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APPLICATION OF REMOTE SENSING OPTICAL INSTRUMENTATION
FOR DIAGNOSTICS AND SAFETY
OF NAVAL STEAM BOILERS

Navy Contract #N00014-87-K-0056

Annual Technical Report

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Prepared by

MHD Energy Center

Mississippi State University

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SUMMARY

Diagnostic sensors for monitoring the flame (flame quality), the presence of unburned hydrocarbon vapors, and the presence of liquid fuel on the floor of a burner are under development. Because safety and burner efficiencies are related to these conditions, sensors whose designs have been aimed at improving safety conditions can simultaneously be used to study efficiencies.

Several techniques for evaluating the operating conditions of boiler flames are currently under investigation at the MHD Energy Center of MSU. These include a capacitance-based liquid monitoring system and two optical experiments for monitoring flame quality and hydrocarbon vapors, and all of these techniques are designed to be used in the flame region of a boiler. At present the optical experiments are bench top experiments which use natural gas flames and a small explosion test cell; however, these natural gas flames do not approximate the flame within an oil-fired boiler closely enough for complete development of these techniques. It will be necessary to scale these experiments up to get temperatures, optical path lengths, etc. which more closely approximate a Navy boiler.



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FACILITIES

The MHD Energy Center operates a fuel-oil test stand which can be used for the next series of scaled-up tests. This facility is computer controlled and was designed to be flexible in simulating various gas stream conditions. The following conditions which will be useful in the development of Naval boiler diagnostics can be safely simulated on the MHD test stand:

1. Steady state combustion with air/fuel ratios in the range of approximately 0.75 to 1.50.
2. Poor fuel atomization.
3. Water in the fuel.

Some of the other conditions which can lead to potentially explosive conditions might also be simulated on our test stand, although it is not clear at this time as to what safety hazards might be produced.

A combustor is on hand that burns fuel oil with or without preheating the combustion air. Test sections with optical path lengths of up to approximately 20 inches and fitted with optical ports for viewing both through and behind the flame are also on hand.

This test facility is well-suited for performing a variety of combustion related experiments because of the ability to provide precisely known air/fuel ratios and gas stream flowrates. However, many of the gas stream conditions necessary for testing the Naval boiler instrumentation are impossible to simulate or are too dangerous to risk trying on the MHD test stand since it was designed to operate under steady state conditions.

At some point in the future, the diagnostic instrumentation will have to be tested in a Naval boiler simulator capable of safely operating under the following hazardous conditions:

- * Unburned fuel on the firebox floor
- * Atomizer malfunctions
- * Atomizing steam problems

* Air/fuel ratio problems

Excess combustion air (white-smoke condition)

Insufficient combustion air (black-smoke condition)

* Water in fuel oil

* Loss of flame

DIAGNOSTIC INSTRUMENTATION

Fuel Sensor

In an effort to develop a detector that would measure the presence of unburned fuel oil in a naval boiler two types of fuel sensors were explored. The initial effort was spent adapting a resistive surface moisture monitor such as one described in a JPL Invention Report.¹ Laboratory testing produced unreliable results which were also less than originally anticipated. This technique was then abandoned as infeasible for the conditions of a boiler.

A more practical detector for unburned fuel oil has proven to be a capacitive sensor. The principle of operation is the change in the dielectric constant of a refractory brick due to the presence of fuel oil. Two porous refractory bricks with embedded parallel plates, each forming a capacitor, were fabricated. The refractory being used in these plates was Korundal Fine Plastic, manufactured by Harbison-Walker Refractories, Pittsburgh, PA. Thermal and other properties of this refractory are:

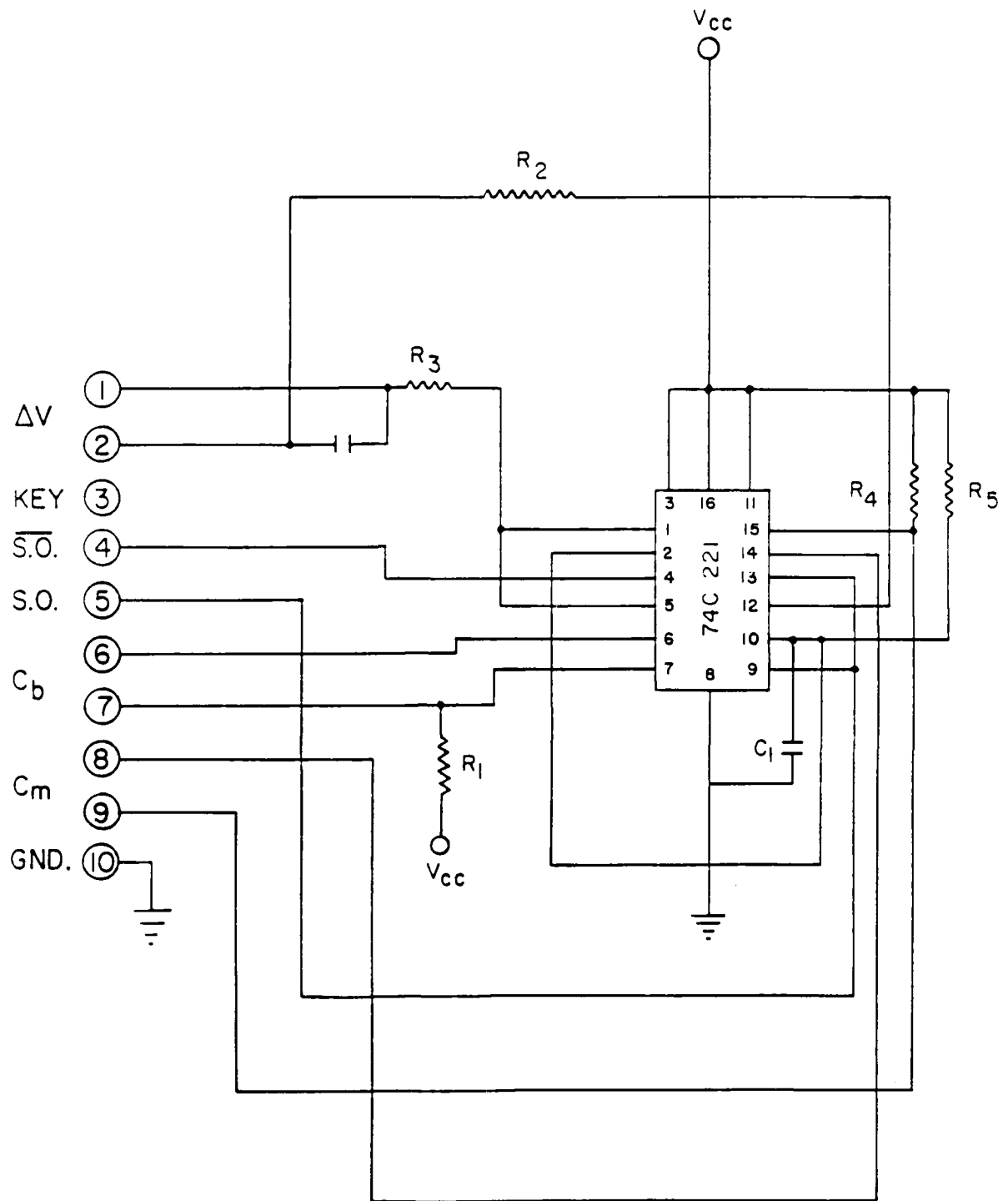
Max service temperature = 3300°F

Bulk density after drying = 182 lbs/cu. ft.

Primary applications: Broad application for very severe service; soaking pit bottoms and slaglines; transfer ladles, etc.

One of the bricks is used as the measurement brick and the other brick is used as a dry balancing capacitor in order that the effects of temperature and other thermal variations in the boiler may be minimized. It is anticipated that in a naval boiler, the measurement brick would be placed on the floor of the boiler and the balancing capacitive brick would be mounted on the walls or ceiling preventing its exposure to unburned liquid fuel.

The detection circuit (Figure 1) consists of a dual multivibrator in which the two bricks replace the timing capacitors. The output of the circuit is a square wave with the up time controlled by the capacitance of one brick and the down time controlled by the capacitance of the other. The duty cycle of the square wave is used to detect a capacitance change. The voltage across terminals (1) and (2) in Figure 1 is proportional to



- C_m = Measured capacitive brick
- C_b = Balancing capacitive brick
- ΔV = Detector voltage output
- S.O. & $\overline{S.O.}$ = Square wave signal outputs

Figure 1. Fuel sensor detection circuit.

the change in duty cycle. This is the most sensitive indication of a capacitive change.

A computer circuit was designed and constructed to measure the actual difference in up and down times from the multivibrator. An MC68705PC single chip computer, which has built-in EPROM memory was used. Measurements of the difference in up and down time to within 1 micro-second were made. This was not accurate enough for the present development work. It will likely be expanded in later work to measure the brick temperature and other parameters that affect the fuel sensor performance.

