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NO_x EMISSION REDUCTION FROM GAS TURBINE COMBUSTOR VIA STAGED COMBUSTION

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ABSTRACT

A two-stage lean/lean gas turbinc combustor was developed with low NO_X characteristics in each stage using small radial swirler of 40mm outlet diameter in the pilot stage. Both flame tubes were arranged in series with the smaller combustor (76mm inside diameter) as the pilot stage and the larger combustor (140mm inside diameter) as the main stage. The pilot stage was fuelled via vane passage fuel injector, while the main stage was fuelled around the wall of the exit plane of the pilot stage, using wall fuel injectors. Tests were conducted using propane as fuel.

Low NO_X emissions, as low as 2ppm were obtained when using fuel staging. A NO_X reduction of more than 40% was obtained at equivalence ratio of near 0.7, when using fuel staging compared to the non-fuel-staging test. This was achieved with very small increase in carbon monoxide emissions and almost no increase at all in the unburned hydrocarbon emissions at the same equivalence ratio.

1.0 INTRODUCTION

The effects of increased levels of oxides of nitrogen (NO_x) in the atmosphere are wide reaching. In the atmosphere nitric oxide (NO) is rapidly oxidised to nitrogen dioxide (NO_2) and in this form plays an essential role in the formation of tropospheric ozone and photochemical smog, and is oxidised to form nitric acid that may then be deposited as acid rain [1]. At ground level, increased concentrations (above 0.06 ppm) of NO_2 can cause respiratory problem [2].

The legislation of NO_x emission limits in many parts of the world has substantially complicated the process of burner design. Attempts at lowering

NO_x emissions by reducing the flame temperature will lead to reduced flame stability or increased carbon monoxide (CO) emissions. Unacceptable stability problems or CO emissions always limit the lowest NO_x emission obtainable in any given configuration.

Basically there are two techniques of controlling NO_x: those which prevent the formation of NO and those which destroy NO from the products of combustion. In the present work both methods are employed: lean combustion for low thermal NO_x followed by second stage fuel injection for combustion in the combustion products of the lean zone, which can destroy first stage NO_x through a reburn mechanism.

The methods that prevent the formation of NO involved modifications to the conventional combustor designs or operating conditions, such as lean primary zone, rich primary zone, rich/lean, or reduced residence time, since the main factors governing formation of NO is temperature and oxygen availability. However, the rich/lean method tends to increase CO and unburned hydrocarbon (UHC). Advanced combustor designs are needed for reducing all four major pollutants simultaneously over a range of thermal or engine power outputs. This gives rise to the use of variable geometry combustor and staged combustion to cope with the demands of burner turndown and power variations in gas turbines, when the overall air-fuel ratio (A/F) is increased as power is reduced. For ultra low NO_x emissions, lean premixed-prevaporised combustors and catalytic combustors are being developed.

In staged combustion, the combustion process is arranged to occur in a number of discrete stages. In theory, either circumferential, radial or axial staging may be employed. However, in practice circumferential fuel staging increases NO_x - instead of the fuel being distributed uniformly around the liner, it is injected at a small number of points, where it produces regions of high temperature [3]. The elaboration's for the above mentioned three types of fuel staging are as follows:

a) *Circumferential.* Usually this entails disconnecting alternately located nozzles from the fuel supply. It is ideally suited to tuboannular systems but on annular chambers the quenching effects of the surrounding cold air on the localised burning zones largely offset its advantages.
b) *Radial.* The simplest application of this technique is to double-banked annular combustors where, at low fuel flows, it is a relatively simple matter to inject all the fuel into the inner or outer combustion zone. (See Figure 1).
c) *Axial.* By designing the primary zone for optimum performance at low power settings, and then injecting the extra fuel needed at higher power levels at one or more locations downstream. (See Figure 2).

