STATUS OF NASA AIRCRAFT ENGINE EMISSION REDUCTION AND UPPER ATMOSPHERE MEASUREMENT PROGRAMS

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SUMMARY

NASA is conducting programs to evaluate advanced emission reduction techniques for five existing aircraft gas turbine engines. Varying degrees of progress have been made toward meeting the 1979 EPA standards in rig tests of combustors for the five engines. Results of fundamental combustion studies suggest the possibility of a new generation of jet engine combustor technology that would reduce oxides-of-nitrogen (NO_x) emissions far below levels currently demonstrated in the engine-related programs. The Global Air Sampling Program (GASP) is now in full operation and is providing data on constituent measurements of ozone and other minor upper-atmosphere species related to aircraft emissions.

INTRODUCTION

This paper briefly describes some of the current NASA programs concerned with evaluating and reducing the potential impact of aircraft operations on the atmosphere. With the passage of the Clean Air Act in 1970, the Environmental Protection Agency (EPA) was charged with establishing acceptable exhaust emission levels of carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO_x), and smoke for aircraft engines. In response to the charge, EPA promulgated the standards described in reference 1 in 1973. Reductions of up to sixfold from present emission levels will be required by the EPA compliance date of January 1, 1979. NASA has responded to this requirement with major programs to evolve and demonstrate advanced technological capability for low-emission gas turbine engine combustors.

The climatic impact studies completed by the Department of Transportation (DOT Climatic Impact Assessment Program (CIAP)) recommended NO_x reductions from 6- to 60-fold (ref. 2). The National Academy of Sciences (NAS) Climatic Impact Committee (CIC) also completed their study in 1975 (ref. 3), relying heavily on the CIAP results. The CIC study recommended 10- to 20-fold NO_x reductions. The first number in each range reflects what was felt to be achievable within a decade. Defining quantitative values for tolerable cruise NO_x emissions is extremely difficult because baseline atmospheric data related to the potential aircraft impact are lacking. The need for these data was responsible for the initiation of CIAP and later GASP and other related efforts.

This paper summarizes the status of emission reduction technological developments both for the local (airport) problem, which is directly related to the 1979 EPA standards, and for the projected high-altitude problem. Progress in the Global Air Sampling Program's (GASP) measurement of upper atmospheric constituents is also reviewed.

Although values are given in both SI and U.S. customary units, the measurements and calculations were made in U.S. customary units.

AIRCRAFT ENGINE EMISSION REDUCTION

The level of undesirable emissions from aircraft engines varies with engine operating characteristics, as illustrated in figure 1. Concentrations of CO and THC, expressed as grams of pollutant per kilogram of fuel burned, are the highest at the low-power (idle) condition. However, concentrations of NO_x (as well as smoke) are generally the highest at the high-power (takeoff) condition. Reducing these emissions at the discrete operating conditions as well as other intermediate conditions requires an understanding of the causes and effects in the combustion process, shown in figure 2. The low values of inlet temperature, inlet pressure, and fuel/air ratio at low power (idle) produce quenching of reactions, poor combustion stability, and poor fuel atomization and distribution. The resultant combustion inefficiency is manifested as carbon monoxide and unburned hydrocarbon emissions. Conversely, the high values of inlet temperature, inlet pressure, and fuel/air ratio that occur at high power (takeoff) cause excessive residence time, high flame temperature, and poor local fuel distribution. The result can be as high NO_x and smoke emissions.

If we evaluate the corrective approaches needed to reduce emissions, we can see that somewhat of a dilemma exists. For reducing CO and THC, the approaches (dictated by the chemical kinetics) are to burn stoichiometric mixtures to increase combustion temperature and to maximize residence time. For reducing NO_x, the approaches are to burn lean mixtures and to minimize residence time. Improving fuel atomization and distribution (eliminating zones where the fuel/air ratio is not optimum) is helpful in reducing all emissions. Thus, to effectively reduce emissions and optimize the combustion process simultaneously over the entire operating range, some form of staging or modulation of the fuel/air ratio and residence time will be needed. To reduce emissions at only one condition, such as CO and THC at low power, staging or modulation may not be necessary.

In discussing the approaches that are being evaluated to control aircraft emissions, we will consider the two flight regions of principal concern, local and upper atmosphere, and describe the activities and progress associated with emission reduction in that region.

The Local Problem

The local problem, in terms of aircraft emissions, is described in the promulgated EPA standards (ref. 1) and is specifically associated with the pollutants emitted during a prescribed landing-takeoff (LTO) cycle, as shown in figure 3. The LTO cycle is divided into four discrete modes of operation: (1) taxi/idle (in and out), (2) takeoff, (3) climbout, and (4) approach, and is limited to flight operation below 914 meters (3000 ft). The varying time segments associated with the operating modes were established as average values and could vary from airport to airport as well as with traffic conditions. The EPA used this cycle to arrive at an EPA parameter (EPAP) for establishing standards for the various undesirable emissions. The EPAP is computed from either of the following definitions, depending on the type of engines being considered:

EPAP = Pounds of pollutant per 1000 thrust (in lbf)-hours per cycle

EPAP = Pounds of pollutant per 1000 shaft horsepower-hours per cycle

Thus, an integrated value for each pollutant over the prescribed LTO cycle is used in the standards. Based on considerations of the time in mode (fig. 3), the engine emission characteristics (fig. 1), and the fuel consumed in each mode, the most effective means of reducing CO and THC EPAP values would be to reduce the emissions at taxi/idle. Conversely, reducing NO_x at takeoff and climbout is most effective. Controlling all emissions at approach is equally important

To evalute the potential of advanced technology to control emissions over the LTO cycle to the levels required by the standards, NASA has implemented an emission reduction technology program. The objective is to reduce aircraft engine emissions to levels consistent with the requirements of the EPA standards. The approach consists of a series of multiphased contracts covering five contemporary engines that fall within four of the specified EPA engine classes: The Garrett-AiResearch TFE731-2 engine, in class T1 (turbofan under 35 584-N (8000-lbf) thrust); the General Electric CF6-50 engine and the Pratt & Whitney JT9D-7 engine, in class T2 (turbofan over 35 584-N (8000-lbf) thrust); the Pratt & Whitney JT8D engine, in class T4; and the Detroit Diesel Allison 501-D22A engine, in class P2 (turboprop engines). In general, the contracts are structured to have three phases: (1) a first phase during which a number of advanced concepts are evaluated for emission control capability and overall performance, (2) a second phase during which the most promising concepts are refined and evaluated in terms of engine compatibility, and (3) a third phase during which one selected concept is tested in an engine to demonstrate emission and overall performance characteristics. The T4 and P2 efforts were terminated at the completion of the first Phase. The T1 effort is currently in the second phase and the T2 efforts are in the third phase.