Table 1 shows the effect of fuel oil addition to one brick. Figure 2 shows the frequency variation of the square wave signal with fuel oil addition and Figure 3 shows the detector circuit's steady state, voltage change with fuel oil addition. Figure 4 shows a typical temporal variation of this voltage change.

The previous report² described some of the results obtained with the lightweight castable refractories. The results showed the temporal variation of detector output voltage with fuel oil addition. This figure showed the edge effect of having fuel oil sitting on the top of the brick before absorption. Maximum detector voltage was obtained at this point and the voltage dropped off exponentially as the fuel oil was gradually absorbed into the brick. Although the response time of this brick design is the shortest, there is an undesirable feature in that the brick would be very susceptible to humidity variations and other noise sources on top of the brick. This could very well mask the actual detection of fuel oil on the brick. To change this feature the current brick design has refractory filled over the top edges of the plates. The effect of this change in design is shown by the change of the brick response in Figure 4. In effect the capacitance of the brick increases to a steady state value as all the fuel oil is absorbed. There is no peak obtained as in the previous cases reported.

The basic electrical circuit for this measurement has been completed. The refractory brick has been tested under atmospheric conditions and is soon to be tested under firing conditions. Significant changes in voltage have been measured under atmospheric conditions. These changes in voltage (230 mV for 75 cc. of fuel added to about 18 sq. in. of exposed brick surface area) are easily measurable. The problem, however, will be more

Table 1. Effect of fuel oil addition on detector outputs.

No.	Fuel added (cc)	Voltage V	Frequency KHz	Signal width (micro secs)	
				Up time	Down time
1	0	0.1034	23.920	21.704	20.105
2	0	0.1033	23.916	21.707	20.109
3	5	0.0822	23.803	21.705	20.297
4	5	0.0625	23.699	21.719	20.477
5	5	0.0420	23.591	21.725	20.668
6	5	0.0274	23.493	21.730	20.839
7	5	0.0084	23.414	21.734	20.979
8	5	-0.0087	23.324	21.738	21.138
9	5	-0.0251	23.237	21.743	21.294
10	10	-0.0615	23.044	21.754	21.645
11	10	-0.0845	22.923	21.760	21.869
12	10	-0.1077	22.801	21.767	21.097
13	10	-0.1269	22.702	21.770	22.281

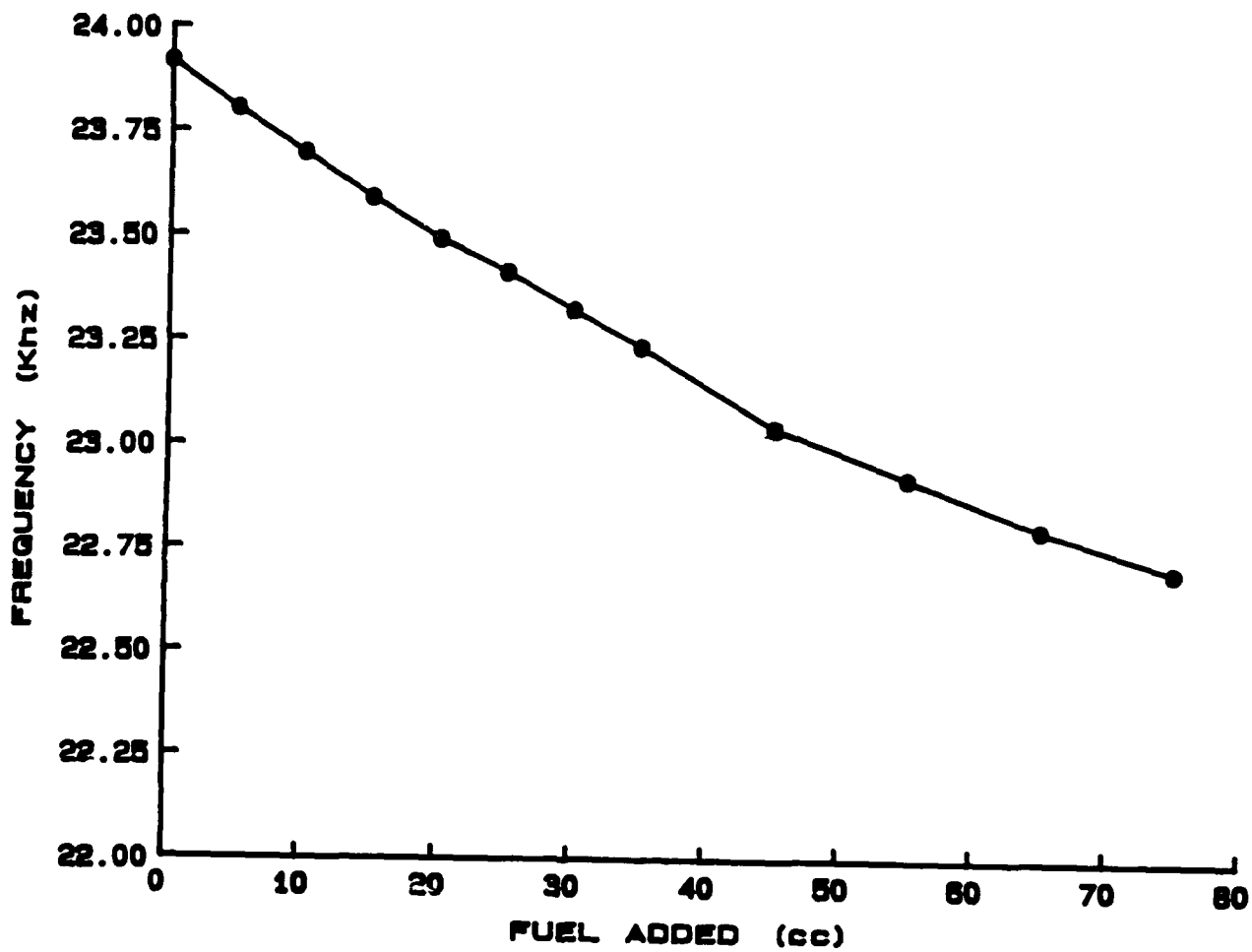


Figure 2. Frequency variation with Korundal Fine Plastic refractory bricks.

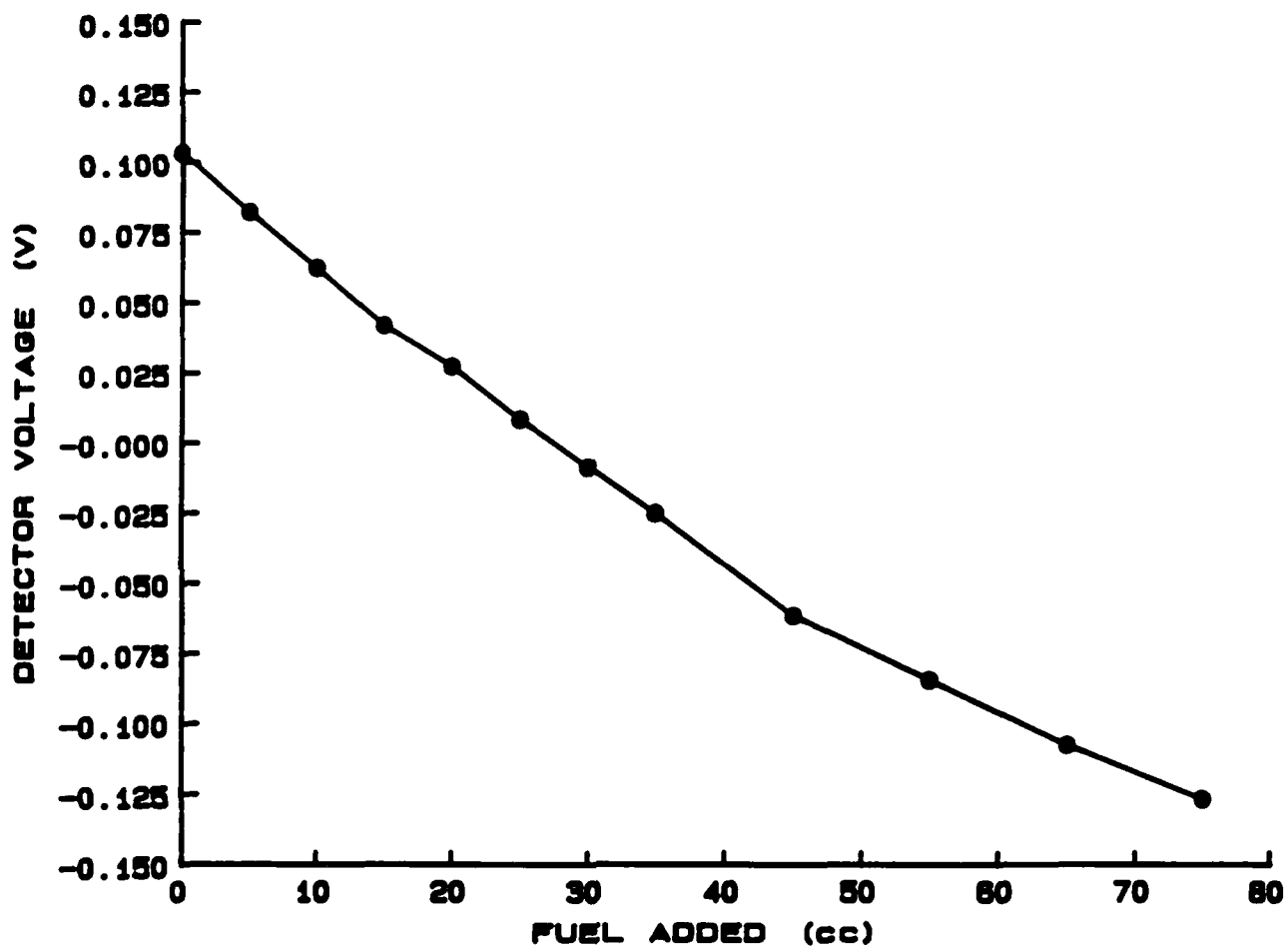


Figure 3. Steady state detector output voltage with Korundal Fine Plastic refractory bricks.

