TECHNOLOGY FOR THE REDUCTION OF AIRCRAFT TURBINE ENGINE POLLUTANT EMISSIONS

Donald W. Bahr and Clifford C. Gleason
General Electric Company
Aircraft Engine Group
Cincinnati, Ohio/Lynn, Massachusetts

Abstract

The exhaust pollutant emissions characteristics of aircraft turbine engines are described. Also, the basic approaches for reducing the levels of these pollutant emissions are reviewed. The results of specific development efforts to define engine combustor design features and operational methods for attaining these more favorable emissions characteristics are presented. Based on these development results and trends, it is concluded that future engines will be developed with significantly more favorable exhaust emissions characteristics than those of current engines. The possible effects of obtaining the low exhaust pollutant emissions levels, required to meet the U.S. Environmental Protection Agency standards, on engine designs and their operating characteristics are also briefly considered.

Introduction

Within recent years, the number of turbine engine-powered aircraft in both commercial and military service has increased at an extremely rapid rate. This rapidly increasing usage of turbine engine-powered aircraft has logically resulted in increased interest in assessing the possible contributions of aircraft turbine engines to the air pollution problems confronting many metropolitan areas throughout the world. Therefore, several studies to define the extent of these contributions have already been conducted and others are in progress. In general, the studies conducted to date have shown that the overall contributions of aircraft turbine engine operations to the air pollution problems of metropolitan areas are quite small, as compared to those of other contributors.(1) These studies have also shown that the exhausts of aircraft turbine engines generally contain low concentrations of gaseous and particulate emissions considered to be in the category of air pollutants. The typically low concentrations of objectionable exhaust emissions are due to the continuous, well controlled and highly efficient nature of the combustion processes in turbine engines and to the use of fuels which contain very small quantities of impurities.

Nonetheless, even though relatively low concentrations and total amounts are generated in most instances, the exhaust emissions in the category of air pollutants resulting from the operations of aircraft turbine engines are of possible concern. The specific aircraft turbine engine exhaust emissions which are of possible concern from an air pollution standpoint consist of carbon monoxide (CO), unburned or partially oxidized hydrocarbons (C_xH_y), carbon smoke particulate matter (C) and oxides of nitrogen (NO_x). The foremost concern associated with these engine exhaust emissions appears to be their possible impacts on the immediate areas surrounding major metropolitan airports. Because of the operating characteristics of most current turbojet and turbofan engines, the highest levels of these various objectionable exhaust constituents are typically generated at engine operating modes that occur in and around airports. Further, because large numbers of daily aircraft operations can occur in and around a given airport, the cumulative exhaust emissions resulting from these localized aircraft operations tend to be concentrated to some extent in the airport vicinity.

For these reasons, the U.S. Environmental Protection Agency (EPA) concluded that standards to regulate and minimize the quantities of CO, C_xH_y, NO_x and smoke emissions that may be discharged by aircraft, when operating within or near airports, are needed. Based on this finding, such standards were defined for several different categories and types of fixed-wing, commercial aircraft engines and were issued by the EPA in July, 1973. For the most part, these standards become effective in 1979.(2)

The introduction of aircraft engine exhausts into the stratosphere is another possible area of concern. Because of the relatively slow mixing rates between the stratosphere and the troposphere, and the resulting tendencies for materials introduced into the stratosphere to accumulate, it is believed that the continuous introduction of some engine exhaust products into the stratosphere by large aircraft fleets might, after extended time periods, result in adverse environmental impacts. The introduction by aircraft engines of NO_x emissions into the stratosphere has, for example, been identified as a particular area of concern by some investigators. The introduction of the generally very small concentrations of sulfur oxides and particulates emissions contained in engine exhausts have been similarly identified as possible areas of concern. The possible impacts of the introduction of these and other engine exhaust products into the stratosphere are the subject of the very extensive Climatic Impact Assessment Program.(3) This major program, which is being conducted by the

U.S. Department of Transportation, is scheduled to be completed by the end of 1974 and is expected to result in preliminary quantitative determinations of the possible effects of introducing various engine exhaust products into the stratosphere. Thus, these findings are expected to result in preliminary determinations as to whether or not the levels of any engine exhaust constituents must be minimized at stratospheric cruise operating conditions.

To minimize these possible adverse environmental effects, significant development efforts to provide technology for the control and reduction of the levels of the objectionable exhaust emissions of aircraft turbine engines have already been conducted and major additional development efforts of this kind are currently underway. Significant advances have already been made in the development of technology for the design of engines with greatly reduced smoke emission levels. As a result of these latter efforts, engines with virtually invisible smoke emission levels have already been developed and placed into service. These latter engines are already in compliance with the smoke emission standards which have been issued by the EPA.

More recently, increased attention has been directed toward the development of technology for the design of aircraft turbine engines with reduced CO, C_xH_y and NO_x emissions levels, as well as low smoke emission levels. One of the major development efforts of this kind, which is currently underway, is the Experimental Clean Combustor Program, which is being conducted by the U. S. National Aeronautics and Space Administration (NASA).(4) Under contract to the NASA, General Electric is participating in this important program. In this latter NASA/General Electric Program, which was initiated during 1972, technology for the design of low emissions combustors for use in large turbofan engines, such as the General Electric CF6-series engines, is being developed.

In this paper, the exhaust emissions characteristics of aircraft turbine engines are briefly described. Also briefly described are the basic engine combustion system design criteria that have been found to be of importance if the CO, C_xH_y and NO_x emissions levels of these engines are to be significantly lowered. Further, the general engine combustion system design approaches and operational methods for attaining these more favorable emissions characteristics, particularly in engines with already developed low smoke emission levels, are discussed. In addition, a summary of some of the key results and trends of the various General Electric development programs to apply and incorporate these emissions control features in engines is presented. Finally, the possible effects and impacts of obtaining the low CO, C_xH_y and NO_x emissions levels required to meet the EPA standards on aircraft engine designs and their operting characteristics are briefly considered.

Exhaust Emissions Characteristics of Aircraft Turbine Engines

A typical illustration of the CO, C_xH_y, NOx, smoke and sulfur oxides emissions characteristics of a non-afterburning aircraft turbine engine is presented in Figure 1. In this figure, the measured emissions characteristics of a large, operational General Electric turbofan engine are presented. As is illustrated in this figure, the CO and C_xH_y emissions levels of non-afterburning engines occur mainly at ground idle and other low engine power operating conditions and are usually very low at high engine power operating conditions. The peak levels of the NO_x emissions, on the other hand, typically occur at takeoff and other high engine power operating conditions and are usually quite low at low engine power operating conditions. In the case of this particular turbofan engine, which is equipped with a low smoke emission combustor, its smoke emission levels are very low and, thus, virtually invisible at all operating conditions. In general, the peak smoke emission levels of non-afterburning engines usually occur at high engine power operating conditions. As is also illustrated in Figure 1, the surfur oxides emissions levels of any aircraft turbine engine are normally quite low at all operating conditions. These typically low sulfur oxides emissions levels are a direct consequence of the low sulfur contents of aircraft turbine engine fuels.

At cruise operating conditions, the levels of these various exhaust emissions which are generated by non-afterburning engines are normally quite low. Of these various emissions, only the NO_x emissions are normally generated to any significant extent at cruise operating conditions. With the possible exception of engines in supersonic aircraft applications, even the NO_x emissions levels of any given engine are significantly lower at cruise operating conditions than those at takeoff and climbout operating conditions. Thus, the highest levels of the various objectionable exhaust emissions of non-afterburning engines are primarily generated at engine operating conditions that occur in and around airports.

At the present time, therefore, the primary exhaust emissions reduction technology needs of non-afterburning engines appear to involve the elimination of visible smoke emissions, the reduction of CO and C_xH_y emissions levels at idle operating conditions and the reduction of NO_x emissions levels at takeoff, climbout and, possibly, cruise operating conditions. In any non-afterburning engine, the source of these emissions is, of course, its main combustor. The attainment of these more favorable exhaust emissions characteristics in future engines, thus, primarily involves providing improved and modified main combustors for use in these engines. For engines with afterburners, methods of reducing the CO, C_xH_y, NO_x, and particulates emissions generated in the reheat combustion system may also be required.

In any given main engine combustor, the total air flow entering the combustor is divided into separate portions, each of which serves a specific and different function. A portion is introduced into the primary combustion zone, or flame zone, of the combustor where it is mixed with fuel and where the major part of the combustion process occurs. In most present day combustors, another portion is introduced downstream of the primary combustion zone as dilution air. Still another portion is used for cooling the combustor liners and other parts. Also, in many engines, another portion is bypassed around the combustor and is used for turbine cooling. For the most part, the emissions of concern are formed in the primary combustion zone. Obtaining reduced levels of these emissions, thus, involves improved control of the processes that occur in this zone. In particular, obtaining these reduced emissions levels involves providing optimum fuel-air mixtures in this zone at all of the engine operating modes, at which these emissions are generated to any significant degree. As is discussed in more detail in the following sections of this paper, the attainment of these more optimum mixtures generally entails the use of more advanced, and often more complex, methods of introducing the air and fuel into the primary zone and of mixing the air and fuel in this zone, as compared to the methods used in most current technology combustors.

Reduction of Smoke Emissions

The smoke emissions contained in the exhausts of aircraft turbine engines are comprised of minute agglomerates of carbon, or soot, particles. The specific chemical mechanisms by which these carbon particles are produced in engine combustion systems are generally quite complex and only partially understood. In general, however, the formation of these carbon particles is known, from thermochemical considerations, to be associated with the combustions of fuel-air mixtures which have high fuel concentrations. In addition to the vapor-phase oxidation of rich fuel-air mixtures, other probable carbon producing mechanisms include the thermal cracking of liquid fuel droplets. The rates of these various formation mechanisms are highly dependent on the ambient pressure level, increasing rapidly as pressure is increased.

Many older technology engines have visible smoke emissions, particularly at takeoff and climbout operating conditions. Even in these engines, these smoke emissions represent quite small losses in engine combustion efficiency and involve relatively low smoke concentrations in the engine exhaust gases - typically less than 0.003 percent (by weight) of the core engine exhaust gas. However, because of the extremely small and finely divided nature of these particulate emissions, even these relatively low concentrations can be very visible. Thus, these emissions can result in objectionable atmospheric conditions and some visibility reduction in and near airports. In military aircraft, visible smoke emissions are also of concern, in some instances, because they can result in unsatisfactory conditions from tactical standpoints.

The smoke standards defined by the EPA for commercial aircraft engines basically require that the smoke emissions of these engines be reduced to invisible levels. To meet this requirement, very low exhaust gas smoke concentrations - generally less than 2 parts per million parts (by weight) of core engine exhaust gas - are required. Exhaust gas smoke concentrations of this order are equivalent to a smoke emission index of about 0.1 gram per kilogram of fuel.

Investigations conducted at General Electric and elsewhere have shown that the design of low smoke emission combustors involves providing both leaner fuel-air mixtures and more effective fuel-air mixing in the primary combustion zone, as compared to those of combustors with high smoke emission levels.(5) These investigations have demonstrated that both of these provisions are needed to eliminate any fuel-rich mixtures within the primary combustion zone and, therefore, that both are of major importance. Providing the required leaner fuel-air mixtures and improved mixing in the primary zone has been found to involve significant changes in the overall design approaches used in the combustors of older technology engines. Also, combustor design features added to reduce smoke emission levels can, in some instances, result in losses in other aspects of combustor performance, especially ignition performance. Thus, the design and definition of low smoke emission combustors have generally been found to entail careful, iterative development efforts to provide the required low smoke emission characteristics, as well as to meet all the usual ignition, stability, combustion efficiency, exit temperature distribution, life and other performance requirements.

At General Electric, efforts to develop low smoke emission combustors were initiated several years ago. As a result of these efforts, combustor designs with significantly higher primary combustion zone air flows and improved fuel-air mixing provisions, as compared to those used in older technology combustors, have been developed. In these combustors, lean and relatively uniform primary zone fuel-air mixtures were, thereby, obtained within very short distances downstream of the fuel nozzles.(5) With these more advanced combustor design approaches, much reduced smoke emission levels have been obtained without any significant losses in other key combustor performance characteristics. Advanced combustors, which incorporate these smoke emission control features, have already been successfully developed for use in the General Electric CF6, TF39, LM2500 and other engines. These engines, with these low smoke emission combustors, are already in service. The smoke emission levels of these advanced and high performance engines are virtually invisible at all operating conditions.

