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### EXPERIMENTAL FACILITIES AND PROCEDURES FOR DETERMINING EFFECTS OF FUEL OIL QUALITY ON BURNER PERFORMANCE

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by

S. Win Lee\*

ABSTRACT

This paper gives a detailed description of the experimental facilities and procedures developed for a combustion program on middle distillate fuel quality. Oils from various feedstocks and with wide range of properties were evaluated to help establish a quality/performance index system.

Special emphasis was given to the design and arrangement of the equipment to ensure that test conditions simulated those of a residential environment. The experimental rig included a domestic warm air oil furnace, fuel temperature controlling equipment, a special cold air return system, continuous emission analyzers, particulate measurement devices, and data acquisition and processing units. Combustion procedures were carefully planned to provide meaningful data when comparing different fuels with respect to burner ignition behaviour, particulate emissions, concentrations of flue gas components, furnace efficiency, excess air, and heat transfer.

This study was recommended by the Canadian General Standards Board 'Committee on Petroleum' and 'Subcommittee on Middle Distillate Fuels'.

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## INTRODUCTION

One form of energy conservation in oil heating is to utilize fuel oil in the most effective manner. This can be achieved by optimizing the combustion process or the mechanical hardware of the heating system. Further cost reductions can be realized by utilizing the least expensive fuel available. Although an ideal situation can be achieved by the above two applications, usually only the combustion related options are utilized (1). The option of utilizing less expensive fuels means the use of lower quality oils which can be produced more economically by the refiners. These fuels may not meet current heating oil standards as certain properties are slightly below specifications. However, such fuels could be utilized for heating provided their combustion characteristics do not have any serious deleterious effects. Until recently, energy conservation by management of fuel blending components was not widely practised due to the complex chemical and physical nature of distillate oils and the various processes applied in refineries.

With the advent of non-conventional synthetic fuels industry's concern over the use of high aromatic oils for heating has increased. Industry's efforts to lower the viscosity of distillate oils for heating in Canadian winter months are well known. A better understanding of fuel properties and their impact on combustion behaviour could offer refiners valuable information on how best to utilize the crude barrel. Use of higher aromatic, higher viscosity fuels can have the effect of extending the crude oil barrel. Future use of lower grade oils as heating fuels could free more distillate for the diesel market.

A major research program to study the effects of varying fuel quality on performance is being carried out at the Combustion and Carbonization Research Laboratory (CCRL) in cooperation with the Canadian oil industry. This report describes the experimental facilities and procedures developed for combustion research on middle distillate fuels.

## EXPERIMENTAL EQUIPMENT

Figure 1 is a schematic of the test assembly designed to study the performance of a fuel in a domestic oil fired furnace\*. The experimental rig facilities can be generally categorized as follows:

- (1) Oil fired furnace and duct system.
- (2) Special equipment for simulation of residential conditions.
- (3) Continuous flue gas analyzers.
- (4) Temperature measurements.
- (5) Data acquisition and processing units.

(1) Oil fired furnace and duct system

Experiments are carried out in a forced air domestic furnace fired with an oil burner. The burner is fitted with a retention head burner and a delayed-action solenoid valve. The furnace has a rated capacity of 21.7 to 35.8 kW (74 000 to 112 000 Btu/h) heat output. It is equipped with standard features such as primary heat exchanger, forced air booster fan, motor pump, and electrical control units. The cold air return is provided with a special inlet cooling system and the heated air is released directly into the laboratory\*\*. The burner operation can be controlled either manually or by a timer. These arrangements are described in the next section. A hollow-spray nozzle with a rating of 2.46 l/h (0.65 US GPH) is used for all experiments.

An induced draft fan installed in the flue exhaust pipe provides control of constant draft and two additional barometric dampers help maintain the set reading of 0.1 cm (0.04 in.) of water column for all test runs.

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\* Details of the equipment utilized in this experimental program are presented in Table 1.

\*\* The warm air is now being exhausted out of the building through a duct.

(2) Special equipment for simulation of residential conditions

Ambient temperatures in the laboratory can vary widely. Summer temperatures and the operation of other combustion experiments significantly affect the test environment. Therefore, an actual residential or comparable environment is simulated by closed loop experimental conditions.

Oil temperature control

Since some fuel properties, e.g., viscosity, specific gravity and pour point are temperature sensitive, the fuel temperature was closely controlled to simulate that found in basement or outside tanks. It was essential to maintain the same temperature for all tests since all fuels were to be under identical experimental conditions. In addition, the oil temperature inside the nozzle line should be close to that found in an actual residential environment. Since very warm laboratory conditions could create an unrealistic differential between the supply and the nozzle oil temperatures, modifications were made to keep the oil supply cold throughout the delivery line. Strict control of all parameters was necessary to provide meaningful performance characteristics for the various fuels. In response to these requirements, a special fuel container-conditioner-delivery system was constructed as illustrated in Fig. 2.

