

THE DESIGN AND CONSTRUCTION OF A
LABORATORY-SCALE FURNACE TO
TEST THE SLAGGING BEHAVIORS
OF BLENDED COAL

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Dedicated to my wife

Huijia Teng

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PREFACE

This study was conducted to learn more about coal slagging phenomena and the problems associated with building an experimental unit in the laboratory.

My interest in this field was initiated by my advisor, Dr. A. Johannes, who has always been more than ready to provide valuable assistance and has done the majority of the work in providing me advise and in proofreading this manuscript. I would like to individually thank each of my committee members, Dr. M. Seapan and Dr. G. Foutch for their concern in the whole process as well as for their time and effort in reading the rough draft of this thesis and providing me with valuable suggestions for further improvement. In addition, I would like to thank Dr. K. Bell for his good suggestions during the facility design and construction.

The department laboratory manager, Mr. Charles Baker has been extremely kind in providing me with some of the equipment I needed for the construction and has always been more than willing to help.

Likewise, I would like to thank Mr. Gary Martin and Mr. Matt Landis for their efforts in purchasing raw materials.

My parents, my wife's parents and my wife have my deepest appreciation for their love, encouragement and

support.

Much knowledge has been gleaned from my working on a project like this; there are many possibilities in this kind of undertaking and I would like to welcome any future student willing to explore more in this field.

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CHAPTER I

INTRODUCTION

This thesis describes the design and development of a laboratory-scale pulverized-coal-fired furnace. The purpose of constructing this device is to study the slagging and fouling problems of blended coal during combustion.

Because of the existence of mineral matter in coal, there are always slagging (radiation zone) and fouling (convection zone) in coal-fired boilers. These kinds of fire side deposition reduce the heat transfer rate so as to affect the boiler operating efficiency and availability. Severe slagging on the walls and boiler tubes may cause structural damage and even result in plant shutdown. There are lots of theoretical and empirical methods available to handle this problem. From practice, engineers have found that the slagging problem is more serious when two or more coals are blended and burned, than if these coals are burned individually. Little is known about the mechanism of this phenomenon. There are few laboratory scale facilities available for studying the behavior of coal slagging. Therefore, coal-fired power plants usually burn only one kind of coal in one period of time. But coal blending will increase gradually, as the electric power plants purchase

larger quantities of coals from the spot market. Blending coal does have some advantages. It will reduce SO₂ emissions, increase average BTU content, reduce operating costs and balance the heating values of the feed so as to reduce major fluctuations during combustion.

Sometimes, power plants have to burn blended coal. For example, Oklahoma coal has high sulfur content in general. In order to burn Oklahoma coal and not violate federal law for SO₂ emissions, power plants must consider blending coal. Blending high sulfur Oklahoma coal with some other low sulfur coal will reduce SO₂ emissions.

Coal blending is therefore becoming more and more common in power plants. But blending does cause some new operational problems. A typical example of this problem occurred at the Public Service Company of Oklahoma's Northeast Power Generation Station. When two kinds of coals, Jacob's Ranch and Clovis Point, were blended and burned, severe slagging and fouling developed. This problem finally caused boiler shutdown and was traced to blends of 75% Jacob's Ranch and 25% Clovis Point fed to the boilers during 1981 and 1982. From this example, we can see that the determination of when a blended coal will cause significant slagging is extremely important and people are taking this problem more and more seriously.

The laboratory-scale furnace described in this work is designed to investigate this problem. This furnace has several characteristics:

1. The real combustion situation in the boiler of a power plant, especially in terms of operational temperatures and residence time, must be simulated by this small-scale device. This kind of similarity is required to make our investigation reflect the real operational problems.

2. The coals can be blended in any desired quantities and the furnace design is flexible so many different blends can be studied under different operating conditions.

3. The solid samples as well as ash and gas samples can be collected easily. This is our main experimental requirement.

4. Cleaning and maintenance are relatively easy.

Considering the special characteristics of slagging and fouling, sample collection and the laboratory limitation to a facility, a suitably-scaled device was designed and built. The furnace development required a knowledge of material selection, the technique of engineering drawing, a knowledge of chemical engineering design and the practical methods of construction and installation.

The aim of this thesis is to document the design, construction and testing of the furnace. The study of blended coal slagging and fouling mechanisms will be investigated in the future from the data supplied by this furnace.

CHAPTER II

GENERAL DESCRIPTION OF PROJECT AND FACILITY

Studying the behavior of blended coal is a relatively new research direction. Often, coals must be blended in order to stay within the limits of sulfur dioxide emissions. But coal blends do cause some unexpected results. Among them is fireside slagging. Severe slagging can cause operational problems and even boiler shutdown.

Much work has been done on fireside deposition for pure coal both from a mechanistic point of view and from an experience point of view. The mechanism of fireside deposition is quite complicated and is not easily formulated. There are certain effects that are of interest, such as slag viscosity, ash adhesion properties and ash constituent reactions. In practice, people usually consider such factors as the content of the impurities in the coal, the make up and content of the coal ash, ash fusion temperatures, operational conditions and coal quantity. The slagging problem can usually be resolved by considering all or some of these factors. But when two or more coals are combined together and burned, unexpected slagging may occur even if these pure coals have acceptable properties when burned individually. This strange phenomenon tells us that

routine prediction methods lack high validity for coal blends and some adjustments are needed in order to describe their behavior. Little is known about the slagging mechanism of blended coals. Some researchers have tried to use the mechanisms for pure coals to predict the slagging potential of blended coals. The accuracy of these predictions remains a question.

This project will ultimately attempt to study the behavior of blended coal. A laboratory-scale device is required to experimentally study the physical and chemical properties of both pure and blended coal. The ultimate aim is to develop some mathematical models as well as some reasonable methods to predict slagging problems of blended coal.

In this study, facility design and construction is the first step. The design of the facility will directly influence the success of the whole project. Therefore, the facility design and construction were considered as the basic item for the coal slagging study.

The steps taken to design and construct the facility were:

1. Literature review of other experimental investigations,
2. Facility design, calculation and technical drawing,
3. Laboratory selection and design,
4. Material selection, purchase and manufacture,
5. Construction and installation, and

6. Facility function test.

Some of these steps were performed simultaneously depending upon the feasibility of these steps and the time requirement of this project.

Literature Review of Other Experimental Investigations

There are many papers in the literature which deal with coal combustion. Each facility described has its own special experimental purpose. The facility developed by Abbott, et al. (20) was used to study the comparative wetting and adhesion properties of a synthetic coal ash slag on boiler steels. The flame is produced from a three-burner ring fed with a methane/oxygen mixture. The flow of each gas is controlled by needle valves and rotameters to be 870 and 950 ml/min of methane and oxygen, respectively, to ensure reproducible flame temperature and melting condition. The adiabatic flame temperature for this gas composition is 3100 °F. A rectangular steel collection plate is mounted in the center post of the bottom heater by screws. After loosening these screws, the collection plate can be slid along to a position which allows a fresh portion of the collection plate surface to be beneath the drop path. More uniform temperature control at high collection plate temperatures was obtained by cementing a heater coil and a platinum wire heating element.

Kurtzrock, et al. (11) designed and built a laboratory-scale pulverized-coal-fired furnace. The complete unit

comprises a coal-preparation and feeding system, furnace, instrument panel and analytical system. The purpose of this device is to perform flue gas and fly-ash analyses. The furnace is designed to burn from 1 to 4 lb of coal per hour and is capable of continuous or intermittent operation under relatively constant and reproducible combustion conditions. According to their description, continuous operation can be obtained if the fly-ash in the furnace is blown out every 4 or 5 days. The temperature in the primary-chamber is about 2000 °F based on a 2 lb/hour coal feed rate and combustion air supplied at 125 per cent of the stoichiometric requirements. Furnace draft was held at a negative pressure of 0.3 in. water. They found that coal feed rates of less than 1 lb/hr or a combustion chamber temperature of less than 1750 °F produced erratic flame patterns and unstable furnace operation.

Mims, et al. (17) designed a small scale coal combustion furnace which was used for collecting and characterizing aerosols produced under well-controlled combustion conditions from a variety of coals. The device affords the possibility of simultaneously monitoring particle coal combustion behavior and mineral matter transformations. The facility is a drop-tube, laminar flow furnace. It consists of an inner alumina muffle tube that confines the central or main oxidizing gas stream. The temperature of the muffle tube is maintained and regulated by resistance heated graphite elements. A dilute stream of coal particles is

injected axially via a water-cooled feeder probe into the hot (up to 2690°F) oxidizing zone. Radial dispersion of the particles is reduced to a minimum in the stable laminar flow field of the main gas. The composition and flow rate of the main gas are accurately specified by dual mass flow controllers. Post combustion products, both gaseous and particulate are collected at pre-determined positions by a movable water-cooled probe on the furnace axis. They consider three variables as their experimental parameters: oxygen partial pressure, particle size and main gas temperature. The facility has the ability to determine the time-temperature history of burning coal particles.

Another approach was developed by How, et al. (12). The furnace they built is used for the study of corrosion problems and also to give some information relating to high-temperature deposits. For this latter purpose, work with their experimental unit suggest that larger equipment is desirable. Another purpose of this device is to yield practical information on the slagging properties of various coals burned in pulverized form. This information supplements the conventional laboratory measurements of ash-fusion temperature. A particular advantage of their furnace is the relative simplicity of firing synthetic mixtures of a fuel, e.g. with mineral additions. The furnace can burn pulverized coal at the rate of 2.5 to 4.5 lb/hour without the need of external heat for maintaining a stable flame. The combustion chamber is fired vertically from the top by a

small burner consisting of three concentric tubes. The furnace exit is provided with a bank of air-cooled tubes which serve the dual purpose of cooling the combustion gases for experimental measurements and collecting deposits on the surface of these tubes. The rate of heat release, gas and metal temperatures, and residence times of the coal particles are all similar to those obtained in large pulverized-coal-fired water-tube boilers. The furnace can be operated continually and little replacement of the furnace fabric and heat-exchanger tubes is required. The furnace is used to evaluate the corrosive nature of the flue gases from a high-sulfur coal and the influence of various factors on the condensation phenomenon.

Flagan, et al. (16) designed a laboratory furnace which can be used for investigating the coal particles in the flue gases of a pulverized coal combustor. The emphasis is on physical and chemical characterization of particles with diameters less than 2 μm . The combustor consists of a vertical alumina refractory cylinder. Low density insulation surrounds the refractory to minimize heat losses. A series of convective heat exchangers are mounted directly below the combustor. The furnace is fired at a rate of 8 to 12 Kw, providing a residence time of 1 to 2 seconds in the combustor. The flow pattern is laminar. Air is heated using electrical resistance heaters. Pulverized coal is fed directly from a screw feed into the high velocity primary air flow, which is metered using sharp edged

orifices. The burner is mounted at the top of a 30° half-angle refractory quarrel. The particle size distributions observed in this one dimensional laboratory pulverized-coal-fired combustor are similar to those observed in the flue gas upstream of an electrostatic precipitator on a coal-fired utility boiler. There are, however, some important differences. The aerosol observed in the laboratory has a more pronounced minimum in the mass distribution at about 0.2 to 0.3 μ m from inlet. This is because the flow in the laboratory furnace is nearly one-dimensional and the coal is distributed fairly uniformly throughout the combustor volume; while in the utility boiler different parcels of gas will undergo very different time-temperature histories. The laboratory furnace also produces a larger number of particles than a utility boiler since the larger furnace has large scale non-uniformities in the flow.

Many researchers have investigated limestone injection into furnaces as a way of reducing the cost of controlling SO₂ emissions from pulverized coal-fired power plants. The facilities used for this purpose range from small scale laboratory furnaces to large utility steam generators. An example of this work is done by Combustion Engineering Inc. (8). They use a pilot scale fireside performance test facility to simulate the heat transfer surface, combustion condition and ash deposit properties in a pulverized coal fired boiler. The furnace is bottom fired with staged combustion capabilities to simulate a low NO_x combustion

environment. The slagging is evaluated based upon the waterwall panel deposit cleanability, physical characteristics and the impact of the deposit on waterwall panel heat flux. The fouling is evaluated based upon the convective ash deposit, physical characteristics, accumulation and cleanability. Located in the radiant section of the furnace is a simulated waterwall test surface which is used to study lower furnace ash deposition. In the convective section, four banks of air cooled probes are used to simulate boiler superheater tubes and evaluate convective section ash deposition. This furnace is designed and operated to simulate utility steam generator operation from the standpoint of ash deposition in both the lower furnace and convective sections. Furnace gas temperature profiles and residence times are all similar to utility boiler operation. Flame temperature is controlled by varying combustion air. As a result, the utility boiler, lower furnace environment, is closely simulated and produces representative waterwall slagging data.

Some researchers have developed measurement instruments for solid sample collection. Representative work was done by Howard (31). The solid sampling probe he developed is composed of a sampling tube with water jacket, a cyclone and a filter chamber. This device is used to collect solid particles. Flue gas at about 1200 °F temperature is sampled at a high suction rate which gives a sampling velocity of about twenty times the flow velocity. He finds that the

high suction velocity is necessary in order to prevent blockage of the tube. In addition, a high velocity is necessary to exceed the lower capacity limit of the vacuum pump. He suggests that a minimum sampling velocity of eight times the flow velocity is required to overcome blockage.

Another sampling device is described by Jackson, et al. (13). This device is an air-cooled probe which can be used to study the deposition of ash constituents from the flue gas in a boiler. The probe is made of austenitic steel (18 percent Cr, 10 percent Ni, 3 percent Mo) tubing. The temperature is measured by a thermocouple mounted on the tube wall. The cooling air can be controlled manually or by an automatic system. Solid samples are deposited on the cold surface of the tube.

After reviewing all these devices and comparing many other different kinds of laboratory facilities, it was decided to design and build a new facility by using the best ideas of past researchers. Since every device built by individual researchers or equipment manufactures had its own unique purpose, as mentioned above, it was impossible to find any commercial facility which fit our purpose. Therefore, the idea of buying a ready-made device was given up. Instead, the decision was made to design and build our own facility.

Facility Design, Calculation and Technical Drawing

The general requirements of the facility are as

follows:

First, the furnace must simulate the real combustion situation of a utility boiler in a coal-fired electric power plant. The experimental results from the laboratory device must simulate the slagging and fouling problems in real life. This means that the scaling effect caused by the size difference between a laboratory device and a utility boiler should be as small as possible.

Second, the equipment should allow studies of both physical and chemical characteristics of coals, which influence the production of slag. Physical characteristics include coal particle size, particle velocity and wall surface temperature, whereas, the chemical characteristics are coal and ash compositions of the pure and blended coals.

Third, the device must have all the common advantages of a laboratory facility. Therefore, in this device, taking solid and gas samples, measuring and analyzing, construction, flexibility and ease of maintenance are required.

Finally, safety and pollution problems must be considered in any circumstances.

Specific details of the final design will be described in the next chapter. However, some general features about the design are given here.

In order to simulate a real boiler, the design of the furnace structure must be considered carefully. Based on the features of this furnace, there should be several

observation holes and sampling ports as well as some temperature measurement points. The requirement to reduce heat losses from these holes and from furnace walls is very important to maintain the combustion temperature. A temperature of 2000 °F was required in the radiation part of the furnace to be representative of a large scale facility.

Another factor which had to be considered during the design period was the difference in residence times between a real boiler and the laboratory device. The laboratory device has scale limitations. It was difficult to simulate the structure of a real boiler by simply reducing the geometrical scale of the boiler while maintaining the residence time and other features of a real boiler. Therefore, a paralleled-chamber design was required to get not only accepted geometrical scale but also reasonable residence time. This design can overcome the disadvantages of a small device in terms of short residence time while getting good combustion conditions.

Burner design is also an important factor. The coal burner must be able to handle various particle sizes, feed rates and air to fuel ratios. The burner must be able to generate combustion temperatures similar to those observed in commercial power plants. It is known that the combustion situation is dependent on the structure of burner. The coal burner designed has three concentric passes. The middle annulus is for pulverized coal and primary air. The center tube and the outer annulus are for secondary air. This

design should provide a uniform mixture of coal and air and should improve the combustion efficiency.

In order to collect representative samples, several practical methods were considered in the preliminary design.

(1) Keep a negative pressure in the chambers by using an induced-draft fan in the stack of the furnace.

Therefore, steady state operation can be maintained during sampling.

(2) Create a water-cooled sampling device in the radiation part of the furnace similar to a water wall in a commercial boiler. The slag samples will be collected on the surface of the water tubes using this device.

(3) Create an air-cooled sampling device in the convection part of the furnace. The function of this device is to collect fouling samples in this chamber similar to the super-heater part of a boiler.

(4) Design several removable heat exchanger tube banks. One purpose of building these tube banks is to reduce the temperature of the flue gases to acceptable stack gas sampling temperatures. Another purpose is to collect the fouling samples on the surface of the heat-exchanger tubes.

(5) Create a gas-sampling port at a suitable location in the chimney. The composition of the flue gases can be monitored by gas analyzers.

(6) Design several special shaped ash-collection hoppers in suitable locations. The ash samples can be collected in accurate quantities.

Since our main purpose is to study the behavior of blended coals, the blending and feeding technique is another factor which has to be considered in the design. This will affect the combustion.

Safety and pollution control must also be considered. Because of the characteristics of slagging sample collection, sufficient quantities of coal must be combusted to get enough sample in a relatively short period of time. Thus, pollution problems had to be considered if coal is combusted in large quantities. The methods used are:

- (1) Create enough stack height in order to reduce dust pollution and air pollution at ground level,

- (2) Carefully adjust the quantities of combusted coal and the ratio of coal to combustion air in order to get the best combustion situation, and

- (3) Create enough heat exchanger surface area to control the stack temperature to just above the level where low-temperature corrosion would occur.

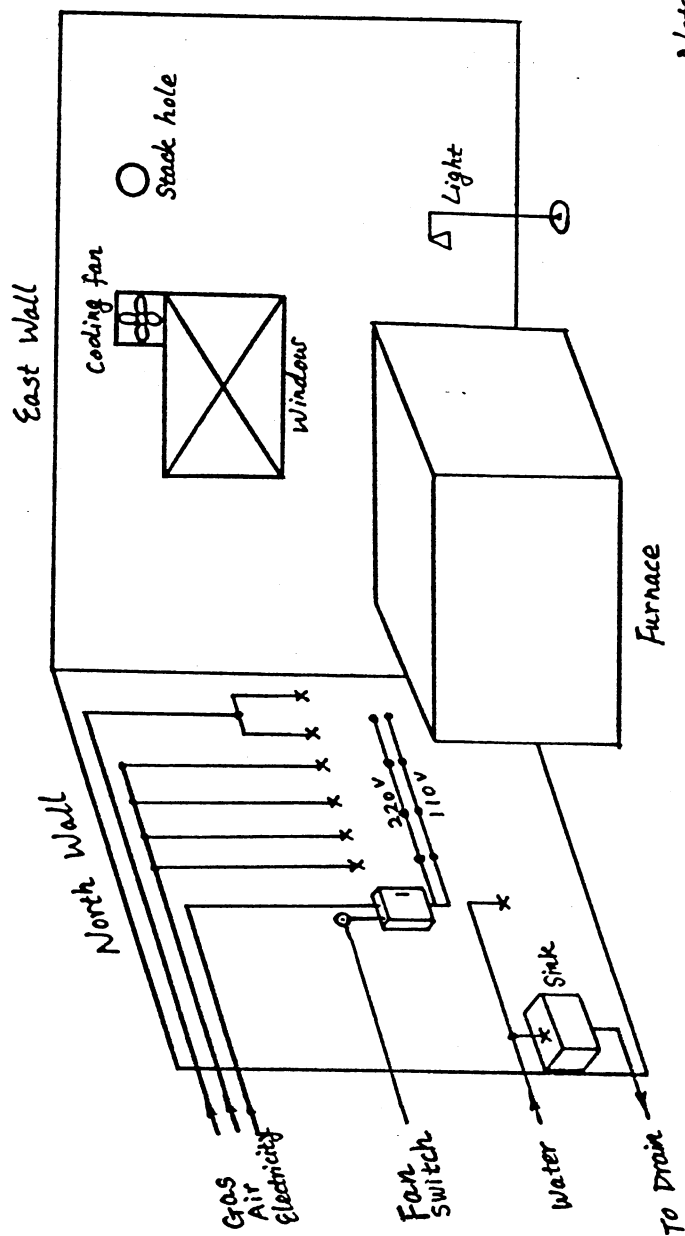
There are many other factors which need to be considered before calculation and construction, including budget constraints. Since the budget for a facility was limited, planning was required for every part, including labor. The variety and quantity of raw materials had to be calculated carefully, so as not to waste any material. In practice these kinds of calculations were latter proved to be necessary and quite helpful.

