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Suppression of Fine Ash Formation in Pulverized Coal Flames

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Introduction

One of the major obstacles to the economical use of coal is managing the behavior of its mineral matter. Ash size and composition are of critical importance for a variety of reasons. Fly ash size and emissivity affect radiant furnace heat transfer.[1] Heat transfer is also affected by the tendency of ash to adhere to heat transfer surfaces,[2] and the properties of these deposits.[3] Removal of ash from flue gas by electrostatic precipitators is influenced by both particle size and particle resistivity.[4] The efficiency of fabric filter-based cleaning devices is also influenced by ash size.[5] Both types of devices have reduced collection efficiencies for smaller-sized particles, which corresponds to the size most efficiently retained in the alveolar region of the human lung.[6] This special concern for finer sized particles has led to PM10 regulations in the last several years (PM10: particles of diameter less than 10 µm).

Laboratory work and studies of full-scale coal-fired boilers have identified two general mechanisms for ash production. The vast majority of the ash is formed from mineral matter that coalesces as the char burns, yielding particles that are normally larger than 0.5 µm. Flagen and Friedlander[7] proposed a simple model for this residual ash, called the breakup model. In this model, each particle is assumed to yield its mineral matter as a certain specified number of ash particles (usually in the range of 1-5). This latter value is termed the "breakup number." In this way, a known pulverized coal size distribution can be transformed into a projected ash size distribution. The presumed mechanism is that each char particle fragments during combustion, carrying mineral matter with it. The major assumptions used in the model include: (1) all coal particles contain the same percentage of mineral matter, independently of size, (2) all coal particles break into exactly the same number of char particles during combustion, (3) each char particle contains the same amount of mineral matter as the other char particles, and (4) no further fragmentation occurs, which means that each offspring char particle yields its mineral matter as a single ash particle. The breakup number has been identified in recent work as being influenced by the breakup of the char during burnout, from shedding at the burning char surface,[8] and from the fragmentation of discrete included and excluded minerals.[9,10] Recent experimental work[11] and elegant site percolation modeling[12] indicate that char macroporosity is the single most important factor governing char breakup and residual ash size. Despite the severity of the assumptions, the basic breakup model has proven to be a useful engineering and interpretative tool.[13]

The second major mechanism is the generation of a submicron aerosol through a vaporization/condensation mechanism. When the ash size distribution is plotted in terms of number density, the submicron mode generally peaks at about 0.1 µm.[4] When plotted in terms of mass, this mode is sometimes distinct from the residual ash mode,[13] and sometimes merged into it.[14] During diffusion-limited char combustion, the interior of the particle becomes hot and fuel-rich. The non-volatile oxides (*e.g.*, Al_2O_3, SiO_2, MgO, CaO, Fe_2O_3) can be reduced to more volatile suboxides and elements, and partially vaporized.[15-17] These reoxidize while passing through the boundary layer surrounding the char particle, thus becoming so highly supersaturated that rapid homogeneous nucleation occurs. This high nuclei concentration in the boundary layer promotes more extensive coagulation than would occur if the nuclei were uniformly distributed across the flow field.[18] The vaporization can be accelerated by the overshoot of the char temperature beyond the local gas temperature.[19]

Although these particles represent a relatively small fraction of the mass, they can present a large fraction of the surface area. Thus, they are a preferred site for the condensation of the more volatile oxides later in the furnace. This leads to a layering effect in which the refractory oxides are concentrated at the particle core and the more volatile oxides reside at the surface.[20] This also explains the enrichment of the aerosol by volatile oxides that has been noted in samples from practical furnaces.[21] These volatile metal oxides include the majority of the toxic metal contaminants, *e.g.*, mercury, arsenic, selenium and nickel. Risk assessment studies suggest that toxic metal emissions represent a significant portion of the health risk associated with combustion systems.[22]

Previous work has shown that pulverized bituminous coals that were treated by coal cleaning (via froth flotation) or aerodynamic sizing exhibited altered aerosol emission characteristics. Specifically, the emissions of aerosol for the cleaned and sized coals increased by as much as one order of magnitude. At least three mechanisms have been proposed to account for this behavior.

Objectives

The goals of the present program are to:

1. Perform measurements on carefully characterized coals to identify the means by which the coal treatment increases aerosol yields.