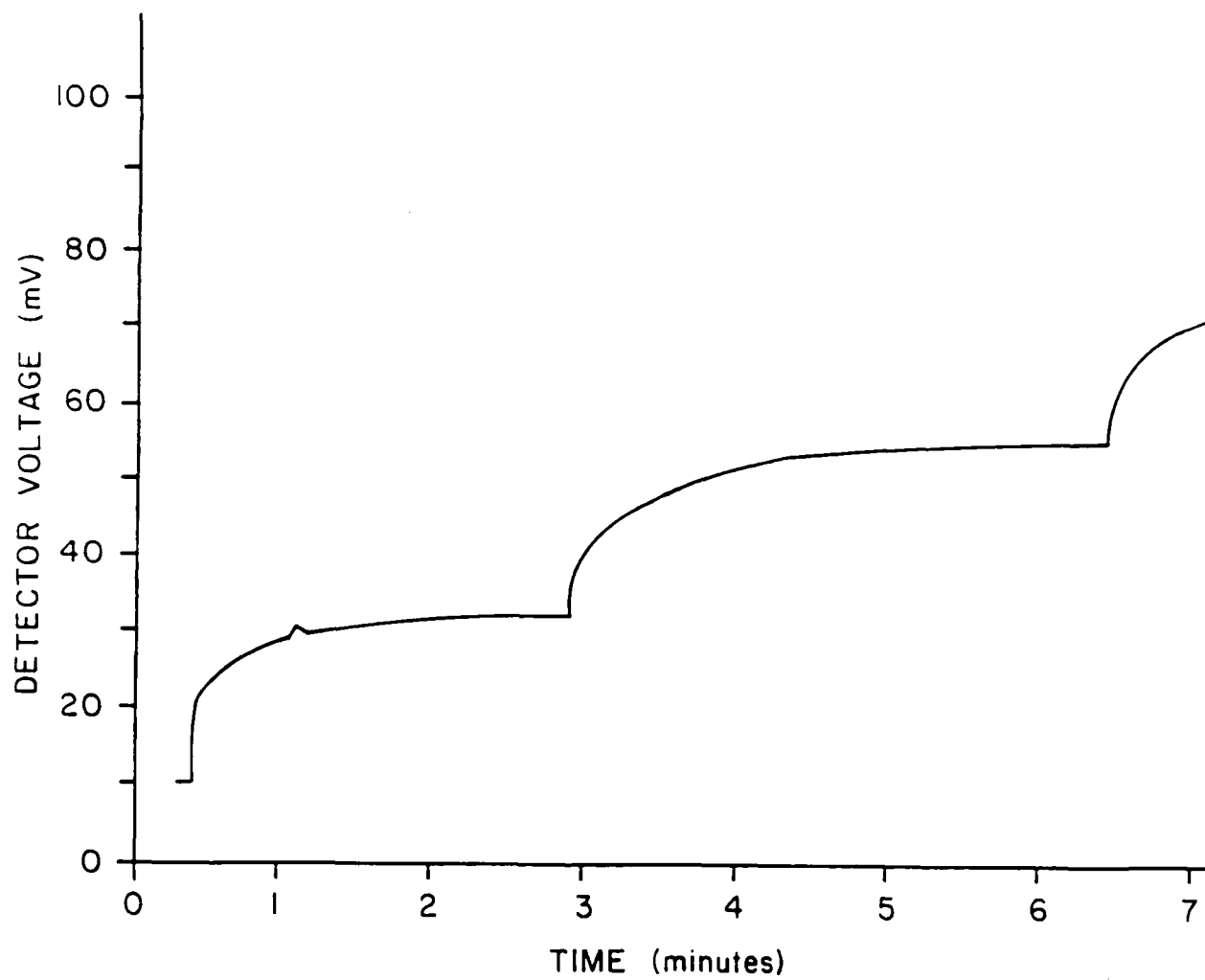


Figure 4. Detector circuit voltage response to 5 cc fuel addition steps.

difficult at elevated temperatures where the changes in dielectric constant might be brought about by rapidly changing temperatures at firing conditions. The change in brick design that has now been incorporated should, however, decrease those effects. Testing under firing conditions will begin shortly and the severity of this problem will be seen then.

The technique so far seems to be a reliable indicator of fuel oil absorption. Its response is good enough and fast enough to be used under practical conditions. Further testing will include boiler on/off conditions, variations in chamber testing conditions, and other scenarios in which this detector might be used.

Cross Correlation Flame Monitor

Current commercial flame detectors use the light emitted by a flame to verify the presence of the flame. However, this light is a complicated phenomenon and contains much information about the combustion process within the flame. This emitted light consists of different wavelengths of radiation, from the ultraviolet to the infrared. Due to turbulence and other factors, the emitted radiation varies with time, containing fluctuations over a wide range of frequencies. Finally, the radiation is not spatially constant, varying from the base of the flame to the tip.

Therefore, as part of the research performed under this contract, development of a flame monitor was begun to more fully exploit the enormous information available in the light emitted by a flame. The ultimate objective is a robust, simple, passive flame monitor which is capable of, in increasing order of difficulty:

1. Adequate spatial resolution to detect loss-of-flame on an individual burner in a naval boiler;
2. Detection of abnormal, unsteady, or irregular combustion which might lead to loss-of-flame; and
3. Measurement, by purely optical means, of the fuel/air ratio of an individual burner, thus allowing automatic control of the fuel/air ratio.

The first phase of activity on this project concentrated on development of a bench-top optical flame monitor, flexible enough to analyze all aspects of the light emitted by a flame. The system has been tested on a bench-top, methane-air flame to verify its proper operation. The system can analyze the light according to wavelength, flicker frequency, and spatial location.

Studies of flames in premixed gases indicate that the relative intensities of different wavelengths of light is an accurate indicator of the fuel/air ratio.^{3,4} Thus, the fuel/air ratio could be determined by measuring the radiation intensity at two different wavelengths and taking the ratio of the two intensities. McArthur, et al., have reported success with this method on industrial oil-fired boilers.⁵

The prototype flame monitor built at Mississippi State University

incorporates wavelength sensitivity by means of a monochromator coupled to a photomultiplier tube detector, allowing the selection of any wavelength in the range 200-800 nm. Figure 5 is a graph of mean light intensity as a function of wavelength. Several peaks are clearly visible. These peaks can be assigned to radicals such as OH, CH and C₂ which are formed during combustion.

Figure 5 was produced by time averaging the output from the photomultiplier tube for each wavelength setting of the monochromator. If this signal is examined as a function of time, the result is shown in Figure 6. The detector output varies with time, principally as a result of turbulence in the flame. A better way to view this information is in the frequency domain. The photomultiplier tube output is processed by a Hewlett-Packard spectrum analyzer, which Fourier transforms the signal into a function of frequency. A typical result ("flicker spectrum") is shown in Figure 7. This spectrum is a potential source of information about the flame and some preliminary surveys have been reported.^{6,7} The bench-top flame monitor built at MSU is equipped to record and analyze this signal, both in the time domain and in the frequency domain.

One limitation of most optical sensors concerns spatial resolution. Although the field of view of a sensor can be limited to a very small angle, the sensor will still detect any light emitted along a line extending from the sensor to the wall. In multiburner boilers, this creates difficulties distinguishing the flame at one burner from the flames at others. To resolve this problem, the MSU flame monitor incorporates a technique known as cross-correlation.^{8,9}

The cross-correlation technique uses two sensors arranged so that their lines of sight intersect at a point (Figure 8). If the flame fluctuations are random and due to turbulence, then the flickering from one part of the flame should be independent of the flickering in another part. Thus, by computing the correlation between the two signals, the flickering originating from the region of intersection can be isolated.

