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Investigation of Radiometric Combustion Monitoring Techniques for Coal-Fired Stoker Boilers

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Fuel-ash bed disturbances are costly problems often encountered in operating coal-fired, mechanical-stoker boilers in military heat plants. In traveling grate, mechanical-stoker boilers, all or most of the coal burns on the traveling grate, so proper control of combustion grate fuel-ash bed thickness is critical for cost-effective, high-availability operation. In these plants, operators must adjust combustion equipment as the coal enters the combustion chamber. Because fuel bed problems take several minutes to develop, operators may not discover problems before they go past the point of easy correction.

This study investigated the use of a remote sensing system to monitor conditions in the fuel bed. It is concluded that the technology to measure mechanical stoker boiler fuel-ash bed temperatures by radiation techniques is sufficiently developed to produce a fuel-ash bed temperatures-monitoring system. Such a system may significantly reduce fuel-ash bed disturbances by detecting bed temperature changes that indicate the onset of bed entrainment and clinker formation. Continuous, reliable measurement of fuel-ash bed temperatures could also detect smoking and conditions leading to smoking, and could be used to improve boiler efficiency through improved control of excess air.

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FOREWORD

This project was sponsored and conducted by the Energy and Utility Systems Division (FE), Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL), under the Intra-Departmental Independent Research (IDIR) Program. The USACERL principal investigator was Martin J. Savoie. Frederick Karlson, Thomas Parsons, and William Scholten are associated with the Science Applications International Corporation (SAIC). Dr. David M. Joncich is Chief, CECER-FE, and Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was William J. Wolfe, Information Management Office.

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1 INTRODUCTION

Background

Fuel-ash bed disturbances—segregation, clinkering, uneven coal and ash bed—are costly problems often encountered in operating coal-fired, mechanical stoker boilers in military heat plants. In traveling grate, mechanical stoker boilers (and hot water generators), all or most of coal combustion occurs on the traveling grate. In these units, proper control of combustion grate fuel-ash bed thickness is critical for cost-effective, high-availability operation.

If portions of the fuel-ash bed become too thin or thick, undergrate combustion air flow distribution becomes uneven. This condition can lead to clinkers in the thick areas of the bed, and blowholes in the thin areas, both of which will greatly increase particulate carryover and reduce boiler efficiency. Undergrate combustion air maldistribution, due to uneven combustion air flow, can also result in bed solids entrainment, resulting in removal of all solids over a portion of a combustion grate. Fuel-ash bed solids (coal, char, and/or ash) entrainment by undergrate combustion air, in addition to reducing combustion efficiency, can reduce heat transfer and damage other furnace surfaces through erosion. Combustion grate surfaces exposed by fuel-ash bed loss can also suffer damage due to excessive heating.

Fuel bed disturbances depend on several factors, including equipment design, equipment condition, operator skill, and fuel quality. Of these factors, operator skill and fuel quality are the most difficult to control, and operator skill is highly dependent on the ability to respond to fuel-related problems. Operational difficulties originate from the nonhomogeneous nature of stoker coal. A particular coal's ability to completely combust in a stoker system depends on its physical and chemical makeup. Some of the most important stoker coal quality parameters are size distribution, ash fusion temperature, free swell index, moisture content, and volatility. These parameters can vary widely among coals from different deliveries or different mines, and can also vary within a single delivery of coal, depending on how it is handled or stored. Even though the coal is analyzed, it is difficult for heating plant personnel to visually distinguish these characteristics from one coal pile in the storage yard to another.

This uneven quality of different coals forces plant operators to adjust the combustion equipment as the coal enters the combustion chamber. Because a fuel bed problem takes several minutes to develop, operators may not discover the problem before it has gone past the point of easy correction. The identification of fuel bed problems is very difficult for operators because of large furnace areas (typically over 100 sq ft),* and intense heat and light in the furnace bed. This situation could be greatly improved by using a remote sensing (spectral imaging) system to monitor the fuel bed. A remote sensing system would improve operator response time to fuel distribution and other fuel-related problems. However, military and commercial applications of such monitors for stoker systems still need to be identified.

* 1 sq ft = 0.093 m^2.

Objectives

The general objective of this study was to investigate the feasibility of developing a remote sensing system for monitoring the fuel bed of stoker-fired boilers.

Specific objectives were:

- to assess current spectral imaging technologies (ultraviolet, visible, and infrared) to identify approaches for developing a commercial traveling grate, mechanical stoker, coal-fired boiler fuel-ash bed, monitoring system for use in military heat plants

- to judge the most promising spectral imaging system for military heat plant applications, and to identify a fuel-ash bed monitoring system conceptual design

- based on the fuel-ash bed monitoring system conceptual design, to create a development and demonstration (D&D) plan and an estimated D&D cost range.

Approach

The following steps were taken to assess the applicability of spectral imaging technology to the stoker fuel-ash bed temperature monitoring problem:

1. Technical literature was reviewed.
2. Spectral imaging equipment manufacturers were surveyed.
3. Other research organizations were contacted.
4. Sites were identified where commercially successful applications of the technology were already in place.

To assess spectral imaging technologies, a reference 70 MBtu/hr spreader-stoker boiler was specified. Actual performance data and experience were used to estimate typical boiler conditions relevant to fuel-ash bed temperature monitoring, such as the temperature profile over the fuel-ash bed, and combustion gas particulates concentration.

Of the two commercially successful applications similar to mechanical stoker boilers that were found, one was used as a starting point to develop a conceptual design for a fuel-ash bed temperature monitoring system. A conceptual design for a fuel-ash bed monitoring system was developed using radiation-imaging technology. A method for interpreting the data from imaging radiation over an entire fuel-ash bed was proposed.

Scope

The results of this project are applicable to most coal-fired stoker systems. Radiometric monitoring methods may also have applications for other fossil fuel-fired boilers and waste incinerators. Since combustion grate fuel-ash bed disturbance problems are most critical in the larger-scale (above 30 MBtu/h heat production) overfeed and spreader-feed, traveling grate stoker boilers currently used at military heat plants, this project concentrated on larger coal-fired systems. However, some of the findings of this study may apply to other types of coal-fired mechanical stokers, such as spreader stokers with dumping grates.

Mode of Technology Transfer

It is anticipated that the results of this study will lead to a Facilities Engineering Application Study (FEAP) demonstration of radiometric combustion monitoring techniques, and that the technology will be detailed in FEAP bulletins and flyers.

2 STOKER TECHNOLOGY

Coal-fired boilers or hot water generators are frequently used to provide central heat (saturated steam or hot water) at DOD bases.* These boilers represent a wide range of designs, from underfeed stokers to pulverized coal boilers. However, large boilers (those rated at 30 MBtu/h heat production) tend to use either direct-feed or spreader-feed traveling grates for actual coal combustion. These boilers are normally referred to as "mechanical stoker boilers." A common problem associated with the designs of these boilers is fuel-ash bed entrainment. Before defining the fuel-ash bed entrainment problem and ways to resolve it, a brief description of typical mechanical stoker boilers is needed.

Coal-Fired Mechanical Stoker Boiler Description

Mechanical stokers are devices that automatically feed coal into a boiler, and in some cases, automatically dispose of the ash. There are many types of mechanical stokers in use, each type differing in the way it feeds coal onto the combustion grate and how it removes ash from the grate. Mechanical stokers can be divided into three categories based on how coal is fed onto the combustion grate:

1. Spreader stoker
2. Overfeed stoker
3. Underfeed stoker.

Within each category, stokers differ in how the grate handles ash.

A typical spreader-stoker boiler consists of a variable-feeding device, a mechanism for "throwing" coal into the boiler, and one or more grates, depending on capacity, with suitable openings for admitting combustion air. The coal-feeding-and-distributing mechanism is located on the boiler front wall above the combustion grates.

The conventional mechanical spreader-stoker feeding-and-distributing device is arranged to supply coal to the boiler grates in quantities required to meet demand. The feeder delivers coal to a revolving rotor with protruding blades. These revolving blades direct the coal and "throw" it onto the boiler grates. The spreader system must be designed to distribute coal evenly over the entire grate area by the shape of the blades.

The spreader-stoker feeder varies the coal supply to the boiler and distributes the coal evenly onto the grates. In a typical feeding-and-distributing system (Figure 1), there is a reciprocating feed plate located at the bottom of a coal hopper. The length of stroke of this plate determines the rate the coal is fed into the boiler. The coal leaving the hopper drops from the end of the spilling plate into the path of the rotor blades, which then distribute coal onto the grates. Coal distribution is regulated by hand adjustment of the spilling plate and by the rotor speed.

The in-and-out adjustment of the spilling plate changes the point where the coal contacts the rotor blades. Moving the spilling plate away from the boiler allows the coal to fall on the rotor blades sooner, so that the blades impart more energy to the coal, throwing it farther into the boiler. Similarly, increasing the speed of the rotor also imparts more force to the coal.

* The term "boiler" will be used throughout this report to denote both boilers (steam producers) and hot water generators.

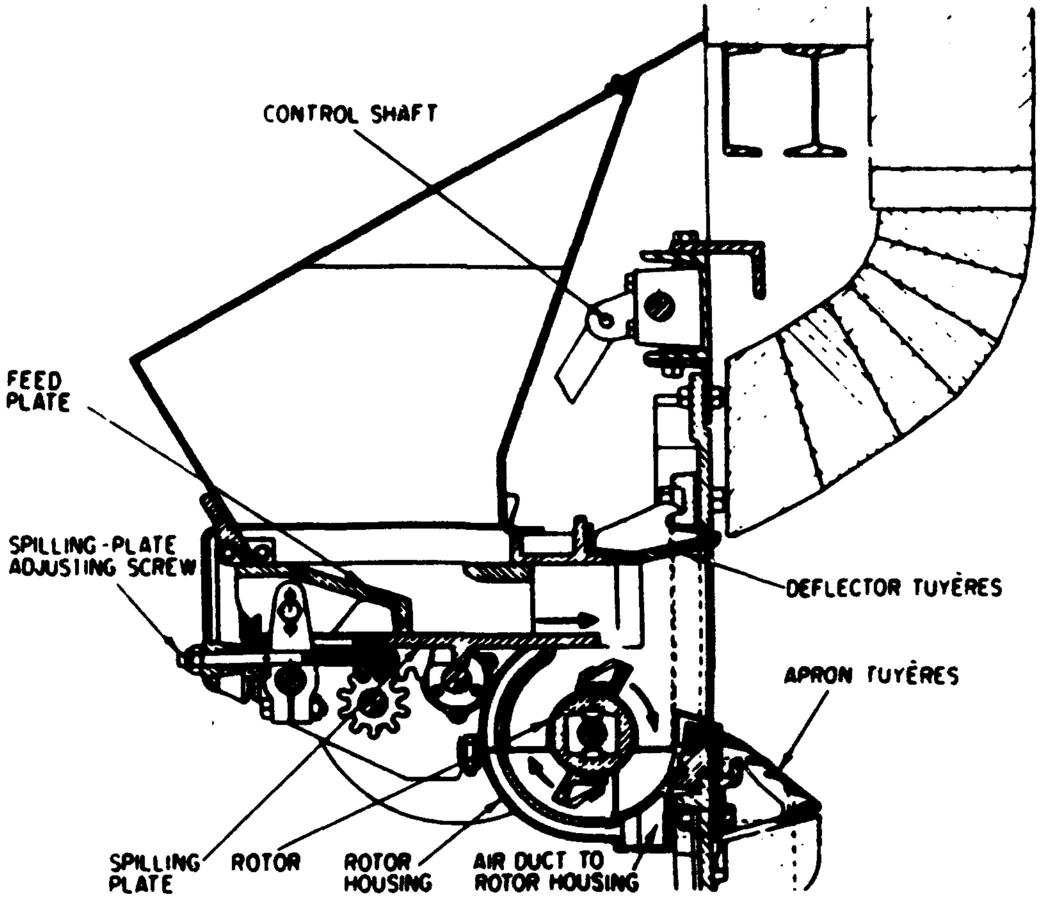

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Figure 1. Spreader Stoker Feeder-Distributor Mechanism.

Figure 2 shows a typical traveling-grate spreader stoker boiler, in which ash is continuously discharged from the grates into an ashpit. The coal is thrown toward the rear of the boiler, and grate speeds are adjusted to give sufficient time for complete combustion before the ash is discharged at the front. When the grates are correctly adjusted, the process is continuous and there is no interference with boiler operation.

As coal is fed into the spreader-stoker furnace, some volatile matter and fine coal particles burn in suspension, and the remainder falls to the grate, where combustion continues. From 15 to 40 percent of combustion will take place in suspension before the coal reaches the coal bed. Pressure created by the forced-draft fan, forces air into the furnace through the openings in the grates. Part of this air is used to burn the thin layer of fuel on the grates, and the rest passes into the furnace where it burns the volatile matter and fine particles. The overfire air fan supplies additional air to the furnace through jets in the wall. This adds to the air supply for suspension burning and causes more turbulence than in on-grate burning (which occurs in underfeed and overfeed stokers).

Suspension burning causes more unburned carbon particles (cinders) to be carried out of the furnace by the gases than in underfeed types. Some of these cinders collect in hoppers beneath the boiler's convection passes. However, a portion is retained in the exit boiler gases and must be intercepted by a

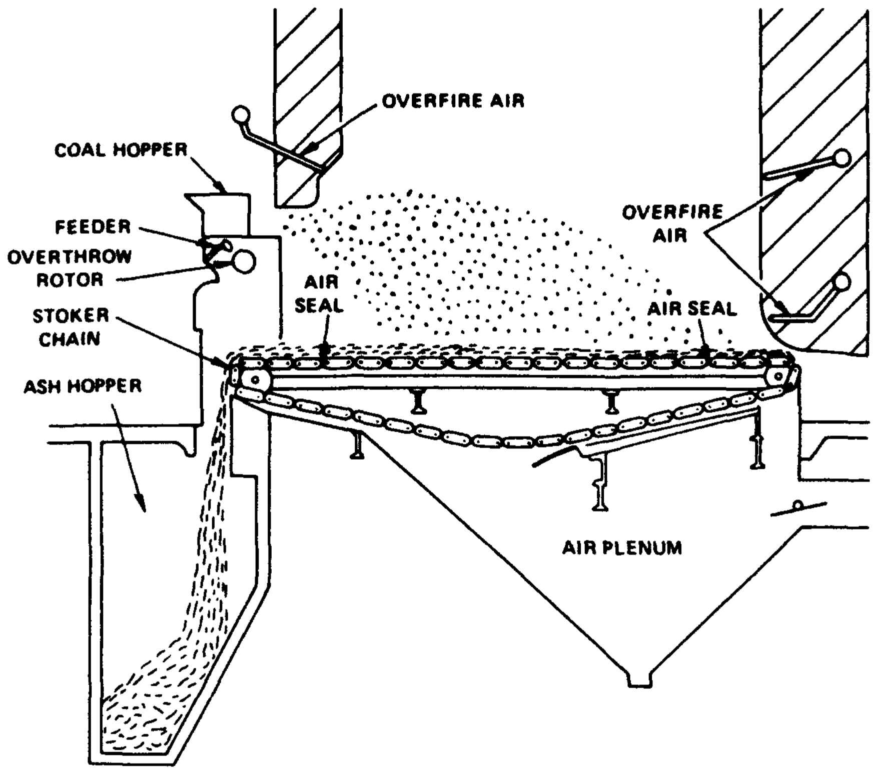

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Figure 2. Spreader Stoker With Traveling Grate.

fly-ash collector to prevent excessive pollution of the atmosphere. Since these particles contain carbon, returning the cinder to the furnace for reburning can improve the efficiency of steam generation.

Cinders are collected in the boiler, economizer, air heater, mechanical dust collector, and baghouse or precipitator hoppers. Cinders with the highest combustible content are deposited in the boiler hoppers, and those with the lowest in the baghouse or precipitator hoppers. The fine particles removed by the baghouse or precipitator must be discarded to the ash-removal system. The baghouse or precipitator is required to reduce the particulate emission from the stack gases sufficiently to meet clean-air standards.

Suspension burning requires a supply of air directly to the furnace. This air is supplied by a high-pressure blower and enters the furnace through ports in the walls. These overfire air fans perform a triple function: they provide combustion air, create turbulence in the furnace, and reinject cinders from the collection hoppers.

Even when spreader stokers are provided with controls to automatically regulate both the fuel feed and the air supply to meet the steam demand, the operator must attend to many details to obtain good operation. The spreader mechanism must be adjusted to distribute the coal evenly over the grates. Irregularities in the fuel bed caused by segregation of coal, wet coal, clinker formation, etc., must be corrected to maintain the fuel bed at sufficient thickness to sustain combustion for 2 to 3 minutes with the fuel feed shut off.

