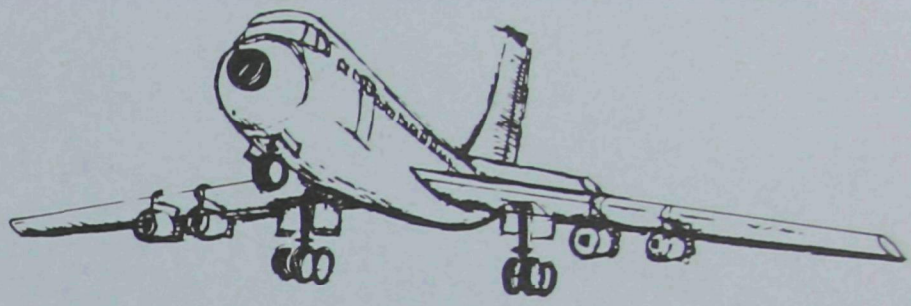

AIRCRAFT EMISSIONS: IMPACT ON AIR QUALITY AND FEASIBILITY OF CONTROL

U.S. ENVIRONMENTAL PROTECTION AGENCY

AIRCRAFT EMISSIONS: IMPACT ON AIR QUALITY AND FEASIBILITY OF CONTROL

ENVIRONMENTAL PROTECTION AGENCY
Office of Air Programs
Research Triangle Park, North Carolina
April 1972

Office of Air Programs Publication No. APTD-0757

PREFACE

This report presents the available information on the present and predicted nature and extent of air pollutant emissions from aircraft operations at major airports in selected air quality control regions. In addition, an investigation on the present and anticipated future technological feasibility of controlling such emissions is presented. This report is published in accordance with Section 231 (a) of the Clean Air Act as amended, which states:

"(1) Within 90 days after the date of enactment of the Clean Air Amendments of 1970, the Administrator shall commence a study and investigation of emissions of air pollutants from aircraft in order to determine--

"A. the extent to which such emissions affect air quality in air quality control regions throughout the United States, and

"B. the technological feasibility of controlling such emissions.

"(2) Within 180 days after commencing such study and investigation, the Administrator shall publish a report of such study and investigation..."

The data base for this report was developed largely by Northern Research and Engineering Corporation, Cambridge, Massachusetts,[1,2] under contract with the U.S. Environmental Protection Agency (EPA). More detail on certain aspects of the study is available in the contract reports.[1,2] Further information on baseline emissions from aircraft was obtained under several other contracts.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

AIRCRAFT EMISSIONS: IMPACT ON AIR QUALITY AND FEASIBILITY OF CONTROL

INTRODUCTION

Public awareness that aircraft were a source of air pollution developed in the late 1950's with the introduction of turbine-engine aircraft. Visible exhaust plumes from the engines and increased levels of exhaust odors at airports caused complaints about the aircraft to be lodged. The complaints, in turn, stimulated investigations into the nature and extent of aircraft emissions. The Air Quality Act of 1967 specifically identified aircraft emissions as a subject of concern and required an investigation by the Department of Health, Education, and Welfare. The study,[3] submitted to Congress on January 17, 1969, concluded, among other things, that reduction of particulate emissions from jet aircraft was both desirable and feasible.

In March 1970, at a meeting held by the Secretaries of Health, Education, and Welfare and of Transportation, representatives of 31 airlines agreed to a schedule for retrofitting JT8-D engines with reduced-smoke combustors, to be substantially completed by the end of 1972. This agreement sought to significantly abate visible (smoke) emissions from aircraft powered by this widely used engine.

The problem of defining the nature and extent of air pollution from aircraft sources has received continuing attention as reflected by recently published studies prepared by the Bay Area Air Pollution Control District[4] and by the Los Angeles County Air Pollution Control District under EPA contract[5] and by the published proceedings[6] of the joint DOT/SAE Conference on Aircraft and the Environment.

To develop additional information helpful in determining the aircraft contribution to air pollutant concentrations and the feasibility of controlling aircraft emissions, the Environmental Protection Agency conducted studies in the following areas.

TECHNOLOGICAL FEASIBILITY OF CONTROLLING AIRCRAFT EMISSIONS

Information on emission control methods was necessary to determine the levels to which aircraft emissions can feasibly be reduced. The specific objectives of the investigation of aircraft emission control technology were:

1. To identify methods of controlling aircraft emissions through modification of engines, fuels, and ground operation.
2. To estimate the effectiveness of these control methods in reducing aircraft emission rates.
3. To estimate the time and cost of implementing these control methods.
4. To assess the technology of measuring emissions from aircraft engines, and to identify areas where advancements in instrumentation or test procedures are required.

It is felt that this analysis and the results obtained represent the best available information on the present and anticipated future technological feasibility of controlling aircraft engine emissions.

EFFECTS OF AIRCRAFT ON AIR QUALITY

While previous investigations had been made concerning the impact of aircraft on air quality, additional study was necessary to assess the severity of this impact. To provide additional insight on the localized impact of aircraft emissions, an airport dispersion modeling study was undertaken.

The dispersion modeling provided estimates of air pollutant concentrations at four major commercial airports - Los Angeles International, J. F. Kennedy, O'Hare, and Washington National and permitted estimates to be made of that portion of total pollutant concentrations attributable to aircraft alone. Pollutant concentrations were estimated by the model at a total of 193 sites within a 5-kilometer radius of the airports; concentrations at over 100 of these sites that are accessible to the public were used in the analysis of the results.

Four additional methods of evaluating localized and metropolitan impact of aircraft on air quality were also used:

1. A limited analysis of the air quality data collected at Los Angeles International Airport under EPA contract in 1970 was performed to further evaluate the impact of aircraft CO emissions.
2. A simplified area-source modeling technique was applied to aircraft hydrocarbon emissions at Los Angeles International Airport to estimate possible aircraft contributions to oxidant concentrations downwind of the airport.

3. Emission densities (tons of emissions per square mile per year) from the four commercial airports were compared with emission densities from their neighboring metropolitan areas to further investigate the potential of localized impact of aircraft emissions.

4. Estimates were made of the present and future contributions of aircraft emissions to the total emissions of the four metropolitan areas studied (Los Angeles, New York City, Chicago, and Washington, D. C.).

CONCLUSIONS

CONTRIBUTION OF AIRCRAFT TO POLLUTANT CONCENTRATIONS

The results of the several approaches used in the study to assess the contribution of aircraft to air quality provide consistent evidence that aircraft are important contributors to air pollutant concentrations in excess of the primary (health-related) and secondary (welfare-related) Federal ambient air quality standards in localized areas of at least four major U.S. airports. These airports, Los Angeles International, O'Hare, John F. Kennedy, and Washington National, are used by over 30 million passengers per year.

In addition to this evidence of an important aircraft air quality impact on a localized basis around airports, the contribution by aircraft to the total emissions from the metropolitan areas of New York City, Los Angeles, Chicago, and Washington, D.C., may become increasingly important in achieving and maintaining air quality standards, especially near airports in these regions, as other emission sources are controlled.

Of the methods used to evaluate air pollutant concentrations, the dispersion modeling provided the most useful information because of its ability to estimate air pollutant concentrations caused by aircraft alone. Atmospheric dispersion models similar to the one used in this study are widely accepted as a means of approximating air pollutant concentrations, and have been specified by EPA as one method of demonstrating that air quality implementation plans for metropolitan areas are consistent with ambient air quality standards.

In estimating ambient air pollutant concentrations, the primary dispersion modeling approach used in this study necessarily takes into account a great deal of measured and estimated input data, including emissions, activity-use patterns, and locations of the various aircraft types and other emission sources at the airport. Meteorological conditions, including wind speed, wind direction, atmospheric stability, and mixing height are also input to the model, as are emissions from areas surrounding the airport. The relationships between these input data and estimated ambient air pollutant concentrations are based on empirical models derived from actual measurements of pollutant dispersion patterns.

It is felt that the results of the dispersion modeling work used in this study represent the best presently available estimates of aircraft contributions to air

pollutant concentrations in the airport areas studied. Even so, the individual concentrations predicted in these modeling results should be considered approximate. Limited comparisons have been made between the model's predictions and air quality data, but it is not possible at this time to state, in general, the extent to which the model may underpredict or overpredict actual pollutant concentrations.

Although it is not possible at this time to assess with confidence the precise impact of aircraft on air quality in airport environs, the total evidence from the dispersion modeling and other methods of evaluation strongly support the general conclusion that aircraft make important contributions to air pollutant concentrations at airports and neighboring areas.

The following specific conclusions indicate the impact of aircraft emissions on air quality at the four commercial airports considered in this study and in their immediate vicinities.

Air Quality Impact of Aircraft in Airport Areas

Hydrocarbons and Oxidants Nonmethane hydrocarbon concentrations caused by aircraft alone, as estimated by dispersion modeling, are estimated to be far in excess of the hydrocarbon standard in a large number of airport areas. High hydrocarbon emission densities from aircraft at these airports support these estimates. Despite substantial projected decreases in total aircraft hydrocarbon emissions at these airports during the 1970's, ambient air hydrocarbon concentrations attributable to aircraft alone are expected to continue to exceed the hydrocarbon standard in many airport areas.

Although hydrocarbon concentrations observed in the atmosphere have not been directly associated with health effects, the nonmethane hydrocarbon standard is based on the role of hydrocarbons as a precursor of photochemical oxidants. Simple area-source dispersion modeling analysis suggests that, under conditions particularly conducive to high oxidant concentrations, aircraft-generated hydrocarbon concentrations may alone result in oxidant concentrations in excess of the photochemical oxidant air quality standard downwind of Los Angeles International Airport.

Dispersion modeling analysis indicates that fuel dumping accounts for maximum ground-level, 1-hour-total hydrocarbon concentrations on the order of 18 $\mu g/m^3$. Hydrocarbon emissions caused by fuel dumping are estimated to range from 3.5 percent of total aircraft hydrocarbon emissions at Los Angeles International Airport to 21 percent of those at Washington National Airport. Widespread complaints about oily films on automobiles and other surfaces in airport vicinities suggest that condensable exhaust hydrocarbon emissions and fuel dumping are at least partially responsible for these films.

Carbon Monoxide Carbon monoxide concentrations, as estimated by the dispersion model, are predicted to exceed the carbon monoxide air quality standards in some airport areas of public access. In these areas, contributions by aircraft to these concentrations are estimated to be major, and in some cases estimated concentrations caused by aircraft alone are in excess of the standards. High carbon monoxide emission densities from aircraft at these airports, plus consideration of air quality data collected at some sampling sites at the Los Angeles Airport,[5] provide additional evidence of important contributions by aircraft to high CO concentrations in airport areas. It is expected that during the 1970's, without aircraft emissions standards, total carbon monoxide emissions from aircraft at the four airports generally will remain about the same. Because of decreasing automobile emissions, however, the relative contributions of aircraft to carbon monoxide emissions in airport areas can be expected to increase.

Nitrogen Dioxide Dispersion modeling estimates indicate that NO_2 concentrations in excess of the Federal annual NO_2 air quality standard exist in areas of long-term public access such as residential areas. Contributions by aircraft to these concentrations are estimated to be significant but well within the standard. In areas of short-term public access on airport grounds, however, concentrations caused by emissions from aircraft are predicted to be larger. In this analysis, NO_x was considered as NO_2.

It is expected that without NO_x aircraft emission standards, NO_x emissions from aircraft during the 1970's are expected to increase by 100 percent at O'Hare Airport, 30 percent at Washington National Airport, 270 percent at Los Angeles International Airport, and 150 percent at John F. Kennedy Airport. In general, these increases in NO_x emissions indicate substantial increases in the relative contributions by aircraft to total NO_x emissions in the airport areas studied, and point up the probability of increasing total NO_2 concentrations in them.

Smoke and Particulates -- Visible smoke emissions from aircraft have resulted in widespread public complaints, and increased soiling effects have been noted in airport areas.[5] The dispersion modeling analysis indicates that estimated particulate concentrations caused by aircraft alone are in excess of the secondary (welfare-related) air quality standard in some airport areas and can be substantial contributors to particulate concentrations in excess of the secondary standard in many other airport areas.

Contributions by General Aviation Aircraft Because the emission levels from piston-powered general aviation aircraft are high for hydrocarbons and particularly high for carbon monoxide in relation to engine size, these aircraft can be important contributors to total emissions from those air carrier airports where general

aviation activity is great. For example, it is estimated that while accounting for 32 percent of total aircraft activity at Washington National Airport, small piston-powered general aviation aircraft account for an estimated 3 percent of the total hydrocarbons and 14 percent of the carbon monoxide emitted from all aircraft using this airport.

Additional dispersion modeling at two general aviation airports indicated that pollutant concentrations attributed to general aviation aircraft were well within existing Federal ambient air quality standards. This modeling indicated, however, that ambient air lead concentrations caused by general aviation aircraft might present a potential problem. Large increases expected in general aviation activity during the 1970's are expected to increase the significance of aircraft emissions at these airports.

Air Quality Impact of Aircraft in Metropolitan Areas

The contributions by aircraft to total emissions in the metropolitan areas of Los Angeles, New York City, Washington, D. C., and Chicago are of concern because of the requirements that these areas meet and continue to meet the ambient air quality standards. The oxidant and hydrocarbon, carbon monoxide, and oxides of nitrogen air quality standards are not met in these cities. For hydrocarbon, carbon monoxide, and oxides of nitrogen emissions, aircraft contributions to the totals in these four areas are estimated to range from 0.5 to 4.6 percent in 1970, and from 1.5 to 7.6 percent in 1980 without aircraft emission controls. These values indicate the present and increasing future significance of aircraft emissions in metropolitan areas, and point up the increasing importance aircraft emission controls could be expected to have in allowing early and continued compliance with ambient air quality standards, particularly in airport vicinities. Additional estimates for the Los Angeles area indicate that in 1980, if aircraft emission standards are not implemented, emissions from light piston-engine aircraft can be expected to account for more than half of the total aircraft emissions of carbon monoxide and about 20 percent of the total aircraft emissions of hydrocarbons.

EMISSION CONTROL OF AIRCRAFT TURBINE ENGINES

1. Carbon monoxide and hydrocarbon emissions can be significantly reduced (50 to 75 percent) at major air carrier airports by the following methods:*

   a. Modifying Aircraft Ground Operational Procedures.
   If these reductions are achieved by increasing engine operating power levels and at the same time reducing the number of engines used in

*A reduction in odor levels at airports may accompany the hydrocarbon emission reduction.

taxi/idle operations, such controls may result in fuel savings yielding a net benefit to the carrier.

b. Engine Modifications.
There are various methods available for achieving such reductions. The cost of these methods would vary depending on the particular control method selected and the number of engines and engine models affected. The cost of implementing any of these methods in the total air carrier fleet would be on the order of $100 million. The time required to implement any of the engine modification control methods in the air carrier fleet is estimated to be from 5 to 10 years.

