XVI. LABORATORY STUDIES OF LEAN COMBUSTION

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Current gas turbine combustors deliver a lean mixture of combustion products, at an equivalence ratio of 1/3 or less, to the turbine. In all cases, however, most of the combustion occurs in a highly backmixed region, the primary zone, where the equivalence ratio is approximately 1 (fig. XVI-1). The combination of rapid fuel evaporation and reaction brought about by the high temperature of stoichiometric combustion and the strong recirculation of the primary zone ensures the stability of the combustion process over a wide range of engine operating conditions. Completion of the oxidation of the hydrocarbon fuel is ensured by maintaining a minimum residence time in the combustor. In addition to providing a high combustion efficiency, it is important that the combustor deliver gases of uniform temperature profile to the turbine.

Unfortunately, the combustor conditions and constraints described can lead to the emission of undesirable pollutants. In practically all cases the fuel is delivered to the primary zone as a liquid and the possibility of soot formation exists. The high temperature of the stoichiometric primary zone leads to high levels of nitric oxide. Any failure to attain high combustion efficiency, as occurs at off-design conditions, especially idle, results in the emission of carbon monoxide and unburned hydrocarbons.

A departure from conventional combustor design to a premixed-prevaporized, lean combustion configuration (fig. XVI-2) is attractive for the control of oxides of nitrogen and smoke emissions; the promotion of uniform turbine inlet temperatures; and, possibly the reduction of carbon monoxide and hydrocarbons at idle. The dramatic reduction in oxides of nitrogen that can be obtained is shown in figure XVI-3. The realization of these potential gains depends, however, on overcoming several substantial problems that

premixed-prevaporized lean combustion introduces. Potential problem areas include

(1) Preparation of the premixed-prevaporized, fuel-air mixture
(2) Prevention of flashback or preignition in the premixing section
(3) Realization of full oxides of nitrogen reduction if less than perfect premixing can be obtained
(4) Maintenance of combustion stability over a wide range of operating conditions
(5) Reignition should blowout occur under extreme operating conditions
(6) Obtaining high combustion efficiency in very lean mixture combustion, especially near cool walls

Primarily experimental studies conducted at the University of California have focused on problem areas 3, 4, and 6 and have included the development of new laboratory combustors and the application of new diagnostic tools to the observation of the fundamentals of the lean combustion process. This work, conducted under NASA sponsorship for the past 30 months (Grant NSG-3028), has come under the direction of four faculty investigators: Professors M. C. Branch (who is now at the University of Colorado), J. W. Daily, A. K. Oppenheim, and R. F. Sawyer. Graduate research students in the Department of Mechanical Engineering have made substantial contributions to this work. Publications resulting to date from this on-going program are identified in the references listed at the end of this paper (refs. 1 to 7).

The objective of the research conducted at the University of California has been the observation and understanding of the fundamental processes controlling lean combustion, with particular emphasis on the formation and measurement of gas-phase pollutants, the stability of the combustion process (blowout limits), methods of improving stability, and the application of probe and optical diagnostics for flow-field characterization, temperature mapping, and composition measurements. Four areas of investigation will be described in greater detail:

(1) Axisymmetric, opposed-reacting-jet-stabilized combustor studies
(2) Stabilization through heat recirculation
(3) Two-dimensional combustor studies
(4) Spectroscopic methods

AXISYMMETRIC, OPPOSED-REACTING-JET-STABILIZED
## COMBUSTOR STUDIES

An opposed-reacting-jet (ORJ) combustor configuration operating at a pressure of 1 atmosphere and inlet temperatures up to 600 K was employed (fig. XVI-4). A premixed propane-air stream was stabilized by a counter-flowing jet of the same reactants. The resulting intensely mixed zone of partially reacted combustion products stabilizes combustion at equivalence ratios as low as 0.45 (fig. XVI-5). Such a flow field has the dual advantages of being similar to that found in the recirculation zone of many full-scale gas turbine combustors and of providing control over those parameters such as equivalence ratio and inlet temperature that most strongly affect pollutant formation. Measurements were taken over a range of equivalence ratios from 0.45 to 0.625 and at inlet temperatures from 300 K to 600 K. Concentration profiles were obtained throughout the combustion zone by using a partially cooled quartz sampling probe. Measurements included NO, NO_2, C_3H_8, CO_2, CO, H_2O, O_2, and N_2 (fig. XVI-6). Temperatures were measured with a coated fine-wire thermocouple. The effects on blowout limits of jet velocity (fig. XVI-7) and main stream inlet temperature (fig. XVI-8) were observed.

The resulting pollutant emission levels and combustion efficiencies are compared with two typical jet aircraft engines in table XVI-1. Emissions levels in the ORJ approached those of a theoretical well-stirred-reactor model. Unburned hydrocarbon and CO levels can be reduced further and efficiency improved through use of residence times longer than those available in the present experiments. It is concluded that fuel-lean premixed combustion is an effective method of achieving low NO_x emissions and high combustion efficiencies simultaneously.

