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DEVELOPMENT AND ENGINE TESTING OF A DRY LOW EMISSIONS COMBUSTOR FOR ALLISON 501-K INDUSTRIAL GAS TURBINE ENGINES

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ABSTRACT

The Allison Engine Company has been developing a low emission, can-annular combustion system for the 501K industrial gas turbine engine to satisfy increasingly stringent environmental requirements. This paper describes the progress achieved, over that previously reported by Razdan et al. (1994), through subsequent design evolution, bench testing, and engine evaluation. Allison's goal is to develop a retrofittable, can-annular combustion system that limits emission levels to less than 25 ppm nitrogen oxide (NO_X), 50 ppm carbon monoxide (CO), and 20 ppm unburned hydrocarbon (UHC), while operating at full load conditions. The interim emissions goals for the combustion system are 37 ppm NO_X, 80 ppm CO, and 20 ppm UHC (all dry 15% O_2 corrected).

The combustion system under development employs a dual mode combustion approach to meet engine operability requirements and high power emission targets without the use of combustor diluent injection or postcombustor exhaust treatment. A lean premixed combustion mode is used to minimize combustion zone temperature and limit NO_X production during high power engine operation. The lean premix mode is augmented with a diffusion flame pilot mode for engine starting and low power operation.

Initial engine testing showed a dry low NO_X combustion system, designed to meet a 37 ppm NO_X limit, produced less than 34 ppm NO_X and less than 10 ppm CO and UHC in test stand verification test. Continued burner rig testing with modified primary combustion zone stoichiometry has demonstrated NO_X less than 25 ppm, CO less than 50 ppm, and UHC less than 20 ppm with simulated engine conditions representing 20 to 100% power. Development activity continues on the combustion system as engine field evaluation trials proceed.

INTRODUCTION

Concern over atmospheric pollution has prompted governmental agencies worldwide to tighten regulations covering pollutant emissions from gas turbines. Depending on the location and engine application, these regulations require NO_X reductions of up to 95% from unregulated engines. Until recently, methods such as diluent (water or steam) injection directly into the combustion chamber or postcombustion cleanup approaches such as selective catalytic reduction (SCR) have been the only means available to comply with these regulations. These methods have many drawbacks, including high installation costs, high operating costs, possible fuel consumption penalties, and reduced engine reliability. The overall emissions reduction potential of diluent injection may be limited, since emissions of CO and UHC increase as NO_X emissions are curtailed significantly.

A better approach to reducing emissions is to alter the basic combustion process where pollutants are formed, making the combustion process inherently clean. Gas turbine manufacturers have almost unanimously adopted the lean premixed (LPM) combustion approach to develop dry low emission (DLE) technology engines as a solution to stringent pollutant regulations (Razdan et al., 1994; Etheridge, 1994; Aigner and Muller, 1992; Jansen et al., 1991; Leonard and Stegmaier, 1993; Snyder et al., 1994; Bahlmann, 1994). In LPM combustion, fuel and air are uniformly mixed in fuel lean proportions prior to combustion. Preparation of fuel and air in this manner avoids the high temperature stoichiometric regions responsible for NO_X formation.

The development of the dry low NO_X combustion system described in this paper has been designed so the system is directly retrofittable into Allison's 501-K engine series. The Allison 501-K family of industrial aeroderivative gas turbines includes single and two-shaft engines producing from 3000 to 8000 horsepower. The single-shaft engines (501-KB series) are used for electrical power generation in standby, continuous, and cogeneration applications on land based, oil drilling

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rig, and shipboard installations. The two-shaft engines are used to drive compressors in oil and gas recovery and pipeline service (501-KC series) as well as providing propulsion power for hydrofoil and conventional hull vessels (501-KF series). A summary of the full power operating conditions for 501-KB5 engine using the new combustion system is provided in Table I. The dry low NO_X, can-annular combustion system for natural gas fueled 501-K gas turbine engines has the following emissions goals at 100% rated power.

- Emissions Goals
  - NO_X - 25 ppmvd (15% O_2 corrected)
  - CO - 50 ppmvd (15% O_2 corrected)
  - UHC - 20 ppmvd (15% O_2 corrected)

To meet the emissions goals in a cost effective manner, the combustion system is designed to be fueled staged and diffuser bleed is used at low power operation (Razdan, et al., 1994). The design ensures the combustor is operable throughout the gas turbine engine cycle from idle to 100% power and the emissions goals are met over a broad engine power range. Use of an active variable geometry to control the combustion stoichiometry during the engine turndown operation was considered but rejected due to concerns about durability problems.

