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INDIVIDUAL BURNER AIR/FUEL RATIO CONTROL OPTICAL ADAPTIVE FEEDBACK CONTROL SYSTEM

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INDIVIDUAL BURNER FUEL/AIR RATIO CONTROL BY OPTICAL ADAPTIVE FEEDBACK CONTROL SYSTEM

Final Report

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Contents

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SUMMARY

Conventional combustion control systems for multiburner installations which rely on monitoring the average CO_2 and/or O_2 content of the gases have a number of inherent limitations on their ability to maintain efficient plant operation. Air infiltration into the flue or sampling lines has the same effect as an instrumental error in causing the control system to adjust the stoichiometry to an incorrect level. Even when the overall stoichiometry of the furnace is correctly and accurately controlled it is still extremely difficult to ensure that no individual burners are operating inefficiently due to local maldistributions of air or fuel, or to poor nozzle spray characteristics. The potential for fuel savings and for improved limitation of pollutant emissions has provided strong incentive for the development of individual burner fuel/air ratio control systems which would eliminate the shortcomings associated with the global control method.

The present report first reviews past attempts to identify some unique property of an individual flame which can be reliably interpreted as an indicator of the flame behavior over a wide range of operating conditions. Information potentially usable in this manner could be contained in the acoustic characteristics of the flame, in the local distribution of key chemical species, or in the electromagnetic radiation or absorption behavior of regions of the flame. For many reasons the previous studies have tended to concentrate on the optical portion of the electromagnetic spectrum, with particular emphasis on emission from flames over much of the ultraviolet (u.v.), visible and infrared (i.r.) wavelength regions. A brief review is given of the pioneering work of Penzias and his associates,

and of the later work carried out at Sheffield University by Smith which led to the development of the Land™ control system. All of these studies dealt with the infrared emission from flames, with particular emphasis on the CO_2 band at 4.3 μm, and on the H_2O/CO_2 bands near 2.8 μm.

The report then addresses the experimental work carried out at M.I.T under the sponsorship of five utility companies supporting the M.I.T. Energy Laboratory Electric Power Program. This focused initially on attempts to use a Land control system in the Combustion Research Facility (CRF), with limited success in terms of achieving stability and adequacy of control when operating conditions were varied over a moderate range. The experiments in the CRF also yielded very useful data on the intensities and sources of u.v. emission from No. 6 fuel oil flames over a wide range of fuel equivalence ratio. One other set of experiments carried out in the CRF made use of equipment and personnel supplied by the Foxboro Company, and results of this work are discussed.

Also included in the report is a summary of measurements carried out on a small methane-fueled burner which add appreciably to the available information on the dependence of the infrared emission on viewing location relative to the flame front and on fuel equivalence ratio.

The overall results obtained under this program do not leave the prospect of individual fuel/air ratio controllers within immediate grasp, but they substantially advance the state of knowledge required for attainment of such control. They give a strong indication that satisfactory control could be obtained over a wide range of furnace operating conditions if both i.r. and u.v. signals were monitored and used in the control system.

1.0 Introduction

There are two distinct yet related aspects to the control of large boilers for utilities or other industrial applications which have received considerable attention in recent years. The first of these deals with what is primarily a safety problem: as furnace sizes have continually increased, the need for positive indication of the existence of a flame has become steadily more critical, because of the potential for very large-scale explosions in the event of undetected malfunctions. Secondly, there is need for control of stoichiometry of a furnace, which is an especial problem for multi-burner installations: -because of the tolerances of the individual burners, the operation generally requires a lower overall fuel/air ratio than if all burners were accurately controlled to operate near maximum efficiency. Stringent environmental controls on emissions, coupled with escalating fuel costs, have produced very strong incentives for improving the accuracy of control for large furnaces.

The first area mentioned above - flame-monitoring - has motivated many studies of flame conditions in large units, and several techniques have been thoroughly investigated and proven in use. Thus there is a fundamental question with respect to the second area - stoichiometric control - i.e., to what extent can proven monitoring techniques be applied to the problems of control of individual burners in a multi-burner unit? The ideal control system - the Holy Grail, as it were - would maintain each burner's fuel/air ratio at an optimum setting, responding to load changes or to performance changes (such as degradation of the nozzle spray characteristics), but unaffected by the behavior of adjacent burners.

The various techniques which have been explored for flame-monitoring include use of in-flame probes and of acoustic methods, and exploitation of

extensive regions of the electromagnetic spectrum. Even for monitoring purposes, in-flame probes suffer severe problems from erosion or corrosion in many utility/industrial flame environments. Temperature determination by means of such probes is inadequate for stoichiometric control, while chemical sampling and analysis methods are slow and incomplete. Acoustic techniques have proved useful in single-burner units for indication of presence of flame, but they will be of no use for multi-flame boilers unless future research is focused on acoustic "radar" techniques, with measurement of wave intensity reflected back from a specific region in the flame-front of a particular turbulent flame. Again, the potential application is for presence-of-flame monitoring rather than for control.

The electromagnetic spectrum has been much more fruitful in yielding potential methods of flame monitoring and control. Some of the techniques studied use the microwave region of the spectrum, but for industrial flames there are serious difficulties in consistently matching the plasma properties with the available instrument capabilities. In the optical region, however, investigations and applications cover the ultraviolet, visible and infrared wavelengths, and the techniques used range from simple emission detectors to relatively sophisticated methods such as "flicker", "differential brightness", and "cross-correlation." All of the latter applications provide excellent safety in ensuring positive indication of existence of flame, but none is directly applicable to control of flame stoichiometry. However, the optical region of the spectrum provides the best prospects for monitoring capability which can be utilized in an automatic control system.

Conventional combustion control systems for multi-burner installations which rely on the average CO_2 and/or O_2 content of the flue gases have

several inherent limitations for efficient control. Air infiltration into the flue would clearly lead to erroneous adjustment of the stoichiometry, while it is also impossible to identify whether any individual burner is operating inefficiently due to fuel/air maldistribution and/or poor spray characteristics of the nozzle. Inefficient operation of individual burners or of the overall furnace is likely to lead to increased pollutant emissions, as well as to wastage of fuel. The increased fuel consumption and pollutant emission (NO_x, particulates) provide adequate incentive for the development of an individual burner fuel/air ratio control system which utilizes optically adaptive feed-back control and thereby eliminates the shortcomings of the conventional system, and the research discussed in this report was directed toward this goal.

In general the research problem was focused on the need to identify a unique optical property of the flame which could be reliably used to determine whether the flame was operating at the optimum setting under a wide range of operating conditions. The measurement of this optical property must then be incorporated into a dedicated feed-back control system which could maintain the flame at the optimum setting. A feed-back control system from flame to burner would eliminate the problems associated with the influence of design tolerances on the conventional open loop control system.

The spectral emissions from pre-mixed gaseous flames are known to consist essentially of banded radiation which is characteristic of the chemical species present in the flame. The science of spectroscopy as applied to flames is well developed and it is known that several of the gaseous species have easily recognizable signatures; e.g., CO_2 and H_2O vapor have distinct emission bands in the i.r. centered at 2.7 μm, OH has a

band in the u.v. at 306.4 nm and CO a band at 4.7 μm. It is also known that the total radiation in the i.r. from a flame will generally increase with flame temperature which in turn is a sensitive function of fuel/air ratio.

The research problem arises due to the significant differences which exist between pre-mixed gaseous diffusion flames and practical turbulent diffusion flames. The part of the flame that is optically accessible in a turbulent diffusion flame is the flame front where combustion is initiated. Depending upon the type of fuel used it will be coal volatiles or hydrocarbon vapors from fast vaporizing small liquid fuel droplets which will burn in this region. During combustion these hydrocarbon vapors are known to give rise initially to CO which then burns out with the OH radical produced from initial oxidation of the fuel-H and decomposition of water vapor. Kinetic studies of the burn-out of CO and hydrocarbon vapor suggest that the fraction of hydrocarbon decomposed and the OH concentration will vary with both local temperature and fuel/air ratio. Hence spectral information obtained from the early part of the flame should provide a measure of the quality of the flame. The absolute value of radiance in the i.r. could be used as a measure of the flame temperature while its spectral composition could give information on the ratio of the species concentrations. This was the theoretical basis for carrying out a systematic study in which fuel/air ratio in a liquid fuel turbulent diffusion flame was varied over practical ranges, and the spectral emissions from various positions within the flame were determined.

The research reported was almost entirely carried out using the M.I.T. Combustion Research Facility (CRF), a 1.2 m x 1.2 m x 10 m single-burner furnace capable of operating at loads up to 3 MW under conditions which

simulate the thermal environment of much larger boilers. Further description of the MIT-CRF is given in Appendix A.

Two principal lines of research were followed in parallel. First, a detailed study of the spectral radiation of the flame front region as a function of fuel/air ratio variations in liquid fuel flames was performed by using a high resolution spectrometer. The objective was to interpret the strength and spectral content of the emission from the various flame zones for the purpose of fuel/air ratio control. Secondly, a commercially available fuel/air ratio control system (the Land™ system), which employs the measurement of a broad band i.r. signal from the flame as the basis of an optically adaptive control system, was tested over practical ranges of fuel/air ratio and turn-down for a variety of flame types, i.e. liquid fuel flames with different swirl numbers.

Other CRF activity briefly reported here describes some measurements carried out at M.I.T. by personnel from the Foxboro Company, using an instrument furnished by their Foxboro Analytical Division. Also reported are spectrometric measurements carried out on a small methane-fueled burner with a turbulent diffusion flame.

The following sections of the report deal in turn with: a) background information on the overall research area; b) the spectrometric measurements carried out in the CRF; c) the spectrometric measurements on the smaller burner; d) the principles of operation of the Land control system, and the testing of that system in the CRF; and e) the measurements made with the Foxboro instrument. The final section presents conclusions and briefly discusses plans for further work in the CRF.

2.0 Background to the Research Problem

It is anticipated that any optically adaptive feed-back control system for individual burner fuel/air ratio control must be sensitive to the spectral and spatial variations of radiation from the flame as a function of burner fuel/air ratio. A review of previous work in this area is presented below, but this is preceded by a brief description of general turbulent flame emission characteristics, adapted from Reference 1.

The principal contributors to radiation in gas, oil and coal fired furnaces are the stable species such as CO_2 and H_2O, and particulates such as soot and fly-ash. In addition to the above there are emissions from the reaction zone (flame front region) in which the combustion chemistry takes place, and which contains free radicals and combustion intermediate species. Characteristic free radicals in this region are OH, CH, CN, and C_2. These radicals are produced in excited electronic states as a result of the chemical processes, and the region is characterized by strong visible and ultraviolet emission spectra.[2] The population distributions of the excited molecules may be characterized by non-equilibrium,[3] radiative lifetimes are short, and some of the radiation is chemiluminescent rather than thermal. The relationships between temperature and ultraviolet radiation are not necessarily unique, but depend on chemical processes going on within the reaction zone.[2] In addition, small quantities of impurities in the fuel, e.g. copper, sodium, chloride ions, can completely overshadow the ultraviolet and visible radiation due to the free radicals present. These extraneous effects can cause the ultraviolet and visible radiation to be somewhat dependent on impurities, so that care must be used in application of control strategies based on this spectral region.

Further downstream from the burner exit and reaction zone, however, the gases consist mainly of CO_2, N_2, and water vapor, together with more or less CO and O_2 depending upon the combustion efficiency. The molecules of CO_2, H_2O, and CO are thermally excited to higher vibration-rotation states in their electronic ground states. Consequently the burned gas region showns strong infrared emission and absorption bands at various wavelengths which can be associated with these molecules.

In most regions of a large industrial flame, suspended solid matter exists in addition to the gas molecules discussed above. The solid particles are heated up by the surrounding gas molecules and emit a continuous radiation spectrum of which most of the energy lies in the infrared region.

Table 1 contains most of the emission bands present in the u.v., visible and i.r. regions of the spectra observed from hydrocarbon flames.

2.1 Previous Studies on Control Methodology Relevant to Multi-Burner Furnaces

In order to apply spectroscopic control to a flame a spectral region must be found in which the radiation varies in a known way with the input fuel/air ratio to the burner.

One of the first proposals for use of spectroscopic data in a combustion control system was made in Reference 4. The author was concerned with achieving a very rapid response system for control of rocket engines or ramjet combustors, and he proposed monitoring two wavelength regions (through use of interference filters), and using the ratio of the emitted signals as a measure of combustor stoichiometric ratio. Use of

possible rotational lines and bands from CH, C_2, CN and OH was discussed in this context.

The pioneering work applicable to industrial and utility furnaces was carried out by Penzias[1,5] and his associates, who undertook preliminary investigations of flame radiation from pulverized coal flames as a possible basis for radiation sensing devices to improve combustion control in steam generators. The experimental approach taken was based on the known spectral characteristics of pulverized coal flames. Three different regions of a flame were identified as:

(i) region of relatively cool fuel reactants,

(ii) reaction zone where the exothermic chemical reactions occur,

(iii) burned gas region where the combustion is almost complete.

In the reactants region one finds relatively cool molecules of fuel and air and this region absorbs infrared radiation at wavelengths characteristic of the fuel molecules. As outlined in Section 2.0 above, the characteristic emitting molecules in the reaction zone are free radicals which emit in the visible and ultraviolet regions, while the burnt gases, downstream of the reaction zone, emit in the infrared region. Different spectral regions can be identified with certain properties of the system; e.g., infrared radiation of the combustion products is closely associated with the kinetic energy of the gas, and therefore can be used for flame temperature measurement and gas analysis . The spectral and spatial distribution characteristics of radiation from pulverized coal flames were measured as a function of combustion conditions in the range of 0.3 to 5.0 μm. Measurements on a small-scale burner (30 lbs. of coal per hour) were carried out at the Warner and Swasey research laboratory, and intermediate-scale flames (350 lbs. per hour) were investigated in an

International Flame Research Foundation (IFRF) facility at IJmuiden. The results established that spectral radiation by a pulverized coal flame in the wavelength region between 1.4 μm and 2.2 μm is sensitive to the fuel/air ratio when measurements are made in the flame-front region. The measurements demonstrate that as the secondary air is increased, the flame spectral emission decreases, as shown in Figure 1. These spectrally-resolved measurements in the 1.4 μm to 2.2 μm region were unaffected by absorption by infrared bands, either of H_2O and CO in the room air or of CO and methane in the flame. However, these bands did influence conventional "total" radiation measurements, integrated over the region 1μm to 5μm, and overall sensitivity to variation in fuel/air ratio was markedly decreased.

In order to apply these results to control a burner, Penzias proposed that a spectral flame monitoring device would be sighted on the flame and the flame radiation signal monitored, in order to operate the furnace at maximum efficiency. If the signal were to decrease from a "set point" value it would indicate too much air and, conversely, if the signal increased it would indicate too little air. Deviations of the signal from the set point could be used to adjust the secondary air to the individual burner. The set point would correspond to a particular fuel/air ratio required to give optimum burner and furnace performance. In order to determine the set point, measurements on a full-scale steam generator would be required, as the emission at the optimum operating conditions would be determined by the burner design and the furnace characteristics.

However, the very interesting results obtained by Penzias led Beér, et al.[6] to propose a significant improvement on the "set point" method of control; making use of the fact that the infrared emission in the flame-front region peaked near the stoichiometric mixture ratio, they

proposed a control system based on the "hill-climbing" or "peak-seeking" technique.

An "adaptative" controller working on this principle adjusts to an optimum which is a function of the physics and/or chemistry of the process being controlled, and thus is not subject to calibration errors or system drift. An essential feature of the hill-climbing method is the application of a modulation to the variable under control (in this case the air/fuel ratio). Pressure modulations on, for example, the air supply produce small but detectable modulations of the flame emission which are sufficient to permit the control circuitry to adjust the air flow towards the desired optimum value; when fuel load is changed, the system can in principle adjust to the correct air flow and restore the optimum air/fuel ratio.

Experiments to verify the applicability of this type of controller were carried out by Smith,[7] and published by Smith et al.[8] Smith studied a small pre-mixed gas flame and found peak infrared emissions at 2.8 μm and 4.4 μm (water vapor and CO_2 bands, respectively) near stoichiometric conditions, as shown in Figure 2. A prototype system was built and tested on a small-scale (2-3 kW_{th}) gaseous flame using either the 4.4 μm band or a wideband detector (1 to 3.5 μm band). Satisfactory control of the burner was effected with both wideband and narrowband monitoring; additional check-out tests of the wideband system were carried out on a 500 kW_{th} gas burner in a furnace, and with a 22 kW_{th} kerosene-fired furnace. The major problem encountered was in failure to detect the flame response to the modulation of air supply pressure under conditions of maximum load, but to some extent this could be alleviated by increasing the amplitude of the modulation. Smith's work did not establish

the extent to which these results can be applied to highly luminous, sooty flames.

This peak-seeking technique has been used in the Land™ instrument,[9] a control system (now commercially available) which is based on monitoring overall radiation in the 1-3 μm band, and which is discussed in some detail in a later section of this report.

An Environmental Data Corporation control system[10] utilizes a spectral flame analyzer. According to the brochure, the operational principle is as follows. Light from the flame is collected and sent to a wavelength selector (no specific wavelength information is given). The selector modulates (a) the signal corresponding to wavelengths emitted by intermediate combustion species, and (b) the signal from a nearby wavelength where these species do not emit. These modulated signals are used to form an intensity ratio which is a function of the fuel/air ratio of the burner; the output signal can be used to effect control of the air/fuel ratio.

Linford et al.[11] studied the spectral radiant intensity of burning aviation jet fuel (JP-4) for small diffusion flames in the range of 0.2 to 15 μm. Pronounced band spectra in the u.v. region were detected in the range of 0.2 to 0.3 μm due to CO and OH radicals. A broad band continuum existed throughout the remainder of the spectral region, i.e., 0.31 to 15 μm.

Sakkal et al.[12] described a fiber optic probe for application in emitting-absorbing flames. The probe is swept through the flame to be investigated and the spectrally resolved light signal transmitted by the probe is recorded. It is claimed this type of fiber optic probe can be used in flames containing solid particles.

Kuhnert and Gunther[13] studied the u.v.-radiation of the OH band (λ = .306 μm) and i.r.-radiation of H_2O and CO_2 (λ = 2.7 μm) with several crossed beam arrangements. Cross-correlation and cross-spectrum analysis were applied to the crossed beam signals. Crossed beam applications for the study of emitted flame radiation were found to be limited to those wavelengths where the flame can be assumed to be optically thin. The u.v. data can be interpreted as giving the dimensions of the reaction zones and the i.r. data as giving dimensions of the burned gas zones. Taken together the two sets of data for the entire flame field reveal a picture of the fuel-air mixing process, and, therefore, have a potential for control of the mixture ratio into a burner.

Harwell et al.[14] studied the spatial and spectral distribution of infrared radiation emitted from the exhaust plume of a small kerosene/oxygen hot gas generator operating at atmospheric conditions; the maximum radiation was found at 4.4 μm corresponding to the CO_2 and water vapor band.

Taylor et al.[15] measured time-resolved and spectrally-resolved radiance and time-resolved concentration and temperature in a turbulent diffusion flame, using a rapid scanning spectrometer with a spectral region of 3 to 5 μm to scan across the flame. As expected, a peak emission at 4.3 μm due to CO_2 was found.