Basic data collection and calculation were pre-

requisites to further design. Basic data was collected from reference books, but most information could only be derived through theoretical calculations. Data thought to be useful in designing the facility included those of coal, air, combustion gases, furnace combustion and basic materials. Calculations included heat exchanger design, combustion air requirements, flame temperature and residence time. Some of these were based on experience. For example, the flow rates of the fluids must remain within certain limits in order to keep the operation stable. In practice, people have already summarized these data. The detailed calculations about the facility design are described in the next chapter and other detailed calculations are included in the appendixes.

Laboratory Selection and Design

In the early days of this project, the facility was in a laboratory in the center of the university. The only problem of that site was that it was nearby classroom and office buildings. This violated the safety requirement of this school. A new laboratory was required, which would meet requirements of the safety department. The new site selected was no more than a store room originally, since there was no water, no electricity, no natural gas and no compressed air, and all of these are necessary to operate the furnace. The utility design and installation needed experience and the co-operation of technical workers. The utility system designed is shown in Figure 1 and 2. This



Note:

1. Need tube Light on the ceiling.
2. Need regulators and gauges for the air.
3. Need rotameters for water and air.

Figure 1. Utility Design

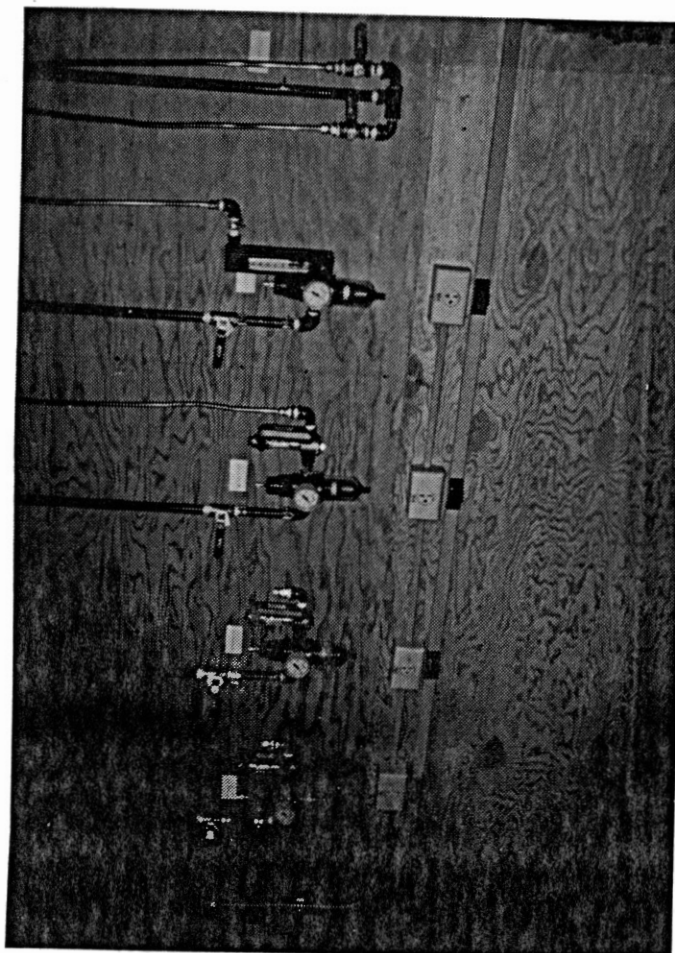


Figure 2. Utility. Photograph

design was based on the principles of convenience and practicality. The natural gas is used for initial ignition of the furnace. There are two natural gas burners located at the top part of first chamber. The air lines supply combustion air and coolant for the heat exchangers. Combustion air includes primary air, secondary air and tertiary air. Cooling air goes through two to three separate heat exchanger tube banks. All of these air lines are controlled individually and metered separately using rotameters. Considering the requirement of removability for a heat exchanger assembly, a special type of pipe material was selected for the cooling air lines. The pressures of the compressed air for furnace supply are controlled and read from pressure regulators and gauges mounted on the inlets of the rotameters. The electricity lines include both 110 v and 220 v outlets. Water lines are mainly used to supply cooling water to the sampling devices. The flow rate of water is measured by a water rotameter. Controlling the flow rate of the water controls the physical condition of the outlet water.

Material Selection, Purchase and Manufacture

There were many materials used for furnace construction and installation. Construction materials were required, which would withstand very high temperatures and be good heat insulators. Usually, measurement instruments have temperature limitations, so special attention was paid

during instrument selection in order to meet the temperature requirements of the system. Commercial products were selected, if possible, for convenience but for some special parts, like heat exchangers, design and construction were required. Heat exchangers were constructed using stainless steel tubing. This had to be bent into a U-shaped tube. In order not to block the way in the curved part, the diameter of the tube and the wall thickness were important and chosen carefully. The bending radius is a parameter which influences the design of heat exchanger scale and tube bank arrangement. Welding between stainless steel and carbon steel is very difficult and special welding material and techniques were required.

Construction and Installation

In order to prevent breakage of the soft insulating fire brick and reduce gas emissions from the furnace, all construction was done in a predesigned steel box. The requirement for the design of this steel box was the accuracy of geometrical scale. The furnace material consisted of two types of refractory brick. High density, 70% aluminum refractory brick which can handle up to 3300 °F and has good strength was used in the inner surfaces. Surrounding this high temperature refractory brick, a lower density brick capable of withstanding 2000 °F was used for insulation. Several different kinds of cement were required to secure the bricks and for other special purposes. The

main concern during construction was gas emission from the sampling ports and from all the cemented bricks. The complete unit, comprising the coal feeding system, furnace, instrument panel and analytical system will be described later in greater detail.

Facility Function Test

The design operating data will be listed and discussed in a later chapter. These data were designed based on a coal feeding rate of 2 lb/hr. The quantities of the combustion air were calculated based on the stoichiometric relations with a 20% excess.

It should be pointed out that all of these data were obtained from the theoretical calculations and experiences. There might be some differences between the tabulated values and real conditions. But these data can be used as the initial setting and can be adjusted during operation.

CHAPTER III

DETAILED DESCRIPTION AND DISCUSSION OF DESIGN

General Operation Principle of Facility

A flowchart of the whole unit is shown in Figure 3 and a photograph of the furnace and facilities is shown in Figure 4. The facility is composed of a utility system, coal feeding system, furnace and measurement system. The furnace includes one coal burner, two natural gas burners, one tertiary air burner, three sight holes, five temperature measurement ports, two solid sampling ports, two clean out ports, two heat exchanger tube banks and one pressure relief valve. Two natural gas burners are located on the top of primary chamber. The natural gas in the line provides initial ignition of the furnace. The gas is lighted by a spark. Check valves are used in the line in order to prevent flash back. When the temperature in the primary chamber of the furnace reaches a high enough level (up to 1700 °F), coal and combustion air are sent into the furnace passing through a coal burner. After coal ignition, the natural gas might be shut off. Pulverized coal is fed from a coal feeder. At the outlet of the coal feeder, there is a T-type pipe. Primary air, flowing past the T-pipe, carries the pulverized coal into the coal burner. Secondary air is

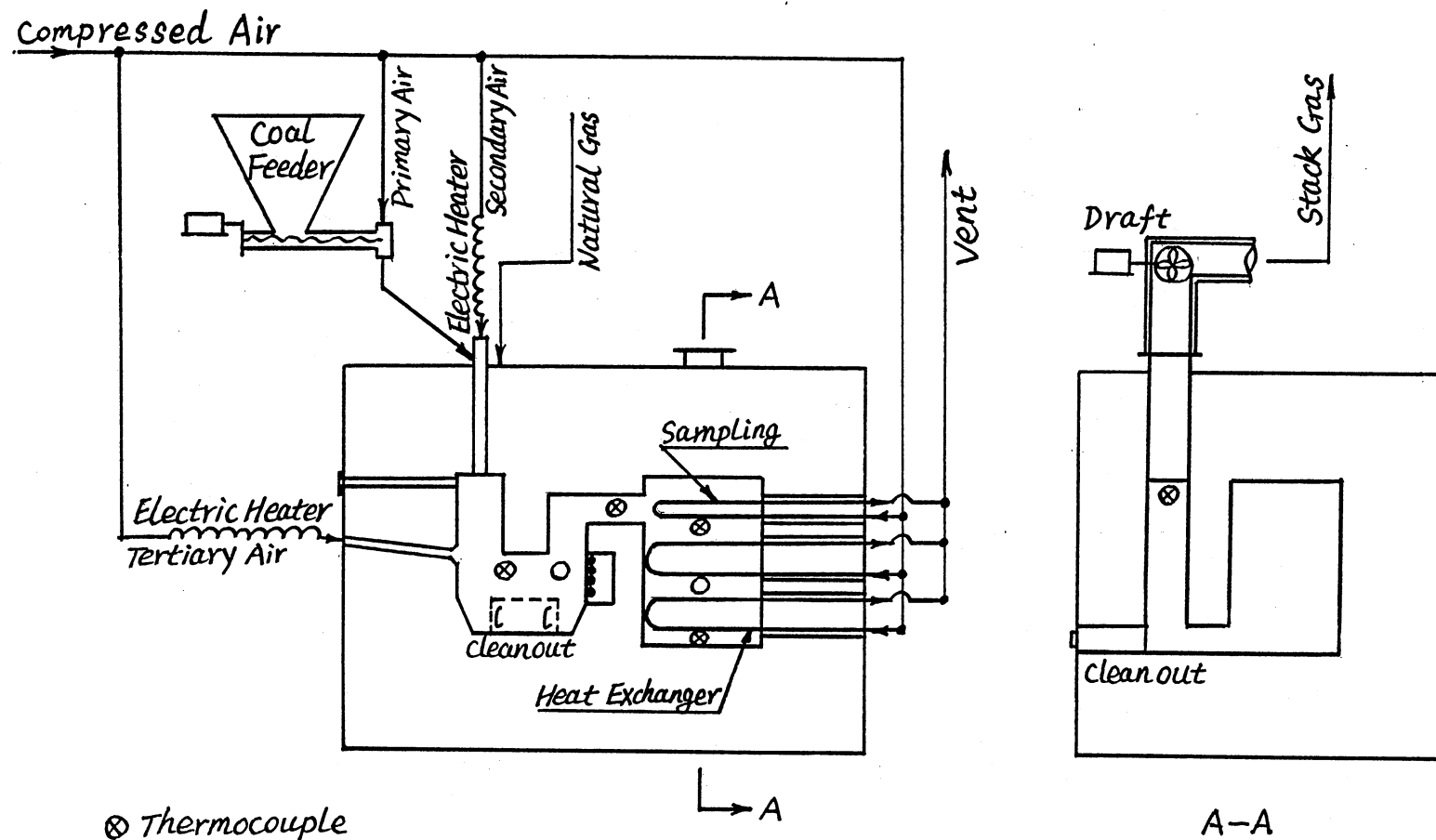


Figure 3. Flowchart

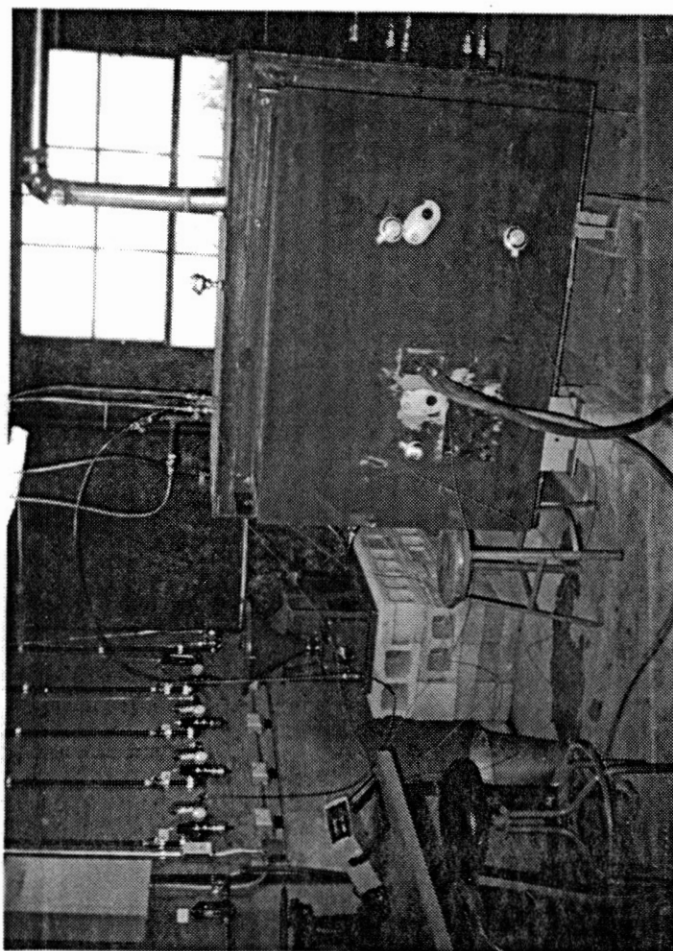


Figure 4. General Photograph

fed into coal burner through a separate line. During combustion, tertiary air is also fed to the furnace. The tertiary air burner is located 10 inches below the coal burner outlet and air is fed in at an 80° angle with the vertical in order to provide a U-shape flame. Both secondary and tertiary air are preheated. Combustion gases pass under the baffle-like arch in the first chamber, over a baffle into the secondary chamber, where the heat exchangers are located, and then under a second arch into the furnace breech. Flue gases leave the furnace through a 4 inch stack. An induced-draft fan is located at a point 2 feet above the furnace top. Gases are finally exhausted to the atmosphere 8 feet above the fan.

In the primary chamber, there is a water-cooled solid sampling device, from which slag samples can be collected. In the secondary chamber, there is an air-cooled solid sampling device, from which the fouling samples can be collected in the same way as slagging sampling device.

Pulverized-coal Feeder

The feeder is a commercial unit made by the Vibra-Screw Company of New Jersey. The coal feed rate, up to a maximum of 4 lb per hour, is controlled by a variable-speed drive. The feeder assembly is continuously vibrated to ensure complete filling of the screw and provides uniform feeding of pulverized blended coal. The coal is carried to the edge of a T-pipe by vibrations transmitted from the feeder.

Primary air entering at this point entrains the coal as it drops off the T-pipe. The velocity of the coal-air mixture in the line varies from 25 to 100 ft/sec, for a coal feed rate of 1 to 4 lb per hour. A photograph of the feeding system is shown in Figure 5. The feeding system is calibrated by collecting the coal ejected from the screw at various screw speeds and with the system disconnected from the coal burner.

Combustion air is calculated based on stoichiometric relations with a 20% excess. Detailed calculations on the air-coal ratio are given in Appendix A. Actual system calibration could be checked during furnace operation by fixing the combustion air flow to the furnace and then adjusting the coal feed until the desired gas analysis, based upon stoichiometric considerations, is obtained. The feeding accuracy is 1 to 2 percent of coal feed. The feed hopper can hold 25 lb of pulverized coal and can be filled in batch or continuous patterns.

Furnace Structure

The entire furnace structure is contained within a steel shell, to which all external furnace attachments are made. The shell provides a relatively air-tight enclosure. The design of the steel shell is shown in Figure 6 and Figure 7. A photograph of the cross section of the furnace is shown in Figure 8 and 9, and drawings of the internal and outside structures are shown in Figures 10-14. All the

