oil and is burned. The temperature of the combustion products is reduced to 600° to 700°F by passing through the boiler. The steam from the boiler is condensed in the air cooled condenser, with the condensate returning to the boiler by gravity. The combustion products then pass through a gas-to-air heat exchanger (an air cooled compressed air aftercooler). The flow of cooling air through the heat exchanger is adjusted to maintain the desired outlet temperature in the range of 200° to 600°F. The inert gas is then used to emplace the fly ash seals or inert the fire area.

In addition to the basic inert gas processing components, the system contains equipment necessary for independent operation in the field. A 60 kilowatt gasoline engine driven electric power plant provides electric power necessary to drive the cooling fans and oil pump and power the control system. Excess capacity is available to power the rest of the Remote Sealing System. Fuel tanks with enough capacity to operate the system at full output for a day and a water storage tank with enough make-up water capacity for a day are included. The water treatment system can accept water of high mineral content or badly contaminated water from a stream or even a mine settling pond and provide acceptable quality, chemically treated boiler feed water. The enclosed control console includes the instruments

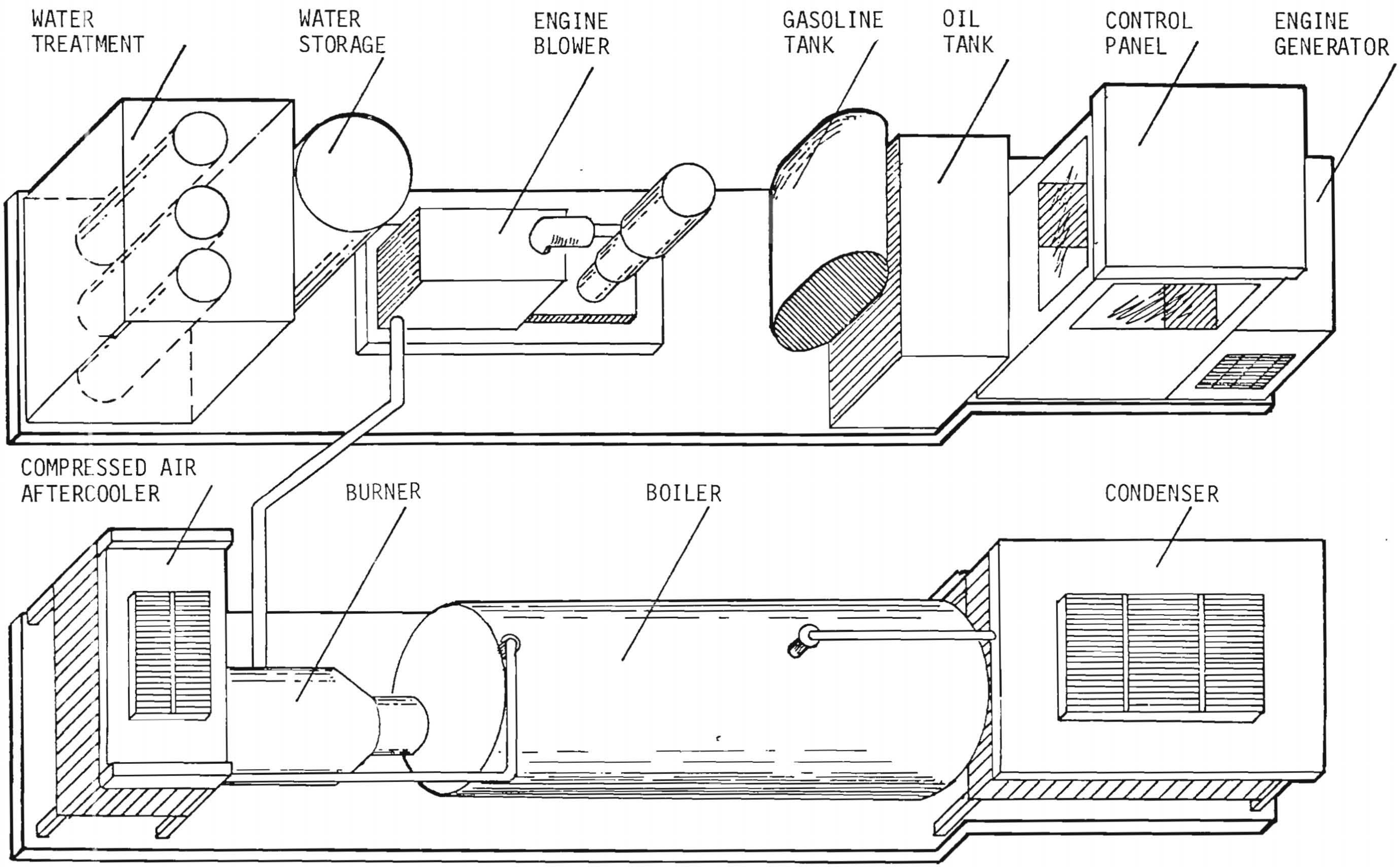


Figure A-1. Compress-Burn-Boiler System

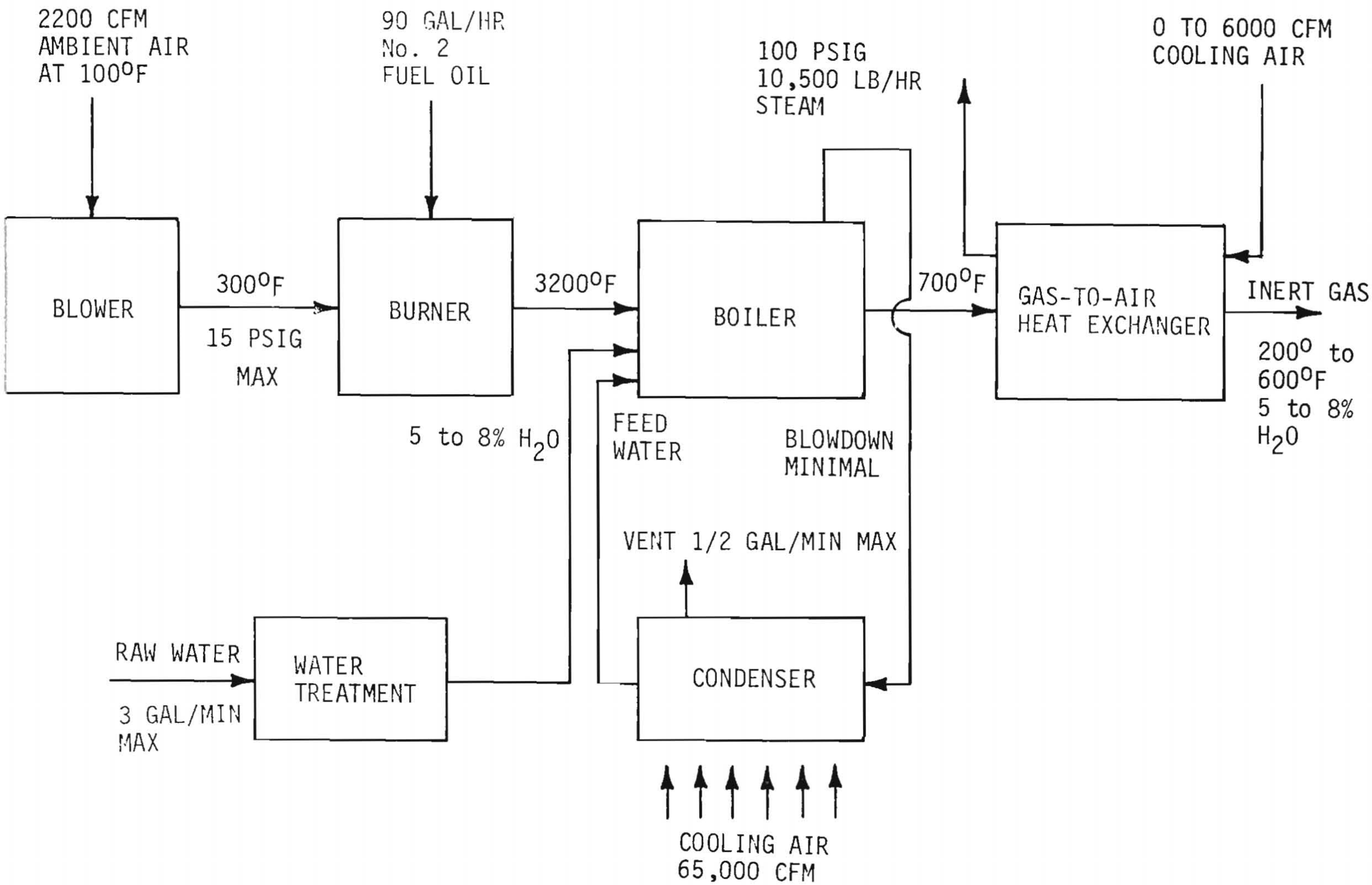


Figure A-2. Compress-Burn-Boil-Aftercool Process Diagram and controls necessary to allow operation of the system from the control console as well as instrumentation to monitor the operation of the system components. Safety interlocks and alarms are provided to prevent damage to the system in the event of a component malfunction.