As used in the past, the cross-correlation technique calculated the correlation by averaging in the time domain and obliterated any frequency information in the data. The MSU flame monitor uses a spectrum analyzer to compute a correlation function of frequency.¹⁰

The effectiveness of the cross-correlation technique can best be seen

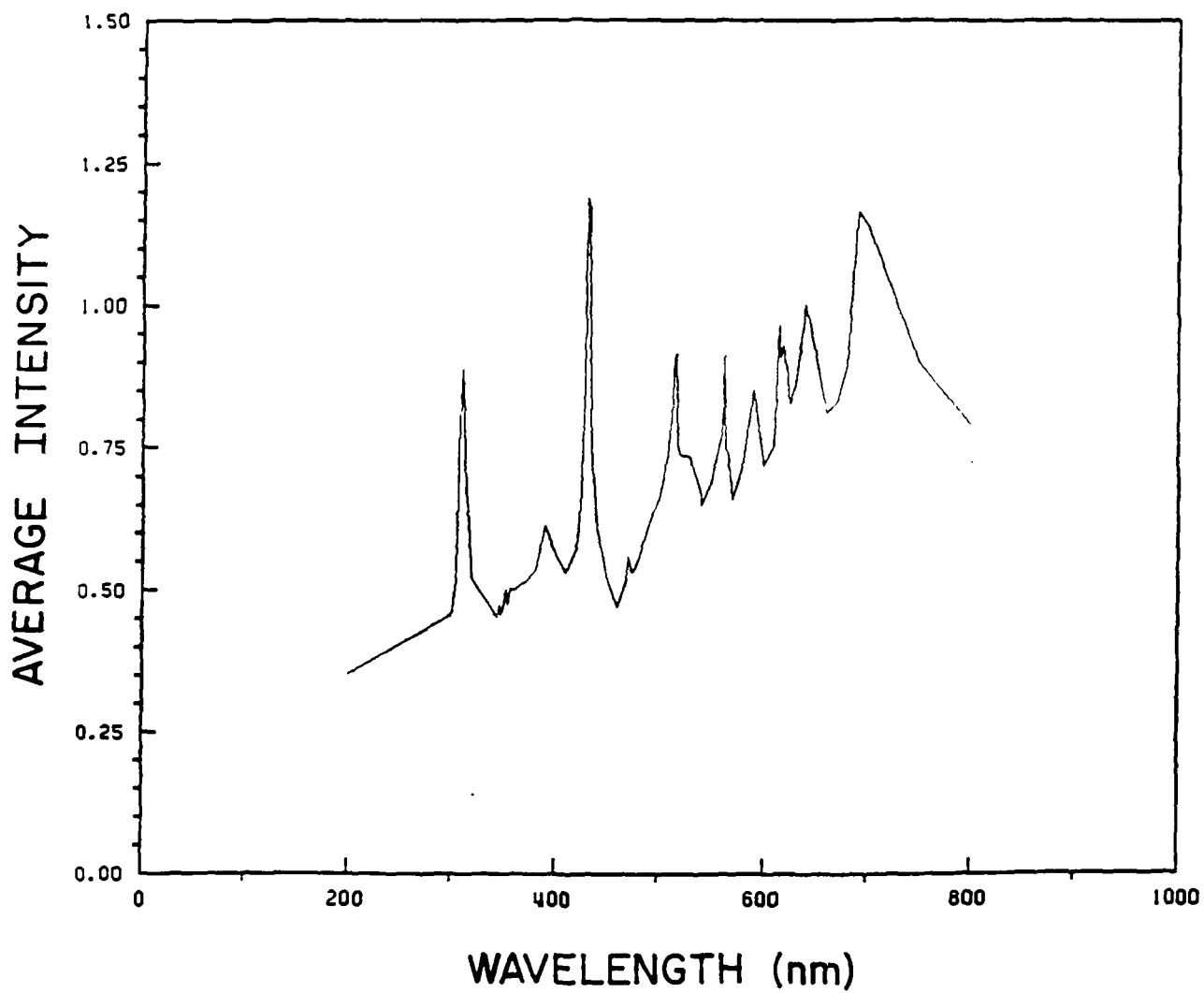


Figure 5. Average signal intensity as a function of wavelength. Several peaks are clearly visible, such as the 310 nm peak due to OH and the 430 nm peak due to CH.

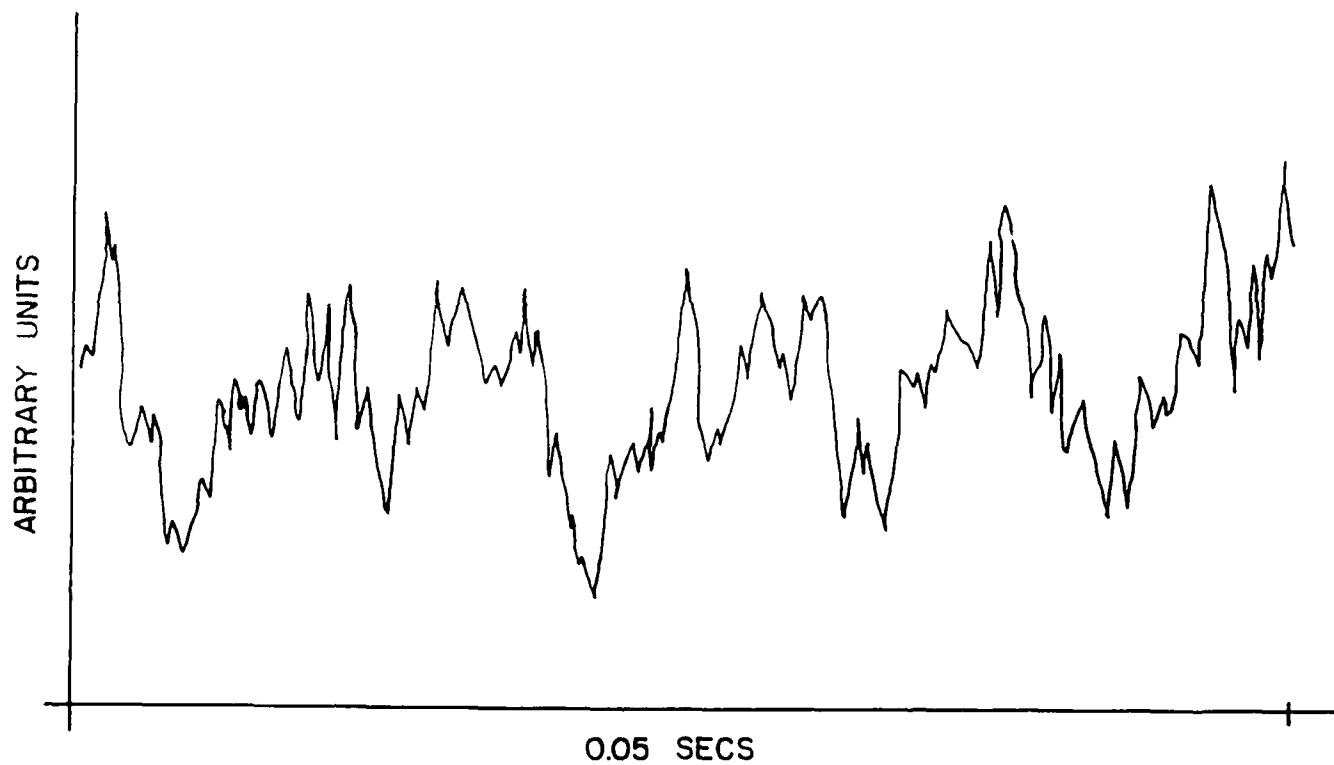


Figure 6. Signal intensity as a function of time. The monochromator is set on the peak at 310 nm, and the graph spans a total time interval of 0.05 seconds.