Hartel[16,17] developed a television technique to investigate the radiation characteristics of luminous flames. The sensor was a television camera looking into the flame. The electronics which evaluate the measurements used the principle of a total- or post-radiation pyrometer. By using electronic compensators the brightness intensity distribution recorded by the camera can be converted to a voltage line diagram which can

then be interpreted as a temperature plot. The T.V. camera normally operates in the total frequency range of the visible electromagnetic emission spectrum, but it can be restricted to selected frequency bands by using optical filters.

Hutchinson[18] examined the spectral emission from gas, oil and coal industrial flames in the range 175 - 350 nm; he was especially interested in the OH bands, and found particularly strong emission in this spectral range.

Researchers[19] of Electricité-de-France examined the variation of flame emissions by altering the input and operating variables of burners in a power plant. They recorded the spectral emission in the range 400 - 750 nm and focused their attention on the measured signal fluctuations.

Gligo[20] reported experimental results obtained on the Loire-sur-Rhone power plant with variation of the air flow rate and the position of the fuel injector. This author suggested the possibility of using the u.v. radiation for the combustion control.

Beretta et al.,[21] working on a 3 MW_{th} boiler, explored the spectrum of oil diffusion flames in the range 250 - 800 nm. They found the strongest emission by gaseous products was due to the OH radical at 306.4 nm, and that the emission peaked near stoichiometric conditions.

Harvey[22] obtained measurements of flame radiation from three coal-fired utility boilers, as functions of both time and wavelength. His analysis of the flame fluctuations led him to conclude that these were caused by at least two independent mechanisms. One of them produced high frequency oscillations (>50 Hz) occupying a relatively narrow wavelength interval at the short wavelength end of the emission spectrum. These fluctuations appeared to be associated with the primary combustion zone,

possibly resulting from ignition of individual fuel particles. Fluctuations of the second type (consistent with turbulence) were at larger amplitude and lower frequency, and contained components which correlated well at different wavelengths. Not all components were correlated in this way, however, implying that the flame must be considered as having a multilayered structure with different emission/absorption characteristics in each layer.

2.2 Concluding Remarks

From the above survey of the relevant literature on spectral radiation from gas, oil and coal flames it is apparent that the following questions need to be answered as a step toward development of a reliable individual burner fuel/air ratio control system based on the spectral emissions from large turbulent diffusion flames:

i) What flame radicals or stable components can be reliably identified from spectral emissions from industrial-scale combustors fired with gas, oil, or coal, and how are these emissions influenced by fuel/air ratio changes?

ii) What is the spatial distribution of these emitters in the flame and what is the optimum detector position to cope with changes in burner loading and flame pattern?

Thus, the first line of research carried out in the CRF, based on this previous work, was an investigation of the spectral distribution and strength of radiation from different parts of No. 6 fuel oil flames as a function of the fuel/air ratio. Particular attention was given to the emission due to the OH radical and to hydrocarbon decomposition (~3.2 μm).

3.0 Spectro-Radiometric Investigation of No. 6 Fuel Oil Flames

Experiments were carried out in the Combustion Research Facility (CRF) on turbulent diffusion flames using No. 6 fuel oil. Fuel loading was typically 1 MW, and flame differences were obtained by variation of fuel/air ratio and of flame aerodynamics through change of swirl number setting. Steam atomization of the fuel was used. Additional details on the CRF are given in Appendix A.

3.1 Experimental System and Techniques for Spectro-Radiometric Study

The spectrometric measurements in the u.v., visible and i.r. spectral regions were made with a 0.6m focal length Jobin-Yvon monochromator. This instrument is equipped with independently adjustable entrance and exit slits, with two spherical mirrors and with two interchangeable diffraction gratings (1800 grooves/mm and 300 grooves/mm) for the u.v.-visible and i.r. regions, respectively. The maximal resolution is better than .015 nm in the visible and the numerical aperture (1/4.9) is very high for an instrument of this size. The internal arrangement is the Czerny-Turner layout; Figure 3 shows a schematic diagram of the system. A photomultiplier, mounted on the exit slit, receives the monochromatic radiation in the u.v.-visible region and gives, as output, a current signal proportional to the intensity of the incident light. The photomultiplier, EMI 9558 QB, in conjunction with a photocathode type S20 and quartz window to assure the transmissivity in the u.v., has a spectral range 150-850 nm; the power supply is an EMI model 300R. The current signal is converted into a voltage signal by a load resistor and sent to an amplifier. The amplified voltage is fed to a Servorecorder SR6252 strip chart or alternatively measured by a Keithley electrometer model 602.

For the i.r. measurements the photomultiplier is replaced by a cooled lead sulfide or lead selenide detector (Infrared Industries Inc. 2700 or 5700 series, respectively) depending on the spectral region of interest. Both these detectors are the photoresistive type, which need a bias voltage. The incident radiation is modulated by a mechanical chopper. The output signal consists of a d.c. and an a.c. component. An Analog Device true rms-to-d.c. converter model AD 536K is used to eliminate the d.c. component and to convert the a.c. component to a d.c. signal, which is successively amplified and recorded. All the instrumentation is mounted on a movable table to permit measurements at various axial locations along the flame.

3.2 U.V. Emission from No. 6 Fuel Oil Flames.

Interest in the u.v. emission centers on the characteristic emission spectra of the OH, CH, and C_2 radicals which have been previously identified in the early parts of both industrial and laboratory scale flames. Each of these radicals provides some measure of the local stoichiometry within the reaction zone of the flame. The OH species is particularly significant; the importance of its role in hydrocarbon combustion processes has been well-established.[23] It serves as an intermediary in the steps between hydrocarbon decomposition and final production of combustion products, being critical in the conversion of CO to CO_2.

Spectral scans (170 nm → 600 nm) made with the monochromator focused onto a flame region close to the exit plane of the burner showed that the OH emission in this region was very strong. CH emission was also detected, but it was not possible to resolve any of the characteristic C_2 emission lines in this region with any degree of confidence.

A typical spectral scan, obtained with constant furnace input conditions of ~ 1 MW firing rate, steam atomization and ~ 10% excess air, is shown in Figure 4. The characteristic OH emissions are clearly resolved with strong band heads at 306.4 nm and 309.0 nm; also clearly resolved is one of the characteristic CH emissions at around 431 nm. C_2 emission in the 500 nm region was not clearly resolved from the background or continuous flame radiation in this spectral region.

A more detailed spectrum of the OH emission is shown in Figure 5 where the fine structure of the emission band is well resolved. The strongest emission occurs at the band heads of 306.4 nm and 309.0 nm.

The effects of varying fuel/air ratio, flame aerodynamics (swirl setting) and viewing position on the OH emission were studied by setting the monochromator at the 309 nm band head in order to obtain maximum signal from the flame front region.

The change in intensity (in arbitrary units) of both the OH emission at 309 nm and the continuum flame emission at 306 nm as a function of fuel equivalence ratio, ϕ, is shown in Figure 6. These data were obtained by viewing the flame front from the front wall of the furnace at an angle of $\sim 20^{\circ}$ to the flame axis. Fuel flow-rate was maintained constant and ϕ varied by adjusting the air flow.

It was important to measure both the OH and the adjacent continuum emission across the fuel/air ratio range since it is to be expected that flame temperature and soot concentration will change with ϕ, thereby changing the level of the continuum emission. The measured OH and continuum emissions in Figure 6 show that the OH emission remains well above the continuum emission throughout the range of ϕ examined. This confirms that OH emission is a good candidate for obtaining a measure of flame quality vs.ϕ.

The OH emission shown in Figure 6 can be seen to decrease monotonically from a maximum at low ϕ (i.e. very lean flame). The continuum emission is seen to pass through a peak at $\phi \sim 0.9$. These data were obtained from a flame with zero swirl.

Figure 7 shows the OH and continuum emission intensities for a flame with swirl number of 0.5, viewed from the side. Also, in this experiment ϕ was changed by varying the fuel flow rate while leaving the air flow rate constant. There is a considerable increase in the OH signal strength over the continuum, indicating that at this viewing position the signal is coming from the early part of the flame front. The insensitivity of the continuum emission to ϕ also indicates that the signal is coming from the initial cone of the flame front where soot concentrations are low and make little contribution to the continuum emission.

Figure 8 illustrates the effect of increasing the burner swirl number to 0.9, producing a short, high intensity flame stabilized very close to the burner exit. The OH emission increases substantially over the continuum and passes through a peak at $\phi \sim .75$. In contrast the continuum emission remains quite flat across the range of ϕ studied. These changes in the OH and continuum emission with respect to ϕ indicate that flame shape and aerodynamics, and viewing position, are important variables which must be considered in any control system design.

Figure 9 shows the intensity of the OH and continuum signals measured at 3.5 inches from the front wall; it should be compared with Figure 7. Both sets of data were obtained from the same flame geometry, with different viewing positions. The OH emission profiles are seen to be quite similar, however at 3.5" from the front wall the difference between the OH and continuum signals decreases significantly as fuel rich conditions are

approached. This is a consequence of the extent of the reaction zone and the increase in continuum emission in this zone of the flame.

The decreased resolution of OH emission above the continuum is seen to be even more pronounced in Figure 10 where the flame was viewed at 6.25" from the front wall.

The fact that the OH emission is seen to be so sensitive to viewing position, and is only detected close to the flame front region, has two important practical consequences. First, any change in fuel/air ratio or burner operation which results in a significant change in the position of the flame front will have a large effect on the measured OH emission detected at right angles to the flame. The most severe case will be when the flame front is moved completely out of the line sight of the detection system.

Secondly, viewing the flame front from the front wall close to the burner axis will produce the smallest effect due to changes in flame front position. Most practical burner systems permit optical access to the flame in this region, which should be advantageous.

The influence of aerodynamic changes within the flame was studied by changing the swirl number as shown in Figures 7 and 9, and by simply changing the air flow rate at constant swirl. Figure 11 shows the effect of varying air flow rate (instead of fuel flow rate as in Figure 10) on the OH and continuum emission, viewed 6.25" from the front wall. The most striking difference in the profiles is that when the air-flow rate is changed the OH emission passes through a peak at $\phi \approx 0.65$. No peak is observed when fuel-flow rate is changed. Direct comparison of Figures 10 and 11 shows that the actual OH emissions are almost identical for $\phi > 0.7$. The decreased OH emission at $\phi < 0.7$ which was observed as the air flow

rate was increased is attributed to the displacement of the flame front from the line of sight of the monochromator as the air velocity in the burner increased.

The pronounced decrease in OH emission as a function of position in the flame is shown in Figure 12 where it can be seen that within 10 inches from the front wall the ratio of the intensities of the OH and continuum emission falls by a factor of ~ 3.

3.3 Conclusions from Spectro-Radiometric Studies

- the detection of u.v. emissions from No. 6 fuel oil flames shows promise for establishing a measurement of flame quality.
- the characteristic OH emissions appear to offer the strongest signal.
- OH emission shows an overall decrease with fuel equivalence ratio, and could form the basis of a flame quality control system.
- interferences in signal characteristics from flame aerodynamics and angle of view require further investigation.

4.0 Spectro-Radiometric Investigation of Methane-Air Flames

Infrared emission from a small (10 KW_{th}) methane-fueled turbulent diffusion swirl flame was investigated with the aid of the monochromator discussed in Section 3 and shown in Figure 3. The burner configuration is shown in Figure 13.

The primary objective of these measurements was determination of the variation of the 2.8 μm emission (CO_2 and H_2O bands) as a function of burner equivalence ratio. This is substantially the same type of measurement carried out by Smith,[7] the principal difference being that Smith worked with a premixed laminar flame, whereas results discussed in the present section are more directly applicable to the large-scale flames which are of major interest in the remaining sections of this report.

The burner was mounted horizontally, perpendicular to the monochromator axis. The flame was typically 100-150 mm in length; the burner could be moved along its own axis so that different cross sections of the flame could be focused on to the monochromator entrance slit. A 250 mm quartz lens was used for that purpose.

The monochromator was fitted with a 300 grooves/mm grating; entrance and exit slits used were both 1.5 mm wide and 12 mm high. The emergent beam was focused on to a lead sulfide detector, which imposed a low energy cut-off at 3.2 μm wavelength. The light beam was chopped at 400 Hz and the a.c. component of the detector output was rectified and fed to a chart recorder.

Each flame was examined at three different axial stations, corresponding to x/d_o values of 0.08, 0.6 and 1.0 (burner exit diameter d_o=31.5 mm). In each case a wavelength range from 2.4 to 3.17 μm was scanned. Excellent spectra were obtained, and plots showing absolute

values of emission intensity (W/cm^3-sr) are given in Reference 24. However, as the qualitative characteristic features of those spectra were insensitive to the variations in fuel load, fuel equivalence ratio or axial station, the spectral data are not presented here.

Figure 14 and 15 summarize the variation of emission with axial location, fuel equivalence ratio and fuel load. The ordinate in both figures is the detector output when the monochromator setting is fixed at 2.7345 μm, picked as one of the most stable wavelengths observed in the spectral scans.

At a fuel load of 15 liters/min (Figure 14) the intensity at x/d_o=0.08 shows a well defined peak at $\phi \sim 1.0$, but at distances further downstream from the burner exit the peak moves progressively to higher values of ϕ. In these cases the burner is operating in a fuel-rich mode, but the peak emission at the downstream location does not occur until the flame has entrained sufficient room air to burn the excess fuel. The effect is qualitatively similar to Smith's results.[7,8]

Operation of the burner at a smaller fuel load (Figure 15) yields a similar pattern of behavior, with peaks moving progressively towards the rich side of stoichiometric at axial locations further from the burner. However, all three peaks shown on Figure 15 occur at lower values of ϕ than the corresponding peaks on Figure 14. Again, similar shifting of values of ϕ_{pe} (i.e., value of ϕ at peak emission) as a function of fuel load was observed by Smith. The direction of the change in ϕ_{pe} with fuel load depends on other factors not determined in the present study; Smith's data showed opposite directions of change for his measurements on propane-air and methane-air flames.

As a check on the behavior of the emission data at λ=2.73 μm, the emission levels recorded on the spectral scans were integrated over the entire 2.8 μm band; peak locations for the integrated intensities as a function of fuel equivalence ratio remained unchanged.

Conclusions

The turbulent diffusion flame behavior is qualitatively similar to that previously observed for laminar flames, with emission at ~2.8 μm exhibiting a peak as fuel equivalence ratio is varied. Close to the burner exit this peak occurs in the vicinity of ϕ=1, but the data show great sensitivity to the flame geometry, fuel load and viewing location. In essence this is further confirmation of the usefulness of this spectral region to burner control applications, as in the Land™ System (see Section 5).

On the other hand, the sensitivity of the emission data implies that a control system based on monitoring a single wavelength region is likely to encounter difficulties if the flame geometry can change appreciably under the desired range of operating conditions.

5.0 Testing of the Land™ Burner Control System.

The Land Mark 3 Series 2 Controller[9], discussed briefly in Section 2, was developed in the U.K. as a sequel to the successful experiments carried out at Sheffield University.[7,8] One of these systems was purchased for evaluation and testing in the CRF; since the unit was not then (1979) available commercially in the U.S.A. it would have been difficult to secure the usual pre-installation survey and commissioning service without incurring excessive additional expense. However, as the M.I.T. research personnel had been closely associated with the early development work, it was considered that adequate expertise existed at M.I.T. for completion of the installation and commissioning of the purchased system.

5.1 Description of the Land™ Burner Control System

The Land Controller is a combustion control system which is capable of bringing the fuel/air ratio of a flame automatically to the stoichiometric point. The controller is an electronic device which effects its control on either the fuel or air flow of the combustion system via a standard pneumatically operated process control valve, whose control pressure (e.g. 3-15 p.s.i.) is derived from an output current from the Controller via an electro-pneumatic converter. If a nominal flow is set on one reactant (either by hand or as a part of some other automatic control loop), the controller should respond via its output circuit and control valve to alter the flow of the other reactant until the stoichiometric point is reached, whereupon that condition should be maintained continually, both major and minor flow adjustments (i.e. flow variations or even variation in chemical composition of the fuel) being corrected automatically.

A schematic of the system is shown in Figure 16. The Controller possesses three basic parts - a process control valve with electropneumatic converter and positioner, a master control unit which houses the electronic mechanism, and a radiation sensor which is mounted in a conventional water-cooled pyrometer housing. The latter is mounted on the furnace so that it is able to receive radiation from the flame.

The control system works by adopting the well known 'hill-climbing' principle, where it is assumed that the magnitude of a signal received by a detector will reach a peak when the point of stoichiometric combustion is reached. The detector involved is a radiation detector and the chosen wavelength of detection varies with the type of fuel being burnt, depending on which wavelength peaks most nearly at the desired point. For gas flames, for example, an infrared sensor at about 2.0 μm is used, whereas for an oil or other 'bright' flame, detection may be more appropriate in the visible part of the spectrum at 0.6 μm.

The system evaluates the burner fuel/air ratio by adding to the d.c. output current which controls the position of the fuel or air valve a small oscillating perturbation amounting to about 2% of the steady signal value, at frequencies ranging from 0.1 to about 1 Hz. This imposes a perturbation on the fuel/air ratio to the burner which provides the necessary modulation in the detected flame signal to apply the 'peak-seeking' control principle. The signal from the radiation detector is processed through an amplifier coupled to a synchronous rectifier which is phase-locked to the imposed perturbation wave, and the 'rich' or 'lean' condition can be derived from the phase of any detected signal content at the perturbation frequency. Figure 17 illustrates the principle of the 'peak-seeking' control system. If, for example, the radiation intensity is tending to increase as the

airflow increases, one can infer that the flame is fuel rich, i.e. increase in airflow has improved the combustion. The rectifier then adjusts the d.c. ouput current in the direction which permits larger airflow or smaller fuel flow. If the radiation intensity decreases in the above situation, the system is running 'lean', and the d.c. output changes to decrease airflow or increase fuel flow. When the imposed perturbation straddles the stoichiometric point, it can be shown that an a.c. component at double the basic frequency is produced by the radiation detector, and this will not pass the synchronous rectifiers. In the latter case, therefore, the rectifiers will produce no change to the d.c. control current. No control current change is produced if the detector is disconnected or if its signals show no correlation at all with the perturbation frequency. Thus there are three recognizable situations which can occur at the rectifier output and each of these states is used to produce system feedback by operating on the output current which in turn influences the fuel/air ratio via the control valve. If the control valve is mounted on the air line, 'rich' detection will cause the airflow to be increased, 'lean' will cause a corresponding decrease, and 'no-output' will leave the airflow unchanged. Thus in the 'automatic' condition, the whole system will behave as a negative feedback loop with stability occurring at the stoichiometric fuel/air ratio.

The actual hardware consists of four electronic modules and a radiation detector. The fuel and air valves, including the modulating valve, are not supplied, and a considerable effort was expended in obtaining and installing a suitable fuel-flow modulating valve and an electro-pneumatic converter system which was compatible both with the required fuel pressures

and flow rates and with the Land modulation module's electronic requirements. It was preferable to modulate the fuel supply rather than the air supply because of the practical problem of obtaining a suitable flow modulation system for the large diameter (28"I.D.) combustion air supply ducts.

5.2 Performance Characteristics of the Land™ Controller.

The system was installed and operated with both No. 2 and No. 6 fuel oil flames. Some difficulties were found in the initial calibration and setting up of the system. Since the controller is sensitive only to the measured phase difference between the fuel-flow modulating signal and the detected flame signal, it is important to accurately compensate for any inherent phase difference between the modulation command signal and the flame modulation which arises from the mechanical and transport delays occurring in the electro-pneumatic converter/actuator system and burner.

