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LOW EMISSIONS RQL FLAMETUBE COMBUSTOR COMPONENT TEST RESULTS

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SUMMARY

This report describes and summarizes elements of the High Speed Research (HSR) Low Emissions Rich burn/Quick mix/Lean burn (RQL) flame tube combustor test program. This test program was performed at NASA Glenn Research Center circa 1992. The overall objective of this test program was to demonstrate and evaluate the capability of the RQL combustor concept for High Speed Civil Transport (HSCT) applications with the goal of achieving NO_x emission index levels of 5 g/kg-fuel at representative HSCT supersonic cruise conditions. The specific objectives of the tests reported herein were to investigate component performance of the RQL combustor concept for use in the evolution of ultra-low NO_x combustor design tools.

Test results indicated that the RQL combustor emissions and performance at simulated supersonic cruise conditions were predominantly sensitive to the quick mixer subcomponent performance and not sensitive to fuel injector performance. Test results also indicated the mixing section configuration employing a single row of circular holes was the lowest NO_x mixer tested probably due to the initial fast mixing characteristics of this mixing section. However, other quick mix orifice configurations such as the slanted slot mixer produced substantially lower levels of carbon monoxide emissions most likely due to the enhanced circumferential dispersion of the air addition.

Test results also suggested that an optimum momentum-flux ratio exists for a given quick mix configuration. This would cause undesirable jet under- or over-penetration for test conditions with momentum-flux ratios below or above the optimum value. Tests conducted to assess the effect of quick mix flow area indicated that reduction in the quick mix flow area produced lower NO_x emissions at reduced residence time, but this had no effect on NO_x emissions measured at similar residence time for the configurations tested.

NOMENCLATURE

A_m mainstream flow area, in^2

AC_d quick-mix injection effective discharge area, in^2

CO carbon monoxide

CO_2 carbon dioxide

EI(NO_x) NO_x emission index, g/(kg-fuel), assuming all emissions are NO_2

EI(CO) CO emission index, g/(kg-fuel)

J quick-mix jet to mainstream momentum-flux ratio

$$J = [(W_q/W_{rb})^2\,(T_3/T_{rb})]/[(A\,C_d/A_m)^2\,(M_3/M_{rb})]$$

M_3 inlet air molecular weight, g/mole

M_{rb} rich-burn zone mean molecular weight, g/mole

NO nitric oxide

NO_2 nitrogen dioxide

NO_x nitrogen oxides (NO + NO_2)

O_2 oxygen

P_3 combustor inlet plenum pressure, psia

P_4 lean-burn section exit pressure, psia

P_{rb} rich-burn section exit pressure, psia

ΔP_{34} pressure drop from rich-burn zone inlet to lean-burn zone exit, psi

T_3 combustor inlet total temperature, °F

T_4 estimated lean-burn section equilibrium temperature, °F

T_{rb} estimated rich-burn section equilibrium temperature, °F

UHC unburnt hydrocarbons

$V_{ref,lb}$ lean-burn zone (cold flow) reference velocity, ft/s

$V_{ref,ov}$ overall (non-reacting flow) reference velocity, ft/s

$V_{ref,q}$ quick-mix zone (non-reacting flow) reference velocity, ft/s

$V_{ref,rb}$ rich-burn zone (non-reacting flow) reference velocity, ft/s

W_d rich-burn zone dome airblast mass-flow rate, lbm/s, all fuel nozzles

W_f total fuel-flow rate, lbm/s

W_i rich-burn zone inner airblast mass-flow rate, lbm/s, all fuel nozzles

W_m rich-burn zone middle airblast mass-flow rate, lbm/s Textron nozzle only

W_o rich-burn zone outer airblast mass-flow rate, lbm/s all fuel nozzles

W_q quick-mix air mass-flow rate, lbm/s

W_{rb} rich-burn zone total mass-flow rate, $W_{rba} + W_f$, lbm/s

W_{rba} rich-burn zone total air mass-flow rate, $W_i + W_m + W_o + W_d$, lbm/s

η combustion efficiency

ϕ_{lb} lean-burn zone equivalence ratio, $(F/A_m)/(F/A_{stoi})$

ϕ_{rb} rich-burn zone equivalence ratio

τ_{lb} lean-burn zone residence time, ms

τ_{ov} overall residence time, ms

τ_q quick-mix zone residence time, ms

τ_{rb} rich-burn zone residence time, ms

1. INTRODUCTION

Low emission technologies evolved in the 1970's and early 1980's for aircraft, stationary power and automotive gas turbine applications indicate that ten-fold reduction of NO_x levels are theoretically possible (refs. 1 and 2). The main source of NO_x in a combustor is thermal oxidation of atmospheric nitrogen (ref. 3). NO will form in any airbreathing propulsion device and is very sensitive to combustion temperature. Nitric oxide (NO) is produced quickly at full power and cruise conditions in the near stoichiometric regions in combustion zones. The NO then oxidizes to NO_2 in the presence of excess oxygen downstream of the combustor. A strategy to reduce NO formation is thus to reduce the combustion temperature. NO_x reductions to environmentally acceptable levels appear achievable through evolution of advanced, low emission combustor designs.

Three promising combustion concepts have been investigated in the HSR emission research program. These concepts include Lean-Premixed-Prevaporized (LPP), Lean-Direct-Injection (LDI), and Rich-burn/Quick-mix/Lean-burn (RQL) combustion. The LPP concept for controlling NO_x first appeared in the early 1970's (refs. 1 and 2). This concept provides a uniform mixture of fuel vapor and air that burns at low temperatures where minimum NO levels occur (refs. 2 and 4). In the LDI concept, all the combustion air enters at the combustor dome region, and the fuel is injected directly into the combustion zone. References 5 and 6 describe the LDI concept and provide emission data. The RQL concept was conceived to control NO_x from alternate fuels with large amounts of fuel-bound nitrogen (refs. 7 to 9). The rich burner functions as a fuel preparation zone where very little of the fuel-bound nitrogen is converted to NO_x. The RQL concept uses the principle that both rich (higher fuel/air ratios than stoichiometric) and lean (lower fuel/air ratios than stoichiometric) mixtures produce lower NO_x. Recently, numerical analysis showed that it is theoretically possible to achieve the ultra-low NO_x goal for the RQL concept for the HSR emission research program (ref. 10).

A major goal of the HSR emission research program was to experimentally verify the ten-fold NO_x reductions at supersonic cruise conditions in laboratory tests. This test program was performed in two tasks. The objective of the first task was to experimentally demonstrate the capability of the RQL concept to reach the program NO_x goal of 5 g/kg-fuel at supersonic cruise conditions. The objective of the second task was to investigate the performance of the rich and mixing zones as a guide for future combustor design criteria. Parametric studies were conducted with an 8 orifice slanted slot mixer to investigate effects of combustor operating variables and fuel injector designs on combustor emissions and performance. These combustor operating variables parametric tests were conducted at inlet temperatures of 600 to 1100 °F, rig pressures of 80-150 psia, exit temperatures of 2600 to 3160 °F, overall reference velocities of 50 to 150 ft/sec, and rich burner equivalence ratios of 1.5 to 2.2. Results from these tests are reported in reference 11. Pratt & Whitney concurrently conducted the RQL flame tube combustor test program at United Technology Research Center (ref. 12).

The purpose of this report is to describe additional test results obtained in the in-house NASA Glenn Research Center HSR Low NO_x RQL flame tube combustor test program. Hardware changes to the combustor for results reported here focused on varying the fuel injector and quick mixing designs. The key was to provide low emission combustion technology for engine development for future HSCT aircraft (ref. 13) that would produce NO_x, an ozone depletion compound in the stratosphere, at such low levels that it would probably not harm the ozone layer (refs. 13 and 14).

2. TEST COMBUSTOR

2.1 Test Rig

Figures 1 and 2 show the RQL flame tube test rig assembly. The RQL combustor operated using Jet-A fuel with combustion air inlet temperatures to 1100 °F, a maximum operating pressure of 275 psia, and a total gas flow reference velocity of 100 ft/sec. The rich burn section operated in a reducing combustion environment with a maximum operating temperature of 4000 °F. The quick mix and lean burn section operated in an oxidizing environment with maximum operating temperatures of 4000 and 3200 °F, respectively.

The construction of the rich burn and lean burn pressure vessel housings each consisted of a 12 in. schedule 40S stainless pipe with ANSI class 300 flanges welded on each end of the pipe. Couplings were welded onto the pipe to allow for the installation of the torch, thermocouples and gas sample probes into the combustion gas stream. Stainless steel tubing welded to the outside of the pressure vessel pipe removed any heat which was conducted from the hot gas stream inside the combustor, through the refractory ceramics and into the pressure vessel housing. Refractory ceramics were used to define the internal combustor geometry and cast into the stainless steel housing using a castable ceramic. The refractory ceramics were installed inside the rich burn housing by first wrapping the inside of the housing with 1/8 in. thick Lytherm ceramic paper. The Lytherm paper was an excellent insulator and its pliant properties allowed for differential expansion between the stainless steel housing and the refractory ceramic.

A high temperature, precast zirconia refractory liner was next positioned inside the housing using a pre-assembled casting fixture. The rich burn housing used a zirconia tube, manufactured by Zircoa, Inc., which had a 6 in. inside diameter tapered to a 4 in. inside diameter at the downstream end with a 45° convergent section (see fig. 3). The rich burn section was 8 in. long. Casting plugs were installed to produce the penetrations for the thermocouples, torch and gas sample probes as required. Once the inner zirconia liner and casting pins were in place, a castable alumina refractory ceramic was used to fill the annular void between the inner liner and the Lytherm paper. The entire assembly was then air cured, the casting plugs removed, and next put inside a furnace for a final cure and bake out of the ceramics to insure hardness and strength. In this design the ceramics acted only as high temperature liners and thermal insulators and did not have to withstand any pressure loading. All of the pressure loads were transmitted out to the water cooled pressure vessel. The same rich burn housing was used to test a multitude of combustor geometries by inserting a different precast zirconia liner. The rich burn assembly permitted the addition of primary air flow into the rich burner through the fuel injector.

The lean burn assembly consisted of a single aluminum oxide refractory liner with a Lytherm paper barrier between the ceramic and the metal housing. The lean burn assembly was constructed by first wrapping the inside of the housing with 1/8 in. thick Lytherm ceramic paper. A plastic plug was machined which defined the internal geometry of the combustor. Casting pins were installed to produce the penetrations for the thermocouples and gas sample probes. A casting fixture was used to align all of the components and then a castable alumina ceramic was used to fill the annular void between the plastic plug and the housing. The assembly was next air cured, the plastic plug and pins removed, and the assembly was then put inside a furnace for a final cure and bake out. An alternate lean burn design was to use a precast inner aluminum oxide or zirconia liner and install it similar to the process outlined for the rich burn assembly. The lean burn section had a 6 in. inside diameter and was 9 in. long (or 2 ft long when an alternate housing was used). The lean burn section had a 45° tapered section at the upstream end for transition from the quick-mix geometry.

The quick mix assembly consisted of a stainless steel housing which was sandwiched between the rich burn and lean burn assemblies. The quick mix housing was fit with a 4 or 3 in. inside diameter by 1/2 in. thick and 5 in. long zirconia liner manufactured by Zircoa, Inc. A variety of flow pattern geometries were cut through the zirconia liner with a water knifing process (see fig. 4). The zirconia liner was grouted inside the quick mix housing using a castable aluminum oxide ceramic. The quick mix assembly permitted the addition of quick mix secondary air flow into the combustor. The effects of the various orifice configurations on the combustion process could be easily obtained by removing one zirconia liner and installing another with a different orifice pattern or mixing section cross section. The proper selection of the refractory ceramics resulted in a combustor with a highly abrasion resistant, high temperature inner liner and a low thermal conductivity castable ceramic filling the annular region between the backside of the inner liner and the water cooled pressure housing. The result was a simple combustor design which could withstand inner combustor temperatures to 4000 °F and an outer housing which was kept relatively cool with minimal water cooling. Thermocouple measurements of the rich burn housing external surfaces showed temperatures of 3000 °F with combustor operating temperatures of 4000 °F.