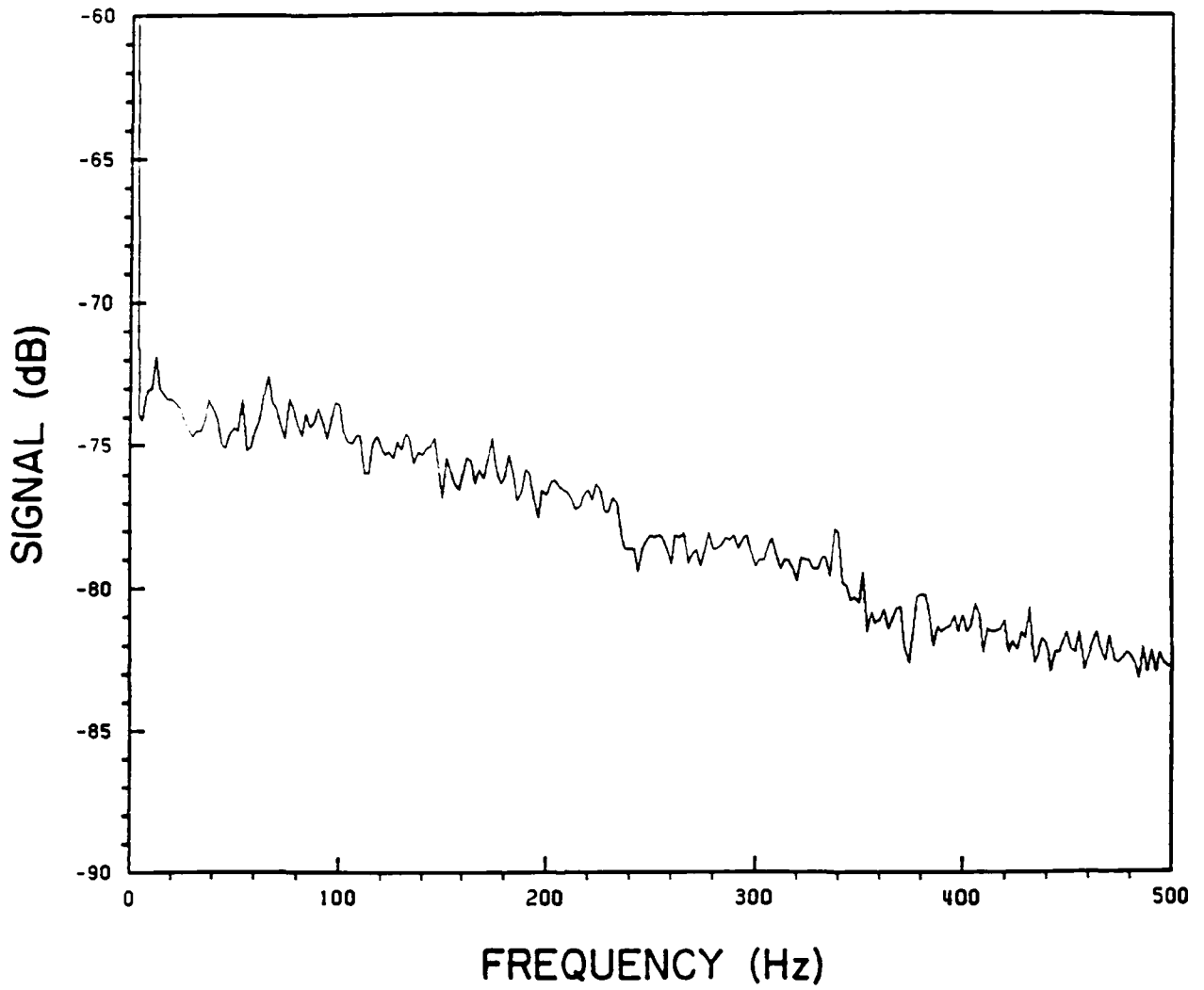


Figure 7. The time-varying signal has been Fourier transformed into the frequency domain.

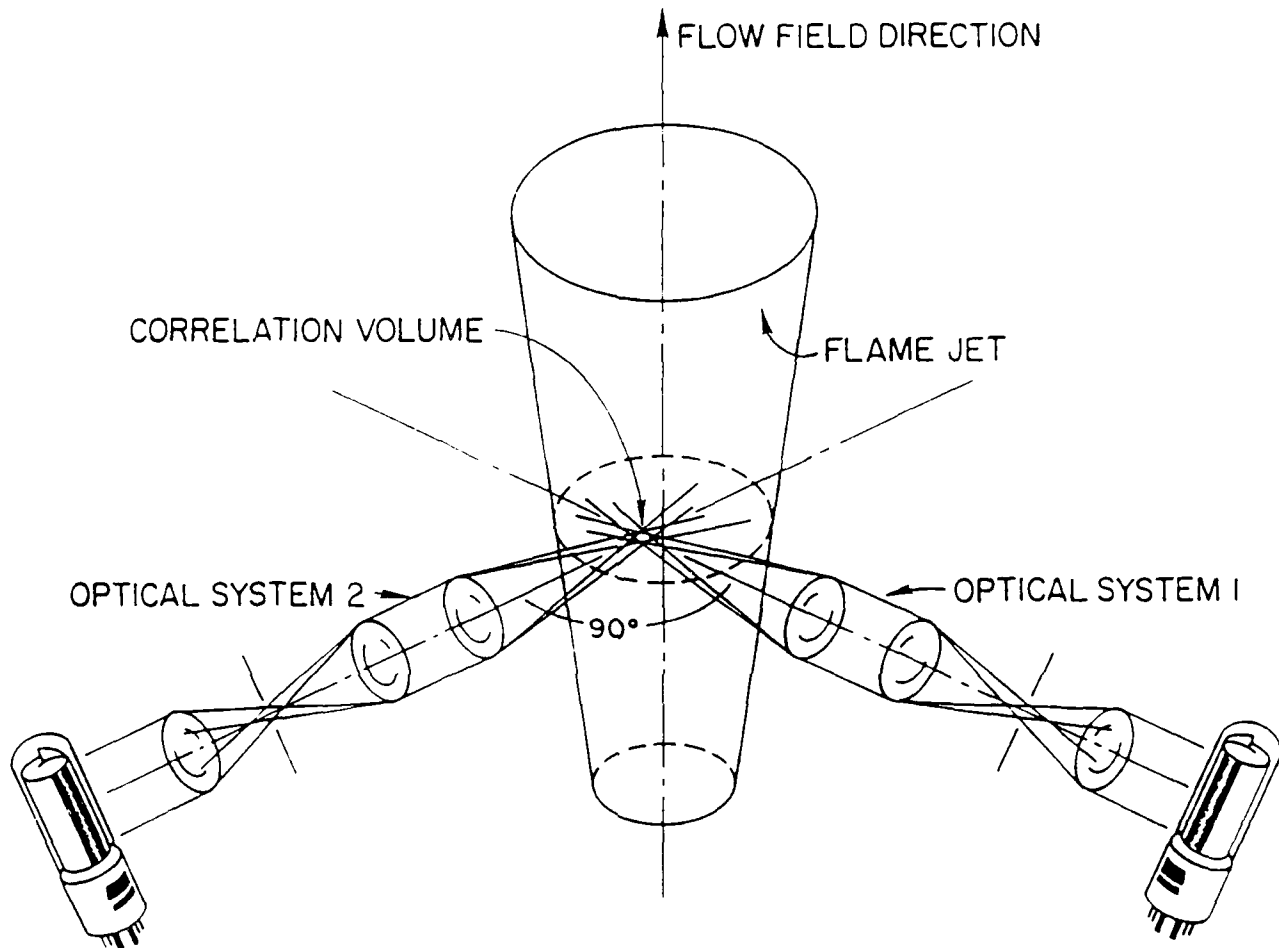


Figure 8. Optical arrangement for the cross-correlation technique.

in Figure 9. This figure was produced by vertically translating one channel so the two lines of sight no longer intersect. When this is done, the level of correlation rapidly decreases. Figure 9 demonstrates that the spatial resolution of the system is on the order of one-tenth of an inch.

The experimental flame monitor described above has been built and tested on a bench-top methane-air burner. This system consists of two identical optical systems which use monochromators to select a given wavelength and photomultiplier tubes to convert the light into an electrical signal. A spectrum analyzer Fourier transforms the signals and transmits the results to a COMPAQ microcomputer. The signal can also be read in the time domain by an analog/digital converter connected to the computer which processes and stores the data. Thus, a very powerful and very general flame monitor has been built. With it, every aspect of the light emitted by a flame can be examined with excellent spatial discrimination.

The next step in the investigation is to examine typical fuel oil flames. The MSU/MHD combustion test stand was used for this phase of the project. The test stand is refractory lined, with an internal diameter of eight inches. Fuel oil and air (nominal flow rates 30 and 500 lbm/hr, respectively) are injected at one end.

The facility is computer controlled and extensively instrumented. To simulate MHD flows, the combustion air is preheated and the resulting flame is a transparent blue, similar to a natural gas flame. For these experiments the preheater was not used and the flame was a much brighter yellow color.

A nitrogen purged window twelve inches downstream from the injector plate provided optical access to the flame. A single channel lens-monochromator-detector system was connected to the A/D converter in the COMPAQ microcomputer. The window on the opposite side of the flow stream was focused on the monochromator slits to ensure that the instrument measured only gas stream radiation and not radiation from the walls.

Scans of mean intensity versus wavelength were made for several different fuel air ratios. The results are shown in Figure 10. Here ϕ is defined as the actual air/fuel ratio divided by the stoichiometric air/fuel ratio, so values of ϕ greater than one refer to flames with excess air and ϕ less than one means the flame is fuel rich.

