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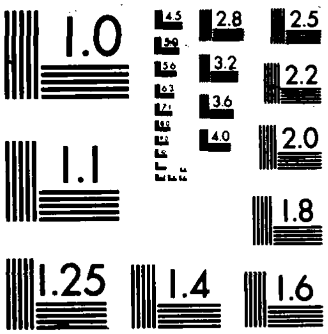

MICROCOPY RESOLUTION TEST CHART

(12)

# Application of Remote Sensing Optical Instrumentation for Diagnostics and Safety of Naval Steam Boilers

Navy Contract #N00014-84-K-0301

Final Report

October 1986

Mississippi State University
MHD Energy Center
Mississippi State, MS 39762

## 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.

## FACILITIES

The MHD Energy Center operates a fuel-oil fired 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

A sensor for detecting fuel oil on boiler floors and in the firebrick on the floor is under development. Such a sensor must be able to detect the presence of liquid fuel on the boiler floor prior to light-off and detect the accumulation of fuel in a cold boiler following an unsuccessful light-off attempt. In addition, the sensor must be able to withstand the extreme conditions in a boiler and still be compact and easily replaced.

The initial effort was spent adapting a resistive surface moisture monitor such as one described in a JPL Invention Report.[1] Model calculations for air-filled and oil-filled cavities indicated that voltage drops resulting from resistance changes would be of the order of 1 mV. Similar calculations for dry brick and fuel-saturated brick indicated drops of approximately 0.5 mV. Laboratory testing later produced unreliable results with absolute voltages which were smaller than originally anticipated. The problems were attributed to limitations of the procedure with firebrick as the medium.

A more practical detector for unburned fuel-oil has proven to be a capacitive sensor. The principle of operation is the change in dielectric constant due to the presence of fuel. A porous refractory brick with embedded parallel plates was fabricated. When fuel-oil is present, the dielectric constant doubles that of air. Initial tests indicated a noticeable response to fuel-oil, with sensitivity greatest at initial contact. The response was not repeatable in early experiments, however, and appears to have been due to three causes: (1) moisture content affected the dielectric constant, (2) the parasitic resistance was significant, and may also have been affected by fuel oil, and (3) the dielectric constant of the initial refractory was close to that of the fuel, diminishing response. Further investigation of refractory combinations with varying porosity and thermal characteristics were carried out, and detector size, which contributes to the parasitic resistance, was studied for each refractory combination. The current bricks use copper plates, and the two refractories which show promise are lightweight, castable materials which can withstand temperatures of 2200°F and 3300°F.

The capacitance differed by 15-25% for the dry versus the fuel-soaked brick. A brick which had already been soaked with approximately 70cc of fuel oil exhibited a capacitance of 1990 pF, and the addition of 30cc more fuel caused a further change of 250pF. An alternate detection system was devised in which this brick was compared to a fixed external reference capacitor by using the two capacitors as timing elements in an oscillator. The measured parameter was the total frequency change with respect to fuel addition. (See Figure 1). Figure 2 shows the temporal variation of output voltage to 5cc additions of fuel oil. The output voltage is a filtered measurement of duty cycle which in turn is proportional to the ratio of brick capacitance and reference capacitance. This method of detection minimizes certain problems and makes the measurements more sensitive and reliable.

At this point, it seems clear that certain factors (like temperature) which affect capacitance can be minimized in the present configuration by replacing the fixed external capacitance with a second capacitive brick. In a Naval boiler, the second brick could be mounted on a wall or ceiling to ensure that it is not exposed to liquid fuel. Additional circuitry is being designed which will involve a microprocessor to count the charge/discharge times of each capac-

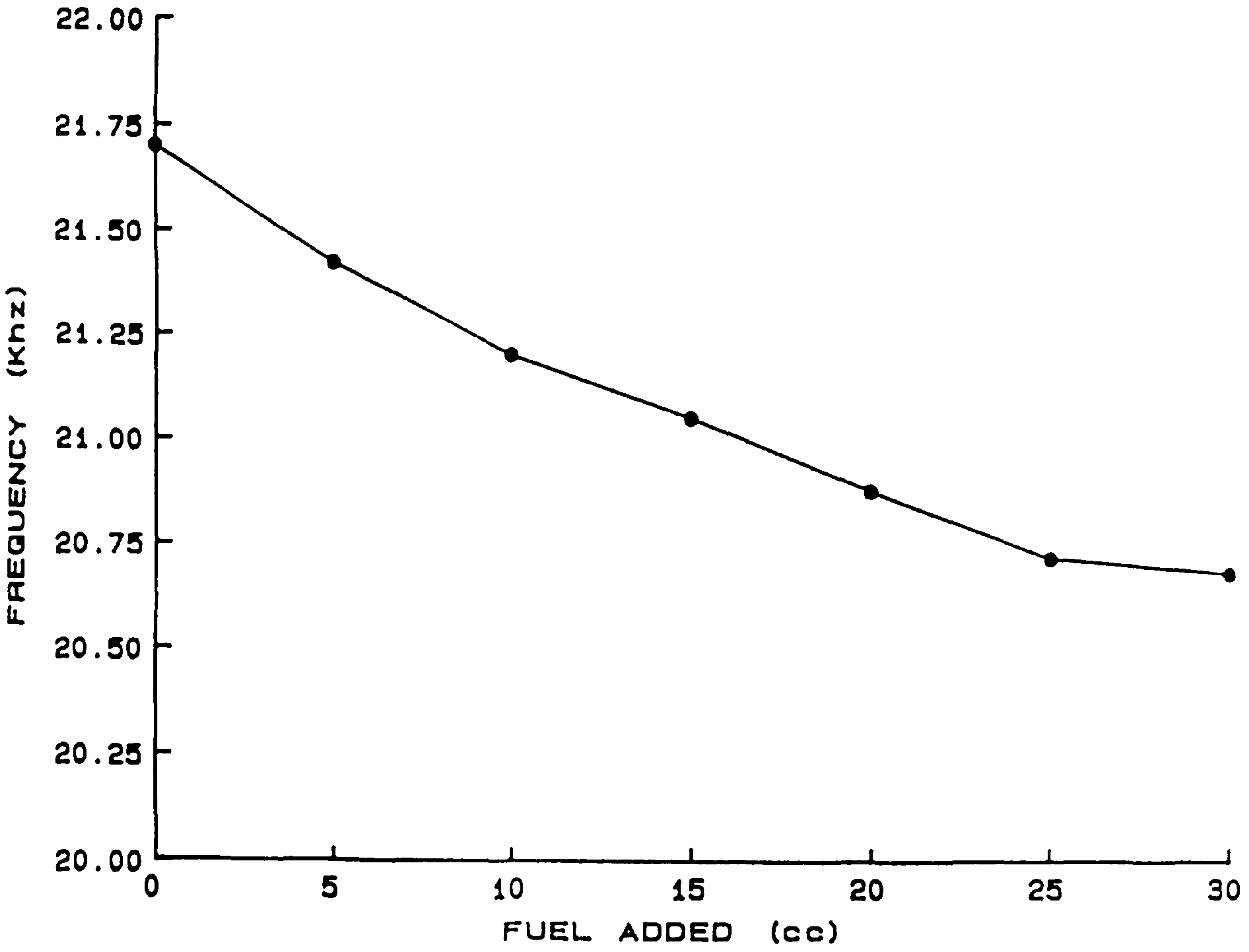

Figure 1

Frequency Response vs Volume of Fuel added for an Oscillator Circuit using a capacitive brick.