The fuel-bed thickness may be changed by adjusting the ratio of fuel to air. An increase in the air pressure under the grates with the same fuel feed will decrease the thickness of the fuel bed; a decrease in air pressure will allow the fuel-bed thickness to increase. The overfire air must be regulated to obtain the lowest amount of excess air (highest carbon dioxide) without permitting temperatures detrimental to the furnace lining, clinkers in the fuel bed, or excessive smoke.

The modern spreader stoker installation consists of: (1) feeder-distributor units in widths and numbers as required (Figure 3) to distribute the fuel uniformly over the width of the grate, (2) specifically designed air-metering grates, (3) forced draft fans for both undergrate and overfire air, (4) dust collecting and reinjecting equipment, and (5) combustion controls to coordinate fuel and air supply with load demand.

Unlike a spreader stoker, in operating an overfeed stoker, coal is gravity fed onto a grate from a coal hopper mounted on the front of the stoker. The depth of coal fed onto the grate is regulated by raising and lowering a sliding coal gate at the hopper coal discharge (Figure 4). The coal burns as the grate travels from one end of the boiler to the other. The ash is continuously deposited off the rear of the grate into an ash pit.

Although not considered in this report, underfeed stokers have many useful applications. Underfeed stokers, developed in the 1800s, were very popular before World War II. However, after World War II, they were gradually replaced by larger spreader stokers and overfeed stokers.

The Problem

In coal-fired mechanical stoker boilers, proper control of combustion grate fuel-ash bed thickness is critical. Undergrate combustion air maldistribution, due to uneven combustion air flow, can result in bed solids entrainment, resulting in the removal of all solids over a portion of a combustion grate. Fuel-ash bed solids entrainment by undergrate combustion air, in addition to reducing combustion efficiency, can result in damage to heat transfer and other furnace surfaces through erosion. Exposed combustion grate surfaces can also suffer damage due to excessive heating. (The materials used in most combustion grates cannot tolerate direct, prolonged exposure to furnace temperatures. The fuel-ash bed in most grate designs is used to insulate the combustion grate from prolonged exposure to maximum furnace temperatures.) Riley Stoker Corporation estimates the budget price to replace a grate to be $190,000, excluding freight and taxes. This price is based on a 70 MBtu/hr spreader stoker-fired boiler requiring about 92 to 100 sq ft of grate surface.

The basic concept behind the work associated with the investigation of optical combustion monitoring technologies is to measure the radiation emitted from the fuel-ash bed of a mechanical stoker coal-fired boiler. The term "optical" is misleading since only a small fraction of the radiation emitted from fuel-ash beds is at visible wavelengths (0.4 to 0.7 micrometers). The technology measures radiation at ultraviolet (0.1 to 0.4 micrometers) and infrared (0.7 to 100 micrometers) wavelengths, as well as at visible wavelengths. A number of terms are commonly used to describe radiation measurement and the instruments for its measurement. In this report, the term radiometry is used to imply the science of radiation detection and measurement at wavelengths from ultraviolet to infrared (synonymous terminology includes radiation thermometry and pyrometry). The actual class of instruments used to make radiation measurements are referred to as radiometers (synonymous terms include radiation thermometers, pyrometers, and IR thermometers).

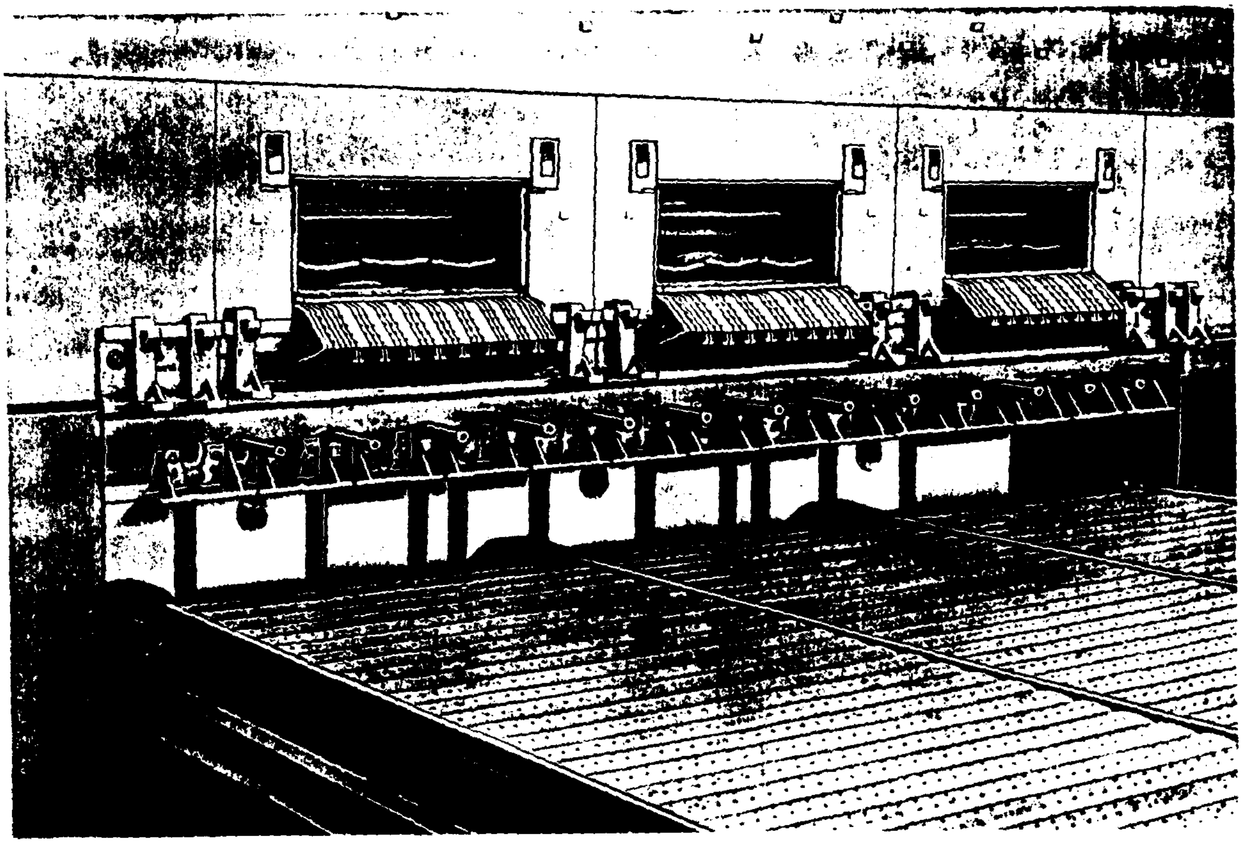

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Figure 3. View Inside of Stoker Front.

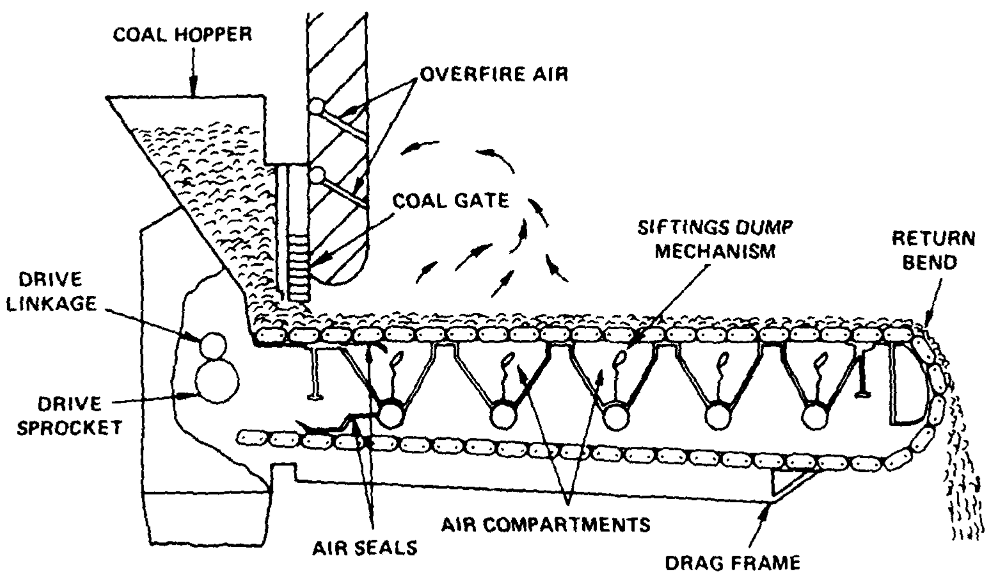

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Figure 4. Chain-Grate Stoker.

Potential Fuel-Ash Bed Disturbance Solutions

Monitoring combustion grate fuel-ash bed temperatures and disturbances is particularly difficult on large furnaces equipped with multiple grates. Two methods currently used in overfeed and spreader feed stoker units are: visual grate inspection through doors and ports, and monitoring of undergrate combustion air compartment pressures. Because of furnace gas conditions (high temperature, highly luminous gases, and the presence of particulates), it is often difficult to view the entire grate area with sufficient clarity to accurately determine initiation of fuel-ash bed disturbances. Fuel-ash bed viewing is especially difficult with spreader stoker furnaces. In these furnaces, incoming coal adds to the particulates and luminous burning volatiles, all of which contribute to poor bed viewing conditions. Visual bed monitoring is limited by poor viewing conditions and sometimes by the viewer's inability to recognize initiation of fuel-ash bed disturbances. Undergrate combustion air pressure monitoring also has limitations, particularly when boiler or heater load is changing. Also, in large furnaces, undergrate combustion air compartments are large and air flows are high. This complicates detection of small changes in air distribution that might indicate initiation of fuel-ash bed disturbances.

One approach to improving monitoring of combustion grate fuel-ash bed disturbances could be direct measurement of bed surface temperatures. High or low temperature bed regions could indicate the start of fuel-ash bed disturbances or other combustion problems. Two possible methods of measuring bed temperatures are with imbedded thermometers, such as thermocouples or resistance thermometers, or with a noninvasive radiation detecting device. Although imbedded thermocouples have been used successfully to measure fuel-ash bed temperatures in the laboratory, maintaining the integrity of imbedded thermometers and their associated wiring would be very difficult, if not impossible, given the internal boiler environment of on-line moving grate spreader stokers. Even if installation were possible, replacement of imbedded thermometers would require shutdown and boiler cool off. (It should be noted, however, that the Detroit Stoker Company* manufactures stokers equipped with thermocouple assemblies attached to the stoker top support rails to accurately measure the temperature of grate castings. If the grate temperature exceeds safe limits, operating personnel can act promptly to make necessary operational changes to keep grate temperatures within safe limits, thus assuring long grate life.) For these reasons, this project concentrated on the use of radiation detection thermometry as a way to measure fuel-ash bed temperatures. Radiation detection also allows full-bed viewing with only one instrument. Directly related to radiation thermometry is the use of special television systems to permit enhanced visual viewing of the fuel-ash bed.

Neither the bed surface temperature measurement nor television improved fuel-ash bed monitoring concepts are new. So far, technical limitations and high costs have prevented these concepts from being commercialized for use in either coal-fired heating plants or electric utility boilers. However, recent technical advances in television and spectral imaging techniques may change this situation. Improvements in imaging sensors/cameras for ultraviolet, visible, and infrared wavelength imaging may allow accurate, continuous, and reliable measurement of fuel-ash bed disturbances at reasonable cost. Also, recent advances in development of control approaches based on application of expert systems may be compatible with the cost-effective application of new imaging technology for improved operation of military heat plants.

* Detroit Stoker Co., a subsidiary of United Industrial Corp., 1510-A East First St., Drawer 752A, Monroe, MI 48161.

3 MILITARY CENTRAL HEAT PLANT CONDITIONS

Army and Air Force Central Heat Plant Survey

As a part of the Army's coal Conversion Program, USACERL maintains a data base of information on all Army and Air Force boilers. A capacity survey was done from this data base of the coal-fired boilers installed at military central heating plants. The inventory of military coal-fired boilers shows 126 units in the 20 to 400 MBtu/h output range, of which 27 are rated at 40 MBtu/h or less. Five units were found to have ratings between 10 and 20 MBtu/h. These results are summarized in Figure 5.

Reference Spreader Stoker Furnace Definition

A well-defined reference boiler will help explain the causes of fuel-ash bed entrainment in mechanical stoker boilers and potential problems associated with bed temperature monitoring. This reference boiler is meant to represent a "typical" military heat plant mechanical stoker boiler that would be a candidate for the installation of a fuel-ash bed temperature monitoring system. A spreader stoker boiler of the type described in Chapter 2 was selected for the following reasons:

1. This boiler type is judged to be the most difficult type for fuel-ash bed temperatures measurement because of the manner of coal feeding. In spreader stokers, coal is flung over the grates with the finer particles burning in suspension above the grates. The combination of unignited coal particles and burning coal particles obscures the grate surface and the fuel-ash bed from view. If a radiometer can view the fuel-ash bed of a spreader stoker, it can very likely view that of an overfeed traveling grate furnace.

2. Spreader stoker boilers range in capacity from 5 to 180 MBtu/h of heat generation, a range that includes 61 units in the military inventory. These units would likely profit most from a fuel-ash bed entrainment and combustion air maldistribution control system.

3. Reportedly, large spreader stoker furnaces experience fuel-ash bed entrainment problems more frequently than other traveling grate mechanical stoker boilers.

Table 1 presents the as-fired coal specified for the reference spreader stoker boiler. To establish boiler maximum continuous rating, the following conditions were used to calculate boiler thermal efficiency:

- 25 wt. percent of the coal feed burns in suspension (does not reach the combustion grate)
- fly ash carbon concentration: 50 wt. percent
- bottom ash (grate discharge) carbon concentration: 10 wt. percent
- stack flue gas exit temperature: 450 °F*
- design excess air: 40 wt. percent
- boiler external surfaces radiation loss: 0.90 percent
- unaccounted for loss: 1.50 percent.

Calculated boiler thermal efficiency is 79.7 percent. This translates to a design coal feed rate of 87.8 MBtu/h or 3.4 t/h.

* °F = (°C × 1.8) + 32.

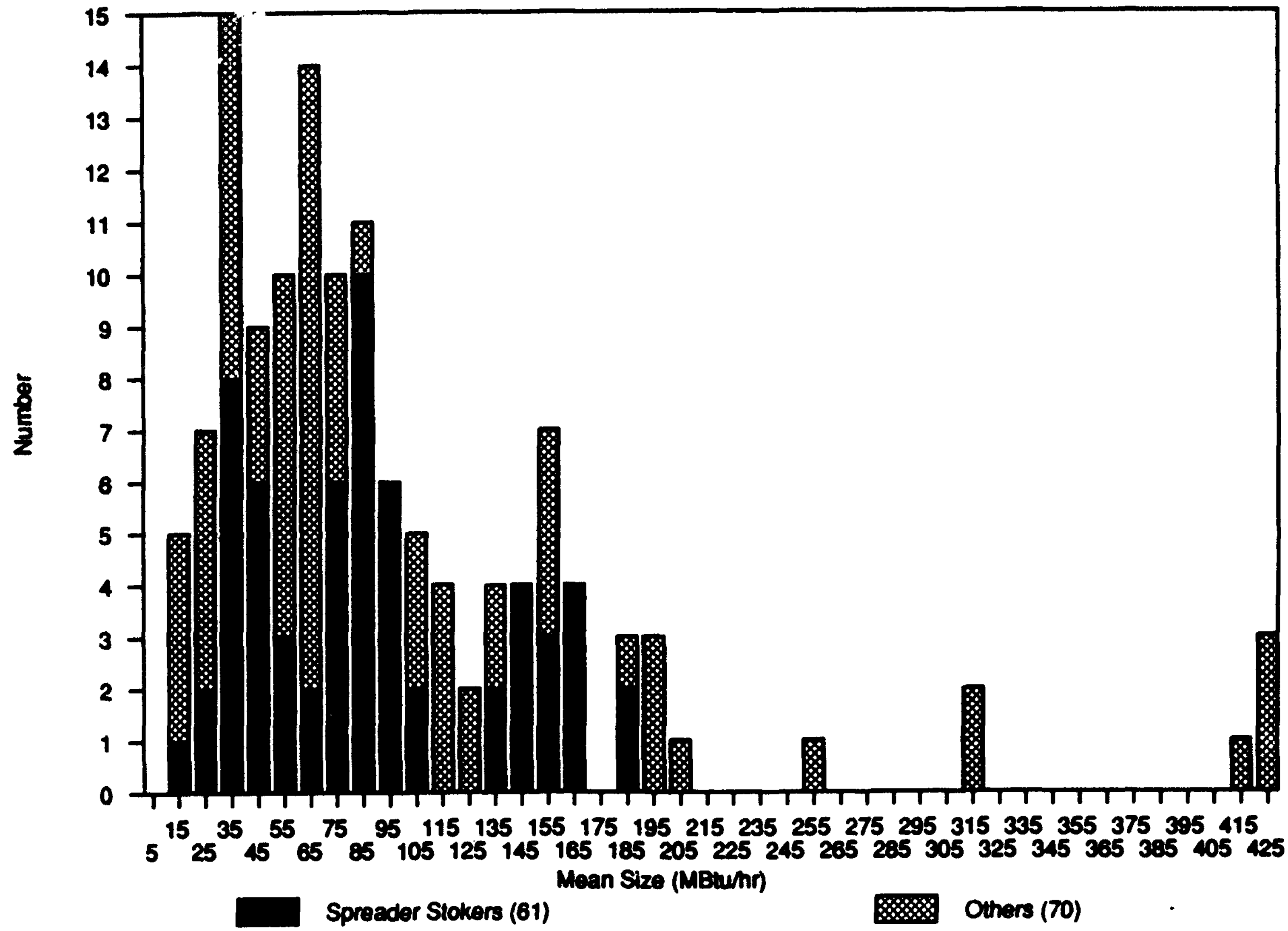

Figure 5. Distribution of Military Coal Fired Boilers by Size.