Several features of Figure 10 should be pointed out. First, the

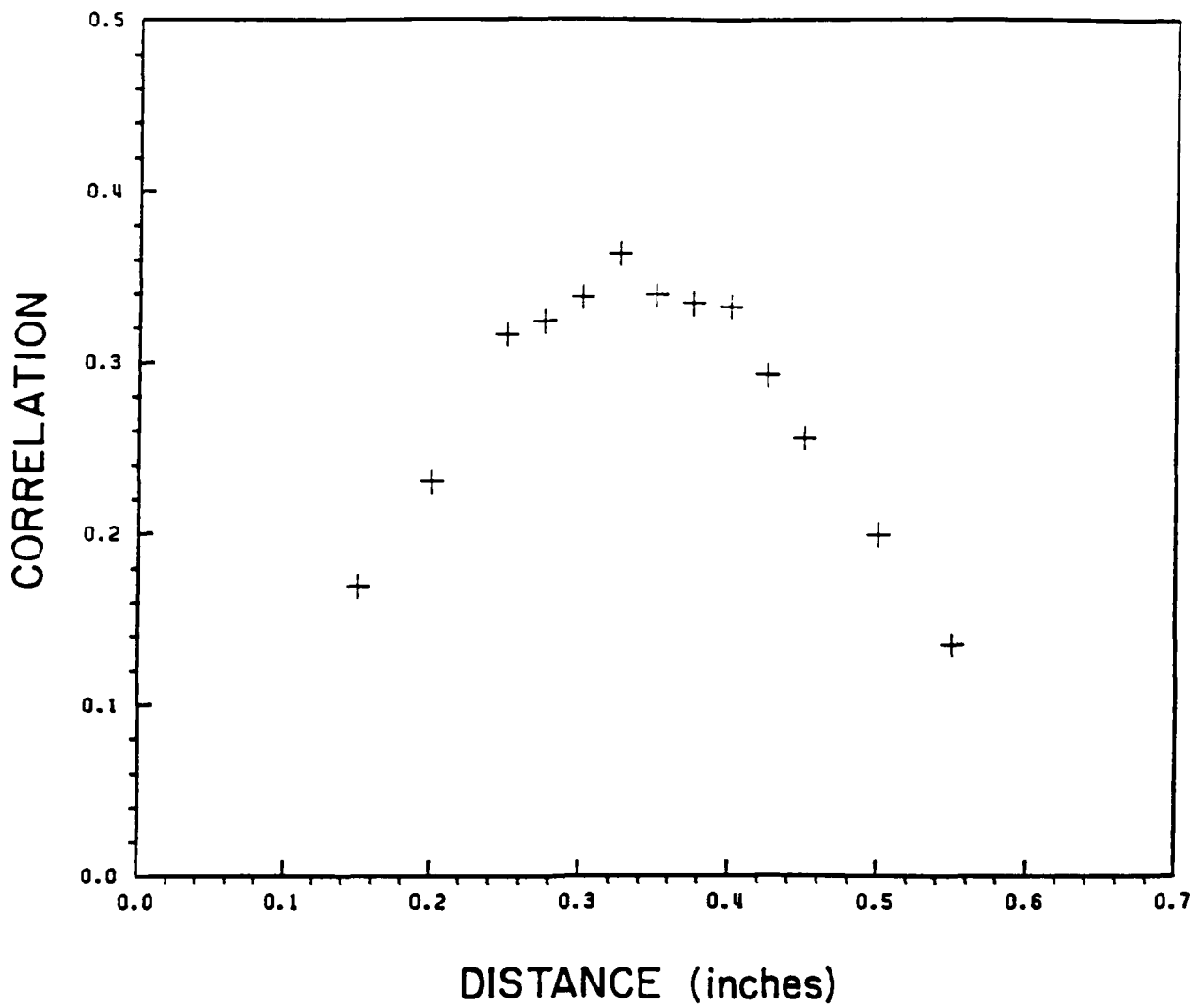


Figure 9. Correlation between the two signals over a frequency range of 400-500 Hz. Misalignment is intentionally produced by translating one channel vertically so the two lines of sight do not intersect. The width of the maximum indicates the spatial resolution of the system.

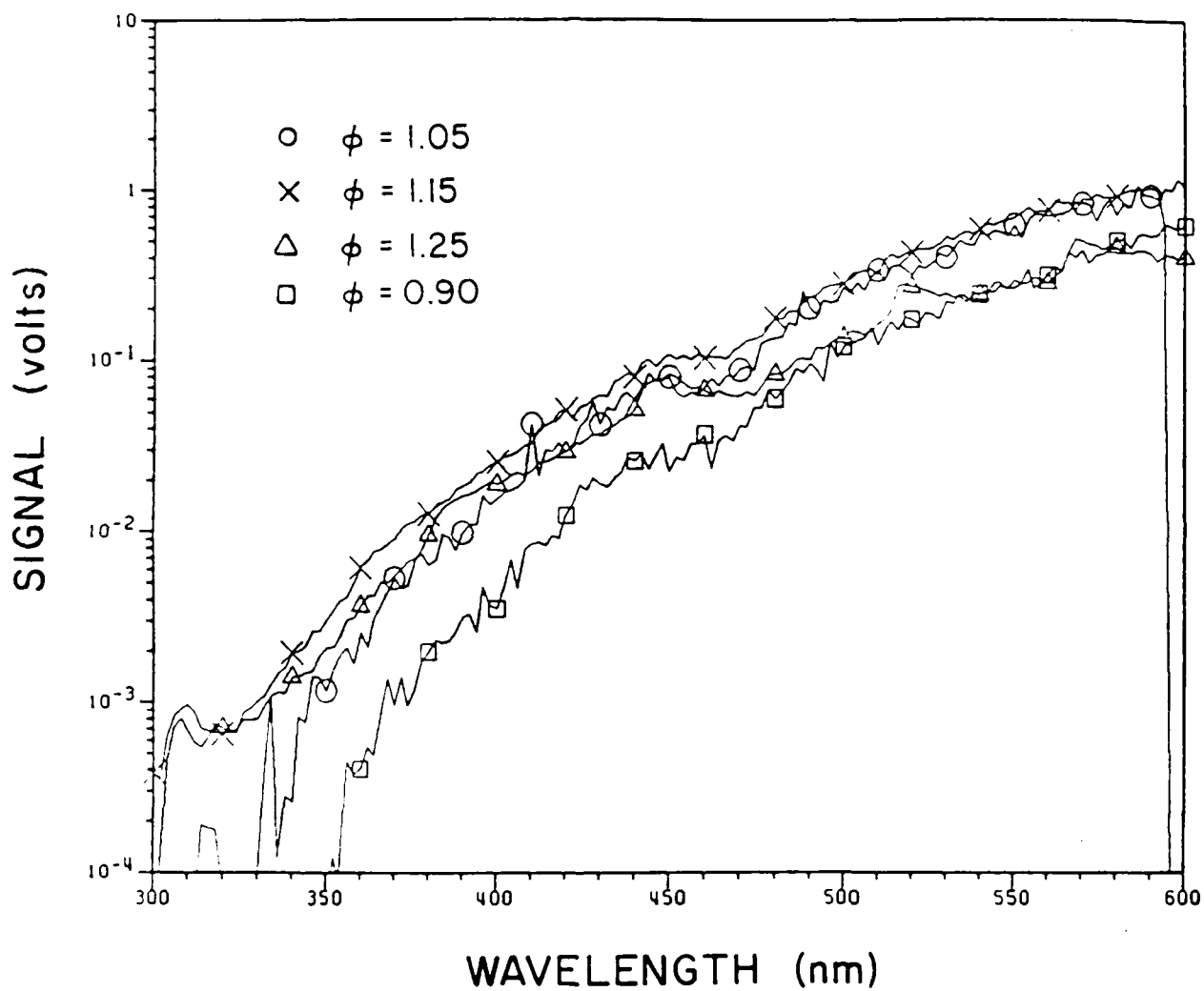


Figure 10. Scans of mean intensity vs. wavelength for several different fuel-air ratios.

emission curve seems smooth and continuous (except for fluctuations caused by statistical sampling error). Figure 5, made using a methane-air flame, shows several features which can be identified with radical species in the flame. Figure 10 is entirely different. It is known that the radiation from such flames is dominated by the luminosity of soot.¹¹ Apparently, the continuous radiation spectrum shown in Figure 10 is the thermal radiation from soot particles.

Examining the figure further, consider the slope of the continuous spectrum. For all cases, the intensity decreases for shorter wavelengths. However, the slope of this decrease is greater for rich flames than for lean flames. Since the emissivity of soot particles is independent of diameter^{12,13} this change in slope is due to changes in the temperature of the particles.

Currently, the monochromator-detector systems are being calibrated for wavelength response using blackbody sources and tungsten lamps. This should allow the soot emission spectra to be interpreted in terms of soot temperature.

More spectra should be taken of fuel-oil flames for different air/fuel ratios, flow rates, and at different locations in the test stand. The bench-top fuel-oil burner will be used for these experiments when it becomes available.