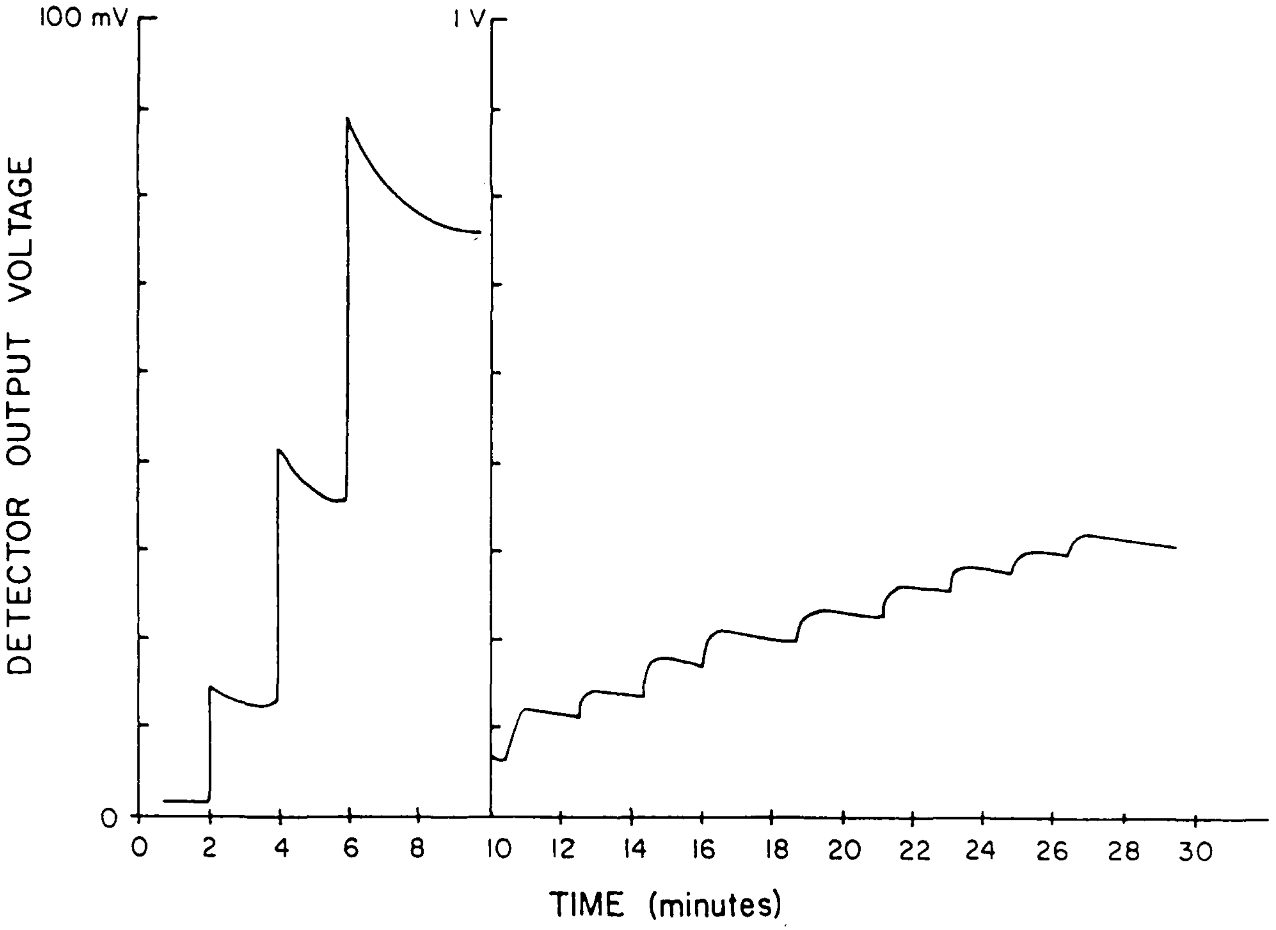

Figure 2

Variation of detector output voltage with addition of fuel oil in 5 cc. increments.

itive brick and ratio the times. This circuit holds the most promise for incorporation into the controls of a Navy boiler.

Future work required for the liquid fuel sensor includes the following tasks:

1. Comparison of two capacitive bricks at room temperature.
2. Construction of the microprocessor-controlled detection circuit.
3. Measurement of capacitance variation of bricks at elevated temperatures.
4. Operation of the sensor (comparison of bricks) at room temperature with a noise source (flame).
5. Operation of the sensor at elevated temperatures with a noise source (flame).
6. Selection of final refractory and capacitor plate materials with suitable temperature characteristics (>2500°F) and acceptable sensitivity/stability.

## 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 either, varying from the base of the flame to the tip.

Therefore, as part of the research performed under this contract, development was begun of a flame monitor 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. When flame is present, ability to detect abnormal, unsteady, or irregular combustion which might lead to loss-of-flame.

3. Measurement, by purely optical means, of the fuel/air ratio of an individual burner, thus allowing automatic control of the fuel/air ratio.

To date, activity on this project has been 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.[2,3] 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.[4]

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 3 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 $C_2$ which are formed during combustion.

Figure 3 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 4. The detector output is varying 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 5. This spectrum is a potential source of information about the flame and some preliminary surveys have been reported.[5,6] 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

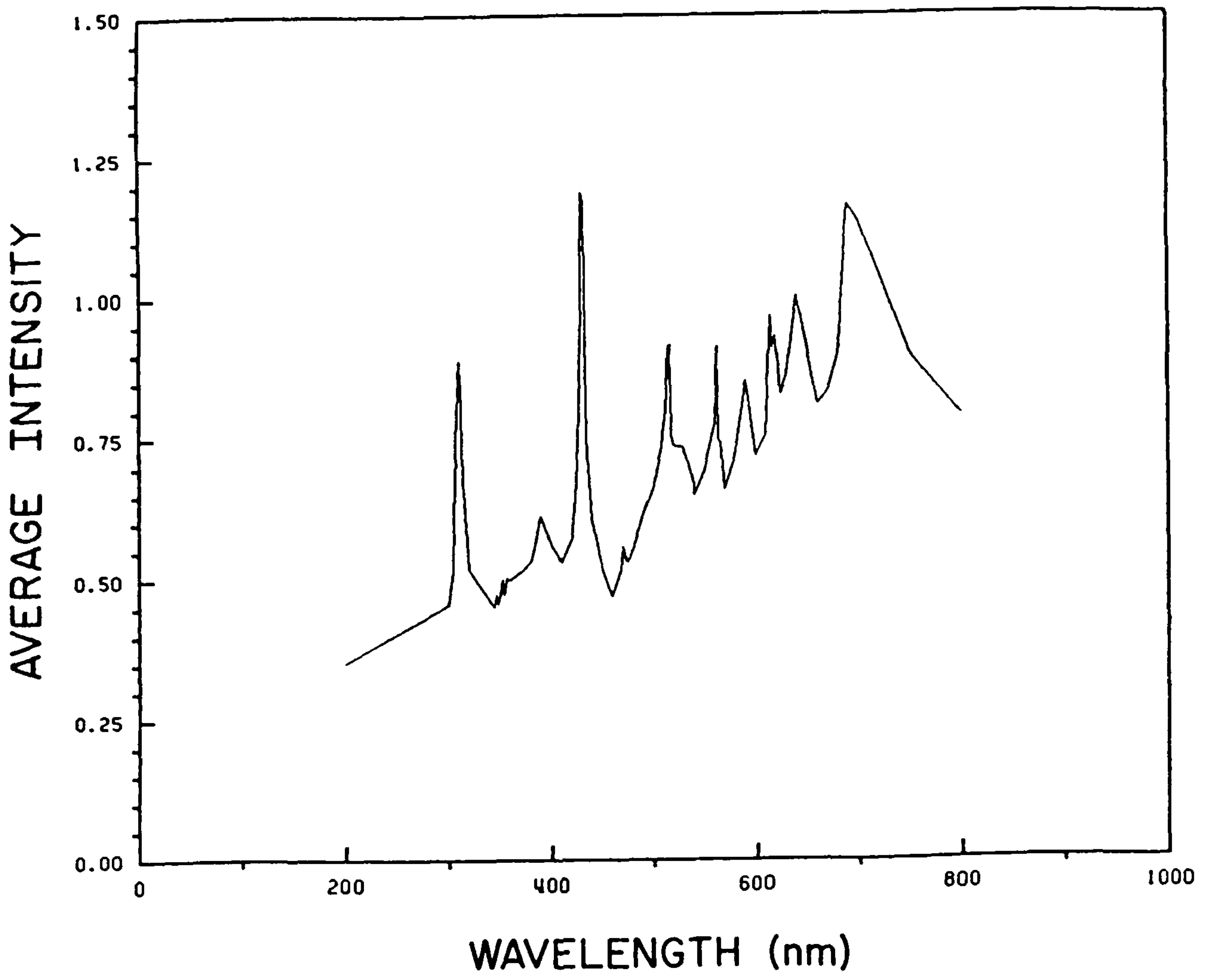

Figure 3

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.