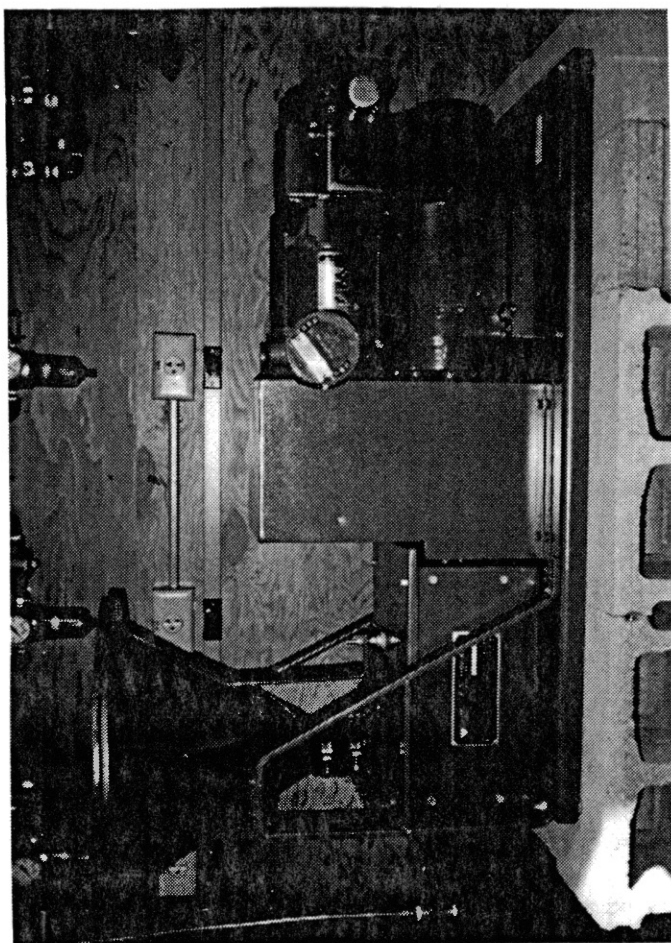


Figure 5. Feeder

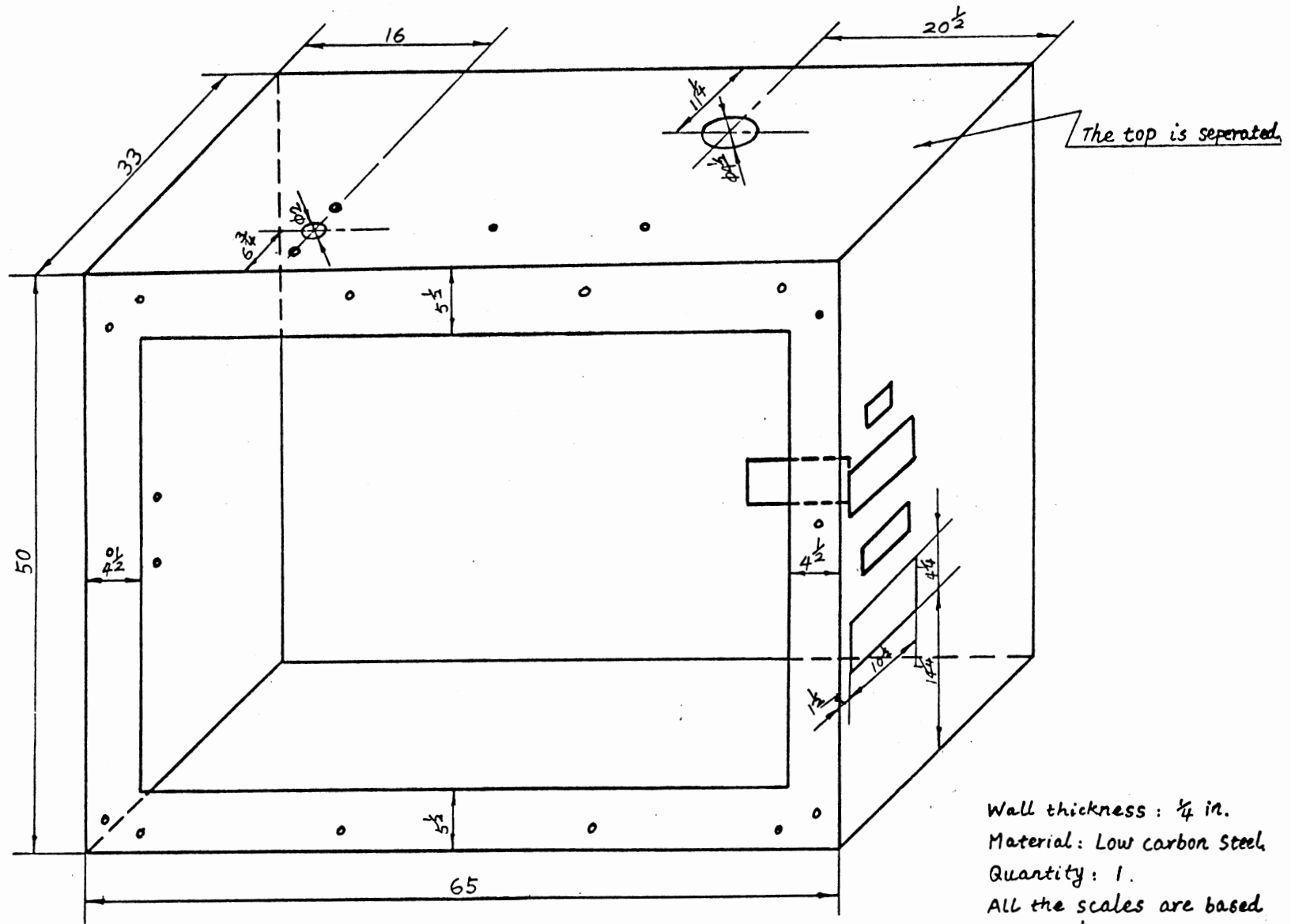
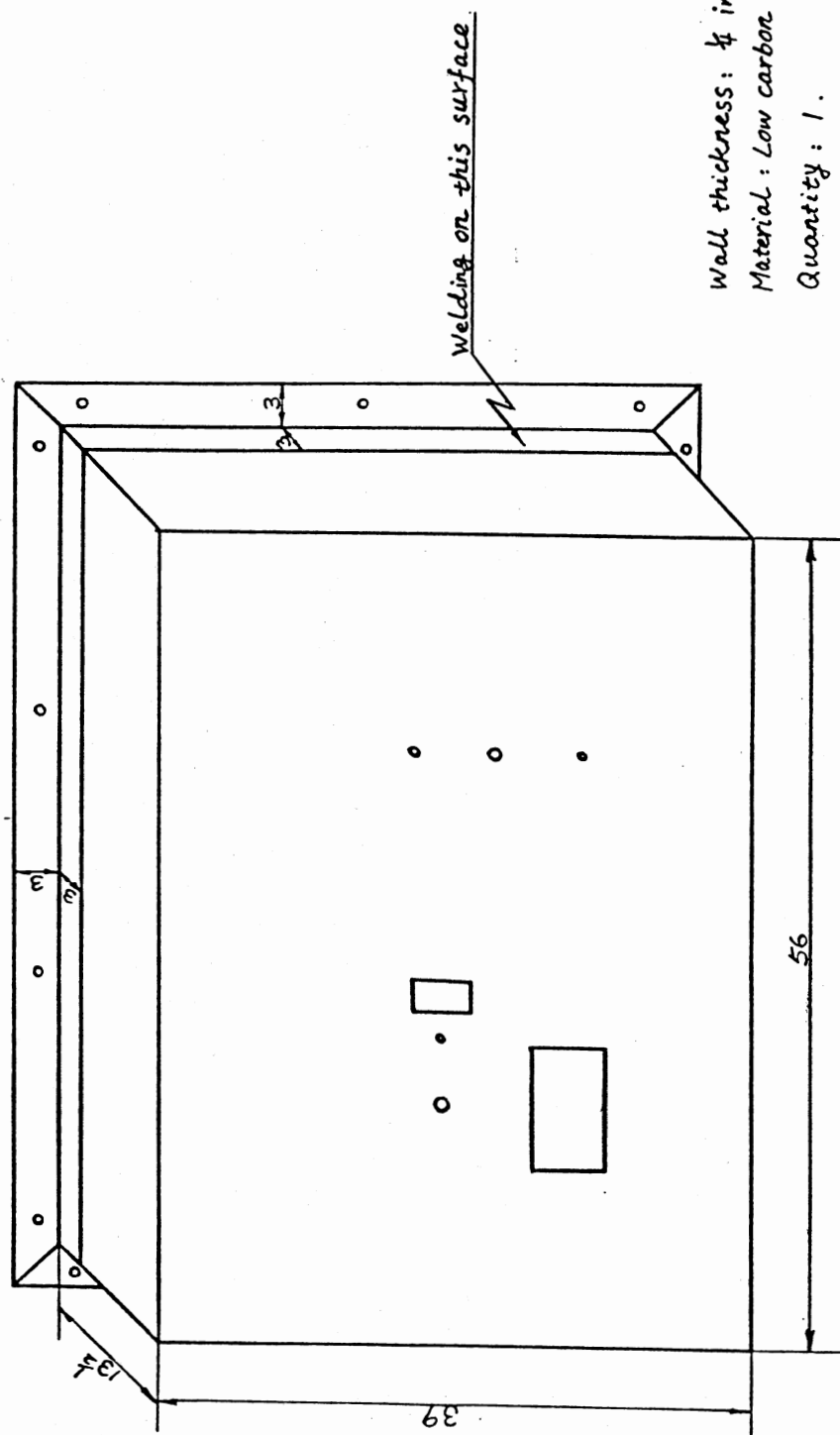


Figure 6. Steel Box (1)



Wall thickness: $\frac{1}{4}$ in.
 Material: Low carbon steel.
 Quantity: 1.
 All the scales are based
 on inside scales. Do not
 include wall thickness.

Figure 7. Steel Box (2)

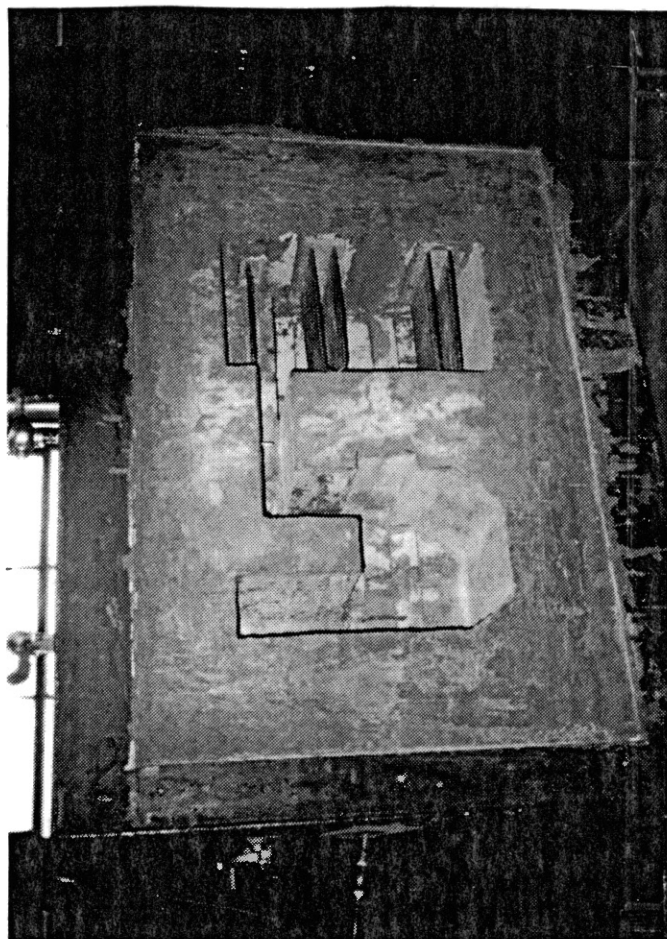


Figure 8. Furnace Cross Photograph

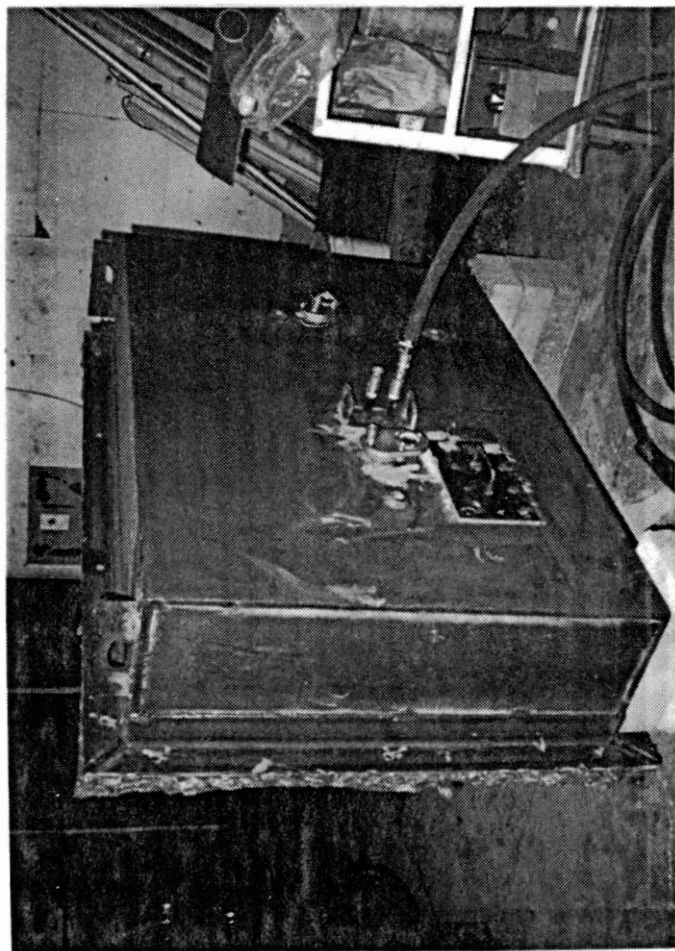


Figure 9. Furnace Door Photograph

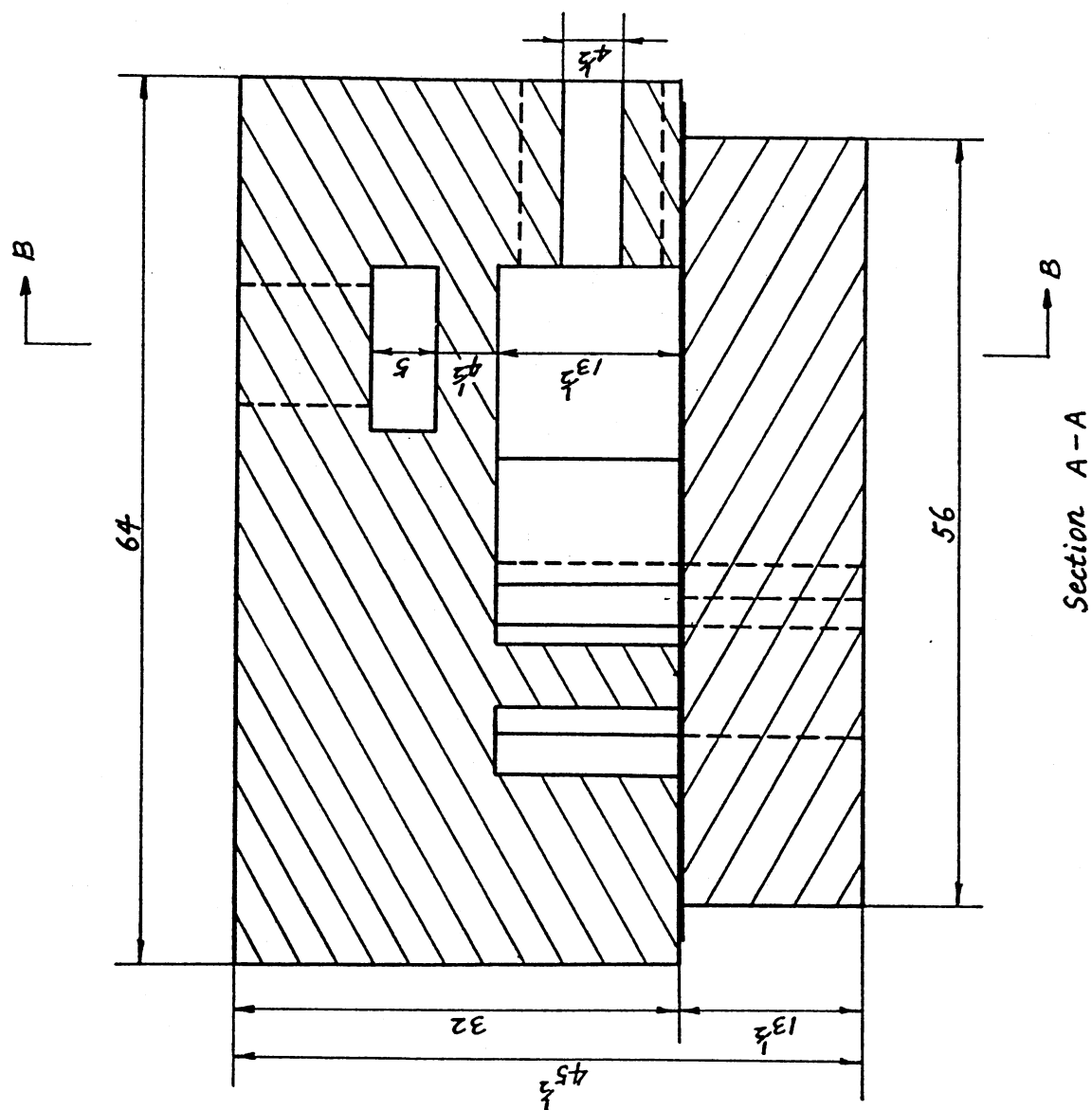
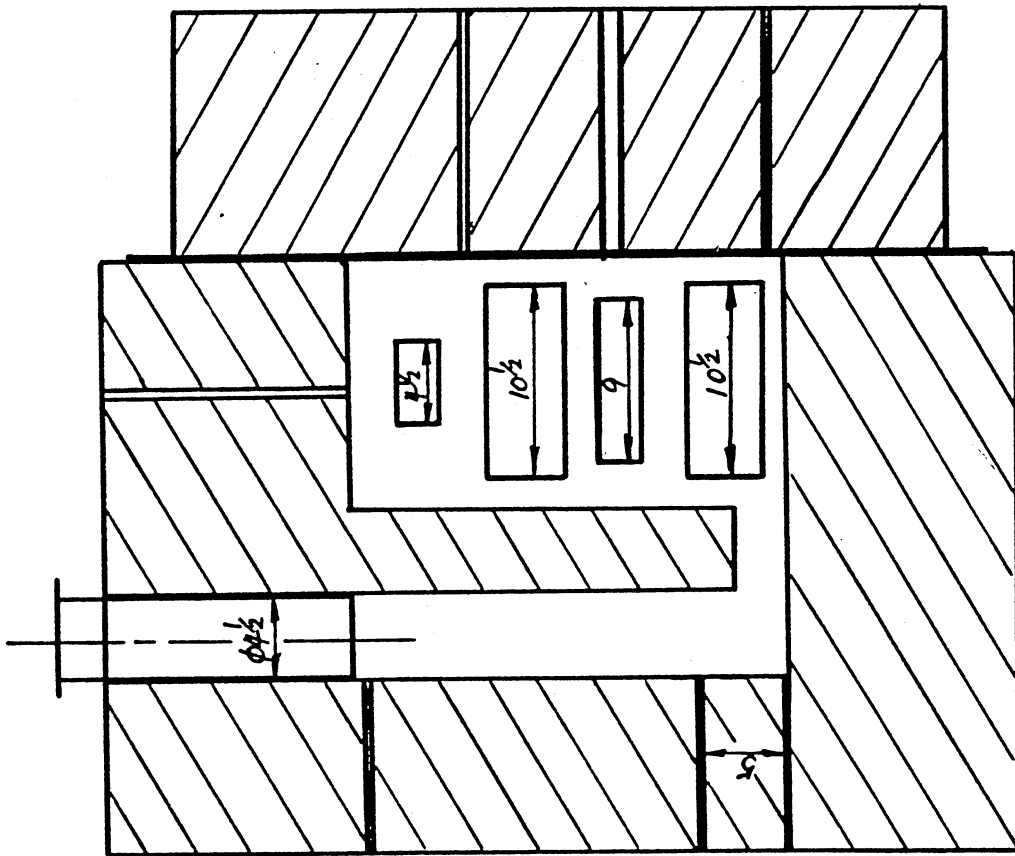


Figure 11. Furnace Scale (2)



Section B-B

Figure 12. Furnace Scale (3)

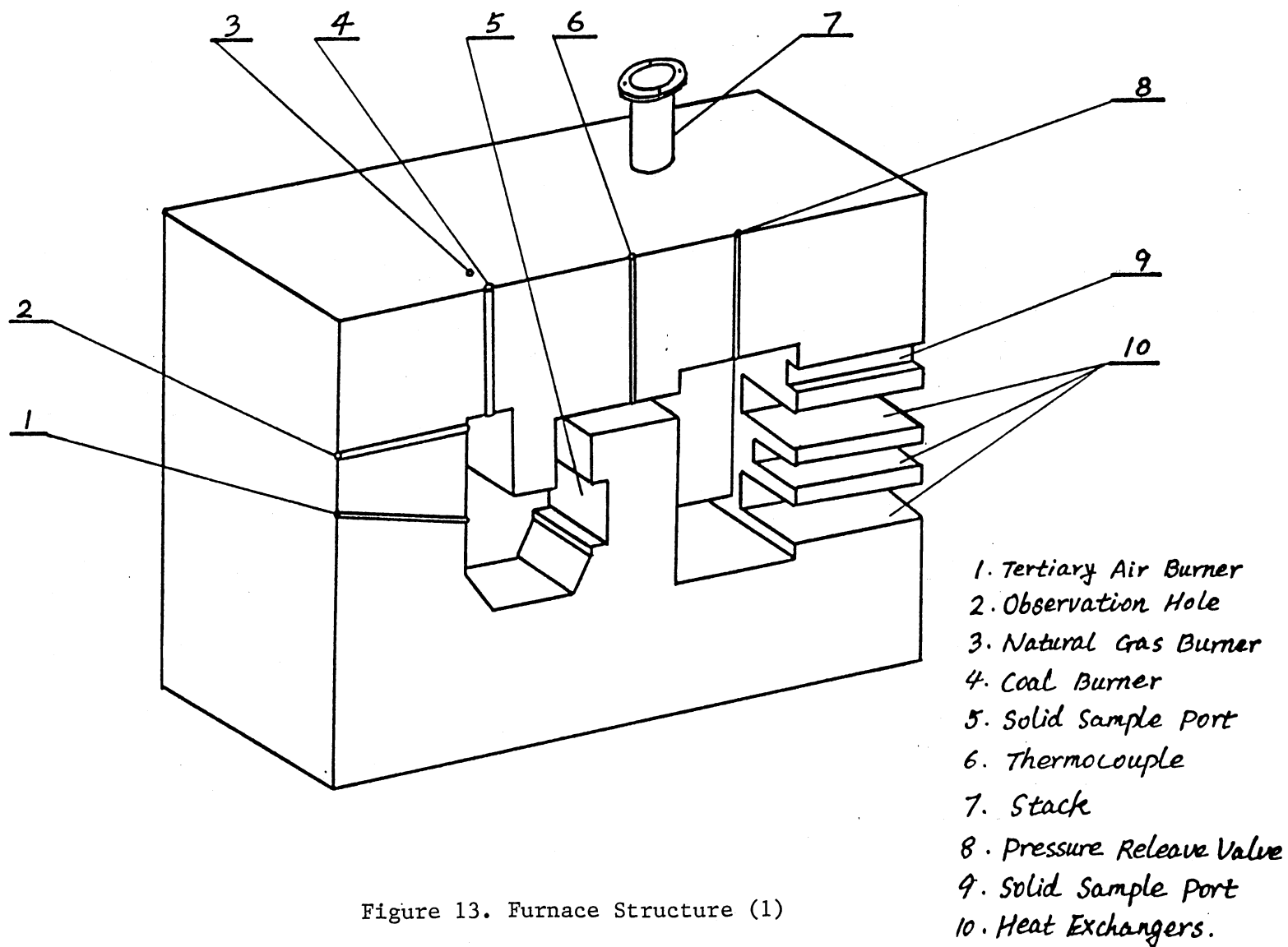
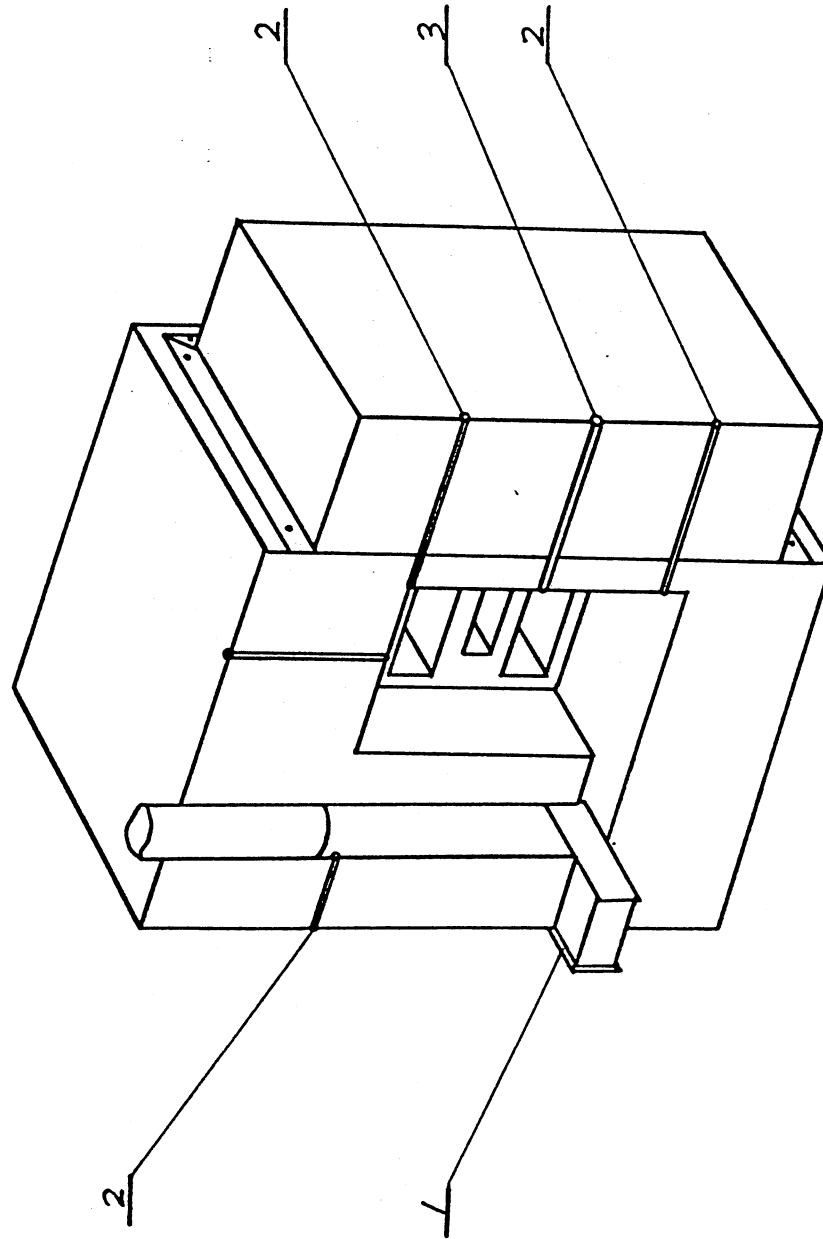


Figure 13. Furnace Structure (1)



- 1, Clean Out.
- 2, Thermocouples.
- 3, Observation Hole.