An indication of the progress made in these development efforts is presented in Figure 2. All of the engines included in this data summary are equipped with annular-type combustors. As is shown, the peak smoke emission levels of the older engines are generally well above the visibility threshold band and are somewhat dependent on engine cycle pressure ratio rating. The peak smoke emission levels of the more advanced engines are generally below a SAE Smoke Number of 20 and, therefore, are below the nominal threshold of visibility. These advanced engines encompass a wide range of sizes and cycle pressure ratio ratings. Considerable experience in both commercial and military service has already been obtained with these advanced, low smoke emission engines.

The smoke emission levels shown in Figure 2 are expressed in terms of the SAE ARP 1179 Smoke Number.(6) On this scale, which runs from zero to 100, low Smoke Numbers indicate low smoke particulates emission levels. Engine tests conducted at General Electric have shown that the visibility threshold Smoke Numbers of various types of engines range from about 20 to 40. The visibility threshold of any given engine is dependent on its size. Thus, larger size engines have lower Smoke Numbers as their visibility thresholds than smaller engines, because of the larger sizes of their exhaust plumes. Larger size plumes result in greater path lengths and, accordingly, greater amounts of light scattering and absorption for the same smoke concentration in the exhaust gas. The visibility of a given exhaust plume is also strongly influenced by the angle at which the plume is viewed. The smoke emissions contained in any given plume, of course, appear less visible when the plume is viewed at a right angle. For engines in the larger size class, visibility threshold Smoke Numbers are normally in the range of about 20 to 30. Engines in the smaller size class generally have visibility threshold Smoke Numbers in the range of about 30 to 40. The core engines of high bypass turbofan engines also generally have somewhat higher threshold Smoke Numbers than pure turbojet engines of a similar size, because of the dilution of the core engine exhaust gases by the bypass air. Generally, a SAE ARP 1179 Smoke Number of about 20 corresponds to or is below the visibility thresholds of most aircraft turbine engines - regardless of the engine size or the angle at which the exhaust plume is viewed. Based on tests conducted at General Electric, a SAE Smoke Number of 20 has been found to be equivalent to a smoke concentration of less than 2 parts per million parts of core engine exhaust gas (by weight). Thus, a Smoke Number of this magnitude not only results in an invisible exhaust, in most instances, but also results in exhaust gas smoke concentrations by weight which are extremely low.

The smoke standards defined by the EPA for aircraft turbine engines are defined in terms of this SAE ARP 1179 Smoke Number parameter. In the definition of these standards, the maximum allowable Smoke Numbers are related to engine size, for the reasons outlined above. Thus, the maximum allowable SAE Smoke Number of an engine with a rated thrust of 17.8 kilonewtons (4000 pounds) is about 40. Engines with higher rated thrusts have progressively lower limits. The maximum allowable SAE Smoke Number for an engine with a rated thrust of 178 kilonewtons (40,000 pounds) is about 20.

As is illustrated by the data presented in Figure 2, many newer technology engines are already in compliance with these EPA-defined smoke emissions standards. It is concluded, therefore, that technology required for the design of low smoke emission combustors, which also meet all engine ignition and other performance requirements, is reasonably well established.

Reduction of Carbon Monoxide and Unburned Hydrocarbons Emissions

Both CO and C_xH_y emissions are, of course, products of inefficient combustion. As is illustrated in Figure 1, these emissions are primarily produced at idle and other low power operating conditions. These emissions mainly occur at these operating conditions because the combustion efficiencies (degree to which the available chemical energy of the fuel is converted to heat energy) of most present day engines at these low engine power operating conditions are not optimum and are typically in the 90 to 96 percent range. At higher engine power settings, the combustion efficiency levels of most engines are generally well in excess of 99 percent and, therefore, virtually all of the fuel is converted to the ideal combustion products, carbon dioxide and water, at these operating conditions. The somewhat reduced combustion efficiency performance of most existing aircraft turbine engines at idle and other low engine power operating conditions is due to the adverse combustor operating conditions that normally prevail at these engine operating conditions. At the low engine power operating conditions, the combustor inlet air temperature and pressure levels are relatively low, the overall combustor fuel-air ratios are generally low and the quality of the fuel atomization and its distribution within the primary combustion zone is usually poor because of the low fuel and air flows. In any given engine, all of these adverse combustor operating conditions are rapidly eliminated as the engine power setting is increased above idle power levels and, accordingly, its combustion efficiency performance is quickly increased to near-optimum levels.

At any given combustion efficiency value below 100 percent, various combinations of CO and C_xH_y emissions levels can exist, depending on the engine type, engine operating mode and other factors. The composite ranges of the various combinations that have been measured in tests of several General Electric engines are presented in Figure 3. As is shown, these ranges are quite broad, especially at the lower combustion efficiency values. The wide variations observed in these tests in the CO and C_xH_y emissions levels combinations, from one engine to another, appear to be mainly associated with differences in the design features of the combustors used in these various engines. In general, however, at the higher combustion efficiency values, the C_xH_y emissions levels were observed to be quite low in all of the engines that were tested. These results indicate, therefore, that as near-ideal combustion efficiency performance is approached, most of the residual non-equilibrium combustion products - or inefficient combustion products - exist mainly in the form of CO.

Some of the combustion efficiency performance values, along with the associated CO and C_xH_y emissions levels, which were measured in these engine tests at ground idle operating conditions are presented in Figure 4. As is shown, the higher cycle pressure ratio engines have significantly higher combustion efficiency values, and lower CO and C_xH_y emissions levels, than those of the lower cycle pressure ratio engines. These results indicate the important effects of the increased combustor inlet air temperatures and pressures that are characteristic of the higher cycle pressure ratio engines at all operating conditions, including ground idle.

To meet the CO and C_xH_y emissions standards defined by the EPA for commercial aircraft engines, combustion efficiency values at the ground idle operating conditions of 98.8 percent or higher are required. For example, in the case of advanced, high cycle pressure ratio turbofan engines, like the General Electric CF6 engines, CO and C_xH_y emissions levels of about 25 and 5 grams per kilogram of fuel, respectively, are required at ground idle to meet the EPA standards. This combination of emissions levels is equivalent to a combustion efficiency value of 98.9 percent. Thus, significant improvements in the combustion efficiency performance levels, which are typical of present-day engines at the ground idle operating conditions, are required to meet these EPA standards.

Based on combustion chemical kinetics considerations, these required significant improvements in combustion efficiency performance at ground idle appear to be obtainable in engine combustors, providing that improved control of the various processes which occur in the primary combustion zones of these combustors can be attained. In any given combustor, CO is formed within its primary combustion zone as a result of the combustion of near-stoichiometric or over-stoichiometric fuel-air mixtures, since CO is a thermochemical equilibrium product resulting from the combustion of such mixtures. Even in combustors designed to have lean primary zone fuel-air mixtures at all operating conditions, relatively rich mixtures generally exist locally within the primary zone, since the fuel-air mixing process is not instantaneous. Considerable amounts of CO can be generated as a result of the combustion of these localized rich primary zone mixtures. Much of this CO is then consumed as additional mixing occurs within the primary zone and as dilution air is added to the primary zone combustion products.

At the high engine power operating conditions, this CO consumption process occurs very rapidly because the high combustor inlet air temperature and pressure levels associated with these engine operating conditions result in very rapid combustion chemical reaction rates. Thus, very low CO emission levels are generally obtained at these engine operating conditions. Some typical CO consumption rate data calculated for a high cycle pressure ratio engine combustor, at high power operating conditions, are presented in Figure 5. These calculated values were defined with the use of a computerized analytical chemical kinetics model of the combustion processes typical of turbine engine combustors. In these analytical assessments, the initial combustion process was assumed to involve a stoichiometric fuel-air mixture. The resulting combustion gases were then assumed to be rapidly mixed to various lower equivalence ratios (ratio of actual fuel-air ratio to stoichiometric fuel-air ratio). As is shown, rapid consumption of the CO within very short residence times is predicted, especially at diluted mixture equivalence ratios in the range of 0.4 to 0.7. In general, the optimum equivalence ratio is about 0.5. Even for these mixtures that are rapidly diluted to equivalence ratios below 0.4, appreciable CO consumption within relatively short residence times still occurs. Typically, the residence times of combustion gas mixtures in the primary zones of combustors are in the order of 1 to 3 milliseconds, depending on the combustor design and its operating conditions.

Some similarly calculated CO consumption rate data at the idle operating conditions of this same high cycle pressure ratio engine are presented in Figure 6. Also included in this figure are the calculated CO consumption rates at idle for a typical low cycle pressure ratio engine. The much lower consumption rates at these low engine power operating conditions, especially those of the low cycle pressure ratio engine, are due to the much lower combustor inlet air temperature and pressure levels that prevail at these engine operating conditions. As is shown in Figure 6, appreciably longer residence times at the preferred diluted mixture equivalence ratios are needed to obtain low residual CO emission levels. Even more significant is the fact that for those mixtures diluted to equivalence ratios below about 0.4, large residual CO emissions levels are obtained even with very long residence times.

Accordingly, to obtain low CO emissions levels at idle operating conditions in any given combustor, very precise control of the equivalence ratios in the primary combustion zone and in the dilution zone immediately downstream and of the associated residence times in these zones is essential. While this precise control is essential in any combustor, the degree of control required in low cycle pressure ratio engines is even somewhat greater than that required in higher cycle pressure ratio engines, for a given objective final CO emission level. As is illustrated in Figure 6 for engines with lower cycle pressure ratios, any primary zone mixtures which are rapidly diluted to equivalence ratios below 0.4 can result in high final CO emission levels, even when the quantities of these mixtures account for only a small percentage of the total quantity of primary zone combustion products. In any given engine, the combustor inlet air temperature and pressure levels that prevail at idle are generally fixed by its overall cycle pressure ratio and by the requirement that its delivered thrust at idle must be maintained at low values to be compatible with the needs of the aircraft in which the engine is used. Typically, idle thrust levels range from 4 to 5 percent of the rated takeoff thrust levels. In a given engine combustor, therefore, the required CO emission level reductions must preferably be attained with the same inlet air temperature and pressure levels at idle that are associated with normal operation at these low idle thrust levels. Thus, the required CO emission level reductions must preferably be attained by modifications in the design and operating characteristics of the engine combustor.

Unlike CO, the C_xH_y emissions are not thermochemical equilibrium combustion products. Moreover, combustion chemical kinetics data show that vaporized hydrocarbons, and any partially oxidized hydrocarbons, are consumed much more rapidly than CO. Thus, as long as these constituents reside in a flame zone for even a very brief time period, they are largely consumed. One of the products of this consumption process may be CO, depending on the flame zone stoichiometry and other factors. It is because of these considerations that, at very high combustion efficiency values, the C_xH_y emissions levels approach zero and any residual inefficient combustion products consist only of CO.

Thus, in any engine, very low C_xH_y emissions levels are usually obtained at the high power operating conditions. Even at idle operating conditions, relatively low levels should be obtainable, based on these combustion chemical kinetics considerations, providing that the fuel is properly vaporized and mixed to some degree with air within the primary combustion zone. Thus, in any given combustor, the primary causes of this category of idle power emissions appear to be associated with its fuel injection characteristics. In particular, coarse fuel atomization may result in large numbers of large fuel droplets which can escape from the primary zone before they are fully vaporized. In many present day combustors, the fuel atomization quality tends to be relatively coarse at the low engine power operating conditions because of the low fuel flows associated with these engine operating conditions. Also, the fuel spray pattern of a given combustor may be such that some of the fuel is directed into the relatively cold air streams used to cool the combustor liners and other parts. At idle, any fuel that is so entrained by these cooling air streams tends to be carried out of the primary combustion zone as unreacted fuel. Accordingly, to obtain reduced C_xH_y emissions levels as well as low CO emission levels, very effective fuel atomization at idle is an important need. This effective atomization is needed both to facilitate rapid and satisfactorily controlled fuel-air mixing in the primary combustion zone and to prevent fuel droplets from escaping from the primary zone.

