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TECHNICAL REPORT NO. 11322

AN INVESTIGATION OF GAS TURBINE COMBUSTORS WITH HIGH INLET AIR TEMPERATURES
PART III: EXPERIMENTAL DEVELOPMENTS

MARCH 1971

U. S. ARMY TANK-
AUTOMOTIVE COMMAND
CONTRACT NO.
DAAE07-69-C-0756

20020726151

R. D. Anderson
A. M. Mellor
by JET PROPULSION CENTER, PURDUE UNIVERSITY

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U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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REPORT NO. 11322

PURDUE UNIVERSITY

AND

PURDUE RESEARCH FOUNDATION

AN INVESTIGATION OF GAS TURBINE COMBUSTORS WITH HIGH INLET AIR TEMPERATURES

SECOND ANNUAL REPORT

PART III: EXPERIMENTAL DEVELOPMENTS

by

R. D. Anderson
A. M. Mellor

Contract Number DAAE07-69-C-0756
U. S. Army Tank-Automotive Command
Warren, Michigan

Jet Propulsion Center
Purdue University
Lafayette, Indiana

March 1971

ACKNOWLEDGEMENT

The authors wish to thank Messrs. G. McFarron, S. Jones, D. Rodda, and T. Miller for valuable assistance in construction and testing of the experimental facility.

This work is sponsored by the U. S. Army Tank-Automotive Command under contract DAAE07-69-C-0756. Mr. Anderson acknowledges partial financial support through a Public Health Service Traineeship in Air Pollution.

ABSTRACT

Current gas turbine combustor design philosophy must reflect consideration of both emission control and high inlet air temperature effects on flame stability, combustor performance, and flame tube life. An experimental facility has been designed for the detailed, systematic study of gas turbine combustion as a function of realistic inlet parameters. In an attempt to provide fundamental gas turbine combustion information, internal gas temperature and gas sampling measurements will be made. In addition to a detailed description of the experimental facility, internal gas temperature and gas sampling probing techniques, facility instrumentation, and future engine parameter settings are discussed.

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CHAPTER I

INTRODUCTION AND OBJECTIVES

The present trend toward higher flight Mach numbers and compressor pressure ratios in aircraft gas turbines and to the use of regenerators in vehicular gas turbines has resulted in a significant increase in combustor inlet temperatures. In addition, air pollution from gas turbine engines is expected to increase relative to total pollution production in the future, not only because of increasing gas turbine usage, but also because stringent controls are being imposed on other sources. Because of these facts, current gas turbine combustor design philosophy must reflect consideration of both emission control and high inlet air temperature effects on flame stability, combustor performance, and flame tube life. It is felt that the present empirical method of gas turbine combustor design, when subjected to the myriad of modern combustor design requirements, would prove prohibitively expensive and generally unsatisfactory.

In an attempt to significantly reduce empirical combustor development work and to provide a very general combustor design procedure capable of satisfying the many current performance requirements, an analytical perfectly stirred reactor-plug flow reactor combustor design model is presently under development by Hammond and Mellor (1970a, 1970b, 1971). Concurrently, prompted by very similar considerations, an investigation of possible general analytical techniques for the prediction of gas turbine combustor liner temperature distributions is being conducted by Owens and Mellor (1971).

An experimental facility for the study of realistic gas turbine combustion has been designed and is partially completed; the test facility will provide data for the analytical research programs detailed above. In particular the experimental facility will, first, provide data for comparision with the analytical performance and emission predictions of the combustor modelling program; second, provide actual flame tube temperature distributions for comparision with analytical flame tube temperature distribution predictions; and finally, provide the gas temperature and gas sampling measurements from which the effects of heat release, flame temperature, local temperature, combustion intensity, and residence time on NO, CO, and hydrocarbon (HC) formation, destruction, and emission can be estimated.

In the following chapters the experimental facility will be described in detail. Chapter II contains a review of the test facility as it presently exists. The general facility specifications are given and the component systems fully described. In addition, information concerning the experimental runs completed to date appears as well as a discussion of the engine parameter settings to be used for future runs in the present experimental configuration. Chapter III includes a complete description of the experimental facility instrumentation. Particular emphasis is placed on the gas composition measurement instrumentation. Future test facility additions are presented in Chapter IV. All remaining component systems as presently visualized are included. Also, some discussion concerning the future run conditions for the remaining engine configurations is presented.

CHAPTER II

PRESENT EXPERIMENTAL FACILITY DESCRIPTION

With the exception of inlet air temperature, the experimental facility completed to date provides for the systematic and detailed study of gas turbine combustion as a function of realistic inlet parameters. The present facility is shown schematically in Fig. 1. It should be mentioned that all component systems described in this Chapter are presently operational. The present control room configuration is shown in Fig. 2, 3, and 4.

A. Air System Description

Because of the very large mass flow rates and high overall compressor pressure ratios used in modern gas turbine engines, a very large air compressor network is essential to any research laboratory attempting to study realistic gas turbine combustion. The air compressor system which feeds the test facility has a capacity of approximately 3000 cu ft and can provide air system pressures of up to 2500 psi. Sustained air flow rates of up to 3 lb/sec are possible for run durations of approximately 30 minutes. In addition, the basic combustion system can pass air flow rates of up to 10 lb/sec for short periods. Although the main air system compressors are in service throughout any run situation, the system is basically of the blowdown type. To date the air system has proven very satisfactory for the needs of the program in most respects.

The basic test cell air system is shown schematically in Fig. 5. In the interest of safety the 3 in main supply ducting is heavy wall carbon steel and all high pressure control lines are stainless steel. The main air supply system includes two 3000 psi inlet capacity remotely controlled air regulators mounted in parallel, a safety burst disc, a 2-1/8 in orifice type flow meter, a pneumatically operated air throttle valve, and finally, a diffuser section. Presently the orifice flow