2. Nitrogen oxide emissions can be reduced significantly (50 to 75 percent) through the use of water injection during takeoff and climb-out modes. The cost of applying this control method to the total air carrier fleet is estimated to be approximately $100 million, and 5 years or more would be required for its implementation. The degree of control can be reduced or increased by reducing or increasing the rate or duration of water injection. The costs will not, however, vary proportionately.

3. Visible smoke emissions from turbine engines can be substantially reduced by minor combustor modifications, and such modifications are already being implemented for certain engines. The additional costs of eliminating smoke emissions from all air carrier aircraft is estimated to be on the order of $100 million.

4. A 50 percent reduction in particulate emissions can be achieved by major modifications of combustors, but at high cost ($600 million) and with long implementation times (7 to 10 years).

5. Large (75 to 90 percent) reductions in carbon monoxide and hydrocarbon emissions and significant (50 percent) reductions in nitrogen oxide and particulate emissions will accompany the introduction of advanced combustor design concepts in future engines. Complete elimination of visible smoke will also be possible with the advanced designs. Associated costs will be on the order of 3 percent of the total engine cost. Engines with these features will not appear in service before the late 1970's.

EMISSION CONTROL OF AIRCRAFT PISTON ENGINES

1. Substantial reduction (50 to 75 percent) in carbon monoxide and hydrocarbon emission rates can be achieved by applying exhaust emission control devices to aircraft piston engines. Retrofitting costs would be high, on the order of $100 million or more, with an estimated implementation time of greater than 5 years.

2. Minor engine design changes can be made to reduce carbon monoxide and hydrocarbon emission rates (50 percent) without the addition of auxiliary control devices. These changes include modifications in combustor chamber geometry, valve and spark timing, and fuel-air ratios. Such changes would probably not result in any significant increase in new engine cost and could probably be incorporated in new engines in 3 to 4 years. Larger reductions can be obtained by adding auxiliary control devices.

3. Lead emissions could be reduced directly by the use of low-lead or lead-free gasoline.

METHODOLOGY FOR IMPACT EVALUATION

On a nationwide mass basis, aircraft have been estimated[7] to emit between 1 and 2 percent of the total hydrocarbons, carbon monoxide, and oxides of nitrogen, and about 0.3 percent of the particulate matter and sulfur oxides. On a more localized basis, however, aircraft emissions can be expected to have much greater significance at airports and in their neighboring communities. As a first step in evaluating the contribution by aircraft to air pollutant concentrations in airport areas, specific airports were chosen for detailed study.

SELECTION OF AIRPORTS

Airports were selected to represent, as nearly as possible, those airports at which the impact of emissions from aircraft and related activities would be greatest. The factors considered in evaluating the potential impact of individual airports included: (1) aircraft activity levels, (2) airport area, (3) mean wind speed, and (4) relative activity of different types of aircraft (commercial air carrier, general aviation, and military). On the basis of these considerations and the availability of airport and aircraft activity data, the airports selected for study were as follows:

1. Commercial Air Carrier
    a. Los Angeles International
    b. Washington National
    c. J. F. Kennedy International
    d. O'Hare International
2. General Aviation
    a. Van Nuys, California
    b. Tamiami, Florida

PROCEDURE OF AIR QUALITY ANALYSIS AT STUDY AIRPORTS

Basic to the air quality analysis was the development of emission factors and aircraft activity data for use in dispersion modeling and in other estimates of total aircraft and airport emissions.

Emission Factors

Pollutants emitted by aircraft engines include gaseous hydrocarbons, carbon monoxide, oxides of nitrogen, particulate matter, and sulfur oxides. Because different types of aircraft emit different concentrations and compositions of pollutants and have different patterns of usage, it was necessary to classify aircraft by type and to define the typical operational modes they go through in their landing and takeoff (LTO) cycles. This classification made possible categorization of emission factors by aircraft type and mode of operation.

The aircraft classification system that was used divided aircraft into 12 separate types that include the currently used commercial air carrier, general aviation, and military planes. Provision was also made in the classification system for the supersonic commercial aircraft of the future. The complete classification system is presented in Table 1.

The aircraft modes of operation that were used, in order of their occurrence, are:

1. Start-up and idle.
2. Taxi.
3. Idle at runway.
4. Takeoff.
5. Climb-out to 3,000-foot elevation.
6. Fuel dumping.
7. Approach from 3,000-foot elevation.
8. Landing.
9. Idle and shutdown.
10. Maintenance.

Emission data were obtained for all operational modes for engines typical of those in each aircraft class.

Emissions on the grounds and in the vicinity of the six airports - from sources other than aircraft - were also taken into account in the air quality analyses. The other sources of emissions included airport heating plants, fuel storage losses, automobiles and service vehicles, and areas neighboring the airports.

Activity Level

To estimate the impact of aircraft emissions on air quality near the ground, it is necessary to take into account aircraft activity from the time an aircraft enters the atmospheric mixing layer during approach until it leaves this layer again during climb-out. In defining an LTO cycle, a height of 3000 feet above the runway was used as a reasonable approximation to the atmospheric mixing depth over major U.S.

Table 1. AIRCRAFT CLASSIFICATION SYSTEM

Aircraft					Representative engine			
Category	Class	Ref 12 classification	Type	Examples	Engine model	Type	Thrust or power[a]	Engines per aircraft
Air carrier	1	-	Supersonic transport	Concorde Tupolev TU-144	R-R/Snecma Olympus 593	Turbojet	39,000 lb	4
	2	-	Jumbo jet transport	Boeing 747 Douglas DC-10	P&WA JT9D	Turbofan	43,000 lb	4
	3	1	Long-range jet transport	Boeing 707 Douglas DC-8	P&WA JT3D	Turbofan	18,000 lb	4
	4	2	Medium-range jet transport	Boeing 727 Douglas DC-9	P&WA JT8D	Turbofan	13,900 lb	2.6
	5	4	Turboprop transport	Lockheed Electra Fairchild Hiller FH-227	Allison 501-D13	Turbo-prop	3,750 hp	2.5
General aviation	6	3	Business jet	Lockheed Jetstar North American Sabreliner	P&WA JT12	Turbojet	2,900 lb	2.1
	7	6	Piston-engine utility	Cessna 210 Centurion Piper 32-300 Cherokee Six	Continental IO-520-A	Opposed piston	292 hp	1[b]
Military	8	-	Over 400,000 lb gross weight	Boeing Stratofortress	P&WA TF33-P-3	Turbofan	17,100 lb	
	9	-	100,000 - 400,000 lb gross weight	Lockheed Starlifter	P&WA TF33-P-7	Turbofan	20,900 lb	
	10	-	10,000 - 100,000 lb gross weight	LTV Crusader	P&WA J57-P-20	Turbojet	18,000 lb	-
	11	-	Under 10,000 lb gross weight	Cessna 172	Continental IO-360	Opposed piston	211 hp	-
	12	7	Helicopters and V/STOL	Sikorsky S-61 Vertol 107	General Electric CT58	Turbo-shaft	1,390 hp	2

[a]Equivalent shaft power.

[b]Representative of Van Nuys and Tamiami.

metropolitan areas.[3] The number of LTO cycles performed, and the relative lengths of time spent in each operational mode of an LTO cycle, combined with the appropriate emission factors, determine the quantities of pollutants emitted by aircraft.

Records of aircraft activity data were obtained for the selected airports for 1970 and were classified by time of day, day of week, and month of year. Prospective growth in activity at the airports was estimated by projecting past and current activity data to 1975 and 1980. The yearly activity data and projections are summarized in Table 2.

The air carrier airports are so-called because of the preponderance of commercial air carrier activity, which, in 1970, ranged from 66 percent of total activity at Washington National to 92 percent at Chicago O'Hare. The activity at Tamiami and Van Nuys Airports is approximately 99 percent general aviation aircraft.

Additionally, data were obtained on the use and locations of taxiways, runways, terminals, hangars, heating plants, fuel storage areas, and roadways at each airport in order to locate and quantify the various sources of emissions during the operation of aircraft.

Methods of Impact Evaluation

The primary and most direct method of impact evaluation involved the application of frequently used dispersion modeling procedures to estimate air pollutant concentrations caused by aircraft alone and by all sources located in the airport vicinity (within a 10-kilometer radius of the airport center). The dispersion modeling was particularly useful in this study because it allowed estimation of pollutant concentrations caused by aircraft alone. Dispersion models similar to the one used in this study have been specified by EPA as one means of showing that implementation plans for certain regions will be adequate to meet the ambient air quality standards. Much of the analysis of aircraft impact presented in this report is based on modeling work performed, under EPA contract, by Northern Research and Engineering Corporation. A general description of the modeling procedure is presented here; a more detailed account of the modeling work and results is available in the contract report.[1]

The general procedure in the modeling study involved: (1) approximating emission sources as continuous, stationary point sources of constant strength over the time period being considered, (2) modeling the dispersion of pollutants from these sources using an empirical mathematical model, and (3) estimating concentrations at specified receptor points by summing the pollutant contributions from each point source.

Table 2. LTO CYCLES FOR 1970, 1975, and 1980

Airport type	Type of aircraft				Total LTO cycles		
	Air carrier	General aviation	Military	Helicopters	1970[a]	1975	1980
Air carrier airports							
Los Angeles International	203,900	59,900	4,200	4,050	272,000	305,200	358,100
Washington National	109,800	55,500	1,500	-	166,700	169,800	173,500
J. F. Kennedy International	188,800	27,800	-	-	219,200	208,500	241,300
Chicago O'Hare	314,300	21,200	-	-	339,900	357,000	410,800
General aviation airports							
Van Nuys, California	20	279,400	2,700	-	281,600	-	700,000
Tamiami,[b] Florida	-	200,800	-	-	200,800	-	-

[a]Where parts do not add up to total, LTO cycles not classified by type were included in total.

[b]1971 estimated activity.

The point sources used in the modeling approximated the location and strength of emission sources at each of the four airports studied. Lines along which automobile or aircraft movement occurred were represented by series of point sources. Area sources, representing airport surroundings out to a 10-kilometer radius from the airport center, were represented by circular arrangements of point sources around the airports. Altogether, 149 to 276 point sources were used for each air carrier airport depending on the size and complexity of the airport. The number of sources was chosen to provide a reasonable approximation to airport and vicinity emissions without excessive computer time and program complexity requirements.

The basis of the atmospheric dispersion modeling is an empirical, mathematical approximation to pollutant dispersion after emission from a point source. This approximation yields a plume whose concentration distribution is Gaussian in the vertical and crosswind direction. The distribution is dependent upon downwind distance from the source and atmospheric stability. Eventually the upper boundary of the atmospheric mixing layer restricts vertical plume spread and modifies the distribution of concentration in the vertical direction. This dispersion model should be considered as a general approximation to airport dispersion patterns, as considerable model development would be required to include more detailed small-scale dispersion patterns, such as those around large buildings or near jet blasts.

In the calculation of long-term concentrations, the fact that there is a distribution of meteorological conditions is used to simplify the basic dispersion model. The result, known as the Martin-Tikvart model, approximates plume spread in the crosswind direction and sums the contributions of all combinations of wind speeds and atmospheric stabilities.

The concentration at any receptor point is obtained as the sum of the contributions from each point source of emissions. The accuracy of the concentration value for this type of model is dependent upon the proximity of the receptor point and the emission sources. Because the sources of emission are actually a collection of points, lines, areas, and volumes, rather than merely a collection of points, as assumed in the model, greater accuracy will generally result when the receptor point is not in close proximity to any sources. In order to limit the portion of a predicted concentration attributable to the point source assumption, receptor locations within 100 meters of a point source were not considered valid in this study.

The model estimated air pollutant concentrations both from aircraft alone and from all sources at a number of sites located in and around the selected airports. Receptors considered in this study were located according to the following overall scheme: (1) one receptor at the center of each major terminal, (2) one receptor 100 meters from the head of each runway, (3) sixteen receptors on the airport boundary, spaced equally on a compass rose located at the chosen center of the

airport, (4) sixteen more receptors located in the airport surroundings, 5 kilometers from the center of the airport and spaced equally on the compass rose, and (5) mobile receptors 100 meters downwind of the two busiest runways for short-term calculations. A maximum of 50 receptors was used, with the actual number depending on the number of terminals and runways at each airport.

Long- and short-term ambient air pollutant concentrations were calculated for 1970 at all the receptor sites for each airport with the exception of Van Nuys, for which no short-term concentrations were calculated because of a lack of local meteorological data. The averaging times used for the air pollutant concentrations corresponded to those for which the National Primary and Secondary Ambient Air Quality Standards apply. The averaging times were: annual, 24-hour, 8-hour, 3-hour, and 1-hour concentrations.

The meteorological data used in calculating the annual average concentrations were based on yearly averages for the specific airports. The short-term concentrations (24-hour and shorter) were calculated using meteorological conditions that occurred during 1970 at each airport, and that would be expected to yield high air pollutant concentrations.

These meteorological conditions were selected on the basis of minimum wind speed and associated maximum atmospheric stability. Examination of 1970 meteorological data for the four air carrier airports indicated that these conditions occurred with the frequency shown in Table 3 for the 1-hour carbon monoxide and 6 to 9 a.m. hydrocarbons averaging times specified by the national ambient air quality standards. This table shows that meteorological conditions conducive to high carbon monoxide and hydrocarbon concentrations occurred at least twice at each airport and over 50 times at Los Angeles International Airport. The frequency of occurrence of these worst meteorological conditions at these airports could be expected to be of the same magnitude for 1971 and future years. This consideration is important because

Table 3. FREQUENCY OF OCCURRENCE OF "WORST METEOROLOGICAL CONDITIONS" FOR HIGH CARBON MONOXIDE AND HYDROCARBONS CONCENTRATIONS AT STUDY AIR CARRIER AIRPORTS IN 1970

Airport	1970 frequency of occurrence for CO, 1-hour period	1970 frequency of occurrence for hydrocarbons, 6- to 9-a.m. period
Washington National	67	6
J. F. Kennedy International	10	2
Los Angeles International	81	52
O'Hare International[a]	29	6

[a]Data for O'Hare are incomplete and are based on 5 months: January, February, March, October, and December.

the short-term pollutant concentrations predicted by the model using these conditions are compared with national ambient air quality standards that are not to be exceeded more than once per year.