Figure 14. Furnace Structure (2)

scales are marked on these figures.

The furnace wall is composed of three layers of brick, each 4.5 inches wide, providing a refractory wall 13.5 inches thick. The reason for using this thickness is to reduce the heat loss from the wall by providing good insulation. Based upon an inner temperature of about 2000 °F and an outer wall temperature of about room temperature, the wall thickness can be calculated from a knowledge of heat conduction and radiation. The inner layer is a 70 percent alumina refractory brick with high density, good strength and low porosity. Its softening temperature is 3300 °F. This kind of brick can withstand the attack of corrosive slags and molten metals without penetration of volatile gases or dust to the furnace atmosphere. Its excellent balance of chemical and physical properties results in longer life when the furnace is operated under severe service conditions.

The middle and outer layers are insulating brick with an upper operating temperature of 2000 °F. This kind of brick has high insulating value, good structural strength and the ability to withstand temperature changes without shrinkage. In the bottom of the primary chamber, an 80 percent alumina ramming mix was used which has a softening temperature of 3300 °F. This extra refractory maintains permanent volume characteristics at high temperatures and helps resist slagging. The heat exchanger blocks and sampling plugs, as well as the clean-out plugs, are made of

2200 °F castable material. This material is an extremely lightweight insulating castable, capable of withstanding temperatures up to 2200 °F. Refractory cement (Sairset Mortar) was used throughout the furnace. This is a wet, high temperature (3000 °F), air-setting bonding mortar that protects firebrick linings against destructive spalling, reduces joint erosion due to chemical attack of slags or dust laden fumes and prevents penetration of joints by molten metal or fluid slag.

The furnace design is a so-called paralleled-chamber arrangement. The first chamber has a volume of 1.8 cubic feet. The bottom of this chamber has a special angled shape in order to keep the flame U-shaped and functions as an ash-hopper. The baffle-like wall helps maintain the shape of flame and increases residence time of combustion. The second chamber has a volume of 2.2 cubic feet. In order to get a uniform temperature distribution on the surface of the heat exchanger tube banks, the space at the top of this chamber is enlarged. The throat part between the two chambers has a cross sectional area of only 22 square inches. This small area makes the velocity of the combustion gases increase and prevents the flame in the primary chamber from passing through to the tube banks in the second chamber.

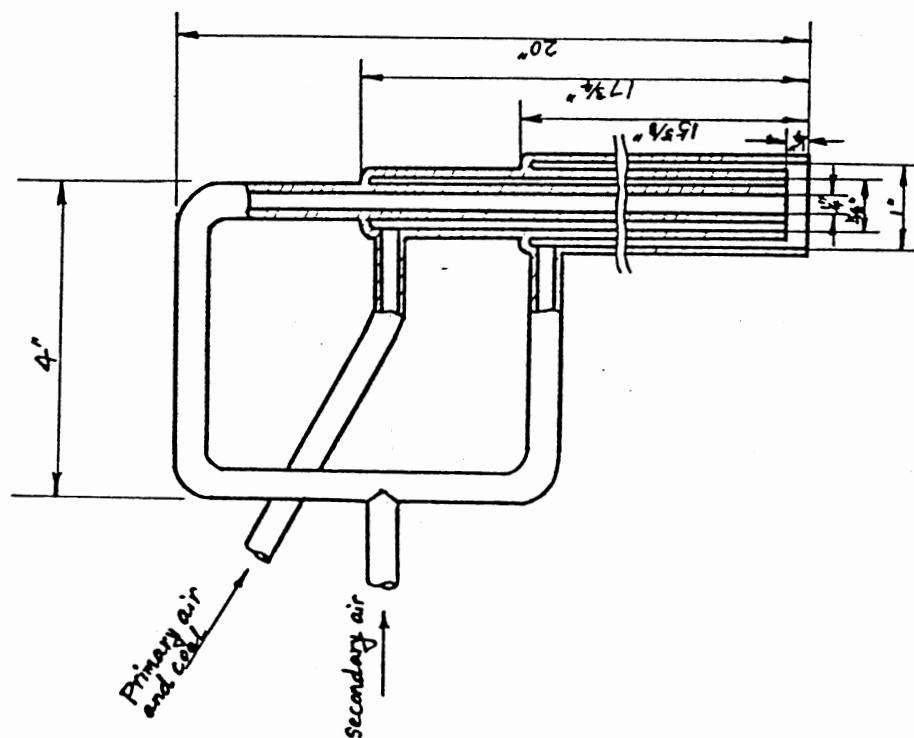
The total weight of the furnace is about 3 tons. The furnace was built in two parts. The door of the furnace can be opened for maintenance. The door weights about 1600

pounds and can be moved by a small hydraulic car or port-a-crane. The door can be easily connected to the main body of the furnace by screws and nuts. Emission problem caused by joining the furnace and door is overcome by putting some insulating material around the joint.

Coal Burner

The pulverized-coal burner, illustrated in Figure 15, is mounted in the center of the burner block between the two gas-fired preheat burners. The coal burner is composed of three concentric tubes. This design allows good mixing of the coal and combustion air and prevents too much flame impingement on the refractory base of the furnace. Secondary air is passed through the inner tube and outer annulus, while the coal and primary air are added tangentially through the middle annulus. The coal-air mixture thus lies between two concentric streams of secondary air and produces a short, highly turbulent flame. The coal burner is made of low carbon steel since burner manufacture is very difficult. People usually think that stainless steel is a better material than carbon steel for a burner. But, low carbon steel can be used in this particular case since the burner is mounted in an insulated wall which prevents it from becoming red-hot. There is also a cone-shaped stream of air and coal just at the outlet of the burner, which helps prevent heat attack.

The velocity of coal and primary air was designed



Material: Stainless Steel
(or Low Carbon Steel)
Quantity: 1

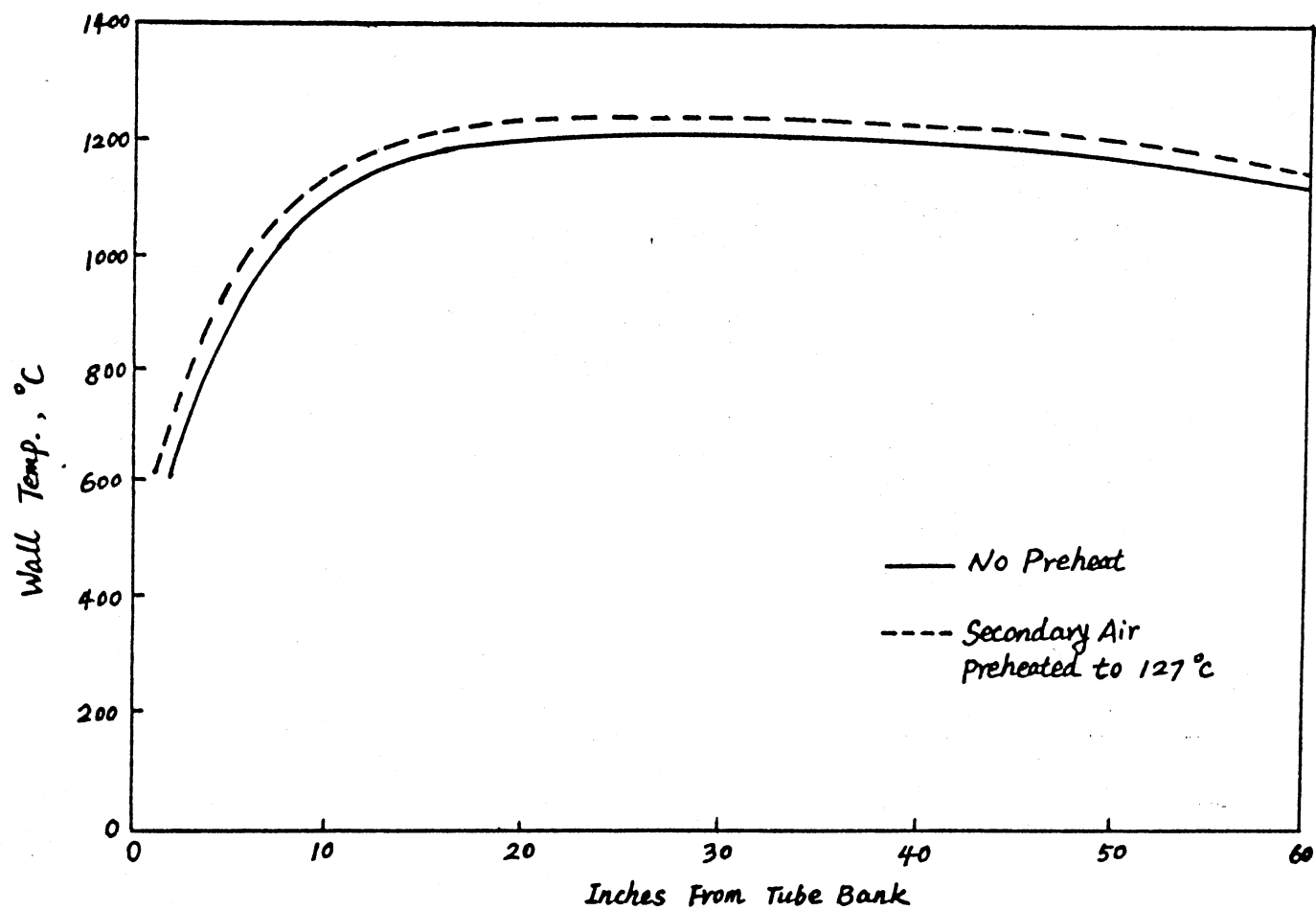
Figure 15. Coal Burner

carefully. At low velocities, pulverized coal tends to settle in the line from the feeder to the burner. When the coal is blown free, an erratic flame may occur. With lower velocities there is also the danger of flash back. Check valves are used for preventing flash back.

Combustion Air

The primary air stream supplies 25 percent of the total combustion air when burning 2 lb of coal per hour. This air is also used as the carrier for the pulverized coal. The secondary air stream is used to control flame stability and ignition point. It supplies 25 percent of the total combustion air for a coal feed rate of 2 lb per hour. Tertiary air is supplied to the furnace by a separate burner which is located in the middle part of the side wall in the first chamber. The tertiary air supplies the remaining 50% of the combustion air for a coal rate of 2 lb per hour. This tertiary air is supplied from a fan-shaped port and impinges upon the coal flame at an 80° angle. This tangential flow creates turbulence to complete the tail end of combustion.

The combustion air streams were designed with no preheating originally. Based on the literature (29), when air is preheated to 270°F , the wall temperature of first chamber is increased only by $90\text{--}120^{\circ}\text{F}$. Figure 16 shows the profile of expected wall temperatures with and without preheat (29). But generally speaking, air-preheating can



Source: Reference 29.

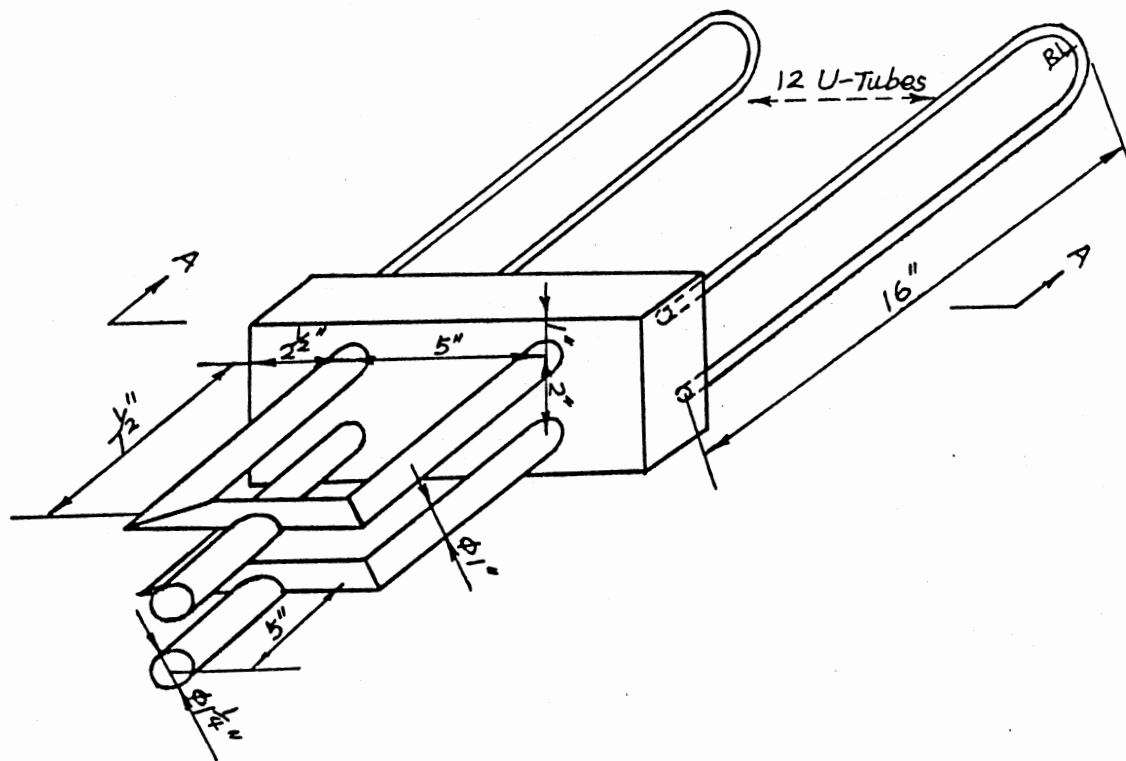
Figure 16. Wall Temperature Distribution With and Without Air Preheat

provide a means of closely controlling the furnace conditions which can increase the temperature and promote slagging. Preheating the combustion air is the major variable used to control furnace temperature on a small-scaled device since the coal firing rate which depends on burner shape, coal flow rate, coal-air ratio, coal quality and coal chamber design is fixed.

There are two methods which can be used to preheat the air. One method is to let the air flow through the heat exchanger section located in the secondary chamber. By carefully designing the heat exchanging surface area and air flow rate, preheated air can be produced in the desired quantity and temperature. But this recycled flow pattern will increase the difficulty of experimental control. Another method is to use an electrical heater. The output temperature can be controlled by means of a variable resistor. Both methods are practically used by many researchers. In this device, the latter method was used. High-temperature beaded heaters which were supplied by Cole-Parmer were wound on the tubes carrying the secondary air to the burner and tertiary air port. With suitable insulation, the temperature of the air entering the furnace could reach over 700 °F and could be varied by voltage controllers in series with the heating coils. The primary air was not preheated. But this stream still could be heated to some extent since it was sandwiched in the preheated secondary air streams when passing through the coal burner.

Heat Exchanger

One purpose of using a heat-exchanger is to cool down the combustion gases to a suitable temperature for stack gas analysis and to protect the induced draft fan. The other purpose is to use the heat exchanger to simulate the convection pass of a boiler, which will collect the fouling samples deposited on the surface of heat exchanger tubes. Therefore, this heat-exchanger should be designed to be movable. There were several kinds of possible designs. The design selected is shown in Figures 17-22. There are two heat-exchanger blocks. Each block has 12 parallel U-tubes. The layout of these tubes is triangular in order to improve the heat-exchanging efficiency. The front header of the heat exchanger has three channels. The two lower channels are cold air inlets. Since there are 12 tube inlets in one line, uniform air distribution in these tubes is a problem when the cold air comes from only one inlet air pipe. In this design, there are two equally divided channels, each for six tube inlets. Two vertical impingement plates just opposite the outlet of the inlet air pipes were designed so the incoming fluid from the inlet pipes can not go into those tubes just opposite the inlet pipes. Instead, air will pass around the baffle plates resulting in a uniform air distribution in tube banks. Between the lower part and the upper part of the front header, there are two layers of dividers. Although heat exchange between the inlet channel and outlet channel is a problem in heat exchanger design,



Note: $\phi 1\frac{1}{4}$ " pipe will connect with soft fiber tube.

Quantities: 2.

Material: 347 Stainless Steel.