To meet customer needs, Allison has decided to introduce an interim dry low emissions combustion system. The interim emissions goals for the combustion system are 37 ppm NO_X, 80 ppm CO, and 20 ppm UHC (15 % O_2 corrected). The goal was also to achieve these emissions levels by use of only fuel staging during engine turndown operation. The following sections provide the details of the dry low NO_X combustion system, and the rig and engine test results.

COMBUSTION SYSTEM DESCRIPTION

The production can-annular 501-K combustion system consists of six axially aligned, interconnected combustor cans contained within an annular combustor case. Each liner is radially supported at the upstream end by a centrally located fuel nozzle. Two of the liners are located axially by igniter plugs located near the upstream end of the liners, and the other four liners are axially located by mechanical fixtures which take the place of the igniter plugs. The downstream end is radially supported by a combustor transition piece which slides over the first-stage turbine stator row inlet. Chemical reaction occurs simultaneously with fuel injection and mixing, creating a diffusion flame combustion process. Flame propagation between liners is provided for by crossover tubes.

TABLE I.
501-KB5 NOMINAL ENGINE OPERATING CONDITIONS

Power	5263 hp
Airflow	34 lbm/hr
Pressure ratio	10
Burner inlet temperature	650°F
Burner outlet temperature	2005°F
Burner fuel/air	0.0200

The Allison dry low emission combustion system for 501-K maintains the same can-annular general arrangement but relies on the LPM approach to achieve low emissions. A cross section of the combustion system is shown in Figure 1 (flow direction in this figure is from left to right). The combustor features dual mode combustion to meet emission goals and engine operability requirements. During the pilot mode of operation, fuel is directly injected into the liner where it is consumed in a diffusion flame reaction, and during high power operation, the fuel and air are uniformly premixed in fuel-lean proportions to control NO_X.

The design of the LPM module is central to achieving low emissions. The mixing module must thoroughly mix the fuel and air in order to avoid localized fuel rich pockets which can greatly increase the production of NO_X (Fric, 1992). The mixing must be accomplished in the minimum possible volume since space taken to premix the fuel and air reduces the space available for combustion. Combustion within the premixer must be prevented both to avoid higher NO_X production due to incomplete mixing and to avoid damaging the hardware.