This must be done electronically within the modulator module in order that the resultant phase difference between the command signal and the meaured flame signal (due only to these mechanical delays) is compensated for by electronically delaying the command signal. This delayed command signal is used for comparing the phases of the imposed fuel flow perturbations and the resultant detected flame signal changes.

Some of the complications arising from phase delays may be inferred from Figure 18, taken from Reference 7. Smith introduced phase shifts mechanically by changing a cam position in the actuator mechanism of his pressure modulator. He showed that it was possible, within certain limits, to maintain a control point at a stoichiometric ratio other than $\phi=1$. Unfortunately the more stable operating regimes were all well into the

fuel-rich region; in the fuel-lean region the control point appeared very sensitive to the value of the phase shift, and therefore potentially unstable in a dynamic furnace environment.

In the CRF tests of the Land system these phase uncertainties caused severe operational problems. Figure 19 shows the phase relationship between the command signal and the burner oil pressure. The sensitivity of the control system to the value of this delay or phase shift was found to be such that it was difficult to maintain accurate monitoring of flame conditions when other system variables were altered.

In essence, it seemed that the Land control system can be set up to provide reliable control within a narrow range of process input changes. Careful positioning of the flame detector, and selection of the optimum modulation frequency and amplitude, did result in the correct response of the control system to changes in fuel/air ratio.

Figure 20 shows the output of the indicator and the response to a step change in air flow rate. The system is seen to respond quite rapidly and to provide an accurate and stable output. (These data were obtained with the control loop open, i.e. the Land system was acting merely as an indicator of flame fuel/air ratio.) However, slight changes in burner load, flame aerodynamics (swirl number), or detector position produced inconsistent indication of fuel/air ratio. Figure 21 illustrates the effect these changes had on the output of the Land control system.

Studies of the effects of these variables were made but the performance of the system remained quite inconsistent.

5.3 Conclusions

- The Land controller functioned adequately in maintaining correct fuel/air ratio over a narrow range of flame conditions in the MIT-CRF.
- Outside this narrow range the existing system's "front-end" flame detection unit is incapable of discriminating between fuel/air ratio changes and flame position changes due to alterations of load or of flame aerodynamics.
- The Land system requires some modification before satisfactory performance can be maintained over the wide range of conditions attainable in the MIT-CRF. Coupling of other optical signals such as those from the resolved OH or continuum emission could conceivably yield a "cleaner" flame signal and provide a more discriminating input for the system.

6.0 Measurements with the Foxboro Wilks Model 80 Spectrometer

Personnel from the Foxboro Company joined staff of the MIT-CRF for a day-long series of measurements on 7 November, 1979. The objective was to examine the spectral emissivity of No. 6 fuel oil flames and its dependence on fuel equivalence ratio. Two instruments were initially set up, one of which was intended for measurements in the microwave region. However, as back-scatter returns measured by this instrument showed no correlation with the burner behavior, no useful results were obtained.

The second instrument was a Wilks Model 80 Spectrometer capable of multi-wavelength recording and modified to accept the flame as a source. A section of flame approximately 12 mm x 55 mm was focused through a circular variable filter onto the spectrometer slit (0.5 mm). Preliminary experiments established that the major effort should be concentrated on the 1.5-4.5 μm region. Eight different wavelengths were selected for detailed study, designated as follows:

λ_3 = 1.780 μm

λ_4 = 2.049

λ_5 = 2.350

λ_2 = 2.670

λ_7 = 2.801

λ_8 = 3.000

λ_9 = 4.052

λ_6 = 4.161

Principal emitting species for this wavelength region were H_2O and CO_2, the latter particularly for the λ_7 and λ_8 settings. It was expected that λ_9 would be reasonably free from emission from gaseous species, and thus available as a reference wavelength. These wavelengths are also

susceptible to self-absorption from the same (cooler) species along the instrument line-of-sight, and no corrections were made to the data for this effect.

Other preliminary experiments established that a viewing angle of 45° to the burner axis was most advantageous, and the principal data-gathering was carried out at this angle.

The data obtained are summarized in the plots of Figure 22, showing instrument response as a function of fuel equivalence ratio. All wavelengths exhibited the same trend, with the response peaking near ϕ = 1.1. An absolute comparison of the instrument response at each wavelength was difficult since the CVF filter response is not flat across the appropriate wavelength range, nor is it uniform from one segment to another. Superimposed on the hot species emission profiles was the emittance curve for soot particles and the furnace wall. In an attempt to compensate for these complicating effects, the individual wavelength data were ratioed against the data at 4.05 μm, which was chosen for its presumed independence from atmospheric absorptions; the resulting ratios are plotted against the appropriate ϕ value in Figure 23. The estimated scatter for each point is ~ 0.07 units and is shown for one data point for the data at λ_7. This error arose from the turbulence in the flame and could be significantly reduced by instantaneous measurements of emittance at all appropriate wavelengths (e.g. rapid scan, multidetectors, FTS). In view of this scatter it seems that no clear trends with ϕ can be deduced from the normalized data, and no conclusions can yet be drawn which would be helpful to the development of adaptive feedback control systems.

7.0 Conclusions

The Land™ burner control was shown to provide adequate control of fuel/air ratio in the M.I.T. Combustion Research Facility, but only over a limited selection of the entire range of flame conditions accessible in that facility. Used in an open-loop mode, the detection unit of the control system was found to be incapable of discriminating between fuel/air ratio changes and flame position changes caused by change of load or of burner swirl.

It appears that substantial increase in the range of stable operation of such a controller might be effected if additional spectral information were coupled into the system to aid in the determination of the correct flame stoichiometry. The spectro-radiometric measurements carried out in the CRF indicate OH emission to be a prime candidate as the source of this additional information. While the OH emission does not peak near $\phi = 1$ (as the infrared emission tends to do), it serves as a clear indicator of the presence of the OH species which is a critical intermediate in the oxidation of the CO formed early in the combustion of hydrocarbon fuel droplets.

At the outset of this study there was an intent to evaluate the performance of another burner control then being marketed - the Spectral Fuel Conservation System (SFCS), produced by Environmental Data Corporation.[10] Unfortunately so little information was available on this system that the intent was abandoned. Recently a version of the SFCS has been donated to M.I.T. by Thermoelectron Corporation, now the parent company for EDC. It is intended that future M.I.T. experiments with this equipment should be carried out in the CRF in "piggy-back" mode while other research is in progress. Thus recommendations for future work on the development of optical adaptive feedback control systems for fuel/air ratio will not be made until initial SFCS data have been gathered and evaluated at M.I.T.

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Table 1a. U.V. and Visible Spectral Emission Bands

The following tabulation includes the predominant band heads observed in emission from C_2H_2-air flames in the wavelength region 180-900 nm. Most of the emission originates in the inner cone of the flame. Source: Flame Spectroscopy (Radu Mavrodineanu and Henri Boiteux), Wiley, London, 1965.

BAND HEAD(nm)	INTENSITY	SHADING	EMITTER
306.4	******	R	OH
312.2	******	R	OH
314.4	*******		CH
315.66	******		CH
318.5	**	R	OH
325.4	*	R	OH
336.0	**	M	NH
358.39	***	V	CN
358.59	***	V	CN
358.76	***	V	C_2
359.04	**	V	CN
386.19	*	V	CN
387.14	******	V	CN
388.34	******	V	CN
387.2	******	R	CH
431.2	*******	V	CH
432.4	*******		CH
436.52	*******	V	C_2
437.14	*******	V	C_2
438.25	*******	V	C_2
466.87	*******	V	C_2
467.86	*******	V	C_2
468.48	*******	V	C_2
469.76	*******	V	C_2
471.52	*******	V	C_2
473.71	*******	V	C_2
477.01	**	R	C_2
499.67	*******	R	C_2

BAND HEAD(nm)	INTENSITY	SHADING	EMITTER
509.77	*******	V	C_2
512.93	*******	V	C_2
516.52	*******	V	C_2
547.03	*****	V	C_2
550.19	******	V	C_2
554.07	******	V	C_2
558.58	******	V	C_2
563.55	******	V	C_2
590.1	**	V	C_2
592.34	**	V	C_2
595.87	*****	V	C_2
600.49	*****	V	C_2
605.97	*****	V	C_2
612.21	*****	V	C_2
619.12	*****	V	C_2
653.37	*	V	C_2
659.92	**	V	C_2
667.73	**	V	C_2
676.32	**	V	C_2
685.88	**	V	C_2
722.7	******		H_2O
746.0	******	R	OH
771.46	******	R	C_2
785.0	******	R	OH
790.77	******	R	C_2
795.7	******		H_2O
810.82	******	R	C_2
822.7	******		H_2O
827.8	******	R	OH
875.08	******	R	C_2
898.05	******	R	C_2

Table 1b. Infrared Spectral Emission Bands

The following tabulation includes the dominant infrared molecular bands seen in emission from hydrocarbon-air flames. Source: The Spectroscopy of Flames, (A.G. Gaydon), Chapman & Hall, London, 1974.

WAVELENGTH (μm) BAND ORIGIN	WAVELENGTH (μm) BAND HEAD	EMITTER	STRENGTH	COMMENTS
1.8752		H_2O	v. strong	
2.3467	2.2929	CO		vib-rotation overtone
2.3762	2.3221	CO		
2.4064	2.3519	CO		
2.6618		H_2O	v. strong	
2.6912		CO_2	strong	
2.7337		H_2O	strong	
2.7672		CO_2	strong	
2.8007		OH	weak	masked by CO_2 + H_2O
3.1722		H_2O	strong	
4.2557	4.1713	CO_2	v. strong	modified by self absorption
4.2790	4.1912	CO_2		
4.2955	4.2110	CO_2		
4.2970	4.2057	CO_2		
4.3014	4.2140	CO_2		
4.6644		CO	moderate	self-absorbed and masked by CO_2
4.7228		CO	moderate	
4.7825		CO	moderate	
6.2698		H_2O	v. strong	
13.8699		CO_2	moderate	intensity about 1/200th of 4.3 μm intensity
14.9794		CO_2		

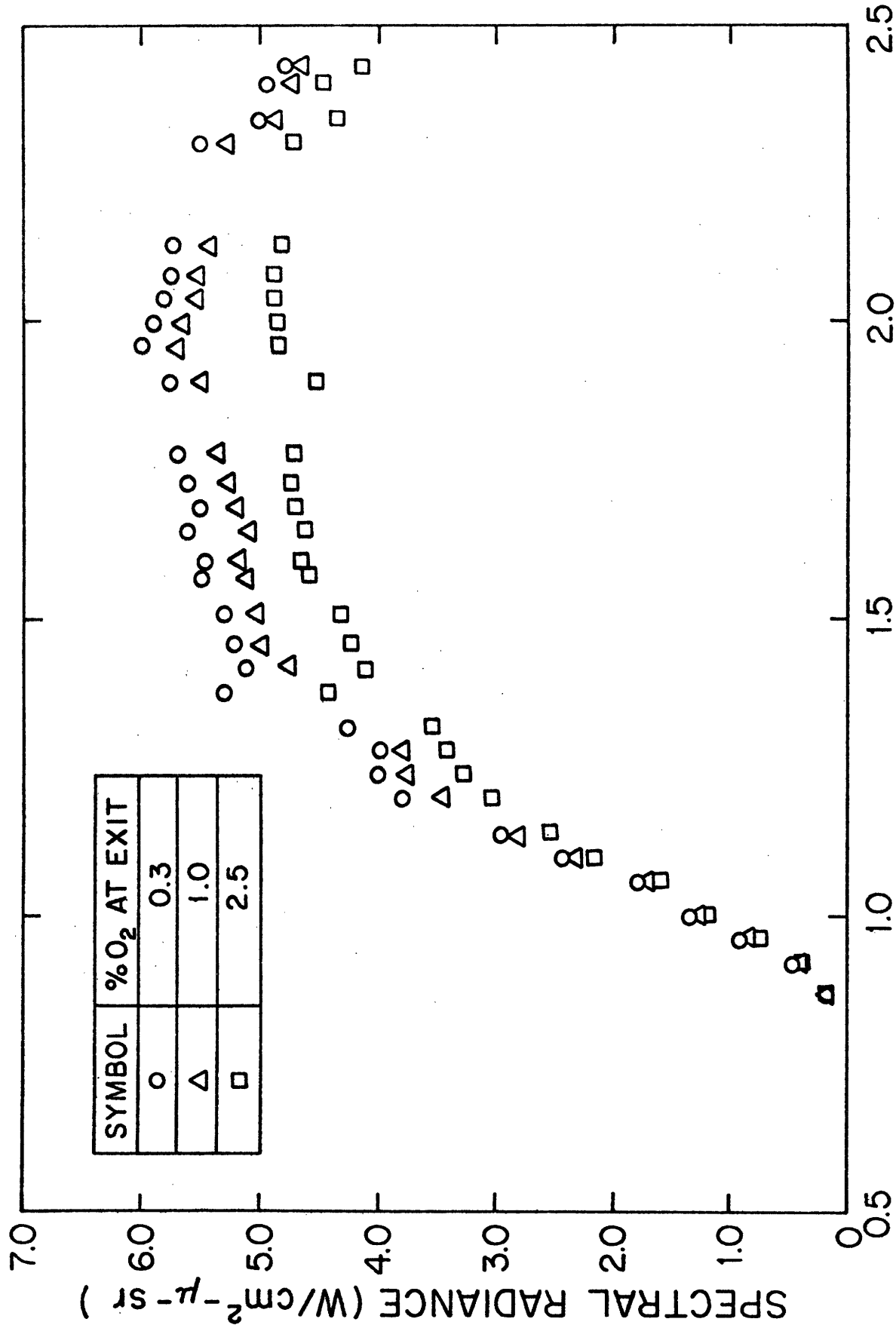


Figure 1. Spectral Radiance of Pulverized Coal Flame. (Penzias, et al. - Reference 1). Hot furnace background. Axial Location: x/d = 4.36

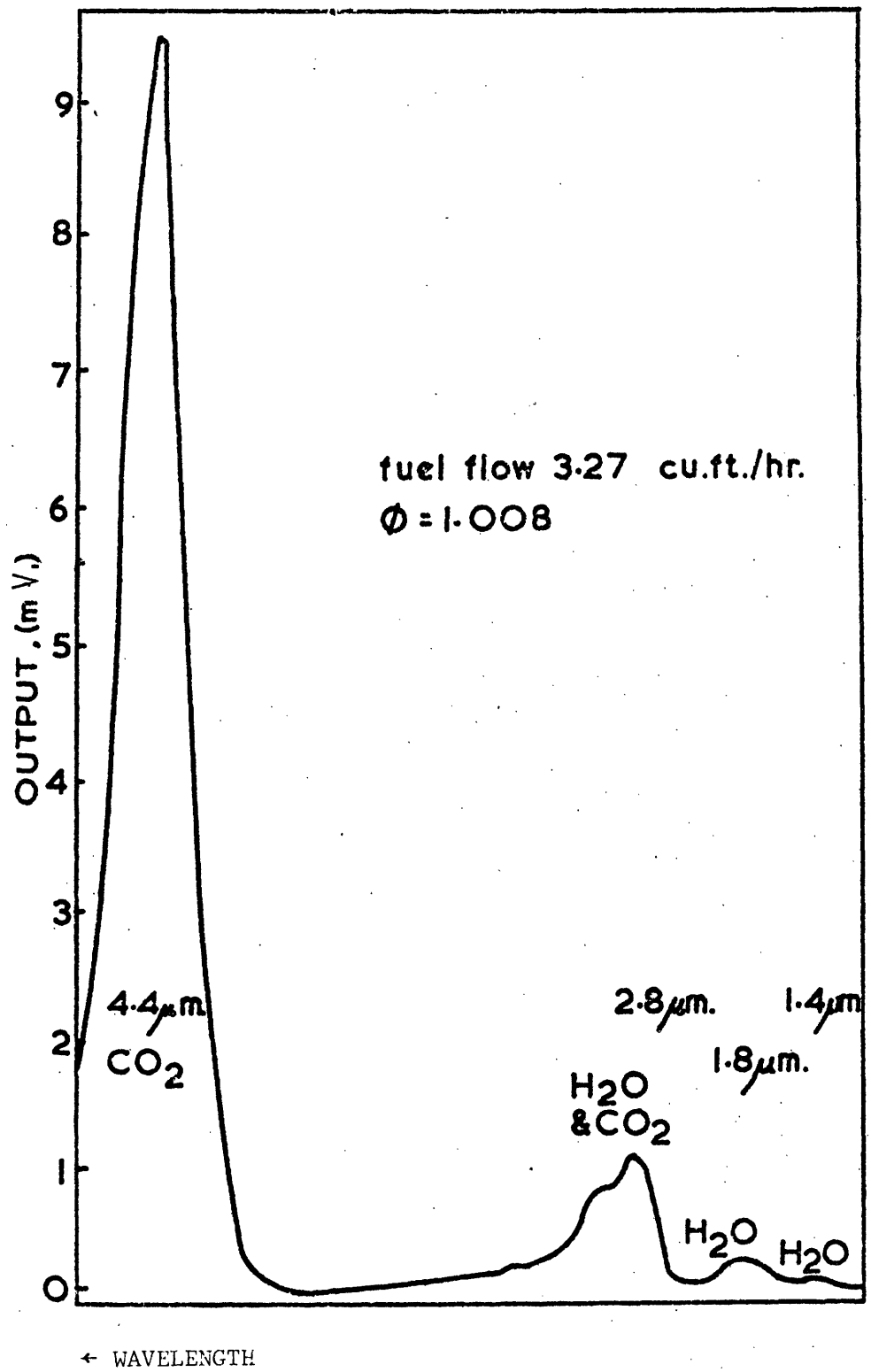


Figure 2. Typical Spectrum from Propane/Air Flame. (Smith, et al. - Reference 8).

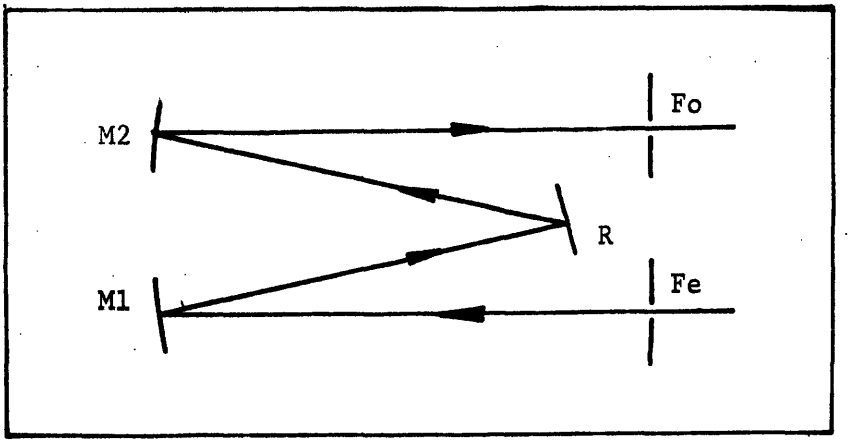


Figure 3. Schematic of Jobin Yvon Monochromator Optics. The light beam originating from the entrance slit is reflected by the collimator mirror M1, which renders it parallel and directs it to grating R; the diffracted beam is focused on the outlet by mirror M2. Rotation of the grating produces wavelength scanning in the outlet slit plane.