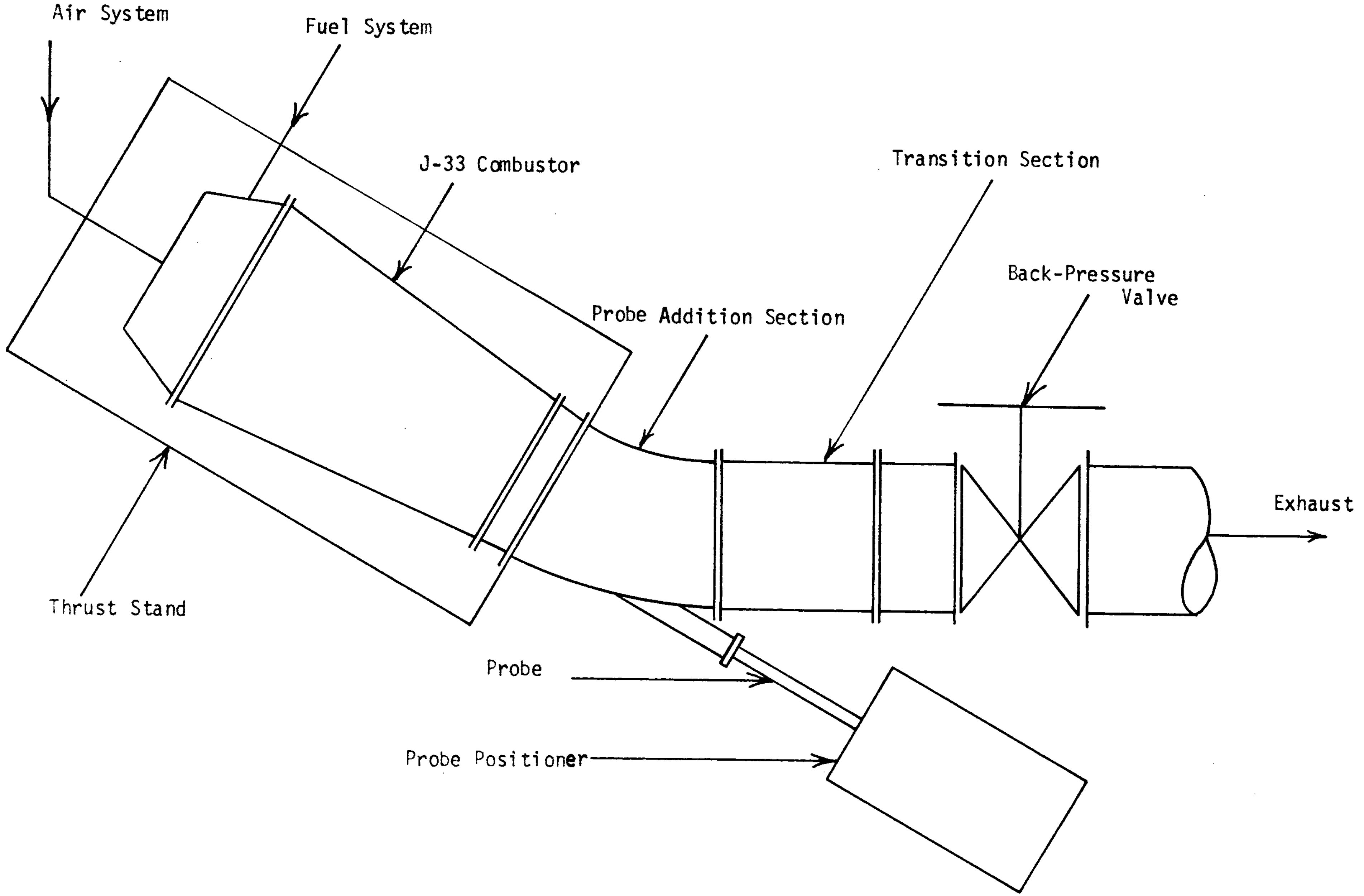

Fig. 1 Present Facility Schematic

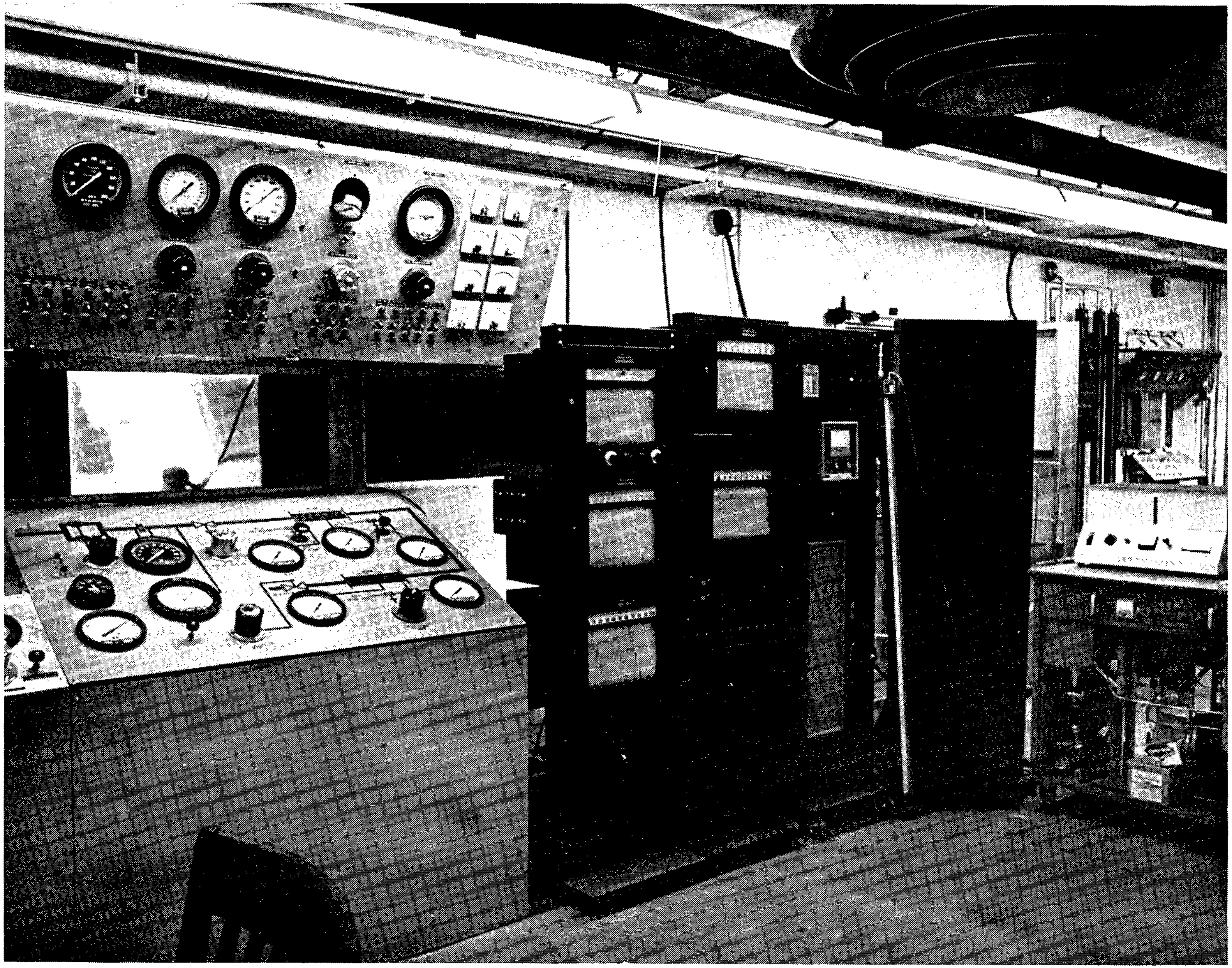

Fig. 2 Control Room

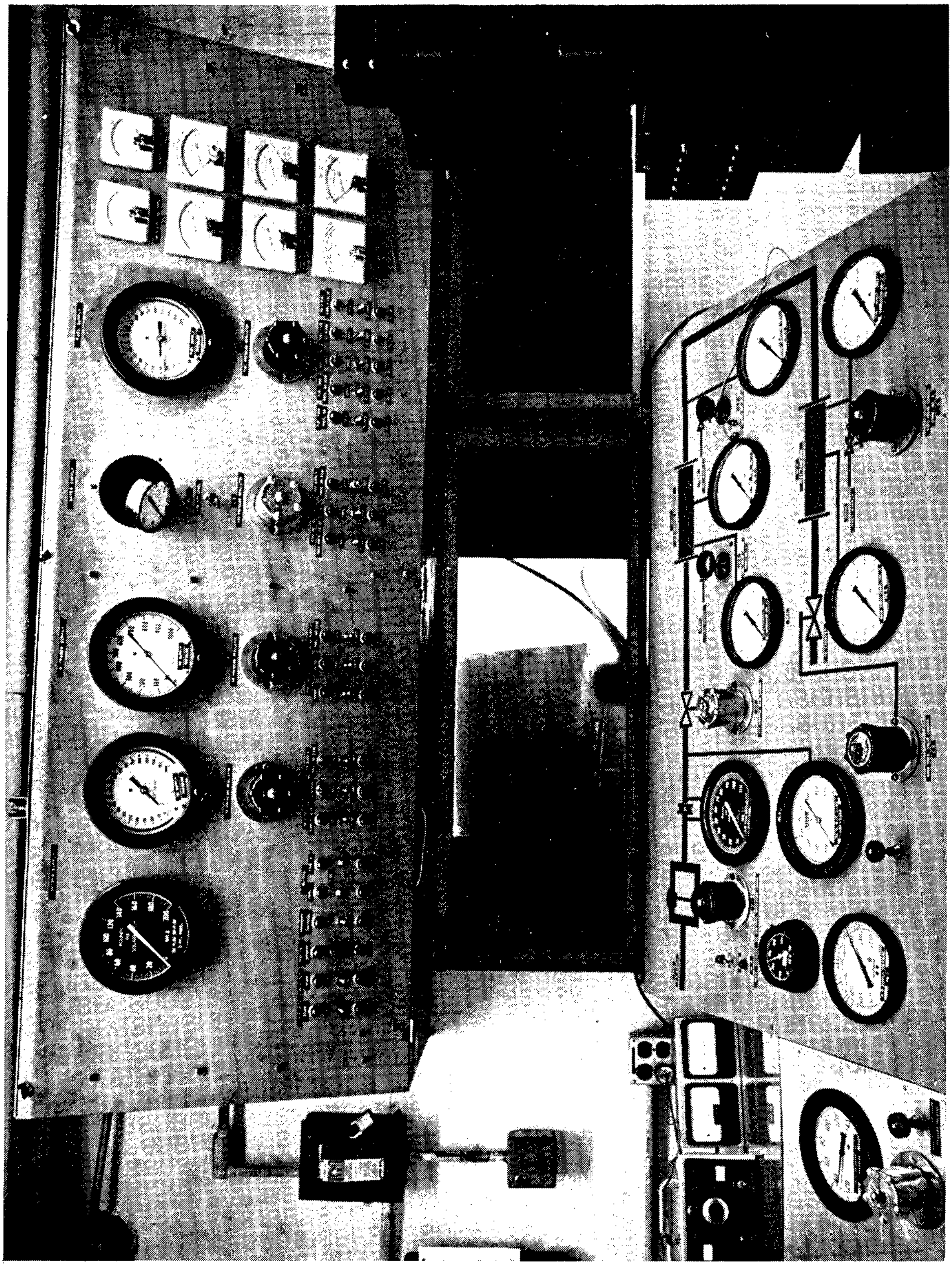

Fig. 3 Combustor Operating Instrumentation

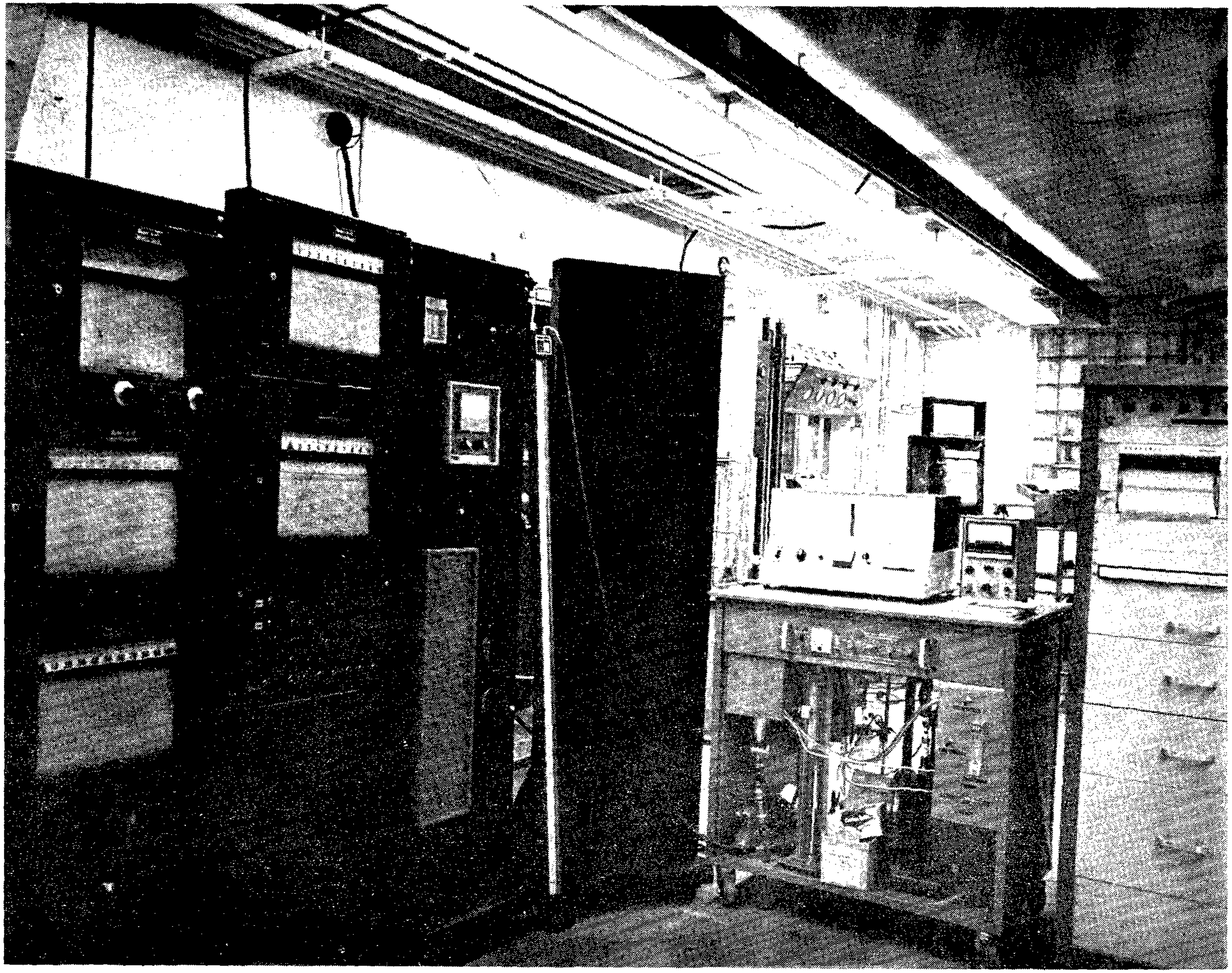

Fig. 4 Emission Monitoring Instrumentation

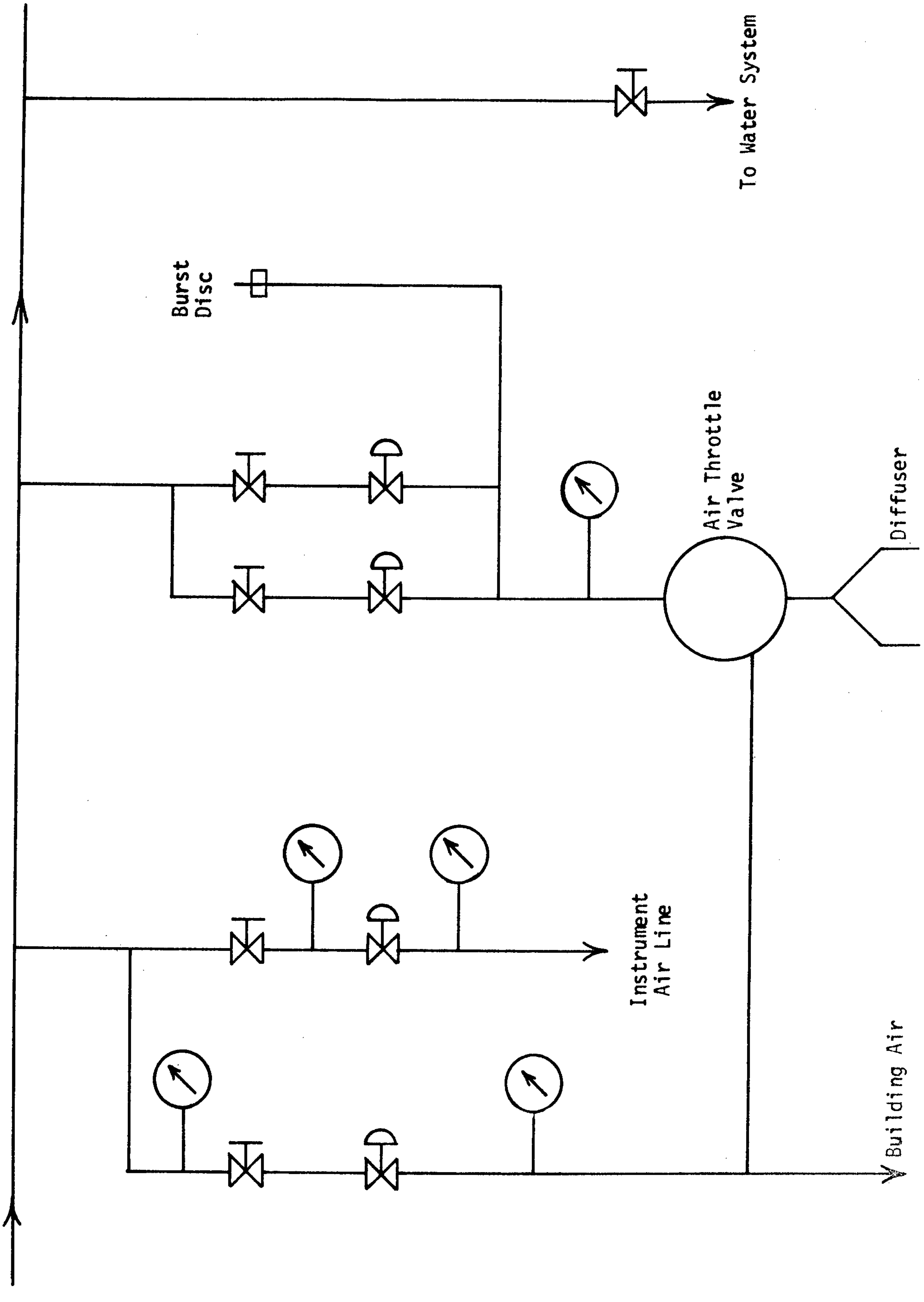

Fig. 5 Air System

meter differential pressure is monitored on a differential pressure gage in the control room. In the near future a differential pressure transducer will also be installed.

B. Fuel System Description

The fuel presently being used in the combustion study is liquid propane. The fuel was selected because it is relatively inexpensive, readily available, and amenable to analytical combustor modelling (Hammond and Mellor, 1971). The fuel system is shown schematically in Fig. 6. When pressurized with nitrogen, the 200 gallon propane storage tank fills the five 10 in x 10 ft cylindrical steel fuel delivery tanks. The propane storage tank is then isolated and the fuel delivery tanks are pressurized to the desired supply pressure using a ten bottle nitrogen supply manifold. All fuel flow is passed through a suitable fuel filter and then underground to the test cell area. Fuel flow rate is controlled by a pneumatically operated fuel throttle valve and measured by a Potter turbine flow meter. Frequency converters are used to convert the flow meter output to a calibrated milliamp output signal.

In the interest of safety the main fuel system tanks have been positioned away from the test cell area, stainless steel has been used for all lines and fittings, both manual and solenoid vent valves and automatic pressure relief valves have been judiciously placed, and all fuel system pressures are continuously monitored. The fuel system as shown in Fig. 6 is fully completed and has performed satisfactorily to date.

C. Primary Combustor Description

In the present engine configuration all combustion occurs in an Allison J-33 turbojet combustor mounted in a stainless steel converging housing. The combustor housing, in turn, is secured to a thrust table. Both the standard J-33 fuel nozzle and magneto-energized igniter are used. The basic combustor arrangement is shown in Fig. 7. In order to provide the desired experimental data for the analytical heat transfer study (Owens and Mellor, 1971), the J-33 flame tube has been outfitted with several chromel-alumel thermocouples arranged as depicted in Fig. 8.