At General Electric, investigations to identify and develop means of reducing CO and C_xH_y emissions levels at idle by providing improved fuel atomization and improved control of the primary combustion zone fuel-air ratios at idle have been underway for the past several years. (7) (8) For the most part, these investigations have been primarily conducted with advanced turbofan engine combustors, with already developed low smoke emission characteristics. A major objective of these annular combustor development investigations has, therefore, been to retain these already developed low smoke emission characteristics. To date, some promising methods of obtaining significant reductions in the CO and C_xH_y emissions levels of these combustors have been identified.

Some results obtained in these investigations which illustrate the CO and C_xH_y emissions level reductions obtainable with improved fuel atomization at idle are shown in Figure 7. As is shown, modest reductions were obtained by the use of fuel nozzles which were modified so that all of the fuel was delivered at idle through the primary orifices of these dual orifice nozzles. Another attractive means of improving fuel atomization at idle in combustors with dual orifice fuel nozzles is to use an air-assist approach. In this approach, the fuel is delivered at idle through the primary orifices and a very small amount of supercharged compressor air flow is introduced through the secondary fuel orifices of the nozzles. In investigations conducted by the NASA, this small quantity of air flow has been found to result in significantly improved fuel atomization quality and, thus, in significantly reduced CO and C_xH_y emissions levels at idle.(9) This approach was found in these investigations to result in CO and C_xH_y emissions level reductions of about 70 and 90 percent, respectively, with only about 0.25 percent of the total combustor air flow introduced through the secondary orifices of the fuel nozzles.

Also shown in Figure 7 are the results obtained in the General Electric investigations with airblast fuel injection techniques. Significant reductions in both CO and C_xH_y emissions levels were obtained with this type of fuel atomization, as compared to the levels obtained with the more conventionly used pressurized spray nozzle atomization techniques. With the airblast methods, the fuel is injected at low pressures and is atomized in swirl cup devices by a portion of the combustor air flow. Since the fuel atomization process is primarily dependent on the air kinetic energy, rather than on fuel pressure, very effective fuel atomization and fuel-air mixing are attained with these airblast fuel atomization methods over wide ranges of engine operating conditions, including idle.

The typical dependence of the CO and C_xH_y emissions levels of a combustor at idle on its overall combustor fuel-air ratio is illustrated in Figure 8. As is shown, increases in the overall fuel-air ratio above the nominal engine design value at idle result in significant decreases in the CO and C_xH_y emissions levels, particularly in the case of the C_xH_y emissions. In most engines, the overall combustor fuel-air ratios at idle are low, generally less than 0.012. In many combustors, especially the more advanced designs in which relatively high primary combustion zone air flows are used to obtain low smoke emission levels, the resulting average primary zone fuel-air ratios at idle are, therefore, quite lean, generally less than 0.04. These average fuel-air ratios are equivalent to fuel-air equivalence ratios of 0.6 or less. Any CO contained in leaner-than-average portions of such primary zone mixtures will be consumed relatively slowly and, if further diluted, the CO consumption process will be largely quenched and terminated. Thus, at idle, somewhat higher average primary zone fuel-air equivalence ratios are generally needed in these advanced low smoke emission combustors to obtain reduced C_xH_y and CO emissions levels. These higher fuel-air ratios are especially important if significant CO emissions levels reductions are to be obtained. These higher primary zone equivalence ratios must, of course, be attained at idle without changing the primary zone equivalence ratios that already prevail at high engine power operating conditions. Thus, simply reducing the percentage of the total combustor air flow that is introduced into the primary zone is not an acceptable approach. An air flow split change of this latter kind would be expected to result in significant and unacceptable smoke emission level increases at the high engine power operating conditions.

One relatively simple means of obtaining these beneficial higher primary zone fuel-air ratios at idle, without adversely affecting combustion performance characteristics at high power operating conditions, is to extract and dump overboard increased amounts of the compressor discharge air flow when operating at idle. This approach results in increased fuel-air ratios throughout the combustor. Some results obtained in tests of an advanced General Electric annular combustor, in which various amounts of compressor discharge air flow were extracted, are presented in Figure 9. These results illustrate the effects of increasing the primary combustion zone fuel-air ratio - at a constant fuel flow rate. The use of increased bleed air extraction also results in small, but beneficial, increases in primary zone gas residence time, which are the result of the lower air mass flows through the combustor. As is shown, significant CO and C_xH_y emissions levels reductions were obtained in these investigations. Since many advanced engines have provisions for extracting large amounts of compressor discharge air flow, this concept appears to be an attractive one.

Still another means of obtaining the required higher primary zone fuel-air ratios is to use fuel injection staging techniques at idle operating conditions. In this type of approach, fuel is valved to only selected fuel nozzles, or fuel injectors, instead of to the full complement of nozzles. This approach not only results in higher primary zone fuel-air ratios in the portions of the combustor annulus where the fuel is concentrated, but also results in improved fuel atomization since the same fuel flow is being delivered through fewer fuel nozzles and the fuel nozzle pressure drops are thereby increased. Various forms of such fuel injection staging can be considered, depending on the nature of the combustor design. Some fuel injection staging techniques that can be conveniently used in conventional annular combustors are illustrated in Figure 10. Some results obtained in investigations conducted at General Electric of fuel staging approaches of this kind in an advanced annular combustor are presented in Figure 11.

As is shown by these results, the use of alternately fueled nozzles did not result in any reductions in the CO and C_xH_y emissions levels of this combustor. This finding appears to be due to the fact that, although repetitive locally enrichened primary zone fuel-air mixtures annulus were formed, excessive quenching of the combustion products apparently occurred in the several regions between these localized mixtures and the alternate non-fueled air streams. However, the use of circumferential sector staging, in which the fuel was supplied to groups of adjacent nozzles, was found to be highly effective. With this latter type of staging, the desired enrichened fuel-air mixtures in the fueled zones were obtained and, at the same time, the number of boundaries between fueled and non-fueled regions was minimized. With the fuel staged to a single 180° sector, the lowest CO and C_xH_y emissions levels were obtained, since only two such boundaries existed with this fuel staging pattern. Circumferential fuel staging of this kind, thus, appears to be an attractive approach for use at idle to obtain much reduced CO and C_xH_y emissions levels. Further studies are, therefore, underway to assess the practicality and suitability of applying this approach in advanced engines.

Accordingly, based on the results obtained to date in these General Electric and other investigations, it appears that significant reductions in the CO and C_xH_y emissions levels of advanced combustors can be obtained by approaches involving improved fuel atomization and primary zone stoichiometry control at idle. In general, these approaches can be used without adversely affecting either the combustion performance or the smoke and NO_x emission characteristics of these combustors at the high engine power operating conditions. In some instances, the use of these approaches can be accompanied by small increases in NO_x emissions levels at the low engine power operating conditions, but the NO_x emissions levels at these engine operating conditions are still quite low. Although progress has been made, significant further development efforts of this kind are still needed to provide versions of these approaches which are fully suitable for use in advanced commercial aircraft engines. Also, methods of obtaining still further reductions in the CO emission levels of these engines are required to meet the EPA standards for this emission. In addition, methods of applying these approaches in future combustors which are also designed to have significantly lower NO_x emission levels remain to be developed. Nevertheless, it is expected that satisfactory approaches of this kind will be successfully evolved with further development effort and that future engines will, therefore, have significantly lower CO and C_xH_y emissions levels than those of current operational engines.

Reduction of Oxides of Nitrogen Emissions

When gases containing oxygen and nitrogen are heated to elevated temperatures, generally above 1900°K, some oxidation of the nitrogen occurs and NO_x emissions are produced. Thus, NO_x emissions are generated, to some degree, in most combustion processes. In the main combustor of a turbine engine, these emissions are primarily formed within the primary combustion zone, and within the dilution zones immediately downstream of the primary zone. These emissions consist mainly of nitric oxide, together with small amounts of nitrogen dioxide. The small amounts of nitrogen dioxide emissions result from the subsequent further oxidation of the nitric oxide that is formed in the primary combustion zone. Once discharged into the atmosphere, however, the nitric oxide is gradually converted to nitrogen dioxide. The thermochemical equilibrium quantities of nitric oxide that can be generated with a given mixture of fuel and air are strongly dependent on the flame temperature levels of the resulting combustion gases and on the availability of oxygen. Thus, these equilibrium quantities increase rapidly as the initial combustion air temperature is increased and as the primary combustion zone fuel-air equivalence ratios approach values in the order of 0.8.

The quantities of nitric oxide that are formed in any given turbine engine combustor are usually far less than the thermochemical equilibrium quantities, since the chemical kinetics of the nitric oxide formation process are relatively slow. The chemical kinetics of the nitric oxide formation process are reasonably well understood.(10) The rates at which nitric oxide is formed are highly dependent on flame temperature level and increase very rapidly as the flame temperature is increased. Thus, with a given initial combustion air temperature, these rates are highest with fuel-air mixtures that have near-stoichiometric proportions. With a given fuel-air mixture, these rates increase very rapidly as the initial combustion air temperature is increased, because of the associated flame temperature increases. Further, these rates also increase as the pressure level of the combustion gases is increased, because of the direct effects of pressure on the chemical kinetics of the formation process. However, because these nitric oxide formation rates are generally far slower than the fuel combustion reactions, the quantities of NO_x emissions generated in turbine engines are limited by the short residence times of the hot combustion gases within the engine combustors. As a result, very high fuel combustion efficiencies can be attained without the generation of thermochemical equilibrium concentrations of nitric oxide. Some typical nitric oxide formation rate data are presented in Figure 12.(10)

Because of the strong dependence of these rates on the initial combustion air temperature and pressure levels, the quantities of nitric oxide generated in a given engine combustor are highest at the high engine power operating conditions. Also, because of this strong dependence, the NO_x emissions characteristics of engines are a direct function of engine cycle pressure ratio. The measured NO_x emissions characteristics of several General Electric engines are shown in Figure 13, as a function of engine cycle pressure ratio rating. As is shown, the NO_x emissions levels at full power (takeoff) of the high cycle pressure ratio engines are significantly greater than those of the low cycle pressure ratio engines.

These same NO_x emissions level data are presented in Figure 14, as a function of the combustor operating conditions of these various General Electric engines at the takeoff power setting. As is shown, the NO_x emissions characteristics of these engines can be conveniently expressed in terms of an empirical severity parameter which incorporates the effects of combustor inlet air temperature, combustor inlet air pressure and combustion gas residence time. In this severity parameter, the temperature effect is by far the most significant one. The combustor fuel-air ratios, with which these engines are operated at takeoff, were not found to be a significant influence. The combustor fuel-air ratios of these engines at takeoff range from about 0.018 to 0.025. This relative insensitivity to overall combustor fuel-air ratio is due to the fact that the amounts of NO_x emissions generated in a given present-day combustor are mainly set by the nitric oxide formation rates of the near-stoichiometric fuel-air mixtures that exist within the combustor. In virtually all present-day combustors, such mixtures do exist within their primary zones or in the immediately downstream dilution zones.

To meet the NO_x emissions standards defined by the EPA for commercial aircraft engines, significant NO_x emissions level reductions are required in the case of the high cycle pressure ratio engines. For example, in the case of the General Electric CF6 engines, NO_x emissions levels in the range of 13 to 15 grams per kilogram of fuel are required at takeoff to meet these standards. Thus, the NO_x emissions levels of these engines at the high power operating conditions must be reduced by about 60 percent.