The important features of the major components selected for the system are noted below.

John Zink HI-10 Custom Burner Package

John Zink Company would provide a burner system based on their high intensity burner, a wide range, low excess air burner. The burner package includes a custom fuel control system to maintain the desired fuel-air ratio (adjustable in the range of 1 to 8 percent oxygen in the combustion products) under the varying back pressure conditions. Standard Factory Insurance Agency and Factory Mutual approved firing controls are included.

Modified Industrial Boiler Company - Firetube Boiler

Out of a total of ten manufacturers of a standard line of firetube boilers who were contacted, Industrial Boiler was willing to modify their basic boiler to withstand combustion gas pressures up to 15 psig. The combustion gas turnaround chambers at either end of the boiler must be stiffened, secured, and sealed against the 15 psig combustion gas pressure. The combustion gas pressure poses no problems elsewhere in the boiler since the steam side design pressure is 150 psi.

Pin Fin Compressed Air Aftercooler

The air cooled compressed air aftercooler supplied by Pin Fin, Inc. is constructed of internally finned tubing that is pin-finned on the outside. The packaged unit includes a cooling fan and louvers to provide required control of the outlet temperature between 200° and $600^{\circ}F$.

Water Treatment Equipment

The water treatment system includes a sand filter to remove the majority of suspended solids in the water, a water softener to eliminate scale causing minerals, and a feed water chemical metering pump to add boiler feed water treatment chemicals. This provides fill water and feed water that will cause neither scaling or corrosion in the boiler.

Gardner-Denver Model 17 CDL-17 Cycloblower

The output range of the blower closely matches the requirements of the Remote Sealing System. The operating speed range of the blower conveniently matches the operating speed range of suitable industrial gasoline engines, with a simple direct drive of the blower providing the required output range. The helical screw type rotary lobes provide good efficiency and minimizes blower "slippage" against back pressure.

APPENDIX B

ALTERNATE SYSTEMS THAT WERE CONSIDERED

Several other alternative systems based on fundamentally different approaches were given preliminary consideration in the program. For each alternative approach, commercially available hardware was identified that could be used to implement the approach. Based on commercially available hardware, the process used to generate inert gas for the remote sealing system was examined and a preliminary layout of the equipment on trailers was prepared. Often, several stages of this process were necessary to arrive at a compact, workable and cost effective system.

The alternative systems that were arrived at by this process and given serious consideration are described in the subsections that follow. Each section includes a description of the inert gas generating process employed by the selected system and a preliminary layout of the components on trailers. The main features of the alternate systems are compared in Table B-1 with the thermal liquid heater system that was actually fabricated and tested.

B.1 Direct Quenched Combustion

The majority of commercially supplied inert gas generation systems are based on direct water quench cooling of combustion products produced by burning gaseous or liquid fuels. The quenching is provided by either spraying water into the combustion products downstream of the flame or by actually submerging the flame in the cooling water. In either case, the quenching cools the combustion products to within 10^{o} to $20^{o}F$ of the cooling water temperature and the cooled combustion products exit the quench zone saturated with water vapor due to the intimate contact with the cooling water.

Table B-1. Comparison of FMA System With Alternate Systems That Were Considered

System Description	Estimated Dry Weight (lb)	Estimated Operating Weight (lb)	Maximum Height Off Ground (ft/in.)	Make Up Water Consumption	Other Delivered Materials Consumed in Operation	Electric Power Consumption (kW)	Major Advantages	Major Disadvantages
Burn-Thermal Liquid Heater - Air Aftercool - Dry-Compress	77,000	84,000	11/2	None	Gasoline Fuel Oil	60	Low weight; low height; no cooling water; low outlet temperature; low outlet moisture content; relatively easy maintenance; overall flexibility in use of system	Relatively high electric power consumption
Direct Quenched Combustion	89,000	98,000	11/8	500 gal to fill 7 gal/min in operation	Gasoline Fuel Oil	90	Low outlet moisture content; low outlet temperature; design can be based on a standard packaged inert gas generator	Consumes cooling water; potential cold weather freeze up; will not fit on two trailers; high electric power consumption; high dry weight
Engine Combustion	73,000	81,000	11/2	None	Gasoline	15	Low weight, low height, no cooling water, redundancy from six gas sources in parallel, low electric power consumption	Uses gasoline for main fuel, more than 50 percent more expensive; noisy; components are crowded on trailers, making maintenance more difficult; less overall flexibility in use of system
Burn-Boiler-Air Aftercool-Dry-Compress	80,000	101,000	11/7	1800 gal to fill 1/2 gal/min in operation	Gasoline; fuel oil; water; treatment; chemicals	35	Low dry weight; low cost; low outlet temperature; low outlet moisture content; low electric power consumption	Requires cooling water; potential cold weather freeze up
Burn-Indirect Fired Air Heater - Air Aftercool-Dry Compress	89,000	96,000	12/0	None	Gasoline Fuel Oil	100	No liquid coolant; low outlet temperature; low outlet moisture content	High cost; high dry weight; high cooling fan power consumption; could not find a commercially available heater than is really suitable for the application
Gas Turbine Combustion	75,000	83,000	11/7	1800 gal to fill 1/2 gal/min in operation	Gasoline; fuel oil; water; treatment; chemicals	35	Low weight; low electric power consumtpion	High cost; requires cooling water; potential field service problems; needs special after burner; high outlet moisture content; high outlet temperature

Since the heat of combustion is removed by increasing the temperature of the cooling water by 20^{o} to $30^{o}F$ as it passes through the Inert Gas Generator, large volumes of cooling water must be circulated. When a large source of cooling water is readily available, water is simply drawn from the source, passed through the Inert Gas Generator, and discharged. For the capacity required by the Remote Sealing System, approximately 1000 gallons per minute of cooling water would be consumed this way. If large volumes of cooling water are not readily available, the used cooling water can be economically cooled in a cooling tower so it can be reused. The heat is rejected by evaporating a portion of the cooling water as it passes through the cooling tower. The water evaporated is replaced with fresh make up water. For the capacity required by the Remote Sealing System, approximately 40 gallons per minute of fresh make-up water would be required.

Commercially produced inert gas generators are used in facilities that have adequate cooling water supplies, at least enough to provide make up water for a cooling tower. For applications where adequate cooling water supplies are available, the direct quench type inert gas generator is inherently simple, compact, and inexpensive.

For applications where make up water for a cooling tower will not always be available, a closed cooling system must be used. The used cooling water is circulated through a finned tube heat exchanger, rejecting heat to cooling air forced over the finned surface of the heat exchanger. For a given amount of cooling capacity, a finned tube heat exchanger is considerably larger and considerably more expensive than a cooling tower. For the Remote Sealing System, several flat-bed trailers would be necessary to carry the required heat exchange surface.

The process diagram in Figure B-1 shows the two-stage direct quench Inert Gas Generator which uses a combination of closed