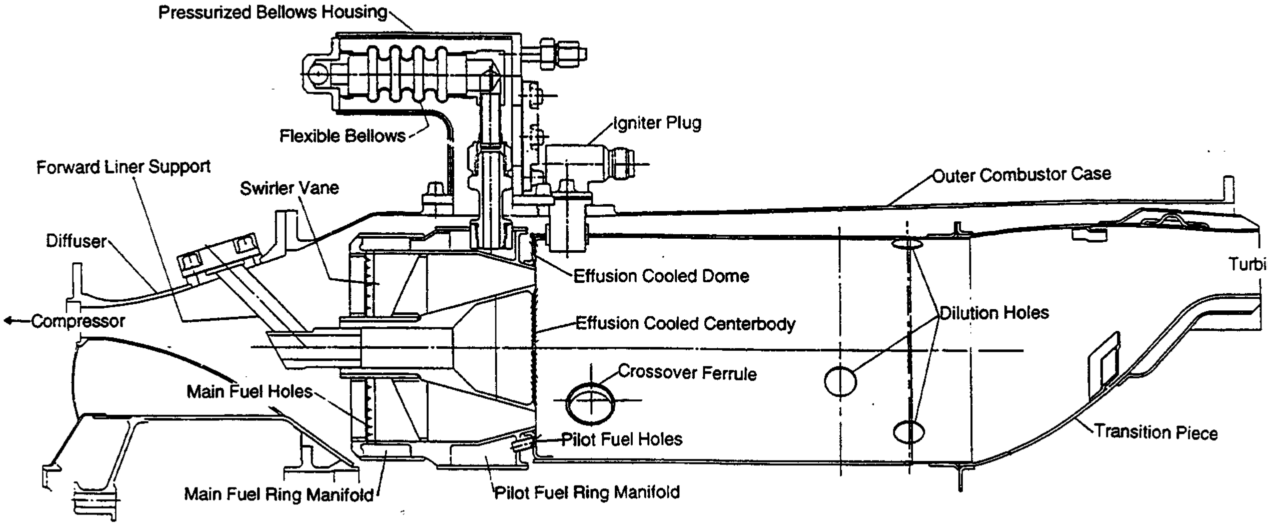

FIGURE 1. CROSS SECTION OF THE ALLISON DRY LOW EMISSIONS COMBUSTION SYSTEM

There are two possible sources of combustion within the premixer module. The time the fuel-air mixture spends in the premixing module can exceed the ignition delay time of the fuel and reactions can begin spontaneously. This applies locally to any wake or recirculation regions in the module, as well as to the module as a whole. Alternatively, the aerodynamics of the module can be such that a flame can propagate upstream from the combustion region (flashback). This might occur during a transient condition such as a sudden change in engine load, even if flashback is not possible at a steady-state operating condition. Due to all of the possible sources of combustion within the premixing module, the design of the premixer must result in a smooth, uniform flow field, free from recirculations, wakes, and low velocity regions. Additionally, the premixer aerodynamics must purge the flame from the LPM module under normal operation if, for some reason, flashback occurs. The premixer imparts swirl to the flow to facilitate mixing within the module and serves as the primary means of stabilizing the flame within the reaction zone of the combustor.

In the LPM combustor (Figure 1) airflow enters the premixer through a large axial swirler. The swirler in this design consists of 12 airfoil-shaped vanes tapering in chord from tip to hub. Fuel passes through the hollow core of each vane and exits into the airstream though small holes located on either side of the vane near the leading edge. Fuel enters the vanes from a ring-shaped manifold circling the mixing module which in turn is fed from a gas-tight threaded connection to the outside of the engines. The necessity of providing a gas-tight connection between the combustion liner and the exterior gas supply requires the use of a flexible bellows allowing for thermal expansion and misalignment. The bellows is enclosed by a bellows housing pressurized to compressor discharge pressure during operation. Figure 2 shows the installation of the fuel manifolds and bellows on the 501-K engine combustor case. After exiting the swirler, the flow passes though a converging section before exiting into the combustion region. This converging section accelerates the flow, providing greater resistance to flashback.

Following the premixing of the fuel and air in the mixing module, the flow enters the combustion region. The flame is stabilized by a combination of swirl and bluff body induced recirculation. In the present design, two recirculation regions are formed; a central recirculation attached to the face of the centerbody and an outer, toroidal recirculation attached to the dome wall. This approach has three advantages to a single, central recirculation zone. First, the flow exiting the mixing module encounters hot, reacted gases in the shear layers surrounding the entering premixed reactants. This results in a faster net rate of reactant consumption. Second, the radially outermost gases, being in contact with the outer recirculation zone, have a chance to react before encountering the relatively cool liner wall where quenching of the CO and UHC consuming reactions may occur. Third, the presence of the outer recirculation has the advantage during starting and low power operation when it provides a sheltered region for pilot combustion. The mechanical integrity of the dome and centerbody walls directly exposed to the high temperature gas is maintained by the use of effusion cooling and thermal barrier coating (TBC).

Liner wall cooling is minimized to avoid high emissions of CO and UHC which can occur due to the quenching of the reactions which locally consume CO and UHC. LPM fuel preparation limits flame zone temperature, thereby significantly reducing heat loading to the combustion liner wall. Figure 3 shows the can-annular dry low NO_X combustion system general arrangement as the 501-K engine is assembled.

During startup, idle, and low power operation, the pilot fuel system is utilized instead of the main fuel system. Premixed combustion with airflow distribution optimized for full power operation is not possible at these conditions. As power output is increased above approximately 25% of full power, the main fuel system is activated and from this point to about 80% of full power the fraction of the total fuel provided through the pilots is reduced while the fraction provided through the main

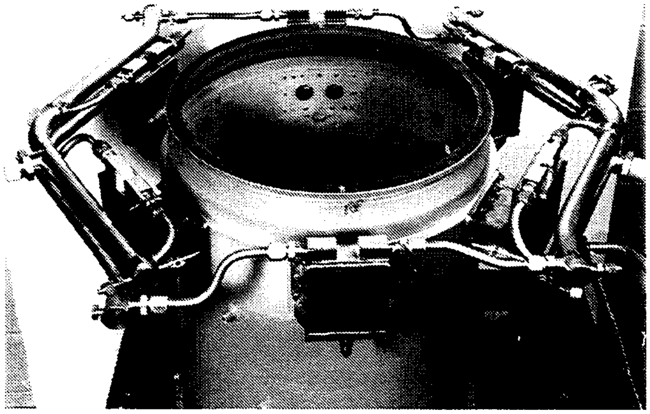

FIGURE 2. ENGINE SUBASSEMBLY OF COMBUSTION CASE AND PRESSURIZED BELLOWS HOUSING WITH SPLIT PILOT AND PREMIX MODULE FUEL MANIFOLDS