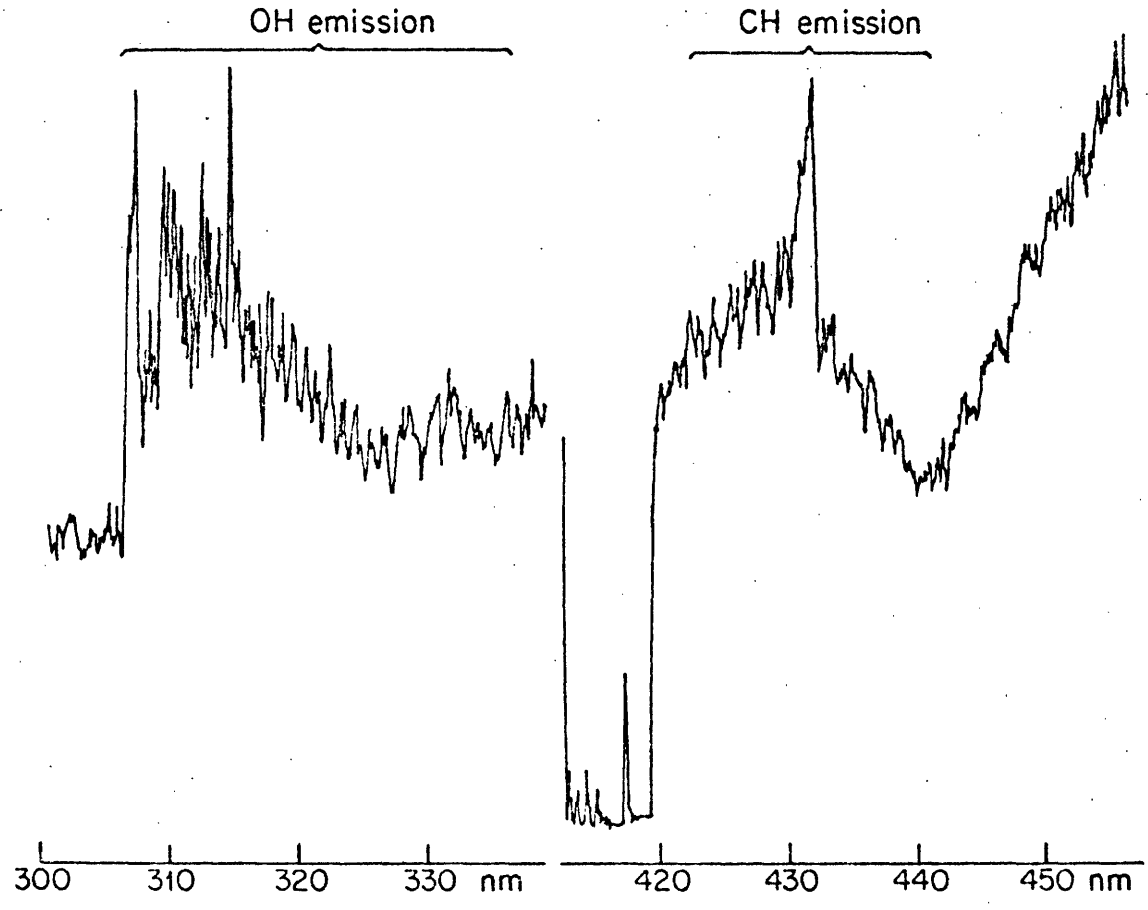


Figure 4. U.V. Emission from No. 6 Fuel Oil Flame.
Characteristic OH and CH band radiation is shown.

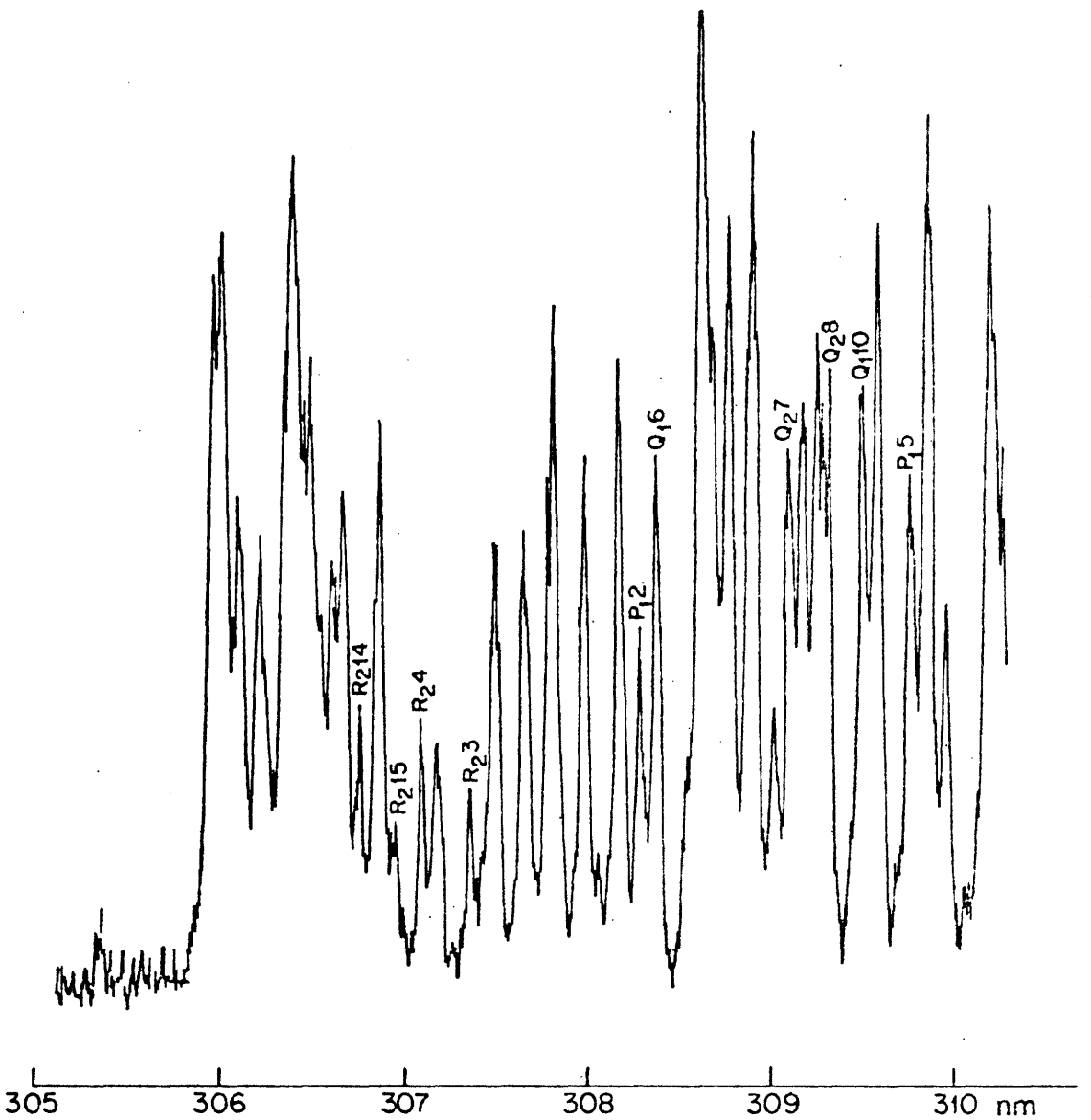


Figure 5. U.V. Emission from No. 6 Fuel Oil Flame - OH Spectral Lines.

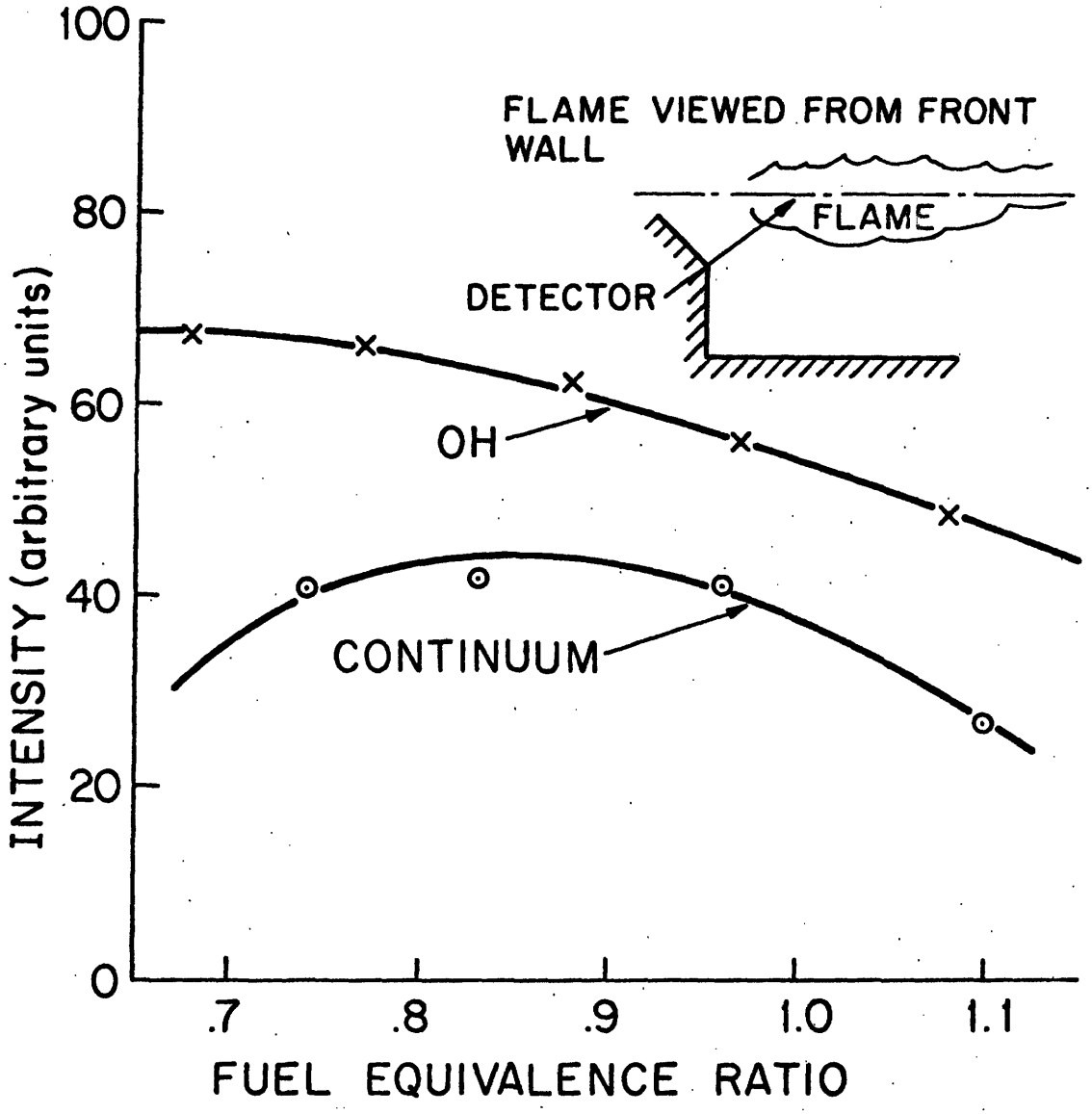


Figure 6. Intensity of OH at 309 nm and Continuum Emission at 306 nm versus Fuel Ratio. No. 6 fuel oil, steam atomized. Zero swirl. Fuel equivalence ratio was varied by changing the air flow rate.

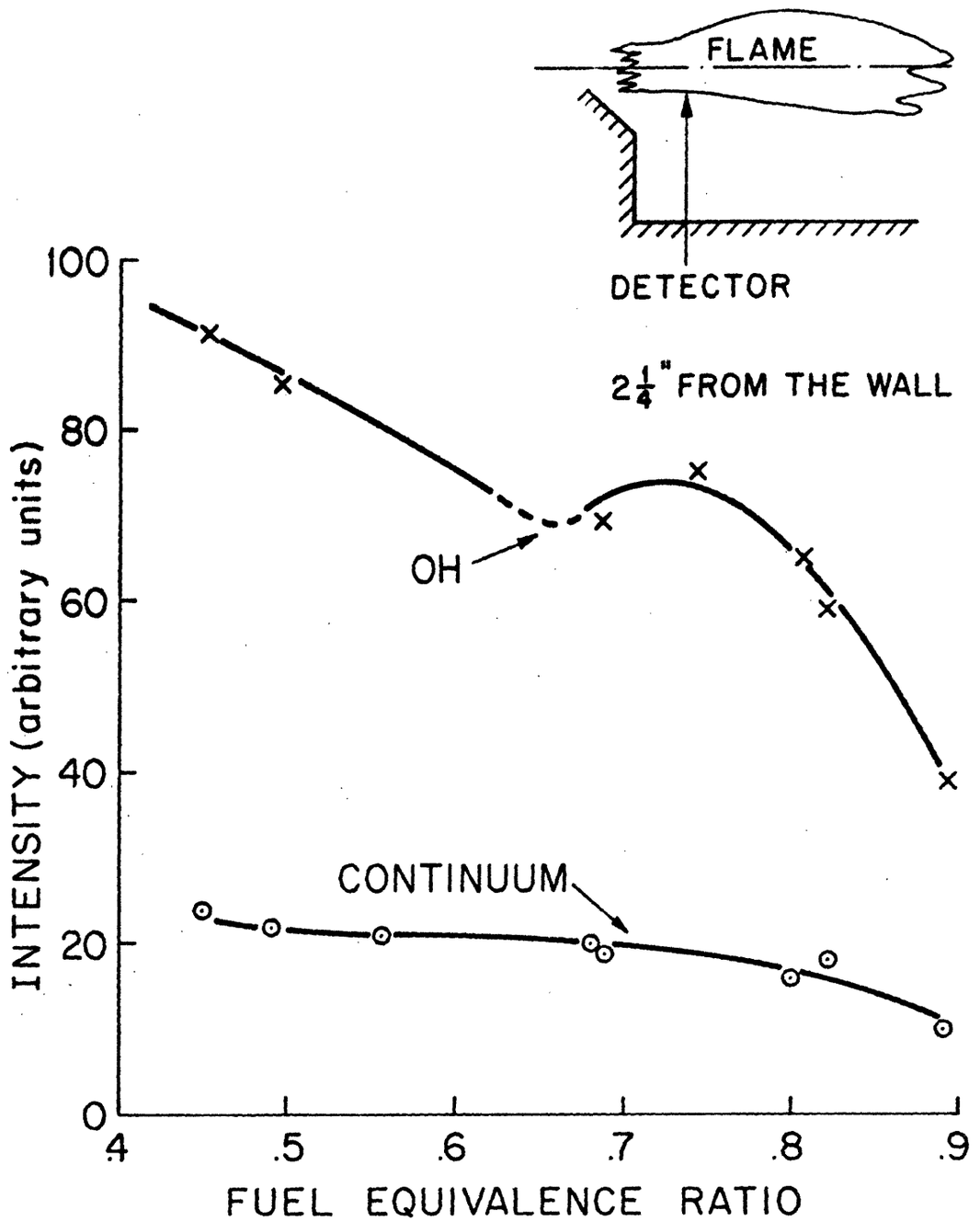


Figure 7. Intensity of OH at 309 nm and Continuum Emission at 306 nm versus fuel ratio. No. 6 fuel oil, steam atomized. Swirl number = 0.5. Fuel equivalence ratio was varied by changing the fuel flow rate.

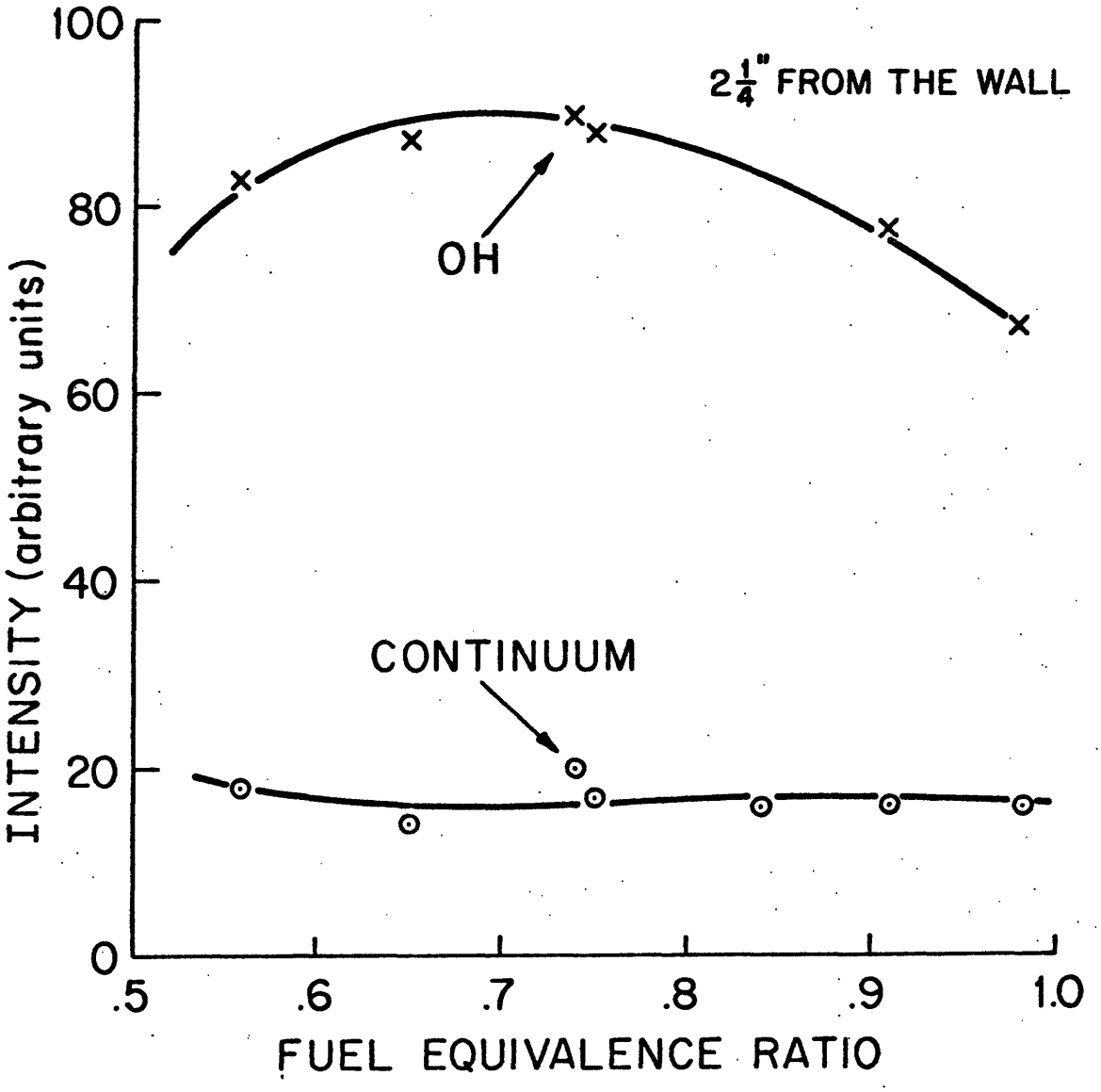


Figure 8. Intensity of OH at 309 nm and Continuum Emission at 306 nm versus fuel ratio. No. 6 fuel oil, steam atomized. Swirl number = 0.9. Fuel equivalence ratio was varied by changing the air flow rate.