Minor cracks were sometimes present in the ceramic materials. These cracks would grow, particularly if rapid thermal transients were imposed on the combustor rig. Re-dressing of the cracked regions was done using the same refractory material. Problems with major cracks could be avoided if reasonable care was taken during the curing process, and the thermal transients during the rig heat up and testing periods were controlled.

This RQL flame tube design had several advantages over the more conventional actively cooled combustor designs. This flame tube test rig eliminated combustion heat loss effects on the emission measurements. This design eliminated complicated combustor liner cooling designs and the problems associated with liner cooling on combustion and pollutant emissions, particularly for the rich burn and quick mix sections of the RQL combustor. This flame tube design was a relatively simple but also an extremely versatile design. The end result was substantial savings in the areas of design and engineering time, fabrication time, materials and labor costs and a shortened delivery schedule. The versatility of the design allowed for changes to the internal geometry of the combustor in a timely manner.

2.2 Fuel Injector

Three fuel injectors were selected for consideration in this test program. Each had sufficient capacity to deliver the range of fuel flow rates required by the test matrix, approximately 680 to 2000 lbm/hr. Each was developed jointly by the fuel nozzle manufacturers and NASA Glenn Research Center.

2.2.1 Parker Hannifin Low NO_x Airblast Fuel Nozzle (Phase I)

This research fuel injector is shown in figure 5. This fuel injector was assembled with co-swirling 60° helical air swirlers for the three air circuits - inner, outer, and dome air, and a 60° straight cut co-swirling fuel swirler. The nominal design air flow splits of this fuel injector were 61.7, 27.2, and 11.1% of the total fuel injector airflow rate for the dome, outer, and inner air, respectively. Bench tests conducted at Parker Hannifin Corporation showed that the injector performance requirements on drop size (< 20 μm SMD) and spray angle (>60°) were bettered at an air pressure drop of 10 in. Hg (ref. 15). This fuel injector was used in the parametric tests reported in reference 11.

2.2.2 Textron Turbo Component Airblast Fuel Nozzle

This dual lip airblast research fuel injector is shown in figure 6. This fuel injector was assembled with co-swirling 60° helical air swirlers for the dome air, outer air, and inner air circuits. A 40 to 60° counter-swirling helical air swirler was used for the innermost air circuit and two 60° co-swirling fuel swirlers were used for the outer and inner fuel passage. The nominal design airflow splits of this fuel injector were 47.6, 25.5, 19.1, and 7.7% of the total fuel injector airflow rate for the dome, outer, inner, and innermost air, respectively. Bench tests performed at Textron shown high levels of atomization achieved (~ 10 μm SMD) at an air pressure drop of 10 in. Hg and at the above airflow splits for selected air-fuel ratios. Further characteristics of this fuel injector are described in reference 11.

2.2.3 Parker Hannifin Multiple Simplex Swirl Air Fuel Injector

This research fuel injector is shown in figure 7. This fuel injector was assembled with co-swirling helical air swirlers for the inner and outer air, and twelve simplex tips. The nominal design airflow splits of this fuel injector were 25.4%, and 74.6% of the total fuel injector airflow rate for the inner and outer air, respectively. Bench tests conducted at Parker Hannifin Corporation showed high levels of atomization achieved (~15 μm SMD) and a fuel pressure drop of 150 psi at ambient temperature conditions.

2.3 Quick mix Configurations

Table 1 presents the quick mix configurations tested in this RQL combustor test program. Summaries of the mixing studies conducted concurrently are given in references 16 and 17.

2.4 Instrumentation

The combustion gases were sampled continuously during testing. Up to seven water-cooled sampling probes were located at various axial and circumferential locations in the lean burner. The probes were either single hole, five hole or ten hole probe designs. The sample holes of the multiple hole probes were located at centers of equal area. The sampling tubes of the multiple hole probes were connected together through a common manifold. Steam-traced stainless steel tubing, 0.25 in. outside diameter and approximately 50 ft long, ran from the gas sample probes to the gas analysis equipment and smoke analyzer. In addition to gas analysis, pressure and temperatures were measured along the test rig.

2.5 Test Facility

The testing was performed in 1991 and 1992 in the Engine Research Building of the NASA Glenn Research Center. The Combustion Test Facility, shown in figure 8, was provided with

450 psig combustion air supply and a 2 psia evacuated exhaust capability by the central air system of NASA Glenn. This 450 psig combustion air supply was preheated to 1100 °F at the test facility by a preheater prior to entering the RQL flame tube combustor. Since the RQL flame tube combustor hardware was rated for 12 lbm/s and 275 psig, the heated combustion air was limited to that condition at the combustor. The combustion products passed through two water sprays on the way to the evacuated exhaust to reduce the temperature of the exhaust gases to an acceptable level for the silicone rubber seals used in the exhaust piping.

Various means of water cooling were used. The test stand housings were water-cooled with stainless tubing wrapped around the exterior skin of the housings. Cooling tower water at 55 psig supplied this system. Instrumentation was water-cooled with passages adjoining the instrumentation hardware. Two pumps at the test facility supplied 350 and 460 psig water for this use. The 460 psig pump also supplied the water used to cool the exhaust products with the sprays injected into the passing gas stream. The preheater utilized 40 psig combustion air and four Pratt & Whitney J47 natural gas-fired combustors to provide heated vitiated air to a heat exchanger. The 450 psig combustion air was heated within the heat exchanger to 1100 °F. Figure 9 shows the control valves used in operating the RQL flame tube combustor. Air flow was measured upstream of the preheater with orifice control valves upstream and downstream to limit the flow conditions as desired and provide up to four different air supplies to the RQL flame tube combustor each with its own venturi to measure flow. Back pressure in the combustor was controlled by two different sized valves in the exhaust to provide fine and coarse control of the back pressure. The limit of 275 psig back pressure was assured by a relief valve in the exhaust piping.

All control, facility monitoring, and data acquisition was performed by the personnel involved with the testing from a protective control room adjoining the testing room. During combustion, no people were allowed in the testing room. Two exhaust fans were used to clear the testing room environment of any vapors due to fuel leaks for the time fuel was available to the room.

Data acquisition included control, readout, and recording. Gas sample analysis equipment was controlled from the control room. Readout of the results and recording the results on the central computer were functions accomplished from the control room.

Control functions were accomplished using a Programmable Logic Controller (PLC). It also provided the necessary electrical interlocks of those functions, monitoring flameout sensors, over-temperature sensors, flow switches, and pressure switches. Preferred control sequences were also provided by the PLC.

The procedure for any test was to energize a hydrogen torch igniter just prior to introduction of fuel to the combustor. Once the combustor was burning, the torch was shut down. Ignition was accomplished at an equivalence ratio in the rich burn section of about 2.0 and in the lean section of about 0.42 to avoid stoichiometric conditions accompanied by higher temperatures. Once steady combustion was established, data were obtained. When fuel or air flow was changed, corresponding to a new test condition, the changes were performed in such a way as to avoid getting unnecessarily close to stoichiometric conditions; increasing air flow and/or decreasing fuel flow in the rich burn section would take the combustion process there closer to stoichiometric conditions, whereas decreasing air flow and/or increasing fuel flow would take the combustion process in the lean burn section closer to stoichiometric conditions.

3. COMBUSTOR TEST RESULTS

Prior to combustion testing of the RQL combustor, cold flow and hot flow shake-down testing were performed to establish the calibration/aerodynamic performance of the facility flow metering devices and subcomponent sections of the combustor.

3.1 Performance Testing

Performance testing of the RQL flame tube combustor was conducted at conditions simulating supersonic cruise: inlet pressure (P_3) of 150 psia, inlet temperature (T_3) of 1100 °F, a rich burner equivalence ratio (ϕ_{rb}) of 1.8 to 2.2 and overall fuel air ratios of 0.028 to 0.0335. The nominal pressure losses of the fuel injector swirlers and the quick mix orifices were 3 and 5%, respectively for the conditions tested.

Figures 10 and 11 present emissions data for the performance tests. The Textron dual lip airblast fuel injector and two different quick mixing sections were used. A 4 in. ID quick mixer with eight 0.905 in. diameter round holes and another 4 in. ID quick mix with eight rain drop orifices (see Table 1) which produced the same net effective flow area as the 8-hole configuration were tested. Figure 11 also shows the NO_x level of conventional combustors over the range of severity factor values representative of supersonic cruise conditions. The severity factor was obtained using the following expression:

$$\text{Severity Factor} = P^{0.5}\, T_4 \exp(T_3/288) \qquad (1)$$

Where T_4 is in °R, T_3 is in K, and P is in psia.

Figures 10 and 11 indicated that the NO_x emissions goal value was achieved with the configurations tested. The nominal secondary hot residence times were 2.4 and 1.3 ms for the quick mixing configurations employing eight circular holes and eight rain drop orifices, respectively. The emissions of unburned hydrocarbons were very low (fig. 12) while the corresponding measurements of carbon monoxide (CO) showed that the levels were very low (fig. 13) and consistent with high combustion efficiencies—about and in excess of 99.9%. Comparison between mechanical and chemical fuel-air ratios for these test runs are shown in figure 14. Mechanical fuel air ratios were determined by calibrated fuel flowmeters and air flow venturi measurements. The chemical fuel-air ratios were computed from measured exhaust gas samples. The exhaust gas sampling system derived fuel-air ratios agree with the metered values.

3.2 Combustor Performance Sensitivity to Fuel Injector

Three advanced research fuel injectors with significantly different geometrical features were evaluated in the test program. Figure 15 shows the NO_x emissions measurements obtained with the Parker Hannifin airblast fuel injector and the Textron dual lip airblast fuel injector. A 4 in. ID quick mix section with eight 45° slanted slots with each slot having a 1.99 in. length and a 0.33 in. width, was used. These fuel injectors produced high levels of performance and showed no observable difference in NO_x emissions, figure 15, with the test rig operating at an inlet pressure (P_3) of 150 psia, an inlet temperature (T_3) of 1100 °F, a rich burner equivalence ratio (ϕ_{rb}) of 2.0 and overall fuel-air ratios of 0.028 to 0.0335. The pressure losses of the fuel injector swirlers and of the mixing orifices were 3 and 5% for the conditions tested. The nominal secondary hot residence time was 2.4 ms for the conditions tested.

3.3 Combustor Performance Sensitivity to Quick Mix Configurations

3.3.1 Effect of Quick mix Orifice Geometry

Tests were conducted at simulated supersonic cruise conditions using the Textron dual lip airblast fuel injector. Figures 16 and 17 show the NO_x emissions and carbon monoxide measurements obtained with quick mix configurations employing eight circular holes, eight 45° slanted slots, and eight rain drop orifices (see Table 1). These quick mix configurations produced the same net effective flow area and hence the same quick mix pressure loss and the same momentum-flux ratio (J). The results indicated that the quick mix configuration employing eight circular holes was the lowest NO_x mixer with the test rig operating at P_3 of 150 psia, T_3 of 1100 °F, ϕ_{rb} of 2.0, and overall fuel-air ratios of 0.028 to 0.0335. The nominal pressure losses of the fuel injector swirlers and of the mixing orifices were 3 and 5%. For the conditions tested, the nominal secondary hot residence times were 2.4, 2.4, and 1.3 ms for the quick mix configurations employing circular holes, slanted slots, and rain drop orifices, respectively.