Under conditions promoting lower flame temperature, NO_2 constituted up to 100 percent of the total NO_x. At higher temperatures this percentage decreased to a minimum of 50 percent. Problems of probe reactions may account for some of the NO_2 that is observed at the chemiluminescent analyzer.

The theoretical part of this investigation was based on a numerical finite difference approach to the solution of the governing partial differential equa-

tions for an elliptic flow field. A simplified kinetic model for propane com-
bustion was developed and used. This approach involved the two-step global
mechanism

$$C_3H_8 \longrightarrow CO + H_2O \tag{1}$$

$$CO \longrightarrow CO_2 \tag{2}$$
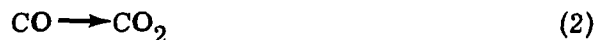
A kinetic rate expression for propane disappearance, step 1, was derived
based on average residence times and experimental composition and tem-
perature measurements. A global rate expression for CO oxidation, step 2,
was taken from the literature. Agreement between predicted results from
this idealized analytical model and experimental results is shown in fig-
ure XVI-9. Predicted and experimental NO_x concentrations agreed within a
factor of 2. Discrepancies were found to be the result of the simplified kinetic
and fluid mechanic approximations used.

STABILIZATION THROUGH HEAT RECIRCULATION

Heat recirculation is a means of avoiding the high temperatures that
produce oxides of nitrogen in diffusion flames. The method employs the hot
products of combustion to heat the incoming premixed fuel and air. This re-
circulation of heat would ideally take place in the combustion chamber of a
gas turbine engine, without mixing the reactants and products, by means of
a heat exchanger. Hardesty and Weinberg (ref. 8) have demonstrated that
with enough preheating almost any fuel-air mixture will burn.

A preliminary feasibility study (ref. 2) of a gas turbine combustor that
would employ a metal-louvered-plate fin counterflow heat exchanger
(fig. XVI-10) defined the following operating parameters:
(1) Combustor inlet temperature, T_1, 600 K
(2) Combustor pressure, P_1, 3.0 atm
(3) Reference velocity, V, 20 m/sec
(4) Equivalence ratio, φ, 0.2

(5) Preheat temperature, T_2, 1200 K

(6) Mass flow rate, 0.3 kg/sec

The model assumed that air leaving the engine's compressor at 3.0 atmospheres would be premixed with methane to an equivalence ratio of 0.2 and enter the combustor heat exchanger at a temperature of 600 K. The fuel-air mixture would be heated to 1200 K before combustion and then produce an adiabatic flame temperature of 1660 K. These gases would then pass through the hot side of the heat exchanger and be cooled to 1100 K before entering the gas turbine. If the methane and air had been burned as a diffusion flame ($\varphi = 1.0$) and then quenched with excess air to bring the overall equivalence ratio down to 0.2, as is now the practice, the exit temperature would have been the same (1100 K) but the adiabatic flame temperature would have been over 2500 K.

Experiments were conducted using a glass ceramic heat exchanger that employed hot exhaust gases to heat a lean methane-air mixture to a temperature where combustion takes place. It was demonstrated that the underlying principle is sound but that material properties are the limiting factor to future gas turbine engine applications. Stable burning at an equivalence ratio of 0.4 was achieved with NO_x emissions of less than 2 ppm.

TWO-DIMENSIONAL COMBUSTOR STUDIES

The axisymmetric geometry of the opposed-jet-stabilized combustor is not well suited to optical observation. Accordingly, a two-dimensional combustor facility has been designed, fabricated, and tested (fig. XVI-11). Operational characteristics are summarized in table XVI-2. Windows on the side walls provide full optical access to the combustion process. Facility checkout has been conducted with a propane-air diffusion flame (fig. XVI-12). Mapping of the flow field is done with thermocouple, pressure (velocity), and extractive (gas analysis) probes. Data on the flow-field temperature profile and combustor stability are shown in figures XVI-13 and XVI-14. An important part of the checkout phase of this facility has been the obtaining of high-speed motion pictures of the combustion process. The relatively stable appearance of the flame as observed visually is misleading. High-speed

motion pictures (taken using the light emitted by the flame; framing speeds to 2500 Hz) show the oscillatory nature of the combustion and apparent periodic reignition of portions of the flame. Color schlieren motion pictures (framing speed of 6500 Hz) provide even greater detail of the combustion process.

The major experimental effort will involve a premixed injector configuration installed in the same test facility (fig. XVI-15). The flow is to be stabilized by a recirculation region in the wake of a step. Initial experimental objectives call for the temperature, velocity, and composition mapping of the flow field using probing methods, flow-field visualization through high-speed motion pictures, establishment of blowout characteristics, and observation of the transient behavior at blowout. Major experimental parameters are the equivalence ratio, reference velocity, and inlet temperature. This characterization of the combustion processes will also provide a base for comparison and evaluation of optical methods to be applied later.