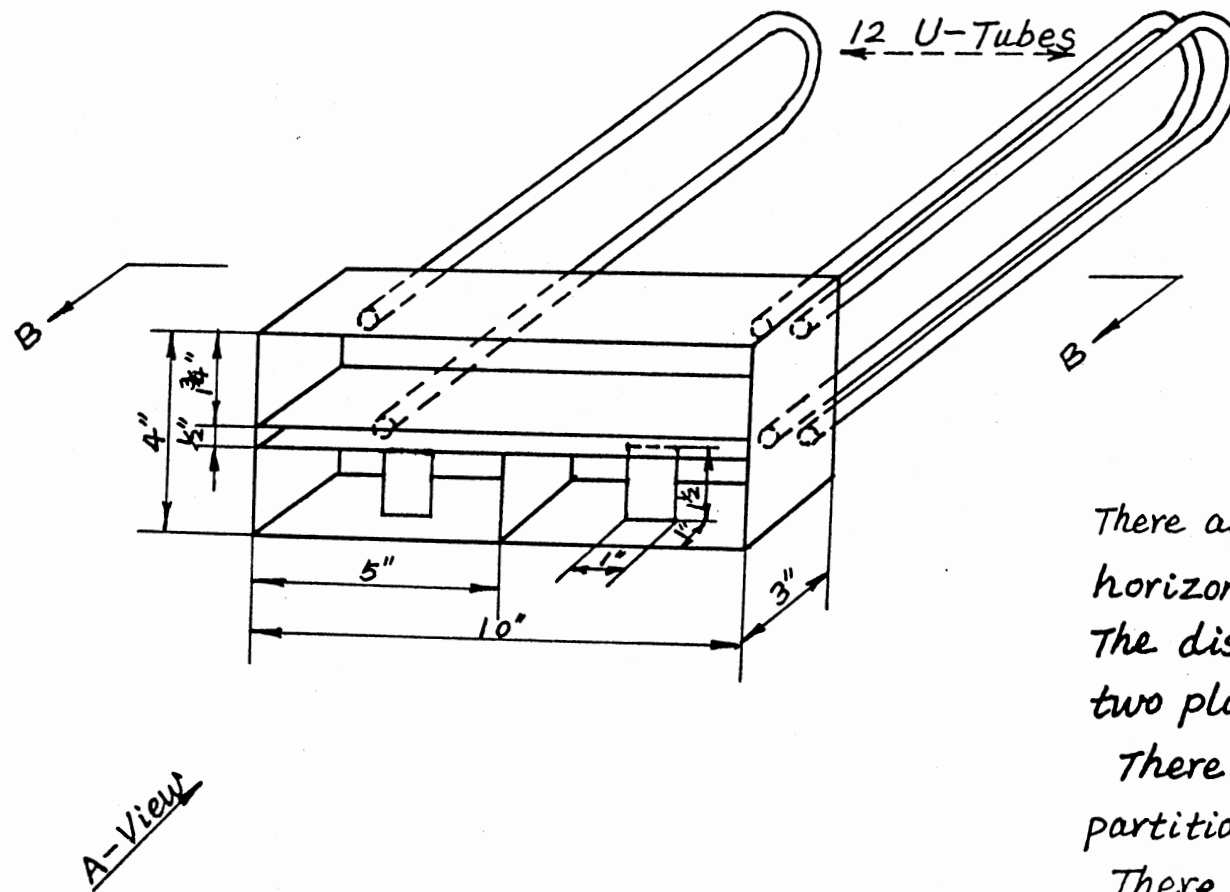
$\phi 1$ " pipe: $D_o = 1$ in. BWG 13.
 $D_i = 0.81$ in.

$\phi 1\frac{1}{4}$ " pipe: $D_o = 1\frac{1}{4}$ in. BWG 13
 $D_i = 1.06$ in.

Pipe Materials: Stainless Steel
 or Low Carbon Steel.

Plate Thickness: $\frac{1}{16}$ in.

Figure 17. Heat Exchanger Design (1)

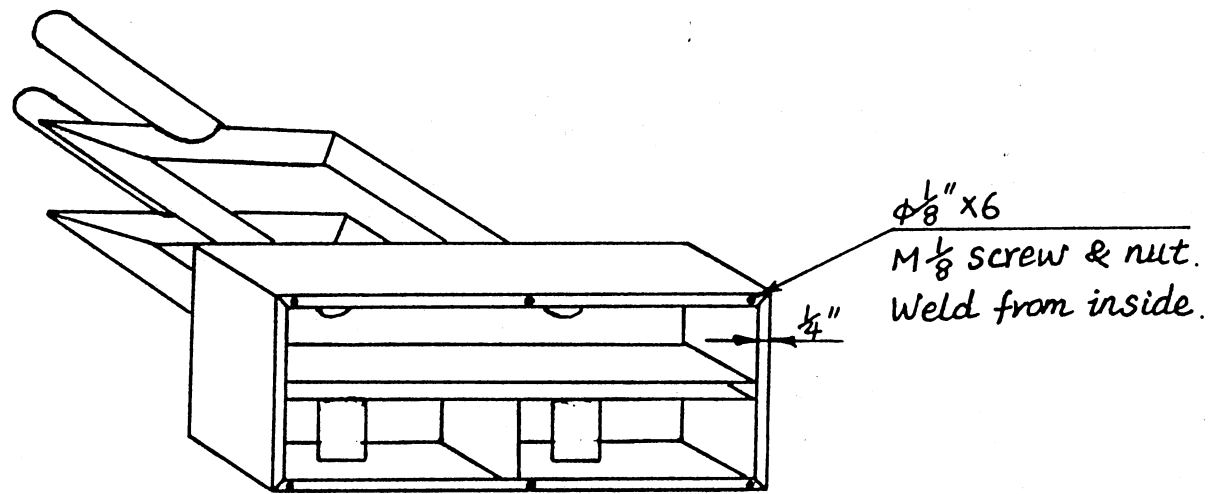


There are two layers as horizontal partition. The distance between two plates is $\frac{1}{2}$ in.

There is one vertical partition at lower part.

There are two $1\frac{1}{2} \times 1$ " Plates just opposite the outlet of Lower pipes.

Figure 18. Heat Exchanger Design (2)



B-View

May use seal strip.
 The seal material should
 stand $1000^{\circ}F$.
 Should consider leakage
 problem from the edge
 of partition.

Figure 19. Heat Exchanger Design (3)

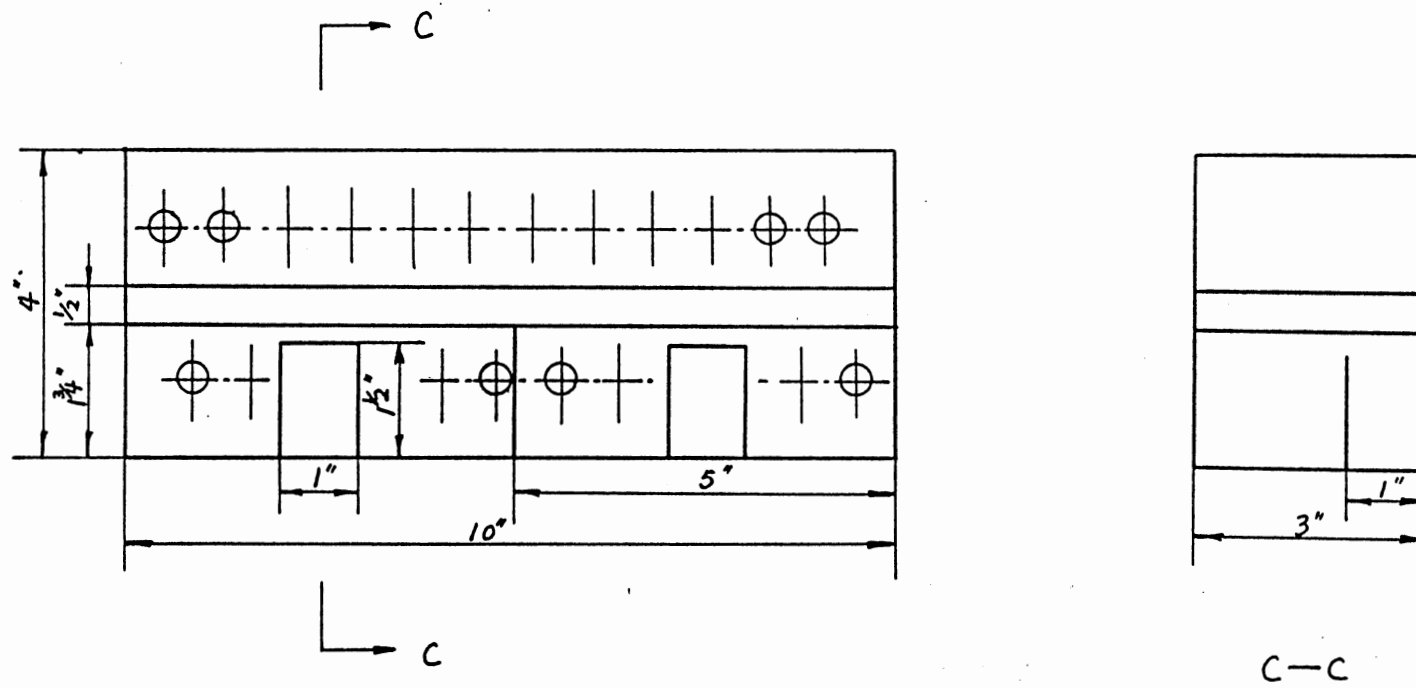


Figure 20. Heat Exchanger Design (4)

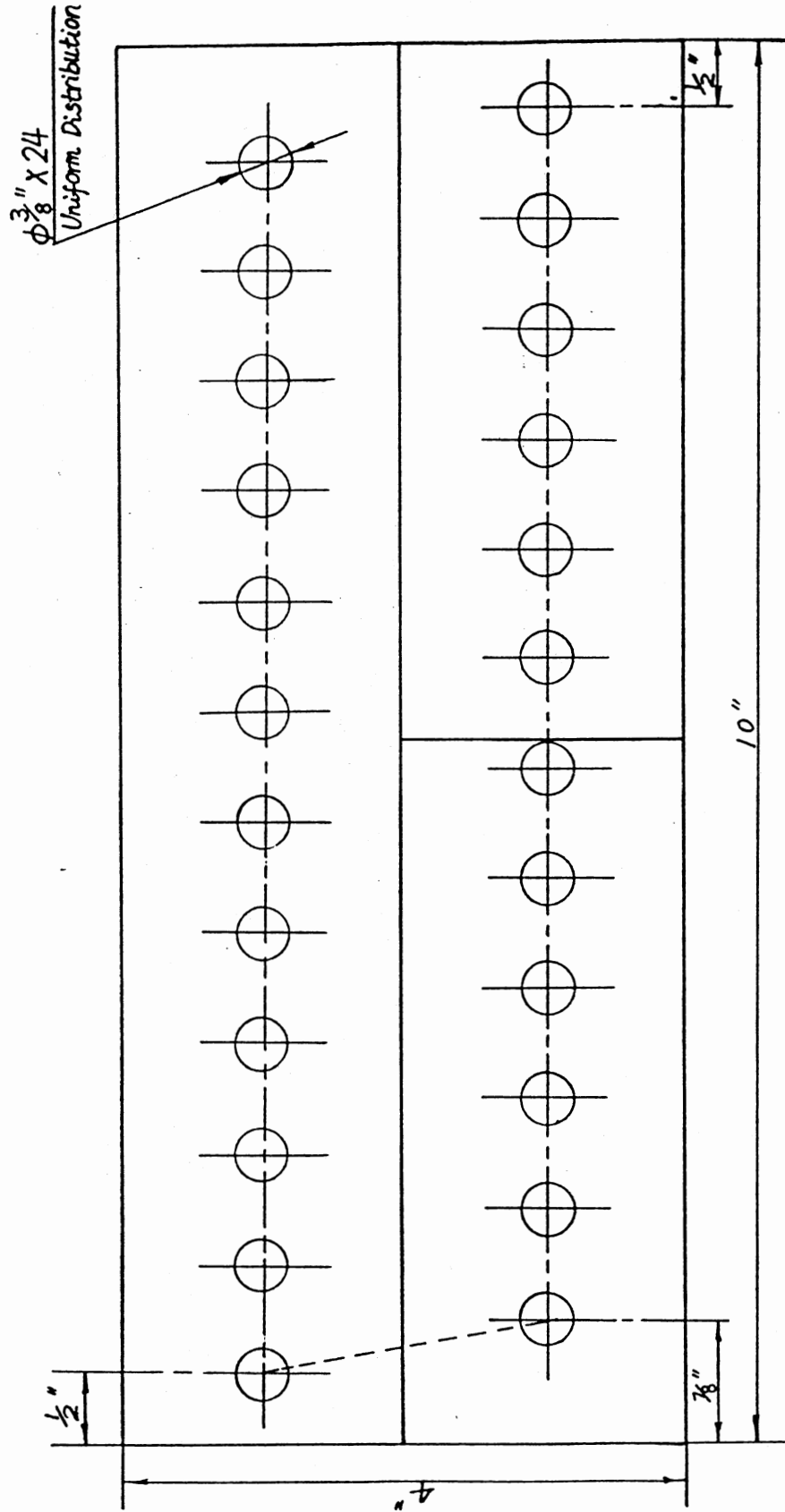


Figure 21. Heat Exchanger Design (5)

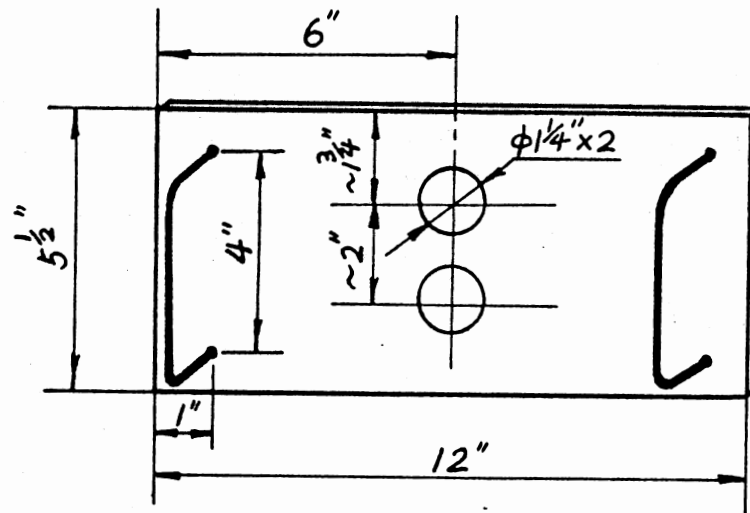


Figure 22. Heat Exchanger Design (6)

Note:

1. Quantities: 2 (two).
 2. Material: Low Carbon steel.
 3. Plate thickness: $\frac{1}{8}$ in.
 4. The plate should fit with the heat - exchanger.
- The distance between two holes depends on the distance between two $\phi 1\frac{1}{4}$ pipes of heat - exchanger.

this double layer divider is thought to have value by reducing this kind of heat emission. The heat exchanger tubes are made of 347 stainless steel. The tubes have 0.375 in. outside diameter and 0.305 in. inside diameter. The tube size selection was based on bending characteristics. The rest of the heat exchanger is made of low carbon steel. Welding between stainless steel and carbon steel is difficult, but fabrication of carbon steel is much easier than that of stainless steel. Use of a silver welding bar is helpful to weld stainless steel with carbon steel. The heat exchanger surface area calculation is based on a cross flow pattern of passing gas through U-tube banks. The hot fluid flows through the shell side and cold fluid through the tube side. The main design data are listed in Table 1 and the detailed calculations are shown in Appendix B.

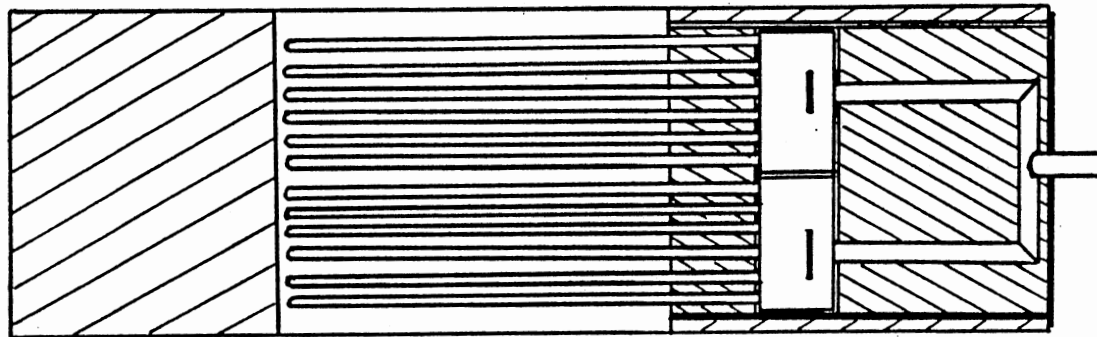
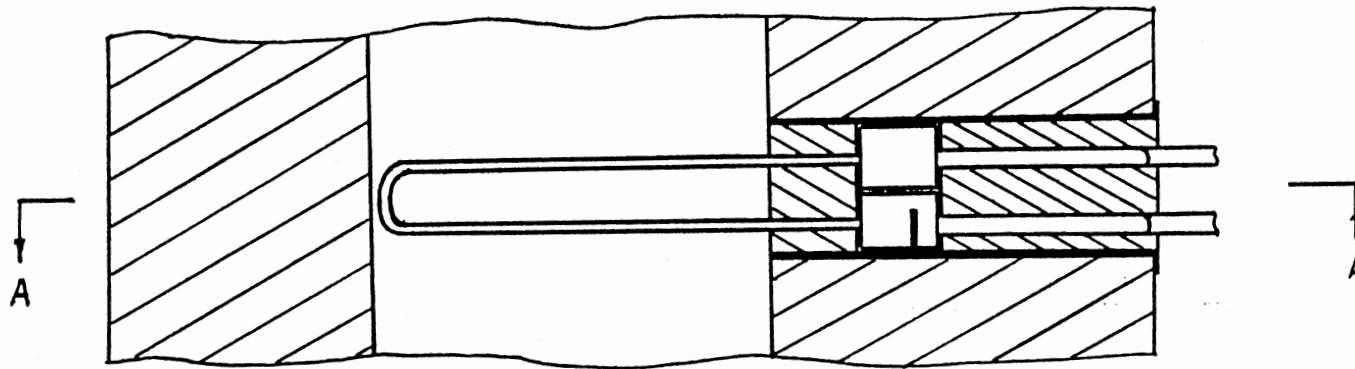
The pressure drops on both tube side and shell side are design factors which must be calculated. The detailed calculations are shown in Appendix C.

The heat exchanger blocks are made of castable insulation material and are casted in shapes to just fit within tunnels passing through furnace wall. Opposite the fire side, there is a three inch cement layer in the front of the heat exchanger header. This layer is used to protect the low carbon steel header from contacting the hot fluid directly. A cross section view of the heat exchanger is shown in Figure 23.

Cooling air is metered by a rotameter and then fed into

TABLE I
DESIGN DATA FOR HEAT EXCHANGER

Hot Fluid Inlet Temperature	2000 °F
Hot Fluid Outlet Temperature	600 °F
Cold Fluid Inlet Temperature	80 °F
Cold Fluid Outlet Temperature	600 °F
Critical Temperature of Hot Fluid	1300 °F
Critical Temperature of Cold Fluid	340 °F
Specific Heat of Gas	0.30 BTU/lb °F
Specific Heat of Air	0.246 BTU/lb °F
Gas Mass Flow Rate	29.8 lb/hr
Density of Air	0.124 lb/ft ³
Cold Air Pressure	25 psia
Overall Heat Transfer Coefficient	3.4 BTU/hr ft ² °F
Tube Outside Diameter	0.375 in.
Tube Inside Diameter	0.305 in.



Section A - A

Figure 23. Heat Exchanger Working Situation

two heat exchanger blocks in different lines. Each line has its own control valve so that the flow rate of air in every block can be adjusted separately. Each heat exchanger block can be moved easily. Fouling samples on the heat-exchanger tube surface can be collected easily. Selection of the outlet pipe material of the heat exchanger must be considered carefully since the temperature of the outlet air is quite high and the heat exchanger blocks are designed to be movable. The pipe which is used here is high temperature steam hose. This pipe can handle high temperature and can be bent without difficulty. The hot air is finally vented to the atmosphere through the stack. If the heat exchanger is used for heating the combustion air, a part of the hot air can be allowed to bypass. This part of the air can then be used as preheated combustion air. The only difference when using the heat exchanger for preheating air is that the air quantity must be measured and controlled before going into the heat exchanger blocks due to the temperature limitation of the air flow meter.

Observation Hole

Observation holes were drilled through the wall of the two chambers after the basic construction was finished. There are three holes, each has a diameter of 1.25 in. The sight glass assembly is connected to the steel shell of the furnace by thread. A picture of the sight glass assembly is shown in Figure 24.