Table 1

Reference Spreader Stoker Boiler
Design As-Fired Coal Data

Component/Property	Value
Volatile matter	38.0
Fixed carbon	48.0
Free swelling index	5.0
Ash fusion temperature	
(hemispherical)	2200 °F (oxidizing)
C	72.0 wt%
H_2	4.4 wt%
S	1.6 wt%
O_2	3.6 wt%
N_2	1.4 wt%
H_2O	8.0 wt%
Ash	9.0 wt%
	100.00
Higher heating value	
size distribution:	12,000 Btu/lb
+1-1/4 in.	
1-1/4 - 3/4 in.	5 wt%
3/4 - 1/2 in.	10 wt%
1/2 - 1/4 in	35 wt%
1/3 in. - 8 mesh	30 wt%
-8 mesh	15 wt%
	5 wt%

Based on this data, a reference spreader stoker having a design generation capacity (maximum continuous rating) of 70 MBtu/h of steam was specified for use in this study. This reference boiler was used to keep in perspective the general dimensions and conditions that would be encountered in monitoring fuel-ash bed temperatures in military heat plant mechanical stoker boilers. However, in evaluating competing radiometry techniques and development of a temperature measurement system conceptual design, the complete range of military mechanical stoker boilers that could be candidates for fuel-ash bed temperatures measurement was considered, including spreader stokers employing multiple feeder-distributor mechanisms (Figure 3).

To estimate approximate reference boiler dimensions, the following parameters were estimated from spreader stoker boiler design data:

- grate length-to width ratio: 1.2
- boiler furnace heat release rate: 30,000 Btu/sq ft-h
- coal feed rating: 50 lb/sq ft-h. (This rate was applied based on the coal feed rate unadjusted for coal combusted above the boiler grate.)

Basic dimensions for the reference spreader stoker boiler are shown in Figure 6. The effective grate length is 12.8 ft; grate width is 10.7 ft; and, furnace internal height is 21.4 ft. One possible application of a radiometer(s) to continuous, on-line measurement of grate fuel-ash bed temperatures for a boiler of the type illustrated in Figure 6 is to mount the radiometer(s) on a furnace wall or roof to view the entire fuel-ash bed area. The lens of the radiometer would actually look through a small penetration in the furnace wall or roof.

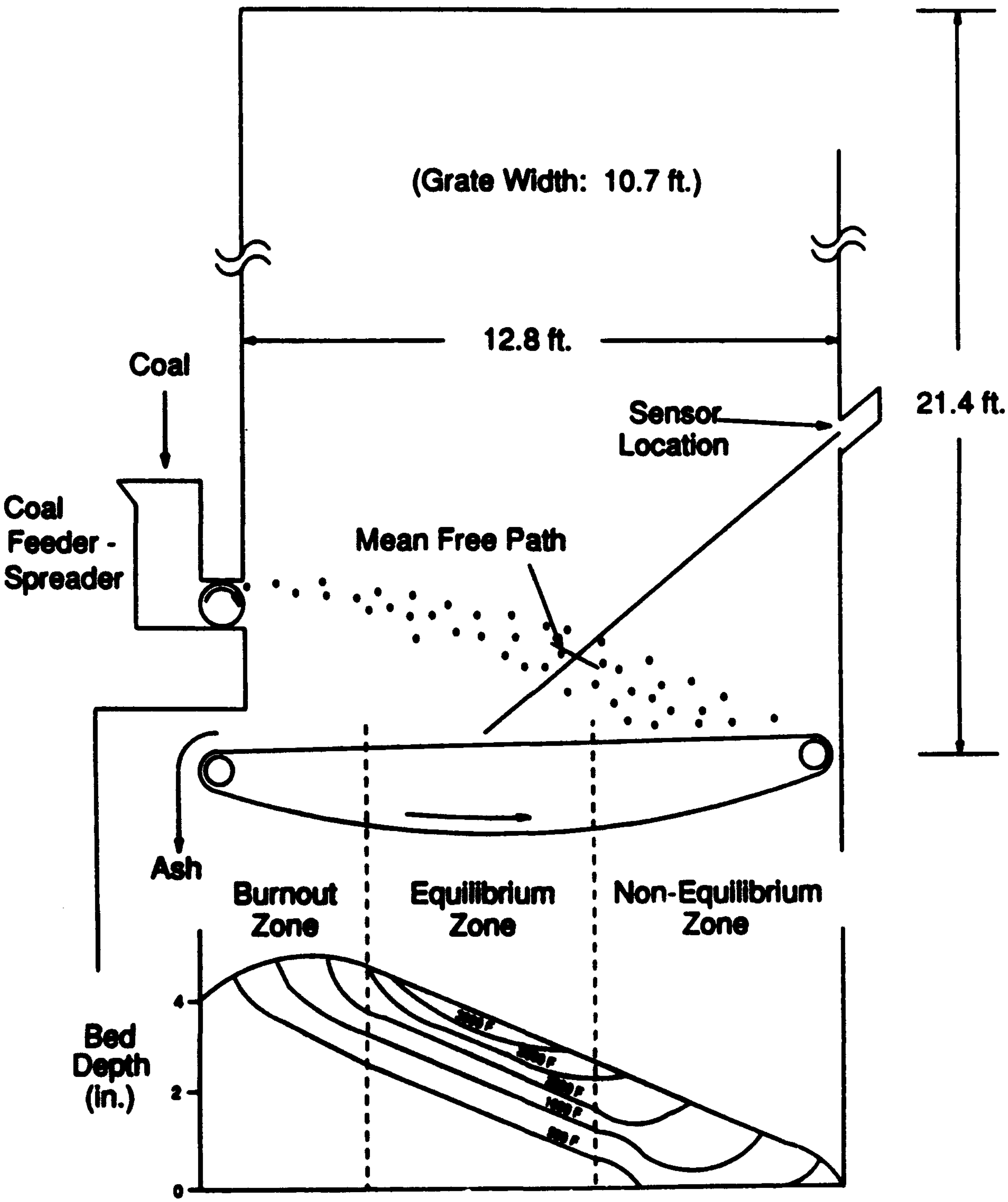

Figure 6. Typical Military Heating Plant Spreader Stoker Unit (Nominal 70 MBtu/hr Output).

There are four areas of critical importance to determining the feasibility of using a radiometer to measure grate fuel-ash bed temperatures (measurement of temperatures over the entire grate area) in a boiler of the type illustrated in Figure 6:

1. Fuel-ash bed temperatures and how these change over the bed

2. Boiler combustion, gases, particulate (entrained ash, coal, and falling feed coal) concentration and size distributions

3. Combustion gases temperatures (particularly in the lower portion of the boiler) and radiation characteristics

4. Boiler wall temperatures and emissivities.

To estimate "typical" fuel-ash bed temperatures, actual measurements for spreader stoker boilers reported in a British paper were used (Marshall and Pratt 1952). Estimated fuel-ash bed temperatures are presented as isotherms at the bottom of Figure 6. All fuel-ash bed temperature data located to date have been in the form presented in Figure 6, that is, the temperatures have been measured through the fuel-ash bed (temperature versus ash depth), rather than across the bed surface. (Note that coal bed depths typically range from 6 to 9 in.)* These values represent temperatures in the main portion of the fuel-ash bed. Some distortion of these temperature profiles undoubtedly occurs as the boiler side walls are approached. No data to estimate side wall effects were located. However, these effects obviously depend on the amount of fouling on the walls.

Both British and U.S. researchers (Marckell, Miller, and Joyce 1952; Carman, Graf, and Corey 1959) have simulated traveling grate combustion using static "pot" type combustors. In these tests, time is used to simulate grate movement. Results from the static tests generally agree with the temperature profiles presented in Figure 6 for a bituminous coal of the quality shown in Table 2 (a good quality spreader stoker boiler coal). This data also clearly demonstrates that coal quality and rank can significantly affect fuel-ash bed temperature profiles. Specific coal quality parameters that significantly affect fuel-ash bed temperatures are: ash concentration, ash form (extraneous versus disseminated), ash fusion temperature, volatile matter concentration, and moisture concentration. As a further check on the estimated spreader stoker fuel-ash bed temperature profiles, Figure 6 and Table 2 were provided to Babcock & Wilcox's (B&W's)** combustion engineers, who concluded that the Figure 6 profiles appear reasonable, but that they could not comment further without running a boiler design model (*Estimation of Fuel Use and Population for Industrial Boilers* 1985).

Estimates of furnace particulates concentrations in the zones relevant to fuel-ash bed viewing indicate that the mean distance between particles (mean free path) over the fuel-ash bed (see Figure 6) is large compared with the wavelengths at which radiometers operate. The estimated mean particulates volume concentration in the boiler combustion gas is less than 0.001 percent of the total boiler internal volume. As a result, attenuation of bed radiation by particulates is not currently judged to be a serious problem. It is more likely that particulates would occasionally and very briefly, block emitted radiation from reaching a scanning radiometer. Such blocking can be handled by short-term averaging of radiation intensity.

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* 1 in. = 25.4 mm.

** Babcock & Wilcox, Power Generation Group, PO Box 351, Barberton, OH 44203, tel. 1-800-354-4400.

Table 2

Wavelengths for Typical Fuel-Ash Bed Temperatures Assuming Blackbody Radiation

Temperature (°F)	Temperature (°K)	Peak Emission Wavelength Micrometers
3000	1922	1.5
2000	1366	2.1
1000	811	3.6
500	533	5.4

A potential particulate problem is smoke. Excess smoke could significantly attenuate fuel-ash bed radiation. However, since a properly operating spreader stoker boiler does not produce smoke, presence of high smoke concentration is assumed to be due to a boiler upset. In fact, a radiometer may be better able than other methods to detect smoke conditions earlier and at low concentrations. This could be a side benefit of using a radiometric system for controlling fuel-ash bed entrainment.

Ability To Detect Conditions Leading to Fuel-Ash Bed Entrainment

Measurement of fuel-ash bed temperatures can only reduce costs if this information can help to eliminate or significantly reduce bed entrainment incidents. In other words, this assumes that irregular fuel-ash bed temperatures either cause, or are associated with, bed entrainment. This assumption was complicated by the fact that no thoroughly documented descriptions of bed entrainment were located. The only information available was the experience of USACERL and contract support engineers.

From knowledge of the combustion processes associated with traveling grates, two phenomena were postulated to be likely causes of fuel-ash bed entrainment: combustion air thermal choking and clinker formation. The concept of combustion air thermal choking was postulated from a review of the British and U.S. static "pot" type combustion tests used to confirm the Figure 6 bed temperature profiles. The term thermal choking was coined to identify this phenomena. Whether or not other terms are used to describe this phenomena is not known.

The British static test data clearly show that localized high grate temperatures result in reduced air mass flow rate through the higher temperature grate area. A graph of both grate temperature and air rate (Figure 6) "shows a rise in grate temperature caused by the burning bed immediately above. This, in turn, by causing an expansion of air passing through the grate, reduces the mass flow. As a shielding ash layer develops on the grate, the grate temperature falls and the air supply increases. Thus, although there are no compartments under the grate and the under-grate air pressure is constant, there is a varying air supply along the grate length."

The British paper describing the static "pot" type combustion testing states that "fuel beds of depths up to 4 in. have little resistance compared with the grate resistance unless abnormal packing or clinkering occurs." This implies that, within limits, thinning of the fuel-ash bed by itself may not be a cause of ash and/or coal entrainment. Such thinning, however, could result in abnormally high grate temperatures.

Researchers from the U.S. Bureau of Mines (Carman, Graf, and Corey 1957) used a pot combustion chamber similar to that employed by the British. They also observed "unexpected" variations in bed air flow rate over the combustion grate. Calculations based on estimated gas analysis and bed temperatures showed this variation was due to an "increase in volume and viscosity of the gases with temperature."

Thermal choking is postulated to occur when a significant fraction of the combustion grate area becomes hotter than the remaining grate area. This diverts excess combustion air through the cooler grate area. When the gas velocity associated with excess air flow diversion reaches a certain level, it entrains the fuel-ash bed over the cooler grate area. Exposure of additional grate area to boiler radiation could expand the fraction of grate area at abnormally high temperature and possibly exacerbate air diversion (maldistribution) and bed entrainment. Note that, although grate combustion air thermal choking is a postulated cause of bed entrainment, it has not actually been proven to cause bed entrainment.

If combustion air thermal choking is a real phenomena and a significant cause of fuel-ash bed entrainment, the onset of conditions that lead to it should be detectable by bed temperatures monitoring. If grate temperatures are abnormally high, fuel-ash bed surface temperatures would also be abnormally high over a similar area. The development of abnormally high bed temperature areas probably has a time constant sufficiently large to allow corrective action before bed entrainment. However, this time constant, and the existence of thermal choking, must be determined by actual testing on a mechanical stoker boiler.

Fuel-ash bed clinkers form when molten ash particles agglomerate and harden as they cool. Clinkers (or a clinker of sufficient size) will impede air flow through the fuel-ash bed and/or plug grate air openings (Figure 7). Blinding of a portion of the grate can result in excess gas velocities over other portions of the grate. If these velocities become high, they will entrain bed material. Since clinkering is associated with high fuel-ash bed surface temperatures for a properly specified coal, its onset should also be detectable by bed temperatures monitoring.

Another possible cause of fuel-ash bed entrainment is oversupply of combustion air. On some stokers, there may be a problem with high pressures if the resulting turbulence lifts particulate matter off the grate. If this does happen, the overfire air pressures should be reduced. However, in most units the available fan capacity is usually, by design, not sufficient to result in bed entrainment. If air oversupply is a cause of bed entrainment and it does not develop suddenly (such as by rapid full opening of a damper), it will result in abnormal bed temperatures, which would be detectable by a temperature monitoring system.

Other conditions leading to the onset of bed entrainment and reduced combustion efficiency are:

- segregation
- uneven coal bed
- uneven ash bed
- uneven burning
- smoking.

These and other conditions are sensitive both to operating conditions and the quality of coal being burned. Key operating conditions that can be adjusted to improve combustion include:

- zone dampers
- overfire air
- coal feeders
- furnace pressure
- grate speed.

Figure 7. Severe Grate Pluggage.

Not burning a properly specified coal can also reduce efficiency and increase maintenance. Some of the key coal parameters that can affect combustion efficiency are:

- Size distribution - For spreader stokers, it is not only important to have the correct top and bottom size, but it is just as important to have a proper distribution between the top and bottom sizes. As coal is distributed onto the fuel bed, the larger coal lands toward the back, while smaller particles land near the front of the grate. If a certain size is missing, holes will form in the fuel bed. More of the combustion air will follow this path of least resistance, causing combustion problems elsewhere on the fuel bed.

- Fines - Excessive fines will magnify coal segregation problems. If there are too many fines, segregation will increase every time the coal is handled or stored. Coal segregation in the stoker feeder system leads to problems with incomplete combustion on the grate. Fine coal piles do not allow the underfire air to penetrate the bed and can lead to clinker formation and high grate temperatures. High grate temperatures will damage the grate and increase maintenance costs.

- Free Swelling Index - A high swelling coal can hamper ignition in two ways. If ignition is accomplished by means of an arch, it is very important that the coal have a high volatile matter content and that enough combustion air moves through the coal bed to enhance combustion. If the coal swells too much, the underfire air is cut off and the flame "walks" away from the arch. When this condition occurs throughout the fuel bed, it is called agglomeration, which causes smoking and can result in the formation of large clinkers. If the coal contains a large amount of fines, the swelling will be more severe.

- Ash Fusion Temperatures - Clinkers are formed when the temperature on the grate exceeds the hemispherical temperature of the ash. The grate holes can become plugged and the underfire air is cut off (Figure 7), increasing carbon losses and decreasing combustion efficiency. If too many of these holes are plugged, the air velocity will increase through the remaining opening holes, which could increase the amount of particulates exiting the furnace chamber.

