APTD - 1441

Low NOx Emission Combustor For Automobile Gas Turbine Engines

Prepared By

David J. White, P.B. Roberts and W.A. Compton

SOLAR DIVISION INTERNATIONAL HARVESTER COMPANY

2200 Pacific Highway

San Diego, California 92138

CONTRACT NUMBER: 68-04-0016

EPA Project Officers

H. F. Butze and Robert B. Schulz

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U.S. ENVIRONMENTAL PROTECTION AGENCY

Office of Air and Water Programs

Mobile Source Pollution Control Program

Advanced Automotive Power Systems Development Division

February 1973

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RDR 1705-5

FOREWORD

This report entitled "Low NO_x Emission Combustor for Automobile Gas Turbine Engines", describes the work performed pursuant to Contract No. 68-04-0016, for the Advanced Automotive Power Systems Development (AAPSD), Office of Air Programs (OAP), Environmental Protection Agency (EPA). The work was conducted at the Solar Division, International Harvester Company in San Diego, California, under the technical direction of the Research Laboratories. Mr. W. A. Compton, Assistant Director - Research, was the technical director and program manager with Mr. David J. White, Research Staff Engineer, as the principal investigator.

Two individual Project Officers have been associated with this program. Initially Mr. Robert Schulz of the Advanced Automotive Power Systems Development Division of the Environmental Protection Agency, held the post, which he relinquished to Mr. H. Fritz Butze, approximately a quarter of the way through the program. Mr. Butze is employed by the National Aeronautics and Space Administration, Lewis Research Center in Cleveland, Ohio.

Solar's internal report number is RDR 1705-5.

ACKNOWLEDGEMENTS

In addition to the authors, Solar personnel and consultants who made an important contribution to the program include L. F. Blinman, Product Engineer - initial principal investigator; J. R. Shekleton, Engineering Specialist - combustor design consultation; R. T. LeCren, Group Engineer - experimental investigation of conventional combustors; T. E. Duffy, Research Staff Engineer and W. E. Reed, Group Engineer - controls analysis; Dr. B. P. Breen and C. Bodeen of KVB Engineering - combustion analysis and computer programs; and Professor R. F. Sawyer, University of California at Berkeley - consultation.

Special credit is given to Mr. John V. Long, Director-Research, for supporting the program from concept to completion.

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INTRODUCTION

1.1 BACKGROUND

Contract #68-04-0016, entitled "Low NO_X Combustors for Automobile Gas Turbine Engines", has advanced a combustor concept which shows excellent promise for low emissions on an automotive gas turbine. The objective of the program was to develop the necessary design criteria for such a combustor and demonstrate the emission characteristics, on the test stand, of a model combustor employing these criteria.

A number of combustor concepts were evaluated for the low pressure regenerative (A-Mod) cycle and the high pressure recuperative (B-Mod) cycle against the requirements of the EPA prototype vehicle performance specification.

The combustor concept finally selected provides the ability to stabilize flames at lean equivalence ratios and reduce the primary zone oxygen content (through dilution with recirculated combustion products) by a method termed "Jet Induced Circulation" (JIC). In order to achieve this type of recirculation, jets are arranged to flow forward toward the dome in a conventionally shaped can combustor so that they impinge on the centerline, producing a derived jet that in turn impinges on the combustor dome. The resulting primary zone flow field is of the nature of a toroidal vortex. It is possible by this method to ensure that the ratio of recirculation mass flow rate to the entering air and fuel mass flow rate be greater than one: a necessary requirement for satisfactory lean extinction limits with a lean reaction zone system.

It has been shown, using interchangeable "fixed" orifices at the primary and dilution ports, that the JIC combustor can operate at set test points representing the Federal Driving Cycle to yield integrated emission levels within the EPA prototype vehicle specifications.

A Data Book documenting this program in considerable detail, is available on request from AAPSD/EPA. This particular report provides the results and discussion of each investigation and test performed during the program.

1.2 PROGRAM PHASES

The program approach dictated that the work be split into five phases:

- Phase I - Development of combustor design criteria through combustor test and analysis
- Phase II - Establishment of parametric combustor designs
- Phase III - Parametric combustor fabrication; test rig fabrication
- Phase IV - Parametric combustor test and final evaluation
- Phase V - Program extension work

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SUMMARY

2.1 BACKGROUND

Because of the increasing concern for a cleaner environment, automotive engines utilizing unconventional thermodynamic cycles have been given serious consideration. In particular, the Brayton cycle engine is considered a prime candidate for reducing the undesirable pollutant emissions produced by present automobiles. The Environmental Protection Agency, Division of Advanced Automotive Power Systems, has recognized that the combustors of present day production automotive gas turbine engines have not been optimized for low emissions of NO_x, and is therefore supporting programs intended to provide both basic design data and demonstrations of combustors that will meet or better the 1976 standards.

2.2 OBJECTIVE

The prime objective of this particular program was to develop, through both analytical and experimental studies, the basic design criteria and data necessary to produce a low emission combustor. In addition, this information was to be utilized in the production of two combustor designs, one for a typical low-pressure regenerative type of engine and the other for a high-pressure engine with partial recuperation. Initially these two designs were referred to as the Class A and Class B combustors, respectively. Later, because of the uprating of the combustor inlet conditions (essentially both classes had their inlet temperatures increased), these classifications were changed to Class A-Mod and Class B-Mod. The 1976 Federal Standards for vehicle emissions together with the derived emission index goals for the two classes are given in Table I.

2.3 RESULTS

Several model combustors were produced employing various concepts to obtain low emissions, and these were evaluated as to their suitability for incorporation into a practical engine system. The criteria for evaluation were in order of importance:

- Low emissions of oxides of nitrogen (NO_x)

TABLE I

1976 FEDERAL STANDARDS
(EMISSION LEVEL GOALS)

Constituent	Emission Level (gm/mile)	Equivalent Emission Index at 10 mpg (s.g. =0.763) (Class B Mod.) gm/Kg	Equivalent Emission Index at 12.7 mpg (s.g. = 0.763) (Class A Mod.) gm/Kg
Oxides of Nitrogen as NO_2 (NO_X)	0.4	1.38	1.78
Carbon Monoxide (CO)	3.4	11.8	14.9
Unburned Hydrocarbons as $CH_{1.85}$ (UHC)	0.41	1.42	1.81

Note: At the start of the program the goals were to have emission indices lower than those in the table for each combustor class. Later in the program Solar set itself the goals of meeting one-half or less of each of the emission indices.

- Low emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC), (high efficiency)
- Acceptable pressure loss ($\Delta P/P$) $\leq 5\%$
- Stability equivalence ratio range sufficient for entire engine operating range
- Simplicity of variable area control (where necessary)
- No smoke or odor
- Reasonable size and weight

Of the various models tested, when operated with liquid fuels, the concept that appeared to show the most promise, particularly in terms of low NO_X emissions, was that designated the Jet Induced Circulation (JIC) combustor system. This system initially had high pressure losses, but a logical approach for reducing these losses without impairing emission performance was apparent; thus this system became the prime choice.

Two combustors utilizing this basic JIC concept were designed and built, one for a low-pressure, regenerative engine cycle and the other for a high-pressure cycle system with partial recuperation. These two designs were designated Class A-Mod and Class B-Mod or JIC-3 and JIC-4, respectively. The results of these two combustors, when tested over a simulated Federal Driving Cycle (conditions specified by EPA), indicated (particularly the Class A-Mod system) that the 1975-76 emission requirements can be easily met and bettered, provided some satisfactory variable area system and control could be devised.

A program extension was granted, which had as one of its aims the generation of additional design data to enable the JIC concept to be scaled to meet any given set of inlet conditions. In addition, an attempt was also to be made to both devise a control system for the combustor and to evaluate various variable area port concepts.

The basic design information, intended for the purpose of combustor sizing, was obtained from a series of uncooled model combustor primary zones and model variable area primary ports. The results obtained have indicated several approaches that could lead to increased operating range for the low emissions section, which in turn would minimize the need for variable geometry.

The evaluation of the various variable area port models led to the conclusion that all of the various concepts tested could, under certain circumstances, be suitable for incorporation into a practical combustor. In general, the problems associated with variable area ports are mainly connected with the necessary auxiliary systems such as the linkage and actuator mechanisms in those cases where mechanical movement is required, and in the provision of the control air supply in the case of fluidic ports. The fluidic ports do have some extra disadvantages when compared with purely mechanical systems, in that under certain flow conditions instability in the form of bistable operation can occur, although this can be allowed for.

In investigating a control system suitable for a typical combustor operating with variable area ports to control local equivalence ratios and thus NO_X, a series of NO_X correlations as a function of the main combustor inlet conditions was initially evolved. Based on the accuracy of these correlations and the errors involved in measuring the various independent parameters, an estimate of the total possible error associated with the control system was obtained. This estimate was then compared with the acceptable operating range and it was found that the two were very close. Thus, the conclusion drawn from this initial phase is that although such control is possible, it would be difficult. In consequence, an approach was taken to minimize the number of independent variables. This was achieved by correlating the NO_X emissions as a function of the inlet pressure and a synthesized primary zone reaction temperature. The ratio of the equivalence ratio entering into the primary zone reaction temperature calculation to the overall equivalence ratio obtained from the fuel control system is a function of the primary port to dilution port area ratio. Thus a schedule of this latter area ratio for different overall equivalence ratios, inlet pressures, and temperatures can be correlated directly as a function of NO_x. This approach does lead to a viable solution to the control problem, assuming that the present operating bandwidth can be increased slightly.

3

OVERALL PROGRAM DESCRIPTION

The overall program approach adopted can be represented by the block diagram of Figure 1.

This diagram shows that Solar's considerable background experience in combustor technology was utilized, together with flow visualization techniques and computer simulations, to provide some basic combustor model designs. These initial models were rig tested, and they provided a basic understanding of the type of parameter important from a point of view of NO_x production and the design of a low NO_x combustor system. From these results, various combustor concepts were designed and tested, including examples of both rich and lean reaction zone systems.

From this second series of rig tests the most promising combustor concept was selected to be the basis of the parametric Class A-Mod and Class B-Mod designs which, after AAPS approval, were fabricated and put through the final test evaluation.

3.1 ANALYTICAL INVESTIGATIONS

The analytical studies were used as a qualitative guide towards the formation of various conceptual designs of low emission combustors during the initial stages of the program. A dual-level approach involving the application of analytical studies in conjunction with an experimental test program was thought to be the optimum method that would minimize the effects of the separate limitations of each approach.

3.1.1 Computer Analyses

Early in the program it was realized that to obtain a detailed understanding of the mechanisms involved in the formation of nitric oxide (NO) within a practical combustion system, a number of analyses involving aerodynamics, heat transfer and chemical kinetics would have to be made. These analyses, although usually applied only to an idealized section of a practical system, are complex, and efficient usage dictated that they would have to be incorporated as computer programs.

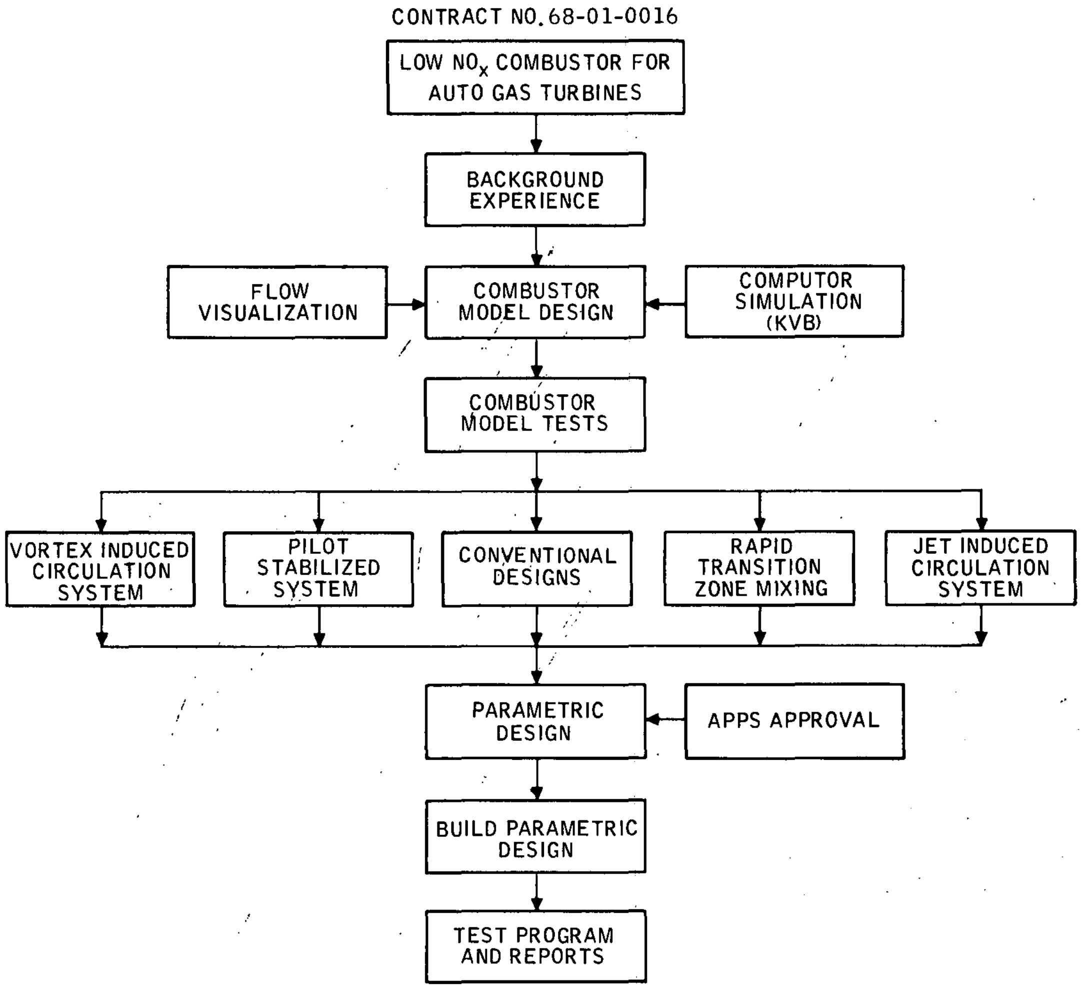


FIGURE 1. PROGRAM ORGANIZATION CHART

The various programs, although specifically applicable to combustor analyses are capable of extensive use in other areas of interest in gas turbines. A listing of the various computer programs available to Solar is given in Table II.

3.1.2 Flow Visualization

As an aid in visualizing the effect on the flow patterns of changes in combustor geometry, and also to verify the results of certain analytical computer programs, a series of Plexiglas models of the preliminary combustor were built. These models, when used with smoke injection, provided qualitative definition of the flow patterns within the combustor.

The flow visualization rig consists basically of the Plexiglas model mounted to an exhauster fan unit, with a light source above the combustor producing an axial, narrow slit of light. This slit of light is directed along a diametrical plane as shown in

TABLE II

ANALYTICAL COMPUTER PROGRAMS AVAILABLE

1. Droplet Evaporation and Combustion	Not a Production Program but Available
2. One Dimensional Chemical Equilibrium (ODE)	Production Program
3. Two Dimensional Chemical Equilibrium (TDE)	Production Program
4. One Dimensional Chemical Kinetics (ODK)	Production Program
5. Two Dimensional Chemical Kinetics (TDK)	Production Program
6. Gosman-Spalding Model	Experimental Program
7. One Dimensional Combustor Aerodynamic Analysis	Production Program
8. Two Dimensional Combustor Aerodynamic Analysis	Experimental Program
9. One Dimensional Combustor Heat Transfer Analysis	Production Program
10. Two Dimensional Combustor Heat Transfer Analysis	Experimental Program
11. Two Dimensional Mixing Program	Experimental Program
12. Jet Penetration Analysis	Production Program
13. Jet Impingement and Flow Split Analysis	Production Program
14. Atomizer Design Program	Experimental Program
15. Swirler Design Program	Experimental Program

the schematic of Figure 2. When operated in a darkened room, with smoke injected discretely in turn through a hole in each row that is in the plane of light, a clear tracing of the flow pattern in that particular plane results.

3.2 COMBUSTOR MODIFICATIONS - RICH PRIMARY ZONE

3.2.1 Conventional Combustors

A key element in this program was the decision to conduct an extensive series of low cost model tests with simplified combustors and use the resultant data, in conjunction with analytical studies, to design a final combustor suitable for engine tests. The lack of detailed analytical data, especially as regards prediction of mixing, was the justification for this broad cover, low cost approach.

The initial rig testing was confined to the regenerative Class A combustor configurations, generally at atmospheric pressure conditions. The FID hydrocarbon

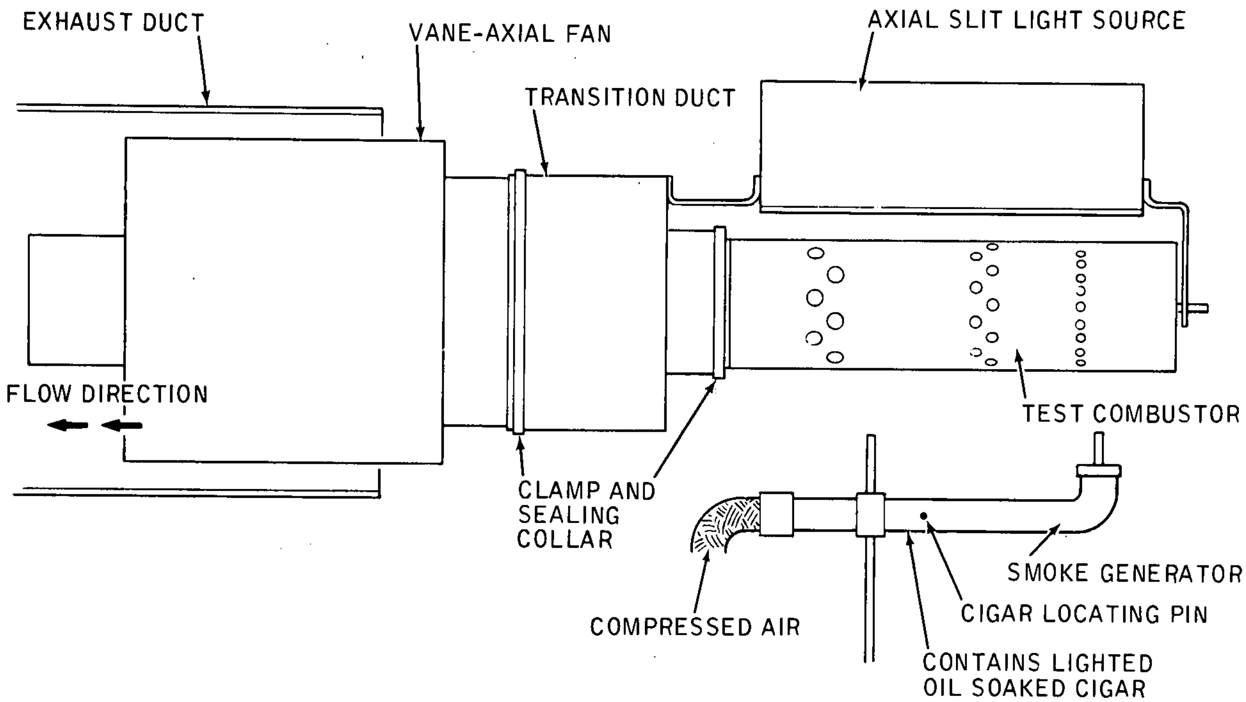


FIGURE 2. SCHEMATIC REPRESENTATION OF FLOW VISUALIZATION RIG

analyzer was not operable, hence results include nitric oxide and carbon monoxide production only.

The various combustor configurations shown in Tables III and IV were tested. The configurations included variations in the fuel atomization system and the air-fuel distribution throughout the length of the combustor. Configurations were tested at varying air mass flow rates, inlet temperatures, inlet pressures and temperature rises.

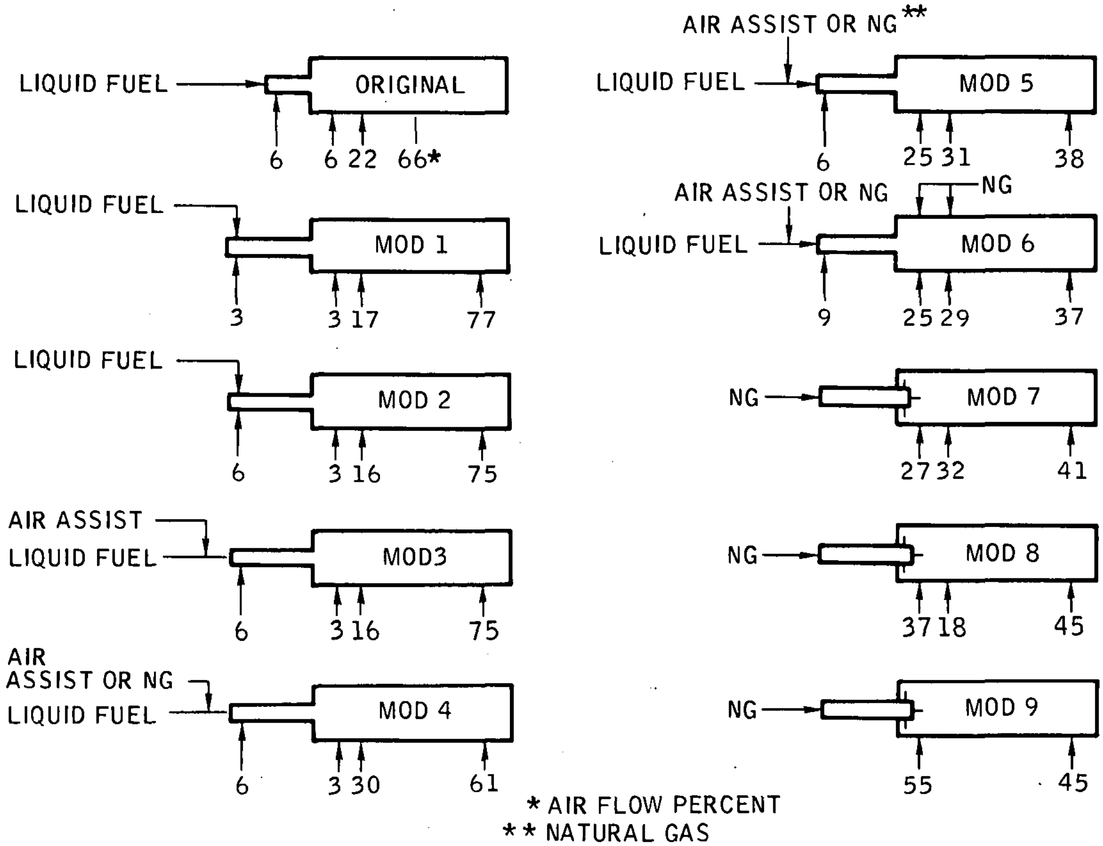
Typical results are presented in Figures 3 and 4. In these graphs the NO_X (calculated as NO_2) and CO emission indices in grams per kilogram of fuel are plotted as a function of combustor temperature rise for various values of combustor loading, expressed as combustor pressure loss, and combustor inlet temperature.

Original Combustor

This combustor was the initial Class A combustor configuration consisting of a rich primary zone for moderate reaction temperatures (and hence low NO production rates) followed by a secondary reaction zone, where enough air was suddenly added to lean out the mixture to a point where the NO production rate was maintained at a low level but the local temperatures were still high enough to permit the continued reaction of CO to CO_2. The remaining air was introduced at the beginning of the

TABLE III

SUMMARY OF COMBUSTOR TEST CONFIGURATIONS



tertiary zone, where final mixing was carried out. A prevaporized fuel injection system was utilized, with the liquid fuel introduced through a plain 1/8-inch diameter tube coaxially with the vaporizing airflow. The results of the concentration of CO and NO_2 are given in Figures 3 and 4.

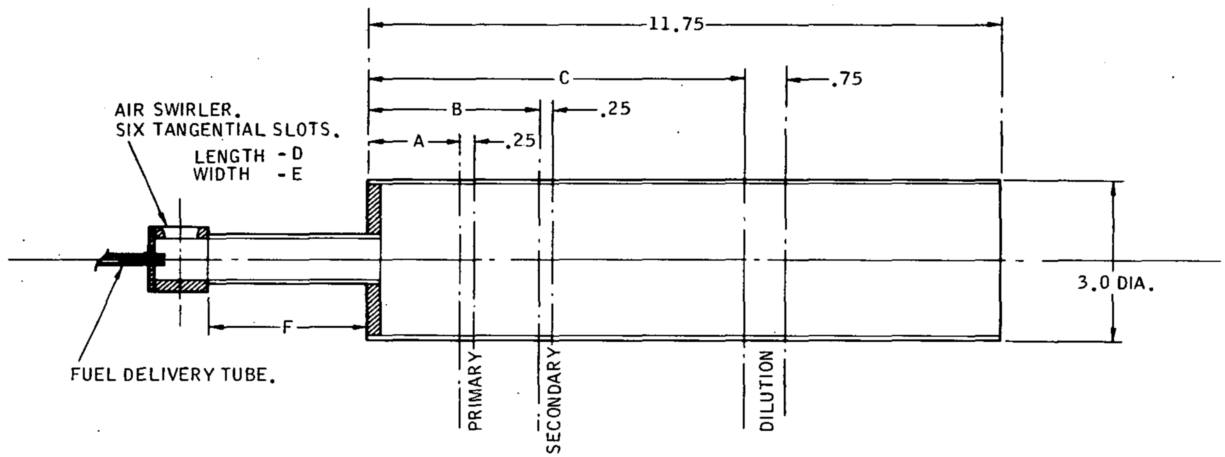
At a given combustor inlet temperature the NO_2 concentrations did not appear to be a function of combustor loading, in contrast to the CO concentrations, where for a given inlet temperature there was an increase of CO level with increased combustor loading, presumably due to the reduction in overall residence time. The NO concentrations, however, are mainly a function of a chemical reaction which is dependent upon the actual reaction zone residence time, which in turn is apparently mixing controlled.

Combustor Mod. 9

This configuration represents the final one in this series and simplifies the combustor to a set of primary and dilution holes only. Figures 5 and 6 give the results

TABLE IV

BRAYTON CYCLE COMBUSTOR TEST PROGRAM CONFIGURATION SUMMARY



MOD. #	DSK 13410	MOD. 1	MOD. 2	MOD. 3	MOD. 4	MOD. 5	MOD. 6	MOD. 7	MOD. 8	MOD. 9
FUEL SYS.	ST. TUBE	ANGLE TUBE	ANGLE TUBE	AIR ASSIST	AIR ASSIST	AIR ASSIST	AIR ASSIST	HI-VELO.	HI-VELO.	HI, LO VELO.
AIR SWIRL.	D = .75 E = .125 F = 3.0	D = .375 E = .125 F = 6.0	D = .75 E = .125 F = 6.0	D = .75 E = .125 F = 6.0	D = .75 E = .125 F = 6.0	D = .75 E = .125 F = 6.0	D = 1.0 E = .187 F = 6.0	NONE	NONE	NONE
PRIMARY	A = 1.75 1x30x.94*	A = 1.75 1x30x.94	A = 1.75 1x30x.094	A = 1.75 1x30x.094	A = 1.75 1x30x.094	A = 1.75 1x30x.157	A = 1.75 1x30x.157	A = 1.75 1x30x.157	A = 1.75 2x30x.157	A = 1.75 2x30x.192
SECONDARY	B = 3.25 2x15x.188	B = 3.5 1x15x.218	B = 3.5 1x15x.218	B = 3.5 1x15x.218	B = 3.25 2x15x.218	B = 3.25 2x15x.218	B = 3.25 2x15x.218	B = 3.25 2x15x.218	B = 3.25 1x15x.218	NONE
DILUTION	C = 7 2x11x.375	C = 10 2x11x.404	C = 10 2x11x.404	C = 10 2x11x.404	C = 10 **2x11x.404	C = 10 1x11x.404	C = 10 1x11x.404	C = 10 1x11x.404	C = 10 1x11x.404	C = 10 1x11x.404
FUEL	JP4	JP4	JP4	JP4	JP4	JP4, NG.	JP4, NG.	N.G.	N.G.	N.G.