Apparently the concentration of mixing air addition over a shorter axial length with the circular holes leads to a more effective and faster mixing than is achieved with the slanted slots or with the rain drop orifices. The inability of the eight slanted slot mixing section to reduce the NO_x production below that of the eight round hole configuration suggested that the expanded circumferential dispersion of mixing air in the slanted slot configuration at the potential risk of increased axial length of mixing air addition and of decreased penetration is not effective (refs. 18 to 20). In the round hole mixing configuration, the main flow blockage produced high temperature wake recirculation between hot rich mixture exiting the rich burner and the mixing jets (ref. 21). The rain drop mixing configuration decreases the volume of the high temperature wake region behind the mixing jets. The inability of the eight rain drop orifice mixing section to reduce the NO_x production below that of the eight round hole configuration implied that the reduced main flow blockage area in the eight rain drop configuration obtained by increasing the axial length of mixing air addition was not effective for the mixing jet effective flow area tested.

The corresponding measurements of carbon monoxide indicate that the combustion efficiency (η) was very high - in excess of 99.9% for these three mixing configurations. Figure 17 shows that the CO levels of the slanted slot mixing configuration were lower than of the eight round hole configuration. Apparently the expanded circumferential dispersion of the slanted slot mixing configuration was more conducive to oxidation of CO.

3.3.2 Effect of Multiple Rows of Orifices.

Tests with 4 in. ID quick mixing sections incorporating a single row of eight or eleven circular holes, two staggered rows of fourteen (total) circular holes, and two aligned rows of sixteen (total) circular holes were conducted at simulated supersonic cruise conditions: P_3 of 150 psia, T_3 of 1100 °F, ϕ_{rb} of 1.8, 2.0, and overall fuel-air ratios of 0.028 to 0.037. Tests of the mixing sections employing a single row of eight circular holes and two aligned rows of sixteen round holes were carried out using the Textron dual lip airblast fuel injector, while tests of the mixing sections incorporating a single row of eleven round holes and two staggered rows of fourteen circular holes were done using the Parker Hannifin multiple simplex swirl/air fuel injector. The quick mixing configurations employing single rows of eight and eleven round holes, and two staggered rows of fourteen round holes had the same mixing orifice effective flow area hence the same momentum-flux ratio and mixing section pressure loss for the conditions tested.

The mixing orifice effective flow area of the two aligned rows of sixteen circular holes was 2.6 in^2, and the area of the other three quick mixing configurations was 4.1 in^2. [Ed: It appears that the original author assumed C_d=0.8 for quick-mix orifices.] The nominal J for all configurations was 65. The mixing section pressure losses of the sixteen in-line circular holes and of the other three mixing configurations were 26.5 and 12.5% respectively. [Ed: Note that these values are significantly higher than the nominal ones quoted in sections 3.1 and 3.3.1.] The nominal secondary hot residence times were 0.4, 1.7, 1.8, and 2.3 ms for the mixing configurations employing single rows of eight and eleven round holes, two staggered rows of fourteen round holes, and two aligned rows of sixteen round holes, respectively, for the conditions tested.

Figures 18 and 19 show the NO_x emissions and CO measurements for these mixing configurations. Data presented for the mixing configurations employing single rows of eight and eleven round holes, and two staggered rows of fourteen round holes indicate that an increase in the number of orifices above eight increases the NO_x emission indexes for the conditions tested. These results suggested that increasing lateral coverage density at the risk of decreased jet penetration is not effective.

The inability of the two aligned rows, sixteen round hole mixing configuration to reduce NO_x emission below that of the eight round hole configuration suggests that air addition to the high temperature blockage regions behind the circular jets was not effective for this mixing configuration at the conditions tested. However, the cases of two aligned rows of sixteen round holes was apparently conducive to CO oxidation; see figure 19.

3.3.3 Effects of Reduced Quick Mix Flow Area.

Tests were conducted at simulated supersonic cruise conditions using the Textron dual lip airblast fuel injector, P_3 of 150 psia, T_3 of 1100 °F, ϕ_{rb} of 2.0 and 2.2, and overall fuel-air ratios of 0.028 to 0.0335. Figures 20 and 21 show the NO_x and CO emissions measurements obtained with a 4 in. ID and 3 in. ID mixing sections with eight circular holes (See Table 1). These quick mixing configurations had the same value for the ratio of mixing orifice effective flow area to the mixer cross sector area. If the discharge coefficients were equal, and the density and mass-flow ratios were the same, J would be equal. The mixing orifice effective flow area of the 4 and 3 in. ID mixing configuration were 4.1, and 2.7 in^2, respectively. The quick mixing nominal pressure drops of the 4 in. and of the 3 in. mixing configuration were 5 and 11.8%, respectively. The nominal pressure loss of the fuel injector swirlers was 3% for the conditions tested. The nominal secondary hot residence time for the 4 in. ID mixing section was 2.4 ms for the conditions tested, while results were obtained at nominal secondary hot residence times of 0.68 ms and 2.6 ms for the 3 in. ID mixing section.

In reference 22 it was experimentally shown that cross-sectional area reduction of the quick mix section (neckdown) produced lower NO_x emissions at increased quick mixing pressure losses. Reference 23 showed that the dimensionless mixing performance was not significantly changed by necking down the quick mixing flow area, but that neckdown of the quick mixing section significantly reduced NO_x emissions by reducing residence time. The penalty for neckdown manifests itself in increased pressure drops across the quick mixing section.

Figure 20 indicated that NO_x emissions for the 3 in. diameter quick mixing section was lower than that of the 4 in. diameter quick mixing section, while the NO_x emissions for the two quick mixing sections were similar at the same residence time. Figure 21 shows that CO emission indices for the 3 in. diameter quick mixing section were in the range of 30 to 125 g/kg-fuel at the reduced residence time conditions. These results correspond to combustion efficiencies in the range of 99.3 to 97% at the reduced residence time conditions. At higher residence time conditions, the combustion efficiency for both the 3 and 4 in. diameter quick mixing sections was very high—in excess of 99.9%.

3.3.4 Effect of Measurement Location.

To assess the level of mixing jet penetration and its effects on combustor emissions and performance, four single-hole gas sampling probes were installed at 1, 1.5, 2.0 and 2.5 in. away from the combustor wall and these probes were located at 5.68 in. downstream of the 4 in. ID mixing section employing eleven round holes. Tests were conducted at these simulated supersonic cruise conditions: P_3 of 150 psia, T_3 of 1100°F, ϕ_{rb} of 1.8 and 2.0, and overall fuel-air ratios of 0.028 to 0.0335.

Figures 22 to 24 show that the NO_x, emission based fuel-air ratio and CO radial profiles exhibit significant variations, implying that mixing is still progressing vigorously at this plane. Figures 23 and 24 indicate that at J below 32, the region of high emission based fuel-air ratio and CO levels near the centerline increases in intensity with decreasing J. This implies that mixing jet under-penetration was observed for test cases with J below 32.

Conversely, at J above 32 (cases of 38 and 45), figure 23 shows that the fuel-air ratio profiles exhibit the low center peaks, suggesting the jets have over-penetrated into the rich gases. Figure 22 shows that for test cases with mixing jet over-penetration; the NO_x profiles exhibit high values in the region near the wall.

The gas composition profiles (See figs. 22 to 24) suggest that J of about 32 is near optimal for the configuration with a single row of eleven holes. This gives a value of 2.3 for the correlation parameter C as calculated in the following equation (ref. 24).

$$n = \frac{\pi\sqrt{2J}}{C} \tag{2}$$

Note that for the RQL flametube with a mixing section pressure loss of 5% at simulated supersonic cruise condition, the value for J is 25. Using the above equation with a value of 2.3 for the constant C would suggest that a 9 hole mixing configuration would be nearly optimum for the single row mixing design.

3.3.5 Smoke Emission Measurements

Figure 25 shows the smoke emissions radial profiles obtained with four single-hole gas sampling probes located at 1, 1.5, 2.0 and 2.5 in. away from the combustor wall and at 6.57 in. downstream of the end of the 4 in. ID mixing section, employing two staggered rows of fourteen circular holes. Tests were conducted at simulated supersonic cruise conditions: P_3 of 150 psia, T_3 of 1100 °F, ϕ_{rb} of 1.8 and overall fuel-air ratios of 0.028 to 0.0335. The region of high smoke emissions levels near the combustor centerline increases in intensity with decreasing momentum-flux ratio, implying jet under-penetration with a decrease in J. Figure 25 also shows the smoke emission levels obtained with a ten-hole gas sampling probe located at 11.72 in. from the end of the 4 in. ID mixing section. This gas sampling probe was extended across the diameter of the combustor. The SAE smoke numbers were below 20 with η in excess of 99.9% for all test conditions simulating supersonic cruise conditions. Figure 25 indicates the smoke emission level increases with increasing overall fuel-air ratio (or increasing T_4). This was due to increase in jet under-penetration with increase in overall fuel-air ratio.

4. CONCLUSIONS

A comprehensive experimental investigation of the RQL flame tube combustor for the High Speed Research Low NO_x Combustor Program was conducted. The study included efforts directed at demonstrating the capability of the RQL combustor concept to reach the NO_x emissions goal at HSCT supersonic cruise conditions and at optimum subcomponent performance of the RQL combustor. Based on the data obtained from these test activities, it can be concluded that:

1. The ultra-low NO_x emission index goal was achieved for the RQL combustor concept.

2. Tests to investigate the effect of quick mixing orifice geometry demonstrated that the quick mixing configuration employing a single row of circular holes was the lowest NO_x mixer configuration tested. However, other quick mixing orifice configurations such as slanted slots produced substantial lower levels of CO emissions, probably due to the enhanced circumferential dispersion of the air addition.

3. Test results suggested that an optimum momentum-flux ratio exists for a given quick mixing configuration which may cause undesirable jet under- or over-penetration for test conditions with momentum-flux ratio below or above the optimum value.

4. Tests conducted to assess the effect of quick mixing flow area indicated that reduction in the quick mixing flow area produced lower NO_x emissions at reduced residence time, while this had no effect on NO_x emissions measured at similar residence time for the configurations tested.

5. Tests of the RQL configuration with a quick mixing section employing two rows of fourteen staggered round holes produced SAE smoke numbers below 20 with combustion efficiencies in excess of 99.9% for all test conditions simulating supersonic cruise conditions.

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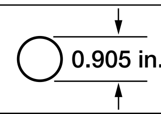
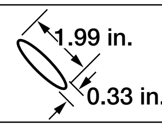
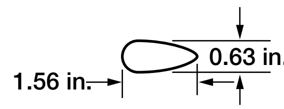
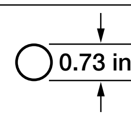
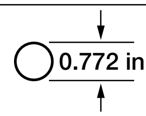
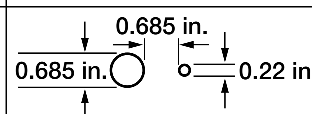
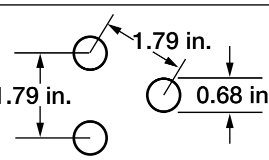
Table 1.—Specifications of mixing orifice configurations.