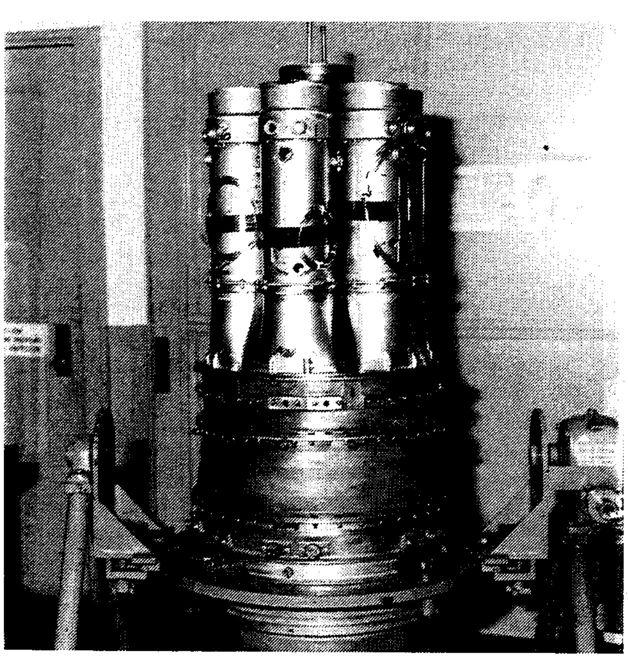

FIGURE 3. PARTIAL ENGINE ASSEMBLY SHOWING ALLISON'S DRY LOW EMISSIONS CAN-ANNULAR COMBUSTION SYSTEM INSTALLED ON A 501-KB5 TURBINE SECTION

system is increased. At power outputs greater than 80%, the pilot system is shut off and full premixed combustion is utilized. The control of the fraction of fuel provided through the pilots is based on an algorithm using measured compressor inlet temperature and measured turbine outlet temperature, so the correspondence between pilot fuel fraction and power level will vary according to local atmospheric conditions and the specifics of the installation.

ENGINE TEST RESULTS

Allison has conducted engine tests to measure emission performance and determine the burner outlet temperature quality of the dry low NO_X combustion system. Prior to initiating engine assembly, the combustion liners were carefully inspected to determine that liner-to-liner variability was within acceptable limits. Measurements of liner features such as the premixer swirler, dome, and dilution zone flow paths showed the effective flow area of the individual flow paths varied less than ± 2%. In addition to the liner airflow variability check, the fuel system variability was measured. Calibration of the premix mode fuel circuit revealed less than ± 3% fluctuation in effective flow area. The results of the liner examination dispelled the fear that liner-to-liner variations could measurably influence engine emission results.

The dry low NOx combustion system designed to achieve the 37 ppm interim NO_X limit was installed in a 501-KB5 engine. Testing was conducted at Allison in the dynamometer test facility with a conditioned inlet air supply providing dry, 59°F air. A standard diffuser was fitted to the exhaust of the engine and a steam ejector was used to control the static pressure at the exit of the diffuser. The six dry low NO_X combustion liners were each instrumented with eight type K thermocouples to monitor wall temperatures. The gas temperature at the exit of each combustion liner was measured by 3 shielded type K thermocouples (a total of 18). The engine was instrumented with transducers to measure vibration. Emission samples were extracted through a rake located at the entrance to the exhaust diffuser. The equal area weighted, mixed sample was obtained with 28 measurement ports from 4 radial positions at 7 circumferential locations. The emissions measurements were made through the use of equipment and test methods called out in the SAE Aerospace Recommended Practice, ARP 1256A. Total unburned hydrocarbons were measured using flame ionization detector, CO and CO_2 were measured using a nondispersive infrared (NDIR) analyzer, NO_X was measured using chemiluminescence analyzer, and O_2 was measured using polarography. Data were recorded automatically and manually. Some of the data were processed on-line to give the test operators immediate feedback confirming test conditions were met and all instrumentation was functioning correctly. The engine was operated with independent, manual fuel control to meter fuel flow for pilot or premixed fuel delivery, and engine speed was automatically controlled to the design value of 14,200 rpm.

The engine started easily and operated smoothly with the new dry low NO_X combustion system. Combustor ignition occurred without incident and the piloting system ignited reliably throughout the test sequence under airflow and fuel flow conditions typically used for testing gas-fueled engine systems. After combustor ignition, the engine accelerated smoothly to idle. No special treatment had to be implemented to accommodate the dry low NO_X combustion system. No difficulties were experienced in transitioning from pilot mode to fully premixed mode, and no combustion flashbacks or instabilities were observed.