2. Investigate means by which coal cleaning can be done in a way that will not increase aerosol yields.

3. Identify whether this mechanism can be used to reduce aerosol yields from systems burning straight coal.

Progress - Mechanistic Interpretation

The modeling and interpretation work presented in the previous quarterly progress report was submitted as part of a revised paper to *Fuel*. During the present quarter, this paper was accepted for publication, and is presently in press.

Progress - Furnace Modification

During the first quarter of the program, the modifications to the furnace were designed. During the present quarter, the designs were completed and the construction was started. This is the subject of this quarterly report.

Furnace Design Goals

The fundamental goal of the furnace design is to provide a sufficient temperature and residence time to ensure complete coal burnout. Based on past experience with similar types of experimental furnaces, a main burner firing rate of 16.1 kW (55,000 Btu/hr) was chosen. Additionally, in order to ensure burnout, the furnace stoichiometry was set to provide 7% free oxygen after combustion.

Figure 1 shows a sketch of the furnace as it will look after installation. The unit will have natural gas, air, and cooling water brought into the appropriate accessories. The main burner sits atop the furnace, and the four back-fired burners, forming two pairs of heating channels, can be seen in the middle section of the furnace. Figure 2 is a cross-section of the furnace showing the multiple refractory layer design. The inner tunnel diameter is 20.3 cm (8 inches) and the overall outside diameter is 91.5 cm (36 inches). This requires 35.5 cm (14 inches) thickness of insulating material. In spite of this relatively thick layer of insulation, heat transfer calculations show that the combustion gas temperature may drop by up to 200°C as the gases move down the tunnel and reach the exhaust piping. Thus, the two pairs of backfire burners were included. These are designed to be operated independently to provide whatever inner tunnel temperature profile is desired. Each of the four back-fired burners can operate at up to 16.1 kW, but will likely run at a lower firing rate. The maximum flame temperature will be 1600°C, and this can be varied by controlling the burner air flow rate.