Catalytic combustion involves the use of catalysts that allow fuel oxidation to take place at temperatures well below the lean flammability limit of the fuel. Due

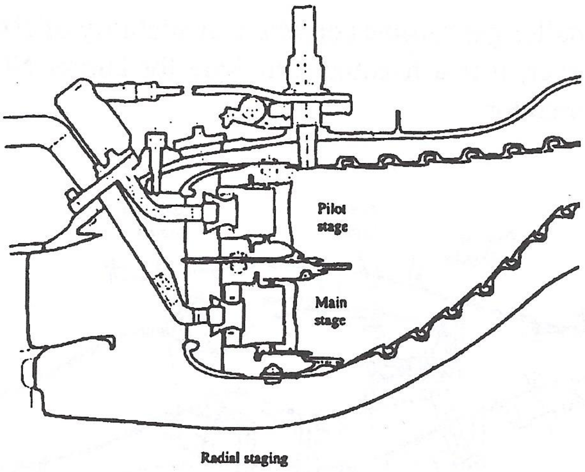

Figure 1 Schematic Diagram of Radial Staged Combustor

to this reason, the use of catalysts in gas turbine combustors to replace part of the thermal reaction zone allows stable combustion with peak temperatures that are about 1000K lower than those of conventional techniques. As nitric oxide emissions vary exponentially with reaction temperature, combustion at much lower temperatures can be expected to decrease the production of thermal NO. Burner system can also operate with catalytic combustion but only by using high excess air (>100%) to limit the catalyst temperature which gives a poor thermal efficiency.

Mularz, Gleason and Dodds [4] investigated the use of a catalytic converter combustor and demonstrated emissions levels for carbon monoxide, unburned hydrocarbon and nitric oxide lower than the proposed standards of EPA 1981. The disadvantage of using catalytic combustor is the tendency of autoignition of the fuel upstream of the catalyst. Another disadvantage pointed by Mularz, Gleason and Dodds [4] is that the temperature of the gases approaching the catalysts bed must be carefully controlled to prevent catalyst bed damage.

Water or steam injection has been shown to be a very effective technique to accomplish the above goal [5]. A typical NO_x reduction curve as a function of rate of water injection is shown in Figure 3 [6]. These data were obtained in an aeroderivative inductive gas turbine at full power. Fox and Schlein [7] testing the FT8 gas turbine combustor in their final test run also demonstrated the same effect. The FT8 engine is an industrial/marine gas turbine engines that is a derivative of the widely used JT8D aircraft jet engine. However, to avoid detrimental effects on turbine durability the water has to be purified to a maximum of 2-5 ppm of dissolved solids ([6], [8]). Furthermore, there are other complications such as incorporating the water injection system to the combustor design. Another disadvantage of water injection is the undesirable side effects of quenching CO burnout. These drawbacks caused water injection method to be unattractive for smaller gas turbines or where availability of sizeable water supply is difficult. However, it is a feasible technique for burner NO_x control in water heater or steam generator.