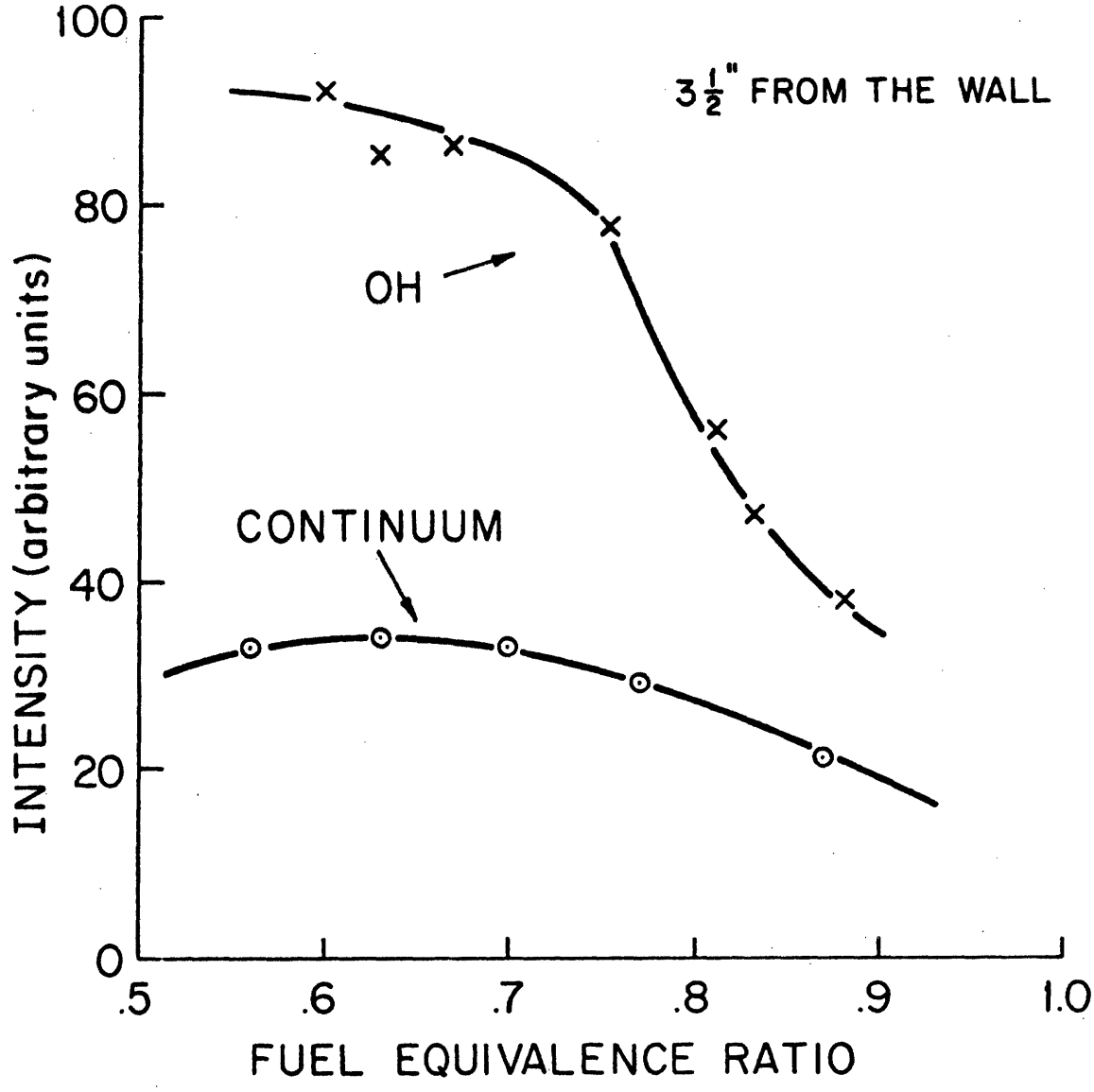


Figure 9. Intensity of OH at 309 nm and Continuum Emission at 306 nm versus fuel ratio. No. 6 fuel oil, steam atomized. Swirl number = 0.5. Fuel equivalence ratio was varied by changing the fuel flow rate.

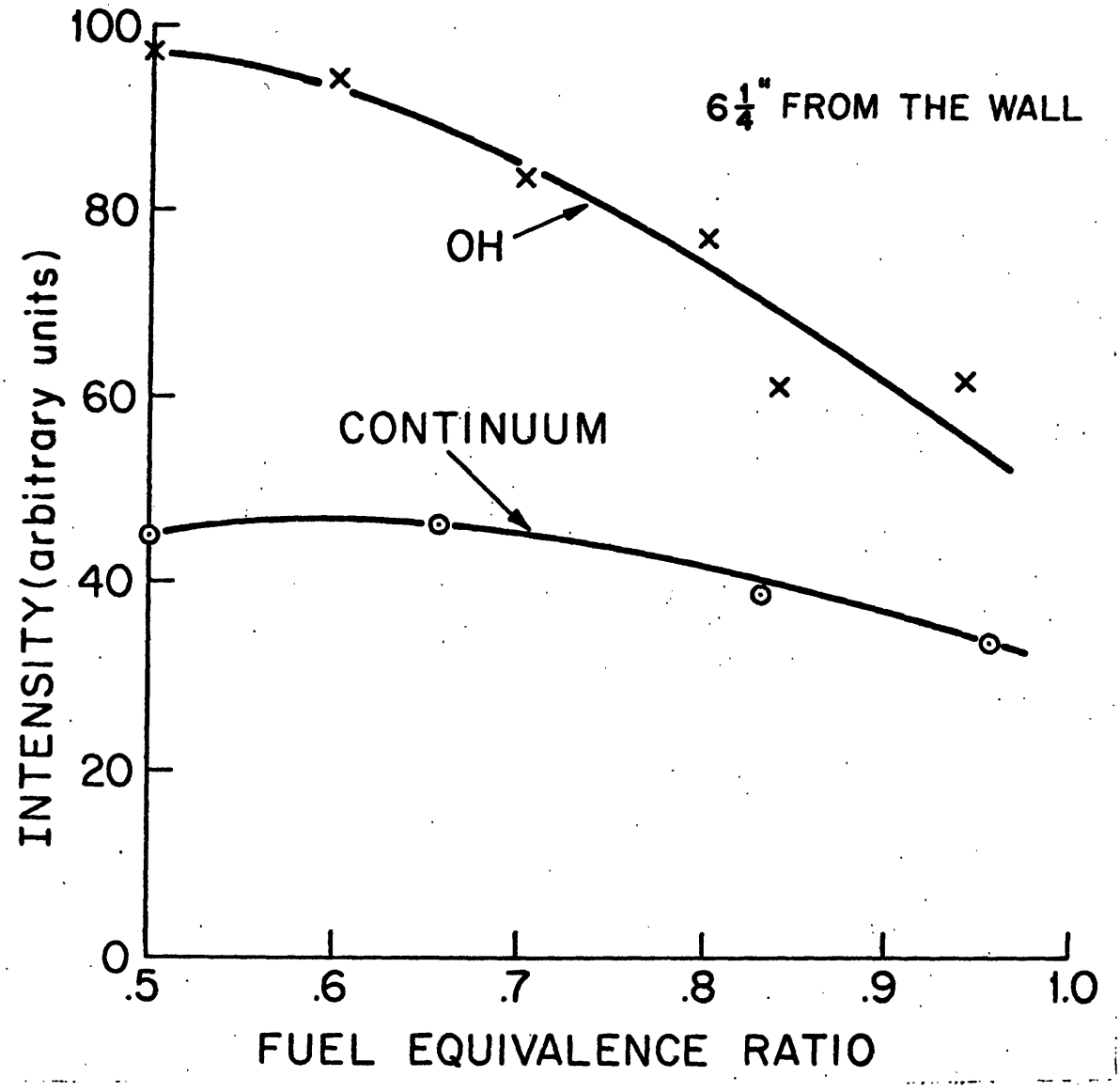


Figure 10. Intensity of OH at 309 nm and Continuum Emission at 306 nm versus fuel ratio. No. 6 fuel oil, steam atomized. Swirl number = 0.5. Fuel equivalence ratio was varied by changing the fuel flow rate.

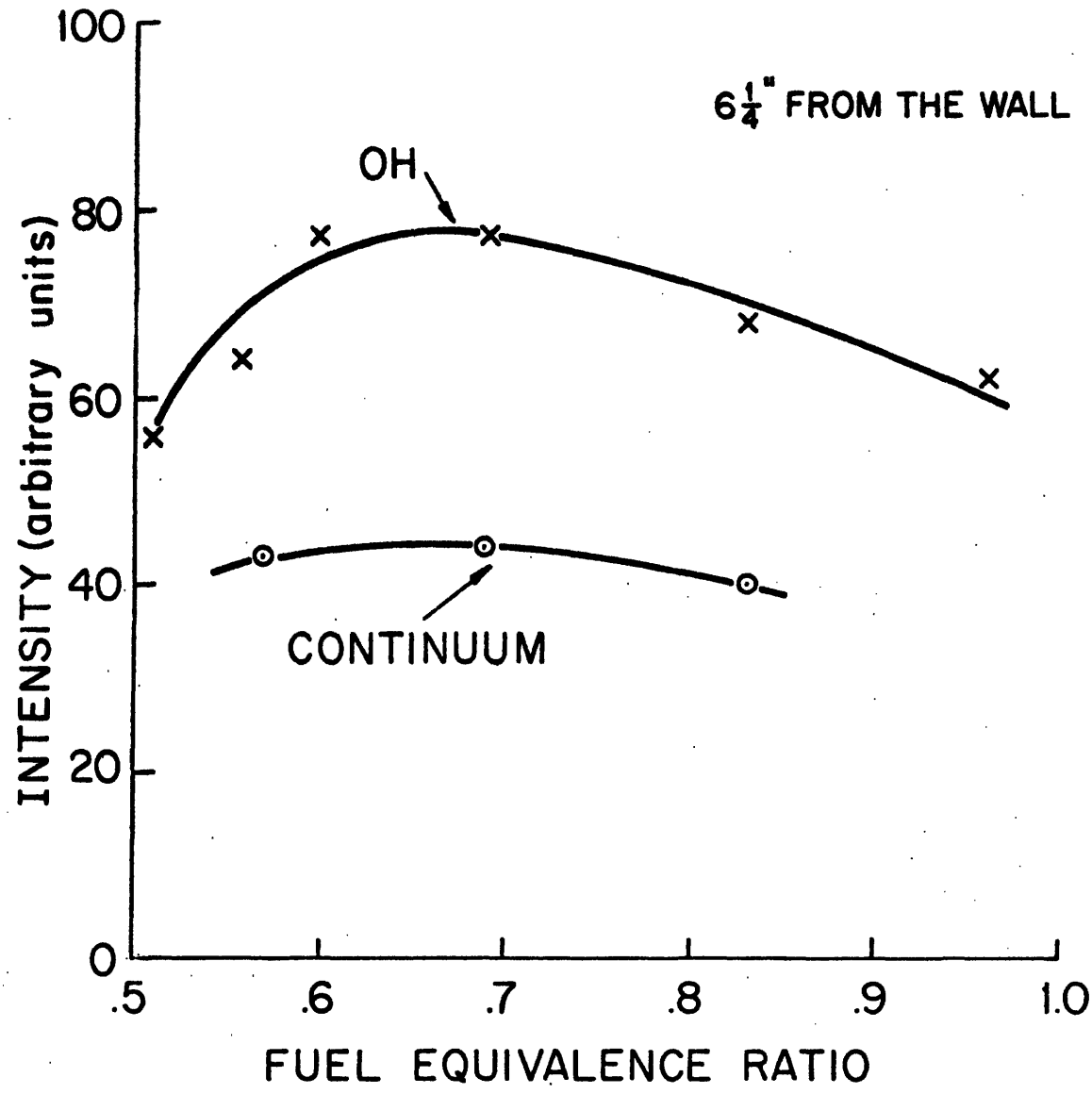


Figure 11. Intensity of OH at 309 nm and Continuum Emission at 306 nm versus fuel ratio. No. 6 fuel oil, steam atomized. Swirl number = 0.5. Fuel equivalence ratio was varied by changing the air flow rate.

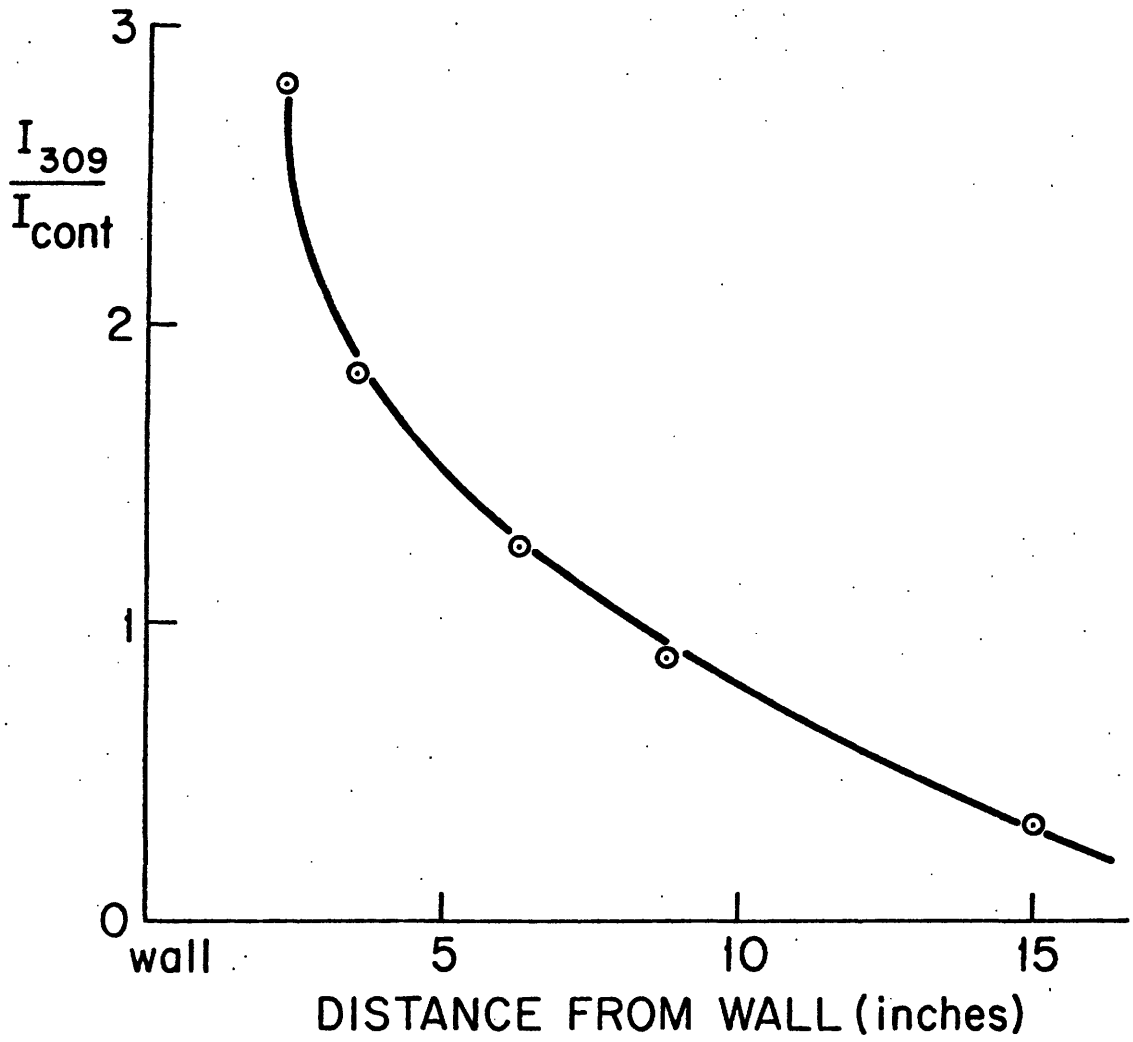


Figure 12. Ratio of Emission Intensities at 309 nm (OH) and 306 nm (continuum), as a Function of Detector Location, Measured from Wall of Furnace. No. 6 fuel oil, steam atomized. Swirl number = 0.6. Excess air ~10%.

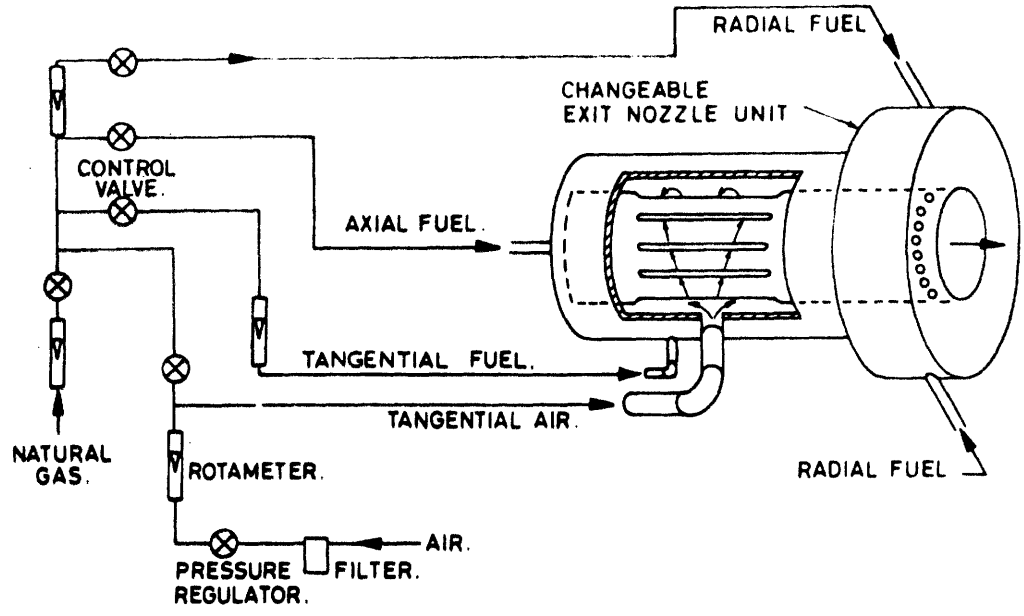


Figure 13. Swirl Burner (Gaseous Fuel).