* 1 x 30 x .94 Equivalent to one Row of 30 Holes of .94-Inch Diameter

** ONE ROW PARTIALLY BLANKED TO MAINTAIN SAME TOTAL HOLE AREA.

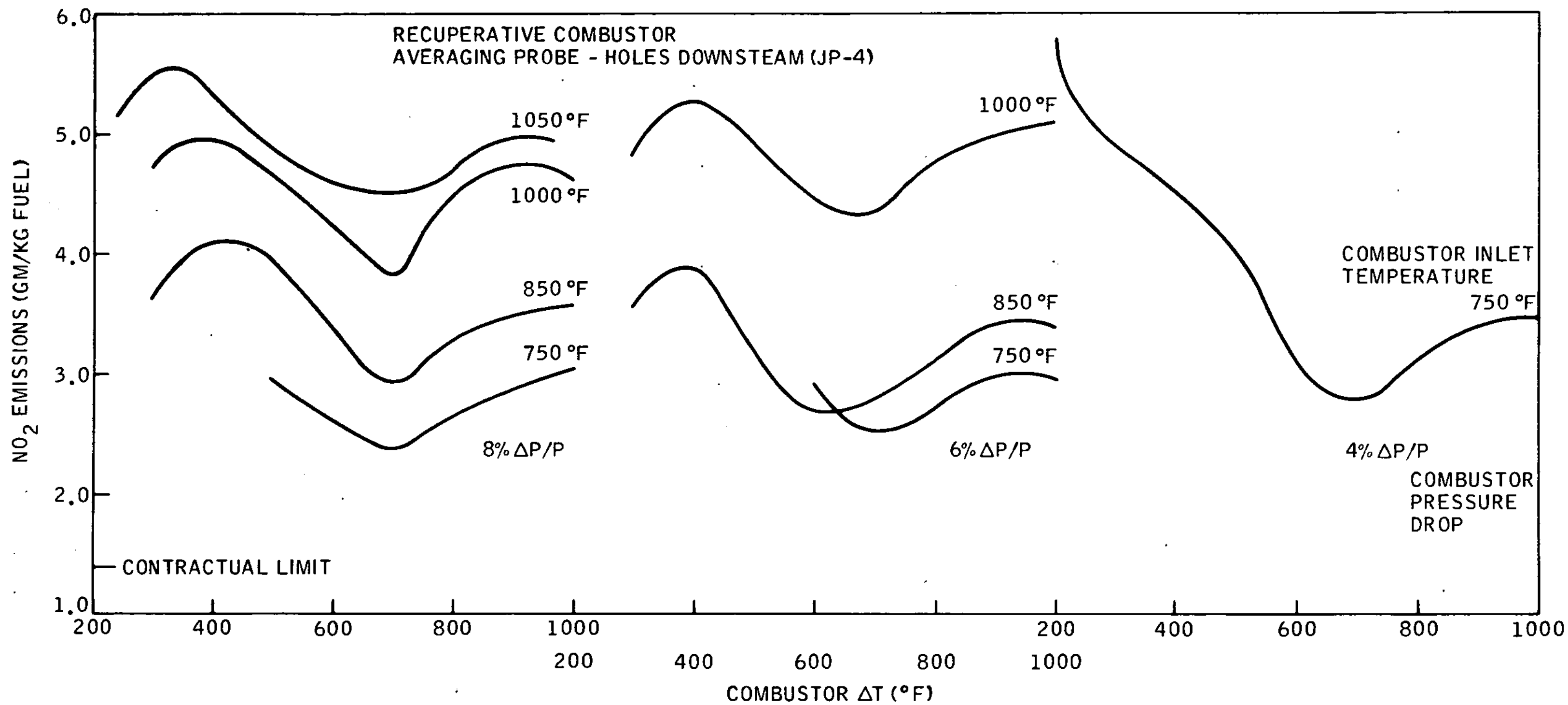


FIGURE 3. EMISSION CHARACTERISTICS OF ORIGINAL (REFERENCE) COMBUSTOR

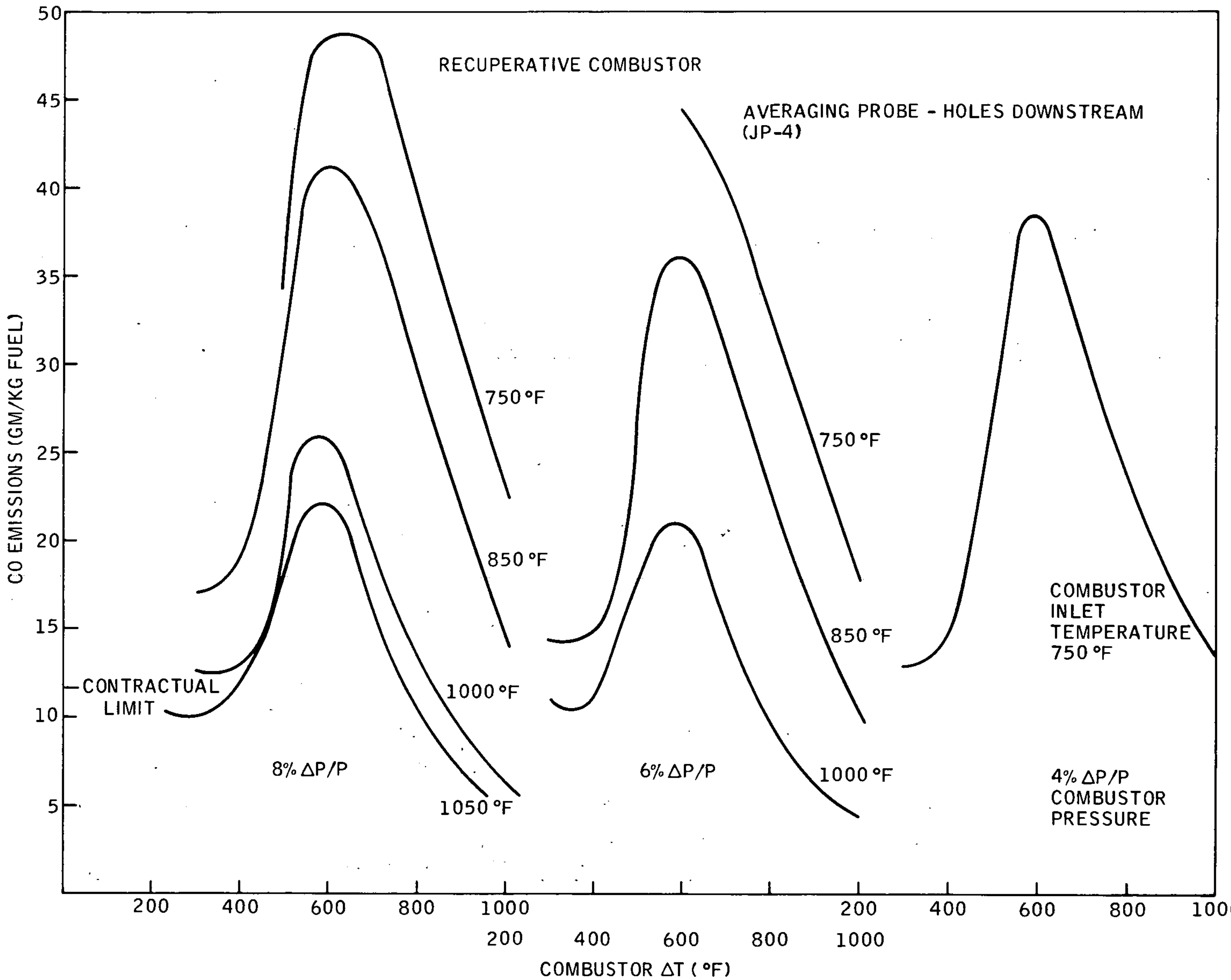


FIGURE 4. EMISSION CHARACTERISTICS OF ORIGINAL (REFERENCE) COMBUSTOR

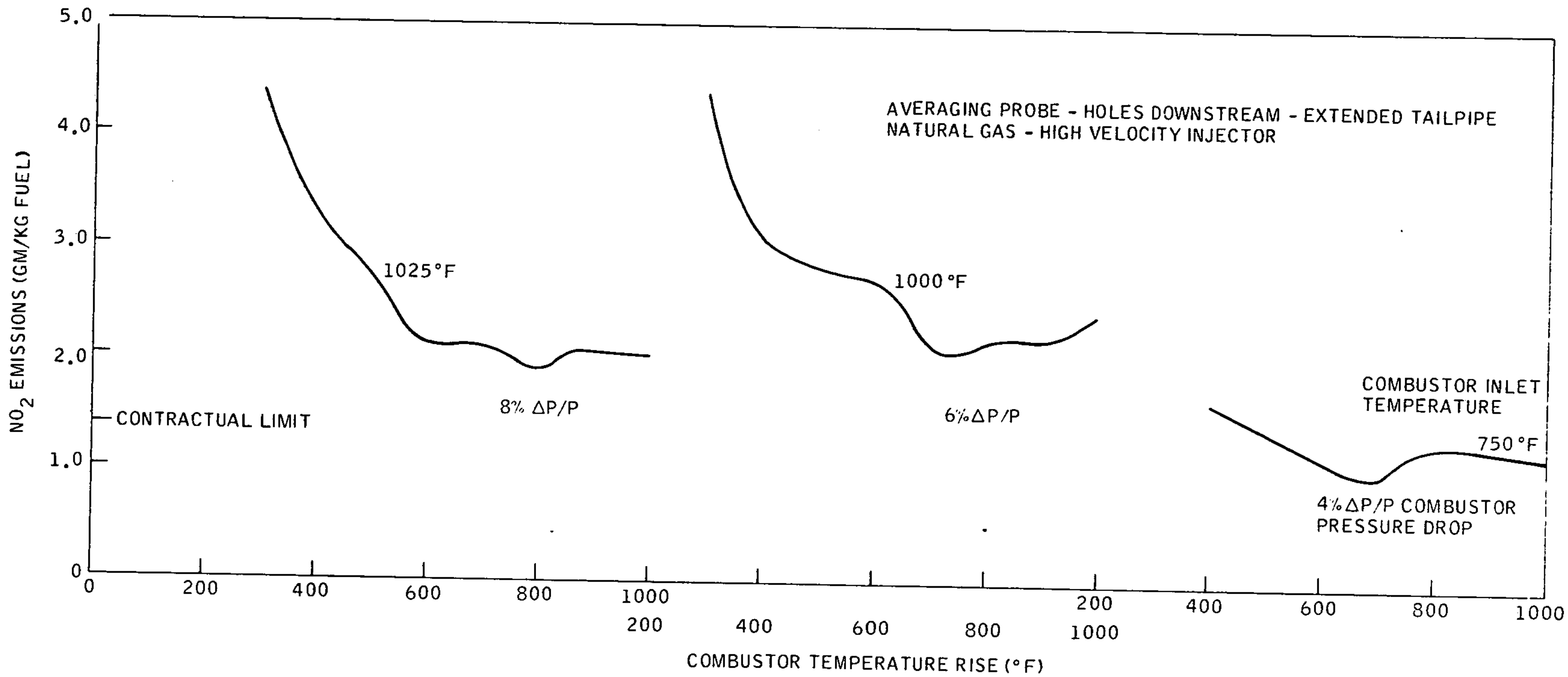


FIGURE 5. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

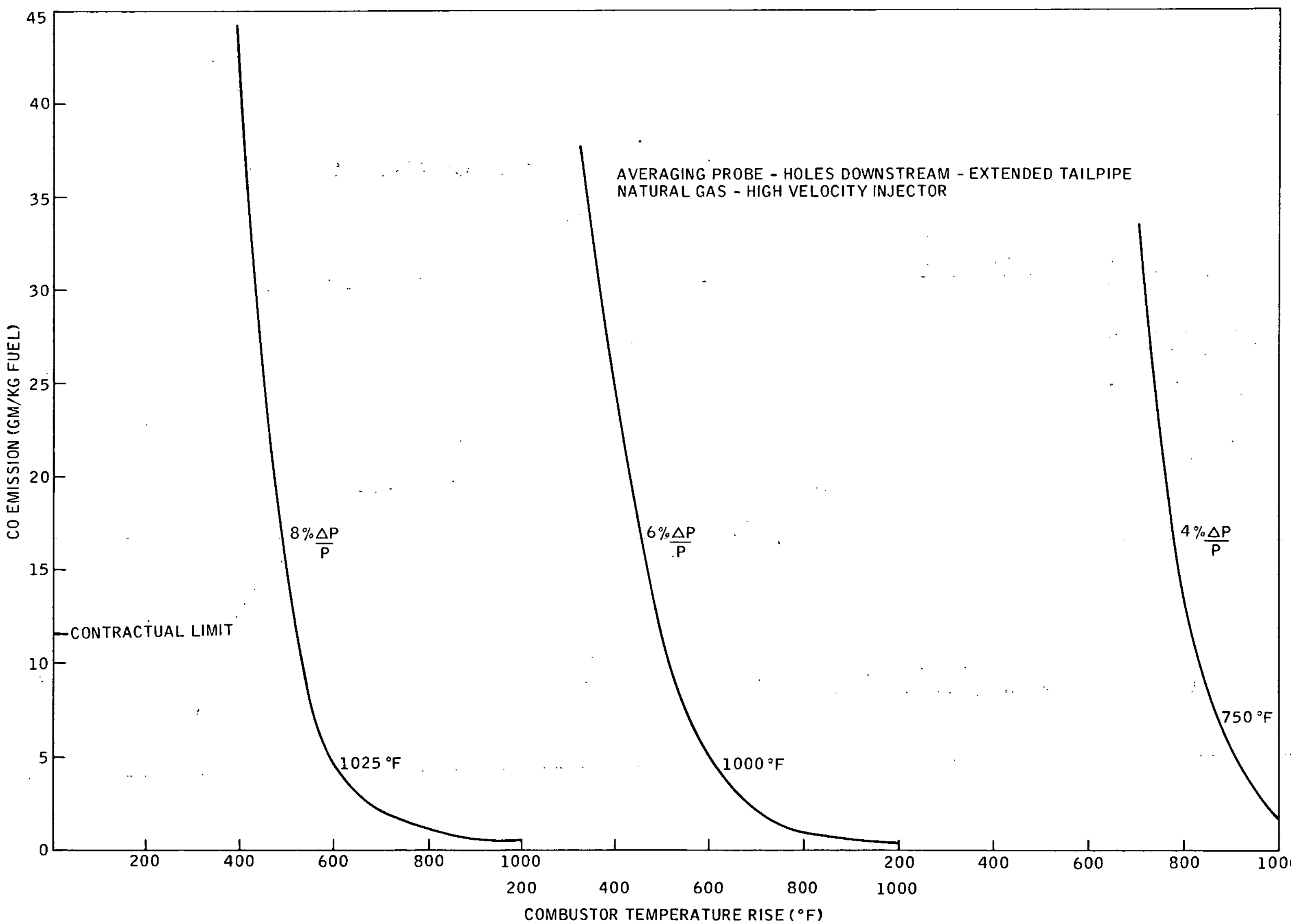


FIGURE 6. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

of running on natural gas fuel at atmospheric pressure, and Figures 7 through 12 depict the results obtained from runs at pressure. The NO results were the lowest obtained during the series of combustor modifications and are below the allowable limit at the lowest inlet temperatures and at atmospheric pressures.

The final Mod. 9 combustor configuration was tested in some detail. In addition to the usual atmospheric runs, the combustor was tested at various pressure levels with two inlet temperatures, 750 and 1000°F. The effect of gas nozzle injection velocity is also shown with two different pressure runs at 750°F inlet temperature.

The pressure dependency of the NO_X formation rates can best be seen at the higher combustor temperature rises. At the lower temperature rises the dependency is masked by the mixing effects, as mentioned before, although this effect is reduced at the higher inlet temperature (1000° F). Although the basic NO reaction rate equation contains the pressure to only the one half power, there appears to be only a slight tendency towards a reduction of pressure effects at higher pressure levels. In all three sets of pressure tests, however, there are reversals where the NO_X emissions at a high pressure are lower than those at some intermediate pressure. The effects of a change in gas injection velocity can be seen from Figures 7 and 11. The repeatability is considered good for those pressure levels that are common to both figures, although some mixing effects are apparent at the low temperature rises.

3.2.2 Rapid Mixing Transition Zone Combustor

The final example of a rich primary zone combustor which was tested incorporated a specially designed transition zone between the primary and dilution sections. The main purpose of this zone was to facilitate the extremely rapid mixing between the fuel rich primary zone product gases and the secondary air, necessary to prevent the formation of long-lived pockets of stoichiometric mixture. A schematic of the combustor showing the main features of the system is provided in Figure 13. Premixing of the air and fuel for the primary zone was accomplished with the swirling air atomizer system shown. This swirler also provided part of the stability by creating a flow reversal within the primary zone. An increase in the amount of products recirculated, thus adding to the stability, was obtained because of the blockage created by the plenum chamber supplying air for the transition mixing zone.

Conceptually, it was felt that a system with a primary zone sufficiently fuel-rich to prevent high temperatures and consequent NO_X formation, together with a secondary and dilution zone so lean to similarly obviate the production of NO_X, could be successful if a transition mixing system could be designed to provide sufficiently rapid mixing rates. Provided these mixing rates are sufficiently high, dwell times at high equivalence ratios or temperature levels could be minimized, which would in turn minimize the NO_X emissions from this zone. The mixing rate in the transition zone would have to be considerably faster than the fuel oxidation rate at any instant

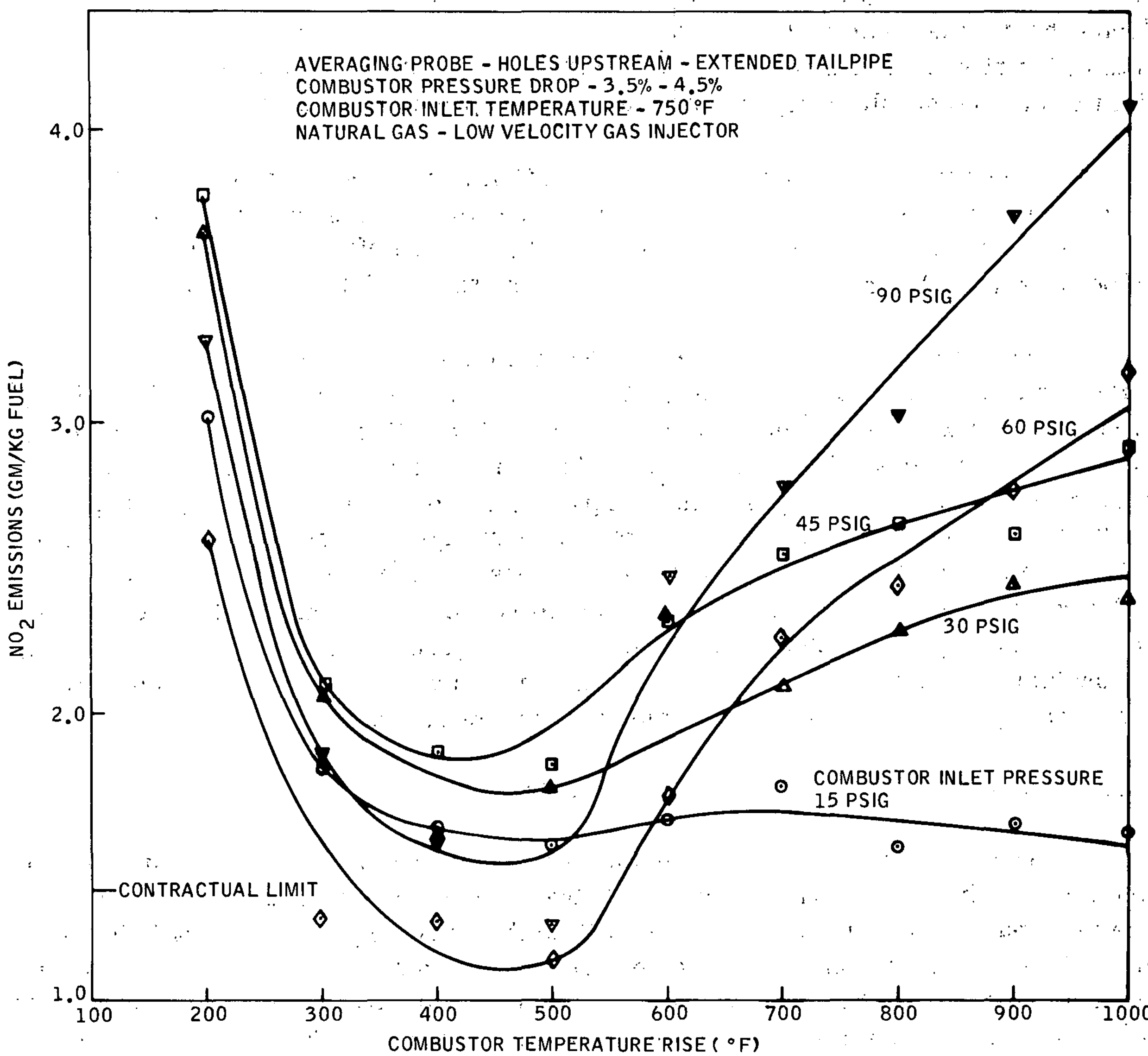


FIGURE 7. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

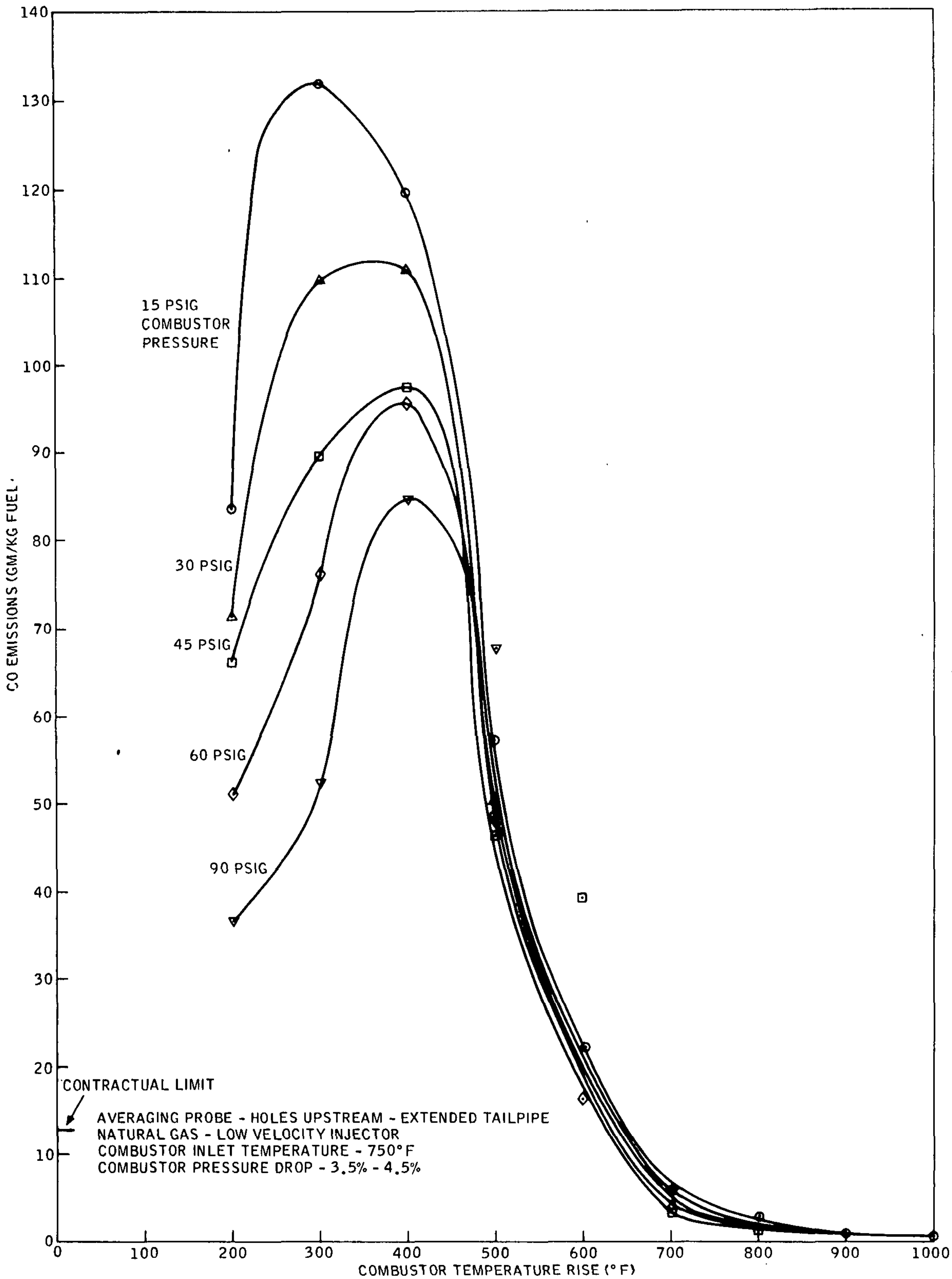


FIGURE 8. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

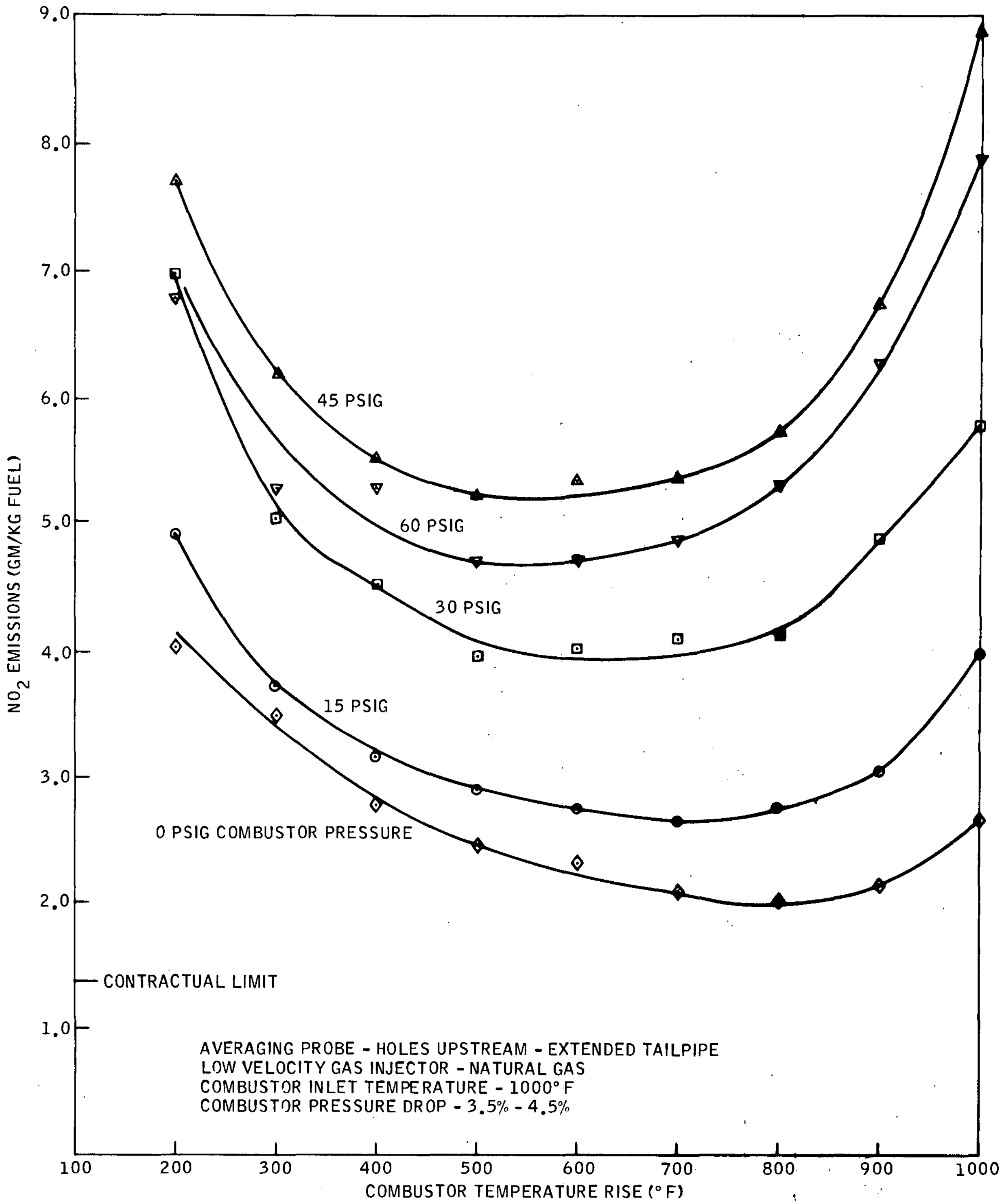


FIGURE 9. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

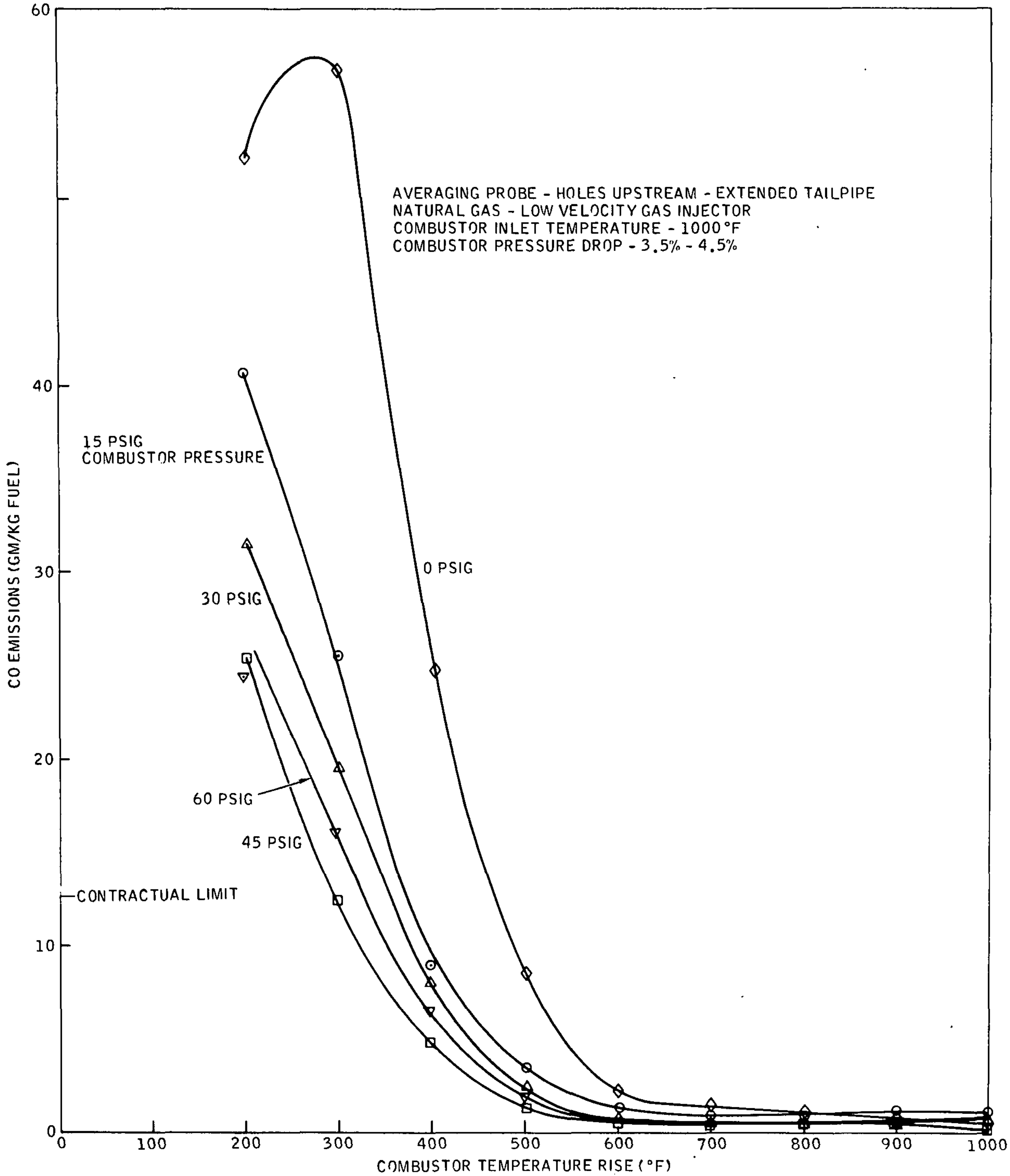


FIGURE 10. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

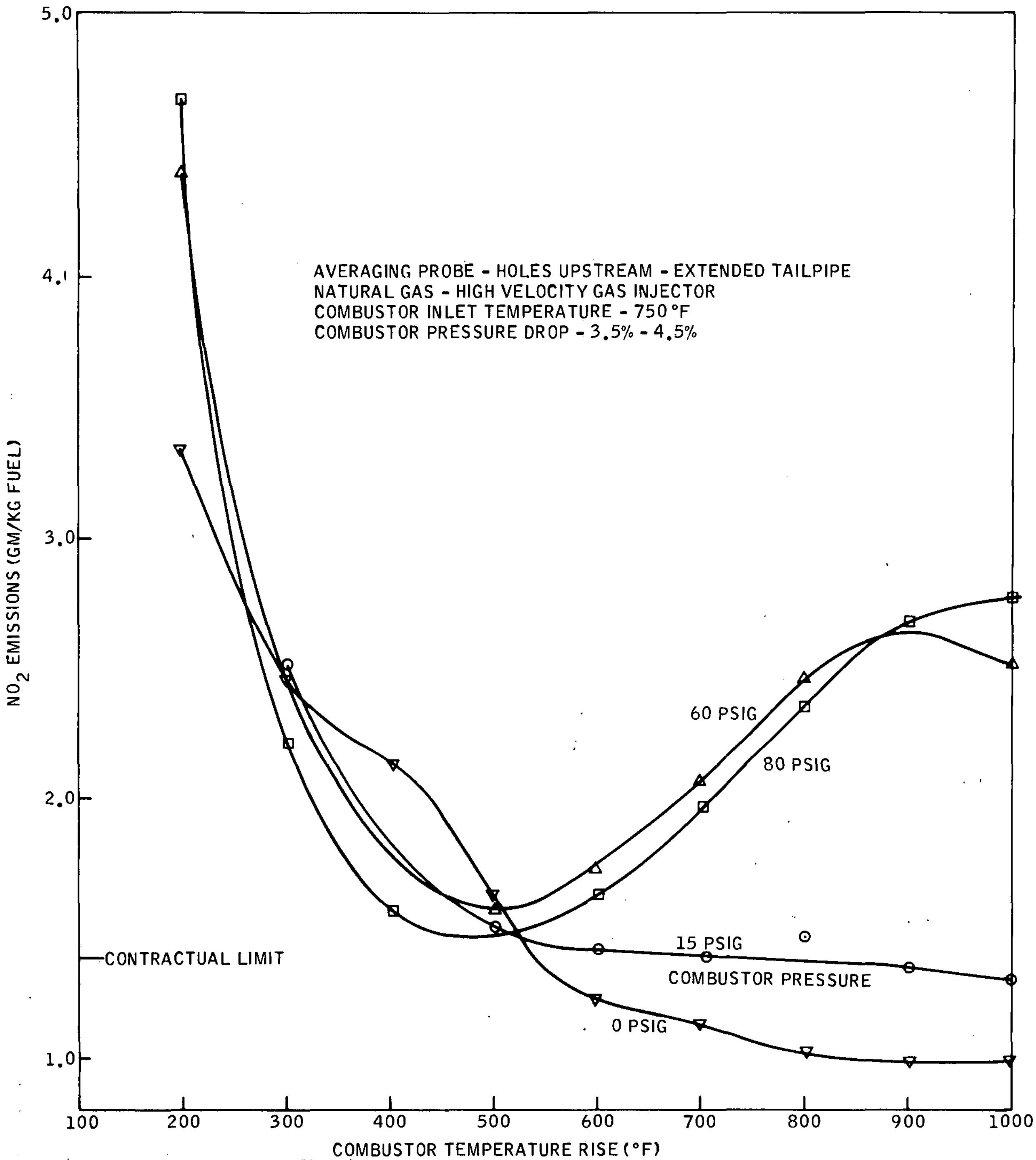


FIGURE 11. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

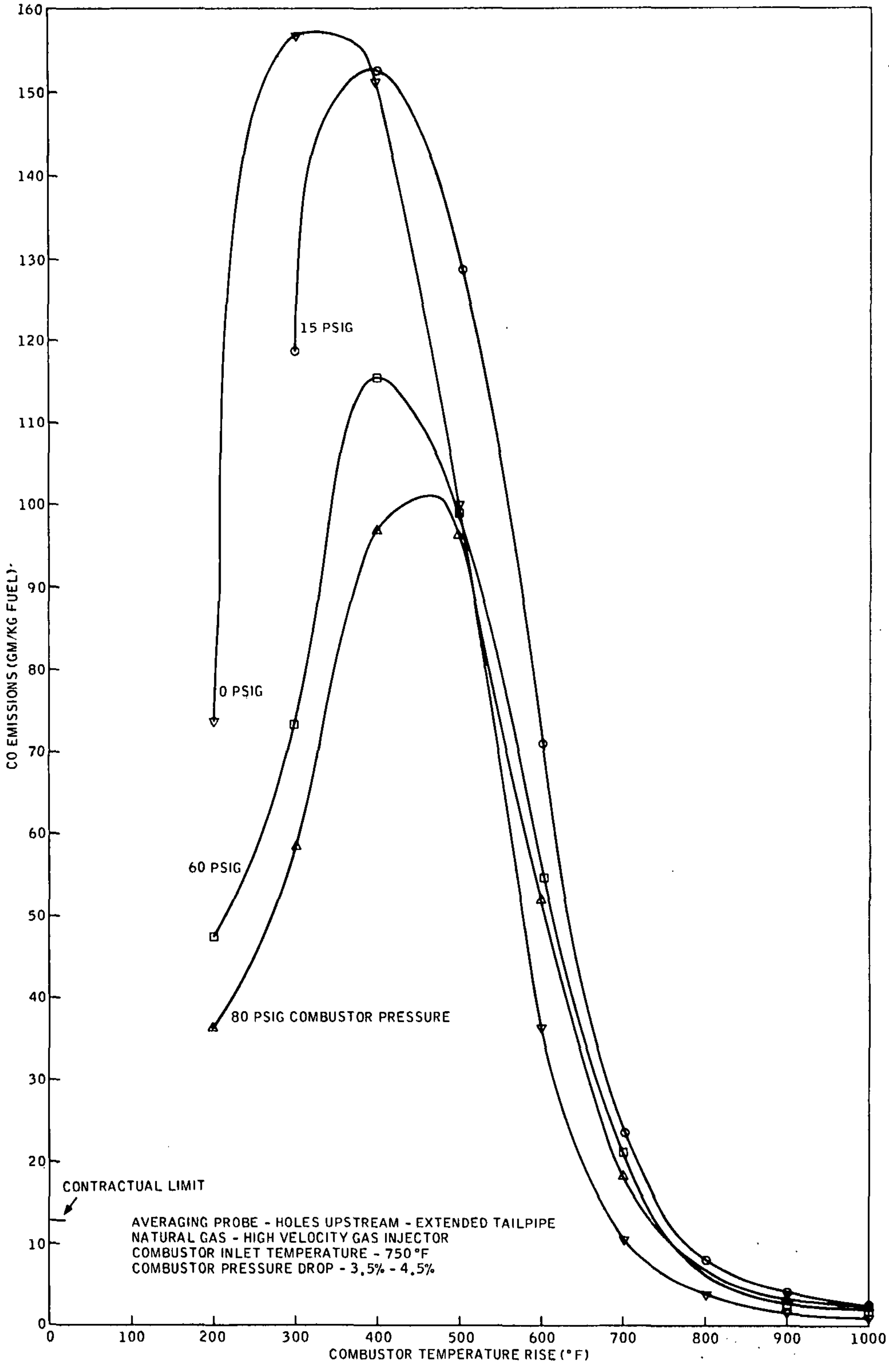


FIGURE 12. EMISSION CHARACTERISTICS OF MOD. 9 COMBUSTOR

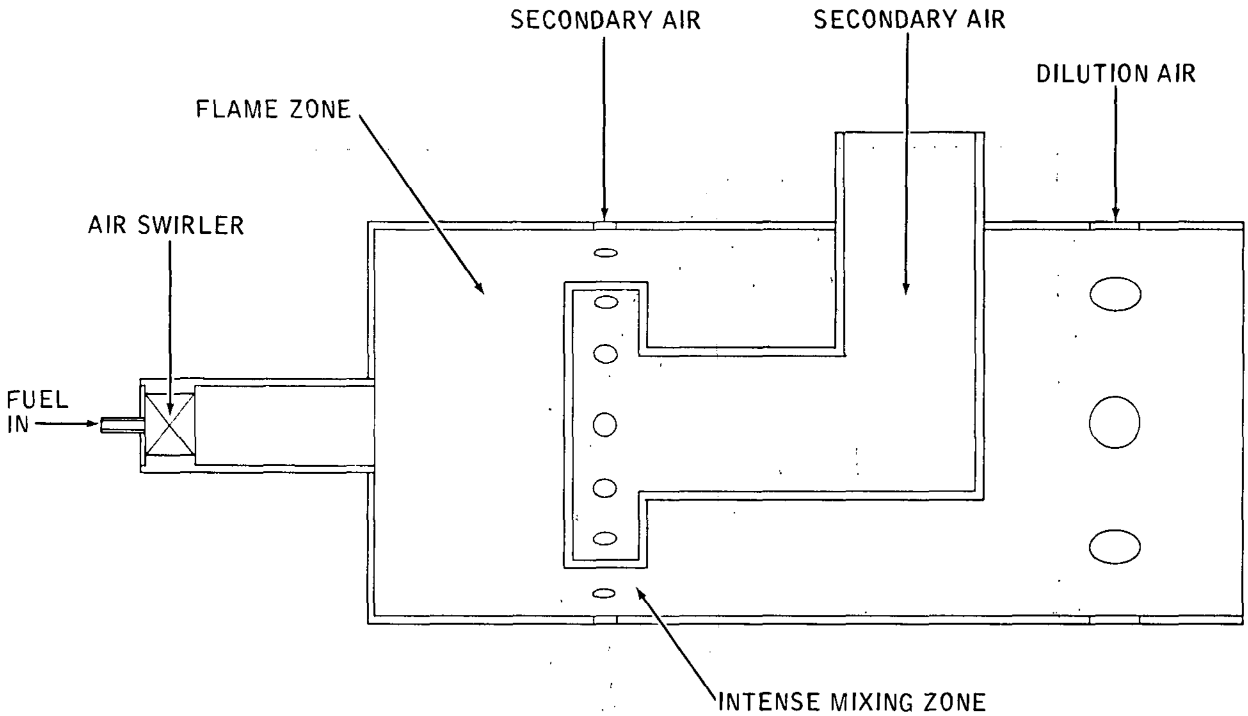


FIGURE 13. RAPID MIXING TRANSITION ZONE COMBUSTOR

during the mixing, if the production of NO_X is to be minimized. In an attempt to provide such mixing rates, a transition zone was constructed to provide opposed air jets, each offset from the other. The resulting turbulent zone along the edge of each jet was intended to provide rapid mixing of the fuel rich product gases from the primary zone as they exit with the incoming secondary air.