Quench section diam, in.	Orifice geometry	Total number of orifices	Total orifice opening area, in.^{2}	Schematic of orifice
4	Round holes	8	5.1	
4	45° slot	8	5.1	
4	Rain drop	8	4.1	
3	Round holes	8	3.3	
4	Round holes	11	5.1	
4	2 rows of in-line roundholes	16	3.3	
4	2 rows of staggered round holes	14	5.1	

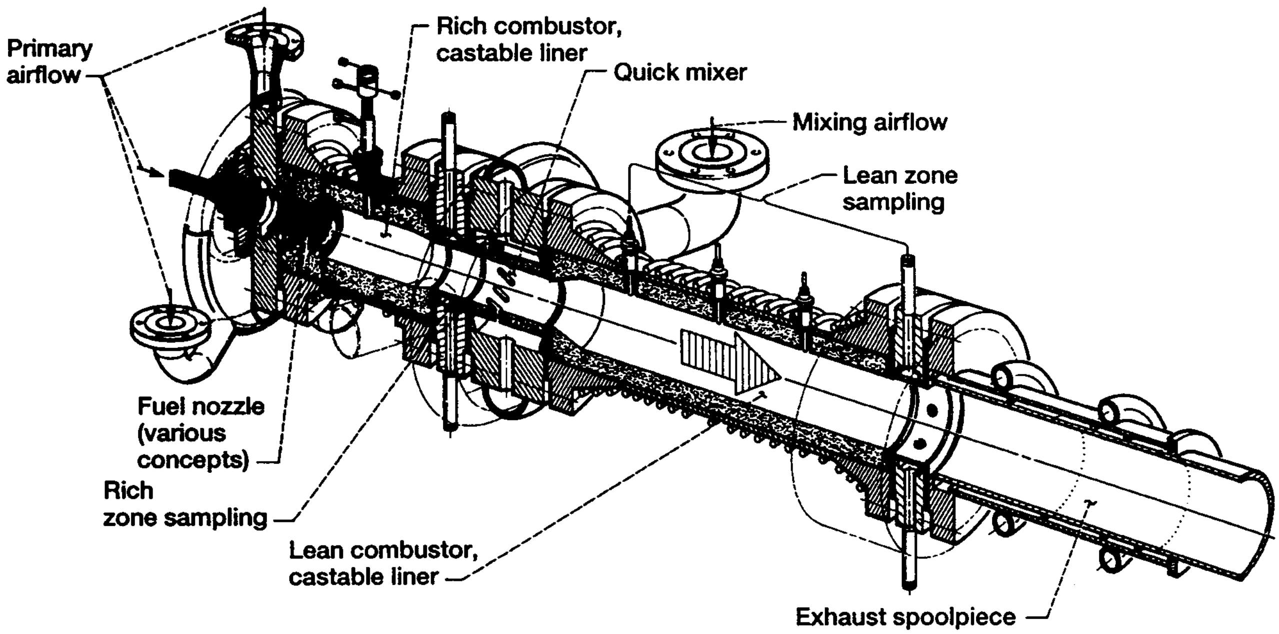


Figure 1a.—RQL flame tube test rig.

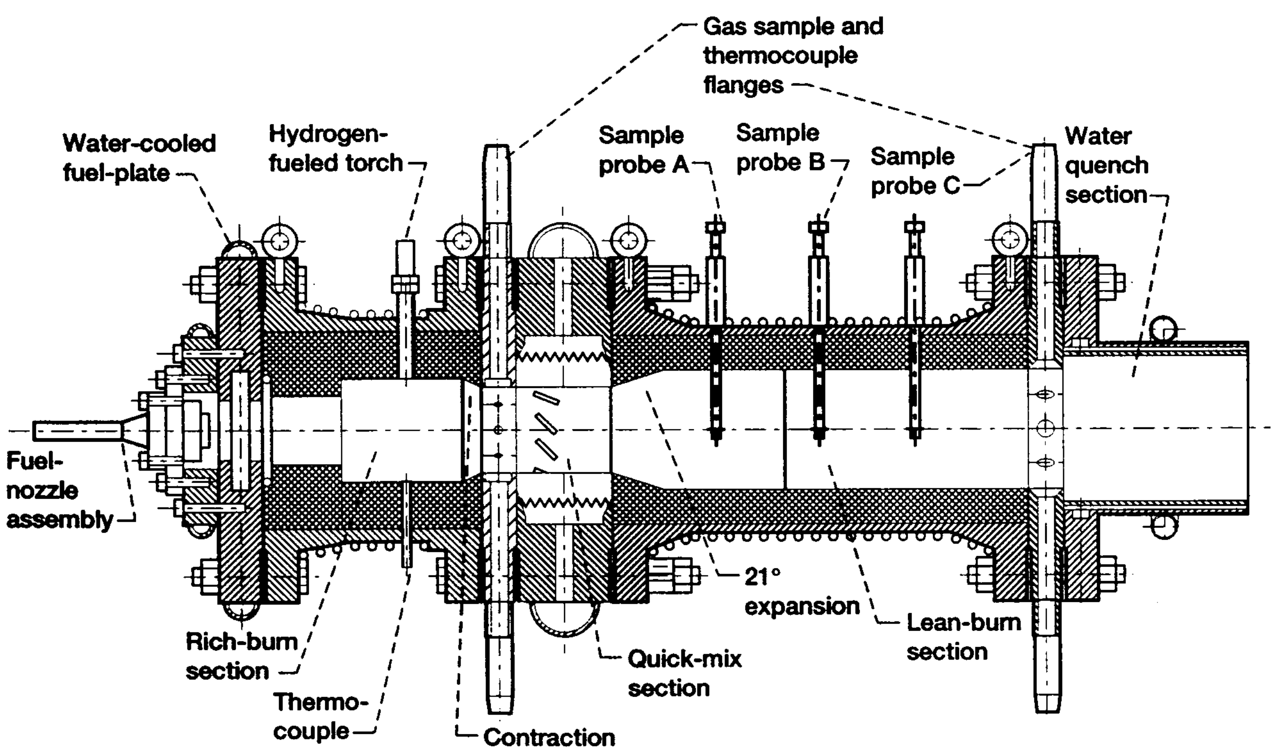


Figure 1b.—Cut-away drawing of RQL combustor test rig with instrumentation locations.

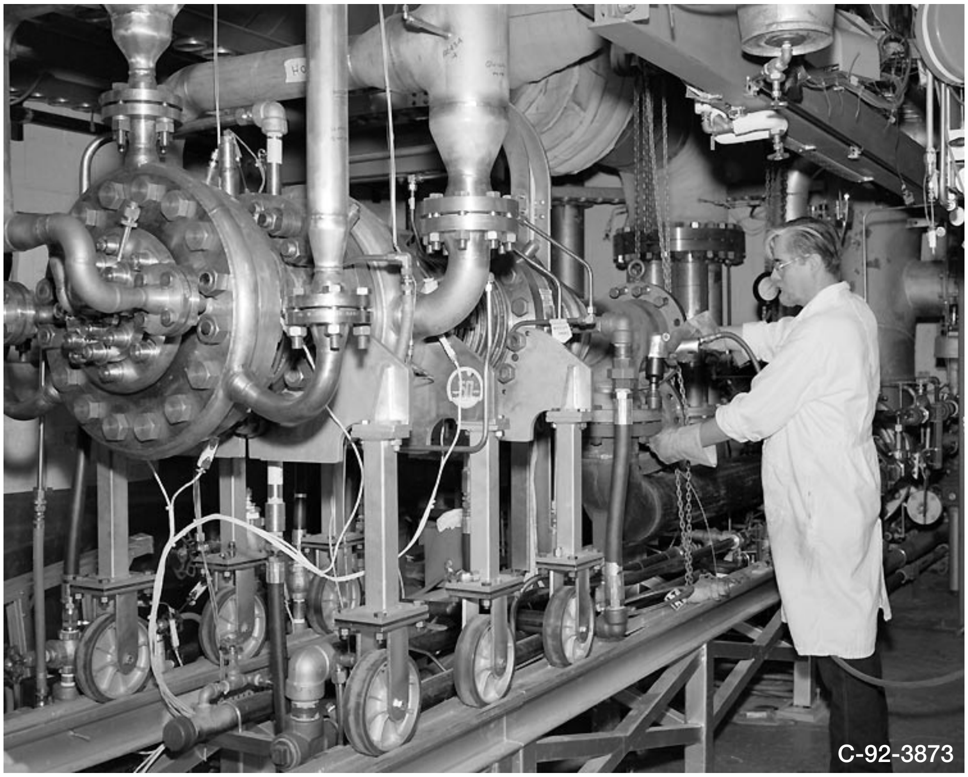


Figure 2.—Photo of RQL flame tube test rig.

Figure 3.—Rich burner module with castable liner.

Figure 4.—Quick mixing module with castable liner.

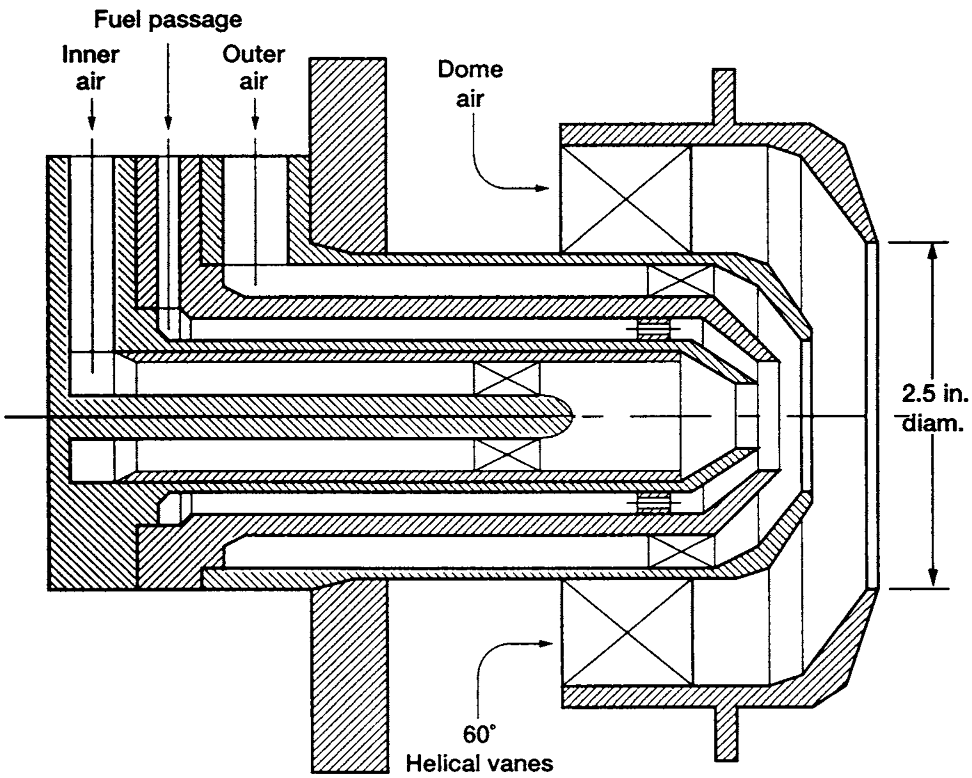


Figure 5.—Conceptual sketch of Parker Airblast Low NO_X (Phase I).

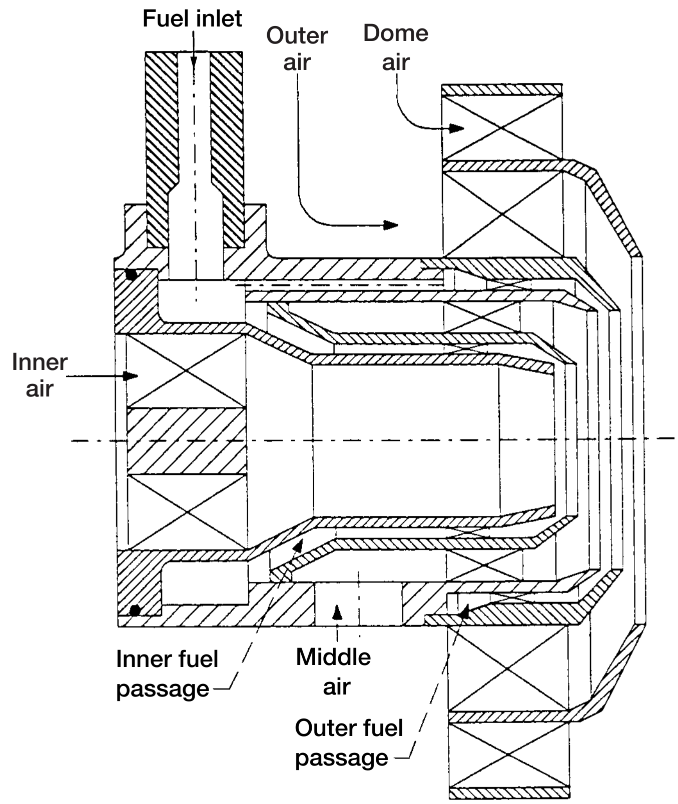


Figure 6.—Conceptual sketch of Textron fuel nozzle cross-section.