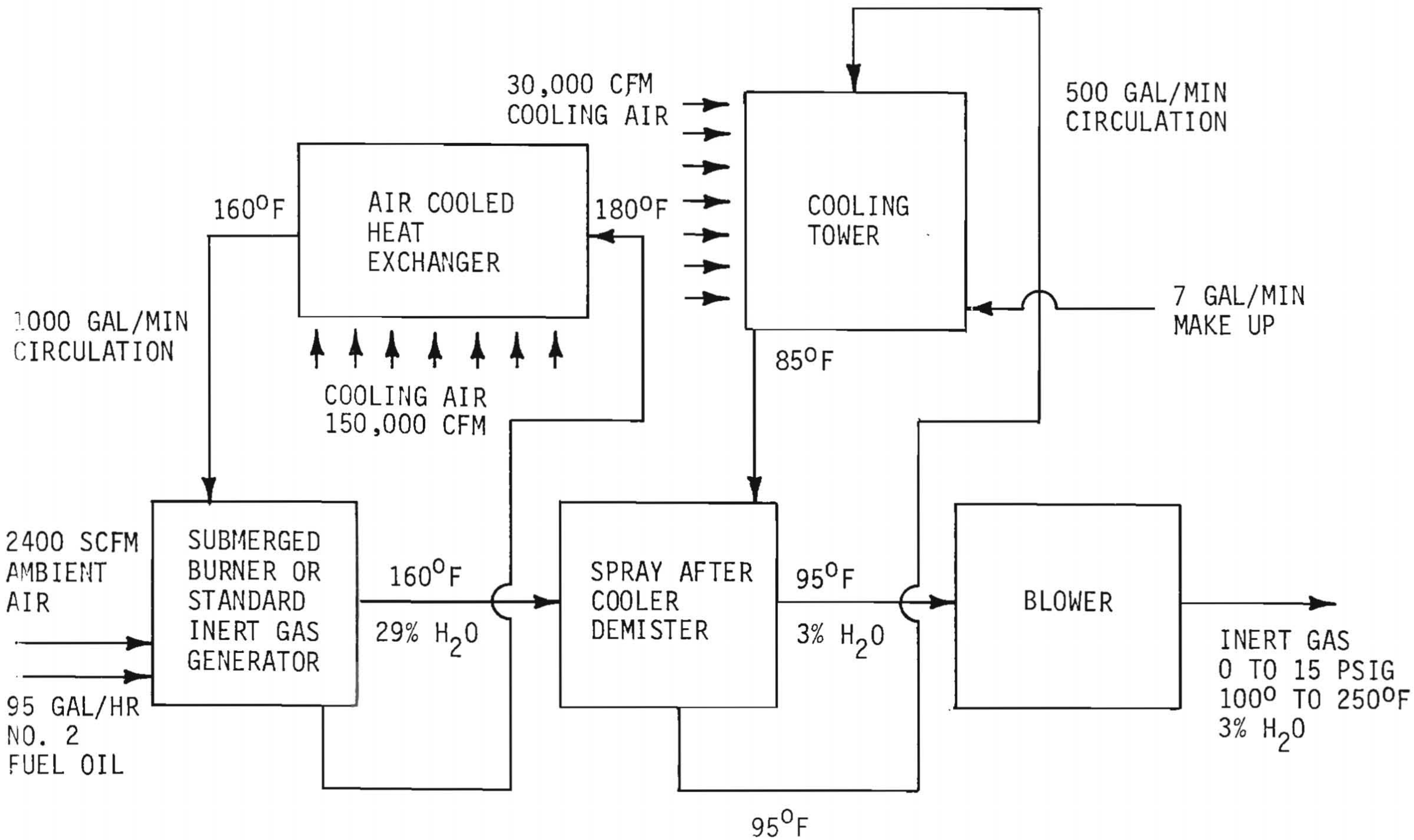


Figure B-1. Direct Quenched Combustion Process Diagram cooling through a finned tube heat exchanger and evaporative cooling from a cooling tower. In the first stage, cooling water at $160^{o}F$ is supplied to a packaged inert gas generator, quenching the combustion products to a temperature close to the $160^{o}F$ cooling water temperature, removing at least 75 percent of the heat of combustion from the inert gas stream. The cooling water is cooled in a finned tube heat exchanger, whose size is reduced (compared to a single stage closed direct quench system) by the increased temperature differential between the cooling water and ambient air. In the second stage, the inert gas stream is quenched to within a few degrees of the temperature of cooling water returned from the cooling tower. Since the majority of the heat of combustion is removed from the combustion products in the first stage quench, the cooling load carried by the cooling tower is reduced and the make up water requirement is reduced. The capacity and size of the finned tube heat exchanger determines the temperature of the first stage quench and the portions of the cooling load carried in each of the two stages.

Reducing the size of the finned tube heat exchanger reduces the overall size and cost of the system and increases the portion of the cooling load carried by the cooling tower and hence the make up water requirement. The system indicated represents a reasonable compromise between system cost and make up water consumption.

The layout of the components on trailers is shown in Figure B-2. The system offers no cost advantage, occupies more than two trailers, requires enough make up water to be a nuisance, and has potential cold weather freezing problems. These disadvantages were sufficient to eliminate this alternative.

B.2 Engine Combustion

In an Inert Gas Generator based on engine combustion, the engine serves two basic functions, combustion and removal of

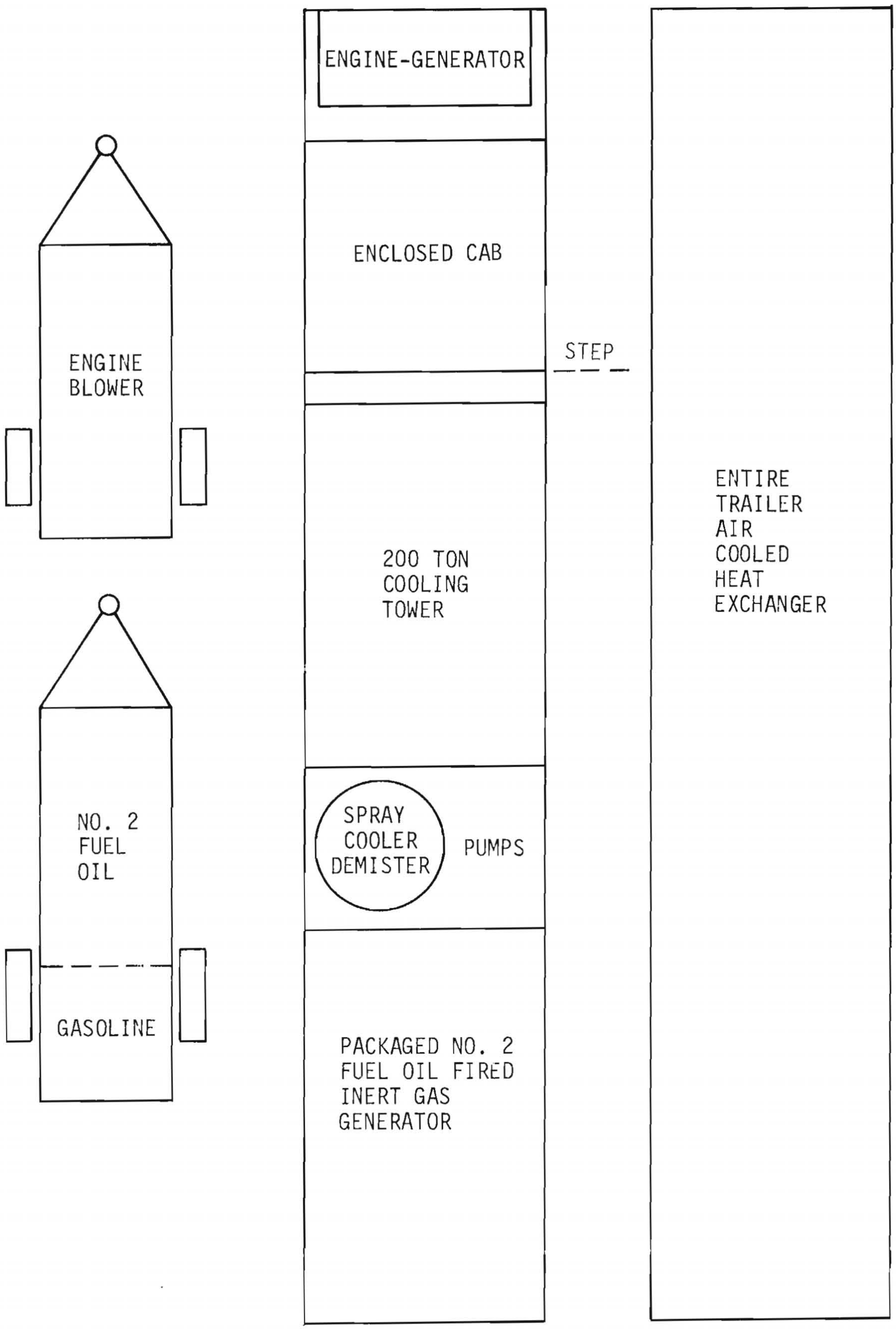


Figure B-2. Trailer Layout for Direct Quenched Combustion heat from the combustion products. The basic process to obtain inert gas suitable for remote seal emplacement is shown in Figure B-3. The exhausts from the engine-blower engine, the electric plant engine, and six 200-hp engines driving centrifugal fans is collected into a common manifold. Combustion in the engines reduces the oxygen content of the exhaust gases to below 1 percent. The combination of engine shaft work output and heat loss to the engine reduces the temperature of the combustion products to approximately 1200°F. The combustion products are then cooled to a temperature of 150°F by passing through a gas-to-air heat exchanger. Ample cooling air for the gas-to-air heat exchanger is provided by one of the engine driven centrifugal fans. The combustion products are then passed through a Cargocaire "enthalpy exchanger" reducing the moisture content of the combustion products to a level acceptable for remote seal emplacement. Desiccant regenerating air at a temperature of 150°F is provided by mixing exhaust cooling air from the gas-to-air heat exchanger with ambient air. The cooled, dried combustion products are then diluted with ambient air if greater than 1 percent oxygen concentration is permitted and compressed by the positive displacement blower to provide the pressure needed for fly ash conveying.

The layout of the system components on trailers is shown in Figure B-4.