In addition to the detailed dispersion modeling, other methods of impact evaluation that were used are listed below:

1. A comparison of hydrocarbon, carbon monoxide, and nitrogen oxides emission densities was made between the four air carrier airports and their respective metropolitan areas.
2. An analysis was made of ambient air carbon monoxide concentrations measured in and around Los Angeles Airport under a previous EPA contract.[5]
3. An area source dispersion model was used to estimate hydrocarbon and possible resulting oxidant concentrations downwind from the Los Angeles Airport.
4. An estimate was made of the air quality effects of fuel dumping from aircraft.
5. An estimate of contributions by aircraft to total emissions from the metropolitan areas of Los Angeles, New York City, Chicago, and Washington, D.C., was made for 1970 and 1980.

RESULTS OF IMPACT EVALUATIONS

NATIONAL AMBIENT AIR QUALITY STANDARDS

To assess the significance of the aircraft contribution to pollutant concentrations, the concentrations estimated by the dispersion model were compared with the national ambient air quality standards.[8] These national standards have been set in accordance with the Clean Air Act, as amended, and are applicable to areas accessible to the general public external to buildings.

The standards consist of primary ambient air quality standards, designed to protect against adverse health effects, and secondary standards, designed to protect against adverse welfare effects such as plant and material damage or reduction in visibility. The standards apply to hydrocarbons, carbon monoxide, nitrogen dioxide, photochemical oxidants, sulfur dioxide, and particulate matter. The primary and secondary standards are the same for hydrocarbons, carbon monoxide, nitrogen dioxide, and photochemical oxidants, whereas the secondary standards are more stringent than the primary standards for sulfur dioxide and particulates. The short-term standards are not to be exceeded more than once per year. The standards are summarized in Table 4.

It should be noted that nonmethane hydrocarbons at concentrations observed in the atmosphere have not been associated with health effects. The relationship between nonmethane hydrocarbons and photochemical oxidants indicates, however, that peak photochemical oxidant concentrations are associated with hydrocarbon concentrations averaged over the 6 to 9 a.m. period.[9] The nonmethane hydrocarbon standard is based on this relationship. Thus, the average nonmethane hydrocarbon concentration of 160 $\mu g/m^3$ for this period could result in a photochemical oxidant concentration of 160 $\mu g/m^3$ several hours later.

RESULTS OF DISPERSION MODEL AIR QUALITY ANALYSIS

Predicted Concentrations Compared with Primary Air Quality Standards at Air Carrier Airports.

Predicted pollutant concentrations in the airport and its vicinity were compared with primary ambient air quality standards only for those sites to which the general public would reasonably have access for the exposure time specified for each air quality standard. For example, a primary standard for a pollutant concentration averaging time of 1 year was assumed not to apply to sites around terminal buildings

Table 4. NATIONAL AMBIENT AIR QUALITY STANDARDS

Pollutant	Standard Description
Carbon monoxide (Primary and secondary standards are the same)	10 milligrams per cubic meter (9 ppm), maximum 8-hour concentration not to be exceeded more than once per year. - 40 milligrams per cubic meter (35 ppm), maximum 1-hour concentration not to be exceeded more than once per year.
Nitrogen dioxide (Primary and secondary standards are the same)	100 micrograms per cubic meter (0.05 ppm), annual arithmetic mean.
Hydrocarbons (non-methane) (Primary and secondary standards are the same)	160 micrograms per cubic meter (0.24 ppm), maximum 3-hour concentration (6-9 a.m.) not to be exceeded more than once per year. For use as a guide in devising implementation plans to meet the oxidant standards.
Particulate matter Primary standard	75 micrograms per cubic meter, annual geometric mean. - 260 micrograms per cubic meter, maximum 24-hour concentration not to be exceeded more than once per year.
Secondary standard	60 micrograms per cubic meter, annual geometric mean, as a guide to be used in assessing implementation plans to achieve the 24-hour standard. 150 micrograms per cubic meter, maximum 24-hour concentration not to be exceeded more than once per year.
Sulfur dioxide Primary standard	- 80 micrograms per cubic meter, annual arithmetic mean. 365 micrograms per cubic meter, maximum 24-hour concentration not to be exceeded more than once per year.
Secondary standard	60 micrograms per cubic meter, annual arithmetic mean. 260 micrograms per cubic meter, maximum 24-hour concentration not to be exceeded more than once per year. - 1300 micrograms per cubic meter, maximum 3-hour concentration not to be exceeded more than once per year.
Oxidant (Primary and secondary standards are the same)	160 micrograms per cubic meter, maximum 1-hour concentration, not to be exceeded more than once per year.

because the general public would not be expected to remain in that area for a year's time. In general, the duration of the public's exposure to pollutants (in agreement with averaging times prescribed by the air quality standards) was estimated for various airport area sites as follows:

1 hour or 3 hours: roads or areas with no official parking facilities or where parking is prohibited, but where people might stay for a short time. (The 3-hour duration is applicable to waterways in the vicinity of airports.)

1 hour, 3 hours, and 8 hours: air terminal areas and parking areas.

1 hour, 3 hours, 8 hours, and 24 hours: areas where a person could reasonably stay overnight.

1 hour, 3 hours, 8 hours, 24 hours, and 1 year: residential areas in proximity to airports.

It is important to note that particularly high concentrations of pollutants from aircraft were predicted in some airport areas, such as ends of runways, where public access is not allowed. Although the questions of occupational exposure are beyond the scope of this report, the likelihood of exposure of airport workers to high air pollutant concentrations should be recognized.

At each of the four commercial air carrier airports, ambient air pollutant concentrations, both from aircraft alone and from all sources (including aircraft) in the airport vicinity, were predicted at a maximum of 50 sites, with the total number being 193 sites for the four airports. These sites were located on or within a 5-kilometer radius of the center of each airport. In general, the highest aircraft-generated pollutant concentrations occurred on the airport grounds or at the airport boundaries, whereas concentrations from aircraft at 5 kilometers from the airport center were low.

Predicted pollutant concentrations, both from aircraft alone and from all sources (including aircraft), are presented in Table 5 for sites that are accessible to the general public for the averaging times specified in the primary air quality standards and at which the total pollutant concentrations were predicted to exceed the primary standards.

The type of area in which each site is located is also indicated in Table 5. The type of area is indicated in the following manner:

T - Terminal area. Includes terminal buildings, observation decks, passenger-unloading areas, and parking areas in the terminal vicinity.

P = Peripheral area. Applies to the vicinity of the airport boundary to which the public has access, or along roadways that are used by the

Table 5. PREDICTED AMBIENT AIR POLLUTANT CONCENTRATIONS FROM AIRCRAFT ALONE AND FROM AIRPORT VICINITY SOURCES AT SITES WHERE POLLUTANT CONCENTRATIONS EXCEED PRIMARY AIR QUALITY STANDARDS AND WHERE PUBLIC COULD BE EXPOSED FOR TIME OF STANDARD

6 to 9 a.m. maximum nonmethane hydrocarbon concentration, $\mu g/m^3$ Standard = 160 $\mu g/m^3$						1-hour maximum CO concentration, mg/m^3 Standard = 40 mg/m^3		8-hour maximum CO concentration, mg/m^3 Standard = 10 mg/m^3		Annual NO_2 concentration, $\mu g/m^3$ Standard = 100 $\mu g/m^3$	
Site location[a]	Aircraft/ total	Site location	Aircraft/ total	Site location	Aircraft/ total	Site location	Aircraft/ total	Site location	Aircraft/ total	Site location	Aircraft/ total
DCA (T)	0/ 900	LAX (P)	0/ 280	JFK (T)	1000/2240	JFK (T)	85/100	JFK (T)	4/28	ORD (P)	23/160
DCA (T)	72/ 950	LAX (P)	280/ 470	JFK (T)	550/1750	JFK (T)	4/ 45	JFK (T)	3/26	ORD (S)	5/140
DCA (P)	0/ 700	LAX (P)	0/ 170	JFK (T)	800/1700	JFK (T)	3/ 44	JFK (T)	4/17	ORD (S)	5/130
DCA (P)	2/ 190			JFK (T)	760/1400	LAX (P)	55/ 62	JFK (T)	11/18	ORD (S)	5/130
DCA (P)	190/ 600	LAX (S)	0/ 770	JFK (T)	860/1250	LAX (P)	32/ 45	JFK (T)	9/19	ORD (S)	6/130
DCA (P)	650/1350	LAX (P)	45/ 160	JFK (T)	540/1090	ORD (T)	21/ 41	ORD (T)	3/12	ORD (S)	5/130
DCA (P)	80/ 700	LAX (P)	45/ 220	JFK (T)	3650/4200	ORD (S)	9/ 41			DCA (S)	2/120
DCA (P)	170/ 700	LAX (P)	50/ 230	JFK (T)	70/ 330	DCA (P)	110/120			DCA (S)	1/100
DCA (P)	140/ 700	LAX (S)	0/ 750	JFK (P)	490/ 800	DCA (P)	45/ 59			ORD[b] (P)	17/130
DCA (P)	190/ 450	LAX (S)	80/ 260	JFK (P)	480/ 950					ORD[b] (P)	19/140
DCA (P)	0/1050	ORD (T)	600/ 600	JFK (P)	420/ 740						
DCA (P)	0/ 850	ORD (T)	320/ 320	JFK (P)	370/ 510						
DCA (P)	0/ 800			JFK (P)	220/ 380						
DCA (P)	0/ 650	ORD (P)	1700/3350	JFK (P)	190/ 420						
DCA (S)	0/ 350	ORD (P)	2400/2900	JFK (P)	0/ 260						
DCA (S)	45/3000	ORD (P)	3/1700	JFK (P)	0/ 380						
DCA (S)	0/1150	ORD (P)	0/3300	JFK (P)	55/ 490						
DCA (S)	0/ 450	ORD (P)	0/2300	JFK (P)	150/ 750						
DCA (S)	0/ 240	ORD (P)	0/ 420	JFK (P)	90/ 450						
DCA (S)	0/ 800	ORD (P)	0/ 400	JFK (P)	70/1380						
LAX (T)	250/ 480	ORD (S)	150/ 800	JFK (P)	80/ 900						
LAX (T)	1/ 280	ORD (S)	860/ 940	JFK (S)	90/ 280						
LAX (T)	160/ 500	ORD (S)	700/1950	JFK (S)	120/ 290						
LAX (T)	0/ 370	ORD (S)	460/1730	JFK (S)	0/ 760						
LAX (T)	0/ 500	ORD (S)	0/4050	JFK (S)	0/2750						
LAX (T)	0/ 550	JFK (T)	1440/2250	JFK (S)	0/ 340						
JFK (S)	120/ 300	JFK (T)	650/1620	JFK (S)	7/ 650						
		JFK (P)	450/ 750	JFK (S)	70/ 300						

[a]DCA = Washington National Airport, LAX = Los Angeles International Airport, JFK = John F. Kennedy International Airport, and ORD = O'Hare Airport, Chicago. Also T = terminal area, P = peripheral area, and S = surrounding area.

[b]Additional sites in residential areas expected to have high NO_2 concentrations.

general public inside or near the boundary of the airport but that are not near the terminal area.

S = Surrounding area. Applies to areas at a 5-kilometer radius from the center of the airport.

There were a few sites that met the site-selection criteria for SO_2 and particulate matter, but the predicted contribution from aircraft at these sites was negligible. Accordingly, data for these sites are not included in Table 5.

It is important to note that the predicted hydrocarbon concentrations are expressed in terms of nonmethane hydrocarbons. Conversion from predicted total hydrocarbon concentrations was accomplished by assuming 50 percent nonmethane hydrocarbons in the total hydrocarbon concentrations. This factor was based on ratios of nonmethane to total hydrocarbons observed in actual air quality data collected in Los Angeles.[9] Thus, the predicted total hydrocarbon concentrations were divided by two to make them comparable with the nonmethane hydrocarbon standard.

It should also be noted that the NO_x emission rates used in this analysis, particularly for newer types of jet engines, were found to yield total aircraft emissions that were underestimated by a factor of approximately three when compared with total aircraft emissions calculated from more accurate emission factors used to establish baseline aircraft engine emission rates. The baseline emission factors were not available in time for use in the dispersion model, but they have been incorporated into estimates of aircraft emissions presented later in this report. By itself, the use of low NO_x emission factors in the dispersion model would be expected to yield underestimated ambient air concentrations. In this analysis, however, it was assumed in predicting ambient NO_2 concentrations that all NO_x could be considered as NO_2. This is a conservative assumption, made because there exists no well-defined relationship for the conversion of NO to NO_2. In the presence of high concentrations of hydrocarbons, the NO to NO_2 conversion is accelerated, with best estimates indicating that 90 percent of the NO is converted to NO_2 within a 2-hour period in the presence of sunlight. The reaction is essentially negligible at night. Considering all NO_x as NO_2 could by itself result in an appreciable overestimation of annual average NO_2 concentrations. This overestimation of NO_2 concentrations and the underestimation of NO_x emissions resulting from the low NO_x emission factors would tend to be counteracting, however.

In Table 5, NO_2 concentrations, estimated by dispersion modeling, are shown for two special sites that were selected because of their proximity to residential areas where high NO_2 concentrations from aircraft were expected to occur. These

sites are footnoted in Table 5, and were included in calculations for the summary in Table 6.

Table 6. PREDICTED AIRCRAFT CONTRIBUTION TO AMBIENT AIR QUALITY AT COMMERCIAL AIR CARRIER AIRPORTS, COMPARED WITH PRIMARY STANDARDS[a]

	Carbon monoxide exposure		Nonmethane hydrocarbons 6 to 9 a.m. exposure (81 sites)	NO_2 annual exposure (10 sites)
	1-hour (9 sites)	8-hour (6 sites)		
Average total concentration, % of primary standard[b]	155 (62 mg/m^3)	200 (20 mg/m^3)	610 (980 µg/m^3)	131 (131 µg/m^3)
Average contribution by aircraft to total concentration, %	65	25	31	7
Average ambient air concentration from aircraft alone, % of primary standard	100 (40 mg/m^3)	60 (6 mg/m^3)	190 (300 µg/m^3)	9 (9 µg/m^3)
Maximum ambient air concentration from aircraft alone, % of primary standard[b]	275 (110 mg/m^3)	110 (11 mg/m^3)	2,300 (3,650 µg/m^3)	23 (23 µg/m^3)

[a]Based on sites listed in Table 5.

[b]Actual average or maximum concentration given in parentheses.

Table 6, which summarizes the values listed in Table 5 in terms of the ambient air quality standards, indicates the following:

1. At the selected sites where the 3-hour hydrocarbon air quality standard is predicted to be exceeded, the average ambient air hydrocarbon concentration from aircraft alone is predicted to be 190 percent of the standard, with a maximum of 2300 percent of the standard.