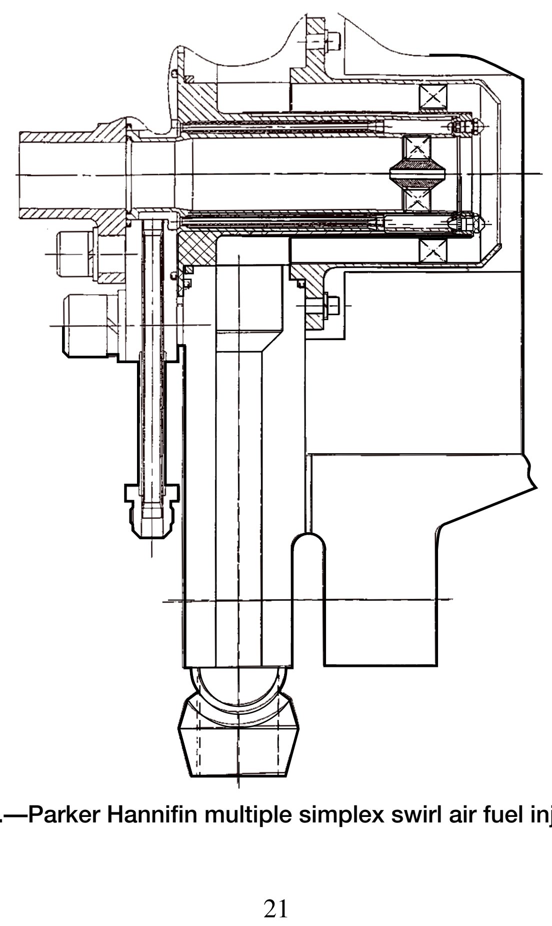


Figure 7.—Parker Hannifin multiple simplex swirl air fuel injector.

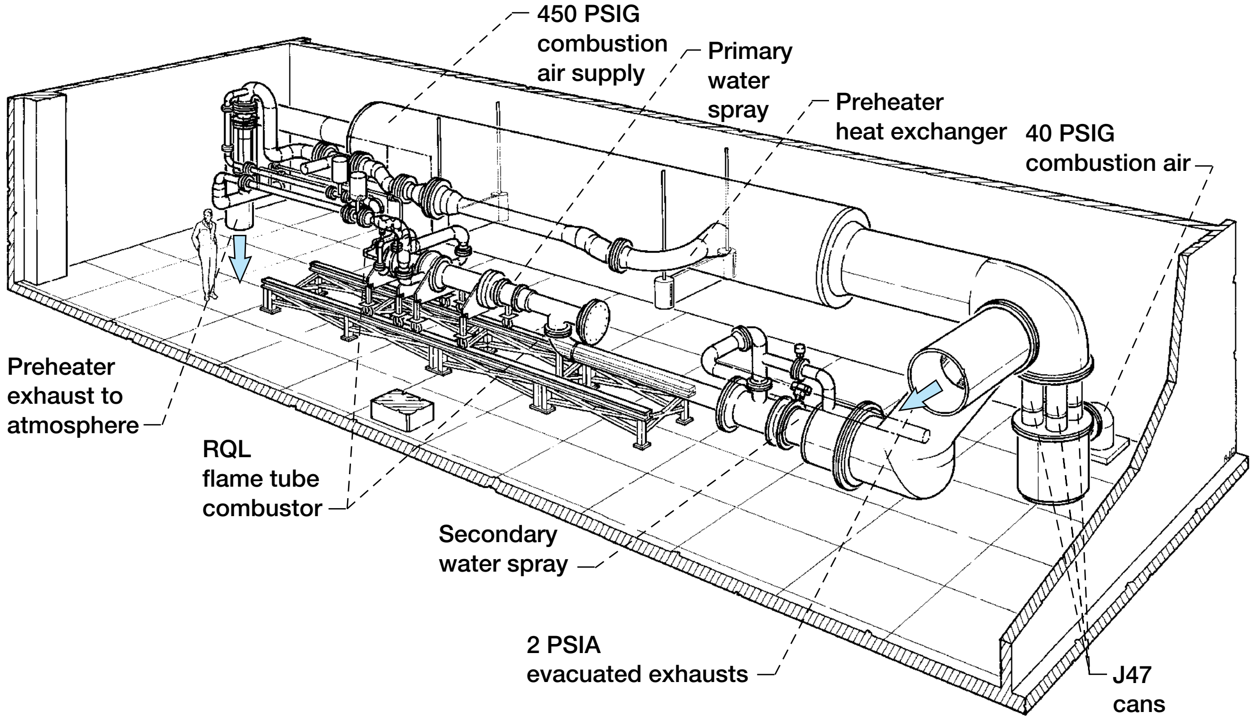


Figure 8.—Axially staged combustor test facility.

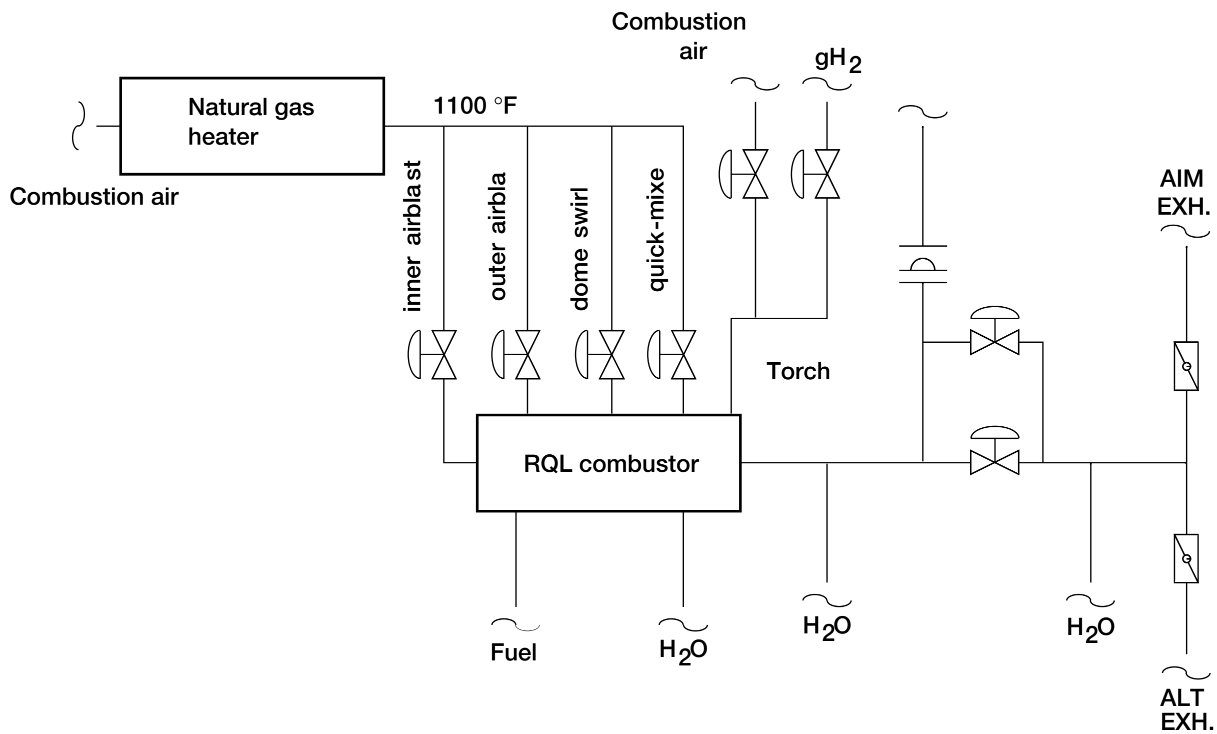


Figure 9.—Schematic diagram of RQL rig flow controls.

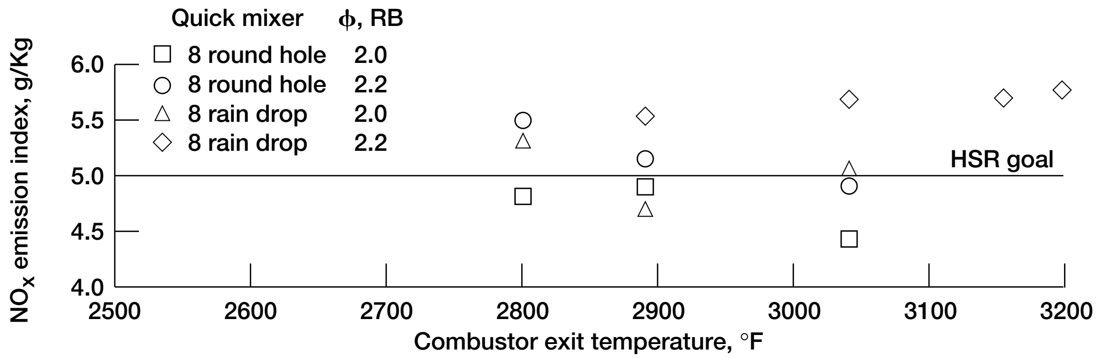


Figure 10.—NO_x emissions data at supersonic cruise conditions as a function of combustor exit temperatures.

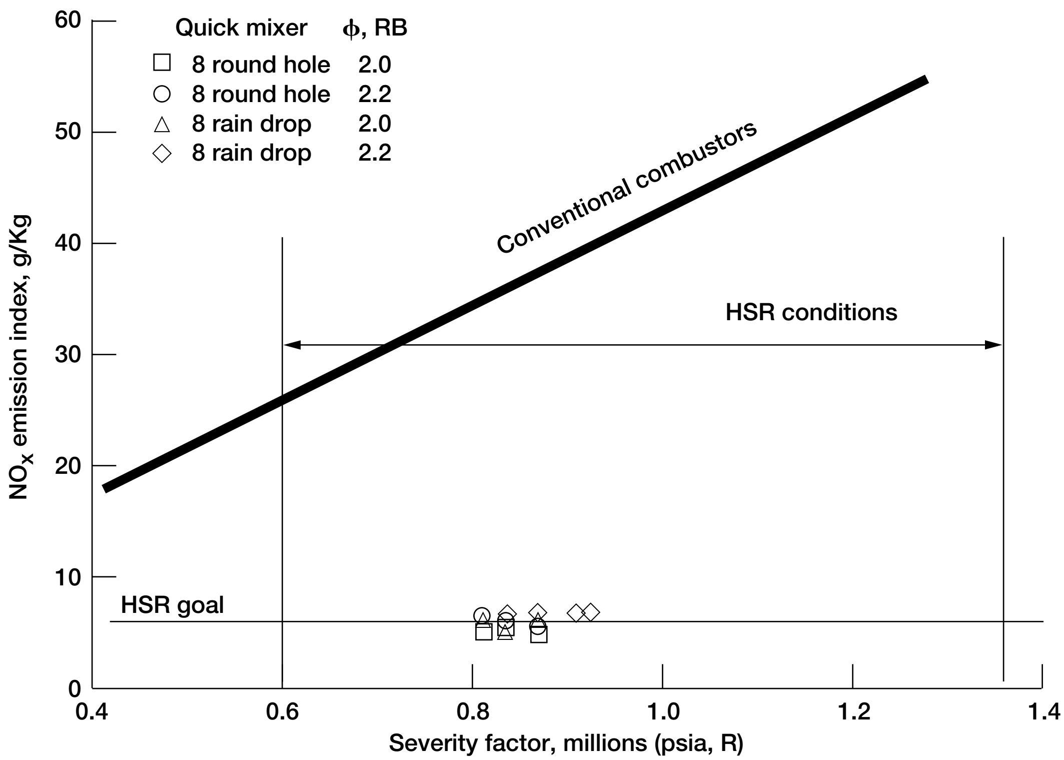


Figure 11.—NO_x emissions data at supersonic cruise conditions as a function of severity factor.