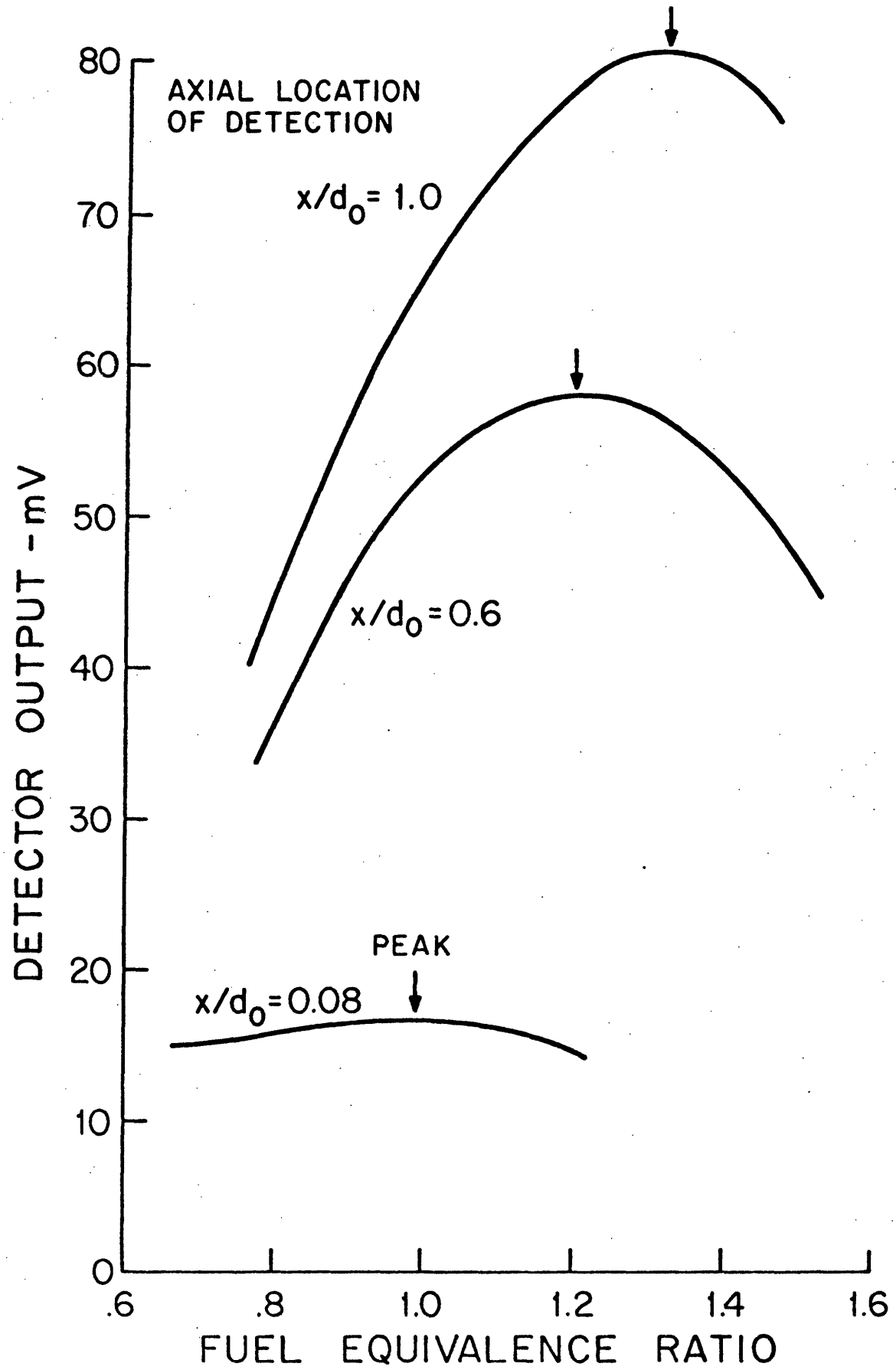


Figure 14. Infrared Emission at 2.7345 μm from Methane/Air Flame. Constant Load: 15 liters/min.

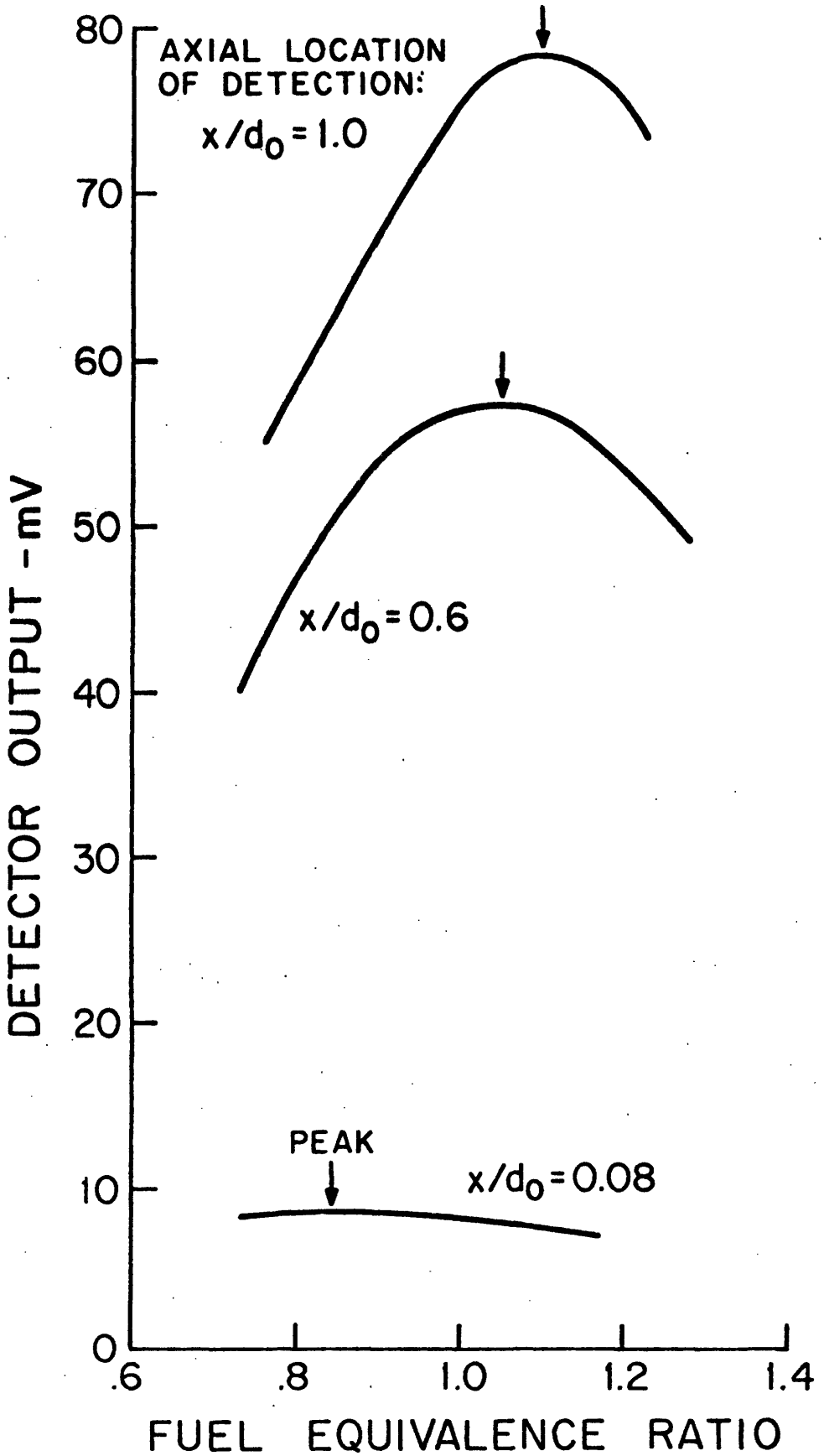


Figure 15. Infrared Emission at 2.7345 μm from Methane/Air Flame. Constant Load: 11.3 liters/min.

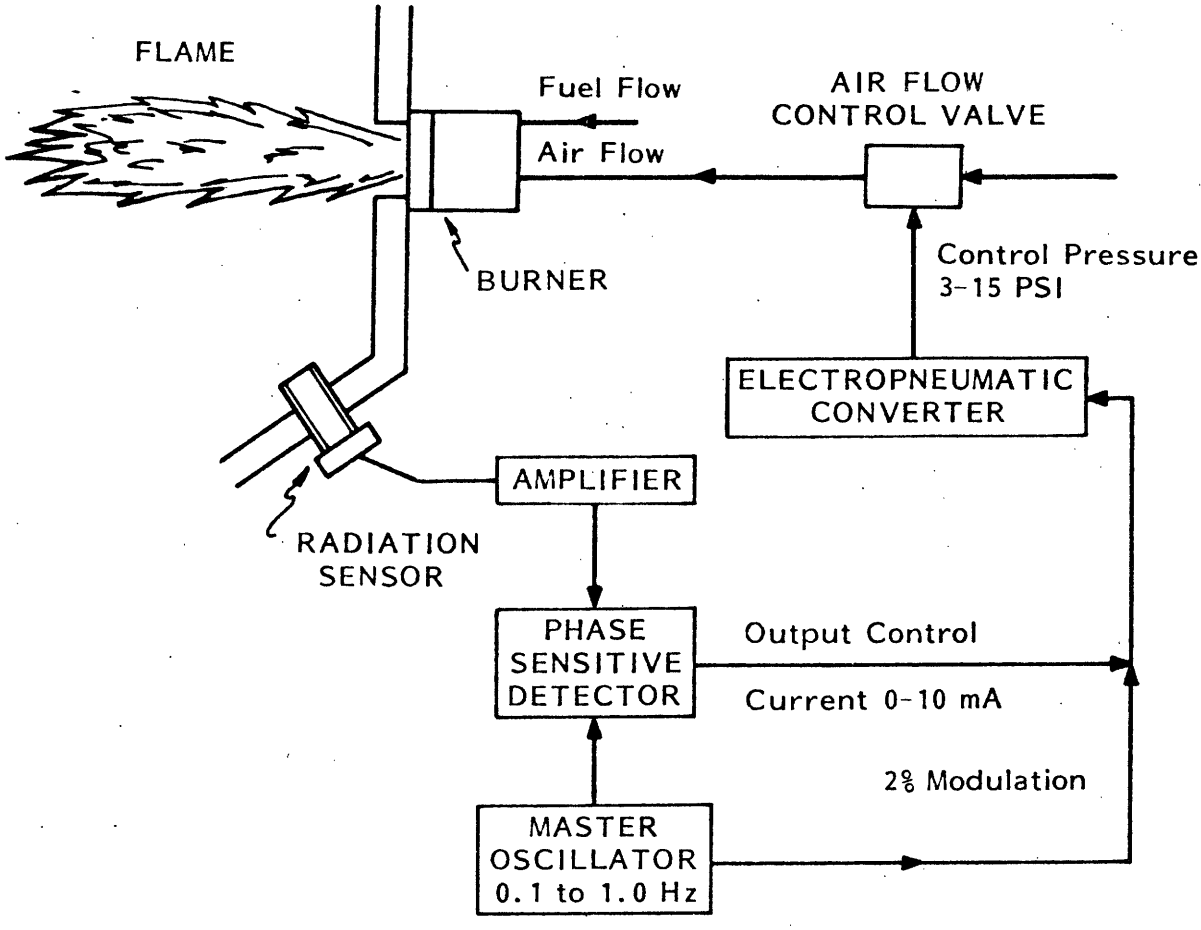


Figure 16. Schematic of Land™ Controller.

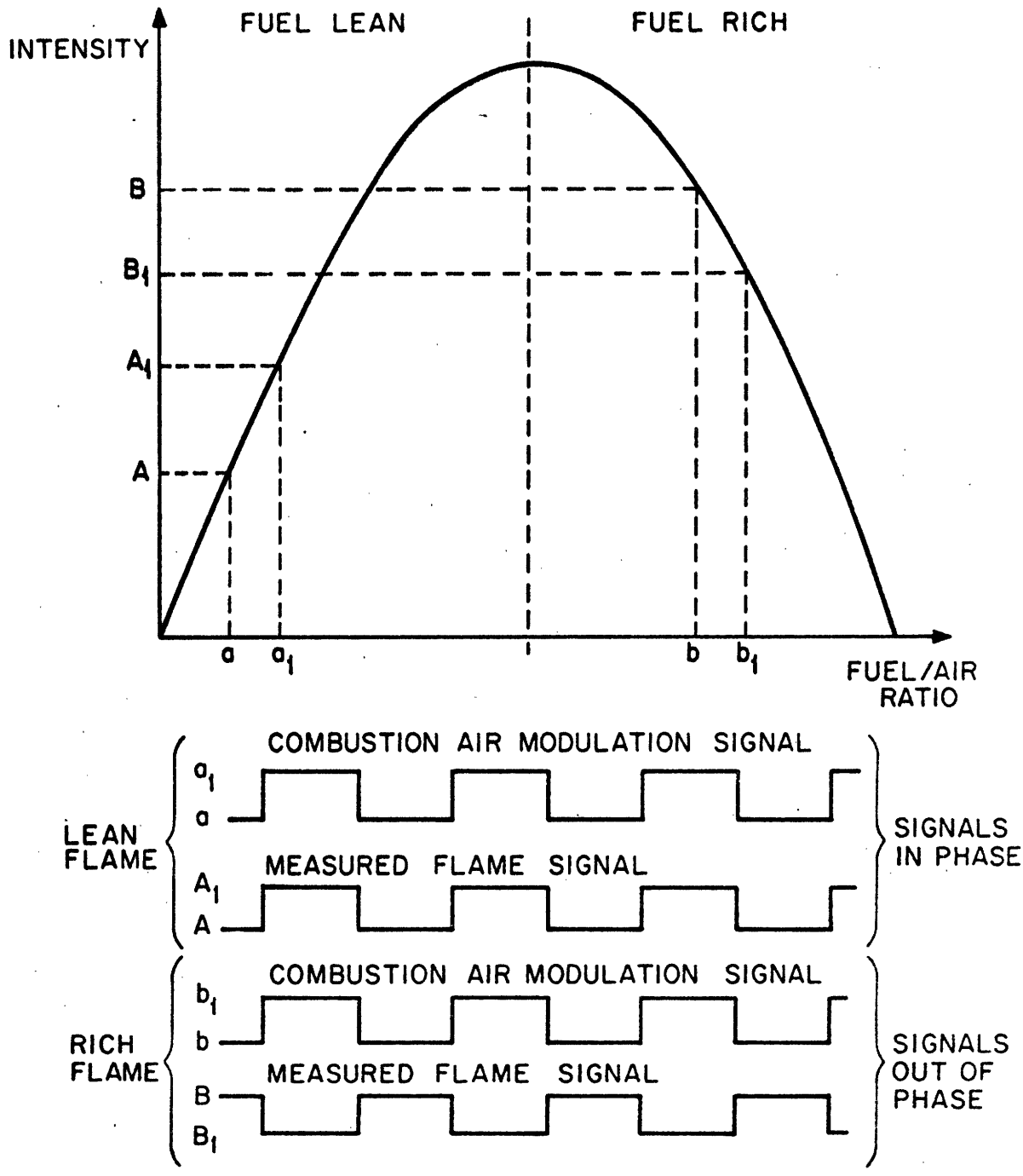


Figure 17. Operational Principle of Peak-seeking Burner Control System.

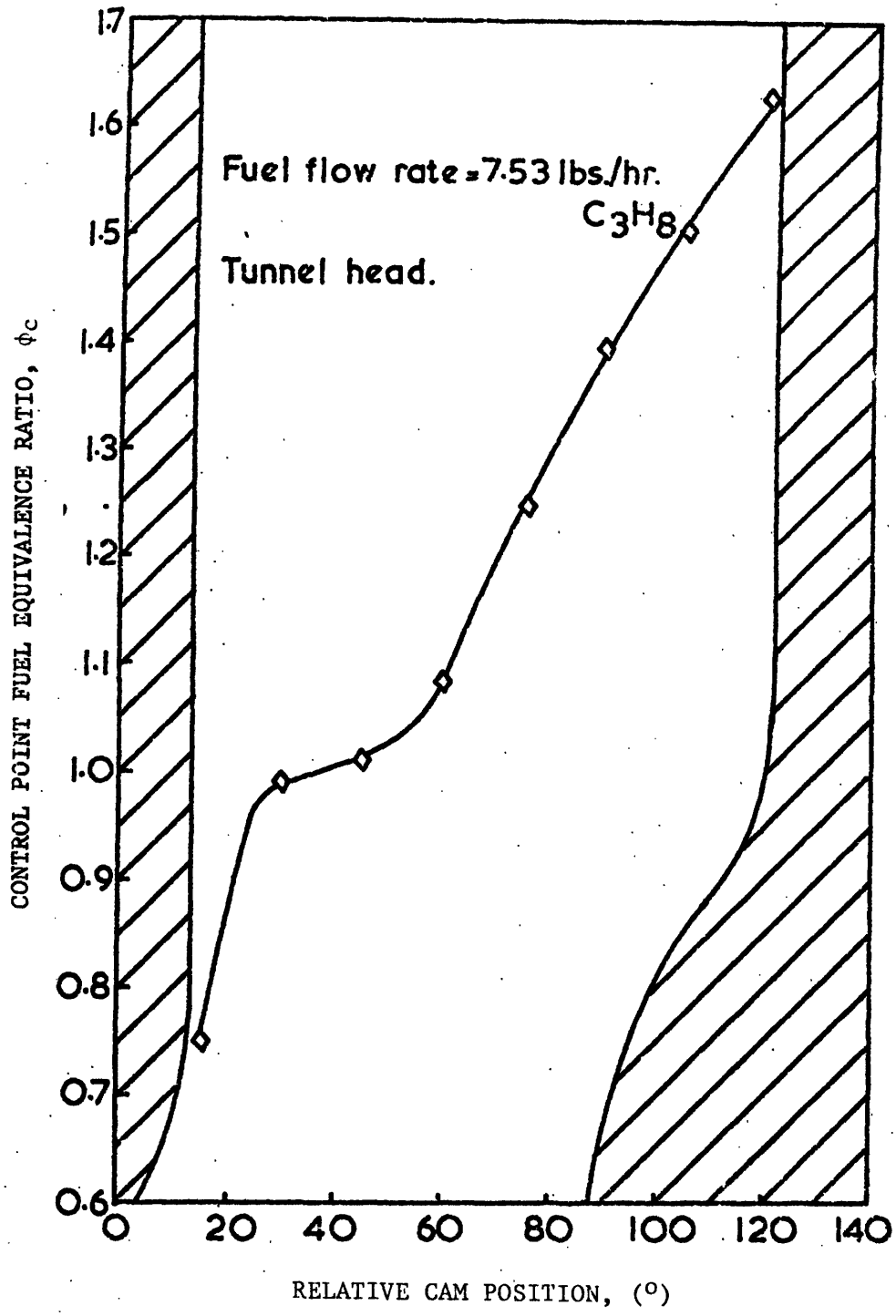


Figure 18. Effect of Modulation Phase on Control Point Stoichiometric Ratio. Phase change is effected by change of cam position in the air flow modulator drive. Shaded areas indicate unstable operation of the control system. (Smith - Reference 7).