   The 81 public access points at which this standard is predicted to be exceeded are located in areas both on and off airport grounds. The points of highest aircraft contribution are located within airport areas that include terminal buildings and their proximity, parking areas, and areas along roadways near the ends of runways. Of the 81 sites, 20 were located in airport terminal areas, 36 were located near the airport periphery, and the remainder were located at a 5-kilometer radius from the centers of the airports.

2. At the selected sites where the carbon monoxide ambient air quality standards are exceeded, the average concentration from aircraft alone is predicted to be 100 percent of the 1-hour standard and 60 percent of the 8-hour standard, with a maximum of 275 percent of the 1-hour standard.

   The 1-hour carbon monoxide standard is predicted to be exceeded at two sites on the periphery of Washington National Airport, at three terminal sites at JFK Airport, at one terminal and one surrounding site at Chicago-O'Hare Airport, and at two sites near the western periphery of the Los Angeles Airport along Pershing Drive. The site of the highest predicted 1-hour CO concentration of 110 mg/m^3 caused by aircraft alone is located at the periphery of Washington National Airport. Carbon monoxide concentrations are predicted to exceed the 8-hour standard in five terminal areas: four at JFK Airport and one at O'Hare Airport. The highest concentration produced by aircraft alone 11 mg/m^3 is predicted to occur at a terminal area of JFK Airport.

3. At the selected sites where the nitrogen dioxide concentrations are predicted to exceed the air quality standard, the predicted average ambient air NO_2 concentration from aircraft alone is about 9 percent of the standard, with a predicted maximum of 23 percent of the standard.

   Predicted nitrogen dioxide concentrations from 10 sites were compared with the standard for NO_2. All the sites were near residential areas, with three of the sites near the periphery of the airport. Among these three sites, the site of highest predicted NO_2 concentration was located within 300 yards of a residential area approximately 2/3 mile east of the O'Hare East-West runway.

Predicted Concentration Compared with Secondary Ambient Air Quality Standards for Particulates and Sulfur Dioxide at Air Carrier Airports

The ambient air concentrations of particulates and SO_2 at sites where the secondary standards are predicted to be exceeded are listed in Table 7. The public has short-term access to many of the sites listed, and such sites are noted. Based on these sites, the aircraft contributions to air quality are summarized in Table 8. This table indicates that the estimated average ambient air concentrations from aircraft alone for particulates are 168 percent of the annual and 33 percent of the 24-hour secondary particulate air quality standards at the sites considered. The maximum particulate concentration from aircraft alone at these sites was estimated to be 200 percent of the annual standard. The concentrations attributed to aircraft are based on dry particulate emissions.

Table 7. PREDICTED AMBIENT PARTICULATE AND SO_2 CONCENTRATIONS FROM AIRCRAFT AND FROM AIRPORT VICINITY SOURCES AT SITES WHERE SECONDARY STANDARDS ARE EXCEEDED ($\mu g/m^3$)

Particulate concentration				SO_2 concentration					
Annual		Maximum 24-hour		Annual		Maximum 24-hour		Maximum 3-hour	
Site location[a]	Aircraft/ total	Site location	Aircraft/ total	Site location	Aircraft/ total	Site location	Aircraft/ total	Site location	Aircraft/ total
DCA_b	67/ 84	DCA_b	140/220	DCA^b	5/ 66	DCA_b	3/ 570	DCA^b	25/1700
LAX_b	86/ 93	DCA_b	0/170	DCA	25/ 69	DCA^b	7/ 320	DCA	0/3700
LAX_b	120/130	DCA^b	0/220	DCA	46/ 79	DCA	2/ 430	ORD_b	2000/2000
LAX^b	97/110	DCA	170/240	DCA_b	3/ 87	DCA_b	2/1500	JFK^b	14/4900
ORD	65/ 86	DCA_b	150/210	DCA_b	2/ 83	DCA^b	0/ 330	JFK	1800/2000
ORD	72/ 91	DCA^b	94/170	DCA_b	3/220	DCA	46/ 310	Standard = 1300 $\mu g/m^3$	
ORD	53/ 91	LAX	280/300	DCA_b	5/ 65	ORD	100/ 380		
Standard = 60 $\mu g/m^3$		LAX	610/630	DCA_b	1/ 70	JFK	15/ 520		
		ORD	150/180	DCA_b	0/ 61	JFK	15/ 760		
		ORD	160/170	DCA_b	0/ 65	JFK	90/ 340		
		ORD_b	80/200	LAX_b	55/ 65	JFK	21/ 300		
		JFK_b	37/250	LAX_b	81/ 91	JFK	25/ 350		
		JFK_b	36/290	LAX^b	64/ 74	JFK	0/ 290		
		JFK_b	80/260	ORD	62/ 80	Standard = 260 $\mu g/m^3$			
		JFK_b	52/200	ORD	54/ 75				
		JFK^b	48/150	ORD_b	36/ 62				
		JFK_b	190/470	JFK^b	5/ 78				
		JFK_b	110/280						
		JFK^b	250/270						
		JFK_b	89/190						
		JFK_b	95/250						
		JFK_b	120/310	Standard = 60 $\mu g/m^3$					
		JFK_b	12/160						
		JFK_b	1/360						
		JFK^b	1/300						
		JFK_b	120/260						
		JFK_b	14/170						
		JFK_b	17/180						
		JFK_b	18/200						
		JFK_b	6/180						
		JFK_b	0/210						
		JFK_b	0/200						
		JFK_b	0/780						
		JFK^b	0/160						
		Standard = 150 $\mu g/m^3$							

[a]DCA = Washington National Airport; LAX = Los Angeles International Airport; JFK = John F. Kennedy International Airport; and ORD = O'Hare Airport, Chicago.

[b]A site to which the public has access.

The SO_2 ambient air concentrations attributable to aircraft alone are estimated to be 37 percent of the annual, 9 percent of the 24-hour, and 2 percent of the 3-hour secondary SO_2 air quality standards at the sites considered. The maximum SO_2 concentration from aircraft alone at these sites was estimated to be 135 percent of the annual standard.

These percentages of the secondary air quality standards are very significant because the secondary particulate and SO_2 standards are set at levels necessary to prevent adverse welfare effects such as material damage, plant damage, and restriction of visibility. Smoke generated by aircraft should be further considered in

Table 8. PREDICTED AIRCRAFT CONTRIBUTION TO AMBIENT AIR PARTICULATE AND SO_2 CONCENTRATIONS COMPARED WITH SECONDARY STANDARDS[a]

	Particulate matter exposure		Sulfur dioxide exposure		
	Annual (3 sites)	24-hour (24 sites)	Annual (10 sites)	24-hour (5 sites)	3-hour (2 sites)
Average total concentration, % of secondary standard[b]	185 (111)	167 (250)	145 (87)	122 (316)	253 (3300)
Average contribution by aircraft to total concentration, %	91	20	25	8	1
Average ambient air concentration due to aircraft, % of secondary standard[b]	168 (101)	33 (50)	37 (22)	9 (24)	2 (20)
Maximum ambient air concentration due to aircraft, % of secondary standard[b]	200 (120)	167 (250)	135 (81)	35 (90)	2 (25)

[a]Based only on sites accessible to public; footnoted in Table 7 with "b".

[b]Actual average or maximum concentration given in parentheses in $\mu g/m^3$.

view of the fact that it causes significant reductions in visibility[5] and results in widespread public complaint.

Results for General Aviation

The two general aviation airports that were studied were Tampa-Miami (Tamiami) Airport in Florida and Van Nuys Airport in California. At Van Nuys Airport, which had higher activity than Tamiami, total emissions from aircraft were less than those at the commercial aviation airports for hydrocarbons, carbon monoxide, sulfur dioxide, nitrogen dioxide, and particulates, although CO emissions from Van Nuys Airport approached those of Washington National Airport. This comparison is evident in a table presented later in this report (Table 10). Lead emissions from aircraft at general aviation airports, however, are roughly a factor of 10 greater than lead emissions from those at the primarily commercial air carrier airports.

At Tamiami Airport, predicted ambient air pollutant concentrations at sites in and around the airport indicated that the contribution from general aviation aircraft to total concentrations of hydrocarbons, carbon monoxide, oxides of nitrogen, sulfur dioxide, and non-lead particulates was well within the ambient air quality standards. At Van Nuys Airport, however, annual average air-lead concentrations from aircraft alone were predicted to be as high as 1.9 $\mu g/m^3$ near the airport boundary. Increased blood-lead levels have been associated[10] with ambient air-lead concentrations above 2 to 3 $\mu g/m^3$. Future increases in total lead emissions may result in concentrations further in excess of these values from general aviation aircraft alone.

Piston-engine general aviation aircraft account for a significant fraction of the total activity at the commercial air carrier airports considered in this study: 32 percent at Washington National Airport, 21 percent at Los Angeles Airport, 13 percent at J. F. Kennedy Airport, and 6 percent at Chicago's O'Hare Airport. At Washington National Airport, piston-powered general aviation aircraft accounted for an estimated 3 percent of the total hydrocarbon, 14 percent of the carbon monoxide, and 1 percent of the NO_x emissions from all aircraft. These values, although maximums among the four commercial air carrier airports, indicate the very significant contributions possible, especially to CO emissions, from general aviation aircraft at some commercial airports. It should be noted that at 7 of the 23 largest hub airports in the United States, general aviation activity comprises larger percentages of total activity than it does at Washington National Airport.

Comparison of the Model's Predictions with Actual Air Quality Data

All atmospheric dispersion models have some inherent uncertainties because of the complexity of simulating weather and dispersion conditions with a mathematical model and because of inaccuracies in emission and activity data. The scarcity of major airport air quality data that were directly comparable with the model's predictions limited any thorough comparisons. Because of the importance that the model's predicted pollutant concentrations would play in estimating the impact of aircraft emissions, however, it was necessary to investigate, within limitations, the uncertainties in the model's predictions. Consequently, data from two studies of air quality at airports were used to compare with the model's predictions. One was conducted at Washington National Airport by EPA personnel during July 20 through 23, 1971; the other was a study done at Los Angeles Airport during May through November 1970 by the Los Angeles Air Pollution Control District under an EPA contract.[5]

The Washington National Airport study was very limited in duration and scope and, consequently, can only be considered to yield approximate results. Areas near the main runway at National were sampled for carbon monoxide and hydrocarbons for 1 hour each day using comparatively crude sampling techniques. Particulate-matter samples were collected with four high-volume samplers around the main runway for three consecutive 4-hour periods from 7 a.m. until 7 p.m. and for one 12-hour period from 7 p.m. to 7 a.m. One sampler at the end of the main runway operated 24 hours from 7 a.m. to 7 a.m., and one located in front of the main terminal operated for three consecutive 4-hour periods and one 12-hour period each day. Meteorological data for the sampling period were obtained from the National Weather Service at the airport, and activity data were obtained by actual observations and from the Federal Aviation Agency for the same days. These data and the actual sampler locations were

used as input to the model in order to reduce possible differences between the model's predictions and the observed concentrations that could be caused by using assumed conditions. The values predicted by the model for the same sampling times were then compared with the observed data. For the carbon monoxide concentrations, 13 comparisons were possible. The model's predictions were lower than the observed concentrations in eight cases and higher in the remaining five cases.

In regard to total hydrocarbons, 13 comparisons between observed and predicted concentrations were possible also. Comparisons of total hydrocarbons showed a much greater variation between the observed and predicted concentrations than existed for carbon monoxide, but for all the comparisons the model's predicted concentrations were much lower than the observed values.

A total of 85 comparisons was possible between the model's predicted concentrations and the observed values for particulate matter. In 82 of the comparisons, the model's predicted concentrations were lower than the measured concentrations. In the remaining three comparisons, the predicted concentrations exceeded those actually observed.

Although for all three sets of comparisons (carbon monoxide, total hydrocarbons, and particulate matter), the scatter in the data and the variations in the comparisons were substantial, the majority of the values predicted by the model were lower than the actual pollutant concentrations.

The study performed at Los Angeles Airport in 1970 obtained continuous carbon monoxide hourly concentrations at fixed receptors near the terminal areas and at the north-eastern and western boundaries of the airport. Additionally, a mobile sampling unit collected hourly carbon monoxide data at points around the perimeter of the airport on a random schedule. Data for the meteorological conditions occurring during the sampling period were obtained and used as input to the model in order to minimize the uncertainties that would have occurred if assumed conditions had been used. Because of the large amount of concentration data collected during the 6-month study, predicted concentrations were not calculated for all of the sampling times. Calculations of concentrations by the model were made only for time periods during the study selected on the basis of meteorological conditions conducive to high concentrations of air pollutants, or on the basis of comparatively high observed concentrations at the sampling sites. A total of 32 comparisons was possible between predicted and the actually observed carbon monoxide concentrations. Of the 32 comparisons made, the predicted concentrations were lower than the observed in 26 cases, and the predicted concentrations were higher than those observed in the remaining 6.

In both the Los Angeles Airport and the Washington National Airport studies, the model's predictions were lower than the corresponding observed concentrations for the majority of the comparisons made. These comparisons suggest that for the majority of hydrocarbon, carbon monoxide, and particulate predictions, ambient air pollutant concentrations may be greater than those estimated by the model. Because of the limited number of total comparisons possible, however, and the large scatter in the available comparisons, it would be premature to form general conclusions regarding the tendency of the atmospheric dispersion model to over- or underestimate ambient air pollutant concentrations.

RESULTS OF OTHER ANALYSES OF AIR QUALITY IMPACT IN AIRPORT AREAS

Emission Density Comparison

Emission densities in airport areas in tons per square mile per year are, in most cases, of greater magnitude than emission densities from their neighboring metropolitan areas for hydrocarbon, carbon monoxide, and nitrogen oxides emissions. Estimated emission densities for airports and for their neighboring metropolitan areas are presented in Table 9. Of the four airports compared in Table 9, Los Angeles Airport has the highest emission densities. The emission densities from aircraft alone at this airport are 1.5 times the CO, 4.4 times the hydrocarbon, and 1.1 times the NO_x emission densities of the Los Angeles area. At the other three airports listed in Table 9, the emission densities from all airport sources are equal to or greater than those in the neighboring metropolitan areas, except for nitrogen oxides in New York and carbon monoxide in Washington, D. C.

This emission density comparison suggests that, in these four airport areas, the contribution by aircraft to hydrocarbon, CO, and NO_x air pollutant concentrations is substantial. Such contributions are particularly important in these instances where major airports lie in or near metropolitan areas in which national ambient air quality standards are currently exceeded.