Based on the above-described chemical kinetics considerations associated with the formation of nitric oxide in combustors, the attainment of these required NO_x emissions level reductions must involve precise control of the flame temperatures and combustion gas residence times within the primary zones of these combustors. Specifically, these flame temperatures and residence times must be minimized. At General Electric, investigations to identify and develop means of attaining this improved primary zone temperature and residence time control have been underway for the past several years.(7) (8) These investigations have been conducted in conjunction with the above described CO and C_xH_y emissions level reduction investigations. As in these latter investigations, the NO_x emissions level reduction development efforts have been primarily conducted with advanced turbofan engine combustors, with already developed low smoke emission characteristics. A major objective of these development investigations has, therefore, also been to retain those already developed low smoke emission characteristics. To date, some promising methods of obtaining significantly lower NO_x emissions levels by the use of advanced combustor design approaches have been identified. In general, however, these investigations have clearly shown that approaches that result in lower NO_x emissions levels tend to result in higher CO and C_xH_y emissions levels, unless added design sophistication is introduced into the combustor.

One general approach for reducing flame temperatures within a combustor involves the addition of inert liquids or gases into its primary combustion zone. The introduction of water into the primary zone is an approach of this kind. Some results of experimental studies conducted at General Electric to evaluate the use of water injection as a means of reducing NO_x emissions levels are presented in Figure 15. As is shown, water injection in amounts of 1 to 2 percent (by weight) of the total combustor air flow was found to provide considerable reductions. These investigations showed that, to achieve these reductions, the water must be injected directly into the primary combustion zone and must be uniformly distributed with the primary zone fuel-air mixtures. If effective atomization of the water and rapid mixing with the fuel-air mixtures are not obtained, greater quantities of water are needed for the same degree of NO_x emissions level suppression.

Based on results of this kind, water injection is a possible means of obtaining significant reductions in NO_x emissions levels during takeoff and climbout operations. The use of water injection at cruise operating conditions is, of course, unacceptable. However, the use of water injection in aircraft engines, even when limited to takeoff and climbout operations, does involve some weight penalties and does require the addition of water tankage, pumping, valving and plumbing provisions to the engine. As such, the use of water injection has some significant drawbacks. Accordingly, means of reducing the levels of these emissions by combustor design modifications, rather than by the use of water injection, represent an important development need. Further if NO_x emissions level reductions at cruise operating conditions are identified as an important need, reductions by means of combustor design modifications will be essential.

Another general approach for reducing flame temperatures and, thereby, of minimizing the quantities of NO_x emissions formed in a given combustor is to minimize the quantities of combustion gas mixtures with near-stoichiometric fuel-air proportions. This type of approach offers a potential means of reducing NO_x emissions levels by combustor design features rather than by the use of water injection. Analytical and experimental studies to define and develop methods of this kind, which involve the difficult problems of precisely controlling the average and local fuel-air ratios within the primary combustion and dilution zones, have also been conducted at General Electric. Some potentially promising results have been obtained in these investigations. The use of advanced fuel injection methods involving airblast fuel atomization has been found, for example, to result in somewhat lower emissions levels as compared to those of combustor designs with more conventional pressurized fuel injection provisions - at the same combustor operating conditions. As is indicated in Figure 16, NO_x emissions levels reductions in the order of 10 to 15 percent have been obtained in tests with these advanced airblast fuel injection techniques. These lower emissions levels appear to be the result of the very effective fuel-air mixing obtained with fuel injection techniques of this kind. Tests have shown that this highly effective mixing process results in more uniform mixtures in the primary combustion and dilution zones than those obtainable with the more conventionally used fuel injection methods, thereby permitting the use of shorter gas residence times in these zones. As a result, more rapid elimination of any localized fuel-air mixtures with near-stoichiometric proportions and, thus, reduced NO_x emissions levels may be attained.

With any type of fuel injection method, a general approach for reducing NO_x emissions is to reduce the dwell time of the high temperature primary zone gas mixtures. An approach for reducing the residence times of these high temperature gases is to cool them as rapidly as possible using the available combustor dilution airflow as the coolant. Investigations of this latter approach have also been conducted as a part of the General Electric development efforts to develop combustors with low NO_x emissions levels. With approaches of this kind, NO_x emission level reductions in the order of 30 percent have been obtained as is indicated by the results presented in Figure 16. In general, the use of approaches of this kind has been found to be acceptable in combustors and to produce no adverse effects on the CO, C_xH_y and smoke emissions characteristics of these combustors.

Other General Electric investigations have shown that reductions in NO_x emissions levels may be obtained by operating with either much richer or much leaner average primary combustion zone fuel-air ratios than those normally used in current combustor designs. Some experimental results of this kind are shown in Figure 17. As is shown, the use of lean primary zone mixtures, in particular, resulted in significantly decreased NO_x emissions levels. These lean mixtures were obtained by increasing the percentage of the total combustor air flow that was introduced into the primary zone. In present day combustors, the direct use of such lean primary zone mixtures at the high engine power operating conditions would, of course, be expected to result in unsatisfactory ignition characteristics and much increased CO and C_xH_y emissions levels at idle because of the very lean primary zone mixtures that would prevail at these low engine power operating conditions.

Smaller NO_x emissions level reductions were obtained in these tests with higher primary zone fuel-air ratios. These findings suggest that the nitric oxide formation process was apparently shifted from the primary zone to the dilution zones immediately downstream, with little net change in the NO_x emissions levels. In any event, the use of higher primary zone fuel-air ratios would be expected to result in unacceptable smoke emission level increases at the high engine power operating conditions.

Based on these findings, it appears that the most promising approach for obtaining low NO_x emissions levels in advanced turbine engine combustors at the high engine power operating conditions is to provide lean and uniform fuel-air mixtures, preferably homogeneous mixtures, in the primary zones of these combustors. However, means of applying this general design approach are required that do not result in unacceptable losses in ignition performance and in unacceptable increases in CO and C_xH_y emissions levels at idle. Thus, means of obtaining the required lean and uniform primary zone mixtures at high engine power operating conditions and, also, of obtaining the relatively richer required primary zone mixtures at idle are needed. The attainment of these somewhat conflicting operating capabilities, in turn, necessitates consideration of combustors within which the combustion process can be staged in appropriate ways or of combustors in which variable geometry features are incorporated to modulate the quantities of the total combustor air flow that are introduced into their primary combustion zones. Accordingly, the preferred combustor design approach for satisfactorily attaining the applicable EPA standards for NO_x emissions appears to involve significant changes and advances in the combustors used in present-day engines.

Advanced combustors with design features to provide both favorable primary combustion zone fuel-air ratios at idle, as well as lean and uniform primary zone mixtures at high engine power operating conditions, are currently being defined and developed in the NASA Experimental Clean Combustor Program. The primary objective of this important program is to develop technology for the advanced turbofan engine combustors which meet the EPA-defined 1979 standards for CO, C_xH_y, NO_x and smoke emissions - without the use of water injection methods for obtaining the objective low NO_x emissions levels.(4) Illustrations, taken from Reference 4 of the four basic advanced combustor design concepts which are being developed at General Electric as a part of this program are shown in Figure 18. All of these advanced combustor configurations are being sized and designed to fit and operate in an existing General Electric CF6 engine. Several versions of each of these four basic design concepts are being defined, evaluated and developed in this program.

The first of these four basic concepts consists of a lean single annular dome approach, in which much increased percentages of the total combustor air flow are introduced into its dome, or primary combustion zone. Of the four basic design concepts, this lean dome approach involves the least degree of design modification of the production combustor currently being used in this General Electric CF6 engine. However, to obtain satisfactory operation at low engine power operating conditions with this lean dome design, variable geometry features to reduce the amounts of air flow introduced into its primary zone at idle would probably be needed.

The second of these four basic concepts consists of a lean double annular dome design. As in the single annulus configuration, a key design feature is its high dome air flow percentage. In this way both primary combustion zones are operated with lean fuel-air mixtures at the high engine power operating conditions. However, the use of two domes, or primary combustion zones, permits the use of beneficial fuel staging methods at idle. Thus, with this approach, all of the fuel may be concentrated in one of the two primary zones at idle, thereby, providing much more favorable local fuel-air ratios and reduced CO and C_xH_y emissions levels.

The third of these four basic concepts of another design in which beneficial fuel staging provisions are an important feature. In this staged combustion design approach, only the pilot (primary) stage is used at the low engine power operating conditions. By limiting the air flow percentage that is introduced into this stage, its fuel-air ratios at idle are quite favorable. At the higher engine power operating conditions the second stage is also fueled. In this latter stage, which handles a high percentage of the total combustor air flow, the fuel is premixed to some degree with its air flow and, therefore, the resulting fuel-air mixtures that flow into its combustion zone are lean and relatively uniform. The burning of these lean mixtures is stabilized by the pilot stage of the combustor.

The fourth of these four basic concepts consists of a modular dome design, which is based on the NASA Swirl-Can-Modular combustor concept. The dome is comprised of a multitude of individual combustor elements, each with its own fuel injector, fuel-air mixing device and flame stabilizer. As in the other three concepts, high dome air flow percentages are being used to obtain low NO_x emissions levels. Various fuel staging patterns may be used at idle, by fueling only selected modules, to obtain reduced CO and C_xH_y emissions levels.

Extensive developmental evaluations of these various combustor configurations are in progress. Significant reductions in NO_x emissions levels, as well as low CO and C_xH_y emissions levels, are expected with these combustor design approaches. Also, these approaches are all expected to have very low smoke emission levels. Overall, however, all of these various design approaches involve significant departures from the annular combustor designs being used in present-day engines. In general, these advanced approaches are considerably more sophisticated and complex in nature. Thus, it is expected that very substantial further development efforts will be needed to provide satisfactory versions of these advanced combustors which meet all engine performance requirements and which also have favorably low CO, C_xH_y and NO_x emissions levels.

Based on the results of the investigations conducted to date, it is apparent that the satisfactory attainment of significantly lower NO_x emissions levels by combustor design methods is the most formidable emission control problem associated with aircraft turbine engines, especially the advanced high performance engines. Based on these preliminary results, however, it is anticipated that suitable reduction techniques involving combustor modifications, rather than the use of water injection, will be successfully evolved. Thus, it is anticipated that the NO_x emissions levels of the advanced engines, especially the high pressure ratio and high performance engines, to be developed and placed into service in future years will be reduced to values significantly lower than those being measured in current engine models with equivalent engine cycle pressure ratio ratings. However, it appears, at present, that much additional combustion research and development effort will be required to bring this NO_x emissions abatement technology to the point where it can be satisfactorily applied and significant emissions level reductions can be realized in future engines.

Conclusions

1. Significant progress has been made in the

development of technology for the design of combustors with much reduced smoke emission levels. As a result of these efforts, combustors with virtually invisible smoke emission levels at all engine operating conditions and which meet the applicable EPA standards have been developed and placed into service. The peak SAE ARP 1179 Smoke Numbers of these advanced combustors are typically in the order of 20 or less. Smoke Numbers of this order correspond to very low concentrations of smoke particulates in engine exhausts, only about 2 parts per million parts (by weight) of the core engine exhaust gas.

2. Based on the results of investigations conducted to date, much reduced CO and C_xH_y emissions levels appear to be attainable through the use of combustor design modifications which provide improved fuel atomization at idle and higher primary combustion zone fuel-air ratios at idle. With the use of these approaches in advanced turbine engines, it appears that CO and C_xH_y emissions levels that approach the values needed to meet the applicable EPA standards, may be realizable.

3. Some potentially promising approaches for providing suppression of the NO_x emissions levels of combustors have also been identified in these development efforts. In particular, the use of advanced fuel injection and atomization methods has been found to be effective. Further, the use of precisely regulated lean primary combustion zone fuel-air ratios at the high engine power operating conditions, appears to offer considerable promise. However, extensive further development effort to permit the satisfactory use of this latter general design approach in advanced turbine engine combustors appears to be needed. Also, the use of this lean primary zone approach is expected to result in the need for significantly more advanced, sophisticated and complex combustor designs. At the present time, therefore, satisfactory attainment of the applicable EPA standards for this category of emissions in advanced turbine engines has yet to be demonstrated.

References

1. Aircraft Emissions: Impact on Air Quality and and Feasibility of Control, U. S. Environmental Protection Agency, July, 1973.

2. Control of Air Pollution from Aircraft Engines, U. S. Environmental Protection Agency, Federal Register Volume 38, Number 136, July, 1973.