A wide variety of low-emission concepts were evaluated during the course of these contracts. Concepts ranging from minor modifications of the existing engine combustors to major changes such as staged combustion were considered. An example of a minor modification is shown in figure 4. The reverse-flow concept shown is applicable to the Detroit Diesel Allison 501-D22A engine. One part of the modification consisted of redirecting the liner cooling air in the primary zone upstream and hence recycling the CO and THC formed by quenching back into the hot combustion zone. In addition, the conventional fuel nozzle was replaced with a more efficient air-blast nozzle. These changes, which reduced the undesirable quenching effects and improved fuel-air distribution and atomization proved to be very effective for controlling CO and THC at low power. No reduction in NO_x was obtained or anticipated. Since CO and THC emissions were the major problem for this engine, this minor modification was all that was needed to meet the standards. Also, since this is a relatively simple modification that should not be difficult to adapt to the engine, the contract effort was not extended into the demonstration phases. Complete results of the contract effort are given in reference 4.

The more complex combustion concepts needed to simultaneously control all emissions are illustrated in figure 5. Figure 5(a) compares a double-annular staged concept (ref. 5) with the conventional combustor of the General Electric CF6-50 engine. This concept employs parallel staging where one stage (the pilot stage) is used at idle and is optimized to control CO and THC emissions and the second stage (the main stage) is used for full power and is optimized to control NO_x emissions. By varying the fuel split to the two stages, various degrees of control are possible. A staged concept that is adaptable to the Pratt & Whitney JT9D-7A (ref. 6) is compared with the conventional combustor in figure 5(b). The function of the two stages is the same as for the CF6-50 engine, but they are arranged in series rather than parallel. Both designs employ improved fuel atomization and fuel-air distribution in both the pilot and main stages and lean combustion and residence-time control in the main stages. Both concepts are currently undergoing engine demonstration tests that are scheduled for completion by the end of 1976 or early 1977.

The rig test results of the advanced concepts shown in figures 4 and 5 as well as the most successful concepts tested in the T1 and T4 efforts (refs. 7 and 8) are compared with the corresponding conventional combustor emissions and the 1979 EPA standards in table I. All values shown are EPA parameter (EPAP) values. All of the advanced concepts were able to meet the EPA standards for THC and smoke. The CF6-50 and 501-D22A concepts were able to meet the CO standards. The other three concepts reduced CO but still did not meet the standards. Further refinement of the TFE731-2 concept can probably produce further reductions in CO. Only two of the five concepts were capable of reducing the NO_x emissions to the standard levels. However, it is significant that substantial NO_x reductions were obtained with all the concepts except the 501-D22A concept, which did not require a reduction to meet the standards.

These results indicate that the CO and NO_x EPA standards will probably not be achieved for any engine evaluated using the technology evolved in the NASA/industry program conducted to date. However, substantial reductions in all emissions are achievable and would certainly lead to beneficial reductions in local aircraft emissions if they are employed in future engines.

Many aspects of local emission reduction capability must still be evaluated. The impact of the real engine environment on emissions must and will be considered in actual full-scale engine tests. Constraints resulting from operational considerations, engine-to-engine variations, safety and maintenance considerations, and overall performance must all be evaluated before absolute achievable levels can be quantified.

The Upper-Atmosphere Problem

In the case of high-altitude emissions, the primary concern is the NO_x emissions of cruising aircraft (both subsonic and supersonic). Most of the studies conducted and sponsored by NASA to date have been aimed at determining the minimum practical level of NO_x emissions that can be obtained for future aircraft engines. In this regard, many fundamental studies have been conducted. A display of typical results is shown in figure 6. This plot illustrates the interdependency between NO_x emission index, equivalence ratio, combustion efficiency, and residence time obtained in a prevaporized-premixed combustion experiment. Extremely low levels of NO_x emissions (~0.5 g/kg) were obtained at acceptable levels of combustion efficiency for simulated cruise operating conditions. However, it must be clearly understood that these results were obtained in a very carefully controlled fundamental experiment and are not necessarily representative of the levels that may be achieved by a prevaporized-premixed combustion system in an actual engine environment. They were, however, obtained at inlet temperatures and pressures that simulated the type of conditions expected in supersonic engines and, therefore, do provide an indication of the minimum NO_x emissions possible at these conditions. The NO_x levels achieved (0.5 g/kg) represent a 40-fold reduction from current aircraft cruise values and fall within the recommended levels of the climatic impact studies (CIAP and CIC).

Based on the results obtained from the fundamental experiments and several of the advanced technology combustors from the clean combustor program described previously, estimates were made with regard to potential cruise NO_x emission reductions. The clean-combustor technology could reduce cruise NO_x emissions by about a factor of two for an engine having a 30:1 pressure ratio in an aircraft cruising at 11.3 kilometers (35 000 ft) and Mach 0.85. Achieving the levels recommended by the climatic impact studies, a 6- to 10-fold (or greater) reduction, will require the use of prevaporized-premixed combustion.