The system is comparable in cost to the thermal liquid heater system. It has the advantage of the reliability inherent in six parallel, redundant gas sources. If one engine were to fail, a sealing operation could continue at reduced capacity until the engine was repaired. However, the engine combustion system does have several significant disadvantages. The system requires gasoline for fuel. Gasoline, on a weight basis, is more than 50 percent more expensive than fuel oil. For remote sealing, the fuel cost difference is not significant, but for a long term inerting operation, the cost difference can be

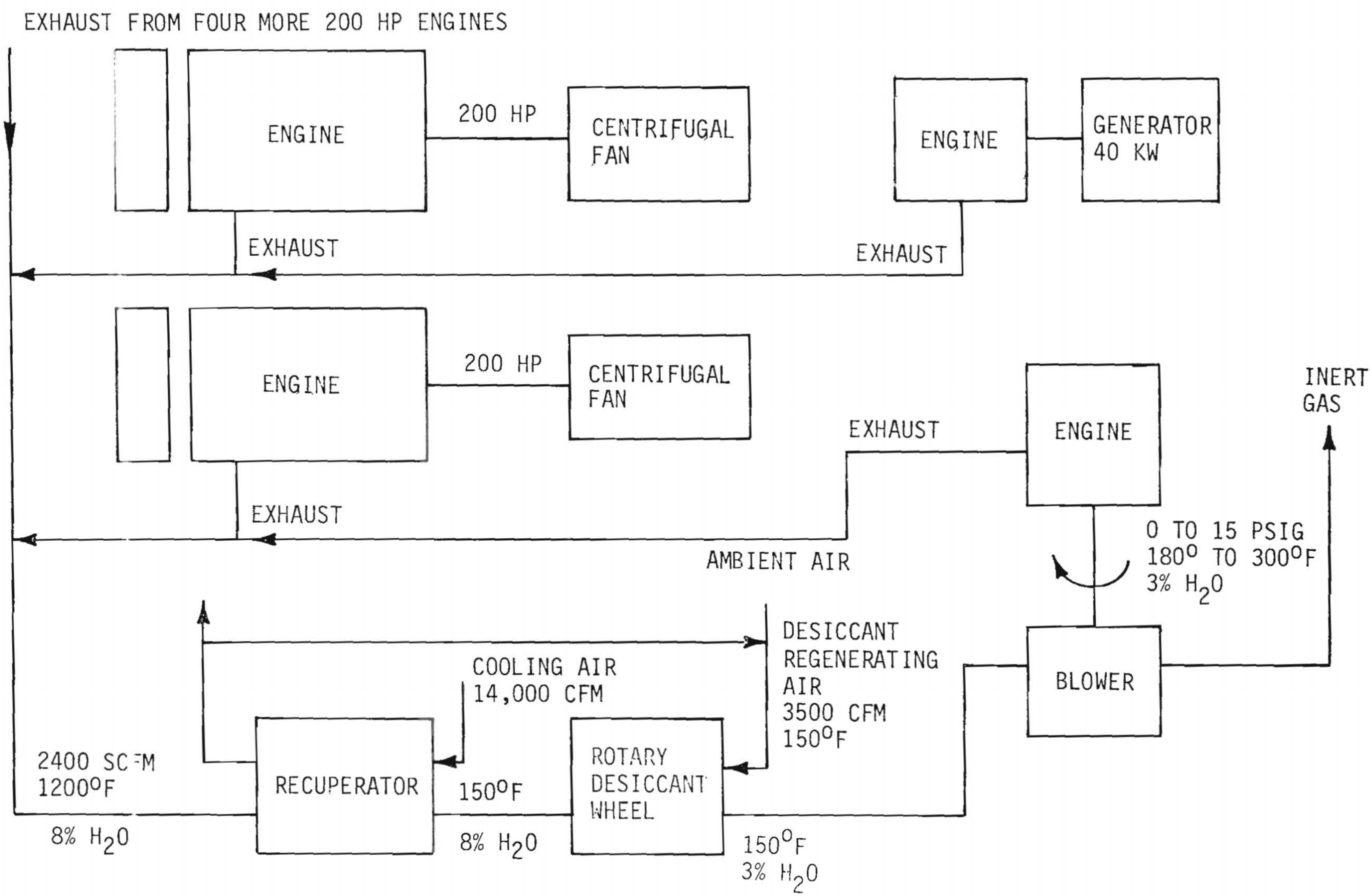


Figure B-3. Engine Combustion Process Diagram

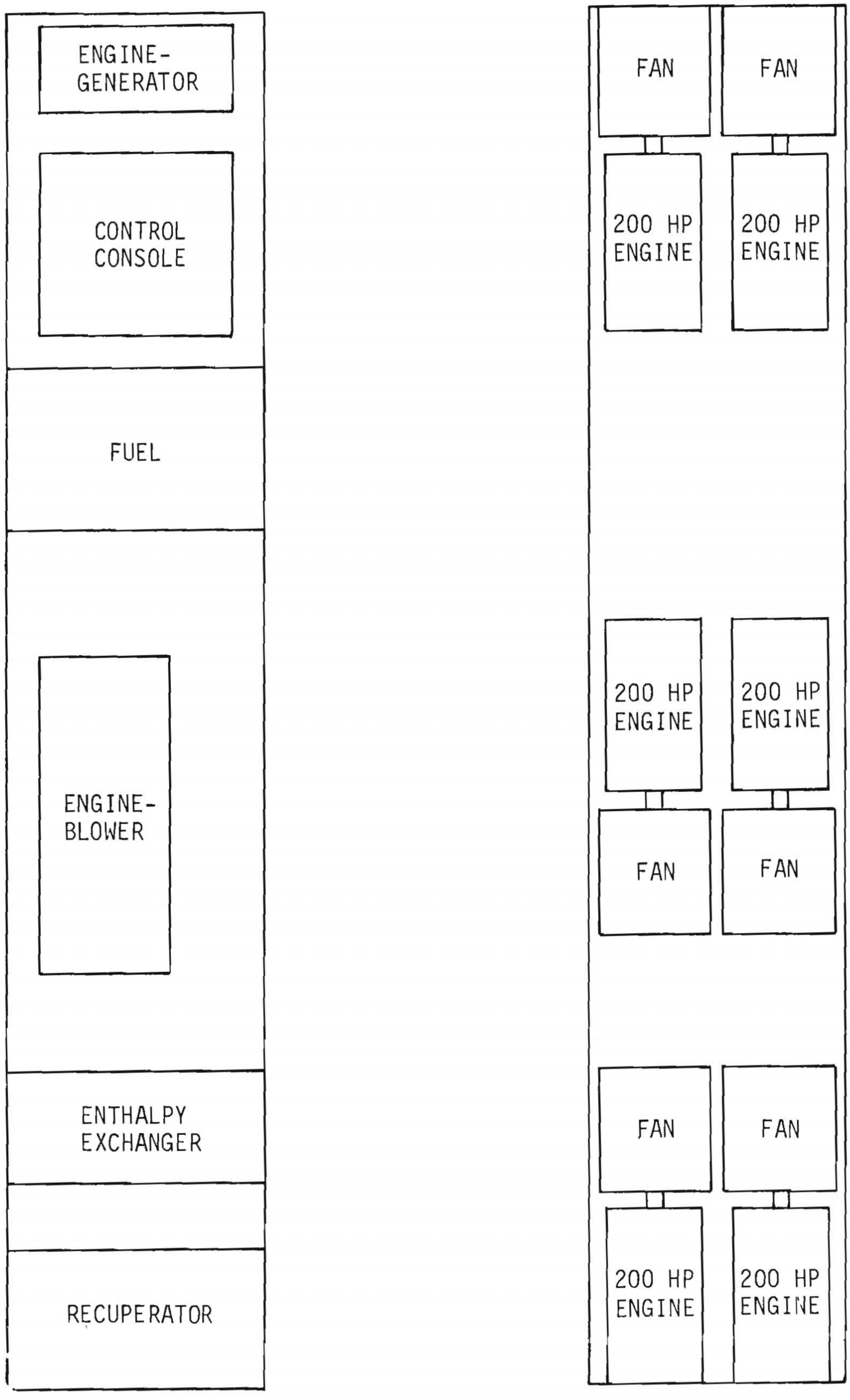


Figure B-4. Trailer Layout for Engine Combustion significant. The system would be very noisy in comparison with the thermal liquid heater system. The primary sources of noise are the six extra engines running at full output and the high pressure (30 inch static pressure) centrifugal fans. These direct driven centrifugal fans have proven to be the most cost effective and by far most compact way to dissipate the engine power output. Replacing the fans with alternate equipment would result in a more expensive system that would not fit on two flat bed trailers. The components are of necessity tightly packed into the trailers, increasing the difficulty of routine maintenance procedures. The engines would require more routine maintenance than the thermal liquid heater. Because the components could not be arranged so that one trailer would be an independent low temperature, low pressure inert gas generator, the system lacks the overall flexibility of the burn-thermal liquid heater system.