Engine emissions were obtained for a range of operational conditions from idle to 100% load. Figure 4 shows the NO_X, CO, and UHC measurements as a function of engine power setting. The plotted data are divided in three categories to illustrate emission performance with the combustor operating in different modes over the engine load range. Exclusive operation in either the pilot mode or LPM mode is denoted as pilot only or main only in the figure legend, and operation with concurrent pilot and premixed modes is denoted as main and pilot. During the dual mode operation with concurrent pilot and premix fuel flows at a given engine power setting, the combustor was operated with several pilot-to-premix fuel flow fractions while maintaining a constant total fuel flow to the engine. The ratio of pilot fuel flow to main fuel flow is indicated for selected data points. Combustor operation under fully LPM conditions produces the classical exponential relationship between NO_X production and temperature. The NO_X measured at 100% load was 34 ppm. NOx emissions reached a minimum below 10 ppm at about 80% of rated power output. NO_X increased above this power level due to increasing flame temperature as a result of increasing fuel/air ratio. NO_X emissions also increased below 80% power due to an increase in the fraction of fuel delivered through the pilot system. Fuel delivered through the pilot system burned in a diffusion flame mode with the associated local stoichiometric temperatures, and these high temperature regions resulted in higher NO_X levels. At power settings above 80%, the combustor was operated in the dual combustion mode (concurrent pilot and LPM modes) to investigate the impact of introducing a diffusion flame. With a fuel split of 9% pilot/91% premix, NO_X increased less than 10%. CO emissions of less than 10 ppm and UHC emissions of less than 5 ppm were measured when the engine was operated above 80% power with LPM combustion.

During the engine test program, no combustion generated acoustic noise was observed through the accelerometers mounted on the engine to detect vibration.

Figure 5 shows the NO_X-CO trade-off characteristics. At high power operation, CO equilibrium was achieved as NO_X production was independent of CO. As engine power decreased, dual combustor mode operation produced nearly constant NO_X with increased CO. Exclusive pilot mode operation at low engine power settings showed an increase in both NO_X and CO emissions. The burner outlet temperature quality measured during the engine tests indicated both pattern factor and radial profile were comparable with current production liners.

RIG TEST RESULTS

Combustor designs are tested in a simulated engine environment using Allison's single burner rig test facility. This facility simulates the flow path for a one-sixth sector of the 501 engine from the discharge of the compressor to the turbine inlet. This test rig is equipped with 30 type B thermocouples and emission sampling probes to quantify the burner exit temperature distribution and emission levels exiting the combustor.