Fuel oil is stored in a double-walled, 40-L capacity temperature-controlled copper tank with an ethanol-water coolant mixture circulating throughout the jacketed space. The coolant temperature is controlled by a constant temperature circulating bath, which maintains its temperature within  $\pm 0.1^{\circ}\text{C}$  of the set point. The internal temperature sensor of the bath is overridden by a remote sensor unit located within the fuel oil. The remote sensor, by measuring the actual fuel temperature, controls the bath by cooling or heating as necessary to maintain the set point. The fuel is thus maintained at the desired temperature.

The fuel delivery system includes three insulated copper lines and a two-way valve installed in the high pressure line. An additional return line was added to a standard fuel pump by inserting a bypass plug into the pump base at the return line port. This second line forces the excess oil from the pump back to the tank when the burner is "on". The third line, which connects the fuel tank and the high pressure line, bypasses the nozzle and returns the oil to the tank, stopping any flow for ignition. This is accomplished by a two-way valve, which allows the oil to flow either to the fuel tank or to the burner. Prior to burner startup, the operator selects the fuel return mode; the circulation action of cold fuel from the tank then equalizes oil temperatures of the tank and the nozzle line. Additional cooling is provided by blowing of chilled air to the burner housing through a specially constructed duct.

#### Circulation air temperature control

The average temperature of the cold air return to the furnace in a home is 18°C. It may vary slightly from one home to another but is unlikely to exceed 25°C. Since the laboratory temperature is higher than 25°C most of the time, a special cold air supply was arranged for the experimental program as illustrated in Fig. 3. Chilled air is produced from a water-cooled air conditioner and supplied to the cold air return duct of the furnace through damper 1. In order to satisfy the total blower demand, ambient air is also introduced into the cold air return duct and blended with chilled air before entering the heat exchanger. By adjusting damper 1, the operator can control precisely the cold air return. A set temperature of 15°C was selected for all test runs.

The temperature is measured accurately by a grid of four K type thermocouples across the furnace blower section and the averaged value is transferred to the data logger.

The rest of the chilled air from damper 1 travels to damper 2, at which point the operator decides how much cold air should go to the laboratory ambient and how much should be returned to the air conditioner. A 100% shutoff is not possible since the dampers are not



sealed. Damper 3 allows the chilled air to be supplied to the burner housing. It helps cool the burner and fuel prior to the furnace startup. However, once the burner is "on" most of the chilled air is released to the laboratory to help lower the ambient temperature.

### (3) Flue gas continuous analyzers

The oxygen analyzer used is a paramagnetic type. Carbon dioxide and carbon monoxide analyzers use the non-dispersive infrared absorption technique. The nitrogen oxide analyzer applies the chemiluminescent principle for determining gaseous concentrations. Total hydrocarbons present in flue gas are analyzed by the flame ionization detection technique. The hot flue gases are sampled via a 3-m long heated probe and line maintained at 205°C and filtered through a glass-fibre filter before entering the detection chamber.

An in-line smoke meter measures opacity readings for particulates in the flue gas stream. This equipment is normally used for emission gases having high particulate concentrations such as those from diesel engines. Therefore, the instrument was calibrated specifically for the low opacity ranges expected with middle distillate heating fuels. Detailed procedures will be described in a subsequent publication.

### (4) Temperature measurements

Control of the fuel and cold air return temperatures is crucial to obtain meaningful combustion data. To enable the operator to make adjustments and monitor the readings throughout the run, K type thermocouples are installed at a number of suitable locations and connected to the data logger-computer interfaced unit. A thermocouple inserted in the fuel container-conditioner provides the tank fuel temperature and another\*\* fitted next to the two-way valve on the high pressure oil line indicates the closest possible reading of nozzle line

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\*\* Relocated recently to the nozzle adapter compartment to obtain the closest as-fired oil temperature by inserting it directly into the oil nearest to the swirl chamber.

fuel temperature. A thermocouple is placed on the furnace side wall surface as a check point for the combustion chamber temperature. It is especially useful when restarting the experiment after an aborted run. The furnace wall temperature is indicative of that of the combustion chamber and burner conditions and allows the operator to wait until the system cools down to a realistic state before restarting the furnace. Similar temperature measurements are recorded from a grid of four thermocouples at each location for the flue gas, cold air return and warm air plenum.

(5) Data acquisition and processing units

An analog digital datalogging system is used for data acquisition. Electrical output signals from analyzers and thermocouples are initially transported to the datalogger; an interfaced computer gathers the experimental digital data at selected intervals. Stored data on tape cartridges are later processed on another computer and plotter.