- Ash - It is important to have enough ash to insulate and protect the grate from the extreme temperatures within the combustion zone. It is also important to acquire coal that does not have too much ash. Excessive ash will increase equipment wear and handling costs. It will also lower the heating value, which will increase the amount of coal required to satisfy the same load requirement. The added coal will increase the amount of ash even further. There will be a notable loss in efficiency due to the increased ash content.

While not exhaustive, this list serves to illustrate the consequences of firing incorrectly specified coal. Incorrect size, free swelling index, ash fusion temperature, or ash content can cause poor combustion air distribution in the fuel bed. Improper air distribution will allow air to bypass the fuel and go directly out the stack, requiring more air to be used to burn the fuel. High excess air can carry unburned fuel out of the furnace. When combustion air cannot pass through the coal, the coal will not burn completely, may form clinkers, and will be discharged into the ash system.

This study was mainly directed at eliminating or significantly reducing fuel-ash bed entrainment. However, there appear to be at least two other benefits that could result from accurate, reliable, continuous measurement of fuel-ash bed temperatures: control of smoking and of excess air. Smoking, which is related to excess air control, is an undesirable situation for both efficiency and environmental reasons. Smoke would likely reduce the radiation observed by a radiometer sufficiently to allow rapid, clear detection. Orsat-type CO and O_2 monitors used in conjunction with an IR system to control smoking and excess air, could be an added benefit to detecting opacity and improving boiler efficiency.

The concept of controlling excess air by fuel-ash bed temperatures monitoring was suggested by B&W, which has developed a radiometric technique using an online, continuous flame quality analyzer for use in utility-scale boilers (see Figure 8). This analyzer measures both the intensity and temperature of burner flames. In a series of tests on an oil-fired package boiler, the flame temperatures measured by this analyzer were found to correlate with burner excess air. Based on this experience and their general boiler design expertise, B&W judged that there is a reasonable chance that moving bed grate surface temperatures could also correlate with combustion excess air. If excess air control by bed temperatures monitoring could be demonstrated, it would likely be of much greater economic value than bed entrainment control since excess air control is a major determiner of boiler efficiency.

Potential Nonmilitary Power and Heat Plant Applications

Stokers, specifically spreader and overfeed stokers, have many useful applications and are still being used today. These applications are widespread throughout many manufacturing industries, such as:

- food
- tobacco
- textiles
- apparel
- lumber
- furniture
- paper
- printing
- chemicals
- petroleum
- rubber
- leather
- stone
- machinery.

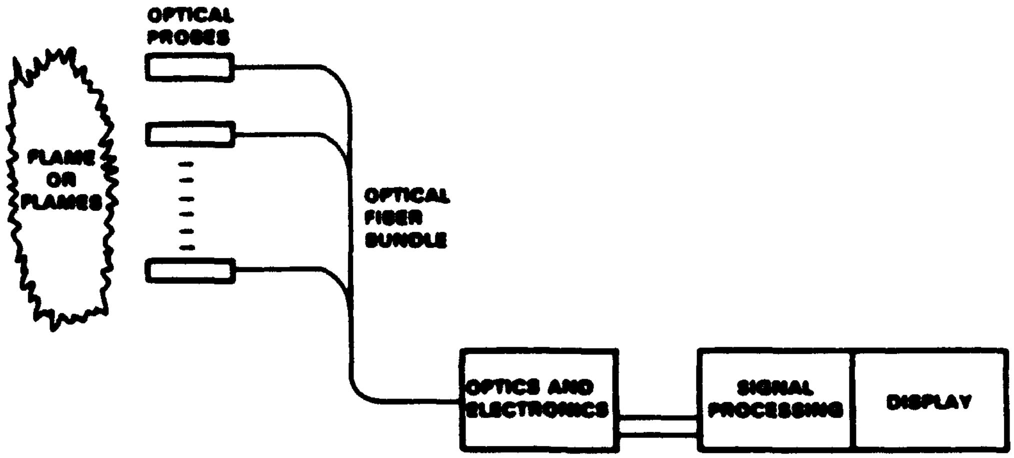

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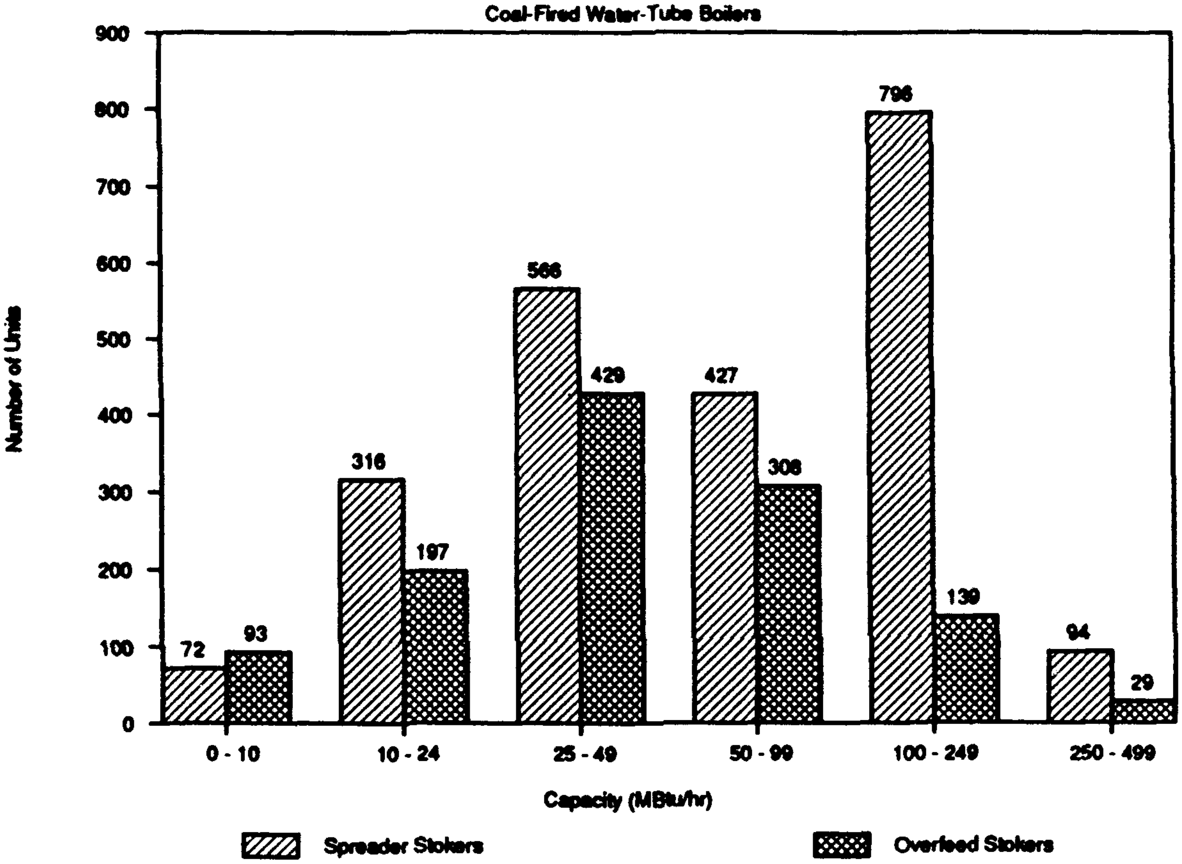
Figure 8. B&W's Fuel Quality Analyzer.

In 1985, there were approximately 2287 spreader stokers and 1200 overfeed stokers in use throughout these industries. These stokers ranged in capacity from less than 10 MBtu/hr to more than 500 MBtu/hr. Figure 9 shows a population distribution of the number and capacity ranges for these two stoker types and is based on information derived from a report prepared for the Burns and Roe Services Company (PEI Associates 1985). The figure also shows that there were approximately 427 spreader stokers and 308 overfeed stokers in the 50 to 99 MBtu/hr capacity range. Furthermore, there were approximately 16 spreader stokers and 5 underfeed stokers with a capacity greater than 500 MBtu/hr. This information implies that the monitoring system being addressed in this report could have widespread applications to many other industries.



Capacity Range (MBtu/hr)	Mean Capacity (MBtu/hr)	Number of Units	
		Water-Tube Spreader Stokers	Water-Tube Overfeed Stokers
0 - 10	5	72	93
10 - 24	17	316	197
25 - 49	27	566	429
50 - 99	74	427	308
100 - 249	174	796	139
250 - 499	374	94	29
> 500		16	5
Total		2287	1200

Figure 9. Boiler Population Distribution.

4 TECHNOLOGY STATUS REVIEW

Radiation Overview

Whenever an electric charge undergoes acceleration, an electromagnetic wave is formed that sends energy through space or other medium—air, gases, liquids, or solids—in somewhat the same way as waves spread out over the water when a stone is dropped into a pond. These electromagnetic waves are referred to as radiation.

Electromagnetic waves are called radio waves when they vibrate slowly enough to cause a response in a radio transmitter. They may be generated when electrons move up and down in the tower of a transmitting antenna. Electromagnetic waves of various high frequency ranges (Figure 10) are known by other names: heat, infrared radiation, visible light, ultraviolet light, x-rays, and gamma rays.

Combustion Radiation Spectrum

In solids such as coal, it is far more commonly the vibratory motion of electrically charged particles (ions) that give rise to the electromagnetic radiation referred to as infrared radiation. Every body radiates not just one type of radiation, but some of each. For example, a white-hot piece of coal in a fireplace (Figure 11) generates the most intense radiation in the infrared (IR) region, with some visible light and a small amount of ultraviolet (UV) radiation (too weak to be seen on the graph).

The three commonly used divisions of the IR spectrum are:

- the near-IR region, from approximately 0.7 to 1.5 micrometers
- the intermediate- or middle-IR region, from approximately 1.5 to 5.6 micrometers
- the far-IR region from approximately 5.6 to 1000 micrometers.

Blackbody Radiation

A blackbody is any object that completely absorbs all radiation incident upon it. Conversely, the radiation emitted by a blackbody at any given temperature is the maximum possible. A blackbody is therefore an idealized or perfect absorber and radiator of radiation, at all temperatures and for all wavelengths. Its radiating and absorbing efficiency, called its emissivity factor, is said to be "unity."

Any object, blackbody or otherwise, whose temperature is above absolute zero radiates energy throughout the IR spectrum. The amount and spectral characteristics of the IR energy radiated depend on the absolute temperature of the object, and also on its nature and surface finish. A highly polished surface such as a silver- or aluminum-surfaced mirror is an extremely poor radiator and absorber of energy; its emissivity factor is close to zero. A black, rough surface is a highly efficient absorber and radiator of energy; its emissivity factor is close to unity. Objects with emissivity factors less than unity are termed "graybodies," and the great majority of objects encountered in practice fall into this category.

The absolute temperature of the radiating object, the wavelength of the peak radiation emitted, the shape of the radiation intensity versus wavelength curve, are related by the following fundamental laws of physics:

- Planck's Law, which states that the intensity of radiation (referred to as spectral radiant emittance) associated with a blackbody is emitted or absorbed within a narrow band of frequencies in amounts that are proportional to the frequency of radiation and the temperature

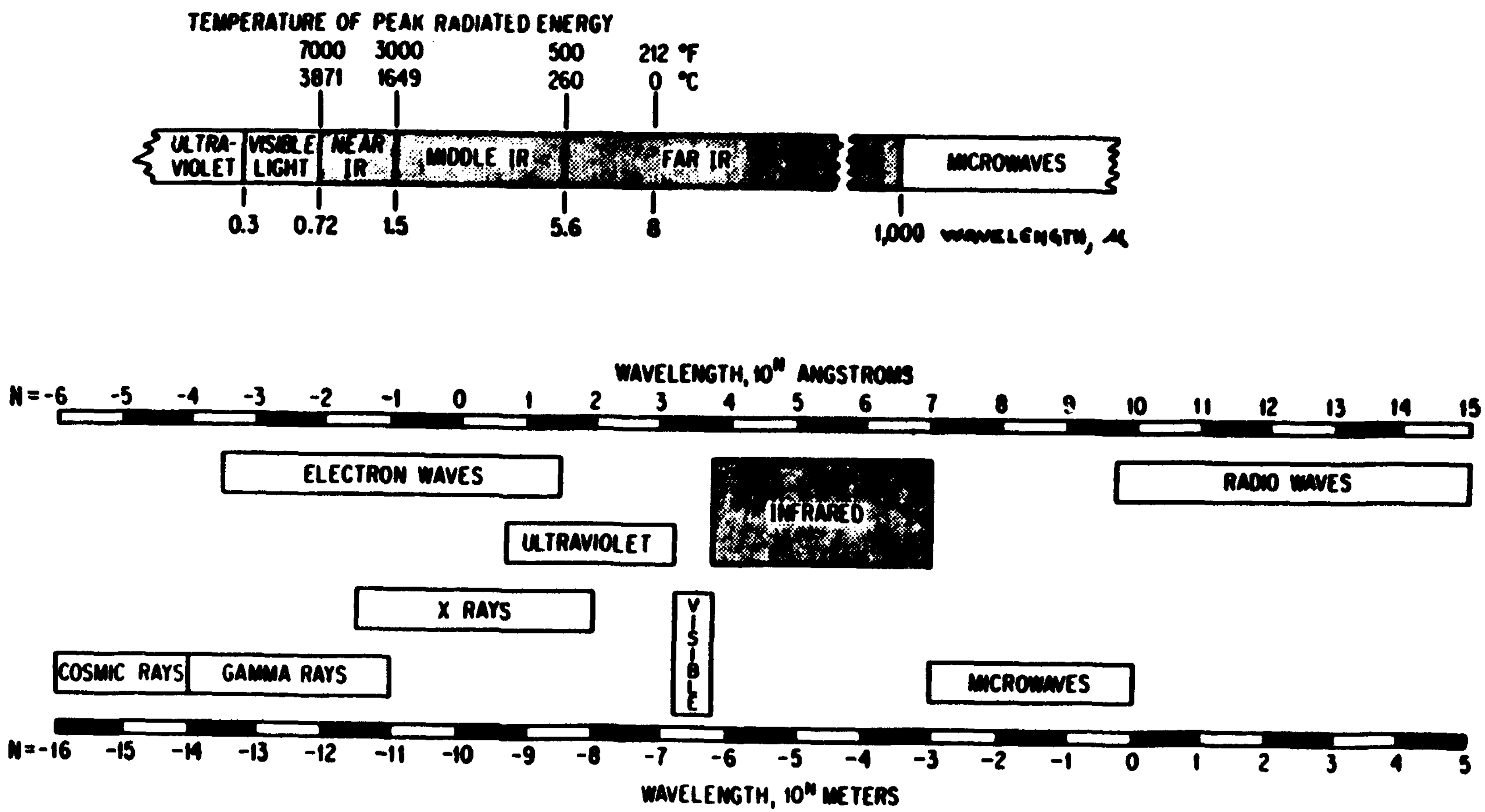


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Figure 10. The Electromagnetic Spectrum.

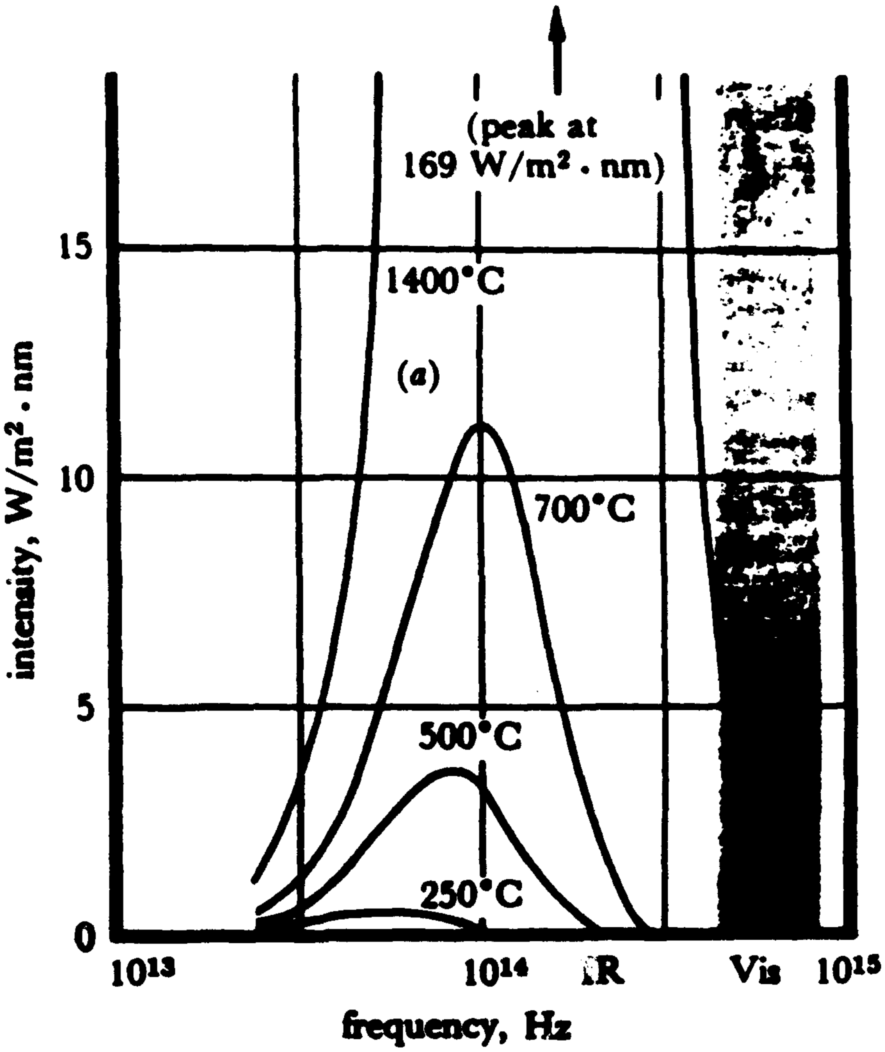

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Figure 11. Blackbody Radiation at Various Temperatures.

of the body. Figure 12 shows the spectral radiant emittance for blackbodies at various absolute temperatures. Note that, as the temperature of the blackbody increases, the intensity of the radiant energy emitted increases rapidly.