The results obtained on the NO_X emissions indicate that at atmospheric pressure the contractual limits can almost be met, but the emissions of carbon monoxide are outside their limit, as can be seen in Figure 14. At higher pressures the results show that although the emission of carbon monoxide is much reduced, the NO_X levels are substantially increased. The reduced NO_X levels at the atmospheric condition could be due to the low combustion efficiency, as indicated by the high emission level of carbon monoxide at the same conditions. Low combustion efficiencies in general would reduce local high temperature zones and thus reduce the NO_X produced. At higher pressures since the combustion efficiency is approximately proportional to the pressure squared, the increased combustion efficiency ensures low carbon monoxide levels but high emission rates of NO_X.

3.3 LEAN PRIMARY ZONE COMBUSTORS

One of the most promising alternate approaches to the design of a low emission (particularly low NO_X) combustor determined during the conceptual model phase of the program was the lean primary zone system. In this approach the problem of low NO_X emission is essentially traded for a problem in flame stability. Provided some means

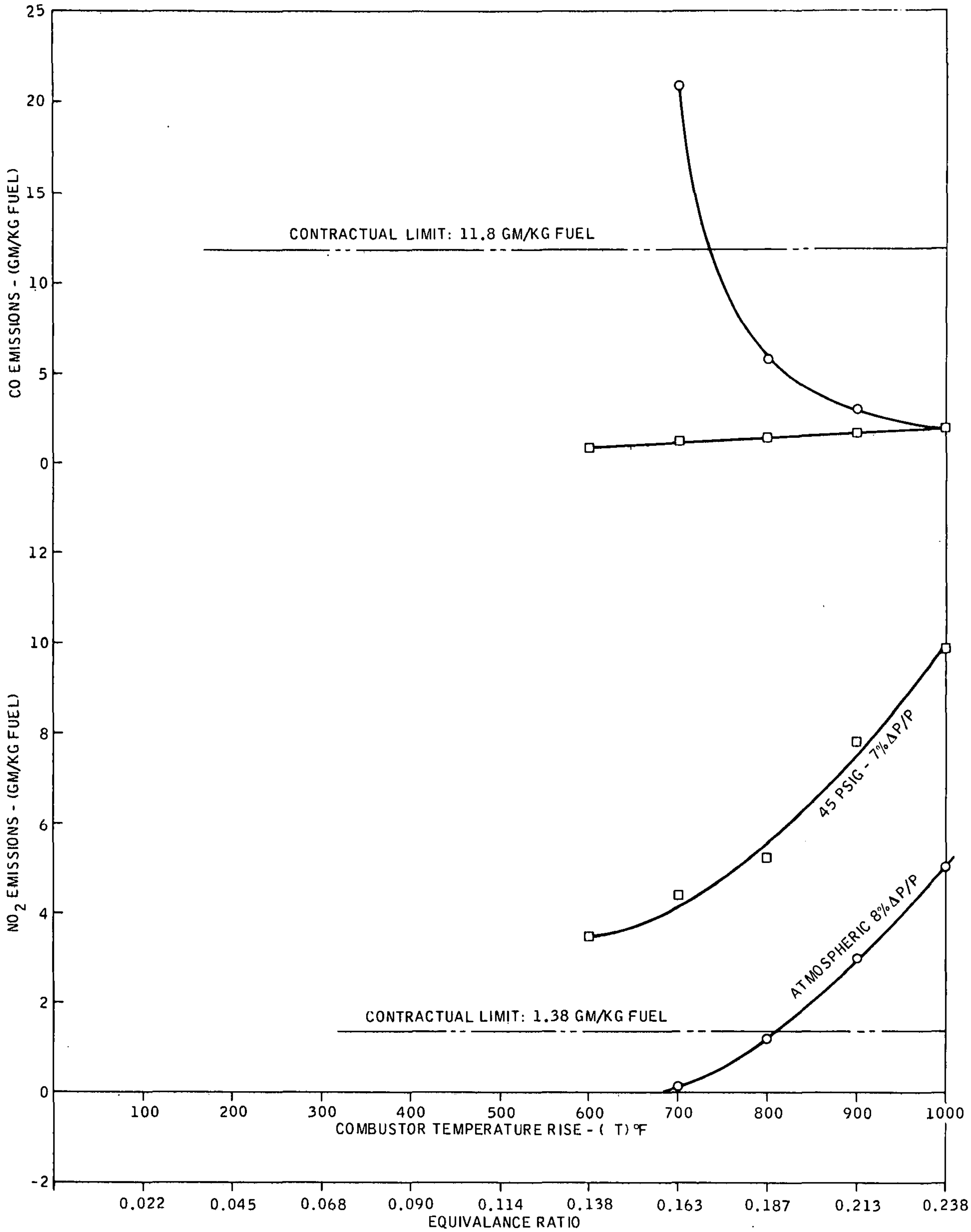


FIGURE 14. RESULTS OF RICH PRIMARY ZONE COMBUSTOR

of stabilizing a flame at primary zone equivalence ratios low enough to produce local zone temperatures less than 3200°F can be devised, then low NO_x levels can be obtained. In addition, sufficient residence time has to be provided in the primary zone to allow the complete reaction of the fuel, thus ensuring concomitant low emissions of CO and UHC. Generally, in lean primary zone combustor designs the problem of mixing the fuel and air is more difficult than that in the rich primary zone designs, mainly because of the increased volume of air to be mixed with the fuel. The percentage of fuel in the primary zone mixture drops from 2 percent for the fuel rich system to 0.55 percent for the fuel lean approach.

Several different methods of obtaining stability at the low equivalence ratios necessary were evolved and these are discussed in the following section.

3.3.1 Lean Primary Zone Pilot System

One of the major problems, as mentioned above, of the homogeneous lean stabilized system is the reduced stability range at low temperature rise levels or low overall equivalence ratios. This in turn indicates a definite need for equivalence ratio control through variable area or geometry control. Since the mechanical control of the flow area could become cumbersome and possibly difficult to operate, an approach was sought which might eliminate the need for such control. The concept used initially to provide the combustion stability needed, over the entire operating range, was that of a "pilot" combustion system. In operation, the main fuel and air were premixed and introduced upstream of a conical stabilizer, which is shown in Figure 15. This stabilizer also provided the housing for the pilot flame.

It can be seen in Figures 16 and 17 that although the contractual limits for NO_x are met for a wide range of conditions, the emissions of carbon monoxide and hydrocarbons are generally above their limits. This poor efficiency was caused basically by using a single flame-stabilizer device with medium blockage (approximately 32%). If multiple, annular ring stabilizers had been used, the efficiency could have been much higher and consequently the emissions of carbon monoxide and unburned hydrocarbons much lower. As a result of the low combustion efficiency, it could be argued that the local temperatures were much reduced, and that this in turn led to the low levels of NO_x. If this were true, then increasing the efficiency by designing a better stabilizing device could lead to increased NO_x emission levels.

3.3.2 Lean Primary Zone Vortex Induced Circulation System

One proven method for achieving rapid mixing of the fuel and air is a vortex or swirl generator. These devices, by virtue of the high shear gradients created, tend to have high mixing rates. In this concept the method of recirculating a large quantity of hot products provides the stability required, by both preheating the incoming air and fuel and then igniting the mixture. The preheating effect is important since, by lowering

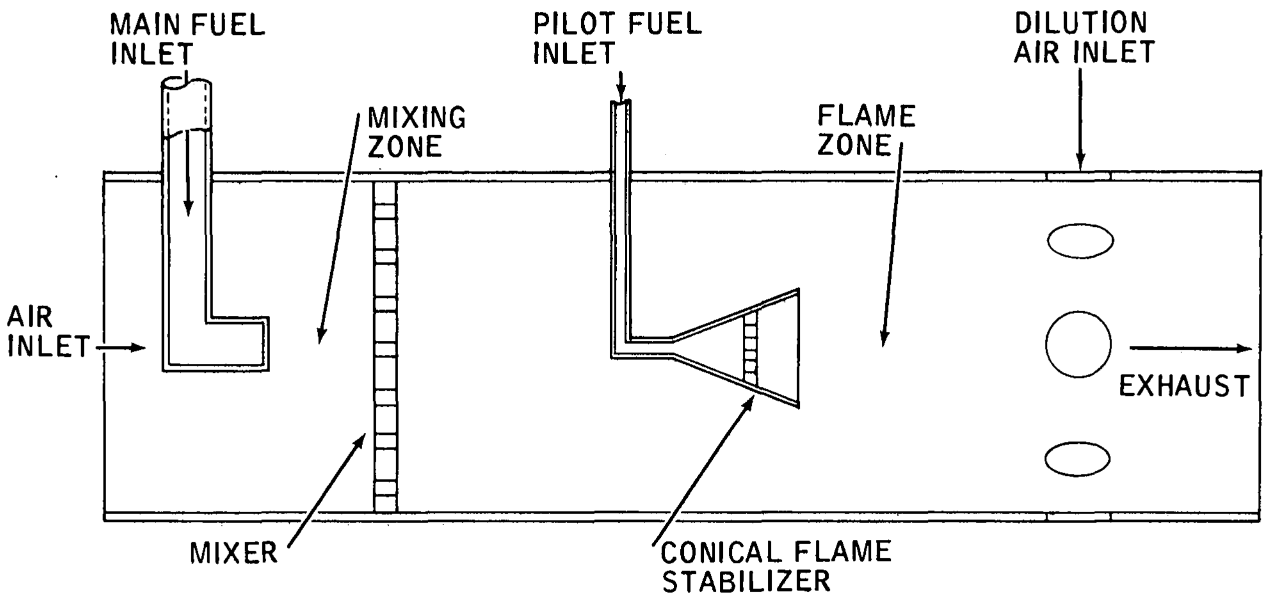


FIGURE 15. SCHEMATIC OF LEAN PRIMARY ZONE PILOT FLAME COMBUSTOR

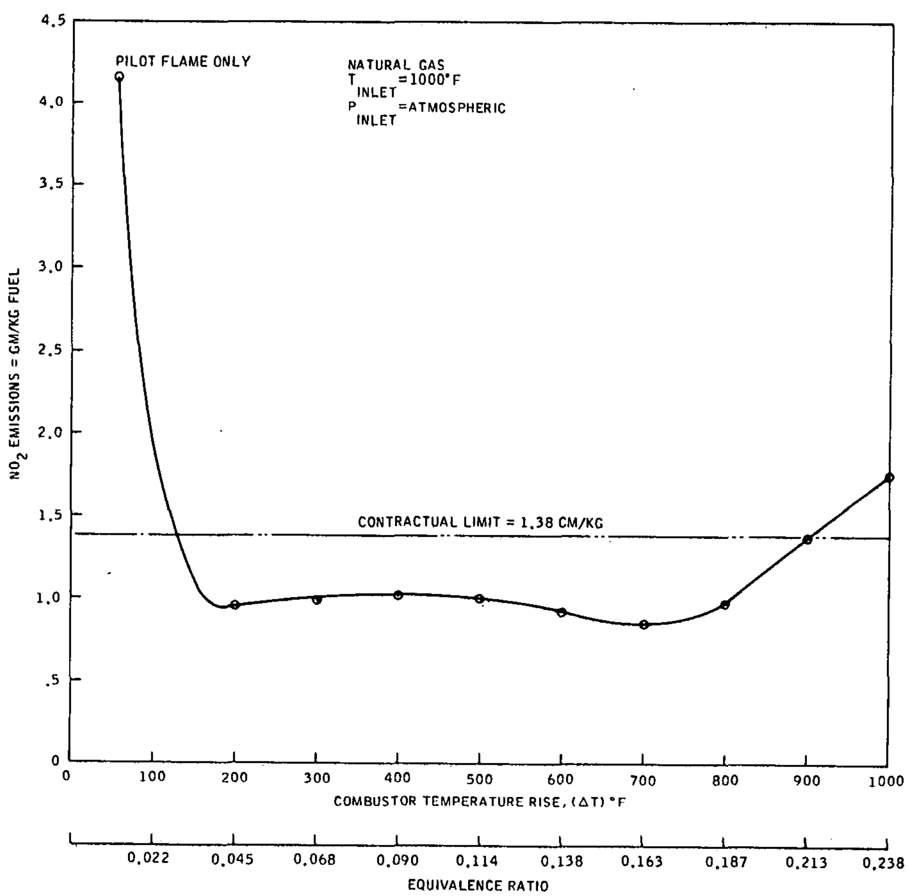


FIGURE 16. RESULTS OF LEAN PRIMARY ZONE PILOT FLAME COMBUSTOR

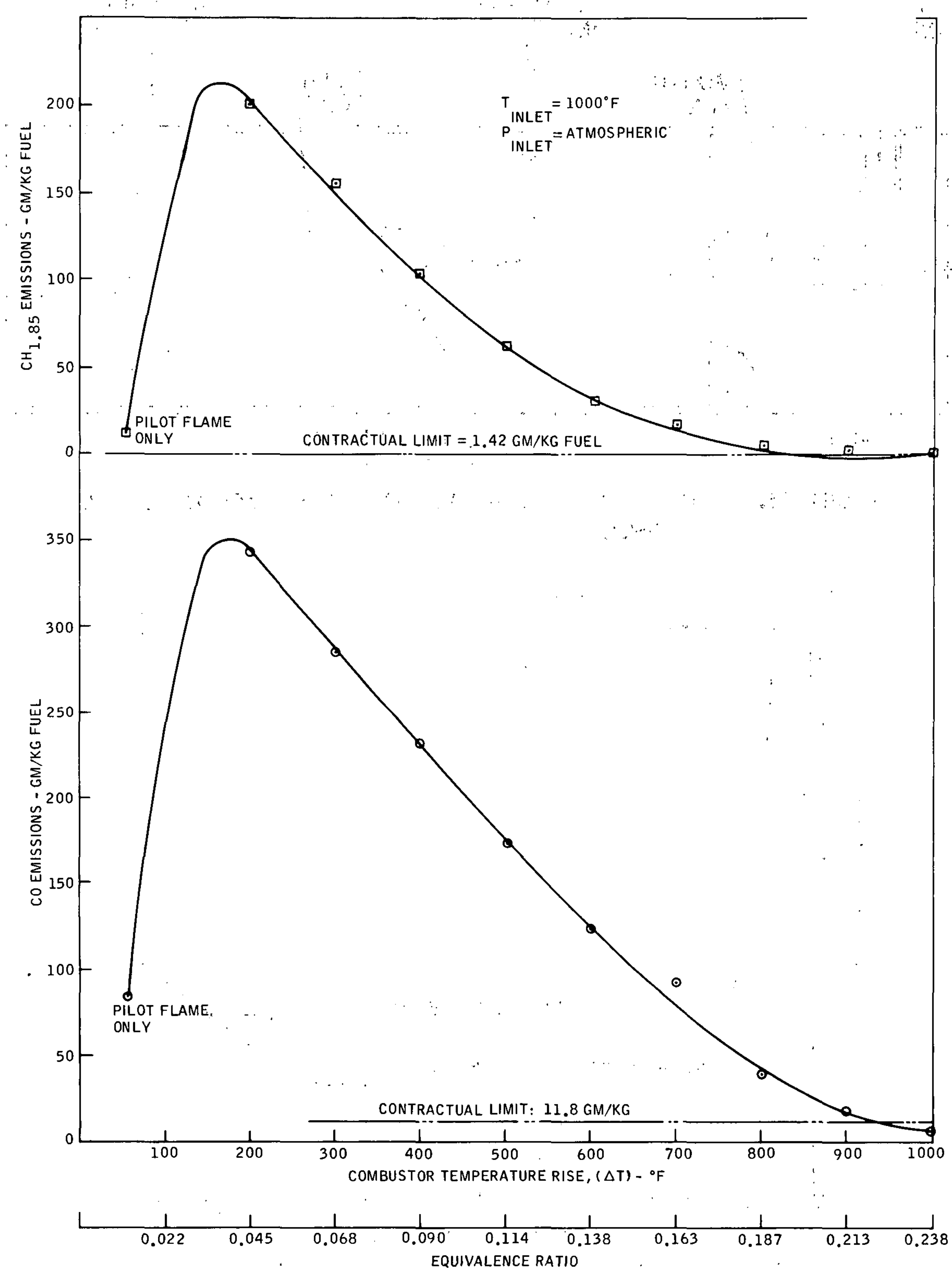


FIGURE 17. RESULTS OF LEAN PRIMARY ZONE PILOT FLAME COMBUSTOR

the ignition temperature, it allows stabilization of the combustor at primary zone equivalence ratios lower than the room temperature flammability limits.

The results of running the swirl or vortex stabilized lean primary zone combustor, as shown in Figure 18, with natural gas as fuel, are shown in Figures 19 and 20. These show that the NO_x level increases rapidly as the equivalence ratio increases toward the stoichiometric value. Essentially, this effect appears to be a chemical kinetic controlled mechanism, in which increased combustion temperature increases the reaction rate. As the equivalence ratio decreases toward zero, the NO_x level again increases rapidly, as does the carbon monoxide level, which is due to a rapid deterioration in mixing between the air and fuel. It is important to note that due to rig limitations the combustor mass flow was such that the pressure drop across the combustor during this test was slightly in excess of 30 percent.

A second version of this type of combustor was tested with the gaseous fuel injector replaced by an air-assist liquid fuel atomizer. Detailed tests with this arrangement of atomizer revealed poor fuel atomization and mixing characteristics, resulting in large areas at near stoichiometric conditions and, consequently, high NO_x emission levels. In order to evaluate the effects of fuel atomization and mixing, and also to provide lower NO_x emissions, a high pressure, simplex, swirl atomizer providing a spray with a SMD* of less than 40 microns was incorporated, replacing the earlier air-

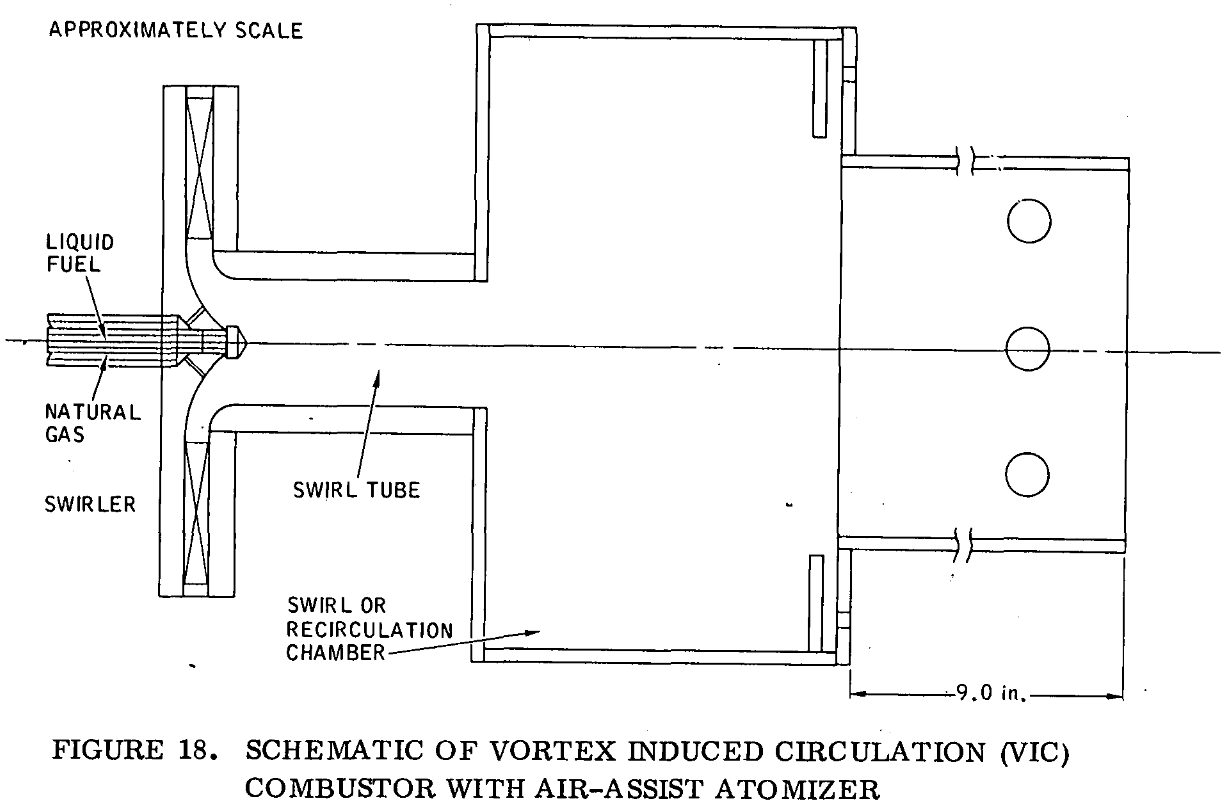


FIGURE 18. SCHEMATIC OF VORTEX INDUCED CIRCULATION (VIC) COMBUSTOR WITH AIR-ASSIST ATOMIZER

*SMD is Sauter Mean Diameter

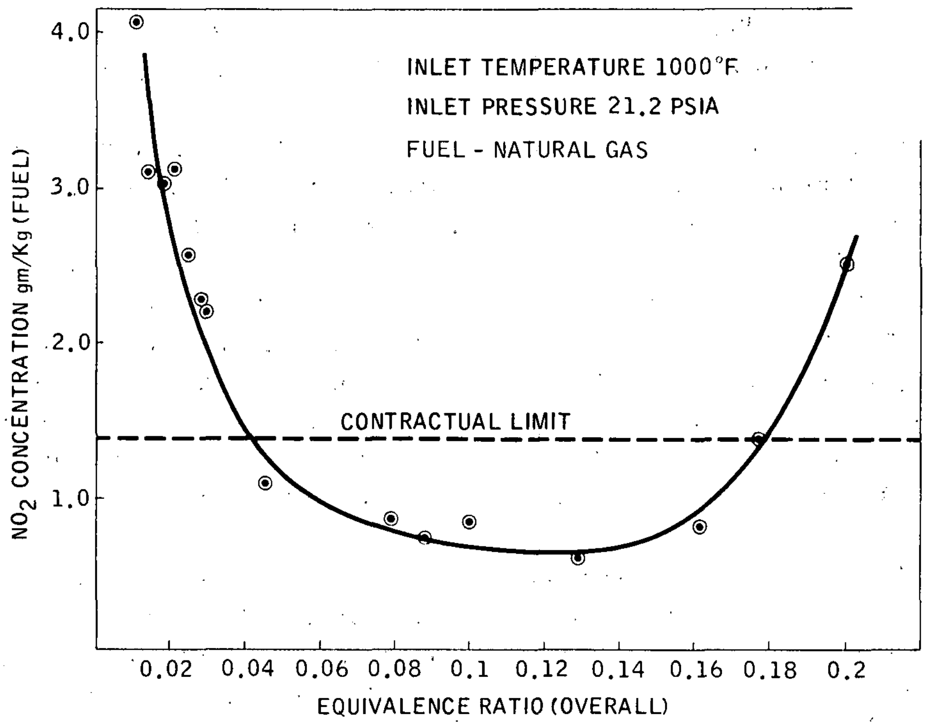


FIGURE 19. VORTEX STABILIZED LEAN PRIMARY ZONE COMBUSTOR (NO_X EMISSION)

assist system. In addition to the simplex atomizer, a further change was incorporated into the design. This change consisted of a cooling strip on the back face of the recirculation zone chamber, as shown in Figure 18. Incorporation of this cooling device was to correct problems encountered during the air-assist atomizer testing when corner weld failures held up the progress of testing. As was expected, the trend of the NO_X emissions is similar to those obtained with the air-assist atomizer but the emissions were lowered and approached the results provided by natural gas, obtained earlier in the program.

Because of the success of the liquid fuel high pressure, simplex atomizer combustor, in meeting the contractual limits in the exploratory tests, it was decided that a map of the emission characteristics at various pressure levels was necessary for a full evaluation. A map of the NO_X emission level at a 1000°F inlet temperature, and with a constant pressure drop, was recorded as a function of combustor temperature rise at various inlet pressures. The results of these tests are shown in Figure 21. As can be seen, the atmospheric pressure results do not extend down to the low temperature rise levels, and thus do not go below the contractual limits. The reason for the omission of these points is that failure of the gas sampling system occurred during the test. It can be surmised from earlier test results with similar trends, that the NO_X emissions would fall below the contractual goals at low temperature rises.

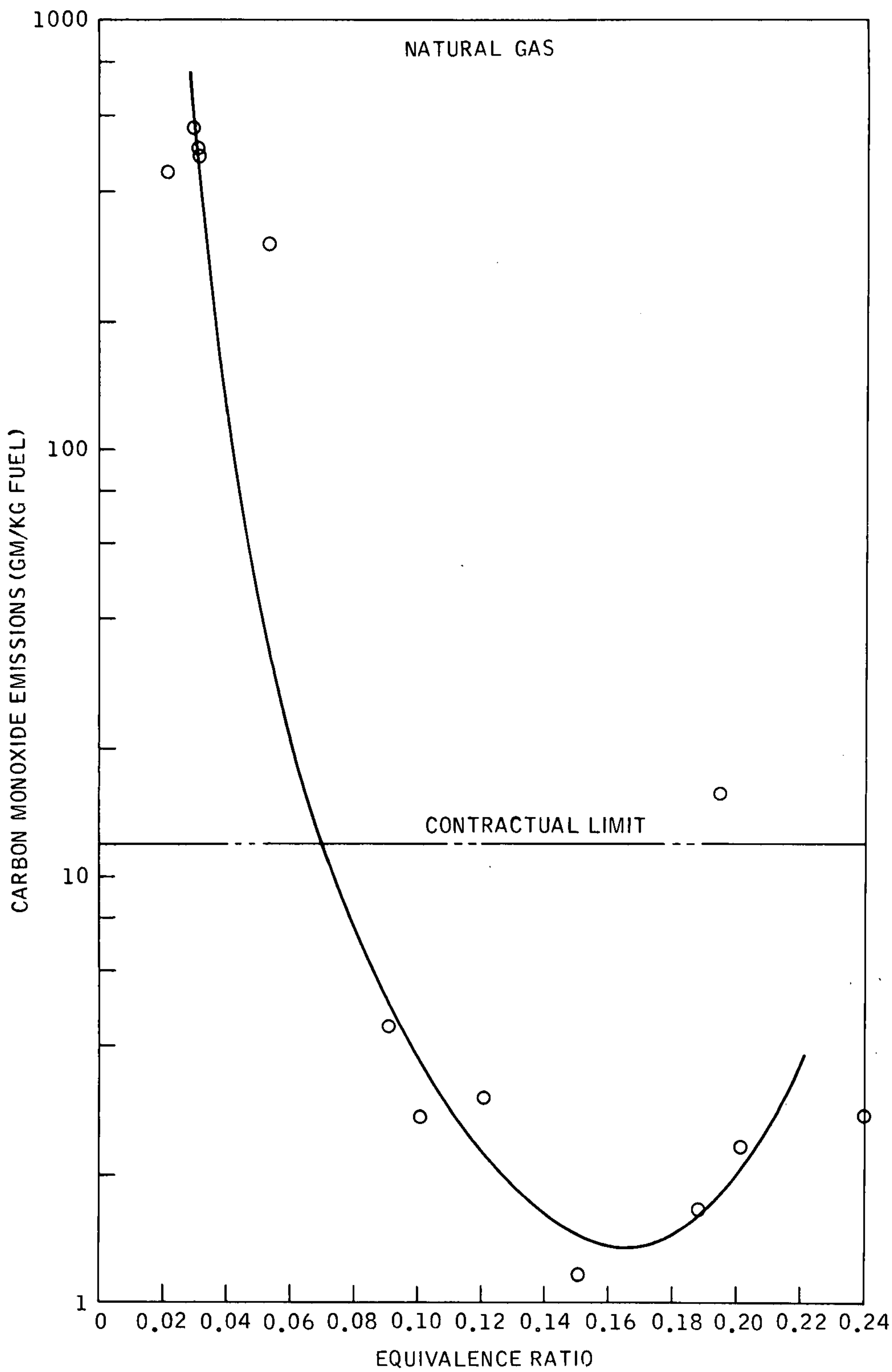


FIGURE 20. VORTEX STABILIZED LEAN PRIMARY ZONE COMBUSTOR (CO EMISSIONS)

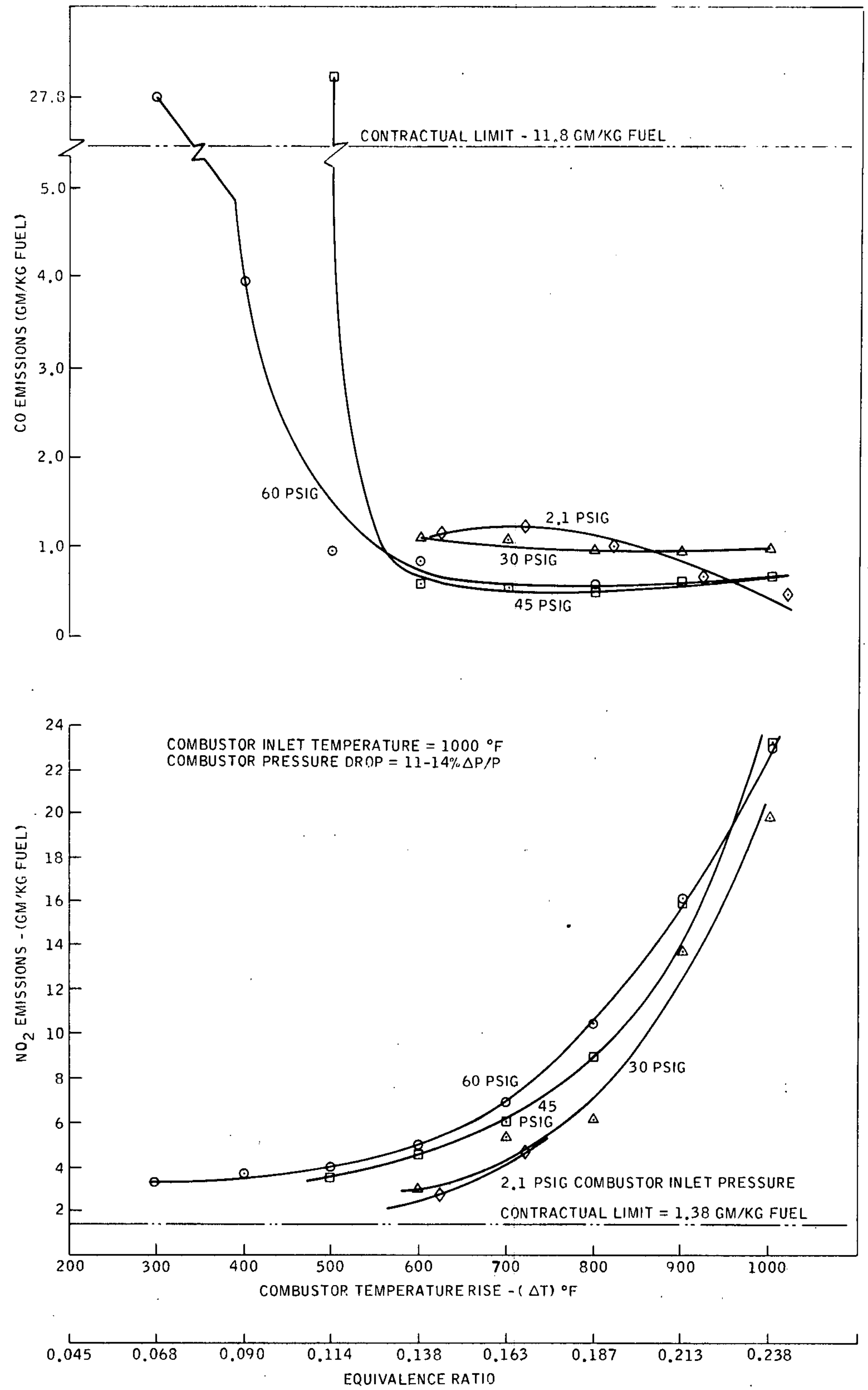


FIGURE 21. RESULTS OF VORTEX INDUCED CIRCULATION (VIC) LEAN PRIMARY ZONE COMBUSTOR

As the pressure level increases, the trend is for the curves of NO_2 versus temperature rise to increase their overall NO_2 levels, although this dependency is not as marked as that exhibited by the initial rich primary zone combustors.

3.3.3 Lean Primary Zone Jet Induced Circulation System

A third lean primary zone approach was also investigated where a large scale recirculation with recirculating mass flows greater than the inlet flow rate by a factor of 1.4 was accomplished by an ejector method. In this system, the injected air and fuel are premixed and act as the motive jet in a jet educer in which the fluid entrained is the hot products of combustion. Using this method of stabilization it is possible to provide stability at an equivalence ratio of about 0.28 in the primary zone with a premixed air and fuel mixture. This model was not produced as a complete combustor but as a primary zone alone without a dilution section.