## EXPERIMENTAL PROCEDURES

(1) Goals

The first phase of the middle distillate fuel research program entailed the development of an experimental program suitable for short term laboratory experiments. The program was systematically designed to provide combustion characteristics of all fuels studied under identical experimental conditions, allowing accurate interpretation of performance data in terms of fuel quality.

The short term experiments involve firing fuel for a 1-h steady state run, with continuous burner "on" operation, followed by five or more on/off cyclic operations lasting 10 min each. This approach simulates part of the usage pattern of a domestic furnace. After overnight thermostat cut-back for energy conservation, the furnace requires a significant period of continuous "on" operation to satisfy the daytime setting, then operates periodically as the thermostat demands.

(2) Experimental conditions:

Controlled parameters for various test equipment were selected as follows:

Fuel temperature: 7°C and 15°C

Combustion air supply: set for Bacharach smoke number 2 at steady state "on" operation prior to the test

Oil pump pressure: 689 kPa (100 psi)

Furnace draft: 0.10 cm (0.04 in.) of water column

Nozzle: Monarch hollow type spray pattern with 80° angle and 2.46 L/h firing rate (0.65 US GPH).

Burner retention head: Aero AFC-2

Cold air return temp: 15 ± 0.5°C

Three replicate runs were carried out for each fuel at each temperature resulting in a minimum of six runs per fuel. If irreproducible data were yielded within runs, equipment hardware and variable parameters were checked thoroughly and tests were repeated until consistent data resulted.

Fuel temperatures of 7°C and 15°C were chosen to represent realistic temperatures of outdoor and indoor oil tanks. A reduced firing rate oil nozzle and a retention head burner were incorporated to represent retrofit measures for energy conservation.

(3) Procedures:

Table 2 presents the detailed procedure of a typical experimental run. It covers the three general stages of the program: pre-startup preparations, 1-h steady state operation, and five consecutive burner "on/off" cyclic runs. Pre-startup preparations help create a comparable residential environment and assure strict control of various experimental parameters.

(4) Combustion data acquisition:

The above experimental procedures were carefully planned in order to capture all combustion performance characteristics from the three phases of each operation. Following is an outline of the data acquisition pattern:

<u>Operation phase</u>	<u>Combustion characteristics observed and recorded</u>
Startup transient	<p><b>Burner characteristics:</b> ignition pattern, ease of ignition, voluntary shutdown, noise, pulsation, nature of flame.</p> <p><b>Particulate emissions:</b> smoke opacity, Bacharach smoke number, visual detection of excessive smoke.</p> <p><b>Gaseous emissions:</b> O<sub>2</sub>, CO<sub>2</sub>, CO, NO<sub>x</sub> and hydrocarbons in flue gas.</p> <p><b>Temperatures:</b> fuel tank, high pressure oil line, furnace wall, oil in nozzle, flue gas, cold air return, warm air.</p>
Steady state (continuous "on" operation)	<p><b>Burner characteristics:</b> flame continuity, noise, pulsation, carbon deposition on nozzle or retention head.</p> <p><b>Particulate emissions</b></p> <p><b>Gaseous emissions</b></p> <p><b>Temperatures</b></p>
Shutdown transient	<p><b>Burner characteristics:</b> oil afterdrip, noise, pulsation.</p> <p><b>Particulate emissions</b></p> <p><b>Gaseous emissions</b></p> <p><b>Temperatures</b></p>

In addition to the "during-run" observations made on burner performance characteristics, visual studies were carried out in a separate portable combustion chamber, outside the experimental furnace. Trial experiments have been carried out recently to record these studies on video tape.

Particulate emissions are measured in three ways; the peak opacity reading, overall opacity time profile as continuously recorded on a strip-chart recorder, and Bacharach smoke number. In addition, the smoke meter was initially calibrated so that smoke opacity could be interpreted in terms of concentration units as milligrams of soot per cubic metre of flue gas.

Data from gaseous emissions and temperature measurements are recorded directly on the computer. Figure 4 shows the data acquisition and storage schematic of the experimental rig. Data acquisition is fully automatic once the operator manually synchronizes the programmable timer and datalogger-computer interfaced unit at the beginning of the experimental run. The timer controls the burner "on/off" operations and synchronizes the strip-chart recorder operations to record the smoke opacity peak trace for all burner startup operations. Volumetric concentrations of flue gas components and temperature readings are scanned on the data logger every 10 s, and are transferred to the tape storage memory at selected intervals. Data acquisition on the tape is programmed on the computer to capture all critical startup and shutdown emission data following the time sequence recorded in Table 3.