- Wein's Displacement Law, which states that the wavelength of peak radiance multiplied by the absolute temperature of the blackbody is equal to a constant. Figure 12 shows that as the temperature of a blackbody increases, its radiation peak shifts to shorter wavelengths.

- Stefan-Boltzmann Law, which states that the total energy radiated by a blackbody is proportional to the fourth power of the temperature of the body.

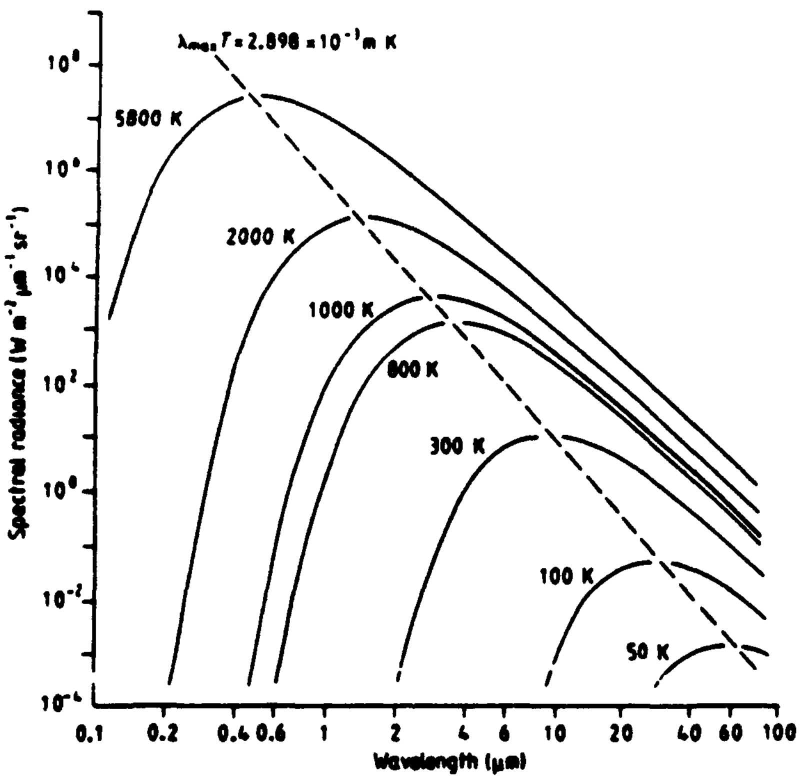

Figure 12. Blackbody Radiant Emittance vs. Wavelength.

Emissivity and Reflectance

The above laws all apply to blackbodies with an emissivity of 1.0. However, most bodies encountered in practice are not perfect blackbodies, but are graybodies, which radiate or absorb less than a blackbody would at the same temperature. Their emissivity is always less than unity (1.0).

The emissivity factor of an object is a measure of its radiation (and absorbing) efficiency. It is defined as the ratio of the radiation emitted by a graybody to the radiation emitted by a perfect blackbody at the same temperature. Graybodies do not therefore obey the laws governing a blackbody. The above laws must be amended by multiplying them by the emissivity factor, which therefore indicates the grayness of the radiating body. The lower the emissivity factor, the grayer the body; the higher the factor (the nearer it approaches to unity) the blacker the body.

Not all sources behave like graybodies. The emissivity on some surfaces varies with the wavelength. The wide range of emissivity factors for different types of commonly encountered low-temperature sources is illustrated in Figure 13.

Radiation Absorption by Combustion Gases

IR radiation emitted by the primary source (of radiation) and its background must pass through an environment or atmosphere before it enters a detecting system. This environment may be a lengthy passage through the earth's atmosphere, it may be a shorter passage through a gaseous atmosphere, or it may be a relatively short passage through a vacuum or an inert gas. Any environment, except for a vacuum, modifies the original IR radiation by absorption.

IR radiation from the primary source and its background, modified by passage through the intervening environment, arrives at the optical system of the IR instrument. Of critical importance in selecting or designing an optical system is its ability to limit the radiation incident on the detector to those wavelengths or wavebands desired.

The transmission of IR radiation through a spreader-stoker boiler depends on the concentration and distribution of combustion gases, specifically CO_2 and H_2O. An IR system that is required to operate over a long sight path must not be affected by variations in absorption arising from changes in the concentration of CO_2 and H_2O. Figure 14 illustrates the spectral transmission of these two substances and indicates a number of transmission windows—regions of maximum IR transmission.

Wavelengths that are transparent to the absorption bands of the combustion products within furnaces are generally readily determined. An overview article in the March 1988 issue of *Power* states that "A

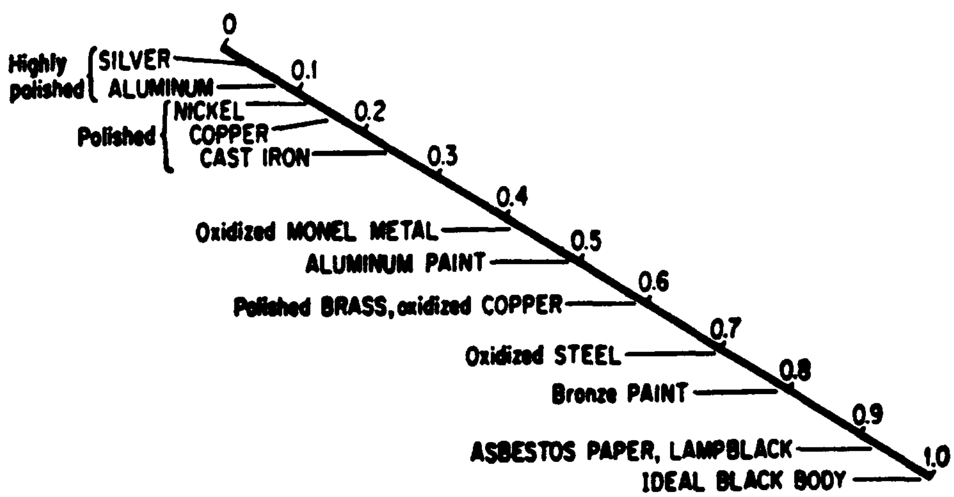

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Figure 13. Emissivity Factors of Various Room-Temperature Surfaces.

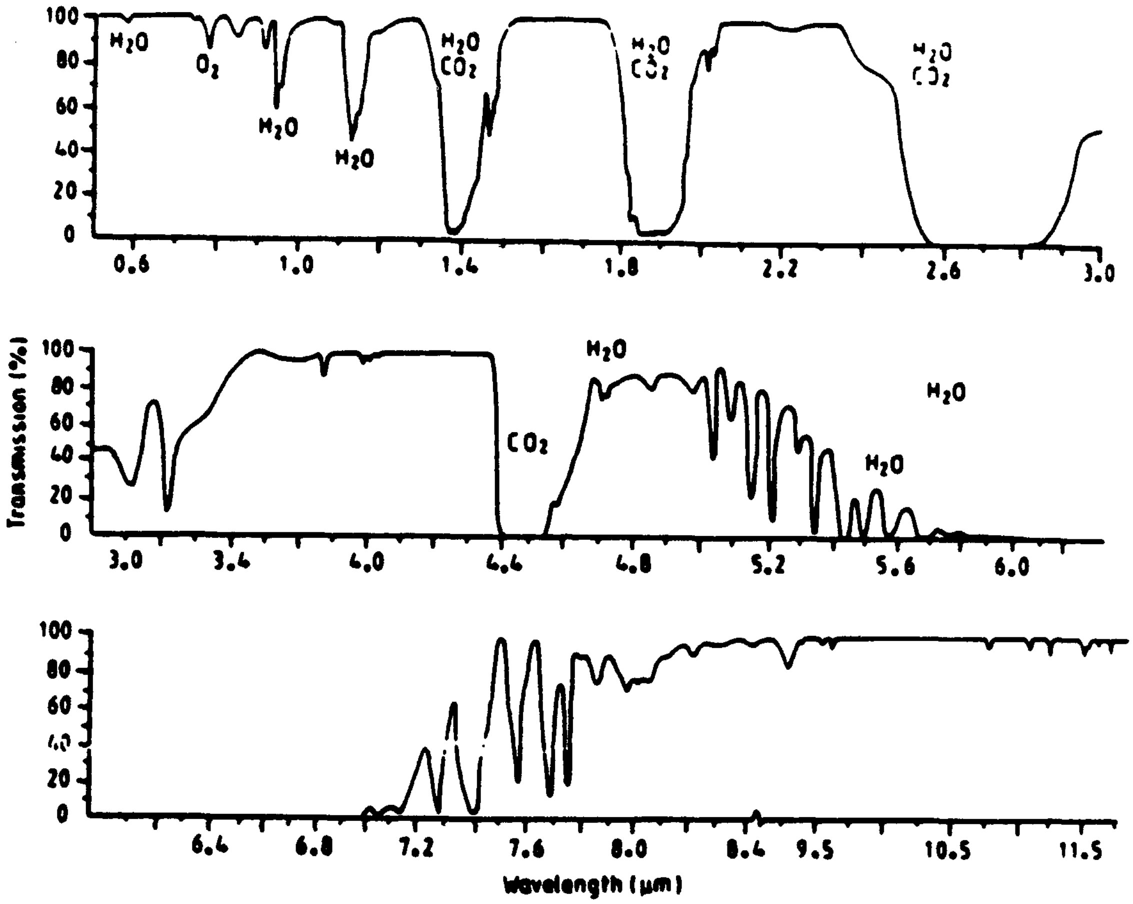

Figure 14. Spectral Transmission of the Atmosphere.

single-wavelength design, with a selective narrowband IR filter, in both portable and on-line instruments, measures fuel-bed and tube temperatures through flames. In this application, the sensor is filtered in the IR spectral region, where the basic components of a flame—water, CO, CO_2, and NOx—are transparent. Filtering in this fashion minimizes the attenuation effects caused by the flames. General-purpose portables, with simultaneous viewing of target and temperature, are also available for troubleshooting."

Radiometry Status Review

Approach

A list of references on relevant temperature measurement techniques was generated from the 1987, 1988, and 1989 volumes of the *Applied Science and Technology Index*. The Library of Congress and the George Washington University Library were visited to locate and obtain these references. Appendix A of this report contains an annotated list of these references.

Another list of references was identified through the Science Applications International Corporation's (SAIC's)* technical resource acquisition center (CTRAC). CTRAC accesses DIALOG, a computerized composite database of titles and abstracts of technical publications. DIALOG searches for keywords input by the user. First a list of titles is generated, then abstracts can be obtained for selected titles. CTRAC can also assist in obtaining copies of the full reports, which must be obtained from sources outside of DIALOG. DIALOG listed 108 titles under keywords relevant to fuel-ash bed temperature measurement, such as "spectral imaging," and "infrared measurement." Under "surface temperature," 59 titles were listed. Titles on imaging and temperature measurement covered many irrelevant topics such as space satellite imaging, a range of material applications, and cryogenic applications. As a result, 12 abstracts were requested from the total of 167 titles listed. These abstracts are included in Appendix A.

Hardware

Two basic types of available radiation temperature measurement instrumentation are point radiometers and imaging radiometers. Point radiometers measure the temperature at a particular point (typically an area 1 to 2 in. in diameter), whereas imaging radiometers view a large area and provide a visual display of varying contrasts (or colors) that correspond to different temperatures or temperature differences. Some imagers consist of a scanning mechanism, such as a system of rotating mirrors, added to a point radiometer, while other imagers, such as video cameras, have inherent scanning capabilities. The output of a radiometer is usually read directly as a temperature. Imagers typically show the output image on a video display terminal. The image from an infrared detector is converted to either shades of gray or different colors to represent different (relative) temperature ranges.

All radiometers have a detector that converts the incoming radiation to a "readable" electric signal (voltage or current). In addition to the subject radiation, detectors also detect "background" radiation that is emitted from its housing and other surrounding material. To minimize the effects of background radiation, detectors must be cooled. For accurate "absolute" temperature readings, cooling to cryogenic temperatures is required. This is commonly accomplished with liquid nitrogen. Other cooling agents are argon gas, built-in thermoelectric cooling, and compressed air. Video-type camera systems are available for both visible and infrared-range detection. These use filtered compressed air for both cooling and lens cleaning. These devices can accurately detect temperature differences, but not absolute temperatures. If the temperature of one point in the image is accurately known, then the temperature at other points can be determined.

In contrast to a visible-range video camera, which needs to be responsive to the broad band of radiation wavelengths covering the entire visible spectrum, infrared detection is usually limited to a narrow wavelength band that represents a "window" to the desired temperature. In the case of surface temperature measurement, a wavelength that can penetrate the atmosphere between the surface and the detector must be used. Both flame filters and smoke filters are used to attenuate radiation outside of the desired band. Wavelength bands centering around 1.2 and 3.9 micrometers are commonly used in boiler applications, as the normal products of combustion (carbon dioxide and water vapor) do not absorb radiation at these wavelengths.

The 1989 *Thomas Register* was consulted for an initial list of possible radiometer manufacturers. Other possibilities were added as a result of subsequently obtained information from personal contacts and the literature survey. For example, E^2 technology did not have any relevant equipment to offer, but suggested contacting SYN-FAB. NANMAC does not manufacture equipment suitable for this Project, but suggested contacting Infraspection Institute, which in turn suggested contacting the Sensor and Simulation

* Science Application International Corporation, 4161-T Campus Point Court, San Diego, CA 92121, tel. 619-458-3700.

Products Division of Weyerhæuser. Table 3 lists names, locations, and phone numbers of the identified manufacturers.

SYN-FAB manufactures a line of high-definition closed circuit TV monitors under the trade name of *Boilervision* that are being used to monitor boiler installations using a variety of fuels, including coal. Cameras are installed at grate level and at 10 to 15 ft above the grate. This system detects radiation in the visible and near-infrared range. They also have an infrared radiometer that is used in "smokey" environments through which visible radiation cannot penetrate. Either type of radiometer can be used with their patented image analyzer to display a temperature image on a video terminal. The temperature at any point is displayed when a moveable crosshair is positioned at that point on the screen. Vertical or horizontal temperature distributions can also be displayed graphically.

Software

Most, if not all, imagers can be obtained with optional software that allows recording of images on video tape, floppy disks, or some other media. Stored images can be "played back" and analyzed through a video monitor. The temperature of specific points on the image can be obtained by isolating the point with movable cross hairs or windows. Other available capabilities include the ability to graph the temperature along either vertical or horizontal lines in the image, or to "subtract" one image from a "reference" image. The latter feature is particularly adaptable to troubleshooting since it shows only areas of abnormal temperature on the monitor.

Table 3

Manufacturers' Information

Name	Location	Phone
Sensor and Simulation Products	Tacoma, WA	206/924-6287
SYN-FAB	Mobile, AL	205/633-4942
B&W Applied Meas. Tech.	Alliance, OH	216/821-9110
Inframetrics	Bedford, MA	508/670-5555
Hughes Aircraft, Ind. Prod. Div.	Carlsbad, CA	619/931-3617
AGEMA Infrared Systems	Secaucus, NJ	201/867-5390
Westinghouse Combustion Control	Orrville, OH	800/628-1200
IRCON, Inc.	Niles, IL	312/967-5151
E^2 Technology Corp.	Ventura, CA	805/644-9544
Omega Engineering, Inc.	Orlando, FL	407/282-7700
Nanmac Corp.	Framingham, MA	508/872-4811
Infrared Associates, Inc.	Cranbury, NJ	609/395-7600
Infrared Services, Inc.	Montville, NJ	201/263-1177
Electro-Optical Systems	Malvern, PA	215/644-4672

Relevant Applications

Radiation spectra have been successfully transmitted from the inside of coal-fired boilers and entrained-flow gasifiers to recording equipment using optical guides. Two-color pyrometry has been used to successfully determine temperatures from the transmitted data. These successes add confidence to the feasibility of measuring fuel-ash bed temperatures.