To determine the applicability of prevaporized-premixed combustion to advanced combustors, NASA has begun a Stratospheric Cruise Emission Reduction Program (SCERP). This program will consist of in-house, contract, and university grant efforts and will use a multiphase approach. Although the program is directed toward reducing the cruise NO_x of subsonic aircraft by a minimum of 6- to 10-fold, the information obtained during the fundamental studies undertaken in the first phase (phase 1) will also be applicable to supersonic aircraft engine combustors. During phase 1, fundamental information regarding lean combustion stability, autoignition and flashback, fuel preparation, and engine-related constraints will be obtained. This information will then form the basis for developing promising conceptual designs to be evaluated in the following three program phases (phases 2 to 4), which are essentially identical to the three phases of the NASA/industry programs currently underway to evaluate advanced concepts for the local emission problem. Since the goal of this program is to meet EPA-established LTO cycle emission standards as well as to reduce cruise NO_x, it is likely that some form of staged combustion or variable geometry will be required. If a successful concept is evolved, the program is structured to provide a full-scale engine demonstration during the early 1980's.

MEASUREMENT OF UPPER-ATMOSPHERE CONSTITUENTS

The objectives of the NASA Global Atmospheric Sampling Program (GASP) are to provide baseline data for selected atmospheric constituents in the upper troposphere and lower stratosphere over a 5- to 10-year period and to analyze these data to assess potentially adverse effects between aircraft exhaust emissions and the natural atmosphere.

The approach chosen was to install automated sampling systems on Boeing-747 aircraft flying the commercial air-routes (ref. 9). The system installation is shown in figure 7. In situ monitoring instruments and the associated gas-handling system are installed in the nose section of the B-747 below the first-class passenger compartment. Four B-747 installations and an NASA CV-990 aircraft installation have been completed and the aircraft are in routine service. Two of the B-747 aircraft installations presently include single-filter samplers. The routes for the aircraft are shown in figure 8. United Airlines flies the routes over the continental U.S. and to Hawaii. Pan American World Airways flies around-the-world routes from the U.S. in the Northern Hemisphere, transpacific routes to the Far East, intercontinental routes to Central and South America, and occasionally transpacific routes to Australia. A Pam Am B-747 SP flies long-range, great-circle routes from New York and the west coast to Tokyo at altitudes up to 13.7 kilometers (45 000 ft). Coverage in the Southern Hemisphere is provided by Qantas Airways of Australia on trans-Australian flights and on flights from Australia to the South Pacific, to the U.S. west coast, and to Europe. The dashed line in figure 8 show CV-990 routes for latitudinal flight surveys scheduled for October-November 1976 and February-March 1977.

Data acquisition begins on ascent through 6-kilometer (20 000-ft) altitude and terminates on descent through 6 kilometers. GASP data are taken during a 16-second recording period at intervals of 5 minutes. Following data reduction and verification, the final data tapes are archived and are available to users at the National Climatic Center (NCC) at Asheville, North Carolina. The parameters measured on the GASP systems, along with subsidiary information added to the archival tapes, are as follows:

(1) Data-point identification: aircraft identification; date and time; and position and altitude

(2) Other flight data: wind speed and direction; static air temperature; and aircraft speed, heading, and acceleration

(3) Constituent data: ozone, water vapor, and particle concentration; filter sample composition ($SO_4^=$, NO_3^-, Cl^-); and analysis of whole gas samples for $CFCl_3$ (Future data will include CO, NO_x, and condensation nuclei (CN) and will expand the whole-gas-sample analysis to include CF_2Cl_2, CCl_4, and N_2O.)

(4) Subsidiary data: tropopause pressure arrays from National Meteorological Center (NMC) objective analysis.

Constituent data available on the GASP archival tapes through calendar 1975 have been limited to ozone and water vapor. Some filter analysis data and analysis of whole gas samples for $CFCl_3$ will appear on subsequent tapes following resolution of earlier problems with the analytical procedures and the cleaning and preparation of filters and sample bottles. Uncertainties in calibrating the particle counter have precluded the inclusion of particle concentration data in the archives to date. New instruments to measure CO, condensation nuclei, and NO_x are in the process of certification testing and installation on the GASP aircraft.

Some examples of ozone data and the effect of atmospheric transport on ozone profiles are shown in figures 9 and 10. Figure 9 (ref. 10) gives the ozone mixing ratio as a function of latitude for several around-the-world flights during March 1975 and includes flights in both the troposphere and the stratosphere. The data show a large scatter in ozone mixing ratio, which is typical of the spring maximum. For comparison, North American, March, mean ozone distributions at 10.0 and 12.5 kilometers (32 800 and 41 000 ft) are also shown in figure 9. These curves were calculated from tabulations of molecular concentration given in reference 11.

As an illustration of ozone variation with respect to the local tropopause as defined by the NMC objective analysis procedure, ozone mixing ratio data from several around-the-world flights during March 1975 are plotted as a function of the altitude pressure increment above and below the tropopause in figure 10. The data have been separated according to the local wind vector curvature (ref. 12) as determined from aircraft-system measurements of wind direction and velocity. The differences, in terms of ozone mixing ratio scatter below the tropopause and ozone gradient below and above the tropopause, are striking when the data for cyclonic and anticyclonic wind curvature are compared. The ozone distribution for anticyclonic streamline curvature (fig. 10(a)) shows the expected steep gradient and increase of ozone in the stratosphere. The cyclonic streamline curvature (fig. 10(b)) indicates a less-steep gradient and high ozone levels below the NMC-defined tropopause. The data illustrate the greater tendency for more intense stratospheric-tropospheric exchange associated with cyclonic curvature of the wind fields.

The single-filter samplers currently installed on two of the B-747 aircraft have limited capability for providing baseline composition data since the filter can only be changed during routine servicing of the GASP systems, which occurs on the average of once every 2 weeks. These single filters will be replaced shortly with an eight-filter magazine. To date, because of limited exposure and earlier problems with analytical and filter washing procedures, limited composition data are available from the B-747's. However three filter-sampling flight series originating from Cleveland and from Holloman Air Force Base in New Mexico have been flown during the past year with the NASA Lewis F-106 aircraft using identical filter samplers. Data on sulfate and nitrate concentrations from the F-106 flights are plotted as a function of pressure altitude difference above or below the local tropopause in figure 11. Although there is considerable variation, the concentrations are low and are consistent with other aircraft sampling flights (refs. 13 and 14). Although the data illustrated represent only a very limited sample, a steep gradient and a peak are indicated above the local tropopause, with considerably lower levels in the troposphere. Sulfate and nitrate are believed to originate from the sulfuric acid aerosol layer in the stratosphere and from absorption of nitric acid vapor on the IPC (cellulose) filter material.