(5) Data reduction:

Data tapes are processed on a computer providing hard copy analytical results and graphical plots of emission and temperature profiles. Furnace efficiency and excess air levels are also determined. **Emission profiles:** These are the volumetric concentration, % or ppm, vs time graphical plots of flue gas components. From an experimental run, gaseous concentrations of oxygen, carbon dioxide, carbon monoxide, nitrogen oxides and hydrocarbon emissions are obtained. The computer program is set to provide emission data from startup, shutdown, and mid-run phases separately for each gaseous component.

**Temperature time profiles:** Six plots result from a typical test run providing temperature readings of tank fuel, furnace wall, nozzle line fuel, flue gas, cold air return and warm air.

## OPERATING PROBLEMS

- (1) Limited capabilities of the existing datalogger and computer prevented monitoring and recording of smoke opacity readings on the data tape. A new more powerful system is being installed for future experiments. The new system includes a Hewlett-Packard (HP) model 3054A data acquisition/control unit, a HP 9000 series computer model 217, a HP 7550A colour graphics plotter and a HP 2225A hard copy output unit.
- (2) Probability of encountering practical problems is moderately high since the testrig requires numerous instruments and accessories.

## CONCLUSIONS

- (1) Performance of fuel conditioning and air tempering equipment demonstrates that the equipment is capable of providing reliable and reproducible temperature readings regardless of change in ambient temperature. This assures the reproducibility of test conditions and thus allows reliable analytical data collection.
- (2) Strict control of test variables, especially temperatures, is crucial to this program to obtain true comparison data for various fuels. Occasional adjustment of damper 1 is necessary to keep the cold air return temperature constant throughout the run. Fuel temperatures stay fairly stable at all times provided the oil tank level is not too low.
- (3) Experimental procedures demand considerable operator attention. A checklist of about 20 items must be observed, prior to a daily experimental run.

- (4) Hard copy emission and temperature profiles are informative and useful. Any abnormal event which occurred during the test run can be observed without having to check the data printout.
- (5) The results and discussions of combustion experiments using various fuel oils will be described in an upcoming report.
- (6) In the second phase of the middle distillate fuel research program, combustion data resulted from those fuels will be correlated and interpreted in terms of their chemical and physical properties.

#### ACKNOWLEDGEMENTS

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#### REFERENCES

1. Hayden, A.C.S. and Braaten, R.W. "Efficient residential oil heating systems - a manual for servicemen, designers and builders"; EL 79-8; Energy, Mines and Resources Canada; Ottawa, 1980.

Table 1 - Equipment utilized in the experimental rig

Item	Description
Furnace:	Brock model LO-1M, 74000-12000 Btu/hr. Brock Engineering Manufacturing Co. Limited, Montreal, Quebec.
Burner:	Brock oil burner with retrofit retention head Areo AFC-2.
Nozzle:	Monarch NS type hollow spray pattern, 0.65 US GPH (2.46l/h) with 80° spray angle.
Draft meter:	Dwyer inclined manometer, 0-0.25 inches of water range. Dwyer Instruments Inc., Michigan City, Indiana 46360.
Air conditioner:	Comfortaire model SW 60-1B. Water cooled unit with 17.58 KW capacity. Aitons Equipment Inc., Mississauga, Ontario.
Thermocouples:	K type, nickel, chromium, silicon and manganese alloy.
Timer:	Chrontrol table top timer model CD-4. Lindberg Enterprises Inc., San Diego, CA 92111.
Cooler for flue gas sample:	Neslab model U-cool bath cooler. Neslab Instruments Inc., Portsmouth, NH 03801.
Constant temperature bath:	Neslab model EX-100DD circulating bath. Neslab model EN 850 flowthru cooler. Neslab model RS-1 remote sensor.
Smoke test instrument:	True-Spot model RCC-B. Bacharach Instrument Co., Pittsburgh, PA.
Smoke opacity meter:	Berkeley Celesco model 107 inline diesel exhaust smoke meter. Berkeley Industries Inc., Laguna Beach, CA 92652.
Oxygen analyzer:	Horiba model MPA 21A, magnet pneumatic analyzer, 0-25% range. Horiba Instruments Inc., Irvine, CA 92714.
Carbon dioxide analyzer:	Horiba model PIR 2000, general purpose infrared gas analyzer, 0-20% range.
Carbon monoxide analyzer:	Horiba model PIR 2000, general purpose infrared gas analyzer, 0-2000 ppm range.