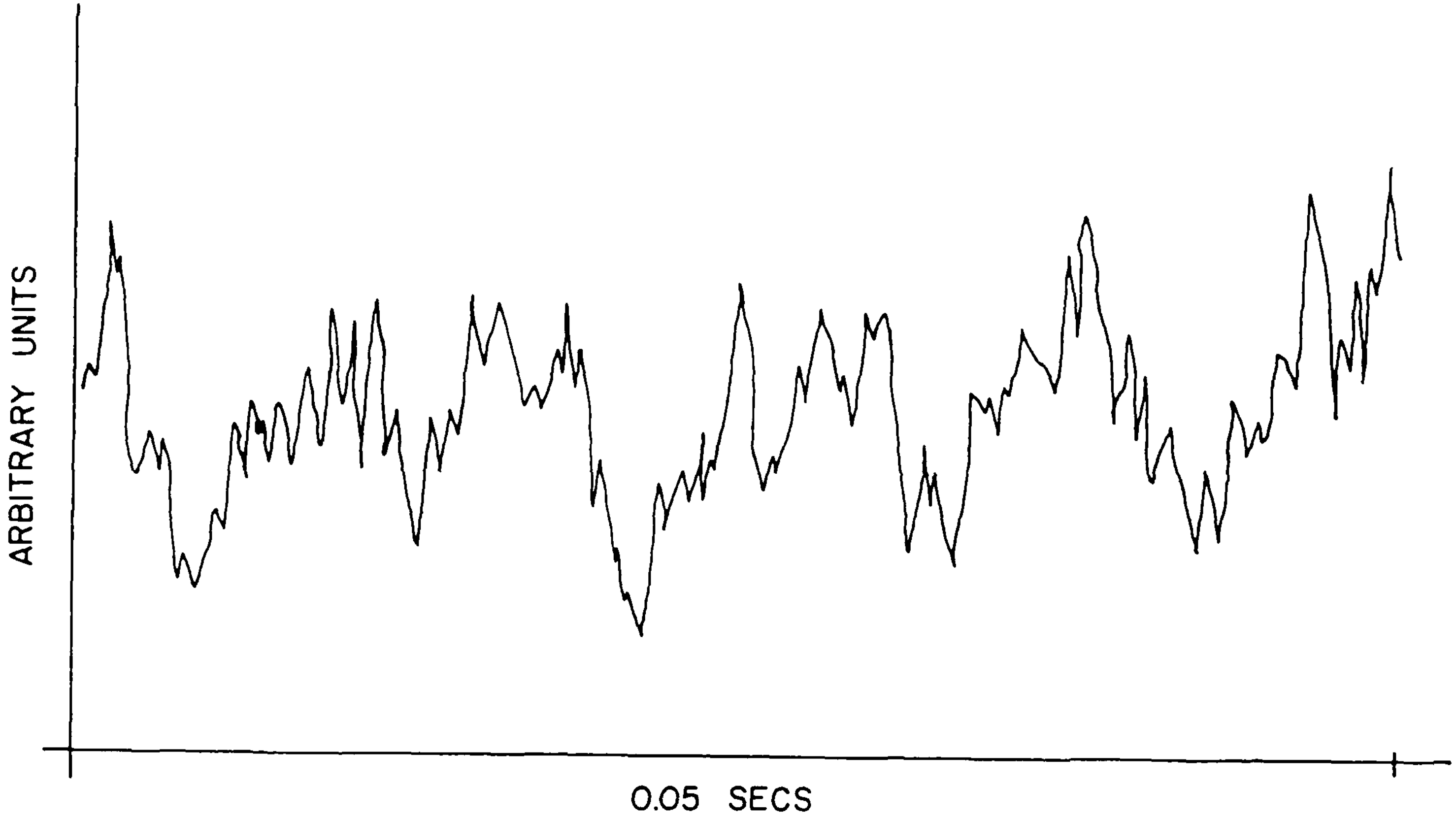

Figure 4

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.

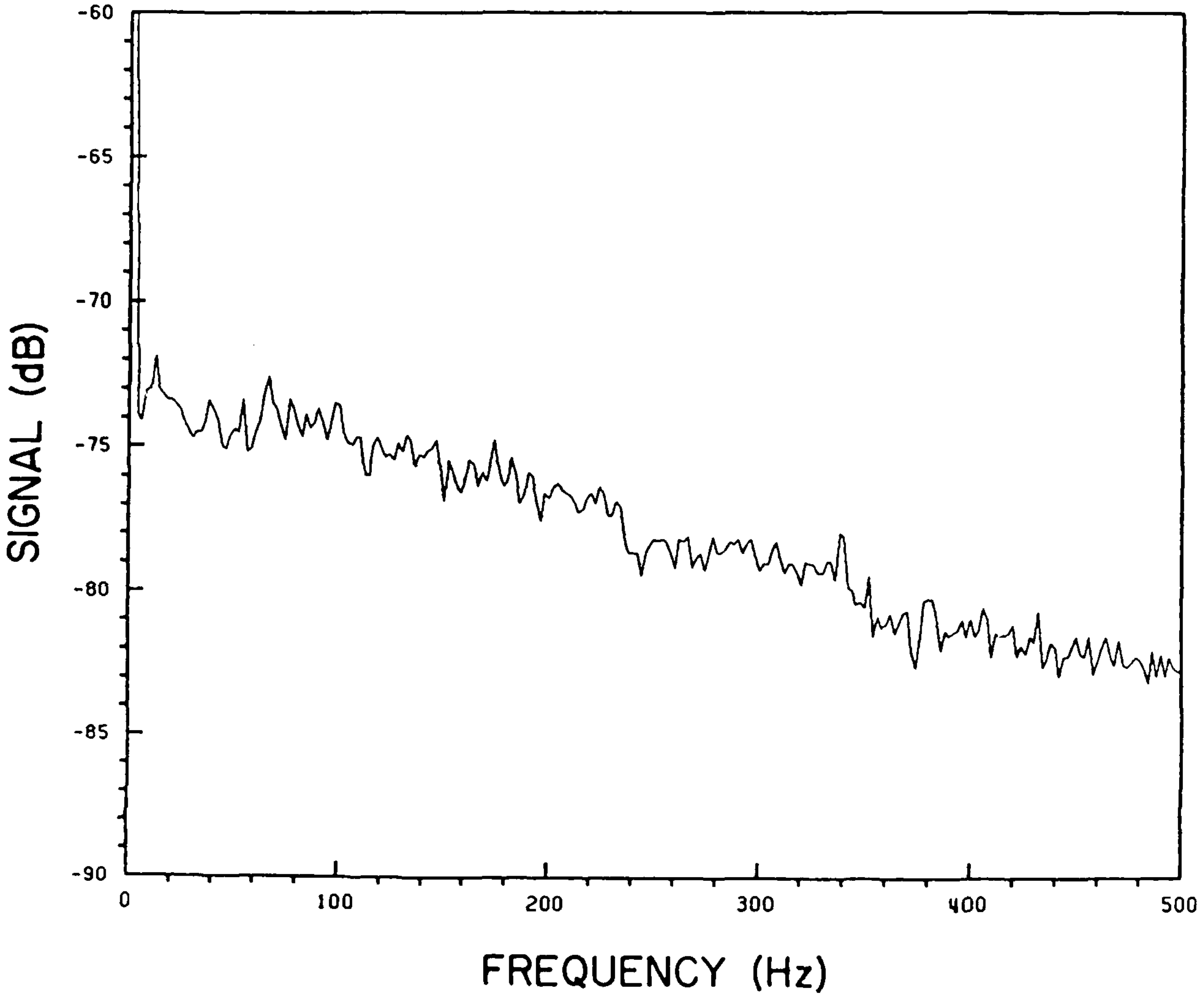

Figure 5

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

distinguishing the flame at one burner from the others. To resolve this problem, the MSU flame monitor incorporates a technique known as cross-correlation.[7,8]

The cross-correlation technique uses two sensors arranged so that their lines of sight intersect at a point (Figure 6). 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, one can isolate the flickering originating from the region of intersection.

As used in the past, the cross-correlation technique calculates the correlation by averaging in the time domain and obliterates any frequency information in the data. The MSU flame monitor uses a spectrum analyzer to compute a correlation function of frequency.[9]

The effectiveness of the cross-correlation technique can best be seen in Figure 7. 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 7 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 indentical 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. The computer processes and stores the data. Thus, a very powerful and very general flame monitor has been built. With it, one can examine every aspect of the light emitted by a flame with excellent spatial discriminiation. The next step in the investigation is to examine fuel oil flames under typical conditions.