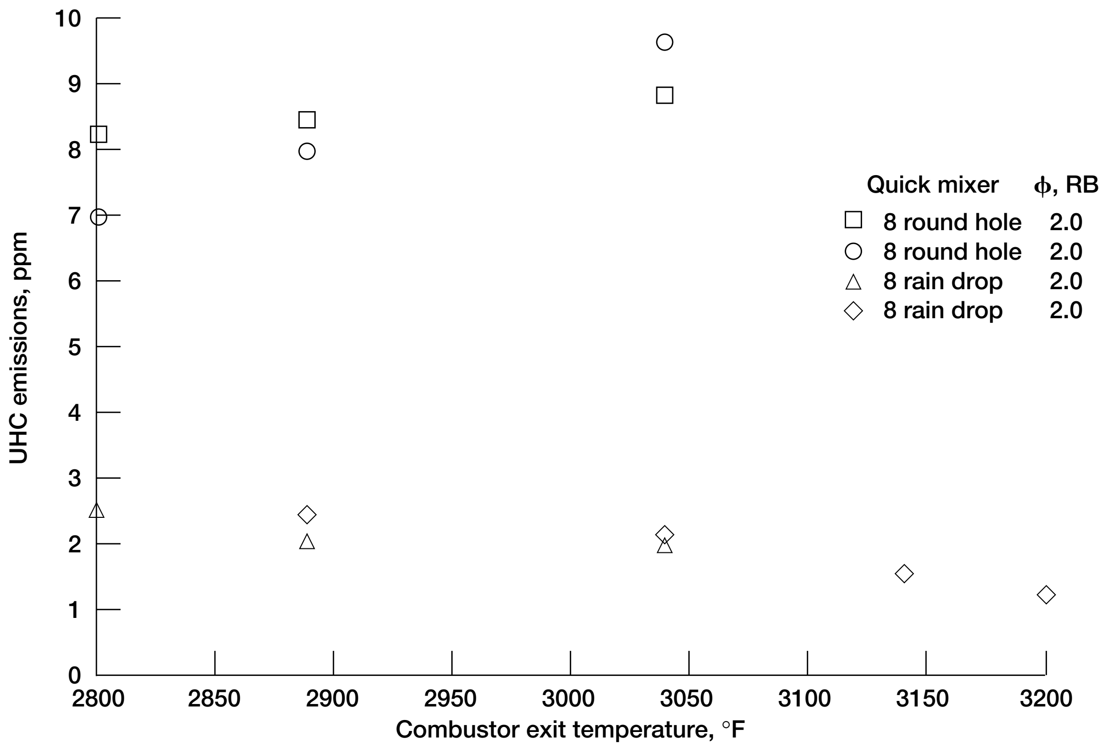


Figure 12.—Unburned hydrocarbon emissions data at supersonic cruise conditions as a function of combustor exit temperatures.

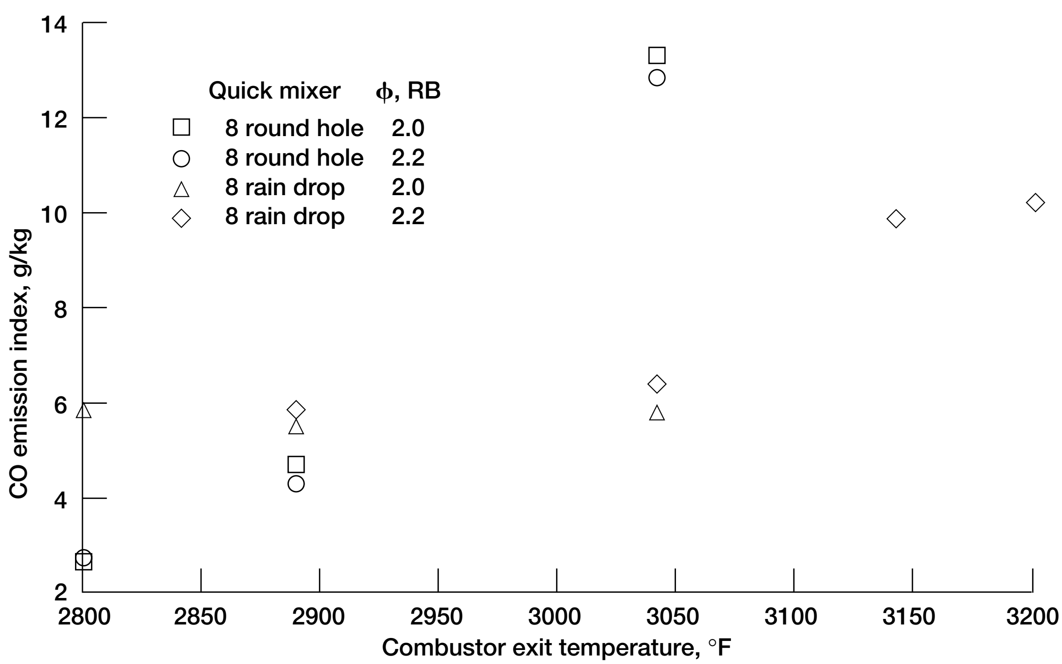


Figure 13.—CO emissions data at supersonic cruise conditions as a function of combustor exit temperatures.

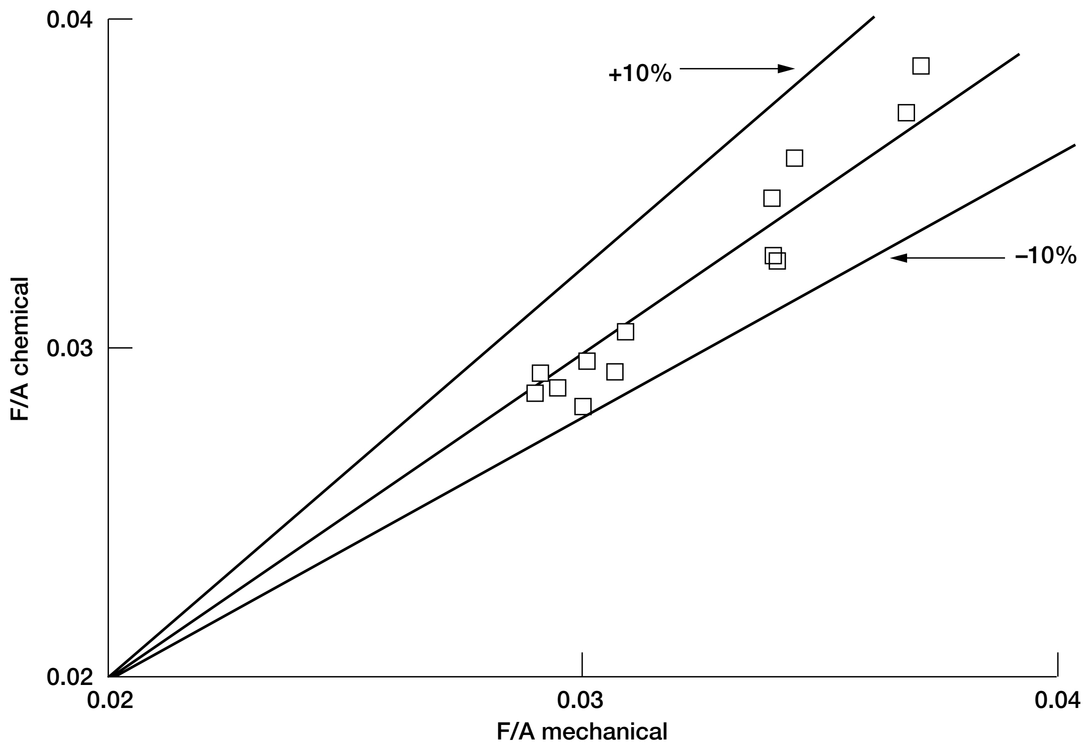


Figure 14.—Chemical vs. mechanical fuel-air ratios of combustor performance data.

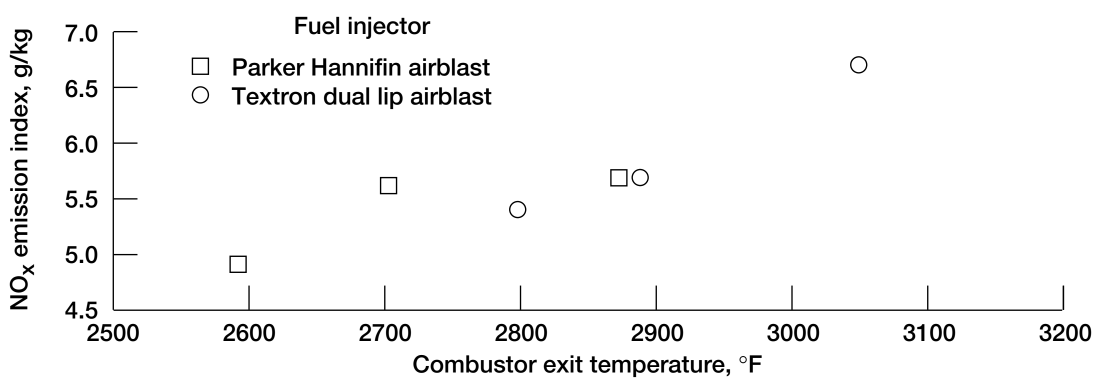


Figure 15.—Influence of fuel injectors on NO_x emissions at supersonic cruise conditions.

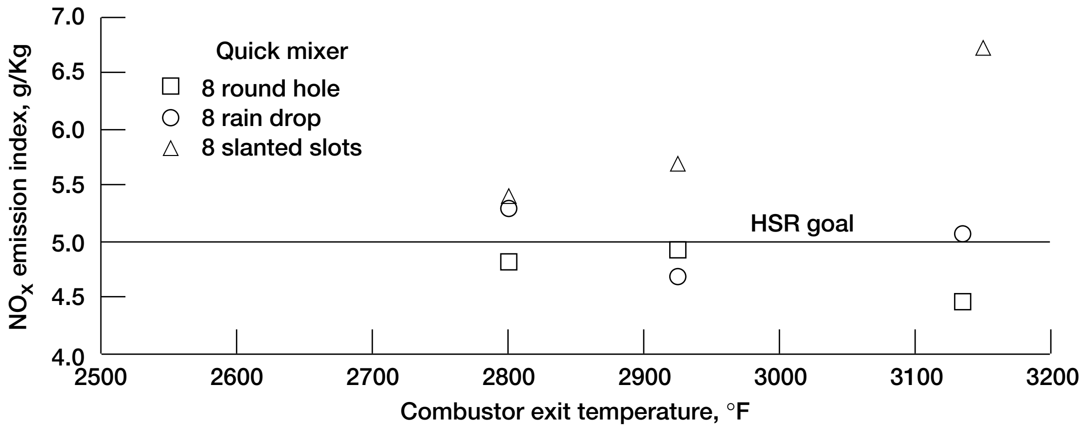


Figure 16.—Influence of quick mixing orifice geometry on NO_X emissions at supersonic cruise conditions.