Table 1 (Cont'd)

Item	Description
Nitrogen oxide analyzer:	Thermo Electron Corporation Model IAR, chemiluminescent NO-NO <sub>2</sub> -NO <sub>x</sub> analyzer, 0-10000 ppm range. Thermo Electric, Brampton, Ontario.
Hydrocarbon analyzer:	Beckman model 402 hydrocarbon analyzer. Beckman Instruments, Inc., Fullerton, CA 92634.
Datalogger:	Fluke model 224A. John Fluke Manufacturing Co. Inc., Everett, Washington 98206.
Computer:	Hewlett-Packard model 9825A. Hewlett-Packard (Canada) Ltd., Ottawa, Ontario.
Plotter:	Hewlett-Packard model 9827B.
Recorder:	Honeywell model Electronik 195. Honeywell Ltd., Ottawa.

Table 2 - Procedural description of a typical experimental run

Time sequence	Status of run	Operations and measurements
T -2 h		Condition the fuel to desired test temperature
T -1 h		Calibrate the analyzers
T -30 min		Adjust the cold air return temperature
T -20 min		Circulate the fuel to cool the nozzle line
T -15 min		Supply chilled air to burner housing
T -60 s	Synchronization of the timer and data logger-computer	Start the computer program, start recording data
T -30 s		Timer starts the smokemeter trace recorder
T -20 s		Switch the oil flow to the nozzle at the two way valve
T = 0	Startup transient phase of the steady state run	Timer starts the burner, burner performance characteristics, particulate and gaseous emissions in the flue gas, temperatures
T = 30 min	Mid-run of steady state run	Burner performance characteristics, particulate and gaseous emissions, temperatures
T = 59 min	Shutdown transient phase of the steady state run	Timer shuts down the burner, burner performance characteristics, particulate and gaseous emissions, temperatures

Table 2 - (Cont'd)

Time sequence	Status of run	Operations and measurements
T = 69 min	Startup transient phase of the first cyclic run	Timer starts the burner, burner performance characteristics, particulate and gaseous emissions, temperatures
T = 74 min	Mid-run of the first cyclic run	Burner performance characteristics, particulate and gaseous emissions, temperatures
T = 79 min	Shutdown transient phase of the first cyclic run	Timer shuts down the burner, burner performance characteristics, particulate and gaseous emissions, temperatures
T = 89 min	Startup transient phase of the second cyclic run	Same procedure as in the first cyclic run
T = 99 min	Shutdown transient phase of the second cyclic run	Same procedure as in the first cyclic run
(T = 109) to (T = 169) min	Third to fifth cyclic run operations	Same procedures as in the first cyclic run
T = 170 min	Completion of one experimental run	

Table 3 - Data collection time sequence

Experiment time	Frequency of collection	Elapsed time (min)
T=0 burner on; steady state run		
T=0 to T+1	Every 10 s	1
T+1 to T+2	20	2
T+2 to T+4	30	4
T+4 to T+7	60	7
T+7 to T+59	180	59
T+59 burner off		
T+59 to T+60	10	60
T+60 to T+62	20	62
T+62 to T+69	60	69
T+69 burner on; first cyclic run		
T+69 to T+70	10	70
T+70 to T+72	20	72
T+72 to T+79	60	79
T+79 burner off		
T+79 to T+80	10	80
T+80 to T+82	20	82
T+82 to T+89	60	89
T+89 burner on; second cyclic run		
T+99 burner off		
T+109 to T+170	Same as in the first cyclic run	170