## Differential Infrared Monitor

A differential infrared monitor capable of detecting the presence of hydrocarbon vapors in a boiler is under development. The technique utilizes two helium-neon (HeNe) lasers operating at different infrared wavelengths and compares the absorption of these two wavelengths in the presence of pure hydrocarbons and/or fuel oil. The differences in the optical absorption can be related

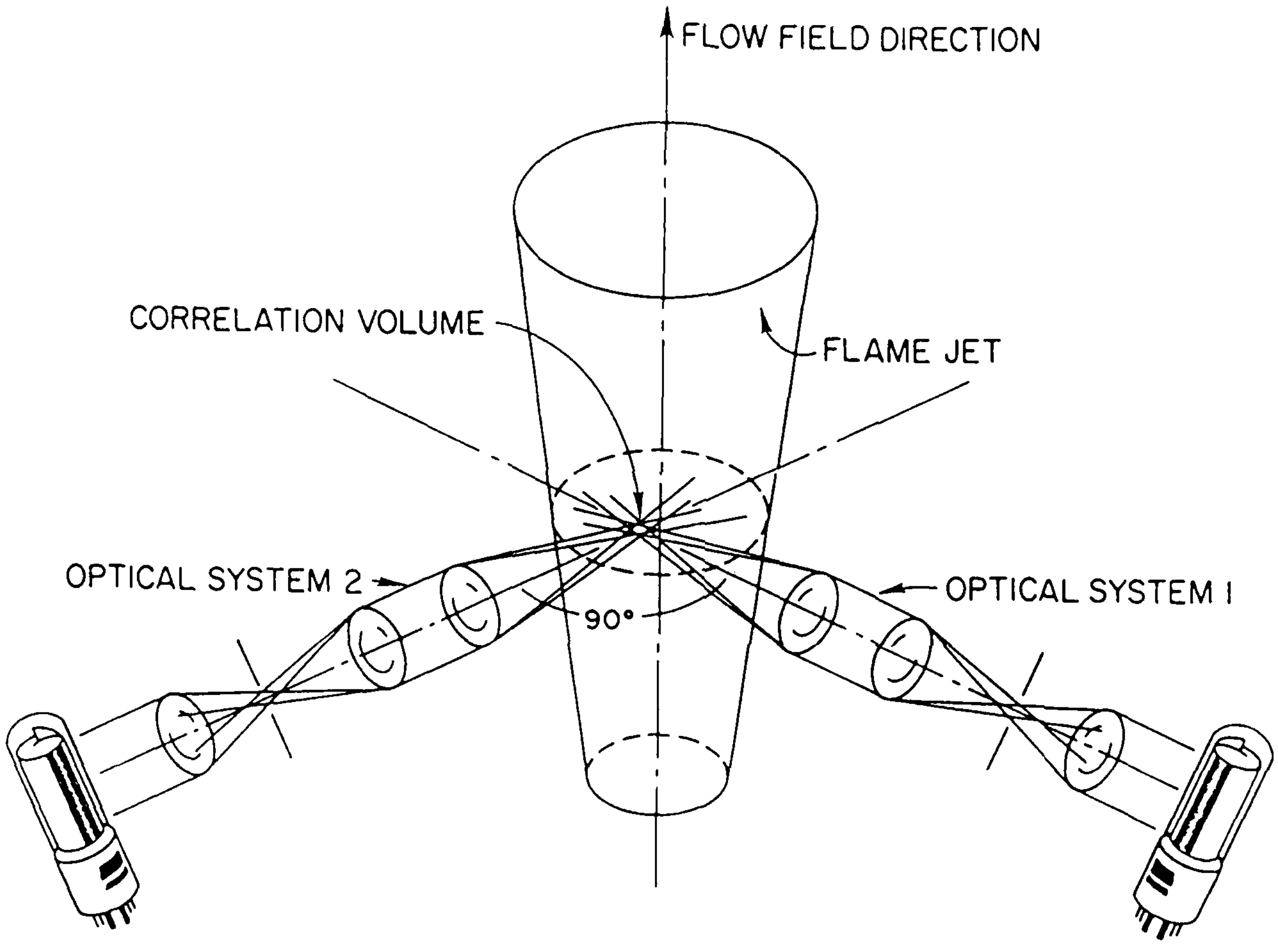

Figure 6

Optical arrangement for the cross-correlation technique.

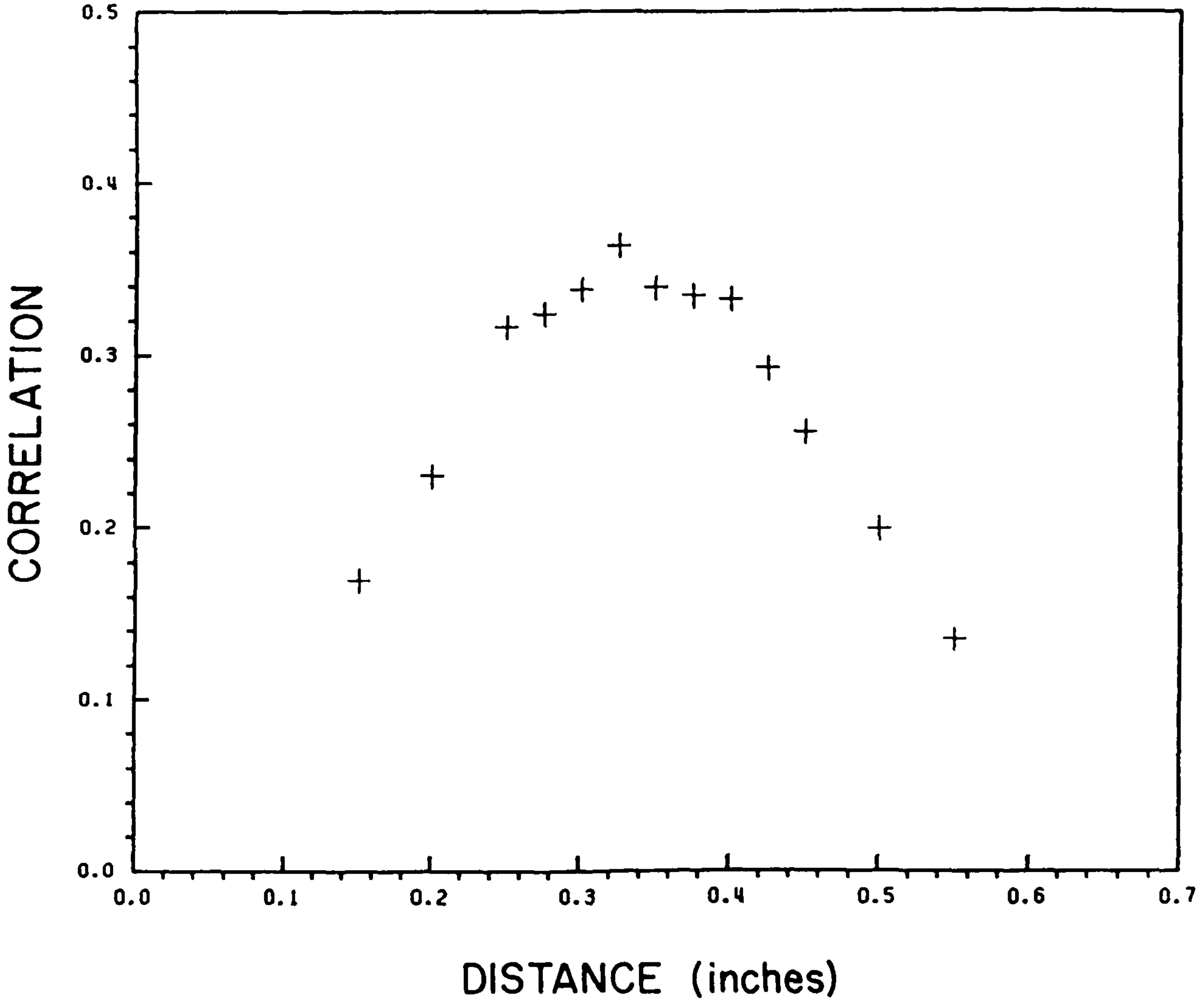

Figure 7

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.

to concentrations of absorbing species in environments similar to those found in Navy boilers.

In a HeNe laser, the most efficient of the neon emissions in the 3.39μm wavelength range is the $3s_2 \rightarrow 3p_4$ transition at 3.3922μm (2947.9 $cm^{-1}$). It has been demonstrated that the inclusion of a sample of methane ($CH_4$) within the optical resonator (intracavity) of a HeNe laser alters the output frequency to that of the $3s_2 \rightarrow 3p_2$ transition at 3.3911μm 2948.9 $cm^{-1}$)[10] (see Figure 8). The absorption of the intracavity methane at 2947.92 $cm^{-1}$ ($P_7$ of the $\nu_3$ band) spoils the threshold condition for the $3s_2 \rightarrow 3p_4$ transition and enhances the emission at 3.3911μm.

With one HeNe laser operating at 3.3911μm (shifted) and another laser operating at 3.3922μm (unshifted), one has a system in which the former wavelength would be weakly absorbed by an external sample of methane while the latter would be strongly absorbed. The difference in absorption provides a sensitive method for detecting methane, and a recent report utilizes this fact to remotely measure methane concentrations over pathlengths of up to 70m in air.[11] Similarly methane can be detected in an explosion test cell (described later) which has been constructed at the MHD Energy Center.

In the experimental layout shown in Figure 9, the two laser beams pass through a chopper which typically operates at 2 kHz. From there the beams traverse the sample cell and fall on the liquid-nitrogen-cooled indium-antimonide (InSb) detectors. The detector signals are amplified and sent to a lock-in amplifier which is tuned to the chopper frequency (see Figure 9). The lock-in amplifier has RS-232 and IEEE data buses which will facilitate connecting the COMPAQ microcomputer to the system in the future. Calibration of the data with known concentrations of sample is necessary, but at this point a partial pressure of 10 torr of methane in a 10-cm cell is totally absorbing as shown in Figure 10. Further tests are necessary at lower pressures.