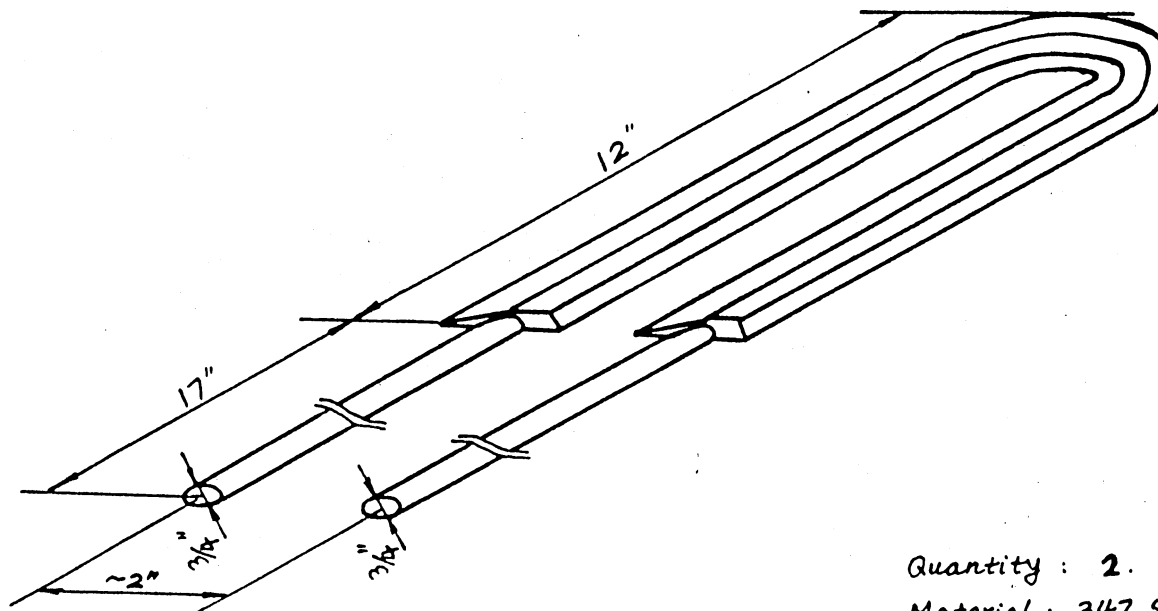


Figure 24. Sight Glass Assembly

Solid Sampling Device

Slag deposition experiments are carried out using a water-cooled stainless steel sampling device. Cold water passes through 1/2 in. pipe into two parallel stainless tubes, each tube having a 3/8 in. outside diameter. The stainless tubes are bent into a U-shape. The hot water will go into another 1/2 in. pipe to drain. Cold water is metered by a rotameter. The physical condition of the working fluid can be changed by controlling the cold water flow rate. The design of this slagging collection device is shown in Figure 25 and 26. The device is inserted into the primary chamber just opposite the fire flow direction. This site was chosen because it is close to the peak wall temperature location. The device can be pushed in and pulled out very easily. When the device is pulled out for sample collection, another plug-liked door, shown in Figure 27, is fitted into the sample port. The filling material for both the sampling device and the door is insulating castable material.

There is a similar device located at the upper part of the second chamber, just opposite the flow direction of the flue gases. The purpose of this device is to collect fouling samples in this part of the furnace. Instead of cold water, cold air is used as the working medium in this device. It should be noted that the working medium can be changed from air to water easily. There was no obvious



Quantity : 2.

Material : 347 Stainless Steel.

U-Tube Outside Diameter:

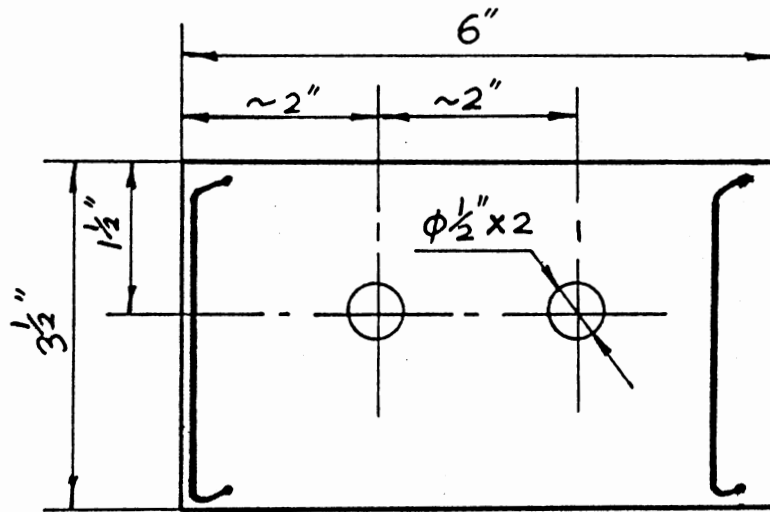
$d_o = 0.375$ in.

$d_i = 0.305$ in.

Straight Pipe: $d_o = \frac{3}{4}$ in.

BWG 14, $d_i = 0.584$ in.

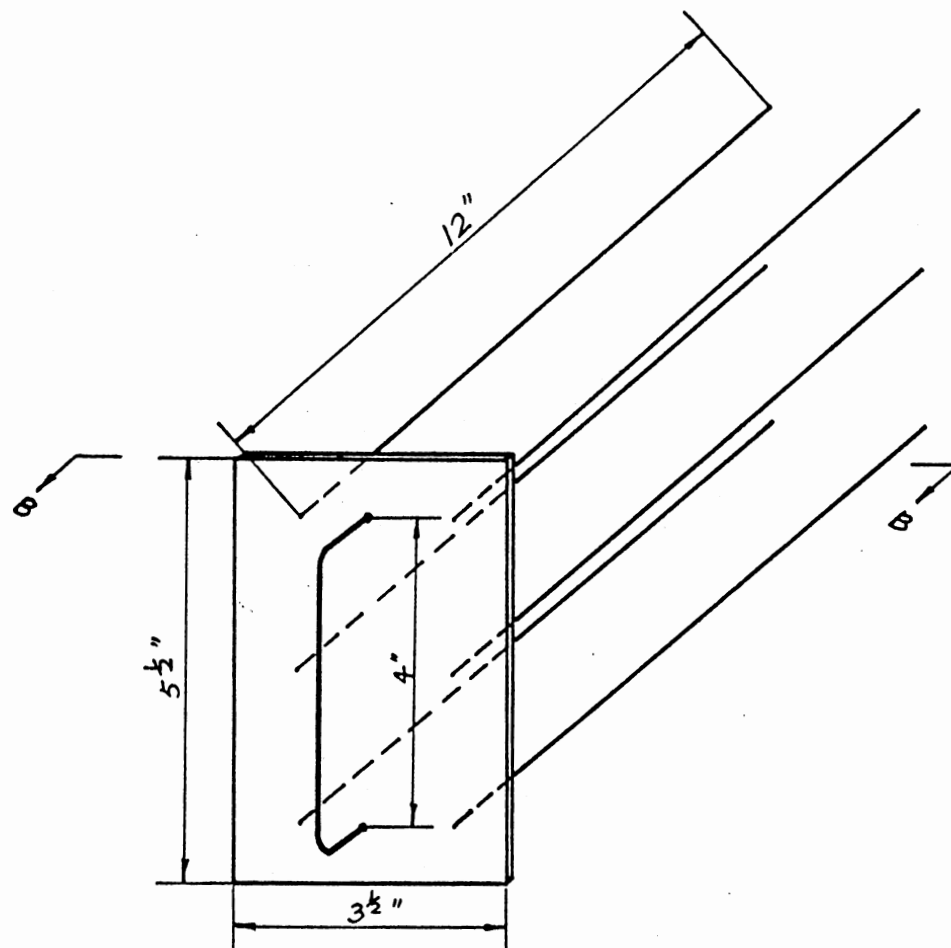
Figure 25. Solid Sampling Device (1)



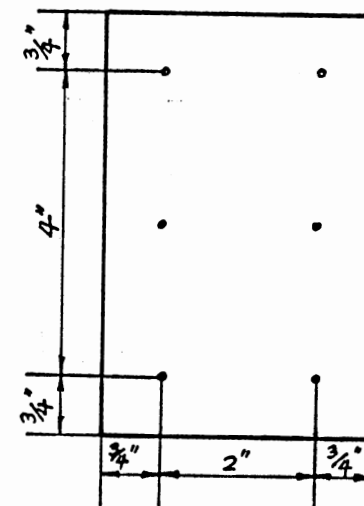
Note:

1. The distance between two holes depends on the distance between two pipes in Fig.(11). The plate should fit with the pipes.
2. The thickness of the plate is $\frac{1}{8}$ in.
3. plate material is low carbon steel.
4. Quantity : 2.

Figure 26. Solid Sampling Device (2)



1. Quantities : 2.
2. Material: Low Carbon Steel.
3. Plate Thickness: $\frac{1}{4}$ in.
4. Steel Bar Diameter: $\frac{1}{8}$ in.
5. Handle Diameter: $\frac{1}{4}$ in.



B-View

Steel Bar Distribution

Figure 27. Plug for Sampling Port

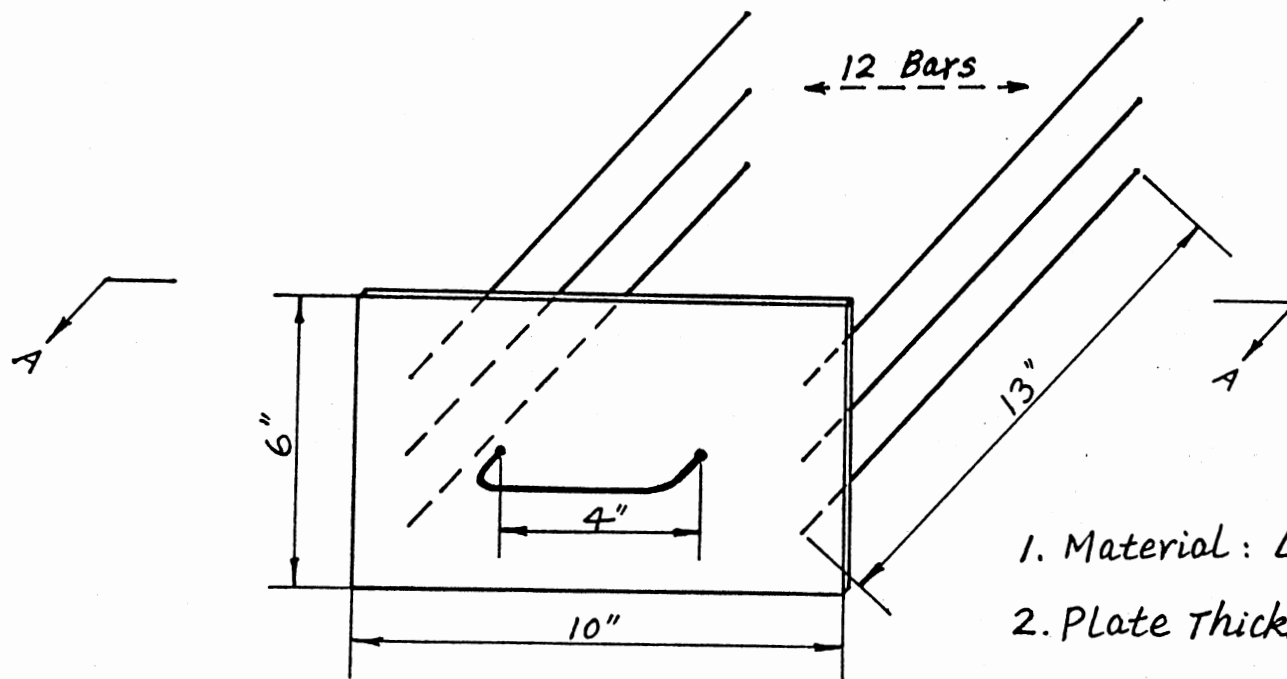
advantage to use water rather than air for collecting solid samples. Therefore, the cooling medium selection was based only upon convenience.

Ash Clean Out

There are two ash clean out ports located in the first chamber and second chamber. The hopper-liked bottoms of the furnace make ash collection easy. The ash should be removed at regular time intervals. Two plugs are designed to fit within the tunnels. Castable insulating cement is used as the plug construction material. There are several horizontal steel bars which are used to support the cement. The design details are shown in Figure 28 and 29. These two ash clean out ports and compressed air blast can serve as the method of routine cleaning. It is anticipated that using these methods every 4 or 5 days a time will allow the furnace to operate continuously without severe blockage by ash.

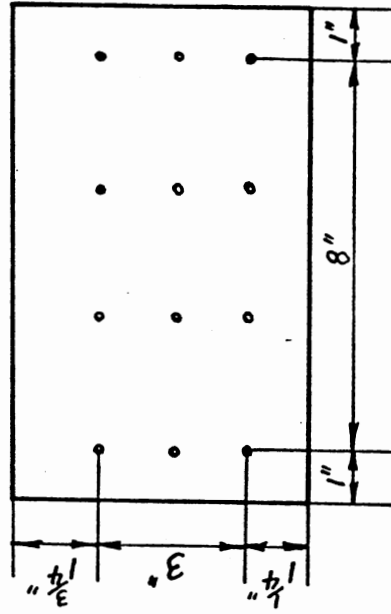
Stack

The flue gases which come from the bottom of the second chamber will pass into a 4.5 inch wide furnace breech and exit through a 4 inch stack. The stack is double-walled for good insulation. An induced draft fan is located 2 feet above the furnace top. The purpose of using an induced draft fan is to control the pressure in the furnace to a desired value. The pressure in the furnace is smaller than



1. Material: Low Carbon Steel.
2. Plate Thickness: $\frac{1}{4}$ in.
3. Steel Bar Diameter: $\frac{1}{8}$ in.
4. Quantities: 2.
5. 12-bars are welded on the steel plate.
6. Handle Diameter: $\frac{1}{4}$ in.

Figure 28. Ash Clean Out (1)



A - View

Figure 29. Ash Clean Out (2)

that of the surroundings since positive pressure operation will cause the fire or flue gases to blow out when taking samples from the sampling ports. One method for positive pressure operation is to install a compressed air line just at the outlet of the sampling port. The air would be controlled by a needle valve. Before taking the sampling instrument out, the air supply valve would be turned on so that there would be some compressed air blowing into the furnace through the sampling port. The advantage of using this kind of method is that people do not need to consider the pressure in the furnace. The induced draft fan is not necessary in this case. The disadvantages are that it will take extra air lines and make the operation more complicated. Therefore it was decided to make the pressure inside the furnace negative. The pressure difference between surrounding and furnace interior will keep the fire or flue gases within the furnace without any blow out problem. The air-flow adjustment on the fan is used for adjusting the venting capacity to control the pressure. The stack and fan assembly is shown in Figure 30.

Temperature Measurement

The temperature in the furnace is measured by high temperature type R, Pt vs. Pt 13% Rh platinum thermocouples. The thermocouples are enclosed in ceramic protection tubes and are inserted into five different locations in the furnace. All five thermocouples are connected through R-

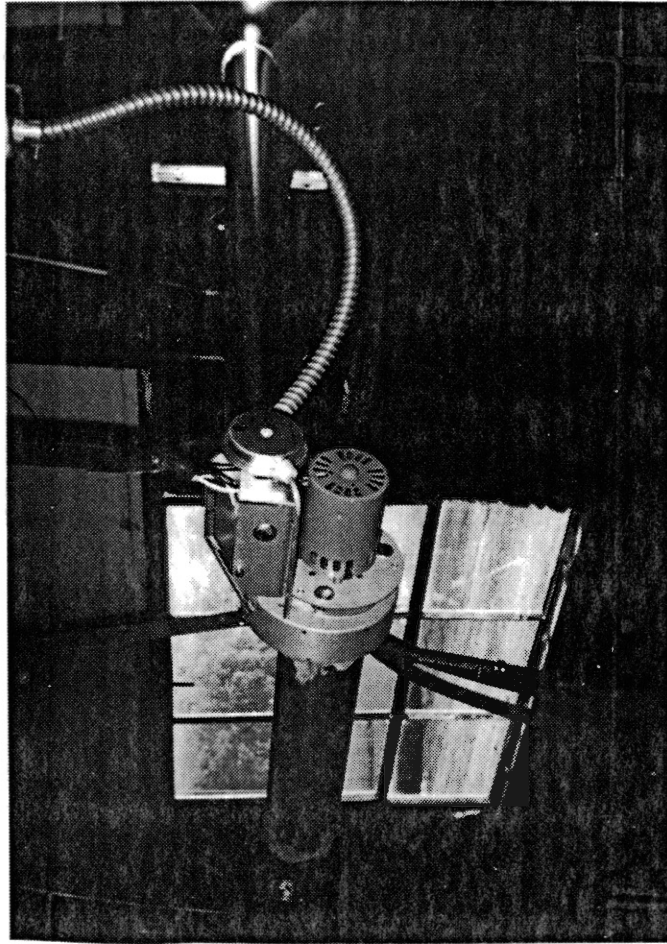


Figure 30. Stack and Fan Assembly

type thermocouple wire to a meter. The meter is a digital one with the capability for monitoring up to 10 thermocouples of the same type. Both the thermocouple and meter are shown in Figure 31. The mounting method of the thermocouple assembly is shown in Figure 32.

Gas Analysis System

Gas samples can be taken from the flue gases in the stack. A small gas sample pump will be used for taking gas samples. If necessary, the flue gas temperature may be further cooled after passing through a pump. The method of doing this is to put a water jacket outside the sampling pipe. The samples, after passing through pump, will go into gas analysis instruments such as an infrared analyzer or a gas emission monitor.

Material Consumed

All the materials used in the furnace construction are listed in Table 2.

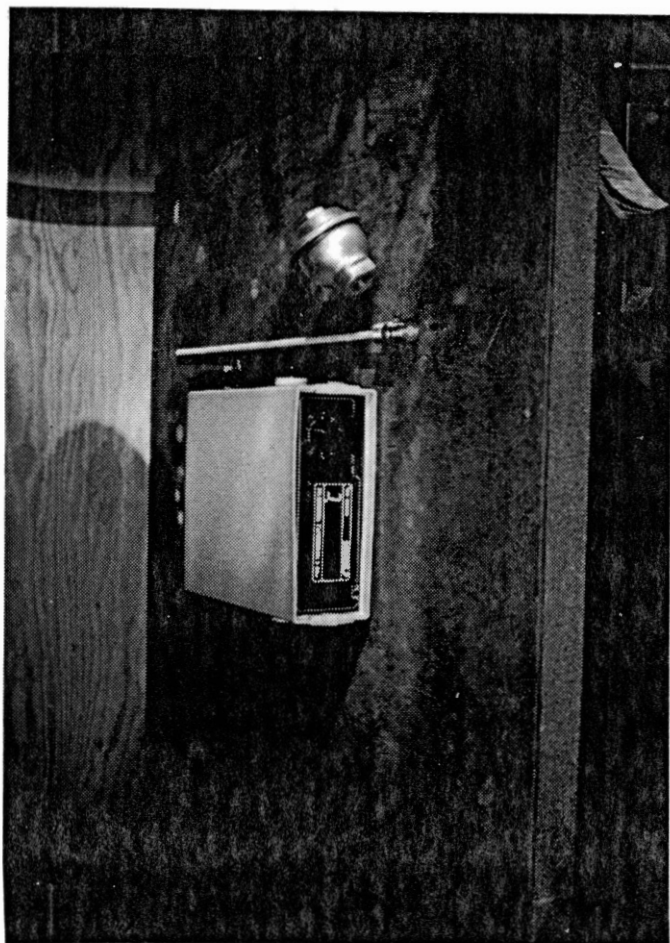


Figure 31. Thermocouple and Meter



Figure 32. Thermocouple Mounting

TABLE II
MATERIAL CONSUMPTION LIST

Material	Quantity
Insulating Brick	960 pieces
Refractory Brick	200 pieces
Castable Insulating Material	100 pounds
Ramming Mix	100 pounds
Mortar	750 pounds
Steel Box	1
Heat Exchanger Tube	90 feet
Coal Burner	1
Other Burners	3
Steam Hose	50 feet
Garden Hose	50 feet
Thermocouple	5
Meter	1
Thermowire	75 feet
Copper Pipe	50 feet
Induced Draft Fan	1
Sight Glass Assembly	3
Rotameter	5
Coal Feeder	1

TABLE II (Continued)

Material	Quantity
Check Valve	5
Needle Valve	3
Heater	2

CHAPTER IV

FURNACE OPERATION

Coals

The pulverized coals selected for initial furnace operation are Jacob's Ranch and Clovis Point. Both coals come from Wyoming and both coals are currently used in the Public Service Company of Oklahoma's Northeast Power Generation Station.

Analysis of these coals are given in Table 3 and 4. In Table 3, I.T. is initial deformation temperature, S.T. is softening temperature, H.T. is hemispherical temperature, F.T. is fluid temperature and H.H.V. is higher heating value.

Design Operating Data

The design data about furnace operation is listed in Table 5.