SPECTROSCOPIC METHODS

The advantages of in situ optical diagnostics over conventional probe methods is obvious. We have the capability to use and have developed a number of techniques in our laboratory for measuring various gas properties. These include conventional absorption spectroscopy for measuring radical species concentrations, the line reversal technique for temperature (refs. 9 and 10), two-line fluorescence spectroscopy for temperature (ref. 11), and Rayleigh scattering for measuring total density (ref. 12). The first two techniques involve line-of-sight averaging; the latter two provide point measurements and show potential for resolving turbulence behavior.

The two-line fluorescence method is particularly attractive, providing both a point measurement and large signals. We have used this technique to measure temperature profiles in a flat-flame burner (fig. XVI-16). The methane-air mixture is seeded with indium, which has three electronic levels. The nonresonant fluorescence of the upper excited state of indium to each of its lower states is observed in the flame. The ground state is selectively pumped to the upper excited state, and fluorescence to the first excited state

is measured. Then, the first excited level is pumped to the upper excited state and fluorescence to the ground state is observed. The ratio of these two separate fluorescence processes is proportional to the ratio of the number densities of the ground state and the first excited state, all quenching parameters dropping out of the ratio. At equilibrium, this is the Boltzmann ratio and thus the temperature can be calculated.

After demonstration of this method in the laboratory flat-flame burner, application in the two-dimensional combustor will be pursued. Direct comparison of the two-line fluorescence-determined temperature with the thermocouple probe measurements will be possible.

SUMMARY

Premixed-prevaporized, lean gas turbine combustion has the potential for reducing pollutant emissions and improving turbine inlet temperature pattern factors. Major problem areas involve the stability of the combustion process and full realization of the emissions reduction potential. Experimental laboratory studies have been conducted that confirm the reduction of oxides of nitrogen to very low levels but, at the same time, indicate difficulties in maintaining hydrocarbons at similarly low levels.

A two-dimensional gas turbine combustor facility provides a laboratory environment for the observation of lean combustion utilizing both conventional probing and optical diagnostic techniques. Continuing experimental studies are designed to provide fundamental information on the effect of primary combustion parameters on flame stability, pollutant formation, and blowout.

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EMISSIONS INDICES FOR LABORATORY EXPERIMENTS AND TYPICAL AIRCRAFT GAS TURBINE ENGINES

	EI_{UHC} (gCH$_2$/kg fuel)	EI_{CO} (gCO/kg fuel)	EI_{NO_2} (gNO$_2$/kg fuel)	η_c
Case 1 (T_{in} = 300K, ϕ = 0.625)	114	76.7	0.11	0.87
Case 2 (T_{in} = 600K, ϕ = 0.625)	6.8	5.2	0.58	0.99
Case 3 (T_{in} = 600K, ϕ = 0.45)	1.2	85.1	0.07	0.98
JT9D, cruise	0.1-0.3	0.2-0.8	16-23	1.00
Olympus 593, cruise	1.0	1-5	18-19	1.00

Table XVI-1.

OPERATING CHARACTERISTICS OF TWO-DIMENSIONAL LABORATORY GAS TURBINE COMBUSTOR FACILITY

Fuel	Propane, 96% purity Temperature control by water/steam to 340 K Flow rate to 30 g/sec
Oxidizer	Air to 900 kPa, 450 g/sec 90 kw preheater, to 650 K maximum Desiccant dried and filtered
Test Section	178 x 51 mm cross section 229 mm length Spark ignited Maximum thermal power 1.4 Mw

Table XVI-2.

CONVENTIONAL AIRCRAFT GAS TURBINE COMBUSTOR (REF. 13)
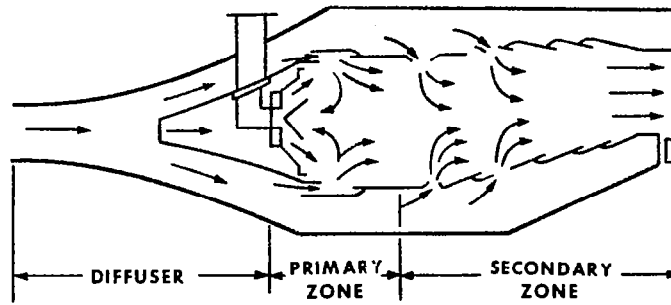
Figure XVI-1.