CONCLUDING REMARKS

NASA is conducting programs to evaluate advanced emission reduction techniques for five existing aircraft gas turbine engines. Although these programs are in various stages of completion, the results suggest that significant reductions in all pollutant emissions (carbon monoxide (CO), total hydrocarbons (THC), oxides of nitrogen (NO_x), and smoke) can be achieved. Progress has been made to varying degrees toward meeting the 1979 EPA standards in rig tests of combustors for the five engines.

Selective reductions in certain emission levels (e.g., CO and THC) can be achieved by relatively minor to moderate modifications to current engine baseline combustors.

Because of the inherent total emission control capability of staged combustor concepts, their continued development for application to future newly manufactured engines seems highly desirable. The added complexity involved in the staged concepts, however, will likely require continued development beyond the scope of the current programs. Proof-of-concept tests in full-scale engines are still needed to quantify the success of the advanced concepts in terms of their absolute level of emission reduction and to demonstrate the capability to successfully satisfy all the engine requirements.

Results of fundamental combustion studies suggest the possibility of a new generation of jet aircraft engine combustor technology that would provide emission levels far below those currently possible with the advanced technology concepts demonstrated in the engine-related programs. Considerable fundamental research is still needed, however, before the techniques being studied can be translated into useful combustors. Successful development of these techniques into operational engine combustors would provide the level of NO_x reductions desired for both local air quality and for minimizing effects on the ozone layer during high-altitude-cruise. The objective of the recently begun NASA Stratospheric Cruise Emission Reduction Program (SCERP) is to evaluate the potential of these techniques to evolve combustors for future aircraft gas turbine engines.

The Global Air Sampling Program is now in full operation. Data taken during the past 2 years on ozone have shown its extreme variability but are also providing some valuable insight into stratospheric-tropospheric exchange processes. The measurement of NO_x and CO, which may be directly related to engine emissions, has not yet been implemented but will begin shortly. The accumulation of an adequate data base for these constituents may take several years before GASP can contribute to an assessment of the potential impact of jet engine cruise operations on the upper atmosphere.

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TABLE I. - EMISSION REDUCTION TECHNOLOGY PROGRAM - SUMMARY OF RESULTS TO DATE (EPAP VALUES)

Engine	Emission[a]								
	Carbon monoxide			Total hydrocarbons			Oxides of nitrogen		
	Conventional combustor	Advanced technique	EPA standard	Conventional combustor	Advanced technique	EPA standard	Conventional combustor	Advanced technique	EPA standard
CF6-50 (double-annular concept)	10.8	3.0	4.3	4.3	0.3	0.8	7.7	4.2	3.0
JT9D-7 (vorbix concept)	8.6	6.5	4.3	3.9	.3	.8	4.9	2.2	3.0
JT8D-17 (vorbix concept)	16.1	8.9	4.3	4.4	.2	.8	8.2	4.4	3.0
TFE731-2 (piloted-airblast concept)	17.5	10.1	9.4	5.3	.4	1.6	5.3	3.9	3.7
501-D22A (reverse-flow concept)	31.5	4.6	26.8	15.0	.3	4.9	6.2	7.3	12.9

[a] Smoke standards should be achievable for all concepts.

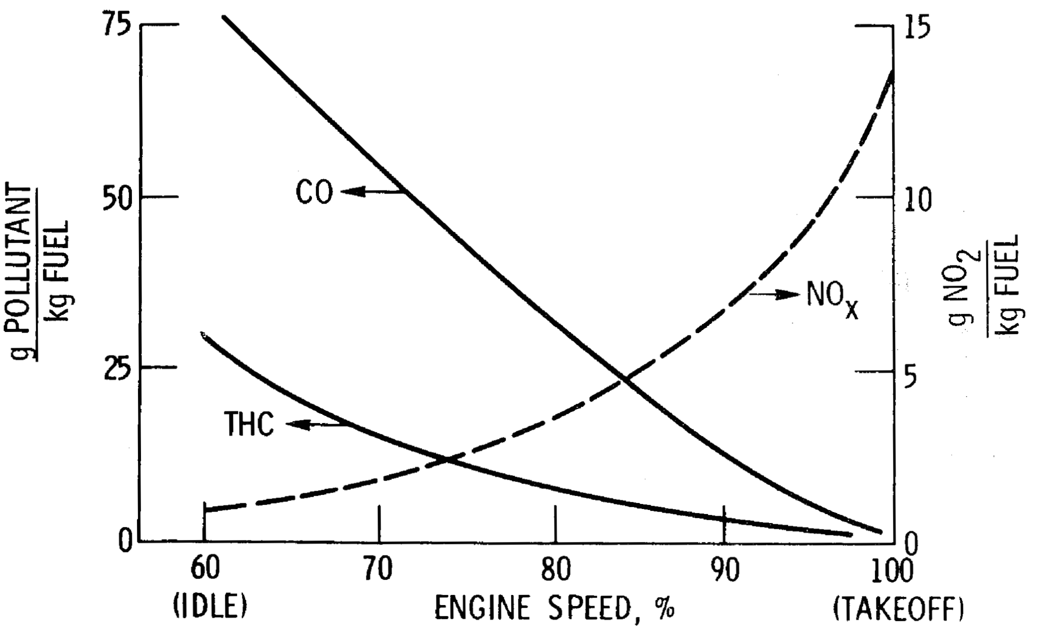


Figure 1.- Typical engine exhaust emission characteristics.