In Figure 22 the results of the ejector recirculation system show a fairly constant trend for the NO_x level versus equivalence ratio. Little variation of the carbon monoxide (Fig. 23) emissions with equivalence ratios greater than 0.40 is also evident. The increase in carbon monoxide at lower equivalence ratios was considered a chemical kinetic phenomenon. Apparently at these low equivalence ratios the hydrocarbon reaction rates decrease rapidly, creating quantities of carbon monoxide. This particular configuration was constructed without any form of cooling, which prevented

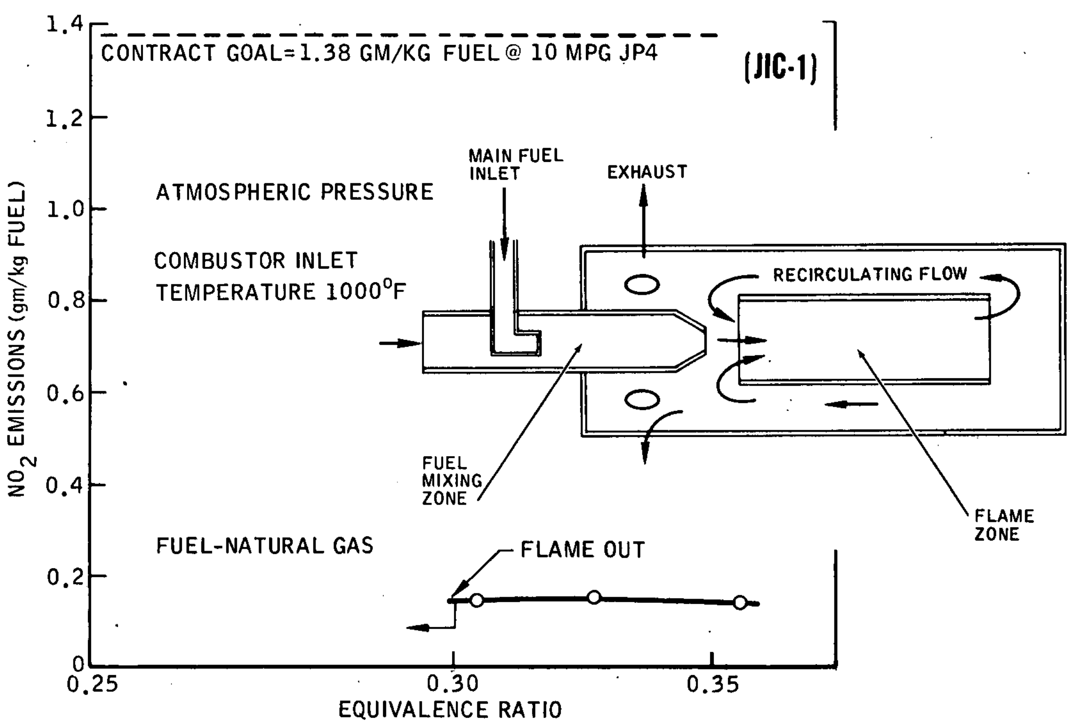


FIGURE 22. HIGH RECIRCULATION STABILIZED LEAN PRIMARY ZONE COMBUSTOR (NO_x EMISSIONS)

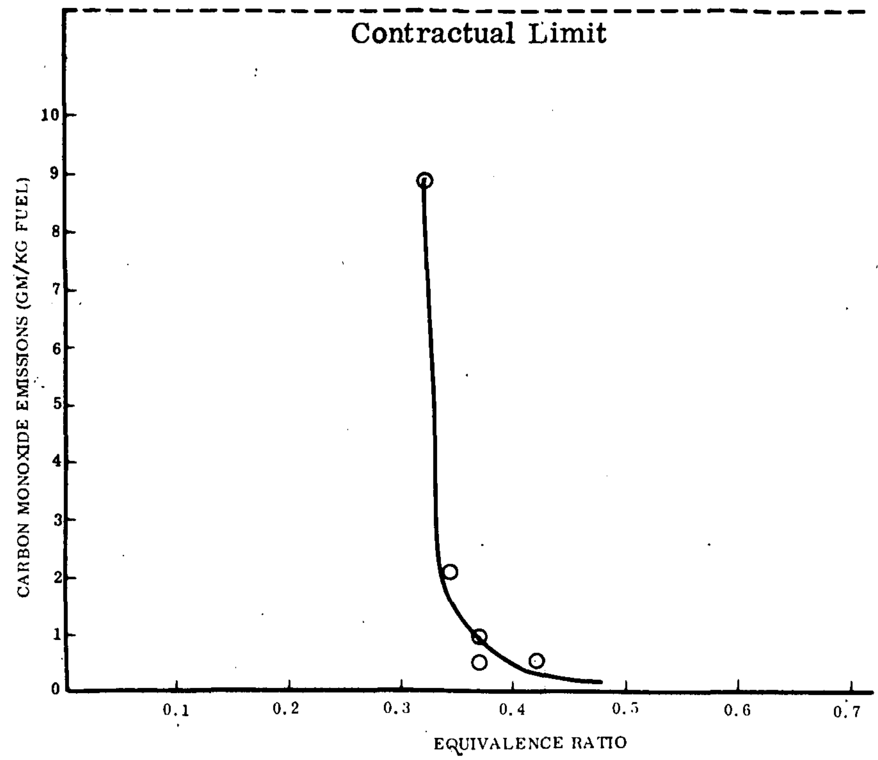


FIGURE 23. HIGH RECIRCULATION STABILIZED LEAN PRIMARY ZONE COMBUSTION (CO EMISSIONS)

extended testing at equivalence ratios greater than 0.4. In addition, the injected air and fuel was fully premixed, which in general reduced the stability limits. The lowest equivalence ratio at which stable combustion occurred was approximately 0.28. This, if considered on an overall combustor basis, remembering that the model was composed only of a primary zone, would represent an equivalence ratio of about 0.07.

Developments of this initial recirculation combustor were also tested. In these combustors a high level of recirculation was obtained by injecting the primary air and partially premixed liquid fuel through a series of ports angled toward the dome at a 45 degree angle to the combustor axis. These angled jets impinged at the combustor axis, forming two axially derived jets, one moving towards the dome and the other downstream toward the exhaust. The major portion of the flow moved toward the dome, providing a jet that behaved in a similar fashion to the motive jet of an ejector.

A schematic of this jet induced circulation (JIC) system is shown in Figure 24. A measure of premixing between the liquid fuel and the air is obtained by using multiple air atomizers as the primary zone feed ports. This premixing prior to reaction minimizes the production of stoichiometric "islands" or areas, where NO_x can be formed, that are normally associated with co-current mixing and reaction. In order to achieve stabilization at these extremely lean equivalence ratios a high degree of recirculation

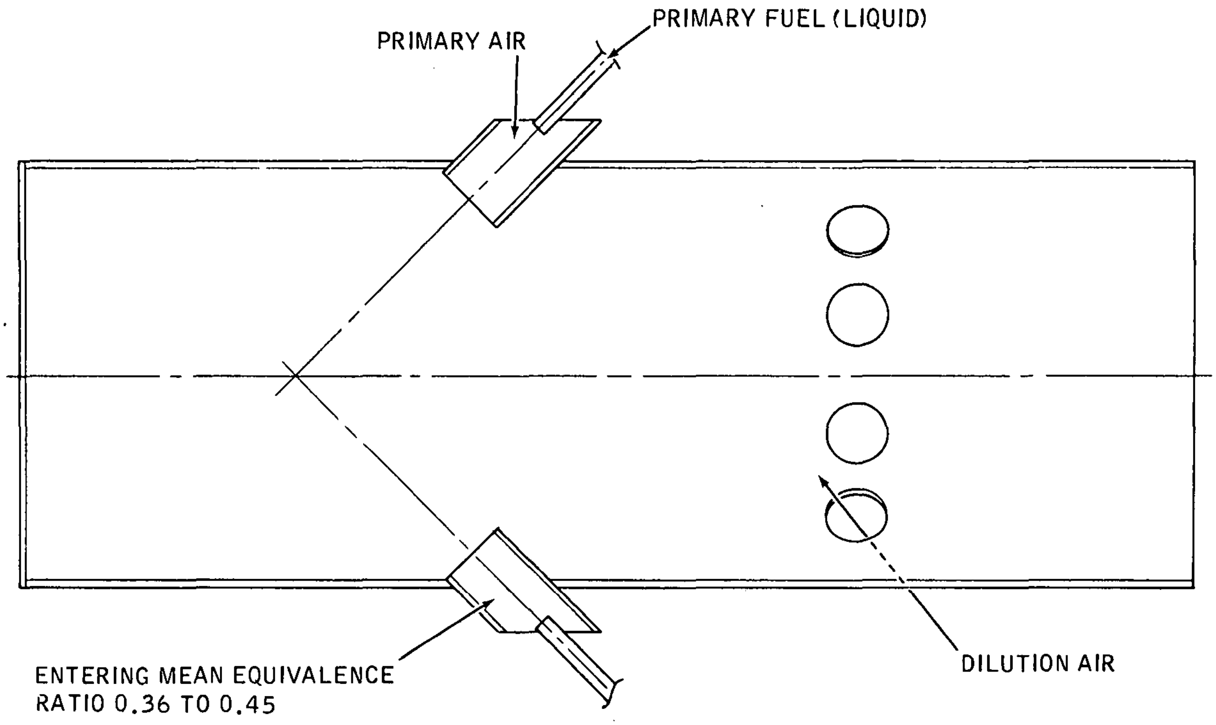


FIGURE 24. SCHEMATIC OF JET INDUCED CIRCULATION COMBUSTOR (JIC)

is required, and this has been provided as mentioned above, by the movement toward the combustor dome of the motive jet produced from the interaction of the impinging jets from the primary zone air atomizers. Recirculation ratios obtained in this particular design are approximately 60 to 70 percent of the primary zone inlet mass flow. A reduced performance map of this combustor was produced and is shown in Figure 25. These results indicate that with an inlet temperature of 1000°F at both atmospheric conditions and at 40 psig the contractual requirements are met over the equivalence ratio (overall) range of approximately 0.1 to 0.126.

The results of the tests at an inlet temperature of 750°F surprisingly show higher NO_X levels than those recorded with a 1000° F inlet. This indicates that the NO_X produced is mainly mixing controlled under these conditions since the major physical change between the two tests is that of the rate of vaporization of the fuel. At the higher inlet temperatures increased vaporization rates result in overall increased air-to-fuel mixing rates and consequently fewer deviations from the mean primary zone equivalence ratio. With the combustor primary zone operating at an essentially uniform (premixed) equivalence ratio, no deviations toward the stoichiometric region occur and hence no "islands" of high temperature occur, which at these lean conditions would produce NO_X.

With the success of the Jet Induced Circulation (JIC) combustor in meeting the contractual requirements at ambient pressure, it was decided to pursue the investigation further and obtain the emissions index at a variety of pressure levels. The results of

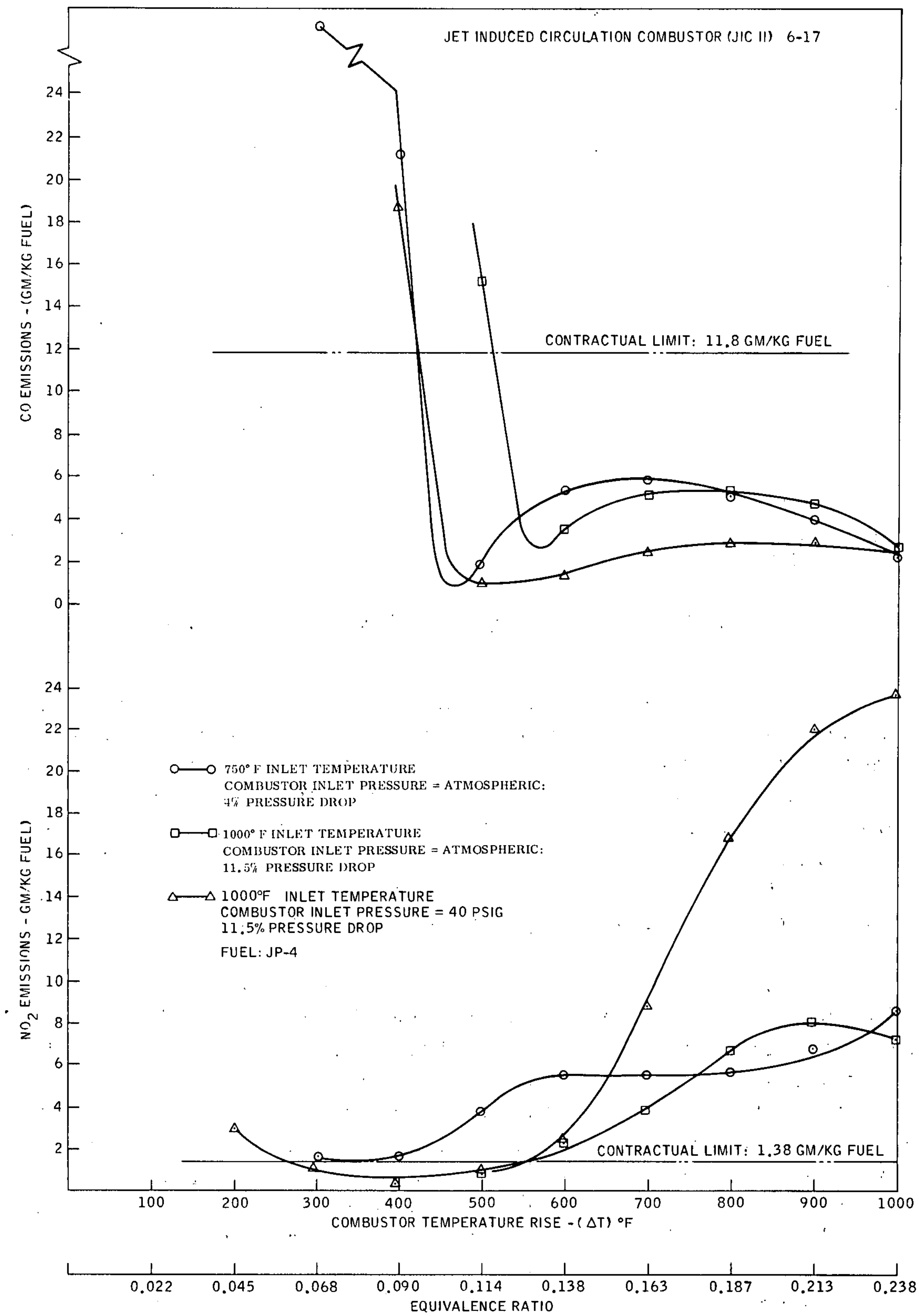


FIGURE 25. RESULTS OF JET INDUCED CIRCULATION (JIC) LEAN PRIMARY COMBUSTOR (INITIAL FUEL INJECTOR POSITION)

these investigations are shown in Figures 26 and 27. A slight modification to the primary zone ports/air blast atomizers was made to the model before running the above tests, which consisted of moving the fuel injector tip further out toward the cooling annulus. This modification in essence provided a longer air-fuel mixing length before reaction thus allowing the production of a nearly homogeneous equivalence ratio in the inlet reactant stream.

As the results indicate, this particular combustor concept is capable of meeting the contractual requirements of both the emissions of NO_X and CO over a discrete range of (overall) equivalence ratio, approximately 0.057 to 0.1. The corresponding primary zone equivalence ratio range, which is the controlling factor for the emissions at a fixed set of inlet conditions, varies from 0.175 to 0.3 approximately. It may be noted from the results that the stability range is less at low pressures, near ambient, than at higher values. This phenomenon may be related to reduced fuel droplet penetration at the higher pressures resulting in a higher peak equivalence ratio in each of the primary zone jets. If this is the correct explanation to the results then a similar effect could be achieved at low pressures by reducing the fuel velocity at the fuel injector tip.

3.4 PARAMETRIC COMBUSTOR DESIGNS

The conceptual designs of both the Class A and B combustors were based on the jet induced circulation (JIC) model combustor configuration (see Fig. 24) and have been designated JIC-3 and JIC-4, respectively. The key feature of the design is the combined primary zone, ports and air blast atomizers, which can be seen in the assembly drawing, Figure 28. By incorporating an air-blast atomizer into each of the primary zone inlet ports, which number eight in total, a very even fuel to primary zone air ratio distribution is achieved. Although this multiple atomizer arrangement poses some mechanical difficulties, it has shown itself to be considerably superior in performance to a single fuel injector. In general, it is extremely difficult to provide the same degree of mixing with a single atomizer that can be obtained with multiple fuel injectors, even when high pressure air-assist atomizer types are considered. In addition to the equivalence ratio uniformity obtained by having multiple fuel injectors, by arranging the fuel to be injected into the primary zone air jets, a substantial mixing length prior to ignition and reaction is obtained. This mixing length is increased further by angling the inlet ports to the combustor axis, as shown in Figure 28. Thus by combining the effects of multiple fuel injectors and a premixing zone, a nearly homogeneous fuel and primary zone air mixture can be obtained. The primary air and mixed fuel jets impinge on the combustor centerline and form two axially derived jets, one moving toward the dome and the other rearward toward the exhaust. The effect of angling the ports toward the dome is to ensure that the bulk of the fuel-air mixture moves into the primary zone section. This main derived jet impinges on the combustor dome, which, in conjunction with the combustor walls, causes the mixture (substantially reacted by this time) to recirculate toward the incoming primary air jets.

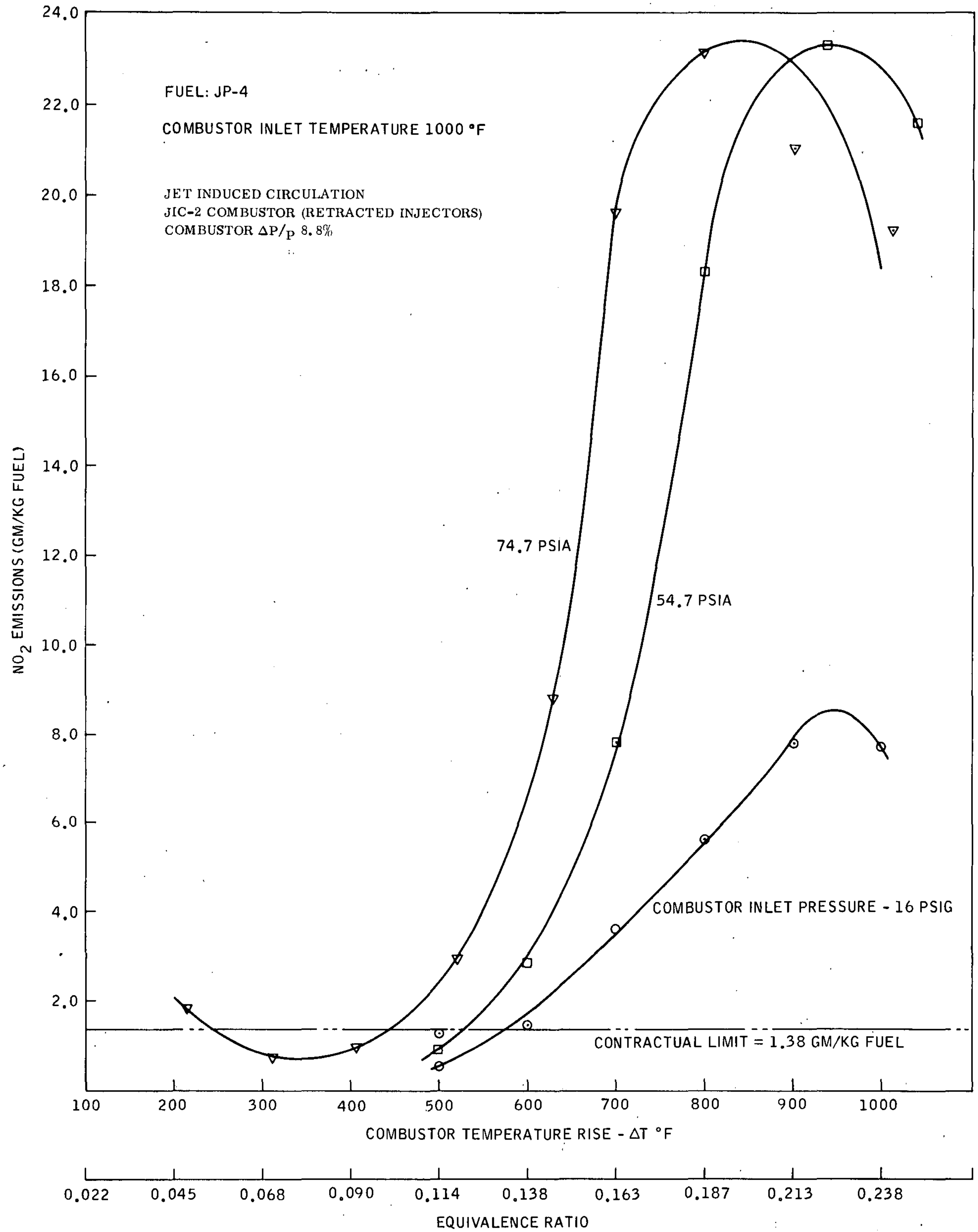


FIGURE 26. RESULTS OF JET INDUCED CIRCULATION (JIC) LEAN PRIMARY ZONE COMBUSTOR (MODIFIED FUEL INJECTOR POSITION)

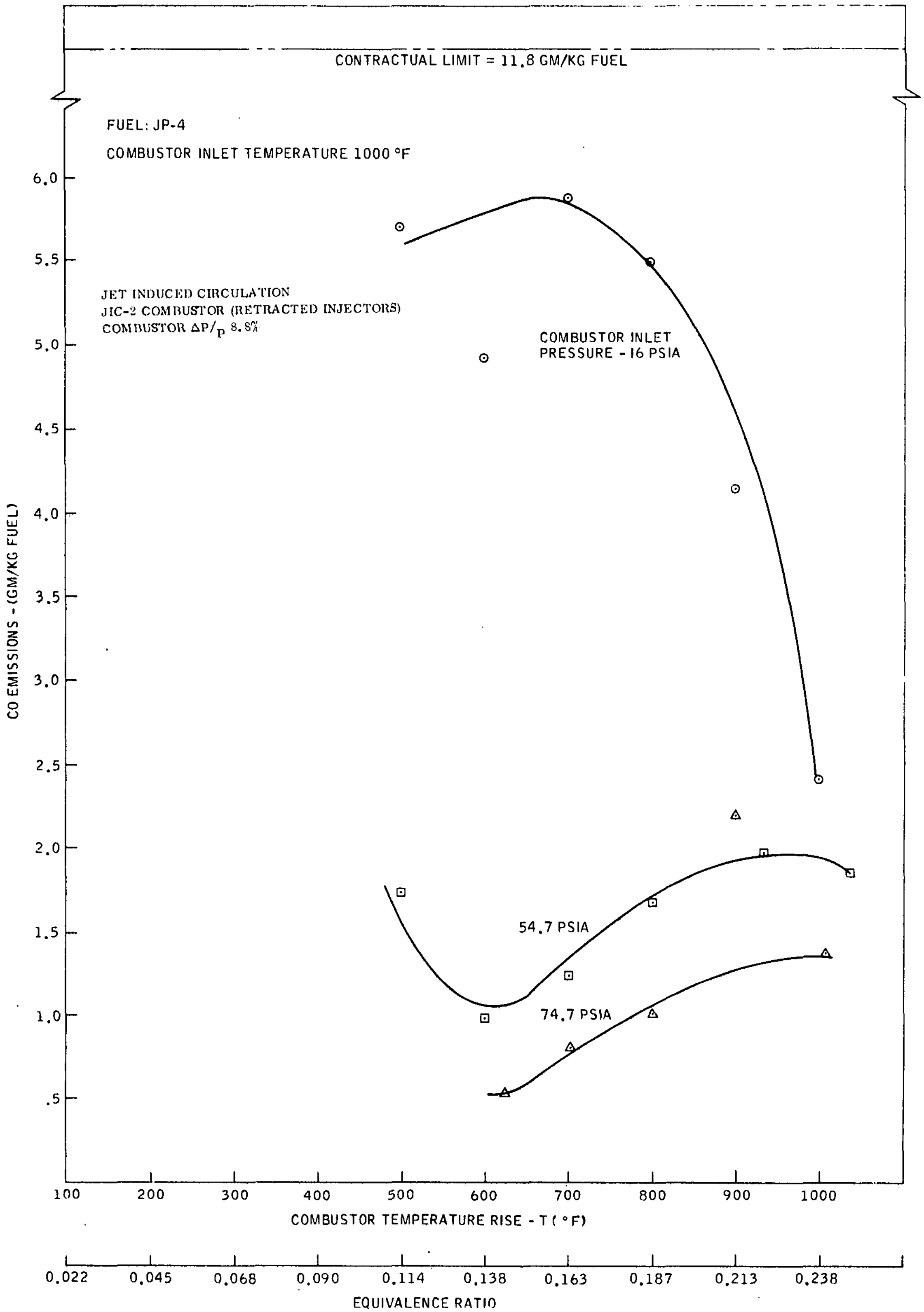


FIGURE 27. RESULTS OF JET INDUCED CIRCULATION (JIC) LEAN PRIMARY ZONE COMBUSTOR (MODIFIED FUEL INJECTOR POSITION)

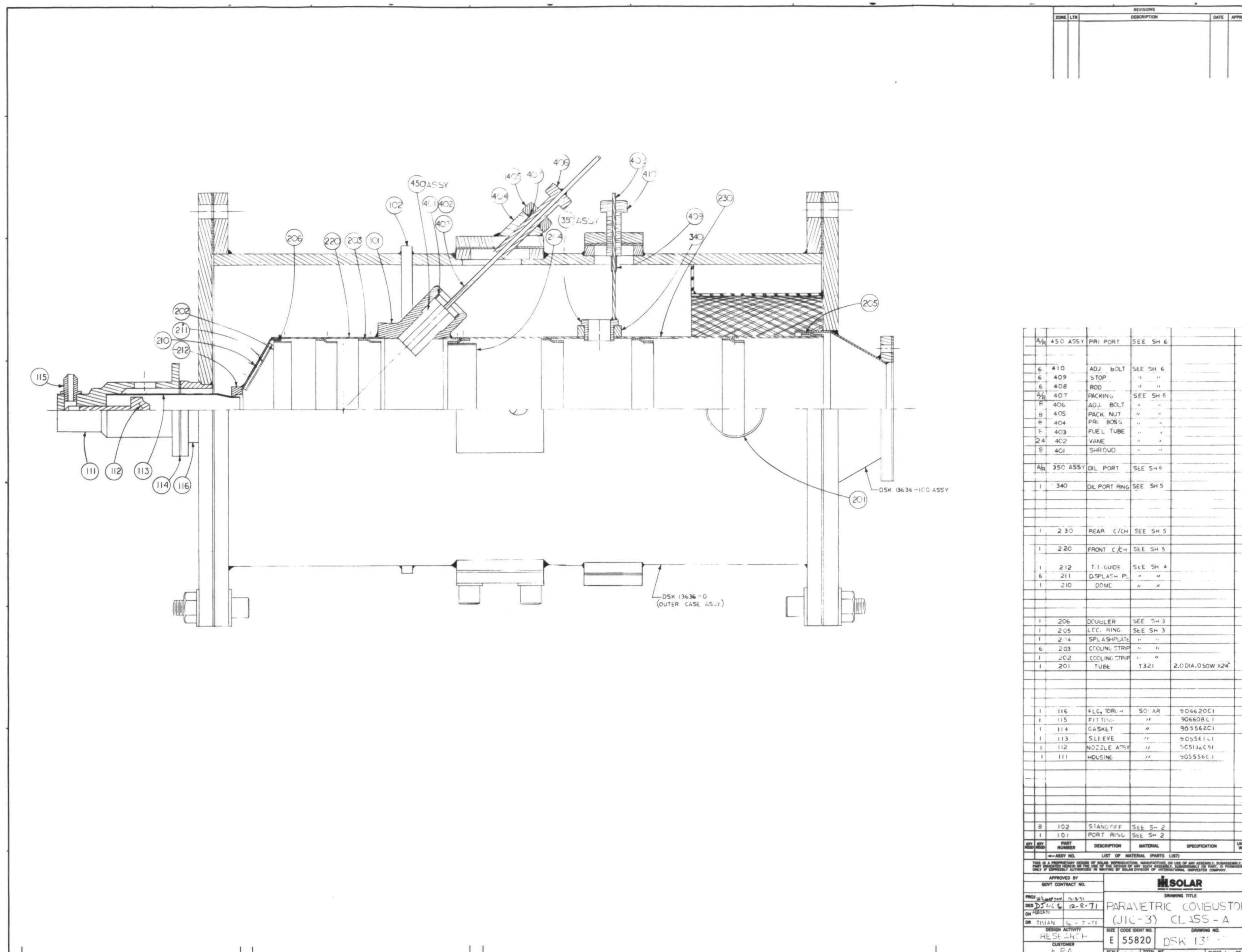


FIGURE 28. ASSEMBLY DRAWING OF PARAMETRIC COMBUSTOR CLASS A

By splitting the primary zone air into a number of jets, the rate of entrainment and thus mixing is much increased over a single jet produced by the same combustor pressure drop. This is to be expected since the entrainment rate increases as the length to diameter ratio of the jet is increased. Consequently, by arranging the air to enter as a number of discrete jets, and by adjusting the aerodynamic blockage of these jets, the quantity of hot products entrained can be maintained at any desired value. This quantity entrained fixes the recirculation ratio of the paired vortex system in the primary zone, and determines to a large extent the stability range of the combustor. It has been shown earlier, with the first of the jet induced circulation combustors, that with high recirculation rates and long reaction lengths or times, the stability of the primary zone can be extended to primary zone equivalence ratios as low as 0.28. At equivalence ratios as low as this, provided the system is well mixed, virtually no NO_x is produced. With this arrangement of primary air injection and fuel atomization it is apparent that good air and fuel mixing is achieved, together with a high level of hot pr ducts recirculation, which can be adjusted to meet the low equivalence ratio stability requirements.

In order to minimize the NO_X emissions over a broad range of fuel to air ratio conditions, it becomes necessary to introduce some variability into the combustor to provide a constant or fixed primary zone equivalence ratio schedule. The primary zone equivalence ratio is critical in obtaining low NO_X emissions, and it has been shown that a value of the order of 0.3 is necessary to provide levels below the contractual requirements when the inlet air temperatures are of the order of 1000°F and pressures in excess of 70 psia. There are several ways of achieving a constant primary zone equivalence ratio. The simplest mechanical system would be one in which the secondary or dilution port area was reduced to provide the desired area and thus mass flow proportionality. This simple approach suffers from the rather severe disadvantage of high pressure drops at high fuel flow conditions, since the total flow area of the combustor would be decreased. Consequently, to obviate the effect of pressure drop during the parametric combustor investigation, both the primary and dilution areas were varied simultaneously to maintain a constant pressure drop and the correct primary zone equivalence ratio.

3.5 PARAMETRIC COMBUSTOR RESULTS

3.5.1 Class A-Mod (JIC-3)

A1 (Federal Driving Cycle) Test Mode

The first section of the test program involving emission testing was the section A1 of the simulated Federal Driving Cycle test mode. This FDC test mode consisted of a series of steady state combustor inlet conditions specified by EPA which were designed to simulate the emissions from a vehicle driven over the Federal Driving Cycle. The various steady state point conditions are given in Figure 29. A series of

A.1. Simulated Federal Driving Cycle Mode

W_f (pph)	P_1 (psig)	T_1 (°F)	T_2 (°F)	W_a* (lb/sec)	Time (%)	Time (Sec)
6	18	1380	1560	0.59	3	41
8	13	980	1300	0.44	34	466
10	13	1000	1400	0.44	22	302
11	13	1100	1550	0.44	22	302
12	18	1380	1740	0.59	18	247
20	13	1000	1900	0.44	1	14
					100%	1372

Compute the projected Federal Driving Cycle Emission Levels (HC, CO, NO_x) by averaging, weighing time.
Total Distance: 7.50 miles.

(See Nomenclature)

A.2. Steady Speed Mode

W_f (pph)	P_1 (psig)	T_1 (°F)	T2 (°F)	W_a* (lb/sec)	Veh. Speed (mph)
8.5	13	1060	1410	0.44	30
9	13	1330	1700	0.44	40
12	18	1380	1740	0.59	50 (repeat
13	20	1320	1680	0.63	60 point)
20	25	1120	1600	0.74	70
32	33	950	1600	0.90	80
40	40	960	1670	1.06	90
60	51	1070	1850	1.31	100
67	59	1100	1900	1.50	108

*Reference only

FIGURE 29. CLASS (A-MOD) - LOW PRESSURE COMBUSTOR TESTS

matched inserts for the primary and dilution ports had already been designed to provide what was throught to be the most effective primary zone equivalence ratio.

As a preliminary to the A1 testing, the combustor was painted with temperature sensitive paints and test run at the A1 #5 test conditions to evaluate the combustor wall temperatures at the extreme case of 1380° F combustor inlet temperature. Inspection revealed that the maximum liner temperature was of the order of 1650° F in the intermediate combustor zone between the primary and dilution ports. No hot spots were apparent and the circumferential temperature distributions were quite even.

Each test point in the Federal Driving Cycle was run as part of a band or range of temperature rises at the correct inlet pressure, temperature and mass flow conditions. In general, each point or range was repeated at least once at a slightly different pressure drop or mass flow to ensure that if the first mass flow was not quite correct an accurate estimate of the emission of the correct value could then be made. The results obtained at each of the simulated Federal Driving Cycle test points are shown in Figures 30 through 36. These basic results were then integrated over the driving cycle according to the test procedure described in the contract and are depicted in Table V. As can be seen, the emissions of nitric oxide, carbon monoxide (CO) and unburned hydrocarbons (UHC) are in excess of the levels desired. On inspection of the test results, this failure to meet the CO and UHC emissions is due to high emissions at two points of the Federal Driving Cycle, #2 and #3. In fact, these high emissions were due to incipient instability at the desired test points, since the operating conditions were such that the combustor was very close to the lean blow-out limit at the design point temperature rise. It was felt the emissions of points #2 and #3 could be reduced by resizing the secondary ports, these modifications were later carried out as part of a program addendum, and did indeed reduce the integrated emissions below the 1976 Federal Standards (see Table XII).