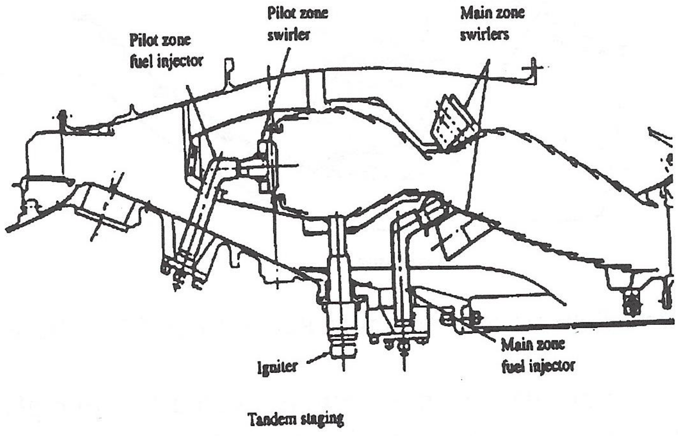

Figure 2 Schematic Diagram of Axial Staged Combustor

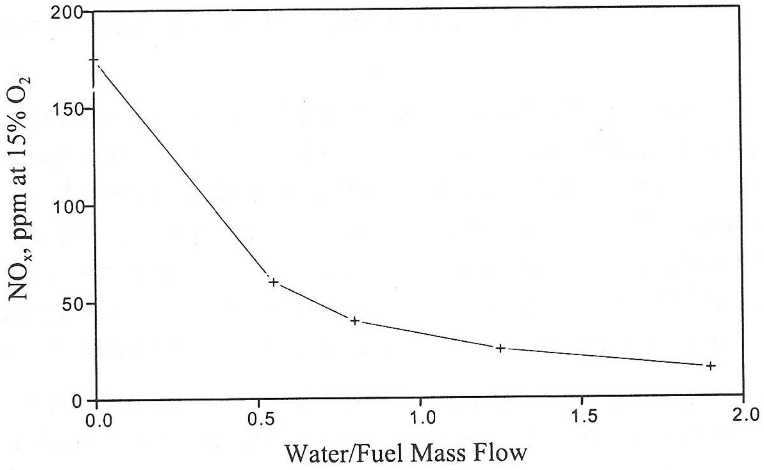

Figure 3 NO_x as a function of water addition in a gas-turbine combustor running on natural gas at a pressure ratio of 30 [6].

Other methods of NO_x control involve staged combustion, variable geometry combustion, lean premixed prevaporised combustion and catalytic combustion.

In the present work axial fuel staging was employed that consisted of lean-lean combustion. The first combustor was operated very lean with all the air needed for combustion introduced in this zone and the operation was set close to the lean stability limit. Fuel, without any air, was then injected into the completely burnt products of this lean primary combustion zone to bring the burner to the desired overall excess air. Typically the lean zone may have an equivalence ratio of 0.6 with fuel injected in the secondary zone to bring the overall equivalence ratio to 0.9. Thus, it is a lean/lean staged system. However, the inert second stage fuel injection will create a local rich zone near the injector prior to mixing with oxygen from the lean primary zone exhaust. Thus, the combustor will have element of lean/rich/lean combustion, which is a key feature of NO_x reduction using staged combustion.

2.0 STAGED COMBUSTION

Staged combustion or reburning, sometimes referred to as in-furnace NO_x reduction, was first proposed by Wendt et al. in 1973 [9]. However, much earlier studies had shown that NO could be reduced by reaction with hydrocarbon fragments ([10], [11]). This method of reducing NO_x emissions only became successful when Takahashi et al. [12] showed that a NO_x reduction of at least 50% could be achieved by applying this method. Fuel staging is primarily the introduction of secondary fuel downstream of the primary zone without any associated airflow. In this method the formation of the NO_x is allowed to be completed in the primary zone. Then the reburn fuel is injected further downstream, where it is expected that the formation of NO_x from the primary zone is completed. This reburn fuel, usually hydrocarbons fuel, is injected to destroy the NO_x that was formed in the primary zone. The reaction of this destruction is given as follows:

$$CH + NO \rightarrow HCN + O \tag{1}$$

HCN participates in a series of reactions leading to the formation of a partially equilibrated pool of NH_i species. The amine radicals either react with NO to produce N_2 or are oxidised to reform NO.

The fuel staging or reburn process is composed of three distinct zones. The first zone is the *primary combustion zone*. In this zone the fuel is burnt lean. For furnace application, usually 80% of the total fuel is introduced in this zone. The formation of NO_x is usually completed in this zone. The next zone is the *reburn zone* or sometimes called the reduction zone since in this zone the NO_x formed in the primary zone is reduced to molecular nitrogen. In this zone the fuel is burnt at rich condition. The reburn fuel is injected downstream of the primary zone. The final zone is called the *burnout zone*. In this zone additional air is added to create an overall lean condition and to oxidise the remaining unburnt fuel fragments and CO, thus, completing the combustion process. The staged combustion system is thus lean/rich/lean staged combustion.

There are several parameters that control the effectiveness of the fuel staging process. These are listed as follows:

i. The initial concentration of NO_x from primary zone ([13], [14] and [15]).
ii. The equivalence ratio of the reburn zone ([13], [15] and [16]).
iii. The residence time in the reburn zone [15].
iv. The completeness of the primary zone combustion prior to the injection of the reburn fuel [15].