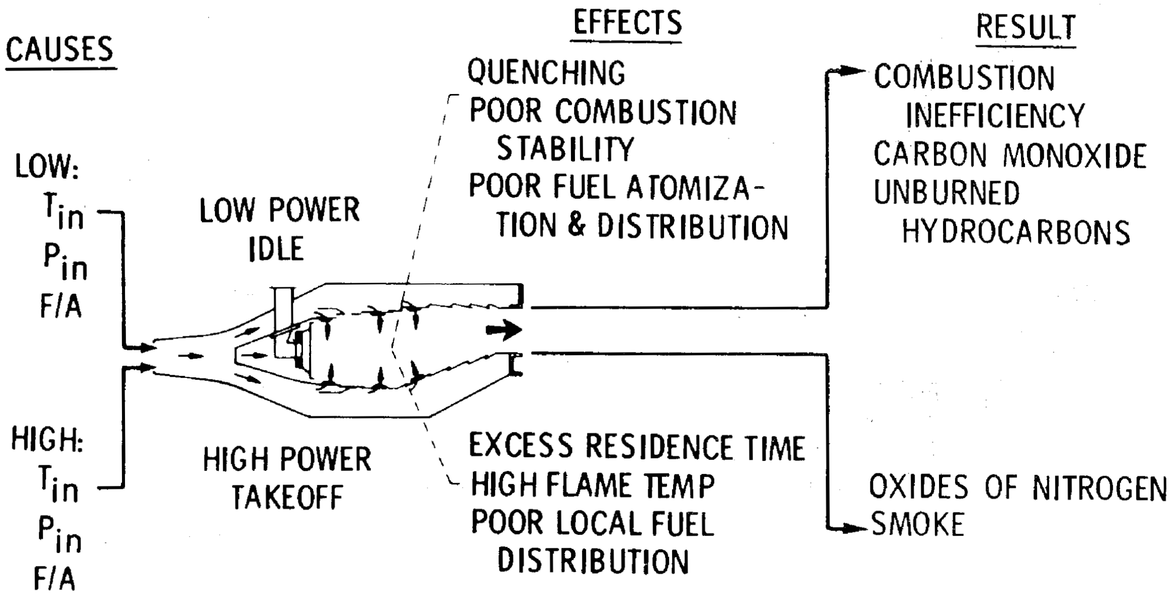


Figure 2.- Aircraft gas turbine combustor pollution considerations.

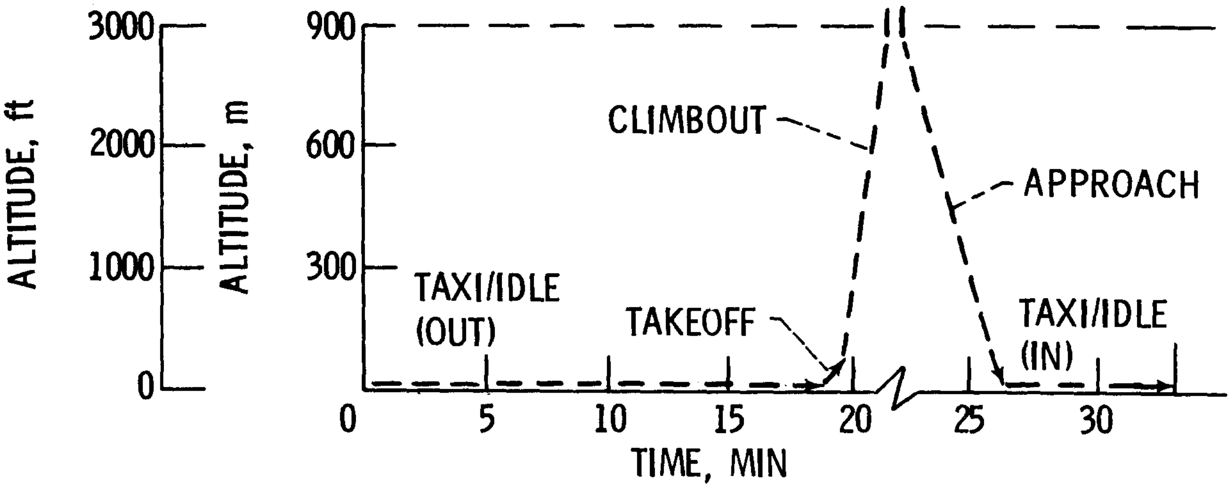


Figure 3.- EPA landing-takeoff cycle.