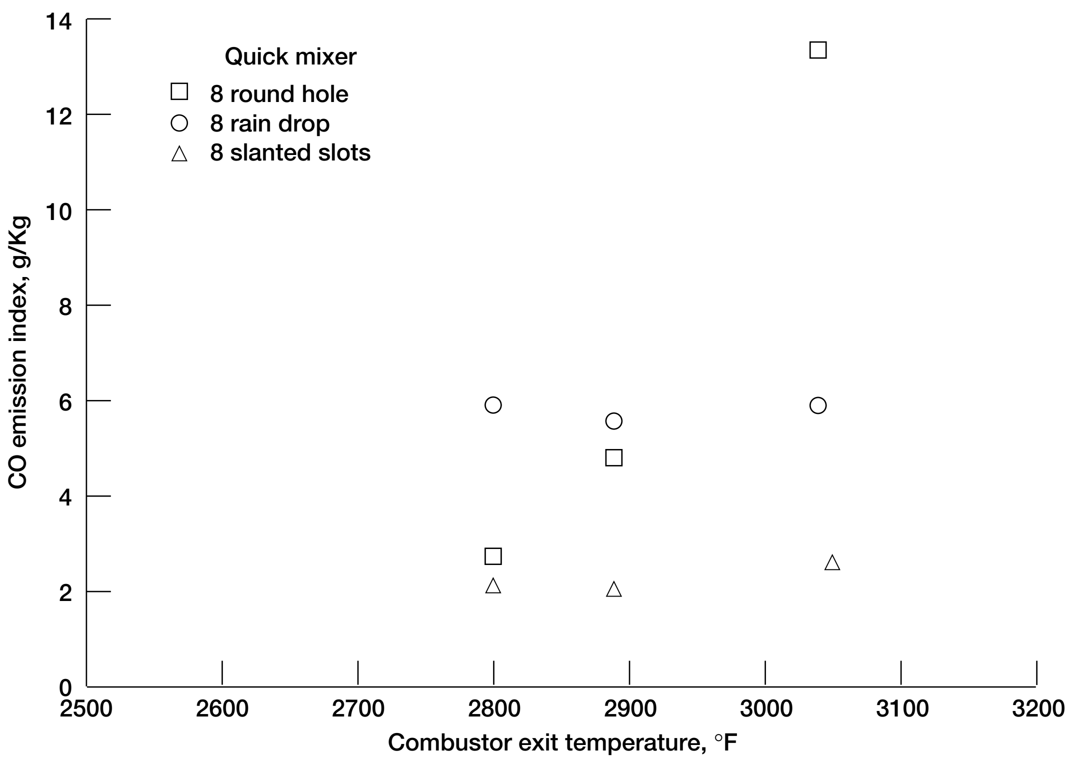


Figure 17.—Influence of quick mixing orifice geometry on CO emissions at supersonic cruise conditions.

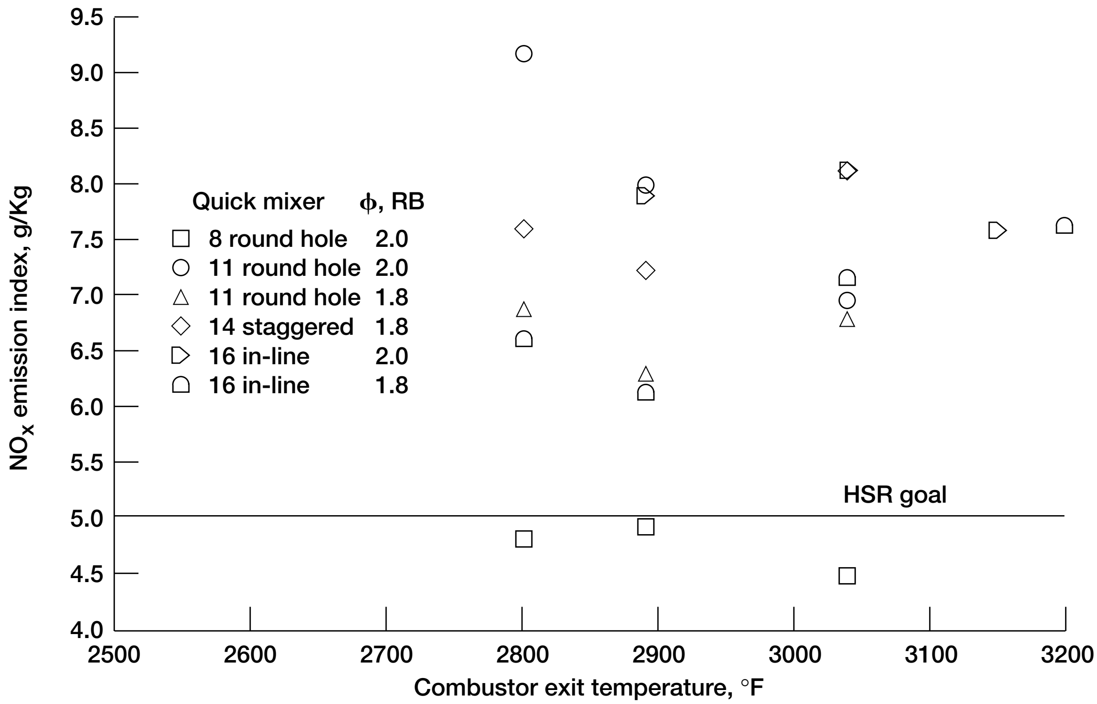


Figure 18.—Effect of number of orifices, staggered, and in-line multiple configerations NO_x emissions data at supersonic cruise conditions.

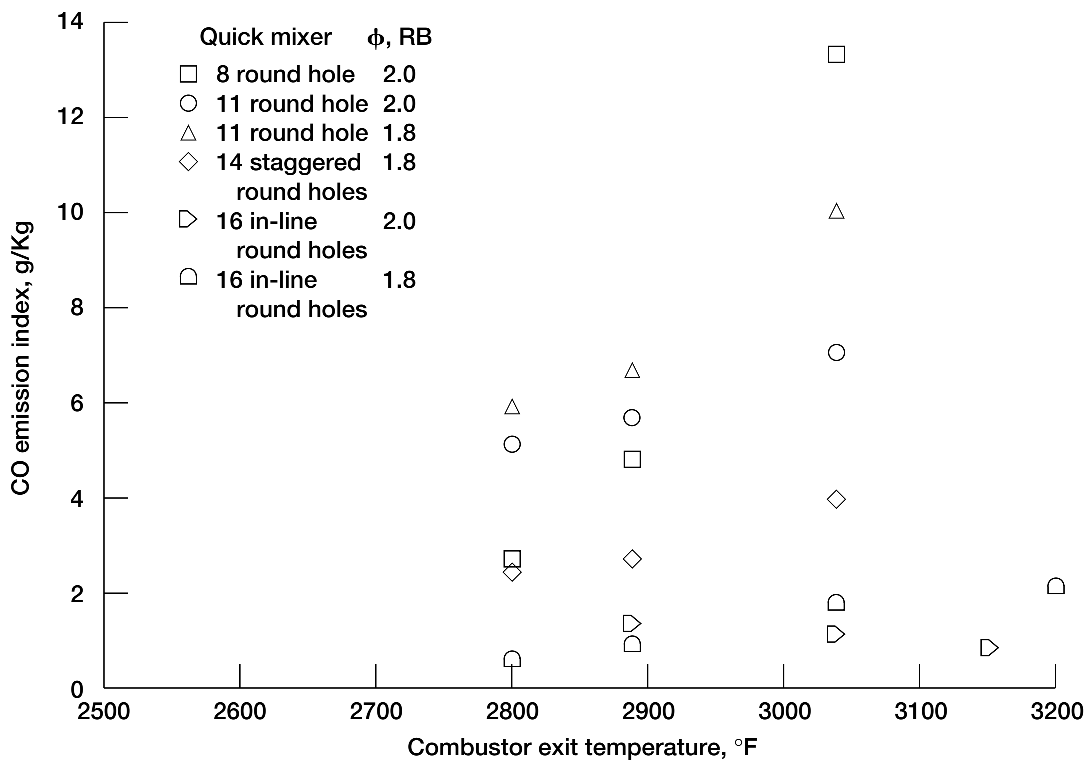


Figure 19.—Effect of number of orifices, staggered, and in-line quench configerations CO emissions at supersonic cruise conditions.

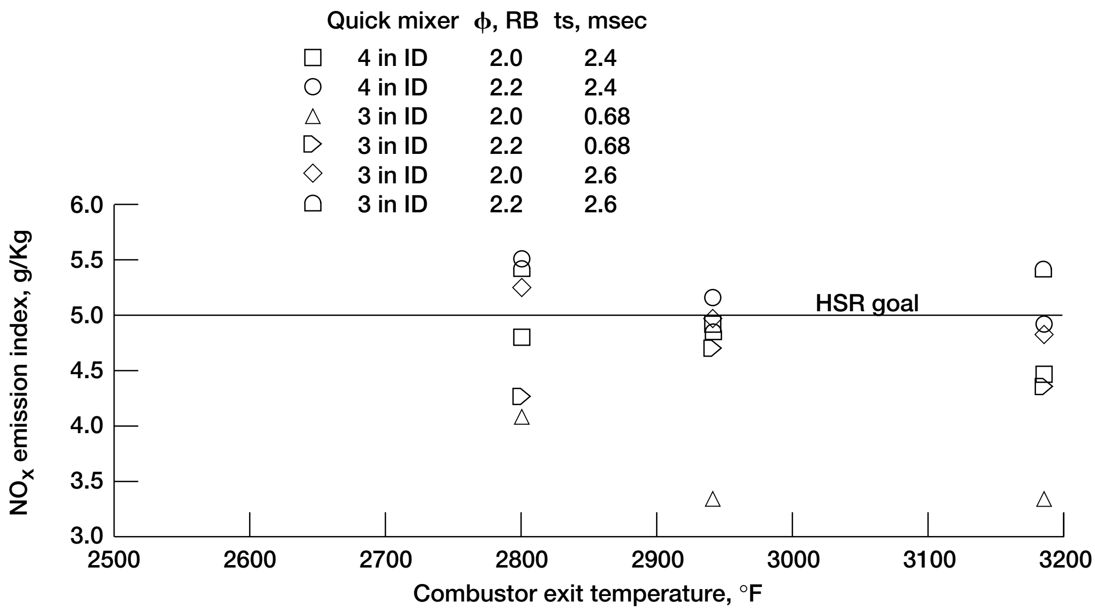


Figure 20.—Influence of reduced quick mixing flow area on NO_x emissions at supersonic cruise conditions.

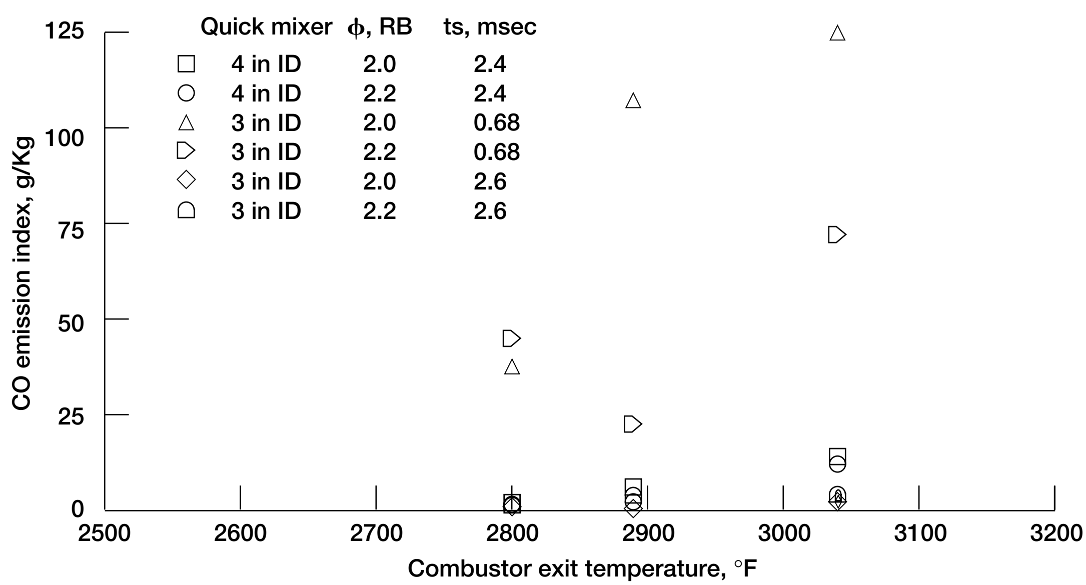


Figure 21.—Influence of reduced quick mixing flow area on CO emissions at supersonic cruise conditions.