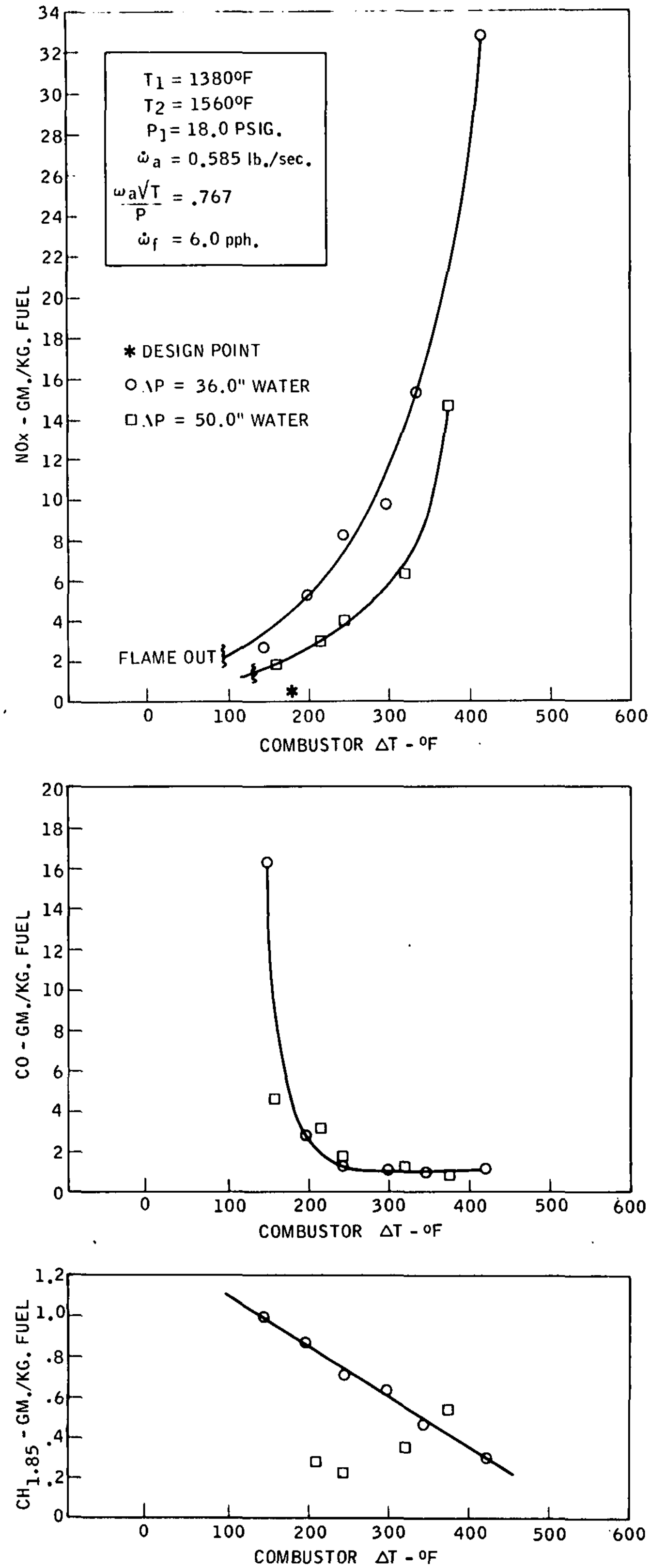


FIGURE 30. CLASS A-MOD COMBUSTOR - JP-4 - FDC #1

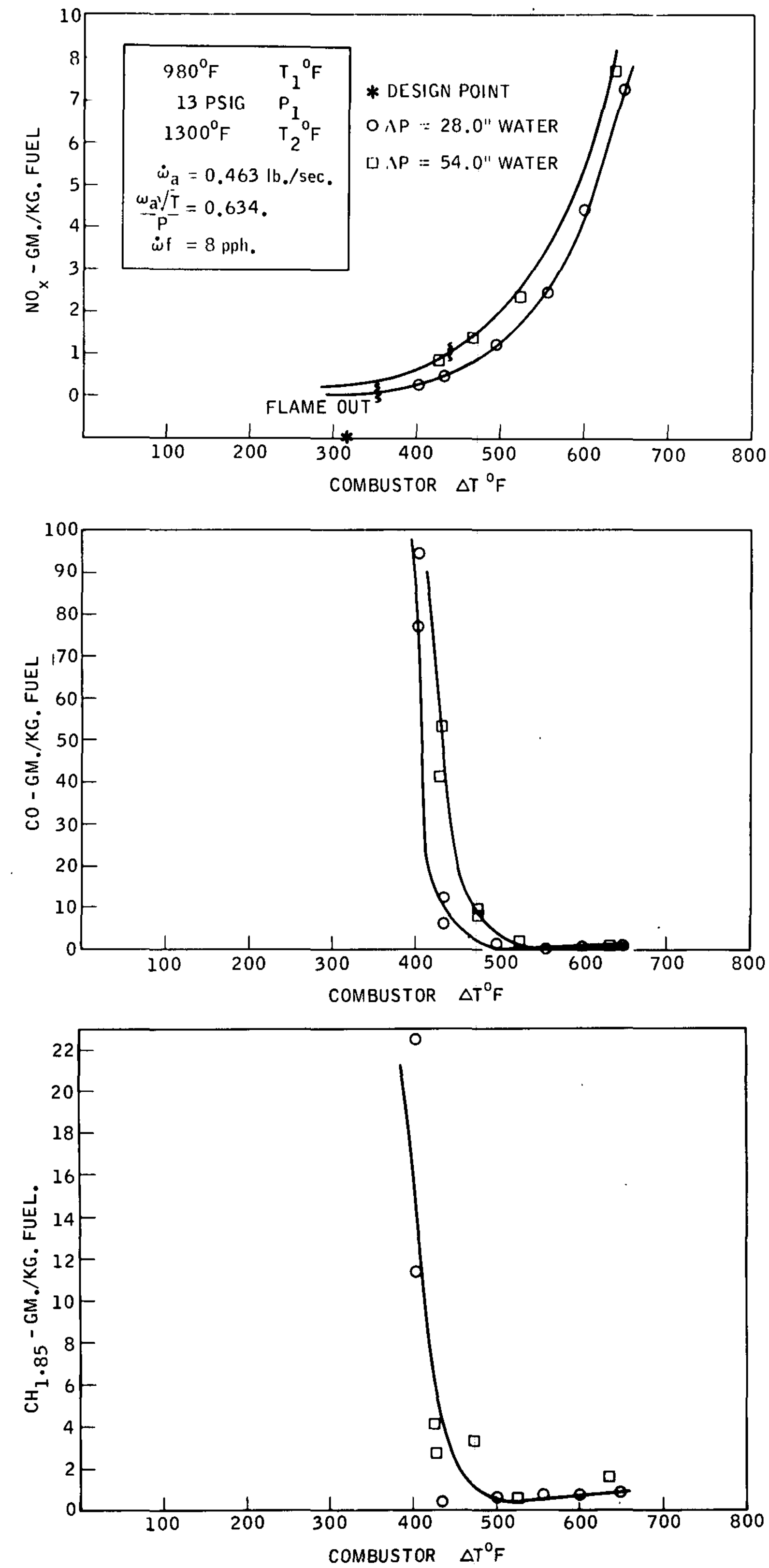


FIGURE 31. CLASS A-MOD COMBUSTOR - JP-4 - FDC #2

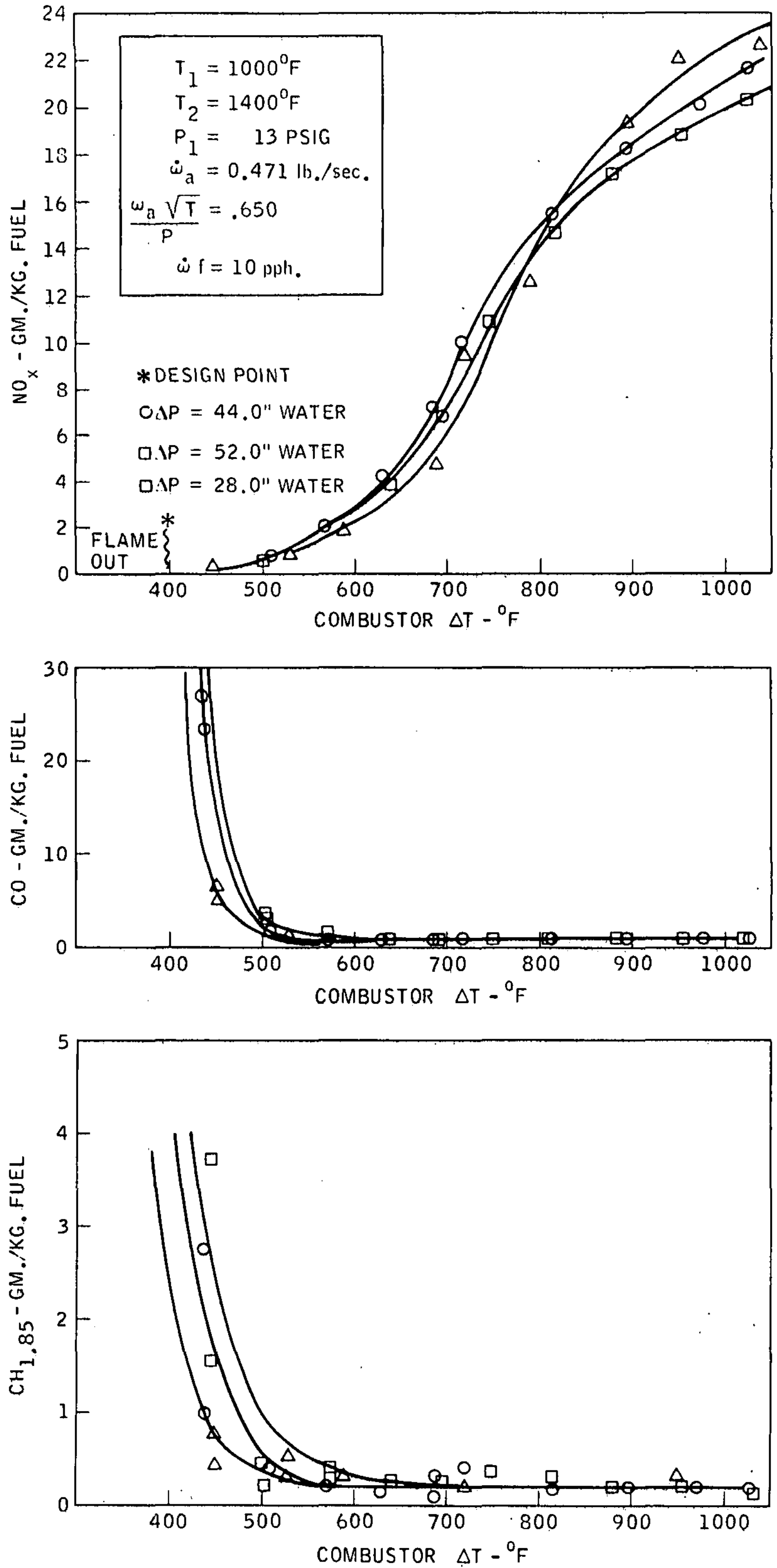


FIGURE 32. CLASS A-MOD COMBUSTOR - JP-4 - FDC #3

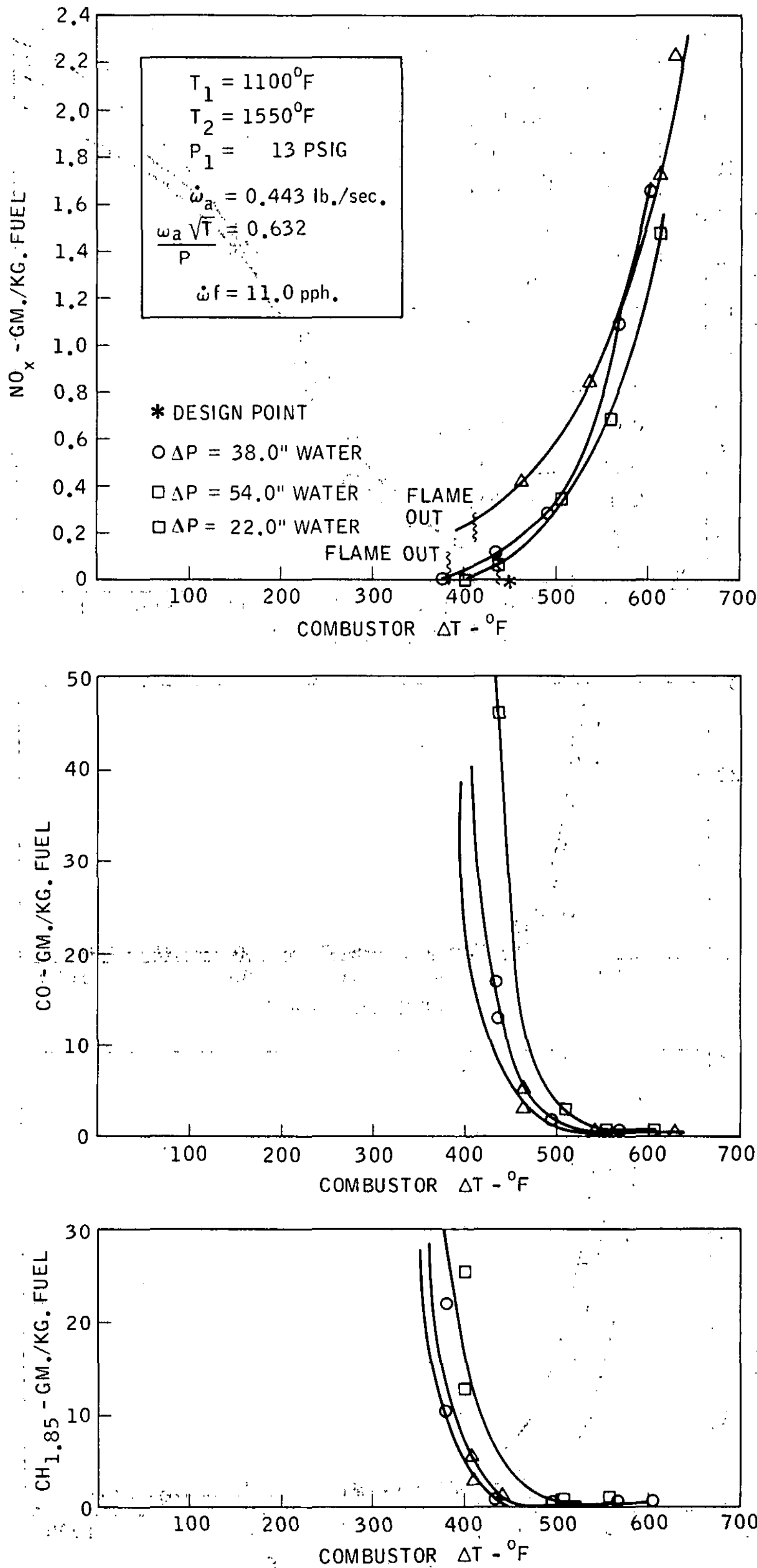


FIGURE 33. CLASS A-MOD COMBUSTOR - JP-4 - FDC #4

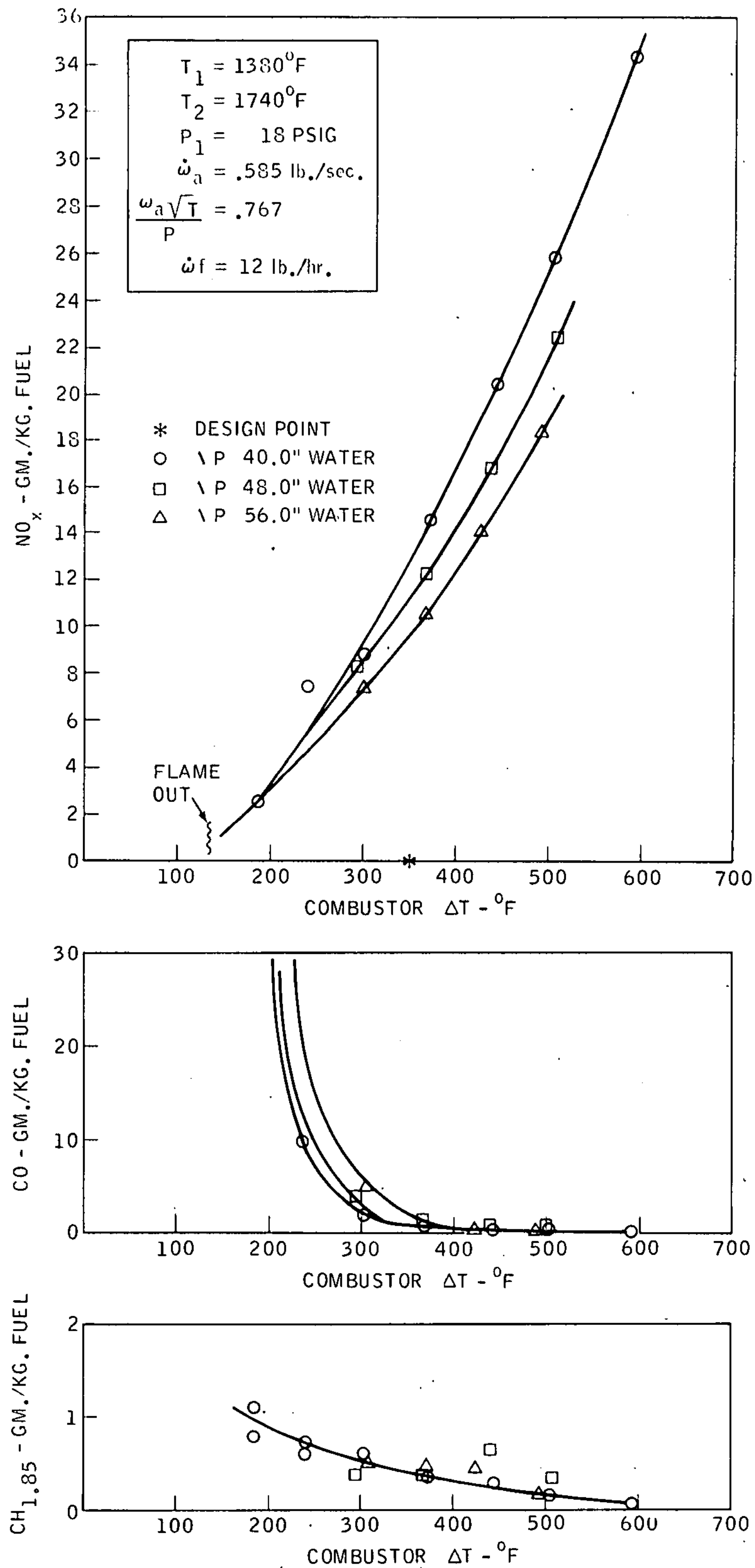


FIGURE 34. CLASS A-MOD COMBUSTOR - JP-4 - FDC #5

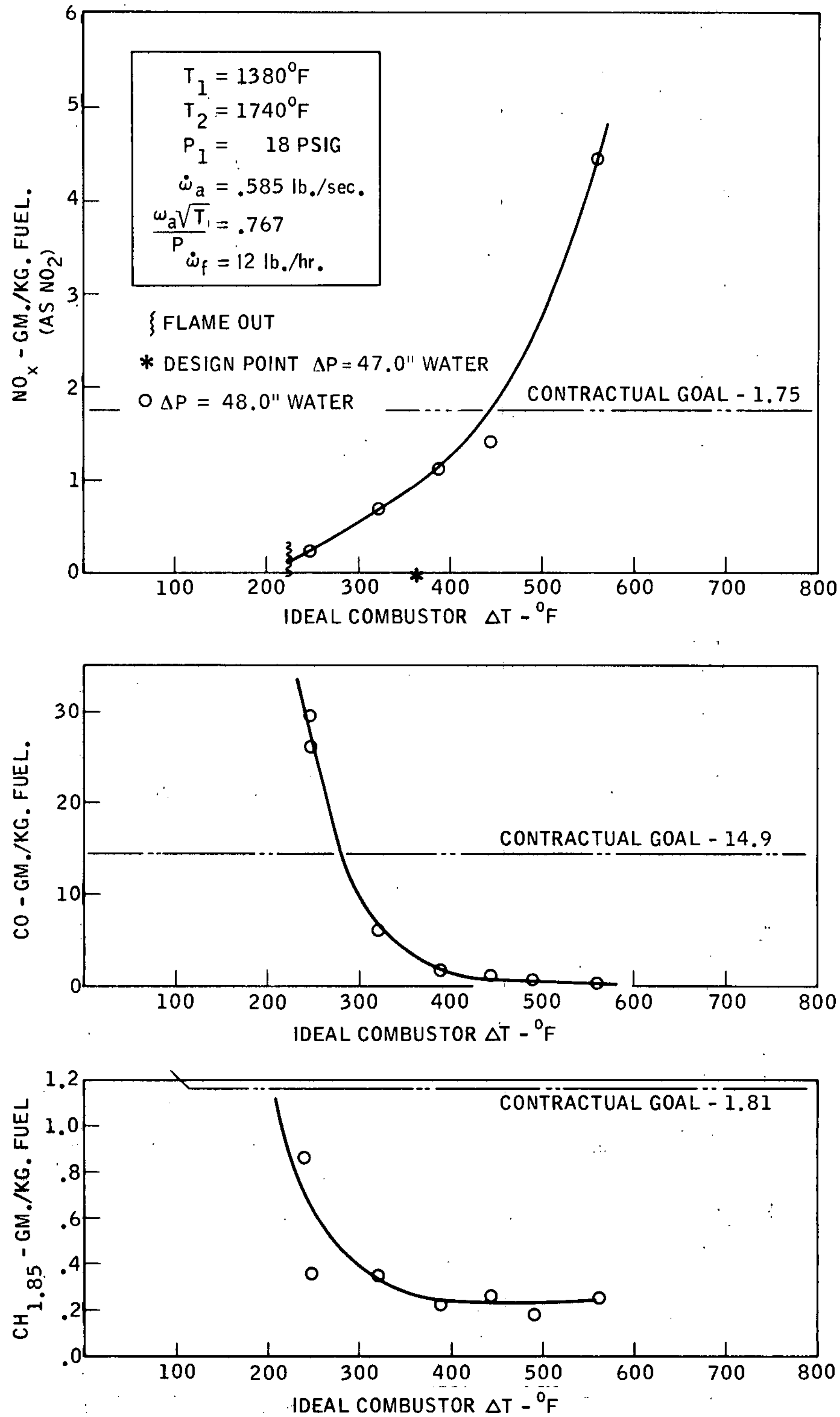


FIGURE 35. CLASS A-MOD COMBUSTOR - JP-4 - FDC #5 REV. 1

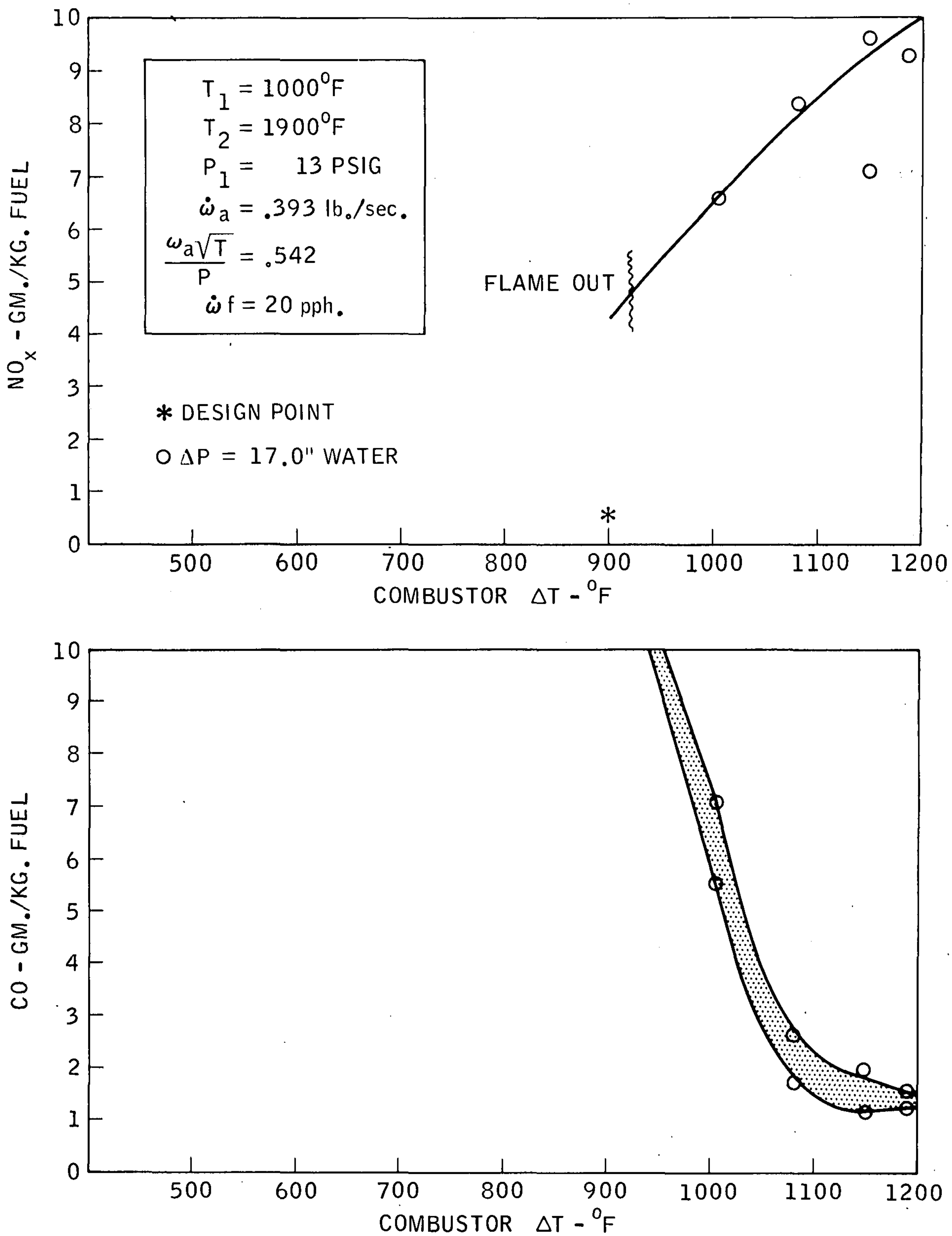


FIGURE 36. CLASS A-MOD COMBUSTOR - JP-4 - FDC #6

TABLE V

BRAYTON CYCLE COMBUSTOR CLASS A-MOD
JP-4, MODE A1
SIMULATED FEDERAL DRIVING CYCLE
(Preliminary Results - See Also Table XII)

FDC #	NO_x lb/1000 lb. Fuel	Fuel Flow lb/hr	NO_x lb/hr x 10^3	Time secs	NO_x lb/test point x 10^6
1	4.5	6.0	27.0	41.0	307.50
2	0.2	8.0	1.6	466.0	207.10
3	0.2	10.0	2.0	302.0	167.78
4	0.22	11.0	2.42	302.0	203.01
5 Rev. 1	0.8	12.0	9.6	247.0	658.67
6	4.3	20.0	86.0	14.0	334.44
				Σ	1,878.5
5	11.6	12.0	139.2	247.0	9,550.67

∴Total Cycle = 1,878.5 x 10^{-6} lb NO_x per 7.5 miles

$$\therefore \text{gm/mile} = \frac{1,878.5 \times 10^{-6} \times 453.6}{7.5}$$

= 0.1136
(Program goal = 0.4 gm/mile NO_x)

Note: Using FDC # 5 instead of FDC #5 Rev. 1 gives 0.6514 gm/mile

FDC #	CO lb/1000 lb. Fuel	Fuel Flow lb/hr	CO lb/hr x 10^3	Time secs	CO lb/test point x 10^6
1	4.1	6.0	24.6	41.0	280.17
2	*200.0	8.0	1600.0	466.0	207,111.11
3	*60.0	10.0	600.0	302.0	50,333.33
4	8.0	11.0	88.0	302.0	7,382.22
5 Rev. 1	3.0	12.0	36.0	247.0	2,470.0
6	12.5	20.0	250.0	14.0	972.22
					268,549.05
5	1.0	12.0	12.0	247.0	823.33

* Estimates only.

∴Total Cycle: 268,549.05 x 10^{-6} lb CO per 7.5 miles

$$\therefore \text{gm/mile} = \frac{268,549.05 \times 10^{-6} \times 453.6}{7.5}$$

= 16.23
(Program goal = 3.4)

Note: Using FDC #5 instead of FDC #5 Rev. 1 gives 16.14 gm/mile

FDC #	$CH_{1.85}$ lb/1000 lb. Fuel	Fuel Flow lb/hr	$CH_{1.85}$ lb/hr x 10^3	Time secs	$CH_{1.85}$ lb/test x 10^6
1	0.9	6.0	5.4	41.0	61.5
2	*40.0	8.0	320.0	466.0	41,422.2
3	2.5	10.0	25.0	302.0	2,097.2
4	0.5	11.0	5.5	302.0	461.39
5 Rev. 1	0.27	12.0	3.24	247.0	222.3
6	**1.81	20.0	36.2	14.0	140.78
				Σ	44,405.37
5	0.4	12.0	4.8	247.0	329.3

* Estimated only.
** Not available - assume 1.81 gm/kg fuel.

∴Total Cycle = 44,405.37 x 10^{6} lb $CH_{1.85}$ per 7.5 miles

$$\therefore \text{gm/mile} = \frac{44,405.37 \times 10^{-6} \times 453.6}{7.5}$$

= 2.686
(Program goal = 0.41)

Note: Using FDC # 5 instead of FDC #5 Rev. 1 gives 2.692 gm/mile

A2 (Steady Speed) Test Mode

Tests at the Steady Speed Mode for the Class A-Mod combustor were run over a band or range of temperature rises, and the trends exhibited by these results follow closely those of the Federal Driving Cycle.

A summary of the results (including A1) is shown in Table VI. In general, these results are similar to those obtained in the Simulated Federal Driving Cycle. As can be seen, the stability limit for most of these various test points does not extend to sufficiently lean equivalence ratios to suppress the emission of unburned hydrocarbons (UHC) and carbon monoxide (CO).

TABLE VI

BRAYTON COMBUSTOR PROGRAM FDC AND STEADY STATE RESULTS, CLASS A-MOD COMBUSTOR

Data Point	T_{in} °F	ΔT °F	$\frac{\Delta P}{P}$ %	Calc. σ prim.	gm/kg Fuel			P psig
					NO_x**	CO	HC**	
1	1380	180	4.26	0.3233	4.5	4.1	0.9	18
2	980	320	4.81	0.3302	0.2	200.0*	40.0	13
3	1000	400	4.02	0.3799	0.2	60.0*	2.5	13
4	1100	450	4.15	0.3821	0.22	8.0	0.5	13
5	1380	360	4.99	0.3509	11.6	1.0	0.4	18
5R1	1380	360	5.19	0.2682	0.8	3.0	0.27	18
6	1000	900	2.49	0.3821	4.3	12.5	-	13
7	1060	350	4.46	0.367	0.2	16.0	1.3	13
8R1	1330	370	3.67	0.275	0.3	10.0	-	13
9R1	1320	360	5.2	0.266	0.3	22.5	0.7	20
9R2	1320	360	6.38	0.25	0.4	25.0	-	20
10	1120	480	4.59	0.376	0.3	4.0	0.55	25
14R1	1100	800	4.52	0.4036	1.1	2.8	-	59
11R1	950	650	3.13	0.411	2.0	110.0	16.0	33
13R1	1070	780	4.22	0.509	2.6	0.55	-	51
12R2	960	710	3.54	0.453	3.5	8.0	4.3	40

* Estimates only.

** HC expressed as $CH_{1.85}$, NO_x expressed as NO_2.

\- Not available.

Several of the Steady Speed A2 test points were "rematched" in primary zone equivalence ratio together with point #5 in the A1 Simulated Federal Driving Cycle. This was done where, as previously mentioned, the stability limit of the tested configuration was insufficient and flame-out was occurring at temperature rises higher than the design point temperature rise.

Rematching was generally performed by increasing the size of the dilution ports. This effectively increased the reaction zone equivalence ratio at the expense of a slight decrease in overall pressure drop. By reducing only the size of the dilution ports , the recirculation and entrainment rates of the primary jets were unchanged. Rematching in this manner gave generally predictable results, whereas when primary port sizes were changed during rematching, the emission characteristics were more difficult to predict.

A second method of improving the lean stability of a given combustor configuration was to reintroduce the torch igniter fuel flow. Introducing a minimum amount of fuel flow to the torch certainly stabilized the combustion process to below the normal flame-out but resulted in some compromise to the NO_x emissions. The attempts were rather cursory in nature and merely served to demonstrate the efficacy of the technique, as optimization of torch ignited fuel flow or method of introduction was not carried out.

Emissions of aldehydes and smoke were also monitored for selected points of the A2 test mode.

No visible smoke was observed from the combustor at any of the test points comprising the Simulated Federal Driving Cycle (A1) or Steady Speed (A2) test modes. Nevertheless, exhaust smoke samples were taken from the rig tailpipe during test points #8R1 and #11R1 of the Steady Speed (A2) test mode using a Von Brand Smokemeter operating at 0.108 cubic feet of sample per square inch of filter paper. The samples were drawn from a single-point probe mounted at the center point of the tailpipe and were taken over a wide range of temperature rises, from a value in excess of the test point rise down to the lean limit point. Analysis of the resulting filter paper tapes with a reflectometer revealed essentially zero smoke emissions at both of the test points, the reflectometer readings being identical to the "clean paper" calibration point.

It is concluded, therefore, that the Class A-Mod combustor operating on JP-4 not only produces no visible smoke at any operating condition, but that the sub-visible smoke emissions are negligible.

Grab samples for aldehyde analysis were taken during test points #7, #10, and #11R1 of the Steady Speed (A2) test mode. The samples were drawn from the tailpipe gas sampling probe into evacuated glass flasks and analyzed using the standard 3-MBTH method. The results are given in Table VII. The samples at all three test points were taken at temperature rise conditions close to the flame-out point; hence, it would be expected that the percentage of aldehydes in the total hydrocarbons would be much greater than at higher temperature rise conditions. An improvement in flame stability margin would result in a much lower percentage of aldehydes.

TABLE VII

ALDEHYDE ANALYSIS

A2 Test Mode Test Point #	(H/C) From FID (ppm)	Total Aldehydes as Formaldehyde (ppm)	Aldehyde % of Total (H/C)
7	10.0	7.0	41.0
10	10.0-12.0	12.0	52.0
11R1	75.0-150.0	29.0	20.0

A3 (Range) Test Mode - Low Baseline

The low baseline test point is a repeat of the A1 FDC #5 Rev. 1 test point and the combustor configurations utilized in terms of primary and dilution port sizes were identical.

Tables VIII and IX show the emission results of the high and low baseline configurations, respectively, together with the approximate ranges of the combustor variables within which the emissions are maintained below the contractual goals.

3.5.2 Class B-Mod (JIC-4)

By arrangement with the Program Officer only the B1 Simulated Federal Driving Cycle and B2 Steady Speed Modes were tested.

TABLE VIII

A3 RANGE MODE RESULTS - HIGH BASELINE
CLASS A-MOD, JP-4

Combustor Parameters - Available Ranges -			
T_1 - °F	P_1 - psig	T_2 - °F	
1100	50.0	1880	
↑	↑	↑	
1100	59.0	1900	← High Baseline Parameters
↓	↓	↓	
1100	>64.0	1960	

High Baseline Emissions - gm/kg Fuel		
NO_x	CO	UHC
1.17	9.0	-

TABLE IX

A3 RANGE MODE RESULTS - LOW BASELINE
CLASS A-MOD, JP-4

Combustor Parameters - Available Ranges -			
T_1 - °F	P_1 - psig	T_2 - °F	
1100	<5.0	1715	
↑	↑	↑	
1380	18.0	1740	← Low Baseline Parameters
↓	↓	↓	
--	>25.0	1920	

Low Baseline Emissions - gm/kg Fuel		
NO_x	CO	UHC
0.3	6.8	0.3

B1 (Federal Driving Cycle) Test Mode

The emission levels monitored during this test section are shown in Figures 37 through 40 and are summarized in Table X. As can be seen, the NO_x and CO emission levels meet the 1975-76 requirements, but the hydrocarbon emissions are slightly in excess. These results are encouraging in that they indicate that this type of combustor is capable of meeting the 1975-76 emission levels with only a little more development.