5 GRATE FUEL-ASH BED TEMPERATURES MONITORING SYSTEM

Conceptual Design

In the course of this project, a large amount of information was obtained from published literature, and from discussions with radiometer equipment manufacturers and current industrial users of radiometers. To put this information into perspective for accurate, reliable, continuous measurement of surface temperatures over a military heat plant, mechanical stoker boiler fuel-ash bed, a conceptual design of a fuel-ash bed temperatures monitoring system was developed. This section presents the rationale for and describes this conceptual system design. It also describes how the system could be used to improve boiler performance and, as a result, to reduce heating cost. In developing the conceptual temperatures monitoring system design, it was not possible to resolve all technical issues. These issues and associated technical risks are also addressed in this section.

Technical Conclusions

Based on the mechanical stoker fuel-ash bed conditions described in Chapters 3 and 4, the following conclusions were reached:

1. No commercial system was identified that can unequivocally continuously and accurately measure mechanical stoker boiler grate fuel-ash bed temperatures. No commercial applications of radiometers to coal-fired mechanical stoker boilers were found. The two commercially successful applications closest to mechanical stoker boilers were: radiometric temperature measurements in Kraft paper chemical recovery boilers and in industrial and utility-scale, coal-fired, bubbling bed, atmospheric pressure, fluidized bed combustion (AFBC) boilers.

2. Though no direct application of radiometry to measurement of mechanical stoker boiler grate fuel-ash bed temperatures was identified (nor any other commercially successful temperature measurement techniques), no definite technical reasons were identified why this technique would not be able to accurately, reliably, and continuously monitor bed temperatures. All radiation specialists contacted in the course of the project expressed the opinion that the technique has a high probability of technical success for measuring fuel-ash bed temperatures. Also, because of the difficulties in accurately simulating radiation measurements, most specialists recommended direct measurements on an actual fuel-ash bed to determine technique feasibility.

3. The most promising portion of the electromagnetic spectrum for radiometric measurement of mechanical stoker boiler fuel-ash bed temperatures is the near-infrared or possible mid-infrared region. At the temperatures encountered on fuel-ash beds (Figure 6), radiation is emitted predominantly in the visible, near-infrared, and middle-infrared region. Table 2 presents the wavelength of maximum radiance (peak emission) for the temperature profiles shown in Figure 6 assuming blackbody radiation. As temperature decreases, the amount of radiation in the small visual spectrum band decreases rapidly. At below about 600 °K, the portion of radiation emitted in the visual region is several orders of magnitude below its peak emission. The potential of the near-infrared region is substantiated by the relatively large number of radiometers operating in it.

4. The most promising portion of the near-infrared spectrum region is judged to be a narrow band centered at 1.5 micrometers. This judgement is a consequence of both technical and economic considerations. Boiler combustion gases are relatively transparent to infrared radiation (do not absorb infrared radiation) at wavelengths around 1.5 micrometers. Also, these wavelengths are being successfully

Table 4

Fuel-Ash Bed Temperatures Monitoring System
General Performance Criteria

Criteria	Comments
1. High durability	Construction consistent with military heat plant operations
2. Stable radiation detector	Electronic components must be very stable to allow long-term comparison of measured temperatures to standard temperatures
3. Monitoring of entire grate arm	
4. Temperature range capability of 300 to 3500 °F	
5. Continuous operation	Minimum temperatures updating of 2 minutes
6. Ability to follow boiler load	
7. Ability to interpret temperatures results	Output to operator as normal or abnormal bed temperature distribution
8. Low operator interaction	
9. Installation compatible with existing mechanical stoker boilers	
10. Self calibration	
11. Accommodate changes in coal quality	
12. Compatible with use of expert control system	
13. Capability to output complete set of radiation measurements	This feature would be used to establish control standards and for special R&D projects

used in the United Kingdom for bed temperature measurements in commercial bubbling-bed AFBC plants. From an economic standpoint, many commercial lens and detector systems operate well in the near infrared.

5. A possible alternative to a wavelength band around 1.5 micrometers is a narrow band centered on 3.9 micrometers. A potential advantage of this wavelength band is that the effect of reflected radiation (radiation from boiler tubes and other surfaces reflected by the fuel-ash bed) is less than at 1.5 micrometers. A potential disadvantage is that SO_2 and NO_X are not as transparent at this band as at 1.5 micrometers.

6. New solid-state infrared radiation detectors, developed for astronomical use from military sensor technology, have the potential to significantly improve the performance stability, and ruggedness of infrared detectors. Currently, infrared detector arrays of 64 x 64 pixels are available.

7. Review of pilot-scale tests that simulate under controlled conditions the combustion processes occurring in grate fuel-ash beds indicates that accurate, reliable, continuous measurement of bed temperatures (absolute or relative temperatures) would allow detection of conditions that would result in

bed entrainment with sufficient time to take corrective action. As discussed in Section 3.3 the two most likely causes postulated for bed entrainment are combustion air thermal choking and clinker formation. Both phenomena would manifest themselves in abnormal bed surface temperature distributions.

8. Discussions with B&W and others indicate that a radiometric system that measures bed surface temperature distribution could also be able to detect the onset of smoking. Smoke initiation would likely be manifested by both abnormal bed temperatures and an overall reduction in bed radiance due to smoke particulates interference.

9. B&W also expressed the opinion that accurate bed temperature distribution data could be used to infer boiler excess air concentration. Excess air estimates could then be used to optimize boiler efficiency.

Fuel-Ash Bed Temperatures Monitoring System Conceptual Design

The technology status review resulted in the selection of a narrow near-infrared wavelength band centered at 1.5 micrometers as a starting point for developing the fuel-ash bed temperatures monitoring system. Selecting this wavelength band is a key decision for developing the monitoring system conceptual design. This design decision can only be confirmed by actual radiation measurements over mechanical stoker boiler fuel-ash bed. These measurements could result in a decision to switch to a different wavelength band. This could, depending on how far the new wavelength band is from 1.5 micrometers, result in significant changes to the conceptual design presented in this report.

A major consideration in selecting a narrow near-infrared wavelength band was how the monitoring system output (results) would be used to improve boiler control. In the proposed temperatures monitoring system, the operator would receive interpreted temperatures measurement results. It would tell the operator whether fuel-ash bed temperatures were normal (within required operating conditions) or abnormal. In abnormal situations, the output would further show the operator bed locations where temperatures were abnormal. Determination of a normal or abnormal condition would be made by the monitoring system, not the operator.

The decision to propose a temperatures monitoring system that interprets actual temperature measurements, rather than leaving this to the operator, was based on a judgement about the capabilities of a typical operator. It was judged that providing a typical operator with a "yes" or "no" type output would be more effective than a display of bed temperature distribution that the operator would have to interpret.

An alternative to the proposed fuel-ash bed temperatures monitoring system would be a visible-range color imaging system using a high definition television display. Such systems are commercially available, e.g., the remote camera systems developed by Weyerhaeuser for inspecting remote areas in hostile environments. However, while these visible systems are useful in observing flaming and other characteristics not obscured by the flame, they cannot look through the flame at the radiant bed to monitor hot and cold spots on the grate. Because of this technical limitation, they were not considered in the project.

Table 4 gives the general performance criteria developed for the fuel-ash bed temperatures monitoring system. Two important monitoring system criteria not addressed in Table 4 are required temperatures measurement accuracy and precision. These were not specified because of insufficient knowledge about the response of fuel-ash bed surface temperatures to the direct causes of bed entrainment. Also, given the current lack of knowledge of bed entrainment causes and temperature distributions, it is not possible to determine if data on relative temperature differences are sufficient to detect the onset of bed entrainment, or if absolute temperature data is required. Answers to these questions require actual bed surface temperature measurements over a controlled range of boiler operating conditions including abnormal operating conditions.

Figure 15 shows a block flow diagram of the proposed fuel-ash bed temperature monitoring system. The proposed system is similar to a radiometer system developed by Weyerhaeuser for use in chemical recovery boilers and kilns at their pulp and paper mills. This radiometer system is also in use at other pulp and paper mills and is a commercial product marketed by Weyerhaeuser. The applications nearest to mechanical stoker boiler fuel-ash bed temperature measurement are measurement of combustion grate surface temperatures in hogged fuel boilers and infrared imaging of the smelt bed in chemical recovery boilers.

The Weyerhaeuser IR system enables continuous, remote monitoring of the fuel bed. This system provides the operator with information needed for real-time control. With these units, the operator can see the fuel spread and adjust feed rates to keep an even, clean-burning bed. The Weyerhaeuser image processing system can produce contrast-enhanced color images that provide a clear, detailed picture of boiler conditions. Subtle features such as flame color and shape, smoke density, grate condition, and fuel bed profile are shown in detail. The color images help the operator identify hot and cold regions at a glance. (Note that future options to the Weyerhaeuser imaging system will include the capability for on-line reference temperature readout on the viewing screen).

The proposed fuel-ash bed temperatures monitoring system consists of two main components: an infrared imaging camera and a computer. The camera looks into the boiler through a wall or roof penetration. Radiation from the fuel-ash bed is focused onto an imaging subsystem consisting of a solid state infrared detector array. A filter located between the focusing lens subsystem and the detector array limits the radiation wavelengths to a narrow band centered on 1.1 micrometers. The image formed on the detector array is periodically read and transmitted to the computer for processing.

Lens and filter subsystems for near-infrared applications are readily available and have been demonstrated under conditions at least as severe as those encountered in mechanical stoker boilers. Ruggedized camera housings are also readily available and demonstrated. Figure 16 shows a typical camera assembly for continuous boiler viewing.

The only new aspect of the proposed camera component is the use of a solid-state infrared detector array. These arrays are new, but appear to be superior to infrared vidicon tubes. The new infrared detector arrays are similar to silicon Charge Coupled Device (CCD) arrays and are read in the same fashion as CCD arrays. Two detector arrays that appear to be suitable for near-infrared imaging use mercury-cadmium telluride and indium antimonide materials. As far as could be determined, near-infrared solid state arrays have yet to be used in applications similar to boilers. However, they are currently being used in astronomical applications. Two potential advantages of using solid state detector arrays compared with a vidicon tube are greater electronic stability (reduced performance drift with time) and greater durability.

A number of subsystems are associated with the system camera component (lens, filter, and imaging subsystem). These are:

- Lens focusing. Lens focusing would only be required when the camera was moved or serviced. Focusing could be accomplished manually or by a remote manual method. Completely automatic focusing may also be feasible but was not investigated.

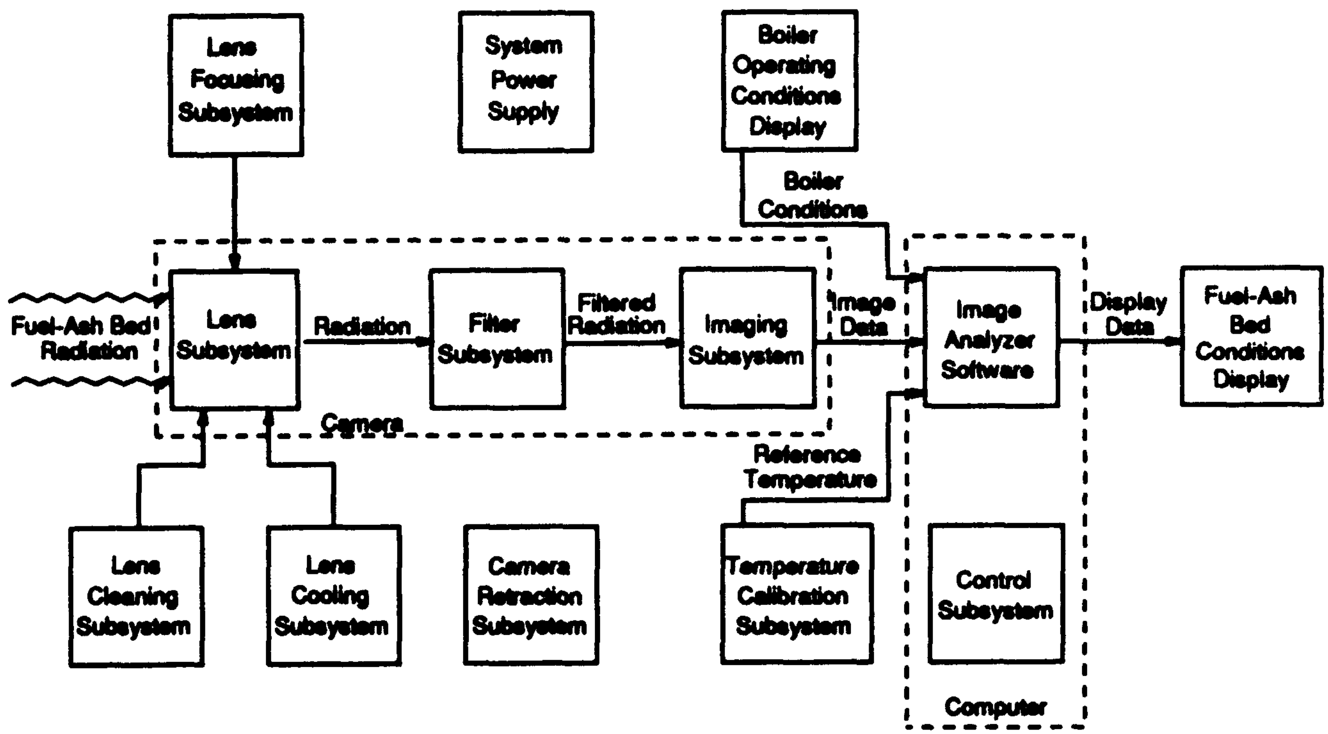

Figure 15. Fuel-Ash Bed Temperature Conceptual Design.

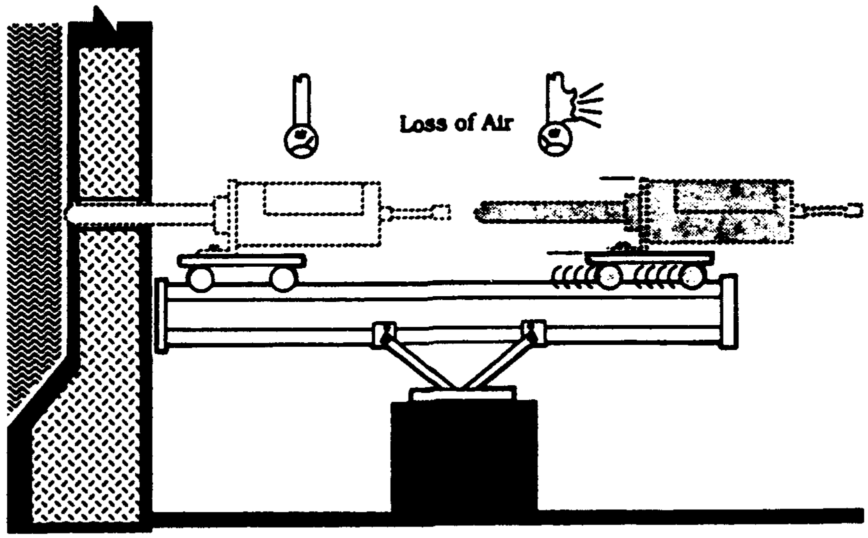

Figure 16. Typical Camera Automatic Retraction Mechanism.

- Lens cleaning. Lenses exposed to boiler environments are usually kept clean by an air flow technique. In this technique, air flowing across the lens is maintained at slightly higher pressure than in the environment being viewed.

- Lens cooling. Both the lens subsystem and the other camera components require cooling. This is commonly accomplished with cleaned air. The air cooling subsystem may also serve as the lens cleaning subsystem.

- Camera retraction. Considering the expense of an infrared camera, the ability to retract it from its normal viewing position to a safe position is recommended. One such subsystem is shown in Figure 16. In this figure, the camera is in the retracted position. Camera retraction and viewing position return is automatic.

Data from the infrared imaging camera are analyzed and interpreted by a computer. Results are displayed on a video terminal. The computer also monitors system operating conditions, such as components temperature and the availability of lens cleaning and cooling air, and shuts the system down and retracts the camera when required.

The main differences between the proposed system and the Weyerhaeuser system are the proposed use of a solid-state near-infrared detector array and imaging data analysis. The Weyerhaeuser system uses a vidicon tube for infrared detection.

Fuel-Ash Bed Temperature Monitoring System Data Analysis and Display

A critical aspect of eliminating or reducing fuel-ash bed entrainment is properly interpreting acquired bed temperature data. A conceptual approach to analyzing bed temperature data has been developed.

However, given the lack of knowledge concerning both the causes of bed entrainment and actual surface temperature distribution, different approaches might be developed once real temperature data is available.