TABLE III
COAL ANALYSIS *

Jacob's Ranch			
Analysis	Weight%	Moisture Free	Moisture and Ash Free
Moisture	25.44	—	—
Vol. Matter	36.55	49.02	53.95
Ash	6.81	9.13	—
Fixed Carbon	31.70	41.85	46.05
H.H.V. Btu/lb	8863	11886	13081
I.T.	2050 °F		
S.T.	2090 °F		
H.T.	2130 °F		
F.T.	2230 °F		

Clovis Point			
Analysis	Weight%	Moisture Free	Moisture and Ash Free
Moisture	31.32	—	—
Vol. Matter	33.85	49.28	54.11
Ash	6.14	8.94	—
Fixed Carbon	28.69	41.78	45.89

TABLE III (Continued)

Analysis	Weight%	Moisture Free	Moisture and Ash Free
H.H.V. Btu/lb	8014	11668	12813
I.T.	2010 °F		
S.T.	2050 °F		
H.T.	2090 °F		
F.T.	2120 °F		

* (30)

TABLE IV
ASH ANALYSIS *

Component	Jacob's Ranch	Clovis Point
	Weight%	Weight%
Iron as % Fe_2O_3	7.15	4.29
Calcium as % CaO	14.22	14.64
Magnesium as % MgO	3.15	3.12
Sodium as % Na_2O	0.68	1.08
Potassium as % K_2O	1.37	1.45
Silicon as % SiO_2	46.38	50.24
Aluminum as % Al_2O_3	13.81	13.55
Titanium as % TiO_2	1.15	0.95
Phosphorus as % P_2O_5	1.11	1.56
Sulfur as % SO_3	6.05	4.53

* (30)

TABLE V
DESIGN OPERATION DATA

<u>Coal</u>		
Coal Feeding Rate	2	lb/hr
Coal Higher Heating Value	8000	Btu/lb
Coal Density (Bulk)	48	lb/ft ³
Ratio of Jacob's Ranch / Clovis Point	75/25	
<u>Combustion Air</u>		
Temperature	80	°F
Preheated Temperature	600	°F
Density	0.073	lb/ft ³
Total Volume Flow Rate	380	ft ³ /hr
Mass Flow Rate	27.8	lb/hr
Primary Air	95	ft ³ /hr
Secondary Air	95	ft ³ /hr
Tertiary Air	190	ft ³ /hr
Mean Molecular Weight	29	
Specific Heat	0.248	Btu/lb °F
Viscosity	0.0556	lb/ft hr

TABLE V (Continued)

Combustion Gas		
Temperature	2000	$^{\circ}\text{F}$
Density	0.016	lb/ft^3
Specific Heat	0.31	$\text{Btu}/\text{lb}^{\circ}\text{F}$
Mass Flow Rate	29.8	lb/hr
Volume Flow Rate	1860	ft^3/hr
Mean Molecular Weight	30	
Maximum Velocity At Throat	3.3	$\text{ft}/\text{sec.}$
Outlet Temperature	500	$^{\circ}\text{F}$
Viscosity	0.105	$\text{lb}/\text{ft hr}$
Residence Time	2.5-3.5	sec
Pressure Drop Passing Through Heat Exchanger Tube Banks	4.3×10^{-5}	psia
Average Pressure in Furnace	14.6	psia
Furnace		
Volume of First Chamber	1.8	ft^3
Volume of Second Chamber	2.2	ft^3
Volume of Chimney	0.8	ft^3
Refractory Brick Thickness	4.5	in
Insulating Brick Thickness	9.0	in
Surface Area of First Chamber	10.0	ft^2
Surface Area of Second Chamber	10.0	ft^2
Thermal Conductivity of Refractory Brick	0.484	$\text{Btu}/\text{hr ft}^{\circ}\text{F}$
Thermal Conductivity of Insulating Brick	0.169	$\text{Btu}/\text{hr ft}^{\circ}\text{F}$

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Studying the slagging properties of blended coal is a relatively new field. At present, there are no good methods or models which predict slagging or fouling potential of blended coals. Many coal fired plants will burn blended coal in the future since the blended coals do have some advantages. Use of blended coal can reduce SO_2 emissions, reduce operating costs and increase average BTU content. The ability to predict slagging or fouling problems caused by coal blending would increase the use of blended coal enormously. The facility which was built will be used to study combustion of blended coal.

Major concerns when designing the facility included:

- (1) How to get uniform blending of coal and controllable feeding conditions,
- (2) How to control the combustion temperature, and
- (3) How to collect representative experimental samples.

There are many factors which can affect the operation of the facility. Of these factors, good design and careful construction are two of the most important. Operating technique is also important. From the description above, it can be seen that the facility design was very complex and the installation of the unit was carefully thought out.

The temperature in the first chamber is designed for about 2000 °F and the exit temperature in the stack for about 500 °F. Slagging and fouling samples can be collected for different periods of time. The quantities of solid samples will depend on the time that the sampling device is in the furnace.

It should be noted that the design of a laboratory-scale apparatus does not permit reproduction of all the conditions occurring in a full-scale plant. Although the residence time of the coal particles in the various passes and the temperatures in furnace chambers are of the same order as those in full-scale plants, the gas velocities are much lower. This facility, however, can still be used for analyzing the slagging behavior of blended coal from both a physical and a chemical point of view.

The facility can be improved by further increasing the preheat temperature of the combustion air. This can be done by either adding another electric heater or increasing the amount of insulation. The combustion situation can also be improved by redesigning the coal burner. The solid sampling device could be changed to some other material such as ceramics or ferritic steel which have similar thermal expansion coefficients to that of the slag. In this case, the attachment of the deposit on the surface of the sampling device would be easier and the sample collection would be more efficient.

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APPENDIXES

APPENDIX A

THE CALCULATION OF AIR-COAL RATIO

Assume carbon content in dry coal is 77 %.

Flue gas analysis:

CO ₂	13 %
O ₂	5.7 %
CO	0.6 %
N ₂	80.7 %

Calculate lbmoles of carbon in coal:

$$2 \text{ lb/hr} * 0.77 * 1/12 \text{ lbmole/lb} = 0.128 \text{ lbmole/hr}$$

Neglect carbon in ash.

Calculate moles of dry stack gas:

$$\begin{aligned} 0.128 \text{ lbmole C/hr} * 100/13.6 \text{ lbmole Gas/lbmole C} \\ = 0.941 \text{ lbmole Gas/hr} \end{aligned}$$

From N₂ balance, calculate total moles of air used:

$$\begin{aligned} 0.941/2 \text{ lbmole Gas/lb Coal} * 0.807 \text{ lbmole N}_2 / \text{lbmole Gas} \\ = 0.38 \text{ lbmole N}_2 / \text{lb Coal} \end{aligned}$$

$$0.38 * 100/79 = 0.481 \text{ lbmole Air/lb Coal}$$

Convert moles to pounds:

$$0.481 * 29 = 13.9 \text{ lb Air/lb Coal}$$

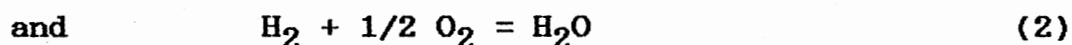
Finally, at T=80°F, consider 2 lb coal/hr feed rate,
then the volume rate of air is:

$$V = W / \rho = 2 * 13.9 / 0.073 = 380 \text{ ft}^3/\text{hr}$$

This result has already considered some extra air (20 % extra) since the stack gas data is based on the real operation.

Alternative Method

Consider the reactions:



Coal analysis:

Moisture	3.29 %
Carbon	77.05 %
Hydrogen	4.53 %
Nitrogen	1.62 %
Sulfur	0.82 %
Ash	9.72 %
Oxygen	2.97 %

Calculate moles of carbon and hydrogen in coal:

$$2 \text{ lb/hr} * 0.77 * 1/12 = 0.128 \text{ lbmole C/hr}$$

$$2 * 0.0453 * 1/2 = 0.0453 \text{ lbmole H}_2\text{/hr}$$

Then, for equation (1), the quantity of O_2 is 0.128 (lbmole/hr); for equation (2), the quantity of O_2 is $0.5 * 0.0453 = 0.0227 \text{ lbmole/hr}$.

The total pounds of O_2 is

$$(0.128 + 0.0227) * 32 = 4.82 \text{ lb/hr}$$

The air quantity then is

$$4.82 / 0.21 = 23.0 \text{ lb/hr}$$

The volume flow rate of air (80°F) is

$$V = W / \rho = 23.0 / 0.073 = 315 \text{ ft}^3/\text{hr}$$

Consider 20 % extra air, then

$$V = 315 * 1.2 = 378 \text{ ft}^3/\text{hr}$$

This result is the same as that based on stack gases.

APPENDIX B

THE CALCULATION OF HEAT EXCHANGER AREA

Design parameters:

Hot fluid - Combustion gas, shell side, inlet temperature $T_i = 2000^\circ\text{F}$, outlet temperature $T_o = 600^\circ\text{F}$.

Cold fluid - Compressed air, tube side, inlet temperature $t_i = 80^\circ\text{F}$, outlet temperature $t_o = 600^\circ\text{F}$.

Average temperature:

Shell side $T = (600 + 2000)/2 = 1300^\circ\text{F}$

Tube side $t = (80 + 600)/2 = 340^\circ\text{F}$

Overall heat transfer coefficient:

$U = 3.4 \text{ Btu/hr ft}^2^\circ\text{F}$

Flow pattern - Cross flow, passing tube bank.

Tube type:

3/8 in. O.D., 0.305 in. I.D., 347 Stainless Steel,
U-tube bank.

Properties of fluids:

Average specific heat of gas, $C_{p_g} = 0.30 \text{ Btu/lb}^\circ\text{F}$

Average specific heat of air, $C_{p_a} = 0.246 \text{ Btu/lb}^\circ\text{F}$

Gas flow rate, $W_g = 29.8 \text{ lb/hr}$

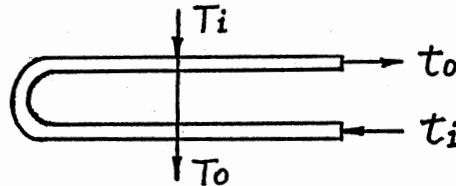
Pressure of compressed air, 25 psia

Density of air $\rho_a = 0.073 * 25/14.7 = 0.124 \text{ lb/ft}^3$

Heat flow rate:

$$\begin{aligned}
 Q_g &= W_g C_{p_g} \Delta T \\
 &= 29.8 * 0.30 * (2000 - 600) \\
 &= 1.25 * 10^4 \text{ Btu/hr}
 \end{aligned}$$

Graph



Area calculation: (7)

$$\begin{aligned}
 R &= C_2 / C_1 = (t_i - t_o) / (T_o - T_i) \\
 &= (80 - 600) / (600 - 2000) = 0.37
 \end{aligned}$$

Here $C = W C_p$

$$\Delta T_m = T_i - T_o = 2000 - 600 = 1400^\circ \text{F}$$

$$\theta = \Delta T_m / (T_i - t_i) = 1400 / (2000 - 80) = 0.73$$

Then from cross flow chart, get $NTU_2 = 0.55$

Here NTU_2 is the numbers of heat transfer units.

Since $NTU_2 = AU/C_2$, then

$$\begin{aligned}
 A &= NTU_2 * C_2 / U = NTU_2 W_g C_{p_g} / U \\
 &= 0.55 * 29.8 * 0.3 / 3.4 = 1.5 \text{ ft}^2
 \end{aligned}$$

Take 100% extra for safety according to experience, then

$$A = 1.5 * 2 = 3.0 \text{ ft}^2$$

Cold air flow rate

$$\begin{aligned}
 W_a &= Q / C_{p_a} \Delta t = 1.25 * 10^4 / 0.246 * (600 - 80) \\
 &= 97.7 \text{ lb/hr}
 \end{aligned}$$

Volume flow rate of air

$$\begin{aligned}
 V_a &= W_a / \rho_a = 97.7 / (0.124 * 60) \\
 &= 13.1 \text{ ft}^3/\text{min. based on 25 psia pressure.}
 \end{aligned}$$

Total length of tube

$$L = A / \pi d_i = 3.0 * 12 / (3.14 * 0.305) \\ = 38 \text{ ft}$$

Design the length of one U-tube, $l = 2 \text{ ft}$, then the numbers of U-tubes

$$N = 38/2 = 19$$

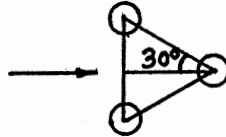
Take $N = 24$ in practice.

APPENDIX C

PRESSURE DROPS ON BOTH COMBUSTION GAS AND COOLING AIR SIDES

1. Pressure Drop of Shell Side

Consider 30° equilateral triangular flow model and $D_t = 3/8$ in.



Then for $Re = 9.8$, get $f_{ct} = 7.2$

Here f_{ct} is the friction factor used for tube banks.

Based on Chilton and Genereaux's Equation (7)

$$f_{ct} = \frac{2\Delta P g_c \rho}{4G_{\max}^2 N} \left(\frac{\mu}{\mu_w} \right)^{0.14}$$

here, N is the number of major restrictions crossed in the tube bank. $N = 4$ in this problem.

Then,

$$\begin{aligned} \Delta P &= \frac{2G_{\max}^2 N f_{ct}}{\rho g_c} \left(\frac{\mu_w}{\mu} \right)^{0.14} \\ &= \frac{2\rho v_{\max}^2 N f_{ct}}{g_c} \left(\frac{\mu_w}{\mu} \right)^{0.14} \\ &= \frac{2 * 0.024 * 0.38^2 * 4 * 7.2 * 3600^2}{144 * 4.17 * 10^8} \\ &= 4.3 * 10^{-5} \text{ psia} \end{aligned}$$

2. Tube side Pressure Drop

Since $Re = 1.02 \times 10^4$, then $f_F = 0.008$

here, f_F is the Fanning friction factor in tube.

From mechanical engineer point of view, use Moody-Darcy friction factor which is 4 times of f_F , $f_{M-D} = 4f_F$

$$\text{Since } f_F = \frac{\Delta P D_i g_c}{2 \rho v^2 L}$$

then,

$$\begin{aligned} f_{M-D} &= \frac{2 \Delta P D_i g_c}{\rho v^2 L} \\ \Delta P &= \frac{2 \rho v^2 L f_F}{D_i g_c} \\ &= \frac{2 * 0.051 * 50^2 * 5 * 0.008 * 3600^2}{144 * 0.305 * 1/12 * 4.17 * 10^8} \\ &= 0.09 \text{ psia} \end{aligned}$$

Entrance, exit and bend loss:

$$\begin{aligned} \Delta P_{\text{loss}} &= 2 \left(\frac{\rho v^2}{2 g_c} \right) + \frac{\rho v^2}{2 g_c} + 2 \left(\frac{\rho v^2}{2 g_c} \right) \\ &= 5 \rho v^2 / 2 g_c \\ &= \frac{5 * 0.051 * 50^2 * 3600^2}{2 * 144 * 4.17 * 10^8} \\ &= 0.07 \text{ psia} \end{aligned}$$

$$\begin{aligned} \Delta P_T &= \Delta P + \Delta P_{\text{loss}} \\ &= 0.09 + 0.07 \\ &= 0.16 \text{ psia} \end{aligned}$$

APPENDIX D

MEAN WALL TEMPERATURE CALCULATION

$$\bar{T}_{w,hot} = \bar{T} - U_o(\bar{T} - \bar{t})/h_{hot}$$

Here,

$\bar{T}_{w,hot}$ — Hot side average wall temperature.

\bar{T} — Hot fluid arithmetic mean temperature.

\bar{t} — Cold fluid arithmetic mean temperature.

Take:

Tube diameter, $D_t = 0.375$ in, $D_i = 0.305$ in

Velocity of air, $V = 50$ ft/sec

Density of air, $\rho = 0.124$ lb/ft³

Viscosity of air at 340 °F,

$\mu = 0.023$ cp = 0.0556 lb/ft hr

Then, Reynolds Number,

$$\begin{aligned} Re &= D_i V \rho / \mu \\ &= 0.305 * 50 * 3600 * 0.124 / (12 * 0.0556) \\ &= 1.02 * 10^4 \end{aligned}$$

Take:

Thermal conductivity of air at 340 °F,

$K = 0.0203$ Btu/hr ft °F

$C_p = 0.246$ Btu/lb °F

$Pr = C_p \mu / K = 0.674$

Assume $T_{w,hot} = 1000^{\circ}\text{F}$

then,

$$\mu_{wall} = 0.087 \text{ lb/ft hr} = \mu_{gas, 1000^{\circ}\text{F}}$$

Sieder-Tate Coefficient

$$\begin{aligned}\phi_v &= \left(\frac{\mu}{\mu_w} \right)^{0.14} \\ &= (0.0556 / 0.087)^{0.14} \\ &= 0.94\end{aligned}$$

According to Sieder-Tate Equation

$$Nu = hD_i/K = 0.023Re^{0.8}Pr^{1/3} \left(\frac{\mu}{\mu_w} \right)^{0.14}$$

then,

$$\begin{aligned}h_{air} &= 0.023Re^{0.8}Pr^{1/3} \phi_v K/D_i \\ &= 0.023 * 0.0203 * 12 * (1.02 * 10^4)^{0.8} * \\ &\quad 0.674^{1/3} * 0.94 / 0.305 \\ &= 24.4 \text{ Btu/hr ft}^2\text{ }^{\circ}\text{F}\end{aligned}$$

For combustion gas, consider Colburn j factor:

$$j = \left(\frac{h}{C_p G_{max}} \right) \left(\frac{C_p \mu}{K} \right)^{2/3} \left(\frac{\mu_w}{\mu} \right)^{0.14}$$

Here,

$$j = f(Re)$$

$$Re = D_t \rho V_{max} / \mu$$

D_t — Tube outside diameter

G_{max} — Maximum mass flow rate per unit area or mass

velocity cross tube bank.

Now,

$$D_t = 0.375 \text{ in.}$$

The cross area of one row of tube bank is

$$a = 13 * 0.375 * 12 / 144 = 0.41 \text{ ft}^2$$

The cross section area of convection pass is

$$A = 13.5 * 14 / 144 = 1.31 \text{ ft}^2$$

The minimum cross area then is

$$S = A - a = 1.31 - 0.41 = 0.90 \text{ ft}^2$$

The volume flow rate in this chamber (consider mean temperature of 1300°F):

$$\begin{aligned} V_g &= M_g / \rho_g \\ &= 29.8 / 0.024 = 1240 \text{ ft}^3/\text{hr} \end{aligned}$$

$$\begin{aligned} V_{\max} &= V_g / S \\ &= 1240 / (0.9 * 3600) = 0.38 \text{ ft/sec} \end{aligned}$$

Then,

$$\begin{aligned} Re &= 0.375 * 0.024 * 0.38 / (12 * 2.92 * 10^{-5}) \\ &= 9.8 \end{aligned}$$

$$\text{Therefore, } j_{10} = 0.36$$

At 1300°F , take,

$$K = 0.0408 \text{ Btu/hr ft}^\circ\text{F}$$

$$C_p = 0.30 \text{ Btu/lb}^\circ\text{F}$$

$$\mu_w = 2.46 * 10^{-5} \text{ lb/ft sec}$$

$$\mu = 2.92 * 10^{-5} \text{ lb/ft sec}$$

Then,

$$h_{\text{gas}} = (j_{12} C_p \rho V_{\max}) (K / C_p \mu)^{2/3} (\mu / \mu_w)^{0.14}$$

here,

$$\begin{aligned} j_{12} &= j_{10} (12 / 10)^{-0.18} \\ &= 0.35 \end{aligned}$$

(Since $Re < 20$, $j_N = j_{10}(N/10)^{-0.18}$. N is tube No. at every row.)

Now,

$$\begin{aligned}
 h_{\text{gas}} &= 0.35 * 0.3 * 0.024 * 0.38 * 3600 \\
 &\quad * \left(\frac{0.0408}{0.30 * 2.92 * 10^{-5} * 3600} \right)^{2/3} \\
 &\quad * (2.92 * 10^{-5} / 2.46 * 10^{-5})^{0.14} \\
 &= 4.2 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}
 \end{aligned}$$

Neglect heat resistance of the tube wall, then

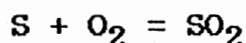
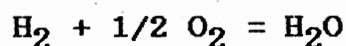
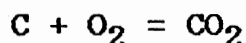
$$\begin{aligned}
 U_o &= \frac{1}{D_o / (h_i D_i) + 1 / h_o} = \frac{1}{0.375 / (24.4 * 0.305) + 1 / 4.2} \\
 &= 3.46 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}
 \end{aligned}$$

$$\begin{aligned}
 \bar{T}_{w, \text{hot}} &= \bar{T} - U_o (\bar{T} - \bar{t}) / h_o \\
 &= 1300 - 3.46 * (1300 - 340) / 4.2 \\
 &= 510 \text{ } ^\circ\text{F}
 \end{aligned}$$

APPENDIX E

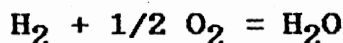
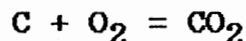
THE CALCULATION OF ADIABATIC FLAME TEMPERATURE

Major combustion reactions

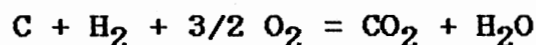


Third reaction can be neglected since sulfur is usually of minor significance as a source of heat, but it can be of major significance in corrosion and pollution problem.