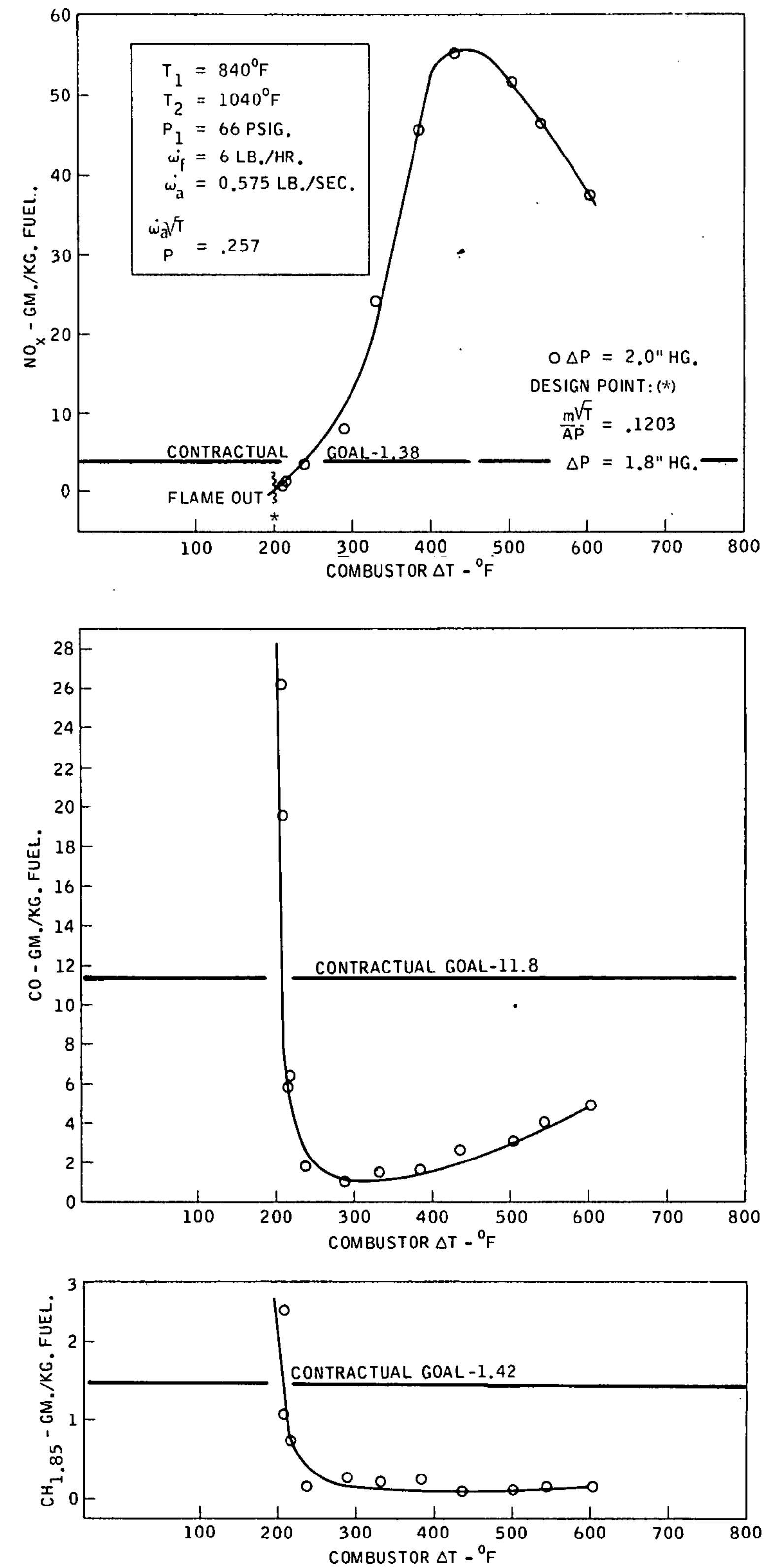


FIGURE 37. CLASS B-MOD COMBUSTOR, FDC #1 REV. 1 (FUEL: JP-4)

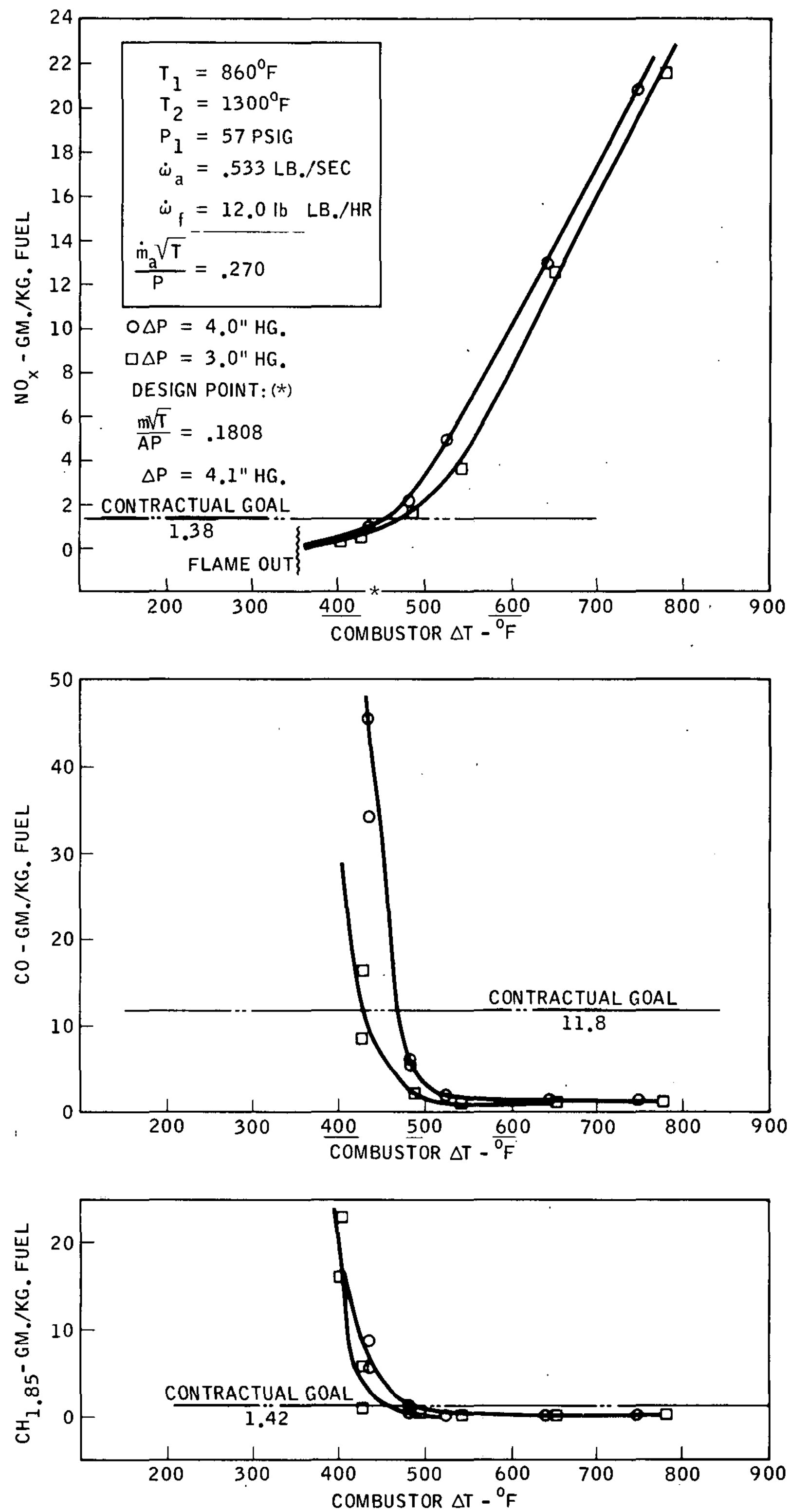


FIGURE 38. CLASS B-MOD COMBUSTOR, FDC #2 REV. 2 (FUEL: JP-4)

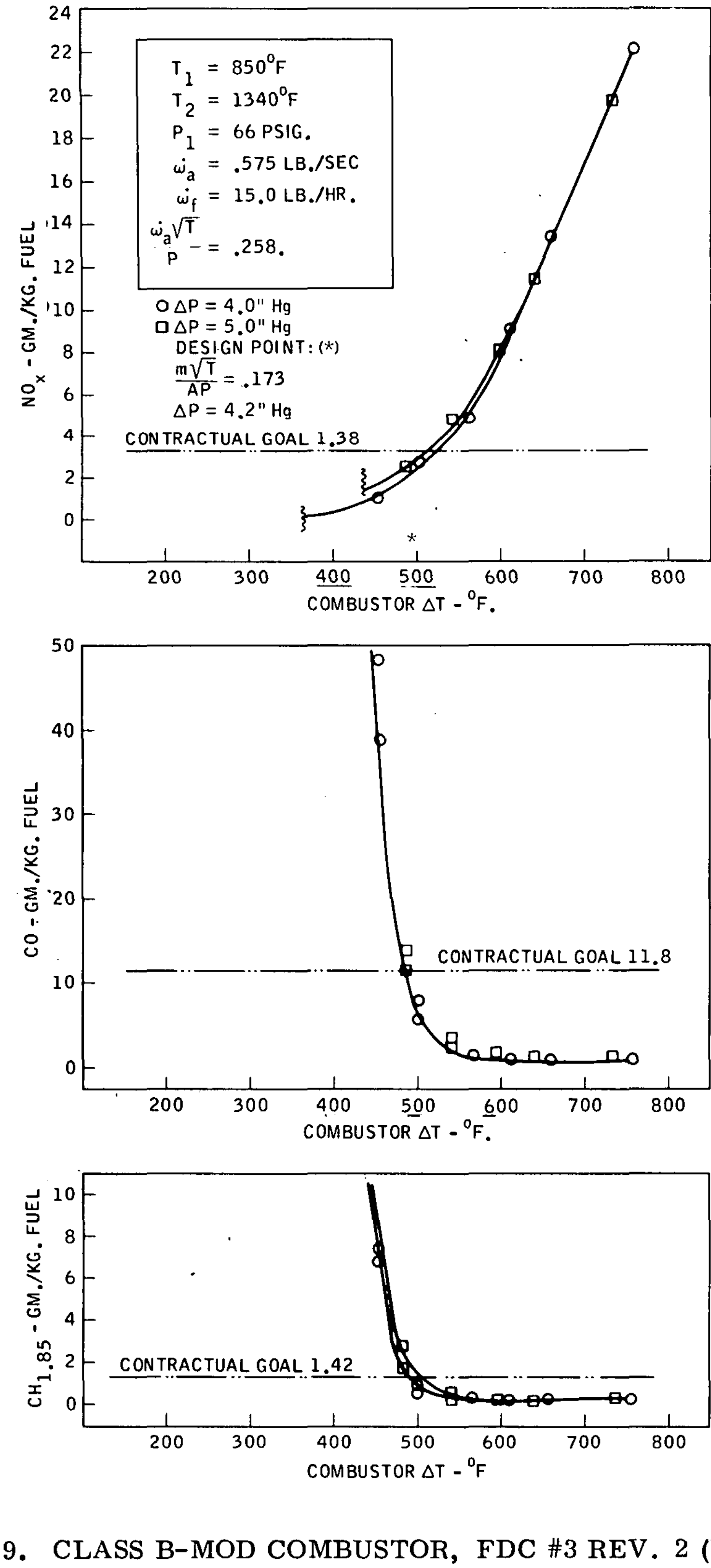


FIGURE 39. CLASS B-MOD COMBUSTOR, FDC #3 REV. 2 (FUEL: JP-4)

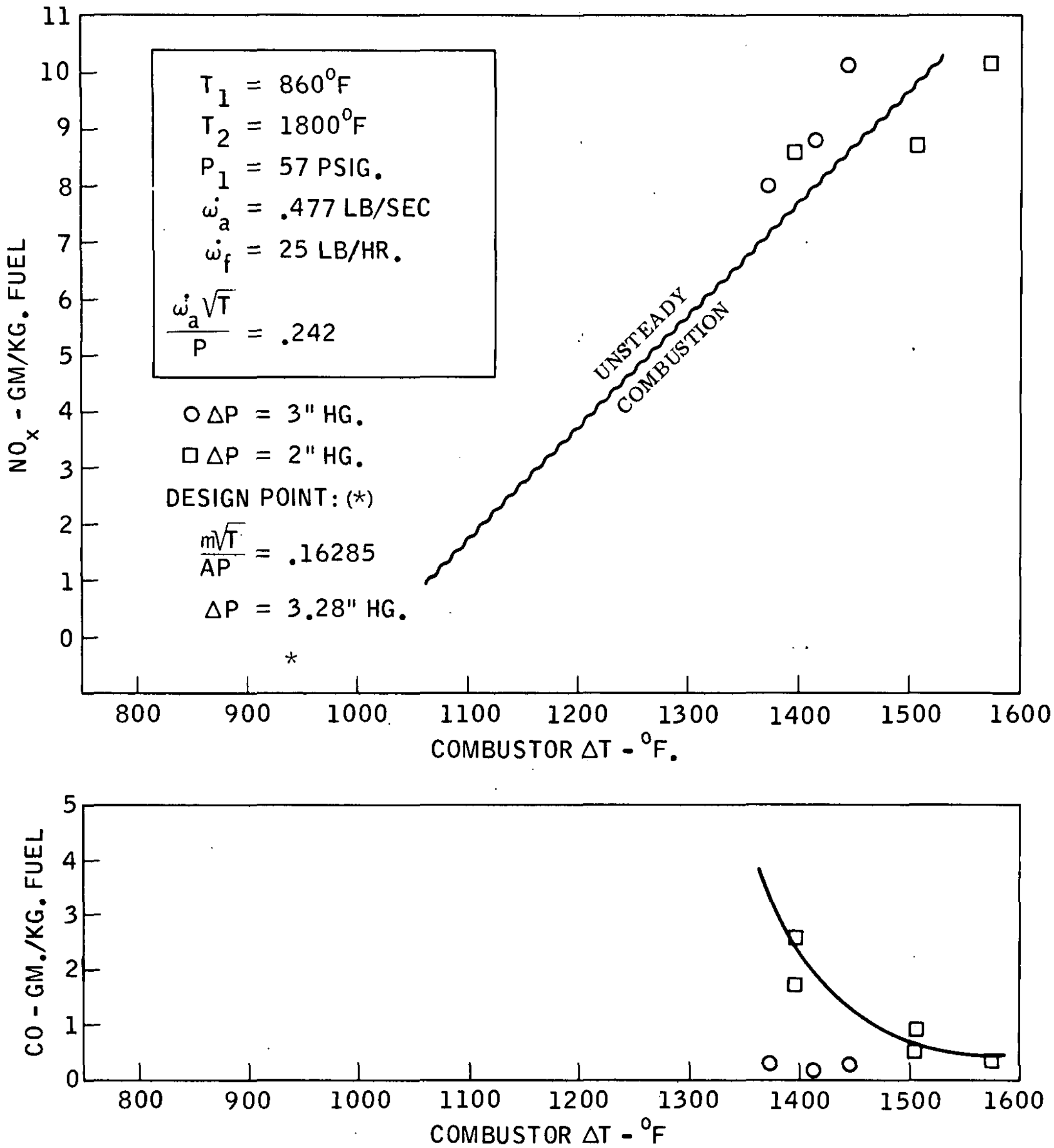


FIGURE 40. CLASS B-MOD COMBUSTOR, FDC #4 (FUEL: JP-4)

TABLE X

BRAYTON CYCLE COMBUSTOR CLASS B-MOD
JP-4, MODE B1: FEDERAL DRIVING CYCLE

Test Point	NO_x lb/1000 lb. Fuel	Fuel Flow lb/hr	NO_x lb/hr x 10^3	Time secs	NO_x lb/test point x 10^6
1 Rev. 1	0.5	6.0	3.0	41.0	34.167
2 Rev. 2	0.7	12.0	8.4	1043.0	2433.67
3 Rev. 2	2.4	15.0	36.0	274.0	2740.00
4	2.0*	25.0	50.0	14.0	194.44
					Σ = 5402.28

* Estimate only.

∴ Total Cycle = $5,402.28 \times 10^{-6}$ lb (NO_x)

$$\therefore \text{gm/Mile} = \frac{5402.28 \times 10^{-6} \times 453.6}{7.5}$$

= <u>0.327</u>

(Program Goal = 0.4 gm/mile)

Test Point	CO lb/1000 lb. Fuel	Fuel Flow lb/hr	CO lb/hr x 10^3	Time secs	CO lb/test point x 10^6
1 Rev. 1	30.0*	6.0	180.0	41.0	2,050.00
2 Rev. 2	8.0	12.0	96.0	1043.0	27,813.33
3 Rev. 2	9.0	15.0	135.0	274.0	10,275.00
4	30.0*	25.0	750.0	14.0	2,916.67
					Σ = 43,054.997

* Estimate only.

∴ Total Cycle = 43,054.997 lb (CO) x 10^{-6}

$$\therefore \text{gm/Mile} = \frac{43,054.997 \times 10^{-6} \times 453.6}{7.5}$$

= <u>2.604</u>

(Program Goal = 3.4 gm/mile)

Test Point	$CH_{1.85}$ lb/1000 lb. Fuel	Fuel Flow lb/hr	$CH_{1.85}$ lb/hr x 10^3	Time secs	$CH_{1.85}$ lb/test point x 10^6
1 Rev. 1	3.0*	6.0	18.0	41.0	205.00
2 Rev. 2	1.8	12.0	21.6	1043.0	6,258.00
3 Rev. 2	1.3	15.0	19.5	274.0	1,484.17
4	3.0*	25.0	75.0	14.0	291.17
					Σ = 8,238.84

*Estimate only.

∴ Total Cycle = $8,238.84 \times 10^{-6}$ lb ($CH_{1.85}$)

$$\therefore \text{gm/Mile} = \frac{8,238.84 \times 10^{-6} \times 453.6}{7.5}$$

= <u>0.498</u>

(Program Goal = 0.41 gm/mile)

The results of FDC #4 test point of the Class B-Mod combustor are given in Figure 40. As can be seen, lean flame-out was occurring at a temperature rise much higher than the design point. This phenomenon was subsequently demonstrated to be unconnected with the combustor configuration but a result of fuel system problems.

A retest of this point was not considered at the time, due to the pressure of the program schedule and the fact that FDC #4 test point represents only a 1 percent contribution to the integrated emissions.

The results for FDC #4, shown in Table X, are not intended to be extrapolations of the test figures but are estimates, considered to be on the pessimistic side.

The final inspection of the Class B-Mod (JIC-4) combustor at the conclusion of the testing, after an estimated total of 30 hours test time at various conditions, revealed some minor erosion/corrosion of the dome cooling strips at the inside diameter of the trailing edges. This was not considered serious and could probably be avoided by a slight redesign of the air admission hole positions on the dome cooling strips.

B2 (Steady Speed) Test Mode

Because of limitations imposed by time and budget, some of the test points of the B2 section were tested with common rather than individual port inserts. In general, the results of these tests follow the same trends as those of the simulated Federal Driving Cycle; a summary of the results is shown in Table XI.

During the testing points 10, 11 and 12 of the Steady Speed Mode (B2) with common port inserts, a reversed NO_x pressure dependency was noticed, complementing the observations of the Class A-Mod results. Essentially, the indications are that at these higher pressure levels, the NO_x emissions decrease with increasing pressure ratios rather than increase. This particular trend is shown in Figure 41 for two different primary zone equivalence ratios. During the tests each of the points 10, 11 and 12 had essentially the same percentage pressure drop and inlet temperature, but the mass flow through the combustor varied as the inverse of the inlet pressure - maintaining a constant ratio. Thus since not all the inlet conditions were held constant, it may be incorrect to infer a true pressure dependency, although it is likely.

Wall Temperatures and Outlet Temperature Profiles

Maximum wall temperatures were found to be of the same levels as found with the Class A-Mod combustor, i.e., around 1650° F at any of the test point conditions.

TABLE XI

BRAYTON COMBUSTOR PROGRAM - B1 AND B2 TEST RESULTS
CLASS B-MOD COMBUSTOR

Data Point	T_{in} °F	Pin psig	ΔT °F	$\frac{\Delta P}{P}$ %	gm/kg Fuel		
					NO_x [2]	CO	UHC [1]
1R1	840	66.0	200	1.10	0.5	30.0	3.0
2R2	860	57.0	440	2.81	0.7	8.0	1.8
3R3	850	66.0	490	2.56	2.4	9.0	1.3
4	860	57.0	940	2.24	2.0	30.0	3.0
5	860	60.0	460	2.5	1.4	5.5	-
6	850	62.0	490	2.44	2.5	2.8	-
7	850	70.0	520	2.77	2.2	50.0*	15.0*
8	830	81.0	600	2.72	6.2	27.0	25.0
9	820	97.0	700	3.28	2.0	100.0*	10.0*
10	810	112.0	800.0	3.38	2.0	70.0	1.0
11	800	138.0	970.0	3.11	6.5	4.0	0.3
12	800	161.0	1100	3.17	11.3	2.0	0.32

* Estimates only
1. Expressed as $CH_{1.85}$
2. Expressed as NO_2

Outlet temperature pattern factors for both the JIC-3 and JIC-4 combustors were generally less than 0.1, with a maximum of 0.15 at high temperature rise levels, (above design point).

Test Point	Pressure at Ms. Abs.	T1	ΔP/P%	NO_x at σ_P=0.4	NO_x at σ_P=0.5
10	8.60	810° F	3.38	5.0	14.4
11	10.40	800° F	3.11	3.1	10.4
12	11.96	800° F	3.17	2.8	9.95

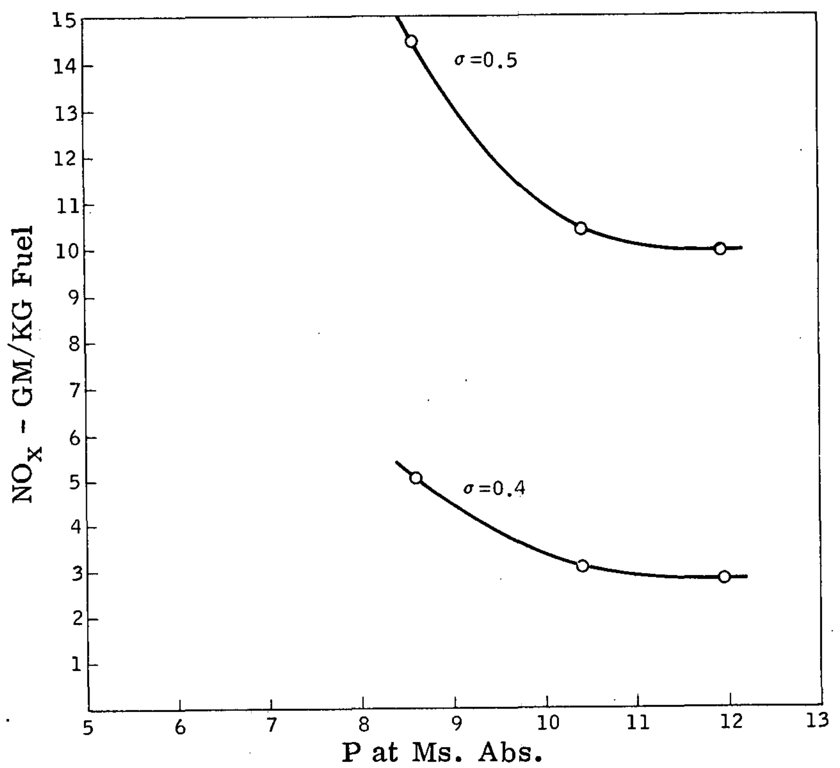


FIGURE 41. NO_x VARIATION WITH INLET PRESSURE, CLASS B-MOD COMBUSTOR (JIC-4)

4

PROGRAM EXTENSION OUTLINE

In April 1972 certain extensions to the original scope of work of Contract 68-04-0016 were agreed to between Solar and the Environmental Protection Agency, Advanced Automotive Power Systems Development.

The extensions are conveniently grouped into Addendums I, II and III and are outlined below.

- Addendum I - Optimized Federal Driving Cycle

  This task consisted of optimizing the configurations of the integrated Federal Driving Cycle test points for the Class A-Mod (JIC-3) combustor in order to ensure that the integrated emissions were each lower than the contractual goals.

  As noted earlier, the results of the initial A1 test mode were encouraging inasmuch as the NO_x level was within requirements but CO and UHC were much higher than requirements.

- Addendum II - Primary Zone Model and Variable Area Port Tests

  The objectives here were twofold: (i) to obtain information on possible approaches to increasing the operating range of the Class A-Mod (JIC-3) type of combustor by rig testing various primary zone model configurations; (ii) to test various cold flow models of variable geometry port configurations in order to investigate such effects as discharge coefficient variation, leakage and repeatability that would contribute to the operation of a successful control system.

- Addendum III - Combustor Control System Analysis and NO_x Correlations

  The two interrelated tasks were as follows: (i) using data obtained during the parametric combustor testing, to develop correlation functions for the NO_x production in terms of the combustor operational parameters; (ii) to perform an analysis of a typical variable JIC type combustor control system in order to assess the complexity of such a system and to estimate overall error levels of such a control.

The detailed results of the above addenda are presented in the following sections.

4.1 ADDENDUM I - OPTIMIZED A1 FEDERAL DRIVING CYCLE RESULTS (JIC-3)

The original results of the A1 test mode on the Class A-Mod combustor showed the NO_X emissions to be well within requirements but the CO and UHC to be approximately a multiple of 5 in excess of the goal.

It was recognized at the time that the undesirably high CO and UHC were the result of the contribution to the integrated cycle of only two test points, #2 and #3, where the combustor had been matched with the test design point too close to the lean extinction limit. The program schedule at that time prevented any further retesting of these points.

Consequently, the optimization of the A1 Federal Driving Cycle was concentrated exclusively on test points #2 and #3 and consisted of rematching the primary zone equivalence ratio to lower the unburned constituents without excessive compromise to the NO_X.

Table XII gives the results of the optimization and, as can be seen, the integrated emissions are all below 50 percent of the contractual goals. The data for test points #1, #4, #5 Rev. 1 and #6 are as previously reported, with #2 Rev. 5 and #3 Rev. 3 representing the optimized results for test points #2 and #3.

4.2 ADDENDUM II - PRIMARY ZONE MODEL AND VARIABLE AREA PORT TESTS

4.2.1 Primary Zone Model Tests

The series of primary zone models produced were intended to provide basic information into the lean extinction and operating bandwidth characteristics of the JIC type combustor reaction zone.

Essentially each model was constructed from two modular sections: a primary zone section in the form of a simple, closed-end cylinder; and a primary port holder ring which was attached to the open end of the primary zone section. To complete the combustor, a plain dilution section tube was attached; no dilution ports were incorporated, however, and thus the models were truly primary zones only. No skin cooling provisions were made for the models.

TABLE XII

CLASS A-MOD COMBUSTOR
OPTIMIZED FEDERAL DRIVING CYCLE

FDC NO.	NO_x LB/1000 LB FUEL	FUEL FLOW LB/HR	NO_x LB/HR x 10^3	TIME - SECS	NO_x LB/TEST PT x 10^6
1	4.5	6.0	27.0	41.0	307.50
2R5	0.6	8.0	4.8	466.0	621.33
3R3	0.8	10.0	8.0	301.0	671.11
4	0.22	11.0	2.42	302.0	203.01
5R1	0.8	12.0	9.6	247.0	658.67
6	4.3	20.0	86.0	14.0	334.44
					Σ= 2,796.06

∴ NO_x (AS NO_2) PER TEST CYCLE = 2796.06 x 10^{-6} LB

∴ GM/MILE = 2796.06 x 10^{-6} $\frac{453.6}{7.5}$

= 0.169

CONTRACTUAL GOAL = 0.4 GM/MILE

FDC NO.	CO LB/1000 LB FUEL	FUEL FLOW LB/HR	CO LB/HR x 10^3	TIME - SECS	LB/TEST PT x 10^6
1	4.1	6.0	24.6	41.0	280.17
2R5	2.0	8.0	16.0	466.0	2,071.11
3R3	2.0	10.0	20.0	302.0	1,677.78
4	8.0	11.0	88.0	302.0	7,382.22
5R1	3.0	12.0	36.0	247.0	2,470.00
6	12.5	20.0	250.0	14.0	972.22
					Σ= 14,853.50

∴ CO PER TEST CYCLE = 14,853.50 x 10^{-6} LB

GM/MILE = 14,853.50 x 10^{-6} x $\frac{453.6}{7.5}$

= 0.898 GM/MILE

CONTRACTUAL GOAL = 3.4 GM/MILE

FDC NO.	$CH_{1.85}$ LB/1000 LB FUEL	FUEL FLOW LB/HR	$CH_{1.85}$ LB/HR x 10^3	TIME - SECS	$CH_{1.85}$ LB/TEST PT x 10^6
1	0.9	6.0	5.4	41.0	61.50
2R5	0.5**	8.0	4.0	466.0	517.78
3R3	0.4	10.0	4.0	302.0	335.56
4	0.5	11.0	5.5	302.0	461.39
5R1	0.27	12.0	3.24	247.0	222.30
6	1.81**	20.0	36.2	14.0	140.78
					Σ= 1,739.31

∴ $CH_{1.85}$ PER TEST CYCLE = 1739.31 x 10^{-6} LB

GM/MILE = 1739.31 x 10^{-6} x $\frac{453.6}{7.5}$

= 0.105 GM/MILE

CONTRACTUAL GOAL = 0.41 GM/MILE

**ESTIMATES ONLY

There were three different diameter primary zone sections manufactured and also three additional sections with varying lengths at constant diameter. Three primary port holders at constant diameter were manufactured with various angles. Each port holder had 16 mounts, hence up to 16 primary ports/fuel injectors could be accommodated.

The modular sections are depicted schematically in Figure 42. A photograph of a built-up model with the three sections tack-welded together is given in Figure 43.

The chart shown on Figure 44 depicts all the various configurational arrangements considered together with the various primary zone lengths and diameters. Not all of the configurations shown have been tested by any means; in fact, much of the hardware described was not produced.

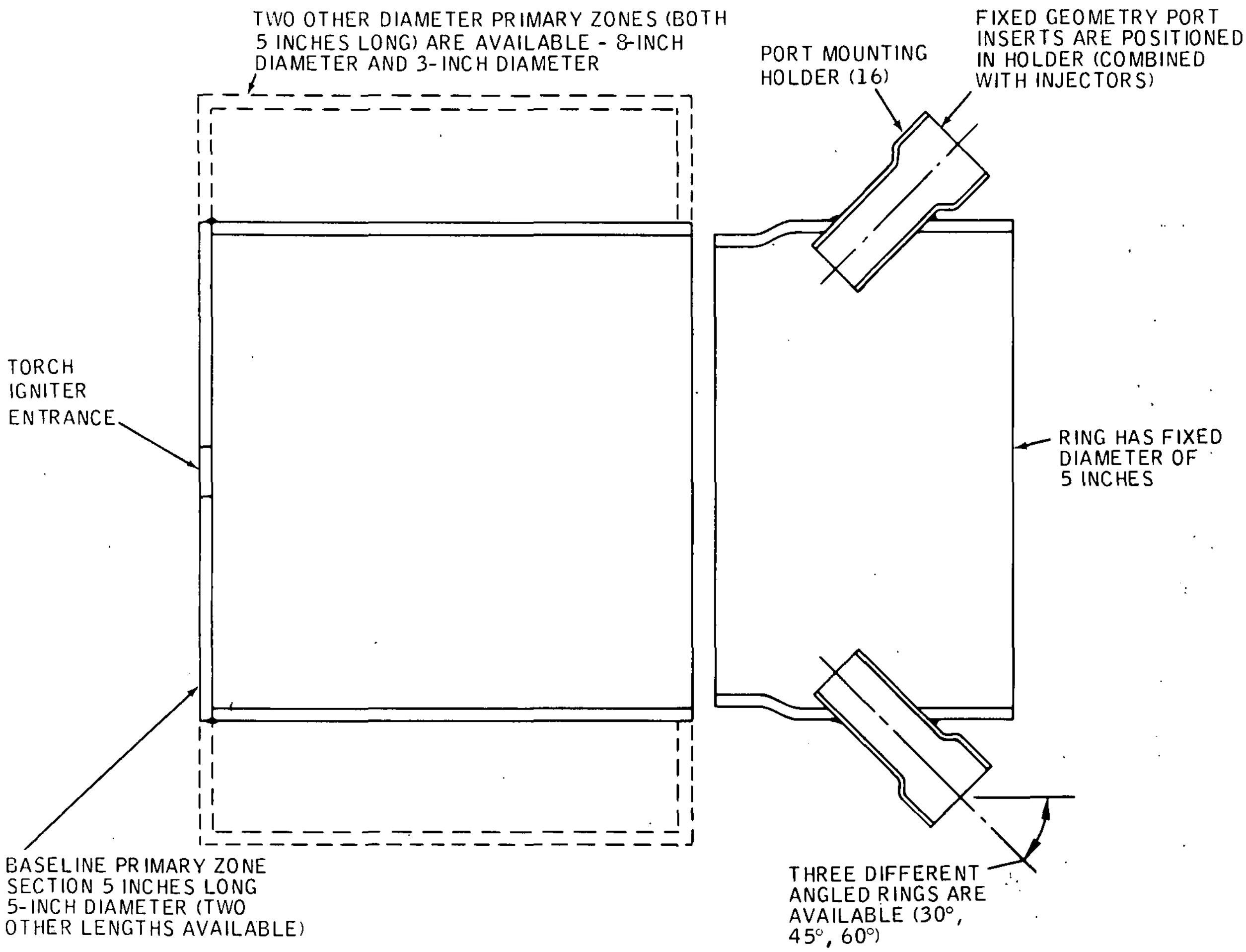


FIGURE 42. SCHEMATIC OF PRIMARY ZONE MODULAR CONSTRUCTION

The chart outlines the reference configuration utilized for the initial test. This version essentially reflects the configuration of the Class A-Mod (JIC-3) combustor inasmuch as the length and diameter of the primary zone are the same. The primary port angle and the number of primary ports are also common to both systems. For the reference configuration, representative primary port diameter and length to diameter ratios were chosen, and a test point combustor pressure drop of 4 percent was chosen for all configurations tested.

Tεble XIII lists the geometries of the various configurations tested. Also shown are the lean "blow out" equivalence ratios, and the values of the equivalence ratio where NO_x emissions exceeded the contractual goals. The difference between these two values represents the useful operating range from both a blow-out and NO_x emission standpoint. From these data are multiple regression analysis a correlation between various combustor parameters and lean blow-out was developed. A plot of predicted value against actual value is shown in Figure 45.