Analysis of Measured Carbon Monoxide Air Quality Data

The likelihood of significant airport and aircraft contributions to local air pollution levels is suggested by carbon monoxide air quality data gathered from May to November 1970, during a Los Angeles Airport study[5] under EPA contract. It is important to realize that not all of the CO impact discussed here is attributable to aircraft. It is possible that automobile activity in some of the airport and "downwind" sampling areas discussed below accounts for very large proportions of the measured concentrations. An estimate presented in Table 10, however, indicates that aircraft were responsible for 55 percent of the total CO emitted at the Los Angeles Airport in 1970.

Table 9. COMPARISON OF EMISSION DENSITIES FOR AIRPORTS VERSUS URBAN AREAS, 1970

	Area,[a] mi^2	Emission densities,[b] tons/mi^2-day		
		Carbon monoxide	Hydro-carbons	Nitrogen oxides
Los Angeles metropolitan area	1250.0	7.2	2.0	1.0
Los Angeles Airport - all emission sources	3.9	20.6	10.3	2.0
Los Angeles Airport - aircraft alone	3.9	11.2	8.8	1.1
New York metropolitan area	320.0	14.5	3.4	3.6
JFK Airport - all emission sources	4.5	19.6	7.7	2.1
JFK Airport - aircraft alone	4.5	7.7	5.8	0.8
Washington, D.C., metropolitan area	61.0	12.5	1.7	1.7
National Airport - all emission sources	1.0	10.2	2.4	1.7
National Airport - aircraft alone	1.0	6.6	1.7	1.0
Chicago metropolitan area	227.0	8.1	2.5	1.4
O'Hare Airport - all emission sources	6.7	14.1	5.4	1.9
O'Hare Airport - aircraft alone	6.7	6.0	3.9	0.8

[a]Includes those areas used in the operation of the airport, but not necessarily the total area owned by the airport.

[b]Emissions used to calculate airport emission densities are based on all aircraft emissions within each airport area.

Table 10. CURRENT AND PROJECTED EMISSIONS[a] FROM AIRCRAFT AND AIRPORTS
(tons/year)

Airport and year	Particulates[b]		NO_x		SO_2		Lead		Carbon monoxide		Total hydrocarbons	
	Aircraft	Airport total	Aircraft	Airport total	Aircraft	Airport total	Aircraft	Airport total	Aircraft	Airport total	Aircraft	Airport total
Los Angeles												
1970	570	616	3,060	4,369	431	434	0.3	35.2	16,030	29,230	12,570	14,660
1975	610	627	6,790	8,110	490	561	0.9	22.0	16,630	28,730	8,660	10,530
1980	680	693	11,490	12,480	623	726	1.0	7.8	18,480	27,280	4,770	5,760
Washington National												
1970	231	253	820	1,074	105	319	0.5	4.8	2,410	3,731	610	864
1975	242	253	980	1,211	121	330	0.5	2.1	2,700	3,691	680	823
1980	286	297	1,090	1,277	143	352	0.5	0.9	3,030	3,470	720	775
John F. Kennedy												
1970	570	660	2,580	4,846	418	902	0.3	53.9	12,590	32,390	9,490	12,680
1975	550	605	4,660	6,640	415	913	0.4	27.5	11,280	26,680	5,700	8,010
1980	550	583	6,370	7,580	442	957	0.9	7.8	10,680	18,380	2,830	3,930
O'Hare												
1970	900	1,001	3,760	6,290	562	605	0.2	63.8	14,740	34,540	9,580	13,210
1975	970	1,023	5,760	7,520	600	660	0.4	28.6	13,840	31,440	6,300	8,830
1980	1,100	1,100	7,440	8,540	718	803	0.6	7.7	13,530	22,330	3,710	4,920
Van Nuys												
1970	3.2	3.7	12.1	27.5	0.033	0.33	3.2	3.6	1,650	1,870	100	132
1975	5.4	5.7	19.8	34.1	0.066	0.55	5.3	5.5	2,750	2,860	165	198
1980	7.7	7.8	28.6	36.3	0.099	0.88	7.6	7.6	3,960	4,070	242	264

[a]Based on aircraft emissions below 3000 feet altitude.

[b]Includes lead.

One-hour CO concentrations at Los Angeles Airport, measured at sampling stations just outside two satellite terminal areas, were 2.9 and 2.8 parts per million greater, on the average, than CO concentrations measured near the western (most frequently upwind) edge of the airport where the average concentration over a 6-month period was 3 ppm. Additionally, the concentration measured near the eastern (most frequently downwind) edge of the airport was an average of 1.1 ppm greater than the CO concentration measured near the western edge of the airport.

Examination of data from a mobile sampling site gives further indication of the potential increases in carbon monoxide concentrations in air passing over the airport. Mobile sampling site 24, located near the east end of the southern runway complex of Los Angeles Airport, was operated for a total of 30 hours between July and October 1970. For 19 of the 30 hours, the wind was blowing across the airport from the west or west-southwest direction, and for 18 of these hours, it was possible to compare CO concentrations at this site with concentrations measured near the western upwind edge of the airport. The average of the 1-hour CO concentrations for the 18 hours was 5.5 ppm at the site downwind of the airport, and 1.9 ppm at the site at the western upwind edge of the airport, an increase of 3.6 ppm. Increases in concentrations ranged from zero to a maximum of 7 ppm. These increases occurred under typical summer and fall Los Angeles meteorological conditions. Under conditions particularly conducive to high CO concentrations, expected to occur more often in the wintertime, these increases could be substantially greater. Such increases in the carbon monoxide concentration in air passing over the airport are significant in comparison with the national ambient air quality standards for CO of 9 ppm for an 8-hour period and 35 ppm for a 1-hour period.

Although the 1-hour CO ambient air quality standard was exceeded infrequently at most outside samplers in the airport area during the study, in October and September alone the 8-hour national ambient air quality standard was exceeded 12 times at site 204 near the western (most frequently upwind) edge of the airport, 31 times at site 208 in the airplane loading area outside satellite terminal 7, and 22 times at site 209 near the eastern (most frequently downwind) periphery of the airport. Monthly carbon monoxide concentrations at downtown Los Angeles (4 to 6 ppm) and Lennox (6 to 7 ppm) were within the range measured at the airport stations (2 to 18 ppm).

Area Source Dispersion Model

The previously discussed modeling analysis estimated that hydrocarbon concentrations from aircraft alone would be well in excess of the standard in airport areas (Tables 5 and 6). The nonmethane hydrocarbon standard of 160 $\mu g/m^3$, however, is to be used as a "guide in devising implementation plans to meet the oxidant standards."

In Air Quality Criteria for Hydrocarbons,[9] the point is made that on "...days... when meteorological conditions were most conducive to the formation of photochemical oxidant, nonmethane hydrocarbon concentrations of 200 $\mu g/m^3$ (0.3 ppm C) for the 3-hour period from 6:00 a.m. to 9:00 a.m. might produce an average 1-hour photochemical oxidant concentration of up to 200 $\mu g/m^3$ (0.10 ppm) 2 to 4 hours later." Therefore, one way to relate the hydrocarbon emissions to oxidant formation would be to examine the hydrocarbons and their concentrations caused by aircraft an average of 3 hours downwind of the airport area. To this end an additional modeling effort was undertaken for Los Angeles Airport to examine the hydrocarbon concentrations 3 hours downwind of the airport. It must be understood, however, that results should be considered very approximate.

The modeling method used in this analysis involved approximating both airport and surrounding emissions by area sources, and relating these emissions to downwind pollutant concentrations by assuming Gaussian pollutant distribution in the vertical and crosswind directions. For each receptor point, the concentration caused by small-area elements was determined by integrating in the crosswind and upwind directions over each source region. The airport and surroundings were considered as separate source regions, and concentrations from each of these two sources were calculated separately and added together to obtain the total concentration at each receptor. Near the airport source, concentrations are the same as from an area source of infinite extent.[11] At greater distances, edge effects caused by the finite width of the airport are considered by including the integration in the crosswind direction. Also included is the limit to vertical mixing imposed by a more stable layer aloft.

For the purpose of this modeling, the airport was assumed to cover an area of 3.2 by 3.2 kilometers. The time period for the analysis, 8 a.m. to 11 a.m., was chosen on the basis of recurring meteorological conditions conducive to high air pollutant concentrations. A diurnal correction factor was applied to the resulting concentrations to correct for the disproportionately greater amount of activity that occurred during this 3-hour period than occurred during other 3-hour periods during the day. The specific meteorological conditions used for the time period considered were representative of severe conditions, from an air pollution standpoint, that are expected to occur at least once a year in the Los Angeles area.

The results of the analysis are shown in Figure 1. The three curves show total hydrocarbon concentrations downwind of Los Angeles Airport resulting from the surroundings plus total airport emissions, total airport emissions alone, and aircraft emissions alone. The initial concentration at the western airport boundary (0 kilometer on the graph) is shown to be zero, which is a result of the proximity

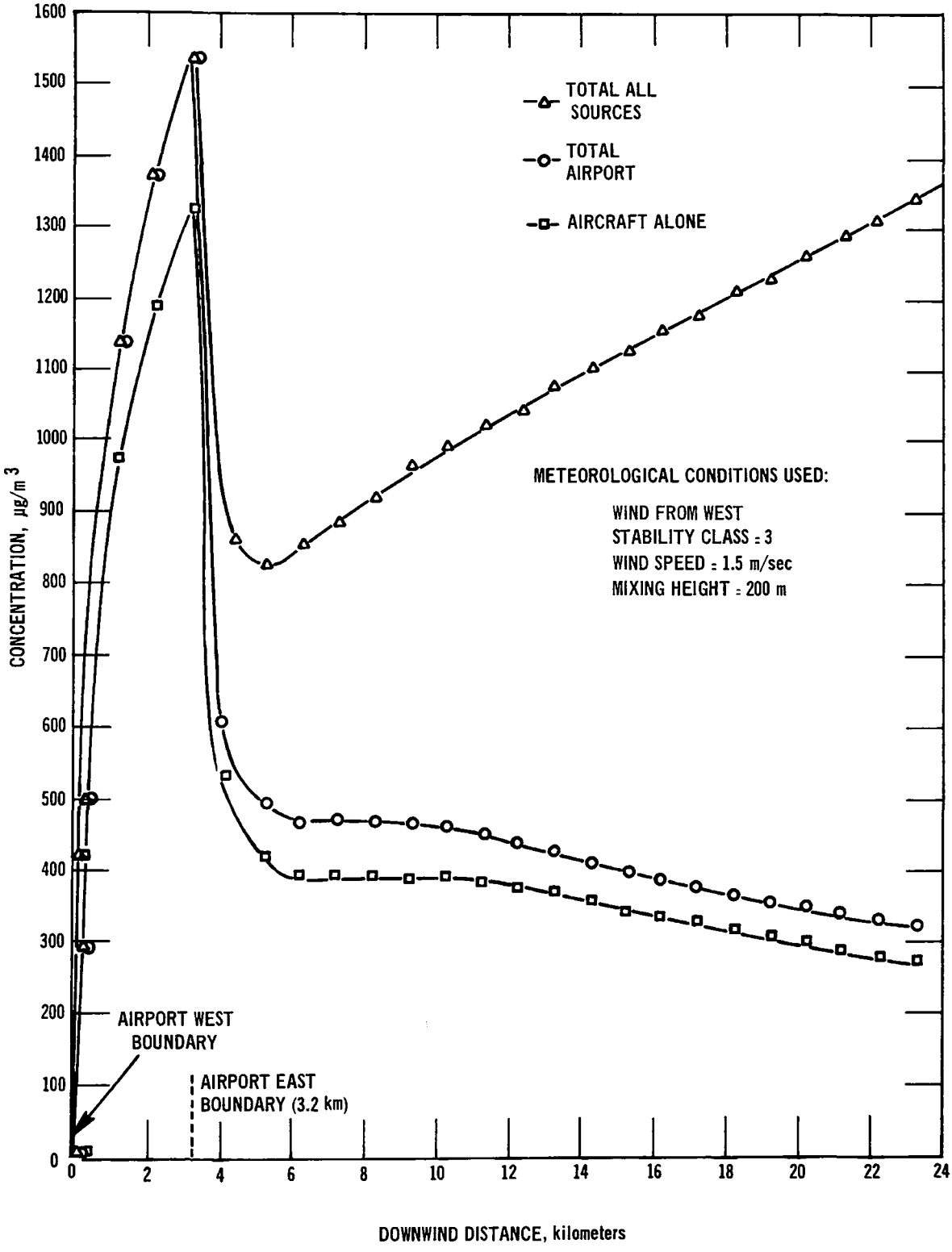

Figure 1. Calculated total hydrocarbon concentrations at Los Angeles Airport and downwind.

of the airport western boundary to the ocean, wind direction from the west, and the assumption of negligible hydrocarbons in air off the ocean. At a point 3 hours downwind (16 kilometers from the eastern boundary), the total hydrocarbon concentration caused by aircraft alone is expected to be approximately 330 $\mu g/m^3$. Assuming that 50 percent of the total hydrocarbons are methane,[9] the nonmethane hydrocarbon concentration 3 hours downwind becomes 165 $\mu g/m^3$, which is 103 percent of the nonmethane hydrocarbon standard of 160 $\mu g/m^3$. Thus, this estimate suggests that nonmethane hydrocarbon concentrations caused by aircraft alone may remain in excess of the standard for the 3 hours necessary for possible formation of oxidant concentrations in excess of the oxidant standard.

Emissions from Unburned-Fuel Dumping

Because of design of turbojet engines currently used by air-carrier airlines, residual unburned fuel is collected in drain cans at shutdown and during start-up. On takeoff, ram air pressure generated as the aircraft accelerates causes these drain cans to vent automatically to the atmosphere. This source of hydrocarbon emissions is seen to be significant when the large number of takeoffs of air carrier aircraft at the commercial airports is considered. The total hydrocarbon emissions resulting from fuel dumping at commercial airports in 1970 were estimated as follows: (1) Los Angeles International, 440 tons; (2) Washington National, 132 tons; (3) J.F. Kennedy International, 360 tons; and (4) Chicago-O'Hare International, 506 tons.

A dispersion model was used to predict total hydrocarbon concentrations, for a 1-hour period, associated with fuel dumping at Washington National Airport. Implicit in this analysis was the assumption that the dumped fuel evaporates fully before reaching the ground. Meteorological conditions assumed in the model were selected to be conducive to high ground-level concentrations of the unburned hydrocarbons. These conditions are of the type most likely to occur around midday in late spring and summer. The results of the analysis indicated that the peak ground-level total hydrocarbon concentration was 18 $\mu g/m^3$, with a concentration of 10 $\mu g/m^3$ occurring over an area of approximately 0.2 square mile.