ADVANCED PREMIXED, STAGED COMBUSTOR (REF. 14)
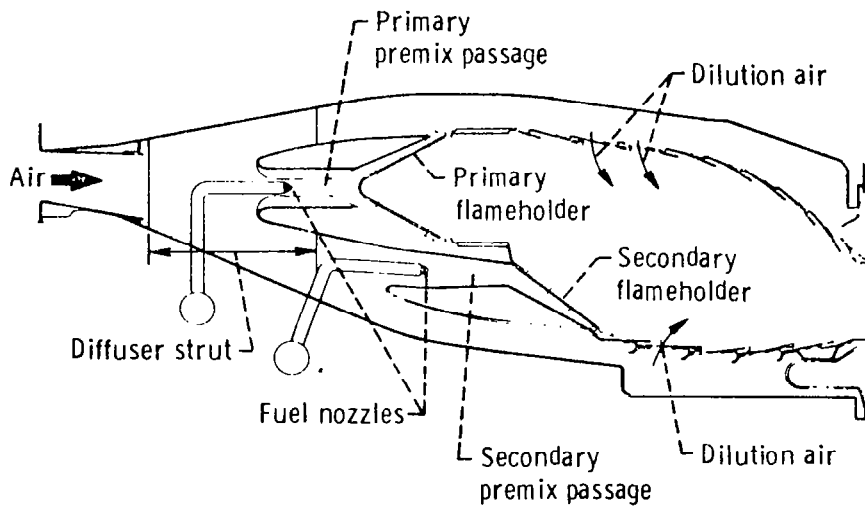
Figure XVI-2.

CORRELATION OF NO$_X$ EMISSIONS WITH COMBUSTOR INLET TEMPERATURE

Figure XVI-3.

EXPERIMENTAL FACILITY
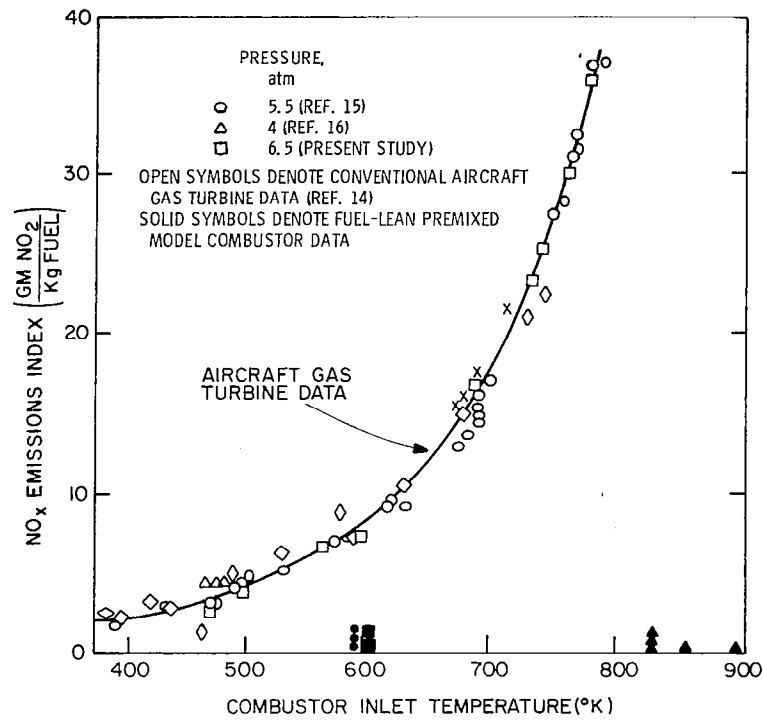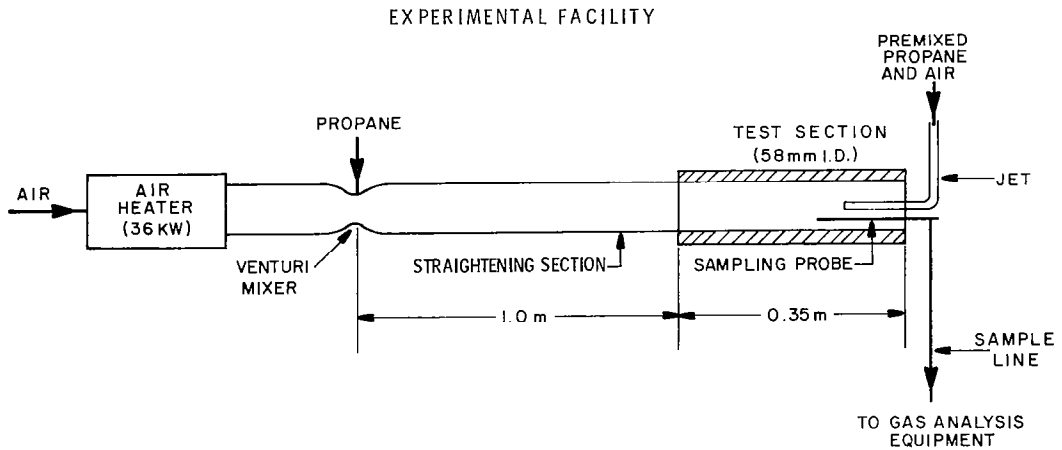
Figure XVI-4.