There are other fuels that can be used as the reburn fuel instead of hydrocarbon fuels. However, many workers in this area agreed that natural gas is the best reburn fuel to be used. The hydrocarbon fuel rapidly forms CH fragments that convert the primary zone NO to HCN via reaction (1). They also agreed that in order to destroy NO formed in the primary zone effectively the stoichiometric ratio of about 0.9 (i.e., 10% rich) is the optimum value for the reduction zone. The stoichiometric ratio is defined as the inverse of equivalence ratio.

2.1 Two Fuel Injection Stages or Lean/ Lean Staged Combustion

In the present work the second stage fuel injection was through eight radial holes on the periphery of the lean upstream combustor. There was no specific third lean stage, but it was anticipated that in the mixing zone of this second stage there would be unmixedness that produced locally rich regions whereby reburns chemistry could take place. The third stage would then be the aerodynamic mixing of the excess air from the lean combustion stage. In the present work the lean stage was operated much leaner than in power station reburn systems where typically the lean stage might be 20% lean of the overall stoichiometry, the rich stage typically 10% rich and the third stage trimming to the required excess air for CO, char and hydrocarbon burn out. In the present work all the air was injected into the first lean stage that was operated at around 0.55 - 0.6 equivalence ratio, which was as lean as a stable lean flame could be achieved. This would then minimise the NO_x formed in the first lean stage. The second stage fuel was burnt in the vitiated combustion products from the first stage with oxygen levels around 9%. The second stage fuel flow was increased keeping the first stage equivalence ratio constant and the overall mixture strength was varied from around 0.6 to near stoichiometric.

3.0 EXPERIMENTAL SET-UP

The system comprised of two different sizes flame tubes. The smaller one of 76mm inside diameter was attached to the plenum chamber and acted as the first stage. The radial swirler of 40mm outlet diameter and 30.5mm depth was used as a flame stabiliser. The first combustor was fuelled via the radial vane passage injection mode. The air and fuel were mixed thoroughly prior to ignition. At the exit plane of the first combustor a wall fuel injector of 76mm diameter was attached. This is the injector for the second stage reburn fuel. The mixtures of flue gas from the first combustor and the reburn fuel were allowed to expand freely into a larger combustor of 140mm internal diameter. The wall injector and the second combustor were attached to the first combustor by the use of flanges. The schematic diagram of the reburn test rig is shown in Figure 4 and the radial swirler geometry is shown in Figure 5.

The reburn tests were run at 2.4% pressure losses to achieve lowest gas turbine combustor condition. The radial swirler in the primary zone in Figure 4 has a swirler outlet diameter of 40mm. This could be fitted with an orifice plate to reduce the swirler outlet area. The role of the orifice plate was to enhance flame stabilisation and provide a better mixing of the air and fuel prior to ignition. It also created the pressure loss at the outlet rather than in the vane passage which generated maximum turbulence in the swirl shear layer. The orifice plate also helped to prevent fuel from entraining into the corner dumped expansion outer recirculation zone and thus create a rich local zone which would lead to higher NO_x emissions from this area. The orifice plate was mounted at the exit plane of the radial swirler as shown in Figure 4. All tests were carried out at atmospheric pressure with an air inlet temperature of 600K, with gas turbine pressure loss of 2.4%, and fuelled with propane. The orifice plate size involved was 25.4mm in diameter.