Through the courtesy of the Detroit Diesel Allison Division of

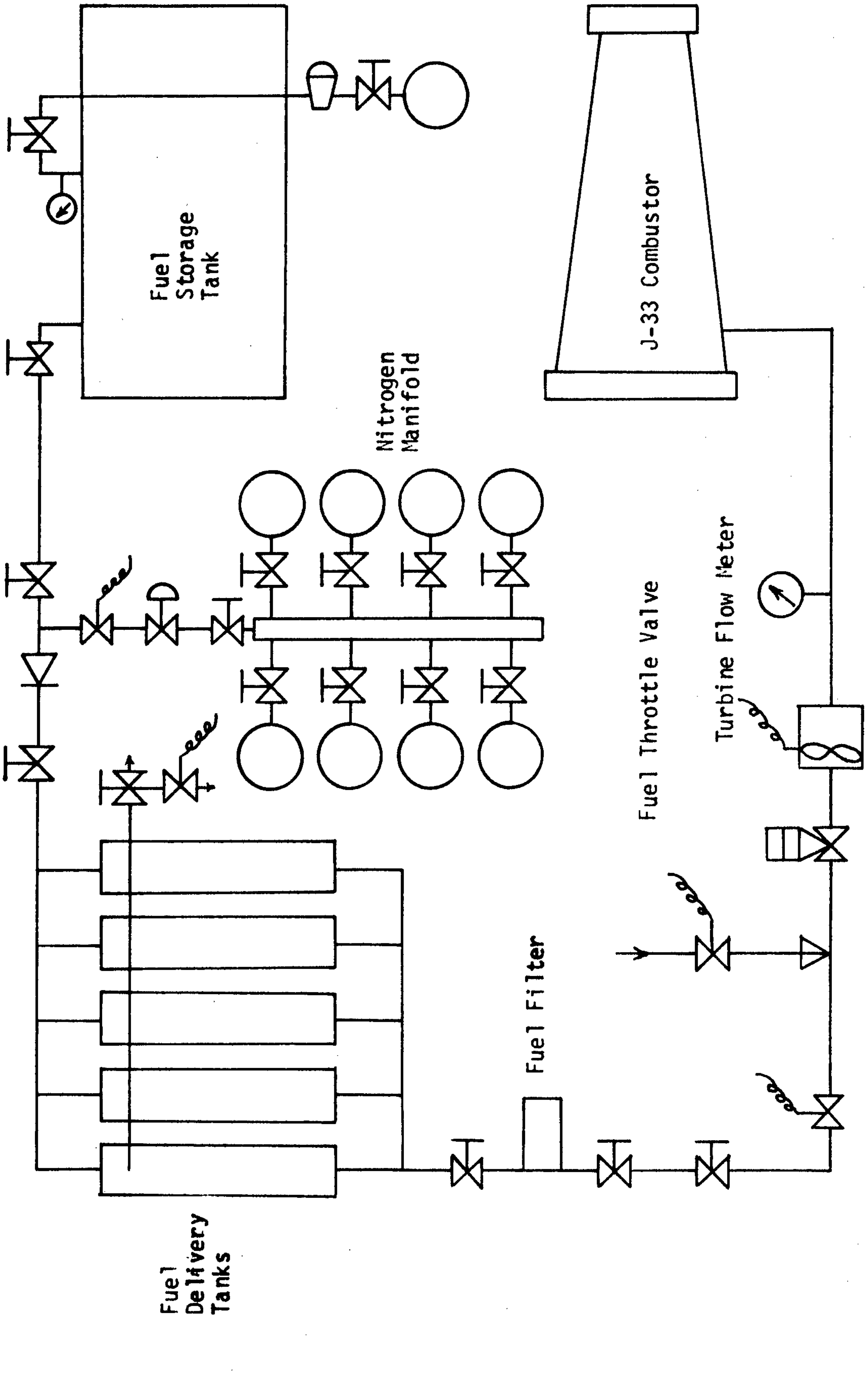

Fig. 6 Fuel System

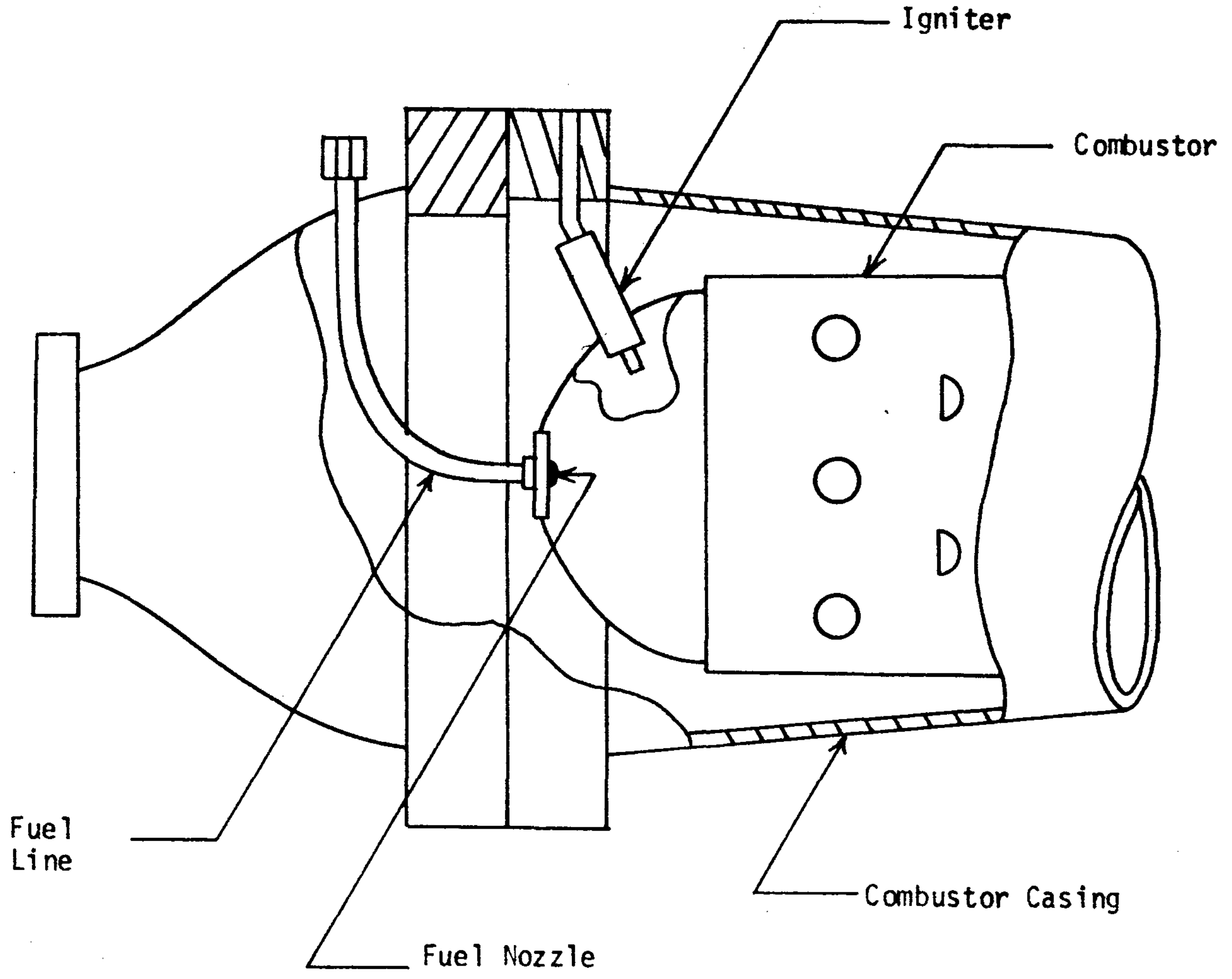

Fig. 7 J-33 Combustor-Casing Arrangement

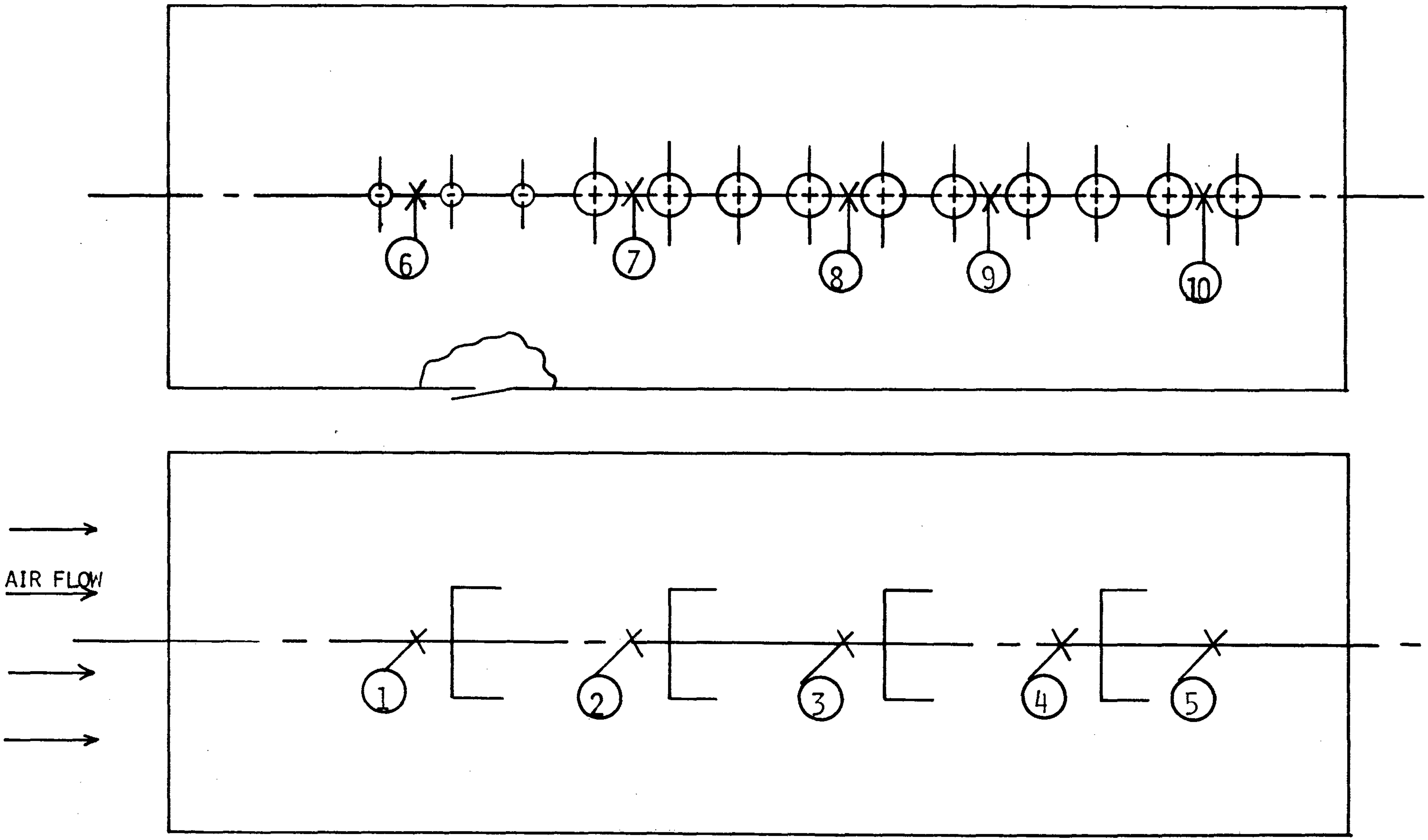

Fig. 8 Flame Tube Thermocouple Arrangement

General Motors, the J-33 design resume shown in Table 1 was obtained.

D. Probe Addition Section Description

The primary combustor casing exit is flanged to accept the probe addition section as shown in Fig. 9. The purpose of this stainless steel section is to change the direction of the exhaust gas flow such that gas sampling and gas temperature probes may be directly inserted into the J-33 Combustor. The surface of this section has been wraped with copper water cooling lines and the probe window is cooled with injected nitrogen. A specially designed fitting insures the prevention of exhaust gas leakage past the inserted probe.

E. Probe Description

As mentioned above, either the gas sampling probe or the gas temperature probe is inserted into the J-33 combustor through the probe addition section and supported at the probe window. The probe body consists of three concentric stainless steel tubes as shown in Fig. 10. These tubes are positioned with tiny silver solder beads and provide three distinct passages inside the probe body. Pressurized cooling water enters the probe block and flows to the probe tip in the outer annulus. At the tip the cooling water flow is turned and proceeds through the inner annulus back to the probe block where it exits. In the gas sampling probe the center probe body tube carries sample gases to the gas sampling system delivery lines, while in the gas temperature probe the center section serves to shield the platinum/10% platinum-rhodium thermocouple wire from the cooling water flow. Cooling water flow pressure is variable up to 230 psi.

Although the probe body assembly is identical for both the gas sampling and the gas temperature probes, as would be expected the tip designs differ radically. The gas temperature probe tip design which was selected reflects consideration of the inherent difficultics of temperature measurement in a high temperature flowing gas stream. In the case of gas turbine combustion such difficulties include radiation losses from the flame to the probe tip, conduction of heat from the probe tip to the cooler probe body, the occurrence of undesirable surface reactions on the probe tip, and, finally, uncertainty as to whether

TABLE 1.

J-33 Design Resume

Military Air Flow	7.64 lb/sec
Normal Air Flow	7.17 lb/sec
Military Inlet Temperature	435 °F
Normal Inlet Temperature	390 °F
Military Inlet Pressure	141 in Hg abs
Normal Inlet Pressure	126 in Hg abs
Military Volume Flow	40.7 cu ft/sec
Normal Volume Flow	40.9 cu ft/sec
Average Pressure Loss	4.5%
Liner Cooling Air Flow	8.0%
Primary Combustion Air Flow	23.4%
Secondary Combustion Air Flow	68.3%

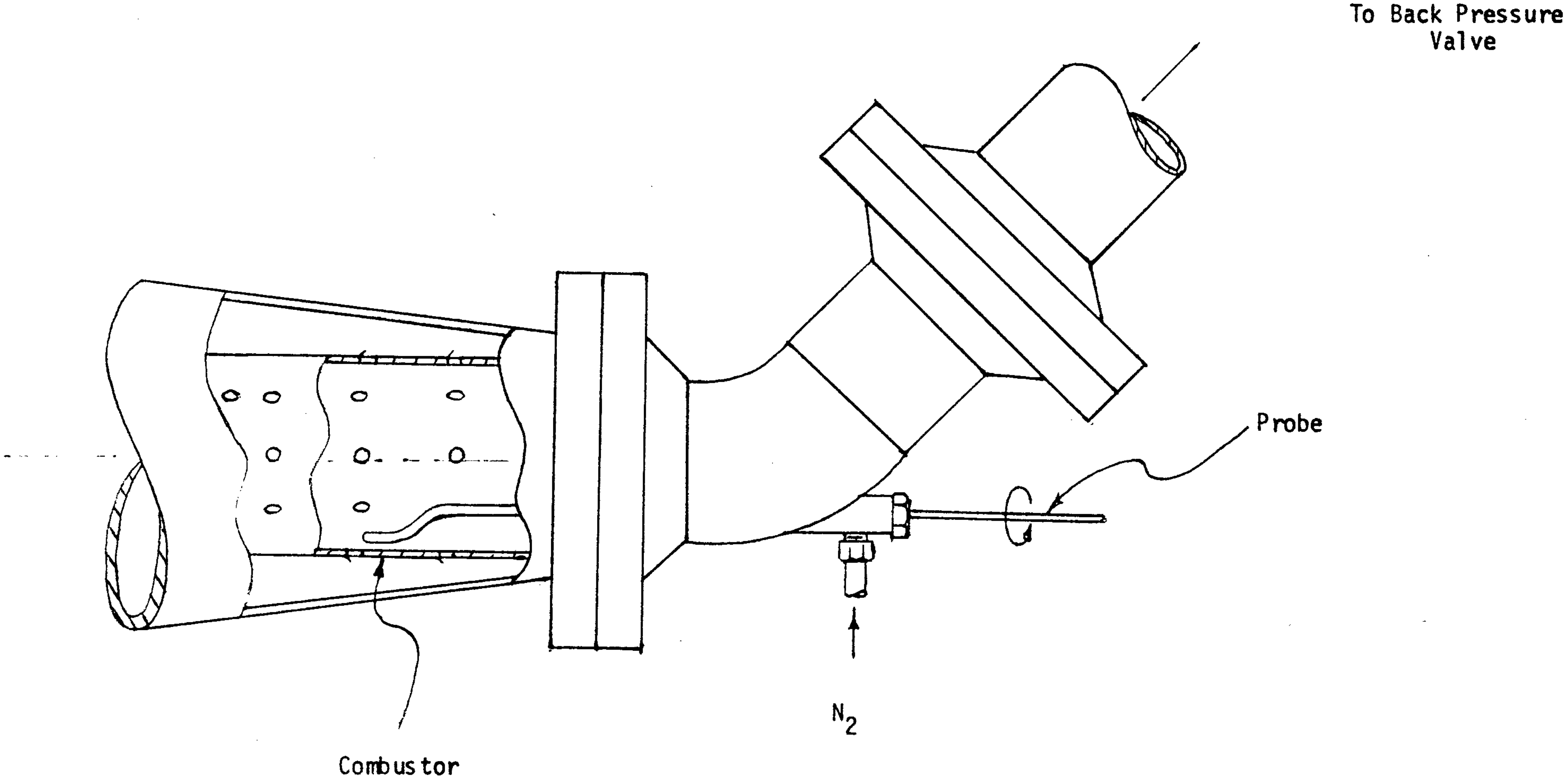

Fig. 9 Gas Sampling Probe Location

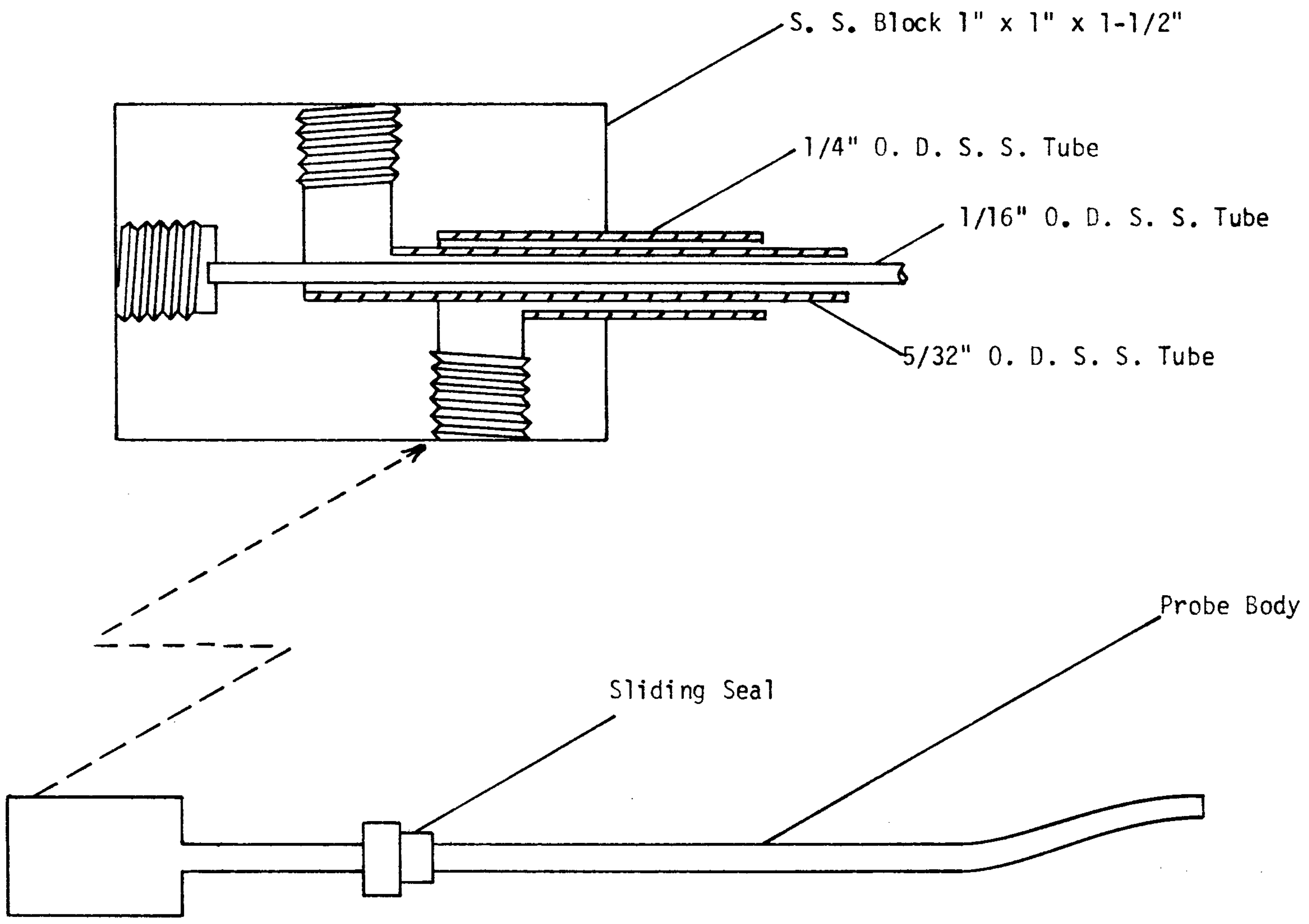

Fig. 10 Probe Body

static or total temperature measurements are being made.

In an attempt to overcome many of these problems, the temperature probe tip shown in Fig. 11 was designed. By using a shielded type of probe tip radiation losses from the thermocouple are minimized; in addition, the effects of scattered flame radiation impinging on the thermocouple tip are reduced by the use of a very small tip gas flow entrance diameter. To help maintain reasonable response time, small vent holes to provide a continuous gas flow past the thermocouple tip have been drilled downstream of the thermocouple junction. In an attempt to reduce surface reactions, the thermocouple tip has been coated with silicon dioxide, and finally, for combustor temperature measurements where the gas velocities are less than 300 ft per sec the static temperature approximately equals the total temperature. Although it is felt that all the major causes of temperature measurement error have been considered,all actual measurements will be continuously reviewed.

At the present time the gas temperature probe has been constructed and calibrated. To insure accurate temperature measurement all calibration points have been plotted as a function of probe cooling water pressure and probe insertion depth into a high temperature calibration furnace.