3. Grobecker, A. J. Presentation to the Second Conference on the Climatic Impact Assessment Program, U. S. Department of Transportation, November, 1972.

4. Niedzwiecki, R. W. and Jones, R. E. The Experimental Clean Combustor Program - Description and Status, NASA TM X-71547, May, 1974.

5. Bahr, D. W., Smith, J. R., and Kenworthy, M. J. Development of Low Emission Combustors for Large Aircraft Turbine Engines, AIAA Paper 69-493, June, 1969.

6. Aircraft Gas Turbine Engine Exhaust Smoke Measurement, SAE Aerospace Recommended Practice 1179, May, 1970.

7. Bahr, D. W. Control and Reduction of Aircraft Turbine Engine Exhaust Emissions, Proceedings of the Symposium on Emissions from Continuous Combustion Systems, 1972.

8. Bahr, D. W. Technology for the Reduction of Aircraft Turbine Engine Exhaust Emissions, Proceedings of the AGARD Propulsion and Energetics Panel Meeting, April, 1973.

9. Jones, R. E. Advanced Technology for Reducing Aircraft Engine Pollution, NASA TM X-68526, November, 1973.

10. Fenimoré, C. P. Formation of Nitric Oxide in Premixed Hydrocarbon Flames, Thirteenth Symposium (International) Combustion, The Combustion Institute, Page 357, 1970.

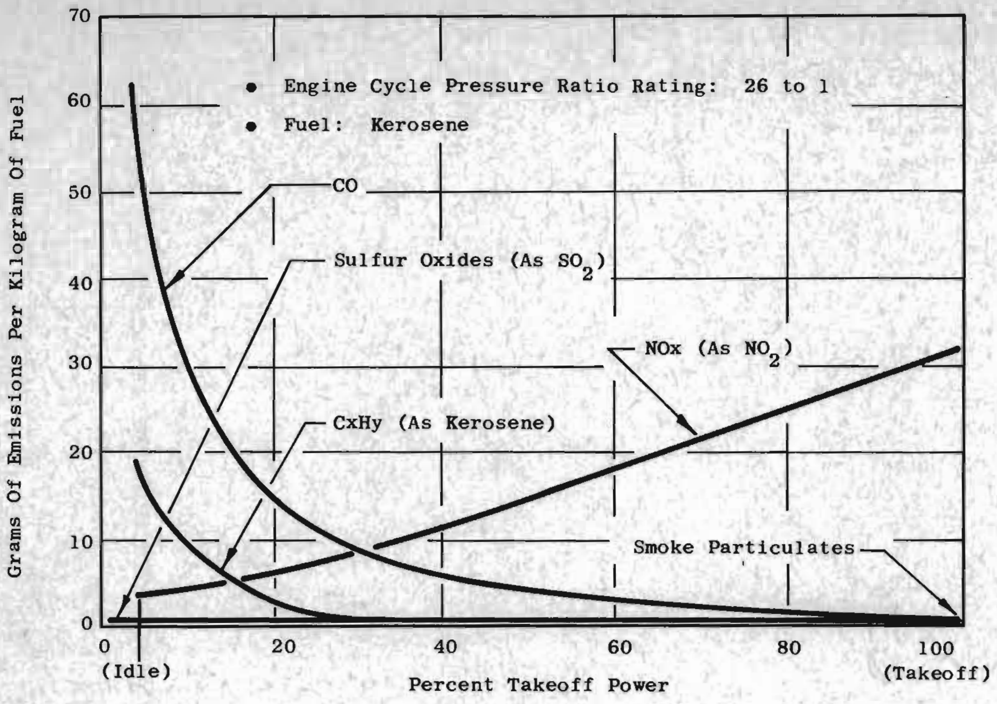


Figure 1. Exhaust Emissions Characteristics Of An Advanced Turbofan Engine, At Standard Day-Sea Level Static Operating Conditions.

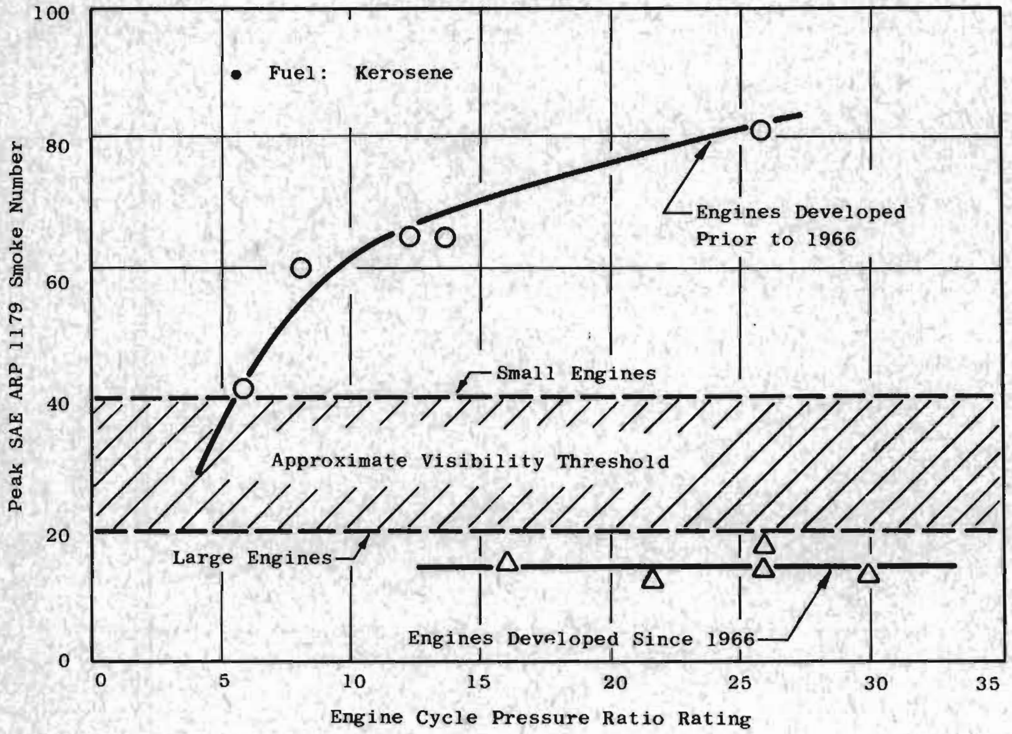


Figure 2. Comparison Of Peak Engine Smoke Emission Characteristics Of Various General Electric Aircraft Turbine Engines, At Standard Day-Sea Level Static Operating Conditions

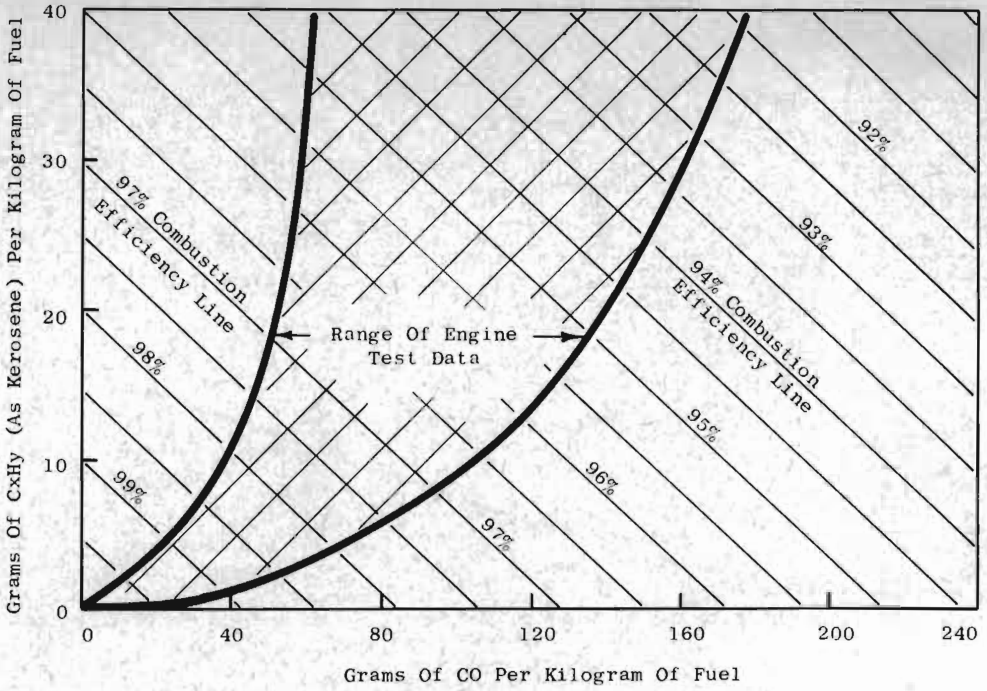


Figure 3. Relationships Between Combustion Efficiency And Levels Of CO And CxHy Emissions.

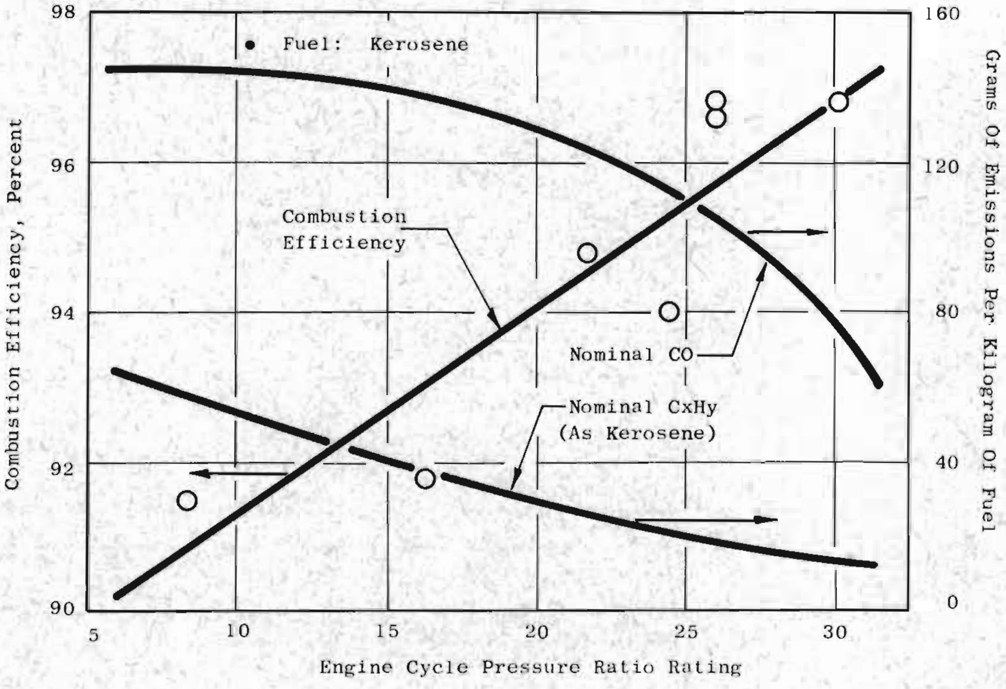


Figure 4. Combustion Efficiency, CO Emissions And CxHy Emissions Characteristics Of Various General Electric Aircraft Turbine Engines At Ground Idle Power Operating Conditions (Standard Day-Sea Level Static).