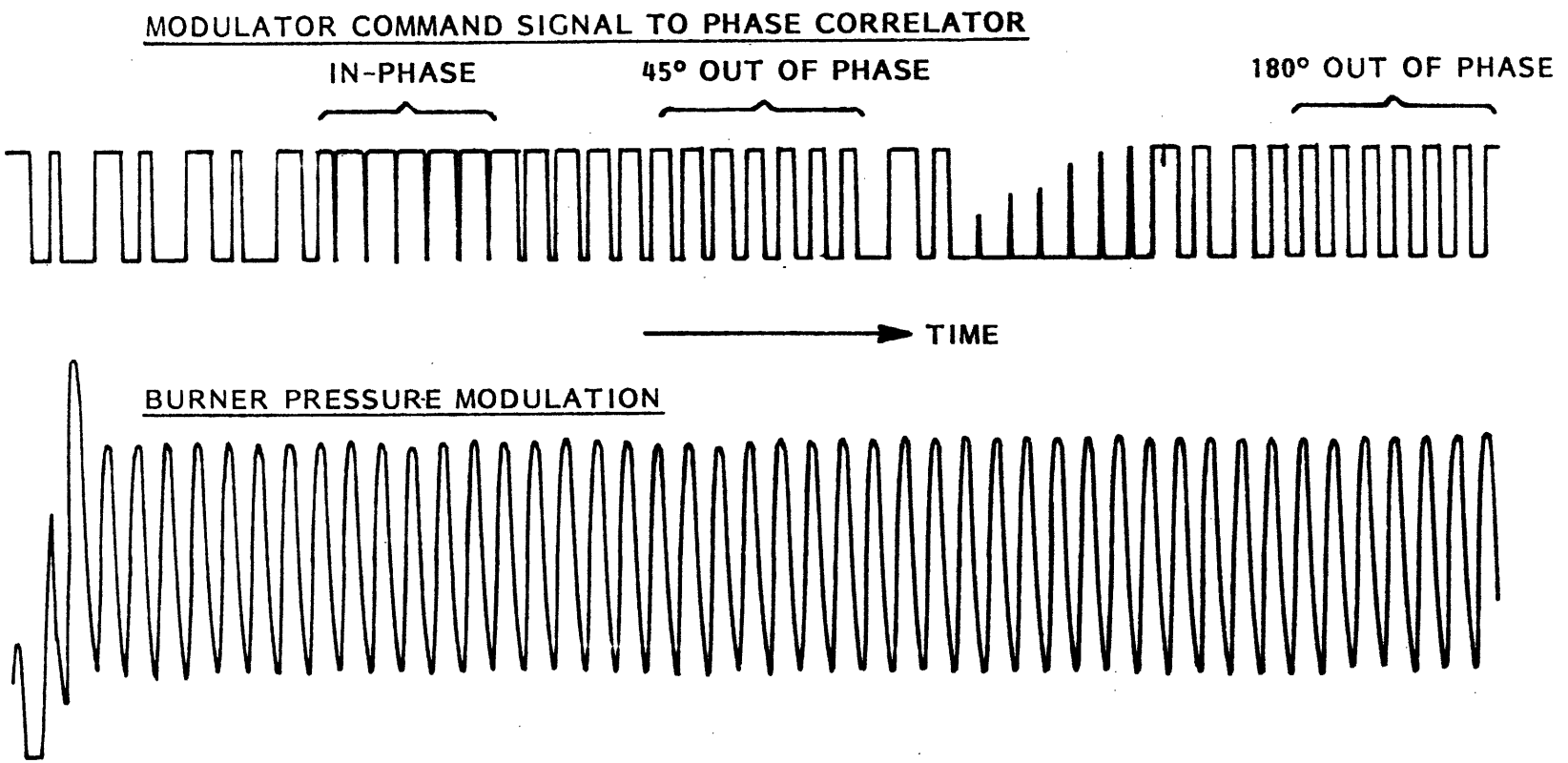


Figure 19. Illustration of Phase Delay Between Modulator Command Signal and Burner Fuel Pressure.

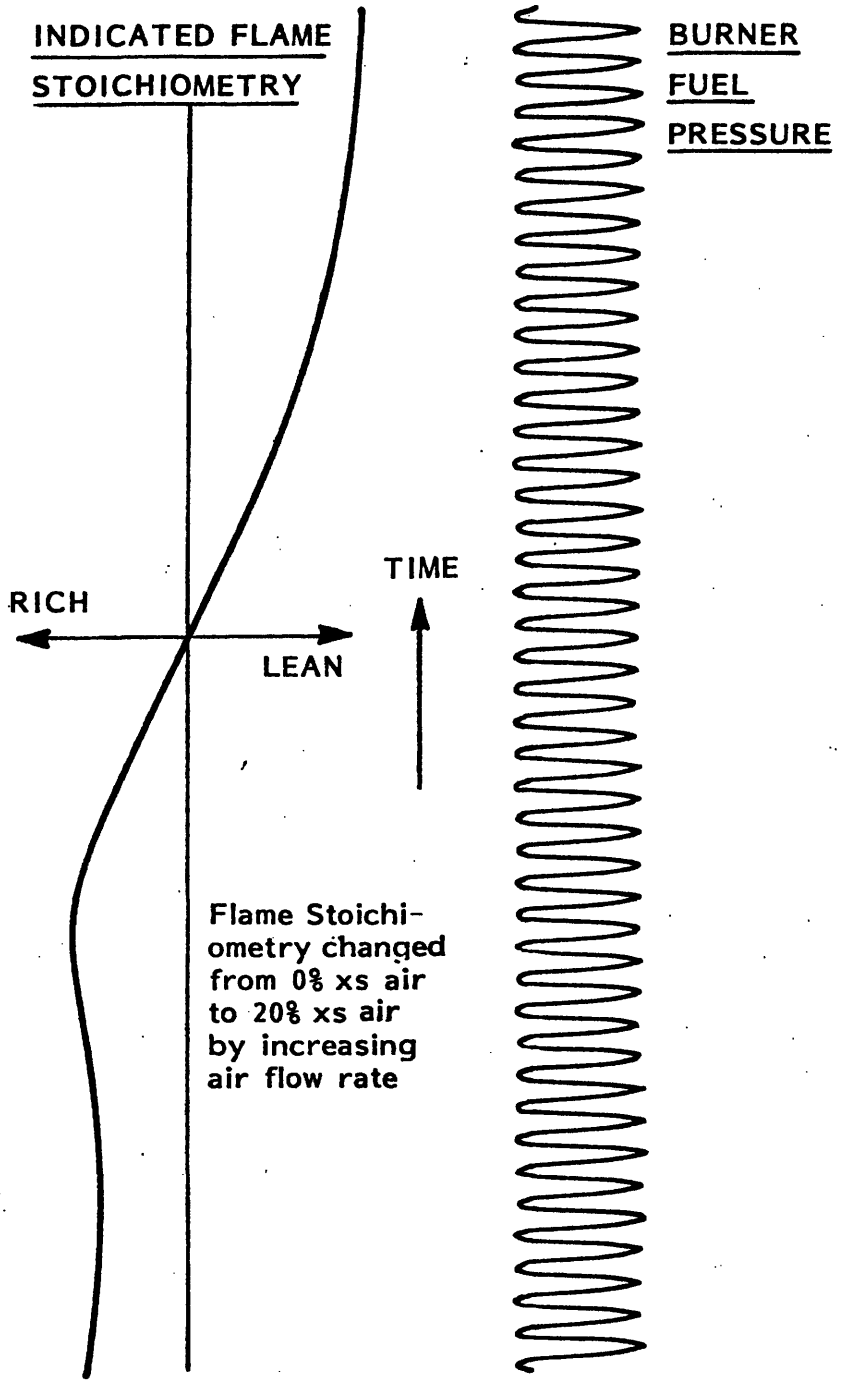
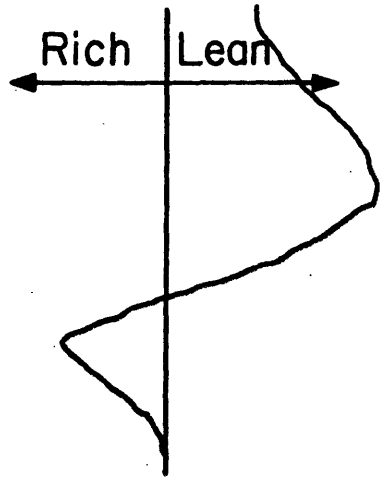
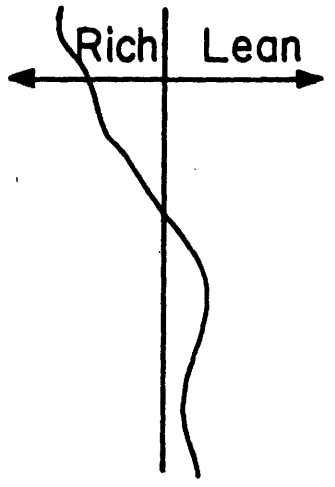


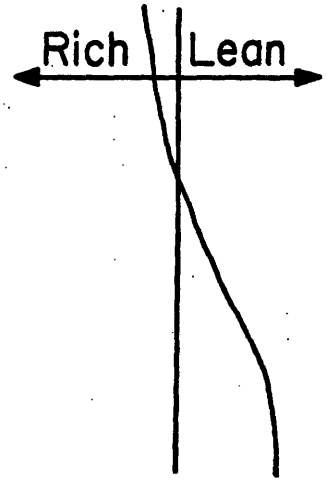
Figure 20. Output of Land System Showing Correct Response to Change in Fuel/air Ratio.
Detector sighted through side wall ~10" from end wall, on 1MW No. 6 fuel oil flame, pressure jet atomizer. Modulation frequency 5.5 Hz, amplitude 4.0, and phase delay setting at 3-5.



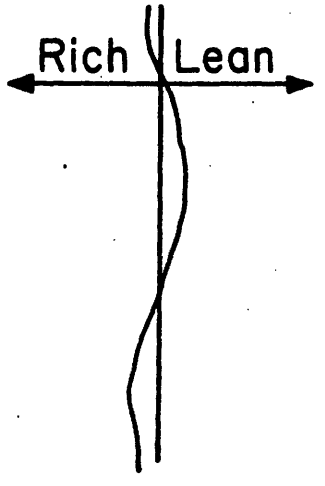
(a) Effect of changing detector position.



(b) Effect of shielding flame detector from stray emissions.-- closing adjacent viewing port.



(c) Effect of increasing swirl.



(d) Effect of changing phase delay of modulator reference signal.

Figure 21. Examples of Incorrect Response of Land System to Combustion and Detection System Parameter Changes.

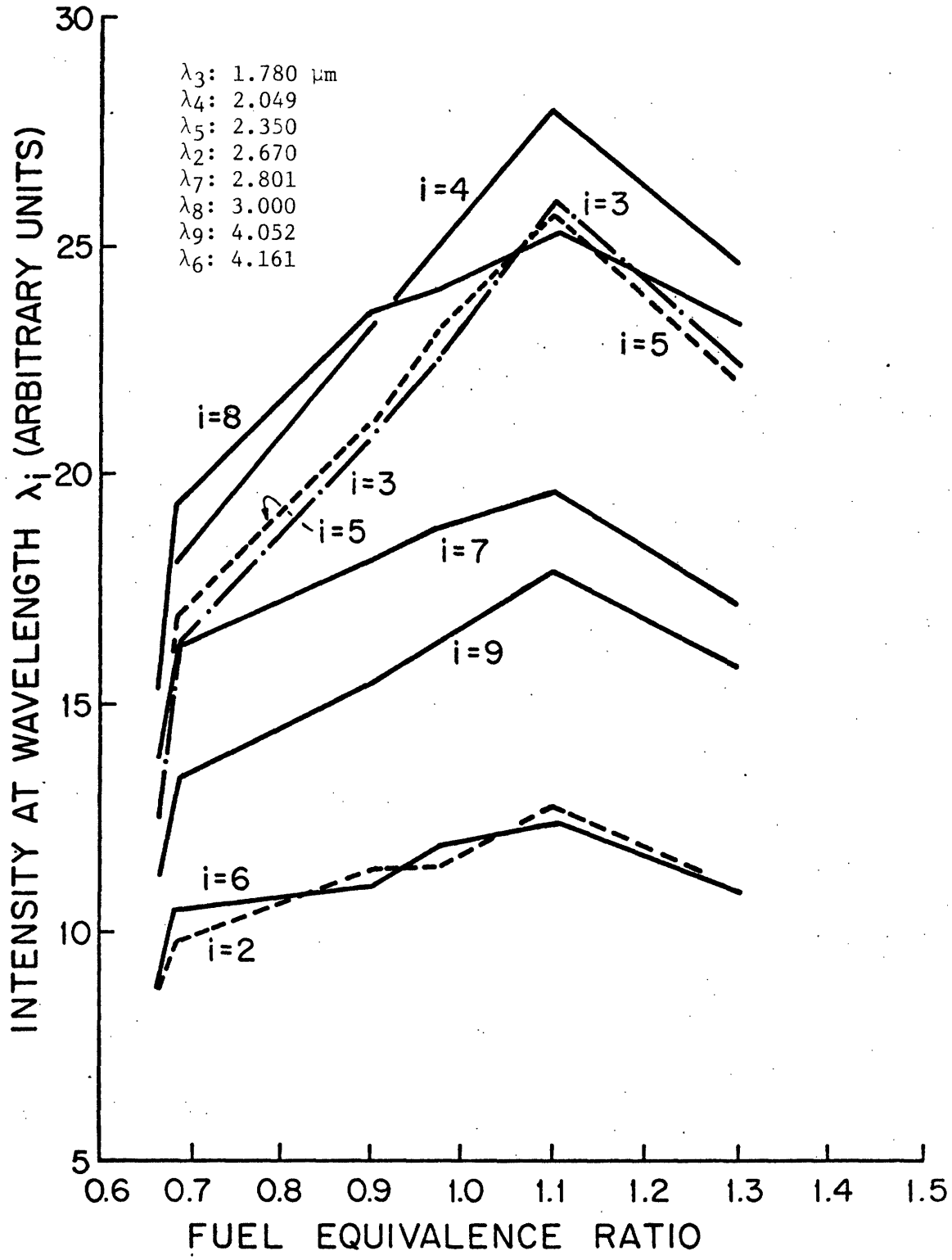


Figure 22. Infrared Emission from No. 6 Fuel Oil Flame.
Data at selected wavelengths recorded by Wilks Model 80 instrument.

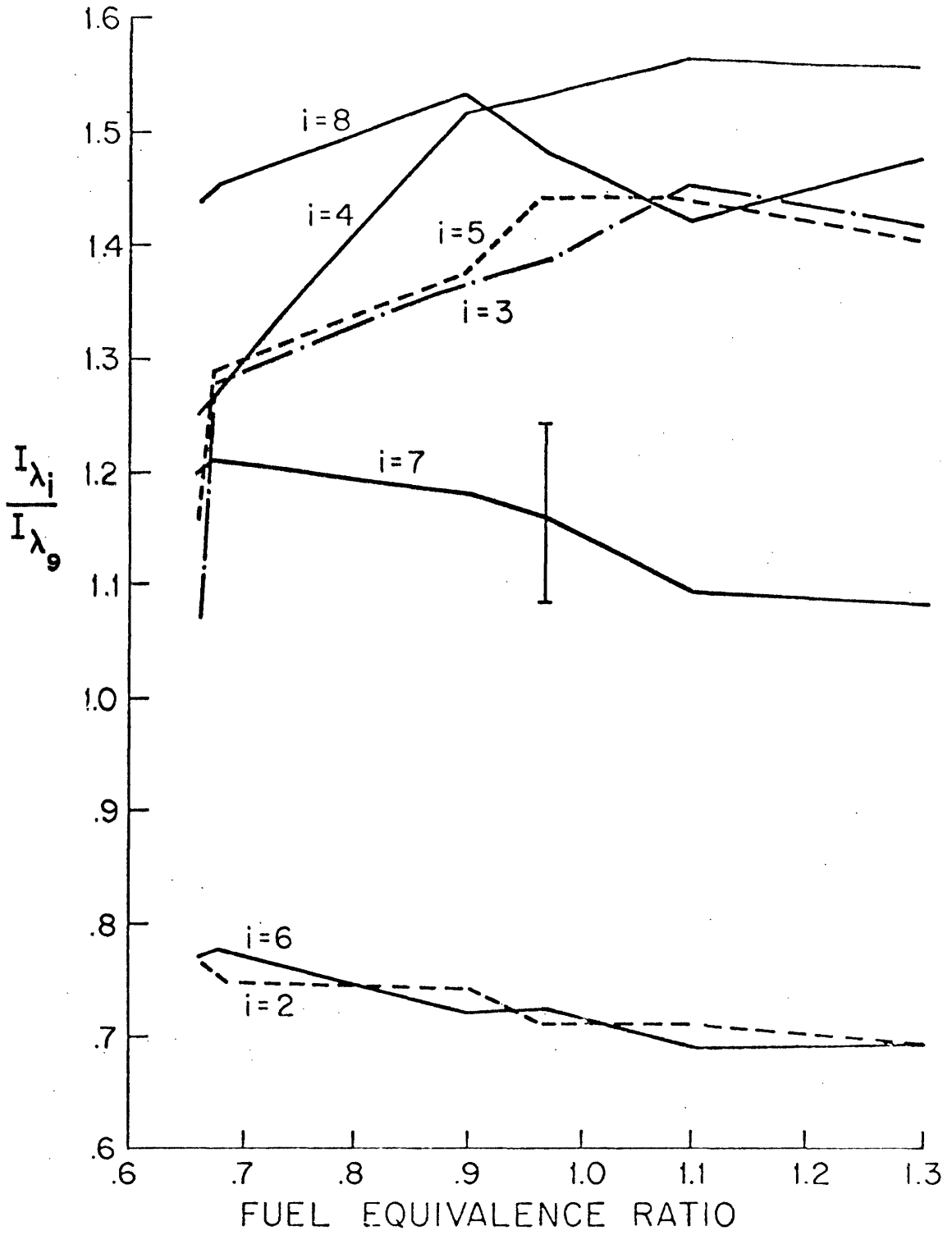


Figure 23. Normalized Infrared Emission Data from Figure 22. At each fuel equivalence ratio the emission intensity at wavelength λ_i is divided by intensity at λ_9 (4.052 μm)

Appendix A

MIT COMBUSTION RESEARCH FACILITY (CRF)

The overall arrangement of the experimental plant is depicted schematically in Figure A-1. The multi-fuel swirl burner and the experimental chamber of the furnace are shown in Figure A-2; the layout of this part of the system is given in Figure A-3 which shows the sequential arrangement of the burner, brick-lined experimental chamber, after burner, and the cold-wall chamber of the CRF. The other major components of the plant include the systems for storage, metering, feeding and control of fuels, for pumping, preheating, and metering of the combustion air, and for cleaning and pumping the combustion products; these systems, together with considerations of instrumentation, data-logging, and control, are briefly discussed below.

FUEL SYSTEM

Fuel Oils

The fuel oil is pumped through a 100-ft long, steam-heated supply line into either of two storage tanks (2000 gallons capacity each). In these tanks the oil can be maintained at a temperature adequate for pumping (e.g., 100-150^{o}F for heavy fuel oils) by two heaters per tank. The tanks have temperature and level controls.

From the storage tanks the oil is pumped either through a fuel conditioning system directly to the burner, or to a 300-gallon day tank where it can be maintained at about 150^{o}F temperature.

The fuel conditioning system filters the oil and heats it to the final temperature necessary for satisfactory atomization. Provision is made for

the mixing and emulsification of fuel oils and for their injection through the burner at controlled flow rates and temperature. These fuels can be atomized in the burner using either steam or high-pressure air.

Natural Gas

Natural gas is supplied to the air preheater, to the afterburner and to the main burner of the experimental furnace. Gas from high pressure mains is distributed to the three supply lines at controlled flow rates and pressures. Diluents (CO_2, N_2) may be added to reduce the gas calorific value if required for experimental purposes.

Solid Fuels/Slurries

In the second stage of its development the experimental plant has been provided with a pulverized coal storage metering and feeder assembly as shown schematically in Figure A-4; this system uses pneumatic transport to deliver pulverized coal from barrels, either to the CRF or to a Fluidized Bed Combustor (FBC).

For coal/oil mixtures (COM) the handling system is comprised of lines which (a) are of larger diameter than for liquid fuel delivery, (b) have large radius bends, and (c) are heated by electricity or steam. The day tank is used as a stirred, heated reservoir. A Moyno pump delivers the COM to the CRF burner, and a second (smaller) Moyno pump replenishes the day tank from barrels.