Widespread complaints about oily films on automobiles and other surfaces in airport vicinities have been voiced. Preliminary investigations at Heathrow Airport in London[6] confirmed the deposition of oily droplets under low-flying incoming flights at the end of a runway under colder, wet conditions; the studies also showed that the localities of complaints about odors or oily deposits were, in the majority of cases, on the flight paths of aircraft. Thus, it is likely that the films are at least partially due to fuel dumping and condensable exhaust hydrocarbon emissions from aircraft.

FUTURE PROJECTION OF AIRCRAFT AND TOTAL EMISSIONS IN AIRPORT AREAS

Based on projections from Reference 1, revised to incorporate more accurate emission factors, total emissions of pollutants from aircraft and from all sources at different airports were projected from the baseline year of 1970 through 1980. These projections are presented in Table 10 for total hydrocarbons, carbon monoxide, nitrogen oxides, sulfur dioxide, particulate matter (including lead), and lead. The aircraft projections are based on present emission rates for each aircraft engine class and do not incorporate potential future reductions in emissions as a result of aircraft emission standards. The projected aircraft emissions reflect increased activity and changes in the mix of existing engines.

At the four air carrier airports during the 1970's, as a result of continued introduction of jet engines found in present-day new jet aircraft, total emissions of carbon monoxide from aircraft are not projected to change greatly. Hydrocarbon emissions, however, although predicted to increase by 18 percent at Washington National Airport, are expected to decrease by about 60 to 70 percent at Los Angeles, John F. Kennedy, and O'Hare Airports. The estimated average increase in aircraft operations is 20 percent at these airports during the 1970's, indicating, in general, lower hydrocarbon and carbon monoxide emissions from the newer and, in many cases, larger engines. The substantial increases in aircraft NO_x emissions of 275 percent at Los Angeles, 146 percent at John F. Kennedy, 98 percent at O'Hare, and 33 percent at Washington National Airports, however, reflect the greater amounts of NO_x emitted during an entire LTO cycle from the newer engines. Some increases in SO_2 and particulate emissions from aircraft are projected to occur, and such increases usually follow increases in aircraft operations.

At Van Nuys Airport, the increases in all pollutants paralleled the large projected increases in activity at this airport. During the 1970's, emissions of hydrocarbons, carbon monoxide, NO_x, and lead from aircraft are projected to increase by about 140 percent.

It is estimated, as Table 10 indicates, that in 1975 CO emissions from aircraft at Van Nuys Airport will exceed CO emissions from aircraft at Washington National Airport. This estimation indicates the increasing importance of general aviation aircraft emissions, and emphasizes that during an LTO cycle, CO emissions from a small general aviation piston engine can, in many cases, be expected to approach CO emissions from a commercial air carrier turbine engine.

The comparison of emission densities (airport versus metropolitan area) for 1975 and 1980 demonstrates that emission densities from all airport sources will, for every city except New York, exceed those of the metropolitan areas in which they

are located. In 1980, the emission densities from aircraft alone at these airports are predicted, except for New York, to exceed emission densities from the metropolitan areas.

Thus the ratio of the airport emission densities to those of the metropolitan areas will, in most cases, be increasing. In some instances they will be increasing dramatically. The trends can be identified in Table 11, which indicates that aircraft can be expected to become increasingly significant contributors to air pollutant concentrations in airports and their vicinities.

CURRENT AND PROJECTED CONTRIBUTION OF AIRCRAFT TO EMISSIONS IN METROPOLITAN AREAS

The contribution by aircraft to total hydrocarbon, carbon monoxide, and oxides of nitrogen emissions from the four metropolitan areas of Los Angeles, New York City, Washington, D. C., and Chicago is of concern because the ambient air quality standards for these pollutants are exceeded in all four cities. While the ambient air quality standards are required to be met by the mid-1970's, preliminary estimates, based primarily on data from drafts of implementation plans, indicate that a great deal of difficulty will be experienced in meeting some of the standards in these and other cities by that time, without highly disruptive changes such as major traffic and land-use controls.

The contributions by aircraft to emissions from these areas may have significant effects on the ability of these areas to meet and maintain air quality standards, particularly in areas neighboring airports. In the Los Angeles basin area, an area of particularly high pollutant concentrations, the estimated contribution by aircraft to total emissions in 1970 and 1980 is detailed in Table 12.

It is evident from Table 12 that aircraft emissions will become increasingly important as other emission sources, particularly automobiles, are controlled. It is also evident that by 1980 the hydrocarbon and, especially, the carbon monoxide emissions from aircraft using airports other than Los Angeles International Airport (primarily single-engine, piston-powered general aviation aircraft) will become particularly significant when compared with emissions from the primarily commercial jet aircraft using Los Angeles International Airport.

In Table 13, the contribution to metropolitan emissions by aircraft from the major airports of each of the three other cities is estimated. The aircraft contributions, as shown in Table 13, are of significance presently and, in general, will become much more significant in the future.

Table 11. COMPARISON OF EMISSION DENSITIES FOR AIRPORTS VERSUS URBAN AREAS FOR 1970, 1975, and 1980

	Area,[a] mi^2	Emission densities,[b] tons/mi^2-day								
		1970			1975			1980		
		Carbon monoxide	Hydro-carbons	Nitrogen oxides[2]	Carbon monoxide	Hydro-carbons	Nitrogen oxides[2]	Carbon monoxide	Hydro-carbons	Nitrogen oxides
Los Angeles metropolitan area	1250.0	7.2	2.0	1.0	4.8	1.1	0.9	2.8	0.9	0.8
Los Angeles Airport - all emission sources	3.9	20.6	10.3	2.0	20.2	7.4	3.5	19.1	4.0	5.6
Los Angeles Airport - aircraft alone	3.9	11.2	8.8	1.1	11.7	6.1	2.6	13.0	3.4	4.9
New York metropolitan area	320.0	14.5	3.4	3.6	11.4	2.4	3.6	5.5	1.3	3.2
Airport - all emission sources	4.5	19.6	7.7	2.1	16.2	4.9	2.7	11.2	2.4	3.0
Airport - aircraft alone	4.5	7.7	5.8	0.8	6.9	3.5	1.5	6.5	1.7	2.3
Washington D.C. metropolitan area	61.0	12.5	1.7	1.7	7.9	1.1	1.5	3.3	0.4	1.3
National Airport - all emission sources	1.0	10.2	2.4	1.7	10.1	2.3	1.8	9.5	2.1	1.9
National Airport - aircraft alone	1.0	6.6	1.7	1.0	7.4	1.9	1.2	8.3	2.0	1.4
Chicago metropolitan area	227.0	8.1	2.5	1.4	6.3	1.7	1.4	1.4	0.9	1.2
O'Hare Airport - all emission sources	6.7	14.1	5.4	1.9	12.9	3.6	2.0	9.1	2.0	2.3
O'Hare Airport - aircraft alone	6.7	6.0	3.9	0.8	5.7	2.6	1.3	5.5	1.5	1.8

[a]Airport areas represent those areas devoted to the operation of the airport, but not necessarily the total area owned by the airport.

[b]Emissions used to calculate airport emission densities are based on all aircraft emissions within each airport area.

Table 12. CONTRIBUTION TO TOTAL EMISSIONS BY AIRCRAFT IN LOS ANGELES BASIN AREA[a]

Pollutant	Estimated contribution, %	
	1970	1980
CO	0.8 (0.5)[b]	3.6 (1.4)
HC	1.4 (1.4)	1.5 (1.2)
NO_x	0.7 (0.7)	3.3 (3.2)

[a]Includes the densely populated 1250-square-mile area of Los Angeles County in the Los Angeles Basin.

[b]Values in parentheses indicate contributions caused by aircraft from Los Angeles Airport alone.

Table 13. CONTRIBUTION TO TOTAL METROPOLITAN EMISSIONS BY AIRCRAFT USING MAJOR AIRPORTS IN THREE CITIES

Metropolitan area and airport	Pollutant	Estimated contribution, %	
		1970	1980
City of Chicago: O'Hare and Midway Airports	CO	2.3	5.9
	HC	4.6	5.1
	NO_x	3.3	7.6
New York City: J.F.K. and LaGuardia Airports	CO	0.9	2.3
	HC	2.5	2.4
	NO_x	0.8	2.1
Washington, D. C.: Washington National Airport	CO	0.5	2.4
	HC	1	4.8
	NO_x	1.3	2.3

Tables 12 and 13 are presented to indicate that control of aircraft emissions could make a significant contribution to allowing both implementation and maintenance of total metropolitan emission reductions consistent with the national ambient air quality standards.

TECHNOLOGICAL FEASIBILITY OF CONTROLLING AIRCRAFT EMISSIONS

Information on emission control methods is necessary to determine the levels to which aircraft emissions can feasibly be reduced. The results of an earlier Federal study,[3,12] indicated that practical control approaches include modification of aircraft engines, fuel, and ground operational procedures. More recently, the Aerospace Industries Association (AIA) has distributed a report[13] that summarizes the results of extensive investigations conducted by industry on: (1) emission characteristics of aircraft gas turbine engines; (2) causes of such emissions; and (3) methods for their reduction. The AIA report also identifies the possibility of reducing emissions through modifications in engines (especially combustor design) and in ground operational procedures.

Thus, the current assessment of control methods must consider each of these approaches. In assessing the feasibility of a control method, four factors must be explored: (1) the effect of the method on the functioning or capacity of the aircraft system; (2) the effectiveness of the method in reducing emissions; (3) the cost of utilizing the method; and (4) the time required for implementing the method. Information on emission-measurement instrumentation is necessary to ensure that aircraft emissions can be measured with the accuracy and sensitivity necessary for enforcing the desired standards.

The specific objectives of this investigation of aircraft emission control technology were:

1. To identify methods of controlling aircraft emissions through modification of engines, fuels, and ground operations.

2. To estimate the effectiveness of these control methods in reducing aircraft emission rates.

3. To estimate the time and cost of implementing these control methods.

4. To assess the technology of measuring emissions from aircraft engines, and to identify areas where advancements in instrumentation or test procedures are required.

The investigation of fuel modification was discontinued after preliminary analysis indicated that no significant reductions in emissions could be achieved by

modifying fuels, except for reductions in sulfur or lead that result in proportionate reductions of SO_2 and lead emissions.

A list of specific emission control methods involving engine modifications was formulated on the basis of preliminary analyses which indicated that each method was feasible and offered a significant reduction in one or more emission classes. Feasibility was based on the following factors:

1. No reduction in engine reliability (safety).
2. Little or no reduction in engine performance (power-weight ratio).
3. Reasonable cost of implementation.

The preliminary list of control methods was then subjected to more detailed analysis of control effectiveness and implementation costs. Control methods involving changes in ground operations were evaluated in a similar manner.

In the evaluation of the emission control methods involving engine modifications, the following emission classes were given primary consideration:

1. Carbon monoxide (CO).
2. Nitrogen oxides (NO_x).
3. Total hydrocarbons (including drained fuel) (THC).
4. Dry particulates (DP).
5. Smoke.

EMISSION CONTROL BY ENGINE MODIFICATION

Engine Classification

To facilitate analyses of engine modifications, aircraft engines have been categorized according to their thrust or power level. The classification system that has been adopted is indicated in Table 14.

Table 14. AIRCRAFT ENGINE CLASSIFICATION

Engine class	Engine type	Power range, lb thrust or eshp
T1	Turbine	Less than 6,000
T2	Turbine	6,000 to 29,000
T3	Turbine	Greater than 29,000
P1	Piston	All piston engines

This classification system, although it is based simply upon power level, effectively groups together engines of similar emission potential (when the emission rates are normalized according to an appropriate engine-size parameter). Also, the effectiveness and cost of the control methods are similar for all engines within each class. Thus, the classification system has been particularly useful for this program and may also provide a rational basis for the formulation of emission control standards.

Three classes of turbine engines are defined, and all piston engines are included in a single class. The system is effective in that it categorizes engines according to their principal applications and according to certain design characteristics that affect emission rates.

The small turbine engine class (T1) includes most of the turboshaft and small turbojet and turbofan engines used in business and small commercial aircraft. These engines should be considered separately because the relatively small size of the combustor components (or large surface-volume ratio) makes control of certain emissions more difficult than with larger engines.

The next turbine engine class (T2) includes most of the turbojet and turbofan engines used in medium-to-large commercial aircraft. The design characteristics of most of these engines are basically similar.

The third turbine engine class (T3) includes large turbofan engines for "jumbo" transport aircraft and the SST engines currently in use or under development.

Emission Control Methods and Effectiveness

An analysis has been conducted of the technology for controlling emissions from aircraft engines by means of engine modifications. The purpose of this analysis was to identify specific methods of reducing pollutant emissions from aircraft engines and to indicate the reductions in rates of emission attainable by these methods. Various engine modifications have been identified that appear to be feasible in the sense that they can be applied to aircraft without degrading engine reliability or seriously reducing aircraft performance. The costs of implementing these control methods also appears to be within reasonable limits, at least from preliminary analysis.

Turbine Engines - The engine modification control methods considered feasible for turbine engines are listed and described briefly in Table 15. Six methods are, at least in principle, applicable to existing engines by retrofitting of new or modified parts, and to engines currently in production. Two methods are considered to be applicable only to future engines of new design, inasmuch as the modifications

Table 15. ENGINE MODIFICATIONS FOR EMISSION CONTROL FOR EXISTING AND FUTURE TURBINE ENGINES

Control method	Modification
Existing engines	
t1 - Minor combustion chamber redesign	Minor modification of combustion chamber and fuel nozzle to achieve best state-of-art emission performance.
t2 Major combustion chamber redesign	Major modification of combustion chamber and fuel nozzle incorporating advanced fuel injection concepts (carburetion or prevaporization).
t3 Fuel drainage control	Modify fuel supply system or fuel drainage system to eliminate release of drained fuel to environment.
t4 - Divided fuel supply system	Provide independent fuel supplies to subsets of fuel nozzles to allow shutdown of one or more subsets during low-power operation.
t5 Water injection	Install water injection system for short duration use during maximum power (takeoff and climb-out) operation.
t6 - Modify compressor air bleed rate	Increase air bleed rate from compressor at low-power operation to increase combustor fuel-air ratio.
Future engines	
t7 Variable-geometry combustion chamber	Use of variable airflow distribution to provide independent control of combustion zone fuel-air ratio.
t8 Staged injection combustor	Use of advanced combustor design concept involving a series of combustion zones with independently controlled fuel injection in each zone.

required are too extensive to be applied to engines for which development has been completed.

The first control method consists of simple modifications of the combustor and fuel nozzle to reduce all emission rates to the best levels currently attainable within each engine class. The degree of control attainable depends upon the performance of specific engines compared with those engines in the same class that have the best emission performances. Each of the other control methods is more specifically directed at one or two pollutant classes.