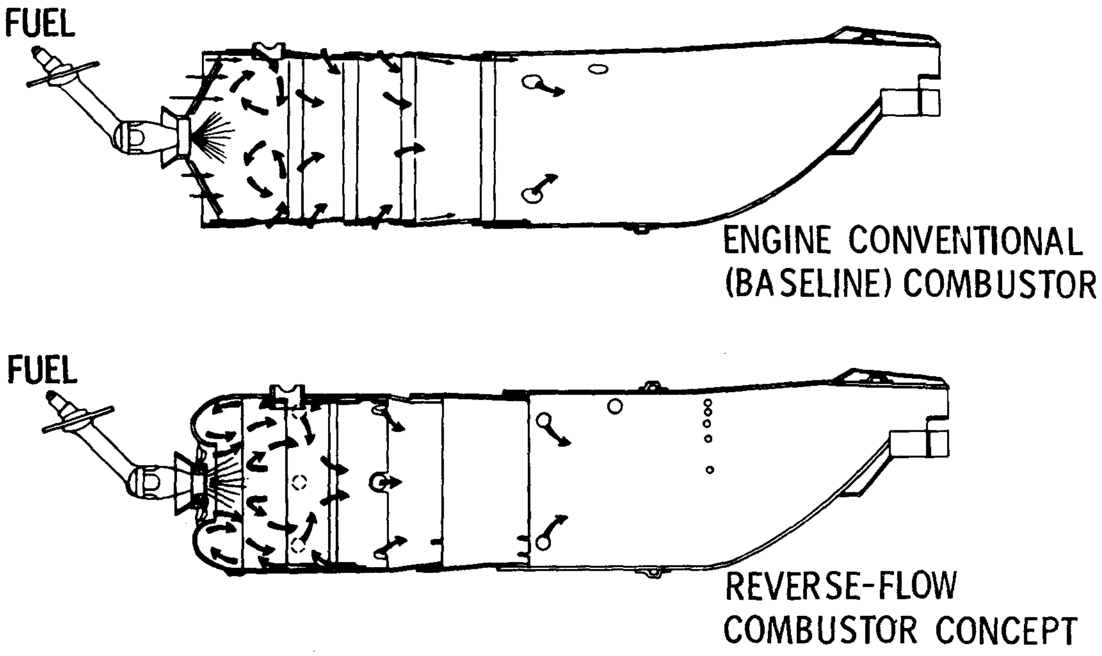
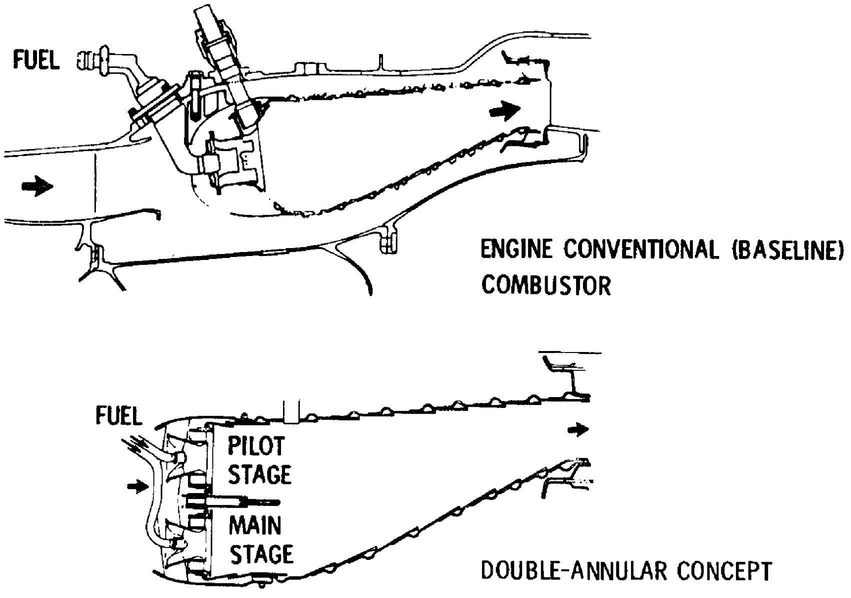
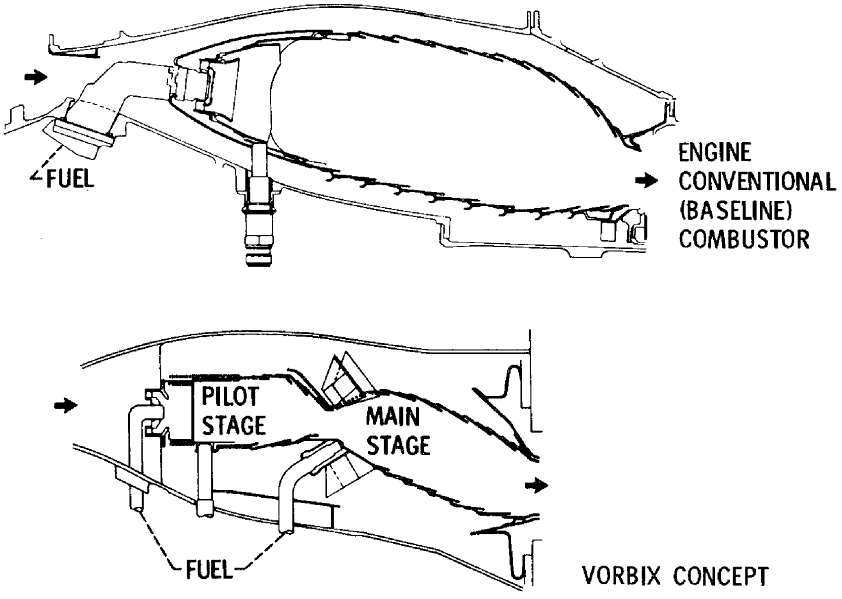


Figure 4.- Reduced-emissions combustor - minor modifications to Detroit Diesel Allison 501-D22A engine.



(a) Double-annular concept applied to General Electric CF6-50 engine.



(b) Vorbix concept applied to Pratt & Whitney JT9D-7A engine.

Figure 5.- Reduced-emissions combustor - staged concepts.

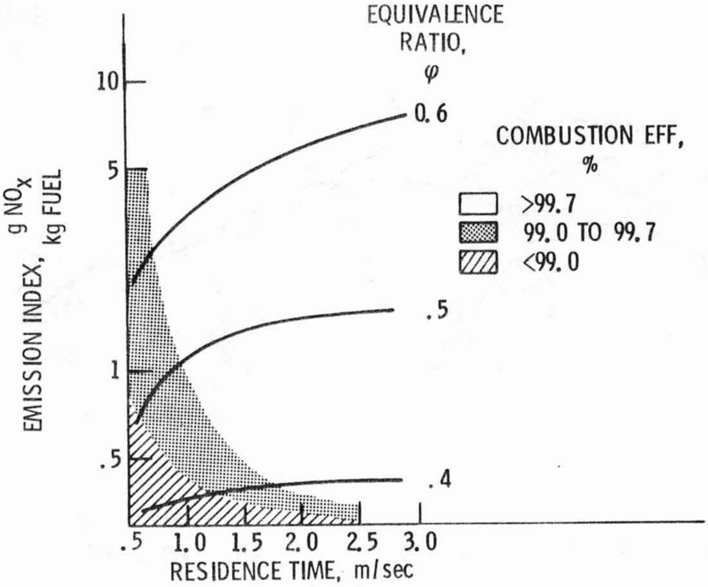


Figure 6.- Combustion efficiency and NO_x emissions.