The final design of the gas sampling tip reflects consideration of gas sampling problems. In order to obtain accurate information from the combustor, the composition of the gases at the entrance of the gas sampling tip must be identical to the gas composition at the entrance of the monitoring equipment. In other words, all gas reactions must be quenched in the shortest possible distance in the sampling probe. The final gas sampling tip design as shown in Fig. 12 reflects this design requirement. In practice reaction quenching is accomplished in two different ways: firstly, as the gases enter the probe tip they are accelerated by passage through a converging-diverging nozzle. Due to this expansion and acceleration process, the static temperature of the gas is reduced. As the gases flow through the probe body, additional reduction in gas static temperature is achieved through the second mode of reaction quenching, that due to the cooling water flow. The combined effects of these two methods of reaction quenching are felt

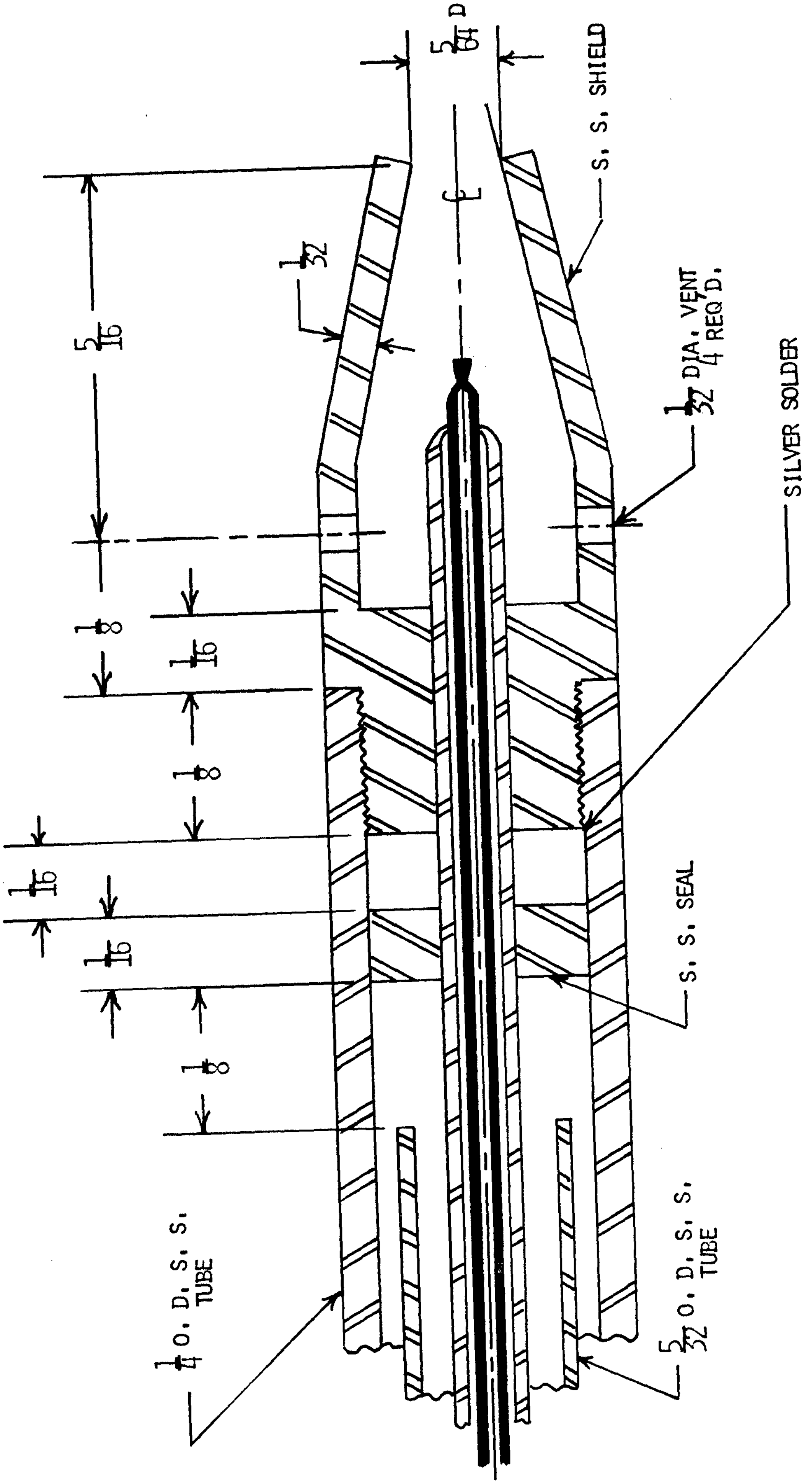

Fig. 11 Gas Temperature Probe Tip

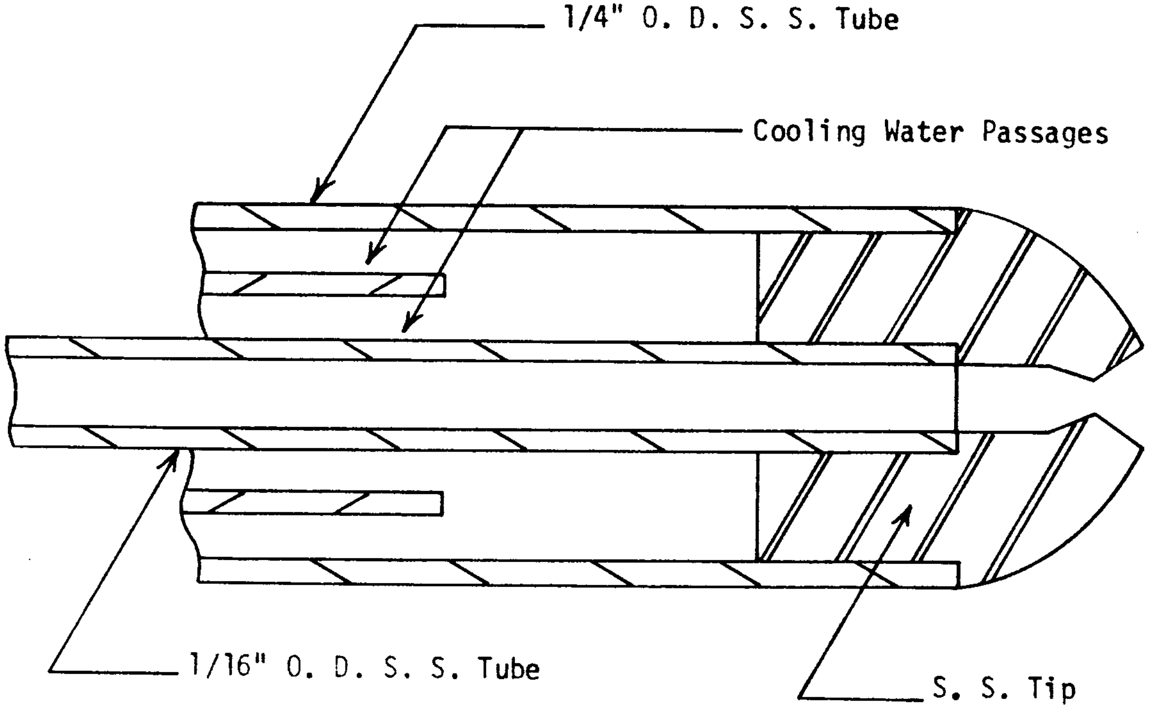

Fig. 12 Gas Sampling Tip

to be sufficient for accurate gas sampling analysis.

Although this two mode type of reaction quenching is the generally accepted state of-the-art method, little experimental verification of its success has been found in the literature. In an attempt to rigorously justify this experimental technique, certain experiments will be conducted and subsequently reported.

In addition to the various particular problems associated with gas temperature and gas sampling probe tip design, three common difficulties become apparent. Due to the fact that both stainless steel probe tips rely completely upon conduction for cooling, actual probe tip life may be short. If experimental usage verifies this fear, a new generation probe tip of similar design will be constructed of a copper-beryllium alloy. Such a tip would exhibit greatly improved heat conduction characteristics and may prove better able to withstand the adverse combustion chamber environment. A second possible problem area concerns probe tip flutter. If widely fluctuating measurements indicate such a problem, an appropriate internal bracket could be installed for stabilization purposes. The third possible area of probe difficulty concerns probe tip blockage. Such a condition would be most likely to occur under starting and transient conditions. To reduce the likelyhood of such blockage, a small shield has been installed in the aft end of the J-33 combustor behind which either probe tip will be hidden during all starting and purposely induced transient combustion modes.

F. Probe Positioner Description

As mentioned above typical gas temperature and gas sampling measurements will be made inside the J-33 combustor as a function of axial and radial position by translation and rotation of the appropriate probe. In order to provide accurate, remotely controllable positioning of the probe tips, the probe positioner as shown in Fig. 13 has been constructed. Two electrically driven motors and appropriate gearing impart rotational and translational motion to the appropriate probe. A series of micro-switches provide accurate control room information concerning both radial and axial position by lighting appropriate panel lamps corresponding to preset lattice points inside the combustor.

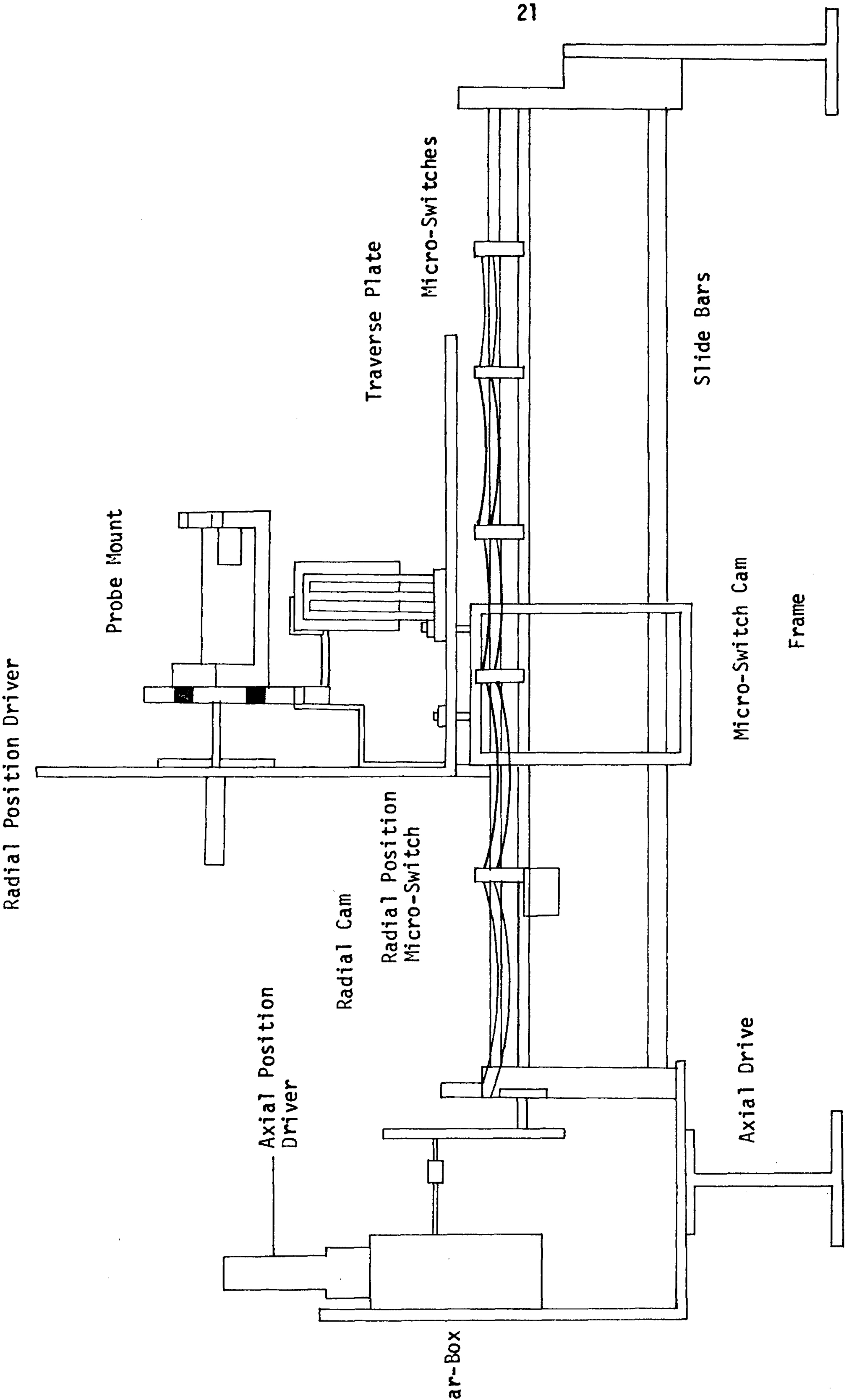

Fig. 13 Probe Positioner

Tests conducted to date indicate that the probe tip position is reproducible to within one-eighth of an inch in both axial and radial directions. Such accuracy is well within the desired limits. Fig. 14 illustrates the probe mounted on the positioner and the control room probe positioning panel.

The design of the probe body and the use of the probe positioner allow for the scanning of approximately one-quarter of any combustor cross-sectional area. By simply rotating the combustor casing the remaining cross-sectional area can be scanned if desired. It is felt, however, that reasonable symmetry should be present in the flame tube as regards all measurements and that the combustor casing rotation will only prove necessary as an occasional check on this assumption.

G. Back-Pressure System Description

In order to simulate modern gas turbine combustion, certain requirements are imposed upon combustor pressure. In some high performance aircraft gas turbine applications, combustor pressures at takeoff are on the order of 20 atmospheres. However, in automotive gas turbine applications combustor pressures rarely exceed 6 atmospheres. Therefore, in an attempt to construct a facility for general gas turbine combustion research, it was necessary to provide the capability for continuous back-pressure regulation from 1 - 20 atmospheres. The device constructed for this purpose is shown in Figs. 15, 16, 17, and 18, and consists of a translating,conical center-body in a divergent section.

In order to insure the survival of the center-body in the hot exhaust gas stream, pressurized cooling water is forced through a number of very small holes in the front center-body cone. This method of cone cooling has proved very successful to date. A thermocouple mounted close to the cone tip on the inside of the center-body provides continuous monitoring of back-pressure cone temperature. The cooling scheme used has continuously maintained center-body cone temperature at approximately 150 °C under all run conditions thus far encountered. Both the front and rear center-body cone are removable for easy inspection.

As can be seen in Fig. 16 the translating section of the back-pressure valve is mounted on a dolly and guided in movement by tracks seured to the top of an adjustable table. In order to insure smooth operation of the extremely heavy back-pressure valve system, great care