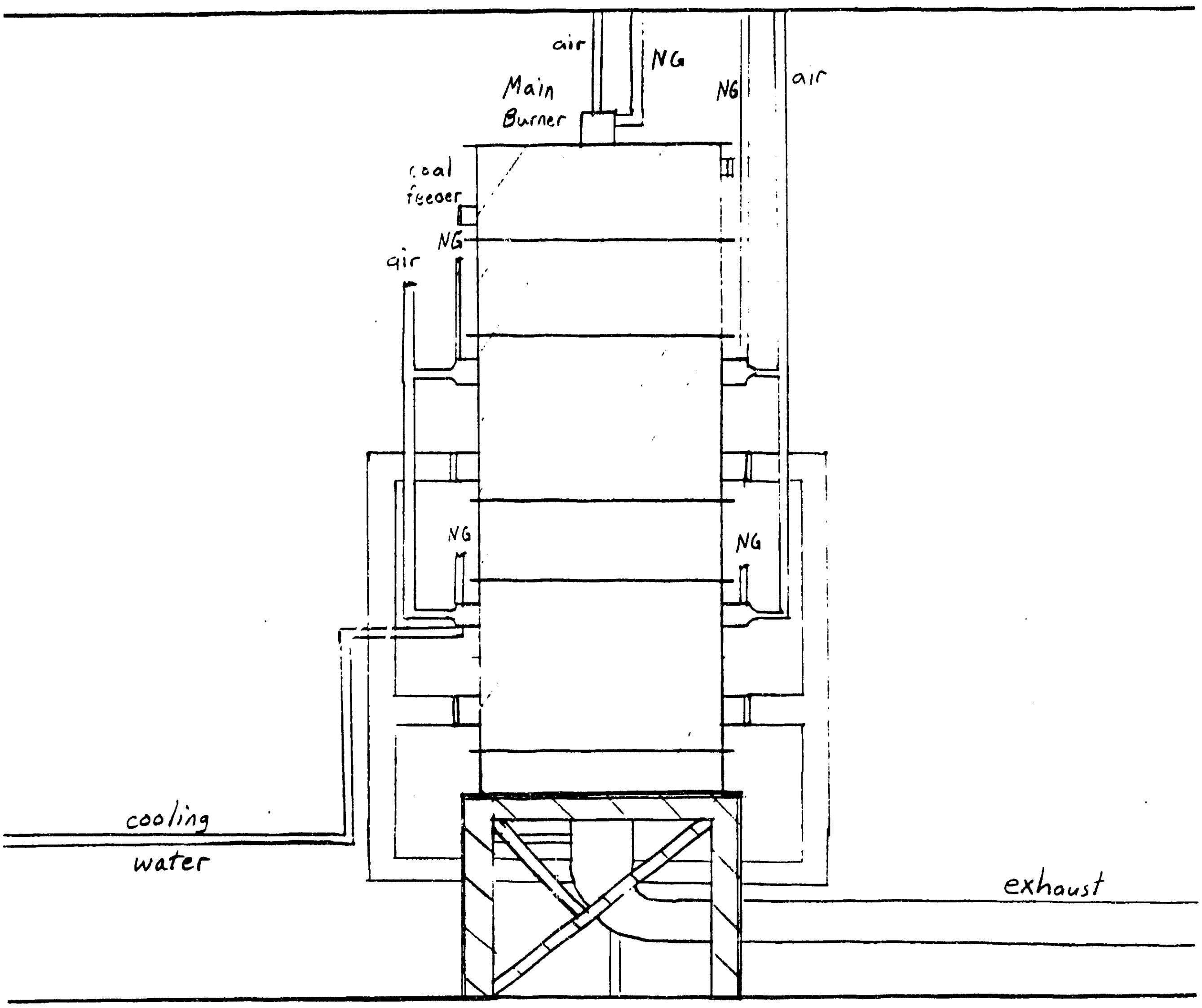

Figure 1. Overview of the tunnel furnace layout.