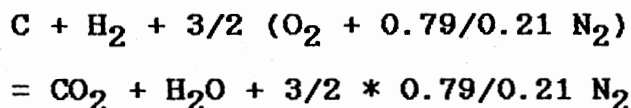
Therefore, consider only



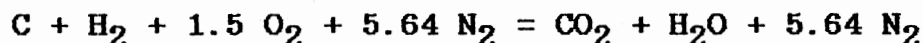
Combine these two reactions, we will get



Since for 1 pound of O_2 , it will need $1 / 0.21 = 4.76$ lb of air and since $\text{O}_2 / \text{N}_2 = 0.21 / 0.79$ in air, then we have



That is



According to heat balance,

$$\begin{aligned} \Delta H = & \sum_{j=1}^N \nu_j'' \{ (\mathcal{H}_{T_f}^0 - \mathcal{H}_0^0) - (\mathcal{H}_{T_0}^0 - \mathcal{H}_0^0) + (\Delta \mathcal{H}_f^0)_{T_0} \}; \\ & - \sum_{j=1}^N \nu_j' \{ (\mathcal{H}_{T_i}^0 - \mathcal{H}_0^0) - (\mathcal{H}_{T_0}^0 - \mathcal{H}_0^0) + (\Delta \mathcal{H}_f^0)_{T_0} \}; \end{aligned}$$

For adiabatic process, we should have $\Delta H = 0$, then

$$0 = \sum_{j=1}^N \nu_j'' \{ (\mathcal{H}_{T_f}^{\circ} - \mathcal{H}_{T_0}^{\circ}) + (\Delta \mathcal{H}_f^{\circ})_{T_0} \} - \sum_{j=1}^N \nu_j' \{ (\mathcal{H}_{T_i}^{\circ} - \mathcal{H}_{T_0}^{\circ}) + (\Delta \mathcal{H}_f^{\circ})_{T_0} \}$$

or $\sum_{j=1}^N \nu_j'' (\Delta \mathcal{H}_f^{\circ})_{T_0} - \sum_{j=1}^N \nu_j' (\Delta \mathcal{H}_f^{\circ})_{T_0} = \sum_{j=1}^N \nu_j' (\mathcal{H}_{T_i}^{\circ} - \mathcal{H}_{T_0}^{\circ}) - \sum_{j=1}^N \nu_j'' (\mathcal{H}_{T_f}^{\circ} - \mathcal{H}_{T_0}^{\circ})$

Now, taking $T_0 = 298^{\circ}\text{K}$, $T_i = 700^{\circ}\text{F} = 644^{\circ}\text{K}$ and using Reference (1), can find $(\Delta \mathcal{H}_f^{\circ})_{T_0}$, $\mathcal{H}_{T_i}^{\circ}$ and $\mathcal{H}_{T_0}^{\circ}$ for every component. Then using trial and error method, can find $\mathcal{H}_{T_f}^{\circ}$ for every component. Finally get T_f .

$$\text{Now, } \sum_{j=1}^N \nu_j'' (\Delta \mathcal{H}_f^{\circ})_{T_0} - \sum_{j=1}^N \nu_j' (\Delta \mathcal{H}_f^{\circ})_{T_0} = \Delta H_r \text{ since } T_0 = 298^{\circ}\text{K}.$$

$$\text{and } \Delta H_r = (1 \times \Delta \mathcal{H}_{f, \text{CO}_2}^{\circ} + 1 \times \Delta \mathcal{H}_{f, \text{H}_2\text{O}}^{\circ} + 5.64 \times \Delta \mathcal{H}_{f, \text{N}_2}^{\circ})_{\text{gas}} \\ - (1 \times \Delta \mathcal{H}_{f, \text{C}}^{\circ} + 1 \times \Delta \mathcal{H}_{f, \text{H}_2}^{\circ} + 1.5 \times \Delta \mathcal{H}_{f, \text{O}_2}^{\circ} + 5.64 \times \Delta \mathcal{H}_{f, \text{N}_2}^{\circ})_{\text{gas}}$$

But the $\Delta \mathcal{H}_f^{\circ}$'s of the elements in their standard state are 0's. Then

$$\Delta H_r = (\Delta \mathcal{H}_{f, \text{CO}_2}^{\circ} + \Delta \mathcal{H}_{f, \text{H}_2\text{O}}^{\circ})_{\text{gas}}$$

$$\text{Now, } \Delta \mathcal{H}_{f, \text{CO}_2}^{\circ} = -94.05 \text{ Kcal/mole,}$$

$$\Delta \mathcal{H}_{f, \text{H}_2\text{O}}^{\circ} = -57.80 \text{ Kcal/mole,}$$

$$\text{So, } \Delta H_r = (-94.05) + (-57.80)$$

$$= -152 \text{ Kcal/mole}$$

$$= -1.52 \times 10^5 \text{ cal/mole}$$

$$\text{Next, let } A = \sum_{j=1}^N \nu_j' (\mathcal{H}_{T_i}^{\circ} - \mathcal{H}_{T_0}^{\circ}), B = \sum_{j=1}^N \nu_j'' (\mathcal{H}_{T_f}^{\circ} - \mathcal{H}_{T_0}^{\circ}),$$

then ,

$$A = 1 \times (\mathcal{H}_{T_i}^{\circ} - \mathcal{H}_{T_o}^{\circ})_C + 1 \times (\mathcal{H}_{T_i}^{\circ} - \mathcal{H}_{T_o}^{\circ})_{H_2} \\ + 1.5 \times (\mathcal{H}_{T_i}^{\circ} - \mathcal{H}_{T_o}^{\circ})_{O_2} + 5.64 \times (\mathcal{H}_{T_i}^{\circ} - \mathcal{H}_{T_o}^{\circ})_{N_2}$$

For $T_i = 644^{\circ}K$, $T_o = 298^{\circ}K$,

$$\mathcal{H}_{T_i, C}^{\circ} = 3300 \text{ cal/mole}$$

$$\mathcal{H}_{T_o, C}^{\circ} = 1559 \text{ cal/mole}$$

$$\mathcal{H}_{T_i, H_2}^{\circ} = 4400 \text{ cal/mole}$$

$$\mathcal{H}_{T_o, H_2}^{\circ} = 2024 \text{ cal/mole}$$

$$\mathcal{H}_{T_i, O_2}^{\circ} = 4600 \text{ cal/mole}$$

$$\mathcal{H}_{T_o, O_2}^{\circ} = 2070 \text{ cal/mole}$$

$$\mathcal{H}_{T_i, N_2}^{\circ} = 4600 \text{ cal/mole}$$

$$\mathcal{H}_{T_o, N_2}^{\circ} = 2072 \text{ cal/mole}$$

then,

$$A = (3300 - 1559) + (4400 - 2024) + \\ 1.5 \times (4600 - 2070) + 5.64 (4600 - 2072) \\ = 2.22 \times 10^4 \text{ cal/mole}$$

From $\Delta H_r = A - B$, get

$$B = 2.22 \times 10^4 - (-1.52 \times 10^5) = 1.74 \times 10^5 \text{ cal/mole}$$

$$\text{But, } B = 1 \times (\mathcal{H}_{T_f}^{\circ} - \mathcal{H}_{T_0}^{\circ})_{\text{CO}_2} + 1 \times (\mathcal{H}_{T_f}^{\circ} - \mathcal{H}_{T_0}^{\circ})_{\text{H}_2\text{O}} \\ + 5.64 \times (\mathcal{H}_{T_f}^{\circ} - \mathcal{H}_{T_0}^{\circ})_{\text{N}_2}$$

$$\text{and } \mathcal{H}_{T_0, \text{CO}_2}^{\circ} = 2238 \text{ cal/mole, } \mathcal{H}_{T_0, \text{H}_2\text{O}}^{\circ} = 2368 \text{ cal/mole.}$$

Now, use trial and error method. Assume the

flame temperature $T_f = 3000^{\circ}\text{K}$, can get

$$\mathcal{H}_{T_f, \text{CO}_2}^{\circ} = 38940 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{H}_2\text{O}}^{\circ} = 32160 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{N}_2}^{\circ} = 24250 \text{ cal/mole}$$

$$\text{Then } B = 1 \times (38940 - 2238) + 1 \times (32160 - 2368) \\ + 5.64 \times (24250 - 2072) \\ = 1.92 \times 10^5 \text{ cal/mole} > 1.74 \times 10^5 \text{ cal/mole}$$

Next try, $T_f = 2500^{\circ}\text{K}$, get

$$\mathcal{H}_{T_f, \text{CO}_2}^{\circ} = 31480 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{H}_2\text{O}}^{\circ} = 25770 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{N}_2}^{\circ} = 19840 \text{ cal/mole}$$

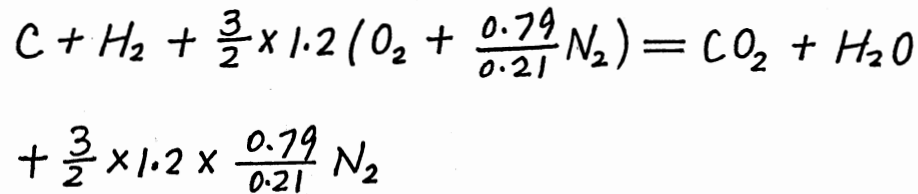
Then,

$$B = 1.53 \times 10^5 \text{ cal/mole} < 1.74 \times 10^5 \text{ cal/mole.}$$

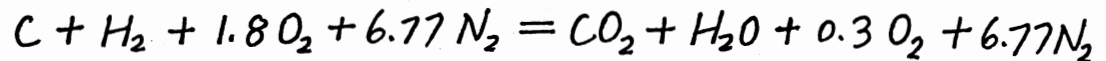
Interpolating, then get adiabatic flame temperature

$$T_f = 2800 \text{ } ^\circ\text{K}$$

This is based on stoichiometric relation. If consider 20% excess air, the relation should be



That is



ΔH_r is unchanged, but

$$\begin{aligned} A &= 1 \times (3300 - 1559) + 1 \times (4400 - 2024) + 1.8 \times (4600 \\ &\quad - 2070) + 6.77 \times (4600 - 2072) \\ &= 2.58 \times 10^4 \text{ cal/mole} \end{aligned}$$

$$B = 2.58 \times 10^4 - (-1.52 \times 10^5) = 1.78 \times 10^5 \text{ cal/mole}$$

Now, try $T_f = 2500 \text{ } ^\circ\text{K}$, get

$$\mathcal{H}_{T_f, CO_2}^\circ = 31480 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, H_2O}^\circ = 25700 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, O_2}^\circ = 20800 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, N_2}^\circ = 19839 \text{ cal/mole}$$

$$\begin{aligned}
 \text{Then } B &= (31480 - 2238) + (25700 - 2368) + 0.3 \times (20800 \\
 &\quad - 2070) + 6.77 \times (19839 - 2072) \\
 &= 1.78 \times 10^5 \text{ cal/mole}
 \end{aligned}$$

Therefore, the adiabatic flame temperature of 20% excess air is $T_f = 2500^\circ\text{K}$.

If no preheating, $T_i = T_o = 298^\circ\text{K}$, then $A = 0$

Since $\mathcal{H}_{T_i}^\circ - \mathcal{H}_{T_o}^\circ = 0$ at $T_i = T_o$.

$$B = A - \Delta H_r = -\Delta H_r = 1.52 \times 10^5 \text{ cal/mole}$$

Now,

$$\mathcal{H}_{T_o, \text{CO}_2}^\circ = 2238 \text{ cal/mole}$$

$$\mathcal{H}_{T_o, \text{H}_2\text{O}}^\circ = 2368 \text{ cal/mole}$$

$$\mathcal{H}_{T_o, \text{N}_2}^\circ = 2072 \text{ cal/mole}$$

$$\mathcal{H}_{T_o, \text{O}_2}^\circ = 2070 \text{ cal/mole}$$

Assume $T_f = 2500^\circ\text{K}$, get

$$\mathcal{H}_{T_f, \text{CO}_2}^\circ = 31480 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{H}_2\text{O}}^\circ = 25770 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{N}_2}^\circ = 19839 \text{ cal/mole}$$

$$\begin{aligned}
 \text{Then } B &= (31480 - 2238) + (25700 - 2368) + \\
 &\quad 5.64 \times (19839 - 2072)
 \end{aligned}$$

$$= 1.53 \times 10^5 \text{ cal/mole}, \text{ OK!}$$

Then get the adiabatic flame temperature

$$T_f = 2500 \text{ }^\circ\text{K}.$$

If consider 20% excess air, then

$$B = (\mathcal{H}_{T_f}^\circ - \mathcal{H}_{T_0}^\circ)_{\text{CO}_2} + (\mathcal{H}_{T_f}^\circ - \mathcal{H}_{T_0}^\circ)_{\text{H}_2\text{O}} \\ + 0.3(\mathcal{H}_{T_f}^\circ - \mathcal{H}_{T_0}^\circ)_{\text{O}_2} + 6.77(\mathcal{H}_{T_f}^\circ - \mathcal{H}_{T_0}^\circ)_{\text{N}_2}$$

Try $T_f = 2200 \text{ }^\circ\text{K}$, get

$$\mathcal{H}_{T_f, \text{CO}_2}^\circ = 27060 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{O}_2}^\circ = 18036 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{H}_2\text{O}}^\circ = 22053 \text{ cal/mole}$$

$$\mathcal{H}_{T_f, \text{N}_2}^\circ = 17223 \text{ cal/mole}$$

$$B = (27060 - 2238) + (22053 - 2368) \\ + 0.3 \times (18036 - 2070) + 6.77 \times (17223 - 2072) \\ = 1.52 \times 10^5 \text{ cal/mole}, \text{ OK!}$$

Therefore, for unpreheated air with 20% excess,

$$T_f = 2200 \text{ }^\circ\text{K}.$$

SYMBOLS IN APPENDIX E

ν_j' — Stoichiometric coefficient for species j appearing as a reactant.

ν_j'' — Stoichiometric coefficient for species j appearing as a product.

ΔH — Heat addition from outside the system.

T_0 — Standard-state temperature.

T_i — The temperature of reactants.

T_f — Adiabatic flame temperature.

h_o° — Molar specific enthalpy at standard condition.

$h_{T_0}^\circ$ — Molar specific enthalpy at T_0 .

$h_{T_i}^\circ$ — Molar specific enthalpy at T_i .

$h_{T_f}^\circ$ — Molar specific enthalpy at T_f .

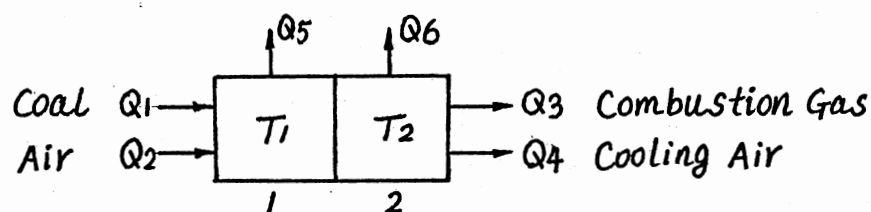
ΔH_r — Heat of reaction.

Δh_f° — Standard heat of formation.

APPENDIX F

THE ESTIMATION OF COMBUSTION AIR TEMPERATURE

The graph of model:



The basic parameters:

Coal

Heat content $h_c = 8000 \text{ Btu/lb}$

Mass flow rate $G_c = 2 \text{ lb/hr}$

Air

Temperature T_a

Heat capacity $C_{p_a} = 0.248 \text{ Btu/lb}^\circ\text{F}$

Mass flow rate $G_a = 27.8 \text{ lb/hr}$

Cooling air

Heat flow rate $Q_4 = 1.25 * 10^4 \text{ Btu/hr}$

Exhaust gas

Temperature $T_g = 500^\circ\text{F}$

Mass flow rate $G_g = 29.8 \text{ lb/hr}$

Heat capacity $C_{p_g} = 0.30 \text{ Btu/lb}^\circ\text{F}$

Furnace

Thermal conductivity
of refractory brick $K_r = 0.484 \text{ Btu/hr ft}^\circ\text{F}$

Thermal conductivity
of insulating brick $K_i = 0.169 \text{ Btu/hr ft } ^\circ\text{F}$

Thickness of
refractory brick $W_r = 0.375 \text{ ft}$

Thickness of
insulating brick $W_i = 0.75$

Temperature of
first chamber T_1

Temperature of
second chamber T_2

Heat conduction surface
area of chamber 1 and 2 $S_1 = S_2 = S = 8 \text{ ft}^2$

Overall heat balance

$$Q_1 + Q_2 = Q_3 + Q_4 + Q_5 + Q_6$$

Now,

$$Q_1 = h_c G_c$$

$$Q_2 = (GC_p T)_a$$

$$Q_3 = (GC_p T)_g$$

Based on Fourier's law of heat conduction under steady
state:

$$\begin{aligned} Q_5 &= K_r (T_1 - T_m) S_1 / W_r \\ &= K_i (T_m - T_o) S_1 / W_i \end{aligned}$$

where,

T_m is the temperature between two layers.

T_o is the temperature of furnace outside surface. Assume
 $T_o = 100 ^\circ\text{F}$ in this calculation.

Then we can get

$$Q_5 = \frac{K_r S_1}{W_r} \left(T_1 - \frac{K_r T_1 / W_r + K_i T_o / W_i}{K_r / W_r + K_i / W_i} \right)$$

For Q_6 , we have similar relations.

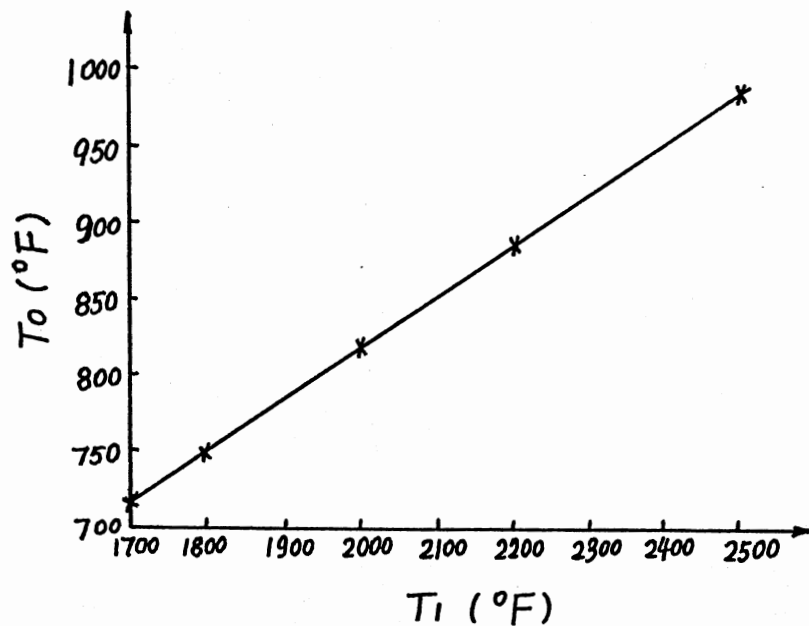
Then,

$$h_c G_c + G_a C_{pa} T_a = G_g C_{pg} T_g + Q_4 + \frac{K_r S_1}{W_r} \left(T_1 - \frac{K_r T_1 / W_r + K_i T_o / W_i}{K_r / W_r + K_i / W_i} \right) + \frac{K_r S_2}{W_r} \left(T_2 - \frac{K_r T_2 / W_r + K_i T_o / W_i}{K_r / W_r + K_i / W_i} \right)$$

$$T_a = \frac{G_g C_{pg} T_g + Q_4 + \frac{K_r S}{W_r} \left(T_1 + T_2 - \frac{K_r T_1 / W_r + K_r T_2 / W_r + 2 K_i T_o / W_i}{K_r / W_r + K_i / W_i} \right) - h_c G_c}{G_a C_{pa}}$$

Now assuming $T_1 = 2000^\circ\text{F}$, $T_2 = (2000 + 500) / 2 = 1250^\circ\text{F}$, we can get $T_a = 820^\circ\text{F}$.

Taking different T_1 's, we will get different T_a 's. The relation of T_a and T_1 is shown in following graph.



VITA 2

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