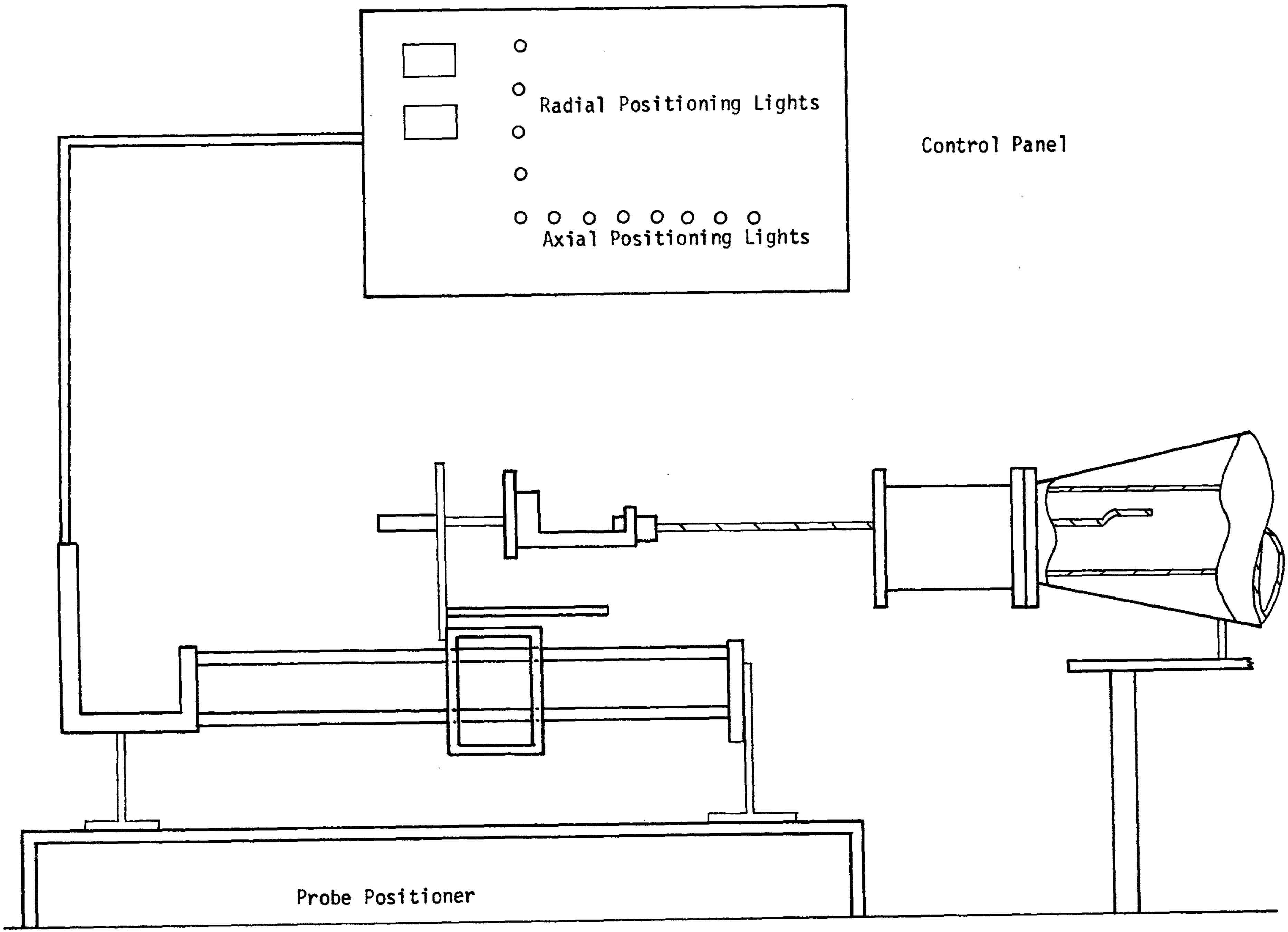

Fig. 14 Probe Positioner System

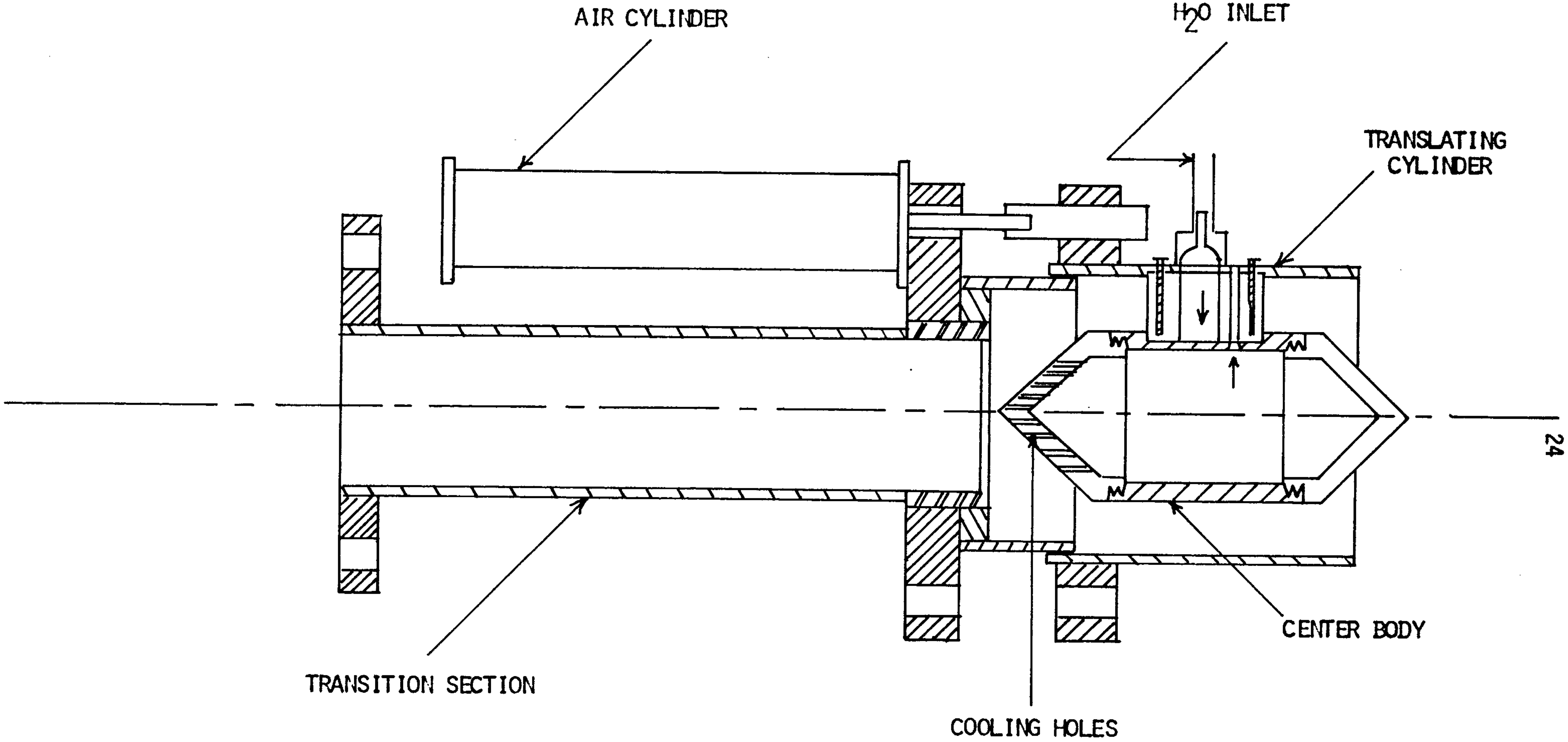

Fig. 15 BACK-PRESSURE VALVE

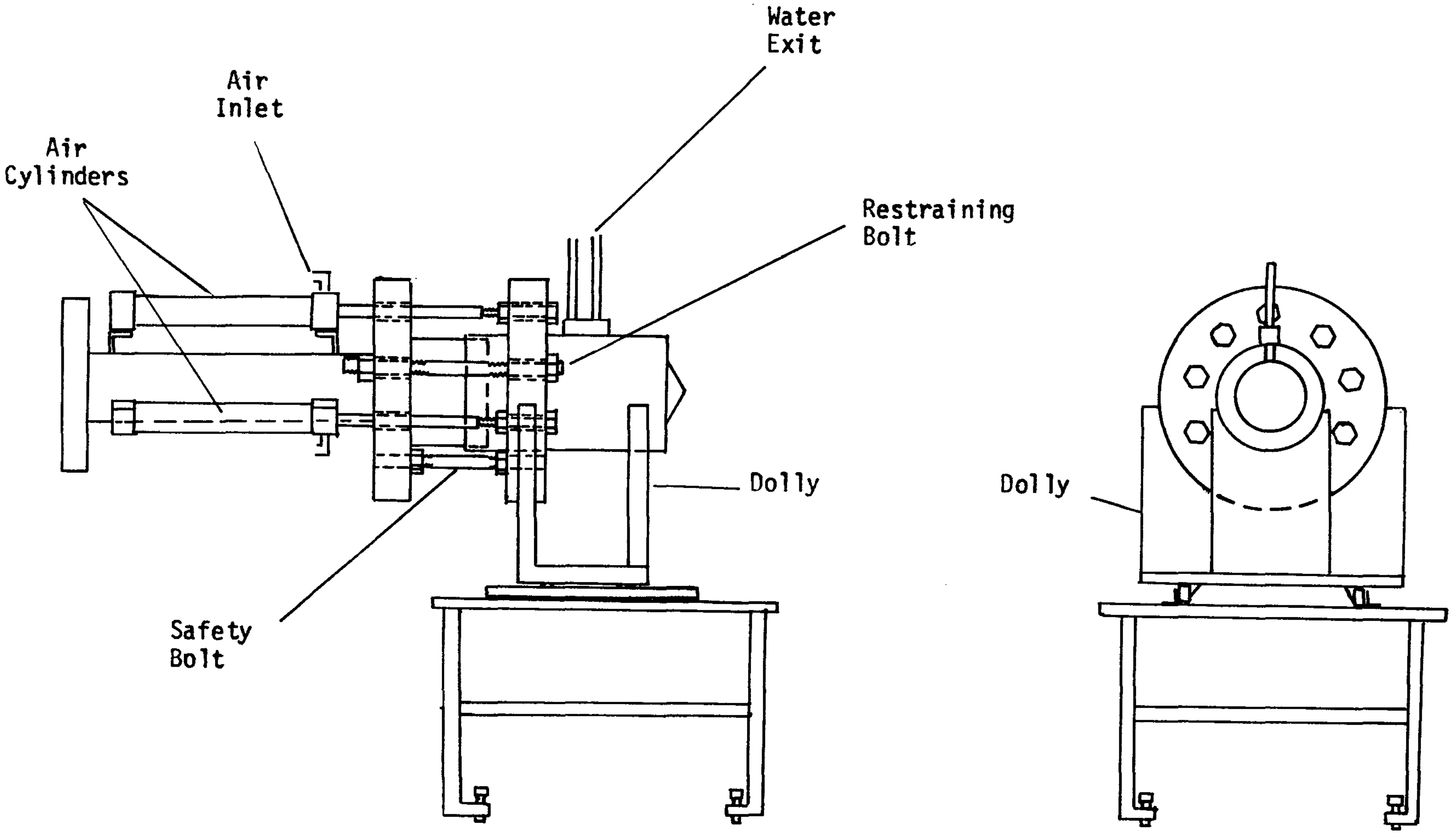

Fig. 16 Back-Pressure Valve System

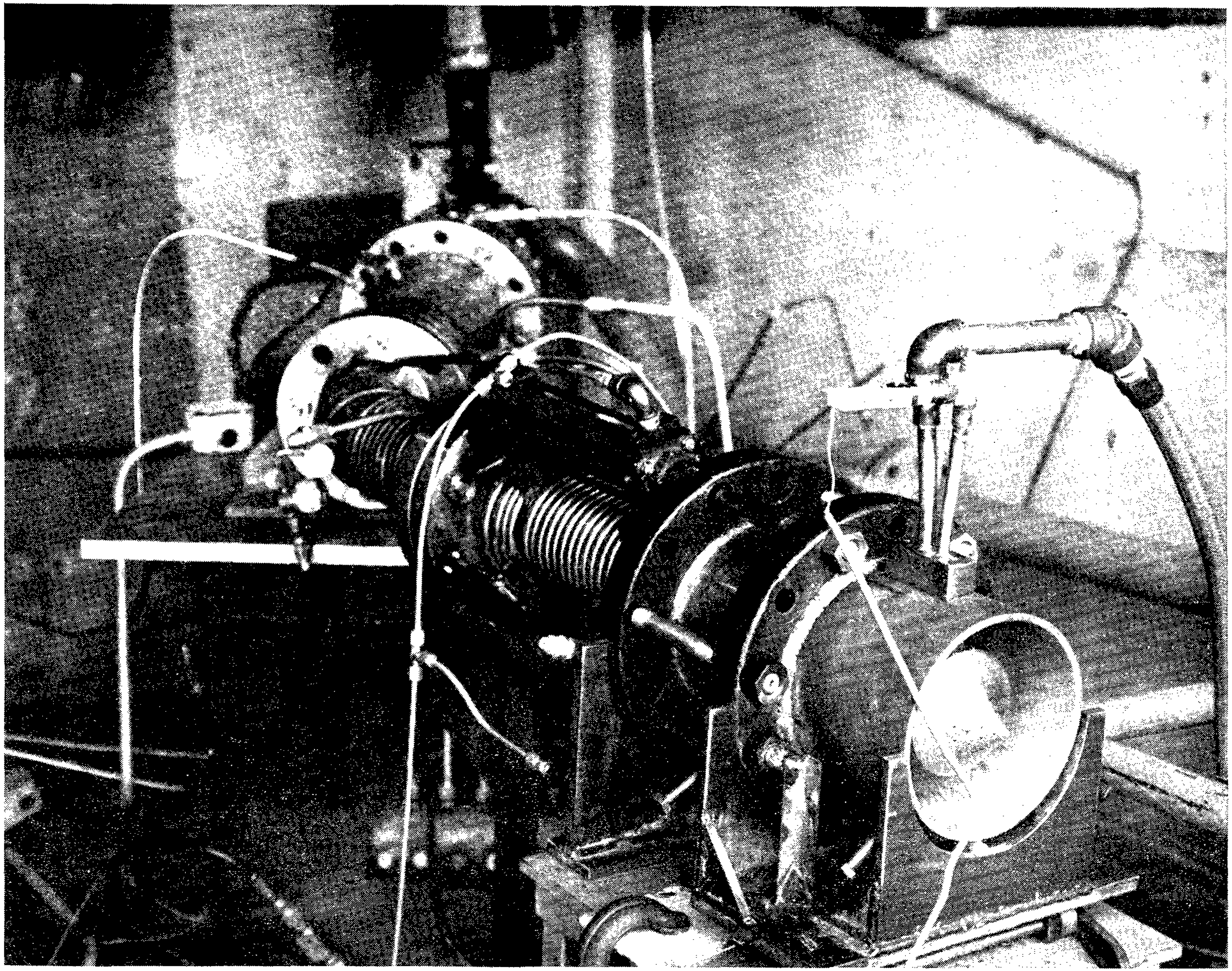

Fig. 17 Back-Pressure Valve

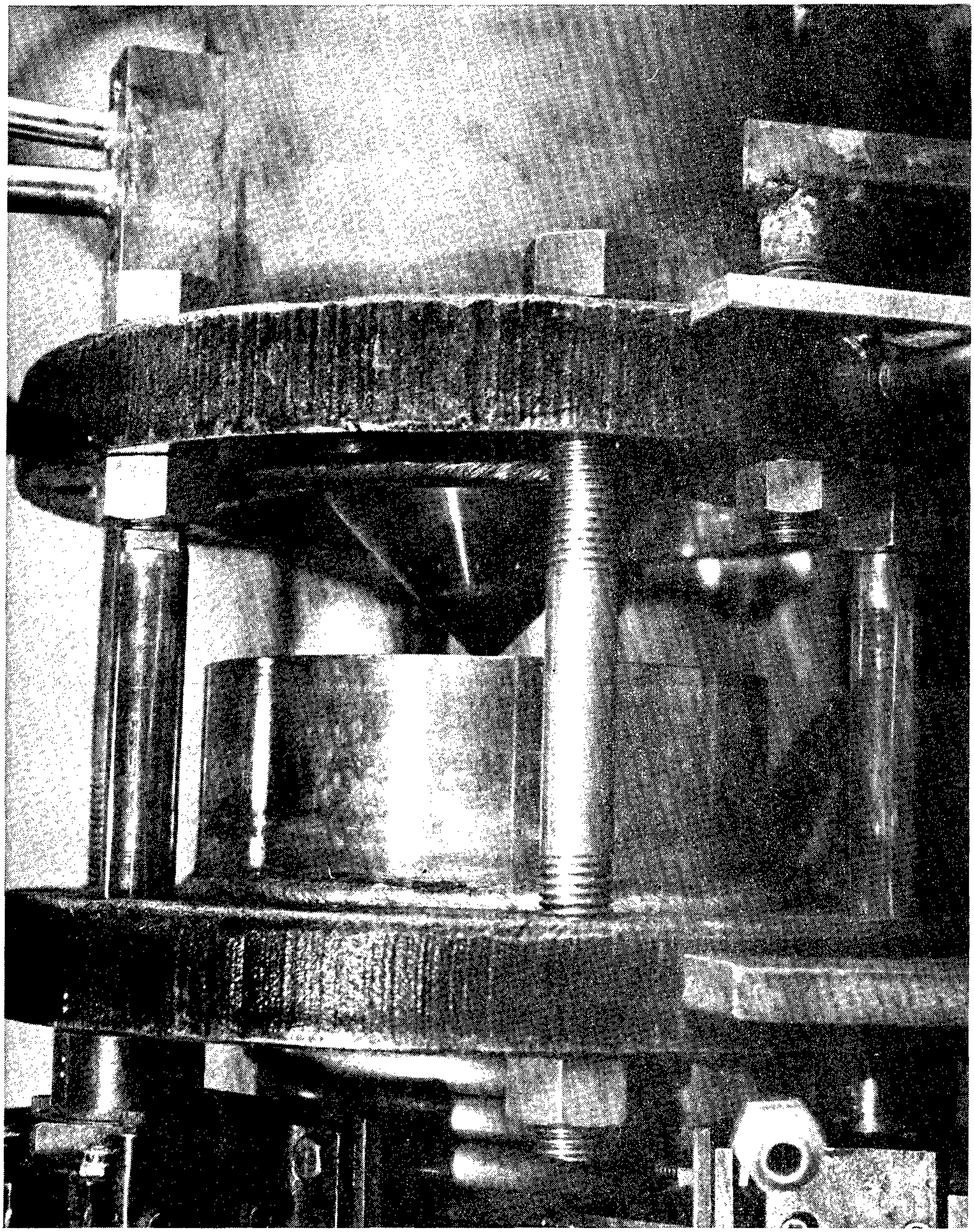

Fig. 18 Back-Pressure Valve Cone

must be used in aligning the system and many adjustment devices are incorporated for that purpose. In addition heavy springs have been placed over the piston rods between the exit flange of the transition section and the front flange of the translating section to overcome the jerky effects of starting friction in the air cylinders. The back-pressure valve system is presently fully operational.