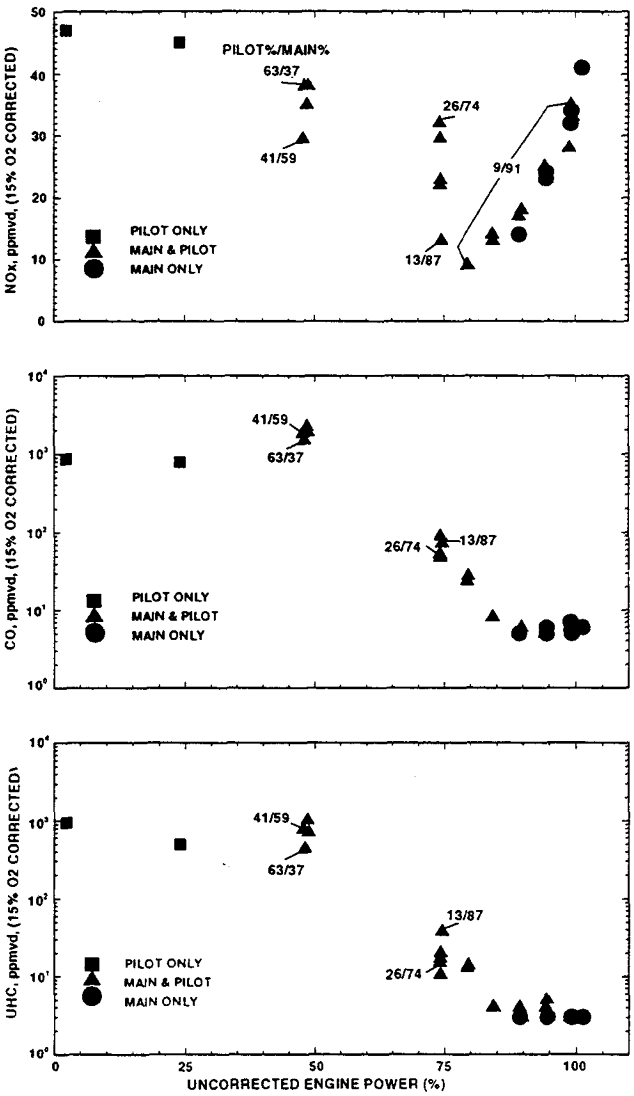

FIGURE 4. EMISSIONS RESULTS FROM 501-KB5 ENGINE TEST

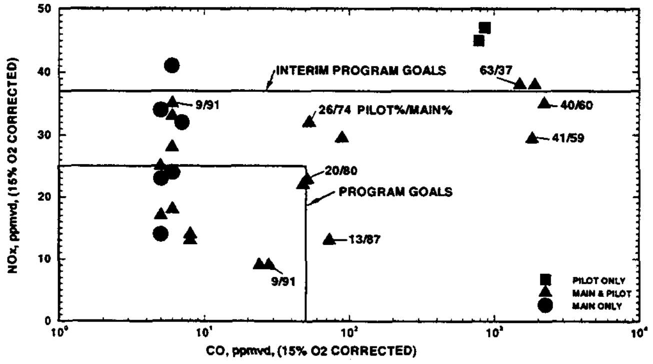

FIGURE 5. NO_X/CO TRADE-OFF CHARACTERISTICS FROM 501-KB5 ENGINE TEST

Progress in achieving a global and true emission reduction can be demonstrated by evaluating the NO_X-CO trade-off characteristics of a particular combustor design. Low NO_X emissions can always be achieved at the expense of greater CO production. A global reduction in emissions occurs when CO and NO_X are reduced simultaneously. Figure 6 illustrates the NO_X-CO trade-off characteristics for five combustors evaluated over the course of this program. The figure shows the impact of the various improvements occurring during development. The most recent combustor configuration shows emission performance falls well within the goal box over much of the engine operating range.

The combustion liner was rig tested over a wide range of airflows, pressures, inlet air temperatures and fuel to air ratios simulating 501-KB5 conditions. The fraction of fuel going to the pilot fuel system was varied in order to find the optimum split between pilot fuel and premixer fuel at various operating conditions. The diffuser bleed was also varied to develop an optimum operating envelope for the low emissions combustion system to meet the 25 ppm NO_X, 50 ppm CO, and 20 ppm UHC goals for widest possible range of engine power. Figure 7 summarizes the rig test results obtained under simulated 501-KB5 conditions. Using only a combination of pilot and main fuel flow and without the use of diffuser bleed (solid symbols in Figure 7), less than 25 ppm NO_X were obtained for 60 to 100% engine power, with NO_X emissions less than 15 ppm at the maximum power point. The corresponding CO and UHC emissions were high for the engine operating points less than about 90% power. CO and UHC goals were met for 90 to 100% power. With the diffuser bleed (open symbols in Figure 7), the NO_X, CO, and UHC emissions goals were met from 20 to 100% power. The rig test results demonstrated that with proper diffuser bleed schedule and fuel staging the current emissions goals were met for wide range of engine operation.

A diffuser bleed system for the engine has been designed to extend the engine's operational range in the LPM combustion mode. This addition will improve emission performance in applications having a wide range of load conditions. The engine test of Allison's 25 ppm NO_X dry low NO_X combustion system with diffuser bleed option is scheduled to be tested shortly.