In the balance, it was concluded that the disadvantages of the system significantly outweigh the advantage of multiple parallel gas sources. The thermal liquid heater system is the more attractive approach.

B.3 Burn-Boiler-Air Aftercooler-Dry-Compress System

The burn-boiler-air aftercooler-dry-compress system is identical to the FMA system except that a boiler, a condenser, and water treatment equipment replace the thermal liquid heater and finned tube heat exchanger in the recommended system. The main process features are indicated in Figure B-5 and the approximate layout of the components on the trailers is indicated in Figure B-6.

The major advantage of the system is a small decrease in initial cost. However, the system will not fit on two trailers, and a large amount of water is required to fill the boiler. Freeze-up during cold weather shutdown is a potential problem.

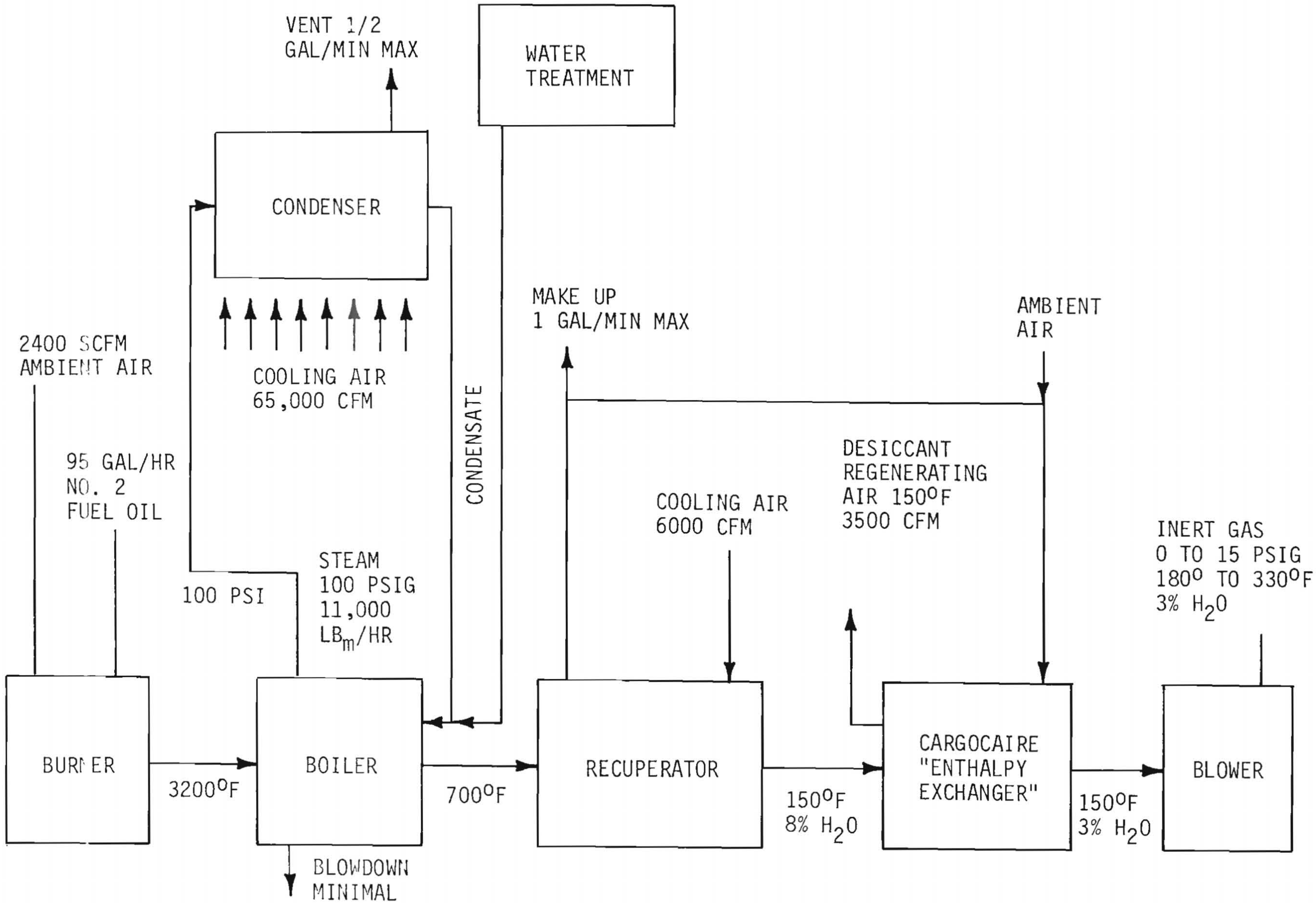


Figure B-5. Burn-Cool in Boiler-Air Aftercool-Dry-Compress Process Diagram

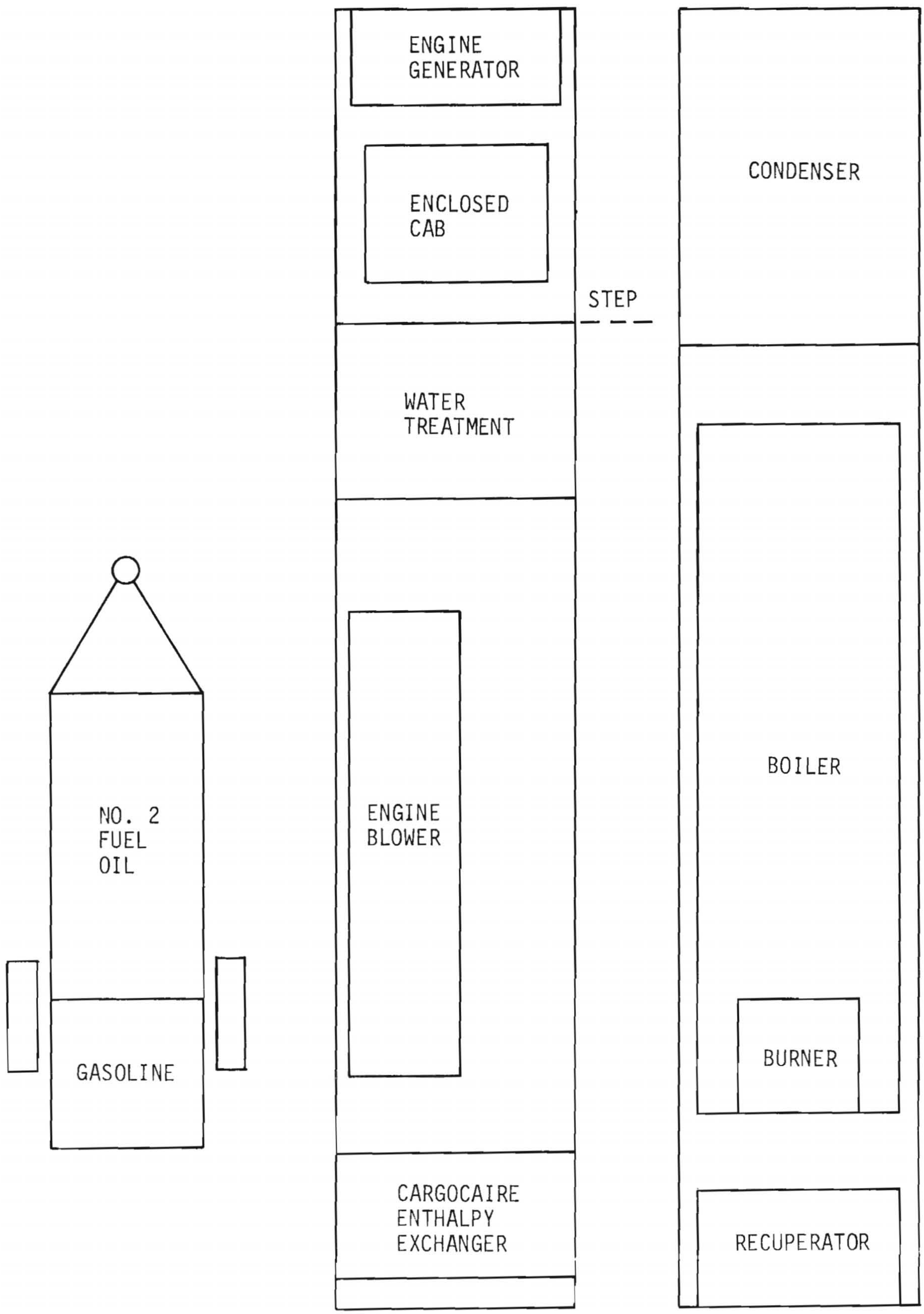


Figure B-6. Trailer Layout for Burn-Boil-Air Aftercool Dry Compress

Boiler maintenance is more involved than maintenance of the thermal liquid heater. It was concluded that the advantages offered by the system based on the thermal liquid heater outweighed the relatively small cost difference between them.