H. Water System Description

In order to provide adequate cooling for the back-pressure valve system and the probes, a high pressure water system has been constructed and is shown schematically in Fig. 19. The total system has a capacity of approximately 200 gallons and can be pressurized up to 400 psi, since a high pressure capability is needed for successful cooling under high combustion chamber pressures. For the purpose of insuring satisfactory water flow control, a remotely controllable water throttle valve has been installed and found to function well. This valve was added to control combustion quenching problems due to back-pressure water flow into the combustor. The water system is controlled from the control room and is fully operational at this time.

I. Run Results To Date

Actual facility operation has been in progress to a certain degree for approximately six months. The purpose of these runs was primarily to thoroughly check out all systems under a wide range of operating conditions as the systems become available. To date all systems so far mentioned in this Chapter with the exception of the gas temperature and gas sampling probes have been thoroughly tested and found satisfactory. A secondary purpose of the runs so far completed was to obtain experience in facility operation. Due to the complexity of the overall experiment and the vast number of instruments which require continuous monitoring during any run, operation of the facility by one individual is not possible.

Average run duration to date has been approximately twenty minutes with a total run time of approximately eight hours. Normal test facility operating conditions are shown in Table 2.

Run conditions are selected in part from reference to Fig. 20 in

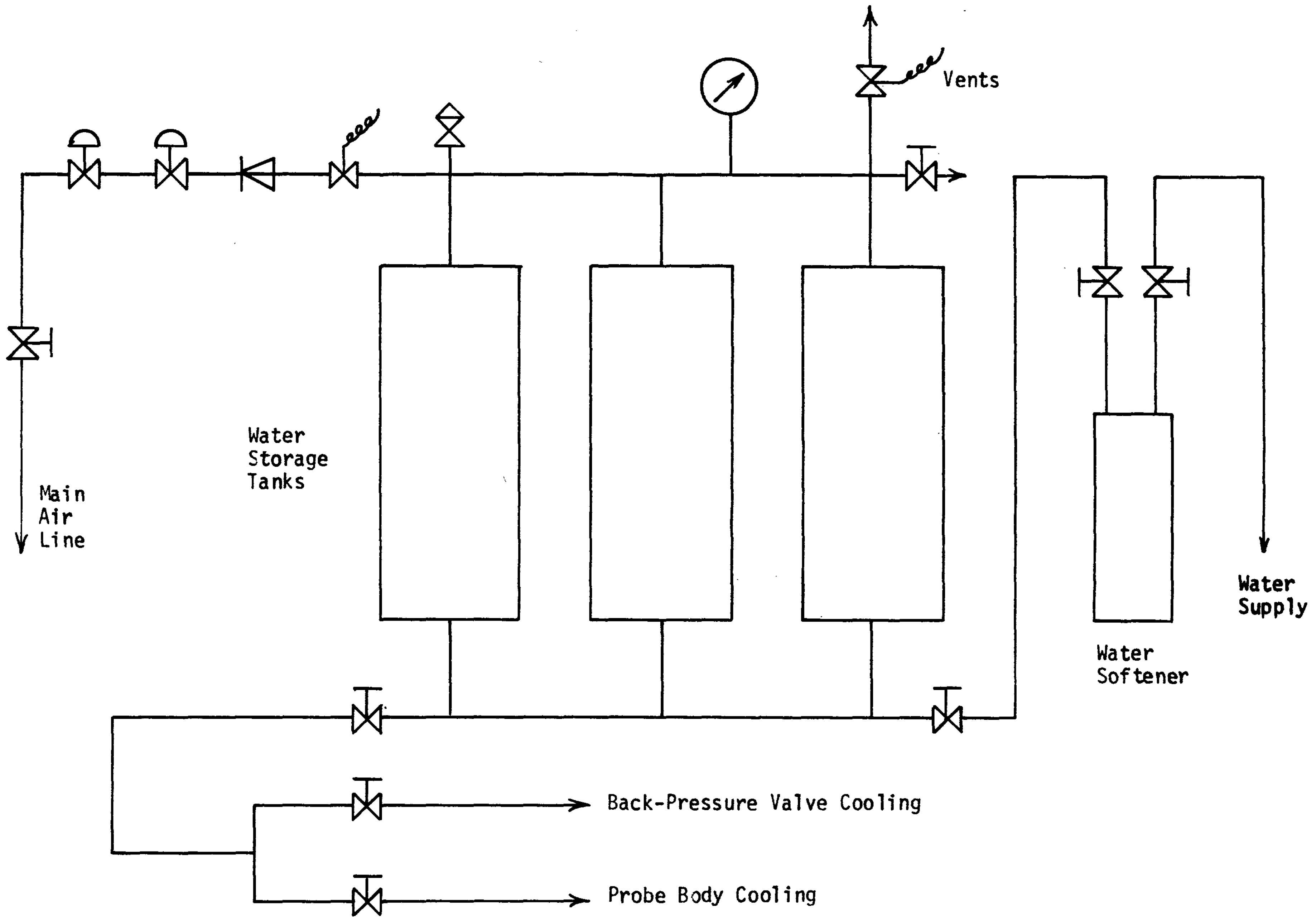

Fig. 19 Water System

Table 2.

Selected Normal System Operating Conditions To Date

Main Air Supply Pressure	1500-2500 psi
Instrument Air Pressure	200-300 psi
Fuel Storage Tank Pressure	250 psi
Fuel Delivery Tank Pressure	225 psi
Water System Supply Pressure	40 psi
Main Air Line Pressure	100 psi
Air Flow Differential Pressure	3-60 in Hg. (0-3 lb/sec)
Fuel Injection Pressure	100-220 psi
Combustor Pressure	1-3 atm
Average Run Time	20 min

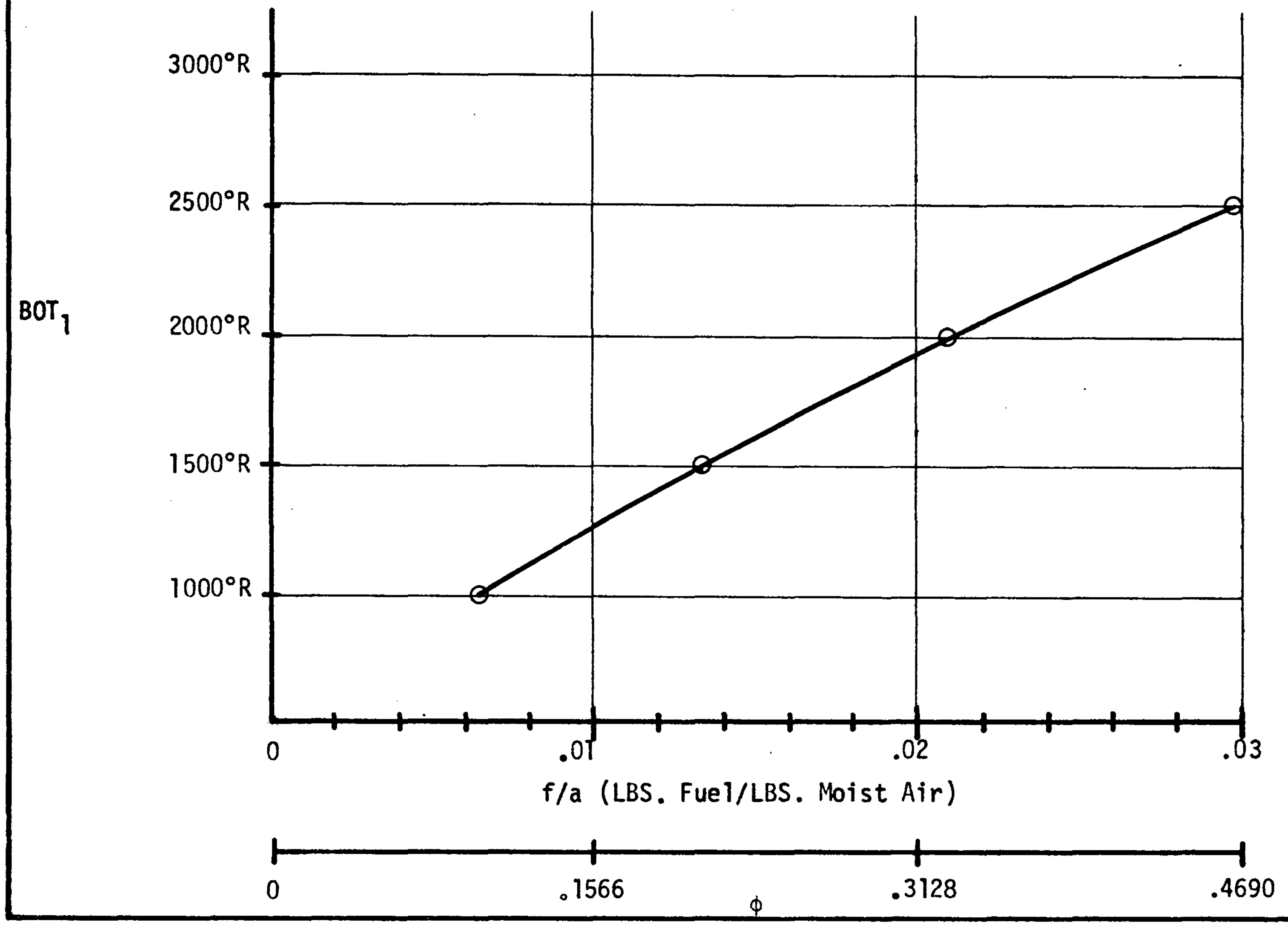

Fig. 20 Primary Combustor Outlet Temperature

which overall combustor fuel-air ratio and equivalence ratio is plotted against a calculated J-33 burner outlet temperature. The graph was constructed from a thermodynamic heat balance on the combustor and includes the effects of moisture in the inlet air, possible species dissociation, liquid propane injection, and variable combustor pressures.

J. Description of Future Runs with Present Engine Configuration

The basic engine configuration that exists presently (i.e., J-33 combustor + probe addition section + back-pressure valve system) will be used for internal gas temperature and gas sampling measurements for approximately the next four months. Table 3 presents in outline form the planned combustor operating parameter settings to be used and the data to be acquired over this period. These studies have commenced.

Table 3.

Future Plans for Present Test Configuration

Basic Configuration: J-33 combustor + probe addition section + back-pressure valve system

1) Test back-pressure valve over range 0-10 atm.
2) Test gas temperature probe (1 atm, low ϕ).
3) Make J-33 gas temperature measurements.
   a) $BOT_1^* \approx 1500°R \rightarrow f/a \approx .0138, \phi \approx .214$

      $BOT_2 \approx 1800°R \rightarrow f/a \approx .018, \phi \approx .282$

      $BOT_3 \approx 2100°R \rightarrow f/a \approx .022, \phi \approx .345$

   b) $\text{Air Flow}_1 \approx 1.5$ lb/sec

      $\text{Air Flow}_2 \approx 3.0$ lb/sec

   c) $P_{comb_1} \approx 1$ atm

      $P_{comb_2} \approx 5$ atm

      $P_{comb_3} \approx 10$ atm

   d) Combustor operating parameters will be set in the following sequence**
      i) air flow
      ii) combustor pressure
      iii) equivalence ratio
4) Reproduce all "step 3" runs.
5) Test Gas Sampling Probe (1 atm, low ϕ).
6) Make J-33 CO and NO measurements
   a) $BOT_1 \approx 1500°R \rightarrow f/a \approx .0138, \phi \approx .214$

      $BOT_2 \approx 1800°R \rightarrow f/a \approx .018, \phi \approx .282$

$BOT_3 \simeq 2100°R \rightarrow f/a \simeq .022, \phi \simeq .345$

b) Air $Flow_1 \simeq 1.5$ lb/sec

Air $Flow_2 \simeq 3.0$ lb/sec

c) $P_{comb_1} \simeq 1$ atm

$P_{comb_2} \simeq 5$ atm

$P_{comb_3} \simeq 10$ atm

7) Reproduce all "step 6" runs

---

*BOT = Burner outlet temperature.

** It is expected that data for three different data points can be taken per run.

CHAPTER III

PRESENT INSTRUMENTATION

The instrumentation assembled for this project can be conveniently divided into three broad classes. The first class consists of all instrumentation necessary for the safe and accurate control of all systems relating to the actual operation of the system. The discussion given to the particular type of instrumentation was covered in Chapter II. The second class of instrumentation includes all temperature monitoring systems assembled for the project. Only the presently installed and operational temperature sensing systems will be described. The final class of instrumentation required to meet the research objectives includes all composition monitoring equipment. These latter systems will be fully described in terms of theory of operation, measurement capability, and overall system layout.

A. Temperature Instrumentation

In order to provide experimental input for the analytical heat transfer study (Owens and Mellor, 1971), the J-33 flame tube has been outfitted with a series of thermocouples as previously mentioned (see Fig. 8). At present chromel-alumel thermocouples are positioned approximately one-half inch from the leading edge of selected cooling slots and primary and secondary air holes. The cold inlet air to the J-33 combustor has resulted in very low temperature readings which are felt to be more a measure of combustor annulus air temperature than flame tube temperature. In an attempt to obtain more meaningful measurements, the thermocouples will be relocated away from the cooling slots and air holes and actually embedded in the flame tube. It is felt that accurate flame tube temperature distributions can be obtained with the described thermocouple system changes.

All thermocouple measurements are made relative to a reference temperature of 0 °C which is maintained through use of an ice bath. A general schematic of the flame tube temperature sensing system is shown in Fig. 21.

In assition to the flame tube temperature measurement and temperature probe output, several other system temperatures are monitored. Temperature gauges mounted on the upper instrument control panel in the control room currently measure main air line, inlet air, back-pressure valve cone, fuel inlet, and combustor outlet temperatures. As the engine configuration is advanced additional temperature measurements will be required.

Currently, five Honeywell class 15 self-balancing potentiometers are available for flame tube and temperature probe measurements. Three of the five recorders have fixed 0-10 millivolt spans, while the remaining two recorders have adjustable 0-36 and 0-51 millivolt spans. As individual systems have become operational, the strip chart recorders have been used for various monitoring applications.

B. Emission Instrumentation

The planned method of gas sampling in the J-33 combustor has been previously explained. Obviously the choice of analytical instrumentation is critical to the success of the research.

The initial gas concentrations to be measured as a function of radial and axial position inside the J-33 combustor are CO and NO. CO concentration is a measure of combustion efficiency (see Hammond and Mellor, 1971), and NO is of interest from a pollution standpoint. The overall gas handling system and specific CO analyzer schematic is shown in Fig. 22. All lines, fittings, and components are stainless steel to guard against possible surface reactions as the sample is transported to the analyzer.