The conceptual data analysis approach begins with the infrared detector array. Though a number of array configuration options are available, an array consisting of 64 x 64 picture elements or pixels was selected for concept development. Each pixel represents a discrete infrared radiation detector.

To interpret the radiation measured by the detector array, the fuel-ash bed grate area is divided into 1-sq ft areas. (Use of 1 sq ft areas is arbitrary, but serves to illustrate the proposed data analysis concept.) For the reference boiler grate (Figure 6), this means dividing the grate area into 120 squares. Since the detector array contains 4096 pixels, each grate square is represented by 34 pixels. (This is only an approximation due to geometric considerations associated with the camera viewing angle, but would be close for a roof-mounted camera.)

Each detector frame represents a measurement of the radiation emitted over the entire bed surface. The detector array needs to be read relatively frequently, at least more frequently than is judged necessary to update the fuel-ash bed temperature information displayed for the boiler operator. This is advantageous because it allows considerable averaging of measured bed radiation. If the detector array is read every half second and the operator display is updated every 2 minutes, each pixel radiation output will be the mean of 240 measurements. This mean value is typical of what might be expected, but there are a large number of averaging possibilities that need to be evaluated in arriving at a final data-averaging technique.

Radiation sensed by the detector array needs to be converted to temperature. This is done by applying Planck's Law. The actual mathematical procedure is moderately complicated, and considers: detector radiation wavelengths, responsivity, viewing geometry, radiating surface emissivity, and the optical properties of the lens and the filter that focuses a specific wavelength band on the detector array. The basic radiance-to-temperature conversion procedure can be visualized by considering the spectral radiance-to-temperature relationships shown in Figure 11. At a given wavelength (or frequency as used in Figure 11), each value of radiance (or radiation intensity) corresponds to a unique temperature. This allows conversion of measured radiance into temperature. Computer software for converting radiance measurements to temperature is widely available.

The greatest problem in interpreting radiance as temperature is determining the emissivity of the radiating surface. Because the proposed data analysis approach is based on a determination of bed surface temperature differences, this may not be a severe problem. However, the temperature accuracy limits depend on how accurately emissivity is estimated. This needs to be evaluated as part of bed temperatures monitoring system development.

To interpret "raw" temperature data for the boiler operator, it is proposed that the surface temperature associated with each detector array pixel in a grate square (1 sq ft of surface) be averaged to present a mean temperature. With 2-minute operator display updating, and half-second detector array reading, each bed surface square mean would consist of about 8160 temperature measurements.

To determine if a given measured fuel-ash bed temperature distribution indicates the onset of bed entrainment, it would be compared, grate-area square by grate-area square, with a set of standard bed surface temperatures. If any surface square is determined to be a certain number of temperature figures higher or lower than the standard temperature, this condition would be displayed to the boiler operator (Figure 17). A surface square within the standard temperature range would be indicated by one color. A square having a higher temperature would be indicated by a second color. And, a square having a lower temperature would be indicated by a third color. The display would also, for each surface square, display the estimated difference between the standard temperature and the mean measured temperature.

Figure 17 shows that the proposed boiler operator display would also contain text. This could advise the operator on the proper response to detection of an abnormal fuel-ash bed temperature distribution.

The standard (normal) fuel-ash bed temperature distribution, at minimum, is anticipated to change with boiler load and the quality of coal fired. To account for these effects, the computer would have in memory as many different standard bed temperature distributions as required. Boiler load condition would be determined from a suitable sensor, and provided to the computer to allow selection of proper boiler load. As-fired coal quality (or type) would likely be input by the operator via a keyboard.

Estimated Order-of-Magnitude Fuel-Ash Bed Temperature Monitoring System Cost

Based on reported costs for a fully developed commercial infrared temperature measurement systems similar to the proposed conceptual design, the estimated range of capital cost in current dollars is $60,000 to $100,000. Annual monitoring system operating costs are estimated to be low because of low power requirements and the reliability of the proposed system components. The main operating cost is expected to be maintenance.

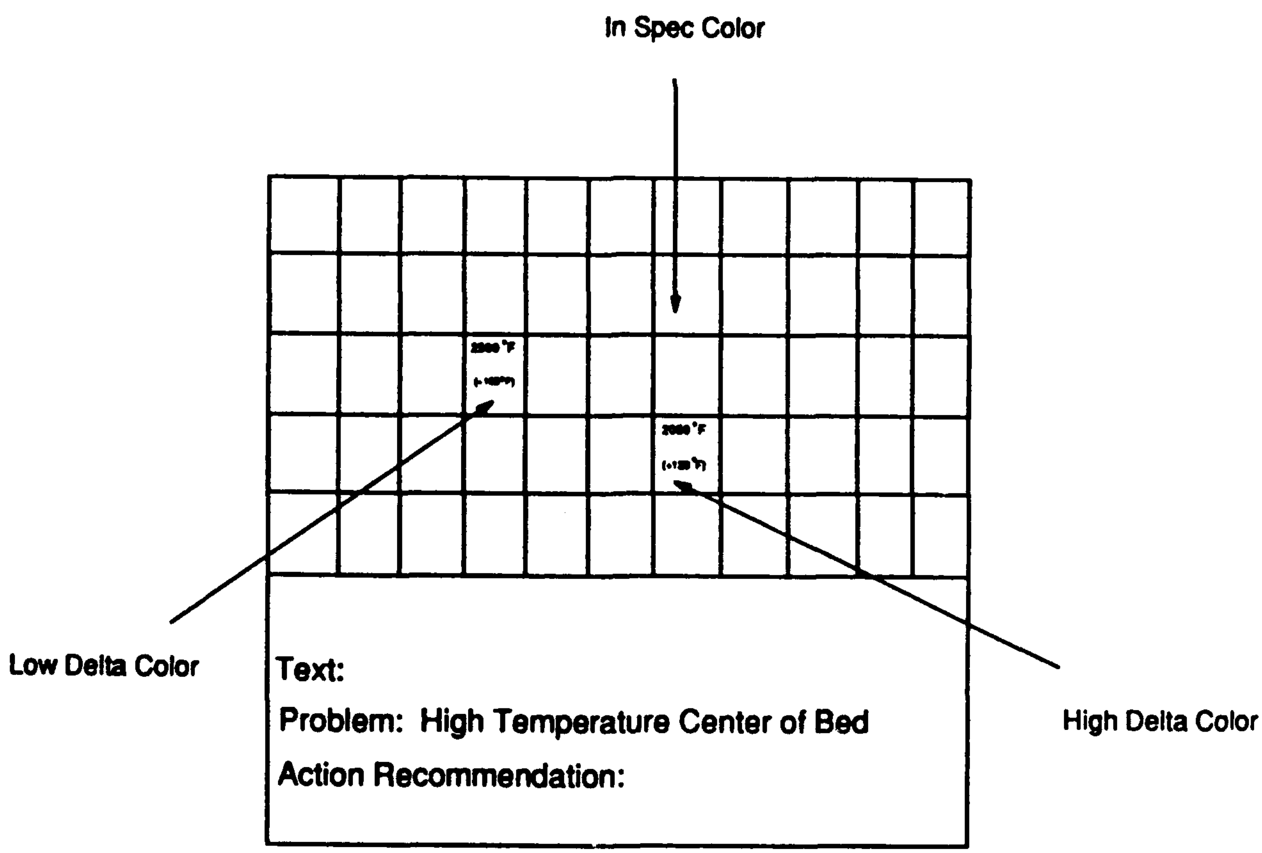

Figure 17. Proposed Fuel Ash Bed Temperatures Monitoring System Screen Display.

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study concludes that, based on currently developed commercial applications, it should be possible to adapt existing, nonintrusive radiation measurement systems to continuously and reliably monitor fuel-ash bed temperatures in mechanical stoker boilers. Newly developed infrared solid state detector arrays offer the best potential for developing a reliable monitoring system. Two commercial applications that support this are the use of radiometry to measure bed surface temperatures in AFBC boilers and smelt bed temperatures in pulp and paper chemical recovery boilers. The estimated cost of a commercial system to monitor mechanical stoker boiler fuel-ash bed temperatures would range from $60,000 to $100,000.

Such a cost would be offset by saving the cost of repairs or replacement of coal-fired stoker grates, which can be destroyed by excessive temperatures that can crack and warp plates. These damaged plates (or grate clips) could cause an unscheduled outage if not replaced. The cost to replace a grate is estimated to be $190,000, excluding freight and taxes (based on a 70 MBtu/hr spreader stoker-fired boiler requiring about 92 to 100 sq ft of grate surface). Considering that an automated monitoring system would substitute for a human operator visually monitoring the boiler, and also considering the high cost of grate replacement, it is likely that installing and using an automated system could significantly reduce the effort and cost required to monitor fuel-ash bed temperatures and correct associated problems and mechanical failures.

A fuel-ash bed temperatures monitoring system would probably eliminate or significantly reduce bed entrainment incidents by detecting bed temperature changes that indicate the onset of fuel-ash bed disturbances leading to bed entrainment. The most promising portion of the electromagnetic spectrum for fuel-ash bed temperatures measurement is a narrow near-infrared wavelength band centered at 1.5 micrometers. An alternative band, also in the infrared region, is centered on a wavelength of 3.9 micrometers.

It should be noted, however, that the ability of any system to detect the development of fuel-ash bed disturbances leading to bed entrainment in time to take corrective action ultimately depends on the root cause(s) of fuel-ash bed entrainment, which have not yet been determined with certainty. However, two causes of fuel-ash bed entrainment were postulated: combustion air thermal choking, and clinker formation. Thermal choking is associated with excessive grate temperature that limits the mass flow of combustion air over a significant area of the grate. This phenomenon is reported in pilot-scale, static combustion tests designed to simulate moving grate combustion, but it was not determined whether or not thermal choking actually occurs and, if so, its importance.

Conditions leading to fuel-ash bed entrainment can probably be detected by comparing measured surface temperature with a set of standard temperatures for normal operation of the boiler at a given load and firing a given coal. Different standard temperature sets would be required for different boiler load conditions and coals.

Continuous, reliable measurement of fuel-ash bed temperatures could, in addition to reducing bed entrainment, detect smoking and conditions leading to smoking, and be used to improve boiler efficiency through improved control of excess air.

No applications were found that use radiometry to measure fuel-ash bed temperatures in mechanical stoker boilers. This is probably because there has been little research to determine the economic benefits of improved boiler control and performance through bed temperatures monitoring. Also, the required radiation measurement technology is relatively new. Of the systems reviewed, however, the specific camera system apparently most suited to this purpose is that offered by Weyerhaeuser, since this system has been applied to an environment similar to mechanical stoker boilers. Though this system uses a vidicon tube rather than a solid state detector array, the manufacturer's information shows that it can accurately measure and analyze radiation at the recommended wavelength.

Recommendations

The recommended next step in developing a system to monitor mechanical stoker boiler fuel-ash bed temperatures is to perform a comprehensive cost-benefit evaluation. The potential cost of a commercial system is reasonably well known. The costs associated with fuel bed disturbance, however, are not well documented. If the cost-benefit of using a fuel-ash bed monitoring system to improve mechanical stoker boiler control is sufficient, temperature measurements at an actual boiler should be taken using a near-infrared camera.

REFERENCES

Carman, E.P., E.G. Graf, and R.C. Corey, *Combustion of Solid Fuels in Thin Beds*, USBM Bulletin 563 (1957).

Estimation of Fuel Use and Population for Industrial Boilers, Report prepared for Burns and Roe Services Company by PEI Associates, Inc., and P.W. Spaite Co., Requisition No. 8227-460 (June 1985).

Marskell, W.G., and C.W. Pratt, "Ash and Clinker in Practice-Handling and Disposal," *Journal of the Institute of Fuel* (1952).

Marskell, W.G., J.M. Miller, and W.I. Joyce, "Pilot Scale Testing of Fuels Under Spreader Firing Conditions," *Fuel* (1952).

Thomas Register (Thomas Publishing Co., New York, 1989).

APPENDIX A: Technical Literature Survey

Title: Pilot Scale Testing of Fuels under Spreader Firing Conditions

Author: W.G. Marskell, J.M. Miller, W.I. Joyce

Institution:

Publication: A Quarterly Journal of Fuel Science Jan. 1952

Comments: Good general description of fuel ash bed behavior and combustion characteristics in spreader stokers.

Synopsis: In a pilot program to simulate both chain grate and dumping grate stokers, temperatures were measured on the grate and at six different depths in the fuel ash bed. During combustion, the fuel ash bed is described as having three zones of non-equilibrium, equilibrium, and burn-out. In a dumping grate type of stoker, combustion proceeds time-wise through these zones from ignition to the dumping of the burned out ashes. In a travelling grate installation the zones occur spatially from the rear of the combustion chamber, where the grate travel begins, to the front, where the ashes are dumped. These zones are described as follows:

> "The 'equilibrium' is that between rate of fuel feed and rate of *combustion.* Equilibrium is indicated by the 1,000°F fuel bed isotherm running parallel to the bed surface."

> "A factor contributing to the lack of equilibrium of the first zone is the reduction in primary air supply. A graph of both grate temperature and primary air supply given in *Figure* 6b shows a rise in grate temperature caused by the burning bed immediately above. This, in turn, by causing an expansion of the air passing through the grate, reduces the mass flow. As a shielding ash layer develops on the grate, the grate temperature falls and the air supply increases. Thus, although there are no compartments under the grate and the under-grate air pressure is constant, there is a varying air supply along the grate length. Fuel beds of depths up to 4 in. have little resistance compared with the grate resistance unless abnormal packing or clinkering occurs.

> "Once the primary air supply reaches a steady value a condition of equilibrium can develop and continues for some time. The equilibrium state is unstable since the build up of the bed would cause a reduction in air supply. In both pilot and full scale practice the ash bed is, in general, never

permitted to interfere with the primary air supply.

"The stoppage of the fuel feed marks the end of the equilibrium zone and the beginning of the burning-out zone, ... With some fuels, usually those with high ash or moisture content, there may be no equilibrium zone *i.e.* the non-equilibrium zone merges directly into the burning-out zone."

Tests were conducted for a range of fuels from peat through bituminous coal. Results are presented using plots of isotherms for comparison of ash content, ash distribution (coarse extraneous or disseminated), volatility, and moisture content.

Title: Ash and Clinker in Practice — Handling and Disposal

Author: W.G. Marskell and C.W. Pratt

Institution:

Publication: Journal of the Institute of Fuel Sept. 1952

Comments:

Synopsis: Discussion of causes of ash and clinker formation and associated problems for spreader stoker and pulverized coal firing. Gives temperature distributions of fuel ash bed for spreader and travelling grate stoker, and discusses relationship to clinker formation. Results are given for coals of differing composition. Firing rates of 450,000 to 950,000 Btu/hr-ft^2 were used.

Title: Use of Jets to Produce Turbulence in Spreader-Stoker Firing

Author: H.G. Meissner and M.O. Funk

Institution: Combustion Engineering

Publication: Combustion Sept. 1944

Comments: Discusses effect of increased turbulence induced by air and steam jets on efficiency and smoke and fly ash emissions.

Synopsis:

Title: **Infrared Measurement of Surface Temperature Now a "Hot" Option**

Author: **Tom Elliot**

Institution: **Power**

Publication: **Power, March 1988**

Comments: **Very relevant overview article.**

Synopsis: **Describes different types of IR instruments and reviews available hardware. Specifically mentions an instrument that appears to be what we are looking for, to wit:**

> **"A single-wavelength design, with a selective narrowband IR filter, in both portable and on-line instruments, measures fuel-bed and tube temperatures through flames. In this application, the sensor is filtered in the IR spectral region, where the basic elements of a flame — water, CO, CO_2, and NO_x — are transparent. Filtering in this fashion minimizes the attenuation effects caused by the flames. General-purpose portables, with simultaneous viewing of target and temperature, are also available for troubleshooting."**

Title: Radiation Thermometry

Author: John Dixon

Institution: Land Infrared Ltd.
Sheffield S186DJ, UK

Publication: Journal of Physics E May '88

Comments: Some references may be of value.

Synopsis: Explains basic Physics and design principles of radiation thermometers. Gives some examples of practical problems and solutions, one of which discusses three possible configurations for measuring furnace temperature.

"An instrument based on a narrow waveband around 3.9 micrometers can be employed to good effect in industrial furnaces where high concentrations of carbon dioxide and water vapor are encountered."

Title: Investigation of Combustion-Chamber Deposit Thermal Behavior Utilizing Optical Radiation Measurements in a Fired Engine

Author: R.F. Harder C.L. Anderson

Institution: School of Mech. Eng. Mech. Eng. Dept. Purdue University Michigan Tech

Publication: Combustion Science and Technology Vol 60 '88

Comments:

Synopsis: Surface temperature of deposits in an IC engine combustion chamber was determined from data from three radiometers. One radiometer measured combustion gas emission, one measured combustion gas absorption, and one measured emission of surface deposits.