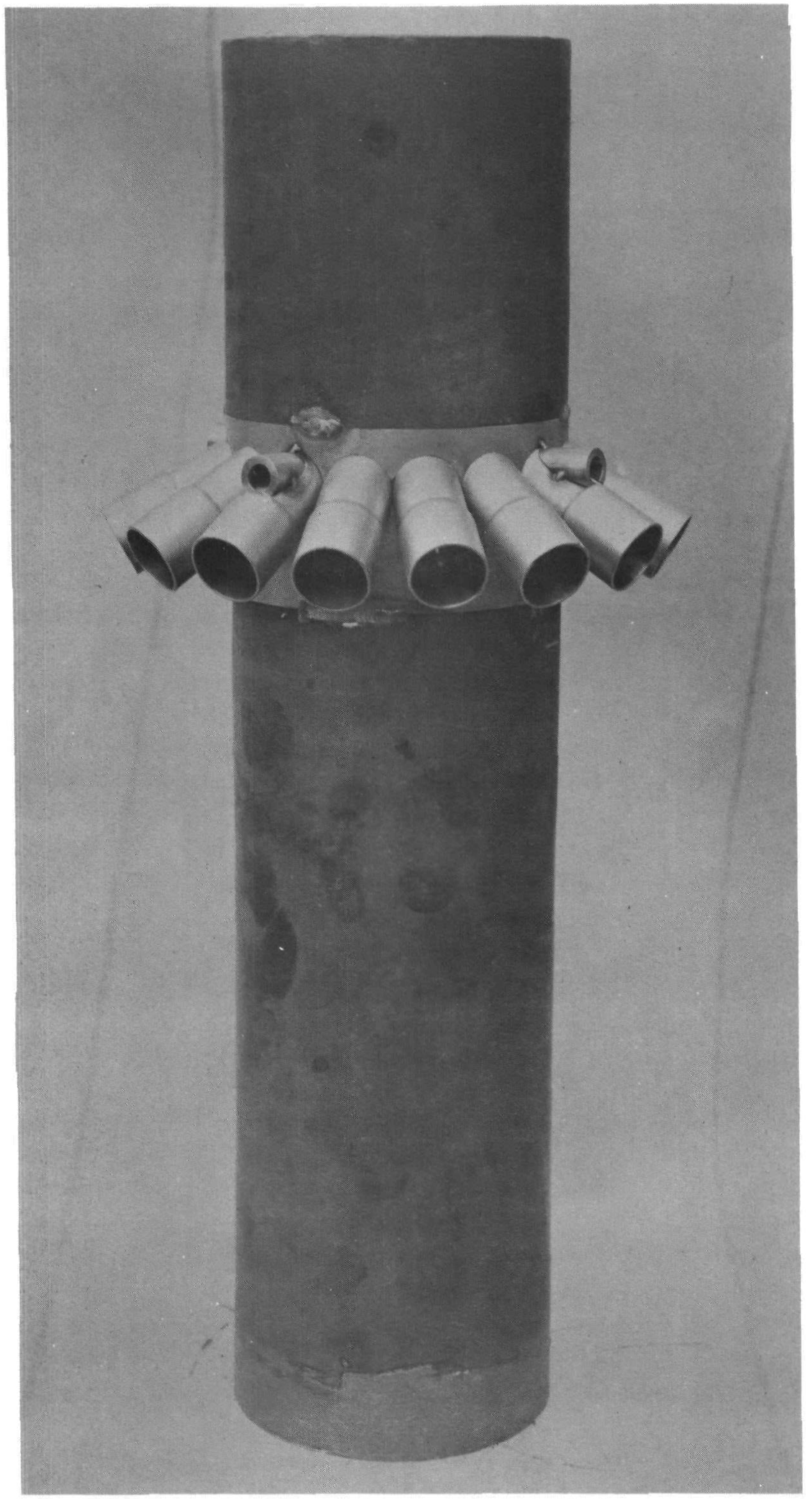


FIGURE 43. MODEL PRIMARY ZONE COMBUSTION SYSTEM WITH ATTACHED TAILPIPE

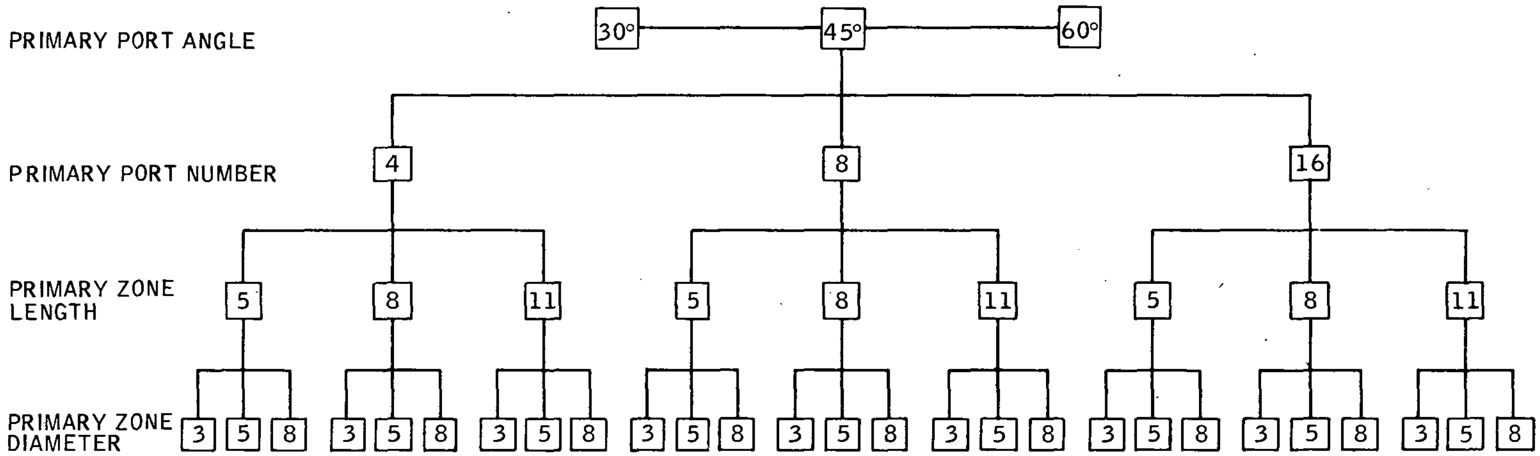
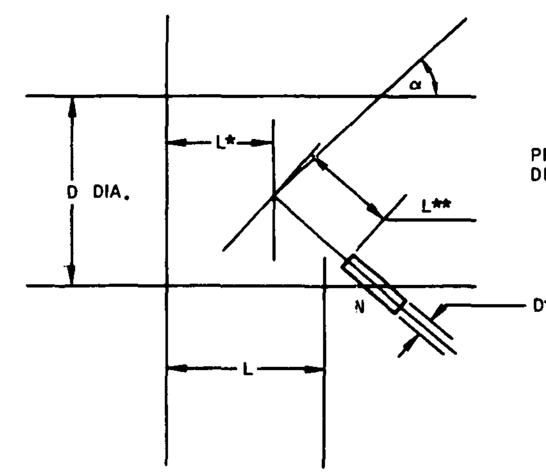


FIGURE 44. BRAYTON CYCLE COMBUSTOR PROGRAM PRIMARY ZONE MODEL TESTING. CONFIGURATION SUMMARY

TABLE XIII
PRIMARY ZONE MODEL TESTS SUMMARY

TEST	DATE	CONFIGURATION α DEG.	N	D INS.	L INS.	T_1 °F.	P_1 PSIG.	Equiv. Ratio at Blow-out ϕ_{BO}	Equiv. Ratio at NO_x Limit ϕ_{NO_x}	Equiv. Ratio Operating Range $\Delta\phi$		L* INS.	L** INS.	D* INS.	$\dot{\omega}_{AIR}$ LB./SEC.	NOTES
BL	7-29	45	8	5	5	800 800 1000 1000	20 40 20 40	.304 .301 .259 .250	.308 .400 .289 .316	.004 .099 .030 .066		3.655	2.75	.683	.509 .803 .473 .746	
M1	8-2	45	16	5	5	800 800 1000 1000	20 40 20 40	-- -- .217 .208	-- -- .292 .263	-- -- .075 .055		3.655	2.75	.500	.509 .803 .473 .746	UNSTABLE BEFORE FLAME OUT - EXCESSIVE CO LEVELS.
M2	8-3	45	16	5	5	800 800 1000 1000	20 40 20 40	-- -- .238 .244	-- -- .246 --*	-- -- .008 --		3.655	2.75	.500	.509 .803 .473 .746	ONLY 8 FUEL INJECTORS. *TOTAL LINE OVER NO_X LIMIT.
M3	8-4	45	4	5	5	800 800 1000 1000	20 40 20 40	-- -- .240 .243	-- -- .283 .308	-- -- .043 .065		3.655	3.5	1.000	.509 .803 .473 .746	
M4	8-5	45	4	8	5	800 800 1000 1000	20 40 20 40	-- -- .159 .160	-- -- .242 .282*	-- -- .083 .122		3.655	3.5	1.000	.509 .803 .473 .746	*ESTIMATE ONLY. UNSTABLE BEFORE FLAME OUT - EXCESSIVE CO LEVELS.
M5	8-10	45	8	8	5	800 800 1000 1000	20 40 20 40	.233 .240 .187 .179	.320 .331 .270 .304	.087 .091 .083 .125		3.655	2.75	.683	.509 .803 .473 .746	
M6	8-11	45	8	3	5	800 800 1000 1000	20 40 20 40	.258 .289 .261 .265	.270 .332 .270 .297	.012 .043 .009 .032		3.655	2.75	.683	.509 .803 .473 .746	
M7	8-12	45	4	3	5	800 800 1000 1000	20 40 20 40	.276 .298 .250 .246	.330 .347 --* --*	.054 .049 -- --		3.655	3.5	1.000	.509 .803 .473 .746	*TOTAL LINE OVER NO_X LIMIT. AT T_1 = 1000°F, NO_X INCREASES TOWARDS FLAME OUT.
M8	8-14	45	4	5	8	800 800 1000 1000	20 40 20 40	.243 .240 .198 .187	.327 .315 .210 .288	.084 .075 .012 .101		5.875	3.5	1.00	.509 .803 .473 .746	
M9	8-15	45	8	5	8	800 800 1000 1000	20 40 20 40	.286 .274 .264 --	.300 .356 .282 --	.014 .082 .018 --		5.875	2.75	.683	.509 .803 .473 .746	
M10	8-16	30	8	5	8	800 800 1000 1000	20 40 20 40	.238 .247 .238 .223	.259 .330 .259 .285	.021 .083 .021 .062		4.125	4.125	.683	.509 .803 .473 .746	
M11	8-18	30	4	5	8	800 800 1000 1000	20 40 20 40	.282 .238 .233 .233	.285 .341 .255 .273	.003 .103 .022 .040		4.125	4.125	1.000	.237 .375 .221 .348	.683 INSERTS RETAINED IN ERROR. FUEL SYSTEM PROBLEMS DURING THIS TEST.
M12	8-19	30	4	5	8	800 800 1000 1000	20 40 20 40	.279 .296 .213 .230	.322 .351 .248 .309	.043 .055 .035 .079		4.125	4.875	1.000	.509 .803 .473 .746	RETEST OF M.11. WITHOUT INSERTS.
M13	8-24	30	4	5	11	800 800 1000 1000	20 40 20 40	.227 -- .176 .178	.350* -- .230 .278*	.123 -- .054 .100		6.625	4.875	1.000	.509 .803 .473 .746	*ESTIMATE ONLY.
M14	9-6	30	8	5	11	800 800 1000 1000	20 40 20 40	.216 .230* .168 .170*	.216 .285 .233 .238*	.000 .055 .065 .068		6.625	4.125	.683	.509 .803 .473 .746	*ESTIMATE ONLY. EXCESSIVE CO LEVELS.
M15	9-8	45	3	8	5	800 800 1000 1000	20 40 20 40	.210 -- .173 .166	.370* -- .336* .370*	.160 -- .163 .204		3.655	3.5	1.000	.509 .803 .473 .746	INJECTOR SPACING 4, 4, 8. *ESTIMATE ONLY.
M16	9-11	45	4	8	5	800 800 1000 1000	20 40 20 40	.205 -- .139 .100	.312 -- .253 .270*	.107 -- .114 .170		3.655	3.5	1.000	.509 .803 .473 .746	REPEAT OF M.4. EXCESSIVE CO LEVELS. *ESTIMATES ONLY. UNSTABLE BEFORE FLAME OUT.
M17	9-13	45	3	5	5	800 800 1000 1000	20 40 20 40	.237 -- .210 .198	.313 -- .260 .258	.076 -- .050 .060		3.655	3.5	1.000	.509 .803 .473 .746	INJECTOR SPACING 4, 4, 8.
M18	9-18	45	3	8	5	800 800 1000 1000	20 40 20 40	-- .242 .178 .182	-- .278 .240 .238	-- .036 .062 .056		3.655	3.5	1.000	.509 .803 .473 .746	INJECTOR SPACING 5, 5, 6. UNSTABLE BEFORE FLAME OUT.
M19	9-21	30	4	8	8	800 800 1000 1000	20 40 20 40	.195 -- .190 .160	.275 -- .270 .285	.080 -- .080 .125		4.125	4.875	1.000	.509 .803 .473 .746	
M20	9-25	30	8	8	8	800 800 1000 1000	20 40 20 40	-- -- .145 .160	-- -- .253 .253	-- -- .108 .093		4.125	4.125	.683	.509 .803 .473 .746	UNSTABLE BEFORE FLAME OUT.



PRIMARY ZONE DIMENSIONS

NOMENCLATURE:

T_1 - COMBUSTOR INLET TEMP.

P_1 - COMBUSTOR INLET PRESS.

ϕ_{BO} - EQUIVALENCE RATIO AT BLOW OUT.

ϕ_{NO_X} - EQUIVALENCE RATIO AT WHICH THE NO_X EXCEEDS THE CONTRACTUAL GOAL OF CLASS AMOD = 1.75 GM./KG.F

$\Delta\phi$ - (ϕ_{NO_X} - ϕ_{BO})

$$\phi_{B.0} = \left[\frac{\dot{\omega}_{AIR}}{P_1^{1.8}\, D^2\, L^*}\right]^{0.1688} \cdot \left[\frac{NL^{**}}{D^*}\right]^{0.0249} \exp\left[1.779 - 0.0009643\, T_1\right]$$

$\dot{\omega}_{AIR}$ - (LB/SEC) AIR MASS FLOW. ϕ_{BO} - REACTION ZONE EXTINCTION EQUIVALENCE RATIO

P_1 - (PSIA) COMBUSTOR INLET PRESSURE

D - (INS) COMBUSTOR REACTION ZONE DIAMETER

T_1 - (^{o}R) COMBUSTOR INLET TEMPERATURE

N - NUMBER OF PRIMARY PORTS

D^* - (INS) PRIMARY PORT DIAMETER. L^{**} - (INS) PRIMARY JET FREE LENGTH

L^* - (INS) REDUCED REACTION ZONE LENGTH

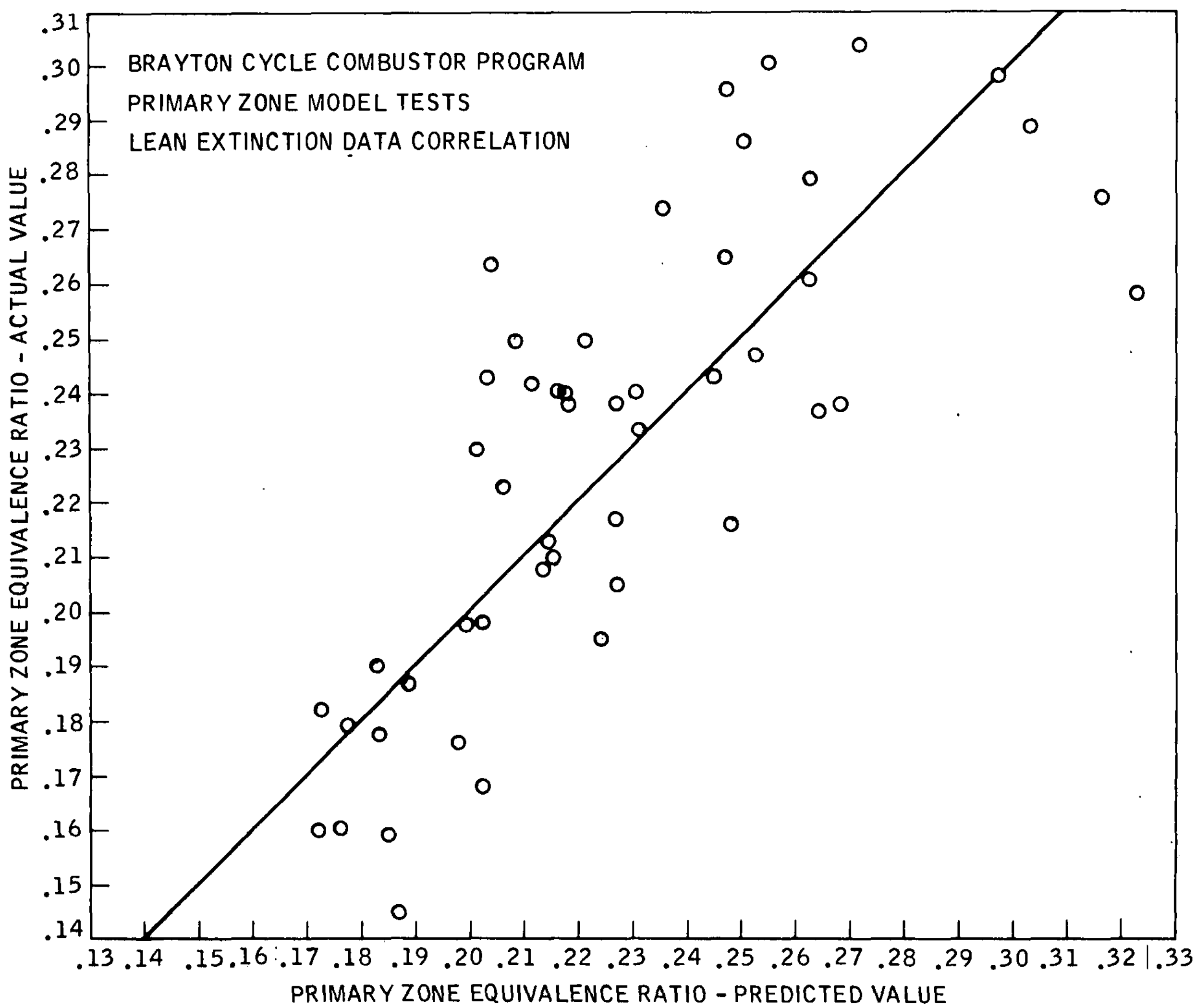


FIGURE 45. LEAN BLOW OUT CORRELATION FOR A JET INDUCED CIRCULATION (JIC) COMBUSTOR PRIMARY ZONE

Characteristic emissions of NO_x, CO and UHC were plotted against overall (reaction zone) equivalence ratio at constant values of combustor pressure drop, combustor inlet pressure and combustor inlet temperature.

The results of the reference combustor are shown in Figure 46, and display the now familiary characteristics of the JIC combustor system. Increasing the combustor inlet temperature from 800 to 1000° F results in increased NO_x levels but improves the lean stability of the combustor. Increasing the combustor pressure from 20 to 40 psig produces an attendant reduction in NO_x with a slight improvement in lean extinction.

The Mod. 19 combustor test results are shown in Figure 47. As can be seen a considerable increase in operating range over the baseline configuration has been obtained, together with a concomittant decrease in the lean blow-out equivalence Compared with the baseline combustor configuration the operating range has been increased approximately threefold, a fact which increases the chances of having a successful variable area control system.

4.2.2 Variable Geometry Port Investigation

Variable Geometry Port Goals

The goals of the variable geometry port investigation were, in general, to provide a design such that its effective discharge coefficient was independent of the annulus crossflow conditions. In the case of the mechanical variable area ports, it was also desired to have a design that produced a perfectly stable exit jet (a jet with non-varying exit angle) with any slide or plug position. Additionally for the mechanical variable area primary ports, a secondary requirement of ensuring that the fuel atomization characteristics were invariant with slide or plug position was considered necessary.

Fluidic variable area ports were required to meet the same general goal as the mechanical devices, but, in addition, a restraint preventing any swirl in the exit was also imposed. It was recognized that fuel atomization could be a problem with fluidic primary ports, and the design had to be such that the fuel spray quality did not vary with the valve internal flow conditions.

Translation Port

A photograph of this arrangement is given in Figure 48. In this system the rectangular sectioned primary and dilution ports are formed between stationary and translatory sections of the combustor. A typical angled primary port and radial dilution port can be seen in the figure.

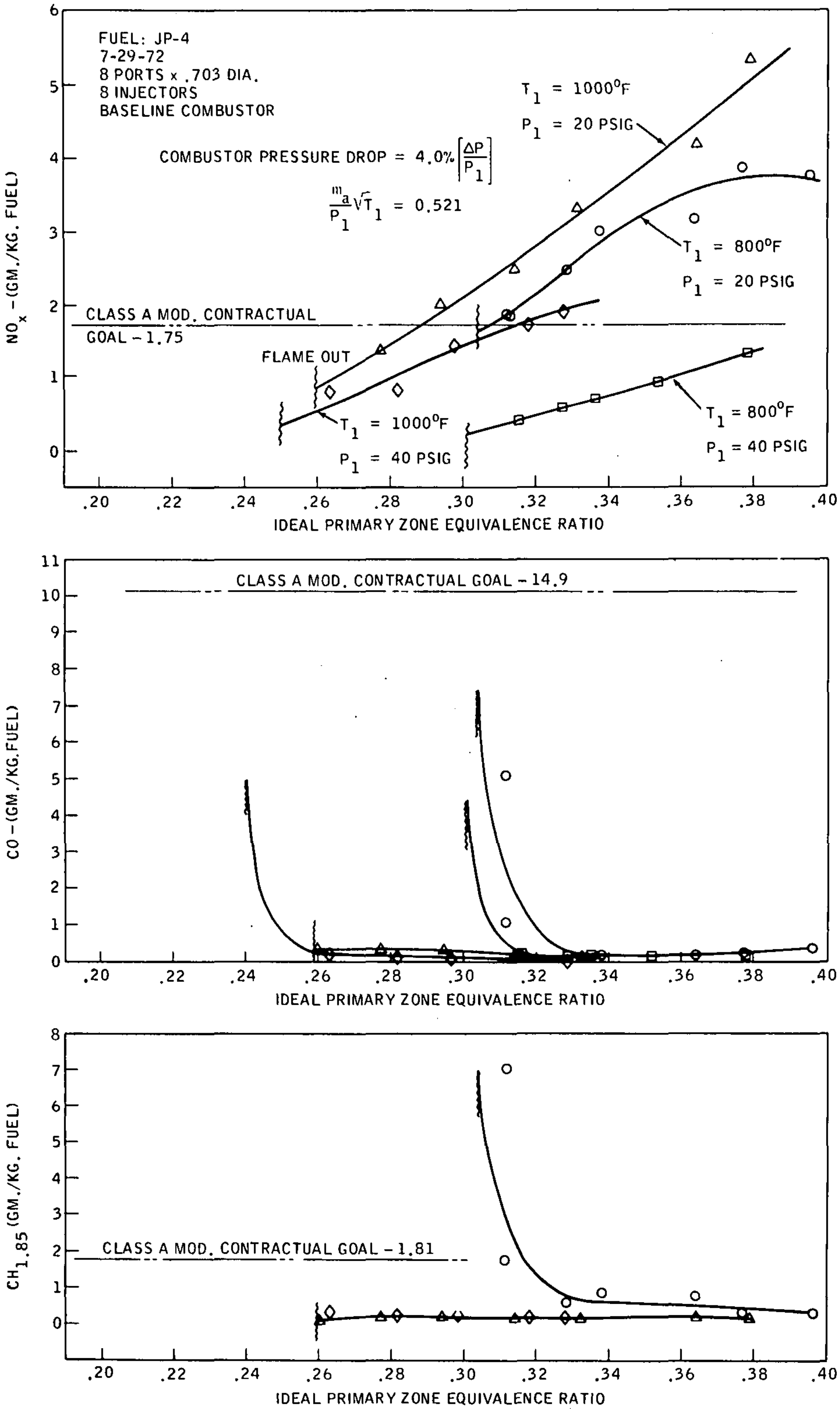


FIGURE 46. PRIMARY ZONE MODEL TESTS, JP-4, REFERENCE COMBUSTOR

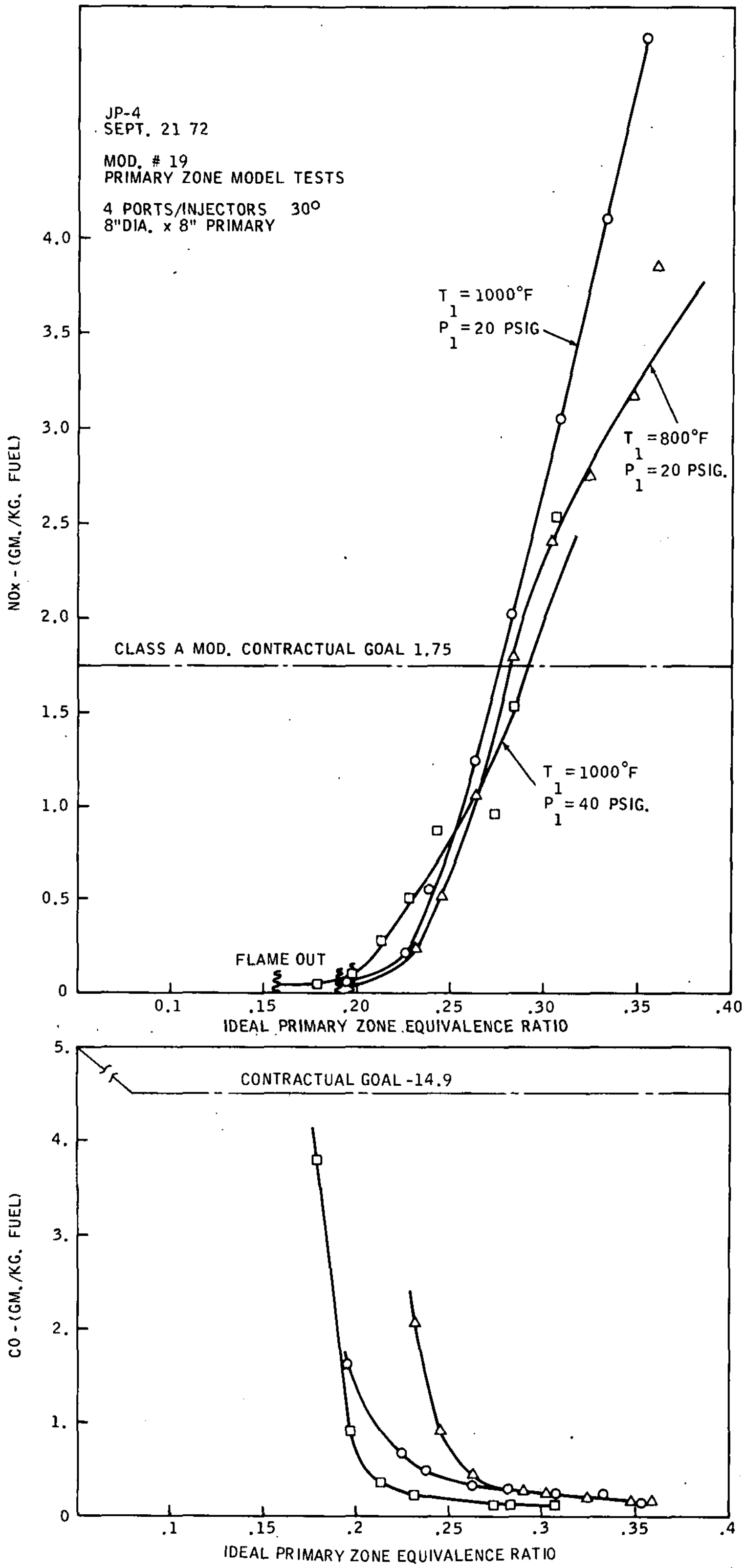


FIGURE 47. PRIMARY ZONE MODEL TESTS, JP-4, MOD 19

TABLE XIV

COMPARISON OF THE REFERENCE PRIMARY ZONE WITH THE BEST OF THE VARIOUS MODIFICATIONS

Combustor Inlet Conditions	Reference			Mod. 19		
	8 Ports @ 45°, 5" dia. x 5" Primary			4 Ports @ 30°, 8" dia. x 8" Primary		
	ϕ_{Bo}	NO_x	Bandwidth on Average	ϕ_{Bo}	ϕ_{NO_x}	Bandwidth on Average ($\Delta\phi$)
T_1 = 800°F, P_1 = 20 psig	0.304	0.308	0.004	0.195	0.275	0.080 ± 17.02%
T_1 = 800°F, P_1 = 40 psig	0.301	0.400	0.099	--	--	-- --
T_1 = 1000°F, P_1 = 20 psig	0.258	0.289	0.030	0.190	0.270	0.080 ± 17.40%
T_1 = 1000°F, P_1 = 40 psig	0.250	0.316	0.066	0.160	0.285	0.125 ± 28.05%

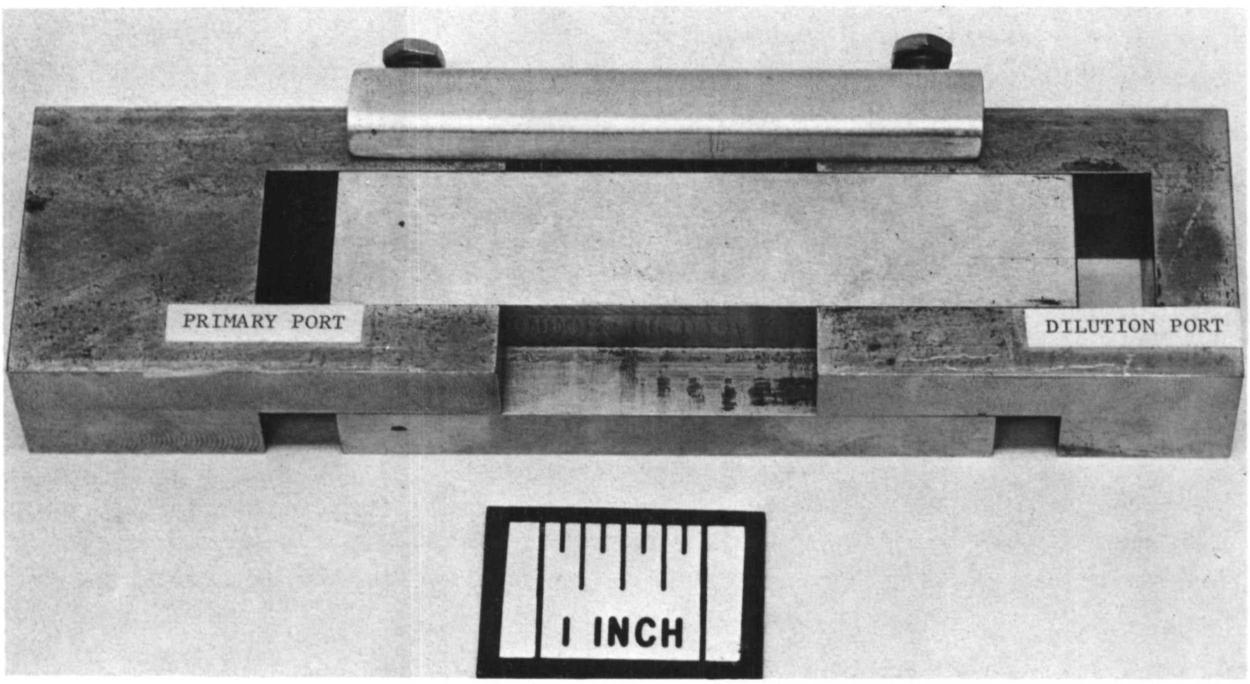


FIGURE 48. VARIABLE PORT MODEL

The system promotes relative simplicity in manufacture and provides an aerodynamically "clean" combustor annulus but has a variable leakage rate with position and a possible problem with fuel injector positioning. The actuation forces required might also be difficult to predict, depending on the state of the sliding surfaces.

The model was tested on the airflow rig previously described, and the results are shown in Figure 49. The results apply only to the 45 degree angled primary port.

Slide Valve Port

The second mechanical system is shown in Figure 50. As depicted, the model consists of combined primary and secondary ports, both rectangularly sectioned, where the area control is performed by the central slide. The primary slide is independent of the secondary slide but could be coupled together for certain ranges of combustor operation. The fuel delivery tube is shown positioned at the primary port throat. A splitter is provided at the dilution port outlet to divide the jet penetration between the primary jets. The dilution port outlet is shown angled to direct the flow downstream to avoid premature quenching. Photographs of the system and the twin central slide are given in Figures 51 and 52, respectively.

The slide valve port was tested only at three discrete positions: the first with the primary side fully open and the dilution closed, the second with the primary and dilution each half open, and the last with the dilution open and the primary closed. A typical characteristic is shown in Figure 53. It can be seen that cross flow over the port entrance has a major effect on the discharge coefficient. In addition to this, it was found that the primary and dilution port jet angles varied with the slide position. With the primary open full, and the dilution side closed, the primary jet angle was found to be 65 degrees. When the slide was adjusted, however, so that both the primary and dilution ports were each half open, the dilution jet angle was 58 degrees while the primary jet angle had increased to 72 degrees. At the other extreme when the dilution port was fully open and the primary closed to its minimum position, the primary jet angle was 90 degrees while the dilution was 65 degrees.