B.4 Burn-Air Cool-Dry-Compress System

The burn-air cool-dry-compress system is identical to the FMA recommended system except that an indirect fired air heater is substituted for the thermal liquid heater and finned tube heat exchanger. The main process features are indicated in Figure B-7. The approximate layout of the components on trailers is indicated in Figure B-8.

The obvious advantage of this approach is the elimination of liquid coolants from the system. However, no commercially supplied indirect fired air heater is really suitable for the application. They tend to be large, expensive, and unable to safely accept the high flame temperatures that result from burning with low excess air. The air heater on which the system cost estimate is based is a commercial air heater incorporating numerous modifications to overcome these difficulties. The major obstacle to implementing a system based on an indirect fired air heater is the high cost.

B.5 Gas Turbine Combustion

Gas turbine combustion inert gas generators can be implemented in two basic arrangements. In one arrangement, a gas turbine exhausts into an afterburner providing oxygen depleted gas that is cooled to 2500°F by the gas turbine shaft work output. The 2500°F combustion products must still be cooled, first in a fired heating device, second in a gas-to-gas heat exchanger, then dried, and finally compressed. The net effect of this arrangement is to grossly complicate the burning function, without simplifying any of the other basic process functions. This

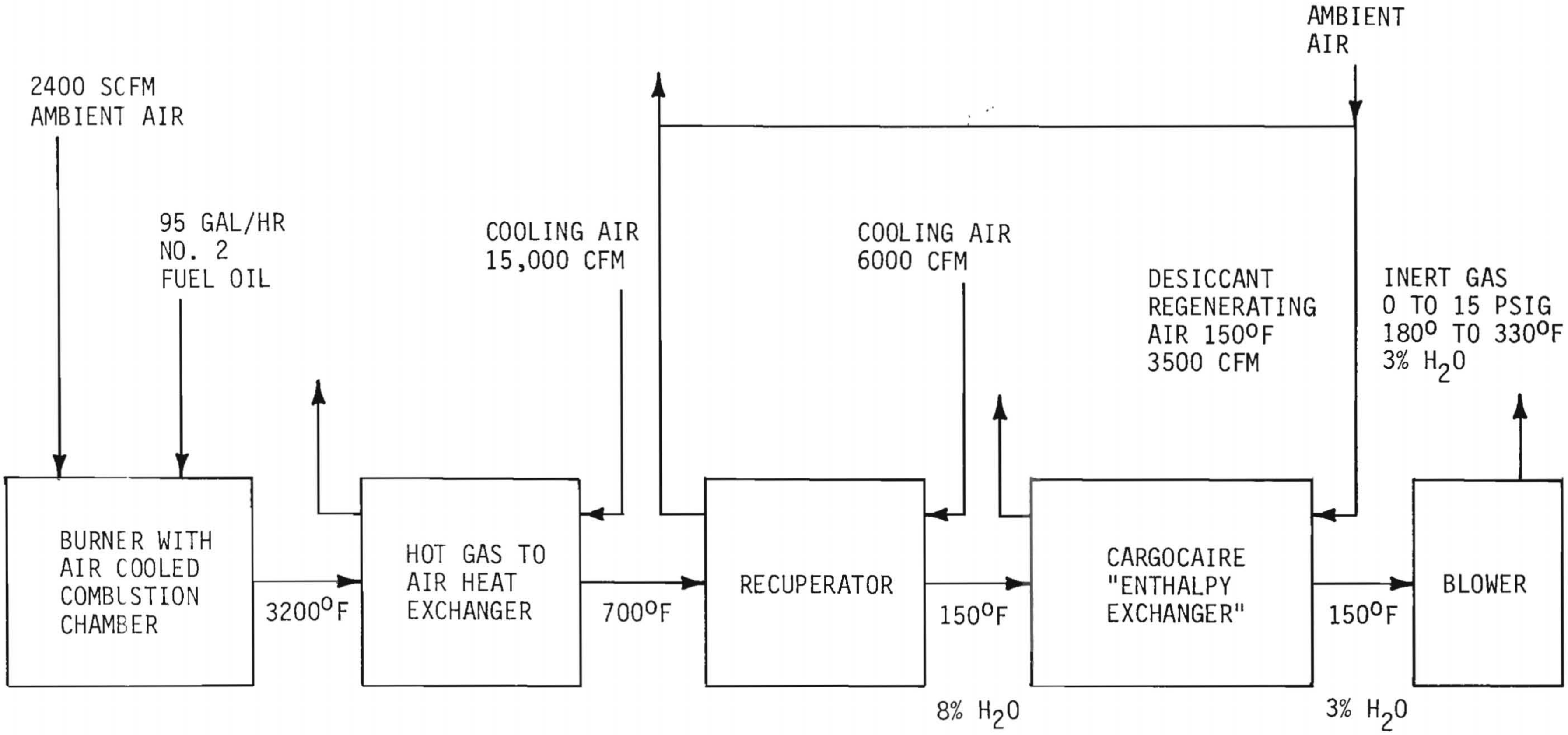


Figure B-7. Burn-Air Cool-Air Aftercool-Dry-Compress Process Diagram

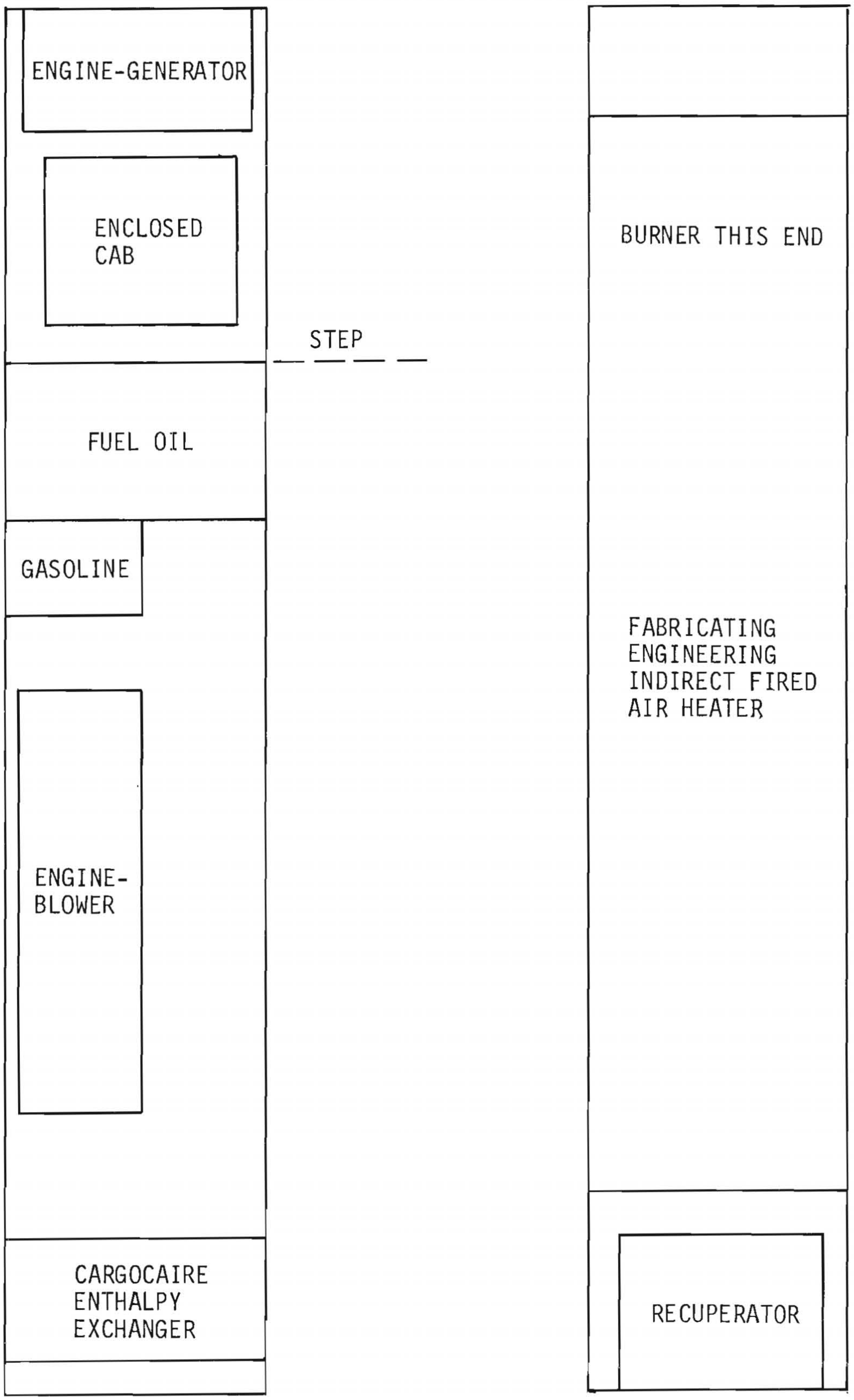


Figure B-8. Trailer Layout for Burn-Air Cool-Air Aftercool-Dry-Compress arrangement was, therefore, not given serious consideration for the remote sealing application.