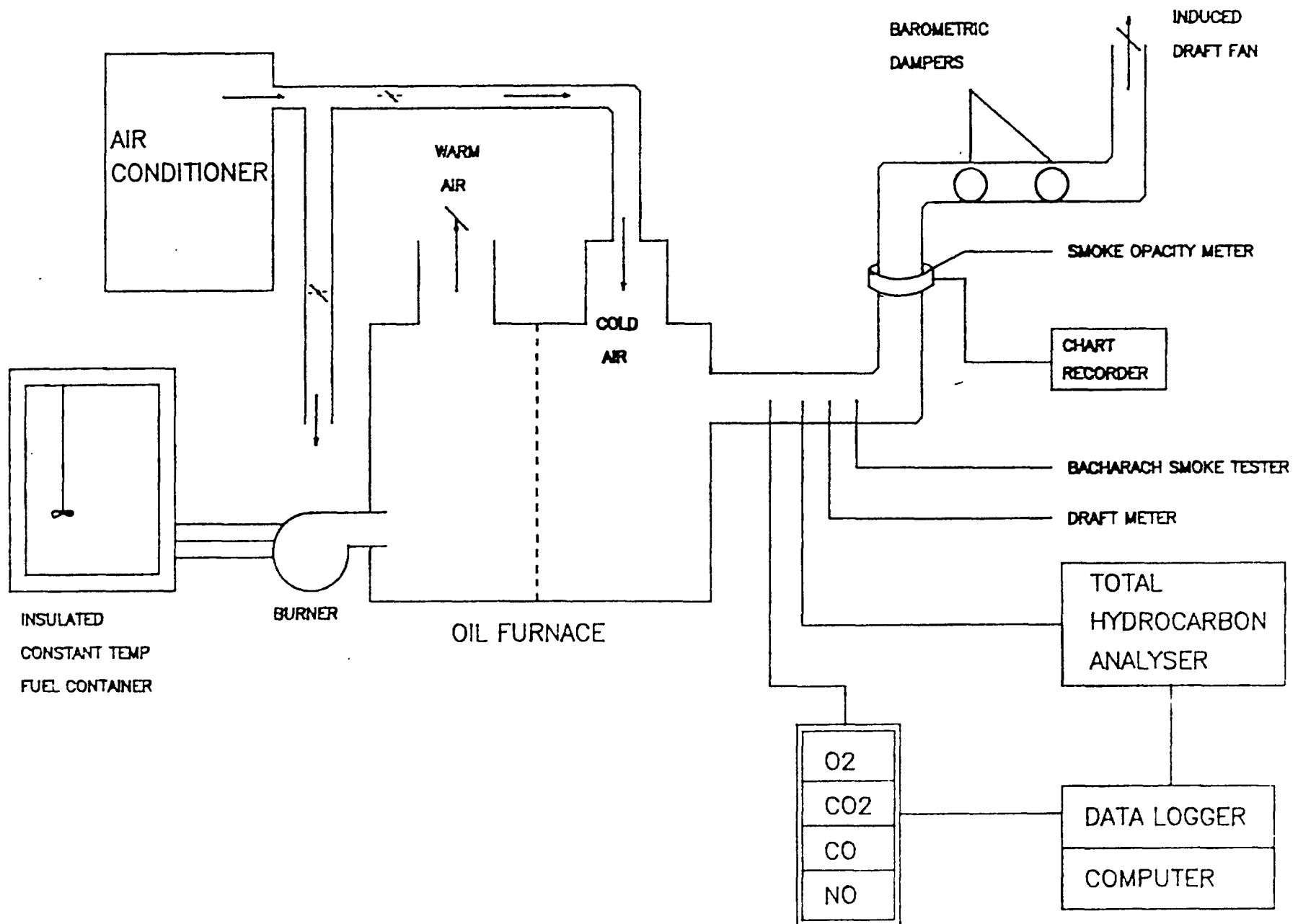


Fig 1 : Experimental equipment for middle distillate fuels project.