OPPOSED REACTING JET FLOWFIELD
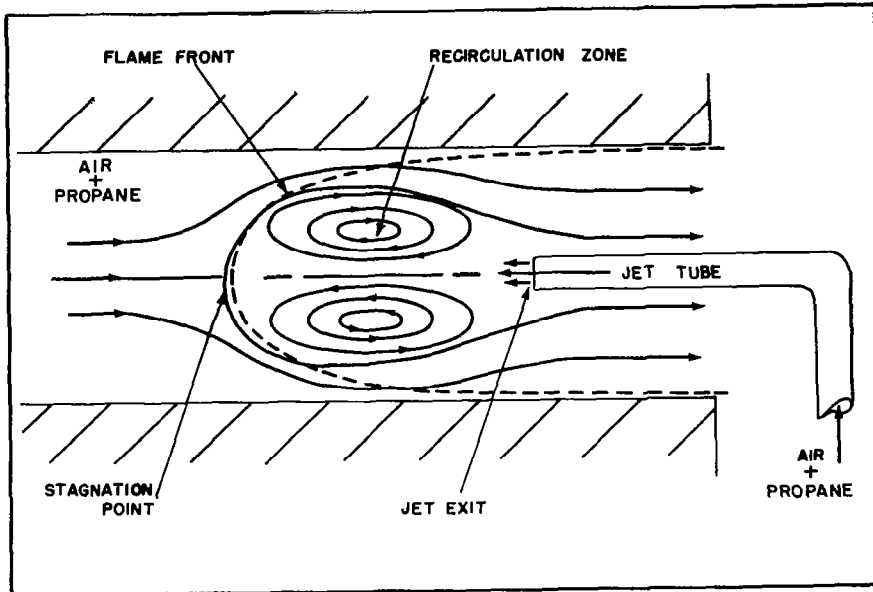
Figure XVI-5.

AXIAL CONCENTRATION AND TEMPERATURE DISTRIBUTIONS
AT RADIAL LOCATION OF 11. 6 mm FROM THE
COMBUSTOR CENTERLINE

$T_p = 600$ K; $\varphi = 0.625$; $V_p = 7.74$ m/s; $V_j = 95.9$ m/s
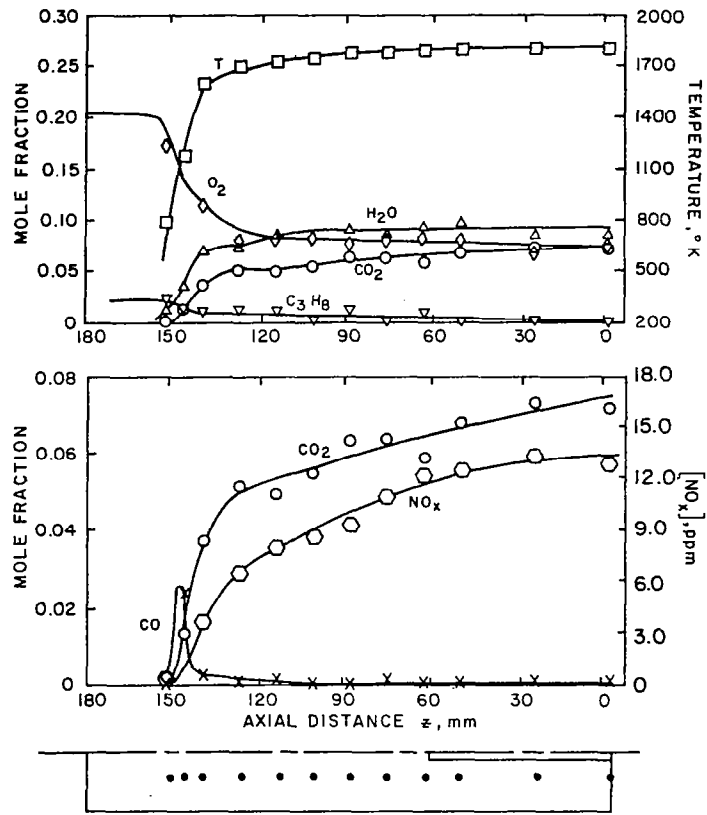
Figure XVI-6.

EFFECT OF JET EXIT VELOCITY ON STABILITY LIMITS OF
OPPOSED REACTING JET COMBUSTOR

$T_p = 300$ K; $T_J = 295$ K; $\varphi_J = 0.625$
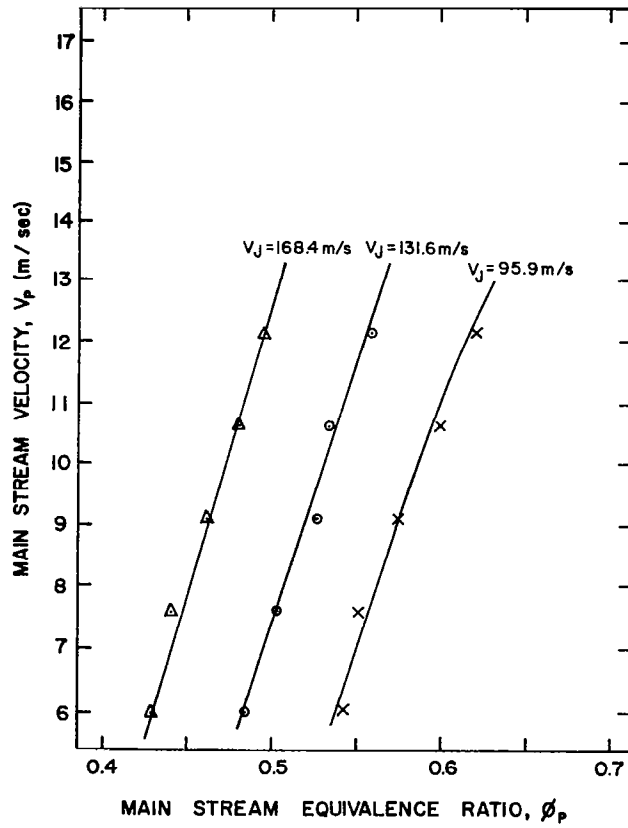
Figure XVI-7.