In the other arrangement a gas turbine gas generator (a gas turbine engine less the power turbine) and an afterburner provide oxygen depleted combustion products at the delivery pressure required for fly ash conveying. In effect the gas turbine gas generator and afterburner serve the function served by the engine-blower and burner in the compress-burn-boiler system presented in Appendix A. The basic process features of this approach are shown in Figure B-9 and the approximate layout of the major components on the trailers is shown in Figure B-10. The approach offers no advantages over the FMA system and the estimated cost is considerably higher than the FMA system.

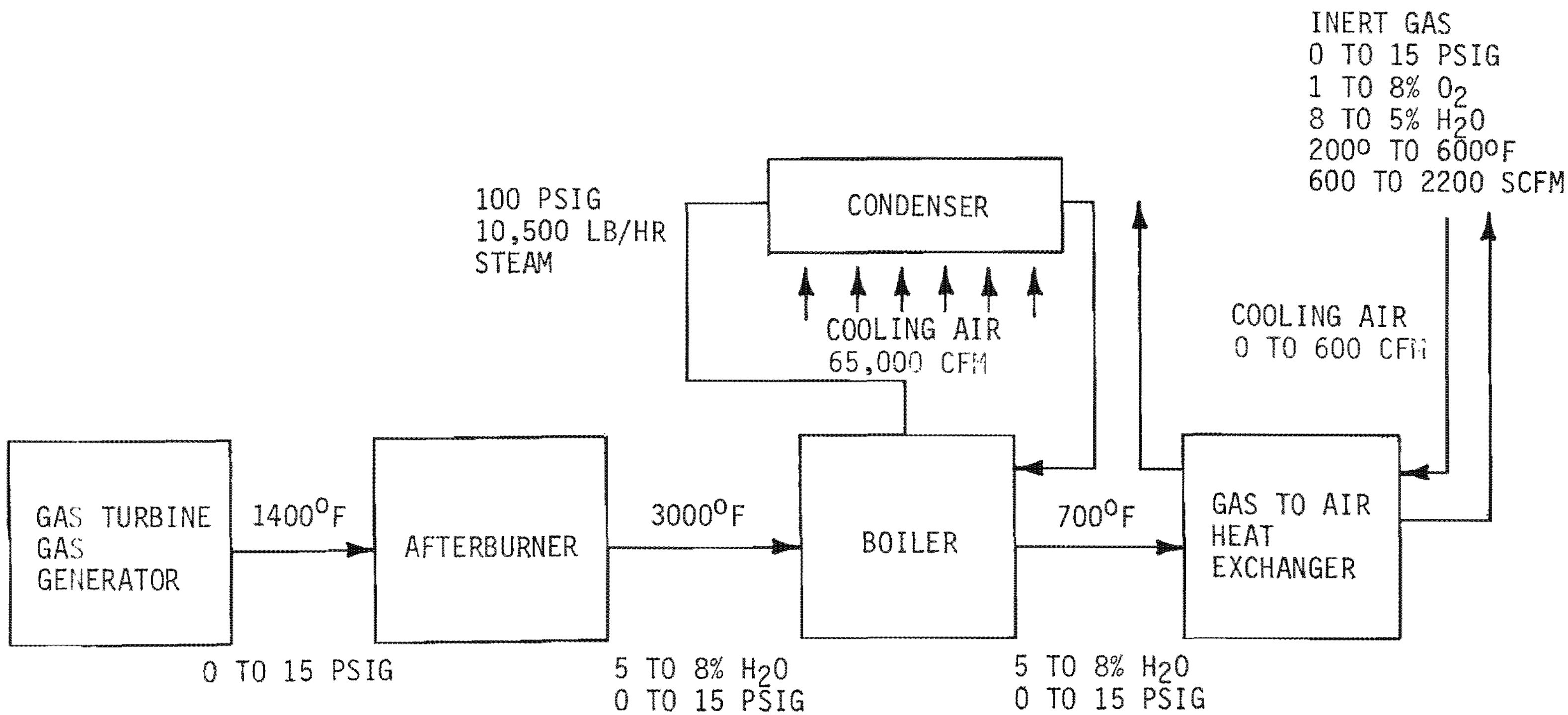


Figure B-9. Gas Turbine Combustion Process Diagram

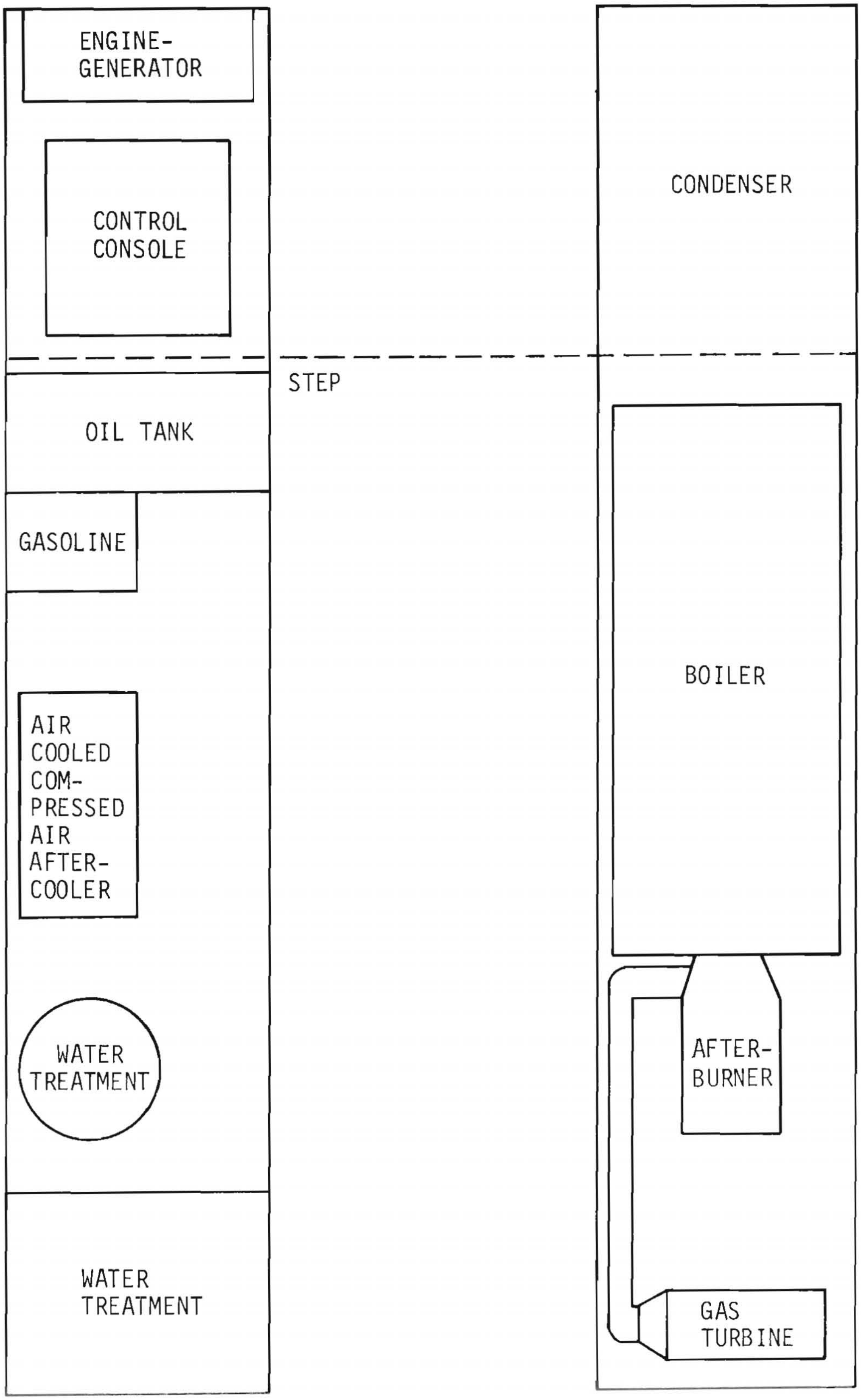


Figure B-10. Gas Turbine Combustion Trailer Layout

APPENDIX C

MANUFACTURERS OF THE MAJOR COMPONENTS OF THE INERT GAS GENERATOR

The manufacturers of the major components of the Inert Gas Generator are listed below. Included are the mailing address and when available the telephone number and the name of the person through whom the component was specified and purchased.