A Beckman Model 315 A (short path) NDIR will be used for continuous monitoring of CO concentration. The analyzer section of this instrument employs a stacked sample cell configuration with a 13-1/2 inch cell for a useful range of 0-250 ppm (without back-pressure), and a 1/8 inch cell for a range of 0-20%. In Fig. 22 it will be noticed that a back-pressure regulator appears in sample line number two. By increasing the analyzer pressure to approximately 75 psig through use of the back-pressure regulator, the sensitivity of the lower range can be improved to 0-100 ppm. Although increased back-pressure beyond the 75 psig limit

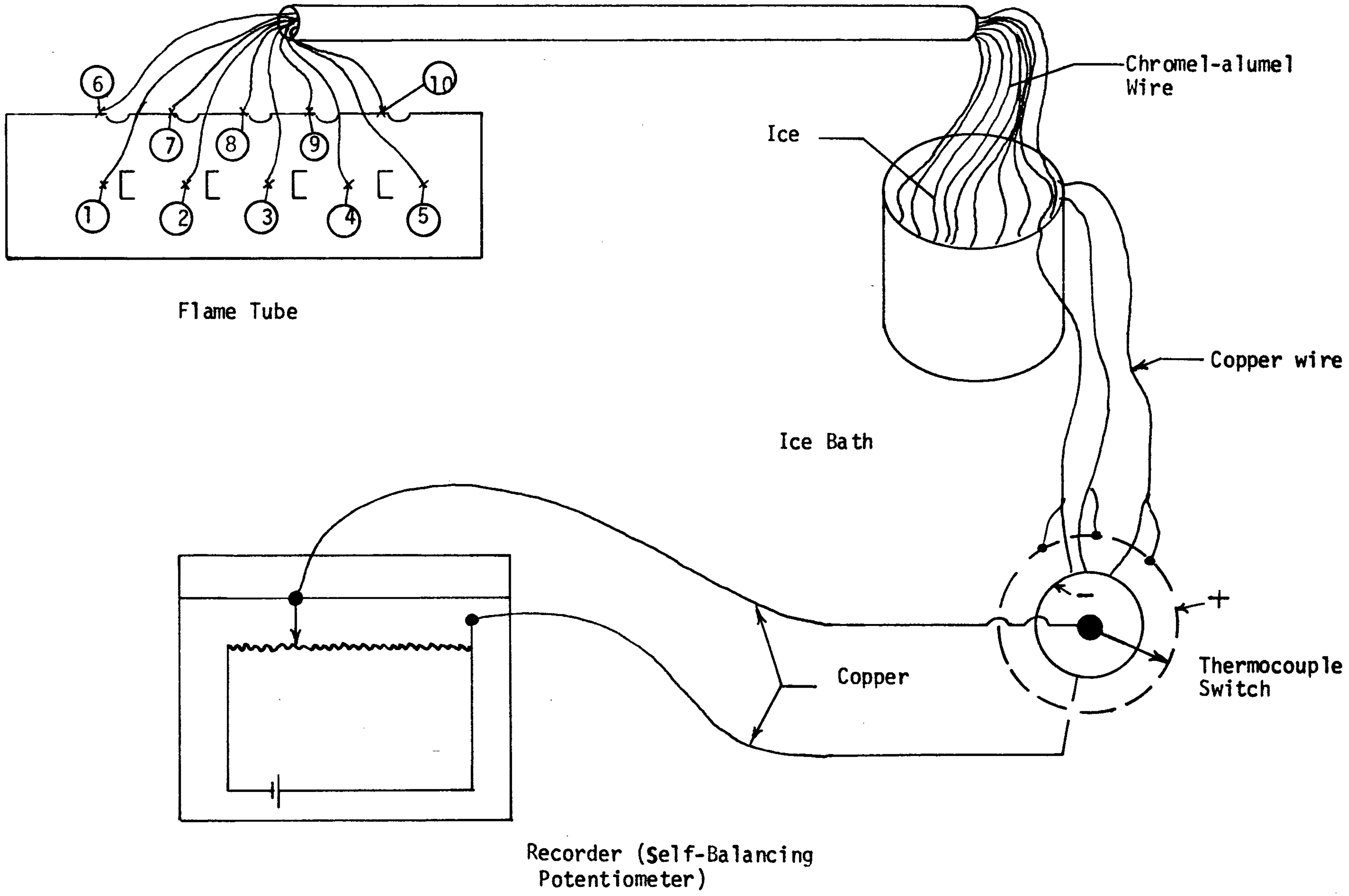

Fig. 21 Flame Tube Thermocouple Scheme

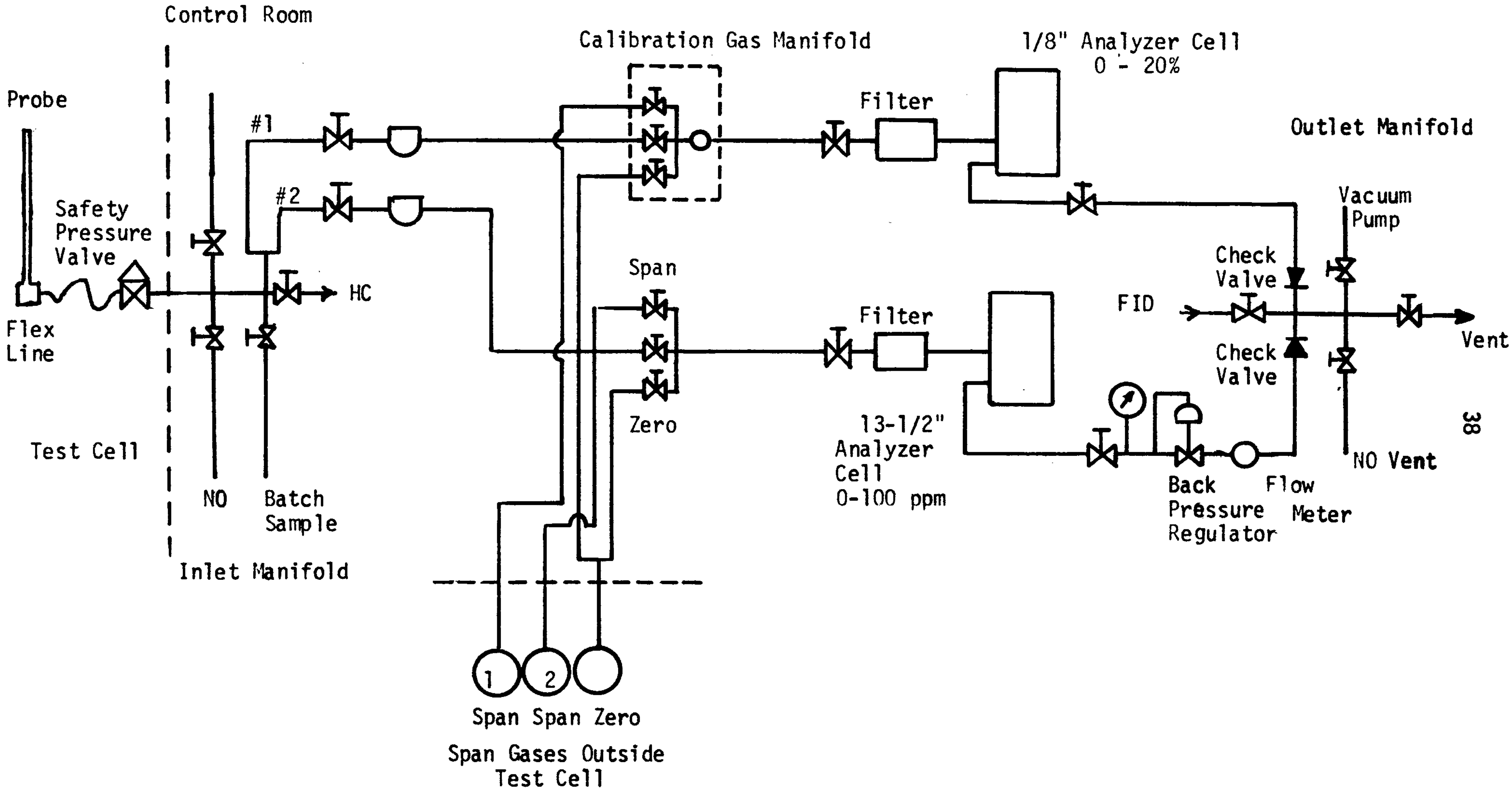

Fig. 22 CO Analyzer System

would result in increased instrument sensitivity, this pressure limit must be observed to prevent damage to the 1 mm sapphire infrared transmitting windows in the analyzer cell. Repeatability of the NDIR measurements is 1% of full scale reading for both ranges.

Condensate traps positioned in the sample line are reported by Beckman to eliminate the problem of water vapor interference on sampling measurement, but it should be mentioned that the presence of CO_2 in concentrations on the order of 300 ppm cause a 10 ppm CO measurement error.

The normal operating pressure for the CO analyzer system is 2-25 psig. A safety pressure valve inserted immediately downstream of the gas sampling probe limits the sample pressure to 25 psig. Above this pressure damage to the condensate traps would result. Because the gas sampling system has not yet been completed, sample flow rates have not yet been established. Although the analyzer is not flow sensitive, a normal sample flow would be approximately 2 cubic feet per minute. In the event that natural sample flow is not adequate for the proper functioning of the CO analyzer, a vacuum pump will be used.

The second gas component to be continuously monitored in the J-33 combustor is nitric oxide, NO. Continuous nitric oxide concentration will be measured using a chemiluminescent technique similar to that recently developed by Fontijn et al. (1969, 1970) of the Aerochem Corporation. The method involves the measurement of the light intensity of the chemiluminescent reaction between nitric oxide and ozone and provides continuous rapid analysis of the combustion products for NO capable of accurate measurement from 5 ppm to at least 100 ppm. A general schematic of the NO detector is given in Fig. 23.

The system is designed to couple maximum accuracy with easy usage. Both single point and variable calibration schemes may be used. Single point calibration is accomplished by flowing a span gas with a known concentration through the system. With this type of calibration appropriate scale factor settings can be obtained on the readout instrumentation. Span type calibration plots may be obtained through the injection of a known volume of a fixed NO concentration sample gas into the exponential dilution flask while pure nitrogen flows through the system. The concentration of nitric oxide inside the dilution flask will vary according to the equation:

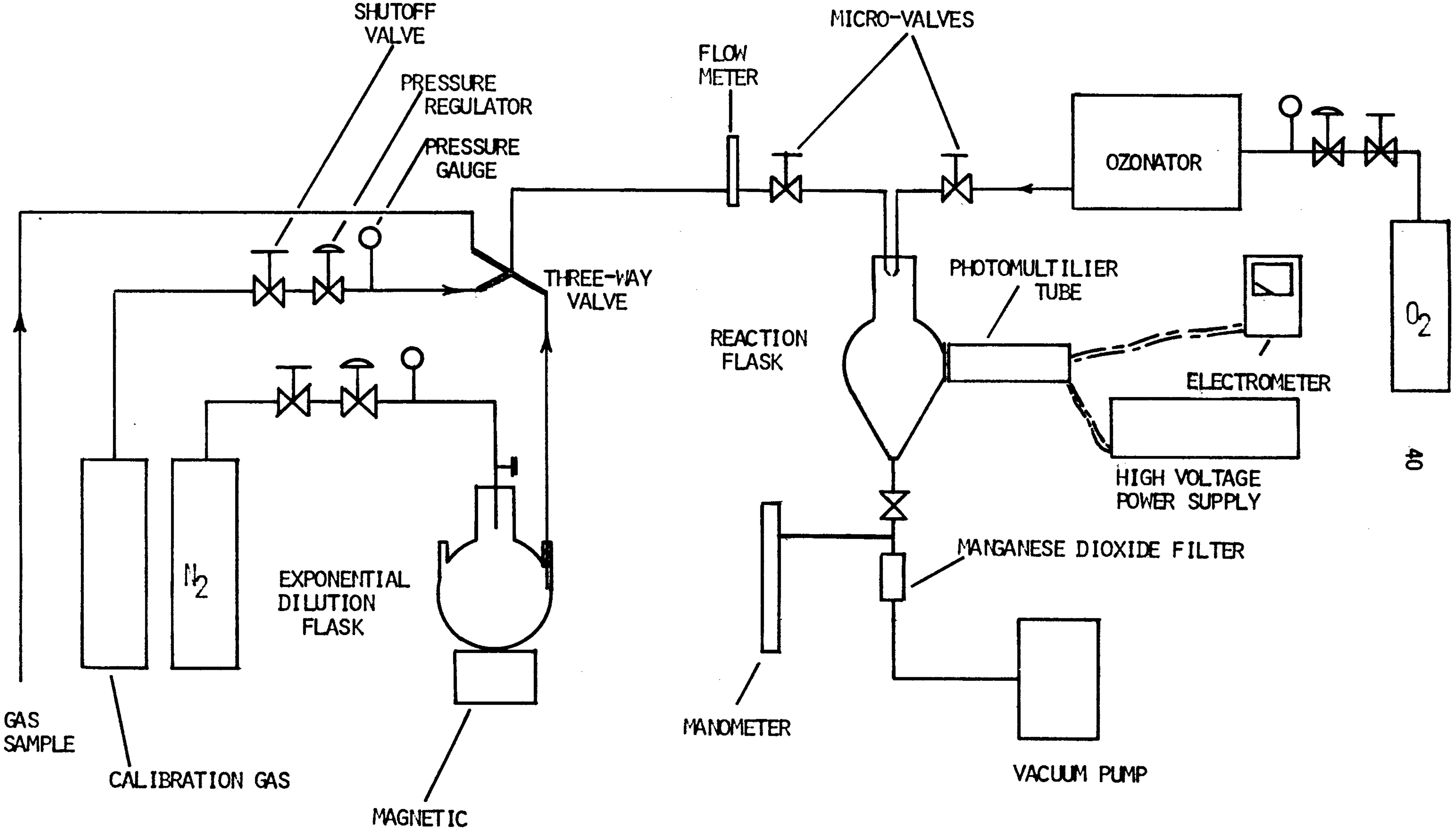

Fig. 23 NO System

$$C = C_0 \exp(-Q\, t/V)$$

where

C_0 = initial concentration of the injected sample

Q = volume flow rate

V = dilution flask volume

t = time

Therefore, the obtained concentration readout, when plotted vs. time on a semi-log scale, is linear and provides a range of calibrations.

In large part responsible for the great accuracy inherent in this type of NO measurement is the relatively complete lack of interference of other sample gas constituents upon NO detection. Table 4 presents data taken by Fontijn et al. (1969, 1970) which illustrate this remarkable quality.

The NO detector as shown in the schematic has been completed. Present efforts are being directed toward complete calibration of the device.

In addition to the CO and NO systems, batch samples can be taken and Orsat apparatus used for combustion gas analysis.

Table 4.

NO Interference Data

(after Fontijn et al., 1969, 1970)

Constituent	Max Concentration Generally Encountered in Air Quality Monitoring, ppm	Concentration Used at which NO Interference Was Detected at NO $\leq$ 10 ppb, ppm
NO_2	3	9
CO_2	500	650
CO	100	300
C_2H_4	1	5
NH_3	3	9
SO_2	3	25
H_2O	100% Saturation	75% Saturation

CHAPTER IV

FUTURE ADDITIONS TO THE TEST FACILITY

All descriptions in the previous Chapters have been concerned with the experimental facility as it currently exists. In this Chapter future plans for the test facility will be presented.

It must be remembered that the study of high inlet temperature combustion is the primary function of the test facility. In order to accomplish this objective the J-33 combustor will be used as a heating combustor to provide high temperature inlet air for a second test combustor. Placed between the heating combustor and the test combustor will be an oxygen addition section. The purpose of this section is simply to replentish oxygen consumed in the heating combustor. Internal probing of the test combustor will be done in a manner similar to that described for the J-33 combustor to obtain gas temperature and gas sampling measurements as a function of axial and radial position. A general schematic of the future experimental facility is shown in Fig. 24.

A. Oxygen Addition Section Description

The oxygen addition section will be a constant diameter, water cooled, stainless steel section constructed so as to mate with the exit plane of the primary (J-33) combustor. Around the circumference of this section close to the front flange will be mounted an annular oxygen injection manifold. From this annulus the oxygen will be injected into the flowing exhaust gas stream through several very small penetration holes. The actual size of the penetration holes and the oxygen injection pressure will be optimized to insure good oxygen jet penetration and concomitant good mixing. Near the outlet of the oxygen addition section a permanent probe will be mounted for the continuous monitoring of outlet temperature. The rear flange of this section will be designed to mate with either the

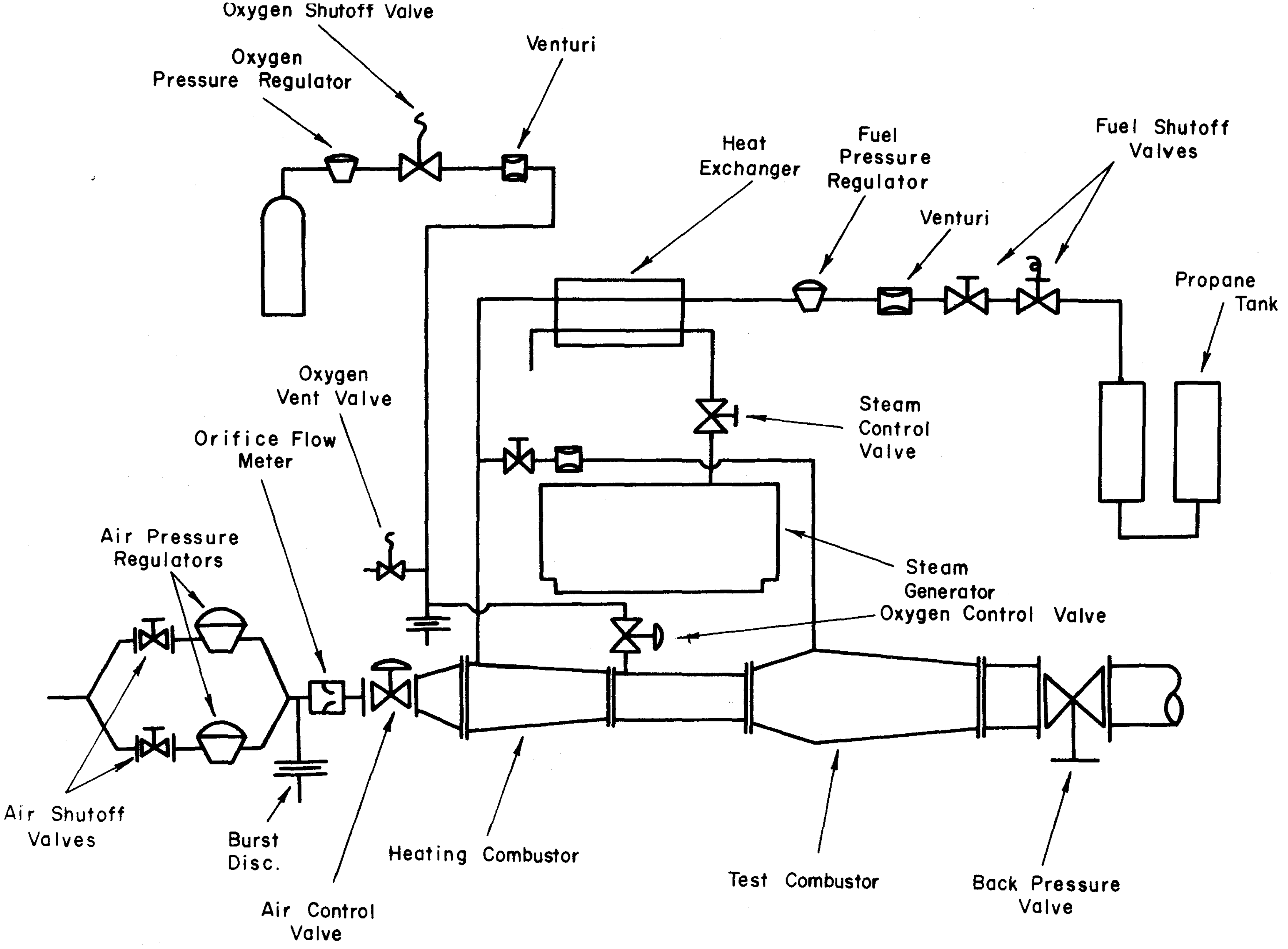

Fig. 24 Future Test Facility

probe addition section or the front flange of the test combustor casing.