EFFECT OF MAIN STREAM INLET TEMPERATURE
ON STABILITY LIMITS OF OPPOSED
REACTING JET COMBUSTOR

$V_J = 95.9$ m/s; $T_J = 295$ K
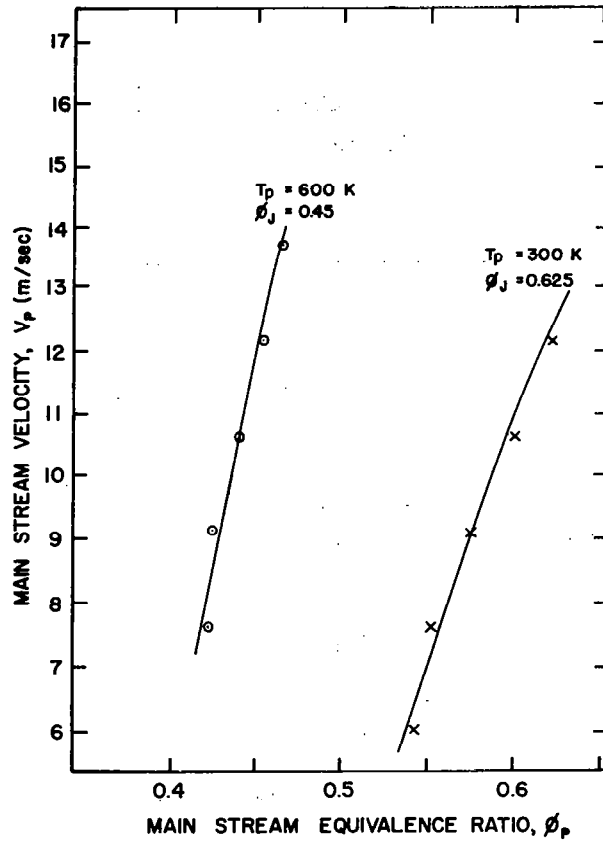
Figure XVI-8.

COMPARISON OF EXPERIMENTALLY OBSERVED AND PREDICTED PROPANE MOLE FRACTION DISTRIBUTIONS
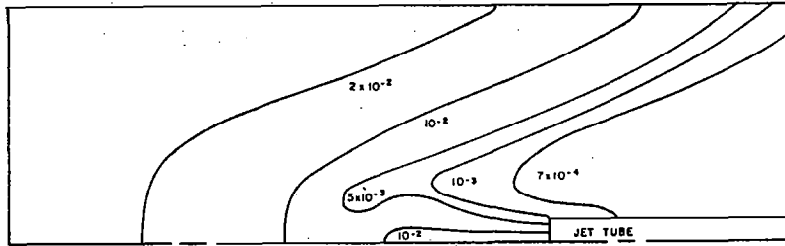
a) Experimental C_3H_8 mole fraction
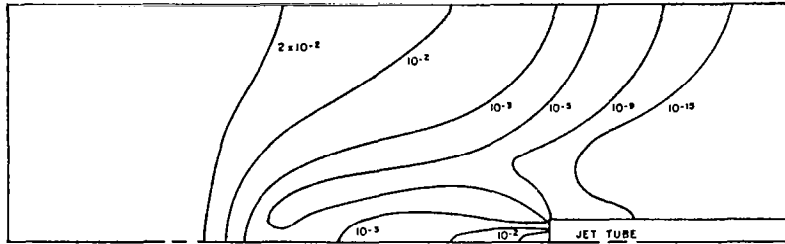
b) Predicted C_3H_8 mole fraction

Figure XVI-9.