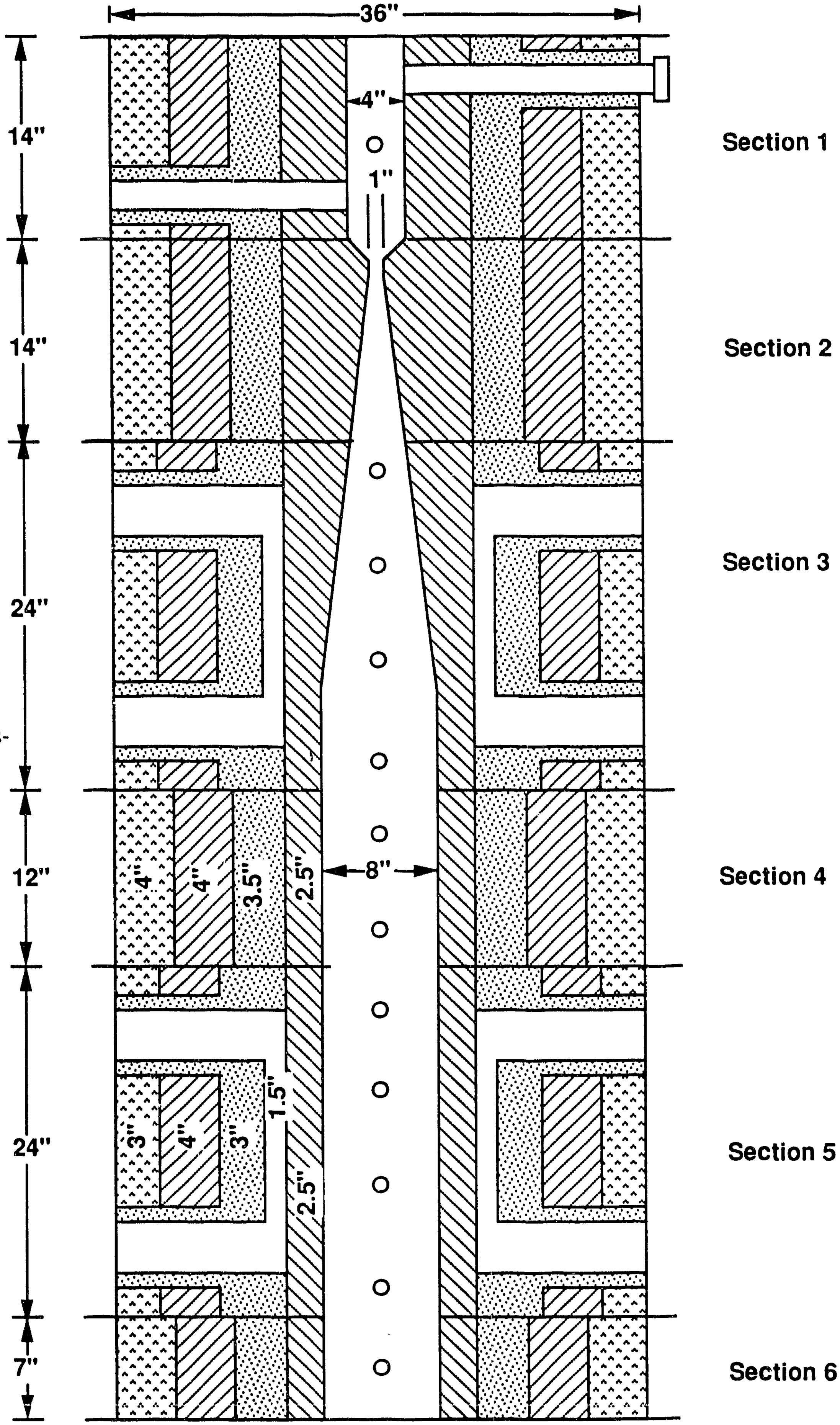

Figure 2.

Furnace cross-section.

Furnace Construction

During this quarter, the following items were completed.

- The reactor shells for each section, including ports and flanges were completed.
- Casting was completed on all of the sections except the two backfire sections shown in Figure 2.
- The furnace support stand was completed
- All measurement systems needed for the ash aerosol determinations were obtained

Auxiliary Systems

In addition to the furnace itself, a number support systems are in various stages of design and construction. The following paragraphs give descriptions of a few of these.

Flow System

Furnace operation is dependent on existing building sources of natural gas and air. The currently available natural gas pressure is about nine inches of H_2O. This is expected to be sufficient to operate burners at necessary levels. The gases will be brought to a flow control panel and then routed to the main and backfire burners. Independent control valves will allow individual control for each of the five burners at the control panel (shown in Figure 3). Rotameters and pressure sensors will be placed on line after the control panel to allow accurate monitoring of flow rates and pressures entering the individual burners.

In the event the burners require additional cooling, water lines will also be installed and controlled from the control panel to operate cooling coils around the individual burners.

Exhaust System

The flue gas will be vented directly into the existing building fume hood. Dilution will be used to reduce the temperature in the duct with free flowing air from the laboratory. After passing through mixing baffles, the flow will be evacuated through the roof blower. The maximum flue gas temperature - occurring when all four backfire burners and the main burner are fired at their maximum rate - has been calculated at about 1300°C (2370°F) with a flow rate about 0.032 kg/s (252 lb/hr). At this rate, with the existing fume hood system capable of passing 1.14 kg/s (9052 lb/hr), the flue gas will never comprise more than 2.8% of the total flow. Consequently, pure dilution should allow a worst-case final exhaust temperature of 60°C (140°F).

Other options considered were cooling coils, which required excessive water flow to be effective, and direct spray cooling. Although the latter system of injecting a fine mist into the flue gas would effectively reduce exhaust temperatures to an estimated 71°C (160°F) before dilution, it does not appear to be necessary. If the previously mentioned dilution process is not adequate, this would be a viable alternative. For robustness and maintainablilty, the simplest solution is desirable.

Safety System

To ensure safety during operation, several precautions will be incorporated into the design. The primary safety control system will focus on immediate gas shut-off in the event of any abnormal situations. Situations mandating this are:

1. *Loss of flame in any of the five burners* - This will be monitored by placing ultraviolet flame detectors near each of the burners.