For higher aliphatic hydrocarbons, specifically those in fuel oil, the sensitivity of the current system is even higher. This is because the absorptions of these molecules are broader, and this results in a smaller difference in the absorptivities at the two wavelengths of interest. At the present time more work monitoring species like hexane, decane, and hexadecane in the test cell is necessary. Additionally work aimed at improving the range of sensitivity of the technique for these species is underway. Applicability to hexane vapor will be enhanced after the output of one laser is shifted farther away from 3.3922 μm.

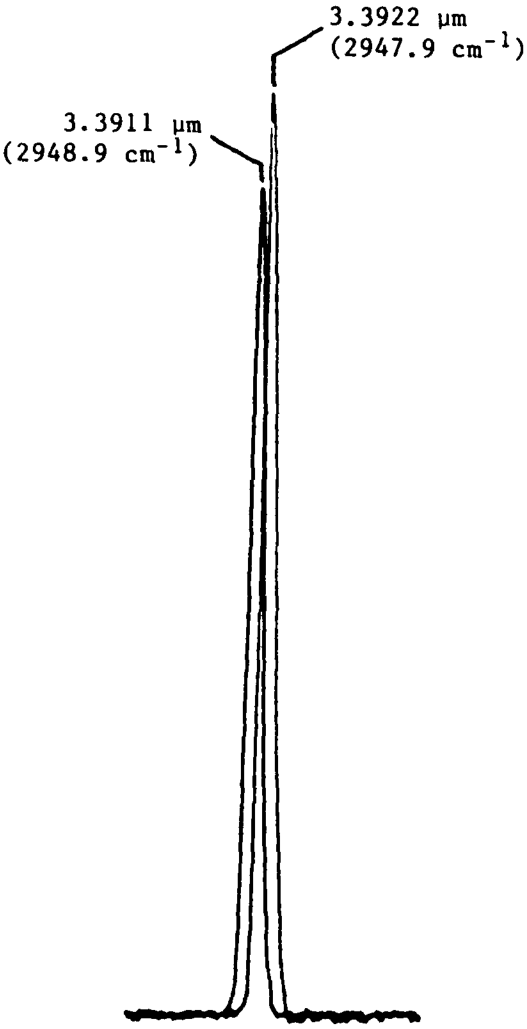

Figure 8

Effect of Intracavity Methane on the Output of a HeNe Laser
(shifted, 3.3911 μm; unshifted, 3.3922 μm)

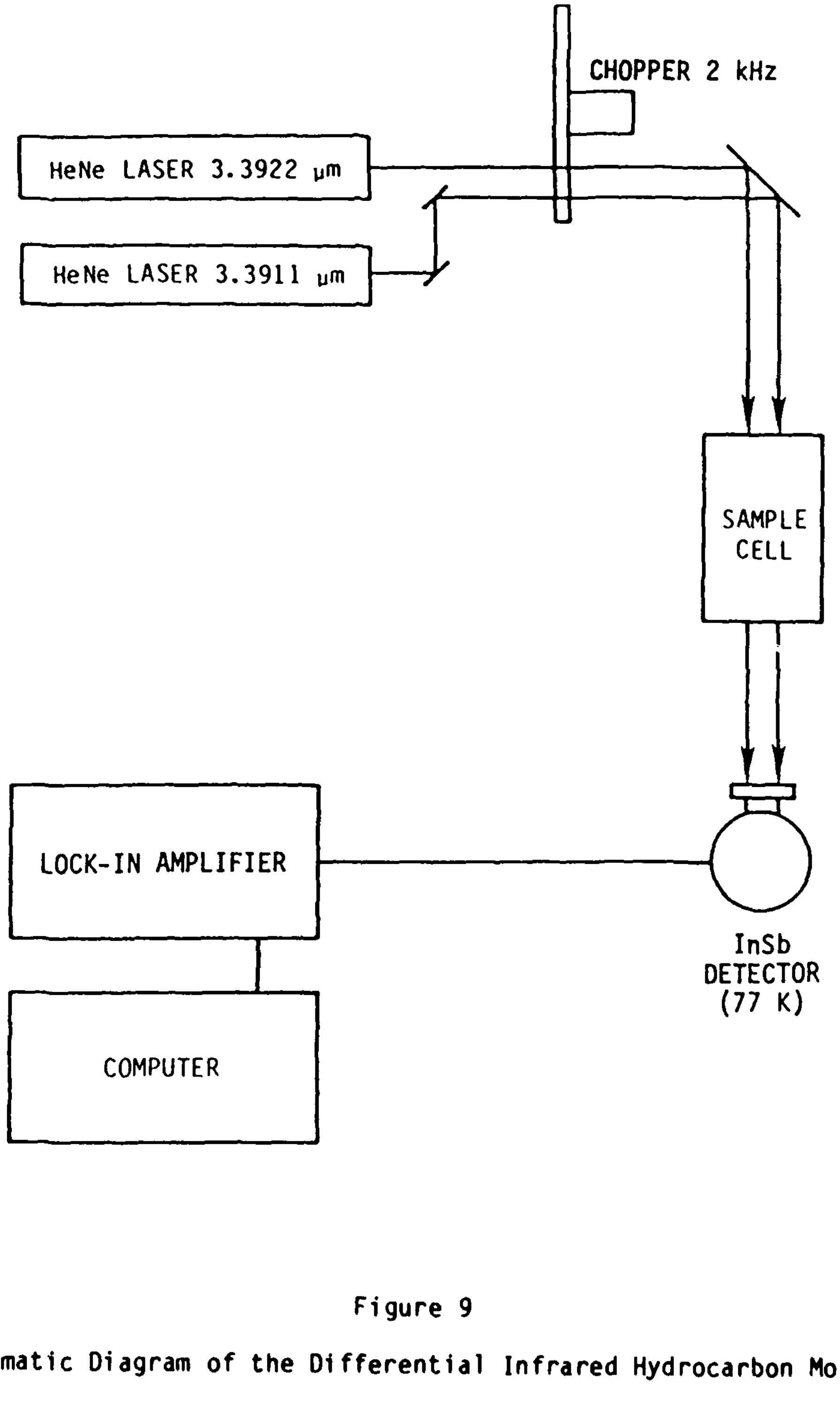

Figure 9

Schematic Diagram of the Differential Infrared Hydrocarbon Monitor.