SCHEMATIC OF CONSTANT PRESSURE COMBUSTOR WITH HEAT
RECIRCULATION FOR STABILIZATION OF LEAN MIXTURE
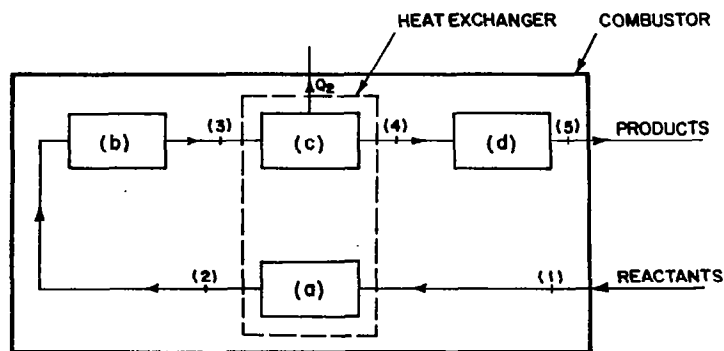
(a)+(c)   HEAT EXCHANGER
(b)   ADIABATIC FLAME ZONE
(d)   EQUILIBRIUM CONVERTER

Figure XVI-10.

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TWO DIMENSIONAL GAS TURBINE COMBUSTOR FACILITY

(1) UNDER TEMPERATURE CONTROL
(2) WATER PRESSURE CONTROL
(3) OVER TEMPERATURE CONTROL
(4) CHAMBER OVER PRESSURE CONTROL
(5) AIR FLOW CONTROL
(6) FUEL LEAK CONTROL
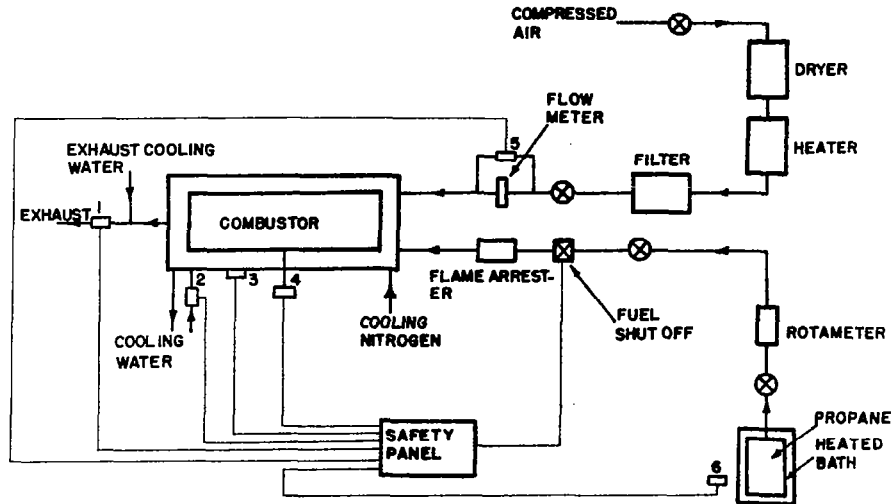
Figure XVI-11.

TWO DIMENSIONAL GAS TURBINE COMBUSTOR TEST SECTION. DIFFUSION FLAME CONFIGURATION
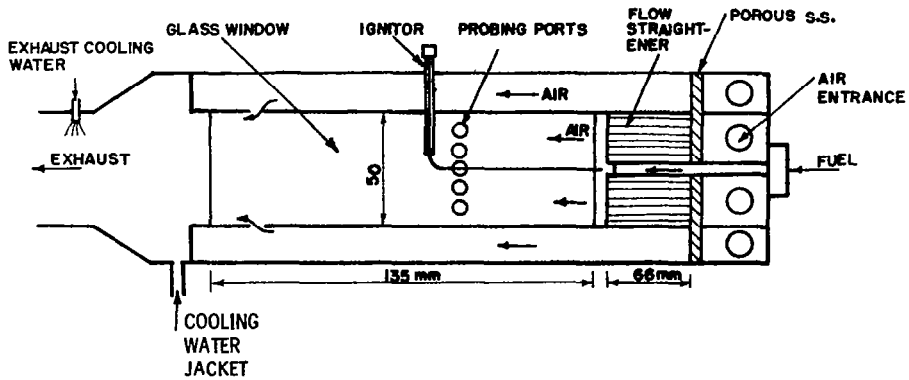
Figure XVI-12.

TEMPERATURE DISTRIBUTION ACROSS THE COMBUSTOR AT A
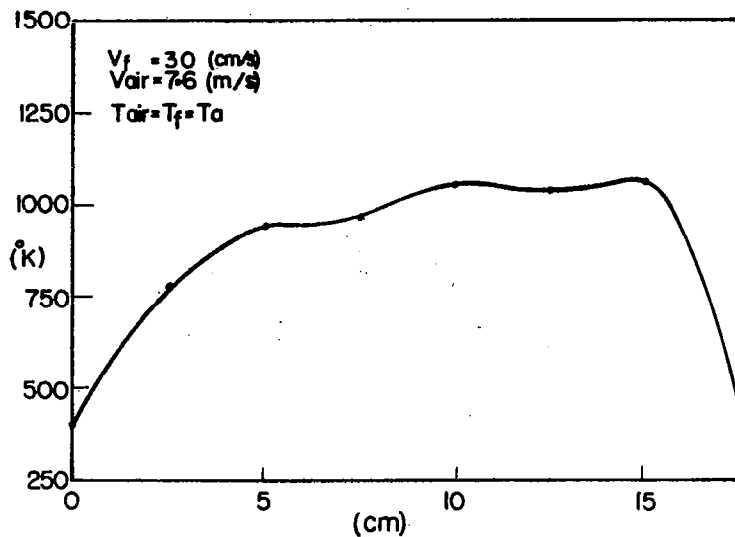VERTICAL POSITION 8.5 mm ABOVE THE CENTERLINE AND
10 cm FROM THE INJECTOR FACE

Figure XVI-13.