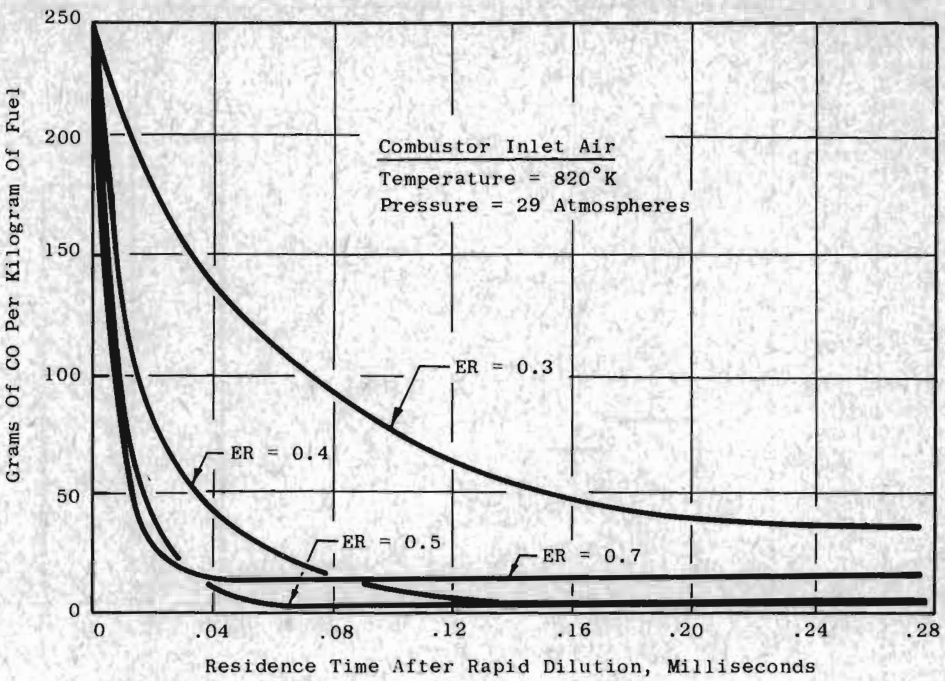


Figure 5. CO Consumption Rates At Typical High Power Operating Conditions, For A High Cycle Pressure Ratio Engine - For Ideal Combustion Gas Mixtures Instantaneously Mixed To Indicated Equivalence Ratio (ER).

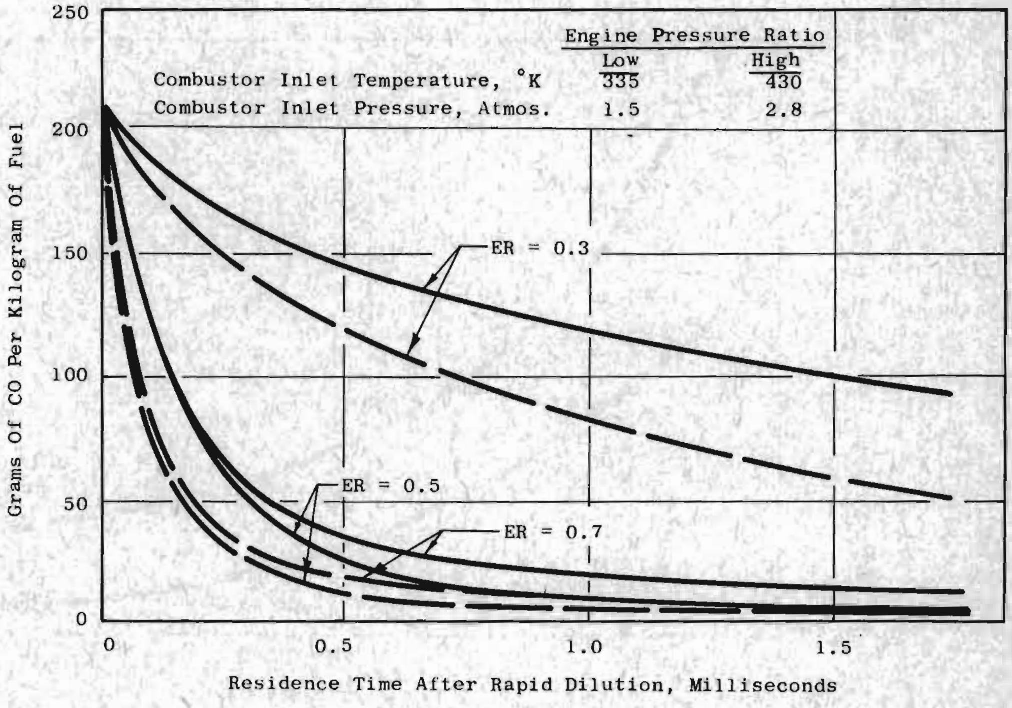


Figure 6. CO Consumption Rates At Typical Ground Idle Power Operating Conditions, For Both A High And A Low Cycle Pressure Ratio Engine - For Ideal Stoichiometric Combustion Gas Mixtures Instantaneously Mixed To Indicated Equivalence Ratio (ER).

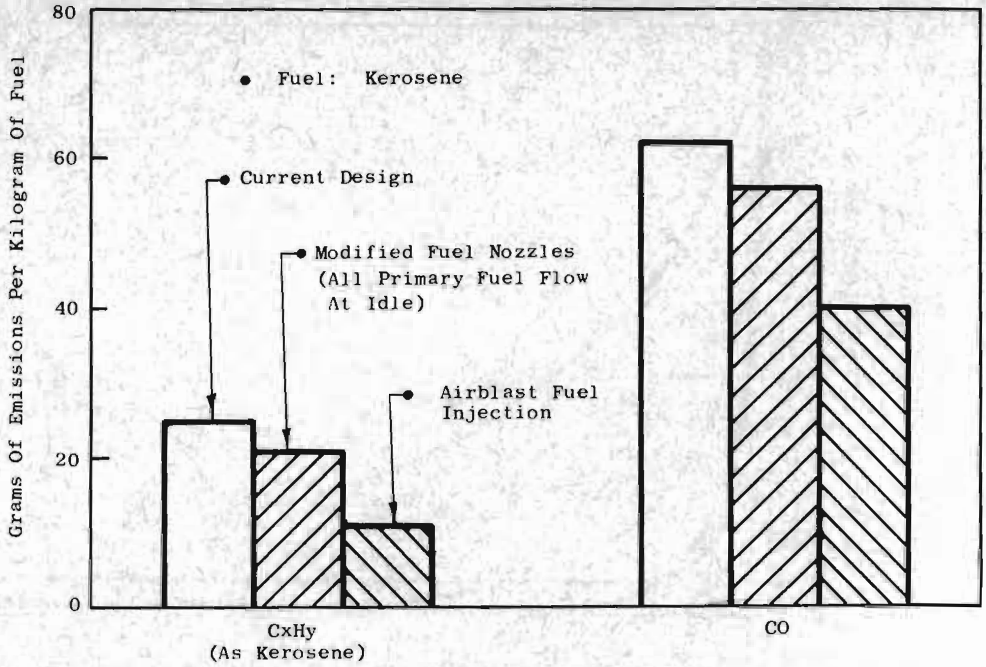


Figure 7. CO And CxHy Emissions Level Reductions In An Advanced Turbofan Engine, At Ground Idle Power Operating Conditions (Standard Day-Sea Level Static), With Improved Fuel Atomization.

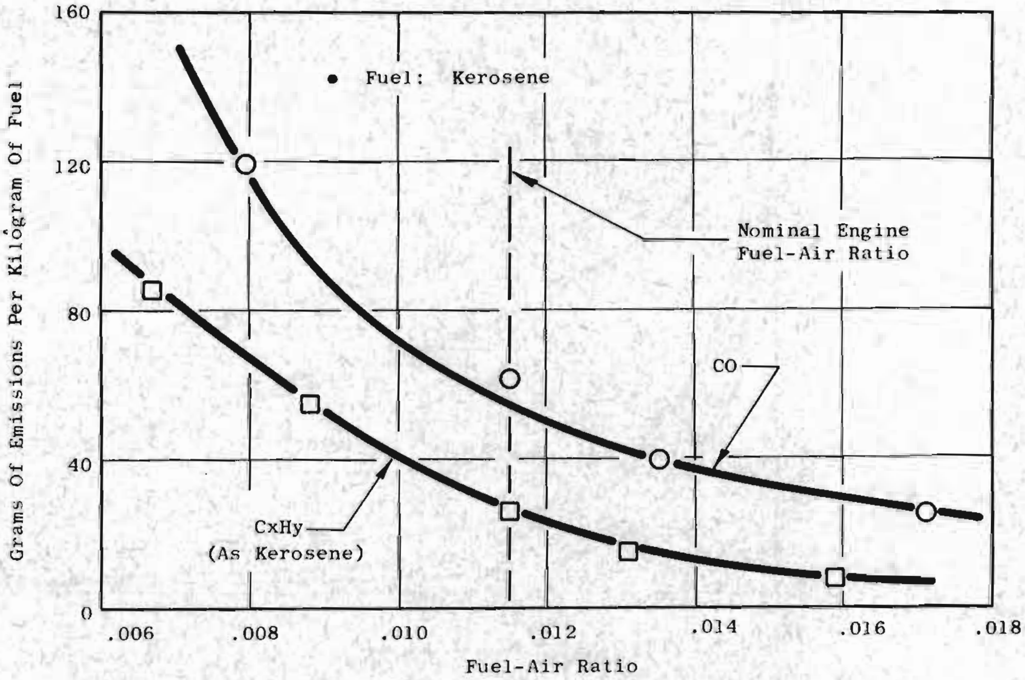


Figure 8. CO And CxHy Emissions Characteristics Of An Advanced Turbofan Engine. At Ground Idle Power Operating Conditions (Standard Day-Sea Level Static).

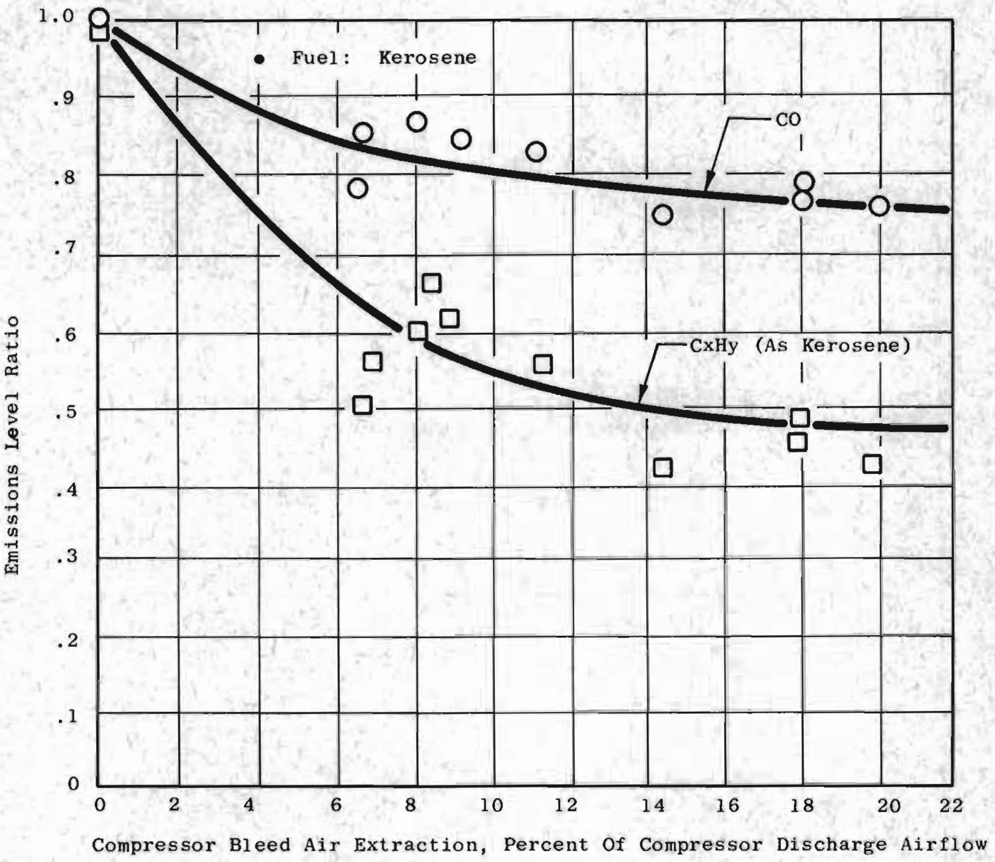


Figure 9. CO And CxHy Emissions Level Reductions In An Advanced Turbofan Engine, At Ground Idle Power Operating Conditions (Standard Day-Sea Level Static), With Increased Compressor Bleed Air Extraction.