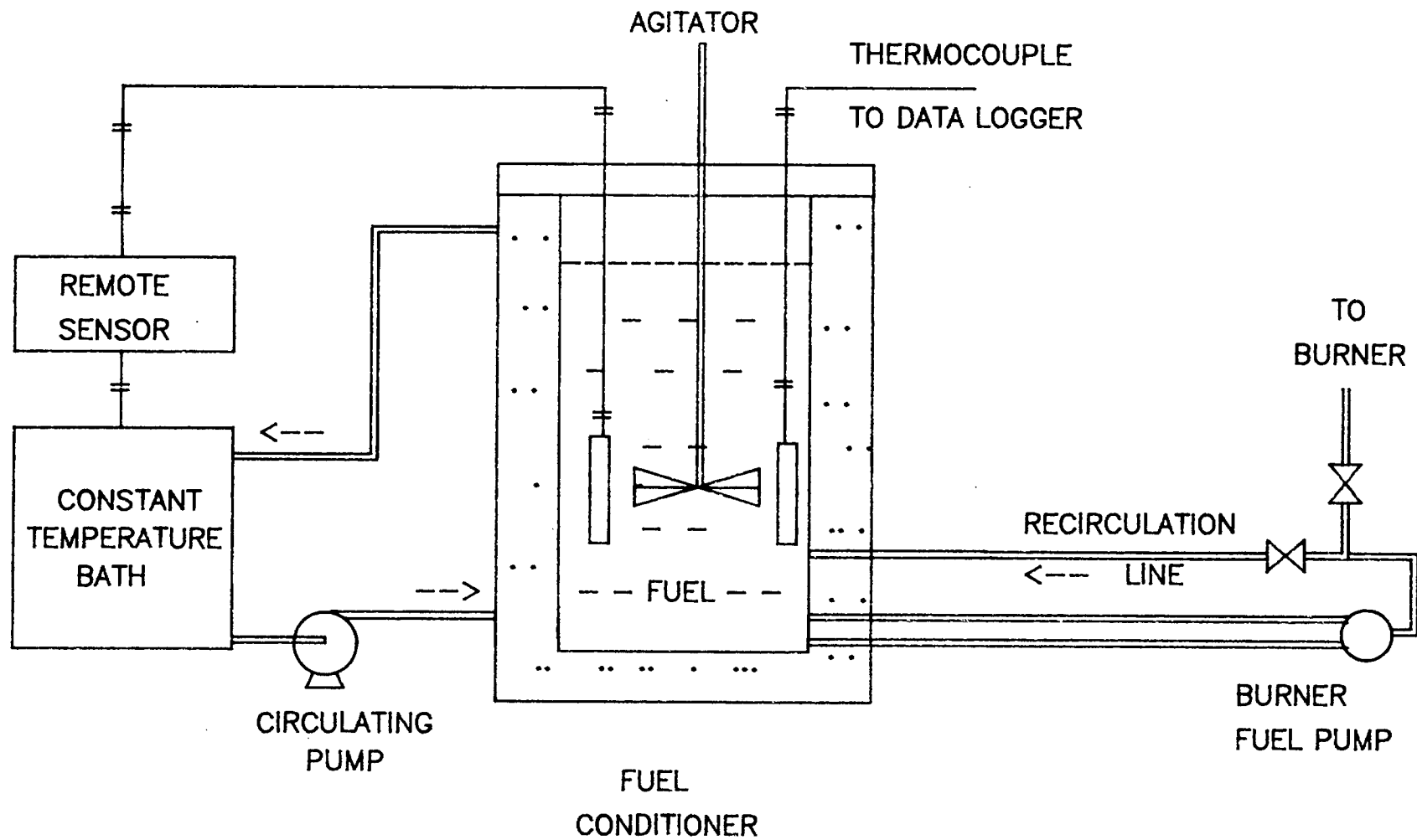


Fig 2 : Fuel conditioning and supply system schematic.