Fluidic Valve Port

The third system is fluidic in nature with no internal moving parts. A section through this design is shown in Figure 54. The static nature of the device is an obvious attraction, although an external compressor would be required to supply the control air. The operation is as follows:

The main supply airflow passes into the swirl chamber through the outer perforated plate and then through the fixed orifice at the swirl chamber outlet into an

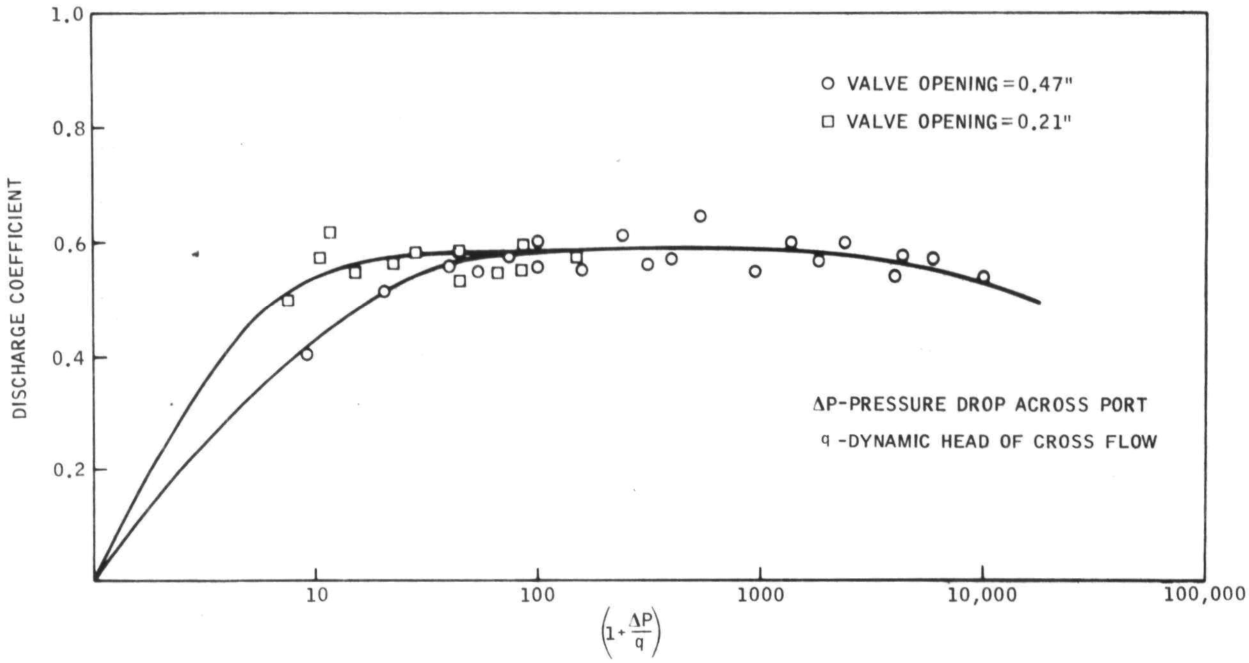


FIGURE 49. VARIABLE GEOMETRY PORT TESTS TRANSLATING VALVE

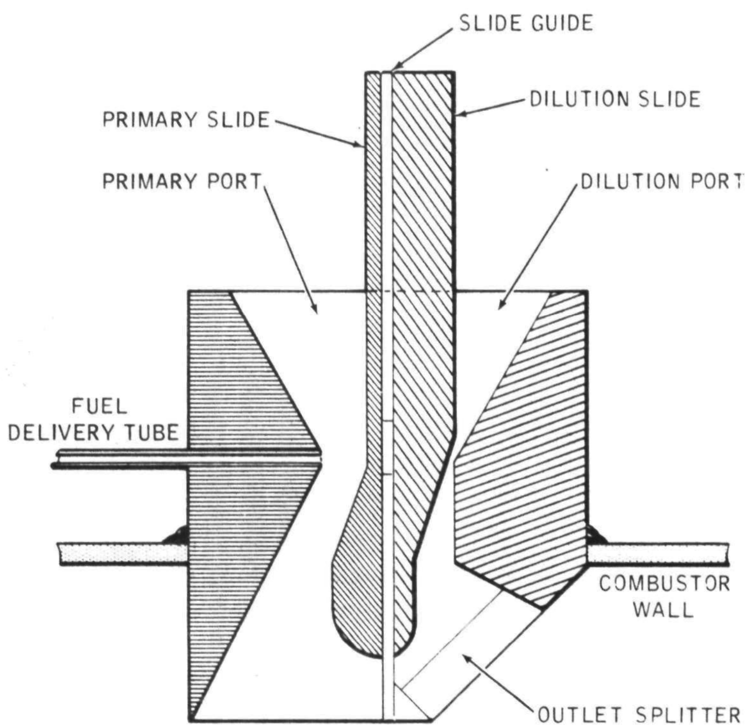


FIGURE 50. VARIABLE PORT MODEL - SLIDE VALVE

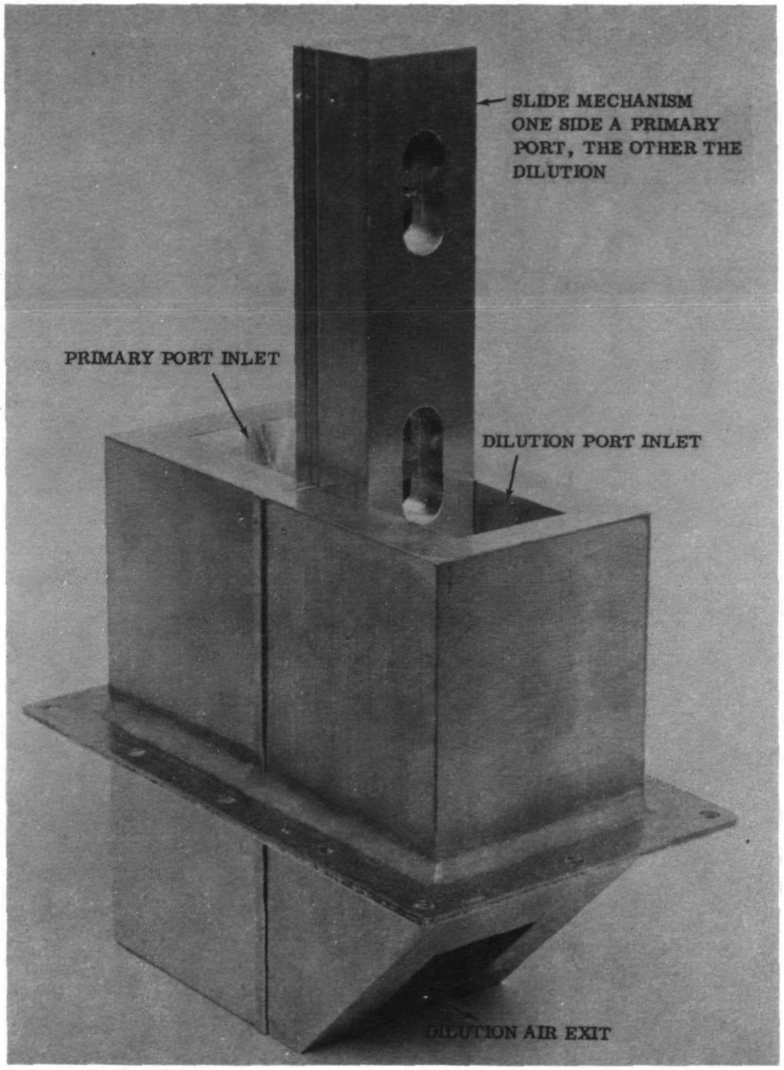


FIGURE 51. CONTROLLED VARIABLE AREA COMBINED PRIMARY AND DILUTION PORT SYSTEM

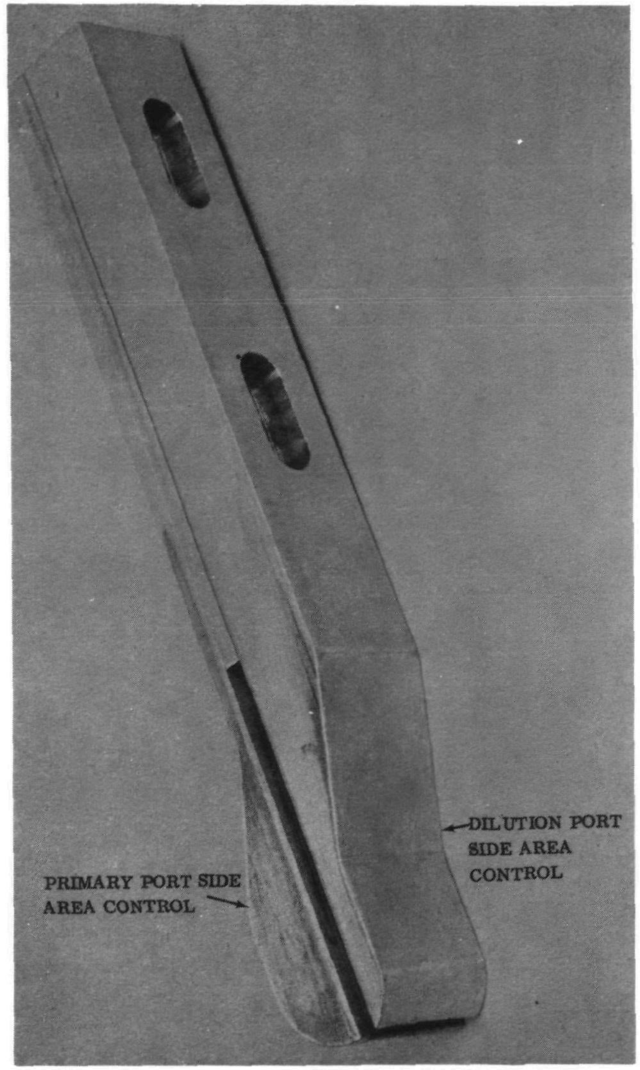


FIGURE 52. DETAILS OF SLIDE FOR SLIDE VALVE PORT

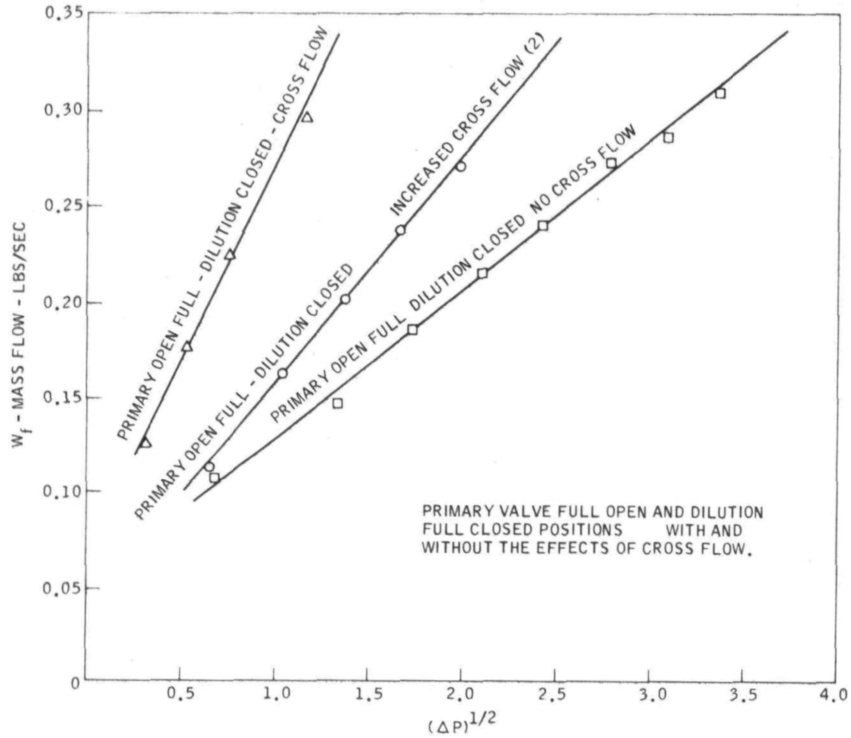


FIGURE 53. MASS FLOW CHARACTERIZATION OF THE SLIDE VALVE VARIABLE AREA PORT

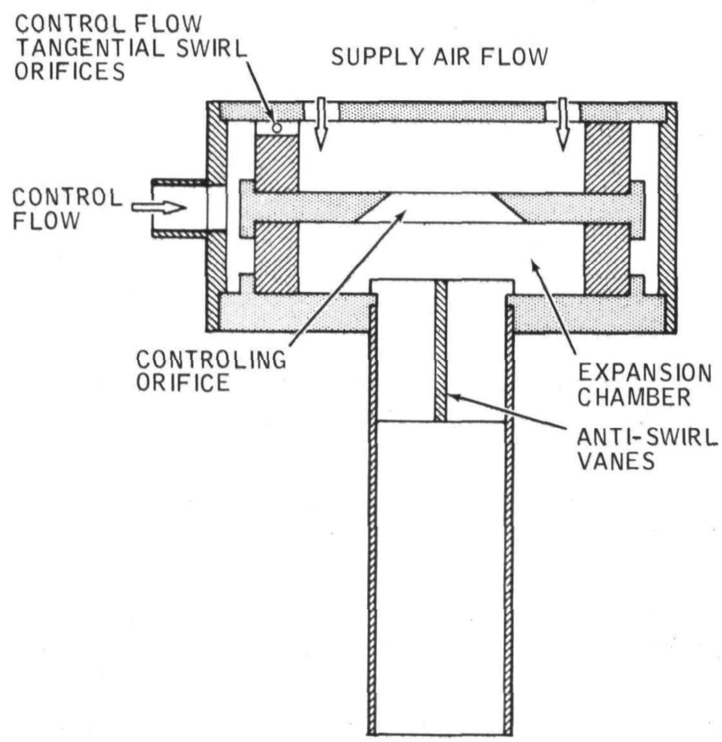


FIGURE 54. VARIABLE PORT MODEL - FLUIDIC OPERATION

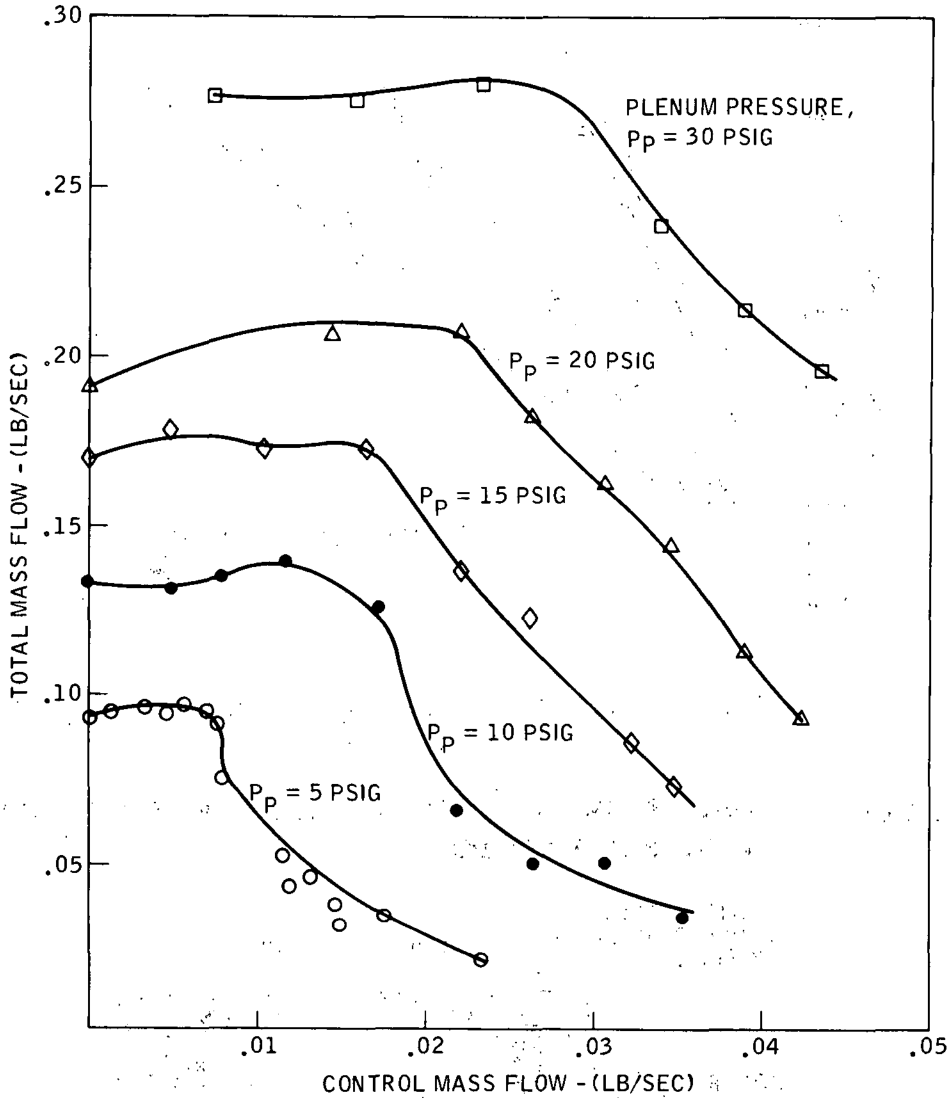


FIGURE 55. FLOW CHARACTERISTICS OF THE FLUIDIC VARIABLE AREA DEVICE

expansion chamber before leaving the port exit tube. The port exit tube is equipped with de-swirl vanes to produce essentially axial flow in the exit tube.

The discharge coefficient of the fixed orifice is varied by imposing a degree of swirl to the airflow.

The swirl component is provided by the control airflow, delivered from an external source, which enters the swirl chamber through tangential orifices.

A generalized characteristic of this device is shown in Figure 55 where total mass flow through the port is plotted against control mass flow for various levels of plenum pressure. The overall pressure drop across the port is the plenum pressure less the atmospheric pressure.

It can be seen that control begins to occur when the control mass flow is approximately 10 percent of the total mass flow and the valve characteristic becomes fairly linear thereafter. Such a characteristic would be amenable to control scheduling although it is considered that the required control flows are excessive. A redesign of the port to increase the swirl chamber diameter, for example, would reduce the required control mass flows.

None of the results from any of the model designs dictate that a particular idea should be ruled out completely, although some redesign would be required in each case before a satisfactory system would result.

It should be possible to design a combustion system around either of the mechanical variable geometry port designs and obtain operation of the port with minimum discharge coefficient variation, although such a variation could, after calibration, be built into a control schedule.

Some redesign would be required to the fluidic port system to reduce the external pumping horsepower requirements.

4.3 ADDENDUM III - COMBUSTOR CONTROL SYSTEM ANALYSIS AND NO_X CORRELATIONS

4.3.1 NO_X Correlation Parameters

The formulation of NO_X correlation parameters is important from two aspects. First, such parameters can provide useful information as to the controlling mechanisms and hence indications as to possible methods of reduction of NO_X. Second, in the absence of a suitable NO_X sensor, the control system of a variable geometry combustor must synthesize the NO_X level from the other more readily obtainable parameters such as pressure, temperature and fuel flow in order to maintain the correct combustor port area relationships. Thus the control must have the correlation parameter 'built in".

The Addendum III work included all the test points of the Class A-Mod and Class B-Mod combustors.

The emissions data obtained on the Class A-Mod and Class B-Mod combustors, when tested over the various specified ranges, have been divided into three categories. The first are those results obtained with the Class A-Mod combustor equipped with a co-axial port fuel injector. Comprising the second set of results are those obtained with the Class A-Mod combustor fitted with a slotted face injector, with the slot oriented toward the primary zone dome. The final set of results were those of the Class B-Mod combustor, which exclusively utilized the coaxial fuel injection system.

The analysis required that each NO_x characteristic be reduced to discrete operating points described by NO_x level and overall equivalence ratio. Approximately four points were selected from each characteristic. On the Class A -Mod results the points were selected below a maximum NO_x level of 3.0 gm/Kg fuel and below a maximum of 5.0 gm/Kg fuel for the Class B-Mod combustor.

Each of the data sets corresponding to the above categories was in turn analyzed to provide a NO_x correlation parameter, using a linear multiple regression computer program. The results for the two fuel injector configurations of the Class A-Mod combustor are shown in Table XV together with a Class B-Mod result. An extremely large variety of correlation parameters can be obtained by simply rearranging the various independent variables, although it is likely that none of these would provide any clues to the controlling physical processes involved in NO_x production. In an effort to provide a correlation parameter that would have some physical significance, the results were constrained to follow, instead of a straight line, a curve of the form $NO_x = \exp(\psi) - 1$, where ψ is a parameter composed of the independent variables and a constant. Such a curve typically represents the behavior of a generalized kinetically controlled chemical process, and it was hoped that the independent variables might be grouped into a form that had some chemical or physical significance. Unfortunately, as can be seen, the results of this latter approach did not produce any correlation functions that could be easily interpreted to provide insight into what might control the production of NO_x.

A further correlation was produced that included the ratio of primary to overall equivalence ratio (see Table XV). This latter term is a function of the primary zone port area to the total area ratio, and thus can be utilized as part of a control function providing a positional reference for the proposed variable area actuating mechanism. Presently the approach to the problem of providing a control function for the actuating mechanism is to maintain the combustor pressure drop fraction ($\Delta P/P$) constant, which provides an easy solution to the total combustor area as a function of the combustor inlet conditions, expressed as ($w\sqrt{T}/P$). Then, from the NO_x correlation described above, the ratio of the primary zone area (plus a constant primary zone cooling area portion) to the total combustor flow area can be obtained, and this, combined with the total value obtained from the pressure drop relationship, provides the actual primary zone area required. This latter value can then in turn be translated into a spatial coordinate reference for the actuator mechanism. This part of the present investigation will be discussed in more detail in the next section.

4.3.2 Control System Analysis

An examination has been made of the feasibility of successfully operating a variable geometry control system.

TABLE XV

SUMMARY OF NO_x CORRELATION PARAMETERS

LINEAR MULTIPLE REGRESSION ANALYSIS

1. Results of the Class A-Mod Combustor (Side Slotted Fuel Injectors) Provide:

$$NO_x = \frac{\dot{\omega}^{10.54} \Delta T^{2.96} D_p^{4.79} \exp(34.7 + 6.67\,\sigma_p + 0.00487\,T_1)}{P_1^{15.1} \left(\frac{\Delta P}{P_1}\right)^{1.43}}$$

2. Results of the Class A-Mod Combustor (Coaxial Fuel Injectors) Provide:

$$NO_x = \frac{\dot{\omega}^{4.57} \Delta T^{2.69} D_p^{1.48} \exp(4.76 + 3.98\,\sigma_p + 0.00383\,T_1)}{P_1^{6.32} \left(\frac{\Delta P}{P_1}\right)^{2.87}}$$

3. Results of the Class B-Mod Combustor (Coaxial Fuel Injectors) Provide:

$$NO_x = \frac{\dot{\omega}^{6.56} \Delta T^{2.59} D_p^{6.767} \exp(15.6 + 12.8\,\sigma_p - 0.0000123\,T_1)}{P_1^{7.158} \left(\frac{\Delta P}{P_1}\right)^{0.336}}$$

CORRELATION WHEN RESULTS ARE CONSTRAINED TO FIT A CURVE OF $NO_x = \exp(\psi) - 1$ WHERE ψ IS THE CORRELATION PARAMETER

1. Results of the Class A-Mod Combustor (Side Slotted Fuel Injectors) Provide:

$$\psi = \frac{(\dot{\omega}/P_1)^{4.14} \Delta T^{2.84} \exp(0.6 + 0.99\,\sigma_p - 0.0032\,T_1)}{P_1^{1.26} (\Delta P/P_1)^{2.62} D_p^{0.6}}$$

CORRELATION USING LINEAR MULTIPLE REGRESSION BUT INCORPORATING THE VARIABLE AREA CONTROL FUNCTION (σ_T/σ_p)

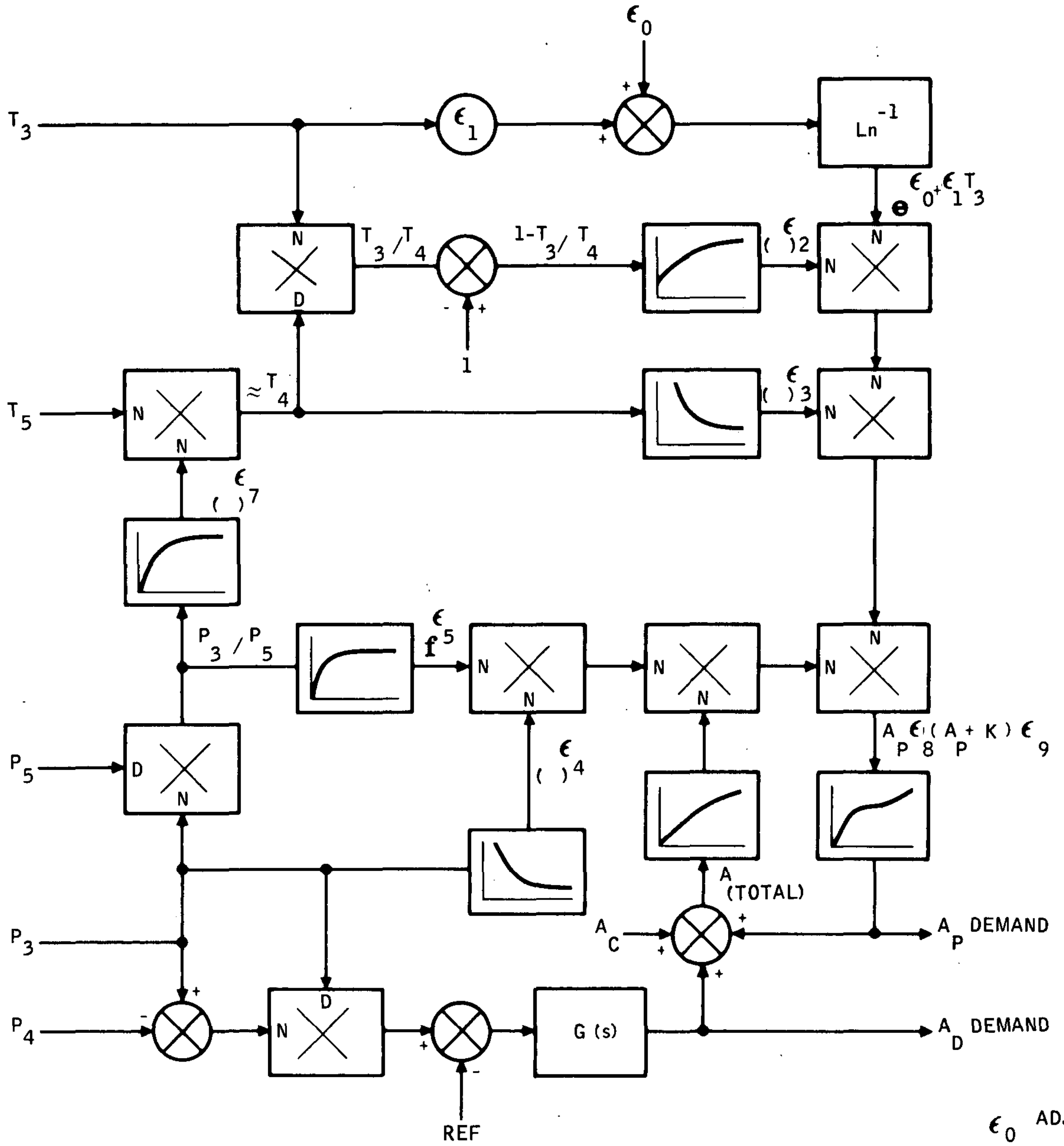
1. Results of the Class A-Mod Combustor (Side Slotted Fuel Injectors) Provide:

$$NO_x = \frac{\dot{\omega}^{10.08} \Delta T^{4.32} (\sigma_T/\sigma_p)^{3.9} \exp(18.37 + 0.00537\,T_1)}{P_1^{11.86} D_p^{9.33} (\Delta P/P)^{5.63}}$$

NOMENCLATURE

D_p	primary port diameter (inch)
P_1	combustor inlet pressure (psia)
$(\Delta P/P)$	combustor pressure drop (%)
T_1	combustor inlet temperature (°R)
ΔT	combustor temperature rise (° F)
$\dot{\omega}$	combustor air mass flow (lb/sec)
σ_p	primary zone equivalence ratio
σ_T	overall combustor equivalence ratio

NOTE: NO_x is the emissions index in gm/Kg of fuel.



A_D CONTROLLED TO OBTAIN $(P_3 - P_4)/P_4$ CONST.

A_P CONTROLLED SO $A_P^{.543}(A_P + K)^{.457} \approx e^{\epsilon_0+\epsilon_1 T_3}(1-T_3/T_4)^{\epsilon_2}(T_4)^{\epsilon_3}(P_3)^{\epsilon_4} f^{\epsilon_5} A_T^{\epsilon_6}$

$$T_4 = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma\eta_P}} T_5 \approx \left(\frac{P_3}{P_5}\right)^{\epsilon_7}$$

ϵ_0	ADJUST	ϵ_7	.284
ϵ_1	.00062	ϵ_8	.543
ϵ_2	.502	ϵ_9	.457
ϵ_3	-.084		
ϵ_4	-.207		
ϵ_5	1.175		
ϵ_6	.457		

FIGURE 56. CONTROL SYSTEM BLOCK DIAGRAM

The variable geometry system is constrained to operate within the boundaries of the NO_x correlation parameter shown in Table XV and containing the equivalence ratio function σ_T/σ_p.

A study was made including the tentative selection of parameters and an error analysis for full speed and idle conditions assuming typical accuracies for parameter sensing. Both analog and digital computation mechanization were considered.

The block diagram of Figure 56 illustrates the mechanization. The results of the two digital analyses are shown in Figures 57 and 58.

Total error in predicted NO_x level is not significantly affected by the difference in operating speed, but is potentially reduced by 50 percent using digital, rather than analog computing techniques.

```
RUN
LONOX

ERROR ANALYSIS, PRIMARY AREA CONTROL
FULL SPEED
DIGITAL COMPUTATIONS MECHANIZIATION
ERROR SOURCE     NOMINAL       TOLERANCE(%)    WEIGHT          ERROR(%)
T3                1525          1               .936589         .936589
P3                66            .8              .193561         .154846
T5                1860          2               .105204         .210409
P5                36            1.5             3.05093E-02     4.57639E-02
F                 1             .3              1.10093         .33028
A(TOTAL)          8             1.2             .428193         .513832
COMPUTE EXP       .00062        .1              .885901         8.85901E-02
COMPUTE EXP       .502          .1              .488694         4.88694E-02
COMPUTE EXP      -.084          .1              .611257         6.11257E-02
COMPUTE EXP      -.204          .1              .800815         8.00815E-02
COMPUTE EXP       1.175         .1              1.54842E-07     1.54842E-08
COMPUTE EXP       .457          .1              .890403         8.90403E-02
COMPUTE EXP       .29           10              1.04927E-02     .104927
COMPUTE EXP       .543          .1              .818837         8.18837E-02
COMPUTE EXP       .457          .1              6.35523E-02     6.35523E-03
MULTIPLIER        1             .1              4.71972         .471971
                                                                ----------
                               TOTAL ERROR (%)=                 3.30457
                               ROOT SUM SQUARE ERROR (%)=       1.26991

ASSUMING 8.5        % UNCERTAINTY IN THE CORRELATION
FUNCTION, AND 2     % ACCURACY OF DELTA-P/P
CONTROL, THE EXPECTED RSS ERROR IN NOX LEVEL IS
 17.4207    %

DONE
```

FIGURE 57. ERROR ANALYSIS - FULL SPEED DIGITAL

RUN
LONOX

ERROR ANALYSIS, PRIMARY AREA CONTROL
IDLE SPEED
DIGITAL COMPUTATIONS MECHANIZIATION

ERROR SOURCE	NOMINAL	TOLERANCE(%)	WEIGHT	ERROR(%)
T3	1450	1	.858582	.858582
P3	23	2.4	.181537	.43569
T5	1360	2	.190533	.381067
P5	17	3	5.52547E-02	.165764
F	.5	1	.996008	.996008
A(TOTAL)	5	1.2	.387384	.46486
COMPUTE EXP	.00062	.1	.762052	7.62052E-02
COMPUTE EXP	.502	.1	1.12849	.112849
COMPUTE EXP	-.084	.1	.523523	5.23523E-02
COMPUTE EXP	-.244	.1	.542202	5.42202E-02
COMPUTE EXP	1.175	.1	.690381	6.90381E-02
COMPUTE EXP	.457	.1	.62347	.062347
COMPUTE EXP	.29	10	1.67024E-02	.167024
COMPUTE EXP	.543	.1	1.40085E-07	1.40085E-08
COMPUTE EXP	.457	.1	.157071	1.57071E-02
MULTIPLIER	1	.1	4.28014	.428014

TOTAL ERROR (%)= 4.33973
ROOT SUM SQUARE ERROR (%)= 1.5975

ASSUMING 8.5 % UNCERTAINTY IN THE CORRELATION
FUNCTION, AND 2 % ACCURACY OF DELTA-P/P
CONTROL, THE EXPECTED RSS ERROR IN NOX LEVEL IS
18.2856 %

FIGURE 58. ERROR ANALYSIS - IDLE SPEED DIGITAL

5

CONCLUSIONS

1. The JIC combustor concept has demonstrated the ability to easily meet the 1975-76 Federal automotive emissions requirements when rig tested over a simulated Federal Driving Cycle test mode and using a pseudo-variable geometry arrangement.

2. For a practical automotive gas turbine power plant the JIC combustor would require a variable geometry system to maintain the emissions below requirements over the complete operational envelope.

3. Sufficient design data are now available to be able to make an initial trial scaling of the JIC-type combustor to any particular regenerative engine cycle conditions with some degree of confidence within the size ranges tested.

4. The available operating range of the JIC-3 combustor could be considerably extended with configurational modifications in the area of combustor diameter, length and number of primary ports.

5. The general performance parameters of the JIC-3 combustor such as outlet temperature pattern factor, smoke and wall temperatures, etc. have to date been acceptable and would likely not be a problem with any other JIC-type combustor design.

6. The control of a variable-geometry JIC type combustor is likely to be a difficult problem although not outside current capabilities. Improvements in the low emission operating range could alleviate the problem considerably.

7. Various variable geometry port designs are available for consideration in a JIC-type combustor system, and both mechanical and fluidic devices appear attractive at this time.

6

RECOMMENDATIONS

1. Because of the very low emission levels at the normal combustor operating conditions, changes to the level or degree of homogeneity of the incoming fuel-air mixture are very important. In consequence, further work investigating improved atomization and mixing arrangements should prove valuable in improving lean blow-out. It is recommended that such investigations would include the testing of the following atomization systems:

- Pressure swirl atomization simplex and/or duplex
- Splash plate impingement atomization
- Contra-flow injection

2. One of the conclusions that can be drawn from the work performed to date is that the number of primary ports can be reduced to four without any major effect on the emissions. Such a reduction is eminently desirable from a control point of view since it minimizes the number of variable area devices required. However, improvements in stability through increases in primary zone recirculation rate could still be achieved by changes in the port shape. It is recommended that further investigations into stability improvements include primary ports with cross-sectional shapes chosen to maximize surface area for a given cross section. An investigation into the possibility of improving the stability through changes in port or jet shape could lead to important changes on future combustor designs.

3. The results obtained on the fluidic valve indicate that with the present configuration the control mass flow rates required for modulation are too expensive to be practical in terms of the external pumping horsepower required. However, in view of the reduction in mechanical complexity of a variable geometry combustor system that is promised by a fluidic device of this nature, it would seem profitable to continue these investigations. The control flow to supply flow ratio could be reduced by increasing the diameter of the swirl chamber, for example. It should also be possible to have the swirl chamber wrapped around the combustor body with a manifold annular exhaust to each port. Design data on such arrangements are not presently available, and it would seem worthwhile to pursue this approach as a separate future investigation.

4. The primary zone model tests were directed towards broadening the available operating range of the JIC type combustor by improving the lean stability with configurational modifications. Some very crude attempts at piloting the reaction were performed during the A2 testing of the Class A-Mod JIC combustor with encouraging results. It would seem worthwhile, therefore, to consider a similar effort to the primary zone model tests in investigating the operation of a piloted combustor concept to be operated in conjunction with the torch ignitor. Such a system could obviate the requirement for a variable geometry combustor.

5. It can be seen that the solution of the variable geometry control problem in any future JIC type combustor system will not be simple, by virtue of the fact that the operational NO_X level of the combustor at any operating point must be synthesized from a variety of independently monitored parameters. The complexity of the control system could be greatly simplified if a "NO_X sensor" were available. This sensor would continuously monitor the NO_X level from the combustor and provide the error signal for the control on a conventional closed loop system. Although such a device is apparently not currently available, it promises such control advantages that its development should be actively pursued.

NOMENCLATURE

$CH_{1.85}$	Arbitrary hydrocarbon composition taken as representative of JP-4
CO	Carbon monoxide
CO_2	Carbon dioxide
D_P	Diameter of the primary zone
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
P_1, P_{IN}, P_{INLET}	Combustor inlet pressure
T_1, T_{IN}, T_{INLET}	Combustor inlet temperature
T_2	Combustor outlet temperature
$\dot{\omega}a$, Wa	Combustor mass air flow rate
$\dot{\omega}f$, Wf	Combustor fuel flow rate
α	Port angle
ΔP	Pressure drop
$\Delta P/P$	Pressure drop as a percentage of the inlet
$\Delta P/q$	Ratio of combustor pressure drop to local cooling annulus dynamic head
ΔT	Temperature rise or increase over combustor

NOMENCLATURE (Cont)

ϕ	Equivalence ratio (actual fuel to air ratio, divided by the stoichiometric fuel to air ratio)
σ_{prim} σ_p	primary zone equivalence ratio
σ_T	overall combustor equivalence ratio