Coal/water mixtures (CWM) are delivered to the CRF through separate (all copper) lines, again with large radius bends. The slurry tank shown in

Figure A-4 serves as a stirred reservoir replenished either from barrels or by batch mixing using the pneumatic coal feed. The two Moyno pumps are shared with the COM system.

The COM amd CWM systems are operational; an additional capability for pneumatic transport of pulverized coal directly to the CRF is planned.

AIR SUPPLY SYSTEM

The combustion air is supplied by a fan capable of delivering 3500 SCFM against 80 inches WG pressure. The air can be preheated in an externally-fired air preheater, up to 500°C (900°F). The preheated air can then be divided into two separately metered branches for introduction to the burner as primary and secondary air flows. (See Figure A-3).

GAS EXHAUST AND COOLING WATER SYSTEM

Furnace Chambers

The pressure in the experimental furnace is maintained close to atmospheric pressure by the balanced operation of the forced draft and induced draft fans. Provision is made for injection of O_2 or additional air into the cylindrical afterburner section to enhance soot burn-out within the cool-wall chamber. Downstream of the latter chamber the combustion products are cooled by water spray to 200°C. The gas/vapor mixture then enters a wet scrubber which removes inorganic particles in excess of 1 mm size with an overall efficiency $\geq$ 90%. An induced draft fan propels the gases through the stack (see Figure A-5).

The Cooling Water System

The cooling water system is used to cool the 0.3 m wide sections of the experimental furnace. The cooling water is circulated in a closed loop cooled by river water in a heat exchanger. The individual furnace sections are instrumented for the measurement of the water flow rate and the temperature rise of the cooling waterto enable sectional heat balances of the furnace to be calculated. The furnace sections are provided with a high temperature alarm system for their protection against dry-out.

City Water Supply

The city water supply is available for the emulsifier, for the spray that cools the exhaust gases before entrance to the scrubber, for the scrubber, and as coolant to the in-flame probes.

INSTRUMENTATION, DATA-LOGGING AND CONTROL

Measurements - Instrumentation

Probe and optical measurements are made within the flames and at the furnace walls. Time average gas temperatures are measured by suction pyrometers and time average velocities with water cooled impact probes capable of measuring axial, radial and tangential velocity components at points in the flame. Gas and solid samples are taken from the same points in the flame for chemical analyses. The probes and probe measurement techniques are discussed in Appendix B.

Laser-doppler velocimetry is used for the measurement of the spatial distribution of time-resolved velocities in the furnace, and laser-diffraction and multi-flash photographic methods employed for determining particle and droplet size distributions in the flame.

The furnace sections are of two types, which have either water-cooled inside walls or refractory-lined inside walls. Wall temperatures are measured at several points in each section. The total heat transfer from the flame to the furnace is determined by using conductivity plug type heat flow meters and the radiative heat transfer contribution is measured by using hemispherical type hollow ellipsoidal radiometers, both instruments being flush-mounted at the furnace wall. Flame emissivities are determined optically according to the Schmidt method using total radiation pyrometers. (See Appendix B for details of radiatiometers and pyrometers)

All measured variables are displayed at the control panel after transduction to their electrical analogs and these analogs are used as the inputs to manual or, in some cases, automatic control loops; a data acquisition computer system based on a PDP 11/60 machine common to several facilities in the building is used to log all data. This automatic data-logging includes fuel- and air-flow rates and inlet temperatures, cooling water flow rates and temperature rises, in-flame temperatures from suction pyrometers, and flue gas analyses. Availability of this information within the computer system permits quasi real-time processing of the data with comparisons between model predictions and current experimental results.

Control and Interlock System

A comprehensive automatic control and interlock system is used for the safe light-up, shut-off and operation of the experimental plant.

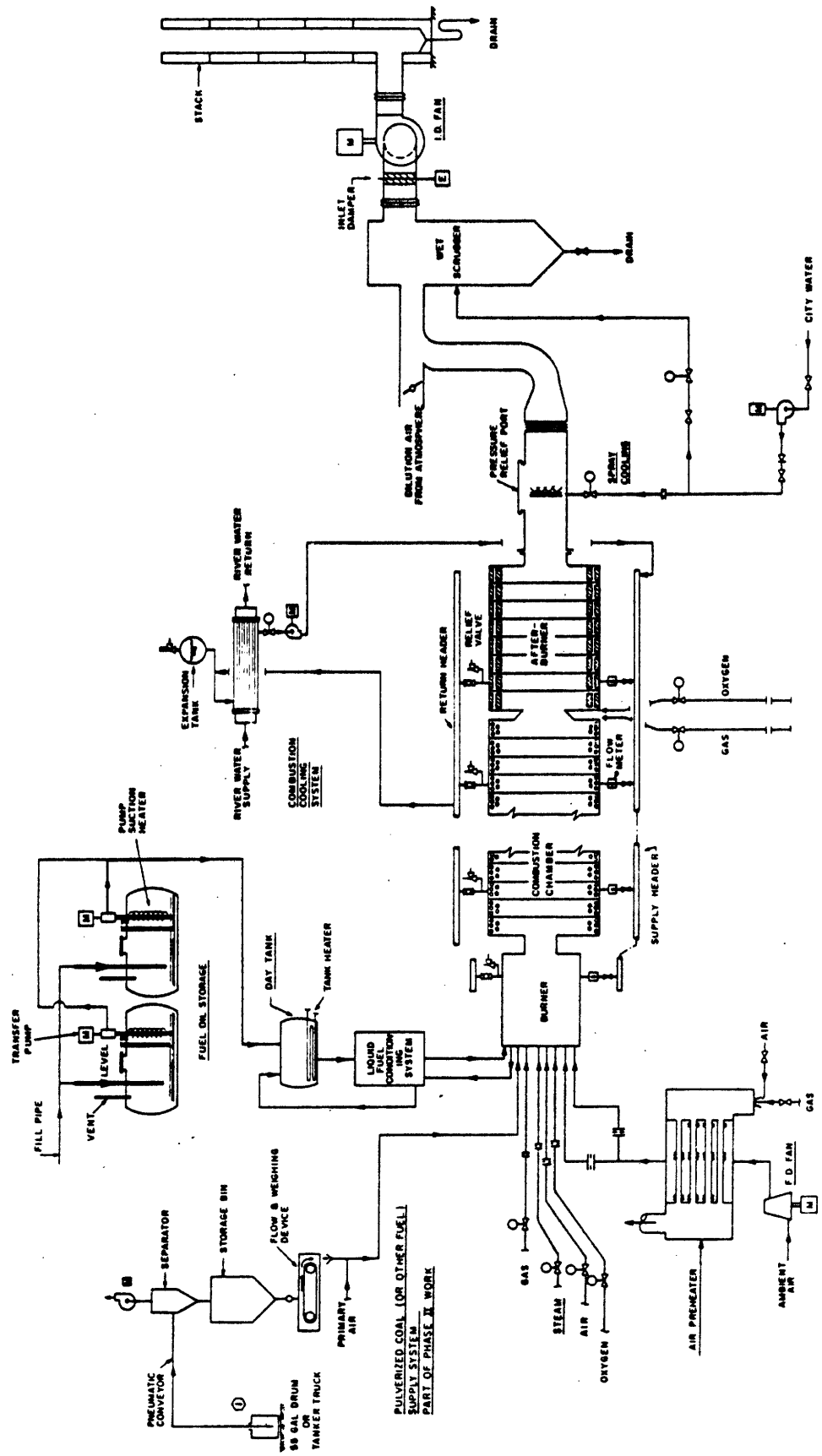


Figure A-1. Schematic of MIT-CRF and Support Systems

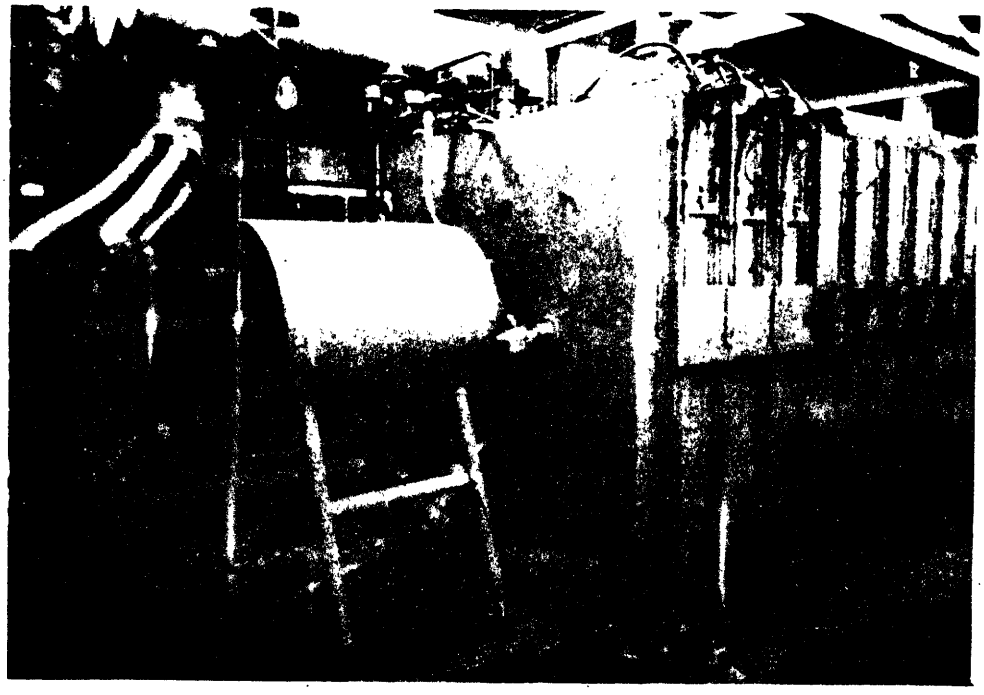


Figure A-2. View of Multi-fuel Swirl Burner and Experimental Chamber of Furnace

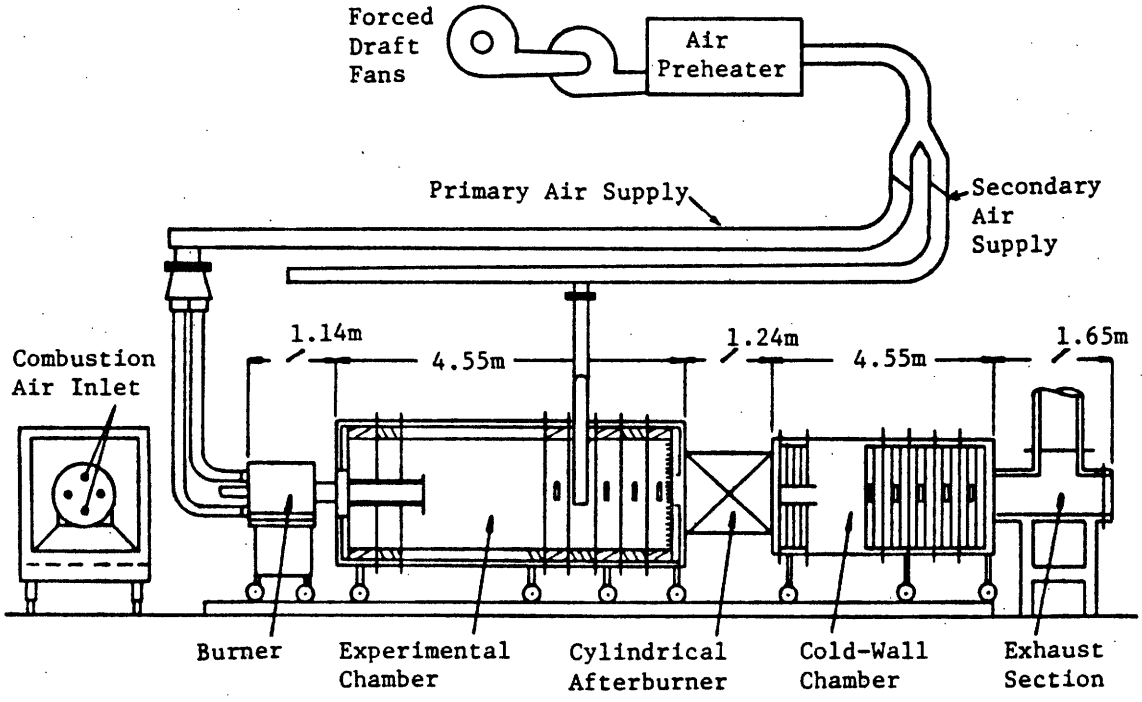


Figure A-3. Furnace Assembly and Air Supply for Staging

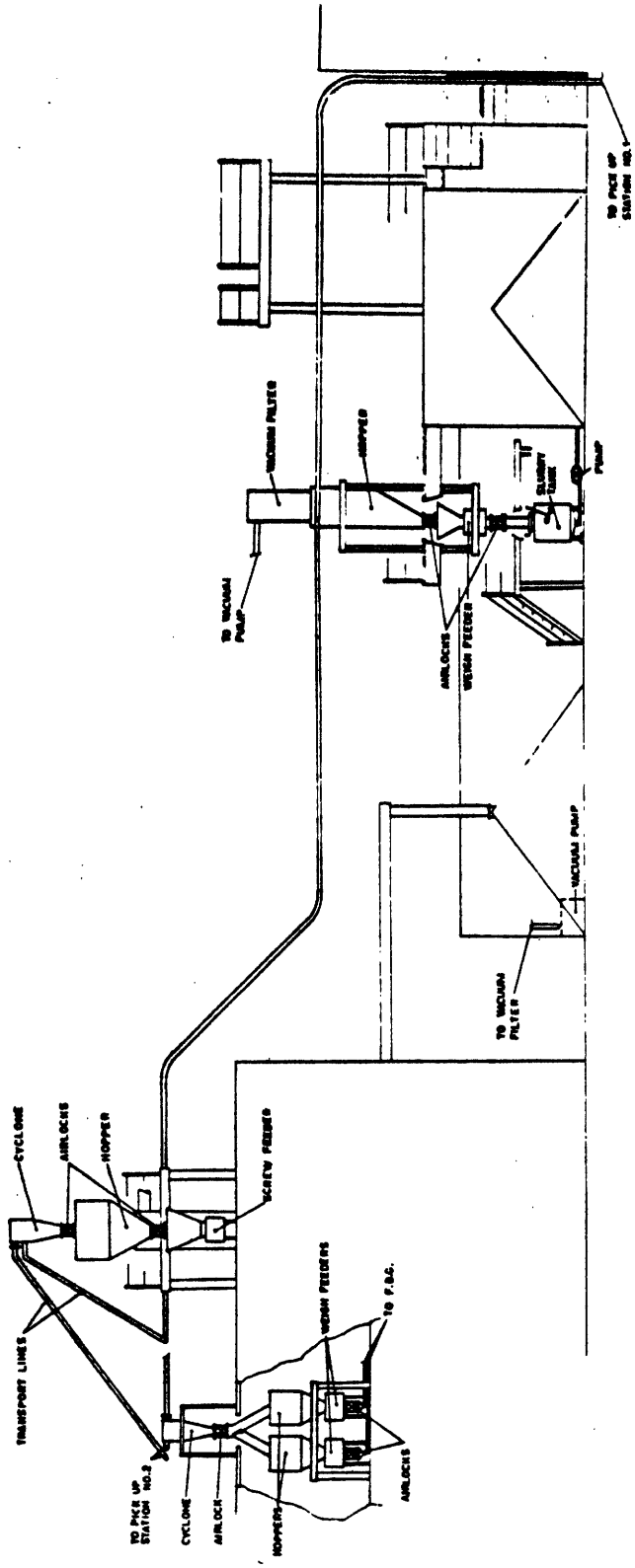


Figure A-4. Solids Handling System for CRF and FBC (Fluidized Bed Combustor)

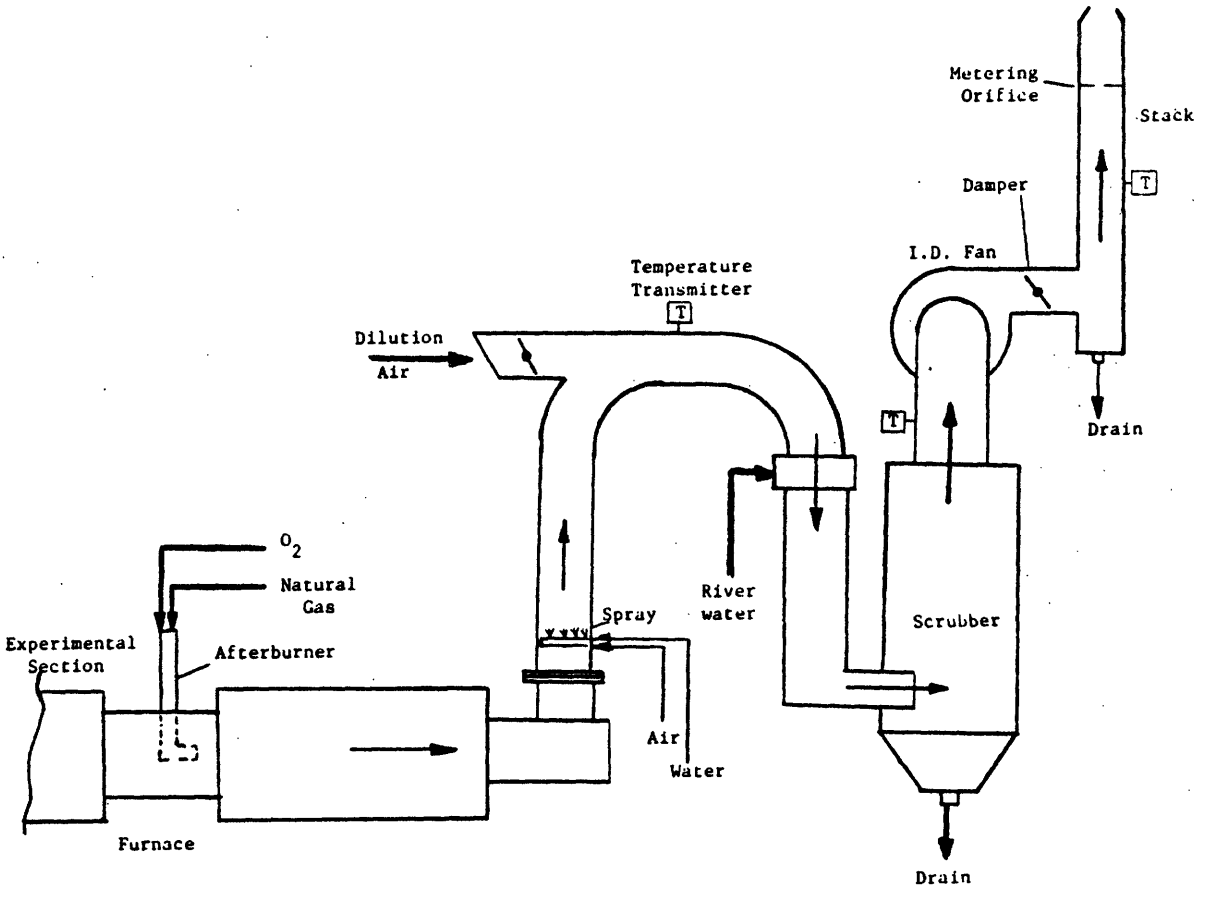


Figure A-5. Schematic of Exhaust System