Flow Control Panel

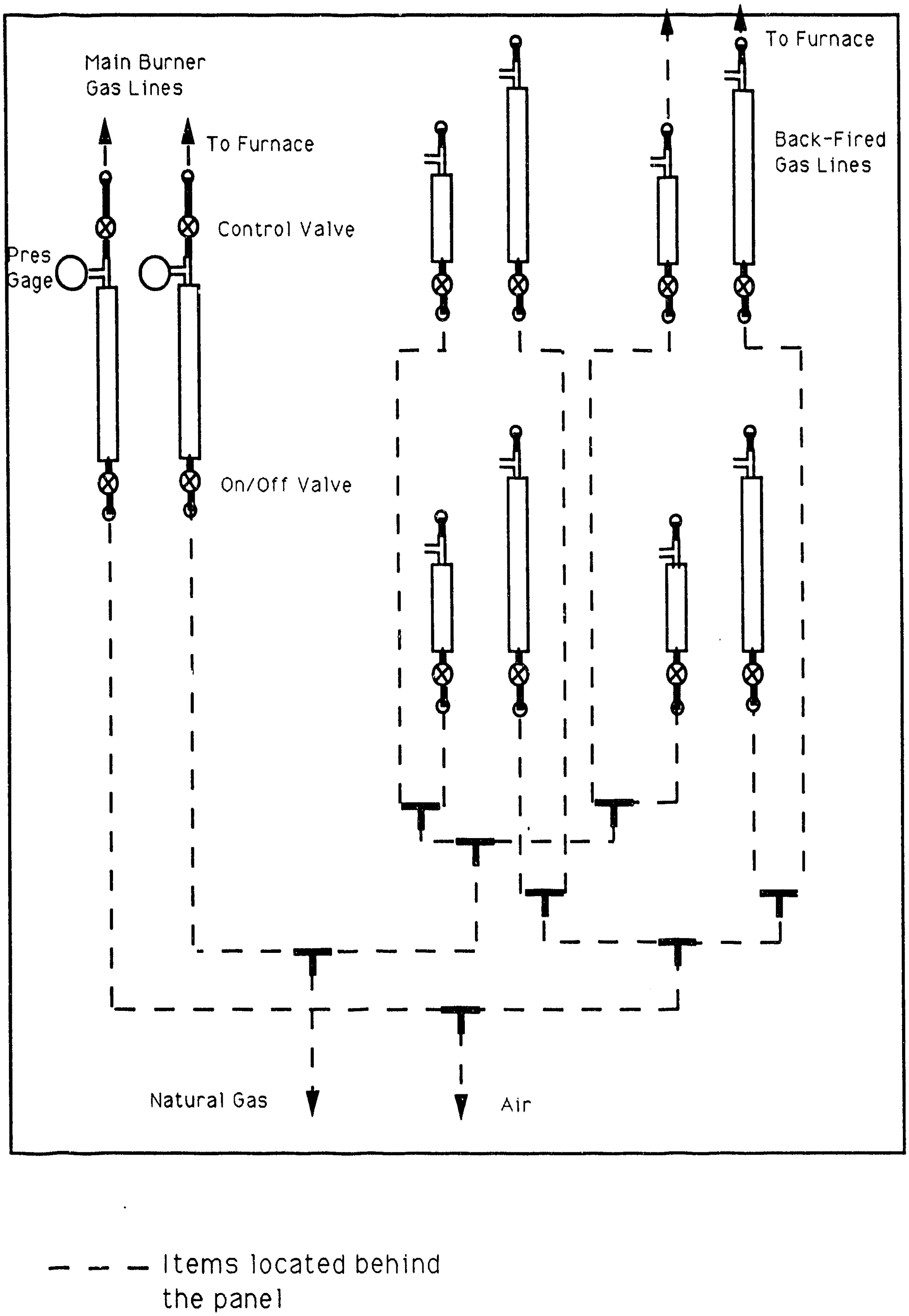

Figure 3. Flow panel schematic.

2. *Loss of either natural gas or air flow* - This will be monitored by pressure sensors in the fuel and air lines.

3. *Loss of electrical power* - In the event power is lost in the lab, an electrical trip will shut down the natural gas.

4. *Appearance of combustion products in the laboratory* - A gas sensor in the laboratory capable of detecting methane and carbon dioxide will be included to detect natural gas or exhaust products released into the lab.

5. *Loss of building ventilation* - A hot wire anemometer will be placed in the ventilation system to monitor flow. The fuel will be shut down if ventilation is lost or significantly reduced.

6. *Excessive flue gas temperatures* - Stack temperature will also be monitored with a thermocouple placed in the exhaust.

Automatic gas shut-down will occur at a safety valve located on the main gas line into the control panel. This will stop the flow to all burners and should stabilize any situation. The air lines and water lines, if burner cooling is required, can be manually shut off without sacrificing safety. A manual bypass of the safety system must be provided for start up.

Since multiple burners will be used, it will be necessary to provide a system which permits operation with some of the burners off. This will require two elements:

1. A switch on the control panel will allow the signal from any of the flame detectors to be disregarded by the control system.

2. If a particular flame detector is disabled, it would be possible to send gas to that particular burner without a flame. This will necessitate the use of an electronic switch valve on the gas line to that burner. The logic of the system will be such that the entire safety system will allow operation when a given flame detector is off *only* if the electrical signal from the valve supplying gas to that burner also shows that the gas flow is closed. If that valve is opened, the control system will shut off the gas supply to the entire furnace.