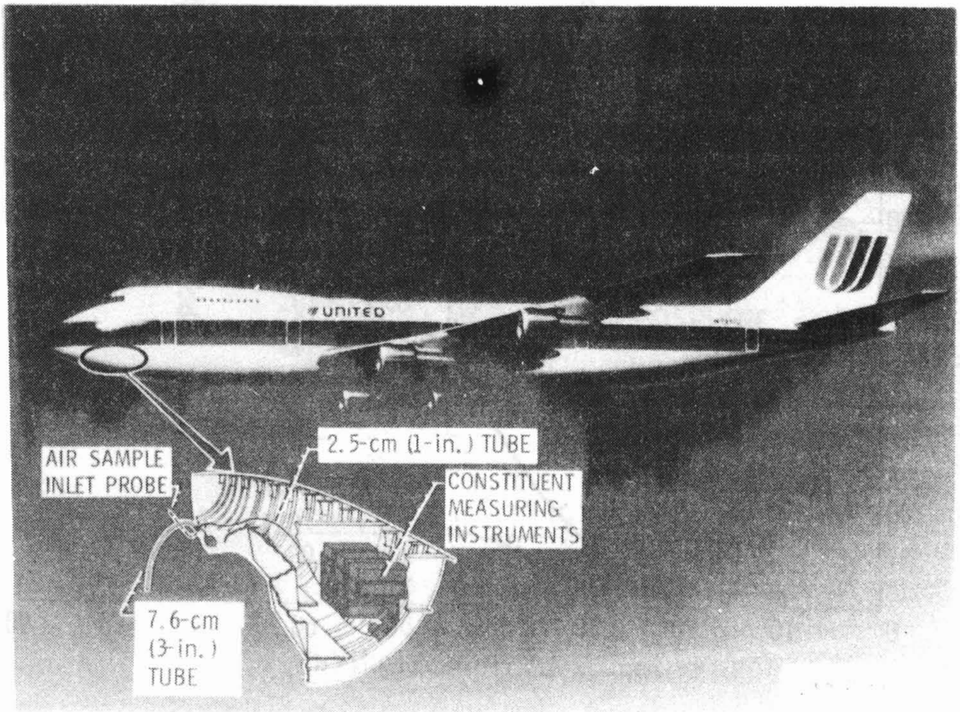


Figure 7.- GASP system installation.

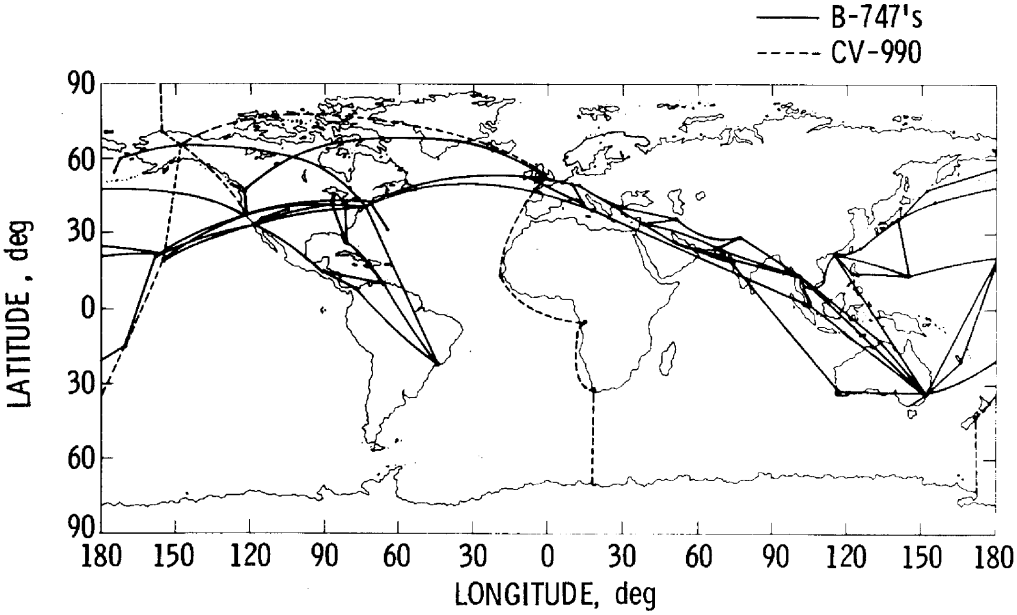


Figure 8.- GASP flight routes.

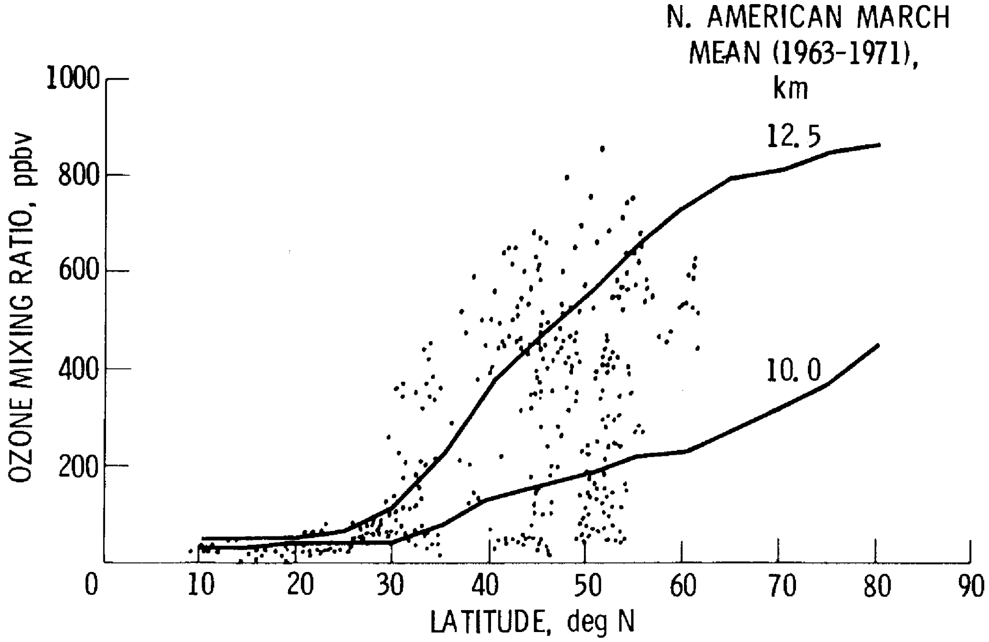
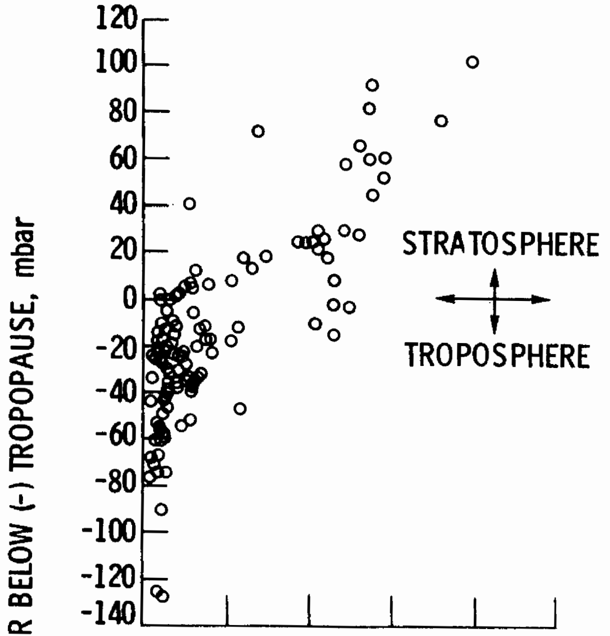
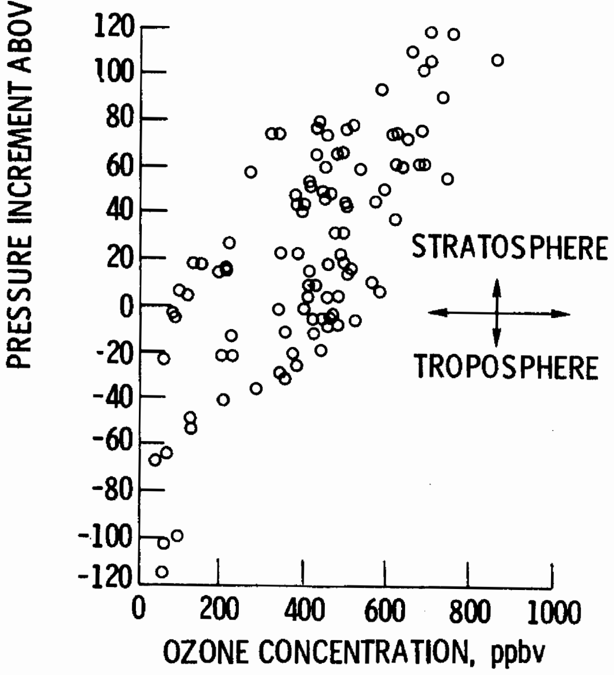