Title: Acoustic Temperature Profile Measurement Technique for Large Combustion Chambers

Author: S.P. Venkatedhan et al.

Institution: Jet Propulsion Lab

Publication: Journal of Heat Transfer May '89

Comments:

Synopsis: Describes a system capable of giving the temperature profile in a nonisothermal gas volume, e.g. inside a large furnace. Good to 2000°F.

Title: Nuclear Magnetic Resonance Imaging of Temperature Profiles

Author: Bryan H. Suits David White

Institution: Physics Dept. Dept. of Chemistry Michigan Tech Univ. of Penn.

Publication: Journal of Applied Physics 15 Nov '86

Comments: Primarily biomedical applications. Probably no application to furnace gases. Might apply to furnace walls.

Synopsis:

Title:	Monitor Furnace Temperatures by Acoustic Pyrometry
Author:	
Institution:	Babcock and Wilcox, Barberton, OH Scientific Engineering Instruments, Inc., Sparks, NV
Publication:	Power Jan '87
Comments:	
Synopsis:	B&W and Scientific Engineering Instruments are developing an instrument to measure furnace gas temperatures by measuring the speed of sound in the gas. Alternative to a water-cooled high-velocity thermocouple probe. Field tests are underway.

Title:	Monitor Furnace Temperature Distribution with Acoustic Pyrometry
Author:	
Institution:	UK's Central Electricity Generating Board Combustion Development Ltd., Bakewell, Derbyshire, England
Publication:	Power Jan '88
Comments:	
Synopsis:	Describes measurement of mean temperature by measuring speed of sound. Temp. range -- 32 to 5000 F.

Title: Two-Colour Pyrometer for the Statistical Measurement of the Surface Temperature of Particles Under Thermal Plasma Conditions

Author: J. Mishin et al.

Institution: Equipe Thermodynamique et Plasma
UA CNRS 320
University of Limoges
87060 Limoges Cedex, France

Publication: Journal of Physics E June '87

Comments:

Synopsis: Measures surface temperature of particles in a plasma (up to 10,000°K). Reference given to temperature of condensed particles in a furnace.

Title: Thermal Measurements in Large Pool Fires

Author: J.J. Gregory et al.

Institution: Thermal Test and Analysis Division
Sandia National Lab, ALbuquerque, NM

Publication: Journal of Heat Transfer May '89

Comments: Concerned with open fires such as those from accidents where inflammable substances are released. Not relevant to our problem.

Synopsis:

Title: Thermal and Temperature Measurement in Science and Industry, 3rd IMEKO Symposium, Sheffield University, 15-17 Sept. 1987.

Author:

Institution:

Publication: Journal of Physics E Jan '88

Comments: The proceedings might be a good reference. Also, there might have been subsequent IMEKO symposia by now.

Synopsis: Summarizes the title conference.

Title:	**Unburned Gas Temperatures in an Internal Combustion Engine**		
Author:	R.P. Lucht et al.	R.E. Teets	C.R. Fergson
Institution:	Sandia Livermore	G.M. Research Lab	Purdue Univ.
Publication:	Combustion Science and Technology Vol 55 '87		
Comments:	Not relevant		
Synopsis:	"CARS" measurement of unburned gas temperatures.		

Title:	Time-Resolved Temperature Measurements of Individual Coal Particles During Devolatilization
Author:	Thomas H. Fletcher
Institution:	Combustion Research Facility, Sandia Livermore
Publication:	Combustion Science and Technology Vol 63 '89
Comments:	
Synopsis:	Uses the signal to one radiometer to determine particle size, temperature, and velocity.

Title:	On Internal Temperature Gradients in Pyrolysing Coal Particle
Author:	Nahum Gat
Institution:	TRW Space and Technology Group, Redondo Beach, CA
Publication:	Combustion Science and Technology Vol 49 '86
Comments:	Not relevant
Synopsis:	Discussion of internal temperature gradients in burning coal particles.

Title: Temperature Measurement in Combustors by Use of Suction Pyrometry

Author: Y. Goldman

Institution: Dept. of Aerospace Engr., Israel Inst. of Tech., Haifa

Publication: Combustion Science and Technology Vol 55 '87

Comments: Not relevant

Synopsis: Concerned with gas temperature measurements.

Title: Bandwidth Emissivities of a Nonisothermal Blackbody Furnace for Calibrating Broadband Pyrometers.

Author: Zaixiang Chu et al.

Institution: Institute of Technology, Harbin, China

Publication: Applied Optics, Jan 15, '87

Comments: Too theoretical

Synopsis: Presents a theoretical method of pyrometer calibration

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Title: Liquid Measures Engine Hot Spots

Author:

Institution:

Publication: Design News, Nov 3 '86

Comments: Not relevant

Synopsis: Uses a temperature indicating material to measure outside surface temperatures of an operating internal combustion engine.

Title: Measuring Temperatures Radiometrically

Author: W.S. Jaroszynski

Institution:

Publication: Machine Design, Jul 9 '87

Comments: Not located.

Synopsis:

Title: Using Thermal Images to Measure Temperature

Author: T.G. Conway

Institution:

Publication: Mechanical Engineering, June '87

Comments: Not located.

Synopsis:

Title: A Fibre-optic Pyrometer for Tuyere Temperature Measurement

Author: J.M. Lucas

Institution:

Publication: ISA Transactions, no1 '88

Comments: Not located.

Synopsis: Might be useful

Title: Radiation Thermometry; Easy and Accurate Without Touching

Author: G.R. Peacock

Institution:

Publication: ASTM Standard News, May '88

Comments: Not located.

Synopsis:

Title: Physics of Free-electron-laser Applications in the Visible and Infrared

Author:

Institution:

Publication: Journal of the Optical Society of America B, May '89

Comments: Not located.

Synopsis:

Title: Slag Deposition Monitor for Boiler Performance Enhancement

Author: F.E. LaVert et al.

Institution:

Publication: ISA Transactions

Comments: Not located.

Synopsis:

Title:	**Prediction of Three-dimensional Flows in Utility Boiler Furnaces and Comparison with Experiments**
Author:	K. Groner and W. Zinser
Institution:	
Publication:	Combustion Science and Technology, Vol 58 no1-3 p43 '88
Comments:	Too theoretical
Synopsis:	

Title:	European Companies Show New IR Detectors and Systems
Author:	B. Dance
Institution:	
Publication:	Laser Focus Sept '88
Comments:	Very general
Synopsis:	Mentions products displayed at the Infrared Technology and Applications Exhibition held in London, U.K., June 1988. All are European companies. No specific applications are discussed.

Title:	Versatile Detectors Meet IR Imaging Needs
Author:	A.R. Tebo
Institution:	
Publication:	Laser Focus Nov '88
Comments:	Not relevant
Synopsis:	Discusses detectors for space observation and astronomical applications.

Title: Infrared Scanning: Broad Range of Powerplant Uses

Author: E. Feit

Institution:

Publication: Electrical World Nov '88

Comments: Not located.

Synopsis:

Title: Keeping a Close Tab on the Heat

Author: G.J. McManus

Institution:

Publication: Iron Age Mar' 89

Comments: Not located.

Synopsis:

Title: 1989 Trends in Detectors

Author: E.L. Dereniak

Institution:

Publication: Laser Focus World Jan '89

Comments: Not located.

Synopsis:

Title: Materials Work Supports Detector Advances

Author: A.R. Tebo

Institution:

Publication: Laser Focus World Jan '89

Comments: Not located.

Synopsis:

Title: Design and Simulated Performance of a CARS Spectrometer for Dynamic Temperature Measurements Using Electronic Heterodyning

Author: M.J. Dean and E.D. Thompson

Institution:

Publication: Applied Optics Apr '89

Comments: Not located.

Synopsis:

Title: Optical Spectral Radiometric/Laser Reflectance Method for Noninvasive Measurement of Weld Pool Surface Temperature

Author: H.G. Kraus

Institution: Idaho National Engineering Laboratory

Publication: Optical Engineering December 1987

Comments: The problems encountered in measuring weld pool temperatures are not very similar to those in furnace temperature measurement.

Synopsis: Describes a complicated experimental procedure for measuring surface temperature of a weld pool of a gas tungsten arc welding 1.5 mm thick stainless steel 304 plates using argon gas cover.

Title: Infrared Sensors Seek Out Hot Spots

Author:

Institution:

Publication: Electrical Construction and Maintenance

Comments: Not Relevant

Synopsis: Discusses the use of IR temperature sensors to locate trouble spots (such as loose connections) in computers.

Title: Combustion of Solid Fuels

Author: B.A. Landry

Institution:

Publication: Encyclopedia of Chemical Technology, 1951

Comments: A good primer for learning the basic aspects of coal combustion.

Synopsis: Covers most types of coal burning technologies. Discusses burning characteristics of solid fuels in different air-feed regimes — overfeed, underfeed, and cross-feed. Discusses variations of coal bed surface temperatures with bed thickness and composition of combustion products. "Little knowledge exists of the burning rates obtained in suspension from spreader stokers".

Title: Combustion of Solid Fuels in Thin Beds

Author: E.P. Carman et al.

Institution: U.S. Bureau of Mines

Publication: Bulletin 503, Bureau of Mines, 1957

Comments:

Synopsis: Investigates effects of various fuel properties on ignition and combustion characteristics in a small pilot scale furnace.

APPENDIX B: Equipment Manufacturers Survey

Company: Weyerhauser Co.
Sensor and Simulation Products Division
Tacoma, WA 98477

Phone: 206-924-6698

Contact: Gary Carlberg

Synopsis: Weyerhauser has developed a detection and imaging system that appears to be totally applicable to our situation. They have both a visible-band and an infrared-band cameras. The camera is mounted in an air-cooled lens tube 3 to 4 feet long. The field of view is normally set between 60 and 90 degrees, but can be larger. They can filter out smoke and flame, and electronically remove moving particles from the image. Images can be displayed in black and white or color. The temperature image and processing system (TIPS) provides a movable window on the screen. By moving the window around, temperatures at different locations can be obtained. Images can be stored automatically or manually. Costs are $15,000 for the basic black and white camera, $20,000 for the color camera, $50,000 for the color camera complete with TIPS.

Mr. Carlberg is sending some descriptive literature and the name of their nearest sale representative.

Company: SYN-FAB
7863 Schillinger Park Road
Mobile, AL 36608

Phone: 205-633-4942

Contact: Diann Ragazzo/Mark Kennedy

Synopsis: SYN-FAB manufacturers a high definition closed circuit TV monitoring system called Boilervision™ that is used to measure temperatures inside boilers, including burning-bed temperatures. Boilervision detects radiation in the visible and near infrared regions (500 to 1100 nanometers). They also have a patented infrared monitor. They also have an image analyzer that can be used in conjunction with the radiation detectors to display a temperature image on a video terminal. The temperature at any point is displayed when a moveable crosshair is positioned at that point on the screen. Vertical or horizontal temperature distributions can also be displayed graphically. The standard field of view is 90 degrees. Costs are $12,500 for the base camera and $5,000 for the image analyzer.

Mr. Kennedy claims their system will provide the capabilities we desire. SYN-FAB has monitoring systems installed in many installations, including coal-fired industrial and utility boilers. They are able to use the visible spectrum system in most (90%) cases, switching to their IR system for "smokey" applications (such as high-moisture fuels like municipal waste). They have sent us more descriptive literature and a video tape of four actual operations, and also will suggest some actual installations where we may see their equipment in operation.

Company: Hughes Aircraft Co. Industrial Products Div.
6155-T El Camino Real
Carlsbad, CA 92009

Phone: 619-931-3000

Contact: Tom Black, area representative, Sparks, MD, 301-472-2416

Synopsis: Hughes has a number of systems that should meet our requirements. Prices range from $11,000 to $50,000. Filters are used to penetrate flames and smoke. He has sent some descriptive literature and a "professional" video tape of numerous installations. After we review his material, we will contact him again.

Company: Inframetrics
12 Oak Park
Bedford, MA 01730

Phone: 508-670-5555

Contact: Tom Scanlon

Synopsis: Their equipment detects temperature differences on "just about any surface". Gases between the burning bed surface and the detector don't pose much of a problem. Particulates could be a problem. If the particulates are uniformly distributed and are cooler than the target, it should be possible to get a good feel for how evenly the bed is burning.

George Baird, 302-658-7590, is Inframetrics' representative in our area. He can demonstrate the equipment.

Company: Westinghouse Combustion Control Division
P.O. Drawer 901
Orrville, OH 44667

Phone: 800-628-1200

Contact: Blane Shank

Synopsis: The temperature range we are interested in is beyond the scope of their instrument. For infrared detection to work, the detector must be fairly close to the object of interest. Temperature may not be the right variable to measure (to determine fuel-ash bed thickness).

Company: IRCON, Inc.
7301-T N. Caldwell Ave.
Niles, IL 60648

Phone: 312-967-5151

Contact: Mr. Hassell

Synopsis: They sell spot radiometers, but no imagers. Prices for portable units start at $2300. A datalogger accessory can store up to 1000 readings. A demonstration can be arranged with a local sales representative. Mr. Hassell was of the opinion that "If you can't see the flame with your eye, then the pyrometer can't see it either.", which seems contradictory with all the other information.

Company: E^3 Technology Corp.
4475-T Dupont Court, No. 9
Ventura, CA 93003

Phone: 805-644-9544

Contact: Brian Smatko

Synopsis: They don't have any equipment applicable to the temperature range of our interest. Mr. Smatko suggested that SYN-FAB's Boilervision might be suitable.

Company: Infrared Associates Inc.
1000 Rte 130 E. Park
Crabbury, NJ 08512

Phone: 609-395-7600

Contact:

Synopsis: They manufacture only components, and do not retail complete assemblies.

Company: Electro-Optical Systems
271-A Grear Valley Pkwy
Malvern, PA 19355

Phone: 215-644-4672

Contact:

Synopsis: They do not manufacture anything for our application. Suggested contacting Omega Engineering.

Company: Land Instruments Inc.
2525 Pearl Buck Rd.
Bristol, PA 19007

Phone: 215-781-0700

Contact: Rich Gagg

Synopsis: They manufacturer spot radiometers. These are not normally used in a "scanning" mode. A thermal imager is what we need for our application. He recommended a system manufactured by Hughes Aircraft, and suggested contacting Tom Black, the area representative for Hughes Aircraft.

Company: B & W Applied Measurement Technologies
Contract Research Division
1562 Beeson St.
Alliance, OH 44601

Phone: 216-829-7617

Contact: Jeff Koksal

Synopsis: The Flame Quality Analyzer (FQA) was originally developed to look at coal flames. The FQA will pick up the hottest temperature in its line of sight. Our application is similar to their "burner" application. The FQA is a two-color pyrometer, which eliminates errors that can occur in a single color radiometer if there are variations in emissivity.

The FQA is not a commercial product because the market does not currently exist in the utility industry. (The FQA can detect areas of uneven air flow distribution, but since there is no method for redistributing the flow in today's boilers, it is of no practical value.) They could sell us expertise and a prototype system.

Company: AGEMA Infrared Systems
550 County Ave.
Secaucus, NJ 07094

Phone: 201-867-5390

Contact: Harry Devlin, area representative, Sparks, MD, 301-771-4506

Synopsis: He recommended a portable scanner with a flame filter. He is sending some literature on the AGEMA line. They can record scanned images on videotape, then get prints of any frame that includes a temperature readout and a date-time stamp. Prices range from $30,000 to $50,000. An imager would probably be better for our application.

Company: Omega Engineering Inc.
One Omega Drive
Stamford, CT 06907

Phone: 800-826-6342

Contact:

Synopsis: They do not sell imagers. They have infrared pyrometers that can see through blue flames, but not yellow flames. Their least expensive hand-held pyrometer costs $700 to $800. Pyrometers are shown in section C-1 in their catalog.

Company: Infrared Industries Inc.
12151-T Research Parkway
Orlando, FL 32826

Phone: 407-282-7700

Contact:

Synopsis: They manufacture only components, and do not retail complete assemblies.

Company: Nanmac Corp.
7 Mayhew Street
Framingham, MA 01701

Phone: 508-872-4811

Contact:

Synopsis: They do not have remote sensing equipment. They concentrate on contact measurement. Suggested contacting Infraspection Institute in Shelburn, VT as a source of pertinent manufacturers.

Company: Infraspection Institute
Shelburn, VT

Phone: 802-985-2500

Contact: Paul Grover

Synopsis: Recommended contacting Sensor and Simulation Products Division of Weyerhauser Co. as having "exactly what we want". Infraspection Institute conducts training sessions on equipment and how to use it. He has sent some literature on their activities.

Company: Infrared Services Inc.
P.O. Box 485-T
Montville, NJ 07045

Phone: 201-263-1177

Contact: Phil Lasker

Synopsis: Waiting for a return call.

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