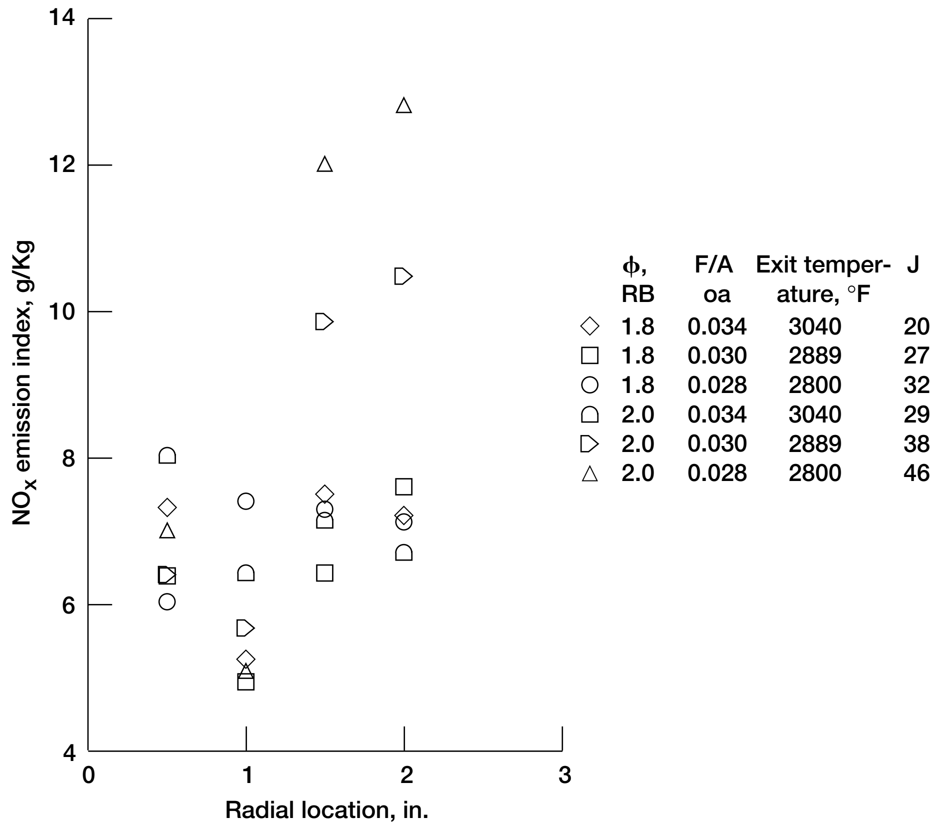


Figure 22.—NO_X emission radial profile downstream of 11 round hole quick mixing section (centerline = 0).

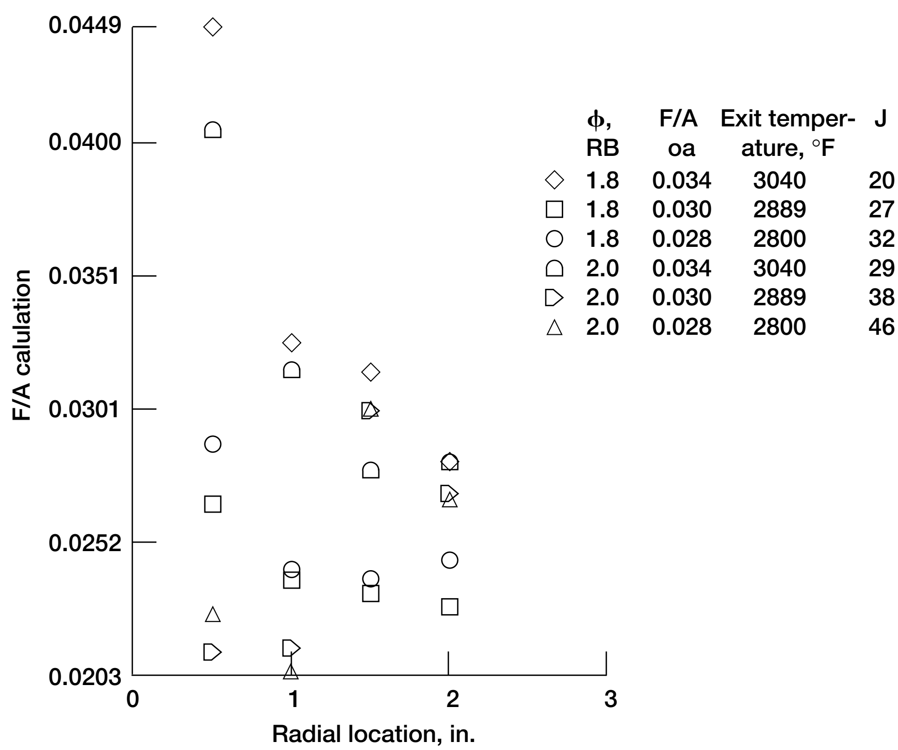


Figure 23.—Calculated fuel-air radial profile downstream of 11 round hole quick mixing section (centerline = 0).

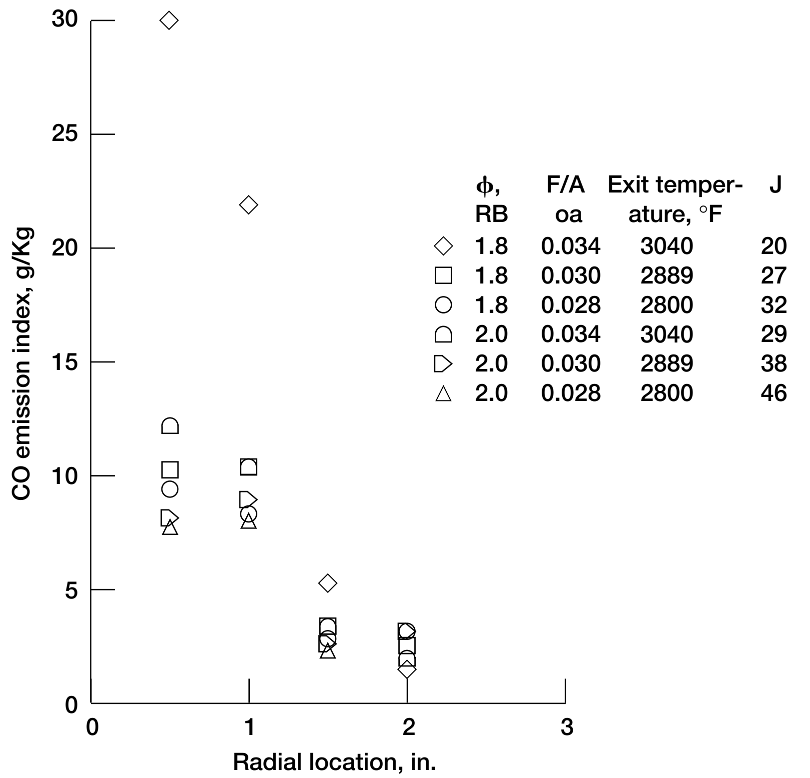


Figure 24.—CO emission radial profile downstream of 11 round hole quick mixing section (centerline = 0).

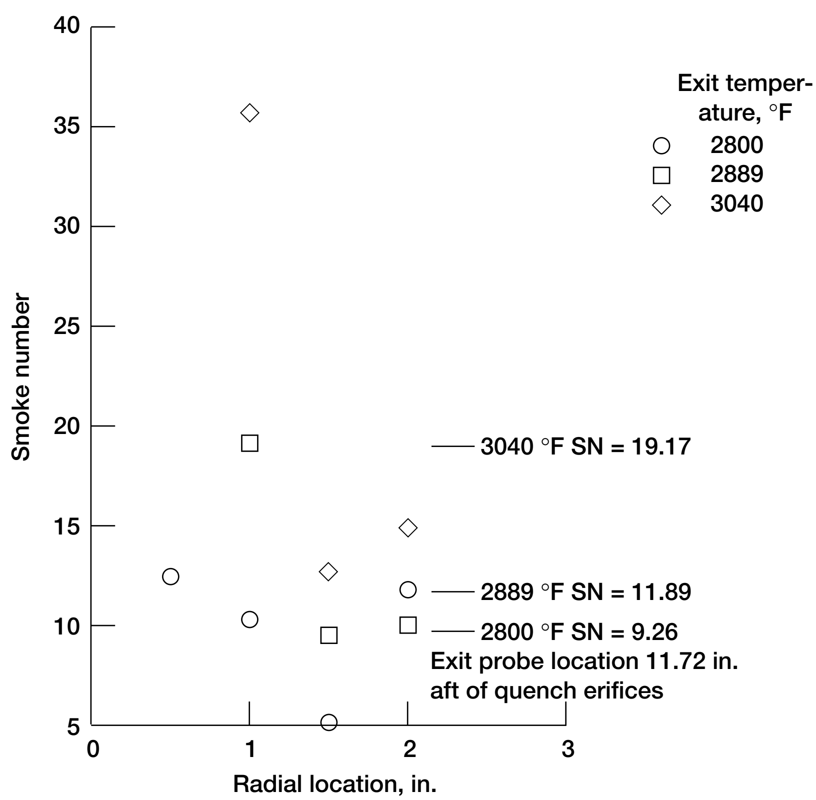


Figure 25.—Smoke radial profiles and smoke emissions downstream of 14 staggered round hole mixing section (centerline = 0).

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13. ABSTRACT ***(Maximum 200 words)***

This report describes and summarizes elements of the High Speed Research (HSR) Low Emissions Rich burn/Quick mix/Lean burn (RQL) flame tube combustor test program. This test program was performed at NASA Glenn Research Center circa 1992. The overall objective of this test program was to demonstrate and evaluate the capability of the RQL combustor concept for High Speed Civil Transport (HSCT) applications with the goal of achieving NO_x emission index levels of 5 g/kg-fuel at representative HSCT supersonic cruise conditions. The specific objectives of the tests reported herein were to investigate component performance of the RQL combustor concept for use in the evolution of ultra-low NO_x combustor design tools. Test results indicated that the RQL combustor emissions and performance at simulated supersonic cruise conditions were predominantly sensitive to the quick mixer subcomponent performance and not sensitive to fuel injector performance. Test results also indicated the mixing section configuration employing a single row of circular holes was the lowest NO_x mixer tested probably due to the initial fast mixing characteristics of this mixing section. However, other quick mix orifice configurations such as the slanted slot mixer produced substantially lower levels of carbon monoxide emissions most likely due to the enhanced circumferential dispersion of the air addition. Test results also suggested that an optimum momentum-flux ratio exists for a given quick mix configuration. This would cause undesirable jet under- or over-penetration for test conditions with momentum-flux ratios below or above the optimum value. Tests conducted to assess the effect of quick mix flow area indicated that reduction in the quick mix flow area produced lower NO_x emissions at reduced residence time, but this had no effect on NO_x emissions measured at similar residence time for the configurations tested.

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