Figure 9.- Variation of ozone mixing ratio with latitude. Altitude, above 10 kilometers; sampling period, March 11 to 30, 1975.



(a) Anticyclonic curvature.



(b) Cyclonic curvature.

Figure 10.- Vertical profile of ozone mixing ratio showing effect of wind vector curvature. Sampling period, March 1975.

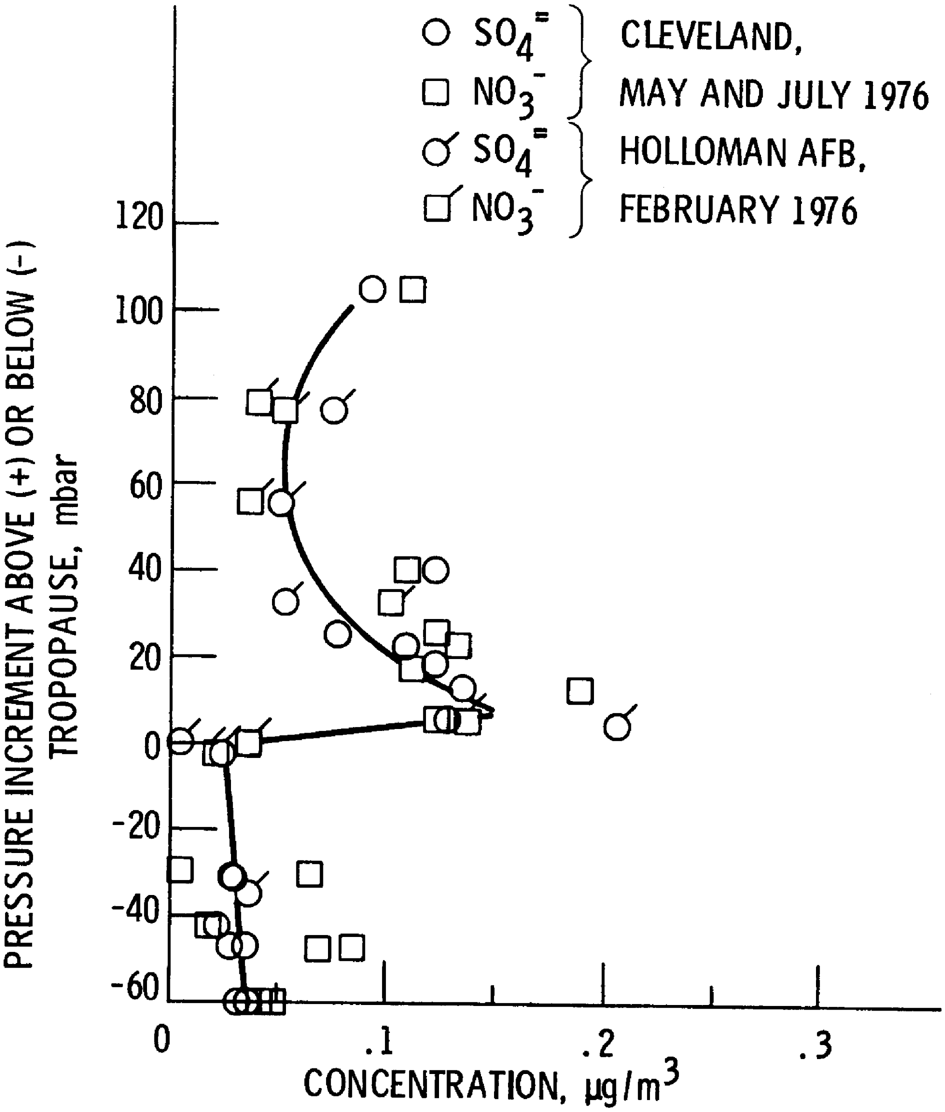


Figure 11.- Vertical profile of $SO_4^=$ and NO_3^- from F-106 filter flights.