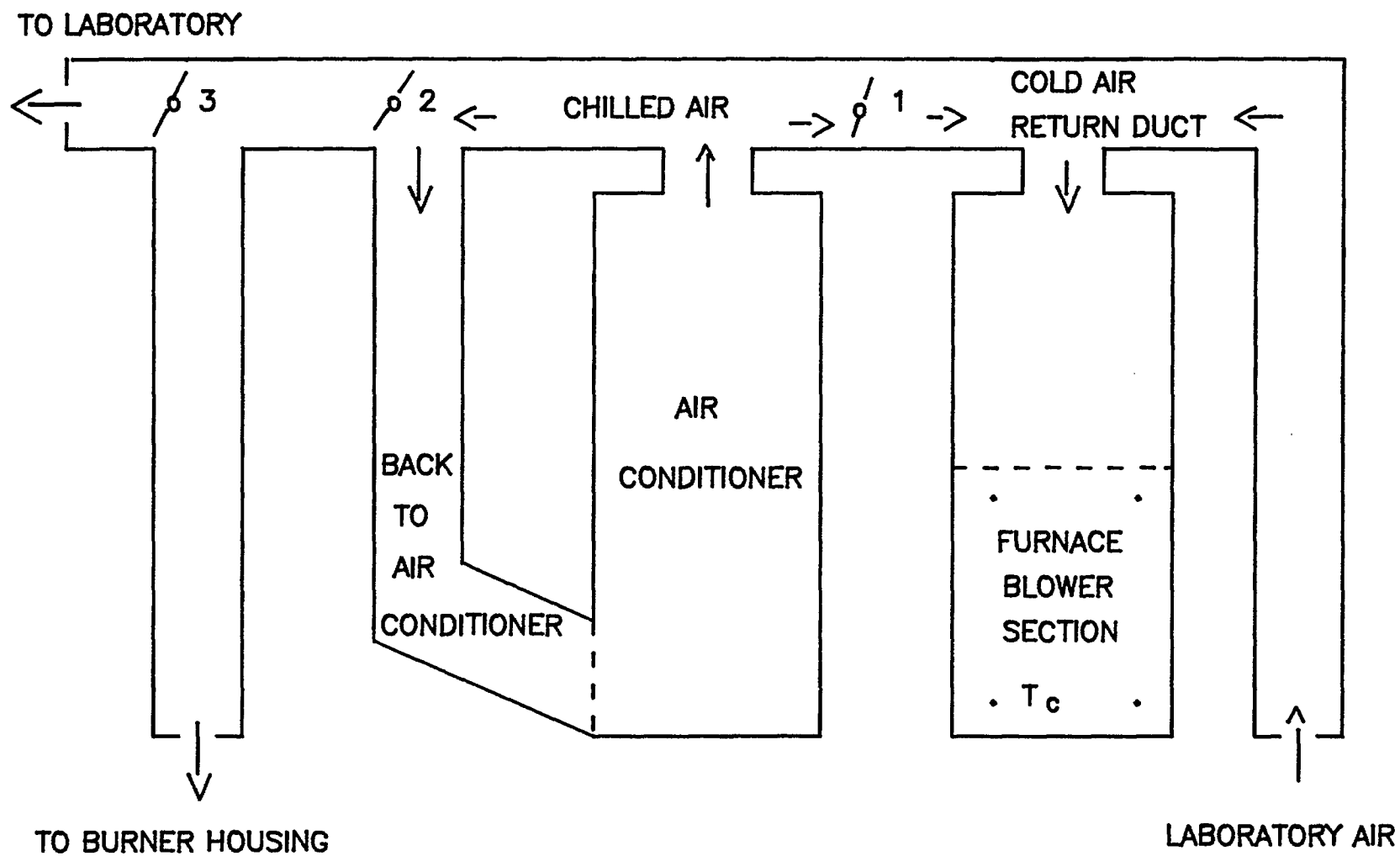


Fig 3 : Chilled air distribution system schematic.

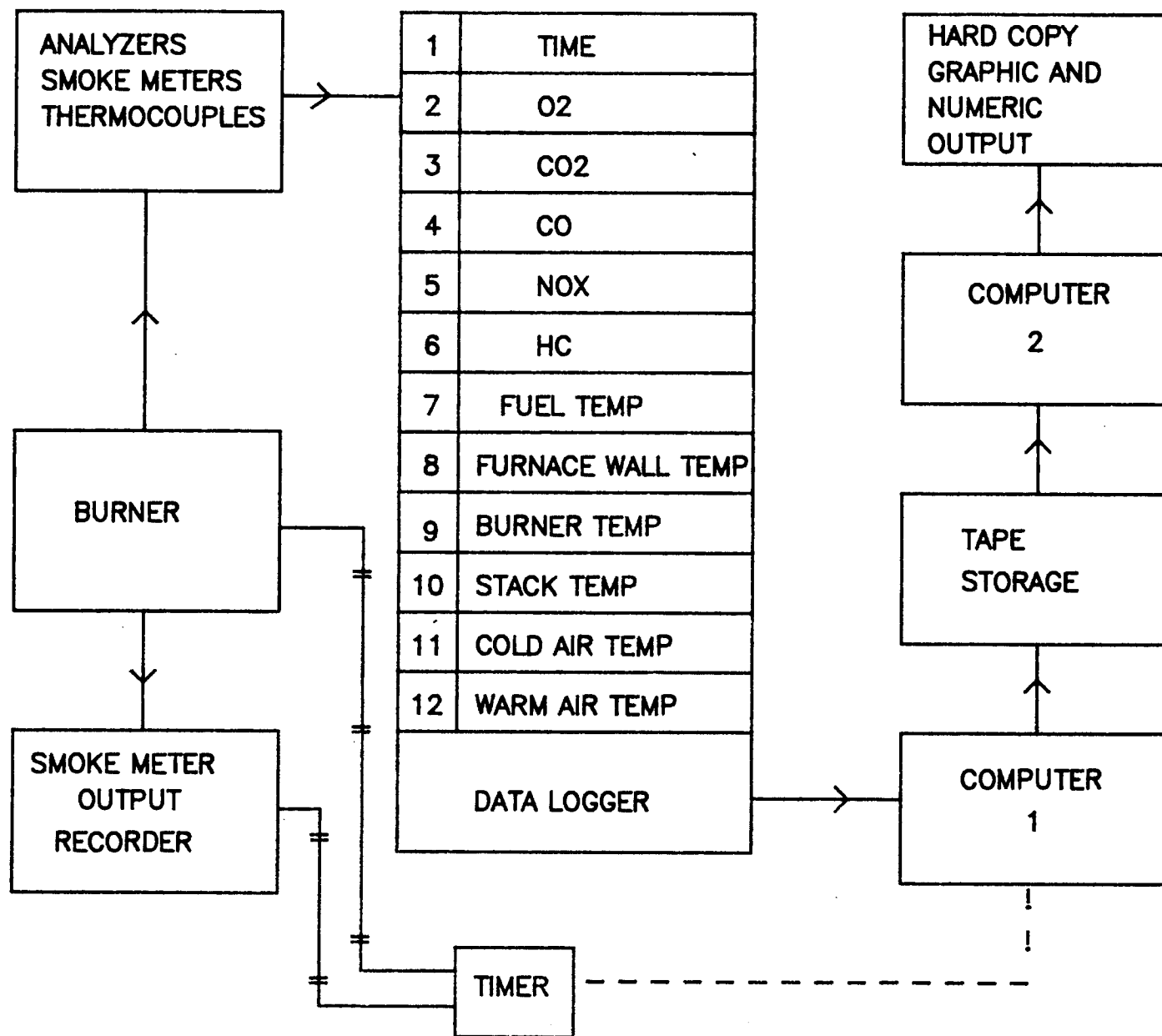


Fig 4 : Data acquisition and processing schematic.