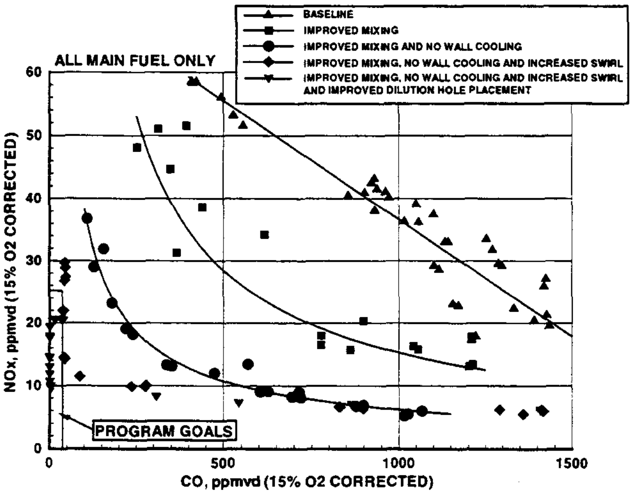

FIGURE 6. ALLISON'S PROGRESS IN LPM COMBUSTOR DEVELOPMENT

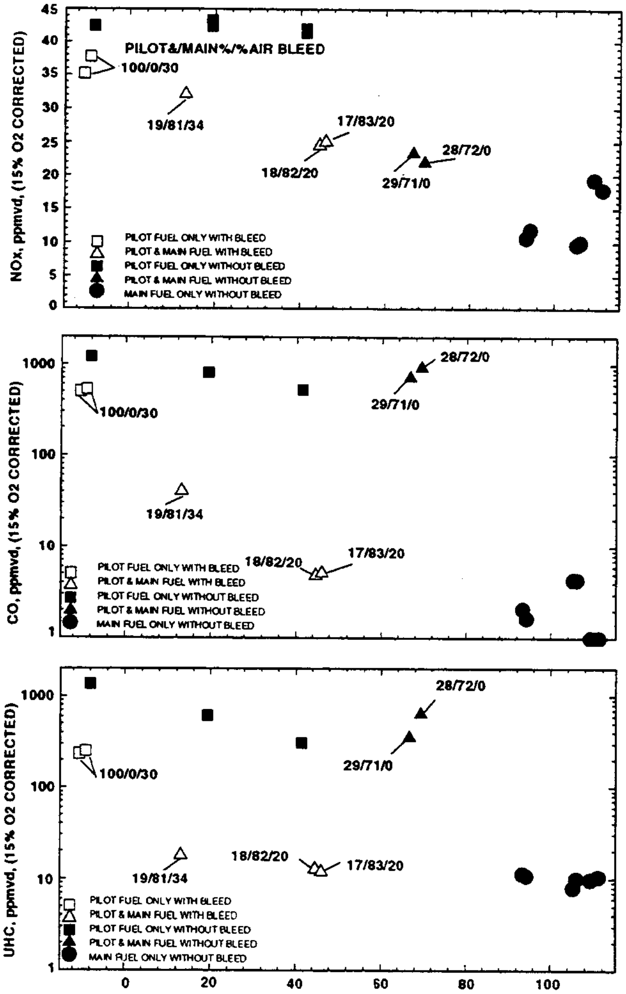

FIGURE 7. MEASURED EMISSIONS FROM SINGLE BURNER RIG FOR 501-KB5 SIMULATED POINTS WITH AND WITHOUT DIFFUSER BLEED

FUTURE DESIGN REFINEMENTS

Development work continues to improve the dry low NO_X combustion system. Future work is planned for refining the pilot mode combustion, extending ultra-lean premix mode operation, and studying the sensitivity of wall cooling air and dilution jet interaction upon emission production. It is believed changes to the pilot fuel system may result in improvements to off design emission performance.

A change being investigated is to provide a second pilot fuel circuit discharging fuel into the center recirculation zone formed aft of the premixer centerbody. With the current pilot fuel system, fuel is delivered only to the outer recirculation zone, and is provided so that during start-up there is a sufficiently rich mixture in the proximity of the igniter. The limited volume in the outer recirculation zone means some partially reacted gases may escape from this region and be quickly cooled by the large quantity of air entering the combustor through the premixing module. By distributing the pilot fuel to both the inner and outer recirculation zones, a larger total volume is available to more completely consume CO and UHC before these gases mix with the bulk flow. The center pilot concept has been investigated using Allison's three-dimensional computational combustor dynamics model which includes multi-step chemical kinetics and a k-ε turbulence model.

Figure 8 shows the results for 501-KB5 idle conditions with the outer pilot only and the center and outer pilots together. The figure shows half of the combustor split at the centerline from the exit of the mixing cup to downstream of the dilution jets; flow is from left to right. Note the more uniform gas temperatures upstream of the dilution jets and the reduction in the temperature of the gas near the liner wall with the center/outer pilot configuration. In addition to the advantages of two pilot circuits when operating with pilot fuel only, there is likely to be an advantage when operating with pilot and main fuel together. When the combustor is operating at a low power setting with pilot and main fuel, the inner recirculation zone may be too lean to act as a source of ignition for the incoming premixed gases. Ignition of these gases must then take place from the outer recirculation zone only and the flame then propagates across the fuel lean, high velocity flow. By providing a second source of ignition in the form of the centerbody pilot, the flame front is initiated on both sides of the premixed gases, resulting in more complete combustion before the entrainment of the dilution air near the end of the combustor. Splitting the pilot flow between the inner and outer recirculation zones should also result in lower wall temperature, since part of the high temperature region is relocated away from the liner walls.

CONCLUSIONS

Allison has engine demonstrated a dry low NO_X combustion system employing LPM technology emitting less than 37 ppm of NO_X and less than 10 ppm of CO and UHC at 501-KB5 full power conditions. The system maintained NO_X levels below 37 ppm at off design conditions ranging from 50 to 100% load. The CO emission level was below 50 ppm and the UHC emission level was below 20 ppm from 75 to 100% power.

The dry low NO_X combustion system has demonstrated low emissions without impacting lean stability, ignition, or overall engine performance characteristics. No combustion generated acoustic instability was observed during the engine tests. The engine field evaluation with the interim combustion system has started.