Differential Infrared Monitor

A differential infrared absorption method is being developed primarily to monitor unburned hydrocarbon vapors in a navy boiler. The technique utilizes two helium-neon lasers operating at different infrared wavelengths and compares the absorption of hydrocarbons at these two wavelengths. One of the He-Ne lasers operates at $3.3922 \mu\text{m}$ (2947.9 cm^{-1}). The second laser operates at $3.3911 \mu\text{m}$ (2948.9 cm^{-1}) when a sample of methane is placed inside the optical resonator (intracavity).¹⁴ The difference in the absorption at these two wavelengths can be related to the concentrations of hydrocarbons in the optical path.¹⁵

Recent work has focused on monitoring methane in a variable temperature/pressure cell mounted on the optical table. Using phase-sensitive detection, the presence of methane in the sample cell induces both a pen deflection and an oscillation in the recorder trace. The magnitude of the deflection and the amplitude of the oscillation are determined by the concentration of methane. The oscillation probably results from a phase mismatch of the two infrared beams, and adjustments of the optical components and mechanical chopper is expected to eliminate this effect if necessary.

To improve the sensitivity of the technique for methane detection, the stability of the laser fitted with the intracavity cell has been studied. A new intracavity cell with increased pathlength and a slightly modified optical orientation reduced the noise in the shifted laser beam to approximately the same as that in the unshifted beam. With satisfactory stability achieved, additional intracavity gases are being investigated relative to their utility in enhancing the sensitivity of the infrared monitor to higher hydrocarbons.

CO/CO₂ Monitoring

It is clear that CO/CO₂ monitoring is necessary for the efficient and safe control of boilers. Present systems, utilizing gas sampling or non-dispersive IR techniques, are slow and stack-based. Laser-based methods should be able to provide rapid, burner specific measurements of this important ratio. A semiconductor diode laser operating at 4.5 microns, where both CO and CO₂ absorb, is currently being evaluated in our laboratory for this purpose.

Diode lasers put out two or more closely spaced, 10^{-4} cm⁻¹ wide lines tunable over their intrinsic bandwidths of 15 - 100 cm⁻¹. Unfortunately, the tuning, which is controlled by temperature in the range of 15 - 45 K and current between 0.2 and 0.9 ranges, is both non-linear and non-continuous. After taking many survey scans of CO₂ and CO absorption spectra, it was found that it is necessary to scan very slowly, 0.2 cm⁻¹/min, and over narrow ranges, approximately 2 cm⁻¹. The use of a marker etalon, with a free spectral range of 0.049 cm⁻¹, is also required to provide a continuous wavelength calibration and to indicate when discontinuities, or mode hops, occur in the spectra. After much experimentation, we have been able to identify many of the CO₂ and none of the CO absorption features that are in the range of this diode.

The current thrust of our efforts is to empirically find the best operating conditions and spectral ranges of this laser for CO/CO₂ measurements. For any wavelength desired, there are many combinations of temperature and current possible, and all of these must be examined to determine the optimum operating parameters. There are also several wavelengths that can be used for CO/CO₂ monitoring, and these will also have to be carefully studied to find the best overlap of good laser operating characteristics and the spectral and concentration properties of the CO and CO₂ absorptions.

The above diode infrared laser source is bulky and expensive, since it requires costly cooling devices. Progress is being made in the design of smaller and more efficient laser sources in this area, but it may be some time until they become practical. One alternative is to use existing room temperature semiconductor lasers operating in the 1.5 μ m region, which overlaps with C-O stretch overtones. These lasers do not require costly

low temperature cooling devices and also have relatively good output powers (as much as 1 Watt c.w.). The only drawback to this possibility is that the absorption coefficients for CO and CO₂ overtones in this region are greatly reduced from their fundamentals.

Little information seems to exist about the structure of the overtone absorption spectra of CO and CO₂ in this region, and about the absorption coefficient of these transitions. From the information that has been found to date, it appears that the CO overtones are extremely weak, while the CO₂ overtones are weak, but probably detectable. It has yet to be determined what the sensitivity of such a measurement would be and how readily available the correct semiconductor laser is.

Bench-Top Fuel Oil Burner

At present two types of combustion devices are used in the development of combustion diagnostic instruments. The availability of a bench-top fuel oil burner would help fill the gap between the Bunsen burner and the oil-fired test stand. This type of burner would speed up the development process for instrumentation and save part of the time and money required to operate the test stand. Many tests could be done on the bench-top that would otherwise have to be done on the test stand.

The basis for this burner is an ultrasonic atomizing nozzle that was bought from the Sonotek Corporation. The advantage of an ultrasonic atomizer in this application is that no high air or fuel pressure is needed. This nozzle works well in its specified operating range of up to approximately 0.25 gpm. Fuel oil passes through the nozzle and exits from its tip in a cloud of droplets of about 30 micron diameter. Ideally these droplets will be entrained in the air flow in the burner throat for a time sufficient for good mixing before exiting to the mouth of the burner.

Several problems were encountered during initial attempts to develop a burner. One of the main problems centered around the cost of the atomizer and its temperature limitations. The atomizing nozzle was always kept at a safe distance from the flame region of the burner. This resulted in good fuel/air mixing, but created a problem with fuel droplets adhering to the burner walls. This resulted in the eventual collection of fuel in the air supply line.

A related problem occurred when a screen was placed across the burner mouth. Fuel droplets stuck to the screen and collected in larger drops in some portions of the screen. The flame would not attach to the screen and was not very stable. Burning was confined to a very narrow range of fuel flows.

Proceeding on the assumption that additional energy had to be added to the flame, the burner shown in Figure 11 was constructed. A helical nichrome spring covers the mouth and acts as an attachment point for the flame. About 20 volts is applied to the nichrome wire to start the burner. After the flame starts the voltage is removed, the nichrome remains red hot, and the flame is stabilized. All fuel reaching the burner mouth is atomized on the hot surface of the nichrome. The range of

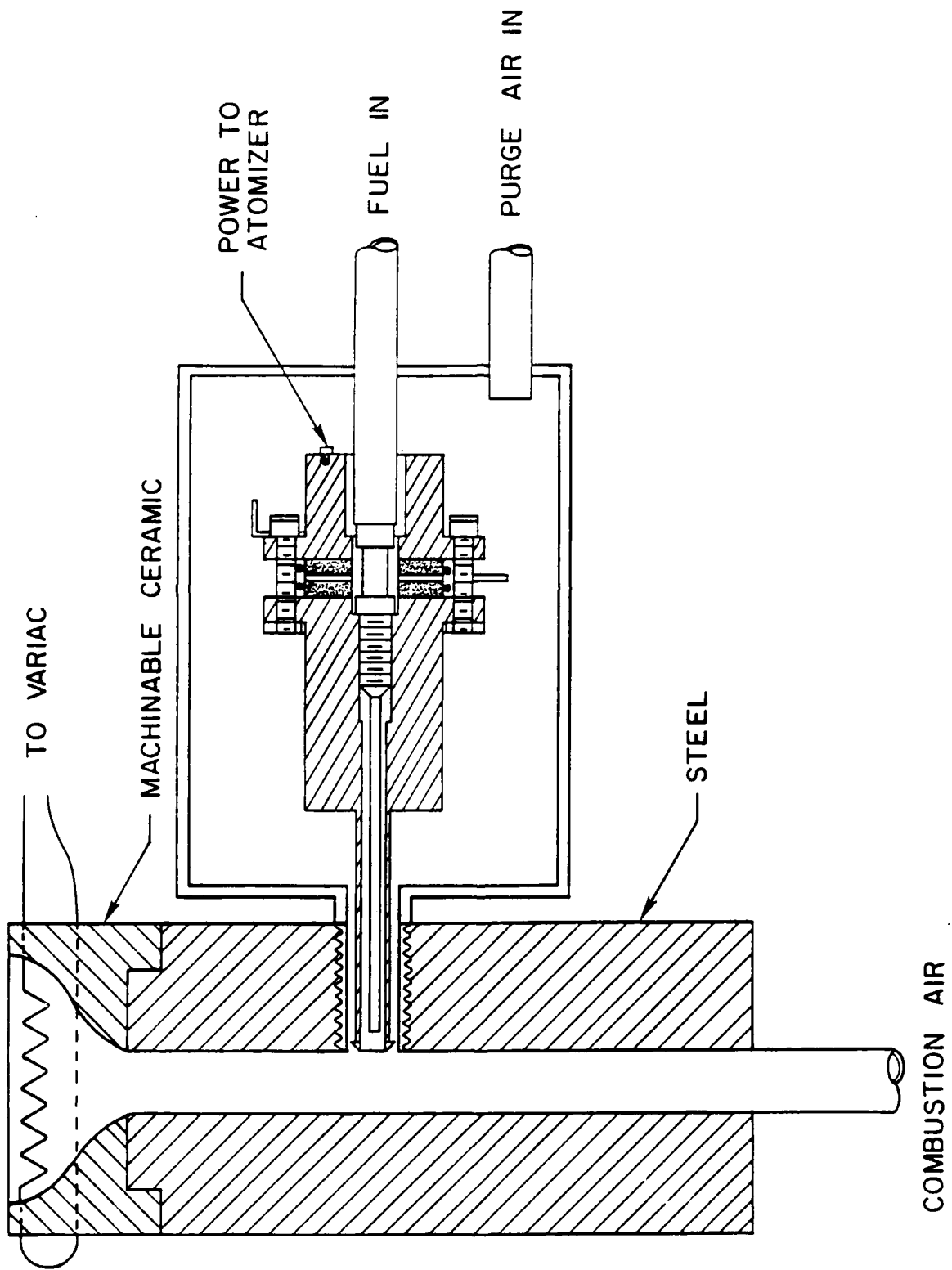


Figure 11. Bench-top fuel oil burner.

useful air/fuel flows is extended to the limit of the atomizing nozzle.