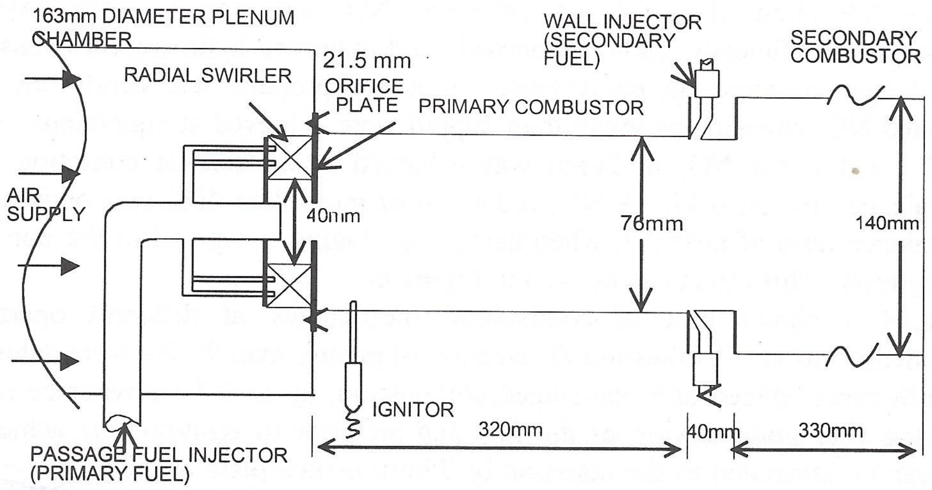

Figure 4 Schematic Diagram of Staged Combustion Test Rig Set-up.

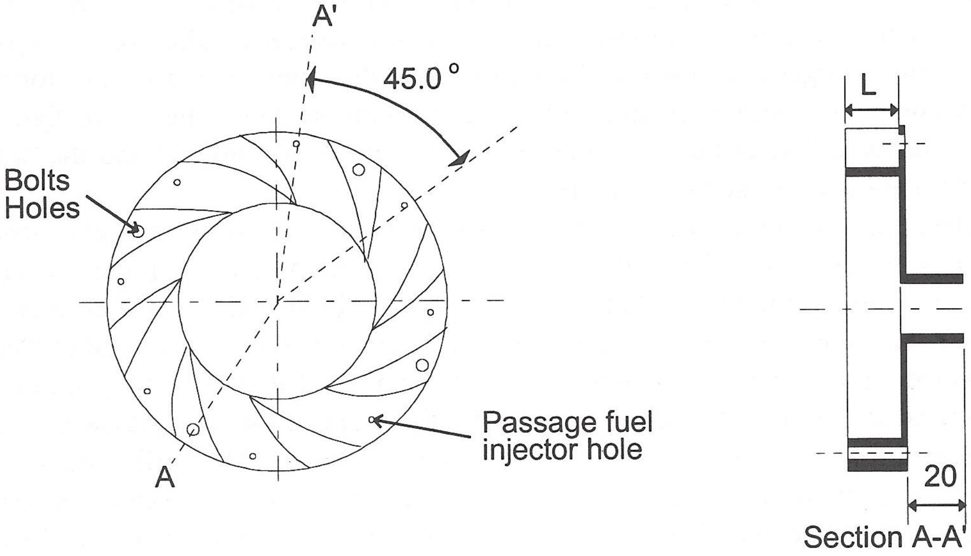

Figure 5 Schematic Diagram of Radial Swirler.

4.0 RESULTS AND DISCUSSIONS

Figures 6-9 show the plots of corrected NO_x emission to 15% oxygen, combustion inefficiency, carbon monoxide and unburned hydrocarbon emissions plotted against operating equivalence ratios for propane test conditions. A corrected NO_x emission of lower than 20ppm were achieved at equivalence ratio of 0.7. Ultra low NO_x of 2ppm was achieved at the leanest condition near equivalence ratio of 0.47. A NO_x reduction of more than 40% was obtained at equivalence ratio of near 0.7, when using fuel staging compared to the non-fuel staging tests. This effect can be seen in Figure 6.

Figure 7 shows plot of combustion inefficiency at different operating equivalence ratios. Combustion efficiencies of greater than 99.9% were achieved for both cases, staged and non-staged combustion, up to 0.7 equivalence ratios implying very good mixing of the fuel and air prior to ignition was achieved. This can be attributed to the insertion of 25mm orifice plate at the exit plane of the radial swirler. The combustion efficiencies for the staged combustion were higher than the non-staged combustion condition up to equivalence ratio of near 0.65. Thereon, the combustion efficiencies for the non-staged combustion were greater.