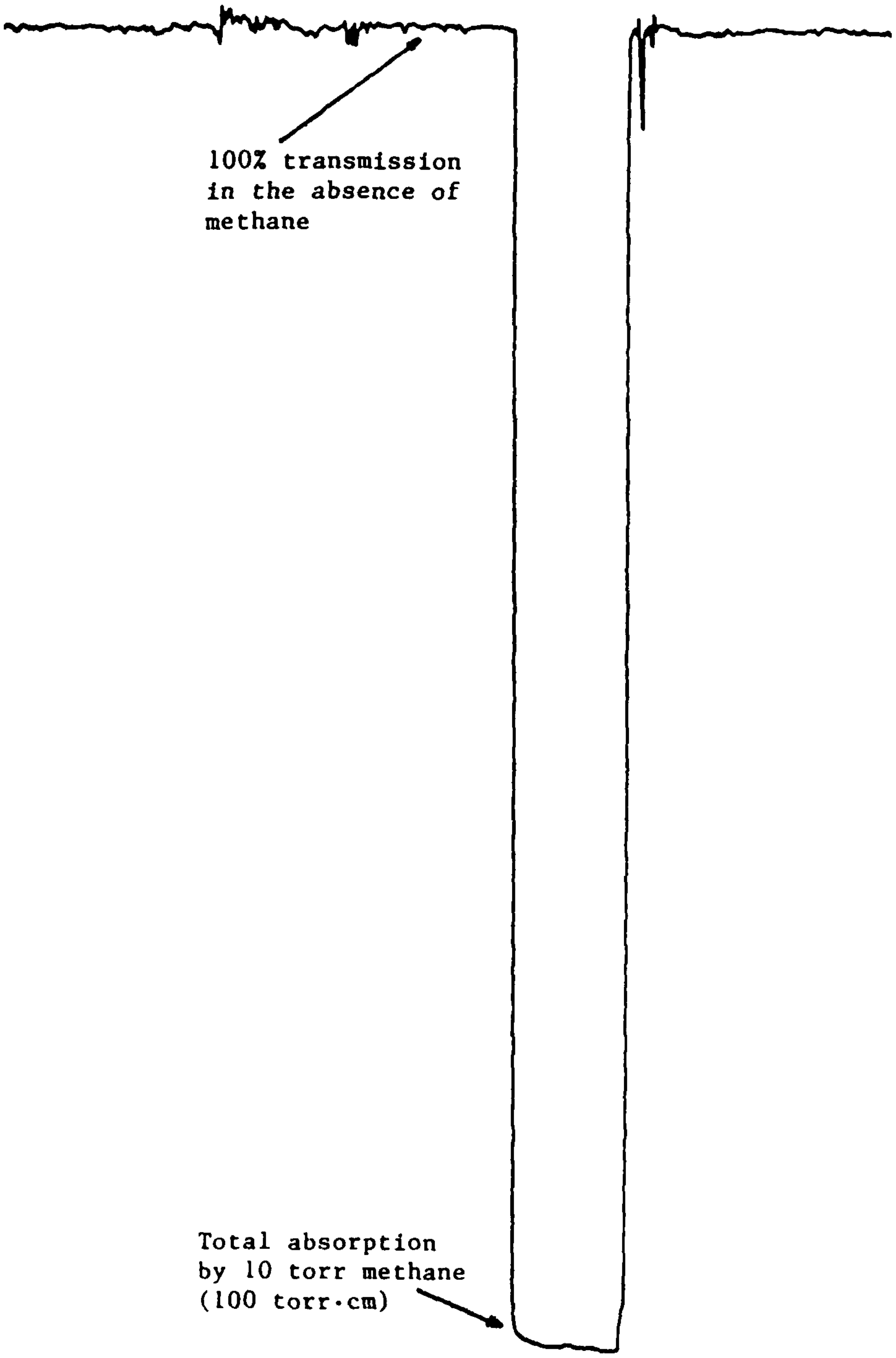

Figure 10

Infrared Detector Response to 10 torr Methane

## Explosion Test Cell

A pressure vessel (shown in Figure 11), dubbed the explosion test cell (ETC), was designed, constructed, and instrumented in such a manner as to allow the accomplishment of two primary objectives: first, to contain a fuel/air mixture at elevated temperature, and second, to allow for the determination of flammability limits of various fuels.

The vessel consists of a 48-inch long schedule 40 5-inch diameter stainless steel shell with 150-lb stainless steel flanges on each end. At the midsection of the ETC are two viewing ports mounted on opposite sides. The viewing ports incorporate sapphire windows to allow transmission of 3.4 μm radiation. Heaters are located on the shell and flanges of the ETC to allow for heating up to 200°C. Five type K thermocouples are mounted inside the ETC to measure the wall temperature and a 0-200 psig flush diaphragm, air-cooled pressure transducer is mounted on the top flange.

After the fuel has been vaporized in the ETC a gas chromatograph (GC) can be used to separate the air from the fuel thereby allowing a fuel-air ratio to be determined. Currently, the GC takes 30-60 minutes to separate the air from diesel fuel marine (DFM). Future work will include decreasing this separation time as much as possible but physical and chemical restraints will preclude a drastic reduction.

Ignition of the fuel is achieved by an electrical spark across two electrodes at the bottom of the ETC. This spark is created by charging a capacitor up to 500V then discharging the capacitor across the electrodes. The relay which dumps the capacitor was initially activated directly by a COMPAQ microcomputer, but under certain conditions, the discharge caused a computer crash. This problem persisted even though optical isolation chips were used. Finally, the problem was solved by linking the computer to the capacitor via a fiber optic cable.

The COMPAQ microcomputer is used to display the temperature and pressure of the ETC before and after ignition, and to collect data during ignition. Initially, the computer would ignite the fuel/air mixture then collect wall temperature and pressure data during combustion. Upon analysis it was found that, as expected, the response time of the thermocouples was too slow to provide any useful information. The computer code was then modified so that on the command to ignite the computer measures the initial temperature of the ETC, sends the command to discharge the capacitor (thus igniting the mixture), collects

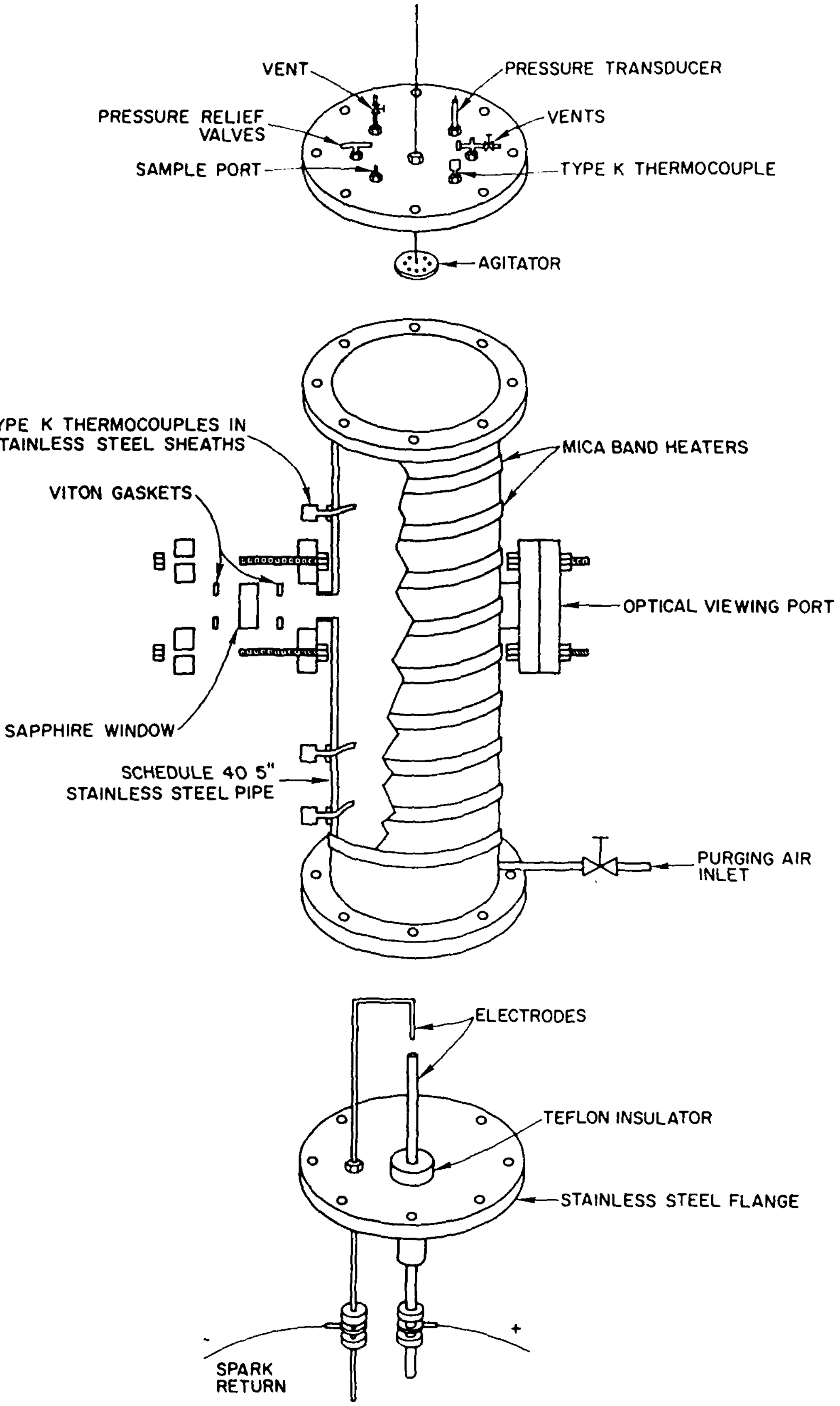

Figure 11

Detailed Diagram of the Explosion Test Cell.

pressure data only for a user-specified period, then measures the final temperature of the ETC. These data are then written to diskette for further analysis.

An ignition of DFM was performed at an initial absolute pressure of 1 atmosphere and an initial temperature of about 170°C (see Table below). The concentration of DFM was not determined but is believed to have been approximately 1% by volume. The computer was instructed to make 3000 pressure measurements over a period of 4 seconds, e.g. sample at 750 Hz. The pressure data from this run is plotted in Figure 12. The graph shows a rise to a maximum pressure of approximately 23 psig at 1.4 seconds then an exponential decrease in pressure due to cooling. Future work will involve investigation into the possibility of using the pressure data to obtain flame speeds.

The explosion test cell will allow the determination of flammability limits of various fuels by varying the fuel concentration and testing for ignition. Fuels for which flammability limits are known will be tested in the ETC to characterize the data obtained with the ETC. The gas chromatograph will be used to determine the degree of combustion and relative hydrocarbon/air concentrations prior to ignition. The white smoke condition has been simulated in the cell, and the ETC will serve as a useful cell for the differential infrared monitor (see above).