A peristaltic pump with a 12-roller head to minimize flow pulsation has been ordered. It will replace the simple gravity-feed system that has been used to deliver fuel to the burner. The prototype burner will be packaged with the pump so it can be tested in the laboratory. Feedback from this test will be used for the final burner design. The current version should be of some use in the laboratory although the problem of fuel sticking to the walls is still present. The final design will have air and fuel flow metering and a simplified operating procedure.

Explosion Test Cell

The Explosion Test Cell (ETC) (shown in Figure 12) is a cylindrical pressure vessel which was designed to accomplish two primary objectives-- to contain an air/fuel mixture at elevated temperatures and to allow the determination of flammability limits of hydrocarbon fuels, diesel fuel marine in particular. The ETC has been described in detail elsewhere¹⁶ and will not be described here except to say that it is instrumented with thermocouples and a pressure transducer.

The first objective has been accomplished and the ETC is ready for use in instrument development. The primary use of the ETC is expected to be in the development of the differential infrared monitor.

Work on the determination of flammability limits for Diesel Fuel Marine (DFM) continued but difficulties have yet to be overcome. The procedure by which flammability limits are to be determined consists of heating the ETC to a predetermined temperature, injecting the liquid fuel, agitating the fuel/air mixture, and extracting a sample for analysis by an HP 5830A Gas Chromatograph (GC). Following the GC analysis, more fuel or air should be added to the ETC to attain a desired air/fuel ratio. After the desired air/fuel ratio has been attained a spark is generated inside the ETC to ignite the air/fuel mixture. This process is repeated until an air/fuel ratio is found which is flammable and where an air/fuel ratio which is slightly lower is not flammable. This ratio is the lower flammability limit at the stated temperature for the fuel.

The main problem in this process is that during GC analysis some of the fuel vapor is slowly oxidizing in the ETC so that by the time the GC analysis is done the reported concentration is no longer valid making an adjustment to the concentration impossible. An additional effect of this slow oxidation is that there is no longer a mixture of fuel and air but of fuel, oxidized fuel components, and air. This means any flammability limit determinations will not truly reflect an air/fuel ratio.

An alternative method of analyzing post combustion gases was found but does not appear to have an advantage over the old way. As reported in the 1986 report analysis of O₂, N₂, CO, and CO₂ was done on two parallel columns of Chromosorb 102 and Molecular Sieve 5A.¹⁶ The new method consists of using two independent columns of Molecular Sieve 5A and Porapak

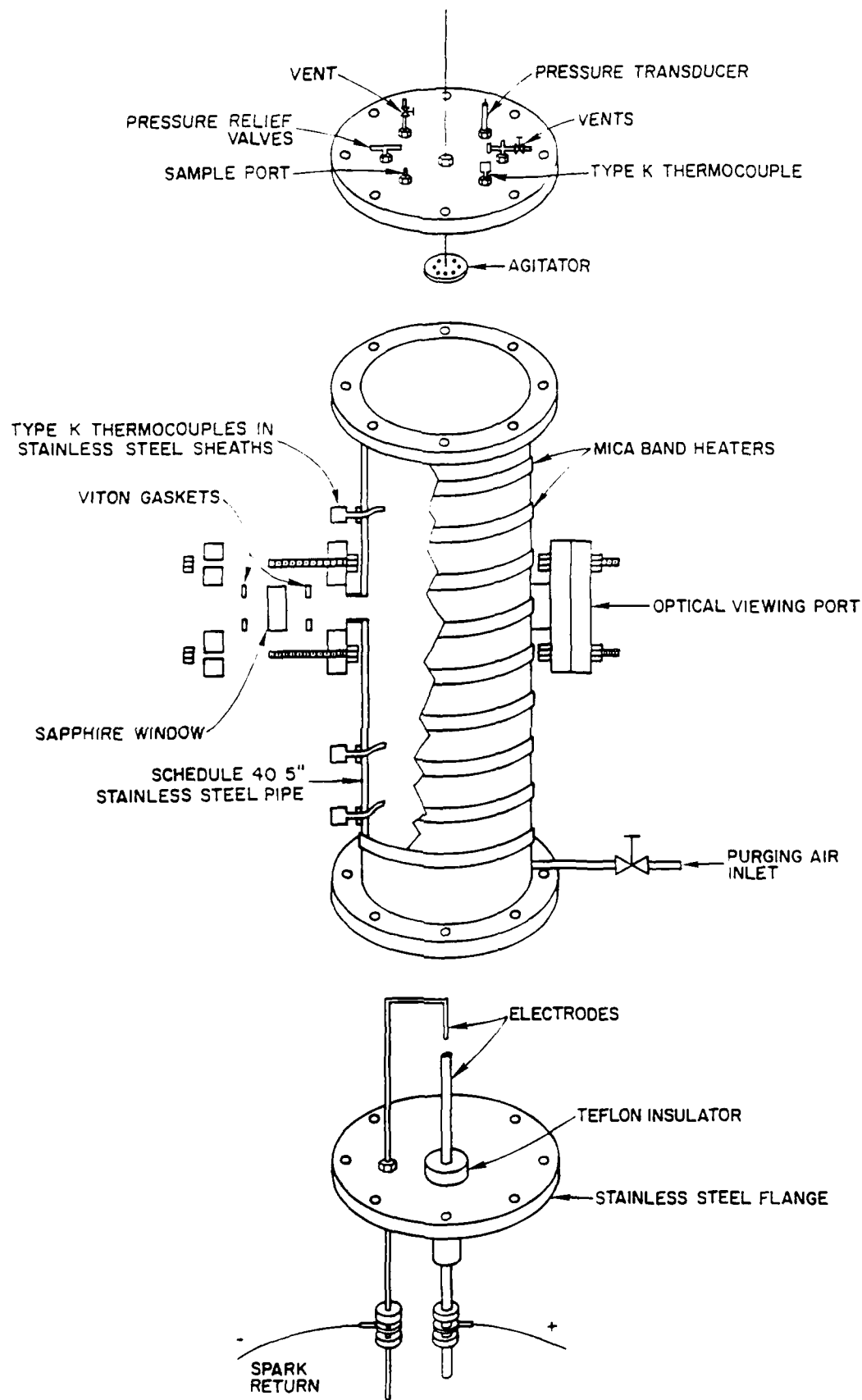


Figure 12. Detailed diagram of the explosion test cell.

Q with each column requiring a separate injection and detector port. This precludes the possibility of doing fuel/air and post-combustion gases separation within a close time frame of each other since the GC only has two injection and detector ports. Operation of the Molecular Sieve 5A and Porapak Q columns in parallel proved unsatisfactory. Splitting of the flow between the columns was unsatisfactory and produced inconsistent results. Further work on the operation of the MS5A and Porapak Q columns in parallel will be continued since they can separate the O₂, N₂, CO, and CO₂ in about nine minutes, a marked improvement over the 14 minutes required for the MS5A--Chromosorb 102 combination.

Preliminary work on the derivation of a relationship between rate or pressure rise and flame speed in the ETC was begun and it appears the derivation will not be as simple as initially thought. Work will continue on this derivation.

CONCLUSIONS

The completed work which is summarized and the work which is planned constitute a comprehensive program to develop monitoring devices which can eventually be incorporated into the control system of a Naval boiler. At this point the individual projects are bench-top prototypes which have the flexibility to be modified as appropriate for problems specific to the Navy. This flexibility is necessary for determining optical experimental conditions and parameters to be incorporated into a field-ready monitor.

The variety of sensors under development address the problems of safety, but, at the same time, it is probable that the efficiency of Navy boilers can be monitored with these instruments. And while each sensor is being developed for a particular task, the interrelationships of the problems dictate that the signal from one sensor will be important for understanding the signal from another. For example, a fuel-rich flame will alter both the frequency spectrum of the cross-correlation experiment and the absorption spectrum of the differential infrared (hydrocarbon) monitor. This complementary nature of the data will allow problems to be solved more efficiently.

Design criteria for each sensor include the requirement that all the sensors be interfaced to a single control unit, and the COMPAQ microcomputer was chosen for this task. A wide variety of software and hardware is available for the COMPAQ, it is IBM-PC compatible, and it can function as a smart terminal for the MHD Energy Center's VAX 11-780 computer if additional data handling capability is needed.

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