Figure 4 shows a basic diagram of the system necessary to satisfy the above conditions. The control panel should centralize all data from the preceding sensors, offering a continual measure for furnace conditions.

Planned Work

During the next quarter, work on the basic furnace and auxiliary systems is expected to be completed. Coal will be obtained and prepared. Initial testing on untreated coals will be performed.

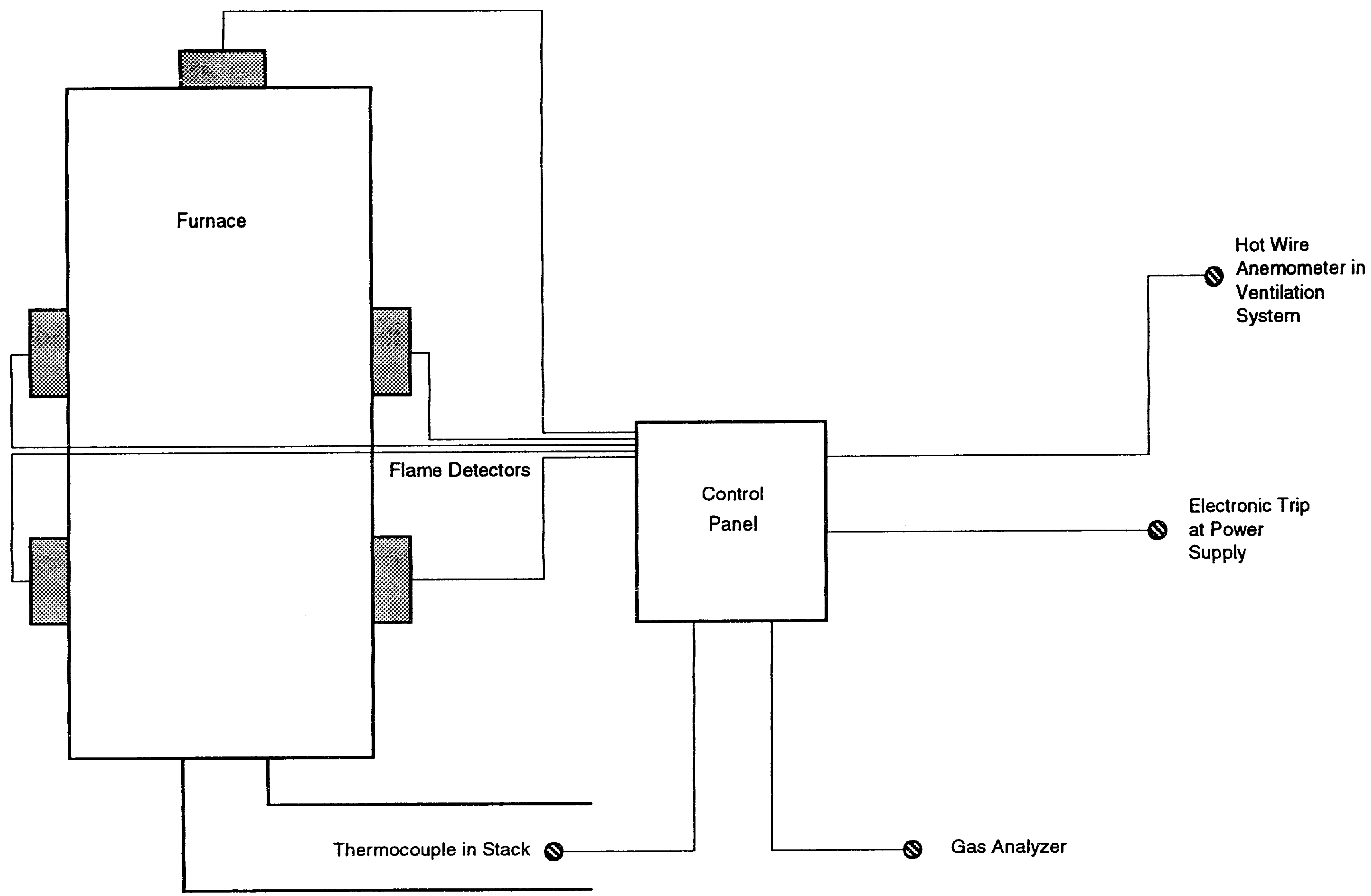

Figure 4. General diagram of control system layout.

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