Figure 8 shows CO emissions of less than 100 ppm were obtained over a wide range of equivalence ratios up to 0.67. This is very close to the condition without fuel staging. However, fuel staging increases the CO emissions higher than 100 ppm for equivalence ratio of above 0.67 due to the lower residence time with reburn and the lower oxygen availability.

Figure 9 shows that unburned hydrocarbon (UHC) emissions of less than 7ppm were achieved for both cases over the entire range of operating equivalence ratios except at the leaner condition for the non-staging tests. This implies that very good mixing of the fuel and air prior to ignition was achieved.

5.0 CONCLUSIONS

- A NO_x reduction of around 40% could be achieved for the two-stage fuel injection with a very lean primary zone.
- Very good combustion efficiencies were also obtained without marked increase in CO and UHC emissions.
- CO and UHC emissions were lower when using reburn compared to the non-reburn test.

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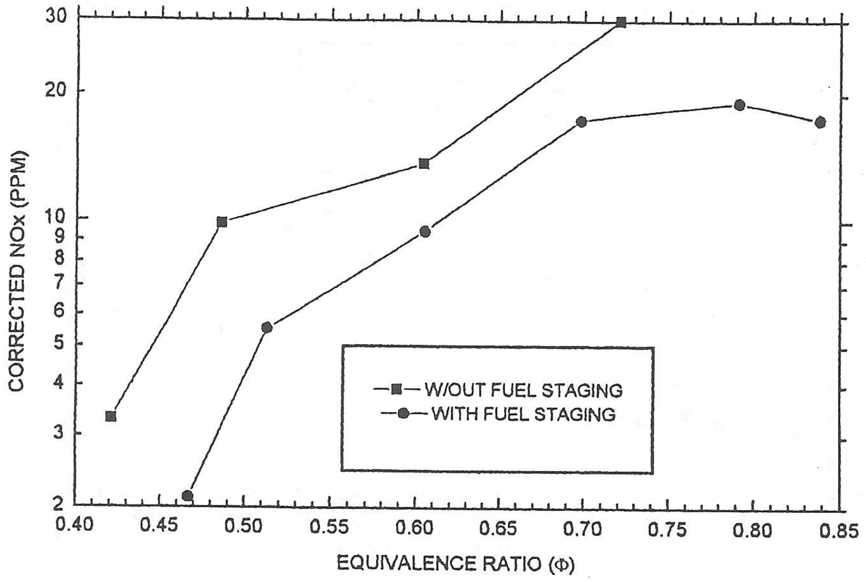

Figure 6 Corrected NO_x Emission vs Equivalence Ratio For $\Delta P/P = 2.4\%$
Mach No = 0.04; Propane; $T_{in} = 600$ K

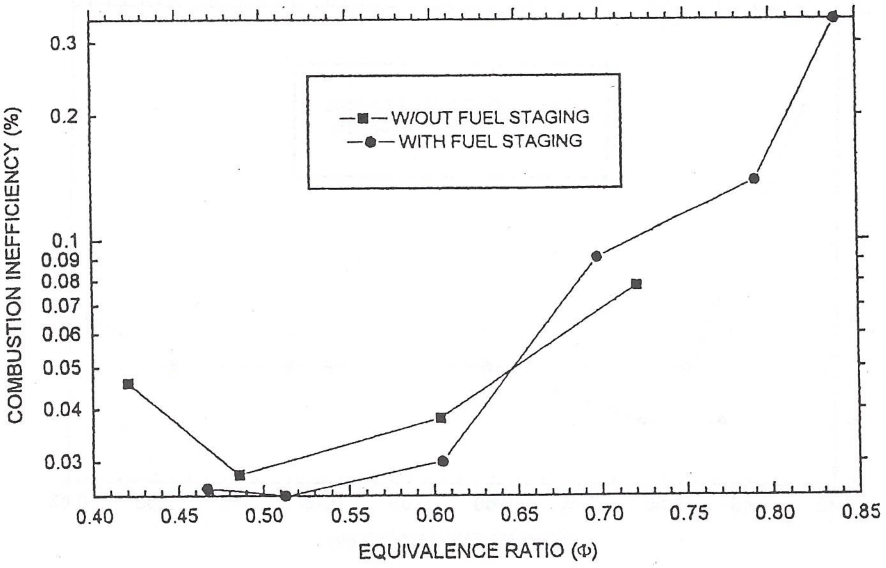

Figure 7 Combustion Inefficiency vs Equivalence Ratio For $\Delta P/P = 2.4\%$
Mach No = 0.04; Propane; $T_{in} = 600$ K