## Fuel Analysis

Fuel analysis is being done by using chromatographic methods. Because of the intrusive nature of these experiments, they are not used as on-line monitors. Instead they are useful for calibrating the instruments and techniques being developed.

A Hewlett-Packard 5830A gas chromatograph (GC) fitted with a thermal conductivity detector is used for analyzing hydrocarbons in fuels and for analyzing the extent of deflagration in the explosion test cell. To separate and monitor $H_2$, $O_2$, $N_2$, CO, $CO_2$, and very light hydrocarbons ($C_1$ - $C_4$), two columns packed with Chromosorb 102 and Molecular Seive 5A are operated in parallel. Higher hydrocarbons ($C_6$ - $C_{22}$) are separated on a OV-17/QF-1 column. Peak areas are used to determine relative or absolute concentrations under appropriate conditions. A schematic diagram of the GC is shown in Figure 13, and a typical chromatogram is shown in Figure 14. Higher resolution chromatograms of the hydrocarbons can be obtained by using a Varian 3700 instrument equipped with

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             EXPLOSION TEST CELL DATA ANALYSIS

DATA FILE NAME: ETC011.DAT
DATA TAKEN ON 01-23-1986 at 02:58:25
FUEL TESTED: DFM   CONCENTRATION:  NOT DETERMINED

IGNITION DATA
ELECTRODES USED: ALUMINUM- FLAT ENDS
SPARK VOLTAGE=  500.0 VDC     SPARK GAP=  1.00 mm



             ETC TEMPERATURES (C)