Both the oxygen addition section and the oxygen delivery system are shown in Fig. 25. The delivery system has been designed to insure the greatest possible safety for equipment and personnel; the solenoid and manual vents, check valves, and manual control room operated oxygen flow shut-off valve have been incorporated for that purpose. All lines and fittings will be stainless steel and will be thoroughly cleaned before installation. It is anticipated that construction of the entire oxygen addition system will be completed by June 15, 1971.

B. Test Combustor Description

The Boeing 502-2E combustor has been selected as the first test combustor. This selection was based on two main considerations: firstly, through the Army Tank-Automotive Command, replacement combustors have been made available in the event of a flame tube failure (the likelyhood of flame tube failure is, of course, much greater for the test combustor than the heating combustor due to the high inlet temperatures seen by the test combustor). The second consideration responsible for the selection of the Boeing 502-2E can is the extremely simple combustor design used in this flame tube. Such simplicity makes preliminary analytical studies somewhat easier and also lends itself to straightforward combustor modification. Although this latter requirement is not immediately important, it is hoped that in the latter stages of the research program analytical suggestions for improved combustor design can be verified experimentally, and thus a simple combustor design like that of the Boeing 502-2E combustor is desirable.

All necessary combustion supporting equipment for the Boeing 502-2E can, such as the fuel nozzle and the ignition system, have been received. The front flange of the test combustor casing will be designed to mate with the rear flange of the oxygen addition section and the rear flange of the test combustor section will mate with the front flange of the probe addition section. It is anticpated that construction of the test combustor section will be completed by July 15, 1971.

C. Gaseous Propane Injection System Description

During all main phases of the research program liquid propane will

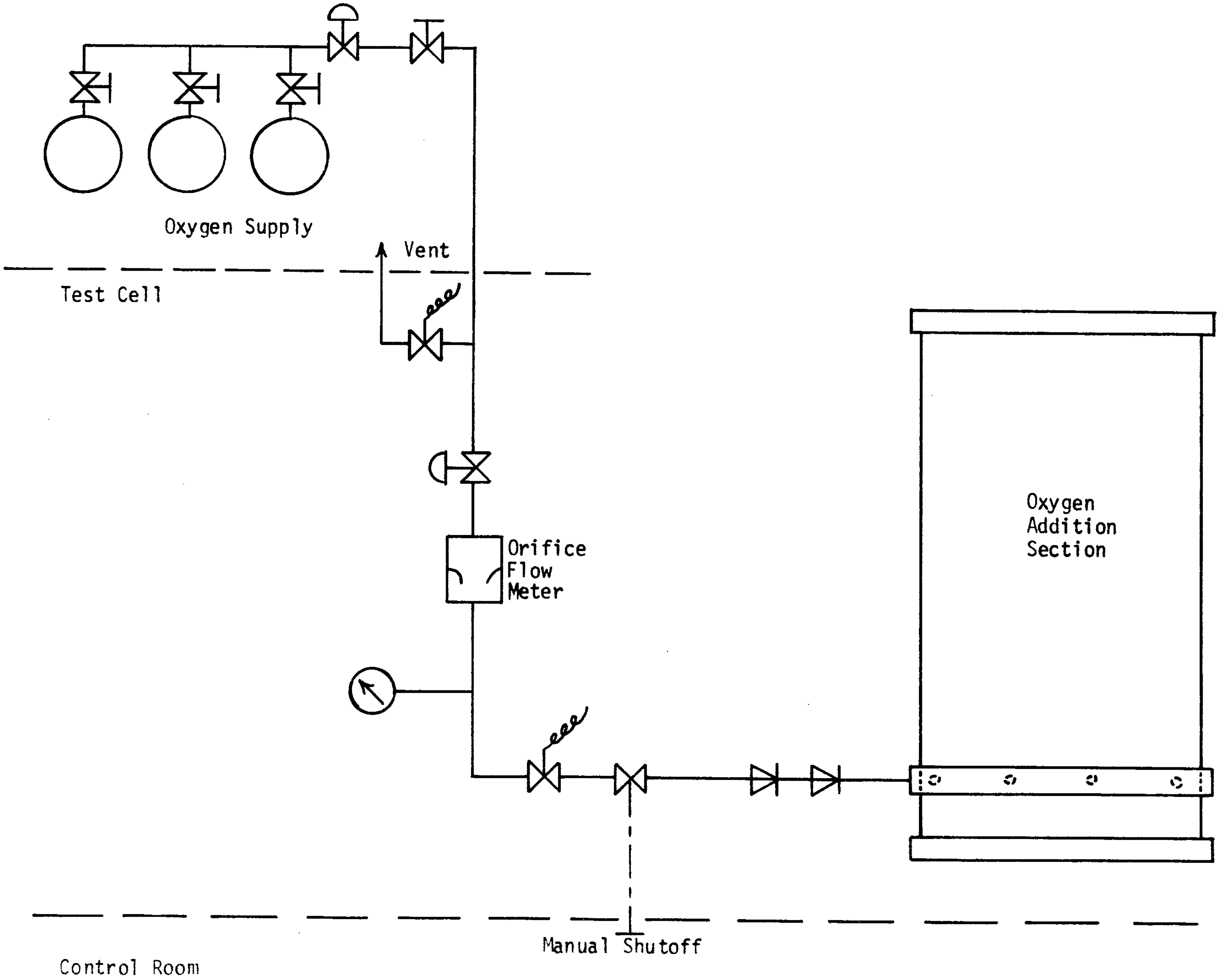

Fig. 25 Oxygen Addition System

be used. It has been reported in the literature, however, that gaseous fuel injection has a significant effect on stability and pollutant emissions. Through the courtesy of the Dow Chemical Company a 17,000 lb/hr Besler steam generator, Model 6X, has been obtained. This steam generator can be used to feed a heat exchanger into which liquid propane will flow and be vaporized. It is not anticipated, however, that such studies will be undertaken during the third contract year.

D. Future Analytical Instrumentation

In addition to CO and NO concentration monitoring, total hydrocarbon measurements will be made at the exit plane of the oxygen addition section and at various axial and radial positions inside the Boeing 502-2E combustor. For the continuous hydrocarbon concentration monitoring which is required either the Beckman Model 400 or Model 402 flame ionization detector will be used. The particular instrument to be used will be selected and purchased with funds provided under contract with the Environmental Protection Agency. It is anticipated that the hydrocarbon analyzer system will be operational by June 15, 1971.

E. Discussion of Future Engine Configurations and Run Objectives

Over the next contract year various engine configurations will be tested. Table 5 presents in outline form the planned Boeing test combustor operating parameter settings to be used and the data to be acquired in future runs. Run conditions have been selected in part from reference to Fig. 26 in which is plotted overall test combustor fuel-air ratio and equivalence ratio against a calculated Boeing 502-2E burner outlet temperature for various values of the burner inlet temperature. This graph was calculated from a thermodynamic heat balance on the combustor and includes the effects of moisture in the inlet "air", species dissociation, liquid propane injection, and variable combustor pressures.

Table 5.

Future Engine Configurations and Run Conditions

Configuration I: J-33 combustor + O_2 addition section + probe addition section + back-pressure valve system

1) Test oxygen addition section

2) Make O_2 addition section exit plane gas temperature measurements

   a) $BOT_1 \approx 1500°R \rightarrow f/a \approx .0138,\ \phi \approx .214$

      $BOT_2 \approx 1800°R \rightarrow f/a \approx .018,\ \phi \approx .282$

      $BOT_3 \approx 2100°R \rightarrow f/a \approx .022,\ \phi \approx .345$

   b) $\text{Air Flow}_1 \approx 1.5$ lb/sec

      $\text{Air Flow}_2 \approx 3.0$ lb/sec

   c) $P_{comb_1} \approx 1$ atm

      $P_{comb_2} \approx 5$ atm

      $P_{comb_3} \approx 10$ atm

3) Reproduce all "step 2" runs

4) Make O_2 addition section exit plane CO, NO, and HC measurements

   Use J-33 combustor operating parameter settings outlined in Step 2 above.

5) Reproduce all "step 4" runs.

Configuration II: J-33 combustor + O_2 addition section + 502-2E combustor

Generally test system

Configuration III: J-33 combustor + O_2 addition section + 502-2E combustor + probe addition section + back-pressure valve system

1) Generally test system (include back-pressure valve test over range 0-10 atm)

2) Test gas temperature probe (1 atm, low ϕ)

3) Make 502-2E gas temperature measurements

    a) from assembled data select appropriate heating combustor operating parameter settings including a large test combustor burner inlet temperature range

    b) For various test combustor burner inlet temperatures vary test combustor fuel-air ratio, pressure, and air flow in a manner similar to that described in Configuration I (see Fig. 26 for possible variation of test combustor equivalence ratio)

4) Reproduce all 502-2E gas temperature measurement runs

5) Make 502-2E NO, CO, and HC measurements

    Duplicate all runs for which 502-2E gas temperature measurements were made.

6) Reproduce all 502-2E gas sampling measurements

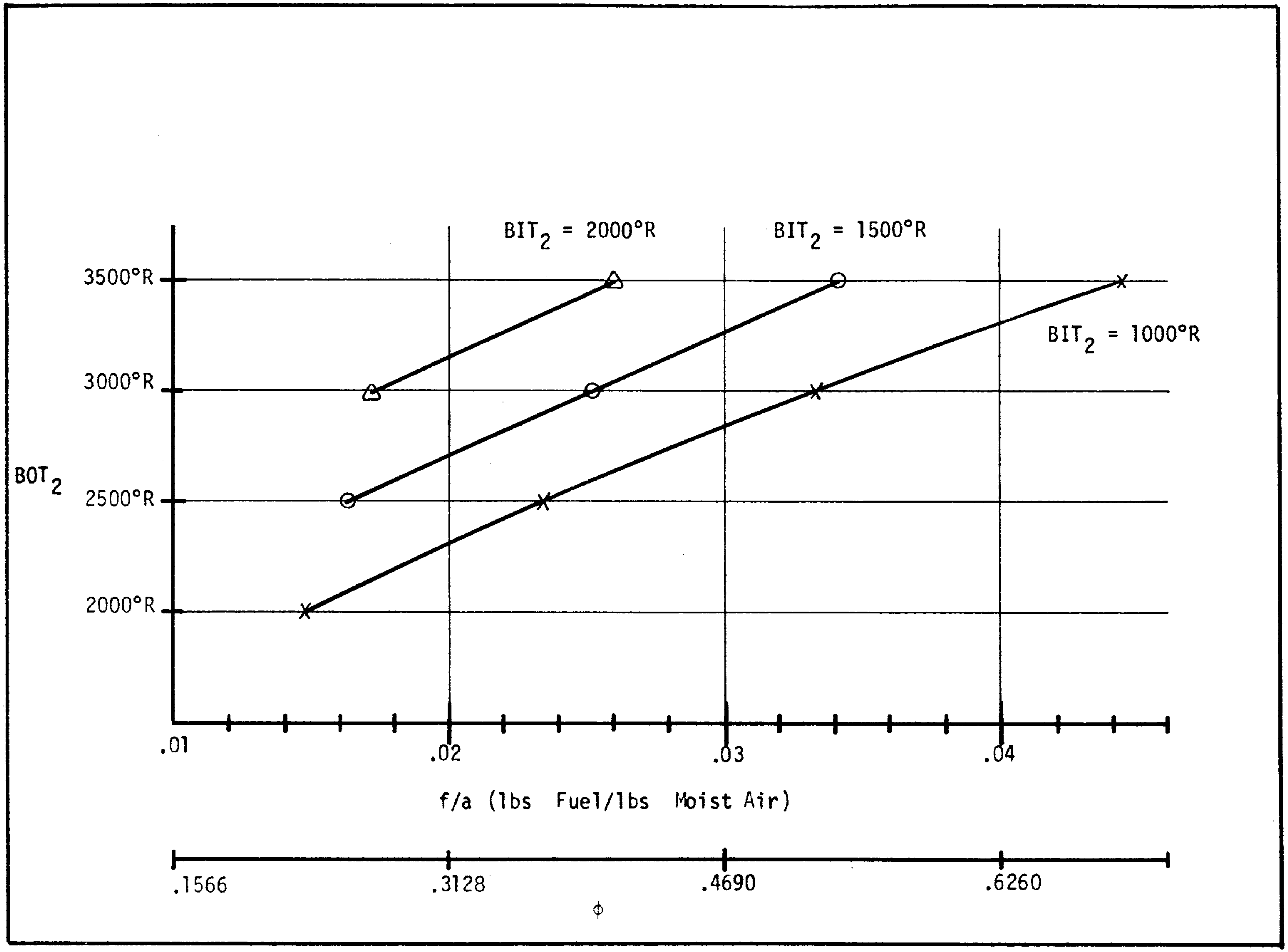

Fig. 26 Test Combustor Outlet Temperature

CHAPTER V

CONCLUSIONS

The experimental facility development is proceeding as scheduled. It is anticipated that all program objectives can be realized. The present facility as described in Chapters II and III has been tested and considered to have performed satisfactorily to date. A plan for future use of the present experimental facility has been outlined and explained in Chapter III. Currently assembled engine, temperature, and composition monitoring equipment has been described in Chapter III. All future engine configurations and run plans have been presented and explained in Chapter IV.

It is anticipated that within the next contract year significant progress will be made in comparing experimental data from the facility with the analytical combustor modelling and heat transfer portions of the program.

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
JET PROPULSION CENTER
PURDUE UNIVERSITY

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
AN INVESTIGATION OF GAS TURBINE COMBUSTORS WITH HIGH INLET AIR TEMPERATURES, PART III: EXPERIMENTAL DEVELOPMENTS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
ANNUAL REPORT MARCH 1970 to MARCH 1971

5. AUTHOR(S) *(First name, middle initial, last name)*
Richard D. Anderson
Arthur M. Mellor

6. REPORT DATE
March 1971

7a. TOTAL NO. OF PAGES
52

7b. NO. OF REFS
6

8a. CONTRACT OR GRANT NO.
DAAE07-69-C-0756

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
TM-71-3

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
11322

10. DISTRIBUTION STATEMENT
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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
U. S. Army Tank-Automotive Command
Propulsion Systems Laboratory
Warren, Michigan

13. ABSTRACT

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

UMCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gas Turbine Combustor Design						
Gas Turbine Emissions						
Internal Probing of a Gas Turbine Combustor						

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Security Classification