1. Combustion System

   Pyronics, Inc.
   17700 Miles Avenue
   Cleveland, OH 44128
   (216) 662-8800
   Gus Dados

2. Thermal Liquid Heater

   International Boiler Works
   P.O. Box 457
   East Stroudsberg, PA 18301
   (717) 421-5100
   Edward Mordt

3. Air Cooled Coolant Heat Exchanger

   MRM Division, Ecodyne Corporation
   607 First Street, S.W.
   Massillon, OH 44646
   (216) 832-5091
   Arlen Climes

4. Coolant Circulation Pump

   Dean Brothers Pumps
   323 W. 10th Street
   Indianapolis, IN 46202
   (317) 293-2930

5. Coolant Piping System

   Middlesex Welding Company
   6 Adele Road
   Woburn, MA 01801
   (617) 935-8870
   Harry Foundes

6. Stack Gas Heat Exchanger

Des Champs Laboratories, Inc.
58 Merry Lane
East Hanover, NJ 07936
(201) 884-1460
Nick Des Champs

7. Fans for Stack Gas Heat Exchanger and Dryer

Hartzell Propeller Fan Company
901 South Downing
Piqua, OH 45356
(513) 773-7412

8. Inert Gas Dryer

Cargocaire Engineering Corporation
6 Chestnut Street
Amesbury, MA 01913
(617) 388-3131

9. Engine Blower Package

Gardner Denver Company
Interstate 83 - Industrial Park
York, PA
(717) 767-6748
Woody Sellers

10. Flex Hose Connecting Hot and Cold Trailers

Flexhaust Corporation
11 Chestnut Street
Amesbury, MA 01913
(617) 388-9700

11. Fuel Tanks

Weymouth Engineering Company
P.O. Box 36 - 100 East Street
East Weymouth, MA 02189
(617) 335-2938
Warren Spear

12. Trailers

Schertzer Sales Corporation
32 Prospect Street
Somerville, MA 02143
(617) 666-9100
Ed Schertzer

13. Electric Generator

Kohler Company
Kohler, WI 53044
(414) 457-4441

14. Control Cab

Providence Body Company
750 Wellington Avenue
Cranston, RI
(401) 781-1000
Tom Monahan

15. Temperature Controllers and Indicators

Love Controls Corporation
1714 S. Wolf Road
Wheeling, IL 60090
(312) 541-3232
Harold Koenan

16. Flow Meters

Elison Instruments
Box 9000
Boulder, CO 80302
(303) 449-9000

17. Oxygen Analyzers

Teledyne Analytical Instruments
333 West Mission Drive
P.O. Box 70
San Gabriel, CA 91776
(213) 283-7181
Dennis Antieau

18. Inert Gas Dewpoint Indicator

Honeywell, Inc.
Process Control Division
1100 Virginia Drive
Fort Washington, PA 19034

19. Coolant Flowmeter

ITT Barton
P.O. Box 2013
Monterey Park, CA 91754

APPENDIX D

PERFORMANCE DATA TAKEN DURING THE FLY ASH CONVEYING DEMONSTRATION

The complete Inert Gas Generator performance data taken during the fly ash conveying demonstration is included in this Appendix as Figure D-1.

Location New England Sand and Gravel Date 9-13-77 Date & Time Started Up 9-13-77, 9:30 a.m.

Personnel on Hand J.Dieckmann, R. Richardson, L.Egan, F.Hartwell, D.Monaghan, R.Berry, A.Guzdar (R.King, G. Colaizzi - USBM)

Description of Setup Complete system setup to convey fly ash for fly ash conveying demonstration

Time	Gas Flow		Oxygen Content		Therminol Flow	Therminol Set Point Temp.	T_1	T_2	T_A	T_3	T_4	T_5	T_6	T_7	Burner Air Pressure	Firebox Pressure	Oil Pressure at Burner	Blower Speed	Blower Discharge Pressure	Borehole Pressure
	Hot Trailer	Bore hole	Hot Trailer	Blower Dischg.																
units	scfm	scfm	%	%	gal/min	°F	°F	°F	°F	°F	°F	°F	°F	°F	osig	osig	psig	rpm	psig	psig
11:40	2320	2200	1.0/1.9	3.5	550	300	791	300+	275	311	365	156	174	193	21	7	29	2100	1/3	0
11:48	2320	2200	1.0/1.9	3.5	550	300	791	300+	275	311	365	156	174	193	21	7	29	2100	2-1/2 to 3	0
NOON	Drying well drive coupling slipped. Stopped to fix it.																			
12:08	2340	1920	1.5	3.2	550	300	790	300+	275	305	360	160	165	200	21	7	29	2100	2-1/2 to 3	0
12:28	2320	2160	1.4	3.8	550	300	790	300+	275	305	360	160	165	200	21	7	29	2400	3-1/2 to 4	0
12:38	2320	2160	1.3	3.3	550	300	790	300+	275	305	360	160	165	200	21	7	29	2400	2-3/4 3-1/4	0
1:00	1520	1900	1.6	7.3	550	300	710	300+	250	286	334	157	153	208	-	-	-	2100	3-6	0
2:10	1320	1360	1.6	4.2	550	300	704	300+	245	274	324	140	132	154	16	7.2	20.2	1450	1-1/2 to 2	0

Heatbank Pressures Heatbank Temperatures

Time	Inert Gas Δp	Cooling Air Δp	Cooling Fan Dschg. Press.	Inert Gas Hot Trailer Dischg. Press.	Inert Gas T 1-1/3	Inert Gas T 1-2/3	Cooling Air Inlet Temp.	Cooling Air T 1-2/3	Cooling Air T 1-1/3	Dew Point	Pumping Fly Ash?	Fly Ash Truck Pressure
units	in. WG	in. WG	in. WG	in. WG	°F	°F	°F	°F	°F	°F	-	psig
11:40	-	-	-	-	-	-	-	-	-	104	no	-
11:48	-	-	-	-	-	-	-	-	-	104	yes	8-9
Noon												
12:08	-	-	-	-	-	-	-	-	-	100	yes	11
12:28	-	-	-	-	-	-	-	-	-	104	yes	10
12:38	-	-	-	-	-	-	-	-	-	104	yes	10
1:00	-	-	-	-	-	-	-	-	-	92	yes	?
2:10	-	-	-	-	-	-	-	-	-	82	yes	?

Figure D-1. Inert Gas Generator Field Data Sheet

APPENDIX E

HUGHES HEAT EXCHANGER PERFORMANCE PROBLEMS

When the hot trailer was first tested the Hughes stack gas heat exchanger performance proved to be so far from meeting its performance specifications that operation of the complete inert gas generator would not have been possible (see Table E-1). Hughes was contacted and appraised of the problem. A number of additional tests were run, verifying that the gas flows were evenly distributed over the face of the heat exchanger. Also discovered were a large number of ineffective heat pipes in the unit.

An additional heat exchanger was supplied by Hughes to provide the additional capacity needed to accomplish the required level of inert gas cooling. Substantial redesign of the duct work and relocation of the cooling fans was required at this stage to accommodate the additional heat exchanger within the overall dimensional constraints of the system.

The additional heat exchanger unit resulted in substantially improved performance (as tabulated in Table E-1). Although the heat exchanger still did not meet its original performance specifications, the performance was adequate for the inert gas generator as a whole. The sensible heat exchange capacity of the inert gas dryer provided the necessary backup cooling.

The stack gas heat exchanger continued to be troublesome in two respects:

a. Heat transfer performance
b. Leakage.

Table E-1. Summary of Hughes Heat Exchanger Performance Data

Performance Measurements	Specified	Actual
Full load heat exchanger effectiveness	90 percent	70 percent
Maximum cooling air side pressure drop	3.0 in. WC	2.0 in. WC
Maximum inert gas pressure drop at full load	3.2 in. WC	8 in. WC
Leakage between sides	0	Enough to add 1 percent oxygen to inert gas

The heat transfer capacity gradually deteriorated after the extra unit was installed. Leakage between the inert gas side and the cooling air side resulted in the addition of approximately 1 percent to the oxygen content of the inert gas when operating at high inert gas output.

As a result of the above problems with the Hughes heat exchanger, a recommendation was made to replace the unit with a Z-duct heat exchanger. This modification was approved and executed. The Z-duct performance has met or exceeded the manufacturers specifications (see Table 6). It has reserve heat transfer capacity, a low pressure drop through the unit, and has accessible heat transfer surfaces for cleaning.