The actual reduction in emission rate achievable through the use of a control method varies with the pollutant considered, the engine class, and the engine operating mode. Estimates of the effectiveness of each control method have been made for all combinations of these factors and are presented in Tables 16 and 17. The estimation of emission control effectiveness for turbine engines is based upon reductions attainable from "best current emission rates." These rates are defined as those attainable through control method t1, minor combustion chamber redesign.

Table 16. EFFECTIVENESS OF t1 MINOR COMBUSTION CHAMBER REDESIGN[a] ON REDUCTION OF EMISSIONS FROM TURBINE ENGINES

(Emission rates in lb/1000 lb of fuel)

Engine class	Pollutant	Mode		
		Idle/taxi	Approach	Takeoff
T1	CO	25	5	2
T1	THC	10	1	0.2
T1	NO_x	3	7	11
T1	DP	0.2	0.5	0.5
T2	CO	45	6	1
T2	THC	10	1	0.1
T2	NO_x	2	6	12
T2	DP	0.2	0.5	0.5
T3	CO	50	3	0.5
T3	THC	10	1	0.1
T3	NO_x	3	10	40
T3	DP	0.1	0.1	0.1

[a]Minor combustor redesign is assumed to reduce the smoke to invisible or "smokeless" levels for all engine classes.

It is predicted that all engines in each class could be modified to achieve these "best rates." The values of these rates are listed in Table 16. These "best rates" are not the lowest rates indicated for each engine class, but are rates near the low end of those emission rates that appear to be realistically attainable. The use of the "best rate" basis is necessary to allow effectiveness estimates to be made for each engine class. Because of the wide variations in actual emission rates for turbine engines, the use of average rates as a basis for an effectiveness analysis would be less significant. Estimates are based upon demonstrated performance in a few cases. In most instances, however, no direct experience has been obtained with these control methods on aircraft engines. Therefore, to a large extent, estimates of effectiveness are based on theoretical analyses of engine performance under the operating conditions associated with the control methods. The bases for these estimates are summarized in Table 18.

Emission-control effectiveness is indicated in Tables 16, 17, and 18 for each control method and for each pollutant for which a significant degree of control would be expected. Pollutants for which little or no control would be expected are not listed. Effectiveness is indicated separately for each engine class. No estimates have been made for control of reactive hydrocarbons, odor, or aldehydes

Table 17. EFFECTIVENESS OF ENGINE MODIFICATION IN CONTROL OF EMISSIONS FROM TURBINE ENGINES, BY OPERATING MODE[a]

Control method	Engine class	Pollutant	Mode		
			Idle/taxi	Approach	Takeoff
t2[b]	T1	DP	0.5	0.5	0.5
t2	T2	DP	0.5	0.5	0.5
t3	T1	THC	NC[c]	NC	0[d]
t3	T2	THC	NC	NC	0[d]
t3	T3	THC	NC	NC	0[d]
t4	T1	CO	0.25	NC	NC
t4	T1	THC	0.25	NC	NC
t4	T2	CO	0.25	NC	NC
t4	T2	THC	0.25	NC	NC
t4	T3	CO	0.25	NC	NC
t4	T3	THC	0.25	NC	NC
t5	T1	NO_x	NC	NC	0.25
t5	T2	NO_x	NC	NC	0.25
t5	T3	NO_x	NC	NC	0.25
t6	T1	CO	0.5	NC	NC
t6	T1	THC	0.5	NC	NC
t6	T2	CO	0.5	NC	NC
t6	T2	THC	0.5	NC	NC
t6	T3	CO	0.5	NC	NC
t6	T3	THC	0.5	NC	NC
t7 or t8	T1	CO	0.1	NC	NC
t7 or t8	T1	THC	0.1	NC	NC
t7 or t8	T1	NO_x	NC	NC	0.5
t7 or t8	T1	DP	0.5	0.5	0.5
t7 or t8	T2	CO	0.1	NC	NC
t7 or t8	T2	THC	0.1	NC	NC
t7 or t8	T2	NO_x	NC	NC	0.5
t7 or t8	T2	DP	0.5	0.5	0.5
t7 or t8	T3	CO	0.1	NC	NC
t7 or t8	T3	THC	0.1	NC	NC
t7 or t8	T3	NO_x	NC	NC	0.5
t7 or t8	T3	DP	0.5	0.5	0.5

[a]Emission rate is fraction of best current rate assumed to be attainable through minor combustion chamber redesign and with control method cited.

[b]t2 Major combustion chamber redesign.
t3 Fuel drainage control.
t4 = Divided fuel supply system.
t5 = Water injection.
t6 = Modify compressor air bleed rate.
t7 = Variable-geometry combustion chamber.
t8 = Staged injection combustor.

[c]NC indicates no change.

[d]Refers to raw fuel drainage only.

Table 18. BASES FOR CONTROL METHOD EFFECTIVENESS ESTIMATES FOR TURBINE ENGINES

Control method	Rationale
t1 Minor combustion chamber redesign	The assumption is made that emission rates for all engines within a given class can be reduced to common, optimum levels (on a lb/1000 lb fuel basis) by minor combustor modifications. These optimum emission rates are based on the best performance reported for each engine class, excluding extreme data points.
t2 Major combustion chamber redesign	Estimates are based on reports of carbureting fuel injector performance and reduction of smoke emission. Concept is incorporated in some Class T3 engines. Estimates are based on assumption that best emission rate for Class T1 and T2 engines is at an exhaust visibility threshold at maximum power. Carburetion appears to reduce smoke level, and presumably particulate emissions, to approximately half that level.
t3 - Fuel drainage control	Estimate is based on the assumption that fuel drainage can be completely eliminated by collecting drained fuel and returning to fuel tank.
t4 - Divided fuel supply system	Control method results in combustion zone fuel-air ratio similar to that at approach condition. Reduction in CO and THC from idle to approach is approximately 90 percent in Class T1 and T2 engines and 90 percent in Class T3 engines. Effectiveness is reduced by one order because combustor is not operating at "well-designed" condition.
t5 Water injection	Water injection is assumed only at takeoff at a rate equal to twice the fuel rate. Water injection into compressor or diffuser is assumed to be by system similar to those in current use. Effectiveness based upon published results with steam injection.[14] Water injection assumed to be of equal effectiveness when injected upstream of combustor.
t6 Modify compressor air bleed rate	Assumptions are (1) fraction of air that can be bled is small so that engine operating point is nearly unchanged, (2) combustor f/a varies inversely with air bleed rate, and (3) CO and THC emissions at idle vary as the (air mass flow rate)^3 and inversely as (f/a)^3. This relationship is based upon data from Reference 12. If maximum air bleed rate is 20 percent, CO and THC emission rates are reduced by 50 percent.
t7 Variable-geometry combustion chamber t8 Staged injection combustor	Combustor primary zone is assumed to operate at a constant f/a equal to normal f/a at approach power condition (primary equivalence ratio = 0.6). CO and THC emissions at idle are reduced to levels corresponding to approach power, or by 90 percent for Classes T1 and T2 and 90 percent for Class T3. Combustor incorporates design characteristics that provide good mixture in combustion zone. This feature and constant f/a operation combine to reduce NO emissions at full power by 50 percent[15] and particulate emissions by 50 percent at all power levels as in t2.

because control methods applicable to these emissions have not been identified. Some reductions in these emissions may occur along with reductions in THC emissions. Any of the modifications defined for existing turbine engines (t1 through t6) could be combined to achieve increased emission control effectiveness with the exception of modifications t4 and t6. These two are mutually exclusive.

Piston Engines The control methods considered feasible for aircraft piston engines are listed with brief descriptions in Table 19. These methods include most of the approaches used to control carbon monoxide (CO) and total hydrocarbon (THC) emissions that have been developed for automotive engines. Methods for controlling nitrogen oxide (NO_x) emissions are not included inasmuch as the fuel-rich operating conditions of aircraft piston engines result in low NO_x emission rates. NO_x emission control may be required, however, in conjunction with any attempt to reduce CO and THC emissions by changing engine operating conditions.

Table 19. ENGINE MODIFICATIONS FOR EMISSION CONTROL FOR EXISTING AND FUTURE PISTON ENGINES

Control method	Modification
Existing engines	
p1 Simple air injection	Air injected at controlled rate into each engine exhaust port.
p2 Thermal reactors	Air injection thermal reactor installed in place of, or downstream of, exhaust manifold.
p3 Catalytic reactors for HC and CO control	Air injection catalytic reactor installed in exhaust system. Operation with lead-free or low-lead fuel required.
p4 - Direct-flame afterburner	Thermal reactor with injection of air and additional fuel installed in exhaust system.
p5 Water injection	Water injected into intake manifold with simultaneous reduction in fuel rate to provide for cooler engine operation at leaner fuel-air ratios.
p6 Positive crankcase ventilation	Current PCV system used with automotive engines applied to aircraft engines. Effective only in combination with one of preceding control methods.
p7 Evaporative emission controls	A group of control methods used singly or in combination to reduce evaporative losses from the fuel system. Control methods commonly include charcoal absorbers and vapor traps in combination with relatively complex valving and fuel flow systems.
Future engines	
p8 Engine redesign	Coordinated redesign of combustion chamber geometry, compression ratio, fuel distribution system, spark and valve timing, fuel-air ratio, and cylinder wall temperature to minimize emissions while maintaining operational reliability.

Eight piston-engine control methods are listed in Table 19 including the use of direct-flame afterburners and water injection, methods that are not being considered currently for automotive engines. Afterburners are included here since they might be used to advantage because they can utilize the high velocity airflow around the aircraft. Then too, the adaptation of other methods may be less feasible for aircraft than for automobiles. The piston-engine emission-control methods were identified and evaluated through reviews of published evaluations of these methods. Of the methods identified, all are considered applicable to existing engines except those that would require redesign of the basic engine or its control systems.

Effectiveness estimates for piston engines are based on reductions from current uncontrolled rates listed in Table 20. Emission rates from piston engines do not vary widely, so that control effectiveness can be based on average rates for existing engines. The effectiveness estimates shown in Table 21 (which are based on published results of effectiveness of automotive emission controls) are based in most cases on the application of individual control methods without other engine changes. Method p6 (PCV) is an exception; it is considered to be useful only in combination with method p1, p2, p3, p4, p5, or p8.

Table 20. CURRENT UNCONTROLLED EMISSION RATES FOR PISTON ENGINES[16]
(lb/1000 lb of fuel)

Pollutant	Mode			
	Idle	Taxi	Approach	Takeoff
CO	896	882	918	849
THC[a]	48	76	80	18
NO_x (as NO_2)	7	4	4	6

[a]Total hydrocarbon (THC) emission rates have been increased by 50 percent to account for crankcase blow-by emissions. Evaporative emissions are not included in these rates.

Piston-engine modifications p1 through p5 are designed to serve the same function and, thus, are mutually exclusive. All of the others could be combined with any of the modifications p1 through p5 to achieve increased emission-control effectiveness.

Cost and Time Requirements for Control-Method Development and Implementation

Existing Engines - The cost and time requirements of applying each control method applicable to existing engines have been estimated. These estimates are of a preliminary nature and are intended to indicate the magnitude of the costs involved in

Table 21. EFFECTIVENESS OF ENGINE MODIFICATIONS IN CONTROL OF EMISSIONS FROM PISTON ENGINES, BY POLLUTANT[a]

Control method	Controlled emission rate		
	CO	THC[b]	Lead
p1 - Simple air injection	0.5	0.5	NC[c]
p2 - Thermal reactor	0.25	0.25	NC
p3 - Catalytic reactor	0.25	0.25	0.1
p4 Direct-flame afterburner	0.1	0.1	NC
p5 Water injection	0.25	0.25	NC
p6 Positive crankcase ventilation (PCV)	NC	d	NC
p7 - Evaporative emission control	NC	e	NC
p8 - Engine redesign	0.5	0.5	NC

[a]Emission rate is fraction of uncontrolled emission rate after installation of control method and applies to all operating modes.

[b]Exhaust HC only.

[c]NC indicates no change.

[d]PCV would eliminate blow-by emissions when used in combination with p1, p2, p3, p4, p5, or p8. Blow-by THC emission estimated to be equal to 30 percent of uncontrolled exhaust emission.

[e]Evaporative controls would reduce THC emissions due to evaporation from fuel supply. Magnitude of uncontrolled emissions is unknown.

controlling emissions from all civil and military aircraft. Cost and time requirements have been estimated separately for control-method development and implementation. Development includes all effort required from initial stages through certification of the control method for a specific engine class and tooling for production. Implementation includes initial installation of the control method on all engines of a given class, and any costs associated with additional effort or materials required for the control method throughout the remaining service life of the engines.

Because few of the control methods have actually been developed for or applied to aircraft engines, and because many factors affect total implementation costs, many uncertainties are involved in the estimates. The estimates of development cost and time requirements are considered to be reliable. They are judged to be accurate within a factor of about 2. The estimates of implementation costs are considered

to be less reliable. The cost and service life of a modified engine component cannot be predicted accurately. Yet these factors strongly affect the cumulative costs of operating and maintaining the modified engine. This uncertainty is unfortunate because implementation costs could be far greater than development costs for some control methods. Thus, the estimates of implementation costs can only be regarded as indicative of cost penalties that might be involved with control-method implementation.

Estimates are given in Table 22 of the development time, development costs, and implementation costs for application of each control method to the current population of all civil engines.

Table 22. TIME AND COSTS FOR MODIFICATION OF CURRENT CIVIL AVIATION[a] ENGINES

Control method	Development time, years	Development cost, 10^6 dollars	Implementation cost, 10^6 dollars
Turbine engines			
Minor combustion chamber redesign	2.5 to 5	37	343
Major combustion chamber redesign	5 to 7.5	74	589
Fuel drainage control	3 to 5.5	35	44
Divided fuel supply	5 to 7.5	84	102
Water injection	2.5 to 4	25	151
Compressor air bleed	4 to 6.5	90	58
Piston engines			
Simple air injection	1.5 to 3	9	165
Thermal reactor	3 to 6	25	424
Catalytic reactor	2.5 to 5	22	535
Direct-flame afterburner	3 to 6	25	424
Water injection	1.5 to 3	9	81
Positive crankcase ventilation	1 to 2	4	94
Evaporative emission control	1.5 to 2.5	4	269

[a]"Civil aviation" includes air carrier and general aviation engines.

The development time requirements listed in Table 22 are the periods required to reach the point where installation of the control methods in existing engines could begin. Installation of any control method in all existing engines would require an

additional time period that is dependent primarily on the availability of engine maintenance facilities.

The time for implementation is estimated to be 2-1/2 years for turbine engines and 5 years for piston engines. Table 23 presents costs by category: air carrier, general aviation, and military.