STABILITY MAP FOR TWO DIMENSIONAL PROPANE/AIR DIFFUSION FLAME
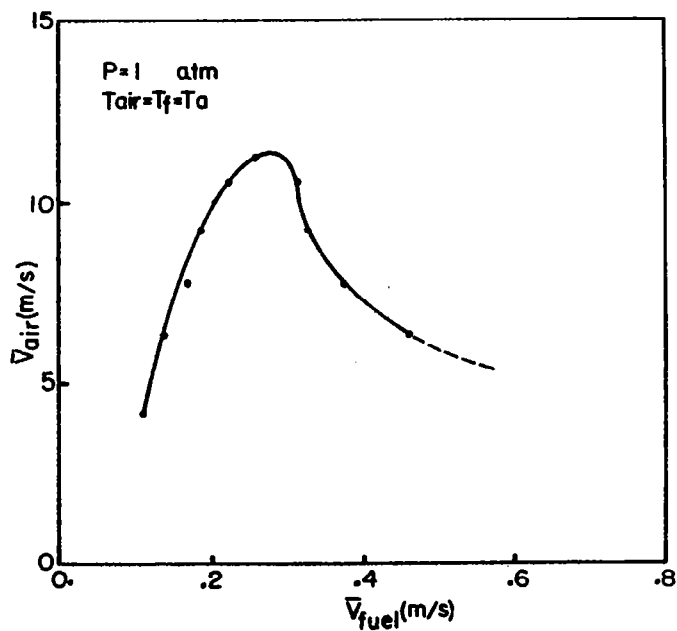
P = 105 kPa, T_{in} = 290 K

Figure XVI-14.

TWO DIMENSIONAL GAS TURBINE COMBUSTOR TEST SECTION
PREMIXED CONFIGURATION

Figure XVI-15.

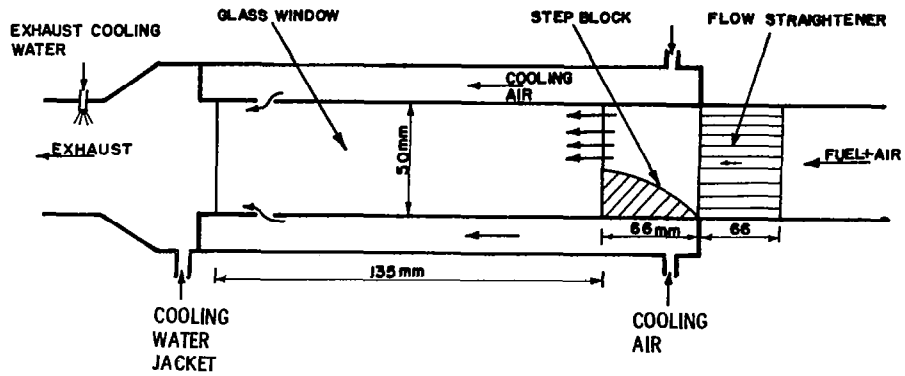## EXPERIMENTAL APPARATUS FOR TWO-LINE FLUORESCENCE
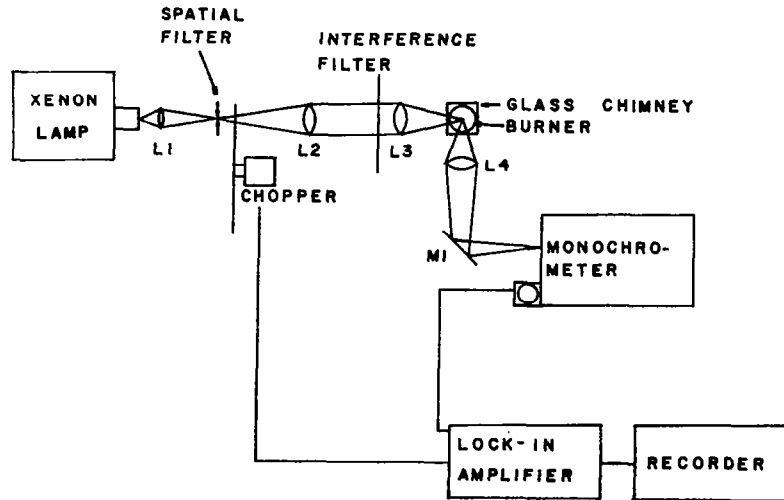## TEMPERATURE MEASUREMENT IN A FLAT FLAME BURNER

Figure XVI-16.