Single burner rig testing has demonstrated less than 25 ppm NO_X can be achieved with a slight airflow redistribution within the combustion liner. With the proposed diffuser bleed option, this combustion system has demonstrated the capability of meeting and exceeding the emissions goals set for this program over a wide range of operating conditions.

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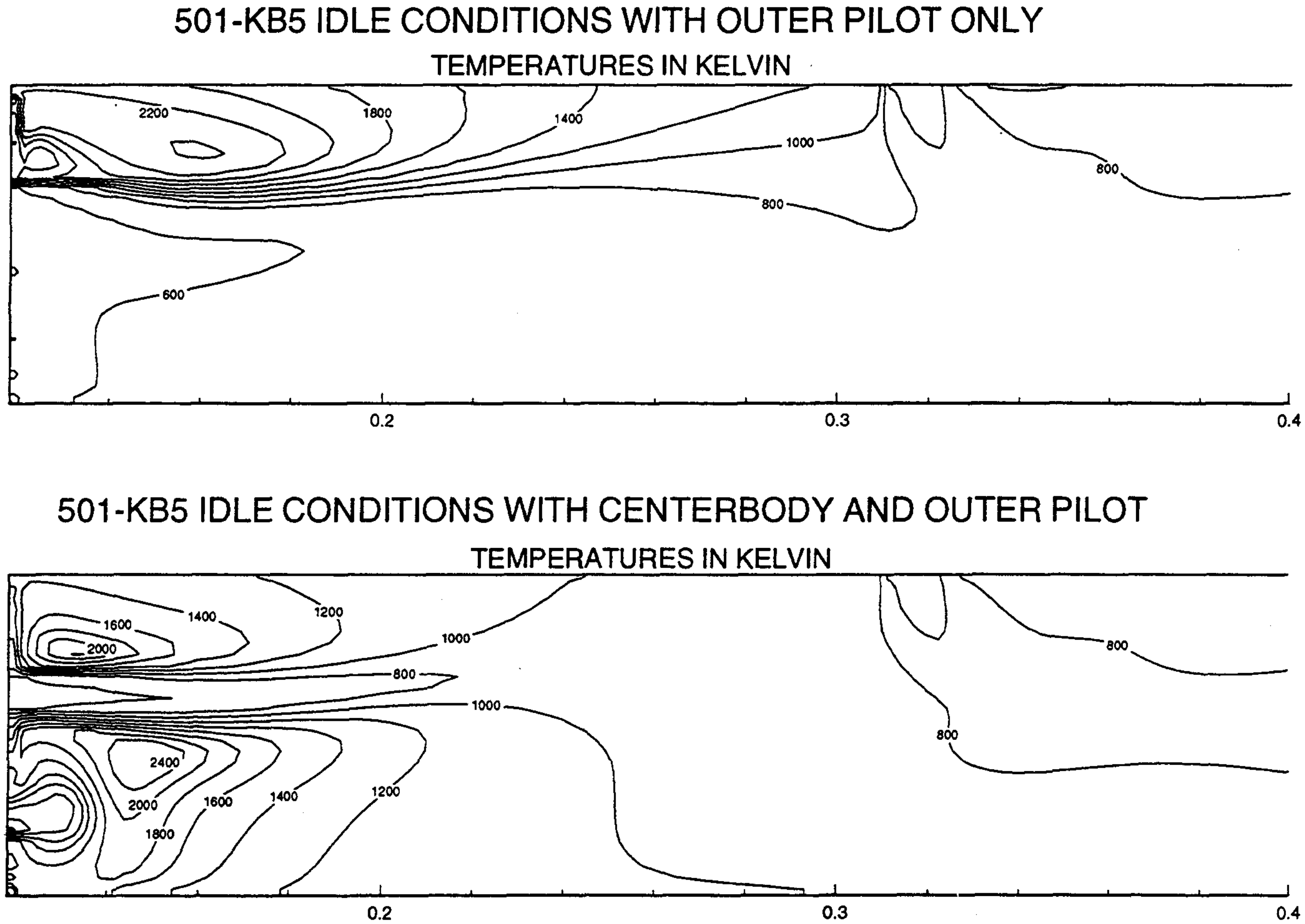

501-KB5 IDLE CONDITIONS WITH OUTER PILOT ONLY

TEMPERATURES IN KELVIN

501-KB5 IDLE CONDITIONS WITH CENTERBODY AND OUTER PILOT

TEMPERATURES IN KELVIN

FIGURE 8. COMPUTATIONAL FLUID DYNAMICS RESULTS FOR TWO VARIATIONS OF PILOT FUEL DELIVERY

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