Table 23. COST RESULTS FOR TURBINE ENGINE POPULATION BY SEPARATE USE CATEGORIES

Engine class	Control method	Cost scaling factor	Development cost per engine family, 10^6 dollars	Implementation cost per engine, 10^3 dollars	Total cost, 10^6 dollars			
					Air carrier	General aviation	Civil aviation[a]	Military aviation
T1	t1	0.35	0.90	12.4	19.2	90.5	109.7	533.0
T1	t2	0.35	1.80	21.3	34.5	159.3	193.8	921.0
T1	t3	0.35	0.99	1.6	7.7	25.6	33.5	87.0
T1	t4	0.35	1.80	3.7	14.9	51.5	66.4	190.0
T1	t5	0.35	0.62	5.5	9.8	43.6	53.4	240.0
T1	t6	0.35	2.20	2.1	15.5	48.1	63.6	131.0
T2	t1	1.00	0.90	35.5	243.0	17.8	259.8	1,032.2
T2	t2	1.00	1.80	69.9	418.0	31.0	449.6	1,774.4
T2	t3	1.00	0.99	4.5	39.5	4.0	43.5	137.9
T2	t4	1.00	1.80	10.5	87.0	8.3	95.3	317.4
T2	t5	1.00	0.62	15.6	108.7	8.2	116.9	454.9
T2	t6	1.00	2.20	6.0	61.5	7.1	68.6	190.6
T3	t1	1.64	0.90	58.3	10.0	0.0	10.0	16.8
T3	t2	1.64	1.80	100.0	19.0	0.0	19.0	29.4
T3	t3	1.64	0.99	7.4	7.4	0.0	7.4	3.9
T3	t4	1.64	1.80	17.2	13.7	0.0	13.7	8.0
T3	t5	1.64	0.62	25.6	5.9	0.0	5.9	7.8
T3	t6	1.64	2.20	9.9	16.0	0.0	16.0	7.0

[a]"Civil aviation" includes air carrier and general aviation engines.

To put the implementation costs in a different perspective, they may be expressed as fractions of total engine costs. For a typical class T2 (turbine) engine, the cost of installing and maintaining control methods ranges from $4,500 to $61,000, assuming a 10-year engine life. Based on a total engine cost of $250,000, these control-method implementation costs represent 2 to 25 percent of the total engine cost. For a typical piston engine, estimated control-method implementation costs range from $600 to $4,000, also based upon a 10-year engine life. For a total

engine cost of $6,000, these implementation costs represent 10 to 65 percent of the total engine cost.

The turbine engine cost and time estimates were developed by using the application of low-smoke combustors to the JT8D engine class as a reference. Cost and time requirements for this modification, which is considered to be a minor combustor redesign for a class T2 engine, were estimated in detail in 1969.[17] Requirements for other control methods were determined essentially by proportioning the cost and time expenditures according to the complexity of the method, with respect to the reference case. Requirements for other engine classes were determined by using appropriate scaling factors and by again using the JT8D modifications as reference.

The piston-engine time and cost estimates are based largely on experience to date with emission controls for automobile engines.

Future Engines - Cost estimates also have been developed for incorporation of emission controls in future engines, that is, engines that have not yet been developed. These estimates have been defined only as fractions of total engine cost inasmuch as no reasonable basis is available for estimating the numbers of engines that would be affected.

Emission control in turbine engines that is attained through the use of advanced combustor-design concepts is estimated to represent an increase in total engine cost of 3 to 4 percent. Emission control in piston engines that is achieved by engine-design modifications would not necessarily result in any significant increase in engine cost. If greater control of emissions is required than can be achieved by engine design modifications, however, one or more of the control methods applicable to existing engines will be necessary. The cost of these control methods, which involve the addition of auxiliary devices such as thermal reactors, will be significant, probably in the range of 5 to 10 percent of total engine cost.

These estimates represent the increased costs of new engines with emission controls installed. It is possible that there may be additional continuing costs for maintenance of the control methods. These maintenance costs would be similar to those for modification of existing engines, which were estimated to represent 2 to 25 percent of total turbine-engine costs and 10 to 65 percent of total piston-engine costs.

EMISSION CONTROL BY MODIFICATION OF GROUND OPERATIONS

Definition of Ground Operations

The cycle of operations performed by an aircraft during its arrival at and departure from an airport can be defined quite precisely because most of these operations

are prescribed by airport or aircraft operating procedures. Characteristic operating or LTO (landing-takeoff) cycles have been defined for various classes of aircraft for purposes of estimating pollutant emissions.

The LTO cycle can be separated logically into flight and ground operations. Flight operations include the approach and climb-out modes as well as the landing and takeoff runs, even though the latter occur on the ground. Ground operations include the taxi and idle modes of the cycle. This separation is logical for two reasons. First, flight operations as defined here are those that cannot readily be modified in order to attempt to reduce pollutant emissions. Second, flight operations are conducted almost entirely with aircraft engines at full or part power, and, under these conditions, pollutant emission rates are quite different from those at the low power levels that are characteristic of ground operations. Aircraft ground operations contribute substantially to the concentrations of CO and THC that exist at air-carrier airports because of the relatively high emission rates of these pollutants at low engine power levels, and because ground operations are largely confined to limited areas within the airport boundaries.

Emission Control Methods

Seven methods have been identified that offer some degree of control of CO and THC emissions at air-carrier airports by modification of ground-operation procedures.

1. Increase engine speed during idle and taxi operations.

2. Increase engine speed and reduce number of engines operating during idle and taxi.

3. Reduce idle operating time by controlling departure times from gates.

4. Reduce taxi operating time by transporting passengers to aircraft.

5. Reduce taxi operating time by towing aircraft between runway and gate.

6. Reduce operating time of aircraft auxiliary power supply by providing ground-based power supply.

7. Manually remove fuel from fuel drainage reservoirs.

The first two methods reduce emissions by requiring that engines be operated at more efficient power settings, and the next four methods reduce emissions by reducing operating time of either main or auxiliary engines. The effectiveness of these methods in reducing emissions varies considerably. Table 24 summarizes the reductions in CO and THC emissions that would result at Los Angeles International Airport from the seven suggested ground-operation changes.

Table 24. COMPARATIVE REDUCTIONS RESULTING FROM CONTROL METHODS APPLIED AT LOS ANGELES INTERNATIONAL AIRPORT

Control method	Resultant emissions, % of uncontrolled emissions	
	CO	Hydrocarbons
1. Increase engine idle speed	71	93
2. Increase idle speed and use minimal engines for taxi		
Two engines	53	66
Single engine	39	51
3. Eliminate delays at gate and runway	90	91
4. Transport passengers between terminal and aircraft	100	100
5. Tow aircraft to avoid taxi emissions	34	42
6. Avoid use of aircraft auxiliary power units (APU)	99.5	98.5
7. Control emptying of fuel drainage reservoirs	100	98.4

The control methods listed above are not, with the possible exception of number 3, applicable to small, piston-engine aircraft, and, therefore, do not seem to offer means for controlling emissions at general aviation airports. Delay times at take-off are significant at some general aviation airports; however, aircraft ground traffic at general aviation airports may not be sufficiently controlled for a system of controlled gate departures or engine start-up to be effective in reducing delays. On the other hand, one operational technique that might be very effective in reducing CO and THC emissions from light aircraft during idle and taxi modes is the required use of leaner carburetor mixture settings during these modes.

Implementation Cost and Time Requirements

The cost and time requirements of the control methods involving ground-operation modifications have been estimated for one specific airport, Los Angeles International. These estimates involve many uncertainties and, therefore, must be regarded as preliminary. The estimates are considered to be accurate within a factor of 2; that is, the true costs and time for implementation at the airport considered probably are within a range of 50 to 200 percent of the estimates. A summary of the estimates is presented in Table 25. Implementation of these methods at other airports would involve costs of the same magnitude. The actual costs, however, would vary with activity level and the present availability of auxiliary equipment.

Table 25. COSTS AND TIME FOR OPERATIONS CHANGES AT LOS ANGELES INTERNATIONAL AIRPORT

Control method	Time, years	Initial cost, 10^6 dollars	Annual operating cost change,[a] 10^6 dollars
Increase engine speed	0	0	8.5
Increase speed, reduce number	0.3	0	-2.5
Control gate departure	5	15	-1.5
Transport passengers	2.5	65	5.0
Tow aircraft	1	1.2	0.4
Reduce APU operation	0.5	1.3	1.5
Manual drainage	0.5	0.04	3.0

[a]Minus sign indicates an estimated savings.

EMISSION MEASUREMENT TECHNOLOGY

Reliable methods for measuring the rates at which pollutants are emitted from aircraft engines are required for the support of an emission-control program. Emission measurements are required for evaluating the effectiveness of control methods, and specific measurement methods must be incorporated in emission-control standards.

An assessment has been conducted of the state of emission-measurement technology to determine whether measurement techniques are sufficiently well advanced to support the development of emission-control methods and the implementation of emission standards for aircraft engines. The conclusion drawn from this assessment is that current measurement technology will meet the requirements of an emission-control program. Measurement techniques for particulate emissions are inadequate at present but development of improved techniques is being initiated through cooperative government-industry action.

Measurement of emission rates from an aircraft engine involves three major requirements:

1. A test procedure specifying engine operating conditions.

2. A sampling technique for obtaining a representative sample of exhaust gas.

3. Analytical instrumentation for determining pollutant concentrations in the exhaust-gas sample.

Aircraft engine manufacturers and certain government agencies have devoted substantial effort toward providing for these requirements for measuring emissions from turbine engines.

Sampling and Test Procedures

Obtaining a representative sample of exhaust gas from an aircraft engine for analysis of emission rates is not a trivial procedure. Sampling emissions from turbine engines is difficult at the outset because of the jet-blast environment in which the sampling equipment must be installed. Beyond that problem, the following factors are all found to have significant effects on the composition of the exhaust sample:

1. Engine power level.
2. Temporal and spatial variations in exhaust composition.
3. Sampling-line diameter, length, material, and temperature.
4. Ambient temperature and humidity.
5. Ambient pollutant levels.

Procedures for sampling and analyzing turbine-engine exhaust gases have been under development for several years by engine manufacturers and various government agencies. More recently, the Society of Automotive Engineers E-31 Committee has been formed to standardize these procedures. Standardization of measurement techniques will minimize the variations resulting from the factors listed above; however, the sources of error in collecting exhaust samples and the variability of samples among different engines must be considered in the establishment of any emission-control standards.

Sampling requirements for aircraft piston engines can be expected to be similar to those for automobile engines. There are no apparent factors that would cause variability in exhaust samples beyond those factors already recognized as affecting automobile exhaust samples.

Emission Measurement Instrumentation

Measuring the concentrations of most gaseous pollutants in exhaust samples from aircraft engines is generally within the capabilities of existing instruments, and should remain so even when engines are modified to reduce emission rates.

The various types of instruments that are available and in current use for aircraft emission measurement have been reviewed. Instruments that appear to be most suitable for measuring turbine-engine emissions at the present time are presented in Table 26.

Table 26. INSTRUMENTATION FOR MEASUREMENT OF TURBINE ENGINE EMISSIONS

Measurement method	Pollutant class
Non-dispersive infrared (NDIR)	CO and CO_2
Heated flame ionization	THC
Chemiluminescence	NO
Chemiluminescence[a]	NO_2
SAE smokemeter (ARP1179)	Smoke
None	Particulates
Determined from fuel analysis	SO_2
3-MBTH	Aldehydes
Human odor panel	Odor

[a]The non-dispersive ultraviolet instrument (NDUV) may also prove acceptable for NO_2 measurement.

REFERENCES

1. Northern Research and Engineering Corporation. The Potential Impact of Aircraft Emissions Upon Air Quality. Final Report to the U.S. Environmental Protection Agency. Research Triangle Park, North Carolina. Contract Number 68-02-0085. December 1971.

2. Northern Research and Engineering Corporation. Assessment of Aircraft Emission Control Technology. Final Report to the U.S. Environmental Protection Agency. Research Triangle Park, N.C. Contract Number 68-04-0011. September 1971.

3. Nature and Control of Aircraft Engine Exhaust Emissions. Report of the Secretary of Health, Education, and Welfare to the United States Congress. December 1968.

4. Aviation Effects on Air Quality. Bay Area Pollution Control District, San Francisco, California. February 1971.

5. Jet Aircraft Emissions and Air Quality in the Vicinity of the Los Angeles International Airport. Air Pollution Control District, County of Los Angeles, California. April 1971.

6. Aircraft and the Environment. Proceedings of SAE/DOT Conference. February 8-10, 1971. Washington, D.C.

7. Nationwide Emission Trends: 1940-1970. U.S. Environmental Protection Agency. Research Triangle Park, N.C. (Scheduled to be published in June 1972.)

8. National Primary and Secondary Ambient Air Quality Standards. Environmental Protection Agency. Federal Register 36(84):8187, April 30, 1971.

9. Air Quality Criteria for Hydrocarbons. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration. Publication No. AP-64. Washington, D.C. March 1970. p. 8-5.

10. Airborne Lead in Perspective. Committee on Biological Effects of Atmospheric Pollutants. Division of Medical Sciences, National Research Council, National Academy of Sciences. Washington, D.C. 1971.

11. Hanna, Steven R. A Simple Method of Calculating Dispersion for Urban Areas. J.A.P.C.A., 21(12):774-777. December 1971.

12. Northern Research and Engineering Corporation. Nature and Control of Aircraft Engine Exhaust Emissions. Final Report to the National Air Pollution Control Administration. Durham, N.C. Contract Number CPA 222-68-27. November 1968.

13. Aerospace Industries Association. A Study of Aircraft Gas Turbine Engine Exhaust-Emissions. Washington, D.C. August 1971.

14. Dibelius, N.R., M.B. Hilt, and R.H. Johnson. Reduction of Nitrogen Oxides from Gas Turbines by Steam Injection. ASME Paper 71-67-58, American Society of Mechanical Engineers.

15. Fletcher, Ronald S., Richard D. Siegel, and E. Karl Bastress. Northern Research and Engineering Corporation. Report Number 1162-1, Design Criteria for Control of Nitrogen Oxide Emissions from Aircraft Turbine Engines.

16. Scott Research Laboratories, Inc. A Study of Exhaust Emissions from Reciprocating Aircraft Power Plants. Scott Project Number 1136. Final Report to the U.S. Environmental Protection Agency. Research Triangle Park, N.C. Contract Number CPA 22-69-129. December 1970.

17. Northern Research and Engineering Corporation. Time Requirements for Retrofitting Jet Aircraft with Improved Combustor Design. Final Report to National Air Pollution Control Administration, Durham, N.C. Contract Number CPA 22-69-90. July 1969.