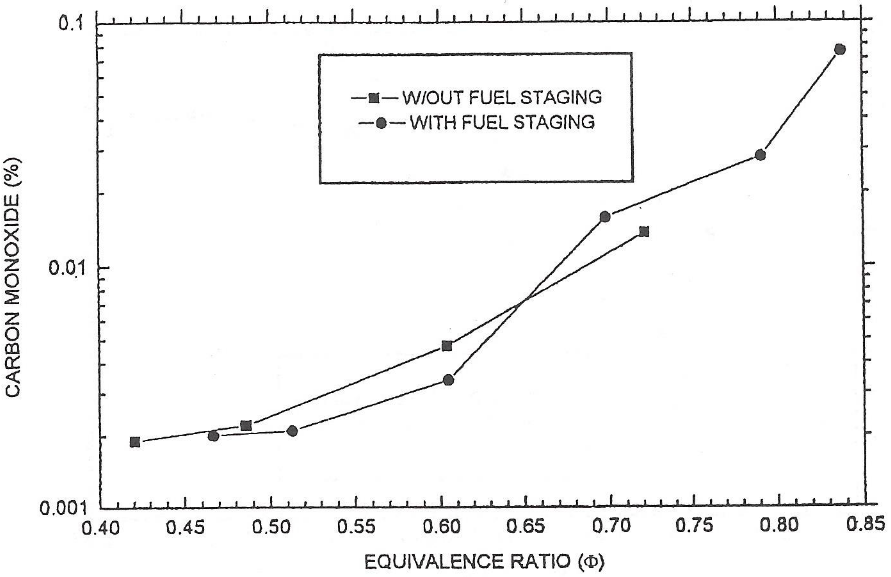

Figure 8 Carbon Monoxide vs Equivalence Ratio For ΔP/P = 2.4%
Mach No = 0.04; Propane; T_{in} = 600 K

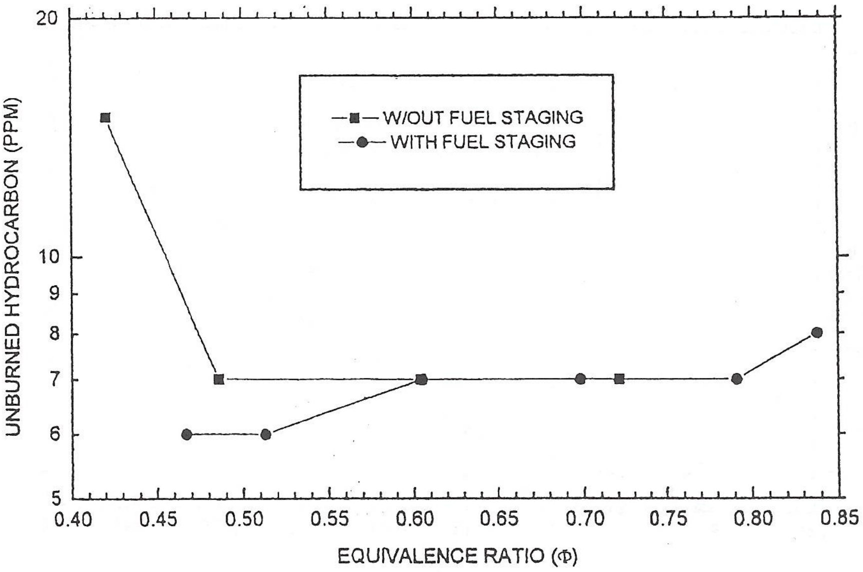

Figure 9 Unburned Hydrocarbons vs Equivalence Ratio For ΔP/P = 2.4%
Mach No = 0.04; Propane; T_{in} = 600 K