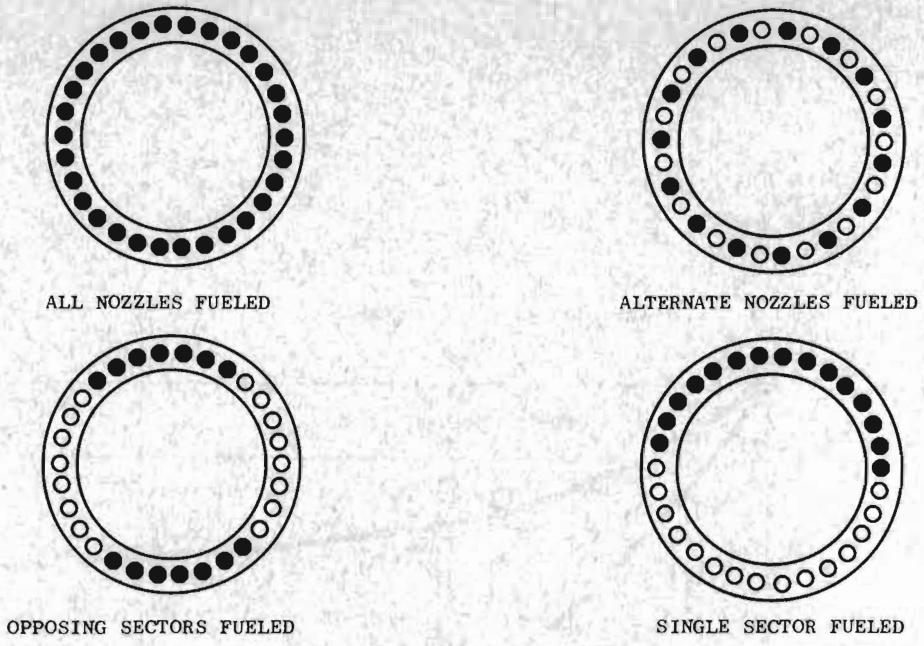


Figure 10. Some Alternate Fuel-Staging Modes Of Operating Annular Combustors At Ground Idle Power.

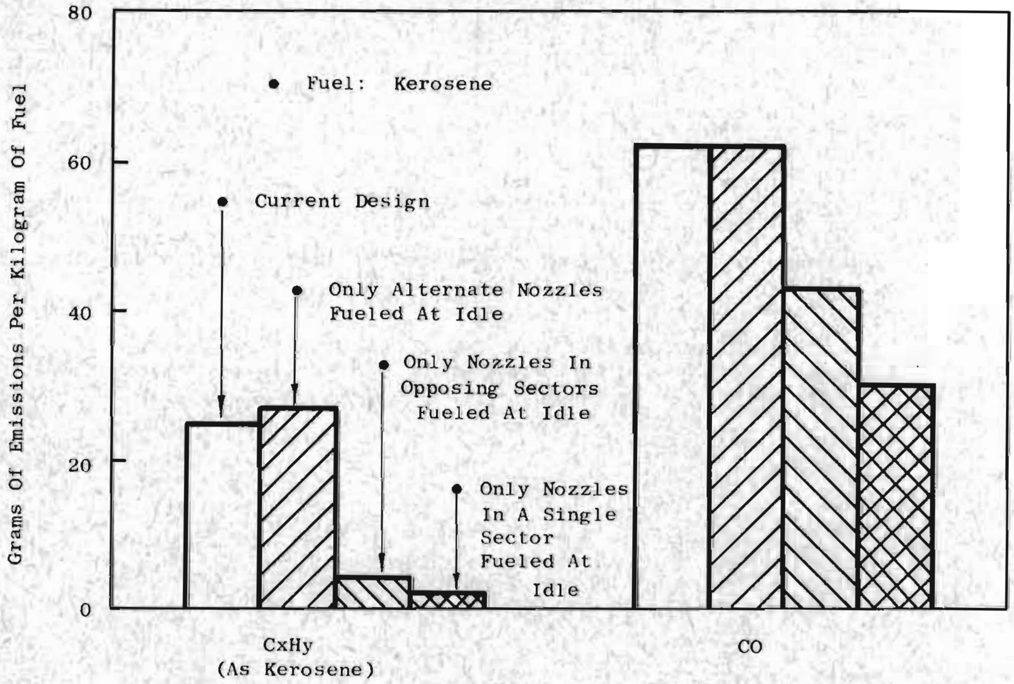


Figure 11. CO And CxHy Emissions Level Reductions In An Advanced Turbofan Engine, At Ground Idle Power Operating Conditions (Standard Day-Sea Level Static), With Staged Fuel Injection.

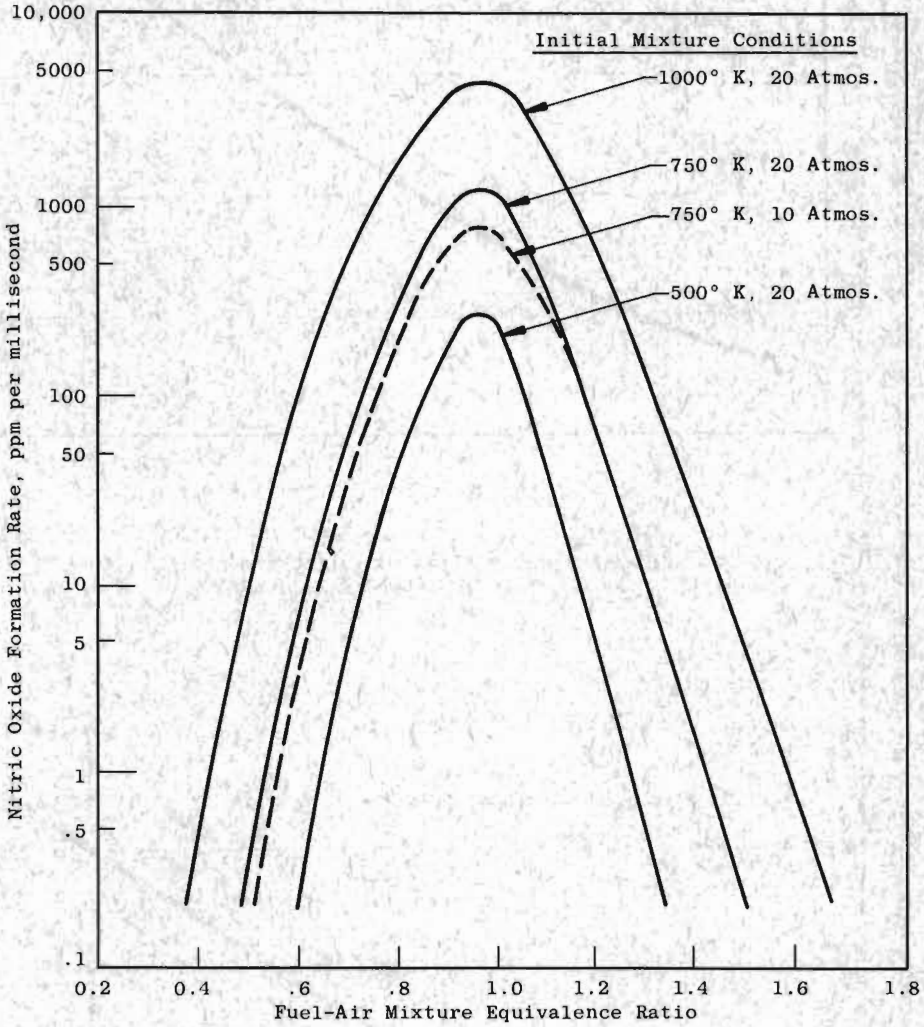


Figure 12. Nitric Oxide Formation Rate Data.

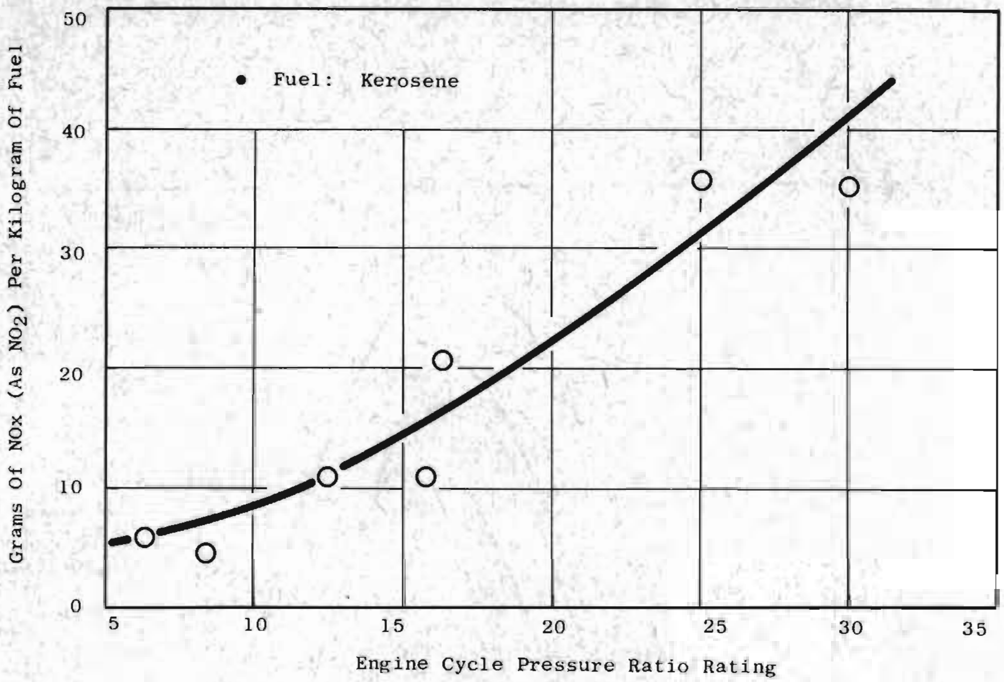


Figure 13. NOx Emissions Characteristics Of Various General Electric Aircraft Turbine Engines At Takeoff Power (Standard Day-Sea Level Static).

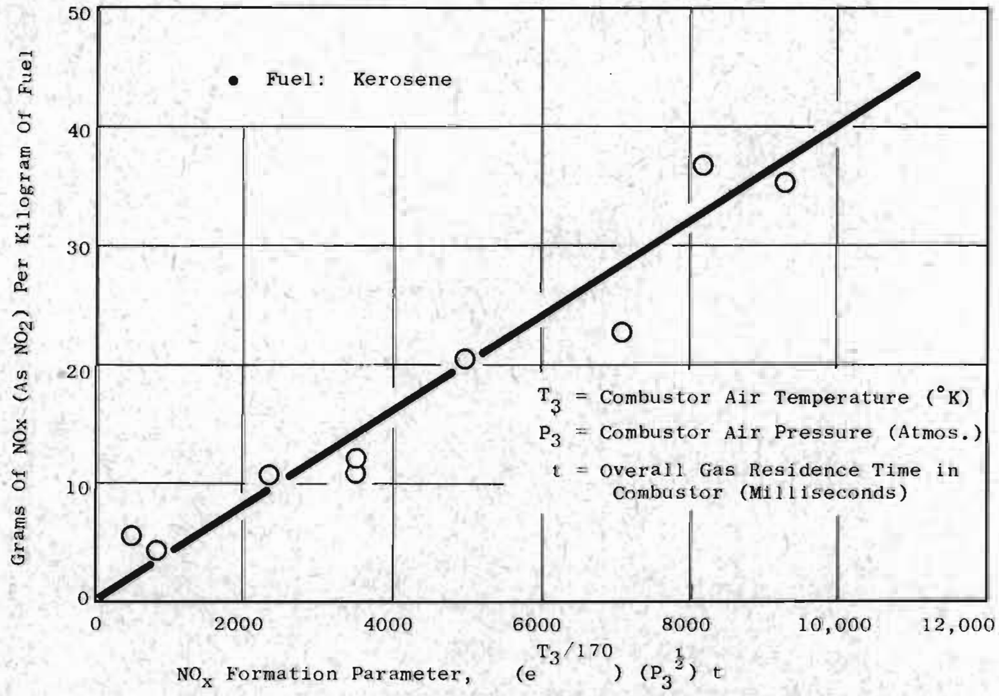


Figure 14. Effects Of Combustor Operating Conditions And Design Features On The NOx Emissions Characteristics Of Various General Electric Aircraft Turbine Engines, At Takeoff Power (Standard Day-Sea Level Static).