T/C NUMBER    1       2       3       4       5
INITIAL     142.0   171.0   148.5   172.2   165.9
FINAL       152.9   176.0   151.4   177.0   170.2
```

Table I

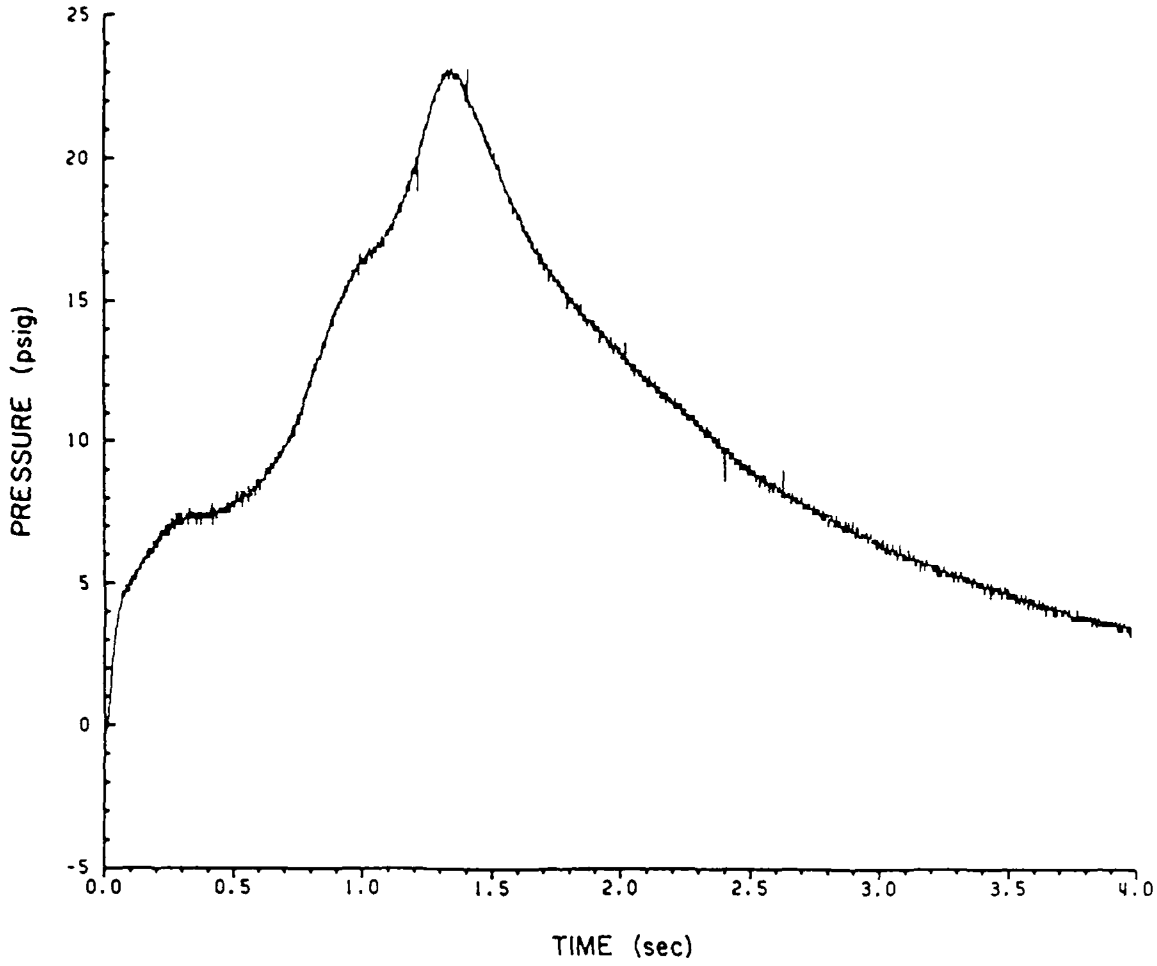

Figure 12

Pressure vs Time Data for the Explosion Test Cell.

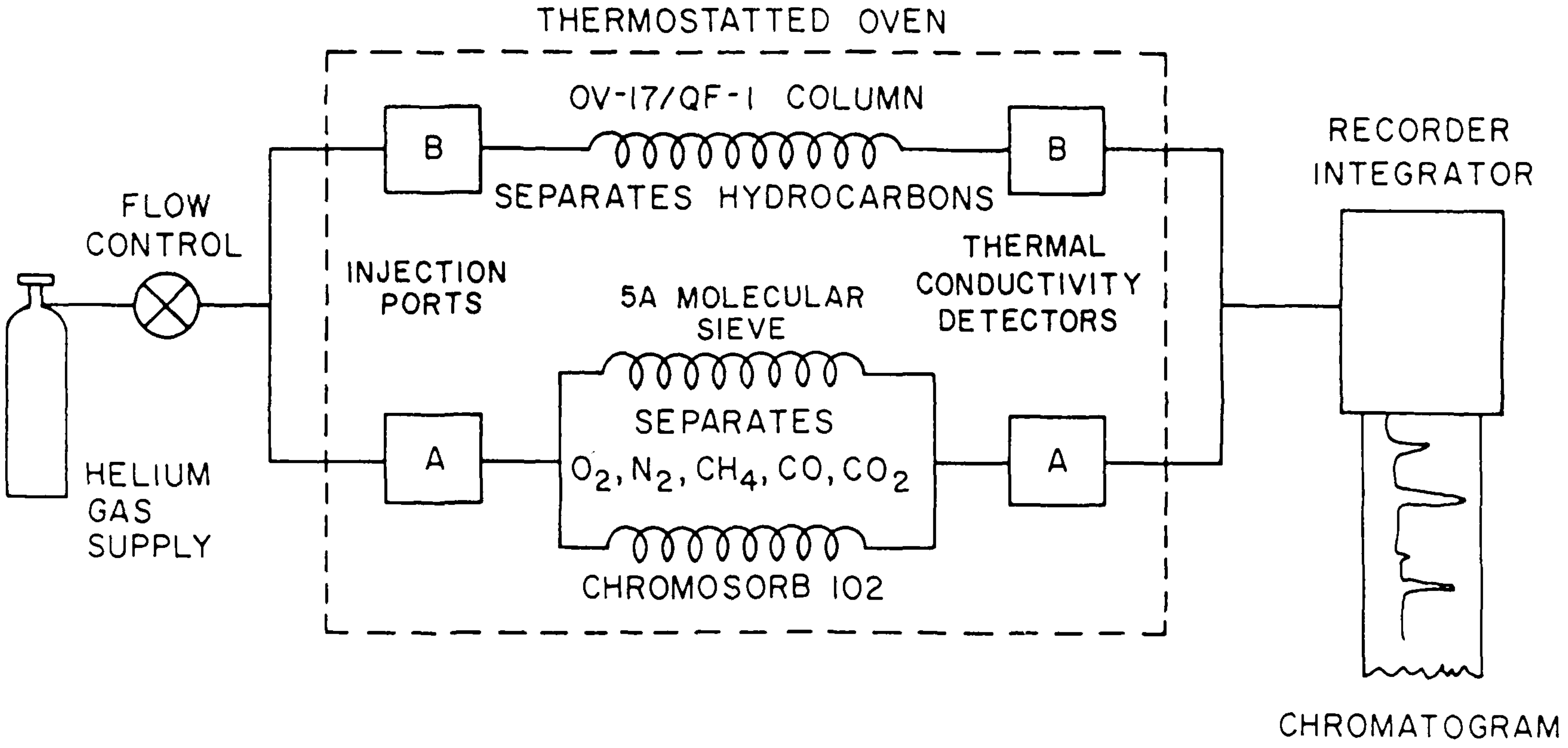

Figure 13

Schematic Diagram of Gas Chromatography System.

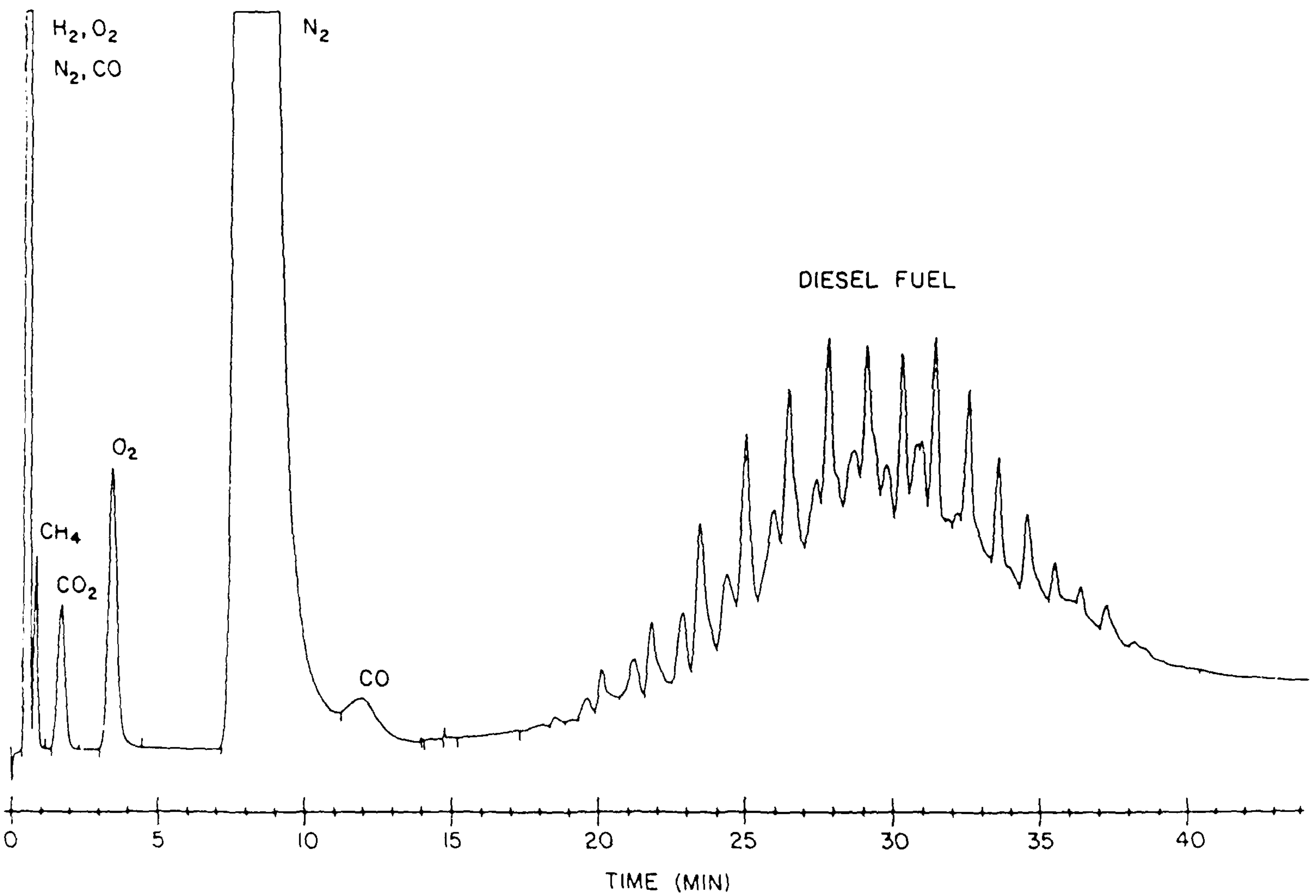

Figure 14

Gas Chromatogram of Gases and Fuel Vapors.

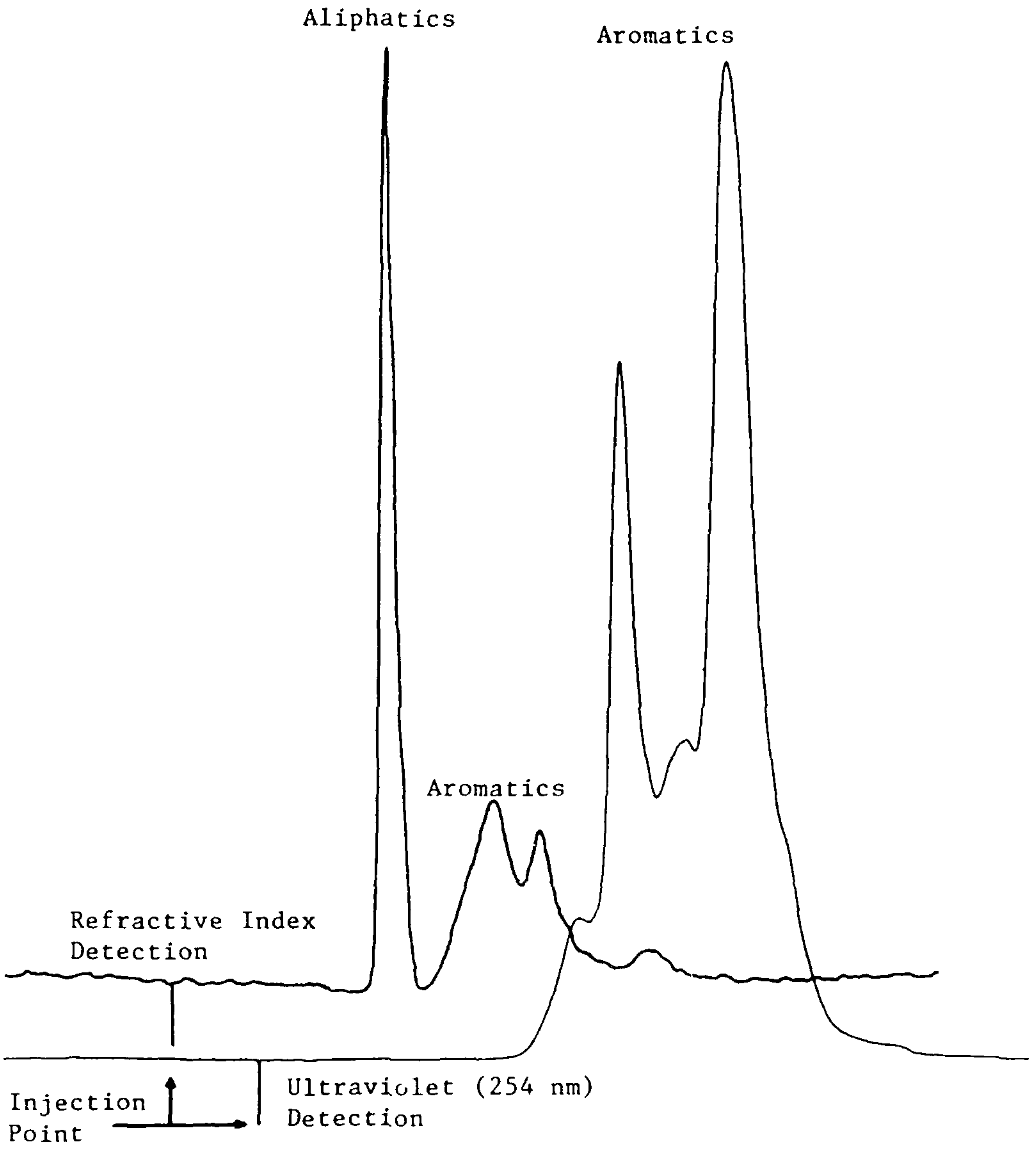

Figure 15

High Performance Liquid Chromatograms of DFM using RI and UV Detection flame-ionization detection and fused silica capillary columns with SE-30 or SE-52 stationary phases.

A Waters liquid chromatography system with refractive index (RI) or ultraviolet absorption (UV) detection is available for separating liquid fuel oil into its components or determining aromatic/aliphatic ratios (see Figure 15). Hexane is used as the isocratic solvent in a 5μ-silica column.

## CONCLUSION

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 optimal 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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