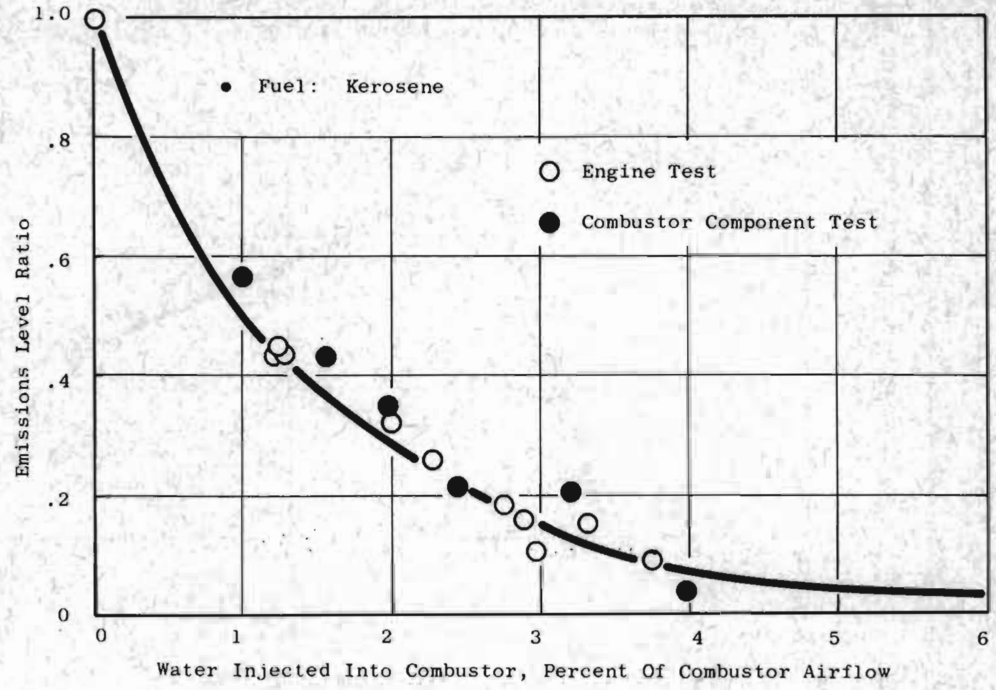


Figure 15. NOx Emissions Level Reductions In An Advanced Turbofan Engine, At Takeoff Power (Standard Day-Sea Level Static), With Water Injection Into The Combustor.

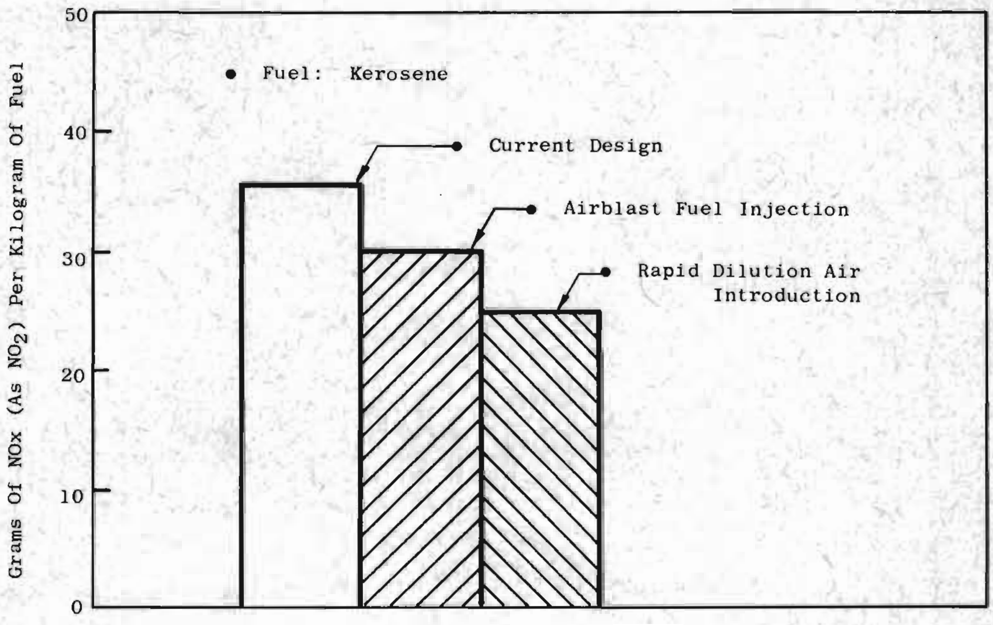


Figure 16. NOx Emissions Level Reductions In An Advanced Turbofan Engine, At Takeoff Power (Standard Day-Sea Level Static), With Combustor Design Modifications.

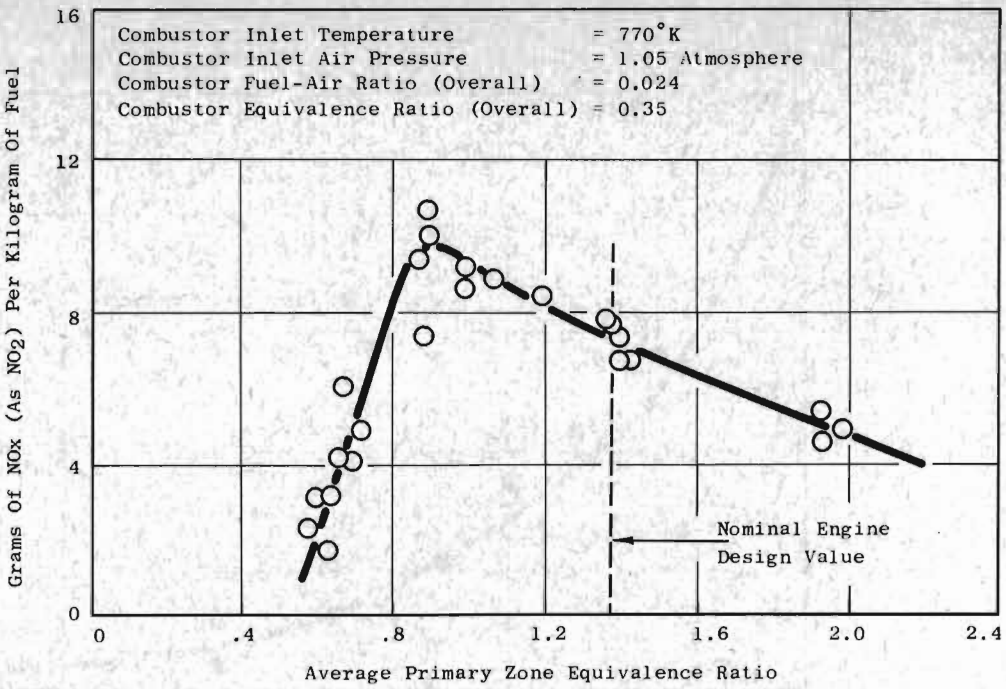
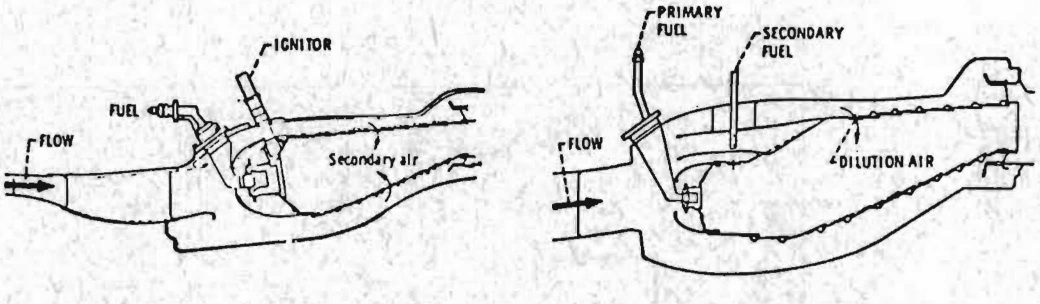
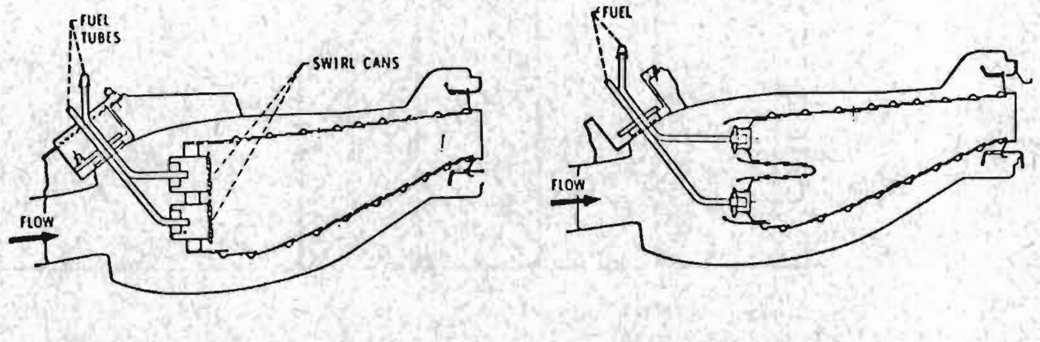


Figure 17. Effect Of Primary Zone Equivalence Ratio On NOx Emissions Characteristics Of An Advanced Turbofan Engine Combustor At Simulated Takeoff Power.



Lean Dome Single Annular Combustor

Radial/Axial Staged Combustor



NASA Swirl-Can-Modular Combustor

Lean Dome Double Annular Combustor

Figure 18. Advanced Low Emissions Combustor Design Concepts Being Developed In The NASA Experimental Clean Combustor Program For The CF6-50 Engine (Reference 4).

DISCUSSION

E. Liban (Engine Branch, Bedek Aviation, Israel Aircraft Industries, Ben-Gurion Airport, Israel): Please comment on the negative impacts of the smoke reduction design features you described on the altitude relight, acceleration and idle performance characteristics of the engine.

D.W. Bahr: No significant changes in the acceleration or idle performance characteristics of the engine were observed as a result of the smoke reduction features incorporated into its combustor. Some losses in altitude relight capability were, however, obtained. By small adjustments of the combustor dome design, the igniter location and the starting fuel flow of the engine, these losses were reduced considerably. As a result, acceptable relight performance over the entire engine flight map was obtained. Thus, although the resulting altitude relight characteristics of the engine when equipped with the low smoke combustor were slightly inferior to those of the engine when equipped with the original combustor, all altitude requirements were fulfilled with the engine when equipped with the newer combustor.

G. Winterfeld (DFVLR, Porz-Wahn, Germany): Rapid dilution air admission as a means for NO_x-reduction may increase the overall pressure loss of the combustor. In what way was the rapid air admission achieved and what change in pressure loss must be encountered?

D. Bahr: In these investigations, the dilution air introduction design changes were made by closing the dilution ports at the aft end of the cooling liners and adding equivalently sized dilution ports at the front end of the liners. By using this approach, the pressure loss across the modified liners was maintained at essentially the same value as that of the original liners.

G. Kappler (Motoren- und Turbinen-Union, Munich, Germany): As you are aware, measuring exhaust emission concentrations is a tedious job because of the small amounts that have to be detected. I would like therefore to know what is the error estimation on the Emission Indexes you have shown on the slides. Is it below 10%? Is the data you have shown valid only for standard day operating conditions?

D. Bahr: Our investigations show that our measurements of CO, C_xH_y and NO_x concentrations in a given sample gas stream are accurate within ± 10%. To obtain an Emission Index, the local concentrations measured across the engine exhaust plane must be combined to obtain an average value. This latter step introduces some additional inaccuracies. Thus, our investigations indicate that our CO, C_xH_y and NO_x Emission Index values are accurate to within about ± 15%.

The emissions level data presented in the paper were all obtained at, or were adjusted to, standard day (15^oC) operating conditions. At other ambient operating conditions, the emissions characteristics of the engines would be different. Hot day operating conditions result in lower CO and C_xH_y levels, and higher NO_x levels. Cold day operating conditions produce the opposite effects.